Zukünftige Herausforderungen in der Leistungselektronik

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Power Electronics 2.0

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Industry Relations
R. Coccia / B. Seiler

AC-DC Converter
M. Leibl
D. Rothmund
S. Schrotth
L. Schrittwieser

AC-AC Converter
G. Ortiz
D. Boillat
Ch. Gammeter
Th. Guillod
J. Huber
H. Uemura

DC-DC Converter
F. Krismer
T. Andersen
P. Bezerra
M. Kasper

DC-AC Converter
D. Bortis
R. Burkart
Y. Lobsiger

Multi-Domain Modeling
I. Kovacevic
A. Stupar

Wireless Power
R. Bosshard
O. Knecht

Advanced Mechatronics
A. Tüysüz
M. Flankl
M. Maurerer

Magnetic Levitation
Th. Nussbaumer
D. Steinert
M. Schuck
T. Wellerdieck

Secretariat
M. Kohn / I. Schnyder

Administration
P. Albrecht / P. Maurantonio

Computer Systems
C. Stucki

Electronics Laboratory
P. Seitz

22 Ph.D. Students
4 Post Docs
→ 1:5 PostDoc/Doc - Ratio

ETH Zürich

Leading Univ. in Europe
Research Scope

- Micro-Scale Energy Systems
- Wearable Power
- Exoskeletons / Artificial Muscles
- Environmental Systems
- Pulsed Power

Cross-Departmental
- Mechanical Eng., e.g.
  - Turbomachinery, Robotics
  - Microsystems
  - Medical Systems
  - Economics / Society

Actuators / EL. Machines

Power Electronics
Industry Collaboration

- Core Application Areas
  - Renewable Energy
  - UPS
  - Smart Grid
  - Automotive Systems
  - More-Electric Aircraft
  - Medical Systems
  - Industry Automation
  - Semiconductor Process Technology
  - Etc.

- 16 International Research Partners
Outline

► Application Areas & Performance Trends
► Component Technologies
► Topologies & Modulation / Control
► Design & Testing Procedure
► Future CHALLENGES
► Future Univ. Research & Education
► Conclusions

→ Challenges
→ Challenges
→ Challenges
→ Opportunities (!)
► Application Areas

- Industry Automation / Processes
- Communication & Information
- Transportation
- Lighting
- etc., etc.

... Everywhere!
Power Electronics Converters
Performance Trends

Environmental Impact...

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

Performance Indices

State-of-the-Art

Future

Time-to-Market

Costs

Volume

Weight

Losses

Failure Rate

[\text{kg}_{\text{Fe}}/\text{kW}]
[\text{kg}_{\text{Cu}}/\text{kW}]
[\text{kg}_{\text{Al}}/\text{kW}]
[\text{cm}^2_{\text{Si}}/\text{kW}]
Performance Improvements (1)

- **Power Density**

  - Telecom Power Supply Modules: Typ. Factor 2 over 10 Years
Performance Improvements (2)

- Efficiency
  - PV Inverters: Typ. Loss Reduction of Factor 2 over 5 (10) Years

\[ 1 - \eta \]
Performance Improvements (3)

- Costs
  - Importance of Economy of Scale

Source: SMA 2006
Challenge

- How to Continue the Dynamic Performance Improvement (?)

- Degrees of Freedom
  - Components
  - Topologies
  - Modulation & Control
  - Design Procedure
  - Modularization / Standardization / Economy of Scale
  - Manufacturing
  - New Applications
Components

Potentials & Limits
Power Semiconductors → Si / SiC / GaN
Si Power Semiconductors

Past Disruptive Changes

- IGBT  Trench & Field-Stop
- MOSFET  Superjunction Technology
WBG Power Semiconductors

- Disruptive Change
  - Extremely Low $R_{DS(on)}$
  - Very High $T_{j,max}$
  - Extreme Sw. Speed

- Utilization of Excellent Properties $\rightarrow$ Main Challenges in Packaging (!)
WBG Power Semiconductors

- Disruptive Change
  - Extremely Low $R_{DS(on)}$
  - Very High $T_{j,max}$
  - Extreme Sw. Speed

- Utilization of Excellent Properties → Main Challenges in Packaging (!)
**SKiN Technology**

- No Bond Wires, No Solder, No Thermal Paste
- Ag Sinter Joints for all Interconnections of a Power Module (incl. Heatsink)
- Extremely Low Inductance & Excellent Thermal Cycling Reliability

**Source:**
Dr. Scheuermann
Dr. Beckedahl
CIPS 2008

- Allows Extension to 2-Side Cooling (Two-Layer Flex-Foil)
- Allows Integration of Passive & Active Comp. (Gate Drive, Curr. & Temp. Measurem.)
- Disruptive Improvement (!)
Multi-Functional PCB

- Multiple Signal and High Current Layers
- Integrated Thermal Management

- Substantial Change of Manufact. Process → “Fab-Less” Power Electronics
- Advanced Simul. Tools of Main Importance (Coupling with Measurem.)
- Testing is Challenging (Only Voltage Measurement)
- Once Fully Utilized – Disruptive Change (!)
3ph. Inverter in p²pack-Technology

- **Rated Power**: 32kVA
- **Input Voltage**: 700V\text{DC}
- **Output Frequency**: 0 ... 800Hz
- **Switching Frequency**: 20kHz

Source: [Energytronics](https://www.energytronics.com)
Latest Systems Using WBG Devices → GaN

- GaN 3x3 Matrix Converter Chipset with Drive-By-Microwave (DBM) Technology
  - 9 Dual-Gate Normally-Off Gate-Injection Bidirectional Switches
  - DBM Gate Drive Transmitter Chip & Isolating Dividing Couplers
  - Extremely Small Overall Footprint - 25 x 18 mm² (600V, 10A – 5kW Motor)

5.0GHz Isolated (5kVDC) Dividing Coupler

Source: Panasonic ISSCC 2014
Power Semiconductors
Gate Drive
Packaging

- Disruptive Changes Happened - WBG, LTJT
- Cont. Further Improvements - Packaging, Reliability (!)

→ Main Challenges to Manufacturers
→ Main Challenges to General Users
Passive Components

→ Capacitors / Magnetics / Cooling
Capacitors

- Relatively (Slow) Technology Progress
- Recently Significant Improvement (Packaging) – e.g. CeraLink

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**Foil Capacitors**

OPP = Oriented Polypropylene  
PHD = Advanced OPP  
COC = Cycloolefine Copolymers

| Source: Dr. Plikat et al.  
Volkswagen AG  
PCIM 2013 |

| Source: EPCOS |

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**Automotive Capacitors for 450V, normalized to 500 μF**

Source: Dr. Plikat et al. Volkswagen AG PCIM 2013
Power Chip (Foil) Capacitors

- Targeting Automotive Applications up to 90kW
- High Voltage Ratings / High Current Densities (>2A/μF)
- Low Volume / High Volume Utilization Factor
- Low Ind. Busbar Connection / Low Switching Overshoot
Magnetics

There is No “Moore's Law” in Power Electronics!

Example: Scaling Law of Transformers

$A_{Core} A_{Wdg} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_w J_{rms} B_{max} f}$

- $\hat{B}_{max}$ ... Relatively Slow Technology Progress
- $J_{rms}$ ... Limited by Conductivity – No Change
- $f$ ... Limited by HF Losses & Converter & General Thermal Limit

No Fundamentally New Concepts of

We have to Hope for Progress in Material Science
**Magnetics**

→ There is No “Moore’s Law” in Power Electronics!

- **Example:** Scaling Law of Transformers

\[
A_{\text{Core}} A_{\text{Wdg}} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_w J_{\text{rms}} B_{\text{max}} f}
\]

- No Fundamentally New Concepts of

→ We have to Hope for Progress in Material Science (Magnetic, Thermal – Could take > 10Years)
Operation Frequency Limit

- Relationship of Volume and Weight vs. Frequency
  - Higher Frequency Results in Smaller Transformer Size only Up to Certain Limit
  - Opt. Frequencies for Min. Weight and Min. Volume (!)

100Vx1A 1.1 Transformers, 3F3, 30°C Temp. Rise

Source: Philips
Influence of Magnetics on System Costs

Example of 20kVA UPS System (Single-Stage Output Filter)

44% of Main Power Stage Costs (!)
∑

Magnetics

- Large Volume Share / Cost Factor
- Only Gradual Improvements

→ Magnetics
- Careful Design Absolutely Mandatory (!)
- Hope for Adv. Power Transformer Materials
- Improved Heat Management

→ Capacitors
- High Frequ. Operation for Minim. Vol. (e.g. DC Link)
- Hope for Adv. Dielectrics
Converter Topologies
History and Development of the Electronic Power Converter

E. F. W. Alexanderson  E. L. Phillipi
Fellow AIEE  Non-member AIEE

The term "electronic power converter" needs some definition. The object may be to convert power from direct current to alternating current for d-c power transmission, or to convert power from one frequency into another, or to serve as a commutator for operating an a-c motor at variable speed, or for transforming high-voltage direct current into low-voltage direct current. Other objectives may be mentioned. It is thus evidently not the objective but the means which characterizes the electronic power converter. Other names have been used tentatively but have not been accepted. The emphasis is on electronic means and the term is limited to conversion of power as distinguished from electric energy for purposes of communication. Thus the name is a definition.

Paper 44-143, recommended by the AIEE committee on electronics for presentation at the AIEE summer technical meeting, St. Louis, Mo., June 26-30, 1944. Manuscript submitted April 25, 1944. Made available for printing May 18, 1944.

E. F. W. Alexanderson and E. L. Phillipi are with the General Electric Company, Schenectady, N.Y.
Auxiliary Circuits

Example: Non-Isolated Buck+Boost DC-DC Converter for Automotive Applications

98% Efficiency
29kW/dm³

Instead of Adding Aux. Circuits
Change Operation of BASIC (!) Structure - “Natural” Performance Limit
Integration of Functions

- Examples:
  - Single-Stage Approaches / Matrix Converters
  - Multi-Functional Utilization (Machine as Inductor of DC/DC Conv.)
  - etc.

Integration Restricts Controllability / Overall Functionality (!)
Typ. Lower Performance / Higher Control Compl. of Integr. Solution
Basic Physical Properties remain Unchanged (e.g. Filtering Effort)
Extreme Restriction of Functionality

- Highly Optimized Specific Functionality $\rightarrow$ High Performance for Specific Task
- Restriction of Functionality $\rightarrow$ Lower Costs

Example of Wide Input Voltage Range Isolated DC/DC Converter
New Topologies

Some Exceptions
- Multi-Cell Converters
- 3-ph. AC/DC Buck Converter
- etc.
Multi-Cell Converters
→ Ultra-Efficient 1ph. PFC
→ 1ph. Telecom PFC Rectifier
Bidirectional Ultra-Efficient 1-Φ PFC Mains Interface

99.36% @ 1.2kW/dm³

- Employs NO SiC Power Semiconductors -- Si SJ MOSFETs only
Bidirectional Ultra-Efficient 1-Φ PFC Mains Interface

99.36% @ 1.2kW/dm³

- Employs NO SiC Power Semiconductors -- Si SJ MOSFETs only
1-Φ Telecom Boost-Type TCM PFC Rectifier

- **Input Voltage**: 1-ph. 184...264V<sub>AC</sub>
- **Output Voltage**: 420V<sub>DC</sub>
- **Rated Power**: 3.3kW

★ 98.6% @ 4.5kW/dm<sup>3</sup>
Topologies
Modulation Schemes
Control Schemes

→ Topologies
- Basic Concepts Extremely Well Known - Mature
- Comprehensive Comparative Evaluations Missing (!)
- Promising Multi-Cell Concepts (!)

→ Modulations / Control Schemes
- Basic Concepts Extremely Well Known - Mature
- Digital Power – All Diff. Kinds of Functions
Observation

- Very Limited Room for Further Performance Improvement!
Design Challenge

- Mutual Couplings of Performance Indices → Trade-Offs

For Optimized System Several Performance Indices Cannot be Improved Simultaneously
Design Challenge

- Mutual Couplings of Performance Indices → Trade-Offs

For Optimized System Several Performance Indices Cannot be Improved Simultaneously
Future Design Process

Challenge: Virtual Prototyping

- Reduces Time-to-Market
- More Application Specific Solutions (PCB, Power Module, and even Chips)
- Only Way to Understand Mutual Dependencies of Performances / Sensitivities (!)
- Simulate What Cannot Any More be Measured (High Integration Level)
Virtual Prototyping

→ Remaining Challenges

- Comprehensive Modeling (e.g. EMI, Reliability)
- Model Order Reduction

... will Take a “Few” More Years
“Power Electronics 1.0”
Maturing → Reduce Costs, Ensure Reliability (!)

“New Challenges”
Consider Converters like “ICs”

- If Only Incremental Improvements of Converters Can Be Expected

$\int_0^t p(t) \, dt$

- “Converter” $\rightarrow$ “Systems” (Microgrid) or “Hybrid Systems” (Autom. / Aircraft)
- “Time” $\rightarrow$ “Integral over Time”
- “Power” $\rightarrow$ “Energy”
Consider Converters like “ICs”

- If Only Incremental Improvements of Converters Can Be Expected

\[ p(t) \rightarrow \int_{0}^{t} p(t) \, dt \]

- Power Conversion \( \rightarrow \) Energy Management / Distribution
- Converter Analysis \( \rightarrow \) System Analysis (incl. Interactions Conv. / Conv. or Load or Mains)
- Converter Stability \( \rightarrow \) System Stability (Autonom. Cntrl of Distributed Converters)
- Cap. Filtering \( \rightarrow \) Energy Storage & Demand Side Management
- Costs / Efficiency \( \rightarrow \) Life Cycle Costs / Mission Efficiency / Supply Chain Efficiency
- etc.

\[ \text{Change Ahead} \]
AC vs. Facility-Level DC Systems for Datacenters

- Reduces Losses & Footprint
- Improves Reliability & Power Quality

- Conventional US 480V\textsubscript{AC} Distribution

- Facility-Level 400 V\textsubscript{DC} Distribution

- Proposal for Public +380V\textsubscript{DC}/-380V\textsubscript{DC} Systems by Philips, etc.
Power Electronics Systems
Performance Figures/Trends

Complete Set of New Performance Indices

- Power Density \([\text{[kW/m}^2]\]
- Environm. Impact \([\text{[kWs/kW]}]\]
- TCO \([\text{[$/kW]}]\]
- Mission Efficiency \([\%]\]
- Failure Rate \([\text{[h}^{-1}\text{]}]\]

Supply Chain & Mission Energy Loss
Manufacturing & Recycling Effort
Total Cost of Ownership
Failure Rate
State-of-the-Art
Future
Floorspace Requirement
System-Oriented Analysis

→ Main Challenges
- Get to Know the Details of Power Systems
- Theory of Stability of Converter Clusters
- Autonomous Control
Remarks on University Research
University Research Orientation

- General Observations

- Gap between Univ. Research and Industry Needs
- In Some Areas Industry Is Leading the Field
University Research Orientation

Gap between Univ. Research and Industry Needs

Industry Priorities
1. Costs
2. Costs
3. Costs
- Multiple Objectives ...
- Low Complexity
- Modularity / Scalability
- Robustness
- Ease of Integration into System

Basic Discrepancy!
Most Important Industry Variable, but Unknown Quantity to Universities
University Research Orientation

- In Some Areas Industry Is Leading the Field!

- Industry Low-Power Power Electronics (below 1kW) Heavily Integrated — PCB Based Demonstrators Do Not Provide Too Much Information (!) Future: “Fab-Less” Research

- Same Situation above 100kW (Costs, Mech. Efforts, Safety Issues with Testing etc.)
- Talk AND Build Megawatt Converters (!)
University Research Orientation

- Bridge to Power Systems
- Establish (Closer) University / Industry (Technology) Partnerships
- Establish Cost Models, Consider Reliability as Performance

MEGA Power Electronics
(Medium Voltage, Medium Frequency)

Micro Power Electronics
(Microelectronics Technology Based, Power Supply on Chip)

10W — 1 MW

“Largely” Standard Solutions

+ System Applications
University Education Orientation

Need to Insist on High Standards for Education

- Introduce New Media
- Show Latest State of the Art (requires New Textbooks)
- Teach Converter Design (Synthesis not Analysis)
- Interdisciplinarity
- Introduce New Media (Animation)
- Lab Courses!

The Only Way to Finally Cross the Borders (Barriers) to Neighboring Disciplines!
Finally, ...
Technology S-Curve

...after Switches and Topologies

“Passives” & Advanced Design

THE Main Challenges of the Next Decade

+ Costs
+ Systems

Paradigm Shift

Super-Junct. Techn. / WBG
Digital Power Modeling & Simulation

Power MOSFETs/IGBTs
Microelectronics
Circuit Topologies
Modulation Concepts
Control Concepts

SCRs / Diodes
Solid-State Devices

2014

2025

Performance
Emerging
Established
Mature
Replacement (Disruptive) Technology

Effort / Time

ETH Zürich

FH JOANNEUM
University of Applied Sciences
Future Developments

- WBG Semiconductors + Next Level of Integration
- New Applications Could Establish Mass Markets solving the WBG Chicken-and-Egg Problem
Future Extensions of Power Electronics Applications

Source: AIST
Power Electronics 2.0

New Application Areas
- Smart XXX (Integration of Energy/Power & ICT)
- Micro-Power Electronics (VHF, Link to Microelectronics)
- MEGA-Power Electronics (MV, MF)

Paradigm Shift
- From “Converters” to “Systems”
- From “Inner Function” to “Interaction” Analysis
- From “Power” to “Energy” (incl. Economical Aspects)

Enablers / Topics
- New (WBG) Power Semiconductors (and Drivers)
- Adv. Digital Signal Processing (on all Levels – Switch to System)
- PEBBs / Cells & Automated (+ Application Specific) Manufaturing
- Multi-Cell Power Conversion
- Multi-Domain Modeling / Multi-Objective Optim. / CAD
- Cybersecurity Strategies
Thank You!
Questions ?