Automotive applications for power electronics is increasing rapidly due to the demand for hybrid and future fuel-cell powered vehicles. The power electronic systems are not only required for driving the vehicle (Fig. 1) but are also used to interface energy storage components and to supply high power auxiliary systems such as active suspension, electric valves and air conditioning units. The automotive industry has specific requirements for its power electronic systems such as a compact design, high reliability, long lifetime and an extremely low cost to power ratio. The systems are further required to operate over a wide ambient temperature range and with liquid cooling temperatures of typically 105°C. In a study from the USA FreedomCAR project, it is projected that the required cost of the power electronic systems has to reduce by a factor of three until the year 2020.

The task of the Automotive Roadmap Committee was to clarify which technologies are needed to achieve the performance and cost targets of the automotive industry. The road mapping effort focused on three systems as circled in Fig. 1:

1. a non-isolated dc-dc converter, in the 40 to 100 kW power range, that can be used as a fuel cell interface,
2. an ac-dc inverter that is integrated into the machine housing of a hybrid drive system (since an integrated solution provides the greatest cost reduction potential), and,
3. an isolated dc-dc converter to provide bi-directional power flow between the high voltage bus and the 14 V accessory power system, where the required power range is 1 to 3 kW.

The main outcomes of the road mapping exercise are that the drive inverter cost target could potentially be met if the power electronics is integrated, and that the maximum achievable power density of the non-isolated dc-dc converter and the isolated dc-dc converter is 50 kW/liter and 10 kW/liter respectively.

The road mapping process utilized a bottom-up approach. Here, mathematical descriptions for the electrical, thermal, packaging and magnetic components are developed. Using these descriptions a component technology space is formed. By using the specifications, topologies, and operating parameters the component space can be optimally mapped into a system performance space, which gives system performance measures such as efficiency, power density and costs. Exploring the performance space and demanding an improved system performance, and then undertaking a reverse mapping from this new point back into the component space, provides information on how the technologies must be developed to achieve the new desired system performance.

Fig. 1  Power electronic key systems for the cars of tomorrow. The three considered systems in the automotive power electronics road mapping exercise are encircled in yellow.
Automotive Power Electronics Research Roadmap Initiative

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Outline

- General Considerations
- Si / SiC Inverter
- Non-Isolated DC/DC Converter
- Isolated DC/DC Converter
- High Temperature Gate Drive
- Optimization
Power Electronic Key Systems for the Cars of Tomorrow

Fuel Cell

Mobile Power

Hybrid Drive

DC

DC

AC

DC

AC

DC

DC

High Power Loads
- X-by-wire
- Active suspension
- Electric valves
- Air conditioning
- Accessory equipment

14V Powernet

Electric Energy Storage
- UltraCaps
- NiMH, Li-ion,...

42...600V

40...100 kW

10...100 kW
More Electric Car

Market Challenges

2015 Cost Target $12/kW x 55kW = $660

Electric Traction Motor
Gearbox
Inverter

- Prius Cost Data
- Typical learning curves for electronics manufacturing and repetitive machining operations
- Required Technology Breakthrough (public/private R&D investment)

$38/kW at 10,000 units
$35/kW at 100,000 units

2020 Cost Target = $8/kW
2020 Cost Target = $8/kW peak
Inverter

Topologies
DOF for Optimization
Technologies
Electric Drive for Hybrid Traction

Alternative Topologies
- Z-Source Inverter
- Current DC Link Inverter
- Matrix Converter

Typ. Inverter Cost Split
- Control, Sensors, and Gate Driver
- Power Semiconductors
- DC Link and EMI Filter
- Mounting and Cooling of Power Semiconductors
Z-Source Inverter

- Two-stage conversion
- High cost and high loss
- Start-up problem
DOF for Optimization

- Adapted Doping Profile
- Partitioning of Total Si Area
- DC Voltage Level \( (P = U \times I) \)
- Modulation Concept
- Output Frequency \( (P = M \times \Omega) \)
- Switching Frequency

- Semiconductor Technology
- Coolant Temperature
- Cooling Concept
- Temperature Swing
  (Cycles to Failure)

- Gate Drive

- Packaging / Integration
  (ECPE Demonstrator)

Optimization on System Level
Traction Drive Inverter

Total Power Semiconductor Needs

- MOSFET
- SJ-MOSFET
- IGBT+Diode

Dashed: $k_V = 1$
Solid: $k_V = 1.7$

Max. Traction Voltage $V_{HV,max}$ [V]

Total Inverter Losses

Power Dissipation [kW]

Dashed: $k_V = 1$
Solid: $k_V = 1.7$

Max. Traction Voltage $V_{HV,max}$ [V]
**Results**

- **IGBT** is the preferred technology for traction voltages above about 150V.
- Total inverter cost, package volume, and losses decrease with increasing traction voltage when using IGBTs.
- The inverter becomes considerably less expensive in the case of a constant traction voltage \((k_v=1)\).
Electric Drive for Hybrid Traction

System Cost Targets

<table>
<thead>
<tr>
<th>Year</th>
<th>System Cost [Euro]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>1200</td>
</tr>
<tr>
<td>2010</td>
<td>1000</td>
</tr>
<tr>
<td>2015</td>
<td>800</td>
</tr>
<tr>
<td>2020</td>
<td>600</td>
</tr>
</tbody>
</table>

Cost cut by system integration

System Cost Targets

- 2005: 1200 €/kW (27 $/kW)
- 2010: 1000 €/kW (14 $/kW)
- 2015: 800 €/kW (14 $/kW)
- 2020: 600 €/kW (8 $/kW)
Comparative Evaluation of SiC for 6-Switch Motor Inverters

Trench IGBT 1200V-50A
SiC MOSFET 1200V-50A (CREE)

SiC
50 A
T<sub>j</sub>=250°C

Si
50 A
T<sub>j</sub>=150°C

Ratio of Conduction Losses

Chip Area Ratio
Comparative Evaluation of SiC for DC/DC Converter

Si CoolMOS C3 1200V-50A (Extrapolated)
SiC MOSFET 1200V-50A (CREE)

Chip Area Ratio

Ratio of Conduction Losses
Switching Transient Shaping

- Minimization of Parasitics
- Passive Damping
- Gate Drive / Active Damping
Thermo-Mechanical Reliability

- Active Cycles: $\gg 3,000,000$
- Passive Cycles: $15,000$

Bond Wire Fatigue Limits

Amplitude is individual for each component (a function of thermal impedance, load profile, etc.)
Thermo-Mechanical Reliability

- SiC Power Device Assembly
- Low Temperature Sintered Silver Die Attachment
- Thermal Cycling  50°C .... 250°C
- 6,000 TC Survived

Die-Shear Test

Source: Lu / VPEC
Non-Isolated DC/DC Converter

Overlapping Input/Output Voltage Ranges
Traction Voltage Converter

Typ. Converter Cost Split

- Power semiconductors
- PS mounting, cooling
- HV DC link
- LV DC link
- Control, sensors, gate driver, CAN interface
- Converter chokes
- Savings vs. single phase

V_HV

V_ES
Bi-Directional DC/DC Converters for Overlapping Voltage Ranges

Cascaded Boost-Buck Converter

Cascaded Buck-Boost Converter

Large Passive Components Count
• 3 Capacitors
• 2 Inductors

Minimum Passive Components Count
• 2 Capacitors
• 1 Inductor
Cascaded Buck-Boost Converter

Methods to Reduce Switching Losses

► Silicon Carbide (SiC)
► Soft-Switching - ZVS, ZCS

Diode reverse recovery losses
Low-Loss Modulation

Operating Modes

Buck operation: \( V_2 < V_1 \),
Energy Transfer: side 1 \( \rightarrow \) side 2

\[ \begin{align*}
V_1 & , \ v_2, \ i_L \\
V_2 & \\
+I_0 & , \ -I_0 \\
t_0 & , \ t_1 \ , \ t_2 \ , \ t_3 \ , \ T_P
\end{align*} \]
Converter Module Hardware

► Peak Power Rating  12 kW
► Power Density      17.5 kW / dm³
Overall Efficiency vs. Output Power

- Relative Converter Output Power [%]
- Overall Efficiency [%]

$V_1 = V_2 = 300V$
Converter Volume Optimization

- Module Count: 2 .. 10
- Switching Frequency: 50 .. 300 kHz

Exemplary 100 kHz
Ultra-Compact Converter Module

- **Output Power**: 12 kW
- **Power Density**: 29 kW/dm³

Components:
- Coolant Inlet
- FPGA
- DSP - TMS320
- Power MOSFETs
Isolated High Temperature SiC J-FET Gate Drive Circuit

$T_a = 250^\circ C$
Phase Difference Circuit

Proposed by D.C. Hopkins, Univ. at Buffalo, USA

Advantages and Drawbacks

- No Duty-Cycle limitation (static Turn-Off)
- High switching speeds (MOSFET half-bridge)
- High complexity
- High costs
Edge-Triggered Driving Circuits

Size of Capacitor $C_g$
- Large capacitances reduce switching speed
- Large capacitances cause significant losses
- Small capacitances limit Off-Time

Second winding due to auxiliary switch $U_{gs}$ limits

Control Pulses

$+U_{drv}$  $-U_{drv}$  $-U_1$

$u_{gs}$  $u_{drv}$

Advantages and Drawbacks
- Moderate Active Component Count
- High Switching Speeds
- Large Duty-Cycle Range (1% ... 100%)
- (Off-Time limited by capacitor size)

► special pulse pattern to provide negative bias useable
Experimental Results

Performance Comparison

Turn-On $t_{\text{fall}} = 13 \text{ ns}$

Turn-Off $t_{\text{rise}} = 18 \text{ ns}$

Edge-Triggered Circuit shows Excellent Performance
Isolated DC/DC Converter

Dual Active Bridge
Magnetically Integrated
Current Doubler
Isolated Bi-Directional DC/DC Converter Topologies

Single-Stage Topologies
- Current-fed Converter Topologies

Multi-Stage Topologies
- Voltage-to-Voltage Converters without Choke
- Series Resonant Converter
- Dual Active Bridge

- No High Current Inductor
Prototype of the Dual Active Bridge

Prototype specifications:
- 2kW
- 11...16V → 220...450V
- η > 90%
- 100kHz
- 2 kW/dm³

2kW @ 12V → 300V

Graphical representation of the prototype with voltage and current measurements.
Experimental Results

Phase-Shift Control

- Total Efficiency
- Output Power

Triangular / Trapezoidal

- Total Efficiency
- Output Power

- Efficiency Increased by 10% at 2kW Output
- Significantly Higher Efficiency at Partial Load
Isolated DC/DC Converter

M magnetically integrated Current Doubler
Current Doubler with Integrated Magnetics

Output Power 5kW  Switching Frequency 200kHz

► Power Density 8.7 kW/dm³

Transformer with Integrated Output Inductance

Gate Driver / Digital Control

Schottky Diodes

4 MOSFETs

Power Density 8.7 kW/dm³
Enabling Technologies Identified in Copenhagen Roadmap Meeting

- Advanced Cooling of Power Semiconductors
- Increased Thermal Cycling Capability / Increased $\Delta T_{j-c}$
- Advanced Packaging Materials
- Advanced Cooling of Passives
- High Current Low HF Loss Interconnection Technologies
- Local EMI Shielding / Filtering
- Integration of Gate Drives and Sensors etc.
- Reliability / Robustness Test Procedures

- Multi-Domain Design / Optimization Platform
System Optimization

Pareto-Optimal Design
Technology Vectors
Sensitivities
Bottom-Up Roadmap Approach for Power Electronic Systems

► How to Identify Future Key Technologies / Required Progress?

1. Clarify State of the Art & Mapping of Component Technologies into System Performance Demonstrator Systems
2. Define Goal - as Resulting from Top-Down Analysis
3. Analyze Sensitivities
4. Identify Most Influential Technologies
5. Derive Required Progress in Specific Technology Metrics / FOM
Sensitivities & Technology Vectors

Conflicting Optimization Goals

► Volume / Weight
► Efficiency
► Costs

Technology Space

Performance Space

Restrictions

s_L ≤ s ≤ s_U

Pareto-Optimal Solutions in a Convex Region

Local Weak Pareto-Optimality