Keywords
Soft switching, Resonant converters, ZVS converters, Power semiconductor devices, Battery charger

Introduction
A quasi-resonant DC link converter earlier proposed in the literature is investigated. Design expressions for selection of the passive component values are derived. The design expressions are derived to limit the output voltage time derivative and the duration of the zero voltage interval. Also one of the resonant link currents is limited to a certain level by application of the design expressions. The quasi-resonant DC link converter is implemented and tested in a battery charger application. The efficiency is simulated and measured.

Passive component values
The battery charger is rated according to the table below

<table>
<thead>
<tr>
<th>Power</th>
<th>( P_n )</th>
<th>10 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage</td>
<td>( U_{line-line} )</td>
<td>400 V, 50 Hz</td>
</tr>
<tr>
<td>Charging current</td>
<td>( I_c )</td>
<td>26.7 A</td>
</tr>
<tr>
<td>Filter inductors</td>
<td>( L_{line/L_{batt}} )</td>
<td>15 mH</td>
</tr>
<tr>
<td>DC link capacitor</td>
<td>( C_{dc} )</td>
<td>2.2 mF</td>
</tr>
<tr>
<td>DC link voltage</td>
<td>( V_{dc} )</td>
<td>750 V</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>( f_{sw} )</td>
<td>4.95 kHz</td>
</tr>
</tbody>
</table>

Design expressions:

\[
L_3 = \frac{2}{\omega_1} \frac{V_{dc}}{(I_{o2} - I_{o3})_{max}} \left[ \arccos(-\alpha) - \sqrt{1 - \alpha^2} \right] + \frac{V_{dc} t_{zero,max}}{(I_{o2} - I_{o3})_{max}}
\]

\[
\left. \frac{dv}{dt} \right|_{max} = \omega V_{dc} \sqrt{A^2 + B^2}
\]

\[
i_{2,max} = \frac{V_{dc}}{\omega_1 L_j (1 + \alpha)} \left[ \arccos(-\alpha) + \sqrt{1 - \alpha^2} \right] (1 + \alpha)
\]

where

\[
\alpha = \frac{L_2}{L_j}, \quad \omega_1 = \frac{L_1 L_2 C}{L_j + L_2}
\]

\[
A = \frac{\alpha}{1 + \alpha}
\]

\[
B = \frac{4 \alpha}{(1 + \alpha)^2} \arccos(-\alpha) \left[ \frac{3 \alpha - 1}{(1 + \alpha)^2} \sqrt{1 - \alpha^2} + \frac{2 \alpha}{1 + \alpha} \right] t_{zero,max}
\]

The simulated IGBT switching waveforms for the resonant link IGBT \( S_1 \) and the upper IGBT of the battery side converter are shown below.

Simulation
The battery charger is simulated at rated conditions. The resonant link waveforms at turn-on and turn-off of the upper transistor of the battery side converter are shown in the figure below.

Loss-less turn-off is not achieved for the IGBTs, due to the tail current bump observed. The tail current bump is a consequence of the presence of stored minority carriers in the IGBT drift region prior to turn-off.
Implementation
The quasi-resonant DC link battery charger is implemented to verify the design expressions and to measure the efficiency. The most demanding devices from a design point of view are the ones located in the clamp circuit, i.e. the clamp transformer \( L_1/L_3 \) and the diode \( D_3 \).

The main issue for \( D_3 \) is that the ideal blocking voltage the diode has to sustain is given by \((1+(L_3/L_1)^{1/2})V_{dc} = 4500 \text{ V}\). Therefore, six diodes are connected in series. Since the reverse characteristics of the diodes are not identical, a voltage-dividing network is needed, see figure below.

\[ \text{The six series connected diodes forming the clamp circuit diode } D_3, \text{ together with the voltage dividing-network.} \]

The parallel resistors, \( R_p \), are needed for stationary blocking conditions due to the possibility of unequal reverse leakage current. The parallel capacitors, \( C_p \), are needed due to differences between the diodes by means of reverse recovery time. The series resistors, \( R_s \), only serves to dampen oscillations between the parallel capacitors and the circuit stray inductance.

For the clamp transformer there are two contradicting demands.

- The leakage inductance must be low to reduce over-voltage at the start of the clamping interval. This implies that the conductors should be wound tight to each other.
- Without taking the effect of stray inductance into account, the maximum secondary voltage is \((L_3/L_1)^{1/2}V_{dc} = 3750 \text{ V}\). The potential risk of partial discharge has to be considered for proper selection of insulation material.

To fulfill the requirements above the clamp transformer is manufactured as follows:

- A band conductor is used for the primary. The secondary is wound with five parallel conductors.
- The distance between the primary and secondary windings are kept as short as possible, to give a low leakage inductance.
- To reduce the risk of partial discharges, an insulating layer of mica bond is inserted between the conductors of each turn and also between the primary and secondary windings.

Laboratory setup

The laboratory setup for the quasi-resonant battery charger.

Measurements

The figure below shows typical resonant link waveforms and filter currents for battery charging at rated current.

\[ \text{Measured waveforms. Left: Quasi-resonant DC link and right: filter currents.} \]

The battery charger efficiencies are listed in the table below. The used semiconductor simulation models are behavioral, for example, the IGBT collector current tail bump is not modeled.

<table>
<thead>
<tr>
<th>Battery Charger</th>
<th>Without filter losses</th>
<th>Including filter losses</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( P_i [\text{W}] )</td>
<td>( P_o [\text{W}] )</td>
</tr>
<tr>
<td>Hard switched</td>
<td>Simulated</td>
<td>5878</td>
</tr>
<tr>
<td></td>
<td>Measured</td>
<td>5765</td>
</tr>
<tr>
<td>Quasi-resonant</td>
<td>Simulated</td>
<td>6025</td>
</tr>
<tr>
<td></td>
<td>Measured</td>
<td>5955</td>
</tr>
</tbody>
</table>

Some results from the measurements on the battery charger:

- The converter efficiency is 94.0% and the total efficiency for battery charging at rated power is 89.9% in the quasi-resonant case. In the hard switched case the corresponding efficiencies are 96.8% and 92.9%.
- The switching instants are delayed a varying time in the quasi-resonant case. As a consequence, low order harmonics appear in the filter currents.
- The output voltage time derivative is limited to 1000 V/\( \mu \text{s} \).