Case Study

Bidirectional Isolated DC/DC Converter with Wide Input Voltage Range for Residential Energy Management Applications

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Motivation

Next generation residential energy management systems

- Renewable energy sources, local storage systems and intelligent load management
- DC distribution bus and single connection point to AC utility grid
- Possible element of a future smart grid system
Challenges

Requirements for DC/DC converters

- High functionality
  - Bidirectional power flow
  - Galvanic isolation
  - Wide voltage range

- High conversion efficiency at low volume and costs
Bidirectional Isolated DC/DC Converter with Wide Input Voltage Range

Universal DC/DC converter
- Meets all requirements at once
  - Bidirectional power flow
  - Galvanic isolation
  - Wide voltage range
  - High efficiency & power density
- Universal building block at low costs
  - Reduced system complexity
  - Development costs only once
  - Economies of scale

Converter specifications
- Rated power $P_r$ 5 kW
- Input voltage range $[U_{DC1,\text{min}}, U_{DC1,\text{max}}]$ [100,700] V
- Output voltage $U_{DC2}$ 750 V
- Maximum input current $I_{DC1,\text{max}}$ 22 A
- Maximum efficiency $\eta_{\text{max}}$ > 98 %
Design Steps

i. Selection of semiconductors & topology

ii. Selection of modulation scheme

iii. Multi-objective modeling and optimization

iv. Experimental verification
Selection of Semiconductor Type

- **Si IGBT**
  - Cheap
  - 1200 V rated available
  - Conduction losses not scalable
  - No ZVS possible
    - Only ZCS
    - Topological restrictions

- **Si super junction MOSFET**
  - Conduction losses scalable
  - ZVS possible
  - Non-zero ZVS losses (due SJ)
  - Large specific $C_{oss}$
  - Only 650 V rated available
    - NPC half-bridge necessary
    - Increased part count

- **SiC vertical D-MOSFET**
  - Conduction losses scalable
  - Very low ZVS losses
  - 1200 V rated available
  - Low specific $C_{oss}$
  - Costs
Selection of Topology: Two-Stage Converter

Two-stage approach
- Boost converter to adapt the voltage
- Resonant converter for galvanic isolation
- ZVS possible in both stages

Pros/cons
- Optimized/tailored converter topology for each task
- Simple control
- High part count
  - Reliability
  - Costs
- High efficiency questionable as many components in series

Variable frequency TCM boost converter

Series-resonant LLC converter
Selection of Topology: Single-Stage DAB Converter

- **Single-stage approach**
  - Integrated voltage adaption and galvanic isolation
  - ZVS possible

- **Pros/cons**
  - Low part count
  - Operation at fixed frequency
  - Optimization more challenging
  - Advanced modulation scheme necessary
Modulation Scheme (I)

Objectives

- Choose control parameters \((D_1, D_2, \phi)\) so as to minimize RMS currents
  - Minimizes the conduction losses
  - Assumption of low switching losses (ZVS)
- Optimization problem must be solved for all operating points \((U_{DC1}, U_{DC2}, P_{out})\)
- Closed form solutions in:

Modulation Scheme (II)

1. Triangular Current Mode (TCM)
   - $u_{FB1}$
   - $u_{FB2}$
   - $i_{FB1}$
   - $D_1 = 0.5$

2. Optimal Transition Mode (OTM)

3. Conventional Phase-Shift Modulation (CPM)
   - $u_{FB1}$
   - $u_{FB2}$
   - $D_1 = D_2 = 0.5$
Multi-Physics Modeling and Optimization Framework

Heat sink and semiconductors
- Experimentally verified heat sink models
- Conduction loss model based on data sheet information
  \[
P_{\text{cond,MOSFET}} = \frac{1}{T} \int_0^T R_{DS,\text{on}}(i_{DS}(t), T_j) i_{DS}^2(t) \, dt
\]
- Switching loss model based on switching loss measurements
  \[
P_{\text{sw, on/off}} = \int_{\text{sw}} E_{\text{on/off}}(I_{\text{sw, on/off}}, U_{\text{sw}}, T_j)
\]

Magnetics
- Core losses based on iGSE and core loss measurements
- HF winding losses based on mirroring method
- Advanced reluctance and thermal models

Capacitors
- Data sheet information
**Optimization Results**

Prototype

\[ f_{sw} = 48 \text{kHz} \]

\[ \eta_{avg} = 98.2\% \]

\[ V_{comp} = 1.8 \text{ dm}^3 \]

**Loss of ZVS!**
Experimental Verification: Hardware Prototype

Semiconductors
- CREE SiC MOSFET C2M0080120D
  - 1200 V  80 mΩ
- 2 x par. on variable volt. side
- 1 x par. on fixed volt. side

Magnetics
- FerroxCube 3C91
- Litz wire 71 µm

\[ V_{\text{box}} = 2.78 \text{ dm}^3 \quad (\text{vs.} \quad V_{\text{comp}} = 1.8 \text{ dm}^3) \]
Experimental Verification: Efficiency

Exceptional performance despite high functionality

- Peak efficiencies of 98.8% (without auxiliary) and 98.5% (incl. 10 W auxiliary power)
- High efficiency over extremely wide parameter range ($\eta_{avg} = 98.2\%$)
- ZVS in most operating points
Experimental Verification: Power Density

Definition of power density

- Power density only meaningful in combination with specification of
  \[ \frac{[U_{DC1,\text{min}}, U_{DC1,\text{max}}]}{[U_{DC2,\text{min}}, U_{DC2,\text{max}}]} / \eta_{\text{avg}} / \text{costs} \]
- DAB specifically designed for narrow input voltage range: \( \rho_{\text{estimated}} > 5 - 10 \text{ kW/dm}^3 \)

\[ \rho_{[100,700]V} = 1.2 \text{ kW/dm}^3 \]
\[ \rho_{r} = 1.8 \text{ kW/dm}^3 \]

\( \rho_{\text{max}} = 3.4 \text{ kW/dm}^3 \)
Summary & Conclusion

Bidirectional isolated DC/DC converter with wide input voltage range

- High functionality for universal application in residential energy management systems
- Experimentally verified performance
  \( \eta_{\text{avg}} = 98.2\% / \rho_r = 1.8 \text{ kW/dm}^3 / U_{\text{DC1}} = [220,700] \text{ V} \)
- Possible cost savings due to lower system complexity, development costs and due to economies of scale
- Performance not achievable without optimized modulation scheme and SiC
Thank you for your attention!

Updated slides on:  http://www pes ee.ethz.ch