ETH zürich

Acknowledgment
Th. Guillot
G. Ortiz
D. Rothmund

Solid-State Transformers

Fundamentals / Future Applications

Johann W. Kolar and Jonas E. Huber
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Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Departments of ETH Zurich

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

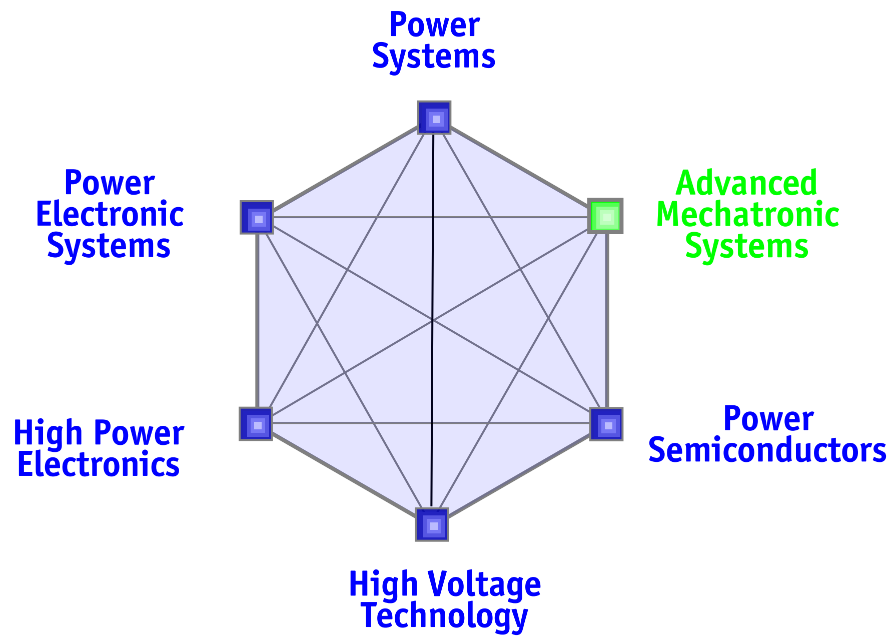
21	Nobel Prizes
413	Professors
6240	T&R Staff
2	Campuses
136	Labs
35%	Int. Students
90	Nationalities
36	Languages
150^{th}	Anniv. in 2005

Students ETH in total

13’500	B.Sc.+M.Sc.-Students
3’500	Doctoral Students

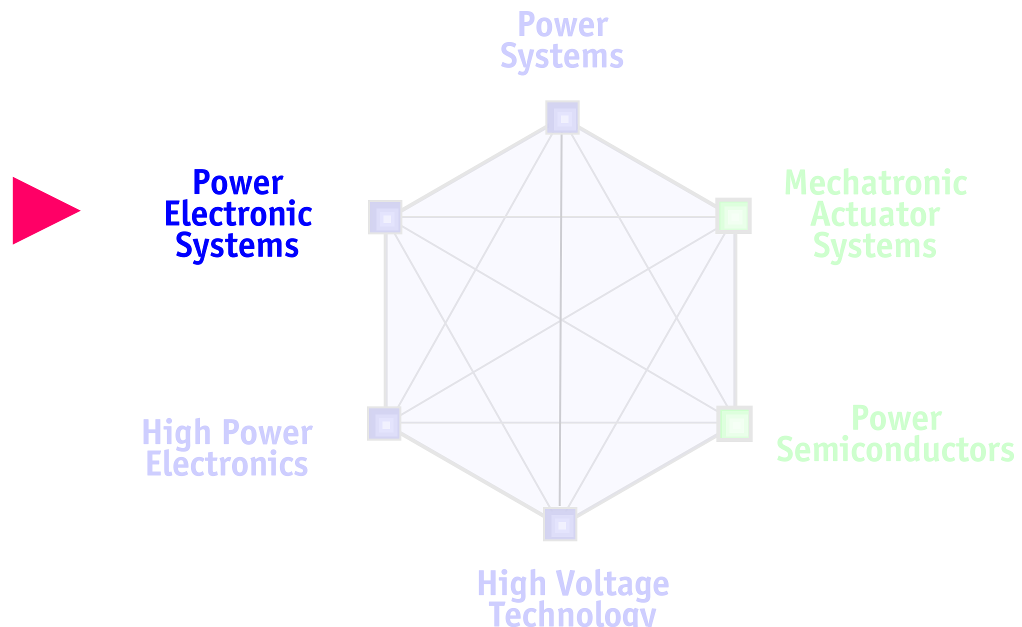
Research in EE @ D-ITET

Energy Research Cluster @ D-ITET



- Balance of Fundamental and Application Oriented Research

Energy Research Cluster @ D-ITET



- Balance of Fundamental and Application Oriented Research

Power Electronic Systems Laboratory

Power Electronic Systems Laboratory
Johann W. Kolar

Industry Relations
R. Coccia / B. Seiler

AC-DC Converter	AC-AC Converter	DC-DC Converter	DC-AC Converter	Multi-Domain Modeling	Wireless Power	Advanced Mechatronics	Magnetic Levitation
		F. Krismer	**D. Bortis**			**A. Tüysüz**	**Th. Nussbaumer**
M. Leibl D. Neumayr D. Rothmund L. Schrittwieser	D. Boillat Ch. Gammeter Th. Guillod J. Huber H. Uemura	P. Bezerra M. Kasper	R. Burkart	C. Dittli	R. Bosshard O. Knecht	M. Flankl M. Mauerer M. Kaufmann	Th. Holenstein D. Steinert M. Schuck T. Wellerdieck

Secretariat
M. Kohn / D. Egger

Administration
P. Albrecht / P. Maurantonio

Computer Systems
C. Stucki

Electronics Laboratory
P. Seitz

22 Ph.D. Students
4 Post Docs → *1:5 PostDoc/Doc - Ratio*

Competence Centre

Leading Univ. in Europe

Outline

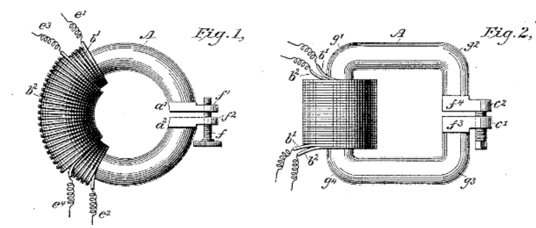
- Transformer History / Basics
- SST Concept / Topologies
- SSTs in Future Traction
- SSTs in Future Smart Grids
- Conclusions

History

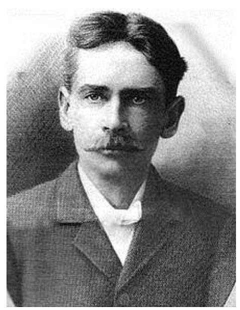
Transformer
“Electronic” Transformer

► Classical Transformer (XFMR) – History (1)

* 1830 - Henry/Faraday → Property of Induction
* 1878 - Ganz Company (Hungary) → Toroidal Transformer (AC Incandescent Syst.)
* 1880 - Ferranti → Early Transformer
* 1882 - Gaulard & Gibbs → Linear Shape XFMR (1884, 2kV, 40km)
* 1884 - Blathy/Zipernowski/Deri → Toroidal XFMR (inverse type)



W. STANLEY, Jr.
INDUCTION COIL.
Patented Sept. 21, 1886. No. 349,611.



* 1885 - Stanley & (Westinghouse) → Easy Manufact. XFMR (1^{st} Full AC Distr. Syst.)

▶ Classical Transformer – History (2)

UNITED STATES PATENT OFFICE.

MICHAEL VON DOLIVO-DOBROWOLSKY, OF BERLIN, GERMANY, ASSIGNOR TO THE ALLGEMEINE ELEKTRICITÄTS-GESELLSCHAFT, OF SAME PLACE.

ELECTRICAL INDUCTION APPARATUS OR TRANSFORMER.

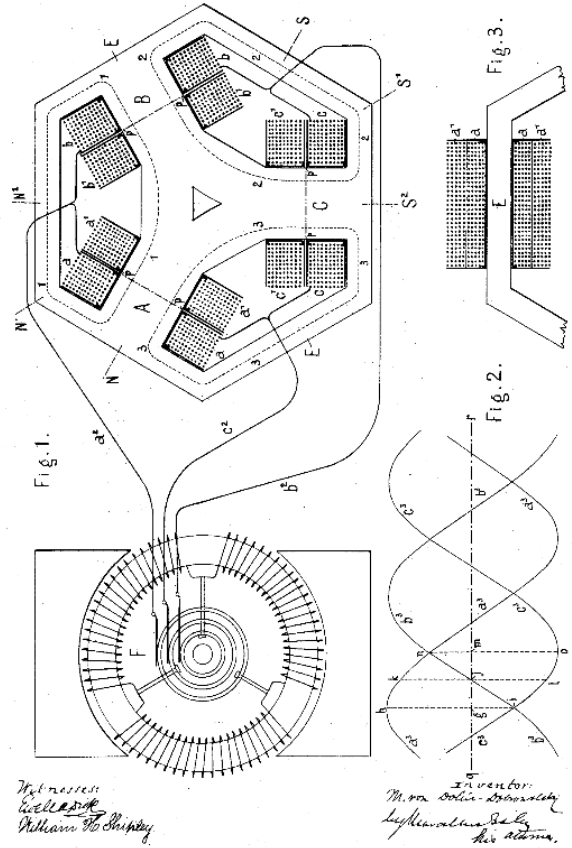
SPECIFICATION forming part of Letters Patent No. 422,746, dated March 4, 1890.

Application filed January 8, 1890. Serial No. 336,290. (No model.)

(No Model.) M. VON DOLIVO-DOBROWOLSKY.

ELECTRICAL INDUCTION APPARATUS OR TRANSFORMER.

No. 422,746. Patented Mar. 4, 1890.



* 1889 - Dobrovolski → 3-Phase Transformer

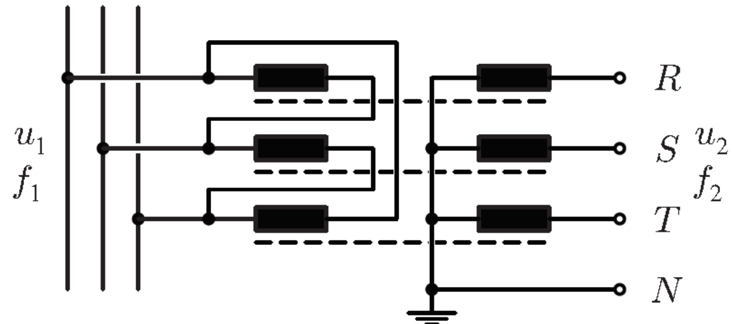
* 1891 - 1st Complete AC System (Gen.+XFMR+Transm.+El. Motor+Lamps, 40Hz, 25kV, 175km)

Classical Transformer – Basics (1)

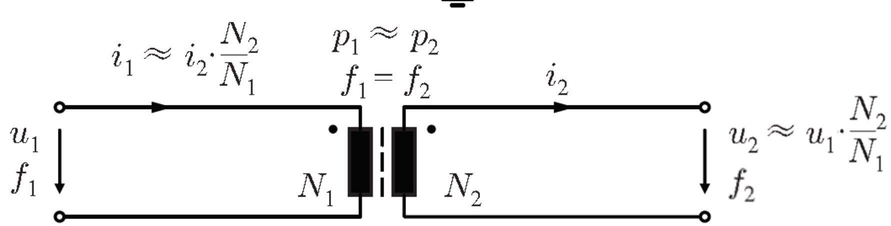
- Magnetic Core Material * Silicon Steel / Nanocrystalline / Amorphous / Ferrite
- Winding Material * Copper or Aluminium
- Insulation/Cooling * Mineral Oil or Dry-Type

- Operating Frequency * 50/60Hz (El. Grid, Traction) or $16^2/_3$ Hz (Traction)
- Operating Voltage * 10kV or 20 kV (6...35kV)
  * 15kV or 25kV (Traction)
  * 400V

- Voltage Transf. Ratio * Fixed
- Current Transf. Ratio * Fixed
- Active Power Transf. * Fixed ($P_1 \approx P_2$)
- React. Power Transf. * Fixed ($Q_1 \approx Q_2$)
- Frequency Ratio * Fixed ($f_1 = f_2$)



- Magnetic Core Cross Section $$A_{Core} = \frac{1}{\sqrt{2}\pi}\frac{U_1}{\hat{B}_{max}\, f}\frac{1}{N_1}$$
- Winding Window $$A_{Wdg} = \frac{2I_1}{k_W J_{rms}} N_1$$



▶ Classical Transformer – Basics (2)

- Advantages

- Relatively Inexpensive
- Highly Robust / Reliable
- Highly Efficient (98.5%...99.5% Dep. on Power Rating)
- Short Circuit Current Limitation

Welding Transformer (Zimbabwe) – Source: http://www.africancrisis.org

United States Patent Office

3,517,300
Patented June 23, 1970

1

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

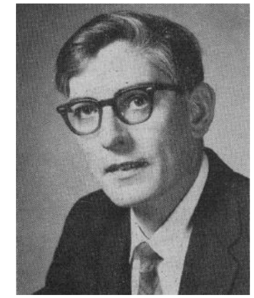
Filed Apr. 16, 1968, Ser. No. 721,817
Int. Cl. H02m 5/16, 5/30
U.S. Cl. 321—60 14 Claims

ABSTRACT OF THE DISCLOSURE

Several single phase solid state power converter circuits have a high frequency transformer link whose windings are connected respectively to the load and to a D-C or low frequency A-C source through inverter configuration switching circuits employing inverse-parallel pairs of controlled turn-off switches (such as transistors or gate turn-off SCR's) as the switching devices. Filter means are connected across the input and output terminals. By synchronously rendering conductive one switching device in each of the primary and secondary side circuits, and alternately rendering conductive another device in each switching circuit, the input potential is converted to a high frequency wave, transformed, and reconstructed at the output terminals. Wide range output voltage control is obtained by phase shifting the turn-on of the switching devices on one side with respect to those on the other side by 0° to 180°, and is used to effect current limiting, current interruption, current regulation, and voltage regulation.

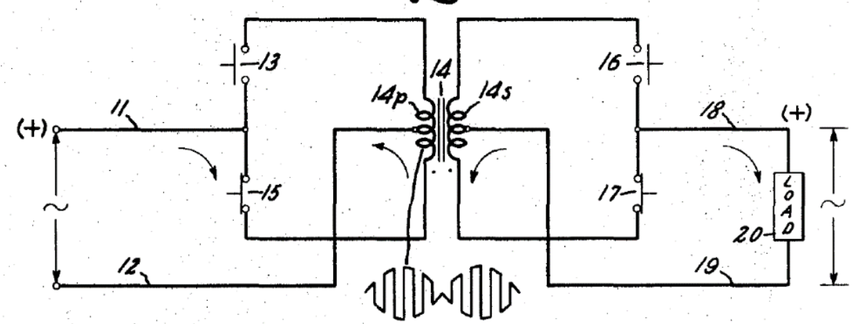
1968 !

Filed April 16, 1968



Inventor:
William McMurray
by Donald R. Campbell
His Attorney

Fig. 1a



- **Electronic Transformer ($f_1 = f_2$)**
- **AC or DC Voltage Regulation & Current Regulation/Limitation/Interruption**

Solid-State Transformer Basics

Concept
Functionality

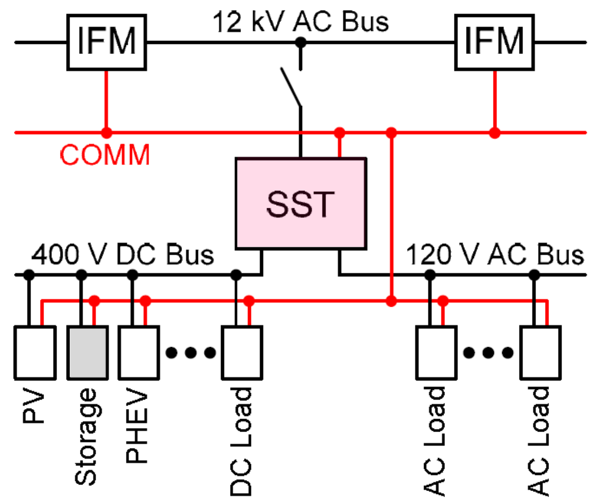
Future Smart EE Distribution

▶ Solid-State Transformer (SST) Concept

- Solid State Transformer (SST) = "Active" Distribution Transformer with AC and DC LV Output
- Enabling Technology for the "Energy Internet"

- Full Control of Active/Reactive/Harmonic Power Flow
- Integr. of Distributed Energy Resources
- Integr. of Distributed E-Storage + Intellig. Loads
- Protects Power System From Load Disturbances
- Protects Load from Power Syst. Disturbances
- Enables Distrib. Intellig. through COMM
- Ensure Stability & Opt. Operation
- etc.
- etc.

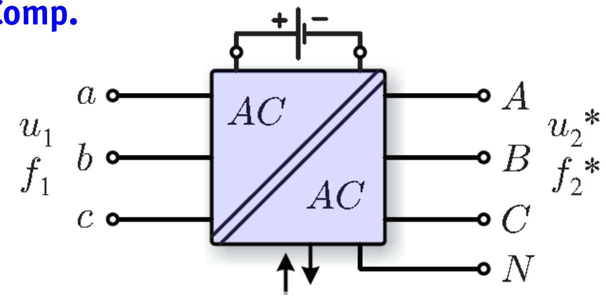
IFM = Intellig. Fault Management



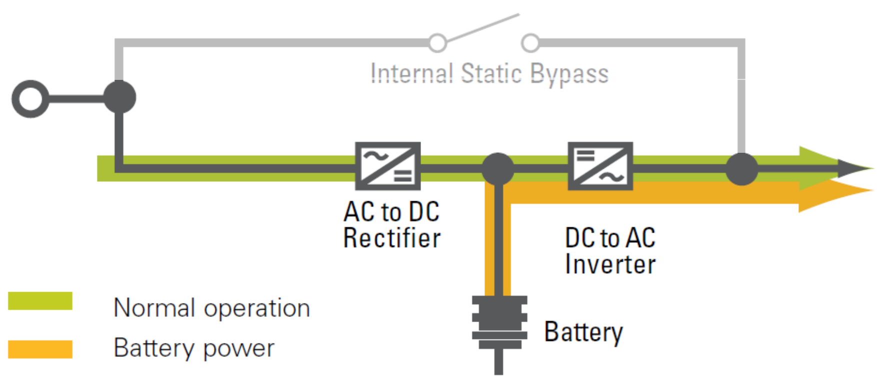
- Medium Frequency Isolation → Low Weight / Volume
- Bidirectional Flow of Power & Information / High Bandw. Comm. → Distrib. / Local Auton. Cntrl

▶ SST vs. Uninterruptible Power Supply

- **Same Basic Functionalities of SST and Double-Conversion UPS (+ Isolation)**
  - **High Quality of Load Power Supply**
  - **Possible Ext. to Input Side Active Filtering**
  - **Possible Ext. to Input Reactive Power Comp.**



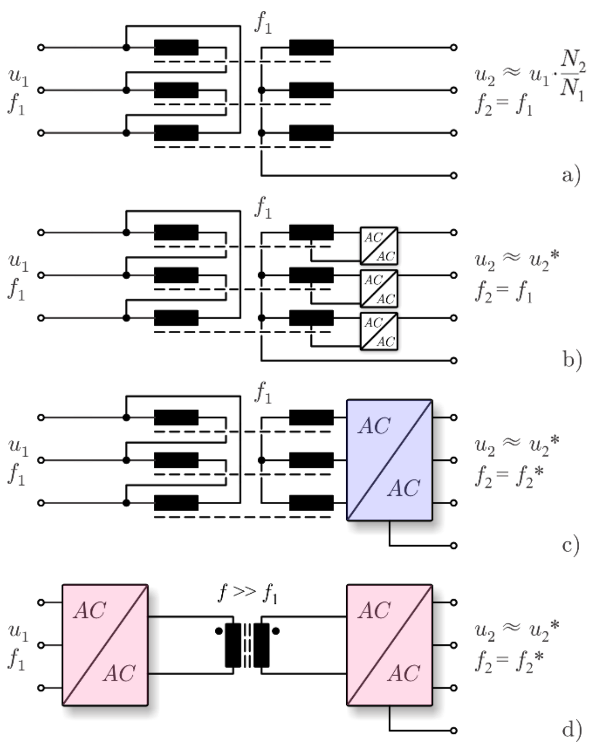
Source: EATON Corp.



- **Input Side MV Voltage Connection of SST as Main Difference / Challenge**
- **Numerous Topological Options**

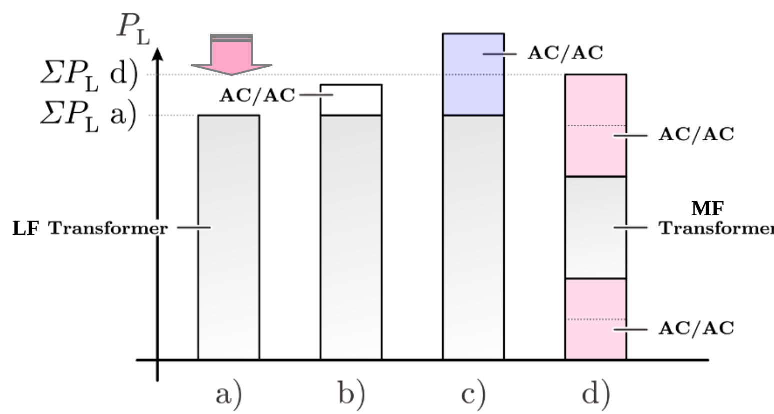
▶ Passive Transformer → SST

- Efficiency Challenge



LF Isolation
Purely Passive (a)
Series Voltage Comp. (b)
Series AC Chopper (c)

MF Isolation
Active Input & Output Stage (d)

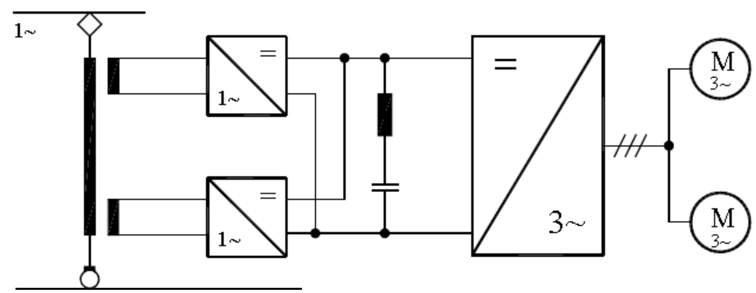


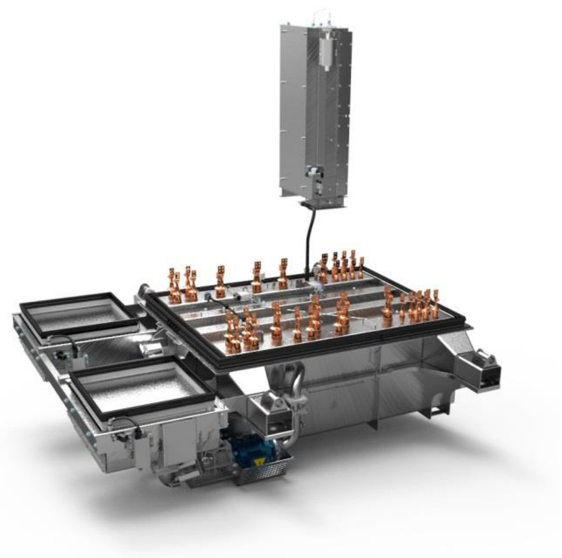
- Medium Freq. → Higher Transf. Efficiency Partly Compensates Converter Stage Losses
- Medium Freq. → Low Volume, High Control Dynamics

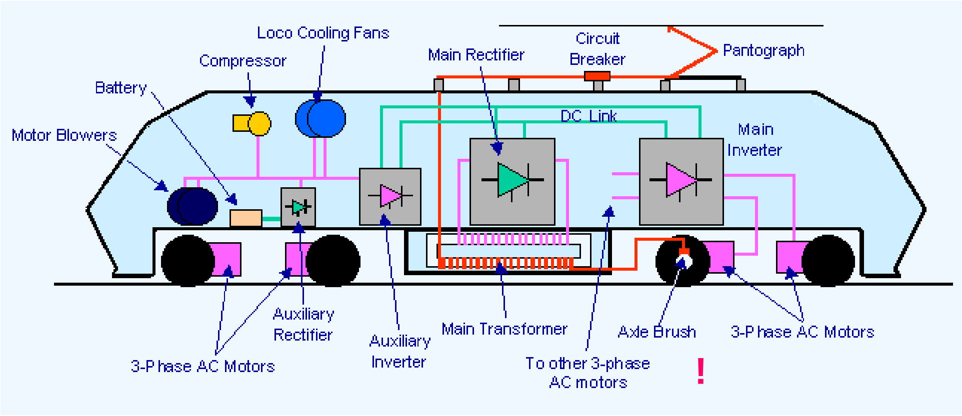
Traction (Locomotives)

▶ Classical Locomotives

- Catenary Voltage 15kV or 25kV
- Frequency $16^2/_3$Hz or 50Hz
- Power Level 1…10MW typ.







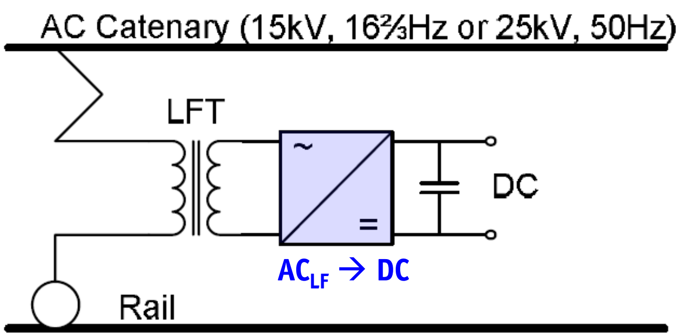
- **Transformer:**

	Efficiency	90…95% (due to Restr. Vol., 99% typ. for Distr. Transf.)
	Current Density	6 A/mm² (2A/mm² typ. Distribution Transformer)
	Power Density	2…4 kg/kVA

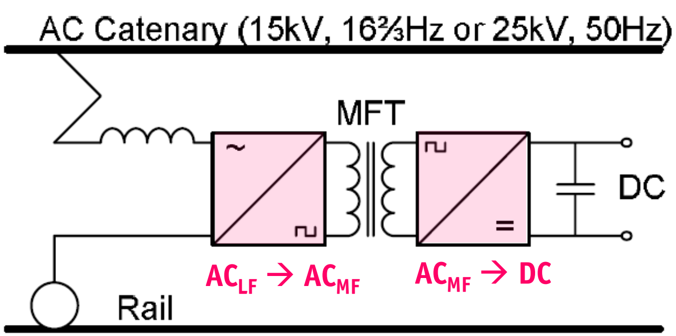
Next Generation Locomotives

- Trends
  * Distributed Propulsion System → Volume Reduction (Decreases Efficiency)
  * Energy Efficient Rail Vehicles → Loss Reduction (Requires Higher Volume)
  * Red. of Mech. Stress on Track → Mass Reduction

Source: ABB



Conventional AC-DC conversion with a line frequency transformer (LFT).

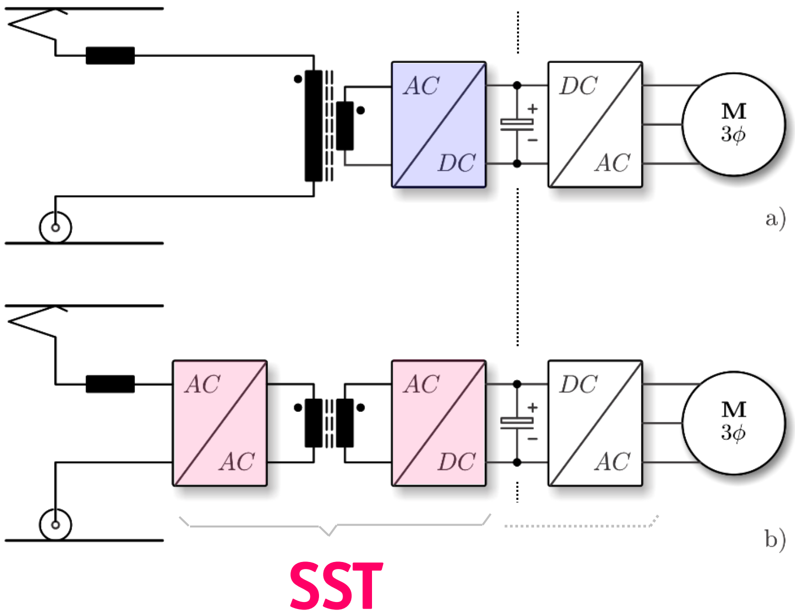


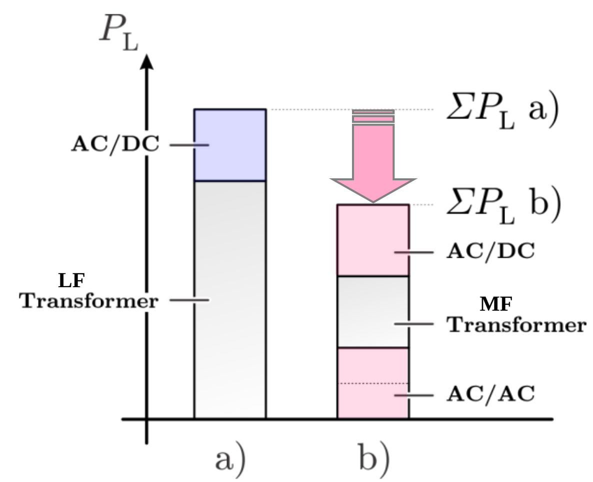
AC-DC conversion with medium frequency transformer (MFT).

- Replace LF Transformer by *Medium Frequency* Power Electronics Transformer → **SST**
- *Medium Frequency* Provides Degree of Freedom → Allows Loss Reduction *AND* Volume Reduction

▶ Next Generation Locomotives

- Loss Distribution of Conventional & Next Generation Locomotives





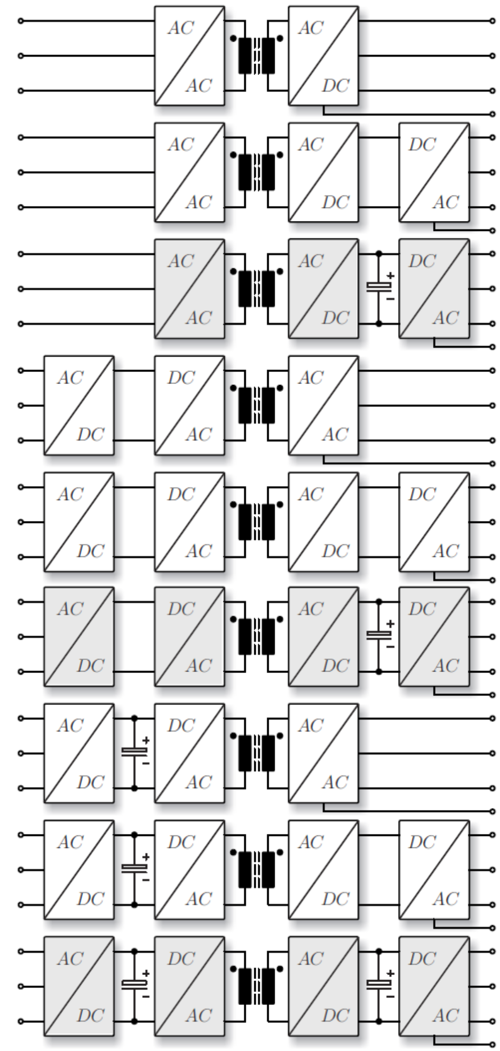
- **Medium Frequ. Provides Degree of Freedom → Allows Loss Reduction *AND* Volume Reduction**

Derivation of SST Circuit Topology →

▶ Basic SST Structures (1)

- 1st Degree of Freedom of Topology Selection → Partitioning of the AC/AC Power Conversion

* DC-Link Based Topologies
* Direct/Indirect Matrix Converters
* Hybrid Combinations

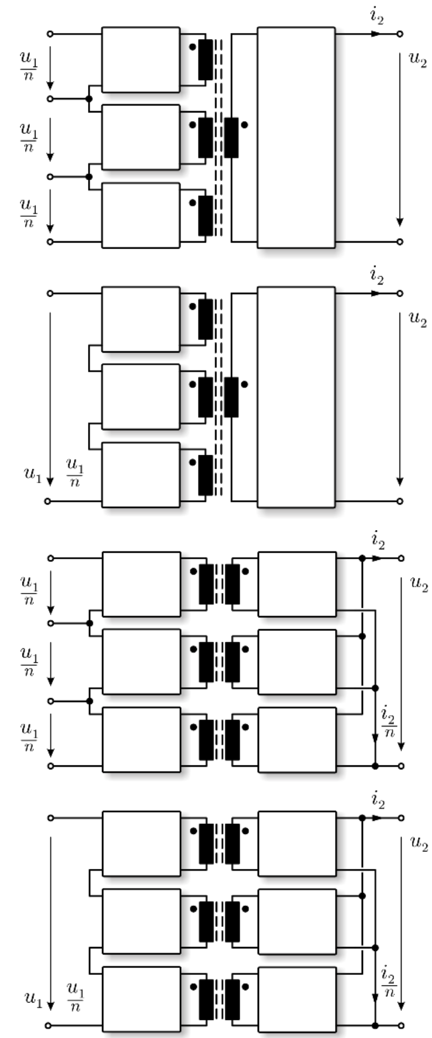


- 1-Stage Matrix-Type Topologies
- 2-Stage with LV DC Link (Connection of Energy Storage)
- 2-Stage with MV DC Link (Connection to HVDC System)
- 3-Stage Power Conversion with MV and LV DC Link

- Only Concepts Featuring MF Isolation Considered

▶ Basic SST Structures (2)

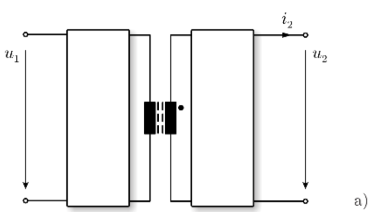
■ 2nd Degree of Freedom of Topology Selection → Partitioning of Medium Voltage



- Multi-Cell and Multi-Level Approaches

- Low Blocking Voltage Requirement
- Low Input Voltage / Output Current Harmonics
- Low Input/Output Filter Requirement

* Single-Cell / Two-Level Topology

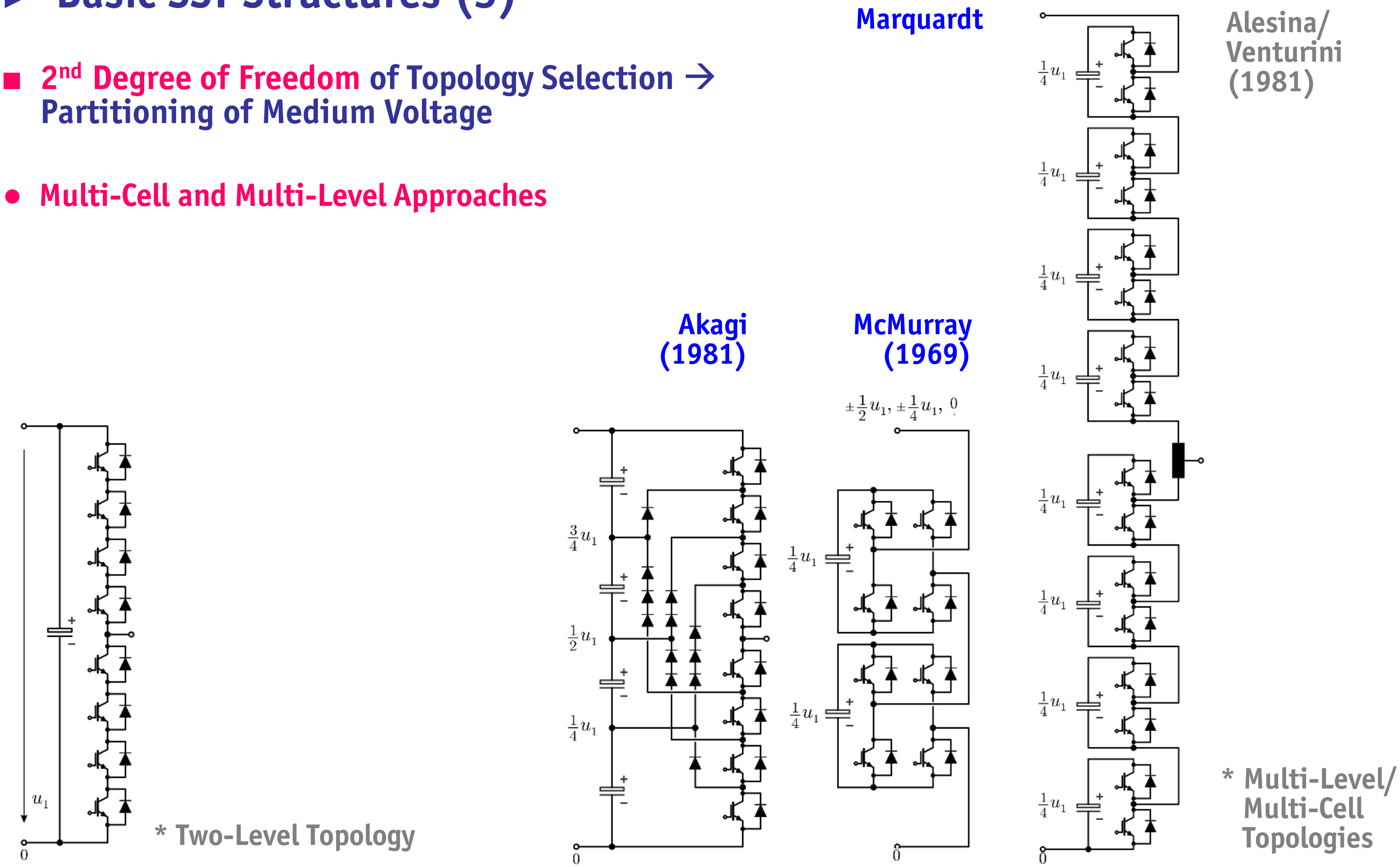


ISOP = Input Series / Output Parallel Topologies

▶ Basic SST Structures (3)

- **2nd Degree of Freedom of Topology Selection → Partitioning of Medium Voltage**

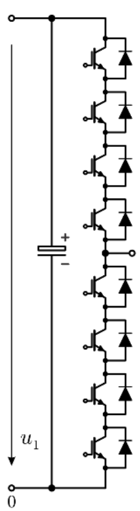
- **Multi-Cell and Multi-Level Approaches**



▶ Basic SST Structures (3)

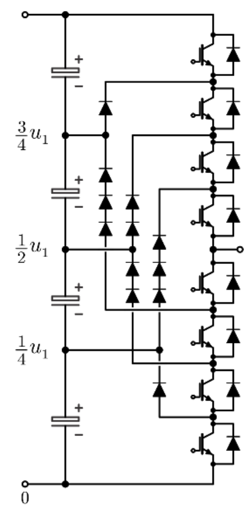
■ 2nd Degree of Freedom of Topology Selection → Partitioning of Medium Voltage

● Multi-Cell and Multi-Level Approaches

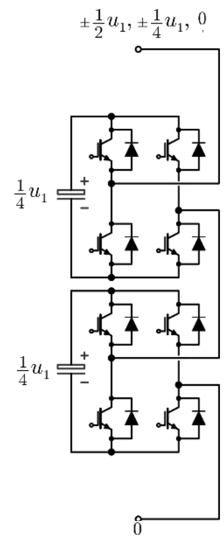


* Two-Level Topology

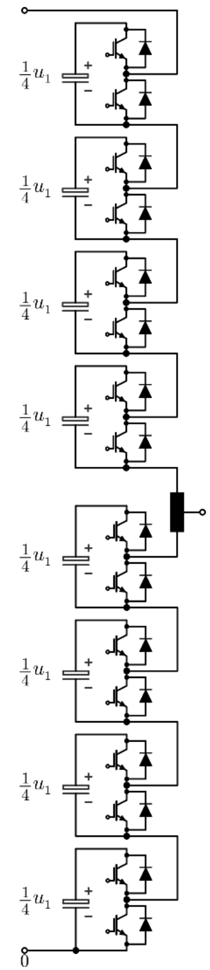
Akagi (1981)



Marquardt



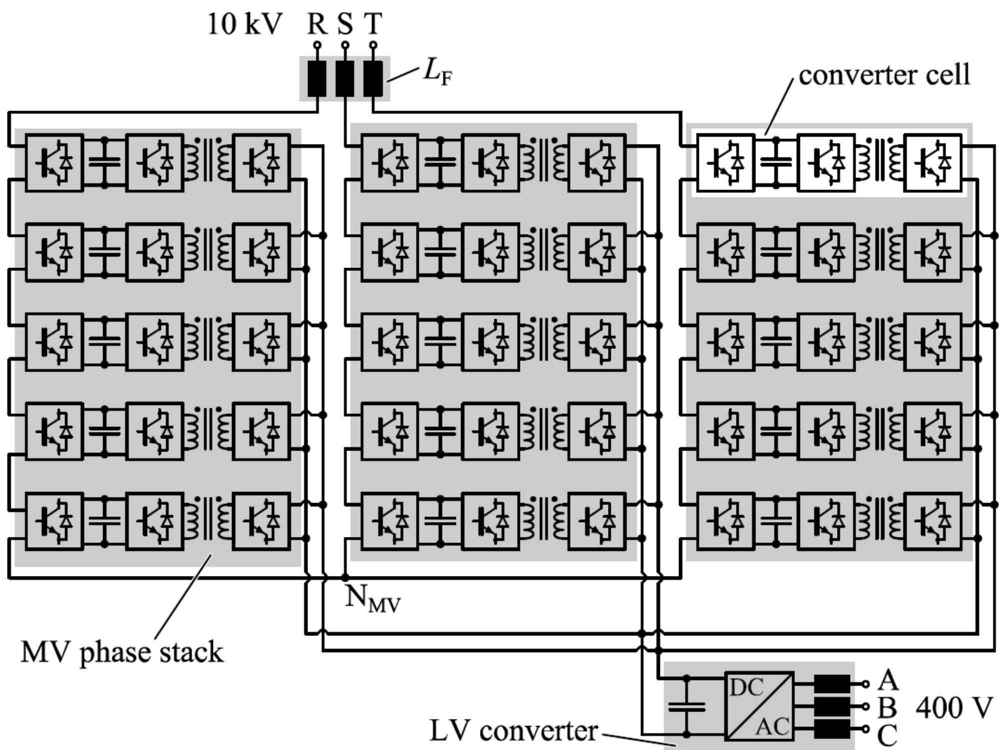
Alesina/ Venturini (1981)



* Multi-Level/ Multi-Cell Topologies

▶ MEGA Link @ ETH Zurich

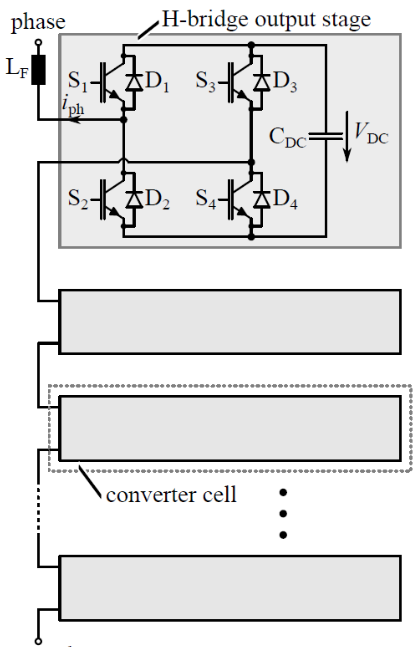
S_N = 630kVA
U_{LV} = 400 V
U_{MV} = 10kV

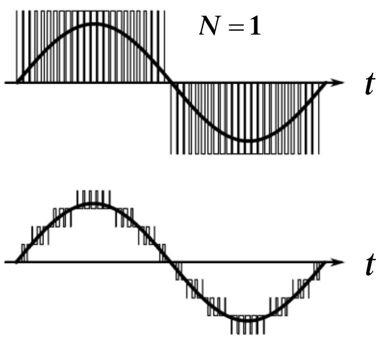


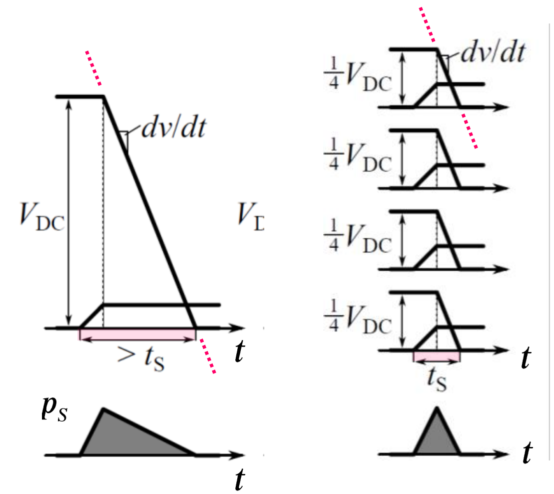
- **2-Level Inverter on LV Side / HC-DCM-SRC DC-DC Conversion / Cascaded H-Bridge MV Structure**

▶ Series Interleaving of Converter Cells

■ **Interleaved Series Connection Dramatically Reduces Switching Losses (or Harmonics)**







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

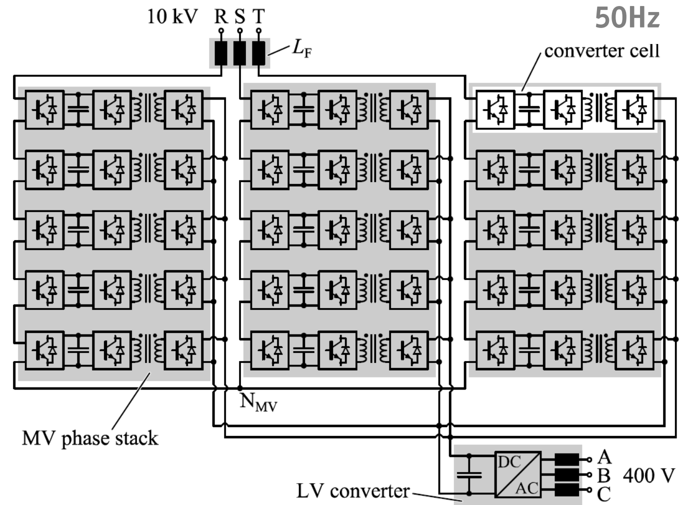
$$P_{S,N} \approx P_{S,N=1} \cdot \left(\frac{1}{2N^2} \dots \frac{1}{N^3}\right)$$

■ **Converter Cells Could Operate at VERY Low Switching Frequency (e.g. 5kHz)**
■ **Minimization of Passives (Filter Components)**

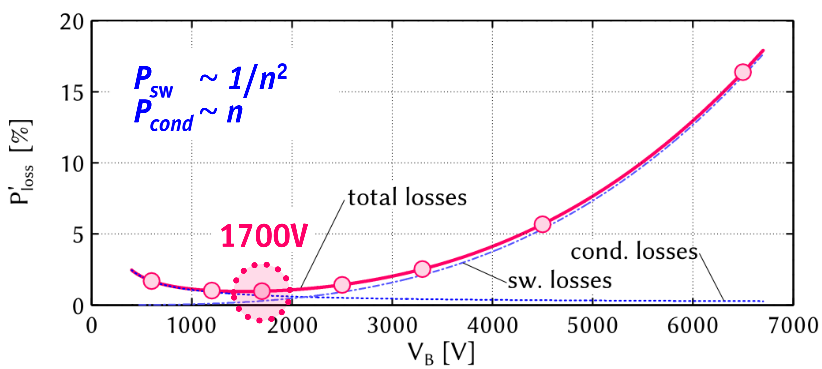
▶ Loss-Optimal Number of Converter Cells

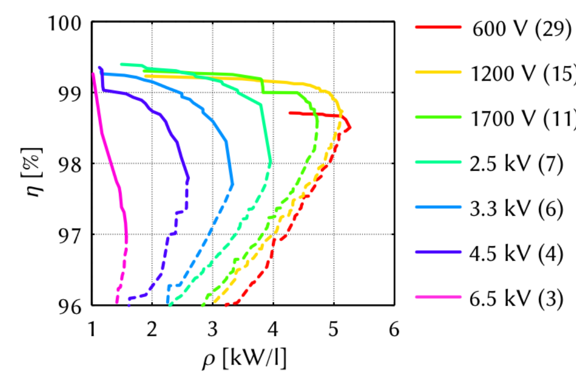
1 MVA
10kV → 400V
50Hz

- **Trade-Off** High Number of Levels →
  Higher Conduction Losses vs.
  Lower Cell Switching Frequency/
  Lower Losses (for Same
  Current Ripple)



- Optim. Device Voltage Rating for Given MV Level
- ηρ-Pareto Opt. (Ind. L_F for Compl. to IEEE 519)

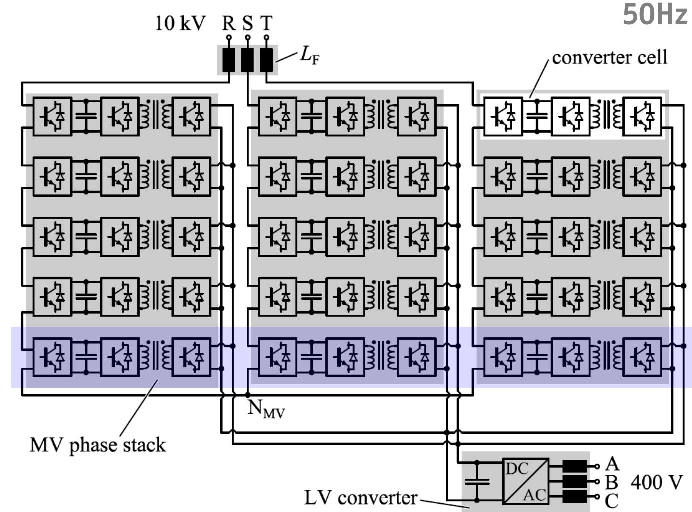




- **1200V ... 1700V Si IGBTs Best Suited for 10kV Mains**

▶ Optimum Number of Converter Cells

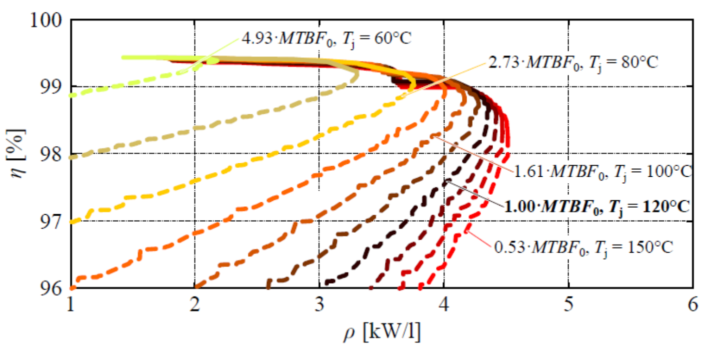
1 MVA
10kV → 400V
50Hz

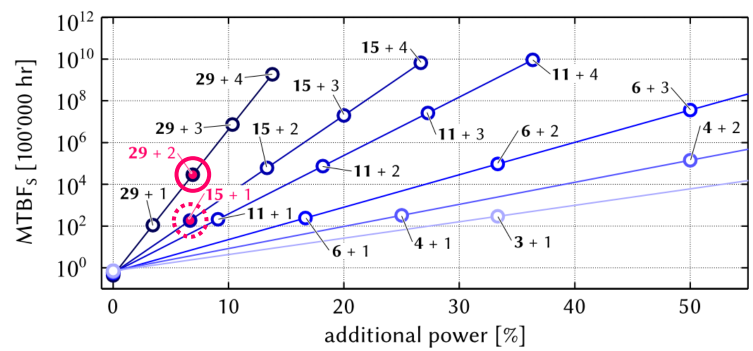


- **Trade-Off → Mean-Time-to-Failure vs. Efficiency / Power Density**

- **Influence of**
  - * **FIT Rate (Voltage Utilization)**
  - * **Junction Temperature**
  - * **Number of Redundant Cells**

No Redundancy
1700V IGBTs, 60% Utilized



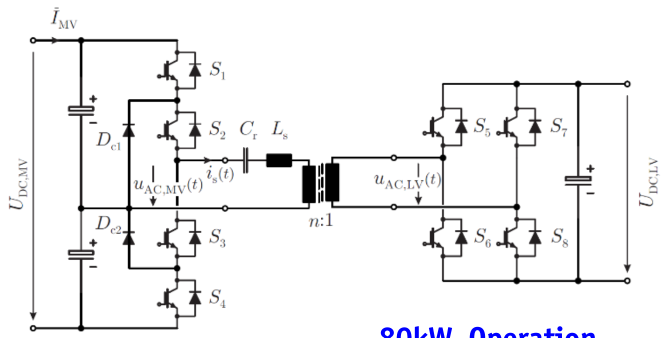


- **High MTBF also for Large Number of Cells (Repairable) / Lower Total Spare Cell Power Rating**

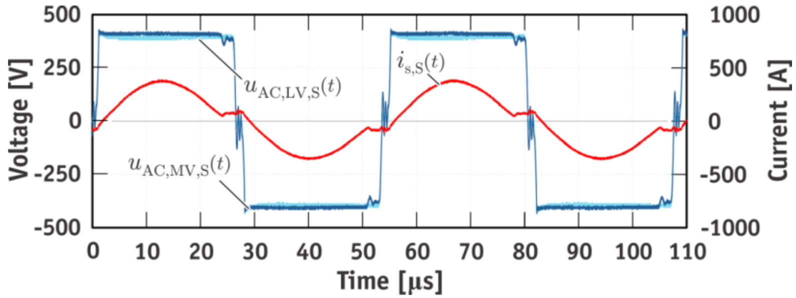
▶ 166kW / 20kHz HC-DCM-SRC DC-DC Converter Cell

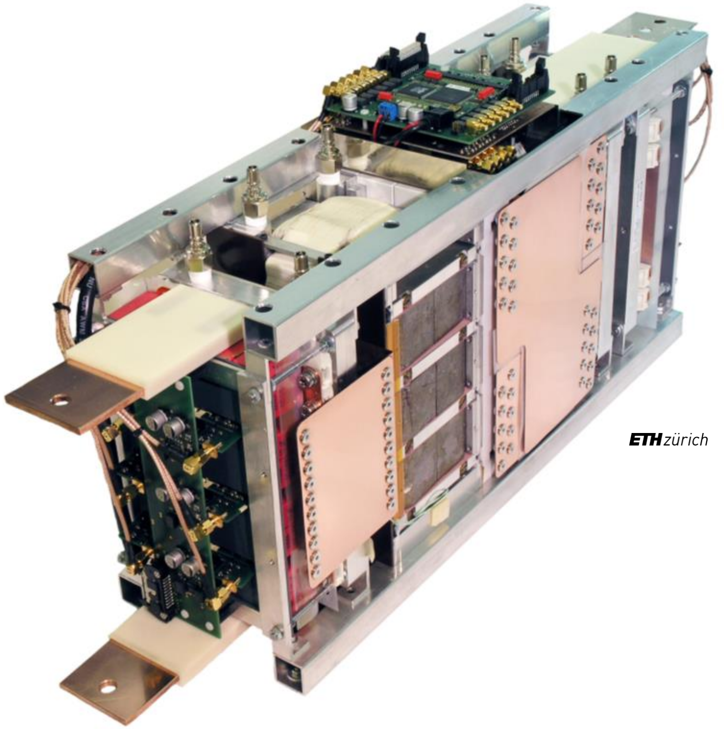
- Half-Cycle DCM Series Resonant DC-DC Converter

- Medium-Voltage Side 2kV
- Low-Voltage Side 400V



80kW Operation

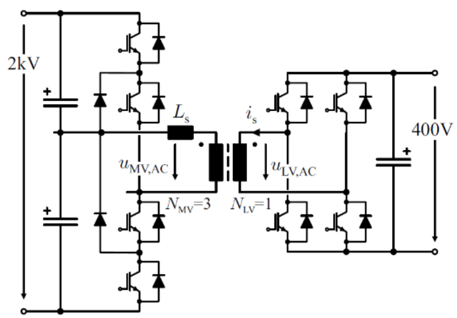


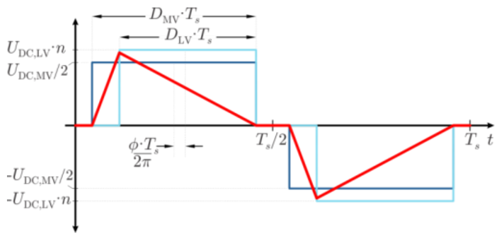


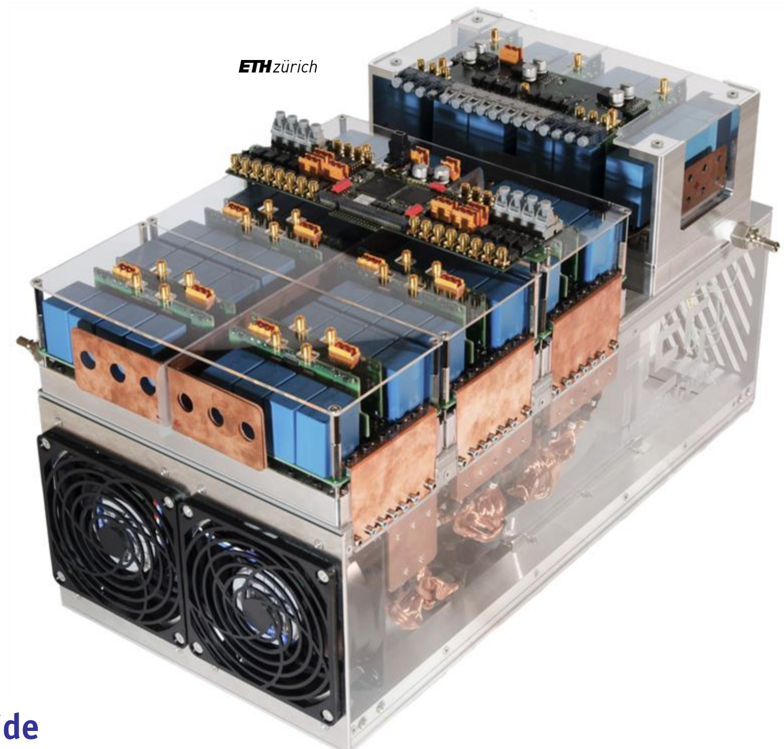
▶ 166kW / 20kHz TCM DC-DC Converter Cell

- **Half-Cycle Triangular Current Mode DC-DC Converter**

- **Medium-Voltage Side** 2kV
- **Low-Voltage Side** 400V







- **Shifts All Active Switching (Losses) to LV Side**

Protection of SSTs

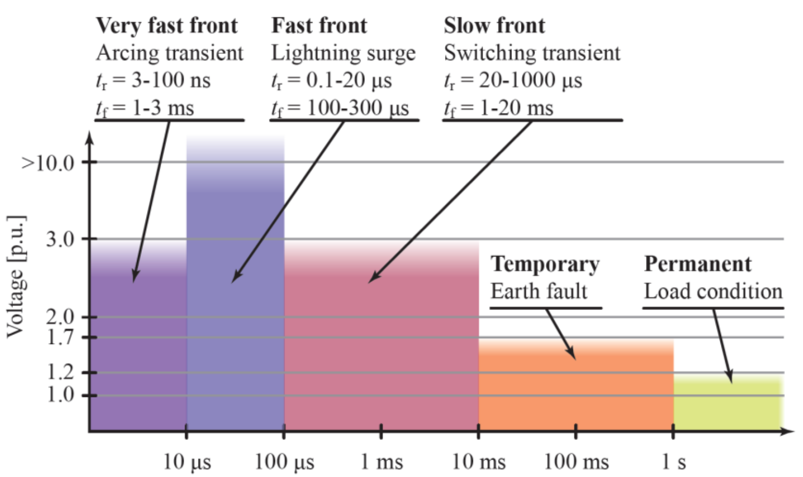
– Overvoltage
– Overcurrent

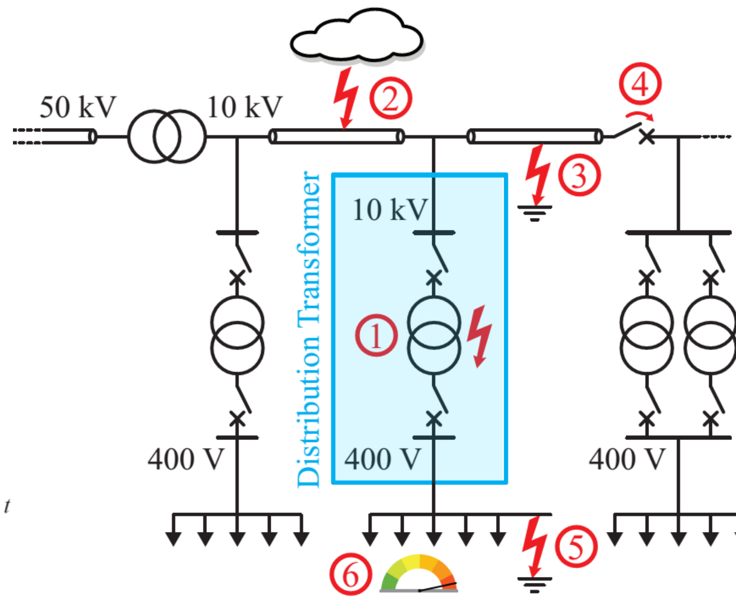
▶ Potential Faults of MV/LV Distribution-Type SSTs

- Extreme Overvoltage Stresses on the MV Side for Conv. Distr. Grids
- SST more Appropriate for Local Industrial MV Grids

1. Internal Fault
2. Lightning Surge
3. Switching Transient
4. MV Short Circuit
5. LV Short Circuit
6. Non-Ideal Load

- Conv. MV Grid Time-Voltage Characteristic





Evaluation of SST vs. LF Transformer

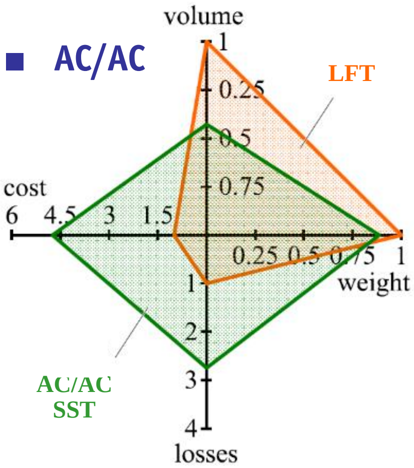
– AC/AC Conversion
– AC/DC Conversion →

▶ SST vs. LF Transformer + AC/AC or AC/DC Converter

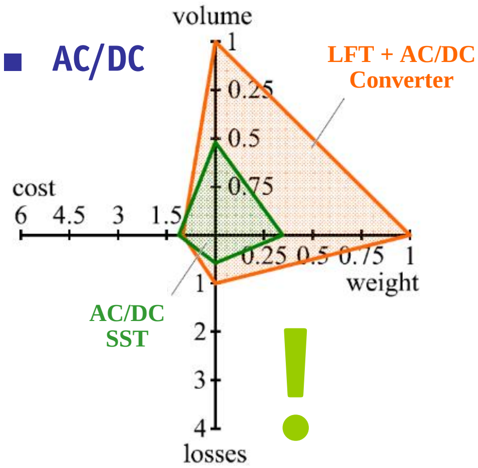
- **Specifications** 1MVA
  10kV Input
  400V Output
  1700V IGBTs (1kHz/8kHz/4kHz)

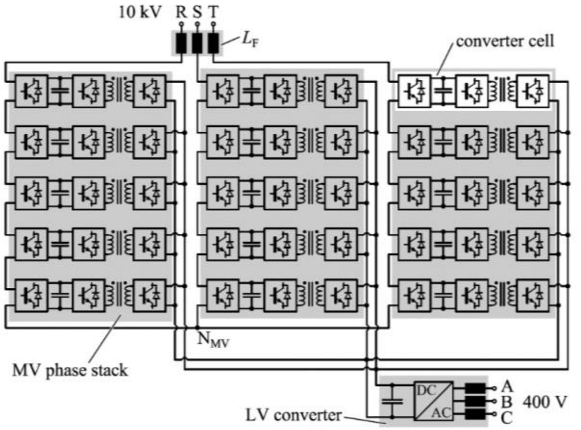
- **LF Transformer** 98.7 %
  16.2 kUSD
  2600kg (5700lb)

■ AC/AC



■ AC/DC



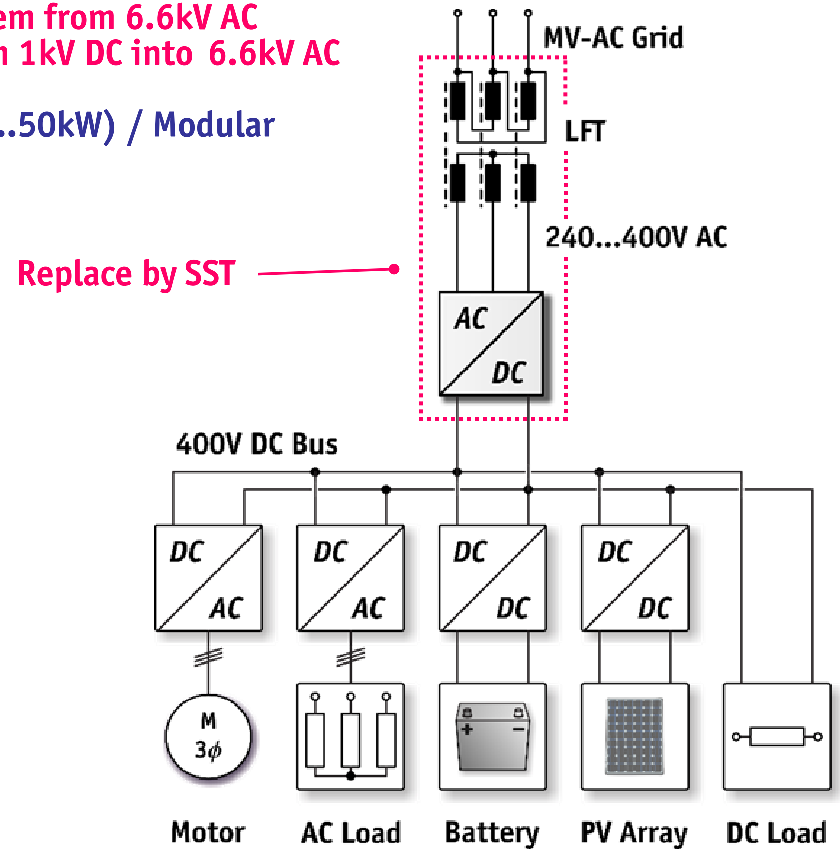


- ■ Clear Efficiency/Volume/Weight Advantage of SST for DC Output (98.2%)
- ■ Weakness of AC/AC SST vs. Simple LF Transformer (98.7%) - 5 x Costs, 2.5 x Losses

▶ Unidirectional SST Topologies

- Direct Supply of 400V/48V DC System from 6.6kV AC
- Direct PV Energy Regeneration from 1kV DC into 6.6kV AC

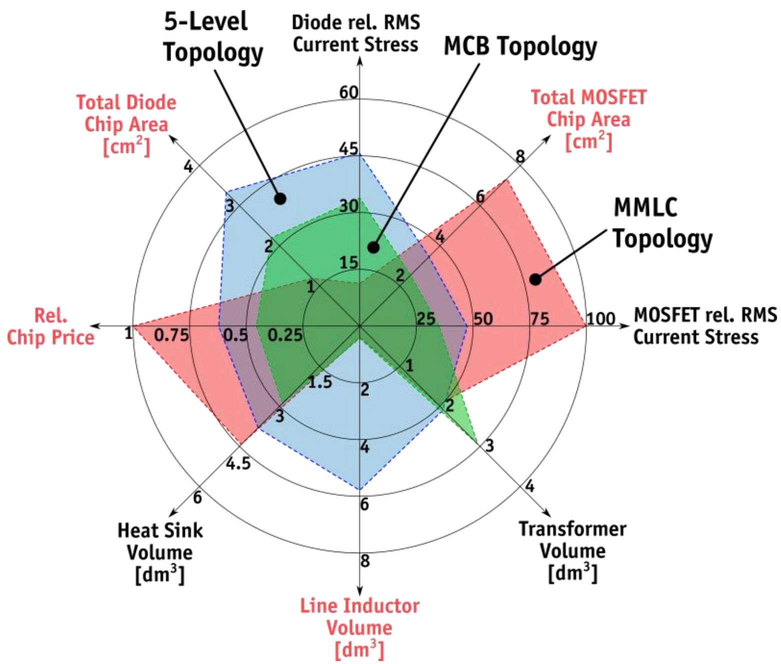
- Even for Relatively Low Power (25...50kW) / Modular
- All-SiC Realization (50kHz XFMR)

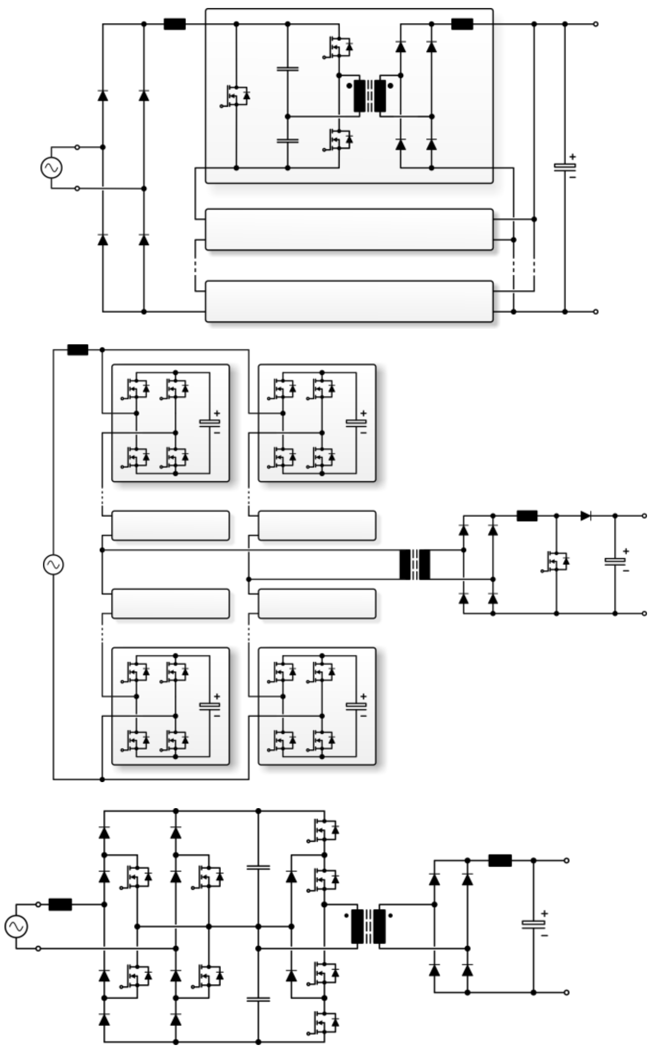


- Comparative Evaluation of SST Topologies based on Comp. Load Factors

▶ Unidirectional SST Topologies

- Direct Supply of 400V DC System from 6.6kV AC
- All-SiC Realization (50kHz XFMR)
- P = 25kW





- Comparative Evaluation based on Comp. Load Factors

Near and Far Future SST Applications

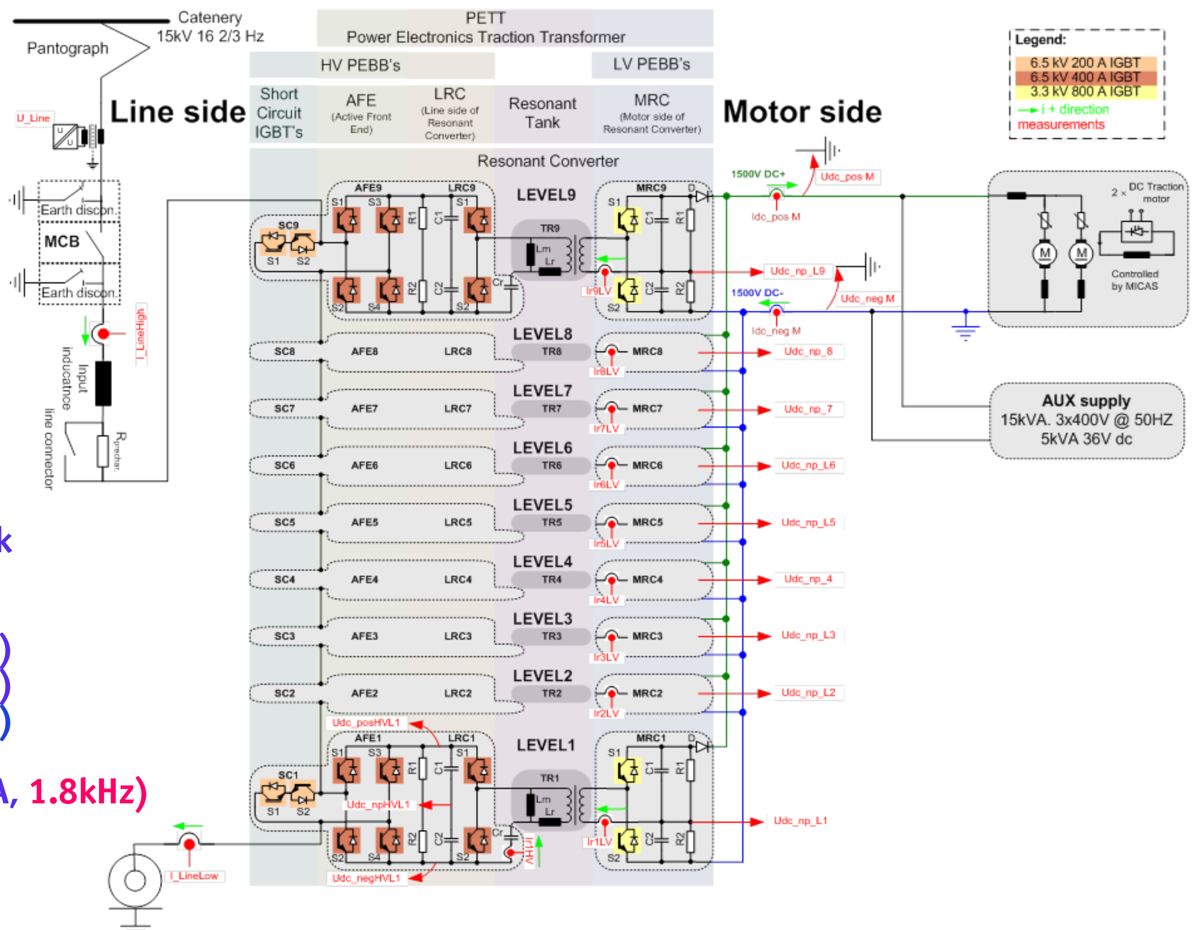
Next Generation Locomotives
Deep Sea Oil & Gas Processing
Power-to-Gas
More-Electric Aircraft
etc.

▶ 1ph. AC/DC Power Electronic Transformer - PET

ABB

- Dujic et al. (2011)

- Rufer (1996)
- Steiner (1997)
- Heinemann (2002)



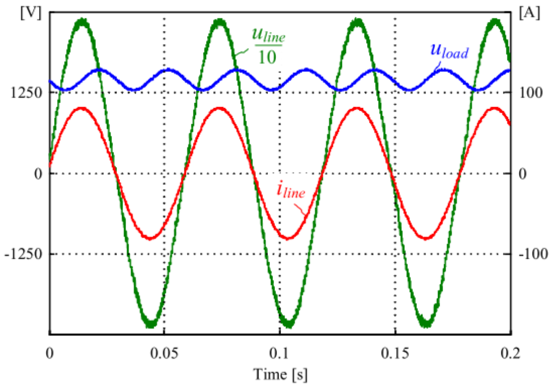
P = 1.2MVA, 1.8MVA pk
9 Cells (Modular)

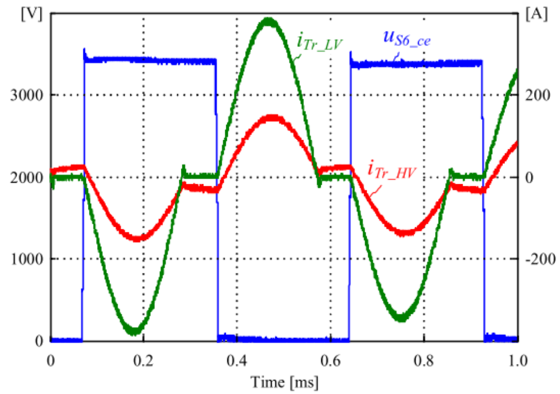
54 x (6.5kV, 400A IGBTs)
18 x (6.5kV, 200A IGBTs)
18 x (3.3kV, 800A IGBTs)

9 x MF Transf. (150kVA, 1.8kHz)
1 x Input Choke

▶ 1.2 MVA 1ph. AC/DC Power Electronic Transformer

- Cascaded H-Bridges – 9 Cells
- Resonant LLC DC/DC Converter Stages

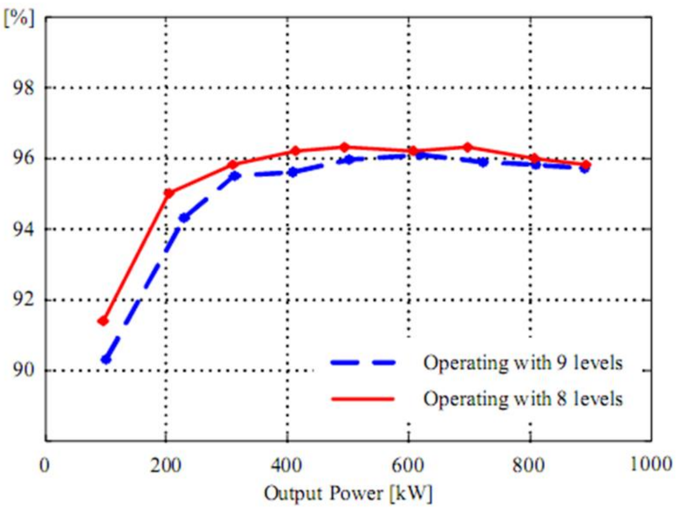




▶ 1.2 MVA 1ph. AC/DC Power Electronic Transformer

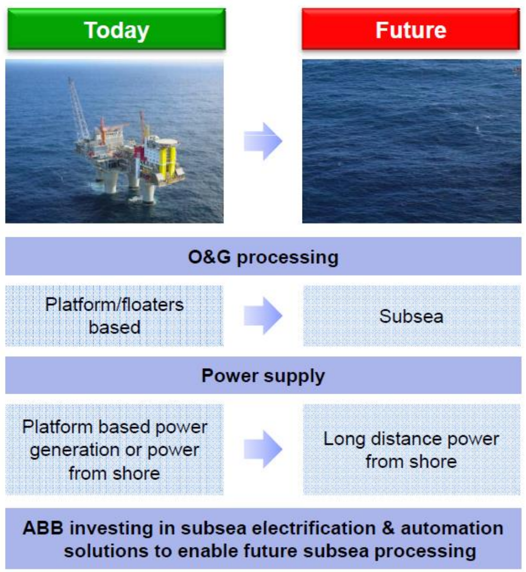
- Cascaded H-Bridges – 9 Cells
- Resonant LLC DC/DC Converter Stages

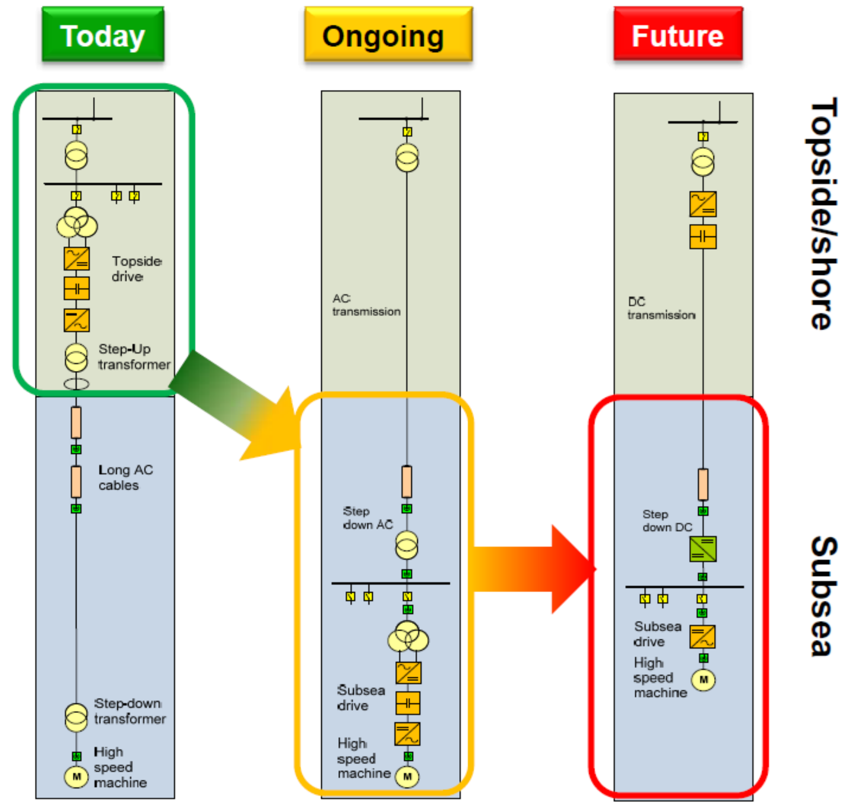
Efficiency



▶ Future Subsea Distribution Network – Oil & Gas Processing

- Devold (ABB 2012)





- Transmission Over DC, No Platforms/Floaters
- Longer Distances Possible
- Subsea O&G Processing

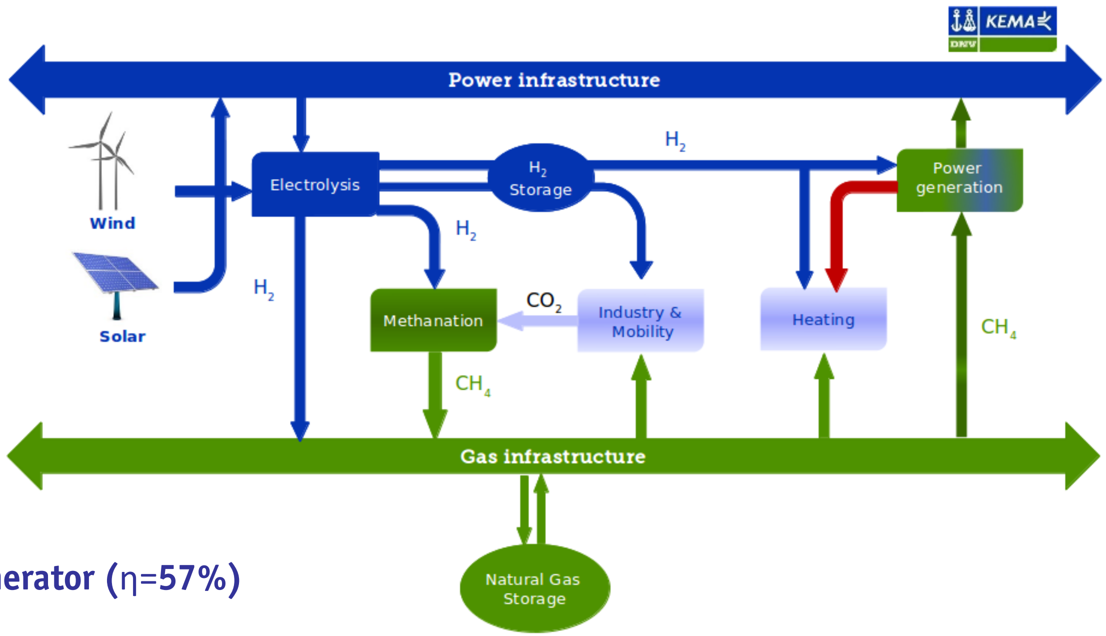
- Weight Optimized Power Electronics

▶ Power-to-Gas

- Electrolysis for Conversion of Excess Wind/Solar Electric Energy into Hydrogen
  → Fuel-Cell Powered Cars
  → Heating

- High-Power @ Low DC Voltage (e.g. $220V_{DC}$)
- Very Well Suited for MV-Connected SST-Based Power Supply

– Hydrogenics 100 kW H_2-Generator (η=57%)



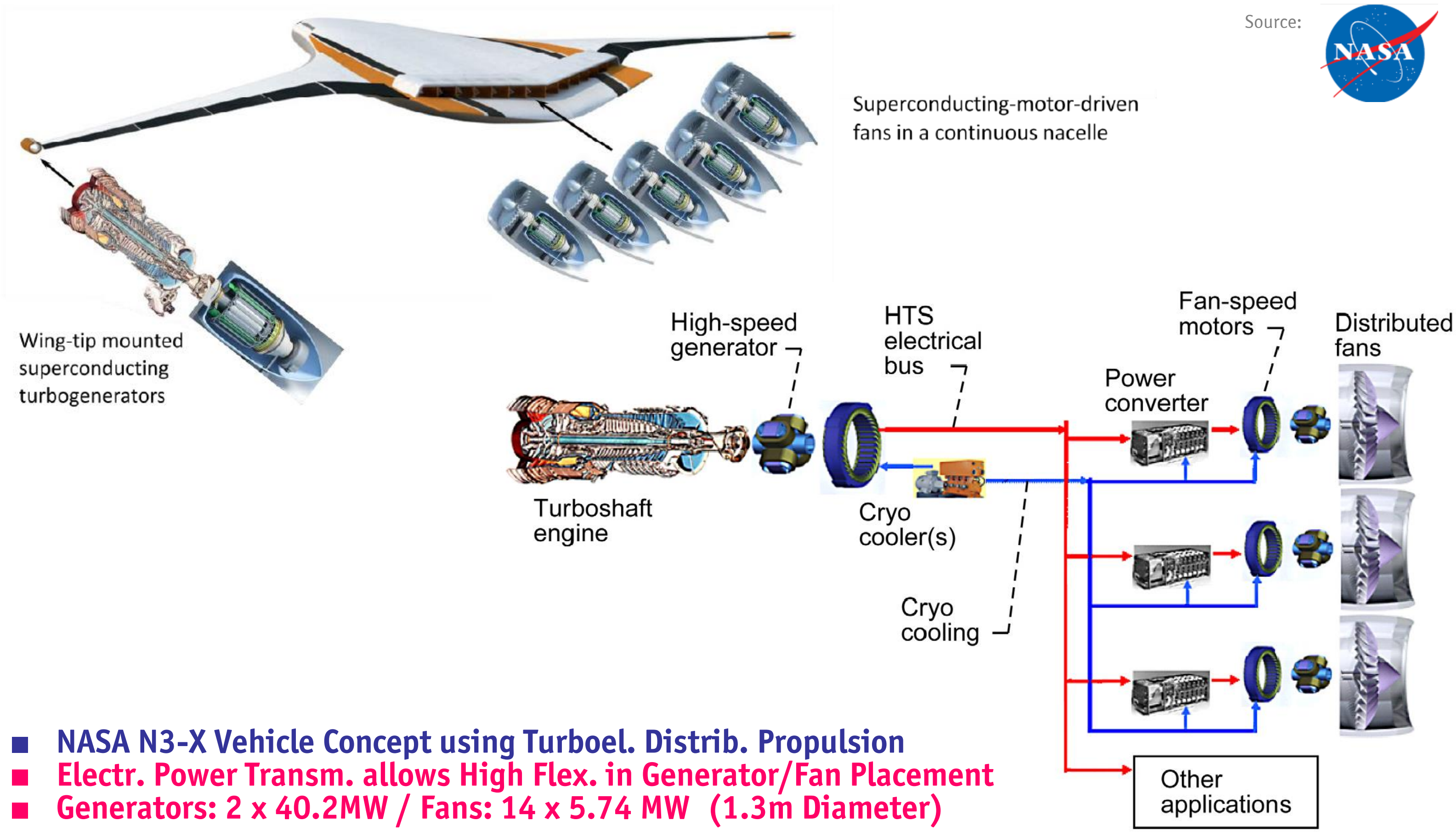
► Future Hybrid or All-Electric Aircraft (1)

Source: EADS

- Powered by Thermal Efficiency Optimized Gas Turbine and/or Future Batteries (1000 Wh/kg)
- Highly Efficient Superconducting Motors Driving Distributed Fans (E-Thrust)
- Until 2050: Cut CO_2 Emissions by 75%, NO_x by 90%, Noise Level by 65%

► Future Hybrid or All-Electric Aircraft (2)

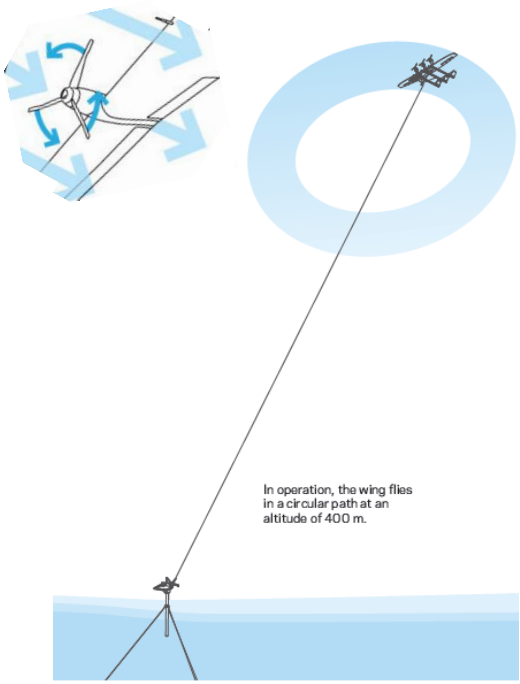
Source: NASA



- NASA N3-X Vehicle Concept using Turboel. Distrib. Propulsion
- Electr. Power Transm. allows High Flex. in Generator/Fan Placement
- Generators: 2 x 40.2MW / Fans: 14 x 5.74 MW (1.3m Diameter)

▶ Airborne Wind Turbines

- Power Kite Equipped with Turbine / Generator / Power Electronics
- Power Transmitted to Ground Electrically
- Minimum of Mechanically Supporting Parts

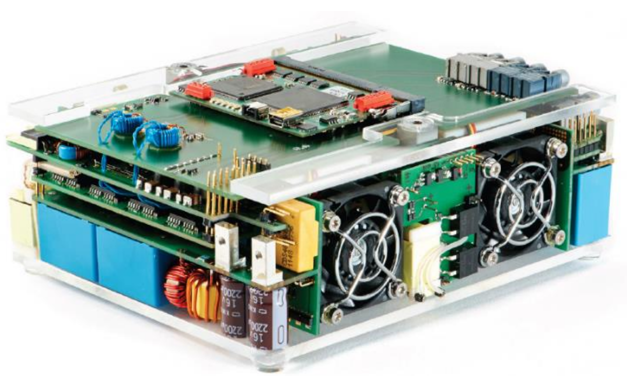


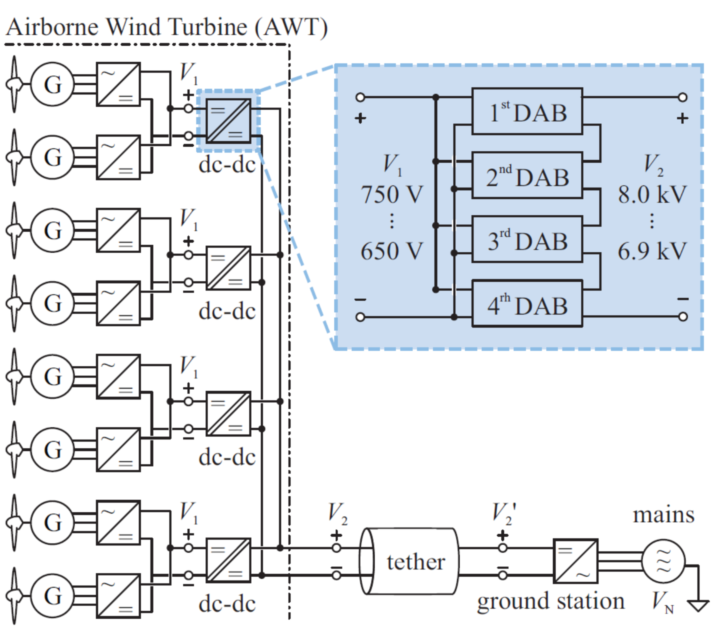
MAKANI POWER Google X

▶ 100kW Airborne Wind Turbine

- Ultra-Light Weight Multi-Cell All-SiC Solid-State Transformer - $8kV_{DC} \rightarrow 700V_{DC}$

– Medium Voltage Port	1750 ... 2000 V_{DC}
– Switching Frequency	100 kHz
– Low Voltage Port	650 ... 750 V_{DC}
– Cell Rated Power	6.25 kW
– Power Density	5.2kW/dm^3
– Specific Weight	4.4kW/kg

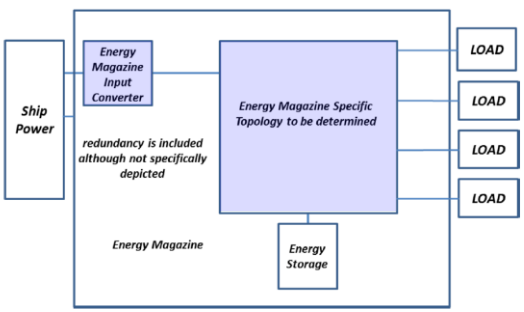




Future Military Applications

- MV Cellular DC Power Distribution on Future Combat Ships etc.

Source: General Dynamics

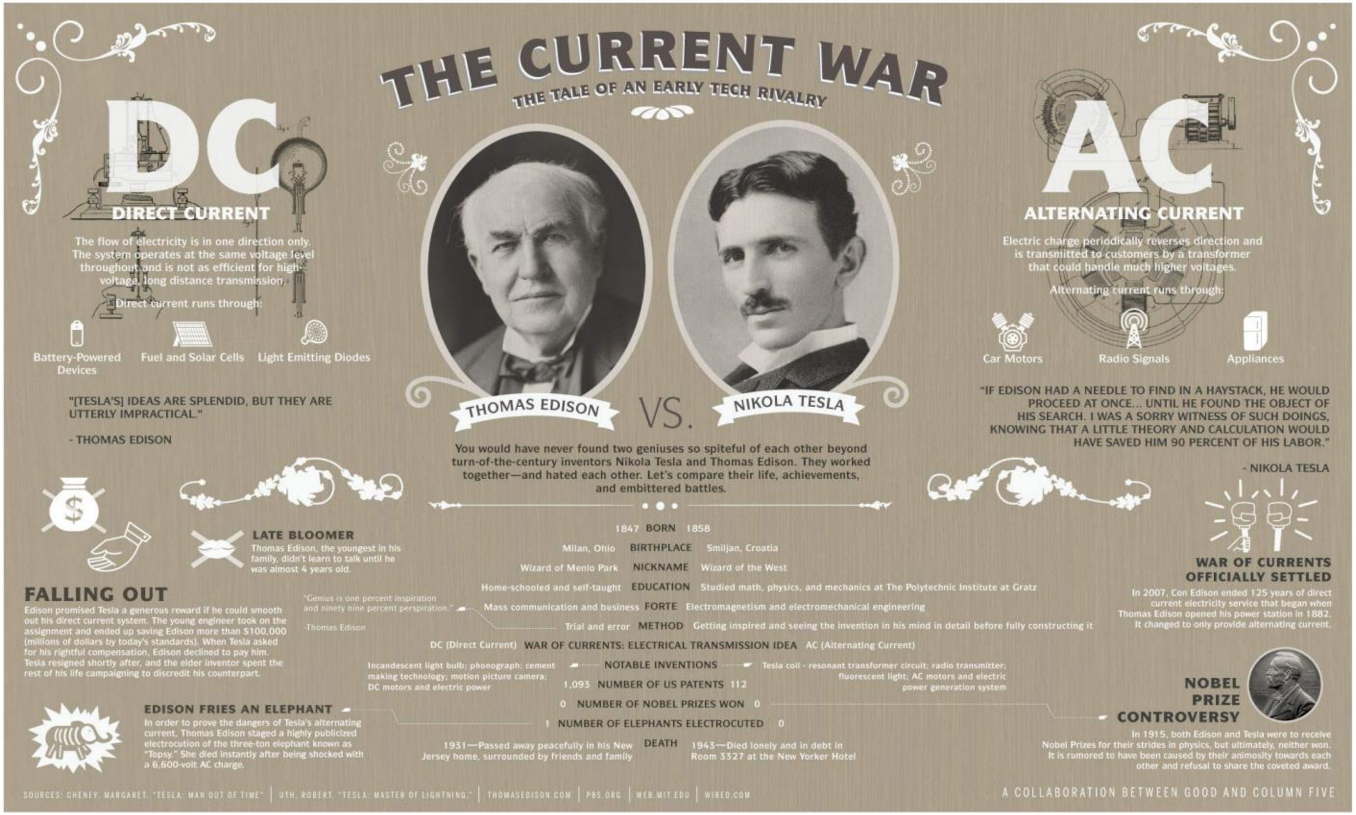


- "Energy Magazine" as Extension of Electric Power System / Individual Load Power Conditioning
- Bidirectional Power Flow for Advanced Weapon Load Demand
- Extreme Energy and Power Density Requirements

Conclusions

SST Evaluation
Future Research Areas

▶ SST Ends the "War of Currents"



- No "Revenge" of T.A. Edison but Future "Synergy" of AC and DC Systems !

▶ SST for Smart Grid Applications

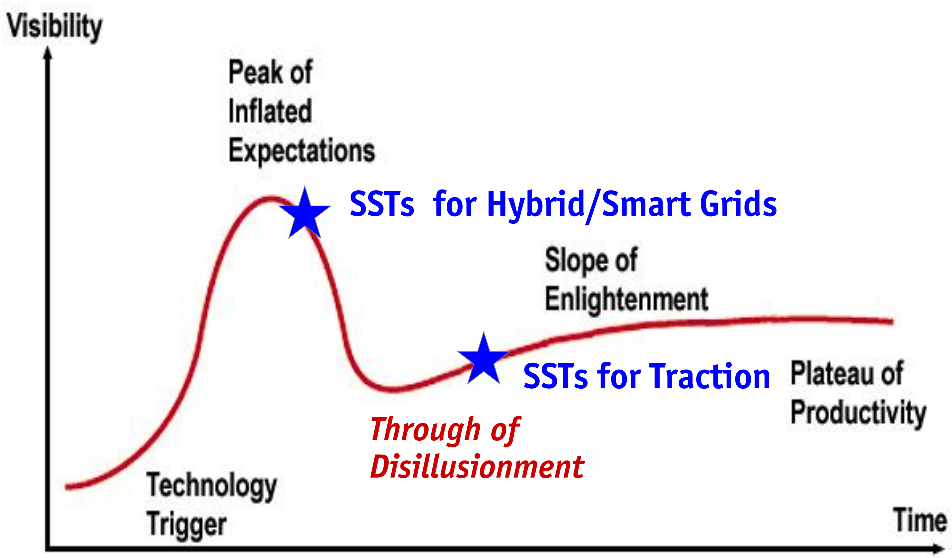
Source: www.diamond-jewelry-pedia.com

SST Research Status

Required for Successful Application

■ Huge *Multi-Disciplinary* Challenges / Opportunities (!)

SST Technology Hype Cycle



- **Different States of Development of SSTs for**
  - **Traction Applications**
  - **Hybrid / Smart Grid Applications**

▶ SST Limitations – Application Areas

■ SST Limitations

- Efficiency (Rel. High Losses 2-6%)
- High Costs (Cost-Performance Ratio still to be Clarified)
- Limited Volume Reduction vs. Conv. Transf. (Factor 2-3)
- Limited Overload Capability
- (Reliability)

■ Potential Application Areas

- Traction Vehicles
- UPS Functionality with MV Connection
- Temporary Replacement of Conv. Distribution Transformer
- Parallel Connection of LF Transformer and SST (SST Current Limit – SC Power does not Change)
- Military Applications

▶ Applications for Volume/Weight Limited Systems where 2-4 % of Losses Could be Accepted

▶ Overall Summary

- SST is NOT a 1:1 Replacement for Conv. Distribution Transformers
- SST will NOT Replace All Conv. Distribution Transformers (even in Mid Term Future)
- SST Offers High Functionality BUT shows also Several Weaknesses / Limitations

→ SST Requires a Certain Application Environment (until Smart Grid is Fully Realized)
→ SST Preferably Used in LOCAL Fully SMART EEnergy Systems

@ Generation End (e.g. Nacelle of Windmills)
@ Load End - Micro- or Nanogrids (incl. Locomotives, Ships etc.)

- Environments with Pervasive Power Electronics for Energy Flow Control (No Protection Relays etc.) →
- Environments which Could be Designed for SST Application
- (Unidirectional) Medium Voltage Coupling of DC Distribution Systems

Questions

Power Electronic Systems Laboratory

ETH zürich

Wireless Charging of EVs

Fundamentals / Performance / Limitations

Johann W. Kolar and Roman Bosshard
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Outline

- Wireless vs. Conductive Charging
- Fundamentals of IPT
- Multi-Objective Optimization
- Demonstrator Systems
- Conclusions

ACKNOWLEDGEMENT

The authors would like to express their sincere appreciation to ABB Switzerland Ltd. for the support of research on IPT that lead to the results presented in this Tutorial

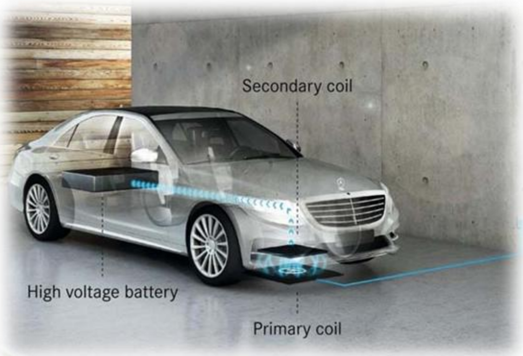
Introduction

Features
Existing Industry Solutions

► Wireless Electric Vehicle Battery Charging

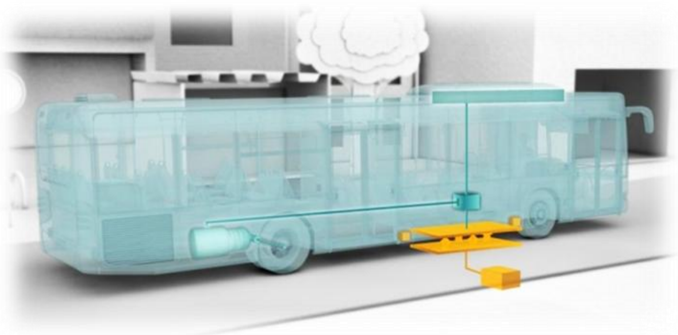
Charge Point,
www.chargepoint.com

Delphi, www.delphi.com



Daimler & BWM,
ww.daimler.com, www.bmw.de

- **Higher Convenience & Usability**
  - No Plug Required: Quick Charging at Traffic Lights, Bus Stops, ...
- **More Frequent Recharging**
  - Longer Battery Lifetime
  - Smaller Battery Volume & Weight
- **Reduced Fleet in Public Transportation**
  - Shorter Time for Depot Re-Charging

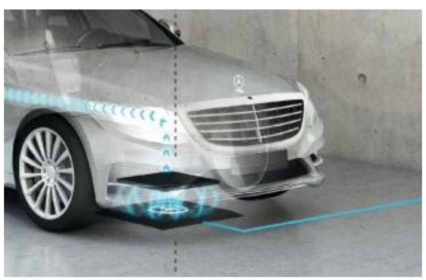


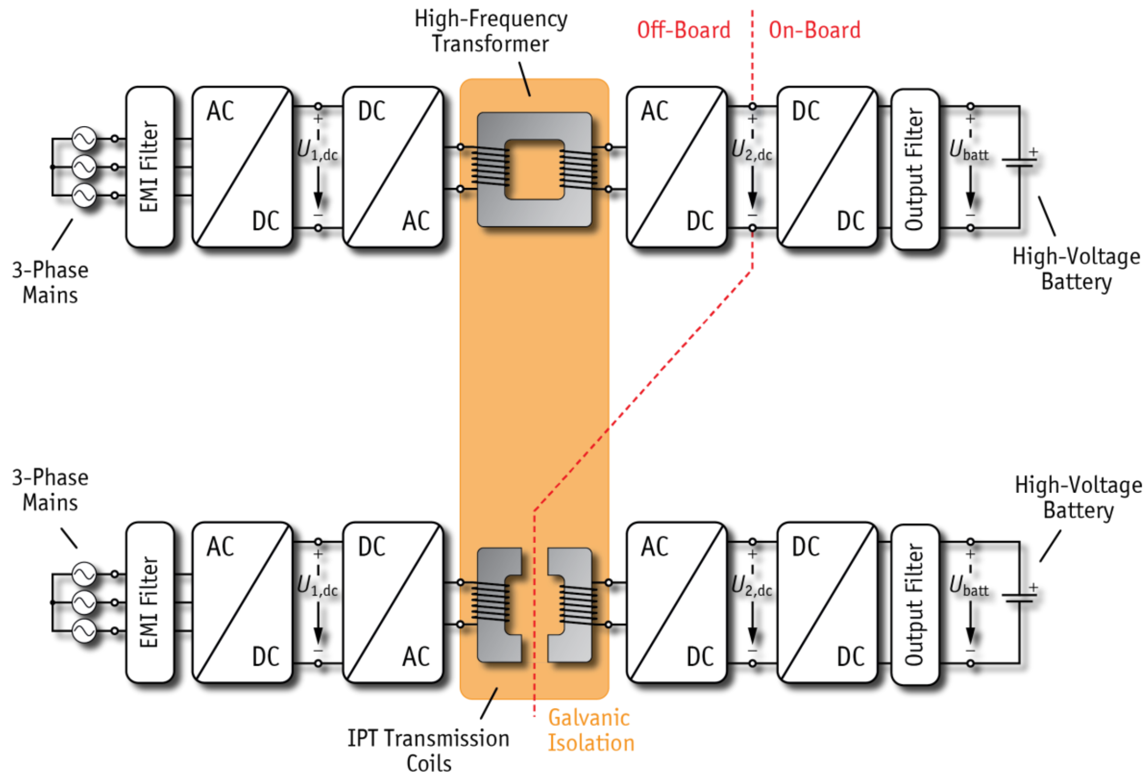
Bombardier PRIMOVE,
http://primove.bombardier.com.

▶ EV Charging – Typical AC/DC Power Conversion Chain

- **Conductive EV Charging**

- **Wireless EV Charging**



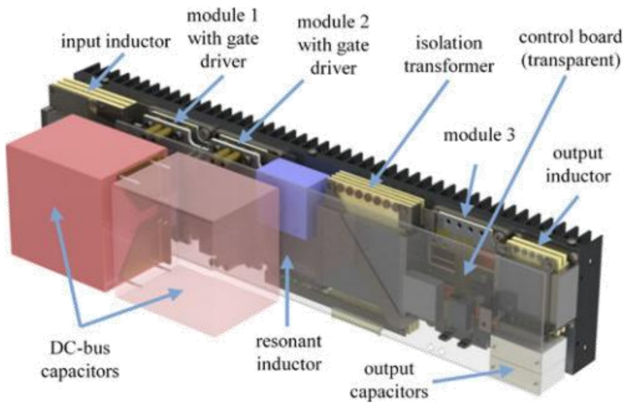


▲ **Structure of a 3-Φ Isolated 2-Stage High-Power Battery Charging System with High-Frequency Transformer or IPT Transmission Coils**

► EV Battery Charging: Key Design Challenges

■ **Conductive Isolated On-Board EV Battery Charger:**
- Charging Power 6.1 kW
- Efficiency > 95%
- Power Density 5 kW/dm³
- Spec. Weight 3.8 kW/kg

→ **Engineering Goal: Design Competitive IPT System**

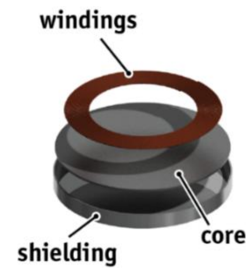


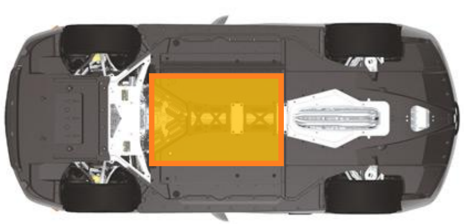
B. Whitaker et al. (APEI), «High-Density, High-Efficiency, Isolated On-Board Vehicle Battery Charger Utilizing SiC Devices,” *IEEE Trans. Power Electron.*, vol. 29, no. 5, 2014.

■ **High Power Density (kW/dm², kW/kg)**
- High Ratio of Coil Diameter / Air Gap
- Heavy Shielding & Core Materials

■ **Low Magnetic Stray Field $B_s < B_{lim}$**
- Limited by Standards (e.g. ICNIRP)
- Eddy Current Loss in Surrounding Metals

■ **High Magnetic Coupling**
- Physical Efficiency Limit def. by k
- Sensitivity to Coil Misalignment





Lexus, www.lexus.com, 2014

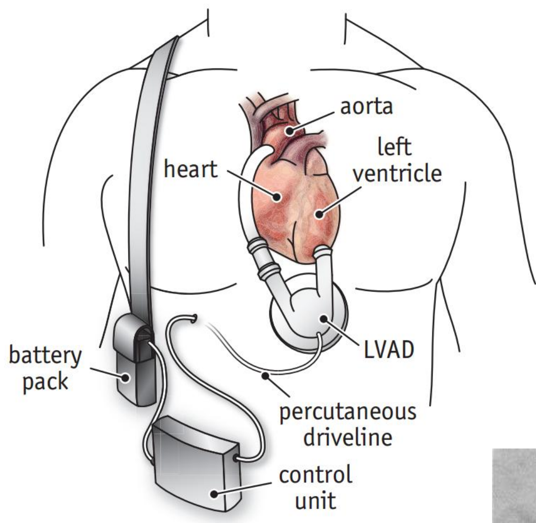
► IPT for EV: Selected Demonstration/Research Activities

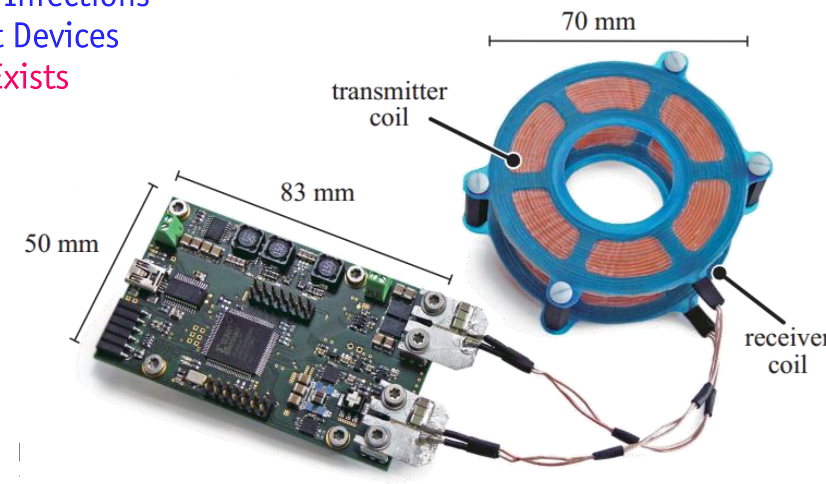
► Historic Background: Medical Applications

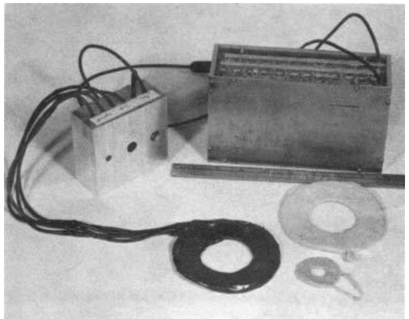
O. Knecht, R. Bosshard, and J. W. Kolar, "Optimization of Transcutaneous Energy Transfer Coils for High Power Medical Applications," in *Proc. Workshop on Control and Modeling for Power Electron. (COMPEL)*, **2014**.

■ Electro-Mechanical Heart Assist Devices

- Percutaneous Driveline Major Cause of Lethal Infections
- Transcutaneous Power Supply for Heart Assist Devices
- No Reliable and Medically Certified Solution Exists







J. C. Schuder, "Powering an artificial heart: birth of the inductively coupled-radio frequency system in **1960**," Artificial Organs, vol. 26, no. 11, pp. 909–915, 2002.

Fundamentals:

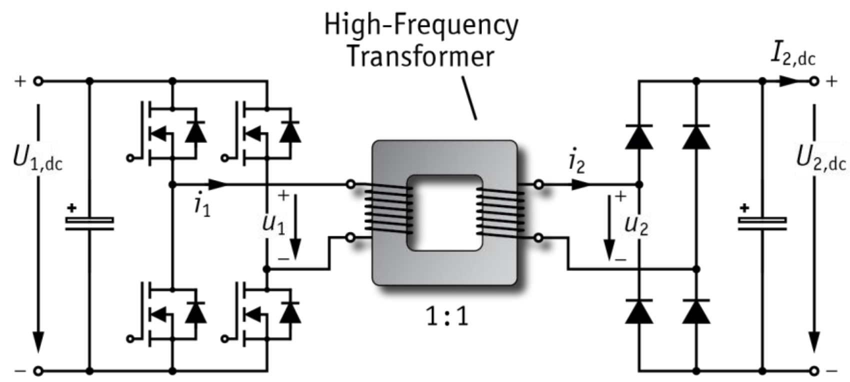
Isolated DC/DC → IPT

Series Resonant Topologies
Load Matching

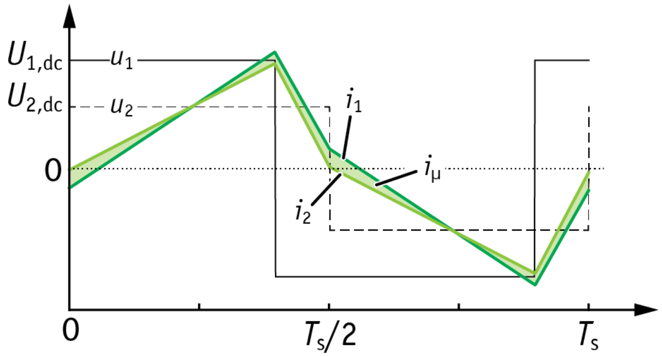
▶ Isolated DC/DC-Converter for Conductive EV Charging

- **Soft-Switching DC/DC-Converter without Output Inductor**
  - Galvanic Isolation
  - Minimum Number of Components
  - Clamped Voltage across Rectifier

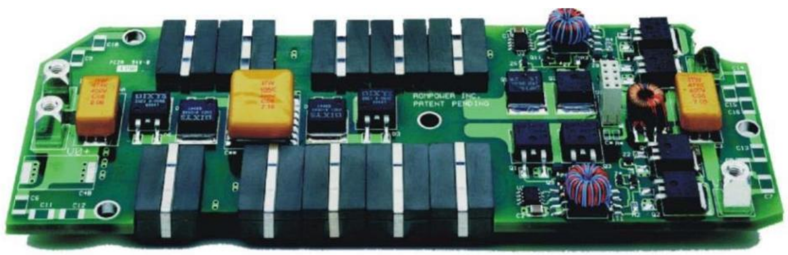
- **Constant Switching Frequency of Full-Bridge Inverter on Primary**
  - di/dt given by Voltage Levels & Transformer Stray & Magn. Induct.



▲ **Isolated DC/DC Converter Topology with MF Transformer**



▲ **Schematic Converter Waveforms (i_1-i_2 not to Scale)**

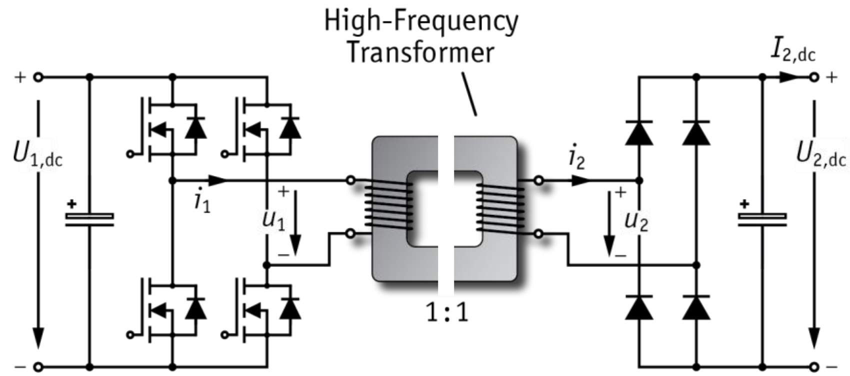


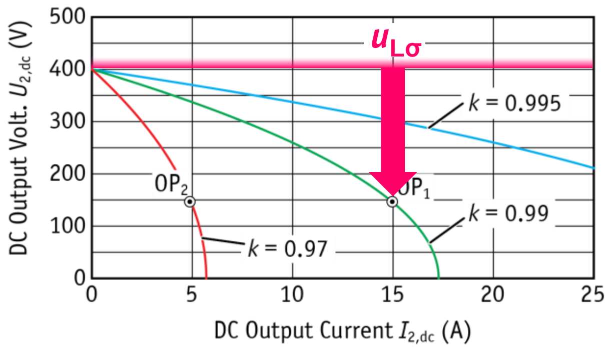
I. D. Jitaru, «A 3 kW Soft-Switching DC-DC Converter," *Proc. IEEE APEC*, pp. 86-92, 2000.

▲ **Realization Example (1 kW Module, Rompower)**

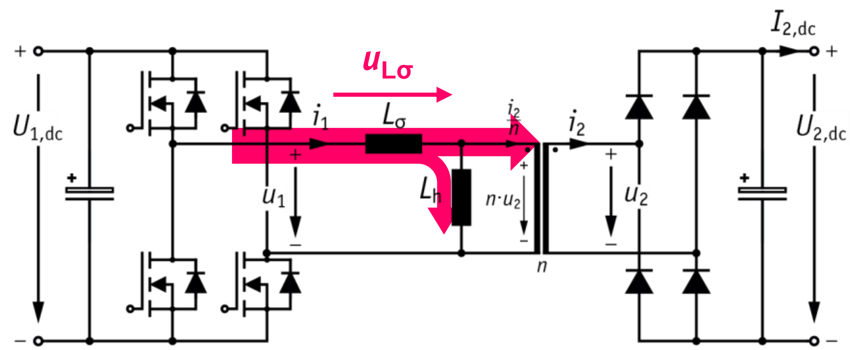
► Transition to IPT System

- **Airgap in the Magnetic Path**
  - Reduced Primary & Secondary Induct.
  - Higher Magnetizing Current
  - Reduced Magnetic Coupling k
  - Load Dependency of Output Voltage due to Non-Dissipative Inner Resist.





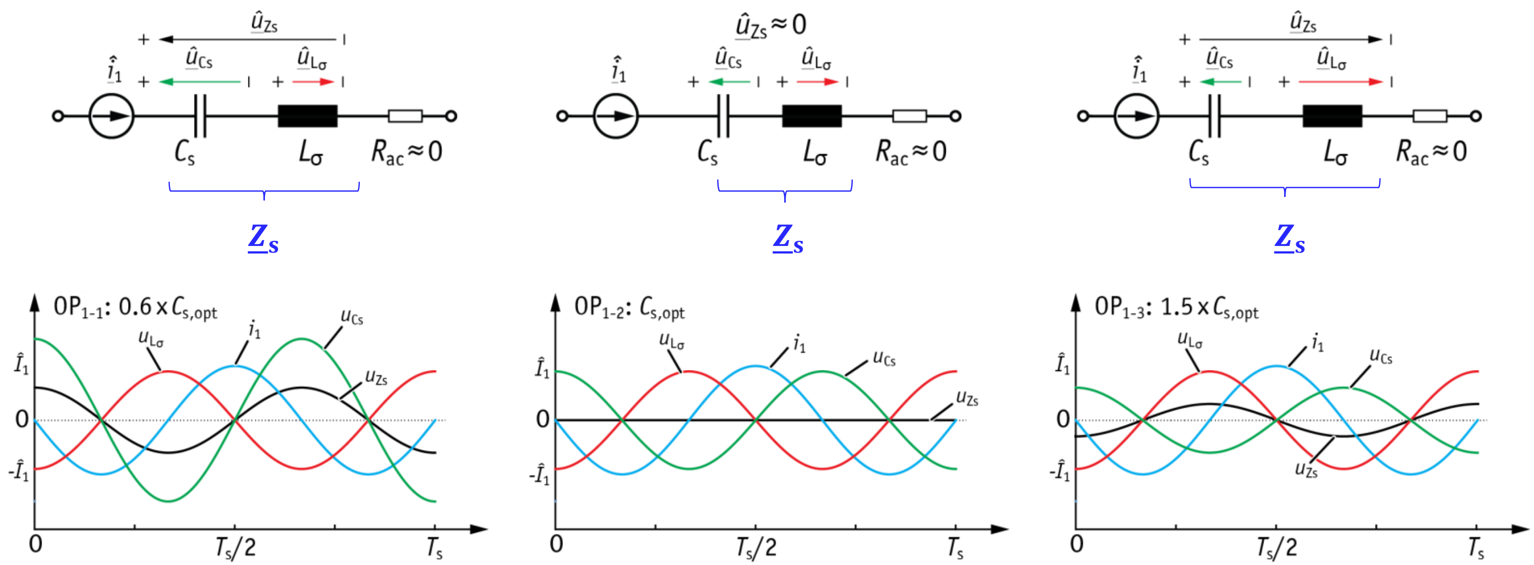
▲ **Converter Output Characteristics**

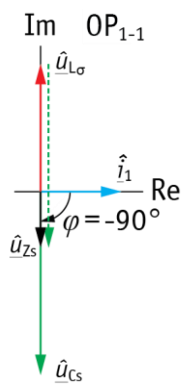


▲ **Effects of an Air Gap in the Transformer**

$$L_\sigma = (1 - k^2)L_1, L_h = k^2 L_1, n = k\sqrt{L_1/L_2}$$

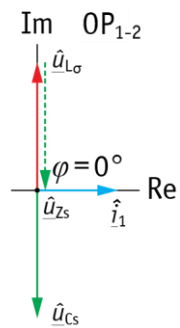
▶ Resonant Compensation of Stray Inductance (1)





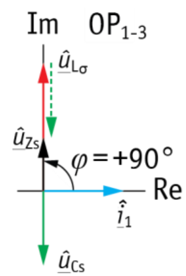
$C_s < C_{s,opt}$

$\underline{Z}_s$: Cap. $\Big|_{\omega = \omega_s}$



$C_s = C_{s,opt}$

$\underline{Z}_s = 0 \Big|_{\omega = \omega_s}$



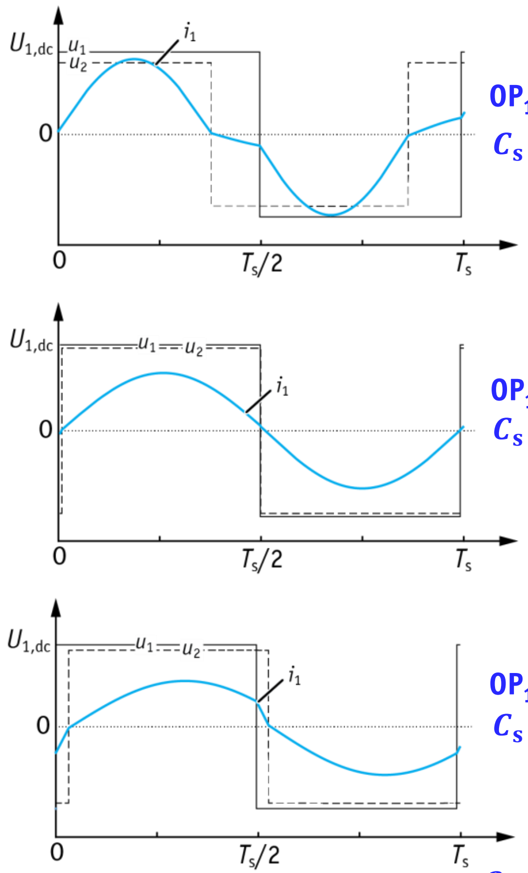
$C_s > C_{s,opt}$

$\underline{Z}_s$: Ind. $\Big|_{\omega = \omega_s}$

$$\underline{Z}_s = \mathrm{j}\omega L_s + \frac{1}{\mathrm{j}\omega C_s} + \underbrace{R_{ac}}_{\approx 0} = \mathrm{j}\left(\omega L_s - \frac{1}{\omega C_s}\right) \rightarrow \omega_s = \frac{1}{\sqrt{L_s C_s}}$$

▶ Resonant Compensation of Stray Inductance (2)

- **Insert Capacitor in Series to Transformer Stray Inductance L_σ**
- **Select Capacitance $C_{s,opt} = 1/(\omega_s^2 L_\sigma)$ to Match Resonance and Inverter Switching Frequency**

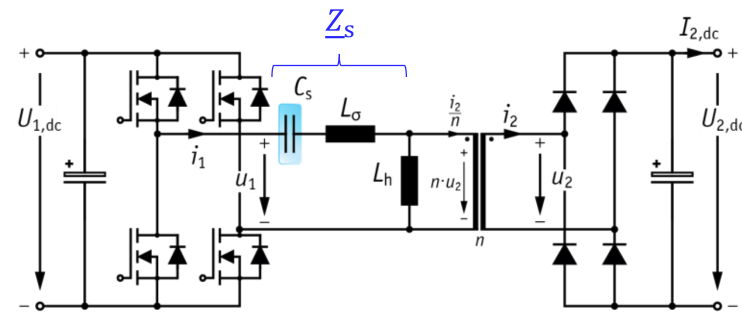


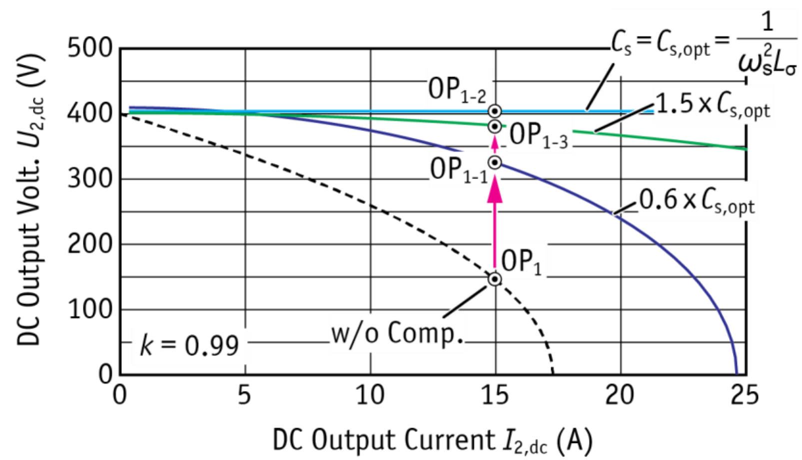
OP$_{1\text{-}1}$: $C_s < C_{s,opt}$

OP$_{1\text{-}2}$: $C_s = C_{s,opt}$

OP$_{1\text{-}3}$: $C_s > C_{s,opt}$

$\omega_s = \dfrac{2\pi}{T_s}$



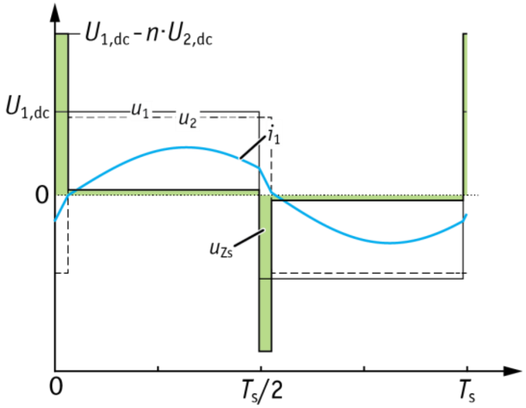


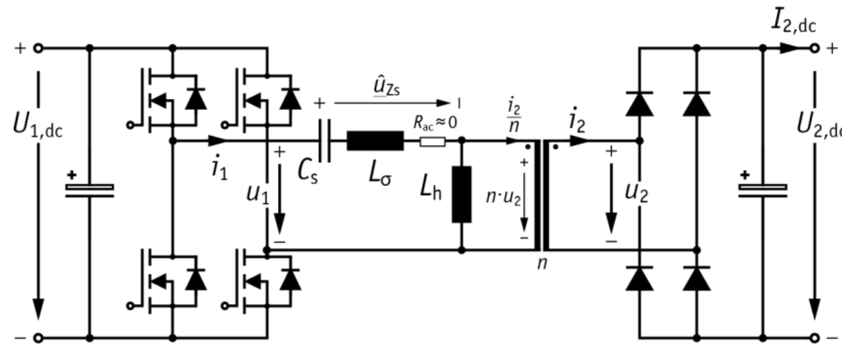
▲ **Converter Output Characteristics**

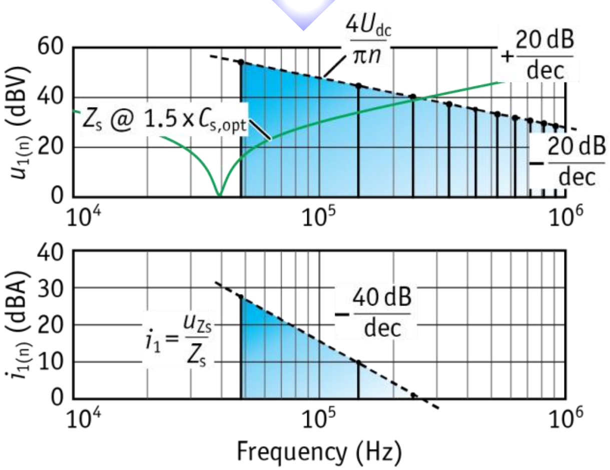
► Fundamental Frequency Approximation (1)

■ Nearly Sinusoidal Current Shape Despite Rectangular Voltage Waveforms

- Resonant Circuit Acts as Bandpass-Filter on Inverter Output Voltage Spectrum







■ Consider only Switching Frequency Components:

- Fundamentals of u_1, u_2, i_1, i_2
- Power Transfer Modeled with Good Accuracy as

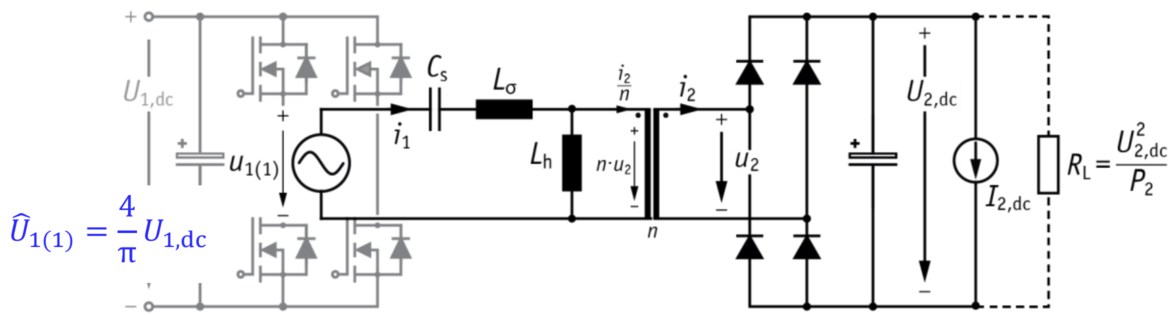
$$P=\sum_{n=1}^{\infty}U_{1(n)}I_{1(n)}\cos(\phi_n)$$
$$\approx U_{1(1)}I_{1(1)}\cos(\phi_1)$$

→ Fundamental Frequency Model!

R. Steigerwald, "A comparison of half-bridge resonant converter topologies," in IEEE Trans. Power Electron., vol. 3, no. 2, 1988.

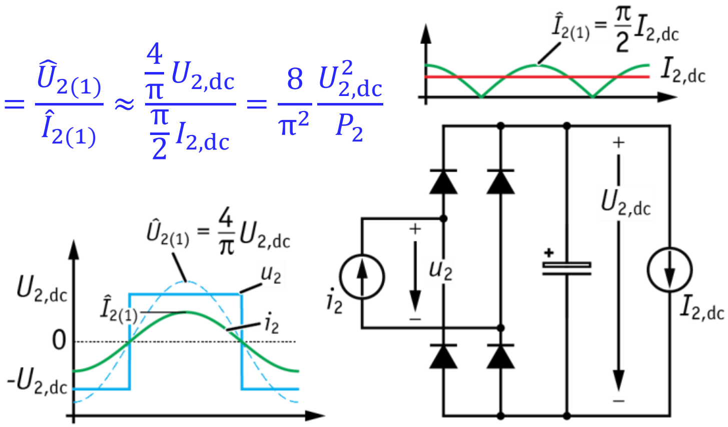
▶ Fundamental Frequency Approximation (2)

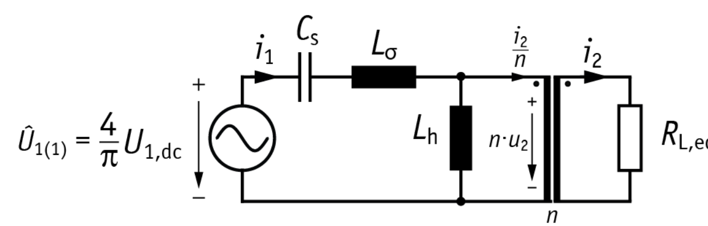
■ **Replace Rectifier and Load $I_{2,dc}$ by Power Equivalent Resistance $R_{L,eq}$**



■ **Fundamental Frequency Equivalent Circuit**

$$R_{L,eq} = \frac{\hat{U}_{2(1)}}{\hat{I}_{2(1)}} \approx \frac{\frac{4}{\pi} U_{2,dc}}{\frac{\pi}{2} I_{2,dc}} = \frac{8}{\pi^2} \frac{U_{2,dc}^2}{P_2}$$

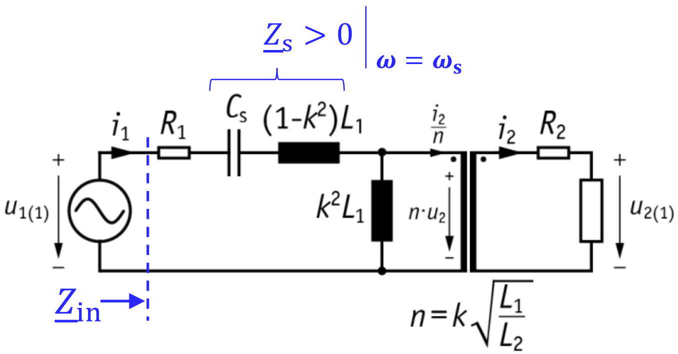


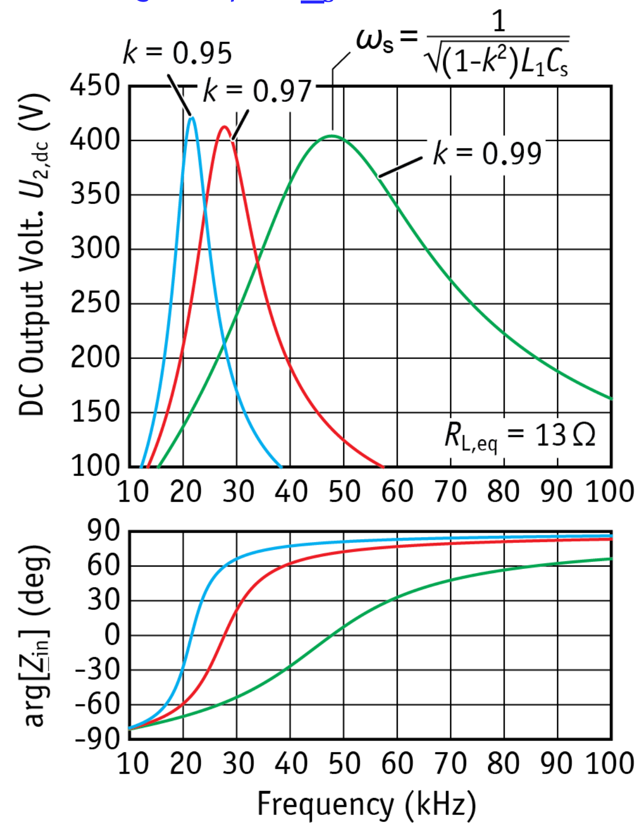


- Simplified Circuit Analysis & Approximate Power Loss Calculations

▶ Resonant Circuit Transfer Characteristics

- **Strong Coupling Dependency of Output Voltage due to Variation of Series Impedance**
  - Variation of Coupling k Changes L_σ which Leads to Series Voltage Drop on $\underline{Z}_s > 0$





▲ **Transfer Characteristics and Phase Angle of Input Impedance for Different Coupling**

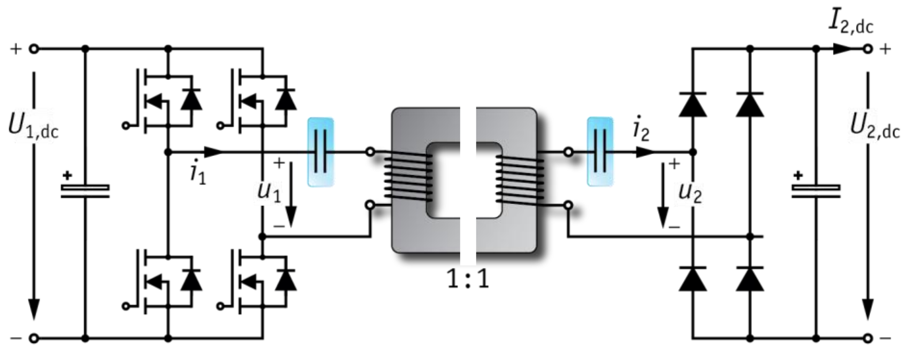
- **Large Variation of Resonant Frequency with Changing Magnetic Coupling**
  - Fixed Frequency Operation Not Possible

- **Not Practical if Coupling is Variable in the Target Application**

► Series-Series Compensated IPT System

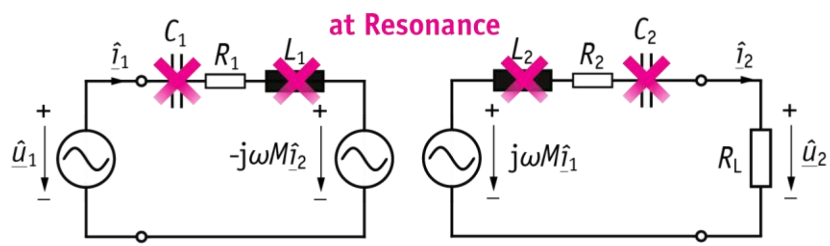
■ **Add Second Series Capacitor to Ensure Fixed Resonant Frequency ($\varphi_{\underline{Z}_{\text{in}}} = 0$) for any Value of the Magnetic Coupling k**

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}}$$

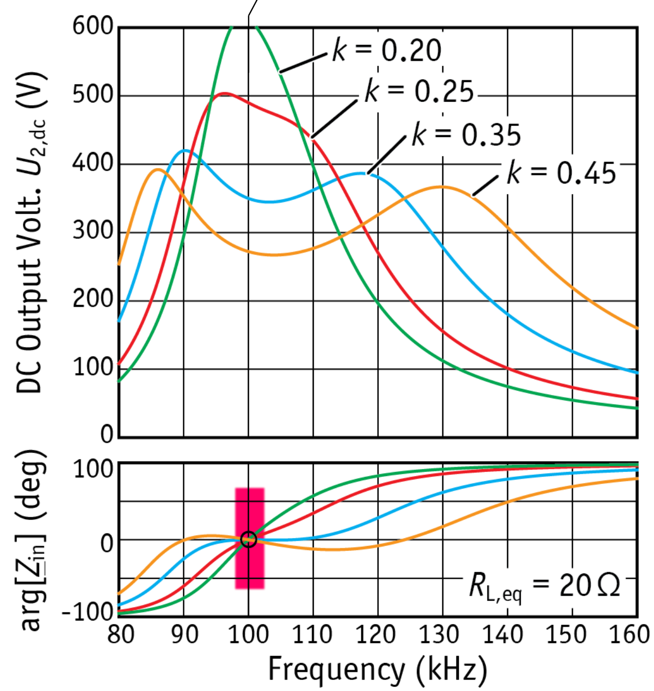


■ **Resulting Equivalent Circuit @ ω_0**

- Cancel Complete Self-Inductance



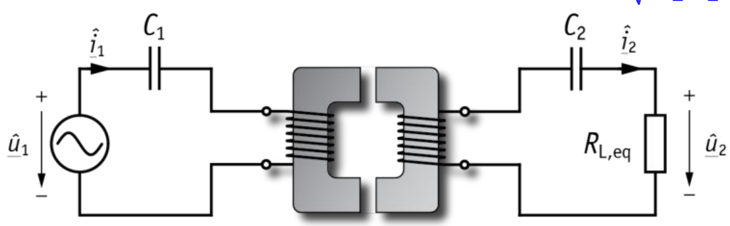
- Voltage Gain is Coupling & Load Dependent

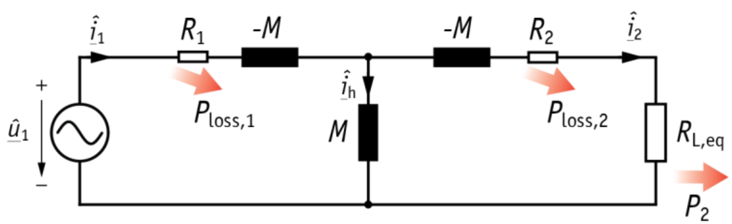


▲ **Transfer Characteristics and Phase Angle of Input Impedance for Different Coupling**

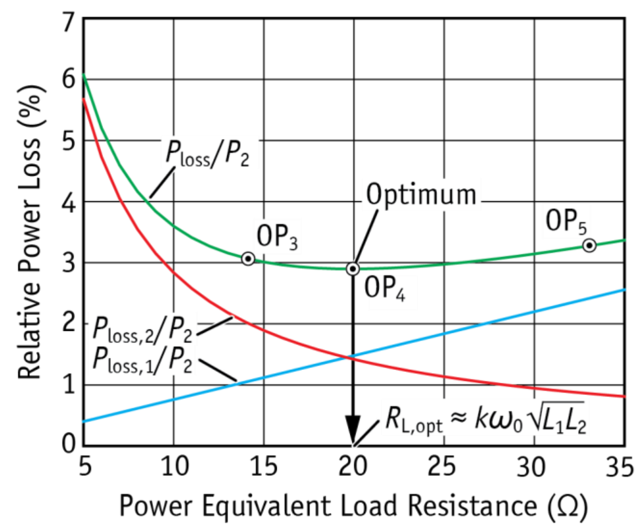
▶ Power Losses of the Series-Series Compensation

- **Operation at Resonant Frequency** $\omega_0 = \dfrac{1}{\sqrt{L_1 C_1}} = \dfrac{1}{\sqrt{L_2 C_2}}$





$$P_{loss,1} = \frac{1}{2}\left|\hat{\underline{i}}_1\right|^2 R_1 \quad P_{loss,2} = \frac{1}{2}\left|\hat{\underline{i}}_2\right|^2 R_2 \quad P_2 = \frac{1}{2}\left|\hat{\underline{i}}_2\right|^2 R_{L,eq}$$



- **Total Power Losses**
  - Core Loss Neglected

$$\underbrace{\frac{P_{loss}}{P_2}}_{\lambda} = \underbrace{\frac{P_{loss,1}}{P_2}}_{\lambda_1} + \underbrace{\frac{P_{loss,2}}{P_2}}_{\lambda_2}$$

- **Minimum Relative Losses**
  - Minimize Loss Factor λ

$$\frac{d}{dR_{L,eq}}\underbrace{\left(\frac{P_{loss}}{P_2}\right)}_{\lambda} = 0 \qquad \rightarrow R_{L,opt} = \sqrt{\omega_0^2 M^2 + \underbrace{R_{ac}^2}} \approx k\omega_0\sqrt{L_1 L_2}$$

$$R_1 \approx R_2 = R_{ac} \text{ @ } \omega_0$$

Design Condition for Maximum Efficiency!

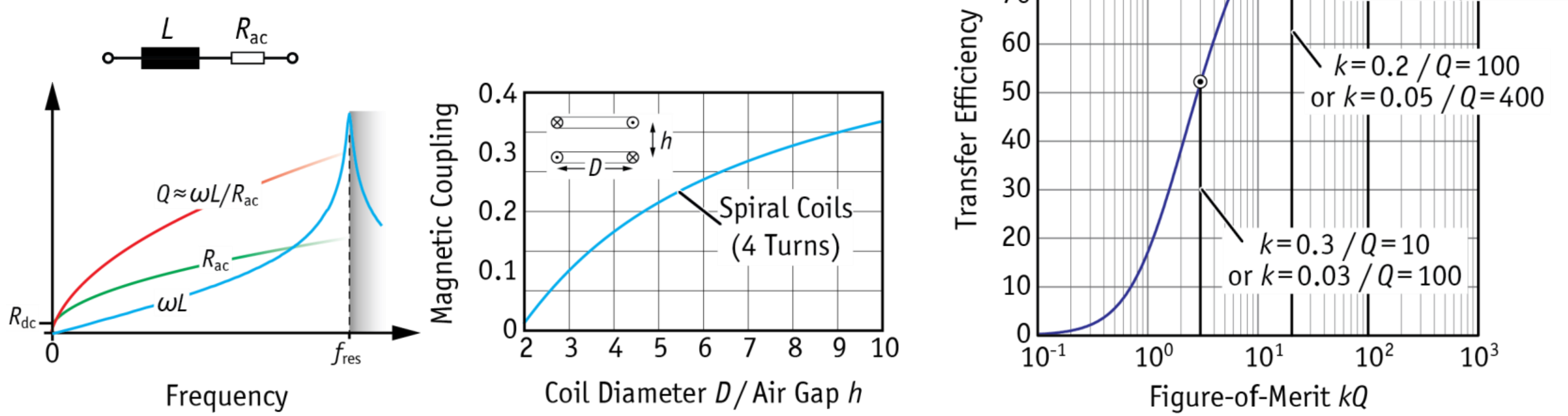
▶ Efficiency Limit of IPT Systems

K. van Schuylenbergh and R. Puers, Inductive Powering: Basic Theory and Application to Biomedical Systems, 1st ed., Springer-Verlag, 2009.

- **Condition for Minimum Total Coil Losses:** $R_{\mathrm{L,opt}} \approx k\omega_0\sqrt{L_1 L_2}$
- **Efficiency Limit of IPT Systems**

$$\eta_{\max} = \frac{k^2 Q_1 Q_2}{\left(1+\sqrt{1+k^2 Q_1 Q_2}\right)^2}$$

→ **Figure-of-Merit** $= k\sqrt{Q_1 Q_2} = kQ$



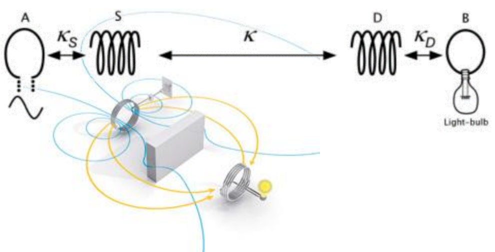
$k = L_h/\sqrt{L_1 L_2}$ .... Magnetic Coupling
$Q = \omega L/R_{\mathrm{ac}}$ .... Coil Quality Factor

▲ **Efficiency Limit of IPT Systems (Coil Losses Only, Core Neglected)**

► *FOM* = Quality Factor x Magnetic Coupling

■ **«Highly Resonant Wireless Power Transfer»**

- Operation of «High-Q Coils» at Self-Resonance
- Compensation of Low k with High Q:
  High Freedom-of-Position
- High Frequency Operation (kHz ... MHz)



WiTricity, www.witricity.com (13.11.2014).

■ **Intelligent Parking Assistants for EV**

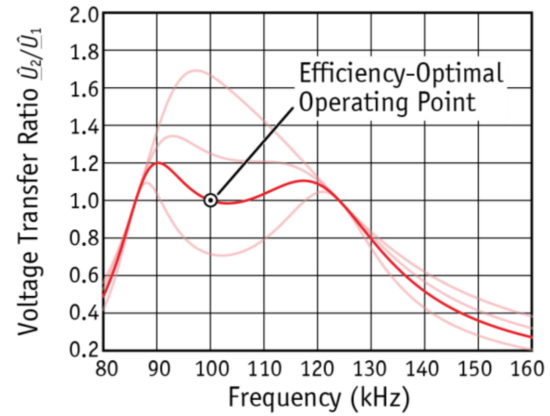
- Maximize k by Perfect Positioning
- Camera-Assisted Positioning Guide
- Achieve up to 5 cm Parking Accuracy

Toyota, www.toyota.com, (18.11.2014).

▶ Efficiency Optimal System Operation

■ Operation of Series-Series Compensated IPT System in Efficiency Optimum

- Given Resonant Circuit
- Given Operating Frequency
- Given Magnetic Coupling
- Given Mains & Battery DC-Voltages



P_2^* ... reference
ω_0 ... selected
U_{batt} ... given
k ... estimated

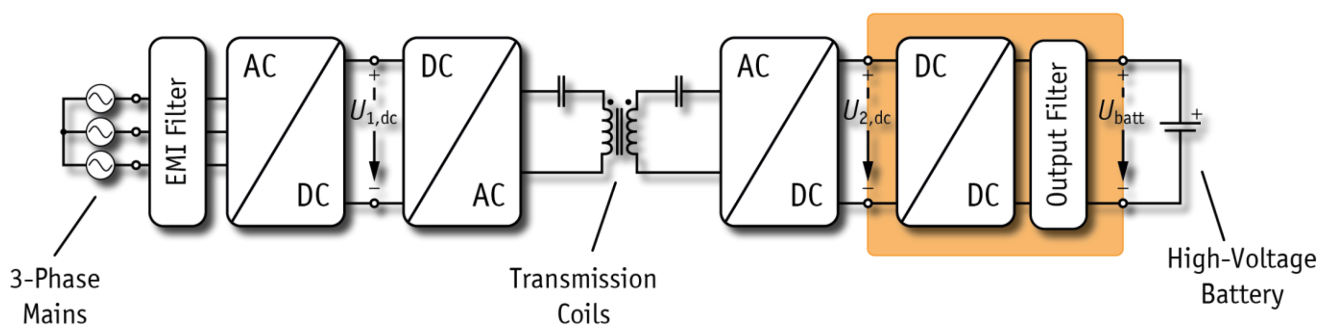
Controller Input Variables

→ $R_L^* \approx k\omega_0 L_2 = \frac{8}{\pi^2}\frac{U_{2,\mathrm{dc}}^2}{P_2^*}$

Maximum Efficiency Condition

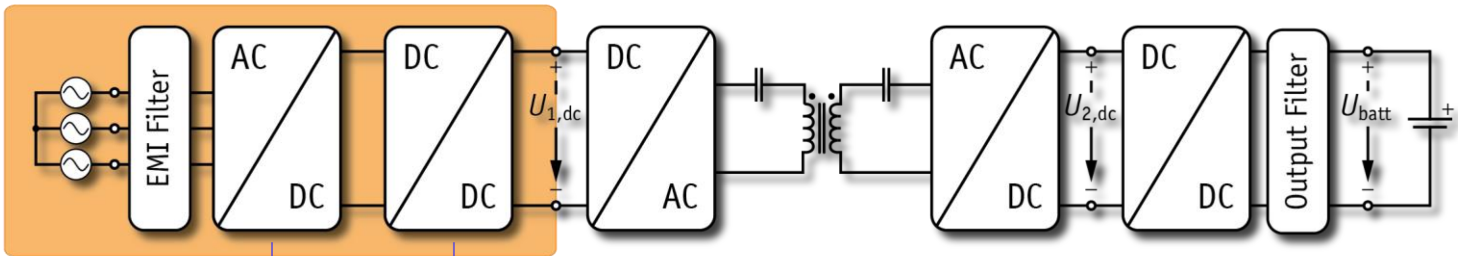
→ $U_{2,\mathrm{dc}}^* = \sqrt{\frac{\pi^2}{8} P_2^* k\omega_0 L_2}$

Controller Reference



▶ Transmitter Electronics

- **Receiver Voltage $U_{2,dc}$ used for Optimal Load Matching**
  → Power Regulation by Adjustment of $U_{1,dc}$ using Characteristic $P_2 = \frac{8}{\pi^2}\frac{U_{1,dc} \cdot U_{2,dc}}{\omega_0 k \sqrt{L_1 L_2}}$
- **Possible Option:** **Cascaded AC/DC, DC/DC Conversion**



- **Transmitter-Side DC/DC Converter**
  - No Isolation Needed
  - Identical to Receiver-Side?

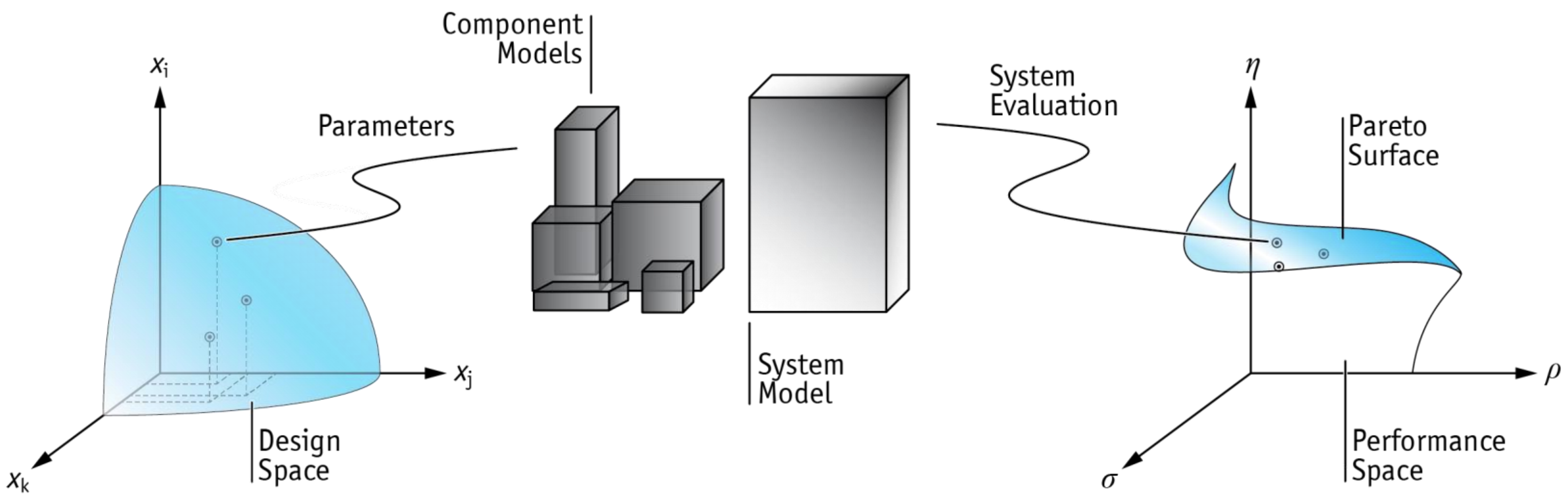
- **3-Phase Mains Interface (Boost-Type)**
  - Power Factor Correction of Phase Current
  - Standard Solutions Exist in Industry

Multi-Objective Optimization of High-Power IPT Systems

Requirements & Limits
Optimization Method
Trade-Off Analysis

► Multi-Objective Optimization

■ **Design of a 5 kW Prototype System with Maximum Possible Performance**
- Use Component Models to Analyze Mapping from Design Space into Performance Space



- Coil Dimensions
- Winding Scheme
- Number of Turns
- Litz Wire Design
- Core Design
- Core Material

- AC-Losses
- Magnetic Fields
- Capacitor Losses
- Converter Losses
- Component Cost
- Component Size

- Efficiency $\eta = P_{out}/P_{in}$ [%]
- Power Density $\rho = P_{out}/V_{tot}$ [kW/dm³]
- Stray Field $\beta = B_{max}/B_{norm}$ [%]
- Tolerance $\delta = \Delta x/D_{coil}$ [%]
- Specific Cost $\gamma = C_{tot}/P_{out}$ [$/kW]
- Material Effort $\sigma = \mathrm{kg}_{Cu/Fe}/P_{out}$ [kg/kW]

▶ Multi-Objective Optimization of 5 kW Prototype

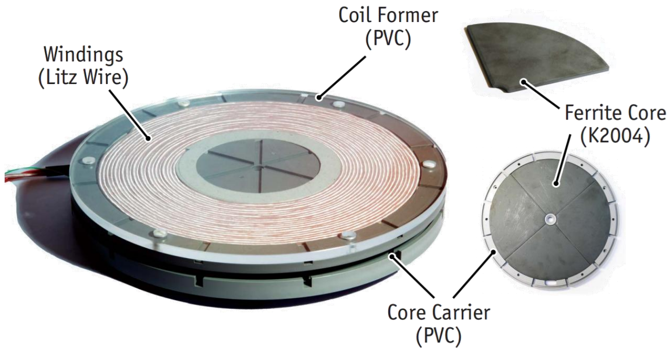
■ Design Process Taking All Performance Aspects into Account

■ System Specification

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

■ Constraints / Side Conditions

- Thermal Limitations [°C]
- Stray Field Limitations [μT]
- Max. Construction 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 $\beta = B_{max}/B_{norm}$ [%]

R. Bosshard, J. W. Kolar, J. Mühlethaler, I. Stevanovic, B. Wunsch, F. Canales, "Modeling and η-α-Pareto optimization of inductive power transfer coils for electric vehicles," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 3, no. 1., pp.50-64, March 2015.

► η-α-Pareto Optimization – Results (1)

■ **Evaluation of Design Options in an Iterative Procedure**
- Evaluation of FEM/Analytical Models for Power Losses, Thermal Constraints, Stray Fields, etc.
- Iterative Parameter / Grid Search for a Given Design Space

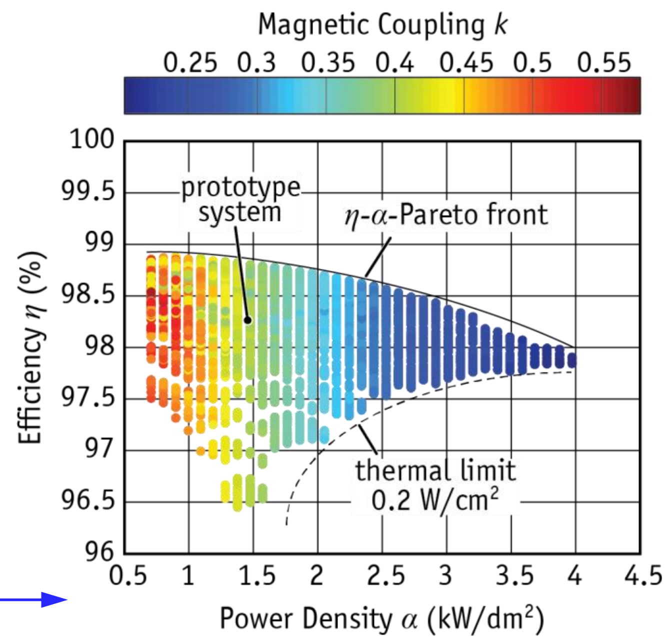
■ **Degrees-of-Freedom:**
- Coil Dimensions
- Litz Wire Dimensions
- Number of Turns
- Operating Frequency

Design Space

Component Models

System Model

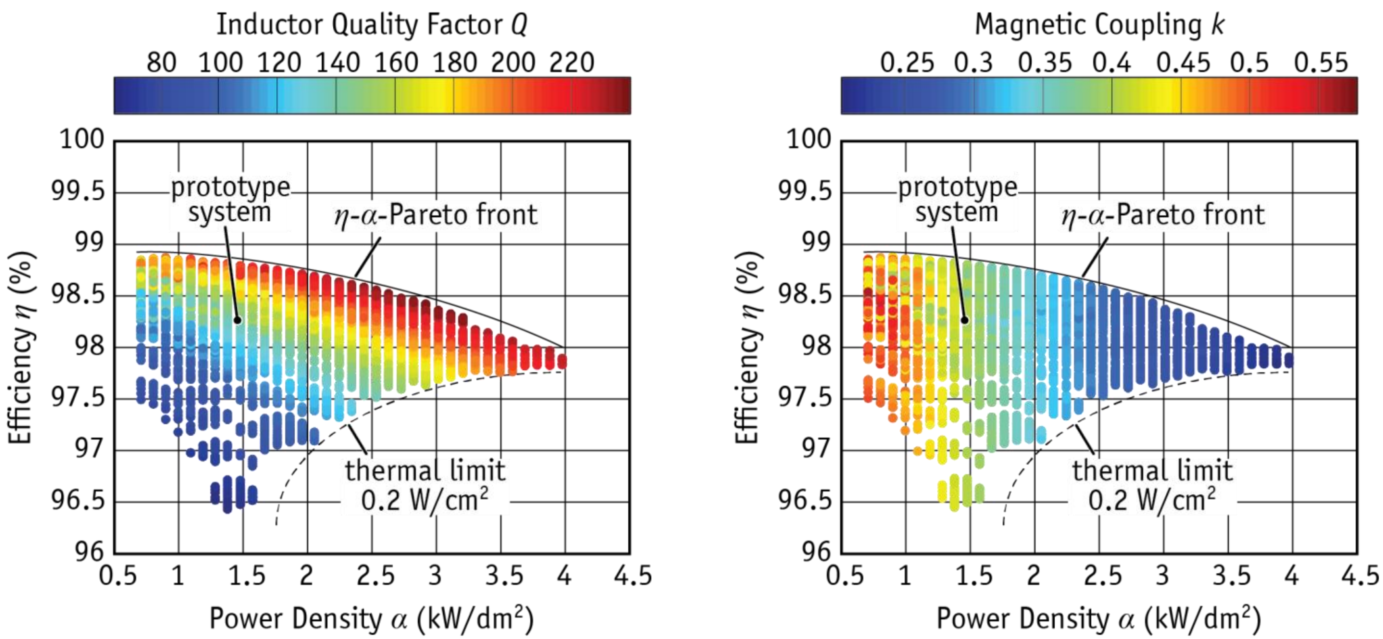
Performance



▲ **Efficiency vs. Power Density of >12k IPT Coils with 5 kW Output Power**

► η-α-Pareto Optimization – Results (2)

- **Analysis of Result Data to Understand Relevant Design Trade-Offs**
  - Confirm Predictions of Analytical Models and Estimations → *FOM = kQ*
  - Identify Key-Parameters that Impact System Performance → High Frequency

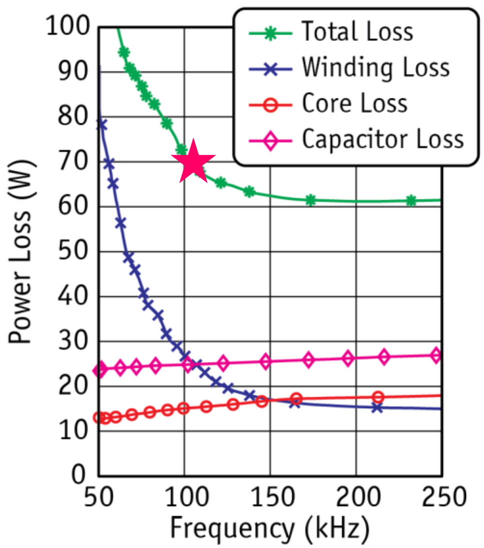


▲ **Trade-Off Analysis with Result Data: Effect of Quality Factor and Magnetic Coupling**

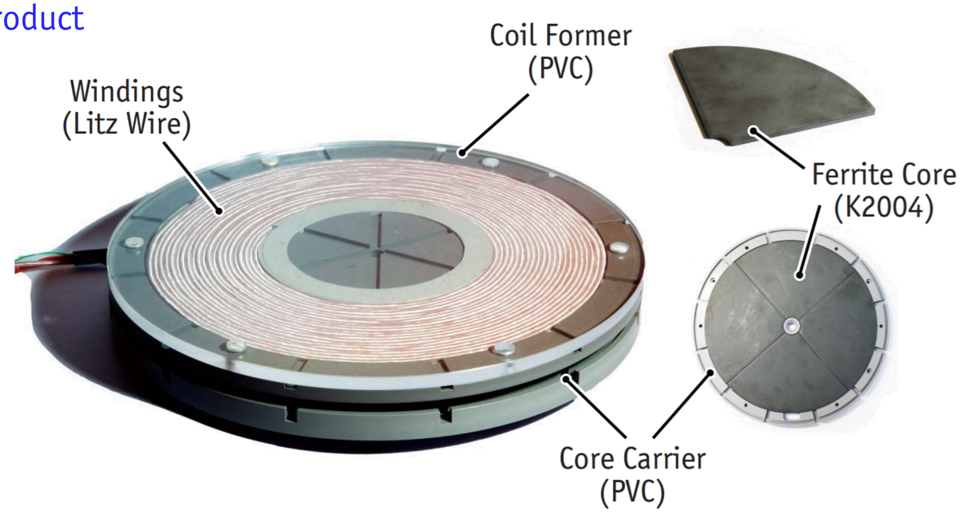
► Selected Design for 5 kW Prototype System

■ **Selection of Transmission Frequency**

- Significant Improvements up to 100 kHz
- Standard Power Electronics Design (5 kW)
- Litz Wire (630 x 71 μm) is Standard Product



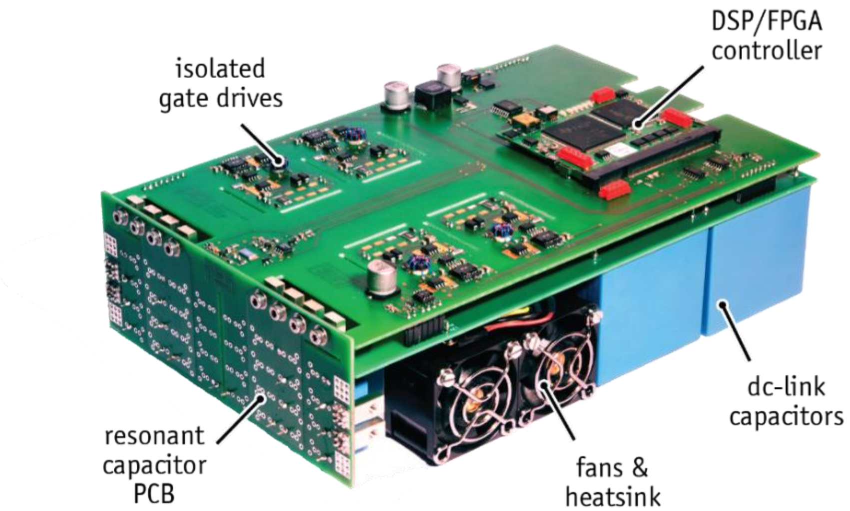
▲ **Power Loss Breakdown at 1.47 kW/dm²**
(Power Density of 5 kW Prototype)



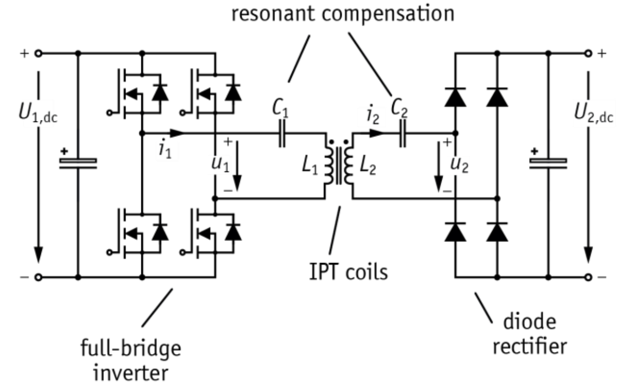
■ **5 kW Prototype IPT System**

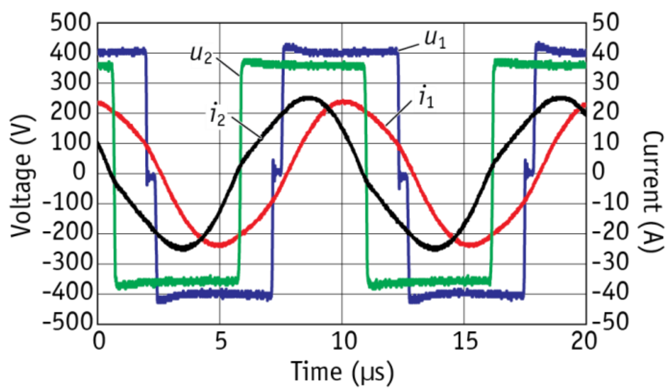
- **Coil Diameter** **210 mm**
- **Trans. Frequency** **100 kHz**
- **Trans. Efficiency** **98.25% @ 52 mm Air Gap**
- **Power Density** **1.47 kW/dm²**
- **Stray Field** **26.16 μT**

► Resonant Converter for 5 kW Testing



▲ 5 kW Prototype Power Converter





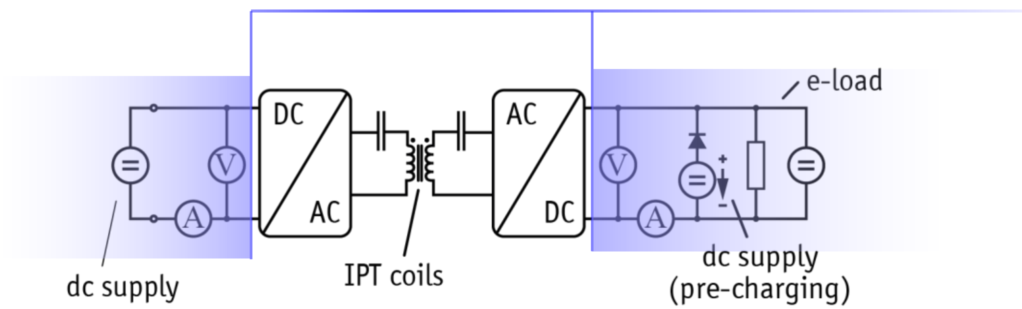
▲ Measured Waveforms at 5 kW / 400 V

- **Full-Bridge Test-Inverter 5 kW @ 400-800 V**
  - Cree 1.2 kV SiC MOSFETs (42 A, 100 kHz)
  - DSP/FPGA-based Control
  - Film Capacitors for DC-Link

► DC-to-DC Power Loss Measurement

■ Difficult to Measure V/I-Phase Shift at High Frequency (100 kHz)

- Indirect Measurement of DC Input and Output Power

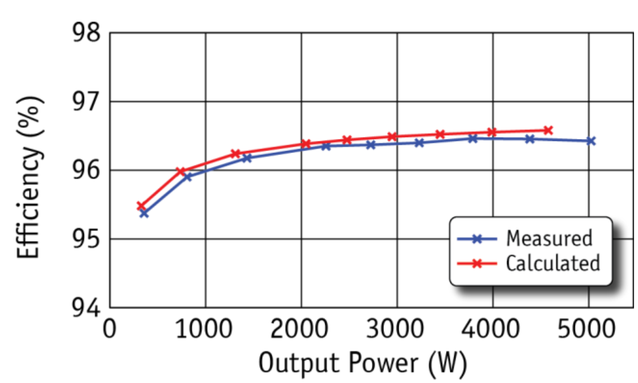


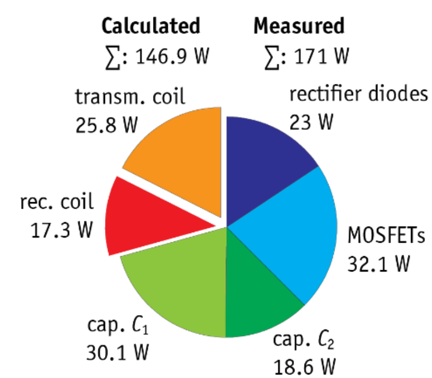
▲ Efficiency Measurement Setup

▲ Yokogawa WT3000

■ Efficiency Measurement

- Maximum Efficiency of 96.5%
- Higher than 96% down to 1 kW
- Flat Efficiency-Curve because of DC-Link Voltage Control





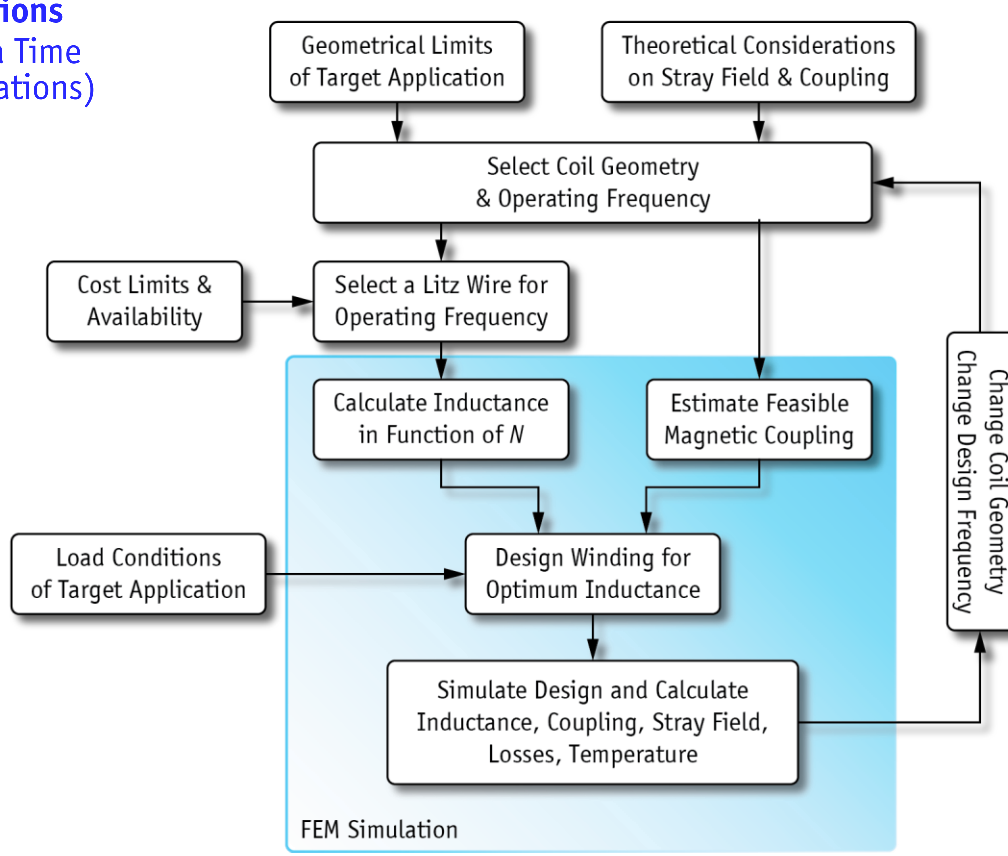
Design of a 50 kW Prototype System

▶ Iterative IPT Coil Optimization

- **Iterative Procedure with Reduced Number of Evaluated Design Configurations**
  - Change only one Parameter at a Time (Instead of all Possible Combinations)

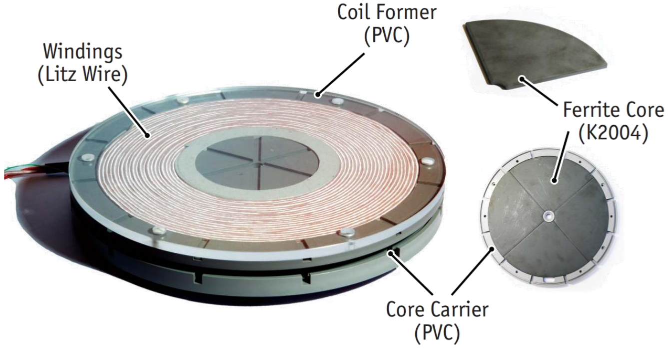
- **Exploit Condition for Pareto-Optimal Designs:**

$$\underbrace{R_{\mathrm{L}}^{*} = \frac{8}{\pi^2}\frac{U_{2,\mathrm{dc}}^2}{P_2} \approx k\omega_0 L_2}_{\text{Maximum Efficiency Condition}}$$



▶ Demonstrator Systems: 5 and 50 kW Output Power

■ **5 kW System for Model Development**
- Output Power 5 kW @ 400 V, 100 kHz
- Lab-Scale Coil and Converter Size (210 mm Diameter / 50 mm Air Gap)
- Basic Geometry for Simplified Modeling
- Verification of Calculation & Optimization



R. Bosshard, J. W. Kolar, J. Mühlethaler, I. Stevanovic, B. Wunsch, F. Canales, "Modeling and η-α-Pareto optimization of inductive power transfer coils for electric vehicles," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 3, no. 1., pp.50-64, March 2015.

■ **50 kW Prototype System for EV Specs**
- Output Power 50 kW @ 800 V, 85 kHz
- Optimized Geometry for EV Charging (450 x 750 x 60 mm, 25 kg)
- Experimental Verification

► Key Figures of Designed Transmission Systems

■ 5 kW Prototype System

- Output Power 5 kW @ 400 V, 100 kHz
- DC/DC-Efficiency 96.5% @ 52 mm (measured)
- Coil Dimensions 210 mm x 30 mm
- Weight Coil + Cap. 2.3 kg

- Spec. Weight 2.2 kW/kg
- Area-Rel. Power Dens. 1.47 kW/dm^2
- Power Density 4.8 kW/dm^3
- Spec. Copper Weight 43 g/kW
- Spec. Ferrite Weight 112 g/kW

■ 50 kW Prototype System

- Output Power 50 kW @ 800 V, 85 kHz
- DC/DC-Efficiency 96.5% (calculated)
- Coil Dimensions 41 x 76 x 6 cm
- Weight Coil + Cap. 24.6 kg

- Spec. Weight 2.0 kW/kg
- Area-Rel. Power Dens. 1.6 kW/dm^2
- Power Density 2.7 kW/dm^3
- Spec. Copper Weight 52 g/kW
- Spec. Ferrite Weight 160 g/kW
- Spec. SiC-Chip Area 9.4 mm^2/kW

Conclusions & Outlook

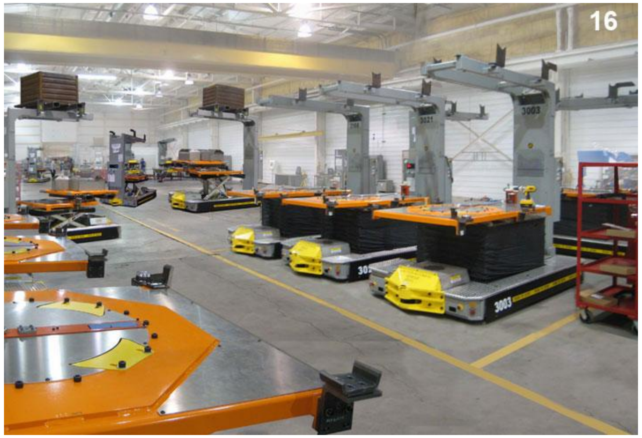
Advantageous Applications
Key Challenge

Inductive Power Transfer

Potential Application Areas

- **Industrial Environments with Power < 50 kW**
  - Conveyor Vehicles at Industrial Sites / Airports / Hospitals
  - Controlled Environment / Autonomous Vehicles
  - Reduced Battery Volume & Weight → Lower Cost

- **Power Supply with High Insulation**
  - Auxiliary Supply with High Insulation Strength,
    e.g. for Gate Drives, Modular Multi-Level, …



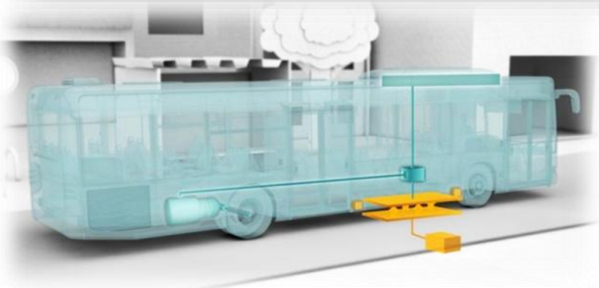
Inductive Power Transfer for

Stationary EV Charging

- **Domestic EV Charging form Household Supply**
  - Lower Power Level Simplifies Design

- **Stationary EV Charging for Public Transportation**
  - Simplified Quick-Charging at Bus Stops
  - Reduced Battery Volume/Weight/Cost
  - Reduced Number of Fleet Vehicles

→ **Reduced Operating Costs!**

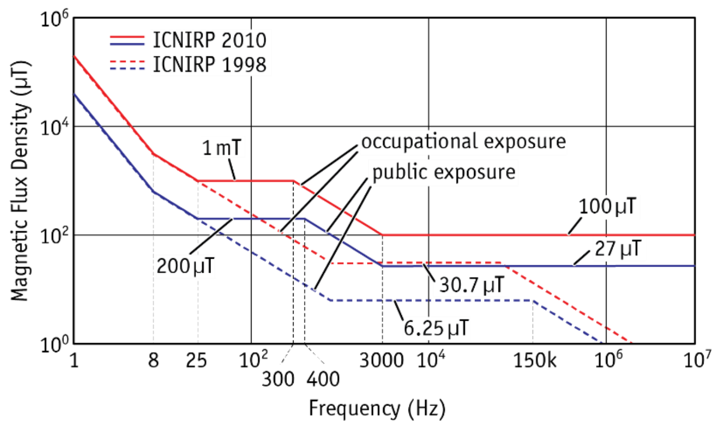


Evatran PLUGLESS, http://pluglesspower.com (6.11.2014).
Bombardier PRIMOVE, http://primove.bombardier.com.

Inductive Power Transfer

Key Challenge

- **Compliance with Field-Exposure Standards at High Power Levels**
  - High Frequency for High Power Transfer → Where is the Limit?
  - Include Modifications on Vehicle Chassis?
  - Positioning of the Coil: On the Floor / the Roof?

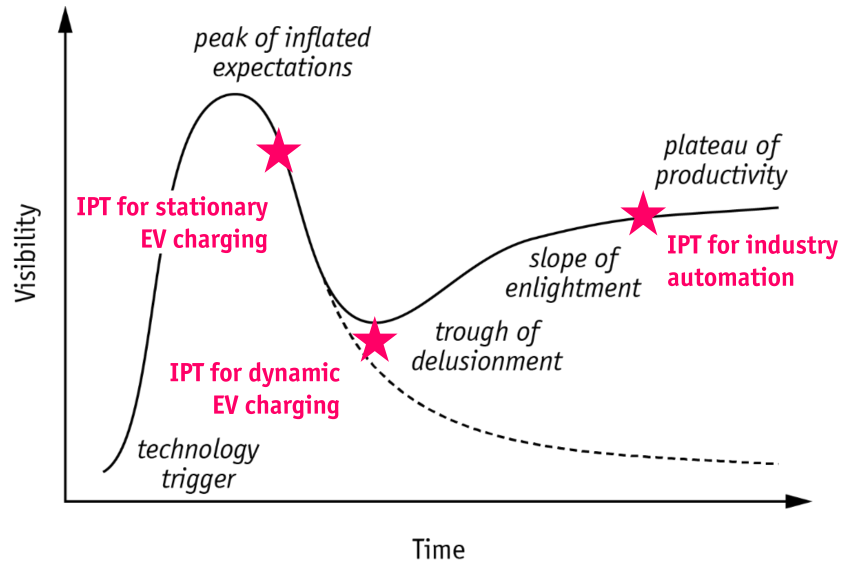


▲ **Field Values are Limiting Factor at High Power**

▲ **Include Chassis Modifications in Design & Re-Consider Coil Positioning**

Inductive Power Transfer

Applications ... the Hype Cycle



Thank You!

Questions?