DC – DC CONVERTER FOR WIDE OUTPUT VOLTAGE RANGE BATTERY CHARGING APPLICATIONS USING LLC RESONANT

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Abstract

The aim of this paper is to maximize the battery life using LLC resonant tank. Resonant tank design methodology and practical design examination are introduced for LLC multiresonant converter. The designed LLC multiresonant dc dc converter increases the battery life by eliminating low and high frequency current ripples. In addition, bridgeless cuk converter is used for power factor improvement. To attain unity power factor and to reduce the conduction losses the cuk converter is aimed to function in Discontinuous conduction mode (DCM). The dc output voltage of 42-24 V for 650 W is obtained from the modelling.
KEYWORDS: Discontinuous conduction mode (DCM), LLC multiresonant converter, Bridgeless cuk converter

1. Introduction

Rechargeable battery supplies power to electric motor to drive electric vehicle [1],[2]. Currently, the standard battery systems storage capability demand is increased. Even though battery technology is improved, the system requires high current and high voltage to charge these batteries. Nowadays the smart charger battery charging methodology becomes very difficult due to the advancement in charging algorithms [3]. A smart charger with low distortion is required because of increased disturbances in quick charging of excessive potential of battery packs. The proposed architecture block includes a bridgeless cuk converter, followed by a resonant converter as shown in Fig. 1 which eliminates the low and high frequency current ripple charging battery using a high frequency transformer.

Figure 1. Block Diagram of Proposed converter

In this proposed work the first section deals with the operation of bridgeless cuk converter in discontinuous conduction mode (DCM) topology. The criterion for selecting discontinuous conduction mode topology includes natural protection against overload current, easy implementation of transformer isolation and less electromagnetic interference. Second section tells about dc-dc converter is a half – bridge multiresonant LLC converter. The condition for selecting these topologies includes high reliability, low component cost and high efficiency. However, the wide output range specifications for a battery charger are extremely different and challenging compared to telecom
applications, which operates in a narrow output voltage. DC-DC converter battery output voltage varies from 36 V to 72 V. therefore the design specifications for choosing the bridgeless cuk converter and resonant tank components are non-identical of those for telecom application with continuous voltage. To achieve high switching frequency and higher efficiency resonant tank is modeled to operate over a wide input voltage. Both zero voltage and zero current switching are achievable over the entire operating range. A new model of an LLC resonant converter is required to meet these specifications.

Chapter 2 tells about the working of bridgeless cuk converter. Chapter 3 follows the design of cuk converter and multiresonant LLC converter. Chapter 4 gives the simulation results. Chapter 5 shows the hardware results. Chapter 6 gives the conclusion.

2. Bridgeless Cuk Converter

2.1 Operation of Bridgeless CUK Converter

The bridgeless CUK is shown in fig 2.

![Bridgeless CUK converter](image)

Figure 2: Bridgeless CUK converter

The operation of converter is explained below. To attain PFC the inductor output current inductor \( i_{L1} \) and \( i_{L2} \) remains discontinuous while the input inductor current (\( i_{L1} \) and \( i_{L2} \)) and the voltage across intermediate capacitors remains continuous.
Fig. 3a and b show the working principle of the converter for a positive and negative half cycles of the AC supply. During the positive half cycle of the supply voltage $V_{ac}$, switch S1 is in conduction through $i_{L1}$ and $Dp$. The capacitor $C1$ transfers energy through $Lo1$ and $D01$. Similarly, for negative half cycle of supply voltage, switch S2 is conducting through $iL2$ and $Dn$. Different modes of operation of cuk converter during positive half cycle is given below:

**Mode I:** When switch S1 is turned on, the input inductor stores energy via diode $Dp$, hence the inductor current $i_{L1}$ increases. The stored energy stored in intermediate capacitor $C1$ is discharged to the DC-link capacitor $C0$ and the output inductor $Lo1$. Therefore the current $i_{Lo1}$ and DC-link voltage $V_{dc}$ are increased and the voltage across the intermediate capacitor $V_C1$ reduces in this mode of operation.

**Mode II:** When switch S1 is turned off, the inductor $i_{L1}$ discharges through intermediate capacitor $C1$ via diode $D1$ and $Dp$. Moreover, inductor $Lo1$ also transfers its stored energy to DC-link capacitor $C0$. Hence, in this mode of operation, the current in inductors $iL1$ and $iLo1$ starts to decrease while the voltage across DC-link capacitor $C0$ and intermediate capacitor $C1$ increases.

**Mode III:** In this mode, the output inductor energy $Lo1$, that is, $iLo1 = 0$. The voltage across intermediate capacitor $C1$ and current in input inductor $iL1$ increases, while the DC-link capacitor $C0$ supplies the required energy to the load, hence $V_{dc}$ reduces in this mode of operation. This operation continues till the switch S1 is again turned ‘on’. The operation of negative half cycle is explained in a similar manner.
3. Design of Converter

3.1 Design of bridgeless cuk converter

The design of the converter is framed under certain mathematical presumption. The operation of a DCM is acquired under the following condition

\[ Ke < Ke_{crit} = \frac{1}{2(M + \sin(oat))^2} \]  

(3.1)

where, \( Ke \) is a dimensionless conduction parameter and is given by:

\[ Ke = \frac{2Le}{R_L T_S} \]  

(3.2)

Based on DCM topology the values of parasitic components are designed such that \( Ke < Ke_{crit-min} \) and those maximum and minimum values of \( Ke_{crit} \) are given below:

\[ Ke_{crit-min} = \frac{1}{2(M+1)^2} \]  

and \[ Ke_{crit-min} = \frac{1}{2(M)^2} \]  

(3.3)

\[ \Delta i_{L1} < 10\% I_{L1} \text{ and } \Delta V_{c1} < 5\% \quad , \quad \Delta I_{L1} = \frac{D(E)}{F_{S,L1}} \]  

(3.4), (3.5)

\[ \Delta I_{L2} = \frac{(1-D)Vo}{F_{S,L2}} \]  

(3.6)

\[ \Delta VC1 = \frac{D V_d I_d}{V_c F_S} \]  

(3.7)

From the equations (3.5), (3.6), (3.7) the values of inductances and capacitances are given by:

\[ L_1 = L_2 = 300mH, \quad L_{01} = L_{02} = 1mH, \quad C_1 = C_2 = 2200\mu F, \quad C_{out} = 2200\mu F. \]
The PFC converter DC link voltage is given below:

\[ V_o = V_{ac} \frac{D}{1-D} \]  

(3.8)

\( V_{ac} \) is the diode bridge rectifier output for a given AC input voltage (\( V_s \)).

\( V_{ac} \) and \( V_s \) are related as:

\[ V_{ac} = 2\sqrt{2} \frac{V_s}{\pi} \]  

(3.9)

### 3.2 Design of Resonant Converter

#### 3.2.1 Initial Design Parameters

The parameter required to design the converter are to be specified. The parameters like input voltage range, maximum output power, output voltage range and resonant frequency are to be cited. At DC link capacitor using PFC bus the dc-dc input voltage is determined. The dc-dc output voltage range will vary from 24 to 43 V. The existing output voltage 43 V is described for the maximum power of 650 W.

#### 3.2.2 Maximum Switching Frequency, Maximum Dead Time

The voltage controlled oscillator and the junction capacitance of the output rectifier limits the value of maximum switching frequency. The ac equivalent circuit of the LLC resonant converter including parasitic components is shown in Figure.4. By adding rectifier diode junction capacitance desired dc gain equation is altered. By increasing the switching frequency the output voltage is decreased until the diode capacitance resonant with the circuit. After resonant if we increase the switching frequency the output voltage also increases. At resonant frequency the diode rectifier junction capacitance and parasitic element causes a drastic change in the output voltage. This can be controlled by limiting the maximum switching frequency of the
converter. Thus the maximum switching frequency is limited to 2–2.5 times of the resonant frequency.

![AC equivalent circuit of LLC resonant converter including parasitic components](image)

**3.2.3 Selecting Transformer Turns Ratio, \( N_n \)**

At unity gain, the transformer turns ratio for the resonant frequency is selected and it is calculated using Equation 3.10, where \( V_d \) denotes the diode output voltage drop of the rectifier

\[
N_n = \frac{Vin(den)}{2(Vo(min) + Vd)} \quad (3.10)
\]

**3.2.4 Calculating Resonant Inductor, \( L_r \)**

The minimum inductance is given by Equation 3.11

\[
L_r(\text{scc}) = \frac{N_n.Vin(\text{nom}).Vo(\text{nom})}{8.f_s_{\text{max}}.Po} \quad (3.11)
\]

**3.2.5 Calculating Resonant Capacitor, \( C_r \)**

Once the value of the resonant inductor is determined, the resonant capacitor value can be calculated using Equation 3.12
3.2.7 Calculating Magnetizing Inductance, $L_m$:

The maximum magnetizing inductance, $L_{m(ZVS)}$, is required as given by Equation 3.16. The maximum gain at the minimum switching frequency as noted $L_{m(max)}$ is given by Equation 3.17

$$L_{m(ZVS)} = \frac{t_{dead}N_nV_o(min)}{C_{HB}V_{in(max)}} \left(\frac{1}{f_{s_{max}}} \cdot \frac{t_{dead}}{2}\right)$$

(3.16)

$$L_{m(max)} = L_{r(scc)} \frac{\pi^2}{4} \frac{f_o}{f_{s_{min}}} \frac{1}{1 - M_{dc_{max}}}$$

(3.17)

Finally, the total inductance value must satisfy the energy balance in the total capacitance of the half-bridge, using Equations 3.18 and 3.19

$$\frac{1}{2} \left(L_{m(min)} + L_{r(scc)}\right)I_{m-pk}^2 \geq \frac{1}{2} C_{HB} V_{in(max)}^2$$

(3.18)

$$I_{m-pk} = \frac{N_nV_o(min)T_o}{4L_m}$$

(3.19)
4. Simulation Results

4.1 Matlab Simulation Circuit

In Figure 5 it shows the complete Matlab Simulation circuit of Proposed Converter

4.1.1 Battery Output Voltage and current waveforms:

Figure 6 Battery Output Voltage \( V_o = 42\text{V} \) and Output current \( I_o = 16\text{A} \) and SOC\% = 50\%
The above Figure 6 shows the battery charging characteristics. The battery state of charge is 50% and the battery charges with output voltage of 42 V and current of 16 A.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>152 kHz</td>
<td>42 V</td>
<td>16 A</td>
<td>672 W</td>
</tr>
<tr>
<td>211 kHz</td>
<td>32 V</td>
<td>13 A</td>
<td>416 W</td>
</tr>
<tr>
<td>250 kHz</td>
<td>24 V</td>
<td>10 A</td>
<td>240 W</td>
</tr>
</tbody>
</table>

Table 1.1 Simulation Results of proposed converter

5. Hardware Results

5.1 Hardware of Prototype Converter

The above Figure 7 shows the prototype of proposed converter which consists of Bridgeless CUK converter, LLC Resonant converter, Pulse generating circuit.
The above Figure 8 shows the Output of proposed converter at load side of Magnitude 6V. The output is ripple free DC voltage.

### Comparison of Conventional and Proposed Converter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conventional</th>
<th>Proposed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power factor</td>
<td>0.96</td>
<td>0.99</td>
</tr>
<tr>
<td>THD of Input current</td>
<td>46.27%</td>
<td>4.07%</td>
</tr>
<tr>
<td>Conduction losses</td>
<td>High</td>
<td>Less</td>
</tr>
</tbody>
</table>

Table 1.2 Comparison of Conventional and Proposed Converter

### 6. Conclusion

To increase the battery life the wide output voltage range LLC multiresonant tank design methodology and practical design examination are conferred. By using LLC multiresonant dc dc converter low and high frequency current ripples are eliminated for
electric vehicles. To attain unity power factor Bridgeless CUK converter is employed and power factor is improved by 0.99. The dc output voltage of 42-24 V for 672 W is obtained from the modelling.

References


