What are the “Big CHALLENGES” in Power Electronics?

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What are the “Big OPPORTUNITIES” in Power Electronics?

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Power Electronics 2.0

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Outline

► Application Areas & Performance Trends
► Conv. Component Technologies
► Conv. Topologies & Modulation / Control
► Conv. Design & Testing Procedure
► Future BIG 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

- 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...
\[
\begin{align*}
\text{kg}_{\text{Fe}} &\text{/kW} \\
\text{kg}_{\text{Cu}} &\text{/kW} \\
\text{kg}_{\text{Al}} &\text{/kW} \\
\text{cm}^2_{\text{Si}} &\text{/kW}
\end{align*}
\]

State-of-the-Art

Future

Time-to-Market

Weight

Volume

Losses

Failure Rate

Costs
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 Years

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

- Costs
  - Importance of Economy of Scale
Performance Improvements (4)

Costs

- Automotive: Typ. 10% / a
- 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)
  - Higher Switching Speeds
  - Smaller Chip Sizes (Higher $R_{th}$, Lower $C_{th}$)
  - Long Lifetime IGBTs for $T_j=200^\circ$ & $\Delta T_j=120^\circ$

  → Wafer Handling Challenge
  → Dyn. Clamping & Low $L_s$ Packaging
  → Low $R_{th}$ Packaging
  → Advanced Packaging (LTJT)

Main Challenges in Packaging (!)

Source: Dr. Deboy / Infineon  IECON 2013
► 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 (!)
Low Inductance Packaging Challenge

- Allowed $L_s$ Directly Related to Switching Time $t_s$ →
- Ensure Very Low Gate Inductance & Kelvin Source
- Ensure Min. Coupling of Gate and Power Circuit

$$L_s \leq \frac{\alpha U_i}{I_L} = \alpha t_s \frac{U_i}{I_L}$$

- Planar Interconnections / Parallel Connection (Increase of $Z$)
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
► **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 (!)
Planar Power Chip Package

- Novel Concepts for Power Packages and Modules

Module with Power and Logic Devices

Single Chip Package for MOSFETs and IGBTs
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 $p^2$pack-Technology

- **Rated Power**: 32kVA
- **Input Voltage**: $700V_{dc}$
- **Output Frequency**: 0 ... 800Hz
- **Switching Frequency**: 20kHz
3ph. Inverter in p²pack-Technology

- Rated Power: 32kVA
- Input Voltage: $700V_{DC}$
- Output Frequency: 0 ... 800Hz
- Switching Frequency: 20kHz

Power Semiconductor PCB Integration

- Current Measurement
- Auxiliary Supply
- Gate Driver
- Protection Circuit
- DSP
- Powerlink
- USB CAN
- Encoder Interface
- Voltage Measurement

Source: SCHWEIZER ELECTRONIC ene.tronics
Active Closed Loop Gate Drive

- Continuous (!) Control of the Switching Trajectory incl. Short Circuit & Overvoltage
- Minimization of Interlock Delay Time / PWM Distortion
- Options for Monitoring / Lifetime Prediction etc.
Active Closed Loop Gate Drive

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

- 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)
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 $\frac{dv_{CE}}{dt}$
► New **Wireless** Measurement Technology

- **Bandwidth** 100 MHz
- **Sampling Rate** 400 MS/s (8 Bit)
- **Bluetooth Communication**
- **NO** $dv_{CM}/dt$ Limit (!)

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Source: enertronics

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![Diagram of electronic circuit with voltage and time graphs]

- $v_{GE}$ (V)
- $v_{CM}$ (V)

- Wireless Voltage Probe
- Differential Probe
- Reference Voltage

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**ETH**

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
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)

Source: Panasonic ISSCC 2014
Latest Systems Using WBG Devices → SiC

- All-SiC Conv. Cell of a 100kHz 25kW Ultra-Light Weight Solid-State Transformer
  - Medium Voltage Port: 1750 ... 2000 V<sub>DC</sub>
  - Low Voltage Port: 650 ... 750 V<sub>DC</sub>
  - Rated Power: 6.25 kW
  - Power Density: 5.2kW/dm<sup>3</sup>
  - Specific Weight: 4.4kW/kg

- High Switching Frequ. @ Med. Voltages Enabled by SiC
WBG Power Semiconductors

Application Perspectives

Source: Dr. Honea
PEDG 2013

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

Application Perspectives

Source: Dr. Honea
PEDG 2013
WBG Power Semiconductors

Application Perspectives

A SiC supplier’s view of future

Source: Dr. Honea
PEDG 2013
WBG Power Semiconductors

Application Perspectives

GaN solution supplier’s view for future
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
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

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Energy Density</td>
<td>100%</td>
<td>100%</td>
<td>110%</td>
<td>120%</td>
</tr>
<tr>
<td>Film Material</td>
<td>OPP</td>
<td>PHD</td>
<td>COC</td>
<td>?</td>
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<tr>
<td>Max. Temperature</td>
<td>105 °C</td>
<td>115 °C</td>
<td>150 °C</td>
<td>160 °C</td>
</tr>
<tr>
<td>Self Inductance</td>
<td>60 nH</td>
<td>30 nH</td>
<td>15 nH</td>
<td>10 nH</td>
</tr>
</tbody>
</table>

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

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/\mu F)
- Low Volume / High Volume Utilization Factor
- Low Ind. Busbar Connection / Low Switching Overshoot

Source: TDK
Condition Monitoring of DC Link 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

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 Magnetics

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 Freq. & High Operating Temp.)
  - Temp. Dependent Lifetime of the Core
  - Skin-Effect Losses
  - Proximity Effect Losses

Source: Prof. Albach, 2011

Adm. Flux Density for given Loss Density

Skin-Factor $F_s$ for Litz Wires with $N$ Strands
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
Required EMI Filter Attenuation

► Higher Switching Frequ. Increases Required Att.  → Only Option $f_s > 500$kHz
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 (!)
Energy Storage and Volume of Inductors

- Example of DC/DC Boost Converter

- Minimize Magn. Volume for High Relative Current Ripple (DCM) & HF
Magnetics

Capacitors

- Large Volume Share / Cost Factor
- Only Gradual Improvements

→ 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.

→ Capacitors
- High Freq. Operation for Minim. Vol. (e.g. DC Link)
- Hope for Adv. Dielectrics
- Improved Heat Management
- Local Lifetime Monitoring
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 29-30, 1944. Manuscript submitted April 26, 1944.

E. F. W. Alexander and E. L. Phillipi are with the General Electric Company, Schenectady, N. Y.
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 (1)

Example: 1-ph. Telekom Boost-Type PFC Rectifier

- Complexity Increases Exp. if “Natural” Limit of a Technology is Approached
- Next Step in Semiconductor Technologies Makes Snubbers Obsolete → SiC Diodes
Auxiliary Circuits (2)

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
New Converter Topologies

- Very Large Number of Options!

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Example

Topologies for Three-Element Resonant Converters

Rudolf P. Sevems

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26 out of 48 Topologies are of Potential Interest

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Fig. 13. Source-network-load combinations.

Fig. 17. Networks with 2L and 1C.

Fig. 18. Networks with 2C + 1L, 3C, and 3L.

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** → **High Performance for Specific Task**
- **Restriction of Functionality** → **Lower Costs**

- **Example of Wide Input Voltage Range Isolated DC/DC Converter**
Extreme Restriction of Functionality

Example: DC-Transformer $\rightarrow$ Isolation @ Constant (Load Ind.) Voltage Transfer Ratio

E.g. adopted by VICOR – “Sine Amplitude Converter” – for Fact. Power Architecture

Resonant Freq. $\approx$ Switching Freq. $\rightarrow$ Input/Output Voltage Ratio $= N_1/N_2$ (Steigerwald, 1988)
Extreme Restriction of Functionality

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

Cost / Performance Ratio is a Key Metric for Industry Success (Sales Argument)
Σ New Topologies

Some Exceptions
- 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 \(\rightarrow\) Allows Large Number of Units without Impairing Reliability

H. Ertl, 2003
Multi-Cell Converters

- Basic Concept @ Example of Parallel Interleaving
  - Multiplies Frequ. / Red. Ripple @ Same (!) Switching Losses & Incr. Control Dynamics

\[
\Delta U_{\text{max}, N} = \Delta U_{\text{max}} \cdot \frac{1}{N^3}
\]

\[
\Delta I_{\text{max}, N} = \frac{\Delta I_{\text{max}}}{N^2}
\]

- 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=2 NOT 4 (!)
- Breaks Cost Barrier - Standardization
- Extends LV Technology to HV

\[ \Delta I_{\text{max},N} = \frac{\Delta I_{\text{max}}}{N^2} \]
Multi-Cell Converters

- Series Connection of LV MOSFETs (LV Cells) Effectively *SHIFTS the Si-Limit* (!)

Assumption:

Chip Area of each LV Chip Equal to the Chip Area of the HV Chip

- Scaling of Specific On-State Resistance

\[
(R_{DS, on} \times A)_{\text{eff}} \approx \frac{1}{N^{1.5}} (R_{DS, on} \times A)
\]

- Excellent Opportunity for Extreme Efficiency Ultra-Compact Converters
Multi-Cell Converters

- Interleaved Series Connection Dramatically Reduces Switching Losses (or Harmonics)

- Converter Cells Could Operate at VERY Low Switching Frequency (e.g. 5kHz)

- Minimization of Passives (Filter Components)

Scaling of Switching Losses for Equal $\Delta i/I$ and $dv/dt$

$$P_{S,N} \approx P_{S,N=1} \cdot \left( \frac{1}{2N^2} \cdots \frac{1}{N^3} \right)$$
Examples of Multi-Cell Converters

- VRM
- Ultra-Efficient 1ph. PFC
- Telecom Power Supplies
Voltage Regulator Module

- Multi-Channel / Parallel Interleaving of up to 12 Channels

- Coupling Inductors (Interphase Inductors) allows Further Reduction of Ind. Comp. Volume
- For On-Chip Integration Challenged by Switched Capacitor Converters
Zero Voltage Switching – Triangular Current Mode

- Synchronous Rectification
- Negative Current Ensures ZVS
12kW TCM Buck+Boost DC/DC Converter

- Overlapping Input and Output Voltage Ranges
  
  \[ U_1 = 150...450V \]
  \[ U_2 = 150...450V \]

- Max. Eff. = 99.3% @ 30kW/l
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\textsubscript{AC}
- Output Voltage: 420V\textsubscript{DC}
- Rated Power: 3.3kW

\[
\eta/\% = 98.0 - 99.0
\]

\[
\begin{align*}
\eta/\% &\quad 99.0 \\
&\quad 98.8 \\
&\quad 98.6 \\
&\quad 98.4 \\
&\quad 98.2 \\
&\quad 98.0 \\
&\quad 97.8 \\
&\quad 97.6 \\
&\quad 97.4 \\
&\quad 97.2 \\
&\quad 97.0
\end{align*}
\]

\[
P_o/W = 1000, 1500, 2000, 2500, 3000, 3500
\]

\[
\begin{align*}
\text{264V} &\quad \times \\
\text{230V} &\quad \cdot \\
\text{184V} &\quad \cdot \\
\text{Limit} &\quad \cdot \\
\end{align*}
\]

☆ 98.6% @ 4.5kW/dm\textsuperscript{3}
KEYS for Achieving the Performance Improvement

- Basic Topology
- ZVS Only Achieved by Modified Operation Mode
- Active ZVS
- Triangular Current Mode (TCM)
- Variable Switching Frequency
- No Diode On-State Voltage Drop
- Continuously Guided u, i Waveforms
- Interleaving
- Utilization of Low Superjunct. $R_{DS(on)}$
- Utilization of Digital Signal Processing
- Low Complexity
- No Aux. Circuits
- No (Low) Switching Losses
- No Direct Limit of # of Parallel Trans.
- Simple Symm. of Loading of Modules
- Spread & Lower Ampl. EMI Noise
- Synchr. Rectification
- No Free Ringing $\rightarrow$ Low EMI Filter Vol.
- Low Cond. Losses despite TCM
- Low Control Effort despite 6x Interl.

... despite Using “Old” Si Technology

... the Basic Concept is Known since 1989 (!)
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
Advanced Design
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
Design Challenge

- Design for Specific Performance Profiles Requires Advanced CAD Tools
  - Avoid Try-and-Error
  - Minimize Design Time
Design Challenge

- Advanced Simulations Based Design Allows Multi-Objective Optimization
- Identifies Performance Limits \( \rightarrow \) Pareto Front

- Sensitivities to Technology Advancements (Example: \( \eta - \rho \)-Pareto Front)
- Trade-off Analysis

Design Space

Performance Space
► Analysis of Performance Limits → Pareto Front

- Clarifies Influence of Main Components and Operating Parameters

![Diagram showing power electronic system with labels for components and operating parameters.](image-url)
Analysis of Performance Limits → Pareto Front

- Clarifies Influence of Main Components and Operating Parameters

![Diagram showing the Pareto front with different configurations and parameters.](image)
Example of Advanced Power Electronics Design Platform

Source: GECKO Simulations

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

GeckoEMC
- 3D-Electromagn. Parasitics Extraction
- Reduced Order Impedance Matrix

GeckoCIRCUITS
- Fast Circuit Simulator

GeckoHEAT
- 3D-Thermal FEM Solver
- Thermal Impedance Matrix

Modeling & Design

- Circuit Simulation
- Thermal Simulation
- EM Simulation

Post Processing
Design Metrics Calculation

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Example – Electromagnetic Analysis

- GeckoEMC – PEEC Based
- Analysis of Parasitic Parallel Winding Cap. Cancellation of CM Inductor
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

→ Shift to New Paradigm

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

- “Converter” → “Systems” (Microgrid) or “Hybrid Systems” (Autom. / Aircraft)
- “Time” → “Integral over Time”
- “Power” → “Energy”
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.
Power Electronics Systems Performance Figures/Trends

Complete Set of New Performance Indices

- Power Density [kW/m²]
- Environm. Impact [kWs/kW]
- TCO [$/kW]
- Mission Efficiency [%]
- Failure Rate [h⁻¹]

Supply Chain & Mission Energy Loss
Manufacturing & Recycling Effort
Total Cost of Ownership
State-of-the-Art Floorspace Requirement Future
Example: SMART GRID

Future Renewable Electric Energy Delivery & Management Systems (FREEDM)

- "Energy Internet"
  - Integr. of DER (Distr. Energy Res.)
  - Integr. of DES (Distr. E-Storage) + Intellig. Loads
  - Enables Distrib. Intellig. through COMM
  - AC and DC Distribution

Bidirectional Flow of Power & Information / High Bandw. Comm. → Distrib. / Local Autonomous Cntrl

IFM = Intellig. Fault Management
SST = Solid-State Transformer
Solid-State Transformer

\[ S_N = 630\text{kVA} \]
\[ U_{LV} = 400\text{ V} \]
\[ U_{MV} = 10\text{kV} \]

- **Trade-Off**: Mean-Time-to-Failure vs. Efficiency / Power Density

(5 Cascaded H-Bridges, 1700V IGBTs, No Redundancy, FIT-Rate calculated acc. to \( T_j \), 100FIT Base)
Efficiency Advantage of Direct MV AC – LV DC Conversion

- Comparison to LF Transformer & Series Connected PFC Rectifier (1MVA)

- MV AC/DC Stage Weight (Top) and Costs (Bottom) Breakdown

---

**Characteristic performance indices for 1000 kVA LFTs and SSTs in AC/AC or AC/DC applications.**

<table>
<thead>
<tr>
<th></th>
<th>LFT</th>
<th>AC/AC factor</th>
<th>SST</th>
<th>AC/DC factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>losses [W/kVA]</td>
<td>13.0</td>
<td>×2.75</td>
<td>35.7</td>
<td>×0.58</td>
</tr>
<tr>
<td>costs [USD/kVA]</td>
<td>16.2</td>
<td>×4.75</td>
<td>77.0</td>
<td>×1.12</td>
</tr>
<tr>
<td>volume [l/kVA]</td>
<td>3.43</td>
<td>×0.57</td>
<td>1.96</td>
<td>×0.48</td>
</tr>
<tr>
<td>weight [kg/kVA]</td>
<td>2.59</td>
<td>×0.89</td>
<td>2.30</td>
<td>×0.35</td>
</tr>
</tbody>
</table>

**Performance characteristics overview.**

<table>
<thead>
<tr>
<th></th>
<th>SST MV</th>
<th>SST LV</th>
<th>SST</th>
<th>LFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>efficiency</td>
<td>98.2%</td>
<td>98.2%</td>
<td>96.5%</td>
<td>98.7%</td>
</tr>
<tr>
<td>volume</td>
<td>1.751 m³</td>
<td>0.211 m³</td>
<td>1.962 m³</td>
<td>3.427 m³</td>
</tr>
<tr>
<td>weight</td>
<td>1262 kg</td>
<td>1036 kg</td>
<td>2298 kg</td>
<td>2591 kg</td>
</tr>
<tr>
<td>cost</td>
<td>49.3 kUSD</td>
<td>27.7 kUSD</td>
<td>77.0 kUSD</td>
<td>16 kUSD</td>
</tr>
</tbody>
</table>
3-ph. BUCK-Type Interfaces for DC Distribution Systems

- Comp. Evaluation of 1-Stage vs. 2-Stage (Boost + DC/DC) Conv. Approach Required
AC vs. Facility-Level DC Systems for Datacenters

- Reduces Losses & Footprint
- Improves Reliability & Power Quality

Conventional US $480V_{AC}$ Distribution

Facility-Level $400V_{DC}$ Distribution

Proposal for Public $380V_{DC}/-380V_{DC}$ Systems by Philips, etc.
System Oriented Analysis

Cascading Effect

1W saved at Telco Loads Saves 2.42W of Total consumption
Smart Grid Control Challenge

- Dynamics → from Transient Balance by Kin. Storage (No Cntrl) to ms-Active Power Flow Control
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

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, ...

Power Electronics 2.0
Technology S-Curve

...after Switches and Topologies

“Passives” & Advanced Design
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
Future Developments

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