Vision – Power Electronics 2025

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Power Electronics 2.0

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Outline

- Evolution of Power Electronics
- Performance Trends / Enablers & Barriers / New Paradigms
- Characteristics of Power Electronics 2.0
- Conclusions
Evolution of Power Electronics
History and Development of the Electronic Power Converter

E. F. W. ALEXANDERSON  E. L. PHILLIPPI
FELLOW AIEE  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 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 28-30, 1944. Manuscript submitted April 24, 1944. Made available for printing May 18, 1944.

E. F. W. Alexander and E. L. Phillips are with the General Electric Company, Schenectady, N. Y.
United States Patent Office

3,517,300
POWER CONVERTER CIRCUITS HAVING A
HIGH FREQUENCY LINK
William McMurray, Schenectady, N.Y., assignor to Gen-
eral Electric Company, a corporation of New York
Filed Apr. 16, 1968, Ser. No. 721,817
Int. Cl. H02m 5/16, 5/30
U.S. Cl. 321—60 14 Claims

1970!

Fig. 1a

Fig. 1b

Fig. 1c

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

ECPE Roadmap
2015 Workshop
[54] THREE PHASE AC TO DC VOLTAGE CONVERTER WITH POWER LINE HARMONIC CURRENT REDUCTION

[75] Inventors: Roger F. Brewster; Alfred H. Barrett, both of Santa Barbara, Calif.

[73] Assignee: General Motors Corporation, Detroit, Mich.

[21] Appl. No.: 894,739

[22] Filed: Apr. 10, 1978

[57] ABSTRACT
A three phase AC to DC voltage converter includes separate single phase AC to DC converters for each phase of a three phase source with the DC voltage output of the three converters paralleled and controlled to provide necessary regulation. Each of the single phase AC to DC converters includes a full-wave bridge rectifier feeding a substantially resistive load including an inverter and a second single phase full-wave bridge rectifier. To the extent that each inverter and second single phase full-wave bridge rectifier approximate a resistive load, the source current harmonics are reduced. Additionally, the triplen harmonics produced in the three phase source lines by each of the three AC to DC converters are cancelled by the triplen harmonics produced in the three phase source lines by the remaining two AC to DC converters.

2 Claims, 1 Drawing Figure
United States Patent [19]

4,412,277


Oct. 25, 1983

1983!

[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
Technology S-Curve

Power Electronics 2.0

- Super-Junct. Techn. / WBG
- Digital Power Modeling & Simulation
- Power MOSFETs/IGBTs
- Microelectronics
- Circuit Topologies
- Modulation Concepts
- Control Concepts

Paradigm Shift (?)

2014

2025

Emerging
Established
Mature

Replacement (Disruptive) Technology

Existing Technology

Effort / Time

Performance

SCRs / Diodes
Solid-State Devices
Technology S-Curve

- **Sub-S-Curves**
  - Overall Development Defined by Improvement of Core Technologies

**Importance**
1. Power Semiconductors (incl. Package)
2. Microelectronics / Signal Processing
3. Topologies
4. Analysis / Modeling & Simulation
Performance Indices → Coupling & Limits
Power Electronics Converters 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 \([\text{[h}^{-1}]\)

- **State-of-the-Art**
- **Future**
- **Time-to-Market**
- **Costs**
- **Weight**
- **Volume**
- **Losses**
- **Failure Rate**

\[
\text{[kg}_{\text{Fe}}/\text{kW}] \\
\text{[kg}_{\text{Cu}}/\text{kW}] \\
\text{[kg}_{\text{Al}}/\text{kW}] \\
\text{[cm}^2/\text{Si}/\text{kW}]
\]
Analysis of Performance Limits \( \rightarrow \) Pareto Front

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

Design Space

Performance Space
η-ρ-σ-Pareto Surface

- σ: kW/$
Experimental Verification of Performance Limits

→ 3-ph. VIENNA Rectifier
→ 1-ph. PFC Rectifiers
Demonstrator #1 → 3-ph. VIENNA Rectifier

Specifications

\[ U_{ll} = 3 \times 400 \, V \]
\[ f_N = 50 \, Hz \ldots 60 \, Hz \ldots 800 \, Hz \]
\[ P_o = 10 \, kW \]
\[ U_o = 2 \times 400 \, V \]
\[ f_s = 250 \, kHz \]

Characteristics

\[ \eta = 96.8 \% \]
\[ \text{THD}_i = 1.6 \% \, @ \, 800 \, Hz \]
\[ 10 \, kW/dm^3 \]
\[ 3.3 \, kg \, (\approx 3 \, kW/kg) \]

Dimensions: 195 x 120 x 42.7 mm\(^3\)
Demonstrator #1 → 3-ph. VIENNA Rectifier

- Experimental Evaluation of Generation 1 – 4 of VIENNA Rectifier Systems

Switching Frequency of $f_s = 250$ kHz Offers Good Compromise Concerning Power Density / Weight per Unit Power, Efficiency and Input Current Quality THD

- $f_s = 50$ kHz, $\rho = 3$ kW/dm$^3$
- $f_s = 72$ kHz, $\rho = 4.6$ kW/dm$^3$
- $f_s = 250$ kHz, $\rho = 10$ kW/dm$^3$ (164 W/in$^3$), Weight = 3.4 kg
- $f_s = 1$ MHz, $\rho = 14.1$ kW/dm$^3$, Weight = 1.1 kg
Demonstrator #2 → 1-ph. Bridgeless PFC Rectifiers

Power Density is Based on Net Volumes → Scaling by 0.6–0.8 Necessary

$u_N = 230V$
Pareto Front of Power Semiconductors

- Trade-Off Between Conduction and Switching Losses

- Improvement Through Changes in Device Structure → E.g. Introduction of Trench Gate and Fieldstop Layer
Observation

- “Standard” / Relatively High Performance Solutions for Nearly All Key Applications Existing Today!

- Very Limited Room for Further Perform. Improvement → only COST Reduction (!)
General Remark

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

- Example: Scaling Law of Transformers

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

- \( \hat{B}_{\text{max}} \) ... Very 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 Passives → We are Left with Progress in Material Science (Takes Decades)
General Remark (2)

- Expected (Slow) Technology Progress of Passives

  - **Foil Capacitors**
    
    OPP = Oriented Polypropylene
    
    PHD = Advanced OPP
    
    COC = Cycloolefine Copolymers
    
  - **Cooling**
    
    Air Cooling
    
    Water Cooling
    
    Refrigeration Technologies
    
- similar for Magnetics
Next Evolutional Step

“... Prediction is Very Difficult, Especially if it's About the Future ...”

(N. Bohr)
“Optimistic” View
Optimistic View → Break Through (Shift) the Barriers

- Degrees of Freedom
  - Topologies
  - Modulation Schemes
  - Control Schemes
  - etc.

Remark: Designer's Point of View (Given Semiconductors & Base Materials)

... only if not Fundamental Physical Properties
New Topologies
"Snubbers" (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
"Snubbers" (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

— Another Indication for a “Natural” Performance Limit

Comparison of various PFC options: complexity of control vs better semiconductors

Source: Dr. Gerald Deboy
Plenary Presentation @ IECON 2013, Vienna

- Minimum Performance Difference for Best Matching of Topology/Semicond./Modulation
- Only Use BASIC Topologies - Costs are THE Deciding Criteria (!)
► New Converter Topologies

■ Very Large Number of Options!

Example: Topologies for Three-Element Resonant Converters

Rudolf P. Severns

26 out of 48 Topologies are of Potential Interest

Fig. 13. Source-network-load combinations.

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

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

■ Tools for Comprehensive Comparative Evaluation Urgently needed!
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
Frequently lower performance of integrated 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

![Diagram showing the relationship between performance, functionality, cost, and improved cost-performance ratio.]

■ Cost / Performance Ratio is a Key Metric for Industry Success (Sales Argument)
■ Extreme Restriction of Functionality

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

Adopted e.g. by VICOR – “Sine Amplitude Converter” - for Factorized Power Architecture

Resonant Freq. ≈ Switching Freq. → Input/Output Voltage Ratio = \( N_1/N_2 \) (Steigerwald, 1988)
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

■ Basic Concept @ Example of Parallel Interleaving

— Multiplies Frequ. / Red. Ripple @ Same Switching Losses & Increases 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

H. Ertl, 2003
Multi-Cell Converters

Example of Series Interleaving

- Multiplies Frequ./Red. Ripple @ Same Switching Losses & Increases Control Dynamics

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

- Especially Advantageous for Ohmic On-State Behavior of Power Switches (!)
- Redundancy → Allows Large Number of Units without Impairing Reliability
Multi-Cell Converters

Example of **Series** Interleaving

Scaling of $R_{DS, on}$ of MOSFETs with Blocking Voltage → Loss Red. by Factor of 8 for $N=4$

- Especially Advantageous for Ohmic On-State Behavior of Power Switches (!)
- Redundancy → Allows Large Number of Units without Impairing Reliability
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

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

- 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)

\[
P_{S,N} \approx P_{S,N=1} \cdot \left( \frac{1}{2N^2} \cdots \frac{1}{N^3} \right)
\]
Multi-Cell Converters – Summary

**Advantages**
- Switching Frequency Multiplication @ No Loss Increase
- Ripple Reduction @ Input and Output
- Distribution of Losses (Parallel Connect. of Therm. Resistances)
- Larger Surface / Volume Ratio of Indiv. Unit (Easier Cooling)
- Redundancy Possible (High Reliability)
- Deactivation of Units at Part Load (High Part Load Efficiency)
- Solves the Impedance Matching Problem @ High I or U
- Multiplies U, I Capabilities of Single Devices (Very High U,I possible)
- Reduction of Eff. RDS(on) (Shifting Si-Limit for Series Connection)
- Eff. Increase of Switching Speed @ Given du/dt, di/dt
- Supports Standardization (Potential Cost Reduction)
- Minimizes Time-to-Market (Allows Platform Solutions)
- Supports PCB Realization even for High Current (Current Partitioning)

**Challenges**
- Handling of Control Complexity (Digital Control)
- Overall Complexity Increasing Costs (Economy of Scale?)
- Symmetrization of the Loading of the Individual Units

**Idea for Supporting Technology**
PCBs with Embedded Optical Fibers / Link

... a Highly Powerful Concept with Large Potential (!)
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
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

- AC-DC Rectifier - Single Boost Cell - Measurements

- Hard Turn-On (Partial ZVS)

- ZVS Turn-On by Ext. On-Interval of $S_{11}$ (TCM)
Bidirectional Ultra-Efficient 1-Φ PFC Mains Interface

★ 99.36% @ 1.2kW/dm³

Hardware Testing to be finalized in September 2011

- 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
Converter Performance Evaluation Based on $\eta$-$\rho$-Pareto Front

![Graph showing efficiency ($\eta$) vs. power density ($\rho$) for different rectifier configurations.]

- **Triple-Interleaved TCM Rectifier (33kHz)**
- **Double-Interleaved Double-Boost CCM Rectifier (33kHz)**
- **Double-Interleaved Double-Boost CCM Rectifier (450kHz)**
- **Triple-Interleaved TCM Rectifier (56kHz)**
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

... despite Using “Old” Si Technology

- 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.

... the Basic Concept is Known since 1989 (!)
Is Another Step of Massive Improvement Possible?

- Triple-Interleaved TCM Rectifier (56kHz)
- Double-Interleaved Double-Boost CCM Rectifier (450kHz)
- Double-Interleaved Double-Boost CCM Rectifier (33kHz)
- Triple-Interleaved TCM Rectifier (33kHz)

99% @ 10kW/dm³
Solution: **ISOP Multi-Cell Approach (!)**

- **Isolated 380V/48V Telecom DC-DC Converter**
- **8 x 300W 48V/48V VICOR Modules**
- **96.5% Efficiency @ 16kW/l Power Density (!)**

![Diagram of ISOP Multi-Cell Approach](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Output Power</td>
<td>2400W</td>
</tr>
<tr>
<td>Rated Input Voltage</td>
<td>384V</td>
</tr>
<tr>
<td>Rated Output Voltage</td>
<td>48V</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>VICOR</td>
</tr>
<tr>
<td>Part Number</td>
<td>V048F480T006</td>
</tr>
<tr>
<td>Rated Power</td>
<td>336W</td>
</tr>
<tr>
<td>Size (W, D, H)</td>
<td>22mm, 32.5mm, 6.73mm</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>26V – 55V</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>26V – 55V</td>
</tr>
<tr>
<td>Efficiency</td>
<td>96.4% (at Full Load)</td>
</tr>
</tbody>
</table>
Solution: **ISOP Multi-Cell Approach (!)**

- Isolated 380V/48V Telecom DC-DC Converter
- 8 x 300W 48V/48V VICOR Modules
- 96.5% Efficiency @ 16kW/l Power Density (!)
“Killer”- Semiconductor Technologies

WBG Power Semiconductors

... Not a Merit of Power Electronics but of Power Semiconductor Research
WBG Power Semiconductors

Example: SiC Schottky Diode – Zero Recovery Rectifiers

General Capabilities
- Higher Switching Frequency
- Higher Operating Temperature
- Higher Blocking Capability
But ...

Today the Capabilities of SiC Cannot be Utilized

- Fast Switching Capability
- High Temp. Capability
- High Blocking Capability

- Limit by Package (Layout) Parasitics
- Missing High Temp. Passives
- Multi-Level Topologies!
- Missing MV / Low Inductance Package
Higher Switching Speed

- Boost inductor
- Termination network
- Output capacitors $C_{out}$

100V/Div

10A/Div

50ns/Div

Missing HF Package

Missing Integrated Gate Drive (Active Control of Switching Trajectory)
Active Closed Loop Gate Drive

- Single Op-Amp as PI-Controller

- Continuous (!) Control of the Switching Trajectory incl. Short Circuit
- Options for Monitoring / Reliability 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 (!)
GE Planar Power Polymer Packaging (P4™)

Oriented Toward High Power Devices
<2400V / 100A...500A
<200W Device Dissipation

Wire-Bonded Die on Ceramic Substrate
Replaced with Planar Polymer-Based Interconnect Structure

Direct High-Conductivity Cooling Path
GE Planar Power Polymer Packaging (P4™)

- Reduces Wire Bond Resistance by Factor 100
- Significantly Lower Switching Overvoltages
- Reduced Switching Losses
- No Ringing
- Reduces EMI Radiation
- Enables Topside Cooling
- No Mechanical Stress of Wire Bond Process
- Reduces CTE Wire Bond Stress on Chip Pads
Novel PCB Technologies for High Power Density Systems

- Chip in Polymer Process / Multi-Functional PCB

- Chip Embedding by PCB Technology
- Direct Cu Contact to Chip / No Wires or Solder Joints
- Thin Planar Packaging enables 3D Stacking
- Improved Electrical Performance and Reliability
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
- Thermal Management

“Fab-Less” Power Electronics
- Testing is Challenging (Only Voltage Measurement)
- Advanced Simul. Tools of Main Importance (Coupling with Measurem.)
3ph. Inverter in p²pack-Technology

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

- Rated Power: 32kVA
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3ph. Inverter in p²pack-Technology

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Power Semiconductor PCB Integration

- Current Measurement
- Auxiliary Supply
- Gate Driver
- Protection Circuit
- DSP
- Powerlink
- Encoder Interface
- USB
- CAN
- Voltage Measurement
High Temperature (I)

Si Temp. Limit $T_j = 175^\circ C$

120$^\circ$C Ambient Air Cooled Automotive Inverter
High Temperature (II)

Thermal Concept of Inverter System
► High Temperature (III)

- Missing HT Package (Reliability)
- Missing HT Sensors  & Control Electronics & Fans  etc.
Power Semiconductors
Load Cycling Capability

- New Die Attach Technologies, e.g.
  Low-Temperature Sinter Technology

Source: Dr. Miller / Infineon
Observation

- SiC … Not Yet a "Killer" Technology  
  Future:  $U > 1.7\, \text{kV}$

- GaN (!) … Cost Advantage  
  Only for $U < 600\, \text{V}$ in 1st Step

- Do Not Forget the Continuous Improvement of Si Devices (!)
- System Level Adv.e of SiC Still to be Clarified (More Basic Topologies, Smaller Passives)
- SiC for High Efficiency (e.g. for PV or for High Power Density / Low Cooling Effort)
New Simulation Tools
Example: Efficiency Optimization

- Constant Inductor Volume
- Variation of $f_p$

99.2% @ 1.6 kW/dm³

“Flat” Optima for Practical (Robust) Systems → Good Engineering – Similar Result
Future Design Process

- 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)
Resulting Research Topics
Potential Research Topics

- **Components**
  - WBG
  - Interconnections
  - Packaging
  - MF Insulation
  - Cooling Concepts
  - Active Gate Control
  - Acoustic Noise of Mag. Comp.
  - Wireless Sensing / Monitoring.
  - etc.

- **Converters**
  - * Magnetic
  - * Semicond.
  - * Power & Information

- **Systems**
  - Benchmark SiC / GaN
  - High Freq. / High Curr.
  - Low Ind. MV Package
  - Partial Discharge @ MF
  - Airbearing Cooler etc.
  - d/dt Feedback and u,i-Limit
  - Magnetic Ear
  - Influence of DC Magn.
  - Wireless Voltage Probe

- **Integration**
  - Inductor/Transformer
  - Interph. Transf., Coupl. Ind.
  - CM/DM EMI Filter
  - RB-, RC-IGBTs

- **Hybridization**
  - Act./Passive
  - Hybrid Filters / SSTs etc.

- More Oriented to Spec. Application
- Important but Mostly Incremental
Potential Research Topics

- Components
- Converters
- Systems

- New Topologies & Modularization
  * MV/MF DC/DC → Const. V-Transf. Ratio
  * Extr. Conv. Ratio → Series Conn. of Switches
  * Extr. Efficiency → Aux. Supplies
  * High Curr. → Datacenters / DC Distr.
  * High Pressure → Parallel Operat. of Conv.
  * Integ. of Funct. → Subsea Appl.
  * Fault Tolerance → Supply & Filtering etc.

- Control
  * Distr. Conv. Syst. → Traction/Ship/Aircraft/Subsea

- Comp. Evaluation
  * Multi-Objective → Cost Models
  → Reliability / Lifetime Models
  → Circ. / Magn. Models

- More Oriented to Spec. Application
Potential Research Topics

- Components
- Converters
- Systems

Systems incl. Hybrid Systems

- Converter & Load
- Power & Inf.
- Hydraulic/El.
- Wireless Power
- etc.

→ Losses Conv. vs. Machine
→ Smart Houses
→ Smart Batteries etc.
→ Hybrid Cranes/Constr. Mach.
→ Ind. Power Transfer incl. Inf.

Important ➔ Large Future Potential!
“Optimistic” View
Barriers can be shifted,
New converter technologies etc.

“Pessimistic” View
”Pessimistic” View \( \rightarrow \) Consider Converters like “ICs”

- If Only Incremental Improvements of Converters Can Be Expected

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

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

Shift to New Paradigm

![Change Ahead Sign]
"Pessimistic" View → 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.
Example: Smart Grid

Hierarchically Interconnected Hybrid Mix of AC and DC Sub-Grids

- Distr. Syst. of Contr. Conv. Interfaces
- Source / Load / Power Distrib. Conv.
- Picogrid-Nanogrid-Microgrid-Grid Structure
- Subgrid Seen as Single Electr. Load/Source
- ECCs provide Dyn. Decoupling
- Subgrid Dispatchable by Grid Utility Operator
- Integr. of Ren. Energy Sources

ECC = Energy Control Center

- Energy Routers
- Continuous Bidir. Power Flow Control
- Enable Hierarchical Distr. Grid Control
- Load / Source / Data Aggregation
- Up- and Downstream Communic.
- Intentional / Unintentional Islanding for Up- or Downstream Protection
- etc.
Example: FREEDM Systems
Future Renewable Electric Energy Delivery & Management Systems

“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
Solid-State Transformer

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

- **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)
Power Electronics Systems Performance Figures/Trends

- Complete Set of New Performance Indices
  - Power Density [kW/m²]
  - Environmental Impact [kWs/kW]
  - TCO [$/kW]
  - Mission Efficiency [%]
  - Failure Rate [h⁻¹]

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

ECPE Roadmap 2025 Workshop
AC vs DC Power Systems for Data Centers
Reduce Loss, Footprint; Improve Reliability, Power Quality

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Possible Future Extensions of Power Electronics Systems Applications

Source: AIST
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

- Establish (Closer) University / Industry (Technology) Partnerships
- Establish Cost Models, Consider Reliability as Performance
University Education Orientation

Need to Insist on High Standards for Education

- Introduce New Media
- Show Latest Stat of the Art (requires New Textbooks)
- 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” & EMI are THE Main Issue of the Next Decade + Costs + Systems

- Super-Junct. Techn. / WBG
- Digital Power Modeling & Simulation
- Power MOSFETs/IGBTs
- Microelectronics
- Circuit Topologies
- Modulation Concepts
- Control Concepts

Paradigm Shift

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Performance

Emerging

Established

Mature

Replacement (Disruptive) Technology

Existing Technology

Effort / Time

SCRs / Diodes

Solid-State Devices

2014

2025
Power Electronics 2.0

New Application Area
- 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 ?