Research of ECPE
European Center for Power Electronics e.V.

Power Supplies with Ultra-High Power Density
Ultra-Compact Three-Phase PWM Converter Systems

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Research

Ultra High Switching Frequency
Highly Compact Converter Systems
Extreme Operating Temperatures

Electromagnetic Integration
Future Energy Distribution

All-SiC Sparse-Matrix-Converter
Fuel-Cell Powered Car
Bi-Directional DC/DC Converter
Three-Port UPS
Power MEMS - Meso-Scale GT Gen. (800,000rpm)
More-Electric Aircraft Actuator Supply
Active EMI Filters
Interactive Multi-Disciplinary Sim.

Ultra-Comp. Telecom Power Supplies
Utility Interface for Drives
Series/Parallel-Res. X-Ray-Generator
Piezoelectric Actuators
Magnetically Levitated Actuators/Sensors

Topics

2005

2010

2015
Meeting the Challenge of Size Reduction

System-Oriented Consideration Related to State of the Art Technologies
Demonstrator Program
3~ AC/DC Power Supplies

10kW/l
System Aspects
Multi-Chip Power Module
Discrete Passive Components

20kW/l
System Aspects
Thermal Integration
EMI Filter Integration

50kW/l
IPEM
Gate Drive Integration
Current Sensor Integration
Integrated Passives
Planar Interconnections
Novel Semicond. Techn.
Advanced Cooling Concept

25 GHz.W

Schedule
09/2004
03/2005
12/2005

12/2006
Comparison to Mesoscale Gas Turbine Generator

Permanent-Magnet Generator

100 W / 800,000 rpm
25 kW/l
Three-Phase Unity Power Factor PWM Rectifier
Three-Phase/Switch/Level PWM Rectifier

High Power Telecommunications Power Supply Modules

- Star-Connection of Single-Phase Systems
- Direct Three-Phase Approach

Derivation of the System Topology
Three-Phase 1-U Power Supply Module

Specifications
- 10 kW
- 3-Φ 480V\textsubscript{AC}
- 800 V\textsubscript{DC}
- 500 kHz
- 10 kW/dm\textsuperscript{3}

Novel Technologies
- COOLMOS / SiC-Diodes
- Micro-Channel Heat Sink
- High-Speed DSP-Control
- Flat Magnetics
- HBW MR Current Sensing
Partitioning of the Converter Volume

About Equal Shares of
- Power Circuit / Cooling
- EMC Filter
- Output Capacitors

EMC Input Filter

Power Circuit / Cooling

Electrolytic Capacitors
Energy Storage for Two-Phase Operation

Electrolytic Capacitors

$U_{DC} = 400V$
Voltage Ripple Amplitude $\pm 5\% \ U_{DC}$

$1kW \rightarrow 200 \mu F, 1.8A_{rms}$

$2 \times 100 \mu F / 450V$
$\phi22mm \times L30mm$
Volume $23cm^3 / 1kW$

Power Density Limit
$\rightarrow 43kW/l$
Three-Phase AC-AC Sparse Matrix Converter
Demonstrator II
Three-Phase AC-AC Matrix Converter

Variable Speed Drives

Conventional

18 Power Transistors
Sparse Matrix Converter

Modulation Scheme

Input Stage Commutates at Zero Current

High Reliability

No Input Stage Switching Losses
Sparse Matrix Converter
Practical Realization

\[
P = 6.8 \text{ kVA} \\
U = 3-\Phi 400V/50Hz \\
T_\alpha = 45^\circ C \\
T_j < 150^\circ C
\]

- Motor / Regenerative Operation
- Operation at Unbalanced / Distorted Mains
- Ride Through Capability
- Active Input Filter Damping
- Full Rated Current at Standstill

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>94.5%</th>
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<tbody>
<tr>
<td>Power Density</td>
<td>3kW/l</td>
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40% Lower Volume
2% Higher Efficiency
Compared to Back-to-Back Voltage
DC Link Converter
SMC / BBC Module with Integrated Filter Components
All-SiC-Sparse Matrix Converter

Switching Frequency: 150kHz
Output Power: 2.5kW @ 10kW/dm³
All-SiC-Sparse Matrix Converter

Switching Frequency: 150kHz
Output Power: 2.5kW @ 10kW/dm³
Three-Phase Hybrid Diode Bridge Rectifier

Demonstrator III
Electronic Smoothing Inductor

5kW
400VAC ±15%
70VDC
70kHz (140kHz)

Circuit Schematic Voltage and Transistor Control Signals
Experimental Analysis

Low Voltage / Low $R_{DS(on)}$ Power MOSFETs

$\eta = 99\%$

10kW/dm$^3$
**Experimental Analysis**

\[ \eta = 99\% \quad \text{10kW/m}^3 \]
Optimization of Forced Convection Cooling

10kW/l → 20kW/l @ 1MHz
Power Density Limit for Forced Convection Cooling

Temperature Distribution

Losses Dominated by the CoolMOS → 90W
Power Density Limit for Forced Convection Cooling

Optimized Heatsink Geometry
Cooling Fan 2 x SanAce 40/28mm

Power Loss per Module
150W

Tj=125°
25kW/l

Tj=125°
40kW/l

Tj=175°
80kW/l
Theoretical Limitation of Power Density for Forced Convection Cooling

Optimized Copper Heat Sink
\[ T_a = 45^\circ C \]
\[ T_j = 175^\circ C \]

\eta = 96\% \rightarrow \sim 80 \text{ (kW/l)}

\eta = 98\% \rightarrow \sim 160 \text{ (kW/l)} \rightarrow \text{Novel Fan}

Geometry

Power Loss Density
Output Power Density Limit
\[ \frac{d_L}{V_{\text{Sink}}} \]
\[ \frac{d_p}{V_{\text{Sink}}} = \eta / (1 - \eta) \]

\[ V_{\text{sink}} = V_{\text{sink}} (T_j, T_a) \]
Hybrid EMC Filters
3D-Electromagnetic Integration
Multi-Disciplinary Simulation

20kW/l → 50kW/l @ 2.5MHz
Matrix Converter EMI Filtering

EN 61800-3 / CISPR 22 - Class B

\[ f_p = 20 \text{kHz} \]

Higher Switching Frequency Increases Switching Losses / Cooling Effort

No Reduction of Required EMI Filter Attenuation

90dB @ 150kHz
Hybrid EMI Filtering

Combination of Active and RF Passive Filter Stage

- Active Filtering up to 2MHz
- 30% Reduction of Overall Filter Volume
- Reduction of Leakage Current
Increasing Power Density

- Increase of Switching Frequency
  - 500kHz → 1MHz → 2.5MHz
- Passives / EMI
  - 3D- Electromagnetic Integration
  - 3D- Thermal Integration / Isolation
  - Ind. Cancellation of Parasitics of Passives
  - Planar Interconnections
  - Modeling of Capacitive / EM Properties
- Local CM EMI Filtering / Shielding
  - Capacitive CM Balancing
  - RF EMI Filters

![Diagram of power switches, microchip, integrated core, and components like integrated resistors, inductor windings, and capacitive layers.]

- 75kV/μs
- 50kA/μs
- 25 GHz.W@10kW
Increasing Power Density cont.

- **Thermal Management**
  - Local Heat Spreading and Heatpipes
  - Local Two-Phase Cooling
  - 3D-Integrated Heatsink
  - All-SiC Realization, $T_j = 250^\circ C$

- **Topology / Control**
  - Fully Digital Control
  - Switching Delay Current Distortion Compensation
  - Gate Drive dv/dt Immunity
  - Gate Drive Power Loss
  - Interleaving of Converter Systems
  - Multi-Cell Converter Topologies
Interactive Multi-Disciplinary Simulation Platform

Integrated Simulation

Conv.

Circuits - Control - Electromagnetic - Thermal
Simulation Supported Measurement in Highly Integr.
Conclusions

Ultra High Power Density requires Considerations on System Level including

- Topology
- Modulation
- Semiconductor Technology
- High Frequency Electromagnetics / EMI
- Thermal Management
- Control / Signal Processing

These Challenges also have to be Reflected into University Teaching