Performance Trends and Limitations of Electronic Energy Processing Systems

J. W. Kolar

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch
Basic Structure of Electronic *Power* Processing Systems

--- *Power Electronics Systems* ---
Basic Electronic Power Processing System

Highest Efficiency
Highest Dynamics
Highest Compactness
Highest Compatibility
Highest Reliability

Mains

Voltage Frequency

EMC

Power Semiconductors
Power Passives
Interconnections

AC

Control

Reference Value

Control Communication

Sensors

Load

Voltage Frequency

EMC

Load
Basic Electronic Power Processing System

Highest Efficiency
Highest Dynamics
Highest Compactness
Highest Compatibility
Highest Reliability

Example of a Three-Phase AC/AC Matrix Converter
Outline

► ETH Zurich
► Power Electronic Systems Laboratory (PES)
► Future Importance of Energy / Power Electronics (PE)
► Inspiring Concepts of Future Renewable Energy Systems
► ETH MEGA Cube Project
► General Applications of PE / Efficiency Challenge
► Pareto-Optimal PE Converter Design Approach
► Potential Future Extensions of PE Applications Areas
► Summary
## Zurich Profile

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETHZ Zurich</td>
<td>14'500 Students</td>
</tr>
<tr>
<td>University of Zurich</td>
<td>20'000 Students</td>
</tr>
<tr>
<td>8 Univ. of Appl. Science</td>
<td>7'000 Students</td>
</tr>
</tbody>
</table>

**Zurich**
- 1 Lake
- 2 Rivers
- 1'100 Fresh H₂O Fount.
- 1'946 Rest. & Bars
- 57 Museums
- 32 Theaters
- 2 Soccer Clubs
- 10 Min. to Airport
- 100km to Snowy Alps

**Zurich Aggl.**
- 370’000

**ETHZ Zurich University of Zurich 8 Univ. of Appl. Science**
Departments of ETH Zurich

AGRL  Agriculture and Food Sciences
ARCH  Architecture
BAUG  Civil, Environmental and Geomatics Eng.
BIOL  Biology
BSSE  Biosystems
CHAB  Chemistry and Applied Biosciences
ERDW  Earth Sciences
GESS  Humanities, Social and Political Sciences
INFK  Computer Science
ITET  Information Technology and Electrical Eng.
MATH  Mathematics
MATL  Materials Science
MAVT  Mechanical and Process Engineering
MTEC  Management, Technology and Economy
PHYS  Physics
UWIS  Environmental Sciences

Students ETH in total

11'300  Diploma-Students
3'200   Doctoral Students
Power Electronics Systems Laboratory

Organization

Spin-off Network
D-ITET Power Electronic Systems Laboratory

Power Electronic Systems Laboratory
Johann W. Kolar

Industry Relations
R. Coccia / B. Seiler

AC-DC Converter
M. Hartmann
Ch. Marxgut

AC-AC Converter
T. Friedli
M. Schweizer

DC-DC Converter
D. Aggeler
U. Badstübner
F. Krismer
G. Ortiz
H. Plesko
St. Waffler
C. Zhao

DC-AC Converter
D. Bortis
Y. Lobsiger
B. Wrzecionko

Pulsed Power
J. Mühlthaler
T. Soeiro

Multi-Domain Modeling
U. Drofenik
F. Giezendanner
I. Kovacevic
A. Müsing
A. Stupar

Mega-Speed Drives
T. Baumgartner
P. Imoberdorf
D. Krähenbühl
A. Looser
A. Tüysüz

Magnetic Levitation
Ph. Karutz
T. Reichert
B. Warberger
F. Zürcher

Secretariat
M. Kohn

Administration
P. Albrecht / P. Maurantio

Computer Systems
C. Stucki

Electronics Laboratory
P. Seitz

28 Ph.D. Students
2 Post Docs

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
PES Spin-Off Network

Industry

ETHZ-PES

Timeline

04-2008

Mega-n-Drives

Celeroton

MD-Simulation

GECKO Research

T-Transfer

enertronics

04-2008

2009

2010
PES Selected Research Results

*Ultra Compact Systems*

*Ultra Efficient Systems*

*Ultra High Speed Systems*
Deep Green IT Power Supplies

164 TWh/year
(110 Mio Tons of CO₂)
Global Telecom
Industry Energy Consumption

Supercomputing
Targets 95% Efficiency
from 3-Φ Mains Input to
POL Converter Output
Single-Phase PFC Rectifier

★ 99.2% @ 1.1 kW/dm³

★ 5.5 kW/dm³ @ 95.8%
Solar Impulse

Attempt to Fly a Solar-Powered Airplane Around the World

▸ Requires Cabin Air Pressurization

Solar Impulse
European Space Agency / B. Piccard
Turbocompressor Prototype

- Operated up to 550,000 rpm
- Rotor and Bearing Cooling by Leakage Airflow
- Maximum Winding Temperature 80 °C
Ultra High Speed Drive Systems

World Record!
100W @ 1,000,000 rpm
Future Importance of EEnergy / Electronic EEnergy Processing

*Energy Technology Roadmaps*

*Increasing EEnergy Demand*
Carbon Dioxide Concentration and Temperature Development

Evidence from Ice Cores

Average Increase 0.4%/a
New Policies - Doing More with *Much* Less!

- Reduce CO$_2$ Emissions *Intensity* (CO$_2$/GDP) to stabilize Atmospheric CO$_2$ Concentration
- 1/3 in 2050 $\rightarrow$ less than 1/10 in 2100 (*AIST, Japan @ IEA Workshop 2007*)
Japan Energy Technology Vision 2100

► Strategic Technology Roadmaps of Energy Sector Developed by Backcasting Starting with Assumed Resource and Environmental Constraints
World Net Electric Power Generation
1980 - 2030


Source: H. Nilsson
Chairman IEA DSM Program
FourFact AB

Trillion Kilowatthours

- **History**
  - OECD
  - Non-OECD

- **Projections**
  - Total

1980 1990 2006 2020 2030

+77%

+33%

40 30 20 10 0

Source: H. Nilsson
Chairman IEA DSM Program
FourFact AB
Electricity Gains a Progressively Larger Share of Total US Energy

Digital Technologies – Precision and Efficiency of Electricity
Inspiring Concepts of Future Renewable Energy Generation Systems

DESERTEC
Airborne Wind Turbines
Concentrating Solar Thermal Power Plant in the Sahara
Transmission Utilizing HVDC Technology (3% Loss/1000km)
Target 2050 - 100GW HVDC, 700TWh @ 5€ct/kWh

Clean Power from the Desert
Technology Overview

Mirrors Concentrating Solar Radiation / Creating Heat

Heat Storage Tanks (e.g. Molten Salt Storage) – Ability to Provide Power for 24h a Day

Conventional Turbine and Generator, Turbines could also be Powered by Natural Gas or Oil

Clean Power from the Desert
Revolutionize Wind Power Generation Using Kites / Tethered Airfoils

► Power of the Wind – Cube of the Wind Speed / Two Times Speed – $2 \times 2 \times 2 = 8$ Times Power
Controlled Power Kites for Capturing High Altitude Wind Power

- Wing Tips / Highest Speed Regions are the Most Efficient Parts of a Wind Turbine
- Generator for Power Kites Moved to Ground
- Minimum Base Foundation etc. Required
- Operative Height Adjustable to Wind Conditions
Controlled Power Kites for Capturing High Altitude Wind Power

- Lower Electricity Production Costs than Current Wind Farms
- Generate up to 250 MW/km², vs. the Current 3 MW/km²
- Research at the POLITECNICO DI TORINO
Controlled Power Kites for Capturing High Altitude Wind Power

- Lower Electricity Production Costs than Current Wind Farms
- Generate up to $250 \text{ MW/km}^2$, vs. the Current $3 \text{ MW/km}^2$
- Research at the POLITECNICO DI TORINO

Carousel Configuration

$1 \text{ km}^2 = 1,000,000 \text{ m}^2$

$6,400 \text{ m}^2$

90 m

150 m

800 m

1,000 m

KITEGEN

All rights reserved
Air Rotor Wind Generator

- Helium or Hydrogen Inflated
- Magnus Effect - Additional Lift
Airborne High-Altitude Wind Turbines

- Wind at High Altitudes is Faster and More Consistent
- Float Wind Turbines at High Altitudes or Even in the Jet Stream
Airborne High-Altitude Wind Turbines

- Multi-Wing Airframe Supports an Array of Turbines
- Turbines Connect to Motor Generators
- Reinforced Tether Transfers MV-Electricity to Ground
- Composite Tether also Provides Mechanical Connection to Ground
Airborne High-Altitude Wind Turbines

- Electrical System Topology
  - 3Φ-AC/DC Rectifier (800V Output) per Turbine
  - Connection to Tether via Bidir. 800V/8kV DC/DC Converter
  - Weight Limit of 25kg / 100kW (MF Transformer)
Airborne High-Altitude Wind Turbines

- Reinforced Tether Transfers MV-Electricity to Ground
- Composite Tether also Provides Mechanical Connection to Ground
Conventional Off-Shore Windfarms

Medium Voltage Power Collection and Connection to On-Shore Grid
Collection Grids for Off-Shore Wind Parks

- High Efficiency DC Energy Transmission
- Low Weight MF DC/DC Step-up Converter
Energy Storage Systems for Renewable Generation

- Redox-Flow Battery for Individual Scaling of Stored Energy and Rated Output Power
- Bidirectional Step-up DC/DC Converter for Connection to Collection Grid

Redox-Flow Battery Concept
ETH MEGA Cube Research Targets

► 1 Mega Watt Bidirectional DC/DC Conversion
► Maximum Efficiency / Minimum Weight Design

► Specifications

• 20kHz Switching Freq.
• Port 1: 12kV
• Port 2: 1.2kV
• 100 kV DC Isolation
• 99% Efficiency
• 250kg Weight Limit
Research Efforts on High-Power MF DC/DC Converters

- Volume vs. Frequency for Published Transformer Designs
- All Scaled to 1MW Power Rating
Research Efforts on High-Power MF DC/DC Converters

2001-2010

Grid Applications (UNIFLEX EU)
* Full Modular Construction
* Full Scale Converter: 5MW

Traction Applications (Bombardier, ALSTOM, ABB)
* Modular MV Side
* Single LV Converter
4.5kV Press Pack IGBT

- 400A Continuous Current
- Slow Switching Behavior
Si/SiC Super Cascode Switch

- HV-Switch Controllable via Si-MOSFET
  * 1 LV Si MOSFET
  * 6 HV SiC JFETs
  * Avalanche Rated Diodes

- Ultra Fast Switching
- Low Losses
- Parasitics
  * Passive Elements for Simultaneous Turn-on and Turn-off
  * Stabilization of Turn-off State Voltage Distribution
Si/SiC Super Cascode Switch

- HV-Switch Controllable via Si-MOSFET
  * 1 LV Si MOSFET
  * 6 HV SiC JFETs
  * Avalanche Rated Diodes
- Ultra Fast Switching
- Low Losses
- Parasitics
  * Passive Elements for Simultaneous Turn-on and Turn-off
  * Stabilization of Turn-off State Voltage Distribution

Synchronous Switching

Turn-On
DC/DC Converter Topology / Modulation

- Dual Active Bridge / Triangular Modulation
- Series Resonant Converter

$$ n = 13 $$

$$ L_S = 2 \mu H $$

$$ L_S / C_s = 5.9 \mu H / 12 \mu F \ (f = 19 kHz) $$

Turn-off Losses only on LV Side

ZCS on MV side

High Voltage and Current Stress on Series Capacitor

All Turn-on Processes Performed with ZCS

ZCS on MV Side
Transformer Concepts

► Core Material – Vitroperm 500F
► LV Winding – Loss Optimized Copper Foil
► MV Winding – Litz Wire / Litz Cable

DBA @ Triangular Modulation

<table>
<thead>
<tr>
<th>Losses</th>
<th>Core</th>
<th>Copper</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.83kW</td>
<td>1.93kW</td>
<td>3.76kW</td>
</tr>
</tbody>
</table>

Efficiency 99.62%
Power Density 84kW/dm³

► Shell-Type Concept
Transformer Concepts

► Core Material – Vitroperm 500F
► LV Winding – Loss Optimized Copper Foil
► MV Winding – Litz Wire / Litz Cable

DBA @ Triangular Modulation

<table>
<thead>
<tr>
<th>Losses</th>
<th>Core</th>
<th>2.23kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>2.28kW</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.51kW</td>
<td></td>
</tr>
</tbody>
</table>

Efficiency 99.55%
Power Density 91kW/dm³
Conversion Efficiencies

- **DAB @ Triangular Modulation**

- **SRC @ Constant Switching Freq.**

![Graphs showing efficiency vs. power for different converters](image-url)

- 600V IGBT/MOSFET 5-Level NPCC
- 1200V SiC JFET 3-Level NPCC

- Semisouth SJEP120R063 SiC JFET
- Infineon IPW60R045CP MOSFET
- Infineon IGW75N60T IGBT

Efficiency (%) vs. Power (MW)
EEnergy Utilization / General Power Electronics Application Areas

$10^1 \ldots 10^3 \text{ W}$
$10^3 \ldots 10^6 \text{ W}$
$10^6 \ldots 10^9 \text{ W}$

___________________________ Extreme Power Range ______________________________
IT Distributed Power Supply

Distributed / Modular Power Supply

Server-Farm
up to 450 MW
99.9999%/<30s/a
$1.0 Mio./Shutdown

Communications Power Systems 12-V Intermediate Bus Architecture

Front-end power supply
Bus converter
Second-level distribution bus
Point-of-load converters
Lighting

Constant Light
Wide Control Range

33% Comm. El. Energy Consumption US
20% Energy Saving Potential of Light Source

100,000h
Vibration-Resistant
Efficiency → +30%
Design

Lamp Ballasts / Energy-Saving Lamps
Gas Discharge Lamps (Automotive Lighting)
LED (semiconducting, organic)
Process Technology

Welding / Laser Cutting

135kA@770V

Plasma Technique
Laser Cutting
Spark Erosion
Ind. Heating / Melting
Aluminium Melting

Power electronics inside

$1,700 Mio. (EU)
50% Automotive Ind.
Metal Processing
Aerospace Industry
Drive Systems

Extremely Wide Appl. Range, e.g. Automation Technology, Assembling, Robotics, HVAC

60% of Electric Energy Utilized in Germany consumed by Drives

5% Employing Electronic Speed Control
35% Possible Share / 40% Energy Saving Pot. (16TWh)

400TWh Drives Energy Consumption in the EU
60% Energy Saving Potential
Hybrid Cars

Series

Parallel

European petrol fleet
European diesel fleet
total

currently 165g/km

target of 140g/km by 2008

Power electronics inside
Traction

Commuter Trains
High Power Locomotives
Multi-Frequency Systems
$16^2/3 \ text{ Hz} \rightarrow 10kHz / \text{ Transformer-less}$
Super-Cap-Storage for Trams

38 MVA
0...56Hz
552km/h

Maglev Trains
More Electric Aircraft

Air Traffic Growth 4.7%/a

360Hz...800Hz VF Power Generation
270V\textsubscript{DC} DC Power Distribution
Replacement of Hydraulic by Electric System
The Efficiency Challenge

**E**nergy Supply Chain

---

**E**nergy Saving Potential of **I**ndustrial Drives Systems
**Negawatts instead of Megawatts**

McKinsey Study Finds Energy Efficiency Will Be the Biggest Source of CO₂ Savings

*The estimate of behavioral change abatement potential was made after implementation of all technical levers; the potential would be higher if modeled before implementation of the technical levers.

Source: Global GHG Abatement Cost Curve V2.0; IEA, US EPA
Industrial Use of Energy

Source: ABB
Potential of Power Electronics Contributions

- Power Electronics is a Cross Cutting Technology
- Allows to Save Energy over all Steps of Energy Transportation / Utilization
Energy Use in Industry / Drives

- Fans
- Conveyors
- Winders
- Roller tables
- Spinning
- Pumps
- Cranes
- Paper machine
- Offshore
- Ski lifts
- Debarking drums
- Centrifuges
- Propulsion
- Drilling
- Decanters

Source: ABB
Energy Saving Potentials for Industrial Drives

- EU study on AC drives 43 billion kWh/year
  - Energy saving potential in the EU industry using AC drives in economically sound applications
- EU study on motors 5 billion kWh/year
  - Energy saving potential in the EU industry by improving the efficiency of electric motors
- US motor challenge study 85 billion kWh/year
  - Energy saving potential in the US industry by using AC drives, high-efficiency motors and other improvements to motor-driven systems
- China study on motors 19 billion kWh/year*
  - Energy saving potential in Chinese industry by improving the efficiency of electric motors
- China study on AC drives 134 billion kWh/year*
  - Energy saving potential in Chinese industry using AC drives in economically sound applications
Energy Saving Potentials for Industrial Drives

- 60% of Industrial Energy Used by Electric Motors
- Motors Frequently Still Running at Fixed Speed / Throtteling
- >40% Energy Saving Potential

- For each 1€ Purchase Costs 100€ are Spent for Energy over Lifetime

Source: ABB
Systematic Approach for Power Electronics Converter Optimization / Evaluation

Performance Metrics
Pareto-Optimal Design
Technology Nodes
Power Electronics Performance Trends

- **Performance Indices**
  - Power Density \([\text{[kW/dm}^3]\]
  - Power per Unit Weight \([\text{kW/kg]}\]
  - Relative Costs \([\text{kW/\$]}\]
  - Relative Losses \([\%]\]
  - Failure Rate \([\text{[h}^{-1}]\)

---

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Abstraction of Power Converter Design

Performance Space
- Efficiency
- Power Density
- Costs
- Reliability
- etc.

System
- Phase-Shift DC/DC Conv.
- Resonant DC/DC Conv.
- DC Link AC/AC Conv.
- Matrix AC/AC Conv.
- etc.

Components
- Power Semiconductor
- Interconnections
- Inductors, Transf.
- Capacitors
- Control Circuit
- etc.

Materials
- Semiconductor Mat.
- Conductor Mat.
- Magnetic Mat.
- Dielectric Mat.
- etc.

Mapping of Design Space into System Performance Space

- Evaluation Formulas
- Lifetime Models
- Cost Models
- etc.

- Specifications
- Operation Limits
- Converter Topology
- Modulation Scheme
- Control Concept
- Operation Mode
- Operating Frequ.
- etc.

- Doping Profiles
- Geometric Properties
- Winding Arrangements
- Magnetic Core Geometries
- etc.
Mathematical Modeling and Optimization of Converter Design

Specifications
- $V_i, V_o, P_o, \Delta V_o, \text{CISPR 11/22 A,B}$

Converter Topology
Modulation Scheme

Electric Power Circuit Model

Component Values, $f_p$

Minimum Losses or Volume

Loss Model
- Transformer / Inductor
  - Windings Geom.
  - Wire Type
  - Core Geom.
  - Core Type
- Semiconductor Type

Reluctance Model
- \( \phi / \phi_{\text{wo}} \)

Thermal Model
- \( T_C / T_W \)

Off-line Optimized Heat Sink

Capacitor Type
- Capacitor Volume
- Capacitor Losses
- Transformer / Inductor Volume

Loss Model
- Transformer / Inductor
  - Windings
  - Core

Thermal Model
- Heat Sink Volume
- Semic. Losses

Total Converter Volume / Losses

Summation of Component Volumes and Losses

Capacitor
- \( C_{\text{CM}} \)
- \( C_{\text{CM}} \)
- \( L_{\text{CM}} / L_{\text{CM}} \)

Filter Inductor
- \( A^*_{\text{CM}} \)
- \( A^*_{\text{CM}} \)
- \( A^*_{\text{CM}} \)

Filter Capacitor
- \( A_{\text{CM}} \)
- \( A_{\text{CM}} \)
- \( A_{\text{CM}} \)

EMI Filter
- \( T_C / T_W \)
- \( T_C / T_W \)
- \( T_C / T_W \)

Min. Vol.
- \( \text{EMI Filter Cap. Vol} \)
- \( \text{EMI Filter Cap. Losses} \)
- \( \text{EMI Filter Ind. Losses} \)
- \( \text{EMI Filter Ind. Vol.} \)
Single-Objective Converter Design Optimization

- Design for Maximum Power Density
Multi-Objective Converter Design Optimization

► Pareto Front - Limit of Feasible Performance Space

Design Space
\( \vec{k} = (k_1, k_2, ..., k_l) \)
\( \vec{x} = (x_1, x_2, ..., x_m) \)

Condition Map

Optimization Algorithm

\[ \Sigma w_i f_i(\vec{x}, \vec{k}) = \Sigma w_i p_i \Rightarrow \text{Max} \]

Performance Space
\( \vec{p} = (p_1, p_2, ..., p_l) \)

Search

Evaluate

\( g_k = (x, \vec{k}, r) = 0 \)
\( h_j = (x, \vec{k}, r) \geq 0 \)
Efficiency Optimization

- Power Semiconductors
- Boost Inductor
- Output Capacitor
- Auxiliaries
Minimum Loss MOSFET Chip Area

- Increasing $A_{chip}$
- Decreasing $R_{DS(on)}$
- Increasing $C_{oss}$

$$P_{V,T} = R_{DS(on)} I_{T,rms}^2 + f_P \frac{1}{2} C_{Eq} U_O^2$$
Minimum Loss MOSFET Chip Area

- Increasing $A_{chip}$
- Decreasing $R_{DS(on)}$
- Increasing $C_{oss}$

$$P_{V,T} = \frac{1}{G^* A_{chip}} I_{T,rms}^2 + \int P \frac{1}{2} C^* A_{chip} U_O^2$$
Ultra-Efficient PFC Rectifier Performance Limits

- Inductor Power Density

\[ \Delta i \propto \frac{U_o}{L} T_p \rightarrow \Delta i \propto \frac{U_o}{L} I \equiv \frac{1}{f_p} \rightarrow LI \propto \frac{U_o}{\alpha_{\Delta i}} \frac{1}{f_p} \rightarrow LI^2 \propto \frac{U_o I}{\alpha_{\Delta i}} \frac{1}{f_p} \]

\[ V_L \propto \frac{1}{2} LI^2 \propto \frac{P_o}{f_p} \Rightarrow \frac{P_o}{V_L} \propto \frac{\rho_L}{f_p} \]

- Optimum Semiconductor Area

\[ P_{VT} = \frac{I_{T,\text{rms}}^2}{G^*} \cdot \frac{1}{A_{\text{chip}}} + \frac{1}{2} V_o^2 C^* A_{\text{chip}} \]

\[ P_{VT} \rightarrow \text{Min} \Rightarrow \frac{dP_{VT}}{dA_{\text{chip}}} = 0 \]

- Relation of Efficiency and Power Density

\[ P_{VT,\text{min}} \propto \sqrt{\rho_L} \sqrt{\frac{G^*}{C^*}} P_o \Rightarrow (1 - \eta_{\text{max}}) = \gamma_T \sqrt{\frac{G^*}{C^*}} \sqrt{\rho_L} \]

\[ FOM_{\eta_p,1} \]
Ultra-Efficient PFC Rectifier Performance Limits

\[
(1 - \eta) \propto \frac{U_F}{U_o}
\]

- Output Diodes
- Power MOSFETs
- Aux. Power

\[
\rho_{HS} \propto \frac{\eta}{(1 - \eta)}
\]

- Inductor
- Output Cap.
- Heatsink

\[
(1 - \eta) \propto \sqrt{\frac{G^*}{C^*}} \sqrt{\rho_L}
\]
Feasible Performance Space

► Bridgeless PFC Rectifiers @ $u_N = 230V$

Power Density is Based on Net Volumes ➔ Scaling by 0.6–0.8 Necessary
Technology Sensitivity Analysis Based on $\eta$-$\rho$-Pareto Front

- Sensitivity to Technology Advancements
- Trade-off Analysis
Converter Performance Evaluation Based on $\eta$-$\rho$-$\sigma$-Pareto Surface

$\sigma$: kW/$
Converter Performance Evaluation Based on $\eta$-$\rho$-$\sigma$-Pareto Surface

► ‘Technology Node’

Technology Node: $(\sigma^*, \eta^*, \rho^*, f_P^*)$
Observation

Very Limited Room for Further Performance Improvement!

97% Expected as Future Maximum Efficiency Target
Observation

► Very Limited Room for Further Performance Improvement!
Research Contribution of Newly Industrialized Countries

► Revision and Extension

Source: International Monetary Fund, as of April 2006

GDP (Nominal) Per capita
2007
Component Technologies

Power Semiconductors
Interconnection / Packaging
Passives
Cooling
Observation

- Overestimation of Progress
- Hype Cycles of Technologies

E.g., 3-Φ AC-AC Matrix Converter vs. Voltage DC Link Converter, SiC, etc.
Observation

► No *Killer Application* for Low-Voltage SiC Switch
► Early Analysis of Technology Mapping Highly Beneficial!
► E.g., Evaluation of GaN
PES Future Activities Profile

- Hardware Prototyping / Experimental Verification: 80% (2005), 20% (2020)
- Multi-Domain Modeling / Simulation / Optimization: 20% (2005), 80% (2020)

Advanced Technology Hardware Mainly Realized @ PES Spin-Off Companies
Possible Future Extensions of Power Electronics Systems Applications
Smart Power Delivery System

Extension of Existing Electricity Network
- Decentralized Energy Generation/DER Integration
- Decentralized Storage
- Decentralized Sensors and Computing
- Data Communication Network
- Advanced Power Electronics Electricity Routers

Virtual Utilities Microgrids

Bi-Directional Flow of Energy and Information – Interactive Highly Reliable and Economical Grid
Smart Grid / Microgrid Concept

Solid-State Power Flow Control
Electricity Routers

Looped Configuration
Self-Sufficient Islands
High Reliability / Power Quality

The Smart Grid Connects Distributed Energy Resources Through Microgrids

Source: EPRI
Summary

► Virtual Prototyping - Multi-Domain/Objective Optimization
► Non-Traditional Topics Still not Well Covered - Reliability/Packaging
► Further Standardization

► New Application Areas – New Challenges - High Voltage/Frequency
► More Application Specific Converters

► Systems Instead of Converters - Smart Grid, Green Buildings etc.
► Converter to be Seen as Building Block – Continuous Improvement
Challenge

► Several Topics Out of Typical Power Electronics Experts Field of Experience - This also Applies for Traditional Academic Education in Power Electronics

Paradigm Shift Required!

► It’s Not Going to be an Easy Task
Thank You!
Questions ?
Transformer Concepts

- Core Material – Vitroperm 500F
- LV Winding – Loss Optimized Copper Foil
- MV Winding – Litz Wire / Litz Cable

DBA @ Triangular Modulation

Losses
- Core 1.26kW
- Copper 1.55kW
- Total 2.81kW

Efficiency 99.72%
Power Density 232kW/dm³

Core-Type Concept
Converter Design

- Transformer Concept
- DAB or SR Converter Topology
Converter Power Loss Partitioning

- LV Switch Realized by Series / Parallel Connection of SiC JFETs (SemiSouth)
- MV Switch Realized by 4.5kV IGBTs in Multi-Level Arrangement
- Matrix-Type Transformer

- DAB Trapezoidal Modulation
- DAB Triangular Modulation
- SRC Constant Frequency Operation
Si/SiC Super Cascode Switch

- HV-Switch Controllable via Si-MOSFET
  * 1 LV Si MOSFET
  * 6 HV SiC JFETs
  * Avalanche Rated Diodes

- Ultra Fast Switching
- Low Losses
- Parasitics
  * Passive Elements for Simultaneous Turn-on and Turn-off
  * Stabilization of Turn-off State Voltage Distribution

Turn-On

JFETs

MOSFET
ETH Zurich Virtual Prototyping Platform

GeckoCIRCUITS

Input
Topology / Device Models / Control Circuit / 3D-Geometry / Materials

GeckoHEAT

3D-Thermal FEM Solver
Thermal Impedance Matrix
HF Magnetics Design Toolbox

Fast Circuit Simulator

GeckoEMC

3D-Electromagn. Parasitics Extraction
Reduced Order Impedance Matrix
EMC Filter Design Toolbox
Heatsink Design Toolbox

Reliability Analysis Toolbox

Post Processing
Design Metrics Calculation

Device Database
Controls Toolbox
Optimization Toolbox
Inductor Losses in Dependency of Volume

- **Scaling of Core Losses**

\[
P_{\text{Core}} \propto f_p \left( \frac{\Phi}{A} \right)^2 V
\]

\[
P_{\text{Core}} \propto \left( \frac{1}{l^2} \right)^2 l^3 \propto \frac{1}{l}
\]

- **Scaling of Winding Losses**

\[
P_{\text{Wdg}} \propto I^2 R \propto I^2 \frac{l_{\text{Wdg}}}{\kappa A_{\text{Wdg}}}
\]

\[
P_{\text{Wdg}} \propto \frac{1}{l}
\]
Minimum Loss MOSFET Chip Area

- Dependency on $f_P$ and $R_{th}$
Ultra-Compact PFC Rectifier Performance Limits

\[ (1 - \eta) \propto \frac{U_F}{U_o} \]

- Output Diodes
- Power MOSFETs
- Aux. Power

\[ \rho_{HS} \propto \frac{\eta}{(1 - \eta)} \]

- Inductor
- Output Cap.
- Heatsink

\[ (1 - \eta) \propto \sqrt{\frac{G^*}{C^*}} \sqrt{\rho_L} \]

- Output Diode + MOSFETs & Inductor
- Output Diode + MOSFETs considering \( R_{DS} \) & Inductor & Output Capacitor
- Heat Sink & Output Capacitor
- Heat Sink

\( \eta - \rho \)-Limit Scaled with Respect to Power Density

Efficiency [%]

Power Density [kW/dm³]