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# *Power Electronics* – A Key Technology for the All-Electric/All-Digital World


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www.pes.ee.ethz.ch


**Nov. 15, 2019**

# Power Electronic Systems Laboratory

**Industry Relations**
R. Coccia / B. Seiler

**Johann W. Kolar**

**Adv. Mechatronic Systems**
D. Bortis

| AC-DC Converter | AC-AC Converter | DC-DC Converter | DC-AC Converter | Multi-Domain Modeling | Measurement Technology | Advanced Mechatronics | Magnetic Levitation |
|---|---|---|---|---|---|---|---|
| | | **F. Krismer** | **D. Bortis** | **F. Krismer** | | **D. Bortis** | **D. Bortis** |
| M. Heller<br>Y. Li<br>D. Menzi<br>D. Neumayr<br>D. Zhang | J. Azurza<br>P. Czyz<br>M. Haider | P. Bezerra<br>T. Guillod<br>G. Knabben<br>J. Schäfer | M. Antivachis<br>J. Böhler<br>M. Guacci | P. Papamanolis | P. Niklaus | E. Hubmann<br>R. Giuffrida | Th. Holenstein<br>P. Püntener<br>S. Miric |

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**Administration**
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**Computer Systems**
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**Electronics Laboratory**
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*22 Ph.D. Students*
*1 PostDoc*
*2 Sen. Researchers*

ECPE Competence Centre

EPSMA

**Leading Univ. in Europe**

# Outline

- Basics
- Megatrends
- X-Technologies
- Research @ ETHZ
- Future

Acknowledgement
D. Bortis
F. Krismer

# *Basic Concept*

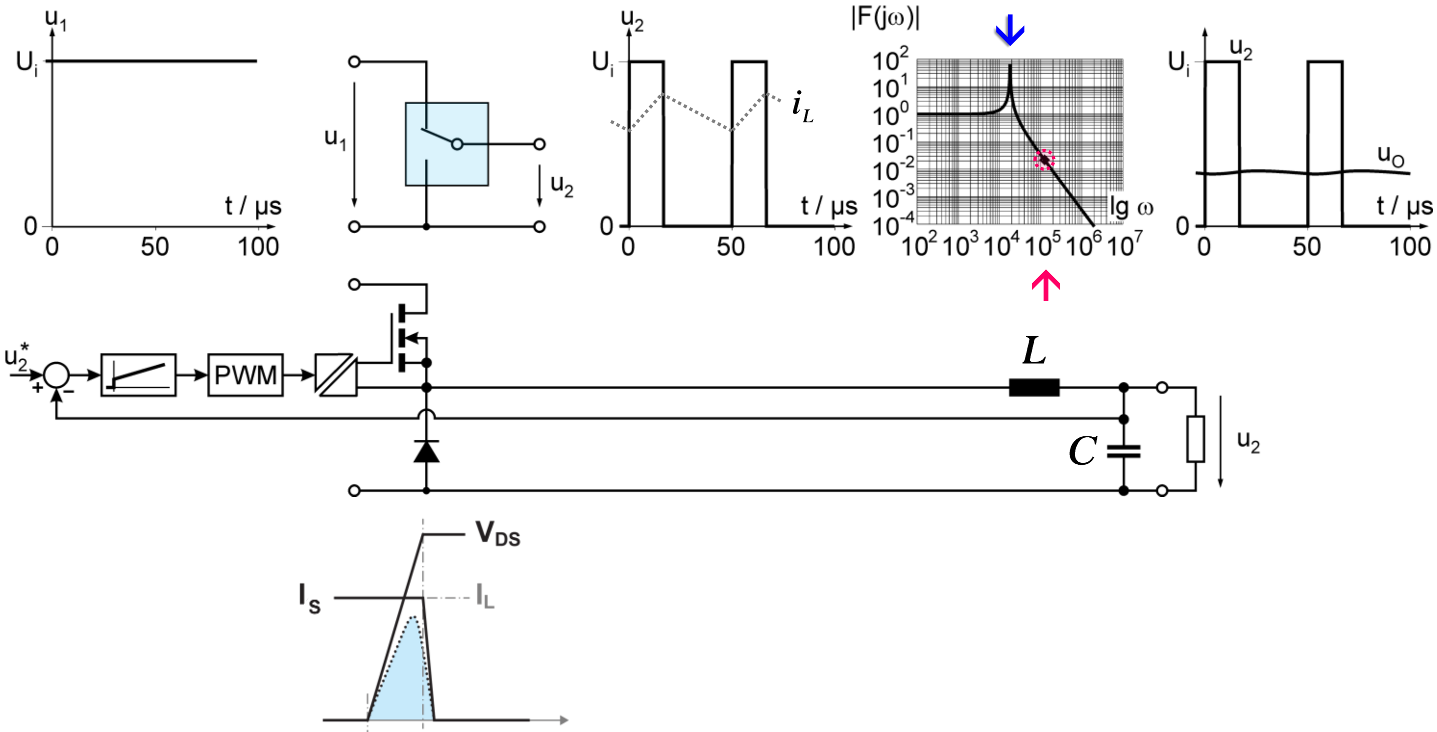
Pulse-Width Modulation
Time/Frequency Domain & Filtering


Source: www.gograph.com

# Pulse Width Modulated Converters

## Basic Concept

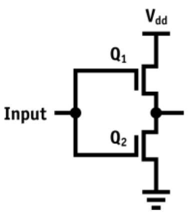
$$\omega_K = \frac{1}{\sqrt{LC}}$$

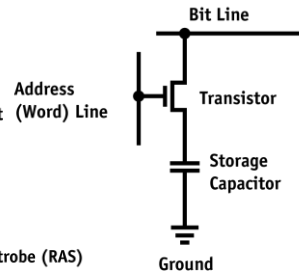


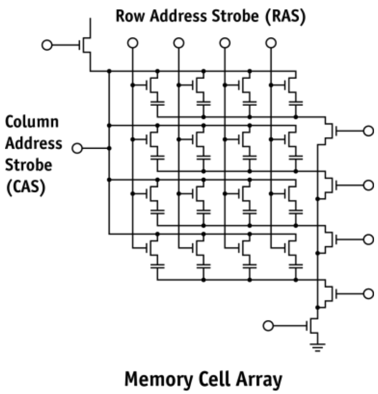

- Switch-Mode Voltage Formation — Subsequent Filtering
- *Higher Sw. Frequency → Smaller Filter Components* (Limited by Sw. Losses, Signal Processing etc.)

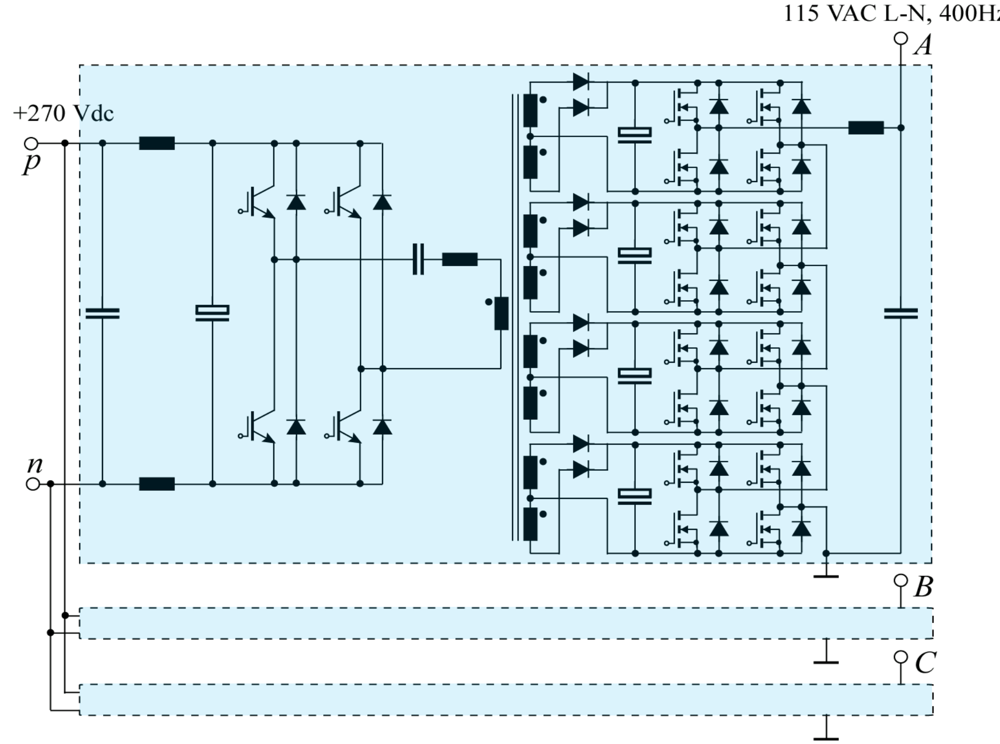
# Converter Topologies

## ■ Multi-Cell Approach

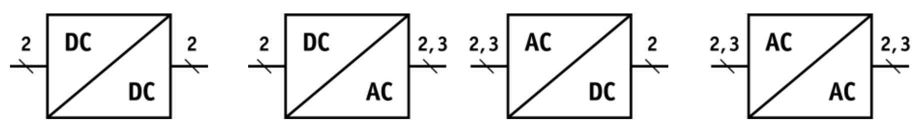



## ■ Types of Power Conversion



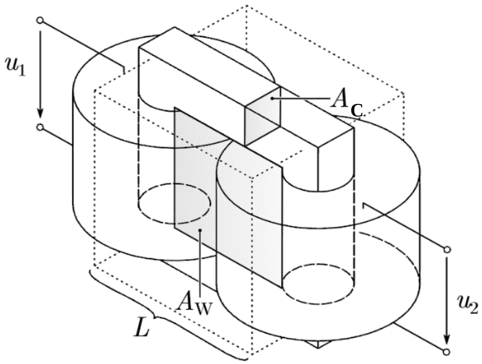
# Remark — *Magnetics*

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

- E.g. Scaling Law of Transformers
- *Size Related to Transferrable Power*

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

$\hat{B}_{max}$ ... Limited (Material)
$J_{rms}$ ... Limited (Material)
$f$ ... Limited (HF Losses)



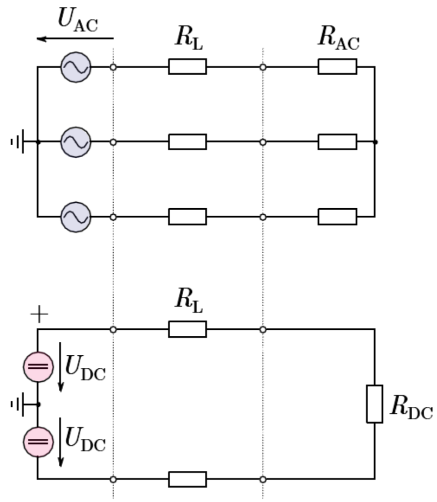

- *Slow Progress in Material Science*
- *New Materials > 10 Years*

# Remark — DC vs. 3-Φ AC Power Systems

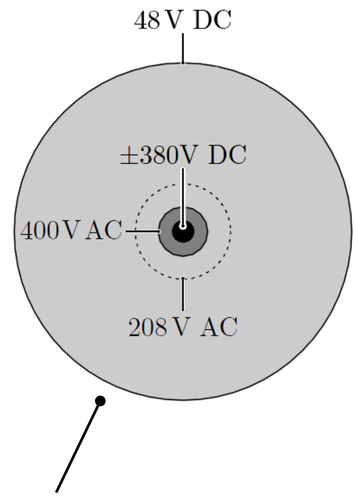
- DC Voltage Ensures Max. Utiliz. of Isol. Voltage → Highest Voltage RMS Value / Lowest Current (!)
- Quadratic Dependency of Losses on Voltage Level → Reduction of Conductor Cross Section

$$P_{V,AC} = 3 \cdot \left(\frac{\frac{1}{3}P}{U_{AC}}\right)^2 \cdot R_L$$

$$P_{V,DC} = 2 \cdot \left(\frac{P}{2U_{DC}}\right)^2 \cdot R_L$$




$$\frac{P_{V,DC}}{P_{V,AC}} = \frac{3}{2} \cdot \left(\frac{U_{AC}}{U_{DC}}\right)^2 \Bigg|_{U_{DC}=\sqrt{2}\,U_{AC}} = 0.75$$




Conductor Cross Sections for Same Losses

- DC Voltage Level Transformation Requires Power Electronics Interfaces
- DC Fault Current Clearing is Challenging (Missing Regular Current Zero Crossing)

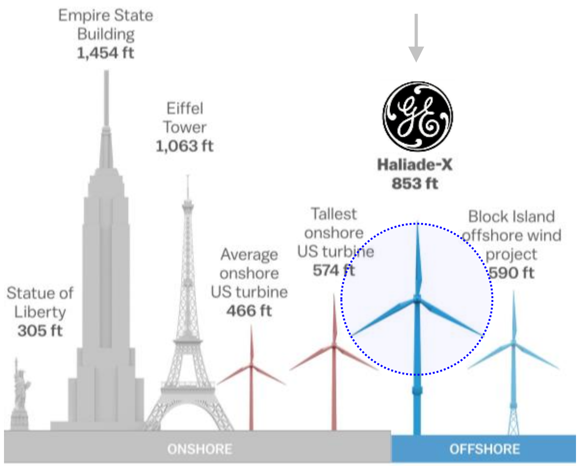
# Global Megatrends

***Renewable Energy*** →
*Digitalization*
*Sustainable Mobility*
*Robotics*
*Etc.*

# *Wind Energy*

- *Power* prop. $D^2$ → "Bigger is Better" / Lower Relative Costs
- 50kW ($D$= 15m) in 1980 → Up to 20MW ($D$= 250m) in Future

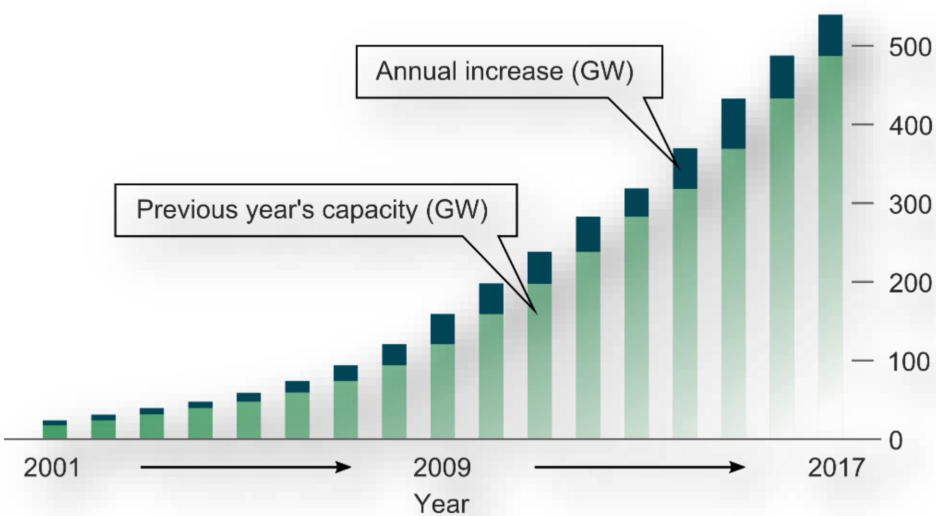
12MW
Under Development




Source: GE, Vox research

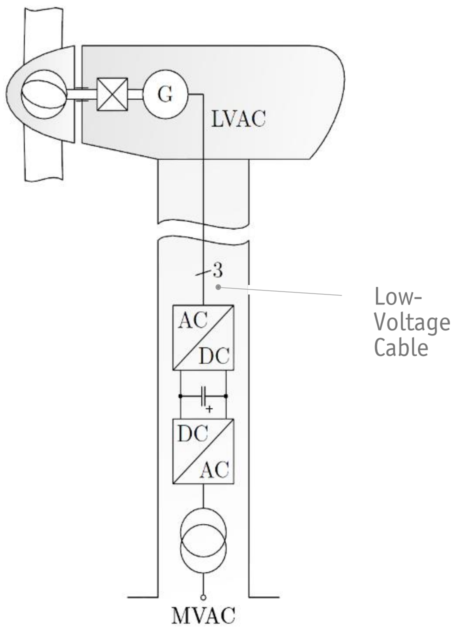
Source: gwec.net/ Blaabjerg

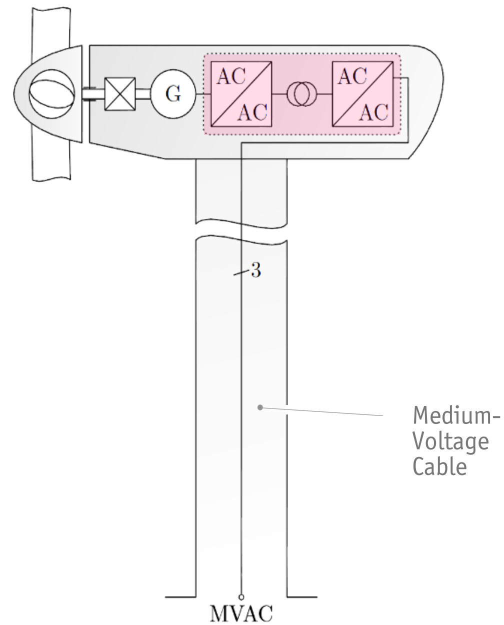
540 GW



# → *Wind Turbine Electrical System*

- 690V Electrical System → Cabling Weight/Costs & Space Requirement
- Future Local Medium-Frequency Conv. to Medium-Voltage AC or DC

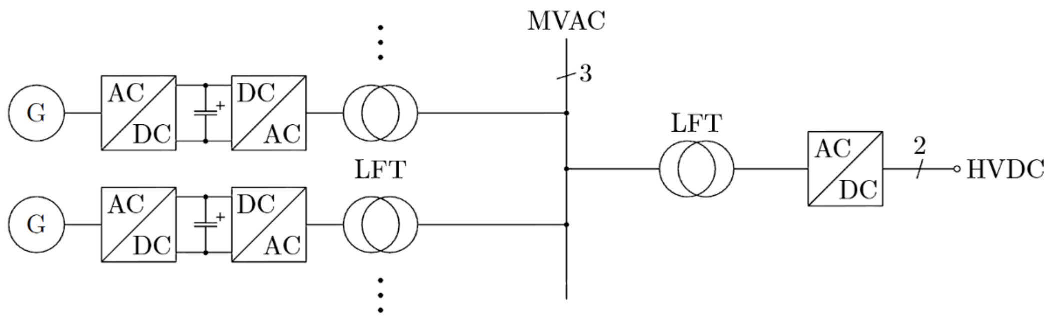


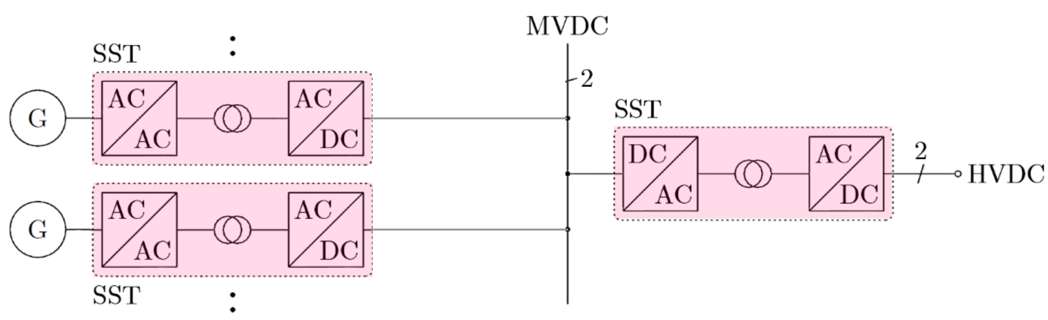

▶ *Conventional* - On-Shore System

▶ *Future* - Off-Shore System

# → Off-Shore DC Collector-Grid




- Conventional AC Collector-Grid




- DC/DC-SST — WT DC-Link to MVDC Collector Grid → Lower Losses (1%) & Volume
- DC/DC-SST — MVDC Grid to HVDC Transmission → Lower Losses (1%) & Volume

# Utility-Scale Solar Power Plants

- Medium-Voltage Power Collection and Transmission

Source: REUTERS/Stringer

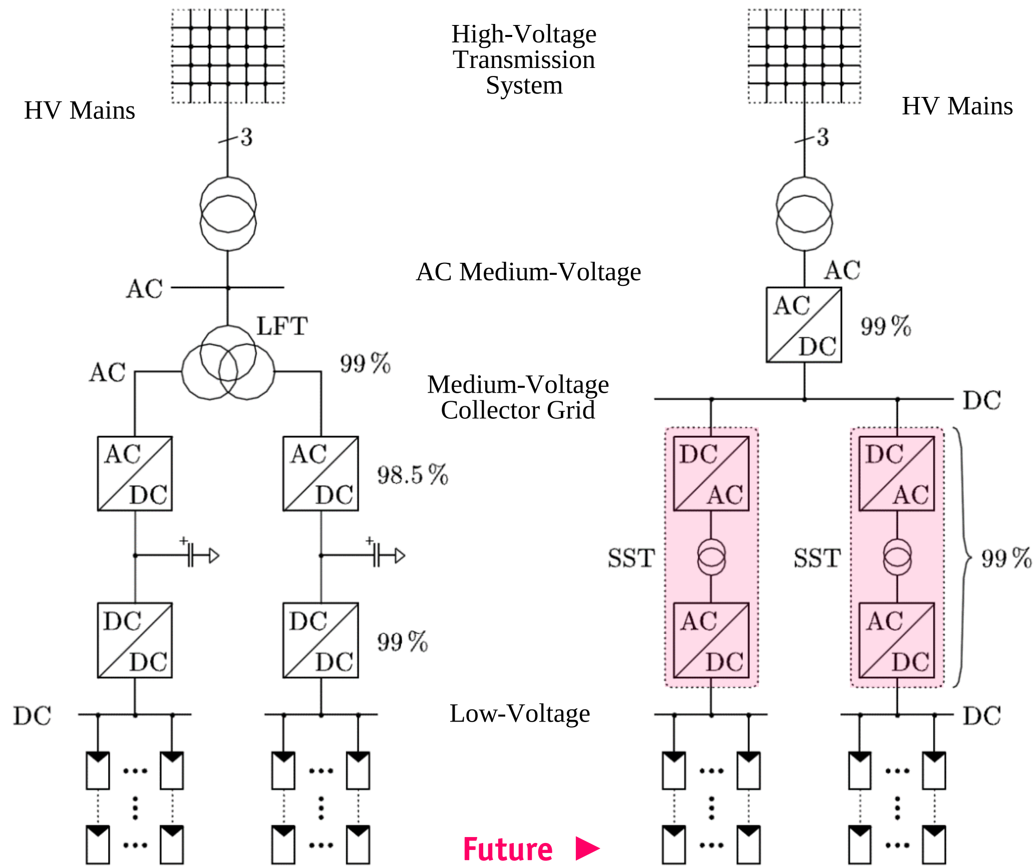
- Globally Installed PV Capacity Forecasted to 2.7 Terawatt by 2030 (IEA)

# → Future DC Collector-Grid

- DC/DC SST for MPPT & Direct Interfacing to MV Collector Grid
- 1.5% Efficiency Gain Compared to Conv. AC Technology

Conventional ▶

Future ▶



# Global Megatrends

- Renewable Energy
- ***Digitalization***
- Sustainable Mobility
- Robotics
- Etc.

# Zero CARBON Datacenters

- Ranging from Medium Voltage to Power-Supplies-on-Chip
- Short Power Supply Innovation Cycles
- Modularity / Scalability

- Higher Availability
- Higher Efficiency
- Higher Power Density
- Lower Costs

Server-Farms
up to 450 MW
99.9999%/<30s/a
$1.0 Mio./Shutdown

Since 2006
Running Costs >
Initial Costs

Source: REUTERS/Sigtryggur Ari

33 Watts

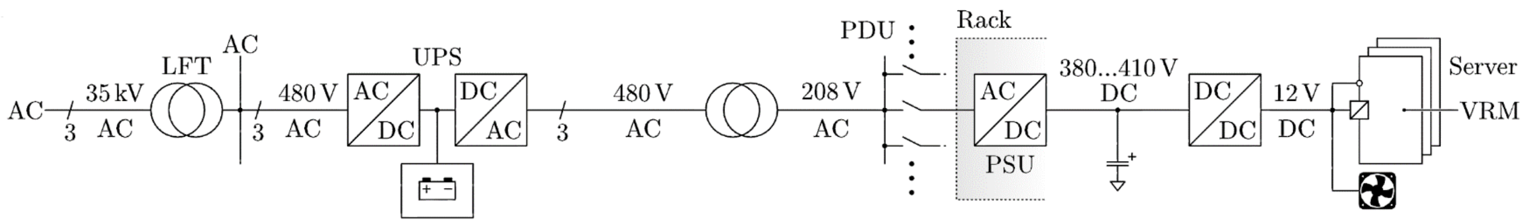
→

60 Watts

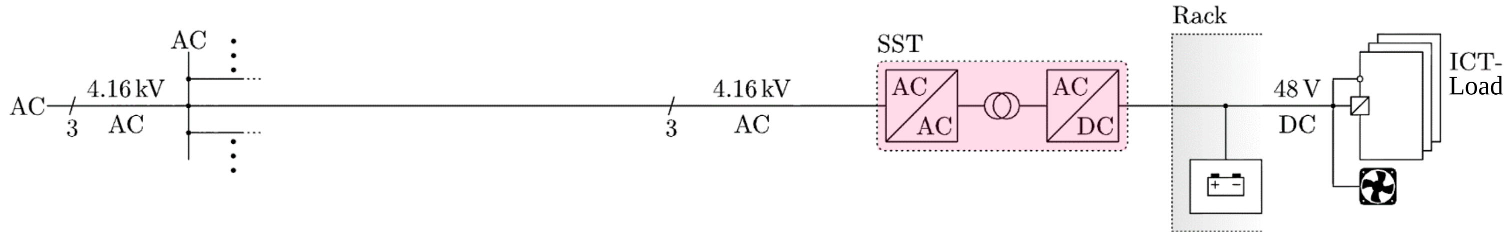
# → Future *Modular* SST-Based Power Distribution

- 5…7% Reduction in Losses & Smaller Footprint
- Improves Reliability & Power Quality

— Conventional




— Future Direct 3-Φ 6.6kV AC → 48V DC




- *MV → 48V → 1.2V - Only 2 Conversion Stages from MV to CPU-Level (!)*

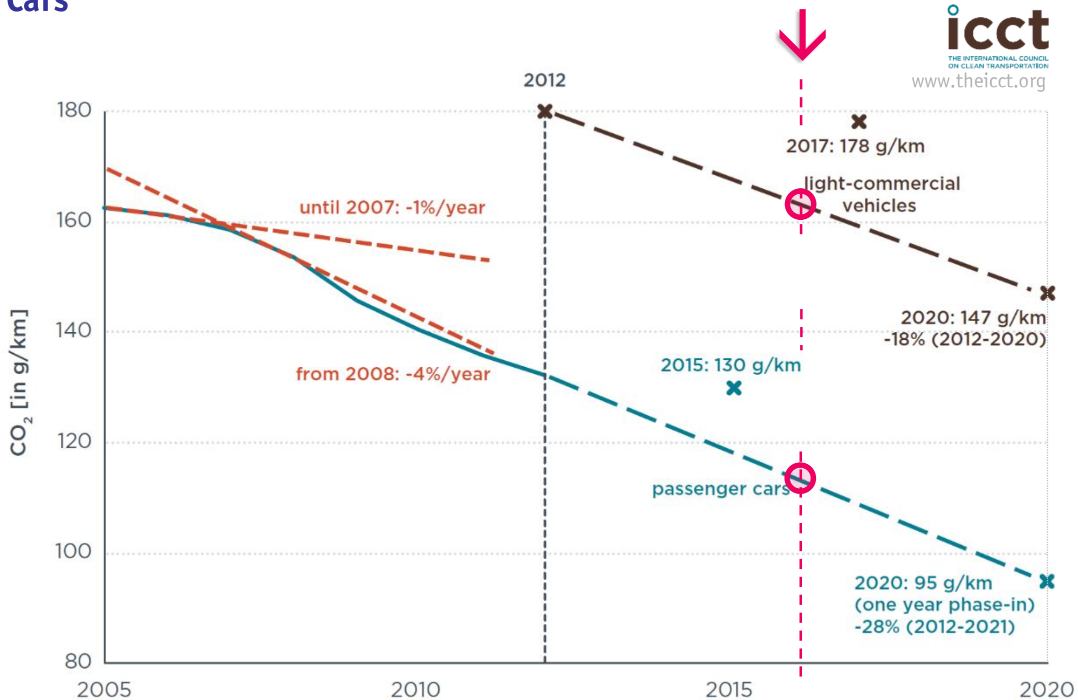
# Global Megatrends

*Renewable Energy*
*Digitalization*
***Sustainable Mobility*** →
*Robotics*
*Etc.*

# Sustainable Mobility

- **EU 2020 $CO_2$ Emission Targets for New Cars**

— 147g $CO_2$/km for Light-Commercial Vehicles
— 95g $CO_2$/km for Passenger Cars
— 100% Compliance in 2021




▶ Hybrid Vehicles
▶ Electric Vehicles

# → Ultra-Fast EV-Charging

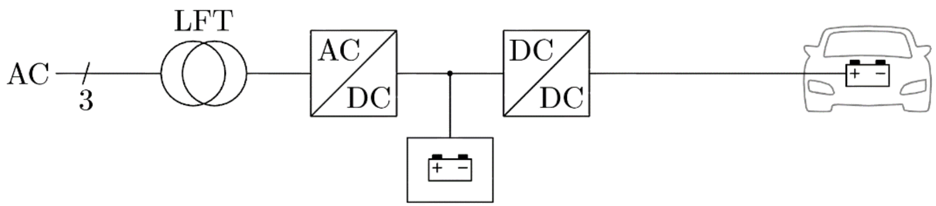
- Medium Voltage Connected Modular Charging Systems
- Very Wide Output Voltage Range (200…800V)

Source: Porsche Mission-E Project

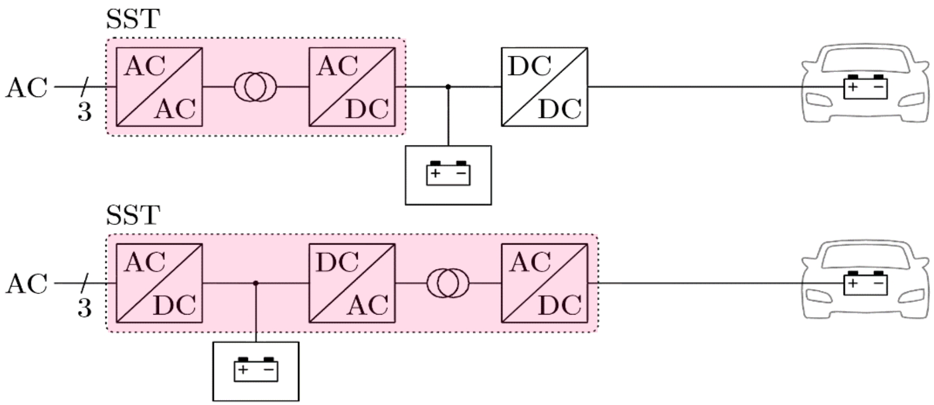
- E.g., Porsche *FlexBox* incl. Cooling
- Local Battery Buffer (140kWh)
- 320kW → 400km Range in 20min

# → Bidirectional MV-Interface

- **Conventional**




- *Future*

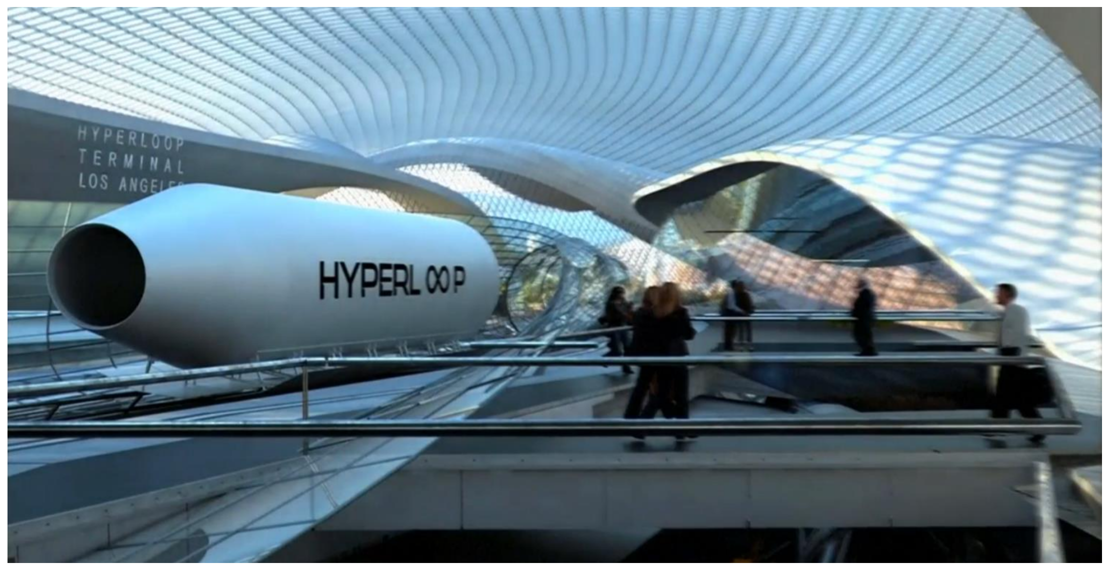



- **On-Site Power / Energy Buffer** → *„Energy-Hub"*
- **Power / Energy Management** → *Peak Load Shaving & Grid Support / Stabilization*

# → *Futuristic Mobility*

- Hyperloop
- San Francisco → Los Angeles in 35min

HYPERLOOP
POD COMPETITION
www.spacex.com/hyperloop

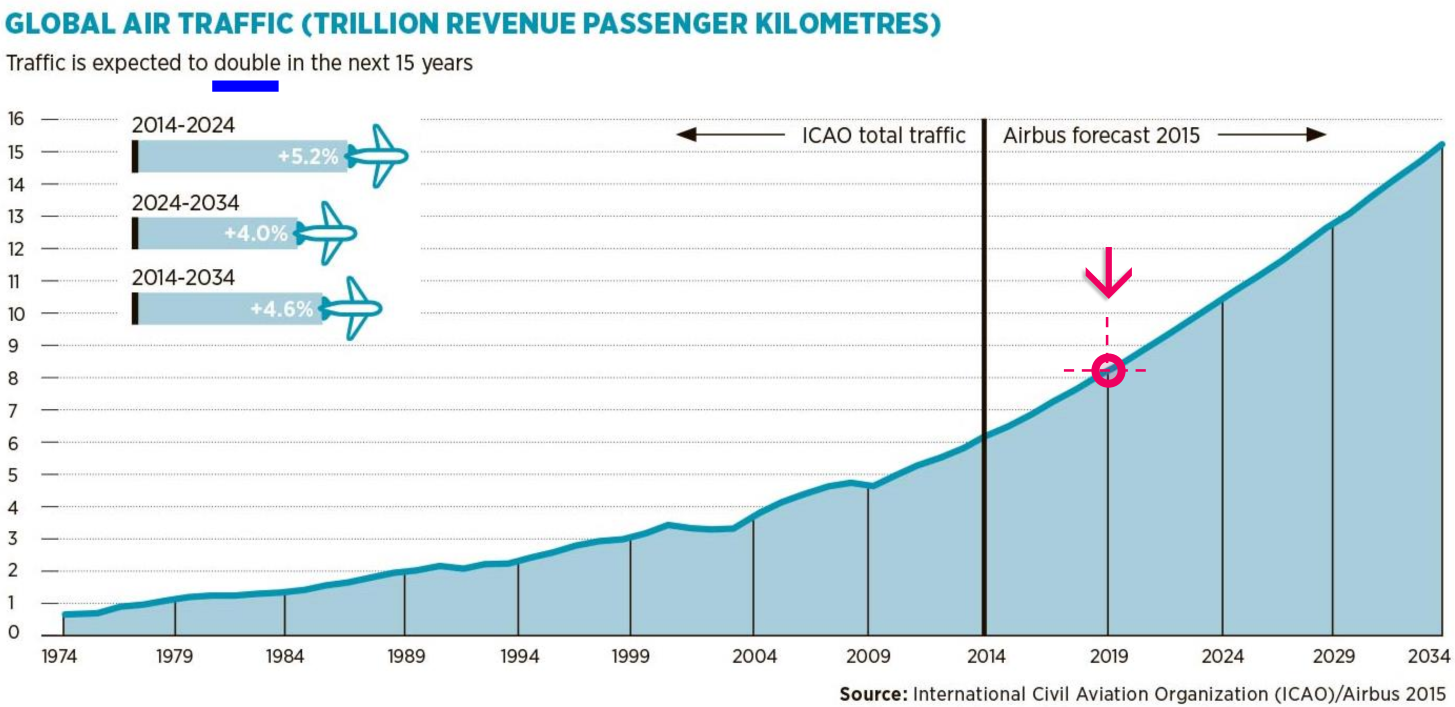




- Low Pressure Tube
- Magnetic Levitation
- Linear Ind. Motor
- Air Compressor in Nose

# Air Transportation

- **Massive Steady Increase of Global Air Traffic Over the Next Decades**

— **Need for 70´000 New Airliners over the Next 20 Years (Boeing & Airbus)**
— **Stringent *Flightpath 2050 Goals* of ACARE → Reduction of $CO_2$/$NO_x$/Noise Emissions**



# → *Future Aircraft*

■ **Cut Emissions Until 2050**

— $CO_2$ by 75%,
— $NO_x$ by 90%,
— Noise Level by 65%

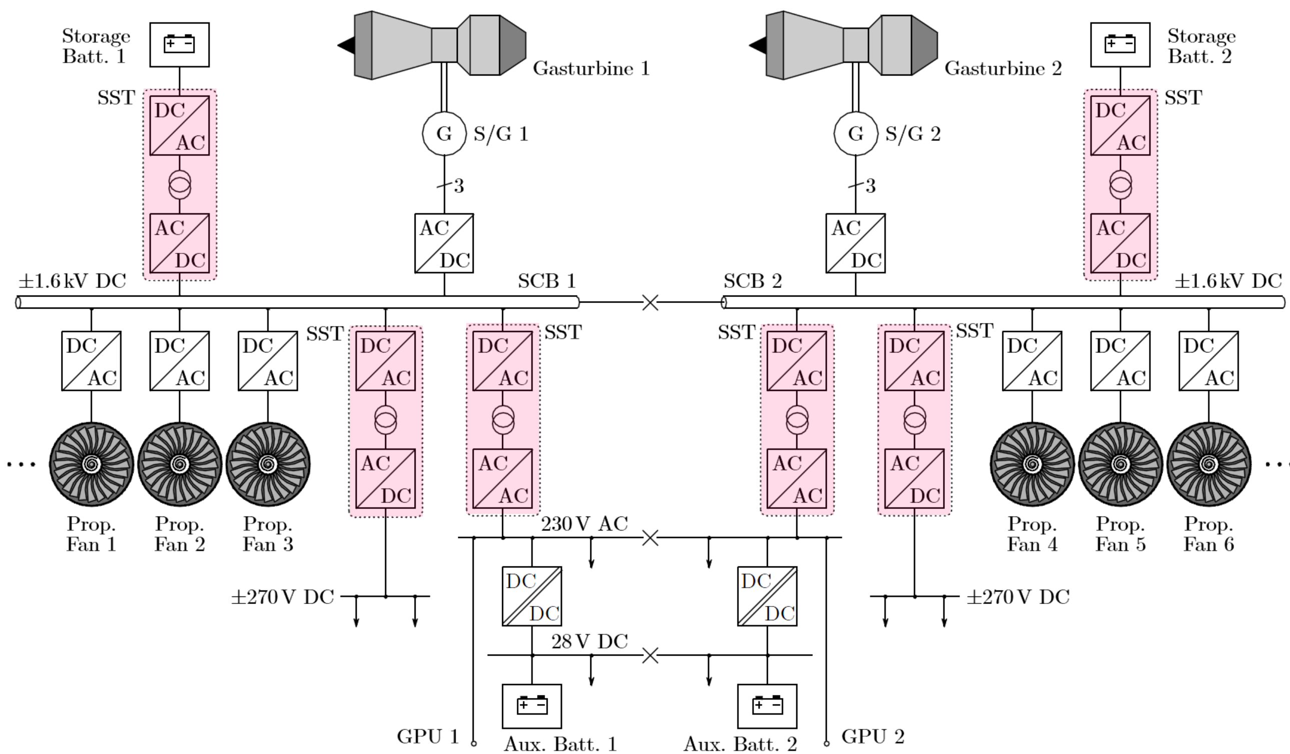
Source:

NASA N3-X
Vehicle Concept


- **Wing-Tip Mounted Eff. Optimized Gas Turbines & Distributed E-Fans (“E-Thrust”)**
- **MV or Superconducting Power Distribution Integr. 1000Wh/kg Batteries (EADS-Concept)**

# → Future Aircraft Electric Power System

- MV or Superconducting Power Distribution Integr. 1000Wh/kg Batteries (EADS-Concept)




- Generators — 2 x 40.2MW (NASA)
- E-Fans — 14 x 5.7 MW (1.3m Diameter)

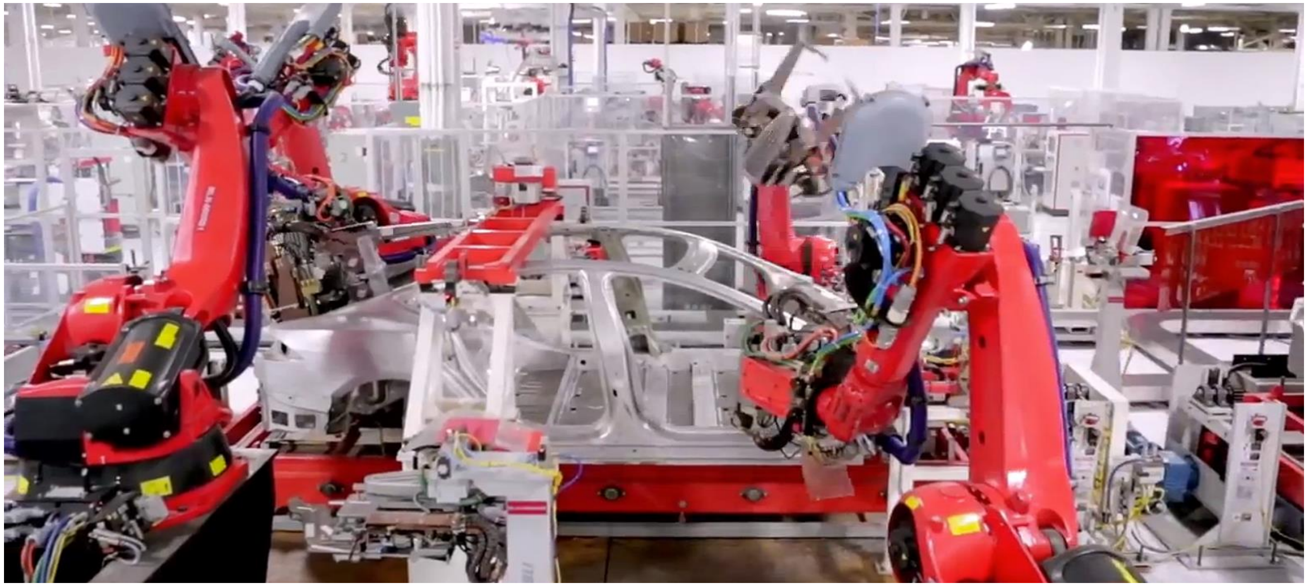
# Global Megatrends

Renewable Energy
Digitalization
Sustainable Mobility
**Robotics** →
Etc.

# *Industry Automation*

- Robotics
- Machining / Processing – Drilling, Milling, etc.
- Pumps / Fans / Compressors
- Transportation
- etc., etc. .... Everywhere !

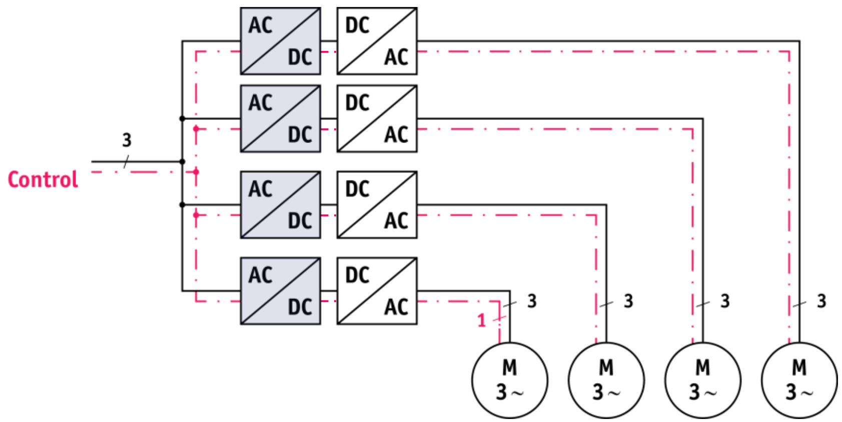
Source: TESLA MOTORS



- *60% of El. Energy Used in Industry Consumed by Variable Speed Drives (VSDs)*

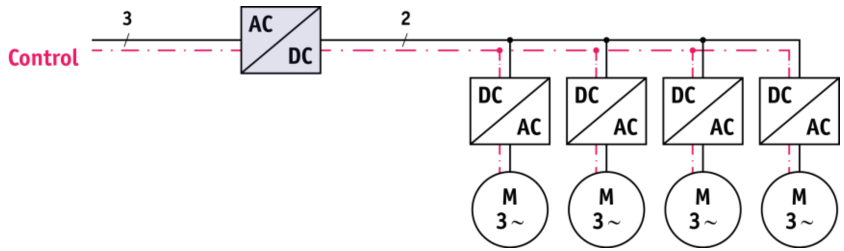
# → Future Integrated Servo Drive Systems

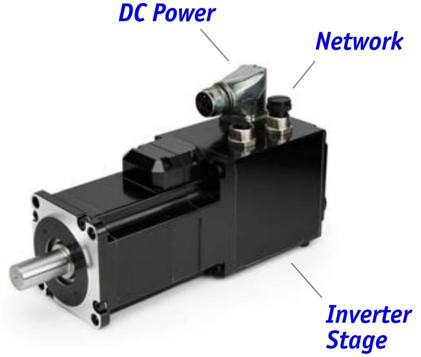
- *State-of-the-Art*




Source: YASKAWA

- *Future — Distributed DC-Link System*




- *SMART Motor — Integr. of Inverter & Motor → High Operating Temp.*
- *Smaller Size & Massive Saving in Cabling Effort / Non-Expert Installation*

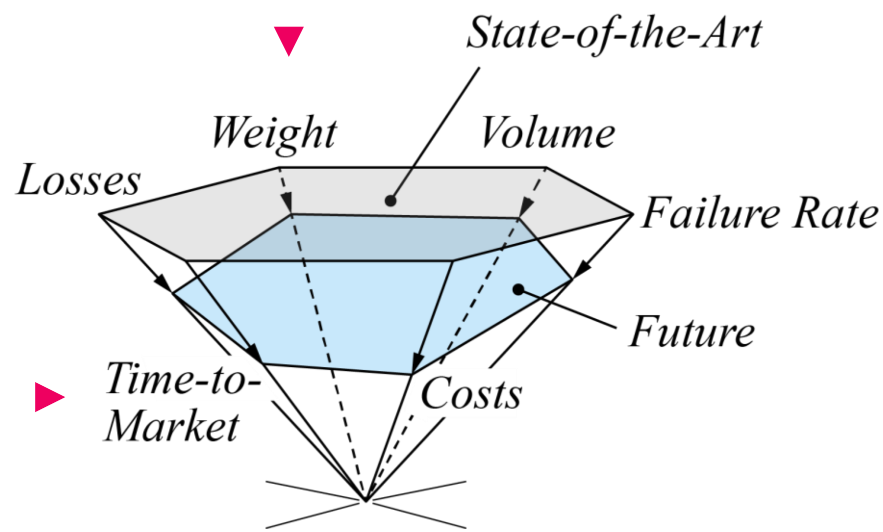
***X-Concepts***


Source: www.terencemauri.com

# *Required Improvements*

Environmental Impact... $[kg_{Fe}\ /kW]$
$[kg_{Cu}\ /kW]$
$[kg_{Al}\ /kW]$
$[cm^2_{Si}\ /kW]$

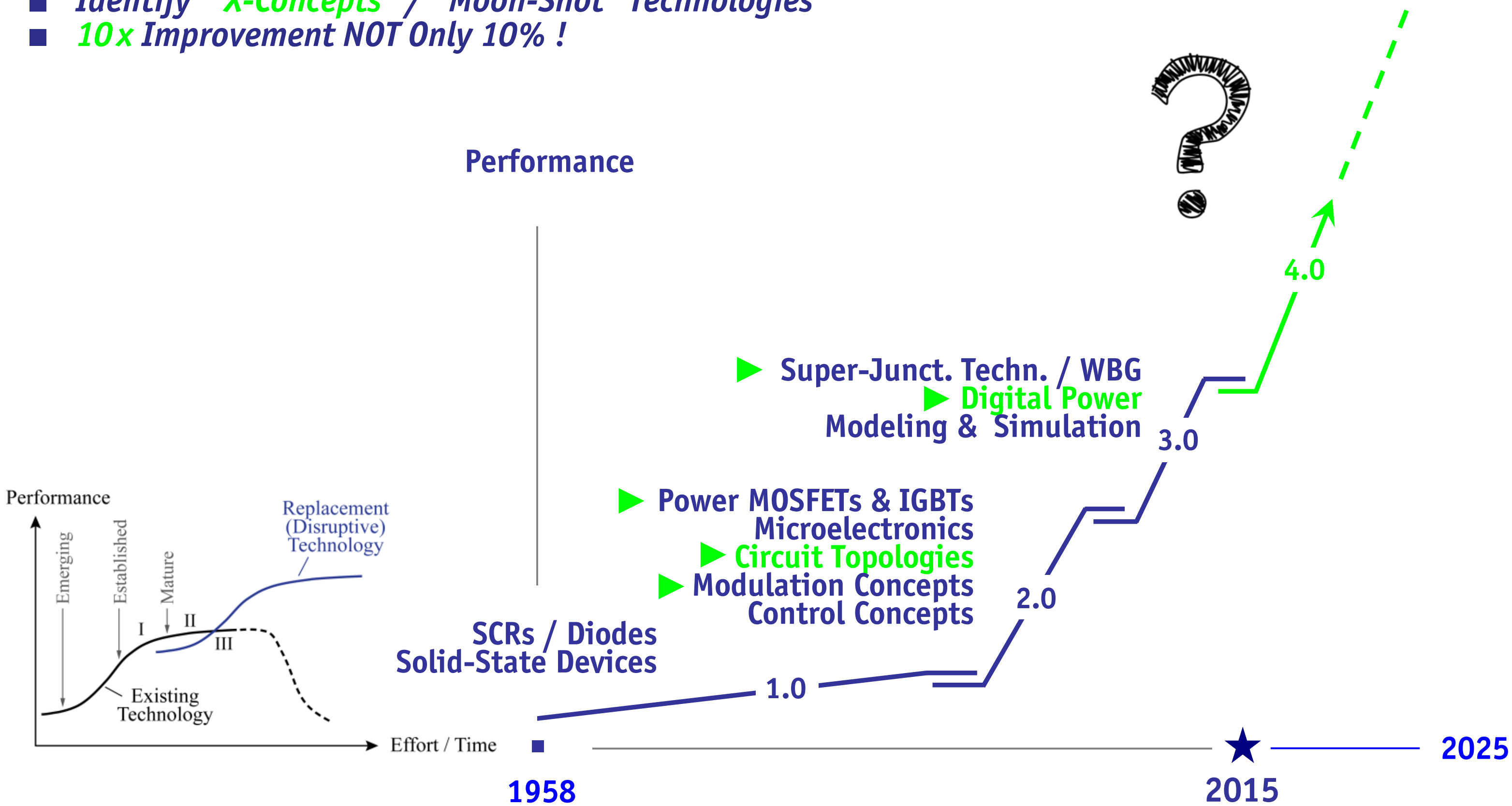
- Power Density [kW/dm³]
- Power per Unit Weight [kW/kg]
- Relative Costs [kW/$]
- Relative Losses [%]
- Failure Rate [h⁻¹]



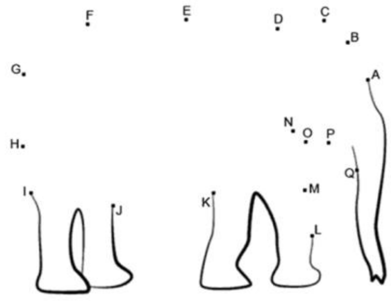

- Future → Cost / Cost / Cost & Robustness & Availability & Recyclability

# S-Curve of Power Electronics

- *Power Electronics 1.0 → Power Electronics 4.0*
- *Identify "X-Concepts" / "Moon-Shot" Technologies*
- *10x Improvement NOT Only 10% !*



***Topologies***
***Modulation &***
***Control***



# 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.

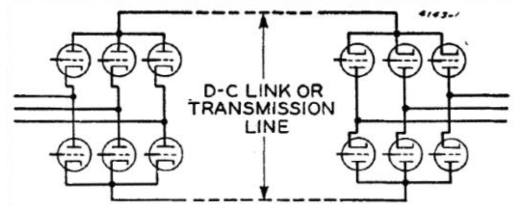



Figure 1. Electronic converter, dual-conversion type

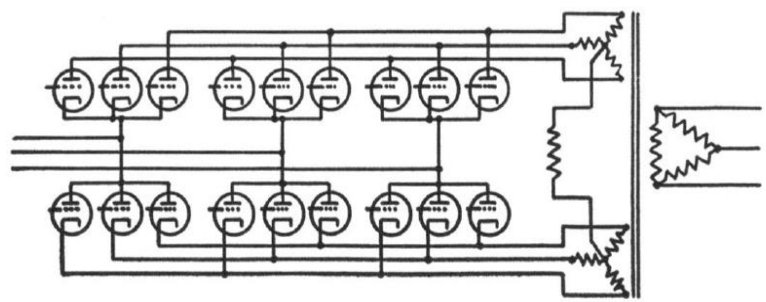
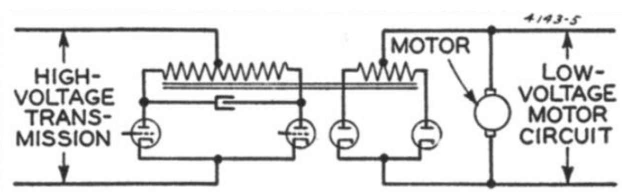


Figure 4 (left). Single - conversion-type frequency changer

Figure 5 (below). D-c transformer

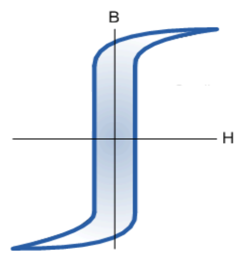



Paper 44-143, recommended by the AIEE committee on electronics for presentation at the AIEE summer technical meeting, St. Louis, Mo., June 26–30, 1944. Manuscript submitted April 25, 1944; made available for printing May 18, 1944.

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

1944 !

# *Passive Components*




Source: www.electronics-tutorials.ws

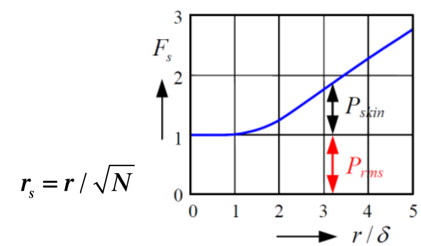
*Magnetics as Example*

# Operation Frequency Limit (1)

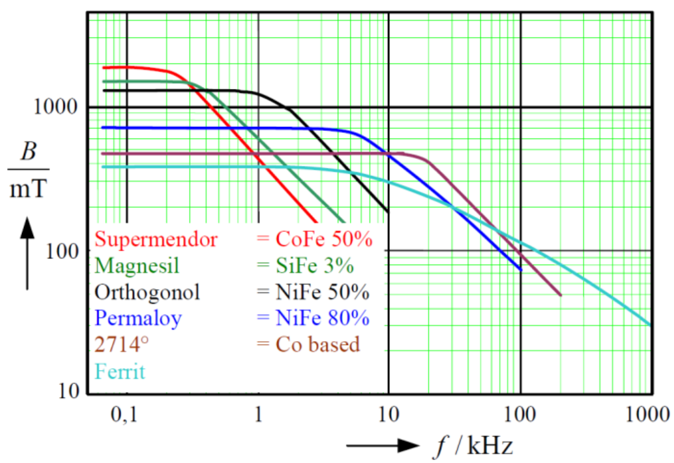
■ **Serious Limitation of Operating Frequency by HF-Losses**

Source: Prof. Albach, 2011

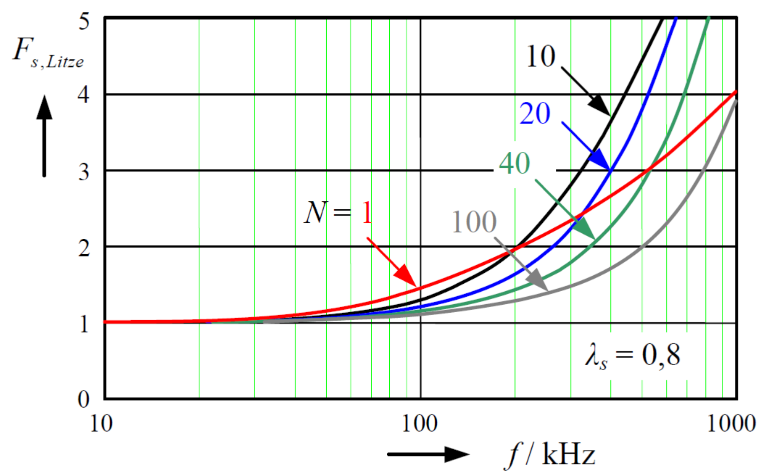
— Core Losses (incr. @ High Frequ. & High Operating Temp.)
— Temp. Dependent Lifetime of the Core
— Skin-Effect Losses
— Proximity Effect Losses




$$p_{VE} = \frac{\Delta P_{VE}}{\Delta V_E} = k\, f^{\alpha} \hat{B}^{\beta} = \text{const.}$$




■ Adm. Flux Density for given Loss Density



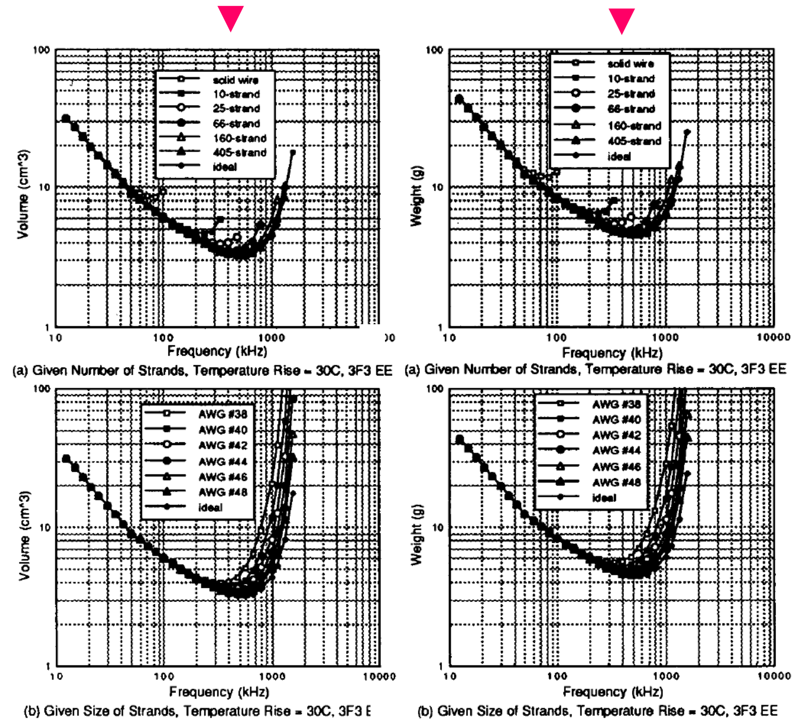

■ Skin-Factor $F_s$ for Litz Wires with $N$ Strands

# Operation Frequency Limit (2)

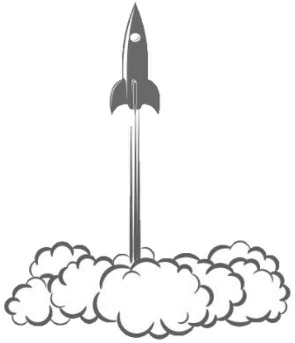
- ***Higher Frequency  Results in Smaller Size only Up to Certain Limit (for MnZn Core-Based Designs)***
- ***Optimal Converter Operating  Frequencies < 1MHz***
- ***Difficult to Manufacture***

Source: Philips

Transformer Volume &
Weight vs. Frequency


- ***Automated Manufacturing → Magnetic Integration / PCB-Windings / Planar Shapes***

X-Technology **#1**  Interleaving & Modularity

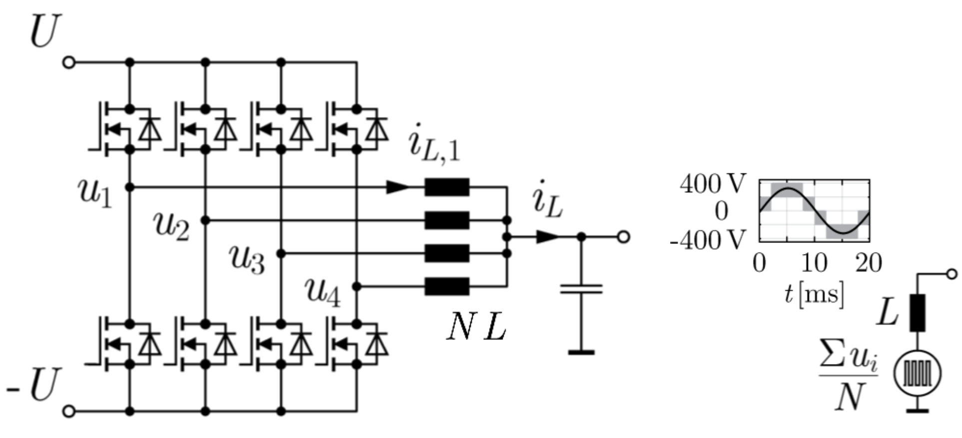
# Parallel Interleaving

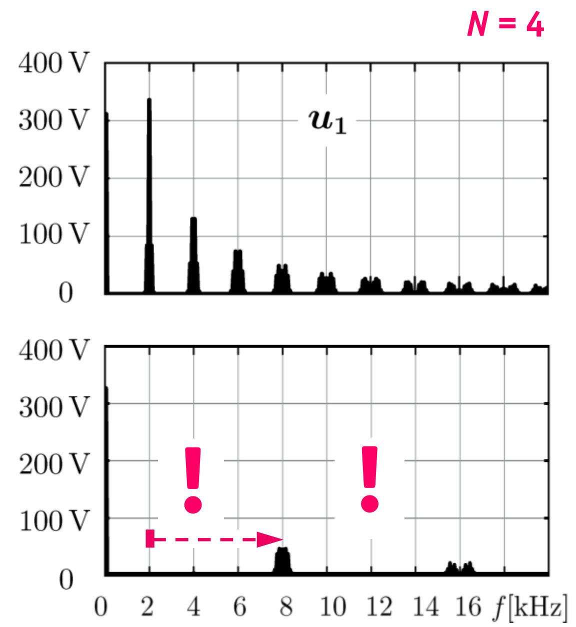
- Loss-Neutral Multiplication of Switching Frequency
- Reduced Ripple @ Same (!) Switching Losses

$$f_{S,\mathrm{eff}} = N \cdot f_S$$

$$\Delta I_{\max,N} = \frac{1}{N^2}\Delta I_{\max,N=1}$$

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

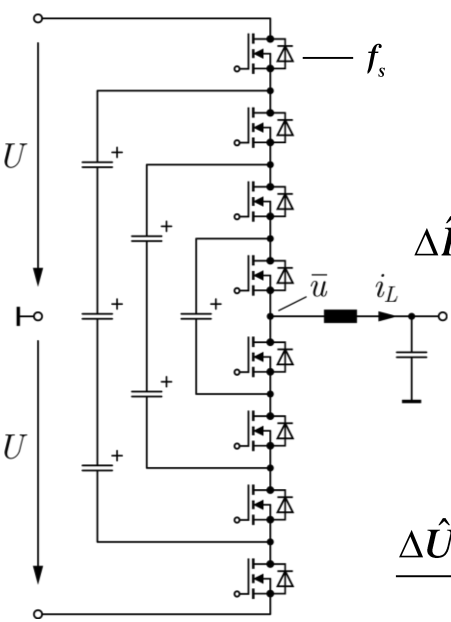



- Scalability / Manufacturability / Standardization / Impedance Matching / Redundancy

# Series Interleaving

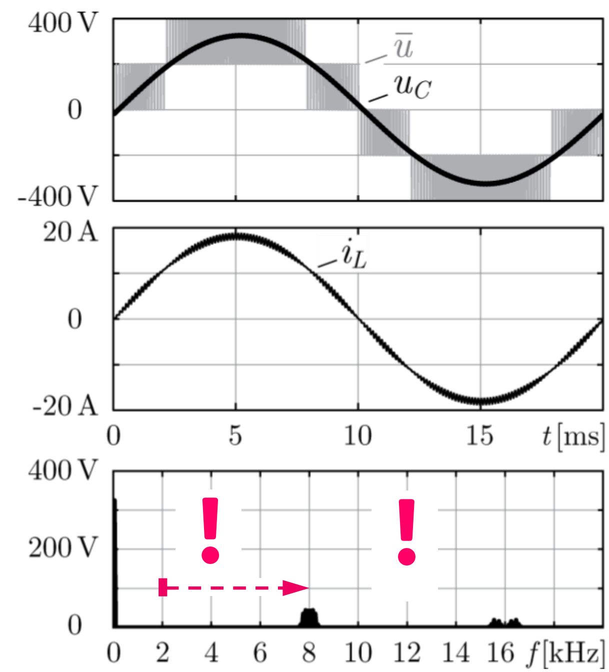
- *Loss-Neutral Multiplication of Sw. Frequency*
- *$N^2$-Reduced Ripple @ Same (!) Switching Losses*
- *Lower On-Resistance @ Given Blocking Voltage → 1+1=2 NOT $2^2 = 4$ (!)*
- *Extends LV Technology to HV*




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

$$\Delta\hat{I}_{\max,N} = \frac{1}{N^2}\Delta\hat{I}_{\max,N=1}$$

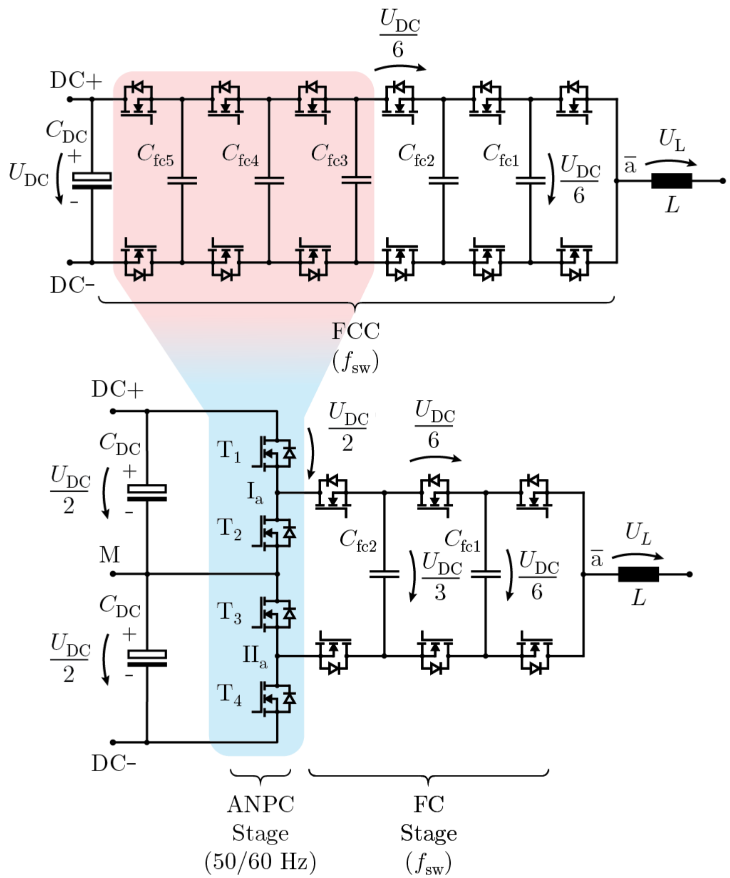
$$\frac{\Delta\hat{U}_{C,\max,N}}{U} = \frac{\pi^2}{32}\left(\frac{f_O}{f_S}\right)^2\frac{1}{N^3}$$

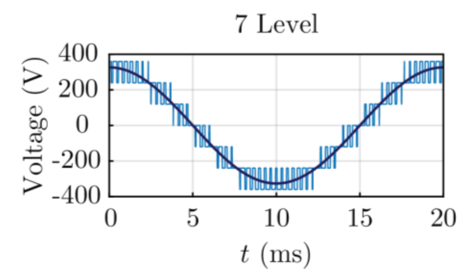



- **Scalability / Manufacturability / Standardization / Impedance Matching / Redundancy**

# Series Interleaving – Example @ ETH Zurich

- *Realization of a 99%++ Efficient 10kW 3-Φ 400V$_{rms,ll}$ Inverter System*
- *7-Level Hybrid Active NPC Topology / LV Si-Technology*

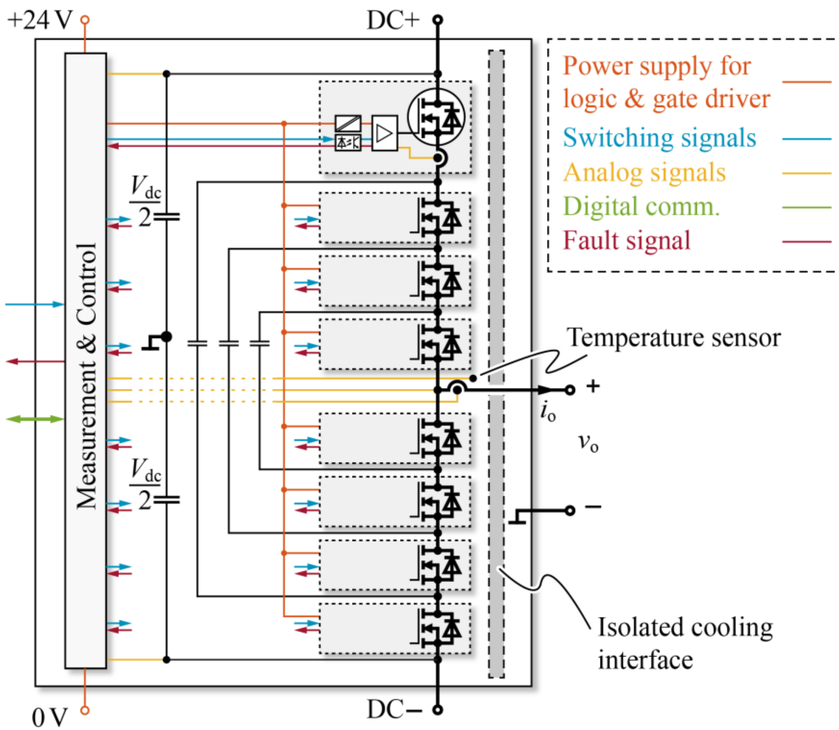


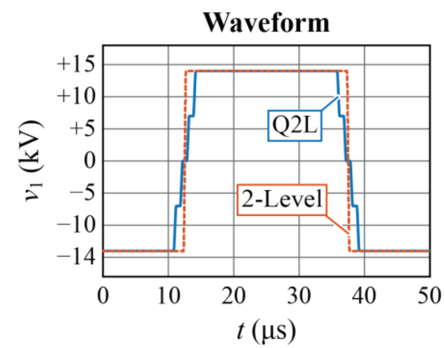



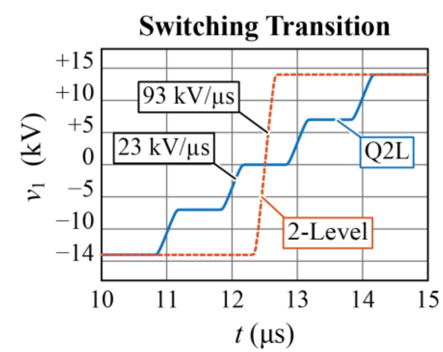

**99.35%**
**2.6kW/kg**
**56 W/in$^3$**

# 40kV SiC Super-Switch @ ETH Zurich

- Quasi-X-Level (Staggered) Switching
- 300kVA Intelligent Power Module — Two-Level Bridge-Leg Appearance




- Integrated Gate Drive / Voltage Balancing / Protection / etc.

# *Ultra-Compact Power Module with Integrated Filter*

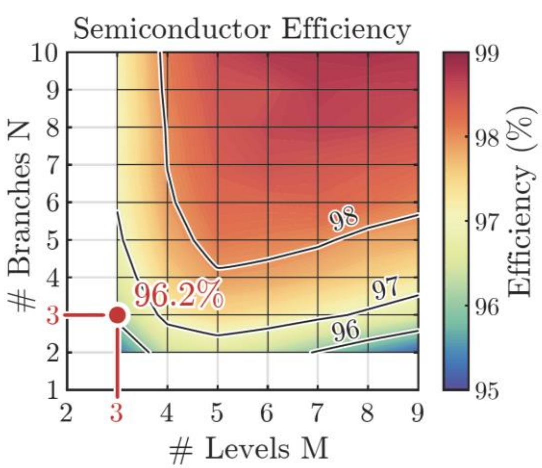
*650V GaN E-HEMT Technology*

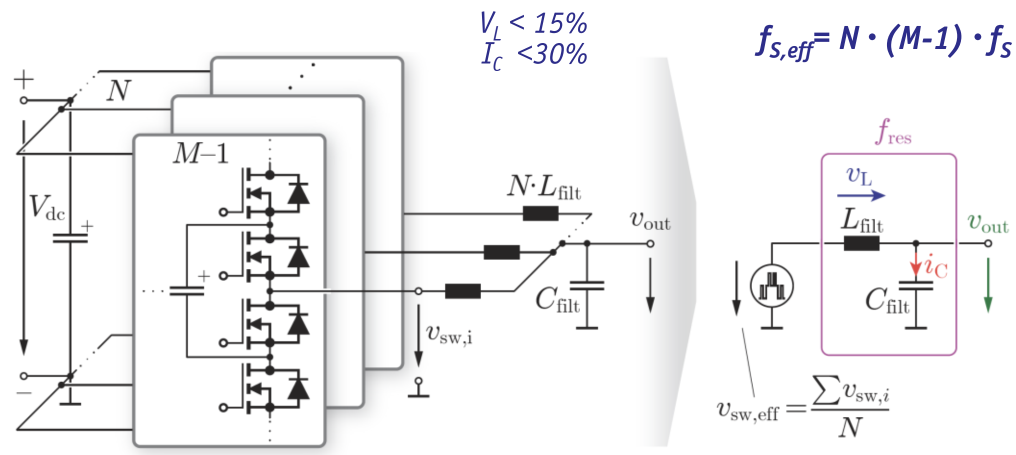
$f_{S,eff} = 4.8MHz$

$f_{out} = 100kHz$

# Integrated Filter GaN Power Module

- Selection of M=3 / N=3 Considering Efficiency / Filter Volume Trade-Off
- $N \cdot L_{filt}$=3.3uH of Branch Inductance / $C_{filt}$ = 90nF
- 650V GaN E-HEMT Technology / $f_S$ = 800kHz
- $f_{S,eff}$= 4.8MHz



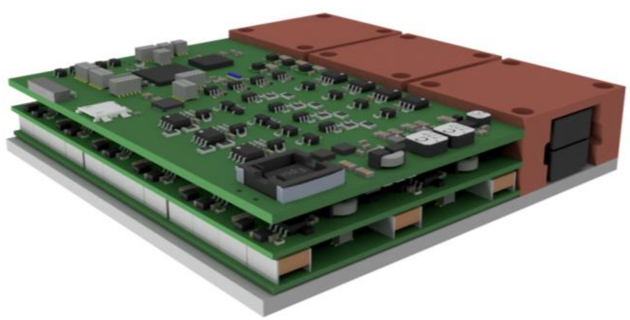

- Design for Max. Output Frequency of $f_{out}$ = 100kHz (!) @ Full-Scale Voltage Swing

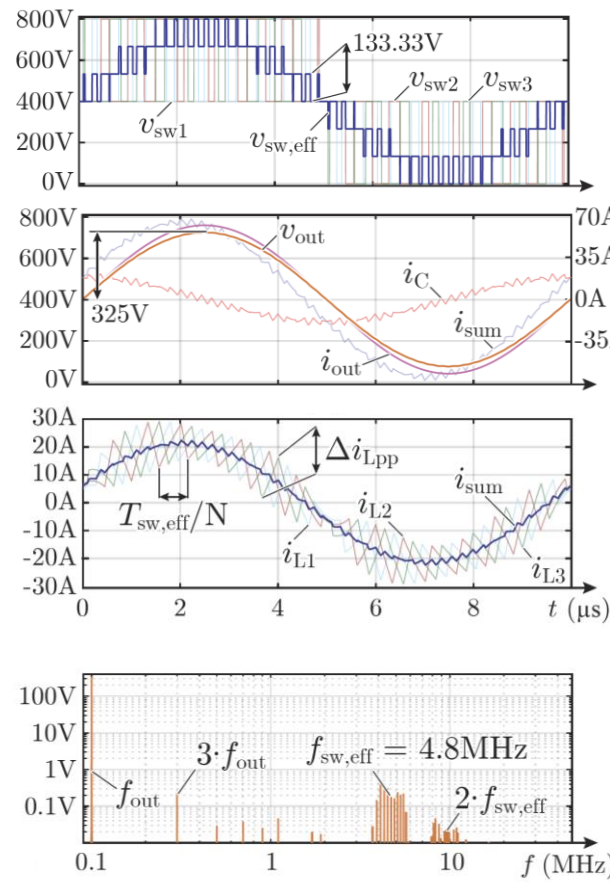
# Demonstrator System

- *Specifications*

— *10kW @ 800V$_{DC}$*
— *650V GaN Power Semiconductors*
— *Volume of ≈180cm$^3$ (incl. Control etc.)*
— *$H_2O$ Cooling Through Baseplate*

*≈ 50kW/dm$^3$*





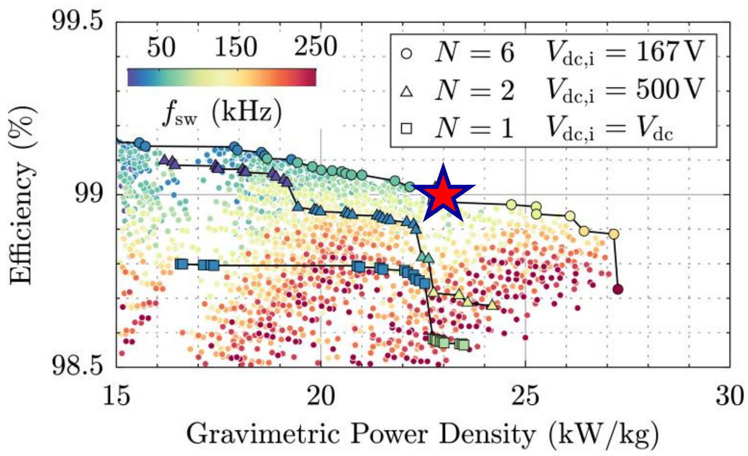

- *Operation @ $f_{out}$=100kHz ($f_{S,eff}$= 4.8MHz)*

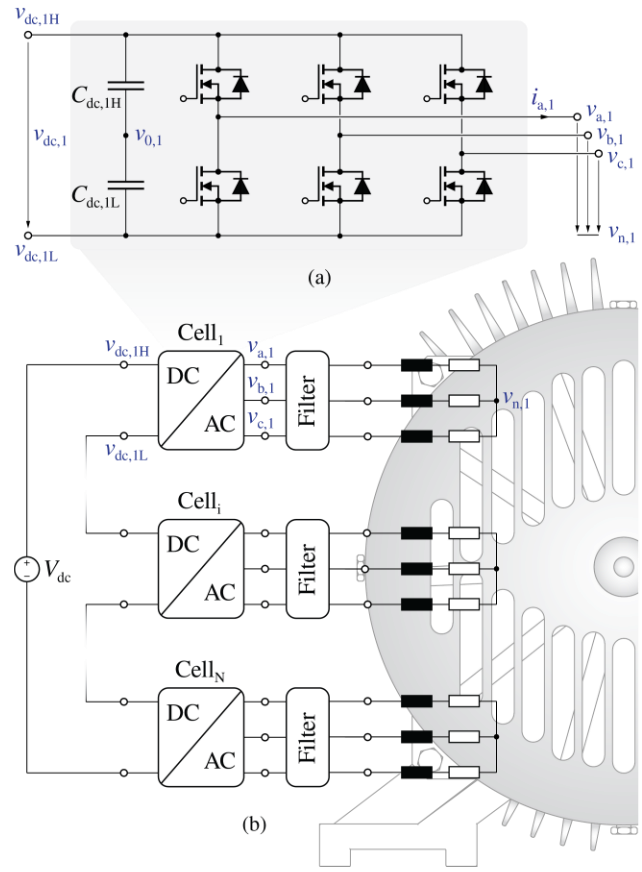
# Motor-Integrated Modular Inverter

# Motor-Integrated Modular Inverter

- *Fault-Tolerant VSD*
- *Low-Voltage Inverter Modules*
- *Very-High Power Density / Efficiency*
- *Low C DC-Buffer Capacitors*

- *Rated Power* 45kW / $f_{out}$ = 2kHz
- *DC-Link Voltage* 1 kV

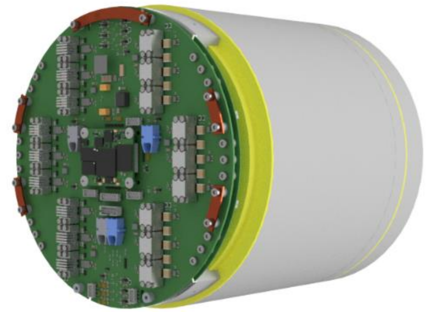


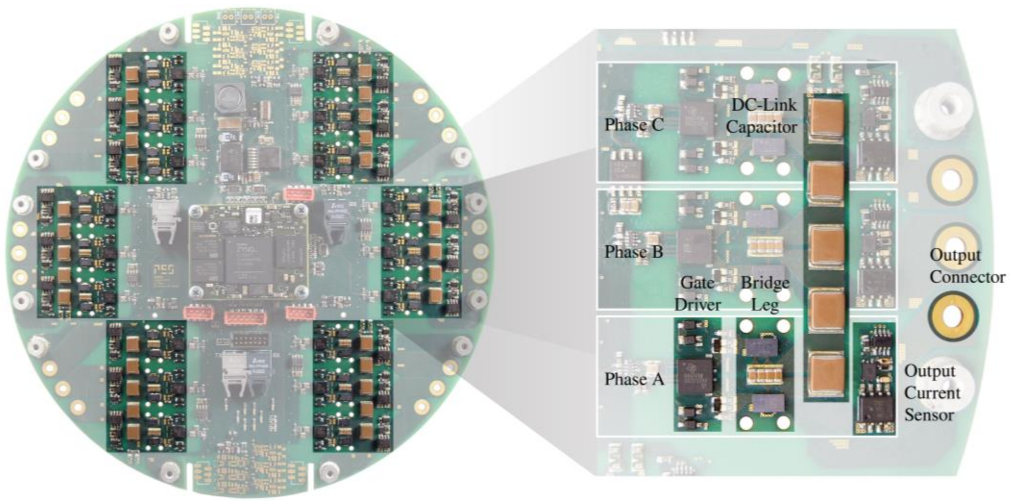




→ *Challenges — Therm. Coupling/Decoupling of Motor & Inverter, dv/dt Limitation, etc.*

# Scaled Hardware Demonstrator

- Rated Power 9kW @ 3700rpm
- DC-Link Voltage 650V...720V
- 3-Φ Power Cells 5+1
- Outer Diameter 220mm

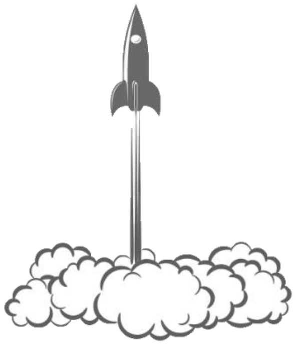





— Axial Stator Mount
— 200V GaN e-FETs
— Low-Capacitance DC-Links
— 45mm x 58mm / Cell

→ Challenges — Therm. Coupling/Decoupling of Motor & Inverter, dv/dt Limitation, etc.

# X-Technology #2



## Wide Bandgap Power Semiconductors

# Low $R_{DS(on)}$ High-Voltage Devices (1)

- *High Critical E-Field of SiC → Thinner Drift Layer*
- *High Maximum Junction Temperature $T_{j,max}$*

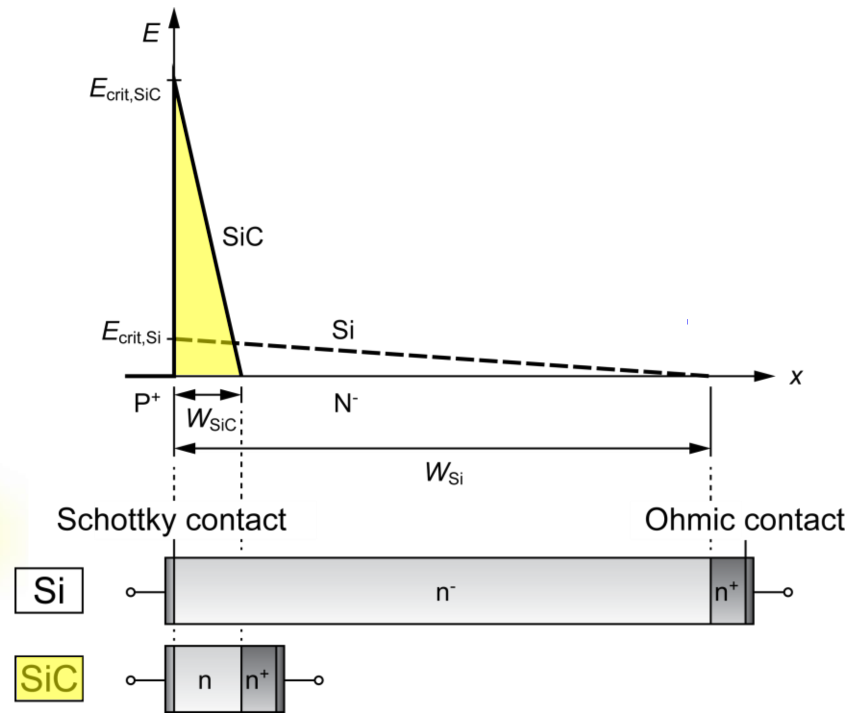
| at 300 K | Si | GaAs | 4H/6H-SiC | GaN |
|---|---|---|---|---|
| $E_g$ (eV) | 1.12 | 1.4 | 3.0-3.2 | 3.4 |
| $E_c$ (MV/cm) | 0.25 | 0.3 | 2.2-2.5 | 3 |
| $\mu_n$ (cm²/Vs) | 1350 | 8500 | 100-1000 | 1000 |
| $\varepsilon_r$ | 11.9 | 13 | 10 | 9.5 |
| $v_{sat}$ (cm/s) | 1x10⁷ | 1x10⁷ | 2x10⁷ | 3x10⁷ |
| $\lambda$ (W/cmK) | 1.5 | 0.5 | 3 - 5 | 1.3 |



$$R^*_{on} = \frac{4V_B^2}{\varepsilon\mu_n E_C^3} \leftarrow$$

| For 1kV: | Si | SiC |
|---|---|---|
| W (µm) | 100 | 10 |
| $N_D$ (cm⁻³) | $10^{14}$ | $10^{16}$ |

$$R^*_{on,SiC} \approx \frac{1}{300} R^*_{on,Si}$$

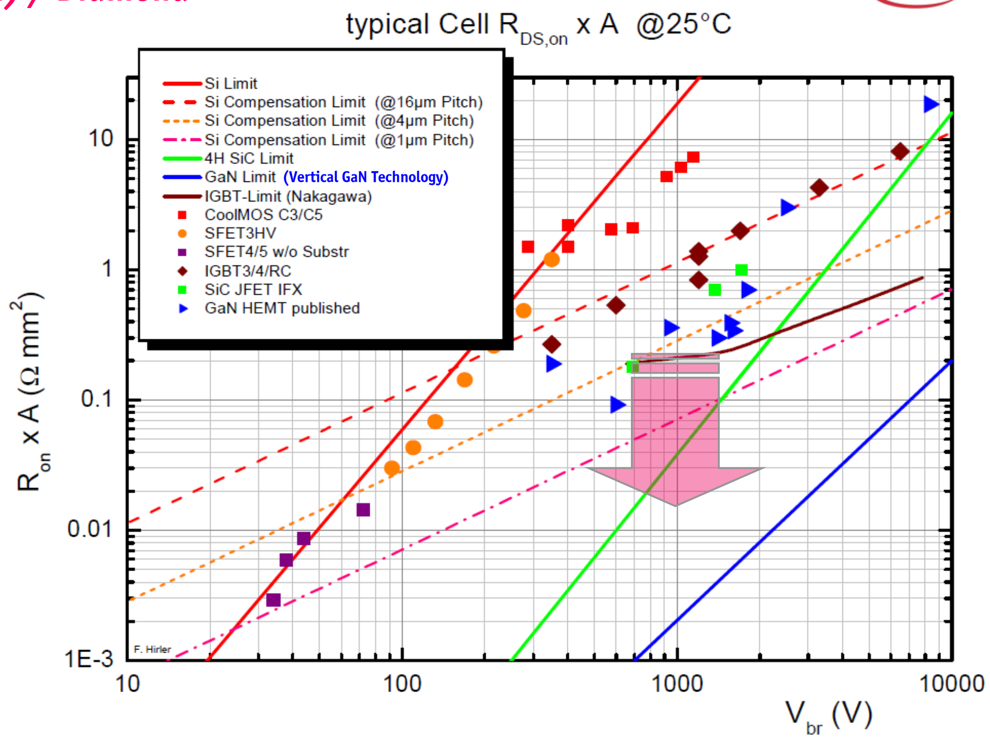



- *Massive Reduction of Relative On-Resistance → High Blocking Voltage Unipolar Devices*

# Low $R_{DS(on)}$ High-Voltage Devices (2)

- Low Circuit Complexity
- High Power Conversion Efficiency
- SiC / GaN (Monolithic AC-Switch) / Diamond

Source: Infineon



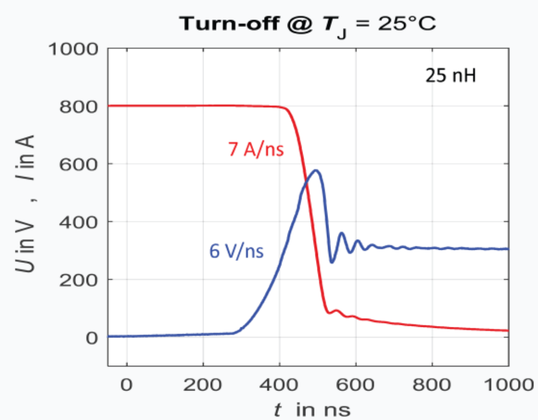

- *High Heat Conductivity & Excellent Switching Performance*

# Low Switching Losses

- *Si-IGBT → Up to 6.5kV / Rel. Low Switching Speed*
- *SiC-MOSFETs → Up to 15kV (1st Samples) / Factor 10…100 Higher Sw. Speed*

Source: M. Bakran / ECPE 2019

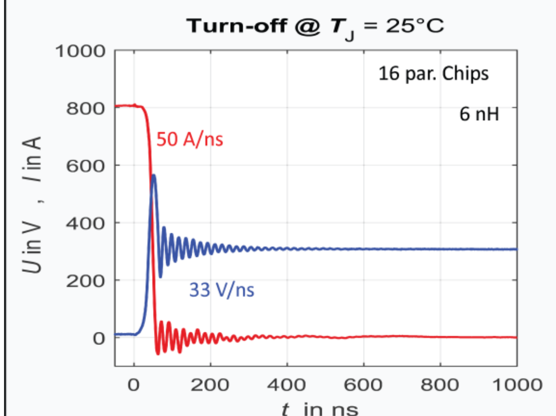
Si-IGBT / Hybrid-Pack 2




$E_{off}$ = 45900 µJ

-> 8 kV/µs at 400V

SiC-MOSFET / (scaled for low inductance)

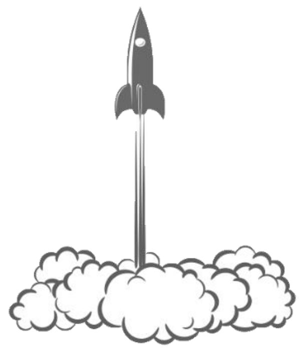



$E_{off}$ = 4672 µJ

-> 44 kV/µs at 400 V

- *Extremely High di/dt & dv/dt → Challenges in Packaging / EMI*

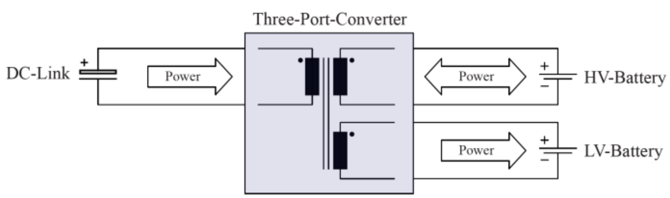
X-Technology **#3**

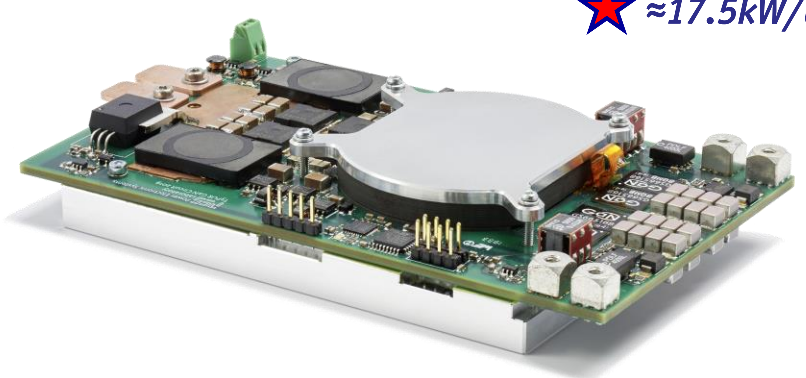


3D-Integration
Automated Manufacturing

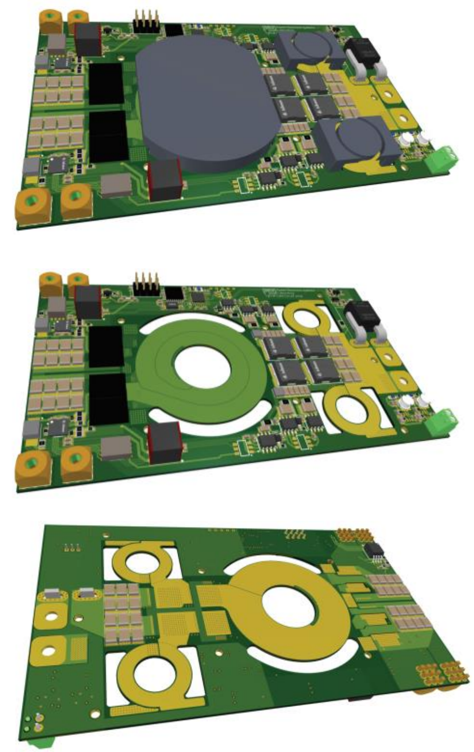
# Isolated 3-Port DC/DC Converter

- *3.6kW / Single Multi-Winding Transformer*
- *Linking of 400V PFC Rectifier / 450V / 12V Aux.*
- *Fully Autom. Manufacturing → PCB-Based Design*



★ *≈17.5kW/dm³*

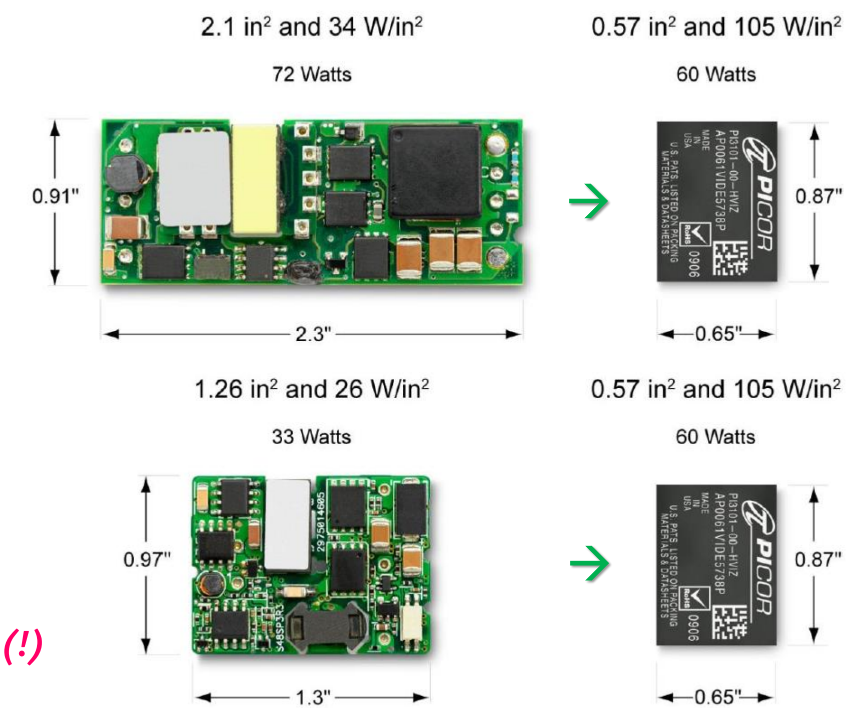


- *Design for Thermal Limit (η≈95%) → Min. Volume / Material Effort / Costs*

# 3D-Packaging

- System in Package (SiP) Approach
- Minim. of Parasitic Inductances / EMI Shielding / Integr. Thermal Management
- Very High Power Density (No Bond Wires / Solder / Thermal Paste)
- Automated Manufacturing

Source: VICOR




- Future Application Up to 100kW (!)
- New Design Tools & Measurement Systems (!)

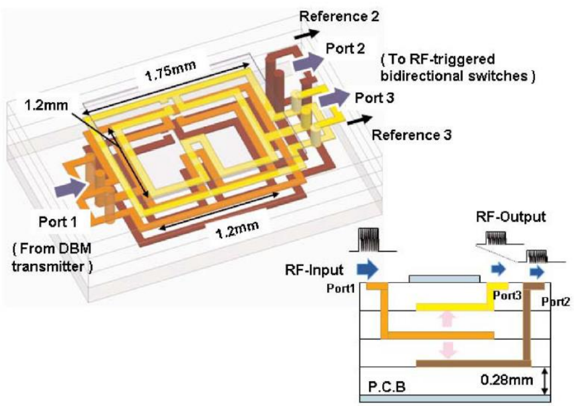
# Monolithic 3D-Integration

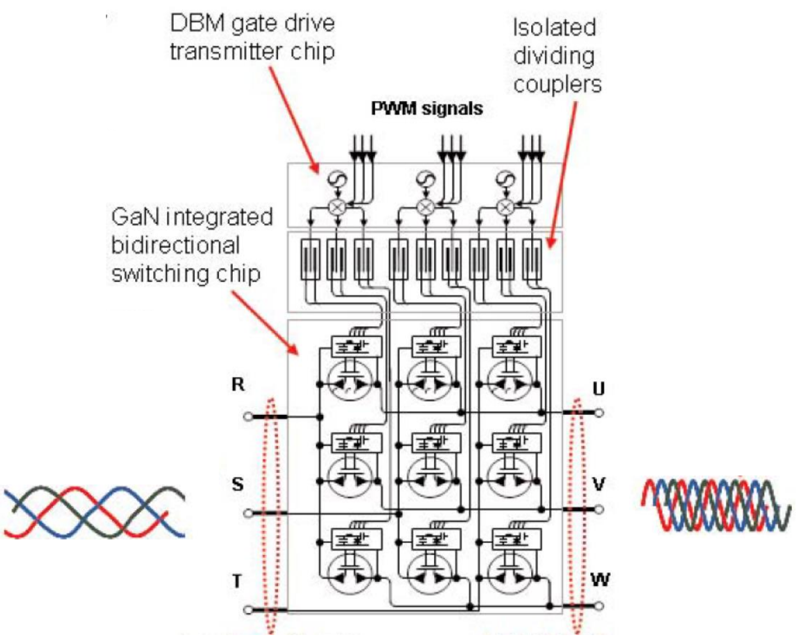
Source: Panasonic ISSCC 2014

- GaN 3x3 Matrix Converter Chipset with Drive-By-Microwave (DBM) Technology

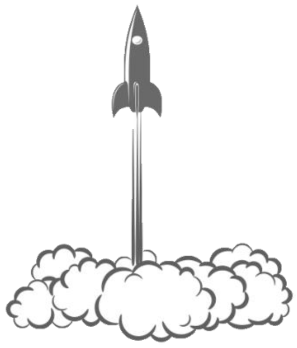
  - 9 Dual-Gate GaN AC-Switches
  - DBM Gate Drive Transmitter Chip & Isolating Couplers
  - Ultra Compact → 25 x 18 mm$^2$ (600V, 10A – 5kW Motor)

5.0GHz Isolated (5kVDC) Dividing Coupler



X-Technology #4

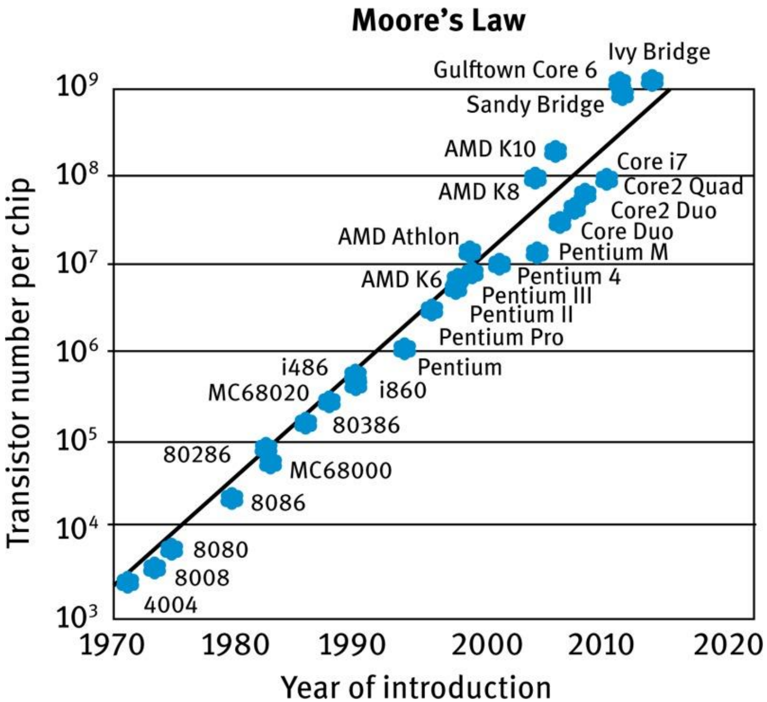


Automated Design
Digital Twin / Industry 4.0

# Digital Technology Push

- *Exponentially Improving uC / Storage Technology (!)*

— *Extreme Levels of Density / Processing Speed*
— *Software Defined Functions / Flexibility*
— *Cont. Relative Cost Reduction*

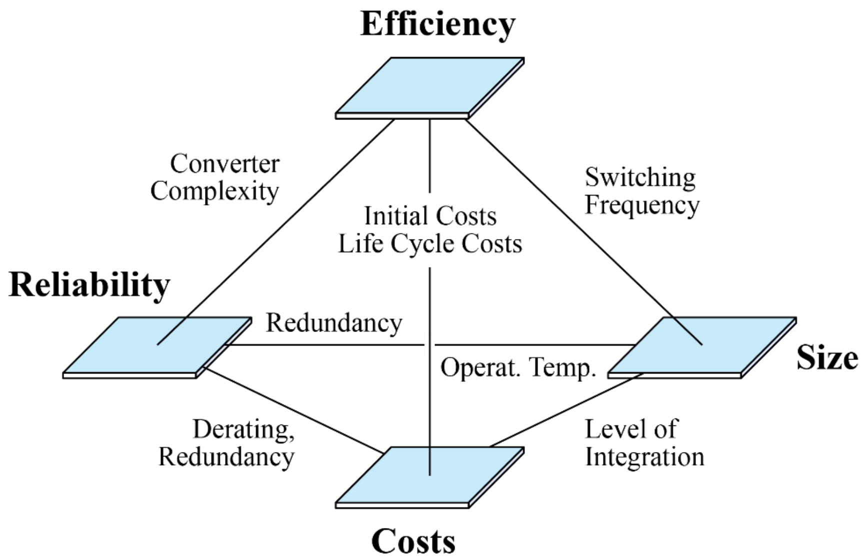



Source: Ostendorf & König / DeGruyter

- *Fully Digital Control of Complex Systems*
- *Massive Computational Power → Fully Automated Design & Manufacturing / Industrial IoT (IIoT)*

# Multi-Objective Design Challenge (1)

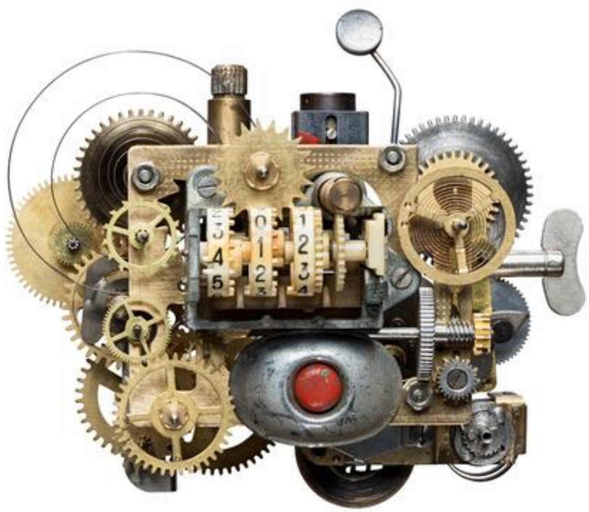
- Counteracting Effects of Key Design Parameters
- Mutual Coupling of Performance Indices → Trade-Offs




- Large Number of Degrees of Freedom / Multi-Dimensional Design Space
- Full Utilization of Design Space only Guaranteed by Multi-Objective Optimization

# Multi-Objective Design Challenge (2)

- Counteracting Effects of Key Design Parameters
- Mutual Coupling of Performance Indices → Trade-Offs

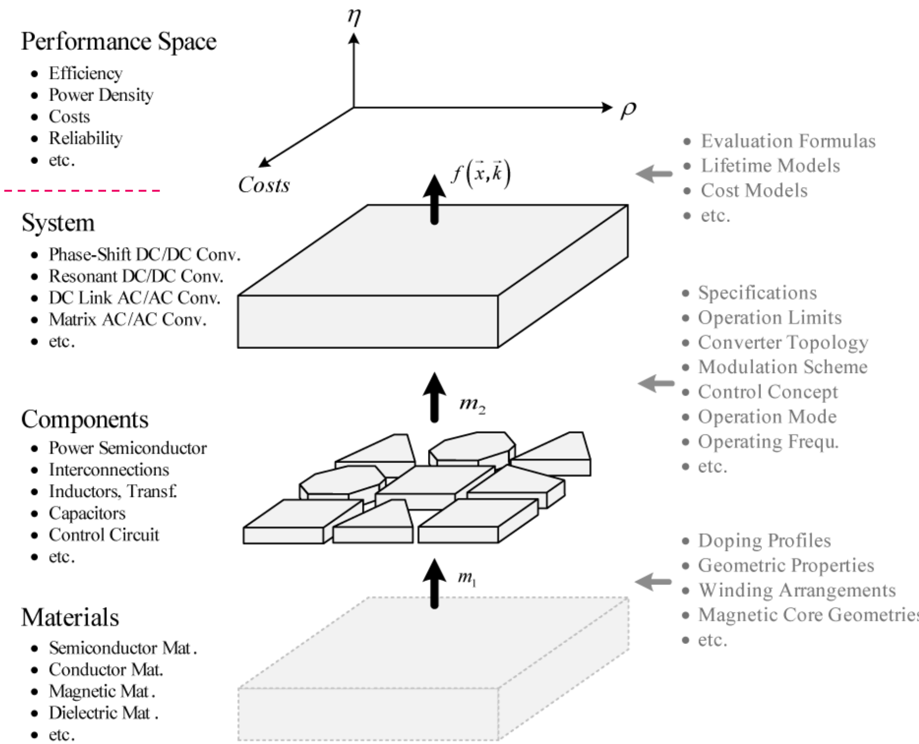



- Large Number of Degrees of Freedom / Multi-Dimensional Design Space
- Full Utilization of Design Space only Guaranteed by Multi-Objective Optimization

# Virtual Prototyping

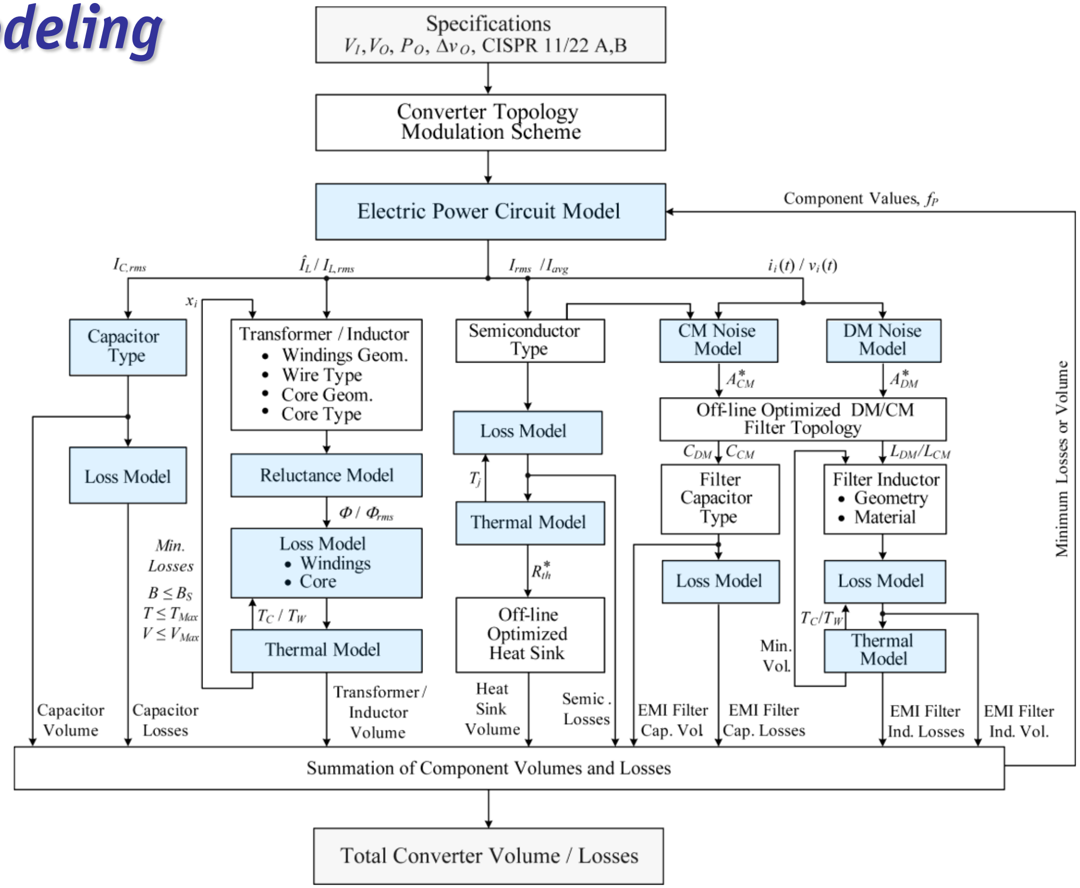
Performance Space

Design Space




- *Mathematical Description of the Mapping "Technologies" → "System Performance"*

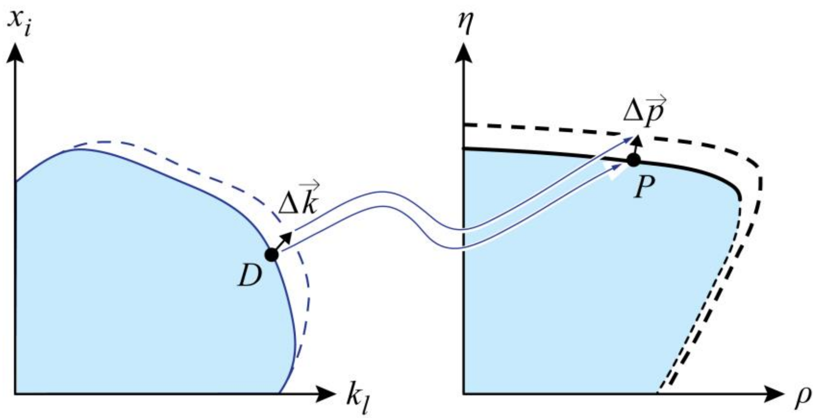
# Mathematical Modeling



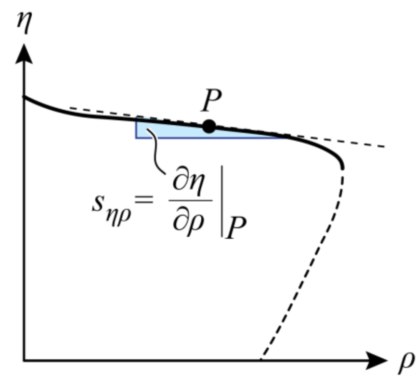

- **Multi-Objective Optimization** – *Guarantees Best Utilization of All Degrees of Freedom* (!)

# Multi-Objective Optimization

- *Based on Mathematical Model of the Technology Mapping*
- *Multi-Objective Optimization → Best Utilization of the "Design Space"*
- *Identifies Absolute Performance Limits → Pareto Front / Surface*



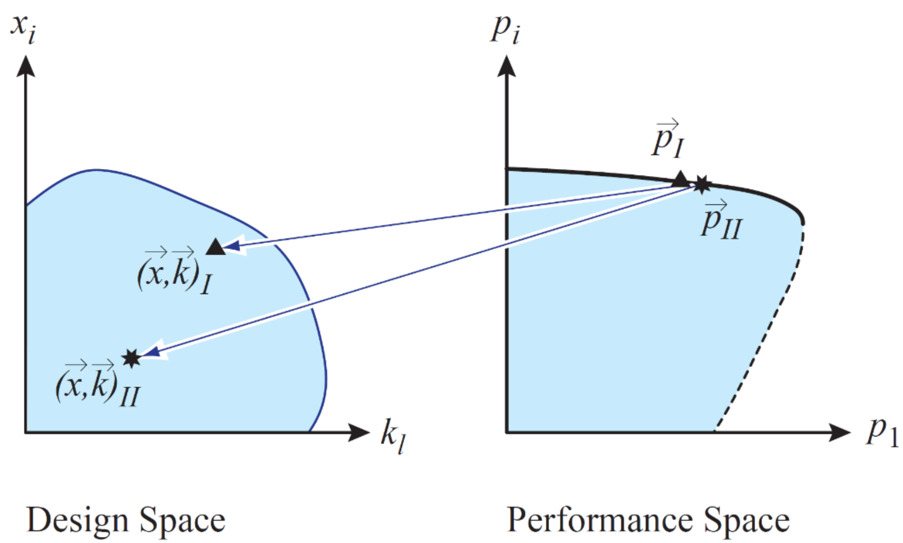

Design Space Performance Space




- Clarifies *Sensitivity $\Delta\vec{p}$ / $\Delta\vec{k}$* to Improvements of Technologies
- *Trade-Off Analysis*

# Design Space Diversity

- Design Space Diversity
- Equal Performance for Largely Different Sets of Design Parameters

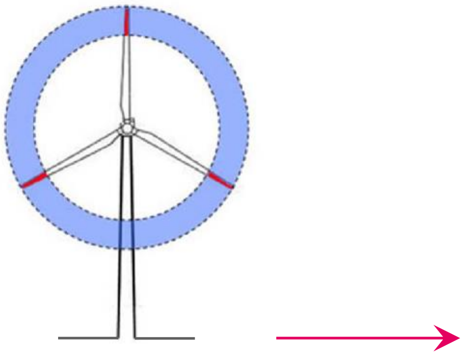



- E.g. Mutual Compensation of Volume and Loss Contributions (e.g. Cond. & Sw. Losses)
- Allows Optimization for Further Performance Index (e.g. Costs)

## Example

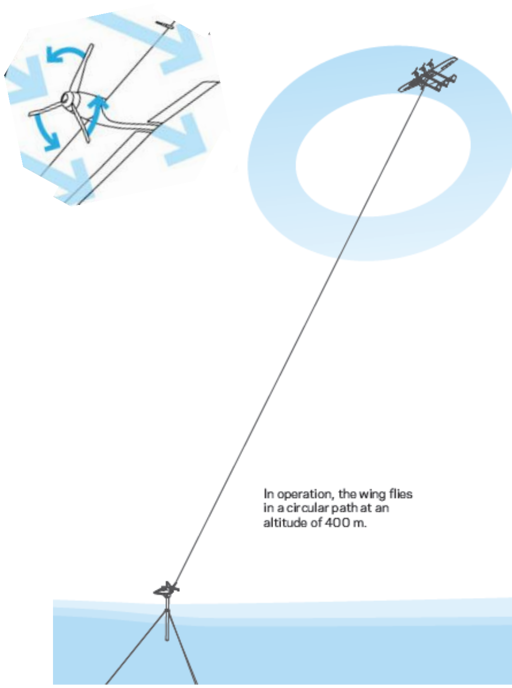
M. Loyd, 1980

### Electrical System of an Airborne Wind Turbine



# Airborne Wind Turbine (AWT) - Google X

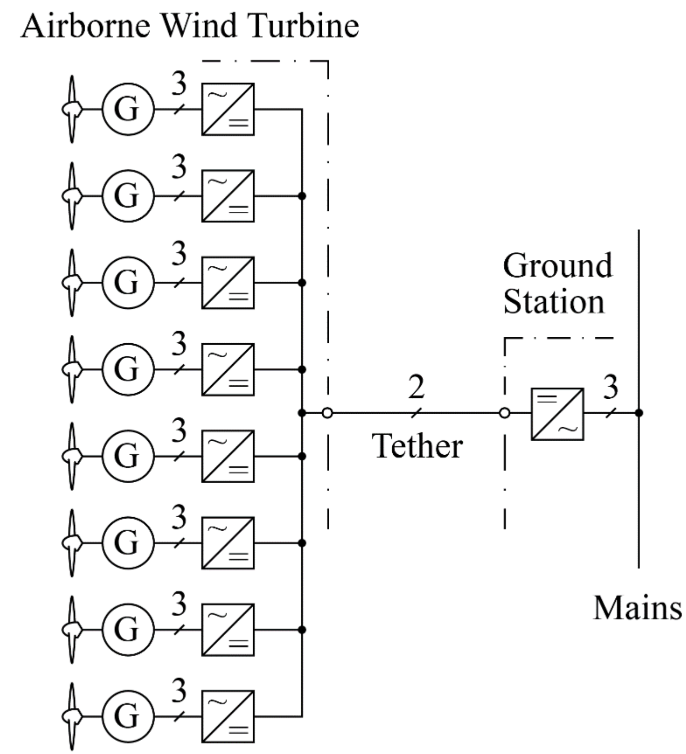
- Power Kite → On-Board Turbine / Generator / Power Electronics
- Power Transmitted to Ground Electrically
- Minimum of Mechanical Support




MAKANI POWER

# *AWT Electrical System Structure*

| | |
|---|---|
| ■ Rated Power | 100kW |
| ■ Operating Height | 800...1000m |
| ■ Ambient Temp. | 40°C |
| ■ Power Flow | Motor & Generator |

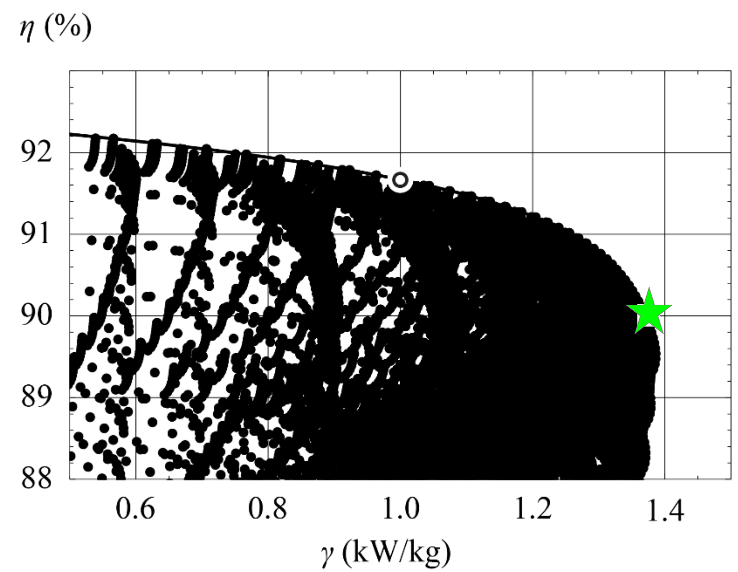


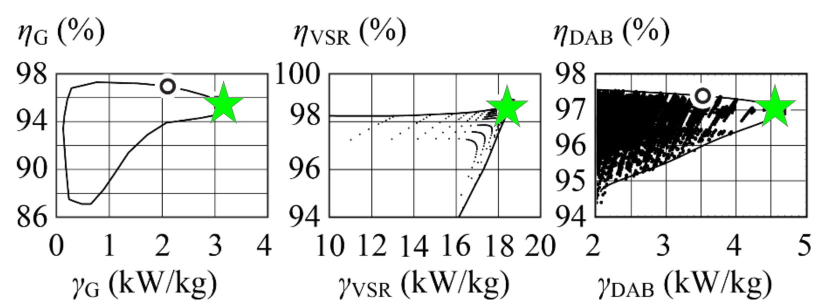

| | |
|---|---|
| → El. System Target Weight | 100kg |
| → Efficiency (incl. Tether) | 90% |
| → Turbine /Motor | 2000/3000rpm |

# Overall AWT System Performance

EFFICIENCIES AND POWER-TO-WEIGHT RATIOS AT THE 2 DESIGN POINTS (CALCULATED FOR NOMINAL OPERATION).

| Total system | Generator, VSR, and DAB converter | | |
|---|---|---|---|
| $\gamma = 1.37\,\mathrm{kW/kg}$ $\eta = 90.0\%$ | Generator: | $\gamma_G = 3.11\,\mathrm{kW/kg}$, | $\eta_G = 95.4\%$ |
| | VSR: | $\gamma_{VSR} = 18.3\,\mathrm{kW/kg}$, | $\eta_{VSR} = 98.6\%$ |
| | DAB: | $\gamma_{DAB} = 4.60\,\mathrm{kW/kg}$, | $\eta_{DAB} = 97.1\%$ |
| $\gamma = 1.00\,\mathrm{kW/kg}$ $\eta = 91.7\%$ | Generator: | $\gamma_G = 2.14\,\mathrm{kW/kg}$, | $\eta_G = 96.9\%$ |
| | VSR: | $\gamma_{VSR} = 18.3\,\mathrm{kW/kg}$, | $\eta_{VSR} = 98.6\%$ |
| | DAB: | $\gamma_{DAB} = 3.53\,\mathrm{kW/kg}$, | $\eta_{DAB} = 97.4\%$ |




- Typically Sub-System Sub-Optima are Resulting in Overall System Optimum

# Automated Design Roadmap

- *End-to-End Horizon of Modeling & Simulation*
- *Design for Cost / Volume / Efficiency Target / Manufacturing / Testing / Reliability / Recycling*

**Autonomous Design → Design 4.0**

– *Independent* Generation of Full Designs for Final Human Expert Judgement

**Augmented Design**

– *Suggestion* of Design Details Based on Previous Designs

**Assisted Design**

– *Support* of the User with Abstracted Database of Former Designs

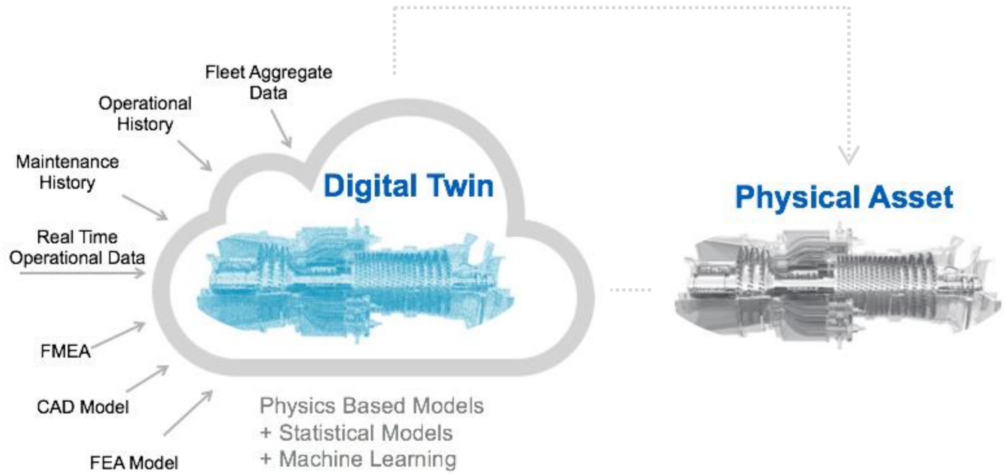
**State-of-the-Art**

– *User Defined* Models and Simulation / Fragmented

- *AI-Based Summaries → No Other Way to Survive in a World of Exp. Increasing # of Publications (!)*

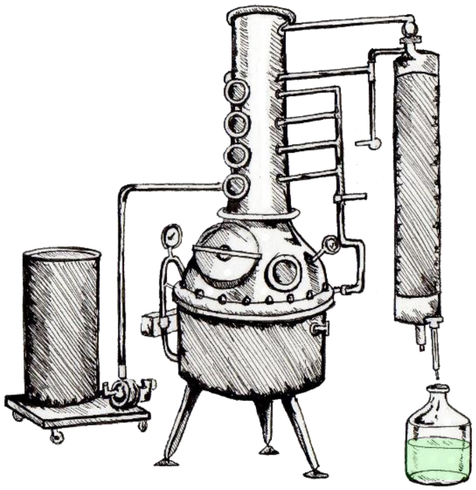
# IIoT in Power Electronics

- *Digital Twin → Physics-Based Digital Mirror Image*
- *Digital Thread → "Weaving" Real/Physical & Virtual World Together*




Source: www.railwayage.com

- *External → Integrated Measurement Circuits & Merging of Oscilloscopes & Simulations*
- *Model of System´s Past/Current/Future State → Design Corrections / Prev. Maintenance etc.*

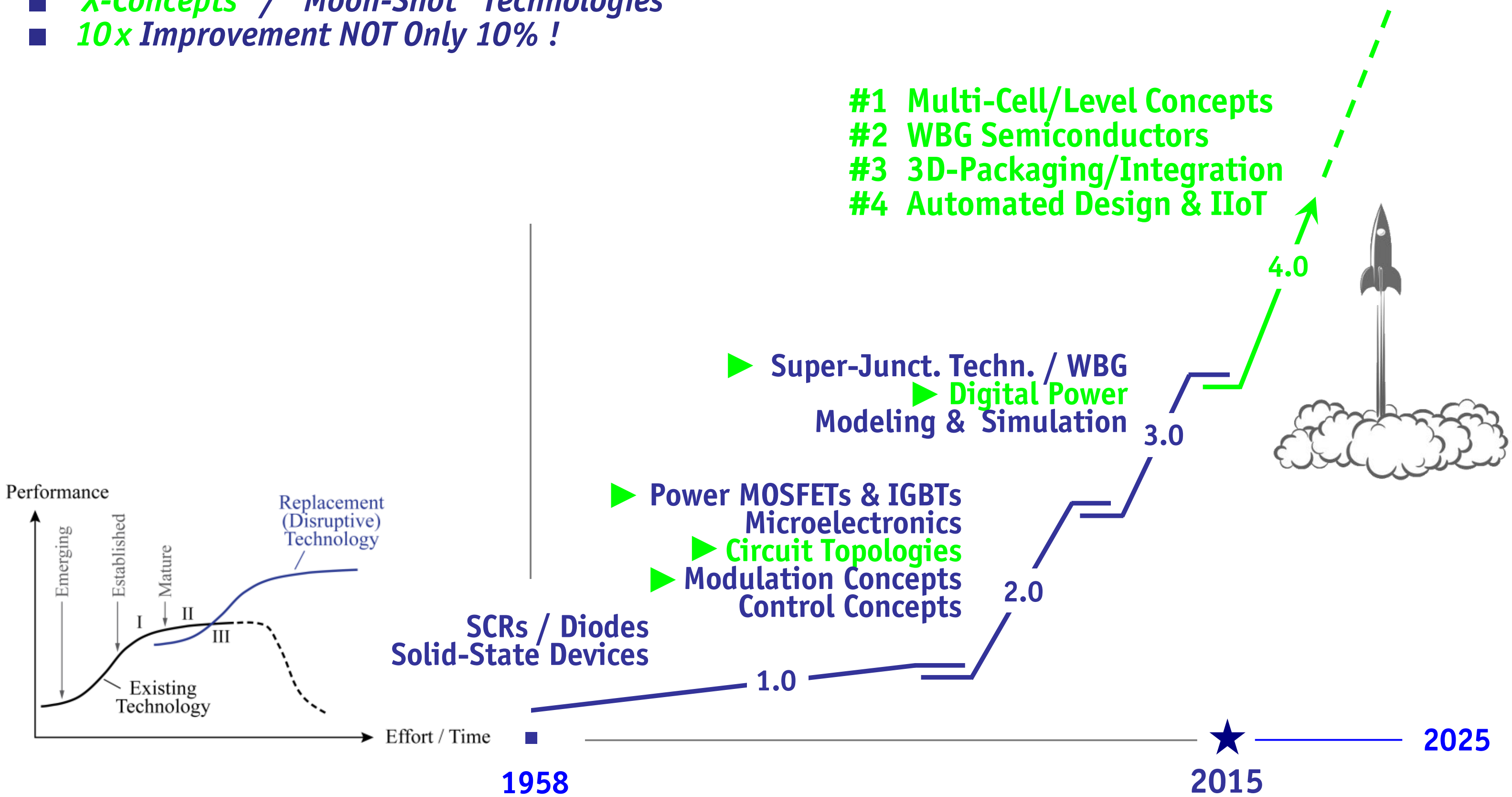


Source: whiskeybehavior.info

## ... in Summary

# *S-Curve of Power Electronics*

- *Power Electronics 1.0 → Power Electronics 4.0*
- *"X-Concepts" / "Moon-Shot" Technologies*
- *10x Improvement NOT Only 10% !*




FUTURE

# Energy Electronics

*MEGA Power Electronics*

(Medium Voltage, Medium Frequency)

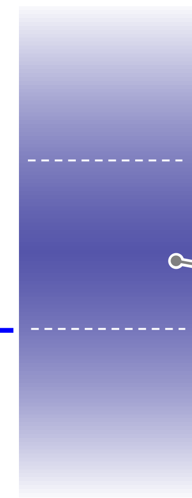
- Complicated → Basic/Standardized
- Discrete → Integrated
- Single-Obj. → Multi-Objective

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

- Power → Energy
- Inner Function → Interaction
- Converters → Systems

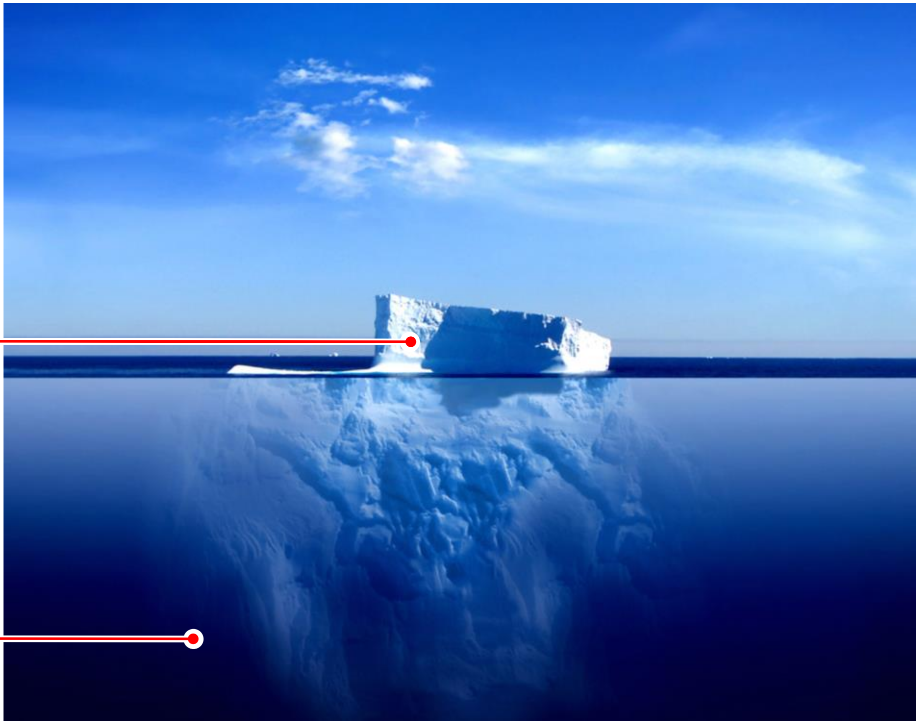
*Micro Power Electronics*

(Microelectronics Technology Based, Power Supply on Chip)



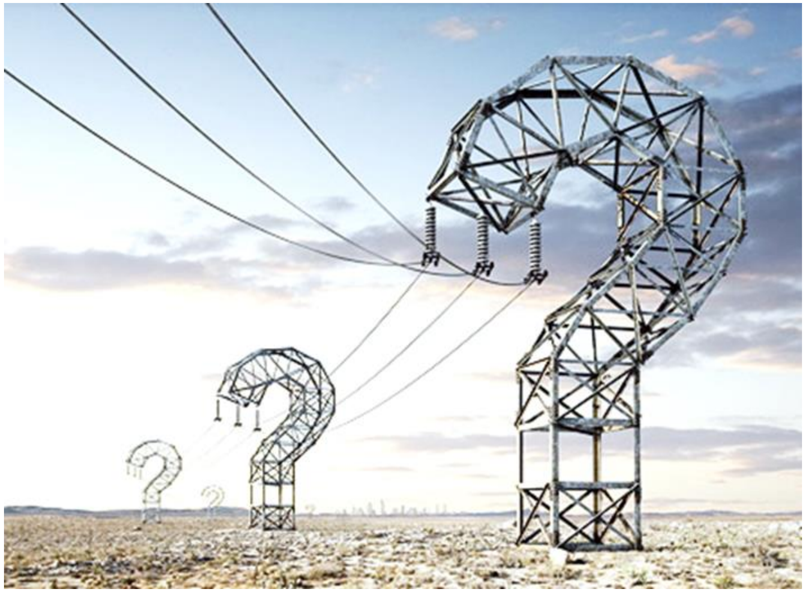

- *Integration into "Multi-Carrier" Energy Networks*

# *Research Potential*

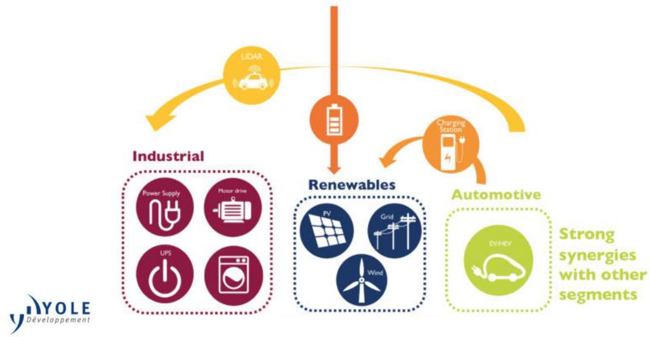



- Huge *Multi-Disciplinary* Challenges / Opportunities (!) are Still Ahead

# Questions



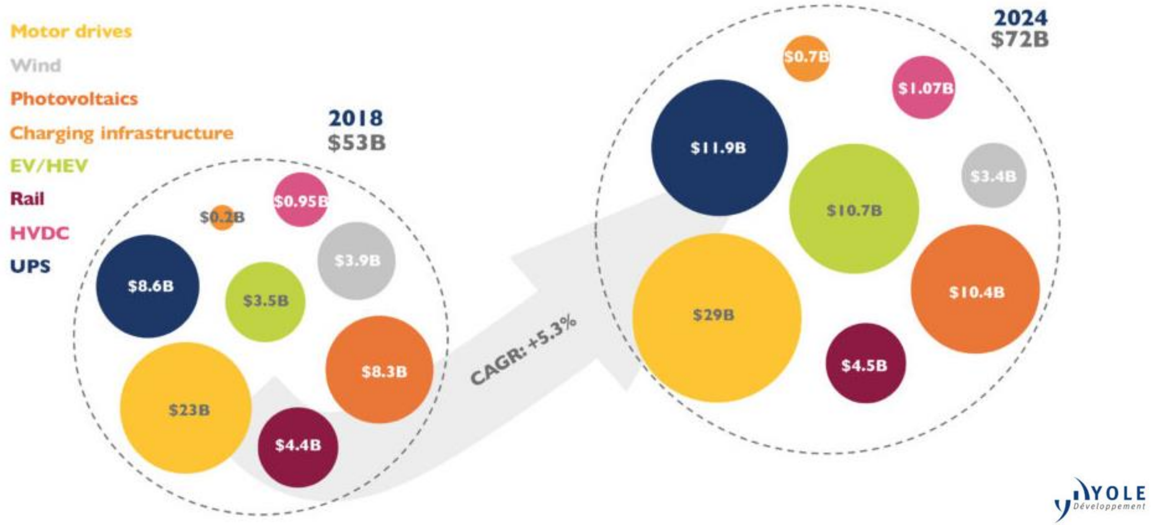

BACKUP




*Economic Potential*

# CAGR Evolution

- *Strong Growth of Power Electronics Industry*
- *Technological Development Driven by EV/HEVs*
- *US$ 53.4 Billion (2018) → US$ 72.6 (2024)*

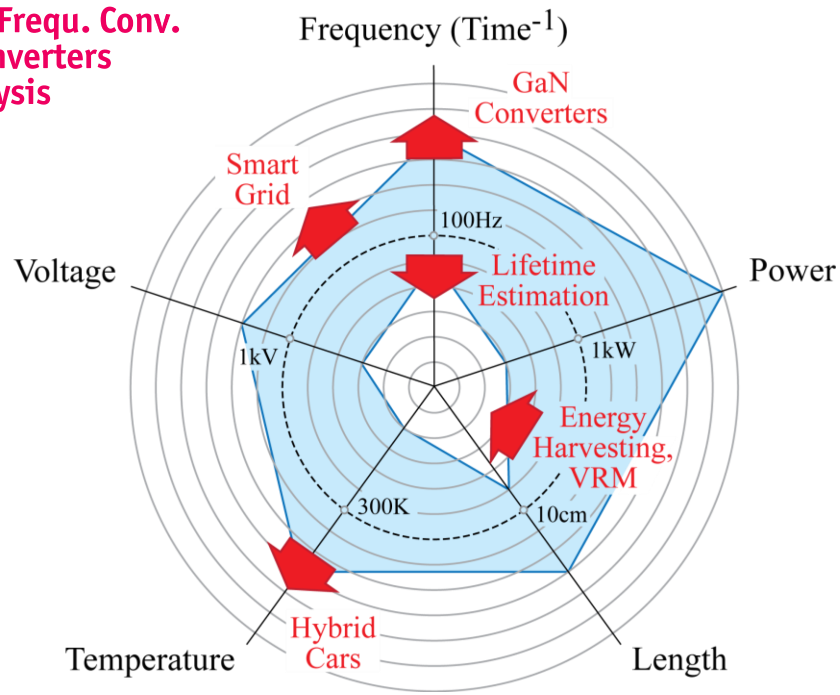



- *EV/HEVs -- Huge Market Potential (Inverter, Boost Conv., 12V/48V Conv., Charger, etc.)*
- *20.7% CAGR Between 2018 and 2024 & Strong Synergies with Other Applications*

# *Current / New Application Areas*

- Extremely Wide Power / Voltage / Frequency Range
- Extensions for *SMART xxx* / Ultra-Compact Converters / Mission Profile Analysis / etc.

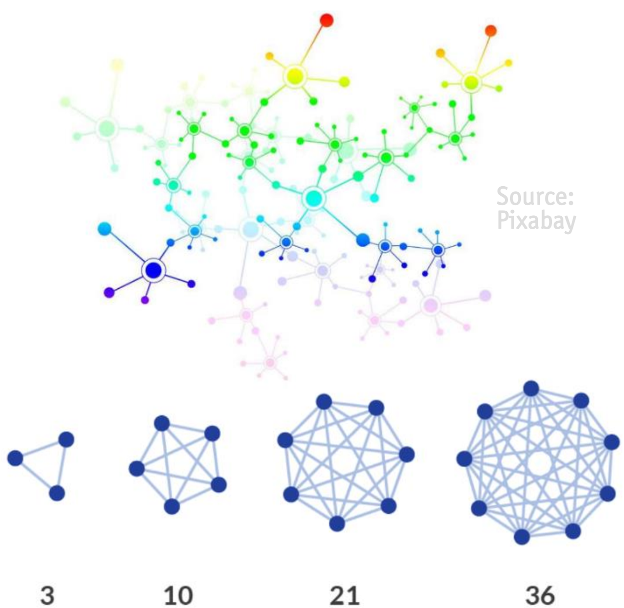
— Medium-Voltage / Medium. Frequ. Conv.
— 3D-Integr. of Low Power Converters
— Life-Cycle & Reliability Analysis
— Etc.

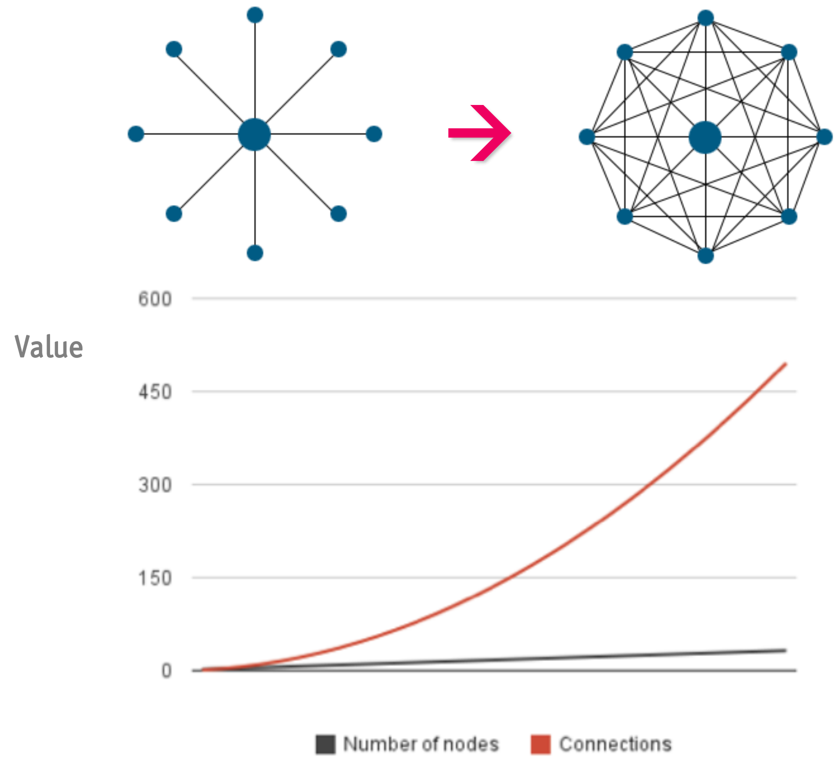



► Future Extensions of Power Electronics Application Areas

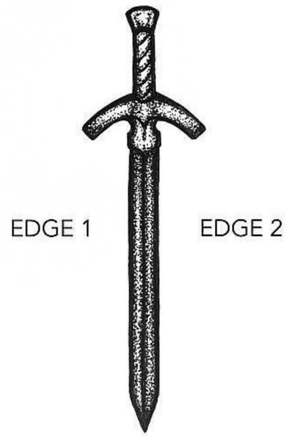
# *Digitalization Driver*

- **Metcalfe's Law**
  - Moving from Hub-Based Concept to Community Concept Increases Potential Network Value Exponentially ~n(n-1) or ~n log(n)



## Challenges



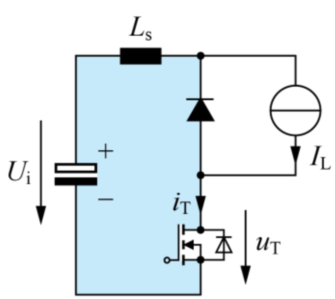

Idea: F.C. Lee

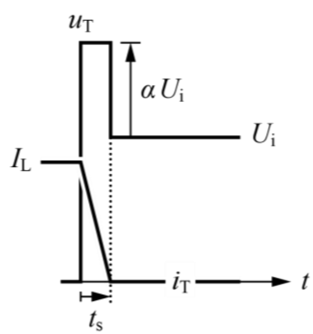
# Circuit Parasitics

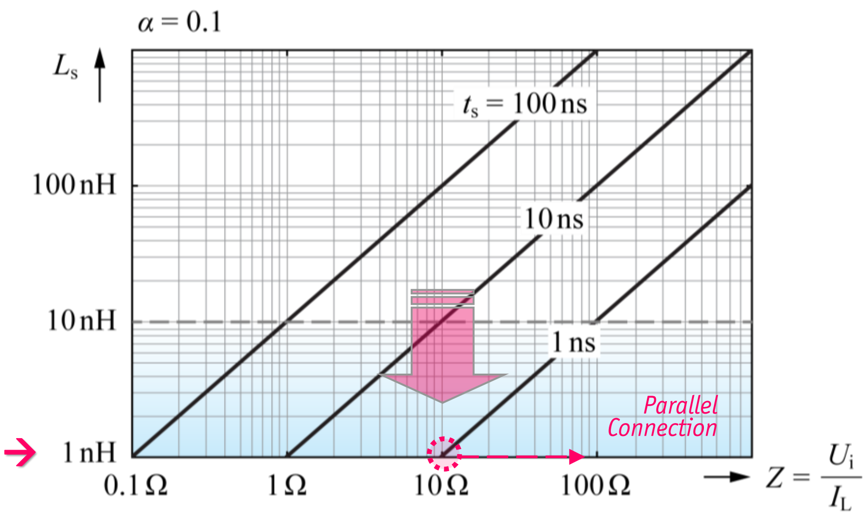
$$L\frac{di}{dt} = u$$

- *Extremely High di/dt*
- *Commutation Loop Inductance $L_S$*
- Allowed $L_s$ Directly Related to Switching Time $t_s$ →

$$L_s \le \frac{\alpha U_i}{\frac{I_L}{t_s}} = \alpha t_s \underbrace{\frac{U_i}{I_L}}_{Z}$$



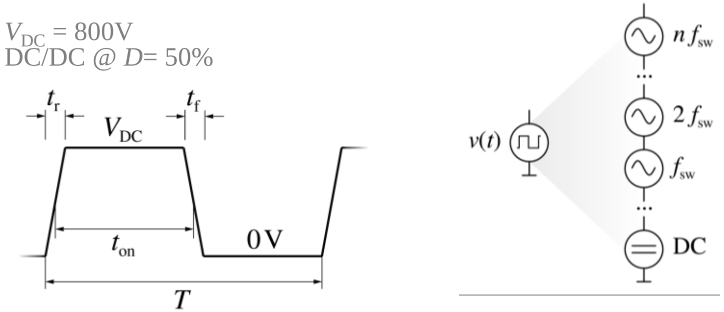

- *Advanced Packaging & Parallel Interleaving for Partitioning of Large Currents*

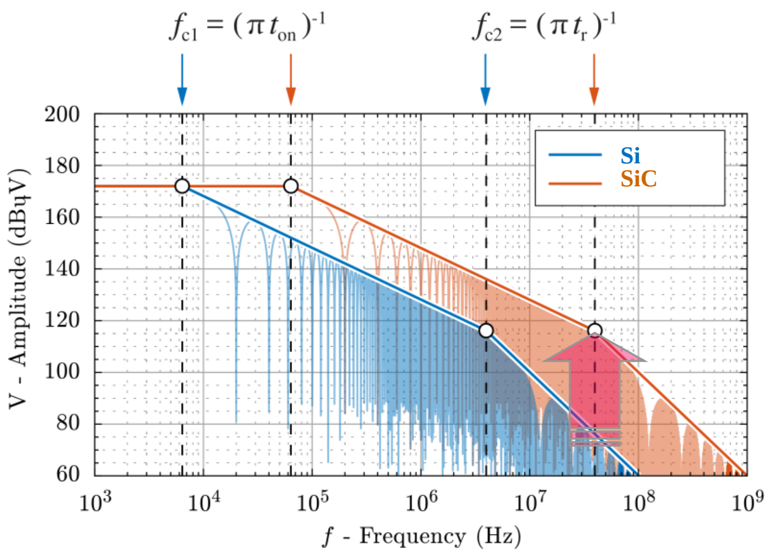
# EMI Emissions

- Higher dv/dt → Factor 10
- Higher Switching Frequencies → Factor 10
- EMI Envelope Shifted to Higher Frequencies

Idea: M. Schutten

$f_S$= 10kHz & 5 kV/us for (Si IGBT)
$f_S$= 100kHz & 50 kV/us for (SiC MOSFET)



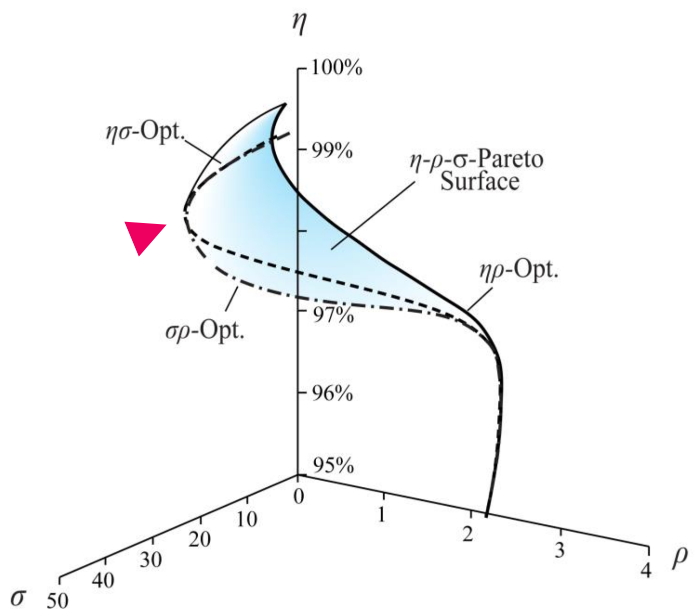



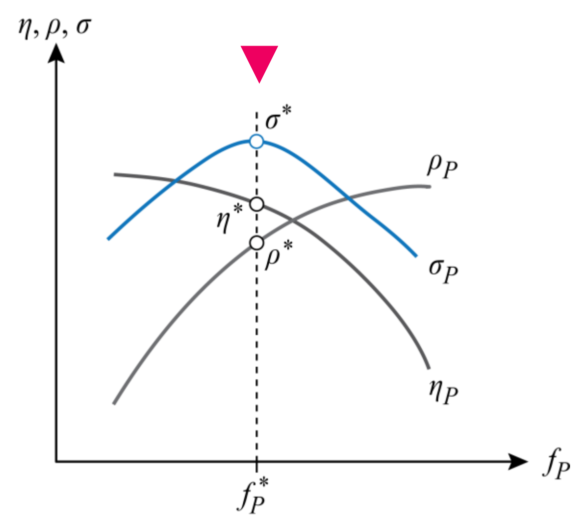

- Higher Influence of Filter Component Parasitics and Couplings → Advanced Design

## *Virtual Prototyping*

# *η-ρ-σ-Pareto Surface (1)*

- **Definition of a Power Electronics *"Technology Node"* → *($\eta^*, \rho^*, \sigma^*, f_P^*$–Node)***
- **Maximum $\sigma$ [kW/$], Related Efficiency & Power Density**

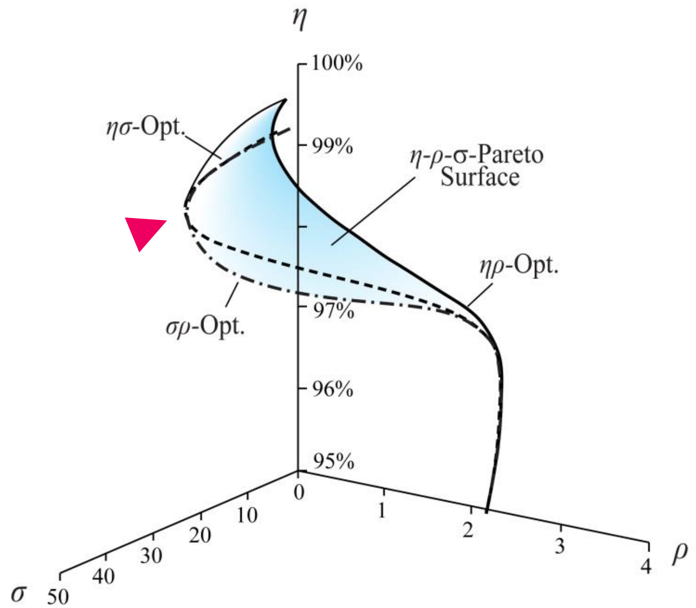


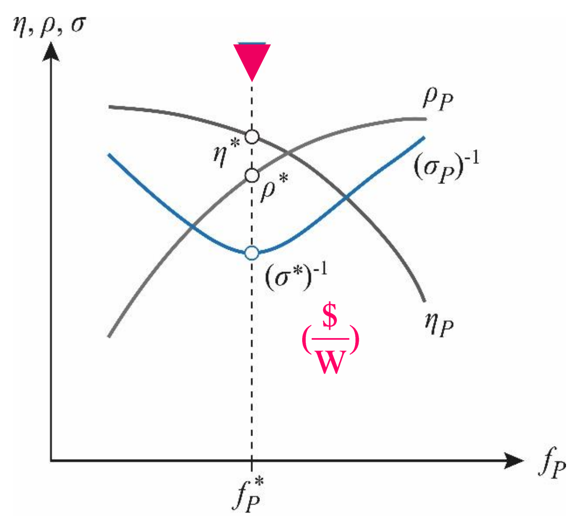




**→ Specifying Only a Single Performance Index is of No Value (!)**
**→ Achievable Perform. Depends on Conv. Type / Specs (e.g. Volt. Range) / Side Cond. (e.g. Cooling)**

# *η-ρ-σ-Pareto Surface (2)*

- **Definition of a Power Electronics "*Technology Node*" → ($\eta^*, \rho^*, \sigma^*, f_P^*$–*Node*)**
- **Maximum $\sigma$ [kW/$], Related Efficiency & Power Density**



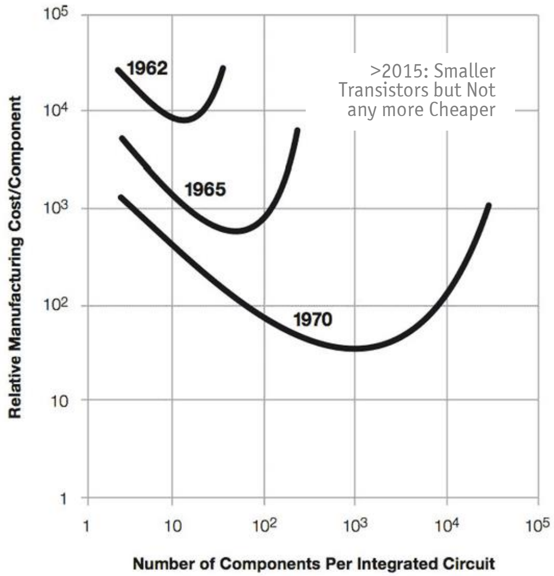

**→ Specifying Only a Single Performance Index is of No Value (!)**
**→ Achievable Perform. Depends on Conv. Type / Specs (e.g. Volt. Range) / Side Cond. (e.g. Cooling)**

# Remark Comparison to "Moore´s Law"

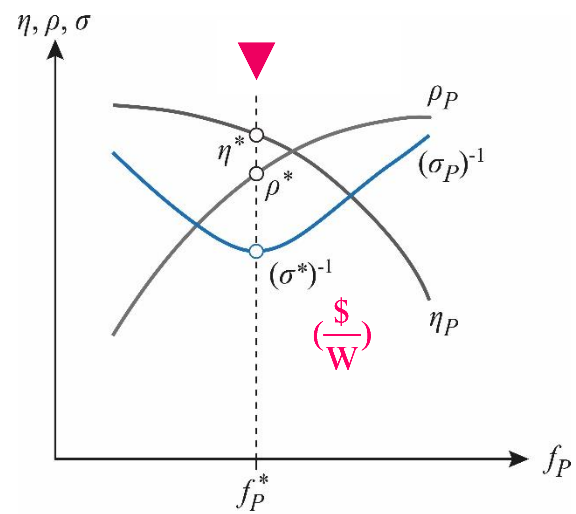
- "Moore´s Law" Defines Consecutive Techn. Nodes Based on Min. Costs per Integr. Circuit (!)
- *Number of Transistors* (Density @ Minimum Costs) *Doubles Every 2 Years*

Economy of Scale →

← Lower Yield

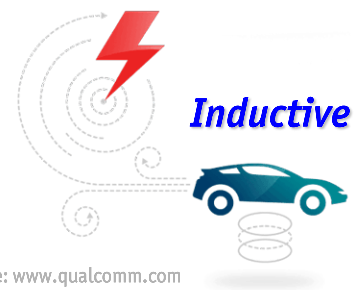



Gordon Moore: The Future of Integrated Electronics, 1965 (Consideration of Three Consecutive Technology Nodes)




- Definition of *"$\eta^*, \rho^*, \sigma^*, f_P^*$–Node"* Must Consider Conv. Type / Operating Range etc. (!)

*Example #1*



Source: www.qualcomm.com

*Inductive Power Transfer* →

# *Multi-Objective Optimization of 5kW Systems*

■ **Design Process Taking All Performance Aspects into Account**

■ ***System Specification***

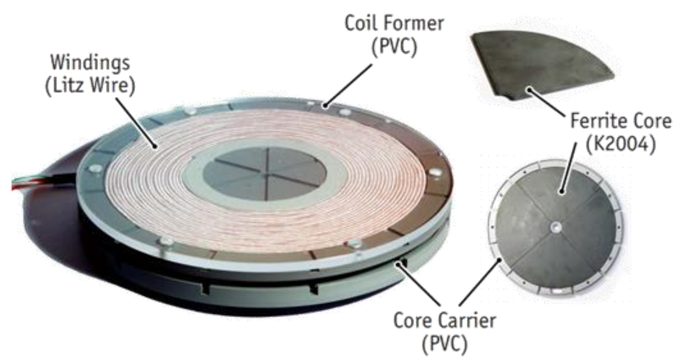
- Input Voltage 400V
- Battery Voltage 350V
- Output Power 5kW
- Air Gap 50mm

■ ***Constraints / Side Conditions***

- Thermal Limitations [°C]
- Stray Field Limits [μT]
- Max. Constr. Vol. [$m^3$]
- Switching Frequency [kHz]

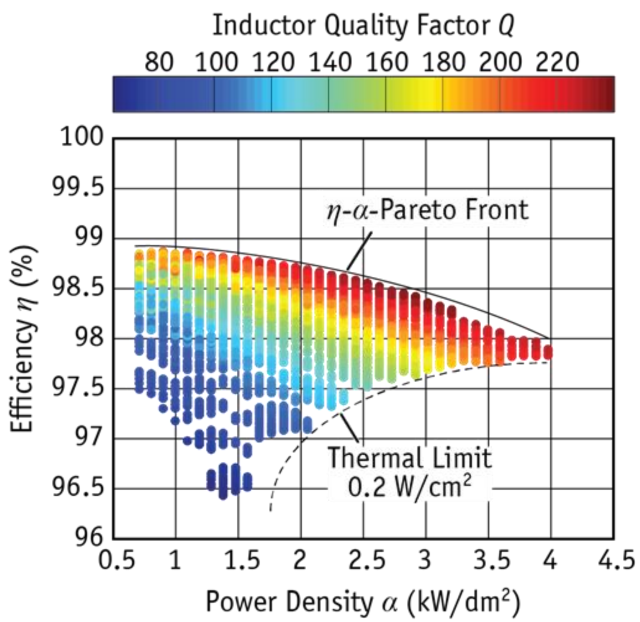
■ ***System Performance***

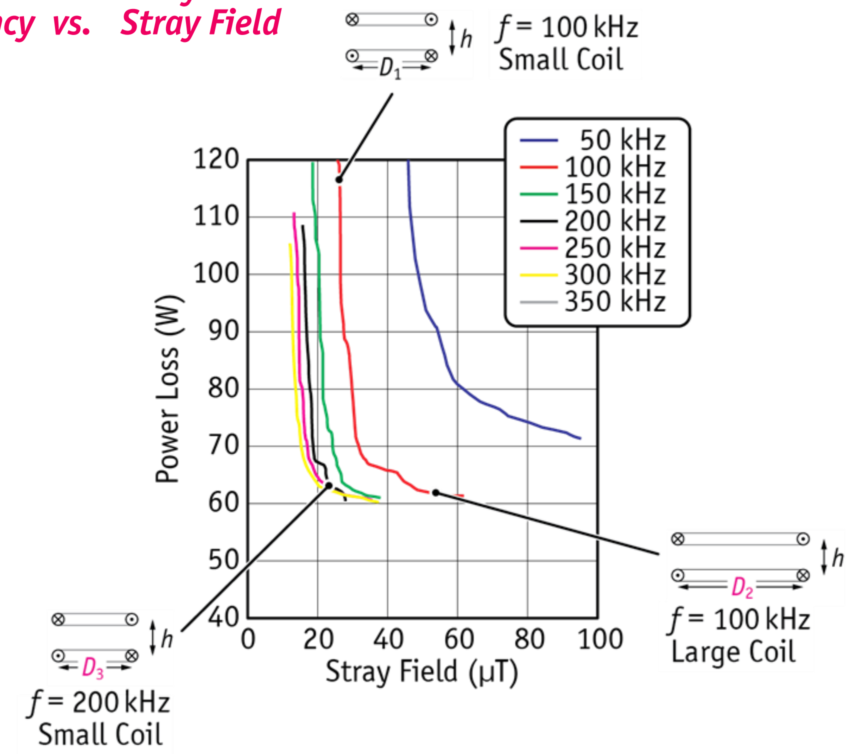
* Efficiency $\eta = P_{out}/P_{in}$ [%]
* Power Density $\alpha = P_{out}/A_{coil}$ [$kW/dm^2$]
* Stray Field $\beta = B_{max}/B_{norm}$ [%]



# η-α-β- Pareto Coil Optimization

- **Encountered Design Trade-Offs**
  * Coil Size vs. Efficiency
  * Coil Size vs. Stray Field
  * Frequency vs. Stray Field




→ **Pareto-Optimization Allows to Study Influence of Key Design Parameters**

# Optimized 50kW Demonstrator

- *All-SiC Power Electronics*
  - Rated Power 50kW
  - Battery Voltage 600...800V
  - Power Density 9.5kW/dm³
  - Sw. Frequency 50kHz/85kHz

- *Inductive Power Transfer Coils*
  - Air Gap 150...220mm
  - Power Density 1.6kW/dm²
  - Frequency 85kHz

★ $\eta_{DCDC}$ = 95.8% @ 50kW & ICNIRP @ 800mm

ETH Zurich / D-ITET

# ETH Zurich

21 Nobel Prizes
530 Professors
6100 T&R Staff

2 Campuses
136 Labs
35% Int. Students
90 Nationalities
36 Languages

150th Anniv. in 2005

## Departments

| | |
|---|---|
| ARCH | Architecture |
| BAUG | Civil, Environmental and Geomatics Eng. |
| BIOL | Biology |
| BSSE | Biosystems |
| CHAB | Chemistry and Applied Biosciences |
| ERDW | Earth Sciences |
| GESS | Humanities, Social and Political Sciences |
| HEST | Health Sciences, Technology |
| INFK | Computer Science |
| ITET | Information Technology and Electrical Eng. |
| MATH | Mathematics |
| MATL | Materials Science |
| MAVT | Mechanical and Process Engineering |
| MTEC | Management, Technology and Economy |
| PHYS | Physics |
| USYS | Environmental Systems Sciences |

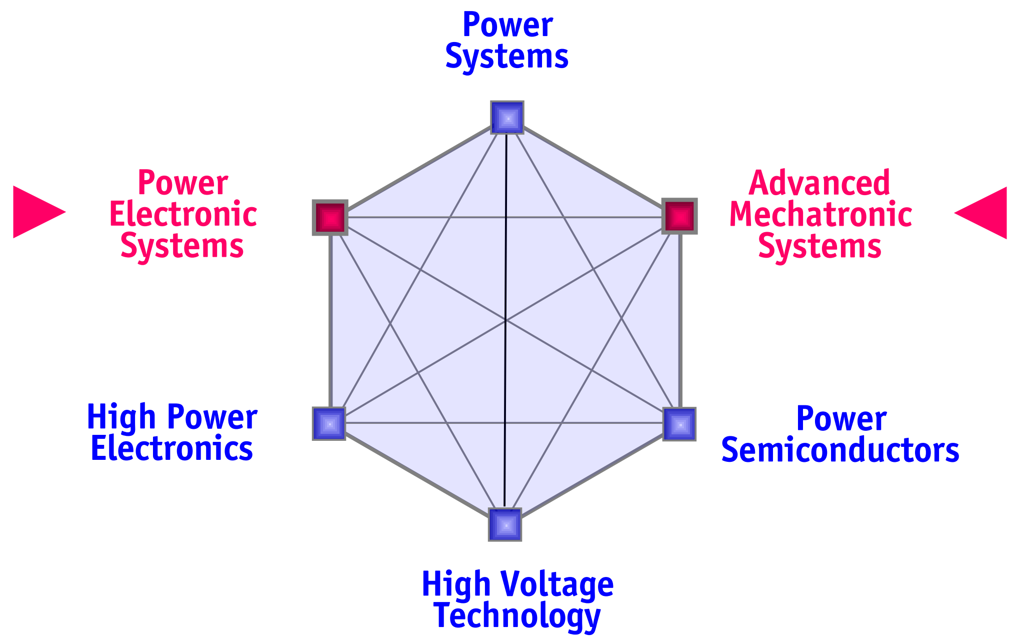
## Students ETH in total

| | |
|---|---|
| 21’000 | B.Sc.+M.Sc.-Students |
| 4’300 | Doctoral Students |

# ITET – Research in E-Energy

Systems

Technologies




- Balance of Fundamental and Application Oriented Research