Leveraging efficiency in automotive on-board chargers

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Agenda

1. Introduction
2. Single-phase chargers
3. Three-phase chargers
4. Case study and conclusion
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1. Introduction
2. Single-phase chargers
3. Three-phase chargers
4. Case study and conclusion
System requirements

- Bi-directional charging?
- Vehicle-to-load?
- Vehicle-to-Vehicle?
- Vehicle-to-Grid?
- AC charging?
- DC charging?
- 1 Phase AC?
- 3 Phase AC?
- Battery voltages 400 V or 800 V?
- Size?
- Efficiency?
- Power class?
- Costs?
- Isolation requirements?
- Reliability?

The system has to cover many different requirements
Typical OBCs are composed of a PFC block and an isolated DCDC block.

- PFC block typically uses CCM (hard commutation).
- DCDC block (primary) typically uses CCM.
- DCDC block (secondary) typically uses ZVS (soft switching).
- HV Battery
Various topologies and semiconductor combinations possible

Final implementation depends on required functionality
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Classic-boost PFC

Grid \rightarrow Filter \rightarrow PFC \rightarrow DCDC (primary) \rightarrow DCDC (secondary) \rightarrow Filter \rightarrow HV Battery

<table>
<thead>
<tr>
<th>IGBT + PN D</th>
<th>IGBT + SiC D</th>
<th>CoolMOS™ + SiC D</th>
</tr>
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<tbody>
<tr>
<td>97.9%</td>
<td>98.3%</td>
<td>98.4% (3pin)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>98.5% (4pin)</td>
</tr>
<tr>
<td>1x PN diode</td>
<td>1x 650 V SiC diode</td>
<td>1x 650 V SiC diode</td>
</tr>
<tr>
<td>1x 650V IGBT with diode</td>
<td>1x 650 V IGBT with diode</td>
<td>1x 650 V CoolMOS™</td>
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</table>

efficiency increase

measured on EVAL_2.5KW_CCM_4PIN
Efficiency measurement

Classic Boost CCM PFC 2500W

Measured with eval board: EVAL_2K5W_CCM_4P_V3
Dual-boost (bridgeless) PFC

Grid → Filter → PFC → DCDC (primary) → DCDC (secondary) → Filter → HV Battery

650 V CoolMOS™ + SiC D

98.6%
2x 650 V SiC Diode
4x 650 V CoolMOS™
2x PN diodes

Very high efficiency
increased number of active switches

Measured on EVAL_3KW_DB_PFC_C7 with bypass transistors parallel to diodes
## Totem Pole PFC

**Diagram:**
- Grid → Filter → PFC → DCDC (primary) → DCDC (secondary) → Filter → HV Battery

### Comparison Table

<table>
<thead>
<tr>
<th>Half-bridge IGBT</th>
<th>Full-bridge IGBT</th>
<th>IGBT and CoolMOS™</th>
</tr>
</thead>
<tbody>
<tr>
<td>98.7%</td>
<td>98.7%</td>
<td>98.8%</td>
</tr>
<tr>
<td>2x PN Diode</td>
<td>4x 650 V IGBT with diode</td>
<td>2x IGBT with diode 2x 650 V CoolMOS™ *)</td>
</tr>
<tr>
<td>2x 650 V IGBT with diode</td>
<td></td>
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</tr>
</tbody>
</table>

*) as long as hard commutation on the body diode is avoided

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**efficiency increase**
TCM PFC (soft-switching)

Grid → Filter → PFC → DCDC (primary) → DCDC (secondary) → Filter → HV Battery

- **650 V CoolMOS™ + SiC D**
  - 99.1%
  - > 4x 650 V CoolMOS™

- **Highest performance with Silicon devices**
- **High control complexity**
- **Interleaving required**

Measured on TCM_PFC
**DCDC (soft-switching)**

Grid → **Filter** → **PFC** → **DCDC** (primary) → **DCDC** (secondary) → **Filter** → HV Battery

<table>
<thead>
<tr>
<th>Phase-shifted full-bridge</th>
<th>Full-bridge LLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>98.1%</td>
<td>98.5%</td>
</tr>
<tr>
<td>4x 65 0V CoolMOS™</td>
<td>4x 650 V CoolMOS™</td>
</tr>
<tr>
<td>2x PN diodes (with ctr-tap)</td>
<td>2x PN diodes (with ctr-tap)</td>
</tr>
</tbody>
</table>

*efficiency increase*
DCDC (soft-switching)

Phase-shifted full-bridge
- Efficiency: 98.1%
- Components: 8x 650 V CoolMOS™

Full-bridge cLLC
- Efficiency: ~98.3%
- Components: 8x 650 V CoolMOS™

Diagram and circuit diagrams showing the flow from grid to HV battery with the specified components and efficiencies.
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</table>
Stacked PFC

Stacked classic boost

- 12x PN Diodes
- 3x 650 V SiC diode
- 3x 650V CoolMOS™

Alternatively:
- 3x 650 V IGBT

IGBT + SiC D

- 12x 650 V IGBT

Alternatively:
- 6x 650 V IGBT
- 6x 650 V CoolMOS™

efficiency increase
PFC with higher DC-link

Grid → Filter → PFC → DCDC (primary) → DCDC (secondary) → Filter → HV Battery

<table>
<thead>
<tr>
<th>3ph full-bridge PFC</th>
<th>3ph full-bridge PFC + N</th>
<th>Vienna Rectifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>6x 1200 V SiC MOSFET</td>
<td>8x 1200 V SiC MOSFET</td>
<td>6x 650 V IGBT or CoolMOS™</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6x 1200 V SiC Diode</td>
</tr>
</tbody>
</table>

- 6x 1200 V SiC MOSFET
- 8x 1200 V SiC MOSFET
- 6x 650 V IGBT or CoolMOS™
- 6x 1200 V SiC Diode
DCDC for 3ph OBCs

Single-stage

PSFB:

CLLC:

8x 1200 V SiC MOSFET

Stacked DCDC

Stacked CLLC with split DC-link:

16x 650 V CoolMOS™
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Case study: OBC efficiency today

Today’s OBCs require only moderate efficiency values

<table>
<thead>
<tr>
<th>EV</th>
<th>Charge standard</th>
<th>Charge power</th>
<th>Energy Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>iOn</td>
<td>10 A @ 1 phase</td>
<td>2.3 kW</td>
<td>$\eta_3$ = 77%</td>
</tr>
<tr>
<td>iOn</td>
<td>16 A @ 1 phase</td>
<td>3.7 kW</td>
<td>$\eta_2,E$ = 70%</td>
</tr>
<tr>
<td>LEAF</td>
<td>10 A @ 1 phase</td>
<td>2.3 kW</td>
<td>$\eta_1,E$ = 79%</td>
</tr>
<tr>
<td>LEAF</td>
<td>16 A @ 1 phase</td>
<td>3.7 kW</td>
<td>90%</td>
</tr>
<tr>
<td>Zoe</td>
<td>10 A @ 1 phase</td>
<td>2.3 kW</td>
<td>90%</td>
</tr>
<tr>
<td>Zoe</td>
<td>16 A @ 3 phase</td>
<td>11 kW</td>
<td>64%</td>
</tr>
<tr>
<td>Zoe</td>
<td>32 A @ 3 phase</td>
<td>22 kW</td>
<td>65%</td>
</tr>
<tr>
<td>Zoe</td>
<td>63 A @ 3 phase</td>
<td>43 kW</td>
<td>63%</td>
</tr>
</tbody>
</table>

$\Rightarrow \eta_{OBC\_max} = 95\%$

Highest efficiency in their experiment

Source: Kieldsen, Andreas; Thingvad, Andreas; Martinenas, Sergejus; Sørensen, Thomas Meier, Proceedings of EVS29 - International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, 2016.

Efficiency from typical OBC spec of today
Which combinations do the job?

<table>
<thead>
<tr>
<th>Topology</th>
<th>Technology</th>
<th>( \eta )</th>
<th>Topology</th>
<th>Technology</th>
<th>( \eta )</th>
<th>( \eta_{OBC} )</th>
<th>ok?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classic-boost</td>
<td>IGBT + SiC D</td>
<td>98.3%</td>
<td>PSFB</td>
<td>CoolMOS™</td>
<td>98.1%</td>
<td>96.4%</td>
<td>✓</td>
</tr>
<tr>
<td>Dual-boost</td>
<td>CoolMOS™ + SiC D</td>
<td>98.6%</td>
<td>LLC</td>
<td>CoolMOS™</td>
<td>98.5%</td>
<td>97.1%</td>
<td>✓</td>
</tr>
<tr>
<td>Totem-Pole</td>
<td>IGBT + CoolMOS™</td>
<td>98.8%</td>
<td>LLC</td>
<td>CoolMOS™</td>
<td>98.5%</td>
<td>97.3%</td>
<td>✓</td>
</tr>
</tbody>
</table>

\( \eta_{req} = 95\% \)

Smart topology choices with Silicon power devices do a great job!
Conclusion

Today’s efficiency requirements are achievable with economic device choices.

Stacking of single-phase topologies for 3phase systems allow usage of 650 V devices.

Leverage efficiency by changing the topology (rather than just changing the power device technology).
Backup slides
Manufacturing

Si

Lower manufacturing complexity
Lower costs for base material
20 years+ experience

SiC

Better Figure-of-Merits (for some parameters)
Higher manufacturing complexity
Higher costs for base material