Future Challenges for Research and Teaching in Power Electronics

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Power Electronics 2.0

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Outline

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

→ Challenges
→ Challenges
→ Challenges
→ Opportunities (!)
Application Areas
Performance Trends
Application Areas

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

... Everywhere!
Power Electronics Converters Performance Trends

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

Environmental Impact... \([\text{kg}_{\text{Fe}}/\text{kW}]\) \([\text{kg}_{\text{Cu}}/\text{kW}]\) \([\text{kg}_{\text{Al}}/\text{kW}]\) \([\text{cm}^2_{\text{Si}}/\text{kW}]\)

State-of-the-Art

Future

Time-to-Market

Costs

Volume

Weight

Losses

Failure Rate

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
► Performance Improvements (1)

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

Inefficiency (Losses)... \(1 - \eta\)

- Efficiency
  - PV Inverters: Typ. Loss Reduction of Factor 2 over 5...10 Years
Performance Improvements (3)

- Costs
  - Importance of Economy of Scale
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

Source: Dr. Miller / Infineon / CIPS 2010
Si Power Semiconductors

Continuous Further Improvement

- Ultra Thin Wafers (Lower On-State & Sw. Losses of IGBTs) → Wafer Handling Challenge
- Higher Switching Speeds → Dyn. Clamping & Low $L_s$ Packaging
- Smaller Chip Sizes (Higher $R_{th}$, Lower $C_{th}$) → Low $R_{th}$ Packaging
- Long Lifetime IGBTs for $T_j=200^\circ$ & $\Delta T_j=120^\circ$ → Advanced Packaging (LTJT)

Main Challenges in Packaging (!)

Source: Dr. Deboy / Infineon IECON 2013
Future Packaging - 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: $700V_{dc}$
- Output Frequency: 0 ... 800Hz
- Switching Frequency: 20kHz
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Power Semiconductor PCB Integration

Source: SCHWEIZER ELECTRONIC
Future 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

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

- Single Contr. for $\frac{du_{CE}}{dt}$ & $\frac{di_C}{dt}$

- Continuous (!) Control of the Switching Trajectory incl. Short Circuit
- Options for Monitoring / Lifetime Prediction etc.
Hardware Prototype

- PCB Dimensions: 50 mm x 130 mm (2 in x 5.1 in)

- Output Stage
- $di_C/dt$-Feedback
- $dv_{CE}/dt$-Feedback
- Control Circuits
Experimental Results – Individual Variation of References

- **Turn-On: Variation of $\frac{di_c}{dt}$**

- **Turn-Off: Variation of $\frac{di_c}{dt}$**

- **Turn-On: Variation of $\frac{dv_{CE}}{dt}$**

- **Turn-Off: Variation of $\frac{dv_{CE}}{dt}$**
► 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 (!)**
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 (!)
WBG Power Semiconductors

Application Perspectives

What Yole Development showed in 2011 as future view
WBG Power Semiconductors

Application Perspectives

A Super Junction supplier’s view of future
► WBG Power Semiconductors

- Application Perspectives

A SiC supplier’s view of future
► WBG Power Semiconductors

- Application Perspectives

Source: Dr. Honea
PEDG 2013

GaN solution supplier’s view for future
Low-Inductance Packaging Challenge

- **600pH DC Link Inductance**
- **“Switching Cell in the Package”**

- SiC Switches on Ceramic Substrate (DCB) Embedded in Top Layer PCB
- 1200V J-FET Half Bridge (50A) incl. DC Link Cap. Soldered to the Module

Source: Fraunhofer IZM
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
Power Semiconductors
Gate Drive
Packaging

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

→ Main Challenges to Module Manufacturers
  - Electromagnetically Quiet Packaging
  - Integrated Programmable Gate Drive
  - Ensuring Reliability – Reliability Testing Procedures (!)
  - Local Measurement and Condition Monitoring
  - Large Scale Applications of WBG (Chicken & Egg Problem)

→ Main Challenges to General Users
  - Higher Level of Integration (e.g. PCB)
  - Fund. Changes in Design / Manufacturing / Measurement Techniques
  - Clarification of Cost/Performance of WBG Semiconductors
Capacitors

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

Foil Capacitors

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

| Source: | Volkswagen AG PCIM 2013 |

| Energy Density | 100% | 100% | 110% | 120% |
| Film Material  | OPP  | PHD  | COC  | ?    |
| Max. Temperature | 105 °C | 115 °C | 150 °C | 100 °C |
| Self Inductance | 60 nH | 30 nH | 15 nH | 10 nH |

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

Source: EPCOS TDK
Future - Monitoring of Electrolytic Capacitors

- On-Line Measurement of the ESR in “Frequency Window” (Temp. Compensated)
- Data Transfer by Optical Fibre or Near-Field RF Link
- Possible Integration into Capacitor Housing or PCB
- Additionally features Series Connect. Voltage Balancing

Source: Prof. Ertl
TU Vienna, 2011
Magnetics

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

Example: Scaling Law of Transformers

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

\( \hat{B}_{\text{max}} \) ... Relatively Slow Technology Progress
\( J_{\text{rms}} \) ... 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

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Example: Scaling Law of Transformers

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\( J_{rms} \) ... 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 (Magnetic, Thermal – Could take > 10 Years)
Operation Frequency Limit

■ Serious Limitation of Operating Frequency by HF Losses

— Core Losses (incr. @ High Frequ. & High Operating Temp.)
— Temp. Dependent Lifetime of the Core
— Skin-Effect Losses
— Proximity Effect Losses

Source: Prof. Albach, 2011
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 (!)
Influence of Magnetics on System Costs

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

44% of Main Power Stage Costs (!)
Capacitors

- Large Volume Share / Cost Factor
- Only Gradual Improvements

→ Capacitors
- High Frequ. Operation for Minim. Vol. (e.g. DC Link)
- Hope for Adv. Dielectrics
- Improved Heat Management
- Local Lifetime Monitoring

Magnetics

- Careful Design Absolutely Mandatory (!)
- Hope for Adv. Power Transformer Materials
- Improved Heat Management
- Magnetic Integration or DCM
- RF Air Core Inductors - Shielding (!)
- Integration of Sensors etc.
History and Development of the Electronic Power Converter

E. F. W. Alexanderson
Fellow AIEE

E. L. Phillips
Nonmember 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 evident that 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 29-30, 1944. Manuscript submitted April 25, 1944. Made available for printing May 18, 1944.
E. F. W. Alexanderson and E. L. Phillips are with the General Electric Company, Schenectady, N. Y.
United States Patent [19]
Mitchell

[54] AC-DC CONVERTER HAVING AN IMPROVED POWER FACTOR

[75] Inventor: Daniel M. Mitchell, Cedar Rapids, Iowa


[21] Appl. No.: 414,757

[22] Filed: Sep. 3, 1982

[57] ABSTRACT

An AC to DC converter utilizes a first power converter for converting an AC signal to a DC signal under the control of a control signal. The control signal is generated by a control circuit that includes a first analog generator that provides a first signal that is analogous to the voltage of the AC signal that is to be converted. A second analog generator generates a second signal that is analogous to the current of the AC signal that is to be converted and a third analog generator generates a third signal that is analogous to the voltage of the DC output signal. The third signal and the first signal are multiplied together to obtain a fourth signal. The control signal is generated from the fourth signal and the second signal and is used to control the power converter such that the waveform of the current of the AC signal is limited to a sinusoidal waveform of the same frequency and phase as the AC signal.

8 Claims, 2 Drawing Figures
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)
Highly Optimized Specific Functionality → High Performance for Specific Task
Restriction of Functionality → Lower Costs

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

- Multi-Cell Converters
- 3-ph. AC/DC Buck Converter
- etc.
Multi-Cell Converters

→ Parallel Interleaving
→ Series Interleaving
Multi-Cell Converters → “Homogeneous” Power

- Example of Parallel Interleaving
  - Breaks the Frequency Barrier
  - Breaks the Impedance Barrier
  - Breaks Cost Barrier - Standardization
  - High Part Load Efficiency

- Fully Benefits from Digital IC Technology (Improving in Future)
- Redundancy → Allows Large Number of Units without Impairing Reliability
Multi-Cell Converters

- Example of **Series Interleaving**

\[
\frac{\Delta U_{\text{max},N}}{U} = \frac{\pi^2}{32} \left[ \frac{f_0}{f_s} \right]^2 \frac{1}{N^3}
\]

- Breaks the Frequency Barrier
- Breaks the Silicon Limit $1+1=4$ NOT $2$ (!)
- Breaks Cost Barrier - Standardization
- Extends LV Technology to HV

\[\Delta I_{\text{max},N} = \frac{\Delta I_{\text{max}}}{N^2}\]
Examples of 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
 теперь визуализация продукции

- **Bidirectional Ultra-Efficient 1-Ф 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$_{AC}$
- **Output Voltage**: 420V$_{DC}$
- **Rated Power**: 3.3kW

★★ 98.6% @ 4.5kW/dm$^3$
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 (!)
  - PWM might be Merged with Model Pred. Control
  - More “Heuristic” Control Schemes
  - Model-Based Max. Utilization of Load/Line/Source
  - Challenge to Guarantee Stability (!)
  - Challenge of Redundancy / Safety Requirements
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 $\rightarrow$ Trade-Offs

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

- Advanced Simulations Based Design Allows Multi-Objective Optimization
- Identifies Performance Limits → Pareto Front
  - Sensitivities to Technology Advancements (Example: $\eta$-$\rho$-Pareto Front)
  - Trade-off Analysis
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
- Minimization of Simulation Time
- Interactive Features

... 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

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

- “Converter” \to “Systems” (Microgrid) or “Hybrid Systems” (Autom. / Aircraft)
- “Time” \to “Integral over Time”
- “Power” \to “Energy”

Shift to New Paradigm!
Consider Converters like "ICs"

If Only Incremental Improvements of Converters Can Be Expected

→ Shift to New Paradigm

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

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

Dynamics → from Transient Balance by Kin. Storage (No Cntrl) to ms-Active Power Flow Control
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 \([\text{[h}^{-1}\text{]}]\)
System-Oriented Analysis

→ Challenges

- Get to Know the Details of Power Systems (!)
- Theory of Stability of Converter Clusters
- Autonomous Control
- Design Tools
- Standardization
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

<table>
<thead>
<tr>
<th>Industry Priorities</th>
<th>Basic Discrepancy!</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Costs</td>
<td>Most Important Industry Variable, but</td>
</tr>
<tr>
<td>2. Costs</td>
<td>Unknown Quantity to Universities</td>
</tr>
</tbody>
</table>
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 (Animation)
- Show Latest State of the Art (requires New Textbooks)
- Teach Converter Design (Synthesis not Analysis)
- Interdisciplinarity
- Lab Courses!

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

...after Switches and Topologies

“Passives” & Advanced Design

as THE Main Challenges of the Next Decade

+ Costs

+ Systems

Super-Junct. Techn. / WBG

Digital Power Modeling & Simulation

Power MOSFETs/IGBTs

Microelectronics

Circuit Topologies

Modulation Concepts

Control Concepts

SCRs / Diodes

Solid-State Devices

Paradigm Shift

2014 - 2025

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Future Developments

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

**Technology Push**
- WBG Semiconductors
- Digital Control
- Adv. Design & Packaging

**Market Pull**
- Standardized
- 3-D Integrated
- Reliable
- Cost Optimized
- Plug & Play
- Environmentally Friendly

- Smart Grids
- Green / Smart Buildings
- HEV & E-Mobility

Graph showing:
- Performance vs. Time
- Technology Push (2010-2025)
- Market Pull (2010-2025)
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) Manufacturing
- Multi-Cell Power Conversion
- Multi-Domain Modeling / Multi-Objective Optim. / CAD
- Cybersecurity Strategies
But, to get there we must ...

“Bridge the Gaps”

- Univ. / Ind. Technology Partnerships
- Power Electronics + Power Systems
- Vertical Competence Integration (Multi-Domain)
- Comprehensive Virtual Prototyping (Multi-Objective)
- Multi-Disciplinary / Domain Education
Thank You!
Questions?