ETH
Eidgenössische Technische Hochschule Zürich
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Envision on Future Power Electronics

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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
FELLOW AIEE

E. L. PHILLIPI
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.

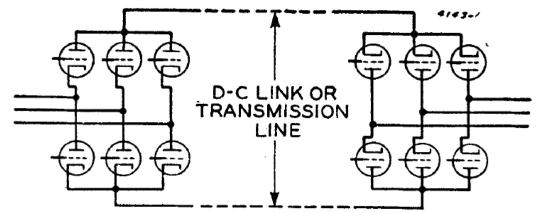


Figure 1. Electronic converter, dual-conversion type

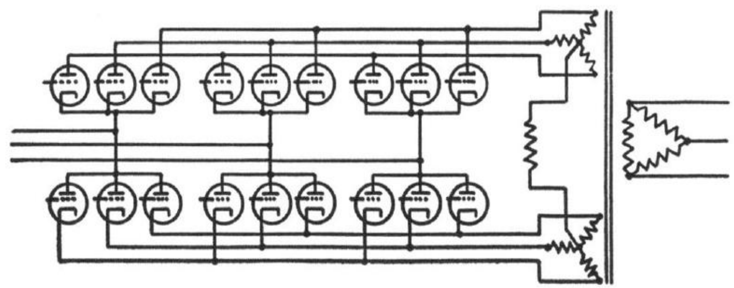
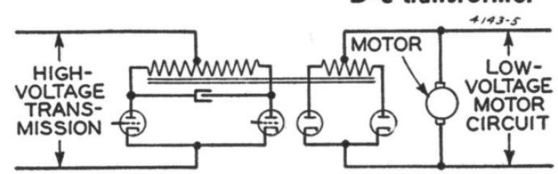


Figure 4 (left). Single - conversion-type frequency changer

Figure 5 (below). D-c transformer



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

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

1944 !

United States Patent Office

3,517,300
Patented June 23, 1970 ← **1970!**

3,517,300
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

Fig. 1a

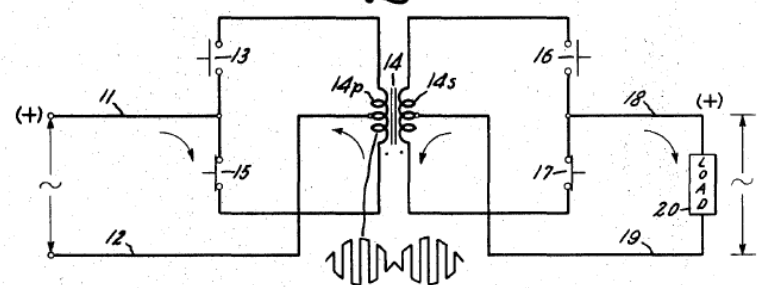


Fig.4(a)
Fig.4(b)
Fig.4(c)

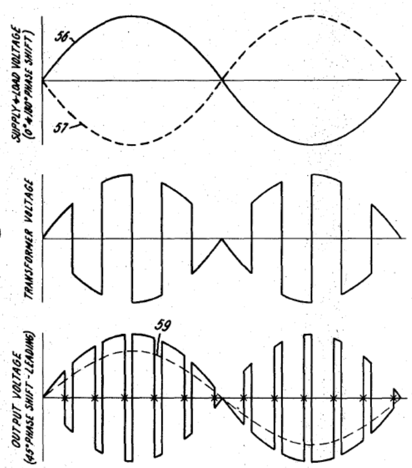
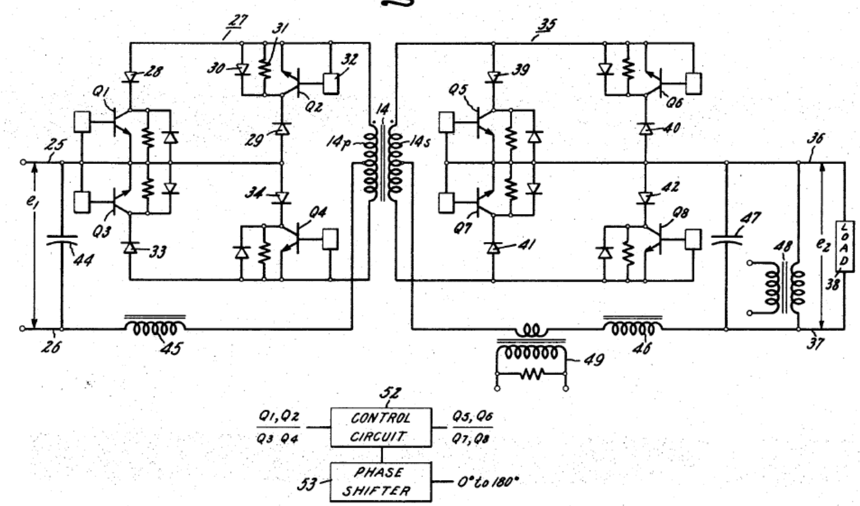


Fig. 3



United States Patent [19] [11] **4,143,414**

Brewster et al. [45] **Mar. 6, 1979** ← **1979!**

[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.

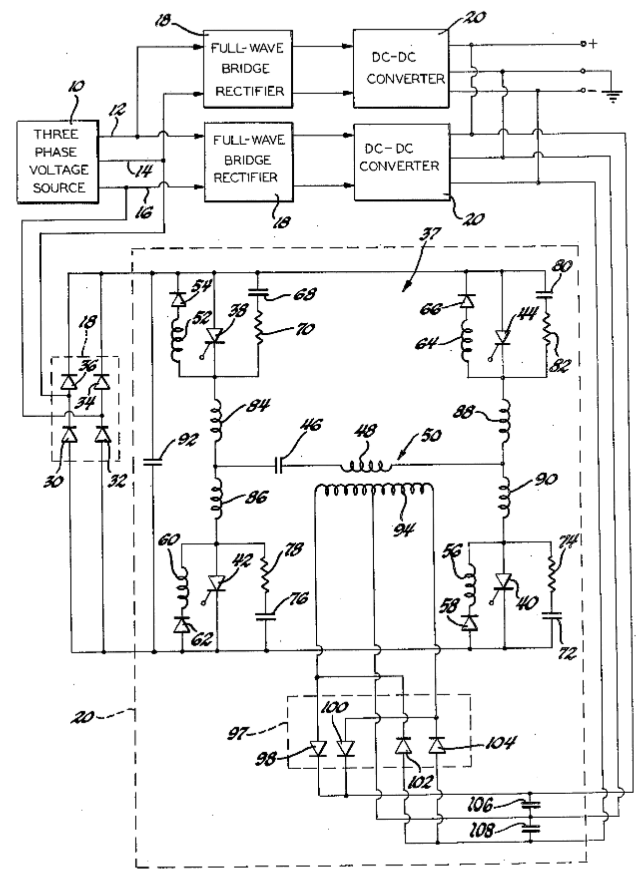
[21] Appl. No.: **894,739**

[22] Filed: **Apr. 10, 1978**

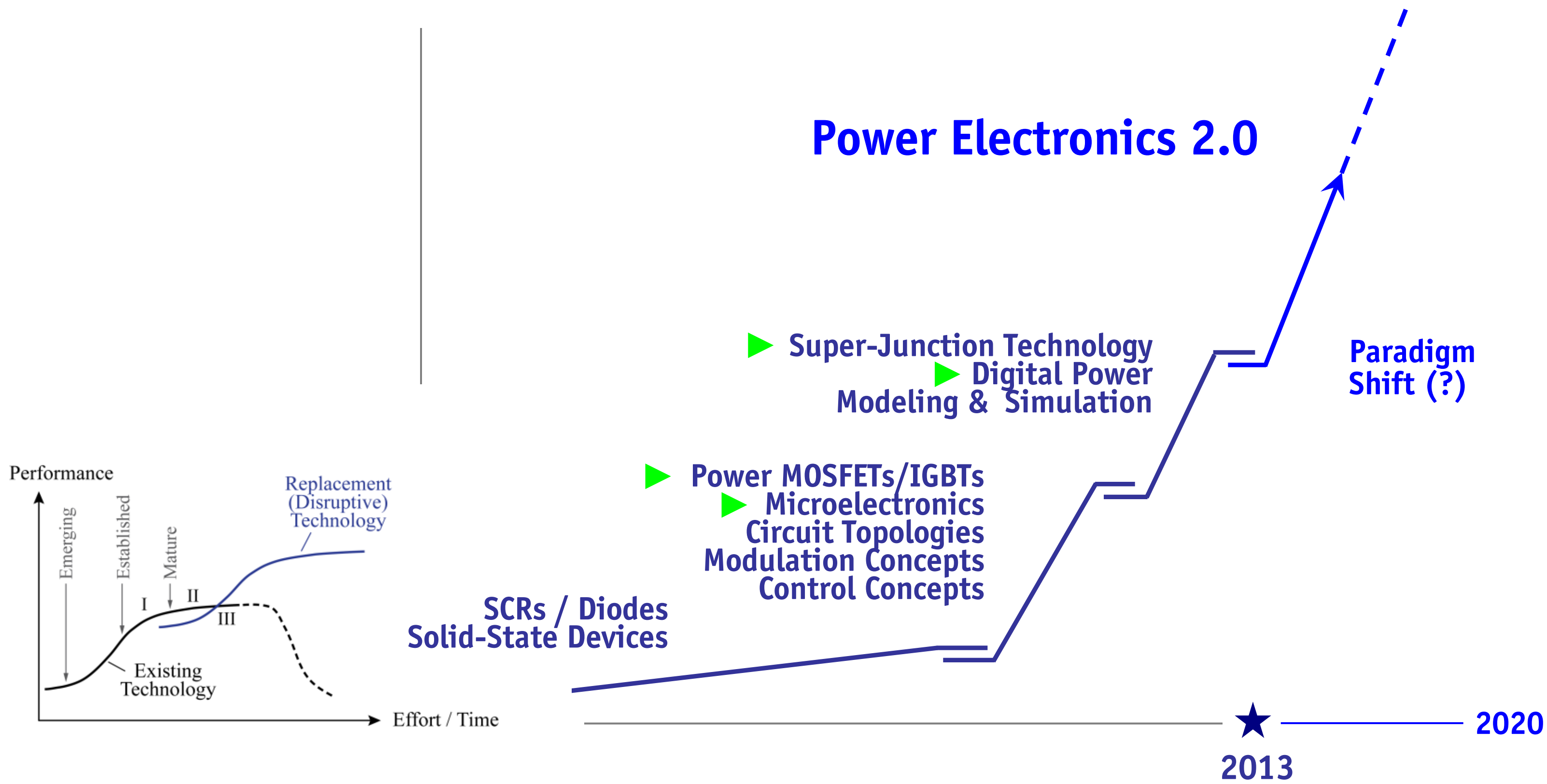
[57] **ABSTRACT**

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



▶ Technology S-Curve

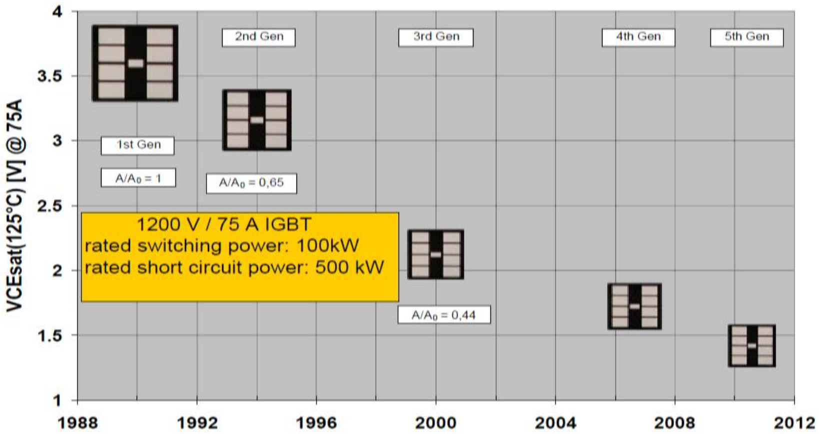


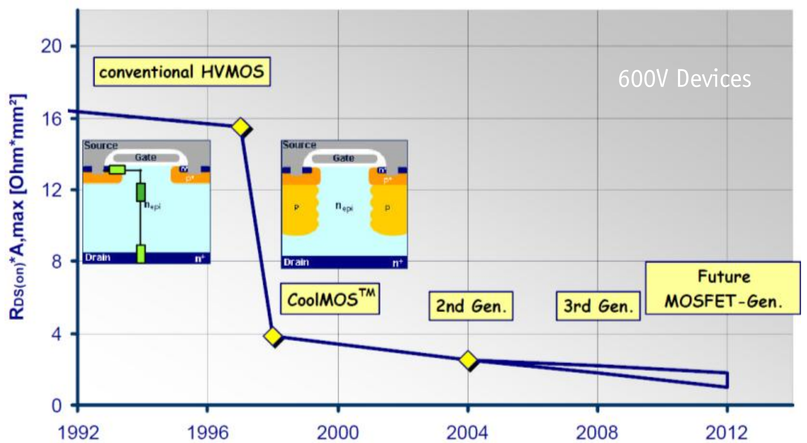
▶ Technology S-Curve

■ Sub-S-Curves

— Overall Development Defined by Improvement of Core Technologies, e.g. Power Semiconductors

Source: Dr. Miller / Infineon





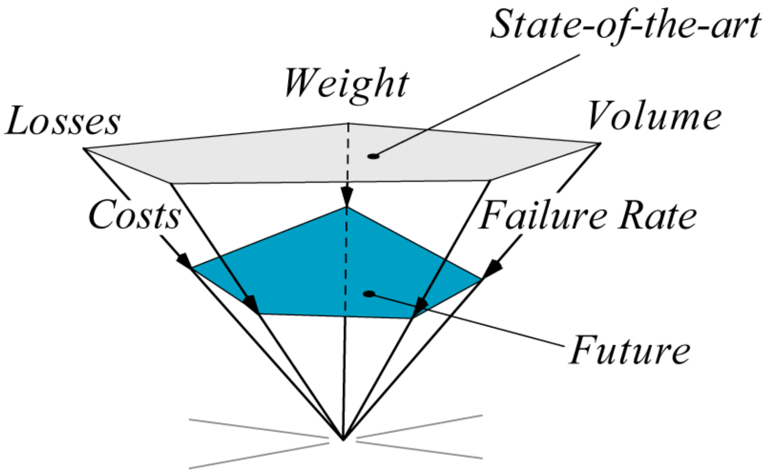
■ Importance

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

Performance Indices

→ Coupling & Barriers

▶ Power Electronics Converters Performance Trends

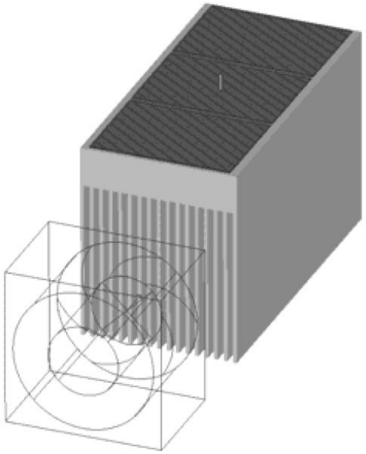


■ Performance Indices

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

▶ Analysis of Performance Limits

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



$$P_O = \eta P_i$$

$$\rho_{lim} = \frac{P_O}{Vol_{CS}} = \frac{\eta}{1-\eta} \Delta T_{s-a} CSPI \, [\frac{\mathrm{W}}{\mathrm{dm}^3}]$$

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

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

@ η = 97%

- ▶ T_s = 90°C → ρ_{lim} = 29 kW/dm³
- ▶ T_s = 135°C → ρ_{lim} = 58 kW/dm³

(T_a = 45°C, CSPI = 20 WK⁻¹dm⁻³)

▶ Analysis of Performance Limits

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

Operating Conditions and Parameters

$$L, f_P, I \qquad \Phi \propto L I$$

– **Scaling of Core Losses**

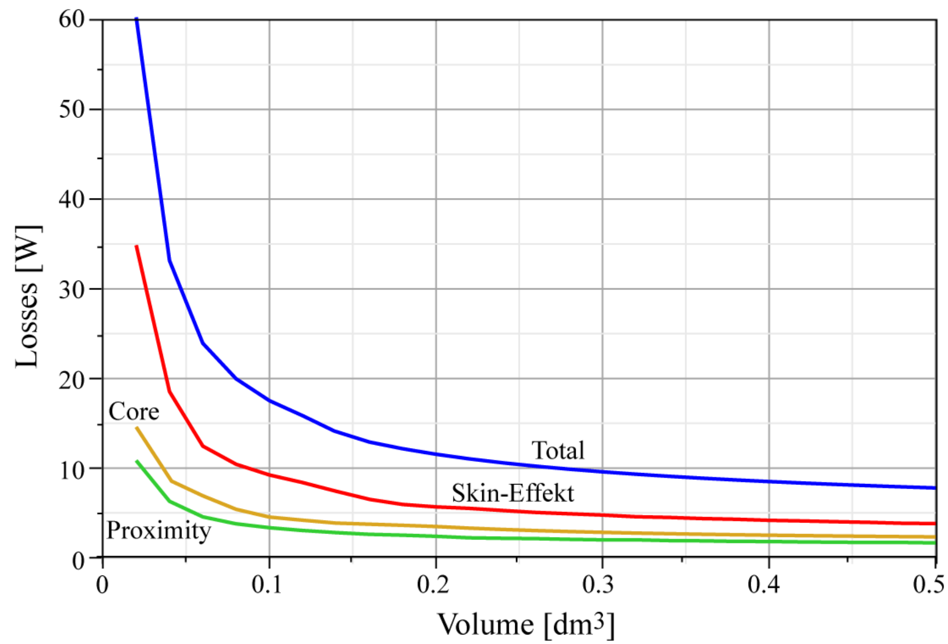
$$P_{Core} \propto f_P \left(\frac{\Phi}{A}\right)^2 V$$

$$P_{Core} \propto \left(\frac{1}{l^2}\right)^2 l^3 \propto \frac{1}{l}$$

– **Scaling of Winding Losses**

$$P_{Wdg} \propto I^2 R \propto I^2 \frac{l_{Wdg}}{\kappa A_{Wdg}}$$

$$P_{Wdg} \propto \frac{1}{l}$$

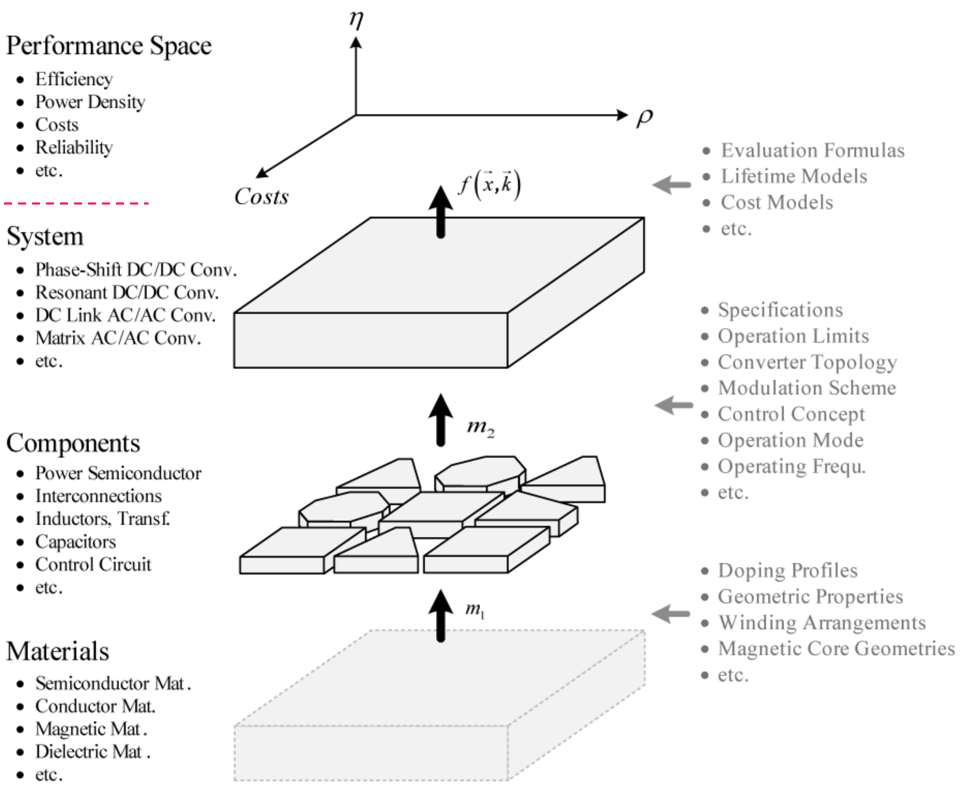


▶ Determine the Barrier(s)

■ Abstraction of Power Converter Design

Performance Space

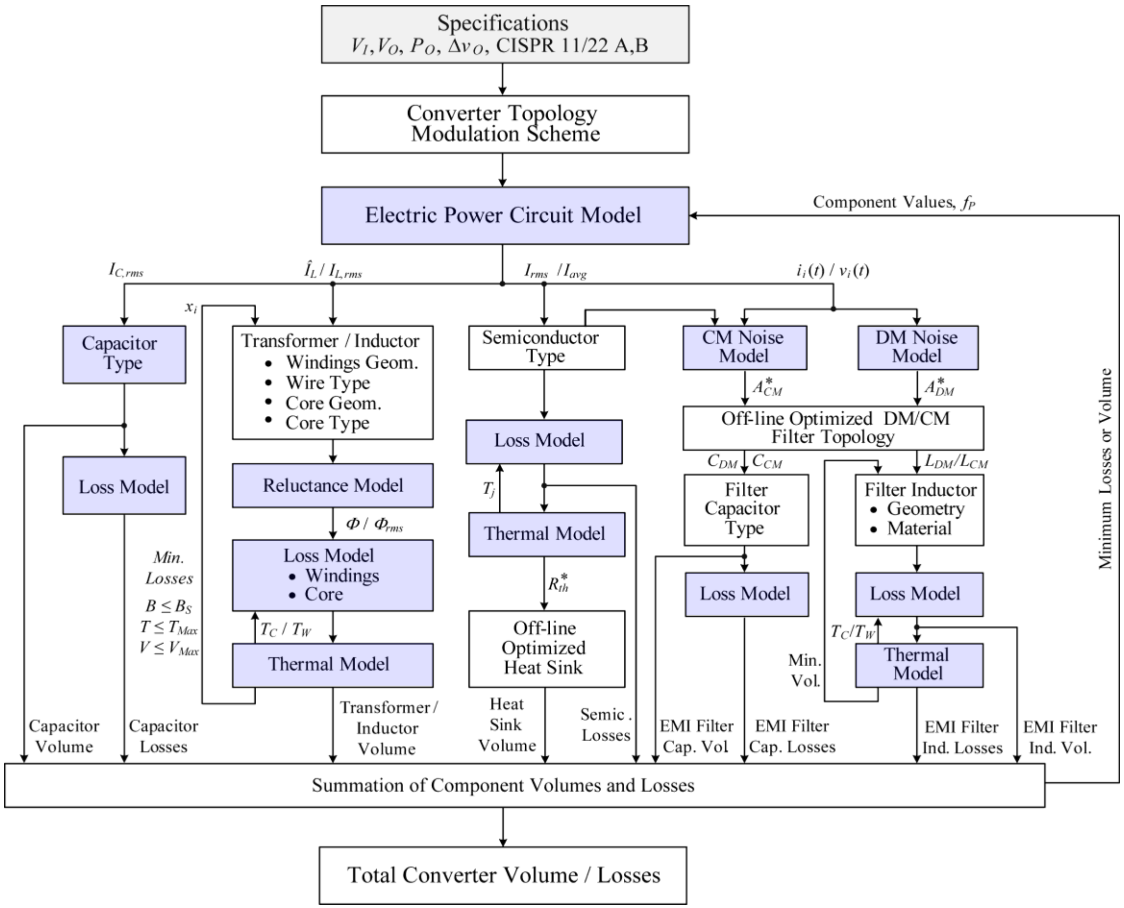
Design Space



▶ Mapping of *Design Space* into System *Performance Space*

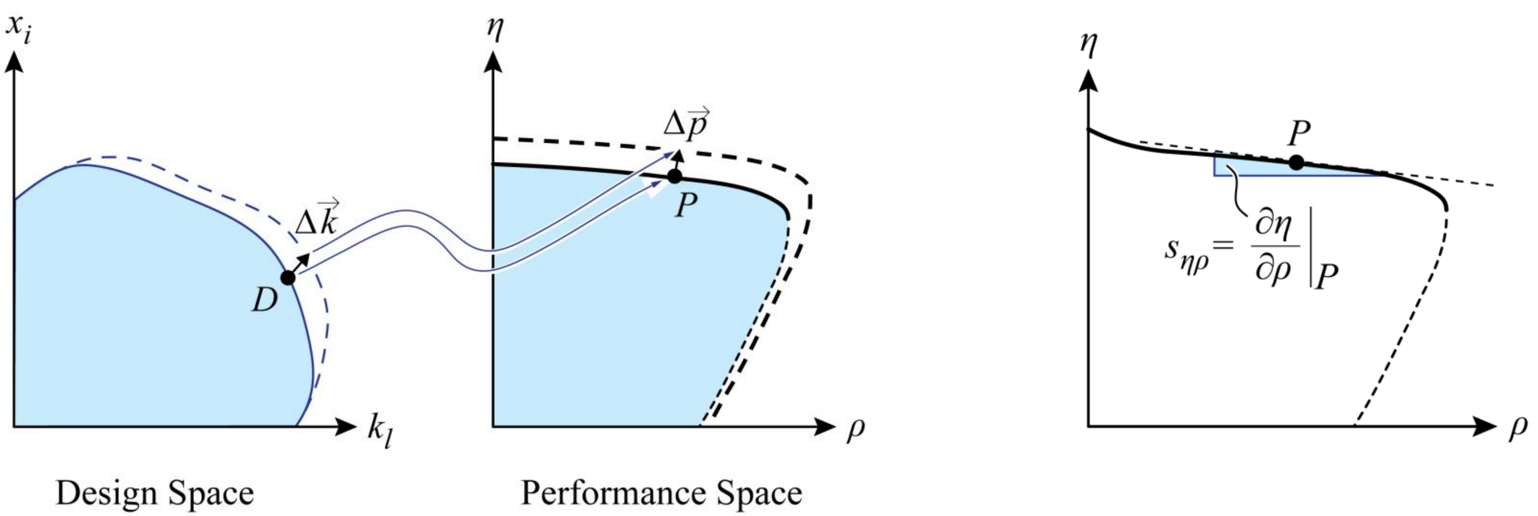
▶ Determine the Barrier(s)

- **Mathematical Modeling and Optimization of the Converter Design**



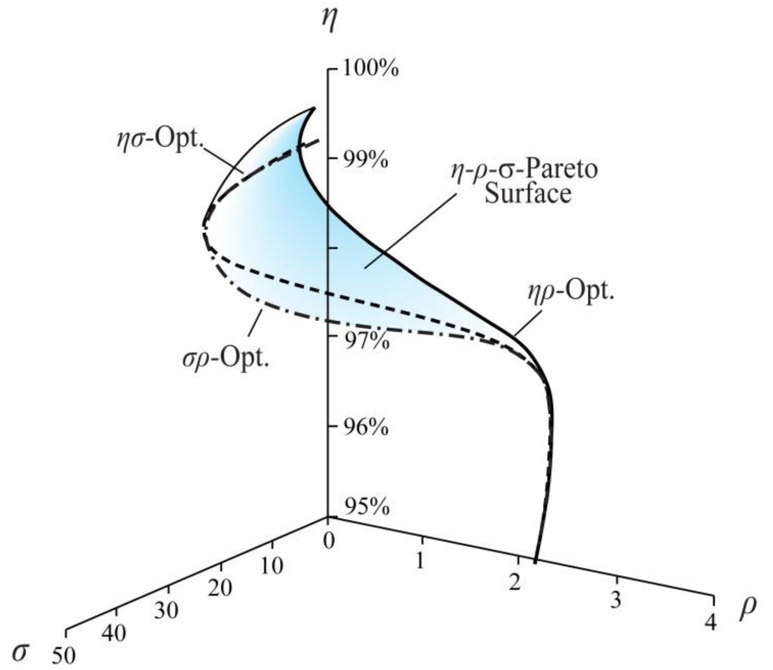
▶ Determine the Barrier(s)

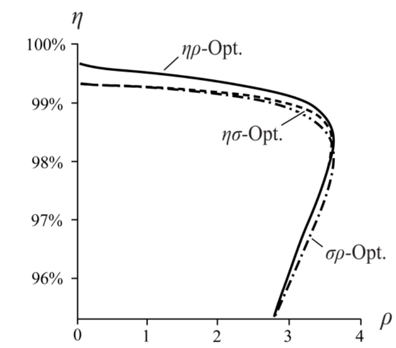
- Multi-Objective Converter Design Optimization
- Limit of Feasible Performance Space (Example: η-ρ-Pareto Front)
- Sensitivity to Technology Advancements
- Trade-off Analysis

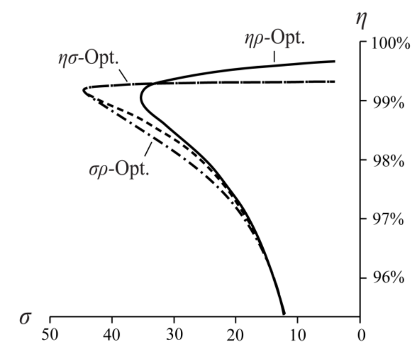


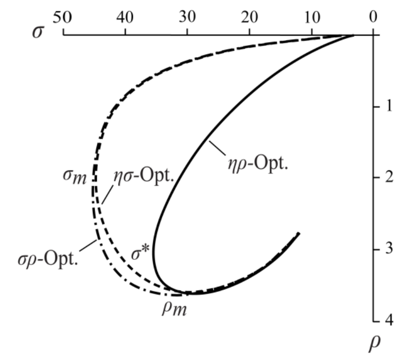
▶ η-ρ-σ-Pareto Surface

- σ: kW/$



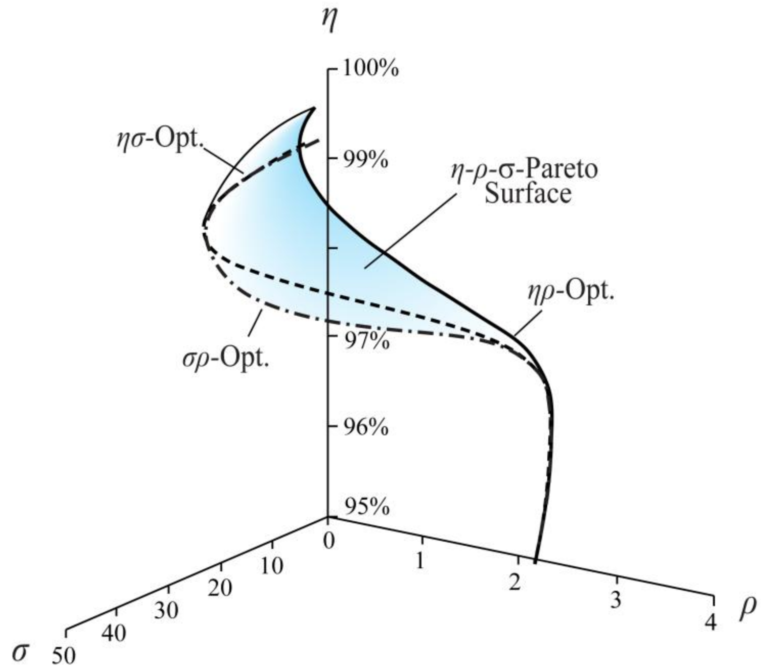


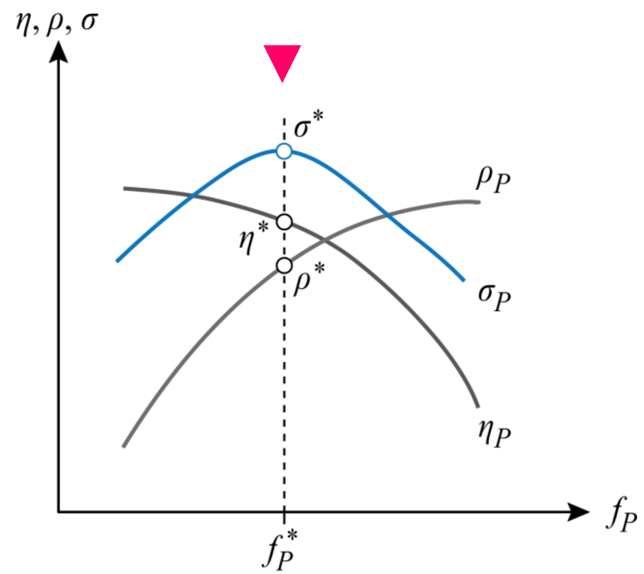




▶ η-ρ-σ-Pareto Surface

■ *"Technology Node"* - **Min. Costs = Max. (kW/$)**





Technology Node: $(\sigma^*, \eta^*, \rho^*, f_P^*)$

Experimental Verification of Performance Limits

→ 3-ph. VIENNA Rectifier

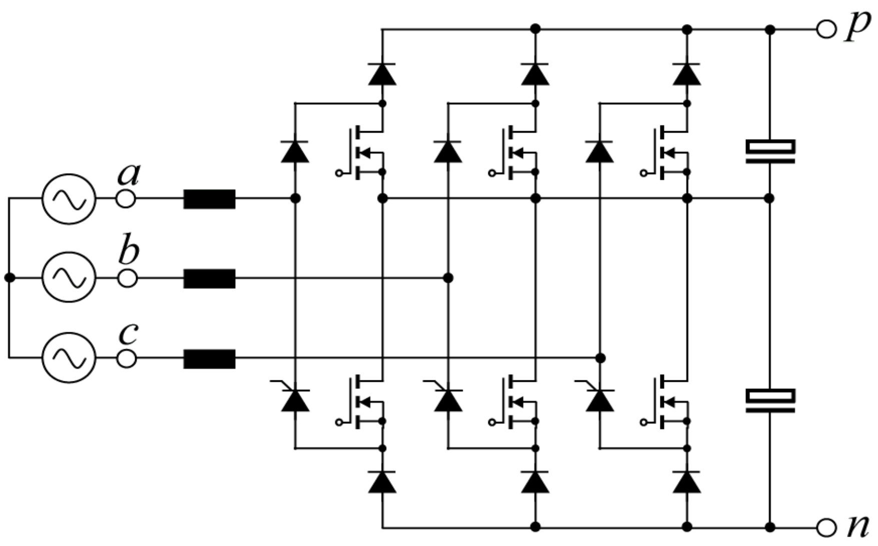
▶ 3-ph. VIENNA Rectifier

■ Specifications

U_{LL} = 3 x 400 V
f_N = 50 Hz ... 60 Hz or 360 Hz ... 800 Hz
P_o = 10 kW
U_o = 2 x 400 V
f_s = 250 kHz

■ Characteristics

η = 96.8 %
THD_i = 1.6 % @ 800 Hz
10 kW/dm3
3.3 kg (≈3 kW/kg)



Dimensions: 195 x 120 x 42.7 mm^3

▶ 3-ph. VIENNA Rectifier

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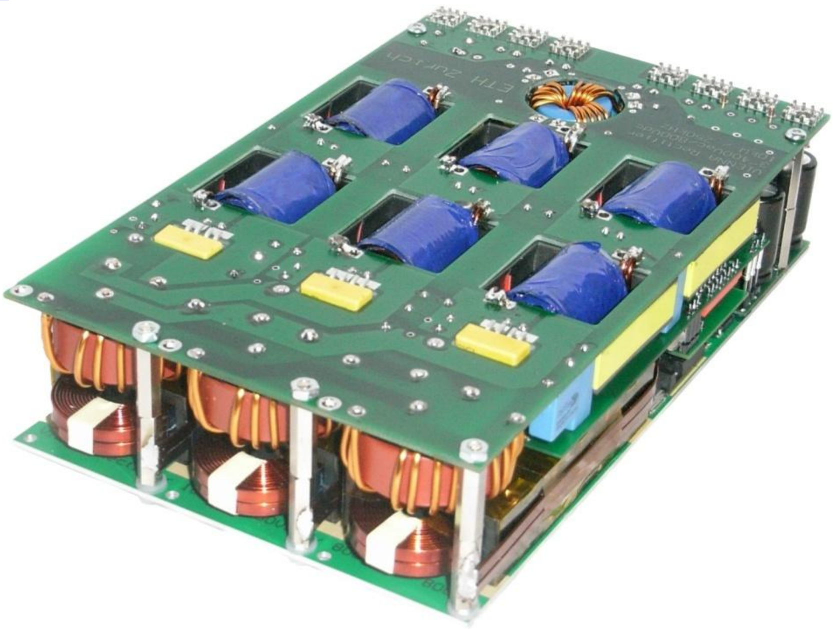


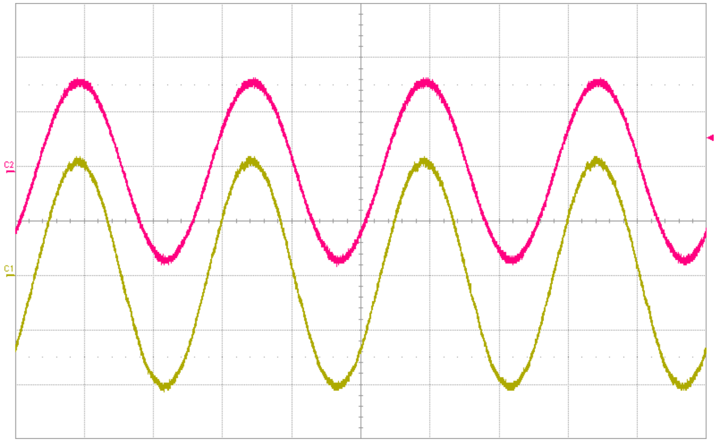
Dimensions: 195 x 120 x 42.7 mm^3

▶ 3-ph. VIENNA Rectifier

- Mains Behavior @ f_N = 400Hz / 800Hz

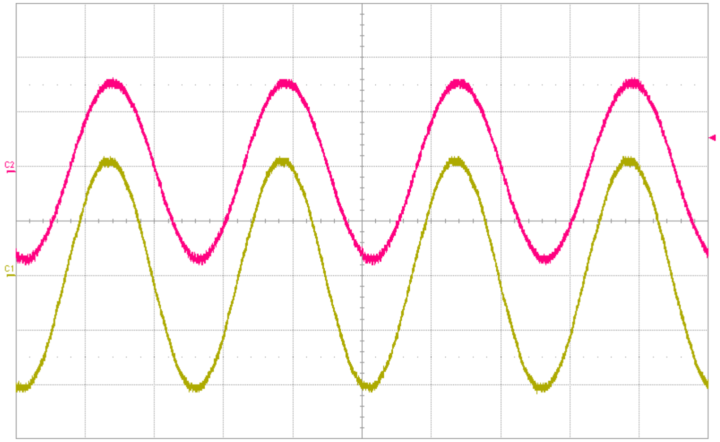
P_0 = 10kW
U_N = 230V
f_N = 400Hz
U_0 = 800V
THD_i = 1.4%

10A/Div
200V/Div
1ms/Div



P_0 = 10kW
U_N = 230V
f_N = 800Hz
U_0 = 800V
THD_i = 1.6%

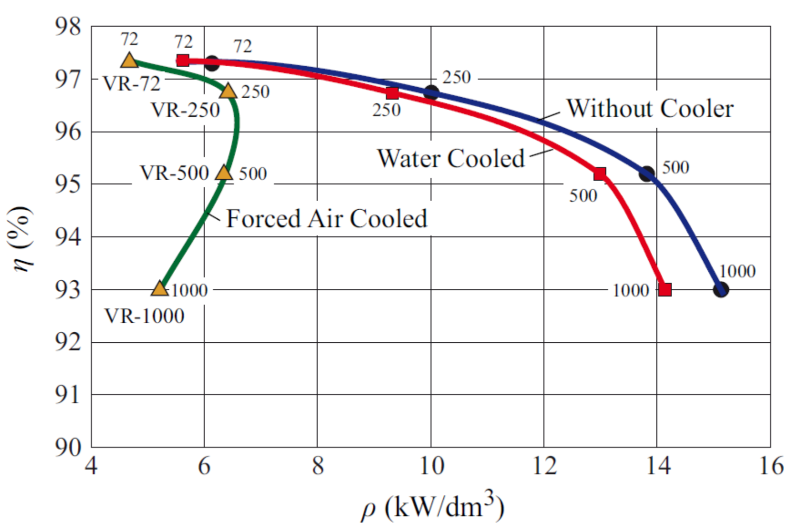
10A/Div
200V/Div
0.5ms/Div



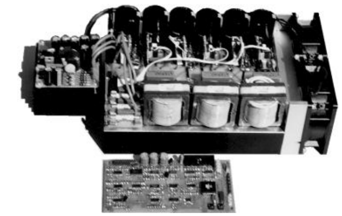
▶ 3-ph. VIENNA Rectifier

- 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_i



f_S = 50 kHz
ρ = 3 kW/dm^3



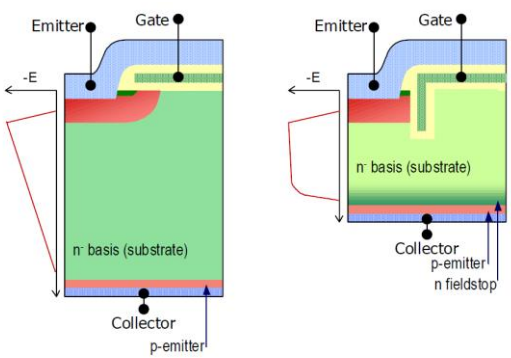
f_S = 72 kHz
ρ = 4.6 kW/dm^3

f_s = 250 kHz
ρ = 10 kW/dm^3
(164 W/in^3)
Weight = 3.4 kg

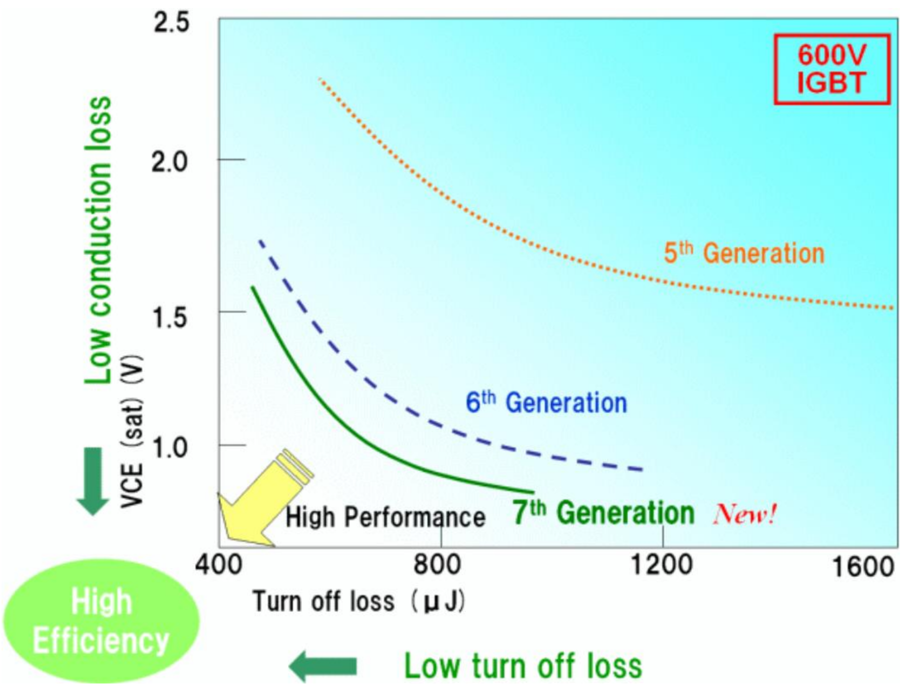
f_S = 1 MHz
ρ = 14.1 kW/dm^3
Weight = 1.1 kg

▶ Pareto Front of Power Semiconductors

- **Trade-Off Between Conduction and Switching Losses**

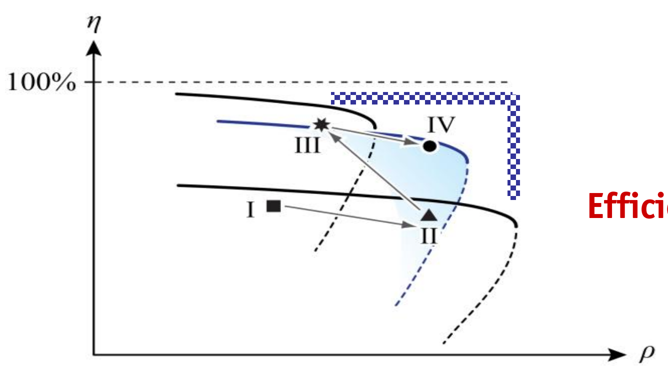


— **Improvement Through Changes in Device Structure → E.g. Introduction of Trench Gate and Fieldstop Layer**

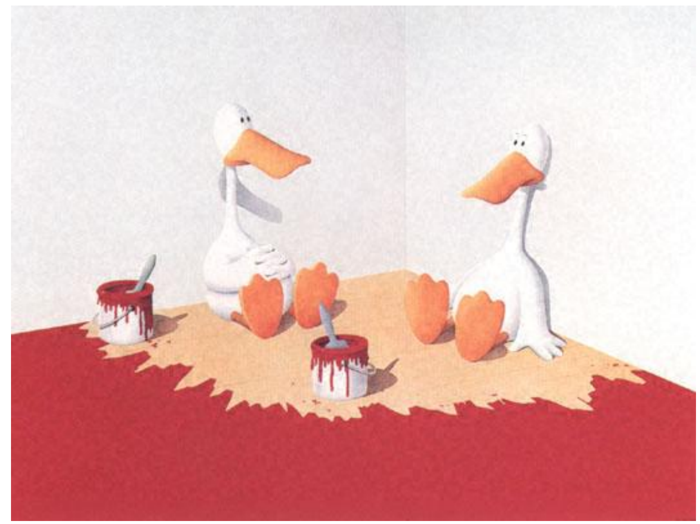


▶ Observation

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



Efficiency



Power Density

- Very Limited Room for Further Performance Improvement

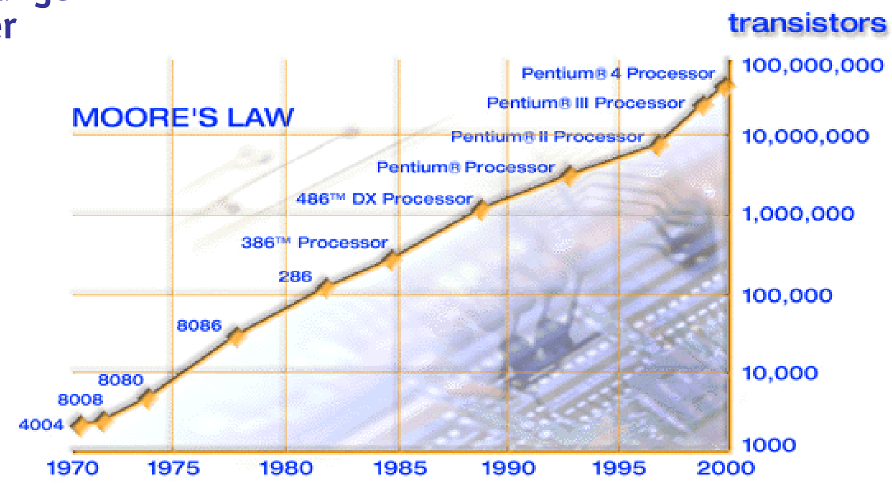
► General Remark

→ There is No "Moore's Law" in Power Electronics !

■ Example: Scaling Law of Transformers

$$A_{Core}A_{Wdg} = \frac{\sqrt{2}}{\pi}\frac{P_t}{k_W J_{rms} \hat{B}_{max}\, f}$$

$\hat{B}_{max}$ ... Very Slow Technology Progress
J_{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)

▶ Power Passives

■ Expected (Slow) Technology Progress of Passives

Source: EPCOS

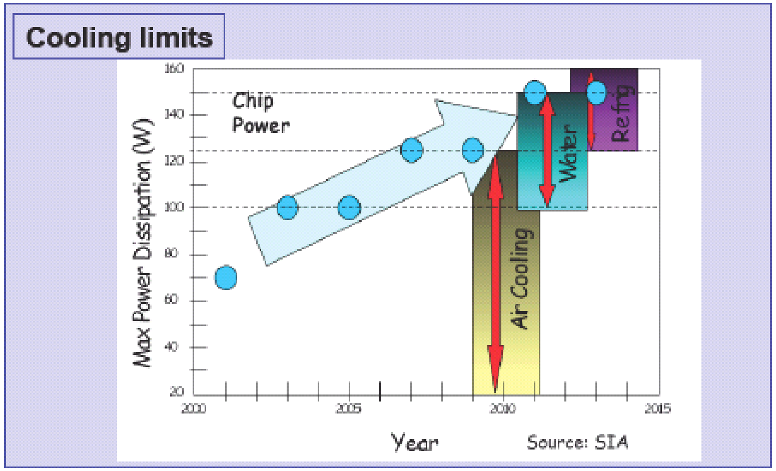
— Foil Capacitors

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

	2000	2005	2010	2015
Energy Density	100%	100%	110%	120%
Film Material	OPP	PHD	COC	?
Max. Temperature	105 °C	115 °C	150 °C	160 °C
Self Inductance	60 nH	30 nH	15 nH	10 nH

— Cooling

Air Cooling
Water Cooling
Refrigeration Technologies



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.

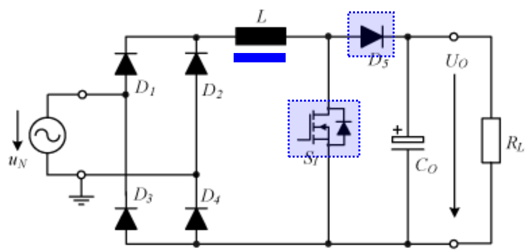
… only if not Fundamental Physical Properties

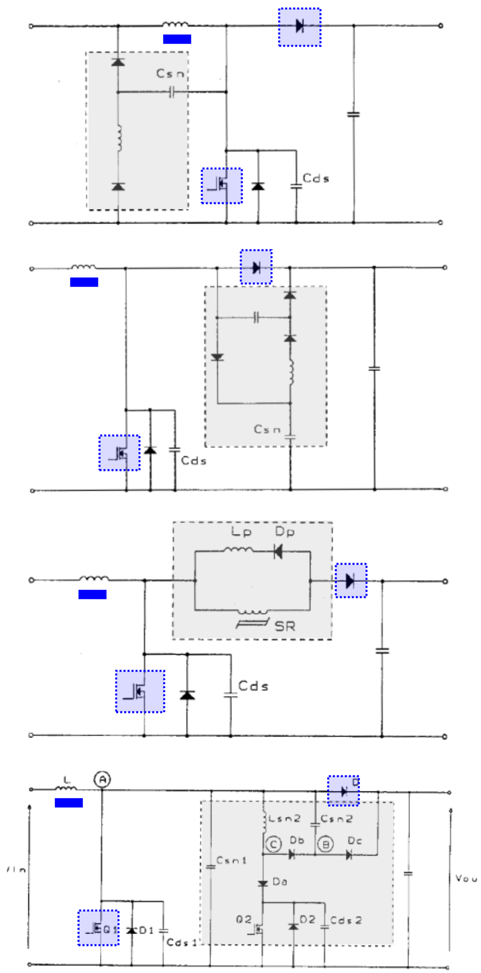
■ Remark: Designer's Point of View (Given Semiconductors & Base Materials)

New Topologies ?

▶ "Snubbers" (1)

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





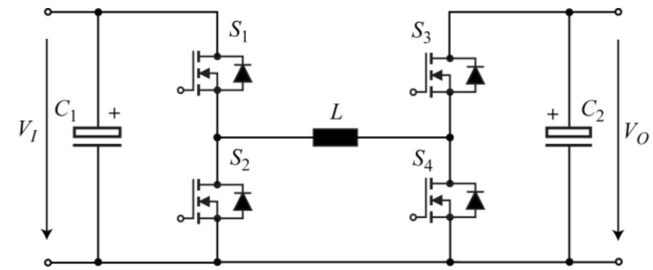
R. Streit/
D. Tollik 1992

- **Complexity Increases Exp. if "Natural" Limit of a Technology is Approached**
- **Next Step in Semiconductor Technologies Makes Snubbers Obsolete → SiC Diodes**

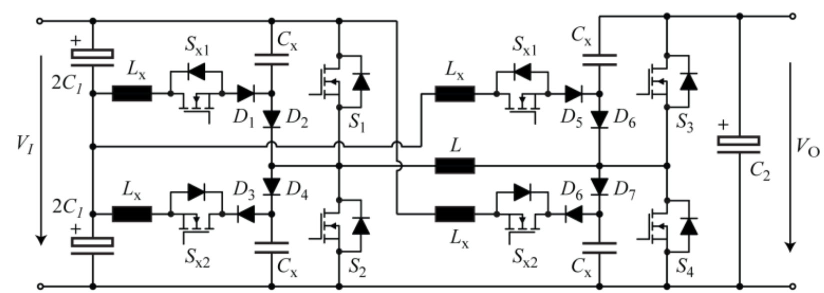
► "Snubbers" (2)

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

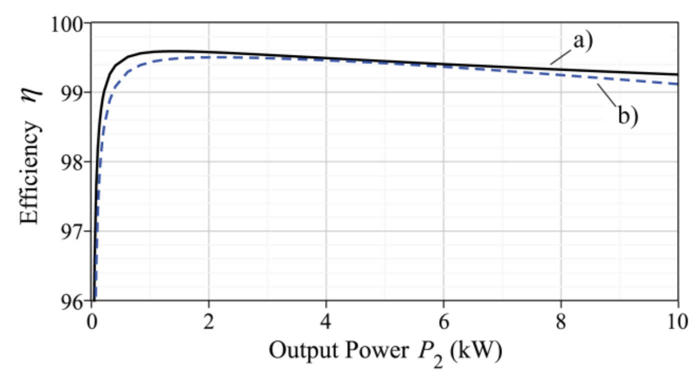
98% Efficiency
29kW/dm^3



a)



b)



■ **Change Operation of BASIC Structure Instead of Adding Aux. Circuits**

▶ New Converter Topologies

- **Very Large Number of Options !**

  – **Example**

IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 7, NO. 1, JANUARY 1992

Topologies for Three-Element Resonant Converters

Rudolf P. Severns

  – **26 out of 48 Topologies are of Potential Interest**

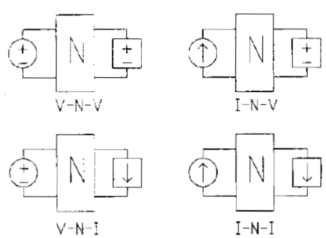


Fig. 13. Source-network-load combinations.

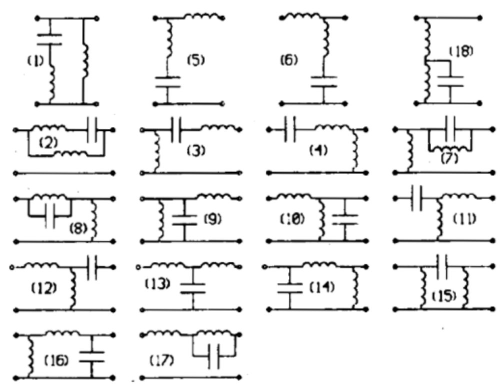


Fig. 17. Networks with 2L and 1C.

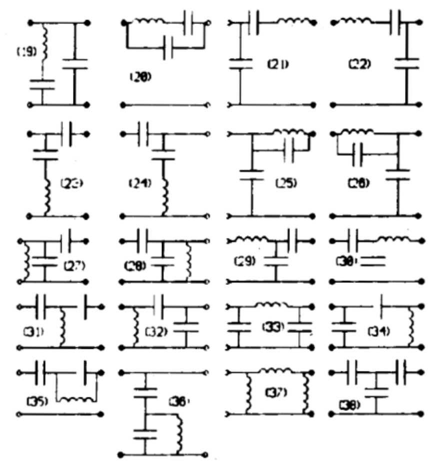
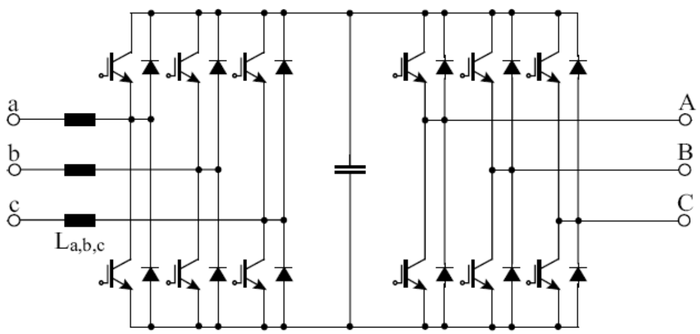


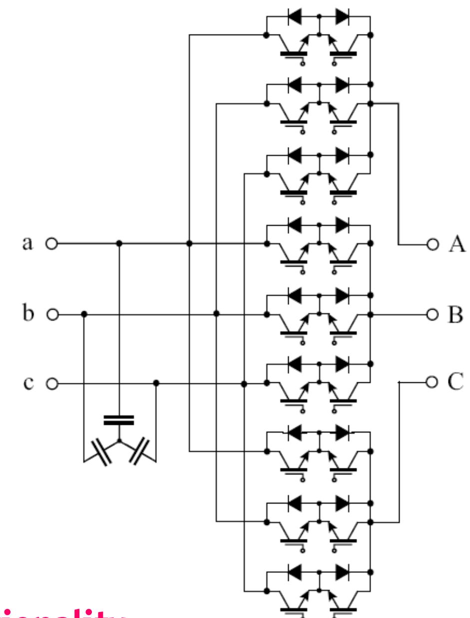
Fig. 18. Networks with 2C + 1L, 3C, and 3L.

- **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.



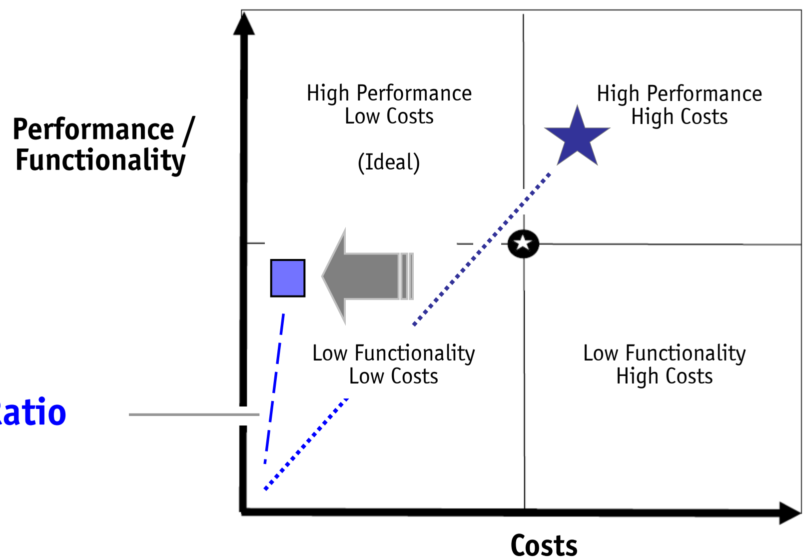


- Integration Restricts Controllability / Overall Functionality
- Frequently Lower Performance of Integrated Solution
- Basic Physical Properties remain Unchanged (e.g. Filtering Effort)

▶ Extreme Restriction of Functionality

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

Improved $\frac{\text{Cost}}{\text{Performance}}$ Ratio

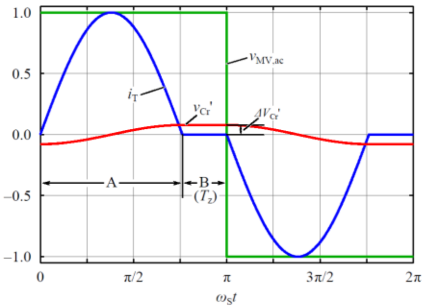


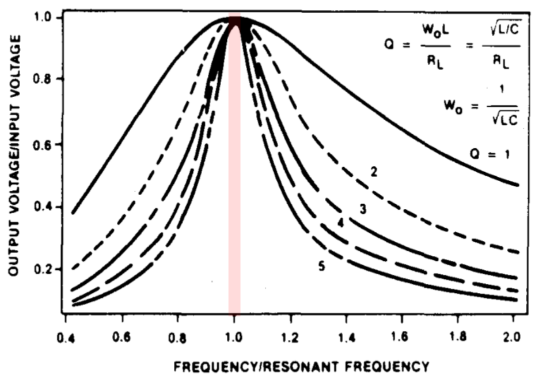
■ Cost / Performance Ratio is a Key Metric for Industry Success (Sales Argument)

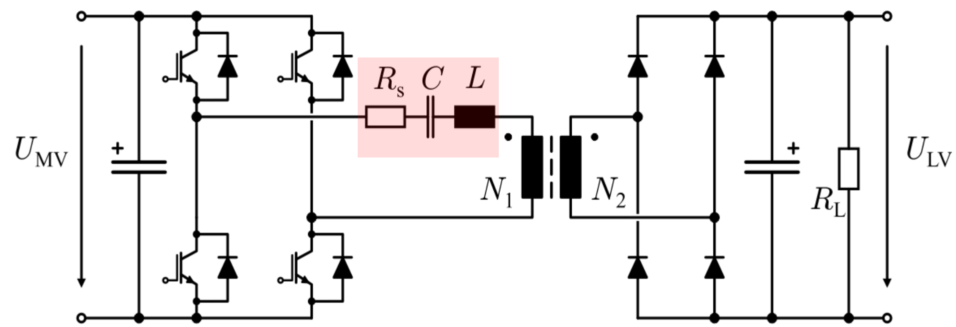
▶ Extreme Restriction of Functionality

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

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







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

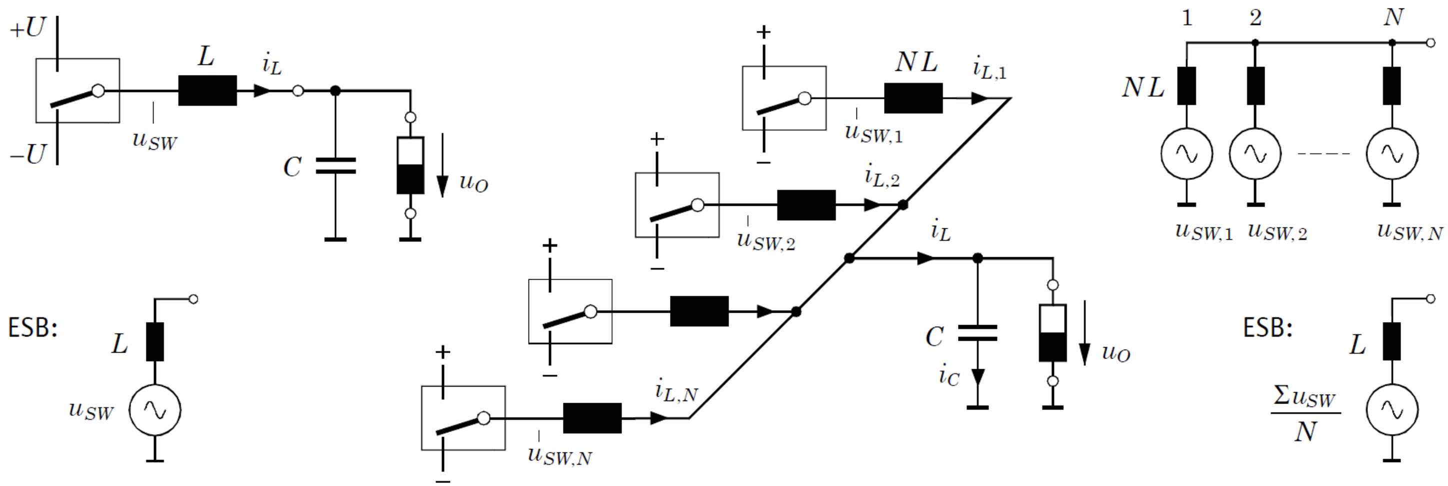
Multi-Cell Converters

→ 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



H. Ertl, 2003

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

▶ Multi-Cell Converters

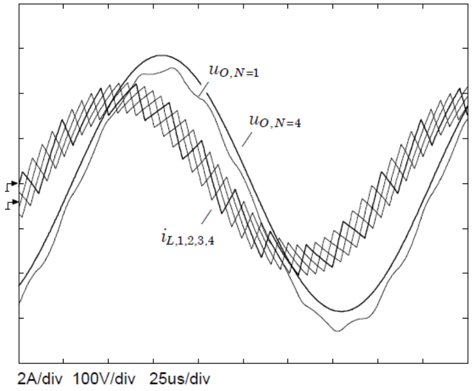
■ **Basic Concept @ Example of Parallel Interleaving**

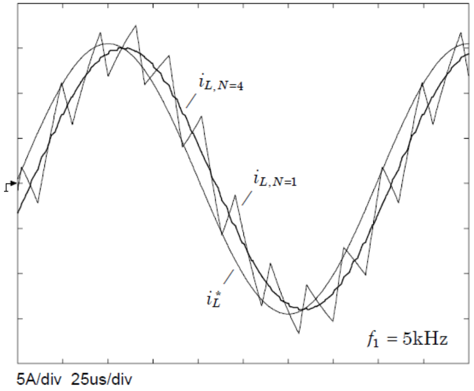
— **Multiplies Frequ. / Red. Ripple @ Same Switching Losses & Increases Control Dynamics**

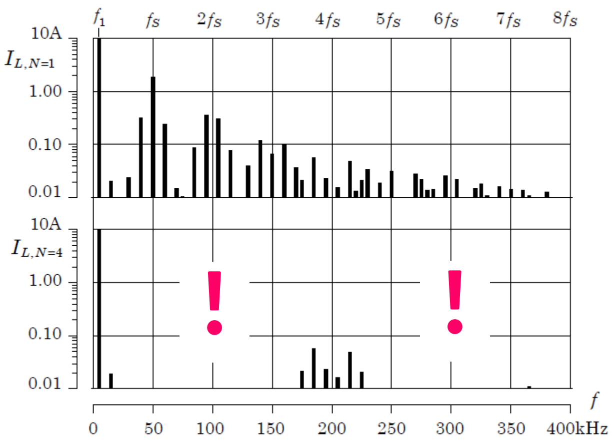
$$\Delta U_{\max,N} = \Delta U_{\max} \cdot \frac{1}{N^3}$$

$$\Delta I_{\max,N} = \frac{\Delta I_{\max}}{N^2}$$

H. Ertl, 2003







■ **Fully Benefits from Digital IC Technology (Improving in Future)**

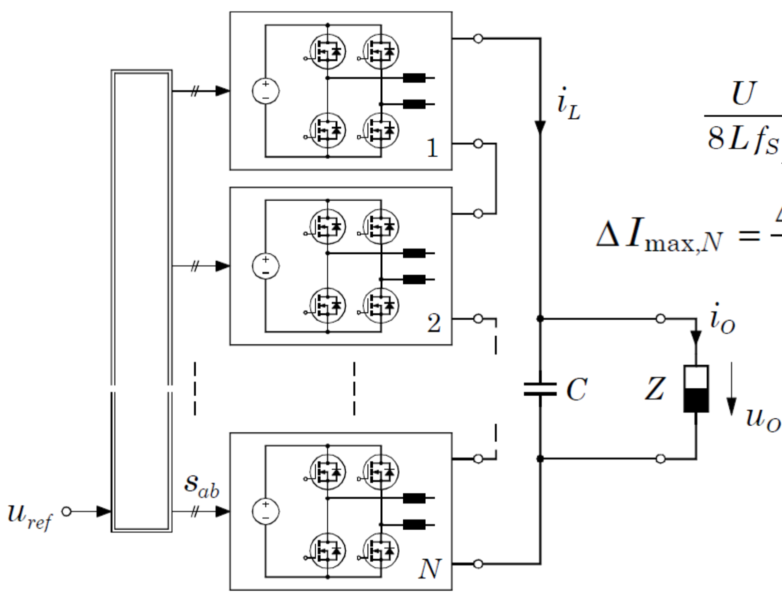
■ **Redundancy → Allows Large Number of Units without Impairing Reliability**

▶ Multi-Cell Converters

- Example of Series Interleaving

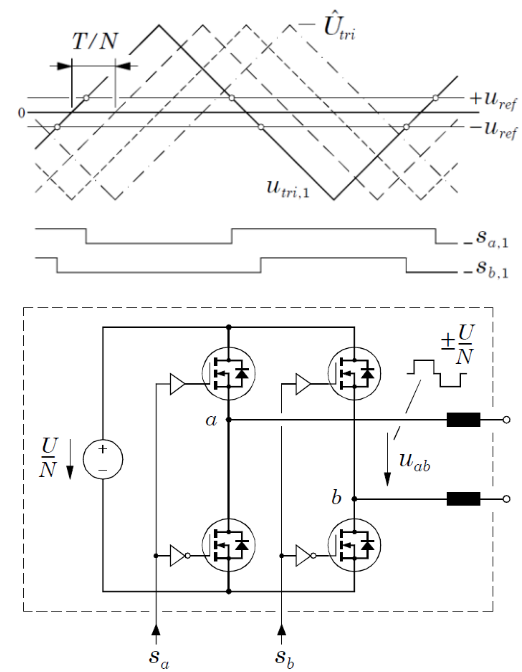
$$\frac{\Delta U_{\max,N}}{U} = \frac{\pi^2}{32}\left[\frac{f_0}{f_S}\right]^2 \cdot \frac{1}{N^3}$$

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



$$\frac{U}{8 L f_S}$$

$$\Delta I_{\max,N} = \frac{\Delta I_{\max}}{N^2}$$

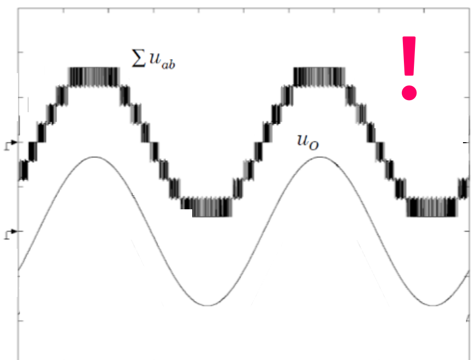


▶ Multi-Cell Converters

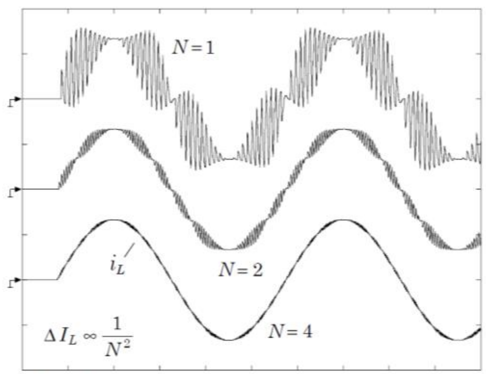
- Example of Series Interleaving

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

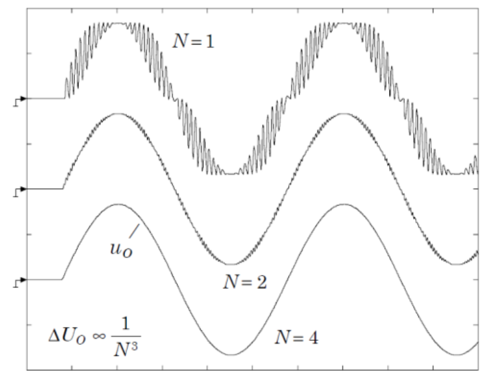
$$\Delta I_{\max,N} = \frac{\Delta I_{\max}}{N^2} \qquad \frac{\Delta U_{\max,N}}{U} = \frac{\pi^2}{32}\left[\frac{f_0}{f_S}\right]^2 \cdot \frac{1}{N^3}$$



60V/div 200us/div



15A/div 200us/div



60V/div 200us/div

H. Ertl, 2003

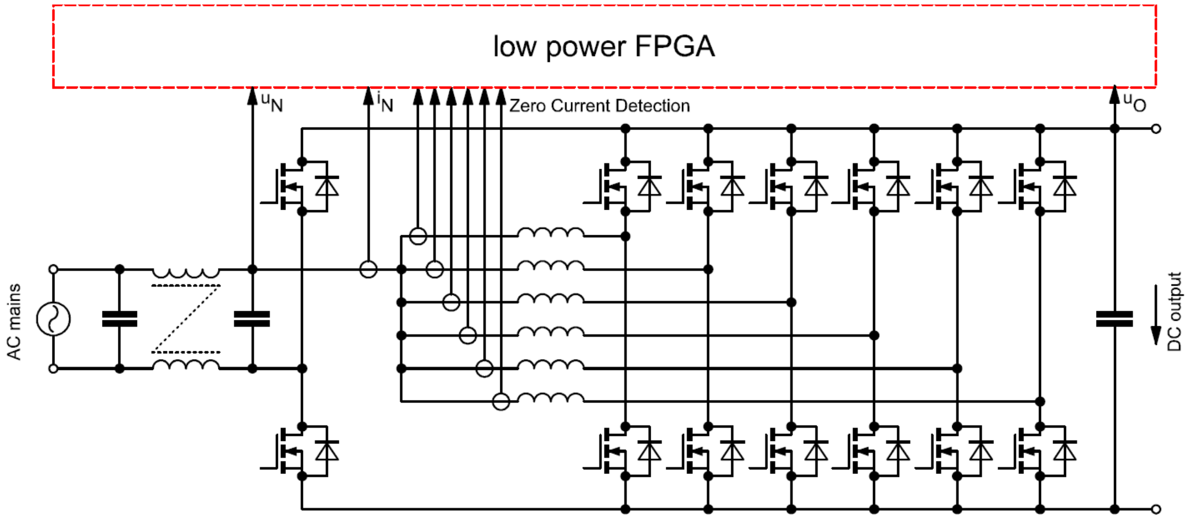
- Especially Advantageous for Ohmic On-State Behavior of Power Switches (!)
- Redundancy → Allows Large Number of Units without Impairing Reliability

Examples of Multi-Cell Converters

→ Ultra-Efficient 1ph. PFC
→ Solid-State Transformer

▶ Bidirectional Ultra-Efficient 1-Φ PFC Mains Interface

★ 99.36% @ 1.2kW/dm³

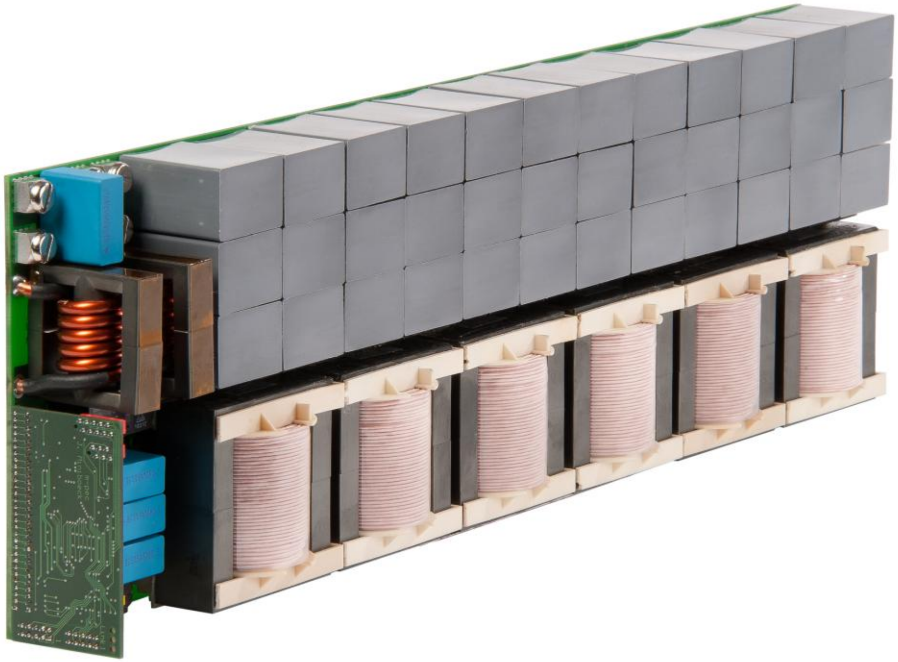


- Employs NO SiC Power Semiconductors -- Si SJ MOSFETs only

▶ Bidirectional Ultra-Efficient 1-Φ PFC Mains Interface

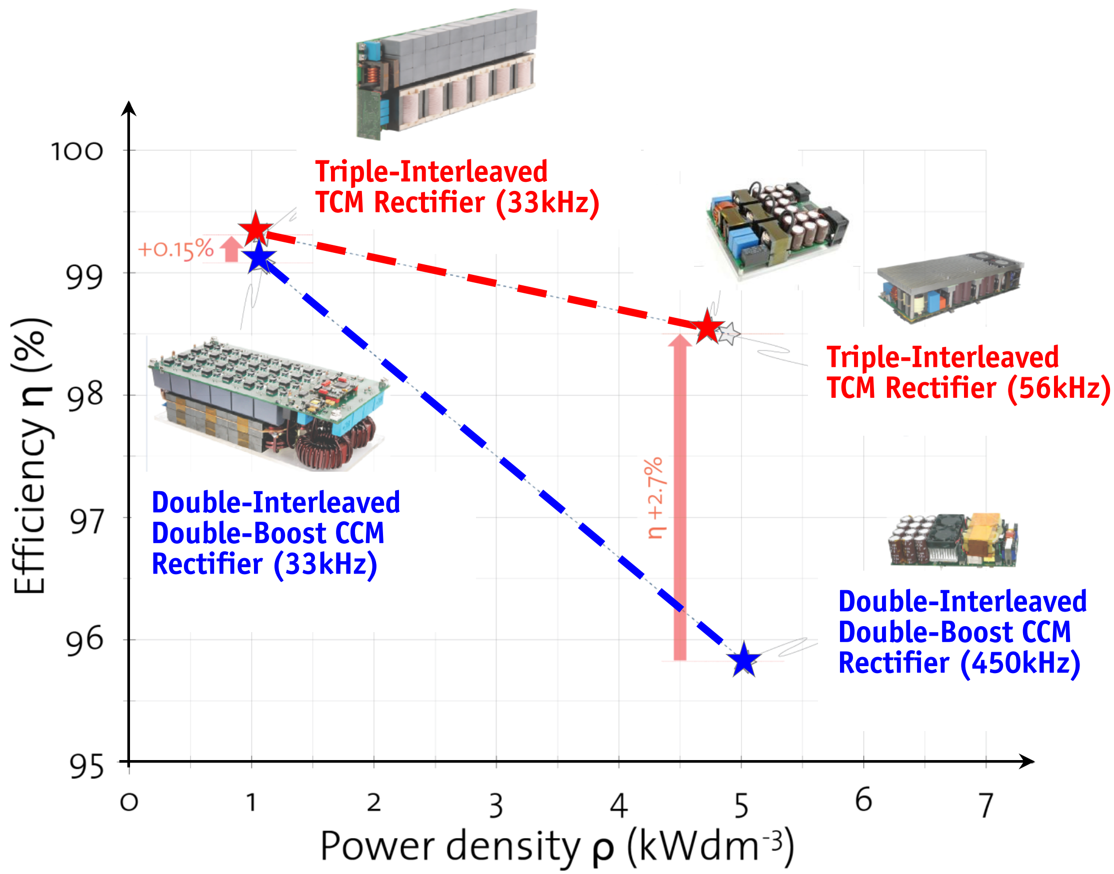
★ **99.36% @ 1.2kW/dm³**

Hardware Testing to be finalized in September 2011



- **Employs NO SiC Power Semiconductors -- Si SJ MOSFETs only**

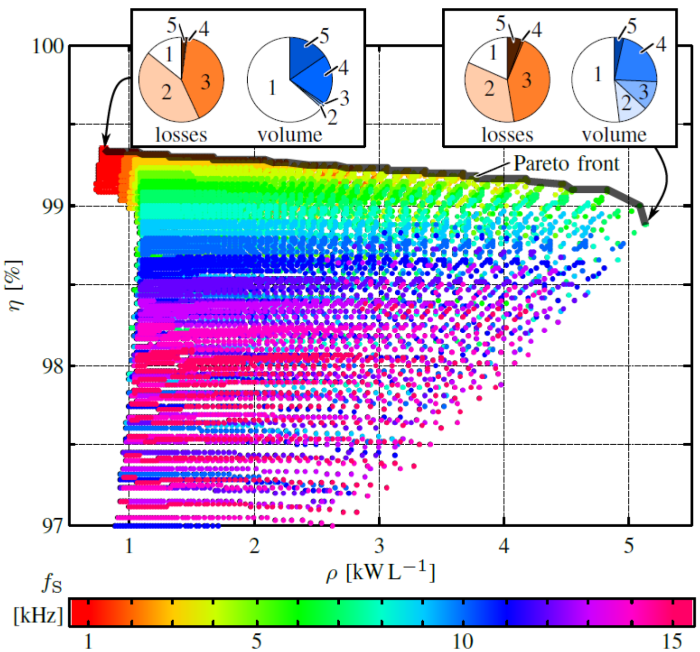
Converter Performance Evaluation Based on η-ρ-Pareto Front



▶ Solid-State Transformer

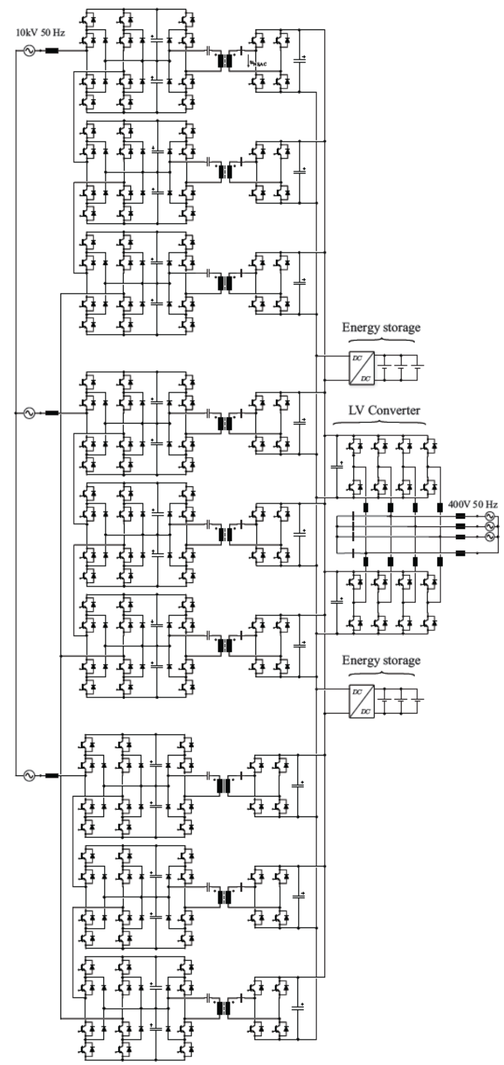
S_N = 630kVA
U_{LV} = 400 V
U_{MV} = 10kV

■ **Trade-Off → Efficiency / Power Density**



DCM Series
Resonant
DC/DC Converter

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



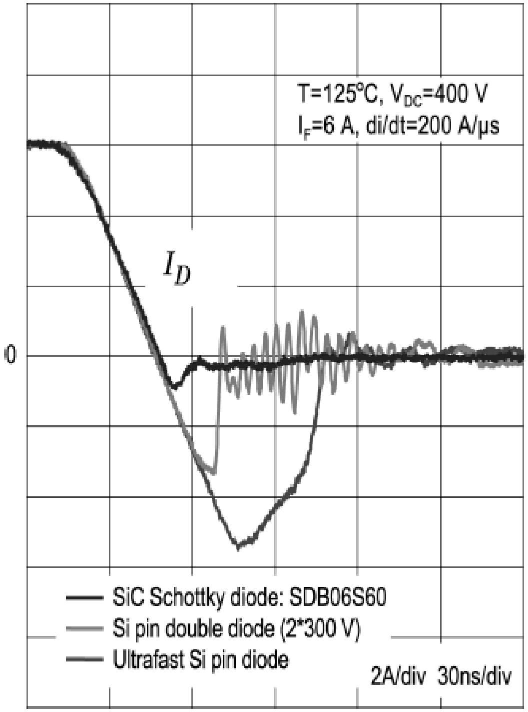
"Killer"- Semiconductor Technologies

WBG Power Semiconductors ?

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

▶ WBG Power Semiconductors

— **Example: SiC Schottky Diode – Zero Recovery Rectifiers**



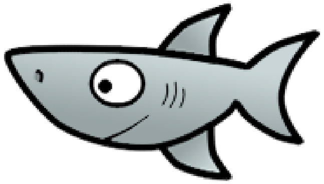
■ General Capabilities

- Higher Switching Frequency
- Higher Operating Temperature
- Higher Blocking Capability

But ...

Today the Capabilities of SiC Cannot be Utilized

— Fast Switching Capability



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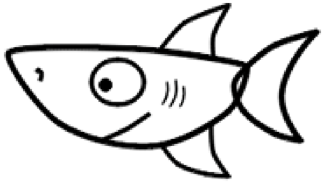
Today the Capabilities of SiC Cannot be Utilized

— **Fast Switching Capability**

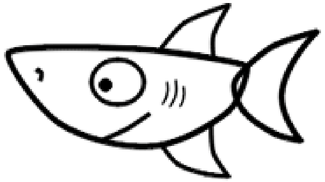


► **Limit by Layout Parasitics**

But ...

Today the Capabilities of SiC Cannot be Utilized

— Fast Switching Capability
— High Temp. Capability



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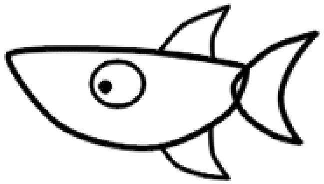

► Limit by Layout Parasitics
► Missing High Temp. Package (Therm. Cycles)

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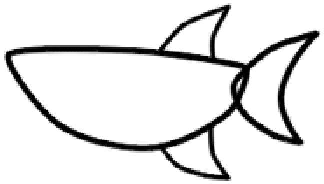

- ▶ Limit by Layout Parasitics
- ▶ Missing High Temp. Package (Therm. Cycles)
- ▶ Missing High Temp. Passives

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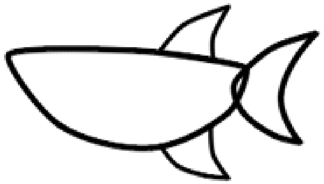

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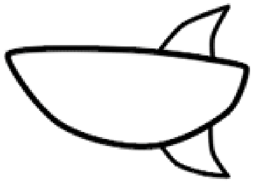


- Limit by Layout Parasitics
- Missing High Temp. Package (Therm. Cycles)
- Missing High Temp. Passives
- Multi-Level Topologies !

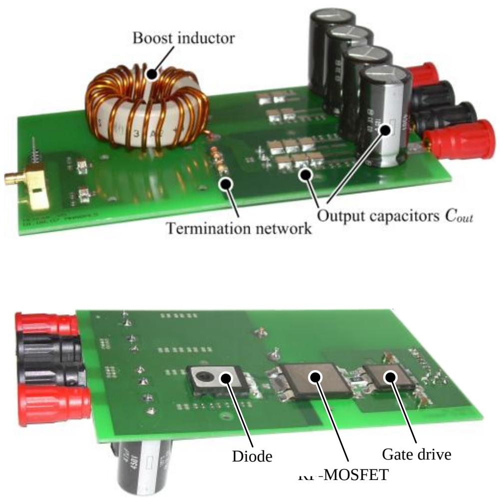
But ...

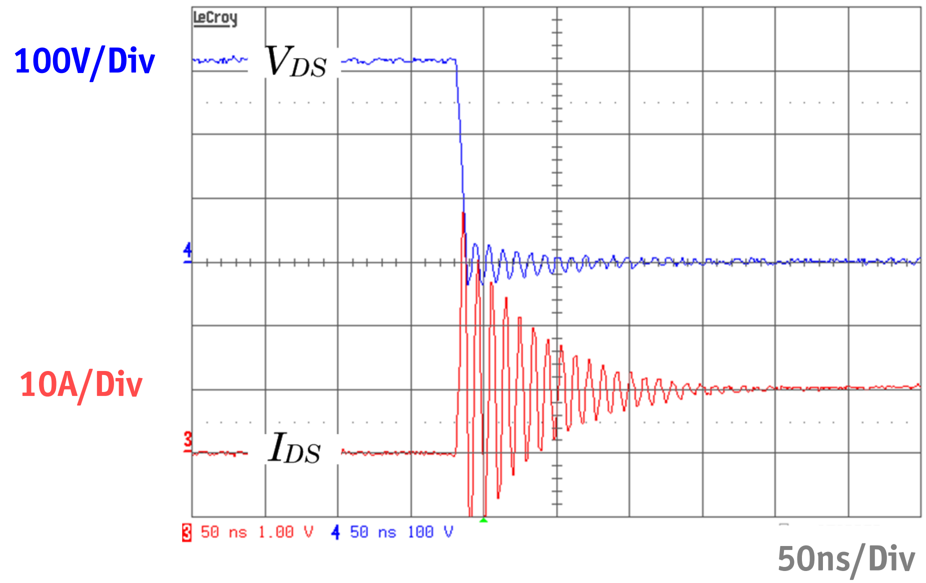
Today the Capabilities of SiC Cannot be Utilized

— 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

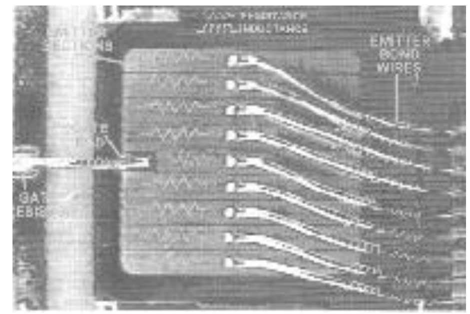


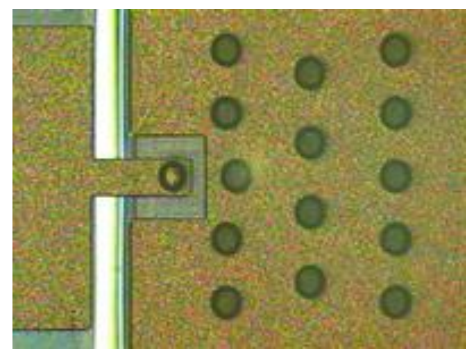


- ▶ Missing HF Package
- ▶ Missing Integrated Gate Drive (Active Control of Switching Trajectory)

► GE Planar Power Polymer Packaging (P4^{TM})

GE Global Research
United States - India - China - Germany





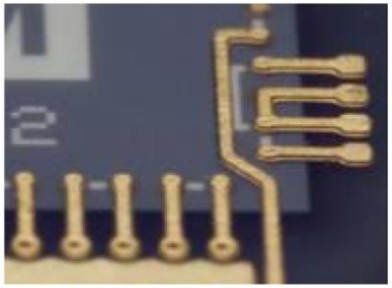
Oriented Toward High Power Devices
<2400V / 100A...500A
<200W Device Dissipation

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

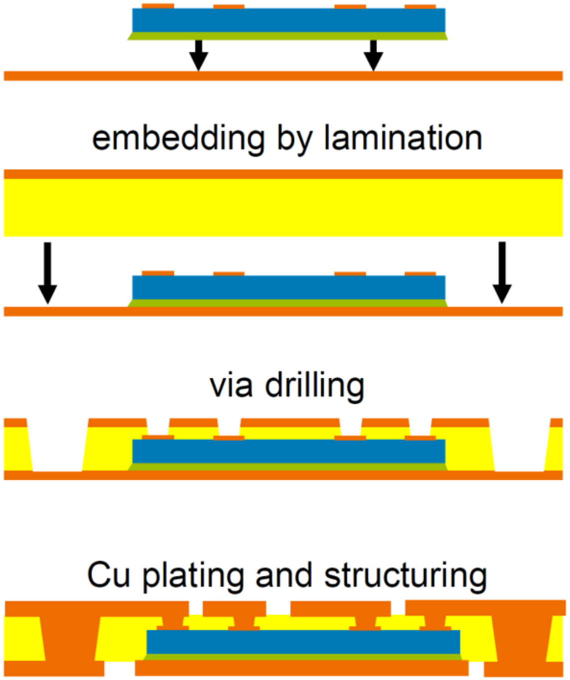
Direct High-Conductivity Cooling Path

▶ Novel PCB Technologies for High Power Density Systems

■ Chip in Polymer Process / Multi-Functional PCB



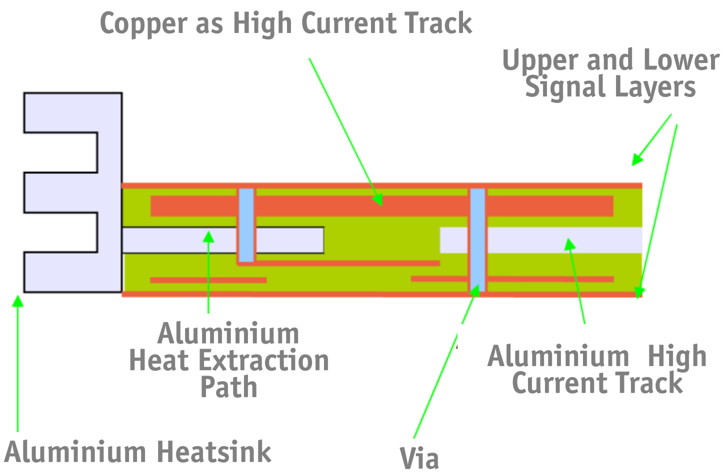
embedded chip in PCB structure.

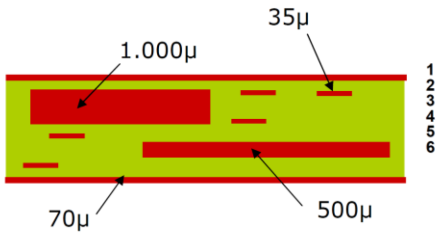


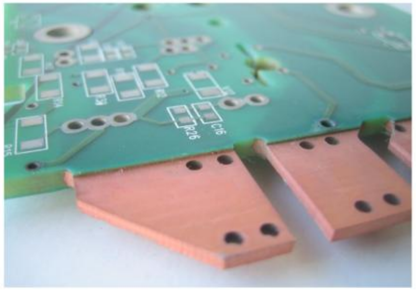
- Chip Embedding by PCB Technology
- Direct Cu Contact to Chip / No Wires or Solder Joints
- Thin Planar Packaging enables 3D Stacking
- Improved Electrical Performance and Reliability

▶ Multi-Functional PCB

- Multiple Signal and High Current Layers
- Thermal Management



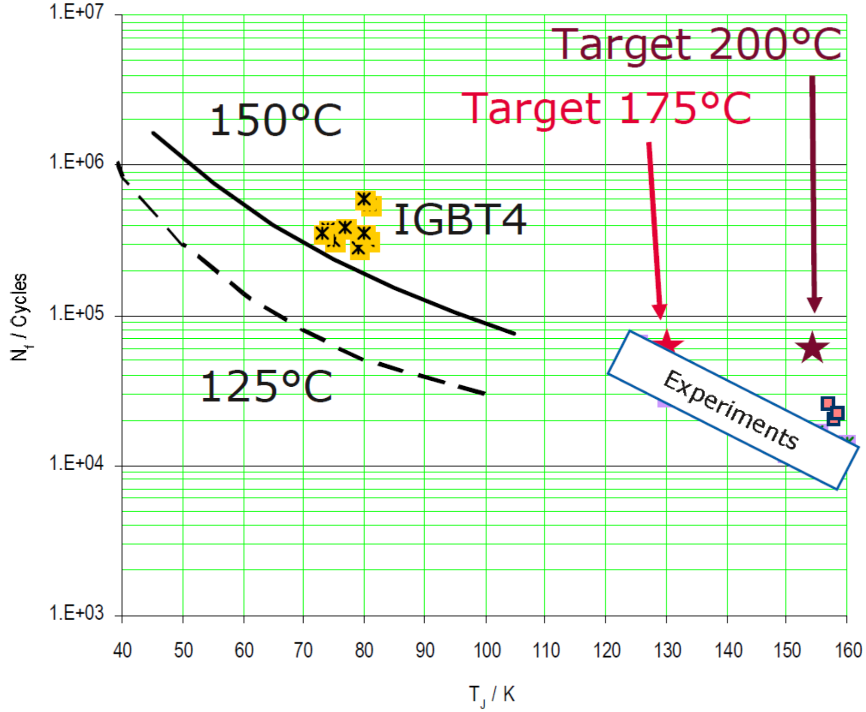




- "Fab-Less" Power Electronics
- Testing is Challenging (Only Voltage Measurement)
- Advanced Simul. Tools of Main Importance (Coupling with Measurem.)

▶ Power Semiconductors Load Cycling Capability

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



Source: Dr. Miller / Infineon

► Observation

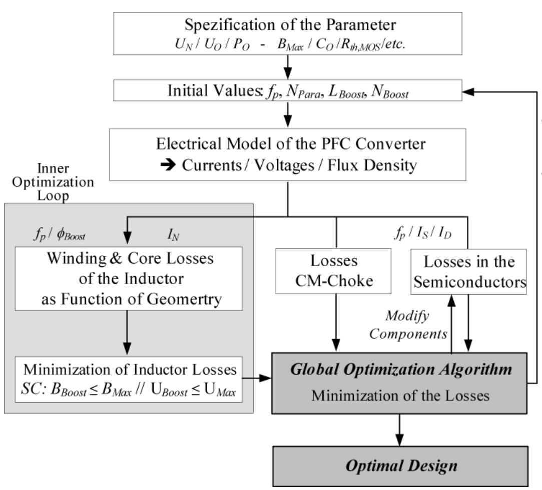
— SiC ... Not Yet a "*Killer*" Technology Future: U > 1.7kV
— GaN (!) ... Cost Advantage Only for U < 600V in 1st Step

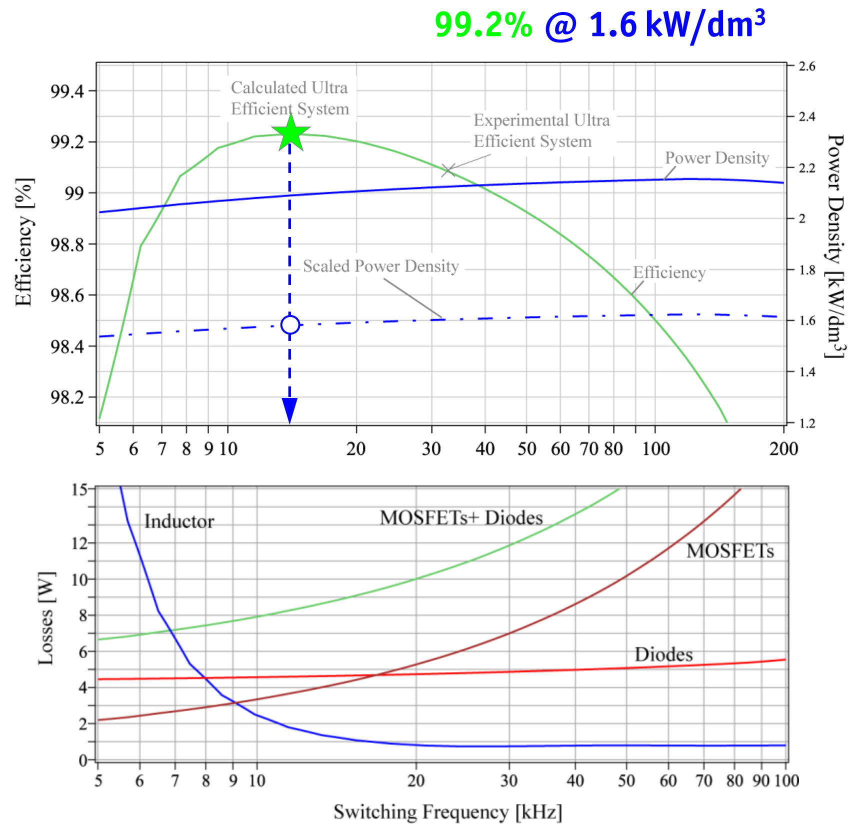
- Do Not Forget the Continuous Improvement of Si Devices (!)
- System Level Advantage of SiC Still to be Clarified (More Basic Conv. Topologies)
- SiC for High Efficiency (e.g. for PV or for High Power Density / Low Cooling Effort)

New Simulation Tools ?

▶ Example: Efficiency Optimization

- Constant Inductor Volume
- Variation of f_P

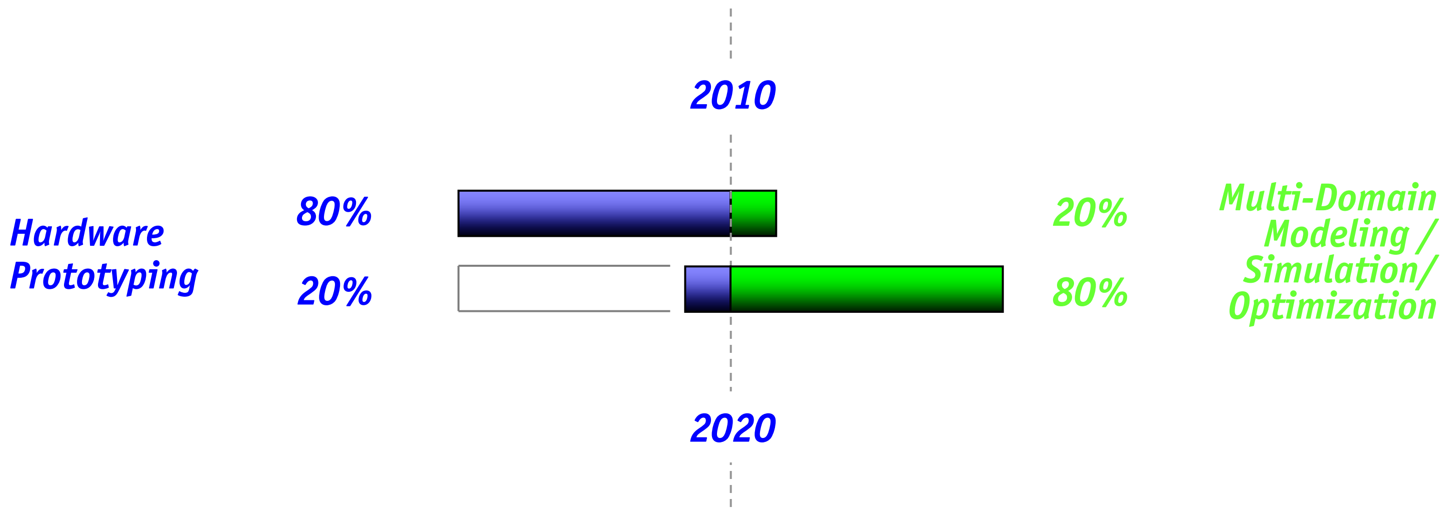




- "Flat" Optima for Practical (Robust) Systems → Good Engineering – Similar Result

▶ Future Design Process

■ Virtual Prototyping



- 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
— Converters
— Systems

Components →

- WBG	→ Benchmark SiC / GaN
- Interconnections	→ High Frequ. / High Curr.
- Packaging	→ Low Ind. MV Package
- MF Insulation	→ Partial Discharge@ MF
- Cooling Concepts	→ Airbearing Cooler etc.
- Active Gate Control	→ d/dt Feedback and u,i-Limit
- Magn. Flux Meas.	→ Magnetic Ear
- Acoustic Noise of Mag. Comp.	→ Influence of DC Magn.
- Wireless Sensing / Monitoring.	→ Wireless Voltage Probe
- etc.	

- Integration	* Magnetic	→ Inductor/Transformer → Interph. Transf., Coupl. Ind. → CM/DM EMI Filter
	* Semicond.	→ RB-, RC-IGBTs
	* Power & Information	
- 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
* MV-Connect. → Inp. Series / Outp. Parall.
→ Series Conn. of Switches
* Extr. Conv. Ratio → Aux. Supplies
* Extr. Efficiency → Datacenters / DC Distr.
* High Curr. → Parallel Operat. of Conv.
* High Pressure → Subsea Appl.
* Integr. of Funct. → Supply & Filtering etc.
* Fault Tolerance

- Control

* Distr. Conv. Syst. → Traction/Ship/Aircraft/Subsea
* Parasitic Curr. → Circul. Curr. / CM Curr. etc.
* Highly Dyn. Conv. → High Bandw., incl. Res. Conv.

- Comp. Evaluation

* Multi-Objective → Cost Models
→ Reliability / Lifetime Models
→ Circ. / Magn. Models
→ Interact. Opt. Tools

■ More Oriented to Spec. Application

▶ Potential Research Topics

- Components
- Converters
- Systems →

Systems incl. Hybrid Systems

- Converter & Load → Losses Conv. vs. Machine
- Power & Inf. → Smart Houses
  → Smart Batteries etc.
- Hydraulic/El. → Hybrid Cranes/Constr. Mach.
- Wireless Power → Ind. Power Transfer incl. Inf.
- etc.

■ 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 !

$$p(t) \quad \rightarrow \quad \int_0^t p(t)\,\mathrm{d}t$$

- "Converter" → "Systems" (Microgrid) or "Hybrid Systems" (Autom. / Aircraft)
- "Time" → "Integral over Time"
- "Power" → "Energy"

▶ "Pessimistic" View → Consider Converters like "ICs"

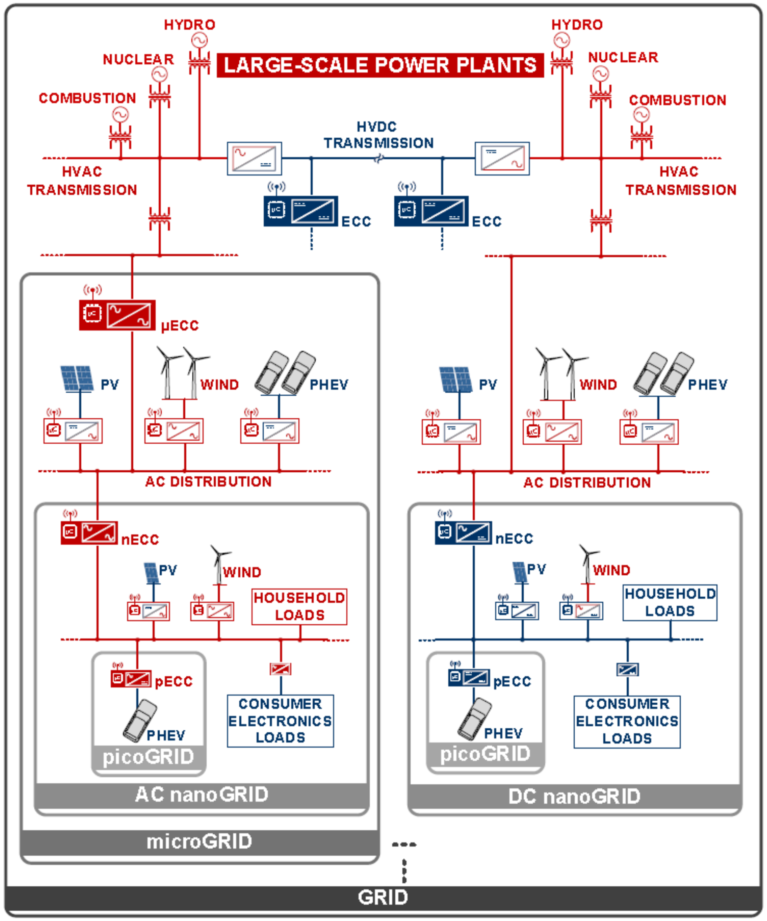
- If Only Incremental Improvements of Converters Can Be Expected → **Shift to New Paradigm !**

$$p(t) \quad \rightarrow \quad \int_0^t p(t)\,\mathrm{d}t$$

- 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

- Borojevic (2010)



- Hierarchically Interconnected Hybrid Mix of AC and DC Sub-Grids

  - Distr. Syst. of Contr. Conv. Interfaces
  - Source / Load / Power Distrib. Conv.
  - Picogrid-Nanogid-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

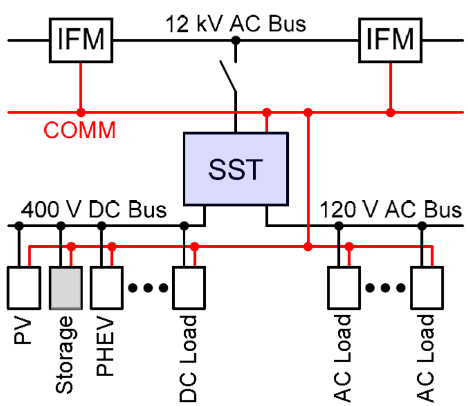
- Huang et al. (2008)

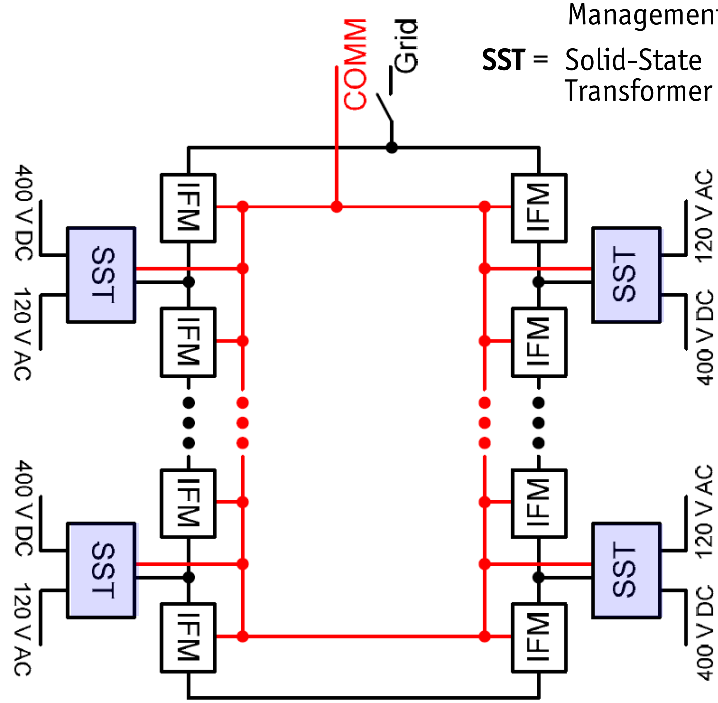
■ **"Energy Internet"**

- Integr. of DER (Distr. Energy Res.)
- Integr. of DES (Distr. E-Storage) + Intellig. Loads
- Enables Distrib. Intellig. through COMM
- Ensure Stability & Opt. Operation
- AC and DC Distribution

IFM = Intellig. Fault Management

SST = Solid-State Transformer





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

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

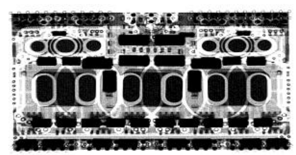
→

— Basic Discrepancy !

Most Important Industry Variable
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 (!)

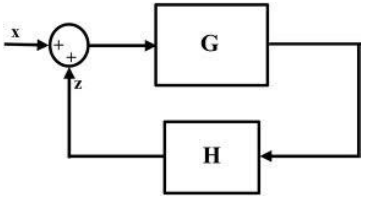
▶ University Research Orientation

■ General Observations

- 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-Discipline Papers

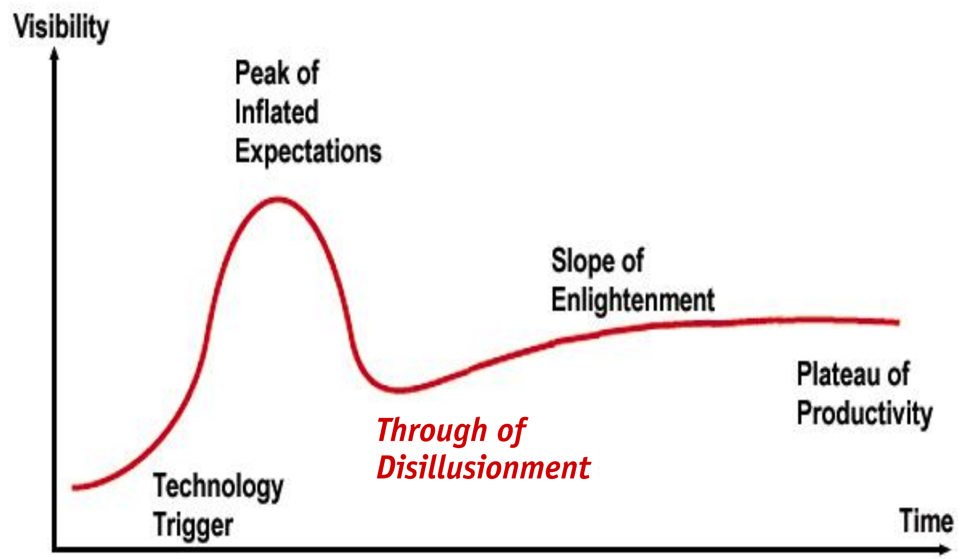
- Limitation in Scope ("Slice-by-Slice")
- Highly Complex Solutions (Ph.D. Thesis, Low Impact)
- Terminology "Hyper-Super-Ultra...."
- Hype Cycles (Citation Index Driven)

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

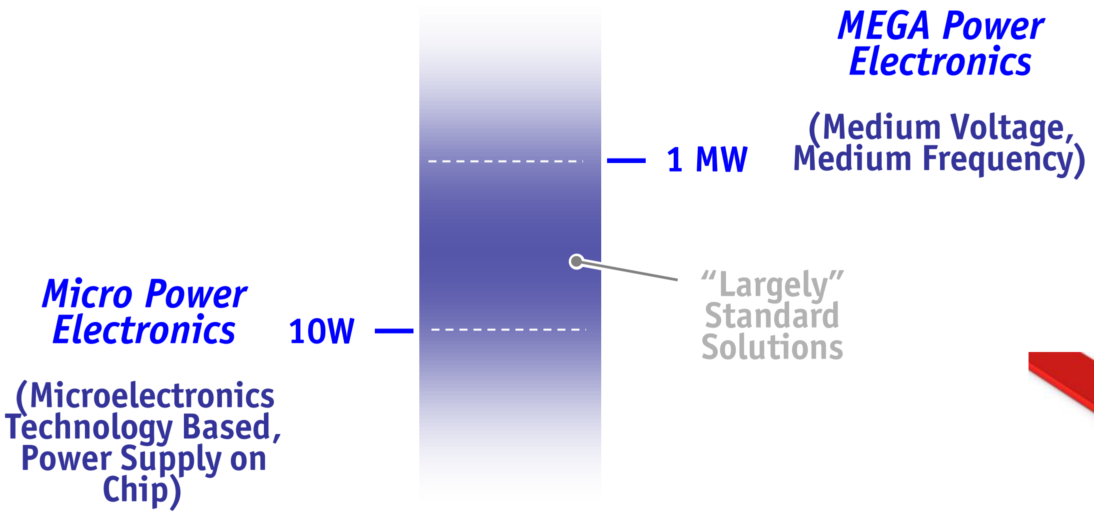
* Compare to Standard Approach Considering ALL Important Aspects
* Compare to Typical Industry Performance
* Show Several Performances (e.g. Not only Efficiency)
* Show Limits of Applicability (only then a Judgment can be Made)

— 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-Parasistics
* 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"

▶ 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

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 ?