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. PHILLIP
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 26-30, 1944. Manuscript submitted April 25, 1944, made available for printing May 18, 1944.
E. F. W. Alexanderson and E. L. Phillip are with the General Electric Company, Schenectady, N. Y.

1944!
POWER CONVERTER CIRCUITS HAVING A HIGH FREQUENCY LINK
William McMurray, Schenectady, N.Y., assignor to General 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
THREE PHASE AC TO DC VOLTAGE CONVERTER WITH POWER LINE HARMONIC CURRENT REDUCTION

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

Assignee: General Motors Corporation, Detroit, Mich.

Appl. No.: 894,739

Filed: Apr. 10, 1978

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
▲ Technology S-Curves

■ Sub-S-Curves

— Overall Development Defined by Improvement of Core Technologies

■ Importance

1. Power Semiconductors
2. Microelectronics / Signal Processing
3. Topologies
4. Analysis / Modeling & Simulation

Source: Dr. Miller / Infineon
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 \([\text{[h}^{-1}\text{]}]\)
Analysis of Performance Limits

- Coupling of Power Density & Efficiency
  (Example of Forced Convection Cooling)

\[ P_O = \eta P_i \]

\[ \rho_{lim} = \frac{P_O}{Vol_{CS}} \]

\[ P_{Loss} = (1 - \eta) P_i \]

\[ Vol_{CS} = \frac{G_{th}}{CSPI} = \frac{P_{Loss}}{\Delta T_{s-a}} \frac{1}{CSPI} \]

\[ \eta = 97\% \]

- \( T_s = 90^\circ C \)
- \( T_s = 135^\circ C \)  
  \((T_a = 45^\circ C, \text{ CSPI} = 20 \text{ WK}^{-1}\text{dm}^{-3})\)

\[ \rho_{lim} = 29 \text{ kW/dm}^3 \]

\[ \rho_{lim} = 58 \text{ kW/dm}^3 \]
Analysis of Performance Limits

- Coupling of Power Density & Efficiency
  (Example of Inductor Losses vs. Volume)

  - Scaling of Core Losses
    \[ P_{\text{Core}} \propto f_p \left( \frac{\Phi}{A} \right)^2 V \]
    \[ P_{\text{Core}} \propto \left( \frac{1}{l^2} \right)^2 l^3 \propto \frac{1}{l} \]

  - Scaling of Winding Losses
    \[ P_{\text{Wdg}} \propto I^2 R \propto I^2 \frac{l_{\text{Wdg}}}{\kappa A_{\text{Wdg}}} \]
    \[ P_{\text{Wdg}} \propto \frac{1}{l} \]
► Determine the Barrier(s)

Abstraction of Power Converter Design

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

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

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

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

► Mapping of Design Space into System Performance Space
Mathematical Modeling and Optimization of the Converter Design

► Determine the Barrier(s)
Determine the Barrier(s)

- Multi-Objective Converter Design Optimization
- Limit of Feasible Performance Space (Pareto Front)
Determine the Barrier(s)

- Sensitivity to Technology Advancements (Example: $\eta$-\(\rho\)-Pareto Front)
- Trade-off Analysis
η-ρ-σ-Pareto Surface

- σ: kW/$
η-ρ-σ-Pareto Surface

"Technology Node" - Min. Costs = Max. (kW/$)
Experimental Verification of Performance Limits

→ 3-ph. VIENNA Rectifier
→ 1-ph. PFC Rectifiers
Specifications

\[ U_{LL} = 3 \times 400 \text{ V} \]
\[ f_N = 50 \text{ Hz} \ldots 60 \text{ Hz or } 360 \text{ Hz} \ldots 800 \text{ Hz} \]
\[ P_o = 10 \text{ kW} \]
\[ U_o = 2 \times 400 \text{ V} \]
\[ f_s = 250 \text{ kHz} \]

Characteristics

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

Demonstrator #1 → 3-ph. VIENNA Rectifier

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

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

- Mains Behavior @ $f_N = 400\text{Hz} / 800\text{Hz}$

\begin{align*}
P_o &= 10\text{kW} \\
U_N &= 230\text{V} \\
f_N &= 400\text{Hz} \\
U_O &= 800\text{V} \\
THD_i &= 1.4\% \\

P_o &= 10\text{kW} \\
U_N &= 230\text{V} \\
f_N &= 800\text{Hz} \\
U_O &= 800\text{V} \\
THD_i &= 1.6\% \\
\end{align*}
**Demonstrator #1 → 3-ph. VIENNA Rectifier**

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

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

- $f_s = 50 \text{ kHz}$
  - $\rho = 3 \text{ kW/dm}^3$
  - Weight = 3.4 kg

- $f_s = 72 \text{ kHz}$
  - $\rho = 4.6 \text{ kW/dm}^3$

- $f_s = 250 \text{ kHz}$
  - $\rho = 10 \text{ kW/dm}^3$
  - (164 W/in$^3$)
  - Weight = 3.4 kg

- $f_s = 1 \text{ MHz}$
  - $\rho = 14.1 \text{ kW/dm}^3$
  - 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 Performance Improvement
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

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<td>30 nH</td>
<td>15 nH</td>
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Source: EPCOS

Cooling limits

Source: SIA
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
  - Thermal Management
  - etc.

... only if not Fundamental Physical Properties

- Remark: Designer's Point of View (Given Semiconductors & Base Materials)
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
Change Operation of BASIC Structure Instead of Adding Aux. Circuits

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

98% Efficiency
29kW/dm³

Snubbers (2)
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)
Cost / Performance Ratio is a Key Metric for Industry Success (Sales Argument)

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

Extreme Restriction of Functionality

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 = \( \frac{N_1}{N_2} \) (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

H. Ertl, 2003
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

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

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

H. Ertl, 2003
Multi-Cell Converters

- Example of **Series** Interleaving

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

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

→ VRM
→ Ultra-Efficient 1ph. PFC
→ Telecom Power Supplies
→ Solid-State Transformer
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

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

Efficiency $\eta$ (%) vs Power density $\rho$ (kWdm$^{-3}$)
**Isolated 2.4kW 380V/48V Telecom DC-DC Converter**

- **8 x 300W 48V/48V High Power Density /Efficiency Converter Modules**
- **Input Series / Output Parallel (ISOP) Connection**

- **96.5% Efficiency @ 16kW/l Power Density (!)**

---

**Parameter** | **Value**
--- | ---
Total Output Power | 2400W
Rated Input Voltage | 384V
Rated Output Voltage | 48V
Manufacturer | VICOR
Part Number | V048F480T006
Rated Power | 336W
Size (W, D, H) | 22mm, 32.5mm, 6.73mm
Input Voltage | 26V – 55V
Output Voltage | 26V – 55V
Efficiency | 96.4% (at Full Load)
Isolated 2.4kW 380V/48V Telecom DC-DC Converter

- 8 x 300W 48V/48V High Power Density /Efficiency Converter Modules
- Input Series / Output Parallel (ISOP) Connection

- 96.5% Efficiency @ 16kW/l Power Density (!)
Solid-State Transformer

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

- Trade-Off \to Efficiency / Power Density

DCM Series
Resonant
DC/DC Converter

(1) Transformer
(2) LV Semiconductors
(3) MV Semiconductors
(4) DC Link
(5) Resonant Capacitors
Solid-State Transformer

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

- Trade-Off \rightarrow 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)
"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
But ...

Today the Capabilities of SiC Cannot be Utilized

— Fast Switching Capability

► Limit by Layout Parasitics
But ... Today the Capabilities of SiC Cannot be Utilized

- Fast Switching Capability
- High Temp. Capability

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— High Temp. Capability

► Limit by Layout Parasitics
► Missing High Temp. Package (Therm. Cycles)
But ...

Today the Capabilities of SiC Cannot be Utilized

- Fast Switching Capability
- High Temp. Capability

- Limit by Layout Parasitics
- Missing High Temp. Passives
But ...  

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But ...

Today the Capabilities of SiC Cannot be Utilized

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

- Limit by Layout Parasitics
- Missing High Temp. Passives
- Multi-Level Topologies!
But ... Today the Capabilities of SiC Cannot be Utilized

— Fast Switching Capability
— High Temp. Capability
— High Blocking Capability

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

- Missing HF Package
- Missing Integrated Gate Drive (Active Control of Switching Trajectory)
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.)
High Temperature (I)

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

120° C Ambient Air Cooled Automotive Inverter
High Temperature (II)

Thermal Concept of Inverter System

- Power Semiconductors and Cooling
- Signal Electronics

Volume Share

- 0.2
- 0.3
- 0.23
- 0.2

T_{amb}=120°C

T=160°C

T_{amb}=120°C
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
- GaN (!) ... Cost Advantage

Future: $U > 1.7kV$
Only for $U < 600V$ in 1st Step

- Do Not Forget the Continuous Improvement of Si Devices (!)
- System Level Advantage of SiC Still to be Clarified (More Basic Conv. Topologies)
- 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** $f_p$

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

- Virtual Prototyping

2010

- Hardware Prototyping
  - 80%
  - 20%

2020

- Multi-Domain Modeling / Simulation / Optimization
  - 20%
  - 80%

- Reduces Time-to-Market
- More Application Specific Solutions (PCB, Power Module, and even Chip)
- 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**
  - 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

- **Systems**
  - Integration
    - * Magnetic
      - Inductor/Transformer
      - Interph. Transf., Coupl. Ind.
      - CM/DM EMI Filter
      - RB-, RC-IGBTs
    - * Semicond.
    - * Power & Information

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

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

- **Components**
  - MV/MF DC/DC
  - MV-Connect.
  - Extr. Conv. Ratio
  - Extr. Efficiency
  - High Curr.
  - High Pressure
  - Integr. of Funct.
  - Fault Tolerance

- **Converters**
  - Const. V-Transf. Ratio
  - Series Conn. of Switches
  - Aux. Supplies
  - Datacenters / DC Distr.
  - Parallel Operat. of Conv.
  - Subsea Appl.
  - Supply & Filtering etc.

- **Systems**
  - Distr. Conv. Syst.
  - Traction/Ship/Aircraft/Subsea
  - Parasitic Curr.
  - Circul. Curr. / CM Curr. etc.
  - Highly Dyn. Conv.

- **Control**
  - 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 → 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"
"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"
- Integ. of DER (Distr. Energy Res.)
- Integ. 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

Example: FREEDM Systems
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
3-ph. PV Inverter Syst. → Si vs. SiC

\[ U_N = 400 \text{ V} \]
\[ U_{PV} = 450 \ldots 820 \text{ V} \]
\[ P = 10 \text{ kW} \]
\[ f_S = 4 \ldots 16 \text{ kHz} \]

Cost Models → Efficiency / Power Density Analysis Extended to Initial Costs & Operating Revenue Calculation
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

- Increasing Number of Papers on Spec. Applications
- Missing Knowledge of High Industry Techn. Level
- Very Few Papers on Basic Questions (Scaling etc.)
- Very Few Cross-Disciple Papers
- Limitation in Scope ("Slice-by-Slice")
- Highly Complex Solutions (Ph.D. Thesis, Low Impact)
- Terminology “Hyper-Super-Ultra....”
- Hype Cycles (Citation Index Driven)

Citation Index Driven Research Potentially Avoids New High Risk Topics
Citation Index Driven Research

Generates Hype Cycles

E.g., 3-Φ AC-AC Matrix Converter vs. Voltage DC Link Converter
University Research Orientation

Need to Insist on **High Standards for Publications**

— E.g. Besides Describing a New Approach

* Compare to Standard Approach Considering ALL Important Aspects
* Compare to Typical Industry Performance
* Show Several Performances (e.g. Not only Efficiency)
* Show Limits of Applicability (only then a Judgment can be Made)

— Example: EMI Filter

* Determine required Attenuation and L and C Values
* Basic Magnetic Design
* Core and Winding Losses (incl. DC, HF) & Thermal Model
* Optim. of L and C Concerning Rippel etc. for Min. Volume/Losses
* Determine Self-Parasitics
* Component Placement and Analysis of Mutual Coupling
* Check for Control Stability

→ Fully Optimized “Embedded” Component (in Relation to Rest of Conv.)
University Research Orientation

- 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
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, ...

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) 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?