Design and implementation of a LLC-ZCS Converter for Hybrid/Electric Vehicles

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Need for clean

Hybrid and Full Electric vehicles allow pollution reduction ⇒ this make them the new generation of transportation.

Traction and power distribution networks are highly impacted by this evolution. HV battery in hybrid/electric vehicles allow traction as well as services to run out of the battery for a medium/long time.
System Specification

Power distribution network: exploiting the energy of a HV battery for traction and services

› While the traction inverter is directly supplied by the HV battery, all services in a car today still run out of a 12V battery, therefore a HV-DC/DC converter is needed to supply this battery line

System has been designed considering these ranges

<table>
<thead>
<tr>
<th>Variable</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input HVB [V]</td>
<td>250</td>
<td>350</td>
<td>450</td>
</tr>
<tr>
<td>Output LVB [V]</td>
<td></td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Load power [W]</td>
<td>400</td>
<td></td>
<td>2400</td>
</tr>
</tbody>
</table>
System design: converter topology choice

1. Galvanic isolated topology
2. Soft switching

- Behaves as current generator \(\rightarrow\) intrinsically protected @ short circuit at the output.
- ZCS has the advantages of using IGBT with co-packed fast diode;
- Simplified output filtering uses only capacitors;
- No need to control the DC current through transformer, resonance Cap solves it.
System design: control strategy

- **AUIRS2191S**
  - Fast HVIC driver
  - SO16

- **IRS27951S**
  - SO8 analog controller
  - Grounded in the HV side

- **AUIRS1170S**
  - Synch. Rect.
  - PS08 analog controller

- **Analog Controller**
  - Cr voltage sense

- **Error Amplifier**
  - Vref

- **HV caps protection loop**

- **Inner Loop**
  - Voltage Control Loop

- **Primary High Voltage Side**
  - Secondary Low Voltage Side

- **Error amplifier and OV protection**
  - Grounded on the LV side

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LLC DC/DC board, prototype picture
Board Layout

- Resonant Inductor at primary side
- Resonant Capacitor tank
- Primary side IGBTs
- Primary side gate drivers
- Transformer Center-tapped output
- Output Capacitors
- Synchronous rectification Fets and control IC
- Loop control board

Layout is optimised for system testing and debugging.
### System design: main BOM components

<table>
<thead>
<tr>
<th>Component</th>
<th>Details</th>
</tr>
</thead>
</table>
| **Output Filter**                | • It is made with only Organic Conductive Polymer capacitor, 4mF in total → no need for output inductor  
• System volume and cost are reduced  
• SR MOSFET voltage rating = 60V-80V → higher power density and cheaper system |
| **Magnetics and Resonant Tank** | • Resonant inductor at primary side reduces size and weight; resonant capacitors also take care of balancing the magnetizing current |
| **Mathlab routine**              | • Resonant inductor and capacitor values have been optimized vs. load and input voltage variation |
| **Transformer**                  | • Magnetizing inductance $L_m = \text{about 6 times resonant inductor value}$  
• Transformer ratio is 16:1+1; $I_{sec} = 170\text{Arms}$  
• Variable frequency from 60kHz to 125kHz |
| **Resonant inductor**            | $L_r = 128\mu\text{H}$  
$\text{Irms} \approx 15\text{A}$  
• System Resonant freq.: 125kHz |
| **Resonant Capacitor**           | $C_r = 12.6\text{nF}$  
$3\text{kV}$  
• C0G (low ESR) |
| **Synchronous rectification Fets** | $R_{ds-on} = 2.4\text{m}/\text{max}, 80\text{V}$  
3x each leg in parallel |
| **Primary switching section**    | $650\text{V} - 40\text{A IGBTs}$  
$V_{ce\_sat} = 1.80\text{V @125C}$ |
Simulation results

Transfer Function: switching from 70kHz to 120kHz at Vin=350V

Simulation at Vin = 350V, Vout = 12V and different power output
Measurements: Operating Frequency vs Input Voltage and load

Fsw vs Vin at Io=100A

Fsw vs Io at Vin=350V

Low switching frequency variation vs. input voltage and load changes
Good matching with simulation
Operation at nominal input voltage: 400V – 100A

Clean sinusoidal voltage across resonance capacitors, some ringing noise visible on transformer’s secondary current.
Operation at nominal input voltage: 400V – 150A

Frequency, capacitors voltage and Primary/Secondary currents increase
Operational waveforms at 400V - 180A

Very close to resonance (~110kHz), waveforms are almost sinusoidal.
Secondary side synchronous rectification

- In a LLC converter the secondary current and primary switching voltage are not in phase and their phase rotation depends on the load, this effect doesn’t allow to use the primary PWM signal to control the secondary side switches.

- A dedicated IC reading the VDS voltage across the Synch Rectification Fets solves this problem

AUIRS1170S

Typical application schematic
Secondary side waveforms at 400V and light load

Waveform obtained at low current output of 30A only: the signal across the 0.8mΩ equivalent Rds-on of the Fets becomes quite small but the gate command signal is regular.
Secondary side waveforms at 400V and high load

Waveform obtained at high current output of 160A: the signal across the 0.8m Ω SR Fets is much more evident as well as switching noise but the gate command signal is regular.
Power Losses Breakdown (350Vin)

Estimation done though thermal measurement and mathematical extrapolations

- Primary side losses look still predominant and increase proportionally with the output current;
- High Vcesat of IGBTs still impact this performances;
- Inductor losses seems to be increasing rapidly with output current, showing undersizing of the component, redesign is advisable;
- Resonant and output Capacitor losses have low impact in the overall efficiency.
• Efficiency at light load is high, thanks to the low frequency operation of the input bridge;
• High $V_{cesat}$ of IGBTs and inductor losses impact overall system performances;
• At $I_{out}=150\,\text{A}$, only $1\,\text{m}\Omega$ pcb trace resistance in the secondary side means 23W dissipated and 1.3% efficiency loss.
Start up and Vin transients

Fast start: Vin rise time is only limited by the Lab power supply
Vin=400V, Io=25A
Experimental results: load transient

Low ESR output caps provide very low output voltage variation at load transients
Load transients: $I_{out}$ from 70 to 140A

Load increase to 140A (traces 2 and 3 with AC coupling)
Load transients: I_{out} from 140 to 70A

Load decrease to 70A (traces 2 and 3 with AC coupling)
Conclusions

1. An Auxiliary DC-DC converter has been designed by using the uncommon LLC ZCS topology

2. System design flow with mathematical and electrical models have been utilized to tune the resonant tank and converter frequency operation range

3. Prototype has been built and verified

4. System efficiency over 90%, limited by high Vce_sat of IGBTs and inductor losses

5. Robustness to load transients has been verified

6. Prototype Max power is limited to around 2.0kW with air forced cooling, because of PCB and heat sinks limitations.