ETH zürich

IECON´ 16

Inductive EV Battery Charging Systems

Requirements, Basics, Limitations, Future Research

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Outline

Acknowledgement

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Introduction

E-Mobility
Motivation for Wireless Charging
Requirements

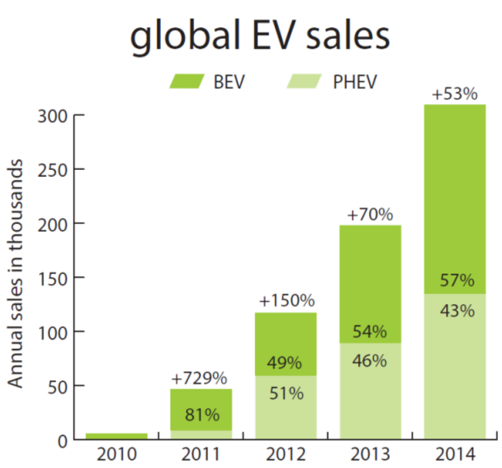
▶ Global Trend Towards E-Mobility

■ **Key Advantages of Electric Vehicles**

- Smaller CO_2-Footprint
- Lower Total Cost of Ownership

■ **Key Aspects for Future Development**

- Emission Limits, "Clean Cities" Projects etc.
- Battery Energy / Power Density & Cost
- Charging Technology & Infrastructure ←



Source: www.networkworld.com

▶ Global Trend Towards E-Mobility

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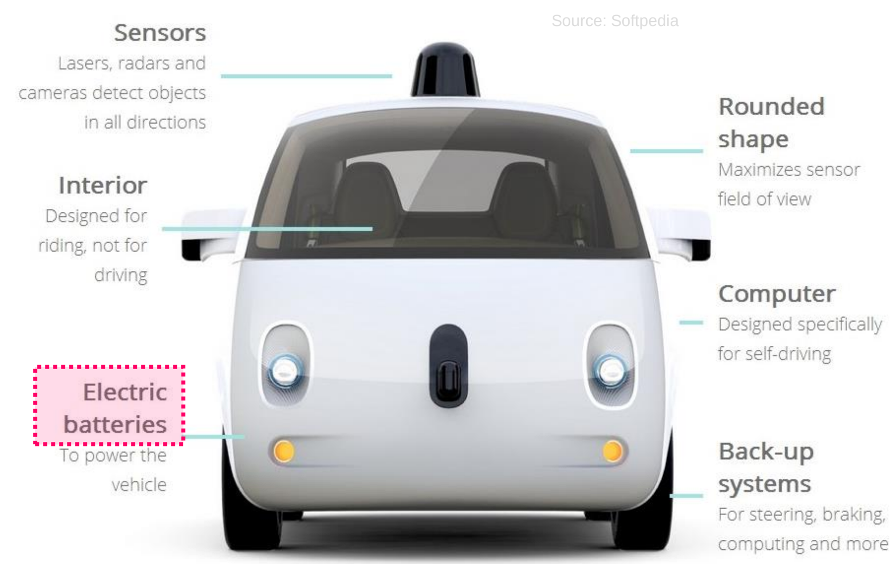
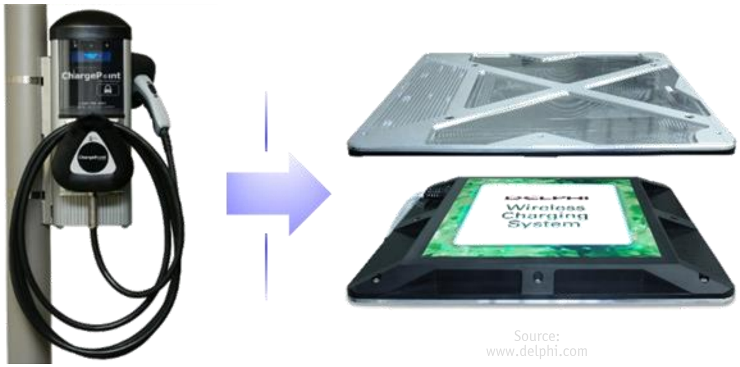
Google
Self-Driving Car Project

←



■ **Self-Driving will be *THE* Main Feature of Future Cars → Requires Compatible Refueling Concept (!)**

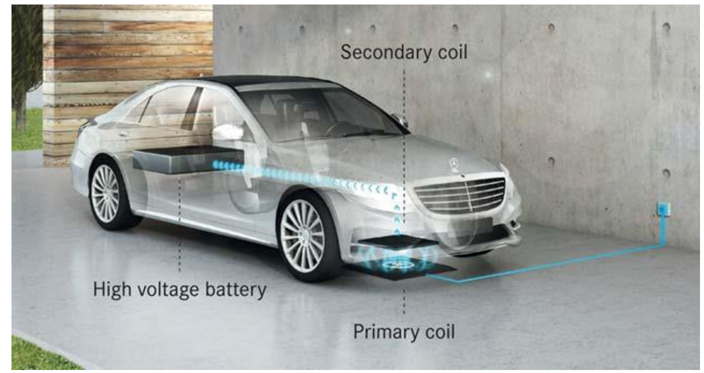
▶ Inductive EV Battery Charging – *Advantages*



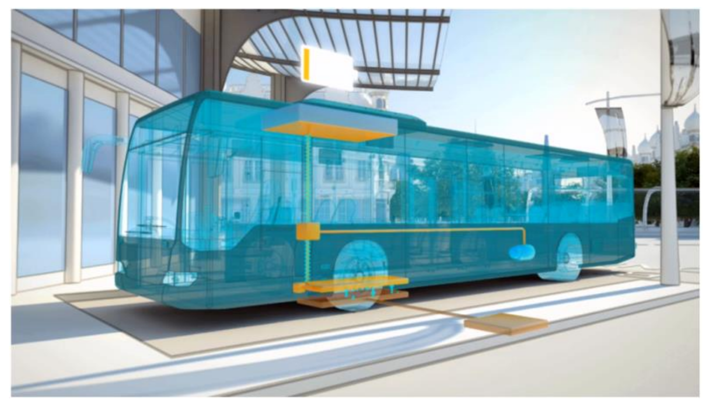
Source:
www.delphi.com

Source:
www.chargepoint.com

Source: www.daimler.com



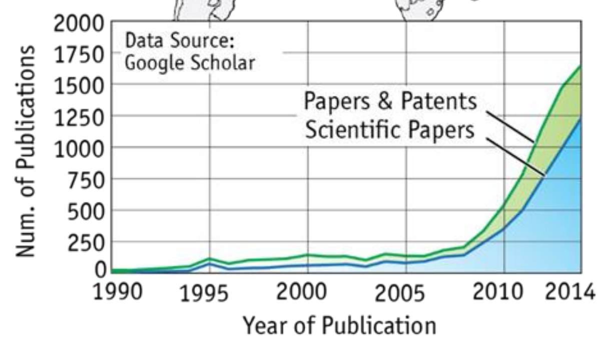
- **Higher Convenience & Usability**
  - No Plug Required
  - Charging @ Traffic Lights, Bus Stops
- **More Frequent Recharging**
  - Longer Battery Lifetime
  - Smaller Battery Volume & Weight
- **Reduced Fleet in Public Transportation**
  - Shorter Depot Recharging Time



Source: Bombardier

▶ Inductive EV Battery Charging – *Research/Demonstration*

- **High Interest in Industry & Academia**
  - Power Range: several kW ... 200kW
  - Private Cars & Public Transport



- **Only Consideration of Single Elements**
  - Coil Designs with High Magnetic Coupling
  - Resonant Compensation Techniques
  - Control for Low Positioning Sensitivity

- **Comprehensive Analysis Missing**
  - Multi-Objective Optimization
  - Comparative System Evaluation

Inductive EV Battery Charging – *Standards*

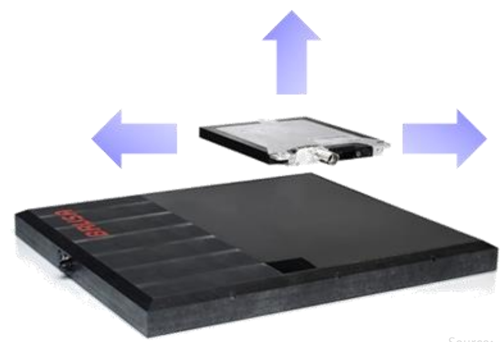
- **SAE J2954 Wireless Charging Standard (under Development, April 2015)**

Source: www.qualcommhalo.com

- Charging Levels: 3.7 kW (WPT1: Private Low Power)
  7.7 kW (WPT2: Private/Public Parking)
  22 kW (WPT3: Fast Charging)

Source: www.chargepoint.com

- Operating Frequency: 85 kHz
- Charging Efficiency: >90 % (Matched Coils)
  >85 % for Interoperable Systems
- Interoperability: Air Gap, Coil Dimensions
  xyz-Misalignment Tolerance
  Communication & Interfaces
- Safety Features: Foreign Object Detection
  Electromagnetic Stray Field
- Validation: Performance, Safety

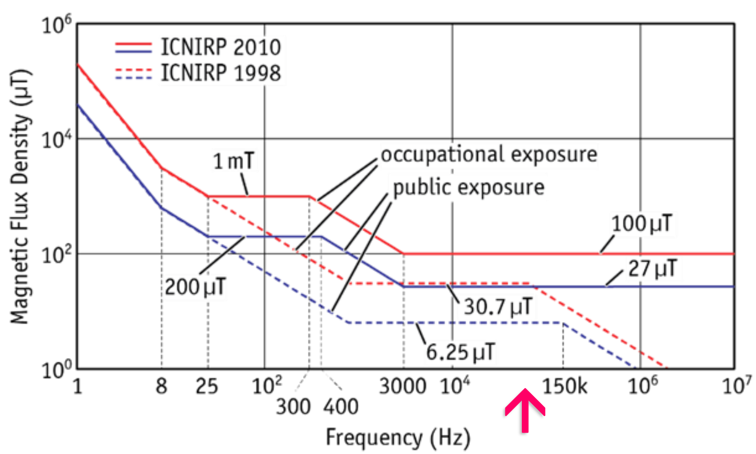


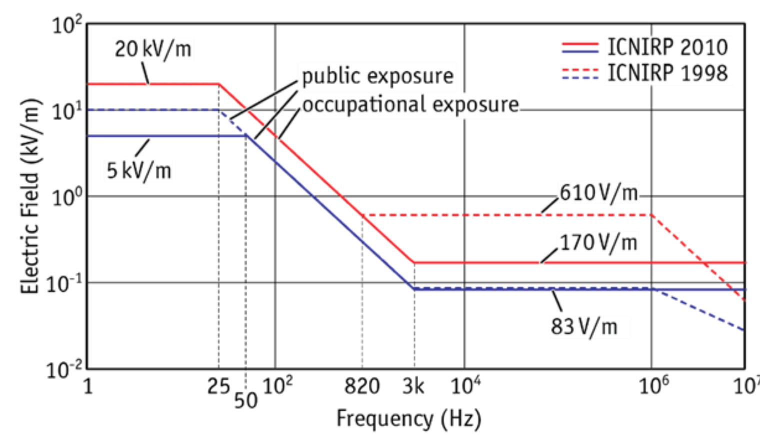
Source: www.brusa.com

▶ Inductive EV Battery Charging – *Regulations*

■ **ICNIRP 1998/2010: Guidelines for Limiting Exposure to Time-Varying EM Fields**

- Living Tissue is Affected by Power Dissipation Caused by EM Fields
- Limitation of Human Body SAR (=Specific Absorption Rate, [W/kg]) by *Limiting H- & E-Field*
- Poynting Vector $\underline{S} = \underline{E} \times \underline{H}$ shows that *H*- and *E*-Field are Required for Power Transfer





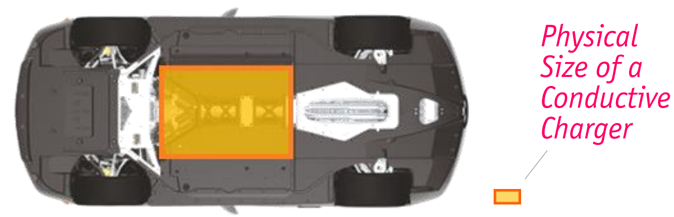
■ **Reference Values for Max. RMS *Magnetic* Flux Density *AND* *Electric* Field (!)**

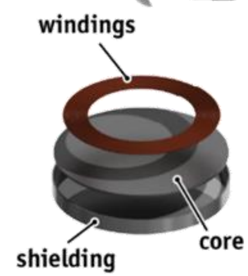
▶ Resulting Engineering Challenges

- **High Power Density (kW/dm², kW/kg)**
  - High Ratio of Coil Diameter / Air Gap Needed
  - Heavy Shielding & Core Materials Necessary
- **High Efficiency η**
  - Efficiency Limited by Magnetic Coupling
  - Sensitivity to Coil Misalignment
- **Low Magnetic Stray Field $B_s < B_{lim}$**
  - Limited by Standards (e.g. ICNIRP or Lower)
  - Eddy Currents in Surrounding Metal Parts
- **High Reliability of Components**
  - Potentially High Mech. Stress for Transmitter (1-10t)
  - Receiver fully Exposed to Environment
- **Low System & Installation Costs**
  - Material Effort for On-Board Components
  - Installation of Transmitter into Road Surface

→ ***Multi-Objective Design / Optimization Problem*** **!**

Source: www.lexus.com

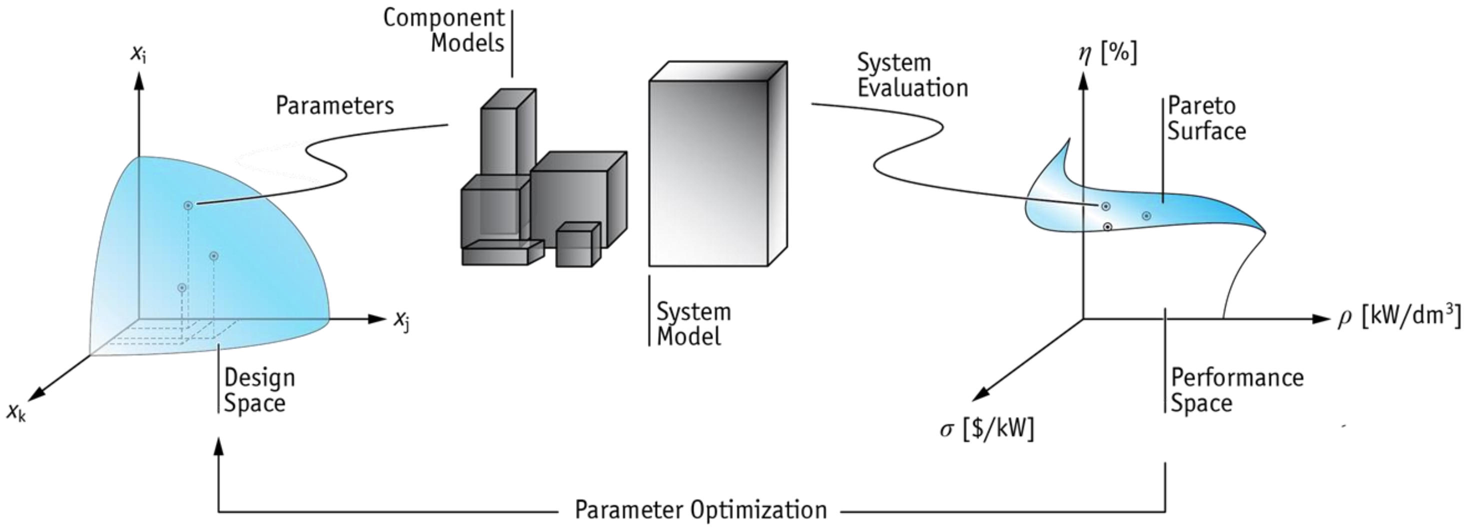




Source: www.tdk.com

▶ Multi-Objective System Optimization

■ **Mapping of "Design Space" into System "Performance Space"**
- Requires Accurate Models for the Main System Components
- Allows Sensitivity & Trade-Off Analysis



■ **Density Space**
- Coil Geometry & Dimensions
- Litz Wire Properties
- Core Material / Arrangement
- Power Electronics Topology
- Control & Modulation

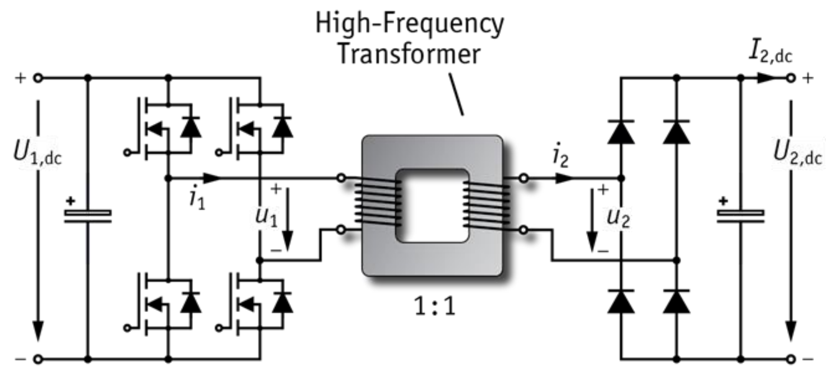
■ **Performance Space**
- Efficiency
- Power Density
- Material Effort / Costs
- Electromagnetic Stray Field
- Misalignment Tolerance

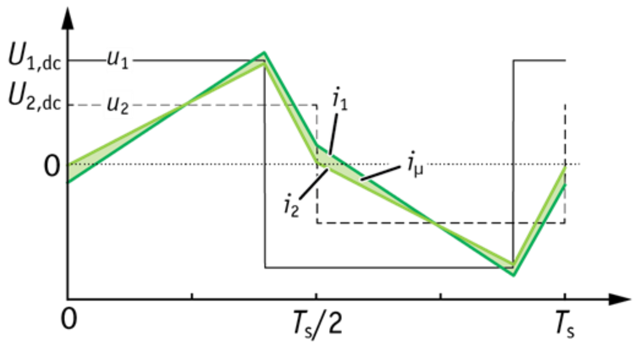
Inductive Power Transfer Fundamentals

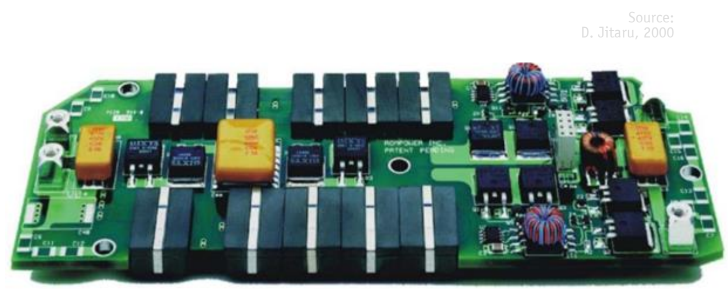
Resonant Compensation
Load Matching
Figure of Merit
Control

▶ 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 Primary-Side Full Bridge Converter**
  - di/dt defined by Voltage Levels & Transformer Stray & Magn. Ind.



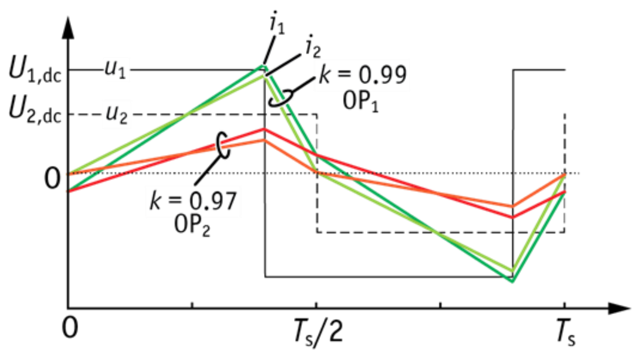


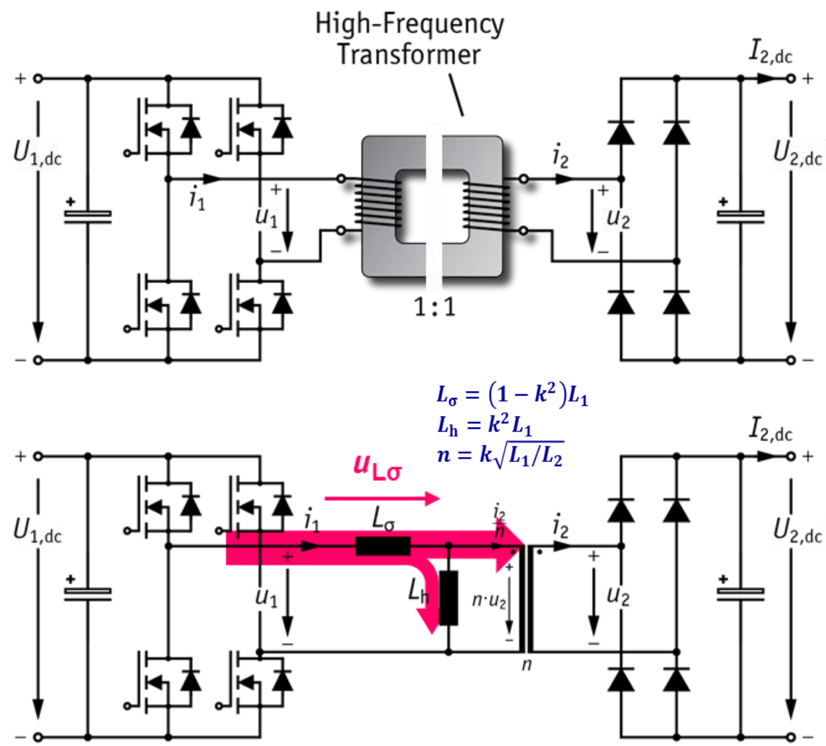


- **Schematic Converter Waveforms**
- **Realization Example**

▶ Transition to Inductive Power Transfer (IPT) System (1)

- **Air Gap in the Magnetic Path**
  - Reduced Primary & Secondary Ind.
  - Higher Magnetizing Current
  - Reduced Magnetic Coupling *k*
  - Load Dependence of Output Voltage

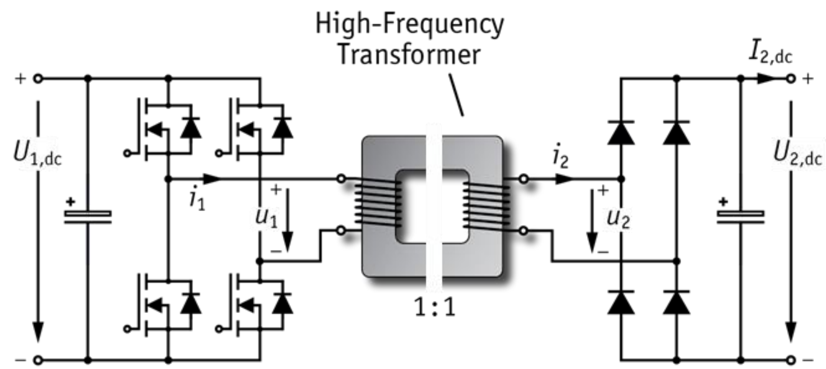


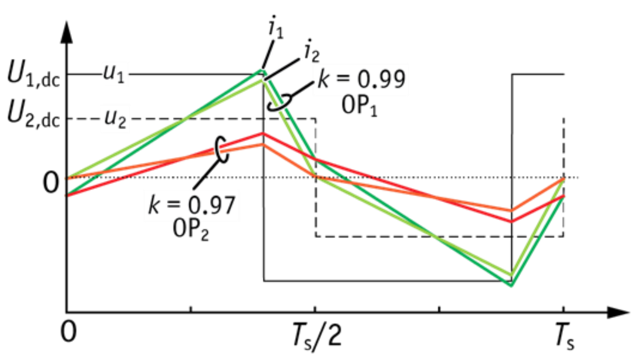


- **Schematic Converter Waveforms**
- **Effects of an Air Gap in the Transformer Core**

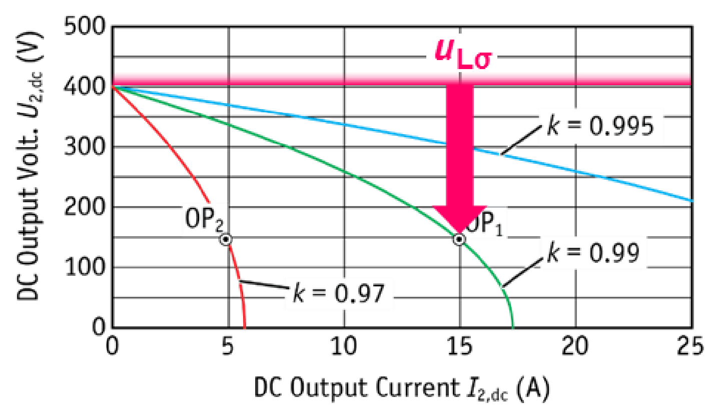
▶ Transition to IPT System (2)

■ **Air Gap in the Magnetic Path**
- Reduced Primary & Secondary Ind.
- Higher Magnetizing Current
- Reduced Magnetic Coupling k
- Load Dependence of Output Voltage





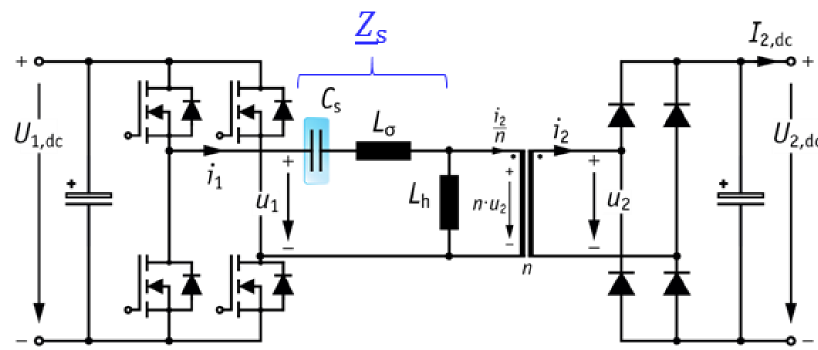
■ **Schematic Converter Waveforms**

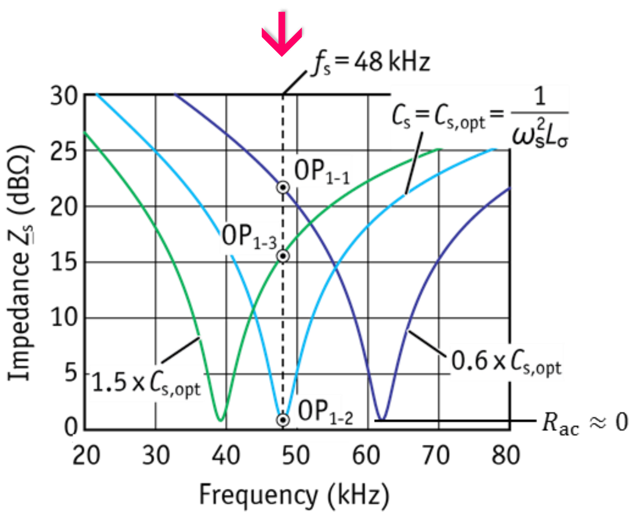


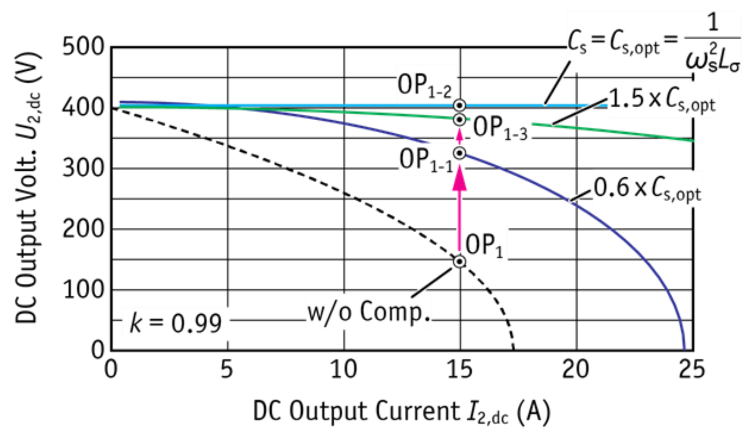
■ **Converter Output Characteristic**

▶ Resonant Compensation of Stray Inductance

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

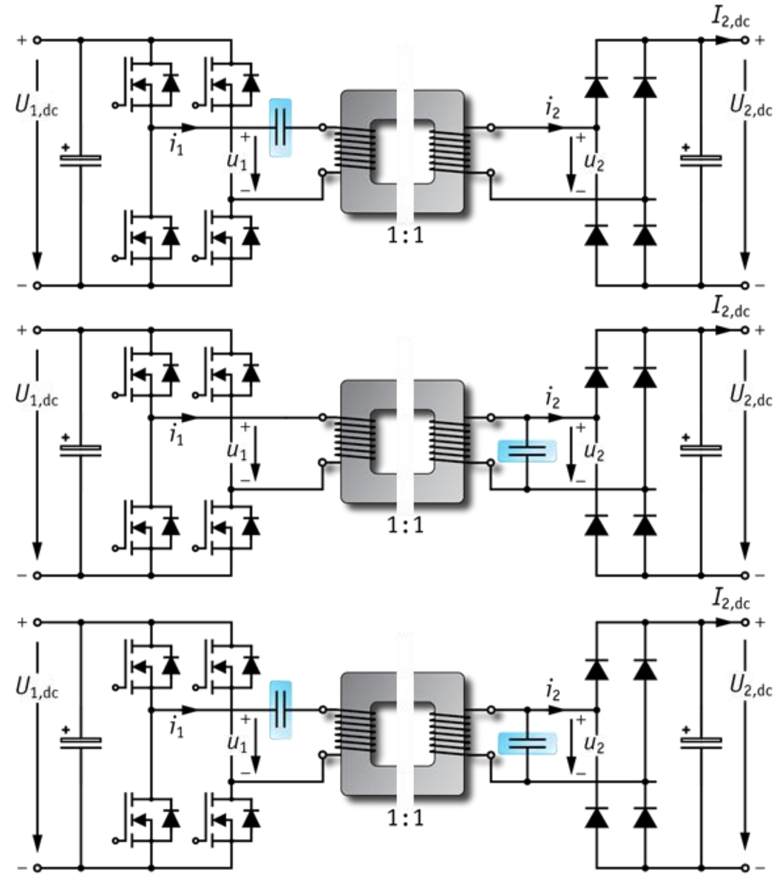






- **Bode Diagram of $\underline{Z}_S$ for Different Values C_s**
- **Converter Output Characteristics**

► Alternative Compensation Concepts



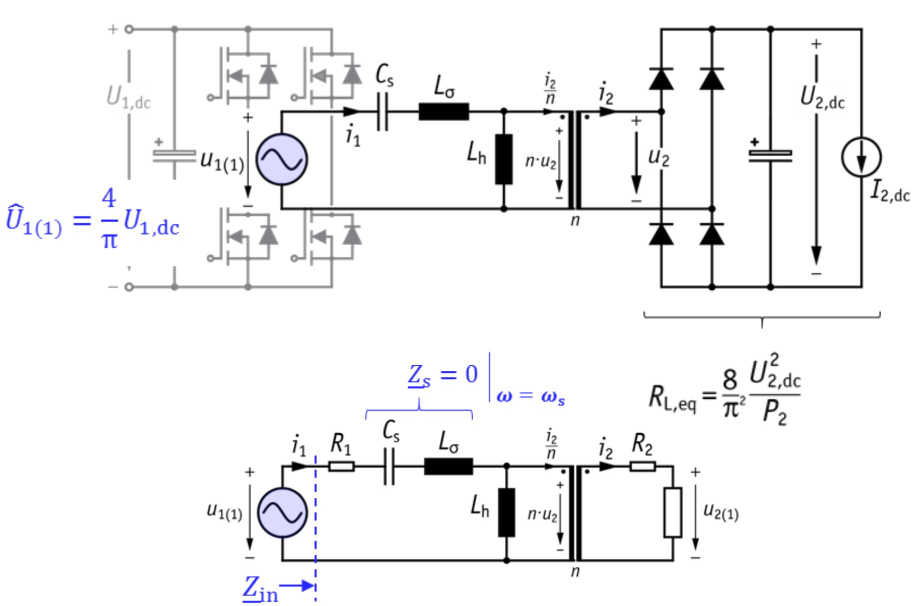
- **Limitations of Series-Compensation**
  - High Voltage across Resonant Elements
  - Limited to Step-Down Conversion
  - No-Load Control Problem (for Frequ. Control)

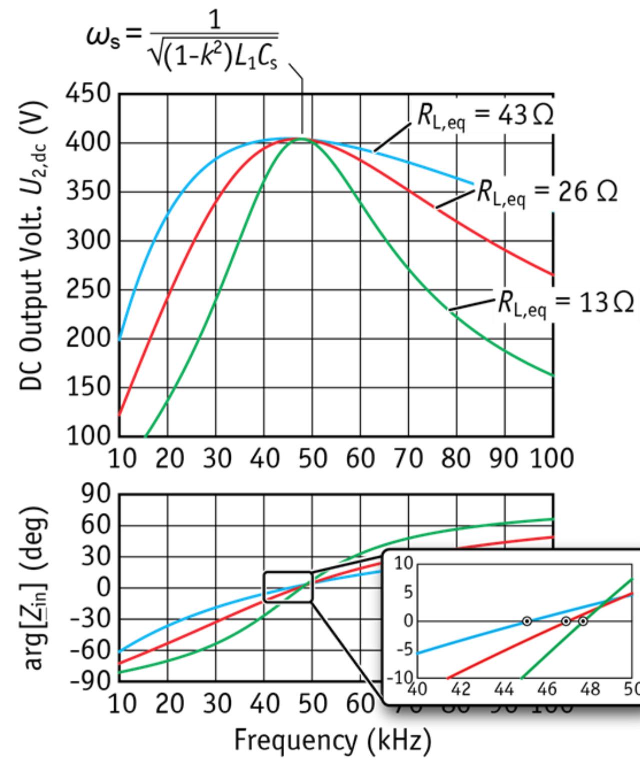
- **Parallel-Compensation (LLC)**
  - Circulation Reactive Current at Light Load
  - Potentially Series Inductor Required

- **Series/Parallel Res. Converter (LCC)**
- **General Matching Networks**
  - Complex Design Process (C_s, C_p)
  - Higher Realization Effort

Series-Resonant Compensated Converter Transfer Characteristic (1)

- **Load-Independent Output Voltage due to Cap. Compensation of Stray Ind. Voltage Drop**
- **Only Small Shift of Res. Frequency with Load at Constant Coupling *k***
  - Fixed Frequency Operation Possible

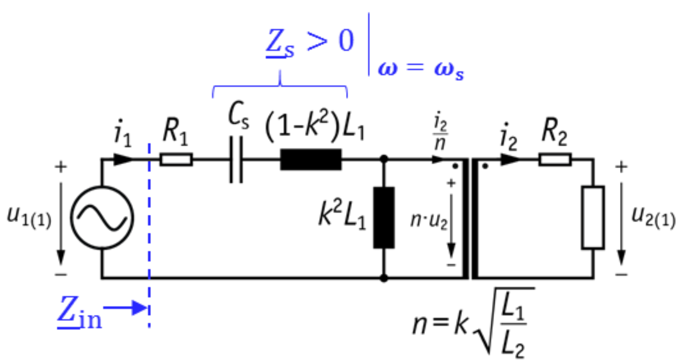


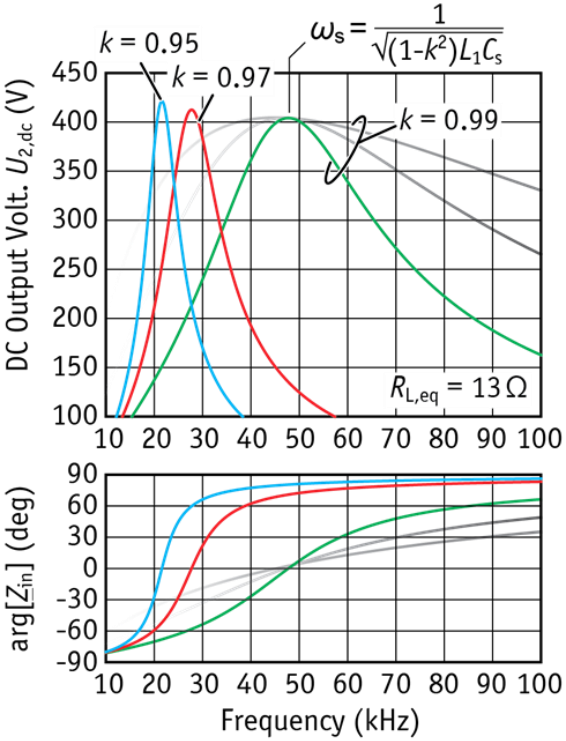


- **Fundamental Frequency Approximation**
- **Voltage Transf. Ratio for k= 0.99**

▶ Series-Resonant Compensated Converter Transfer Characteristic (2)

- **Large Variation of Resonant Frequency with Changing Magn. Coupling *k***
- **Coupling-Dependent Output Voltage due to Changing Series Impedance**
  - Fixed Frequency Operation Not Possible



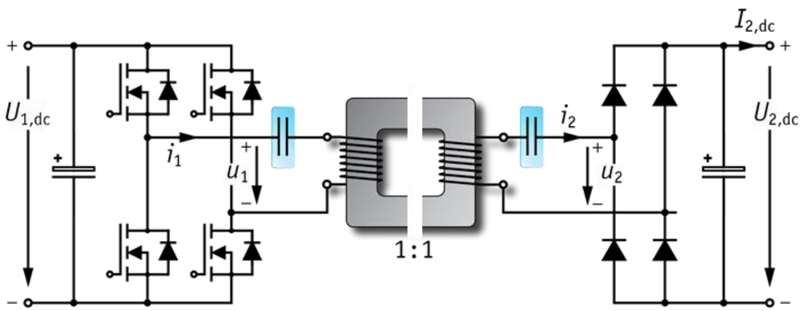


- **Different Compensation Concept Necessary as Coupling is Variable in the Target Application**

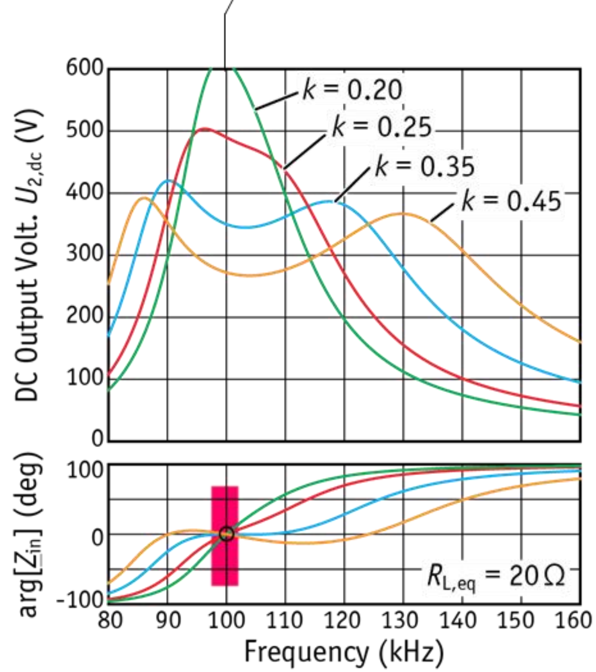
- **Voltage Transf. Ratio for *$R_{L,eq}$= const.***

▶ Series-Series Compensated IPT System (1)

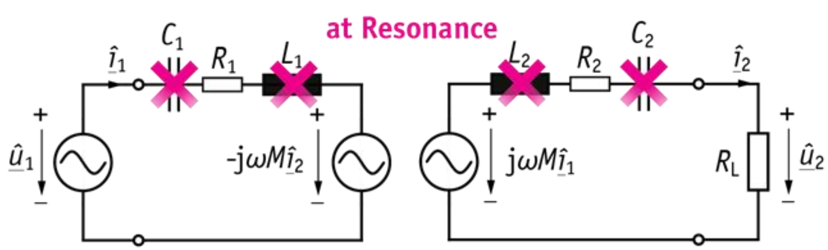
- **Add Second Series Capacitor to Ensure Fixed Res. Frequency for any Value of Magnetic Coupling *k***



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



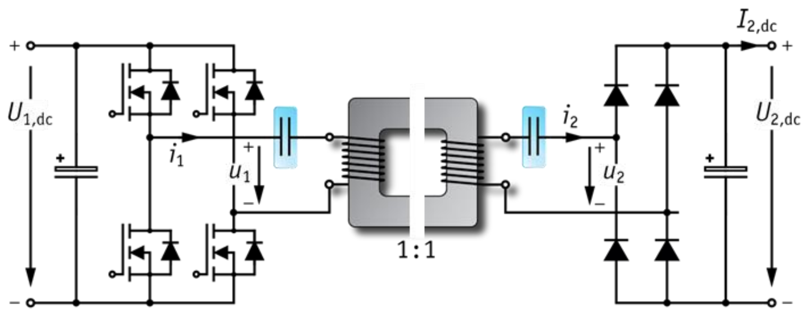
- **Complete Cancellation of Self-Inductance @ω_0**
- **φ_{Zin}=0 @ ω_0 Independent of k and $R_{L,eq}$**

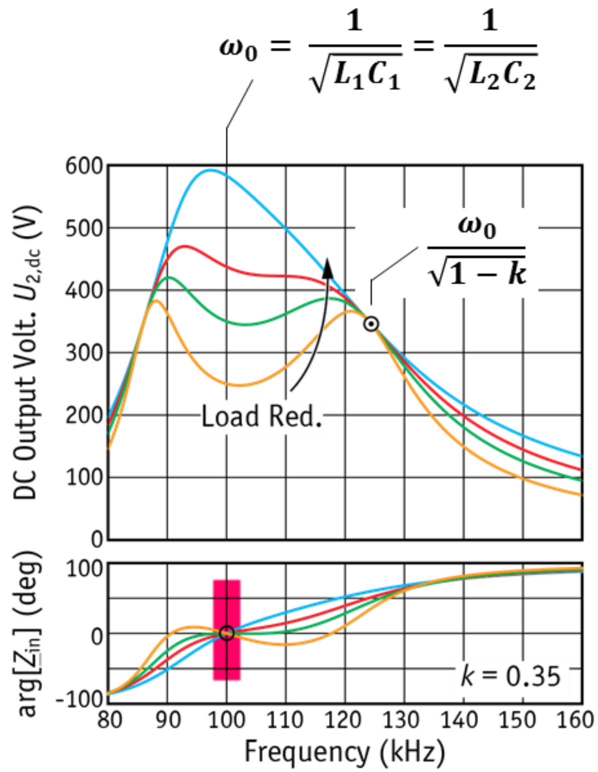


- **But: Voltage Gain @ ω_0 Still Coupl. and Load Dependent !**
- **Voltage Transf. Ratio for $R_{L,eq}$= *const.***

► Series-Series Compensated IPT System (2)

- Resonant Frequency (φ_{Zin}= 0) Independent of Magnetic Coupling k and Load $R_{L,eq}$
- Fulfills Necessary Condition for Minimum Input Current → Maximum Efficiency!





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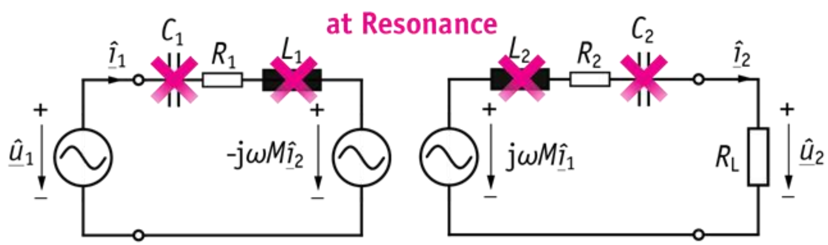
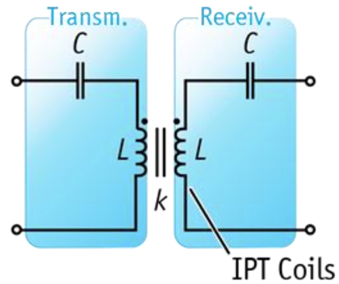


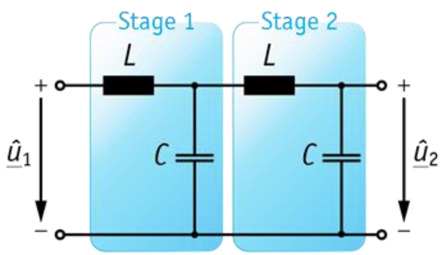
- But: Voltage Gain @ ω_0 Still Coupl. and Load Dependent !
- Voltage Transf. Ratio for k= *const.*

▶ Explanation of "Pole-Splitting"

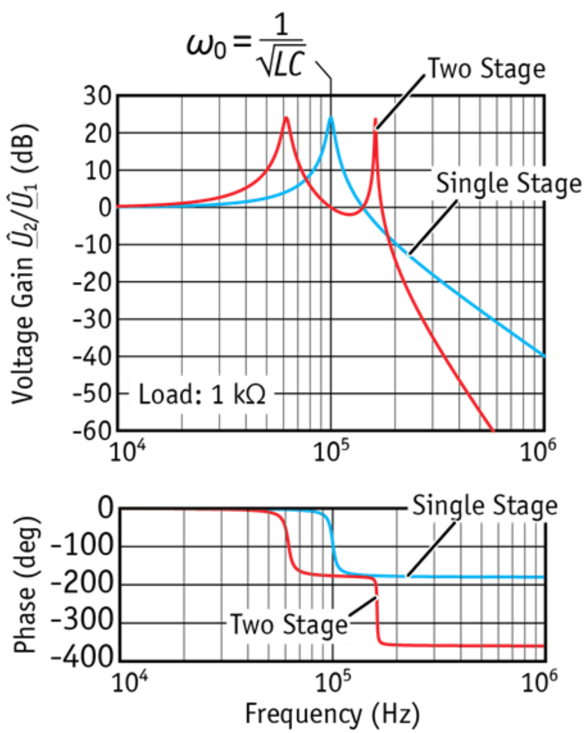
- **Interaction of Coupled Res. Circuits Tuned to Same Frequency**
- **Magnetic Coupling Determines the Strength of the Interaction**
  - Could Result in Non-Monotonic Phase Behavior
  - Has to Be Considered for Soft-Switching Inverters



- **Example of a Two-Stage LC-Filter**



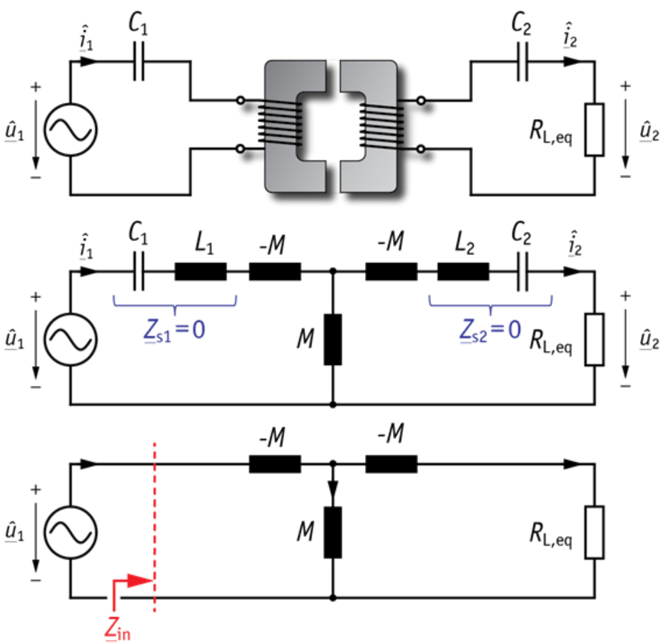
$$\omega_1 = \omega_2 = \frac{1}{\sqrt{LC}} = \omega_0$$

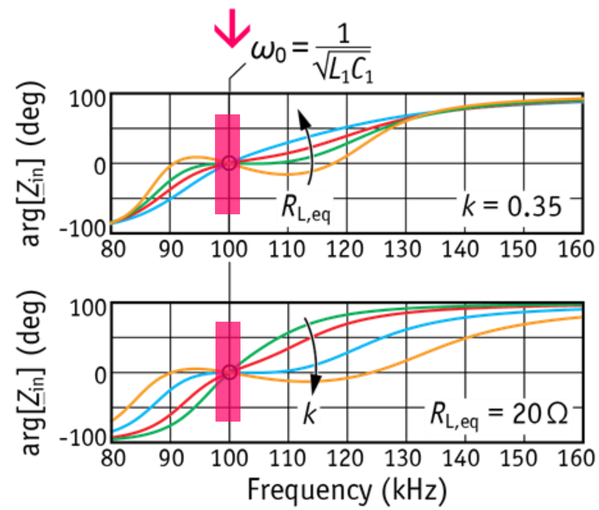


- Both Stages Tuned to Same Frequency (100kHz)
- Two Res. Peaks of Voltage Transfer Characteristic

Interesting Properties of Series-Series Compensation (1)

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





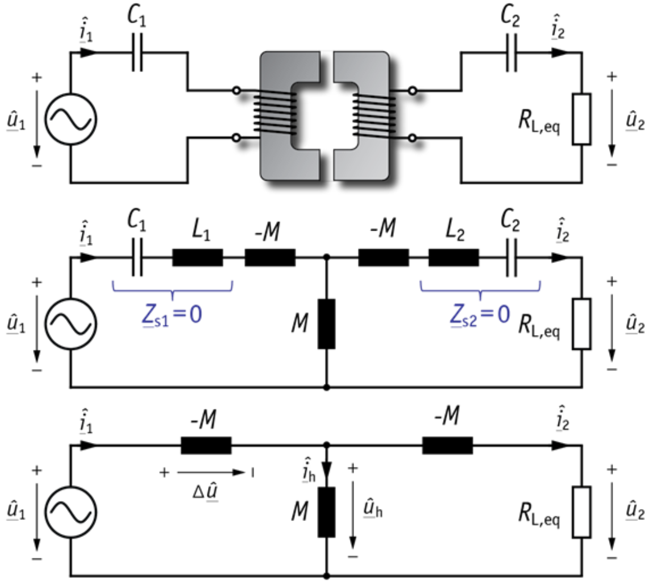
$$\underline{Z}_{in} = -j\omega_0 M + \frac{j\omega_0 M \cdot (R_{L,eq} - j\omega_0 M)}{j\omega_0 M + R_{L,eq} - j\omega_0 M} \rightarrow \underline{Z}_{in} = \frac{\omega_0^2 M^2}{R_{L,eq}} \rightarrow \arg[\underline{Z}_{in}] = 0$$

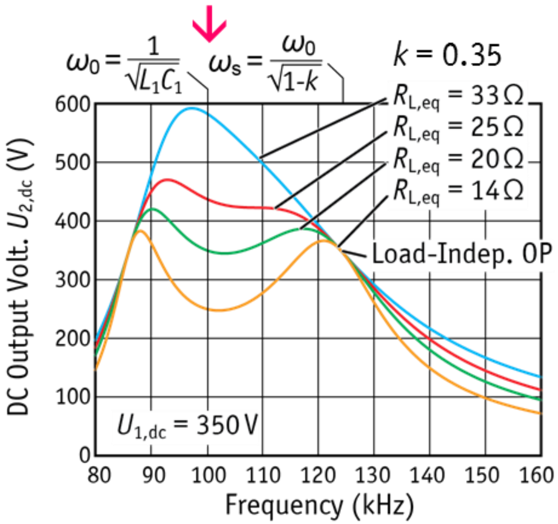
$$k = 0 \rightarrow \underline{Z}_{in} = 0$$
$$R_{L,eq} = 0 \rightarrow \underline{Z}_{in} = \infty$$

- **Purely Ohmic Input Impedance for Any Load & Coupling @ ω_0**

▶ Interesting Properties of Series-Series Compensation (2)

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





$$\underline{\hat{u}}_h = \underline{\hat{i}}_2(R_{L,eq} - j\omega_0 M)$$

$$\underline{\hat{i}}_h = \frac{\underline{\hat{i}}_2}{j\omega_0 M}(R_{L,eq} - j\omega_0 M)$$

$$\Delta\underline{\hat{u}} = -j\omega_0 M(\underline{\hat{i}}_2 + \underline{\hat{i}}_h) = -j\omega_0 M\underline{\hat{i}}_2 - \underline{\hat{i}}_2(R_{L,eq} - j\omega_0 M)$$

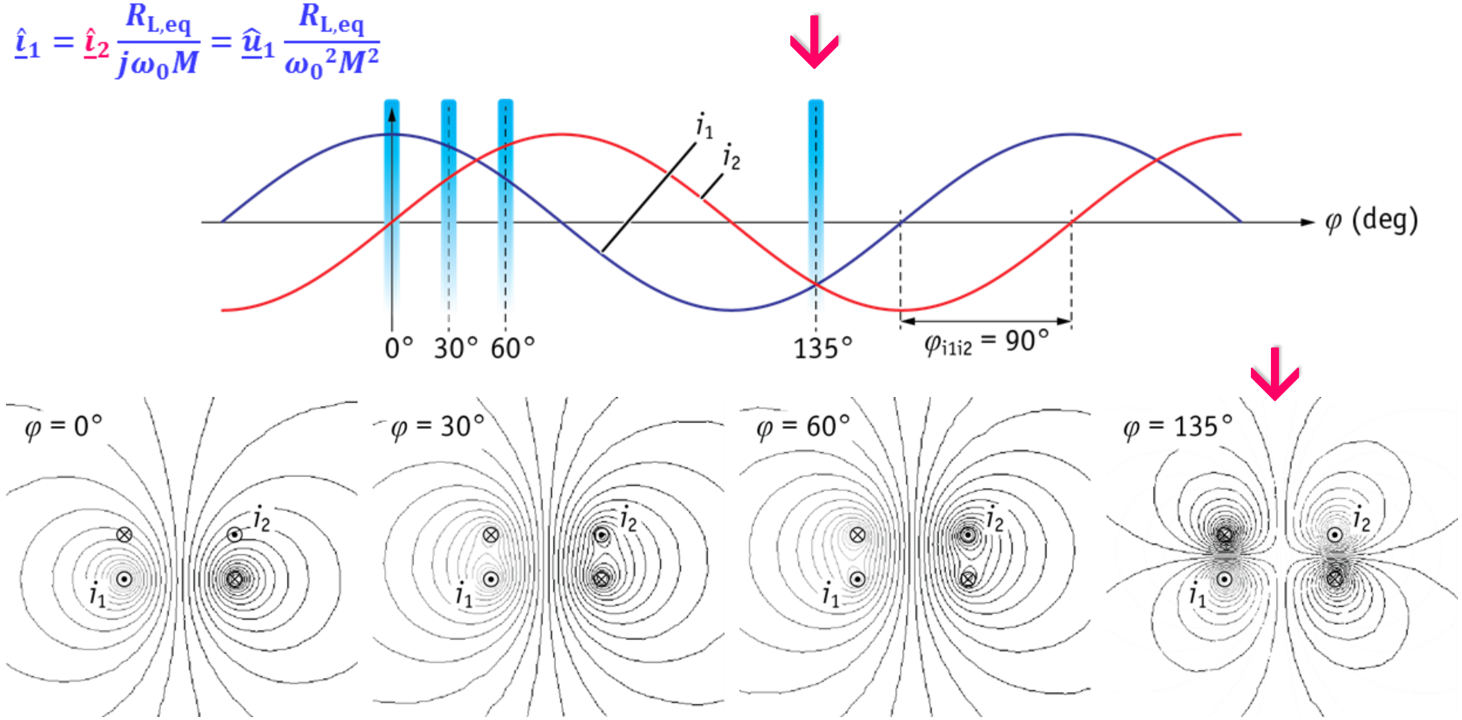
$$\underline{\hat{u}}_1 = \Delta\underline{\hat{u}} + \underline{\hat{u}}_h = -j\omega_0 M\underline{\hat{i}}_2$$

- **Output Current @ ω_0 Independent of Load Resistance $R_{L,eq}$!** → $\underline{\hat{i}}_2 = j\frac{\underline{\hat{u}}_1}{\omega_0 M}$

Interesting Properties of Series-Series Compensation (3)

- **Coupling and Leakage Inductance are Not Immediately Evident from FEM Field Images !**
  - Field Distribution Depends on Time Instant and Phase Displacement of the Winding Currents
  - For Series-Series Compensation $\underline{i}_1$ and $\underline{i}_2$ are Displaced by 90°

$$\hat{\underline{i}}_1 = \hat{\underline{i}}_2 \frac{R_{L,eq}}{j\omega_0 M} = \hat{\underline{u}}_1 \frac{R_{L,eq}}{\omega_0{}^2 M^2}$$



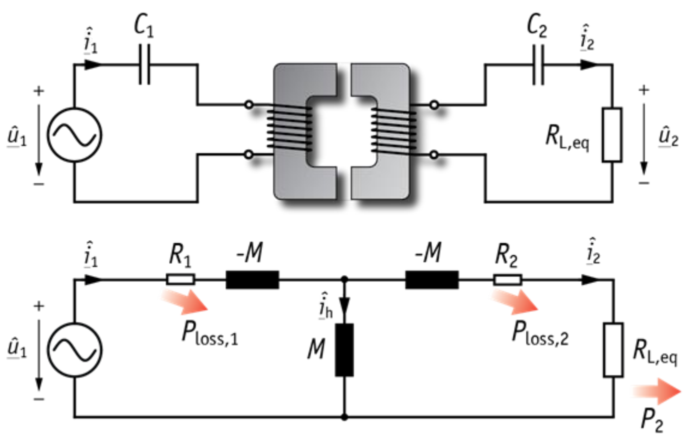
- **For φ=135° a *Poynting Vector* Analysis Confirms Power Transfer Despite Decoupled Field Lines**

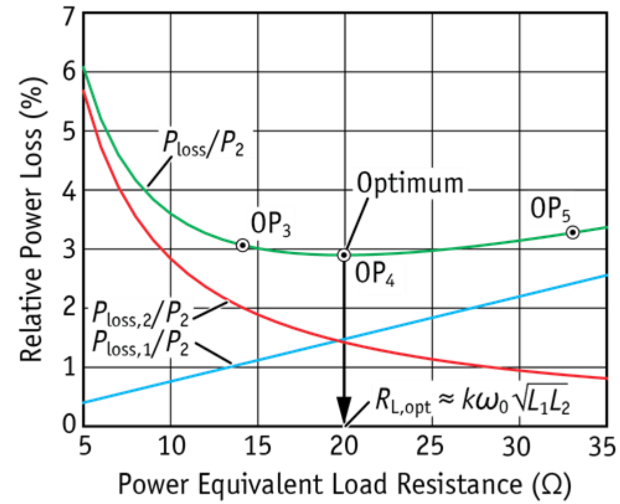
Maximum Efficiency of the Resonant System

– *Load Matching*
– *Figure-of-Merit*

Power Losses of Series-Series Compensation - *"Load Matching"*

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





- **Total Power Losses**
  - Core Loss Neglected **(!)**

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

- **Min. Relative Losses**
  - Min. Loss Factor λ

$$\frac{d}{dR_{L,eq}}\underbrace{\left(\frac{P_{loss}}{P_2}\right)}_{\lambda} = 0 \rightarrow$$

- **Load Resistance for Max. Efficiency**

$$R_{L,opt} = \sqrt{\omega_0^2 M^2 + \underbrace{R_{ac}^2}_{R_1 \approx R_2 = R_{ac} \text{ @ } \omega_0}} \approx k\omega_0\sqrt{L_1 L_2}$$

► Efficiency Limit & "Figure-of-Merit" (FOM)

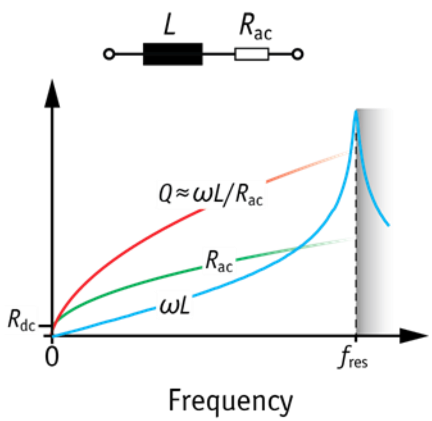
- **Maximum Efficiency for Opt. Load Resistance**

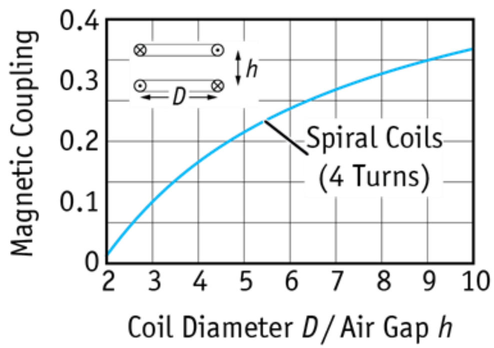
$R_{L,opt} \approx k\omega_0\sqrt{L_1L_2}$

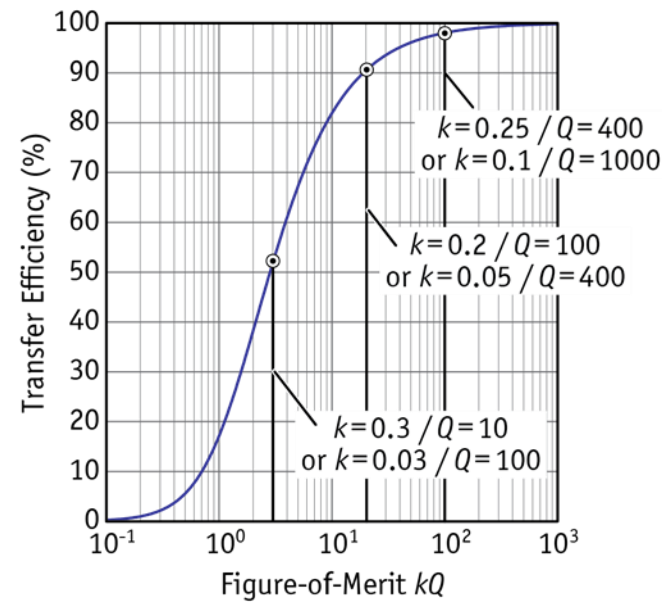
$$\eta_{max} = \frac{k^2Q_1Q_2}{\left(1+\sqrt{1+k^2Q_1Q_2}\right)^2} \approx 1 - \frac{2}{k\sqrt{Q_1Q_2}}$$

→ *Figure-of-Merit* $= k\sqrt{Q_1Q_2} = kQ$

$k = L_h/\sqrt{L_1L_2}$ ... Magnetic Coupling
$Q = \omega L/R_{ac}$ ... Coil Quality Factor

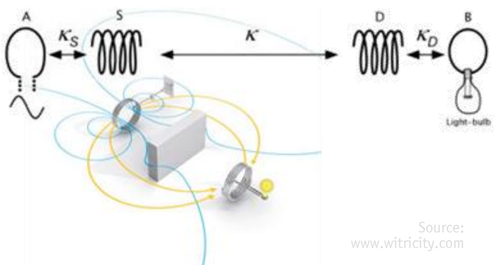






▶ Maximizing *FOM = Quality Factor x Magnetic Coupling*

■ **«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 (MHz)



Source: www.witricity.com

■ **Intelligent Parking Assistant for EVs**
- Camera-Assisted Positioning Guide
- Maximize *k* by Perfect Positioning
- Achieve up to 5cm Parking Accuracy

Source: www.toyota.com

Efficiency Optimal Control of the System →

– *Load Matching*

▶ "Load Matching" - Emulation of Opt. Load Resistance $R_{L,opt}$

■ **Output Voltage $U_{2,dc}$ Adjusted according to Power Level P_2***
- Given Resonant Circuit
- Given Operating Frequency
- Given Magnetic Coupling
- Given Input and Battery Voltage

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

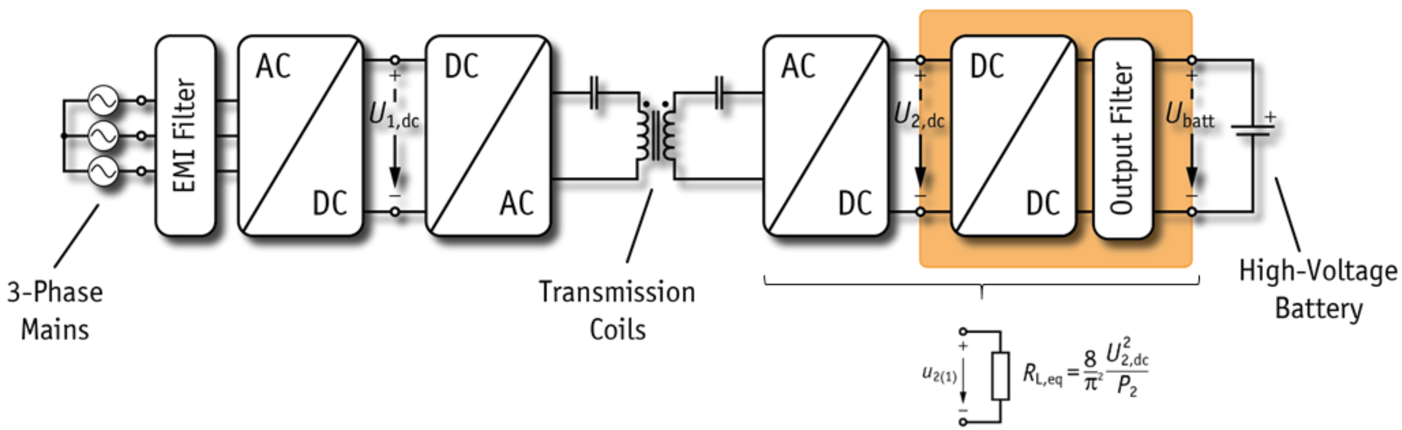
Controller Input Variables

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

Maximum Efficiency Condition

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

Controller Reference

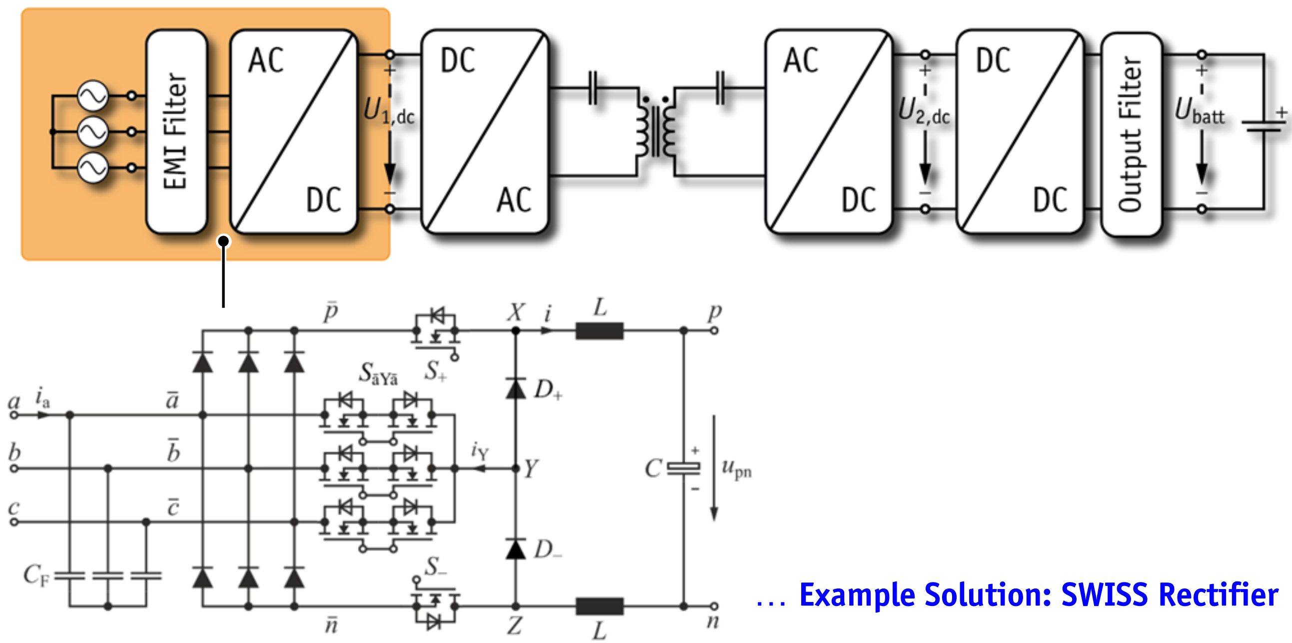


▶ Control of the Transferred Power

- **Receiver Voltage $U_{2,dc}$ used for Optimal Load Matching**
- **Power Regulation by Adjustment of $U_{1,dc}$ using Characteristic**

$$P_2 = \frac{8}{\pi^2}\frac{U_{1,dc} \cdot U_{2,dc}}{\omega_0 k \sqrt{L_1 L_2}}$$

- **Three-Phase AC/DC Converter with Controllable Output**
  - Boost-Type PFC Rectifier and DC/DC Converter
  - Integrated Buck-Type PFC Rectification and Voltage Control

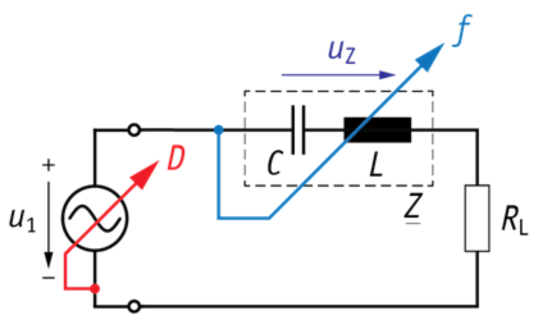


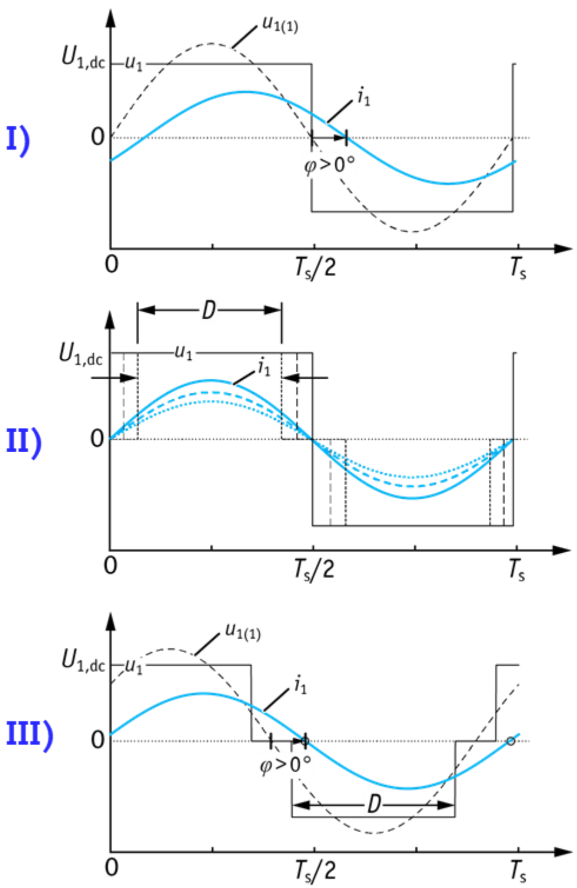
… Example Solution: SWISS Rectifier

► Alternative Control Concepts for Series-Resonant Converters

- **Degrees of Freedom for Control**
  - Inverter Sw. Frequency (Cntrl of Series Impedance)
  - Duty Cycle of Inverter Output Voltage
  - DC-Link Voltage (with Front-End DC/DC Conv.)

- **Standard Control Concepts**
  - I) Frequency Control @ Fixed Duty Cycle
  - II) Duty Cycle Control @ Fixed Frequency
  - III) Self-Oscillating/Dual Cntrl
    (Comb. Duty Cycle & Frequ. Cntrl)

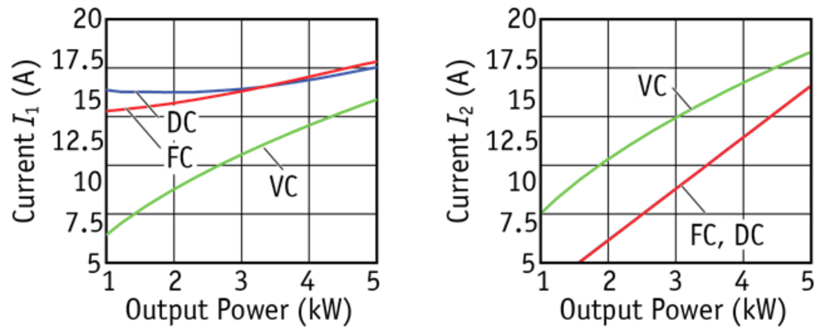




▶ Comparison of Control Methods

■ **Frequency Control Methods Show (almost) Load-Independent Transmitter Current**

VC … DC-Link Voltage Cntrl ("Load Matchg")
FC … Frequency Control
DC … Dual / Self-Oscillating Cntrl

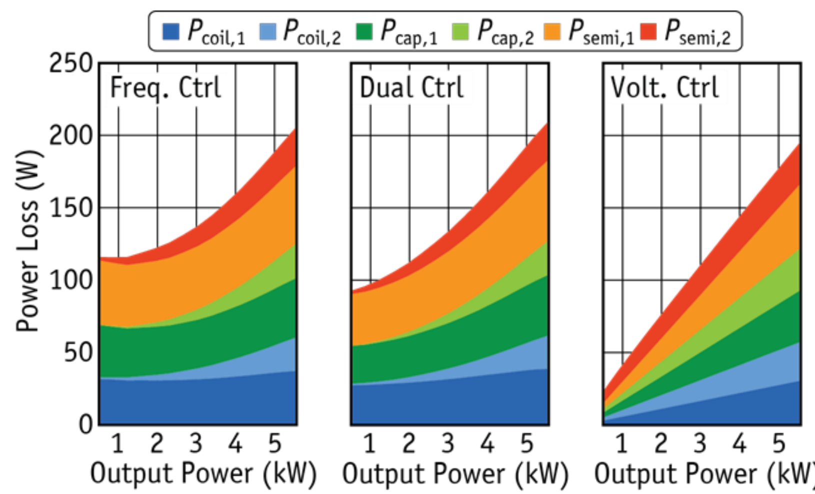


■ **Low Transmitter Current I_1 for "Load Matching"**

- Over-All Loss Reduction Despite Higher I_2 due to Lower $U_{2,dc}$

■ **Large Reduction of Power Losses in Partial Load Condition**

- Reduced Transmitter Coil RMS-Current
- Decreasing instead of Constant I^2R Losses in Coils/ Caps/ Switches



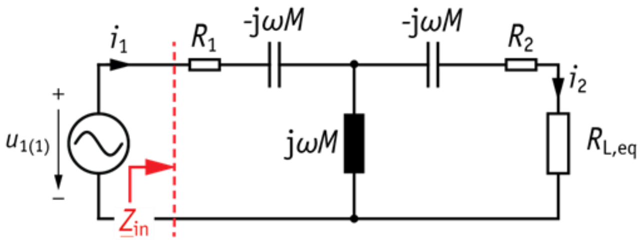
Maximum Efficiency Operation of the Inverter

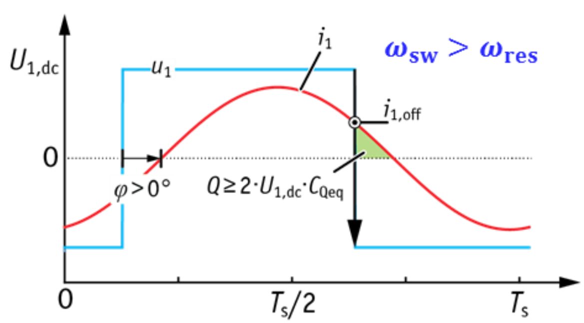
– *Soft-Switching* →

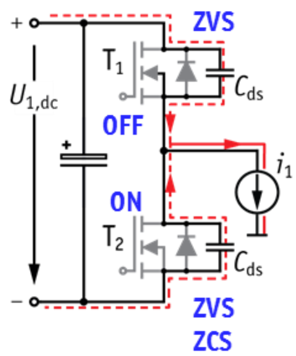
▶ *Power MOSFETs* - Zero Voltage Switching

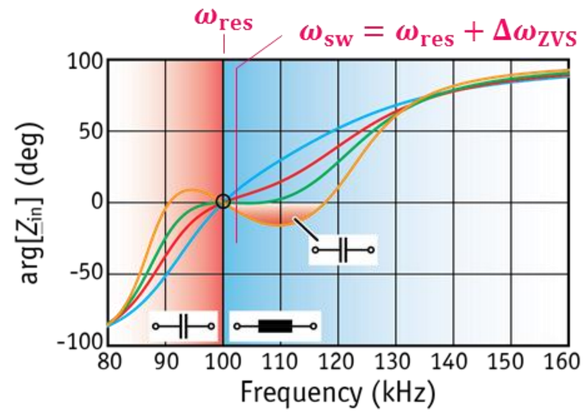
- **Operation Slightly Above Resonance $\omega_{sw} > \omega_0$**
  - Sufficient Inductive Load Current to Charge/Discharge the Charge-Equivalent MOSFET Output Capacitance

- Pole Splitting / Non-Monotonic Phase Behavior Could Result in Hard Switching



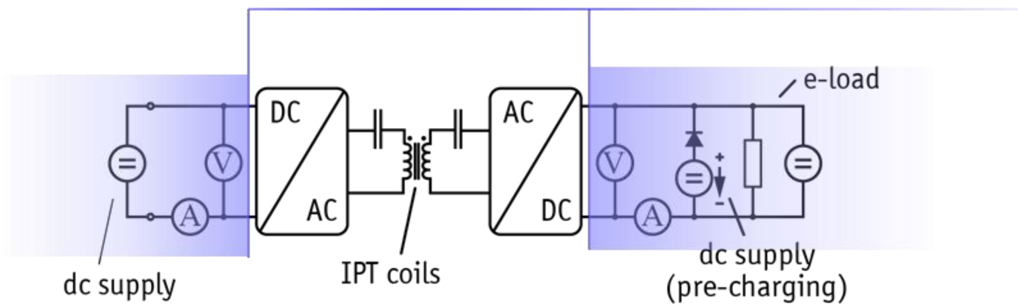






▶ Measurement Results for Optimal Control (VC)

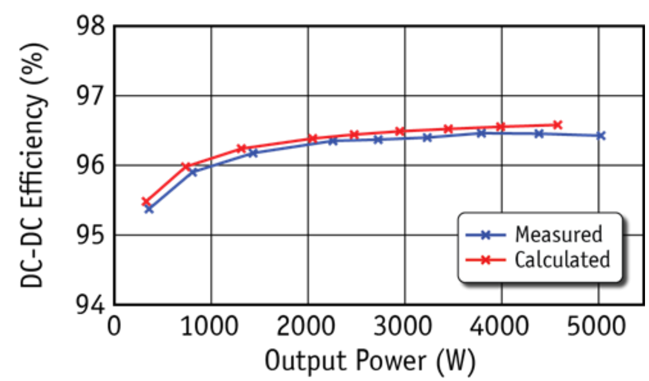
- "Load Matching" allows Large Reduction of Power Losses especially in Partial-Load Condition



Source: Yokogawa

- Power Analyzer

- Extremely Flat Efficiency Characteristic Even at Low Output Power thanks to Constantly Operating at Optimal Conditions



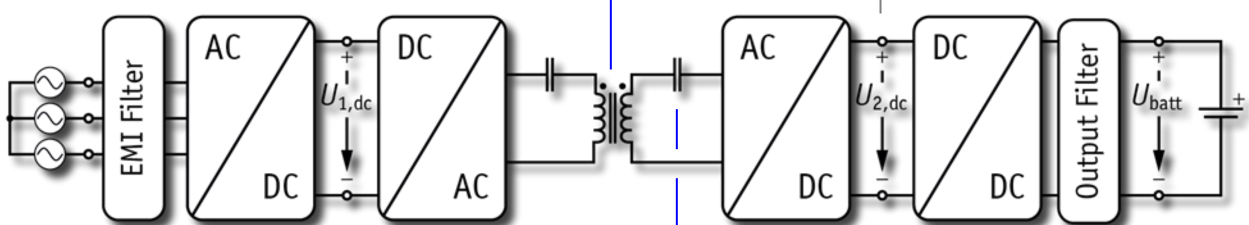
Design Considerations

Coil Arrangements
Component Models

▶ System Overview

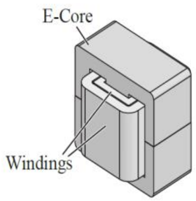
■ **Transmission Coils**
- Magnetic Design using FEM
- Winding and Core Losses (FEM)
- Thermal Model
- Shielding of Stray Field

■ **Receiver-Side Power Electronics**
- Synchronous Rectification
- Battery Current Regulation
- Load Matching

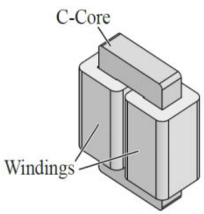


■ **Transmitter-Side Power Electronics**
- 1/3-Phase PFC Mains Interface
- DC Link Voltage Control
- High-Frequency ZVS Inv. Stage

■ **Resonant Compensation**
- Voltage and Current Stresses
- Loss / Lifetime Analysis

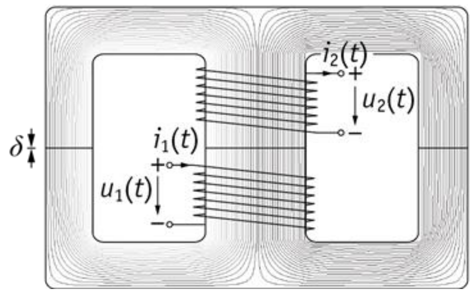


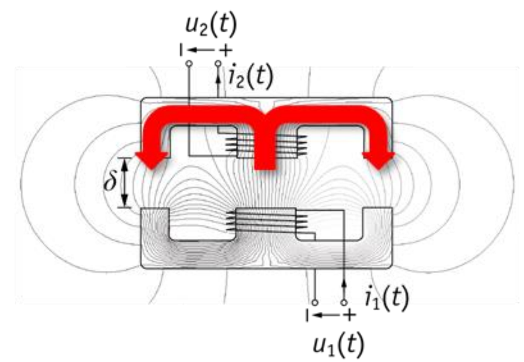
Selection of Transmission Coil Geometry

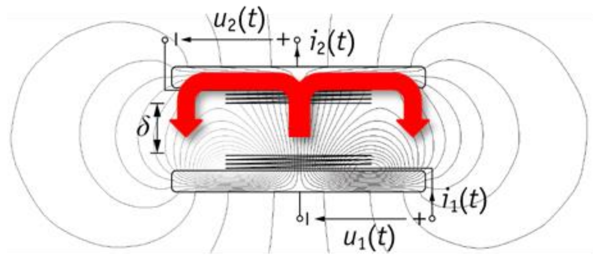


▶ Coil Geometry Option #1

■ **E-Core Transformer**
- Flux Divided into Two Equal Loops



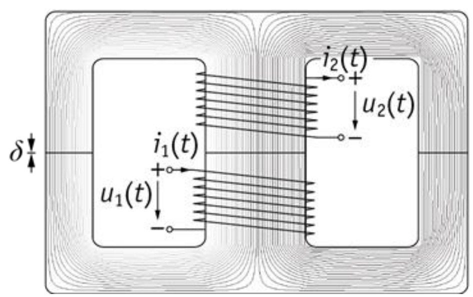


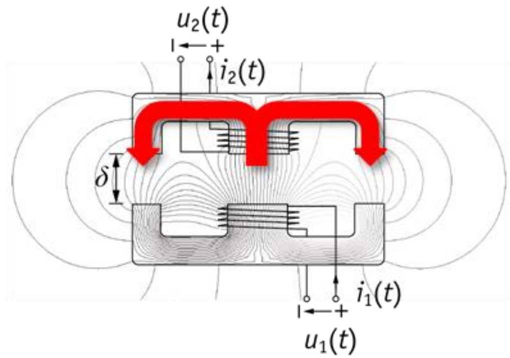


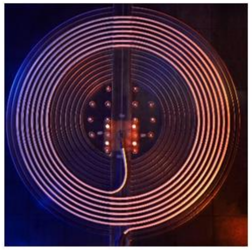
■ **E-Type Transmission Coils**
- Flux Divided into Two Equal Loops
- Relatively Large Stray Field
- Coupling Strongly Dependent on Diameter/Airgap Ratio
- Max. Coupling for Certain Core Overlap

▶ Coil Geometry Option #1

- **E-Core Transformer**
  - Flux Divided into Two Equal Loops





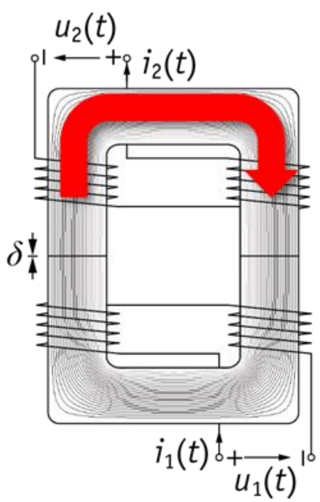


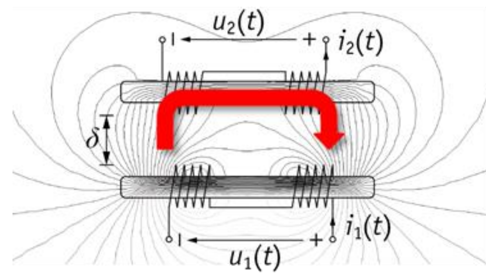
Source:
Fraunhofer ISE

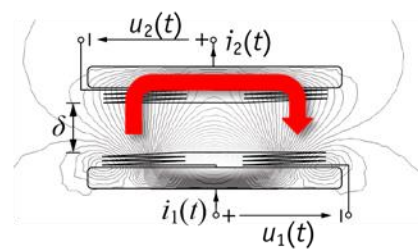
- **E-Type Transmission Coils**
  - Coil Geometry does Not Guide Return of Flux
  - Relatively Large Stray Field
  - Coupling Strongly Dependent on Diameter/Airgap Ratio
  - Max. Coupling for Certain Core Overlap

▶ Coil Geometry Option #2

- **U-Core Transformer**
  - Low Stray Ind. for Windings on Both Legs



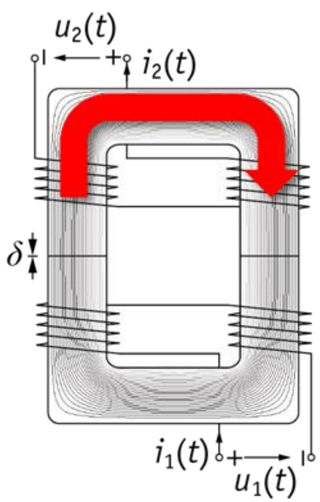


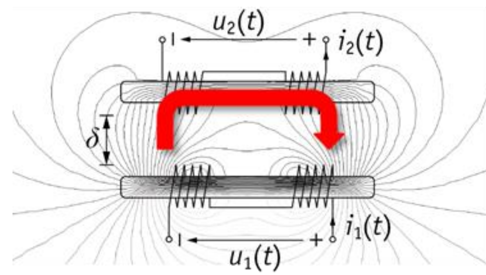


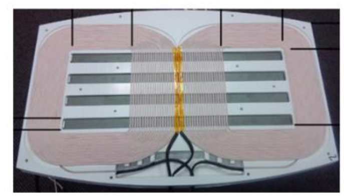
- **E-Type Transmission Coils**
  - Coil Geometry Guides Return of the Flux
  - Relatively Low Stray Field
  - Coupling Strongly Dependent on Diameter/Airgap Ratio
  - Max. Coupling for Certain Core Overlap

▶ Coil Geometry Option #2

- **U-Core Transformer**
  - Low Stray Ind. for Windings on Both Legs







Source: G. Covic / J. Boys et al.

- **E-Type Transmission Coils**
  - Coil Geometry Guides Return of the Flux
  - Relatively Low Stray Field
  - Coupling Strongly Dependent on Diameter/Airgap Ratio
  - Max. Coupling for Certain Core Overlap

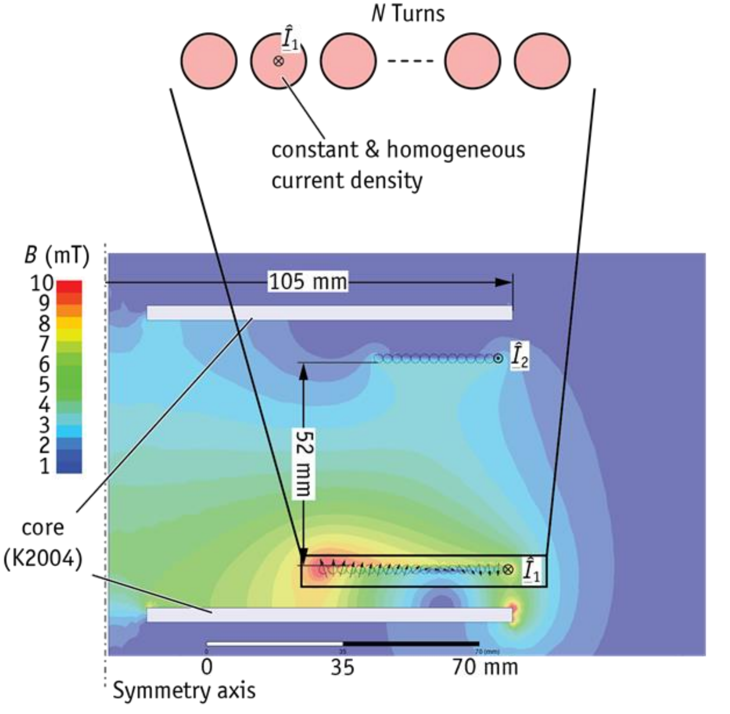
Design of a
5kW Demonstrator System

5kW @ 400V
Forced Air Cooled
210mm/50mm Diameter/Airgap
E-Type Coil Geometry

▶ Calculation of High-Frequency Winding Losses

- **Consideration of Skin- and Proximity Effect**
  - Based on Fundamental Frequency Model
  - Asymmetric Geometry
  - Analytical Field-Calculation Not Possible
- **Field Calculation w. Finite Element Method**
  - Based on Fund. Frequency Model
  - Extraction of *H*-Field for Proximity Loss Calculation in Litz Wire Winding

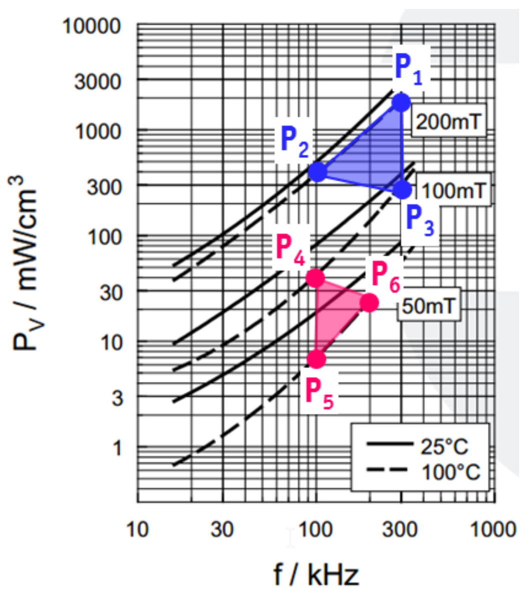
- **5kW Transmitter Coil Prototype**

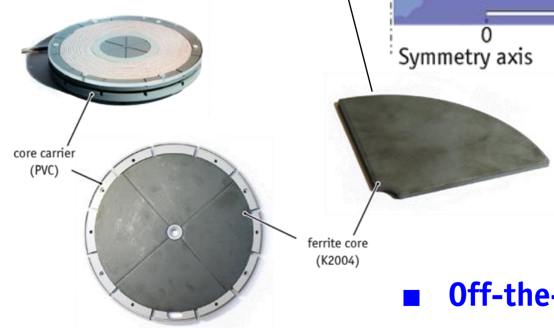


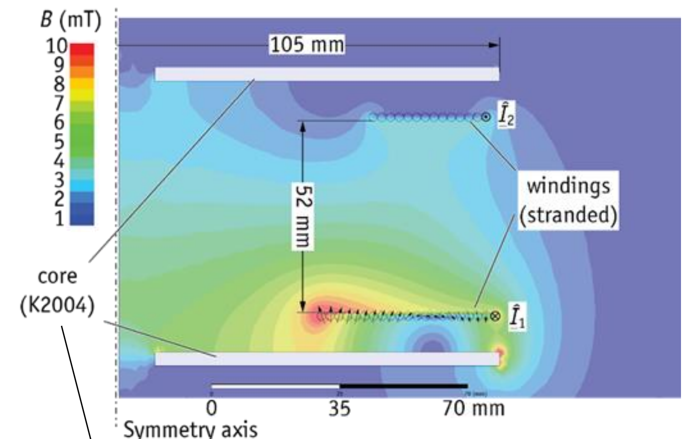
- **2D-FEM Proximity Effect Calculation**

▶ Calculation of High-Frequency Core Losses

■ **Core Loss Calculation with FEM & Steinmetz Equation**
- Approx. Sinusoidal Magnetic Excitation
- Integration of Steinmetz Eq. over Core Volume using FEM
- Steinmetz Parameters must be Iteratively Extracted for Flux Density, Frequency, Temperature Values similar to those of the Final Design!





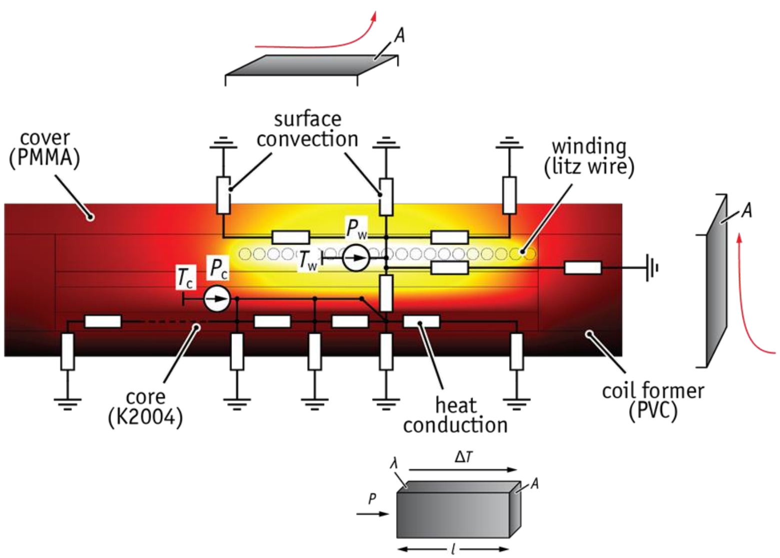


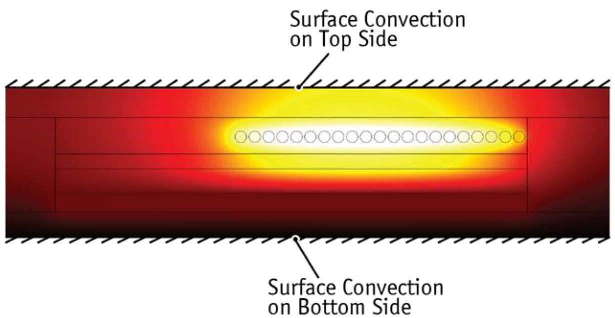
■ **MnZn Ferrite K2004 Datasheet**

■ **Off-the-Shelf 90°Ferrite Segments**

▶ Thermal Modeling of the Coils

- **Detailed Thermal Network incl. Heat Cond. & Convection at Surfaces is Complex**
- **Iterative FEM-Based Loss Calculation w. Thermal Feedback results in Long Calculation Time**
  - No Thermal Feedback but Assumption of Elevated Temp. (80-100°C)
  - Assumption of Uniform Loss Distribution over the Coil Volume
  - Thermal Limit in Coil Optimization based on Typ. Values for Forced-Air and Nat. Conv. Heat Transfer ($50W/(K{\cdot}m^2)$ and $10W/(K{\cdot}m^2)$)





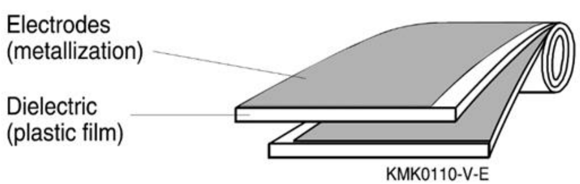
- **Exp. Measurement Verifies < 5% Error**
- **$0.2W/cm^2$ is a Reasonable Assumption for Forced Convection**

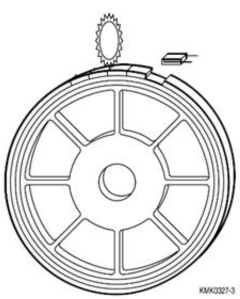
▶ Selection of the Resonant Capacitors (1)

■ **Polypropylene Film Capacitors for Resonant Applications**

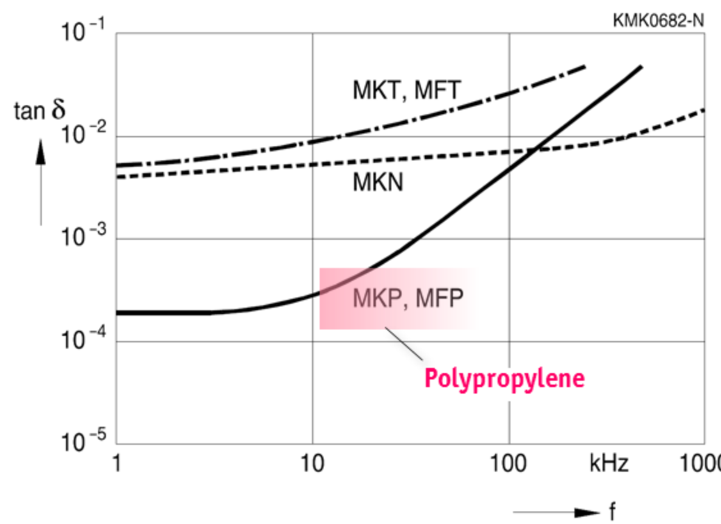
- Low *tan*(δ) (Low High–Frequency Losses) and Low ESR
- Least Affected by Temperature / Frequency / Humidity (Could Lead to Changing Resonant Frequency)

Polyester ... T
Polypropylene ... P
Polyethylene Naphthalate ... N
Metalized Plastic Film / Metal Foil ... MK/F





Source: EPCOS



■ **Frequency Dependency of *tan*(δ)**

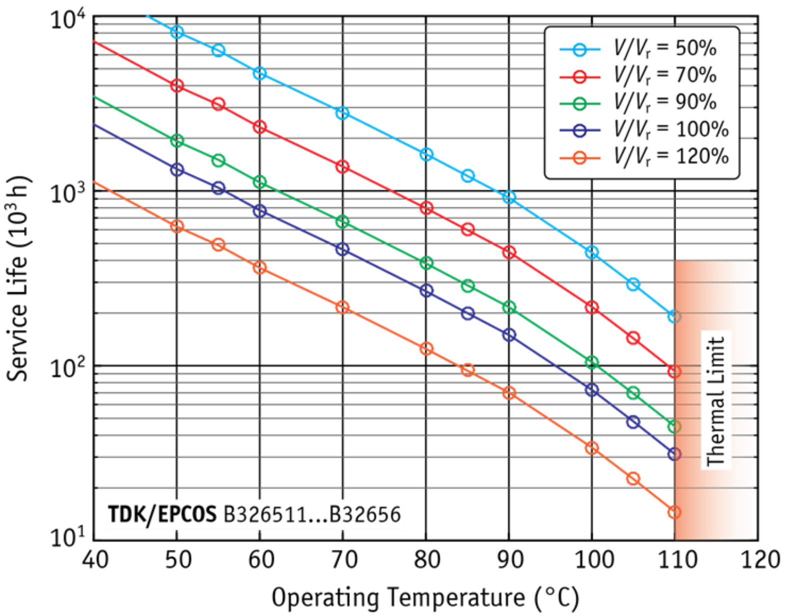
▶ Selection of the Resonant Capacitors (2)

- **Service-Life of Film Capacitors Strongly Depends on Operating Temperature and Voltage Utilization (!)**

  - Temp. Dependency acc. to Arrhenius Law (Exp. Funct.)
  - Change of 10°C Reduces t_{Life} by Factor of 2 !

$$t_{\text{life}}(T,V) = t_{\text{life},0} \cdot \frac{1}{\pi_T} \cdot \frac{1}{\pi_V}$$

T (°C)	π_T	V / V_R	π_V
≤ 40	1	10%	0.26
50	1.8	25%	0.42
55	2.3	50%	1.00
60	3.1	60%	1.42
70	5.2	70%	2.04
80	9	80%	2.93
85	12	90%	4.22
90	16	100%	6.09
100	33	110%	9.00
105	50	120%	13.00



- **Service Life vs. Operating Temp. for Diff. Levels of Voltage Utilization**

Multi-Objective Optimization

Specifications / Constraints
Optimization Procedure
Trade-Off Analysis

Multi-Objective Optimization of a 5kW Prototype

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

- **System Specification**

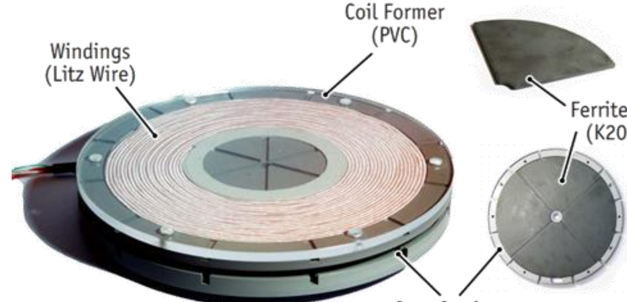
  - Input Voltage 400V
  - Battery Voltage 350V
  - Output Power 5kW
  - Air Gap 50mm

- **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 $\beta = B_{max}/B_{normi}$ [%]

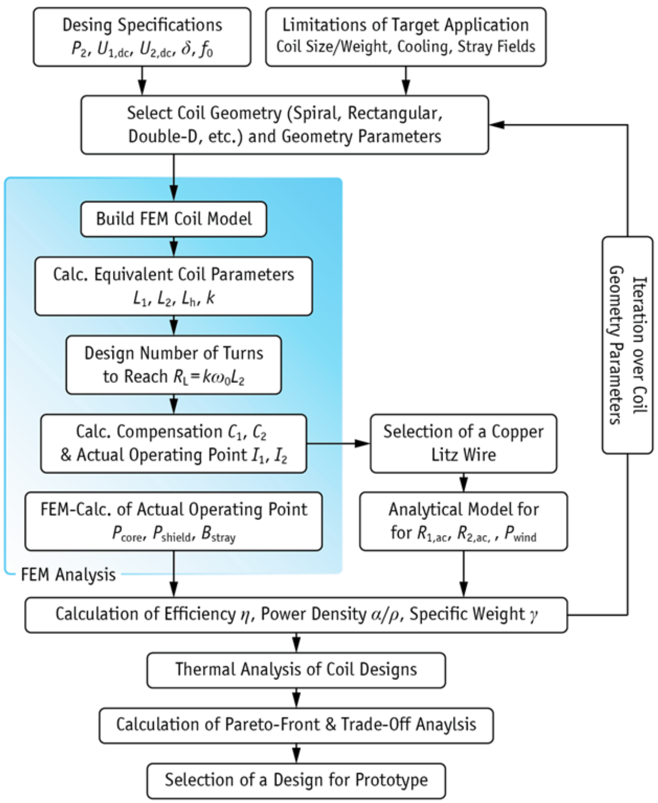


▶ η-α-Pareto Coil Optimization (1)

- **Determine the Physical Performance Limit**
  - Select Best Design for Defined Trade-Off

- **Analysis of the Mapping of the "Design Space" into the "Performance Space"**
  - Influence of Constraints & Side Conditions
  - Influence of Component Technologies
  - Analyze Design Space Diversity

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



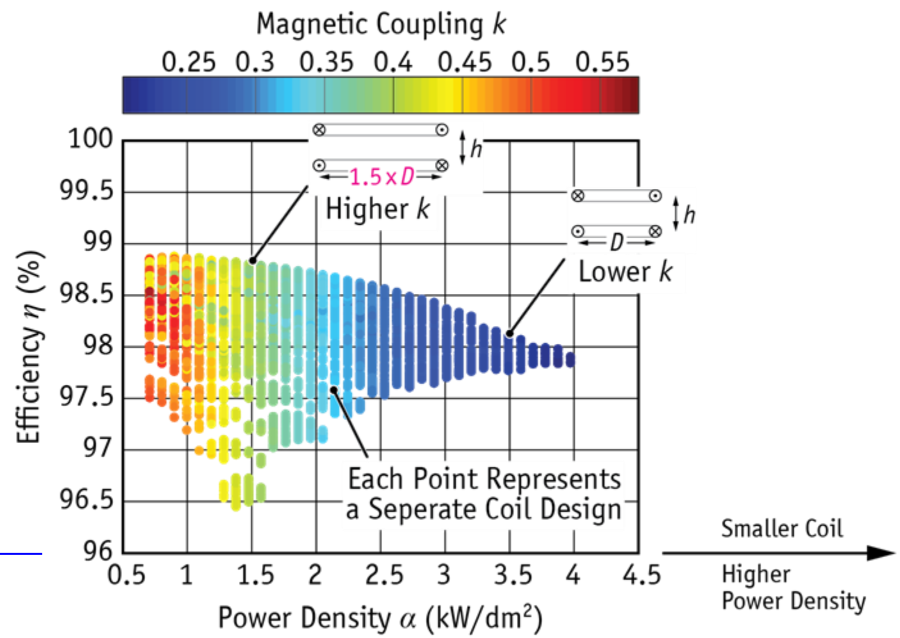
▶ η-α-Pareto Coil Optimization (2)

Design Space

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

Component & System Models

Performance Space

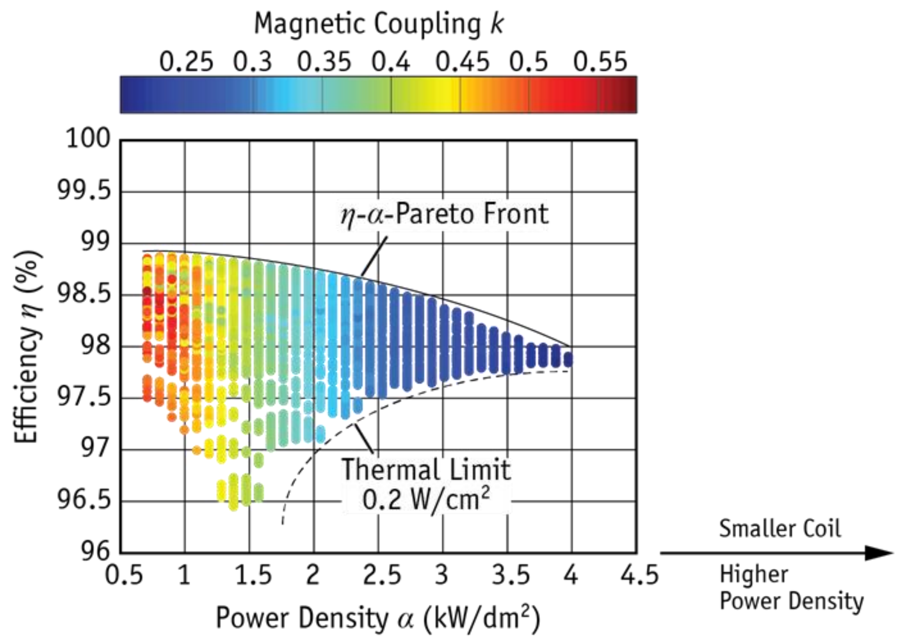


▶ η-α-Pareto Coil Optimization (3)

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

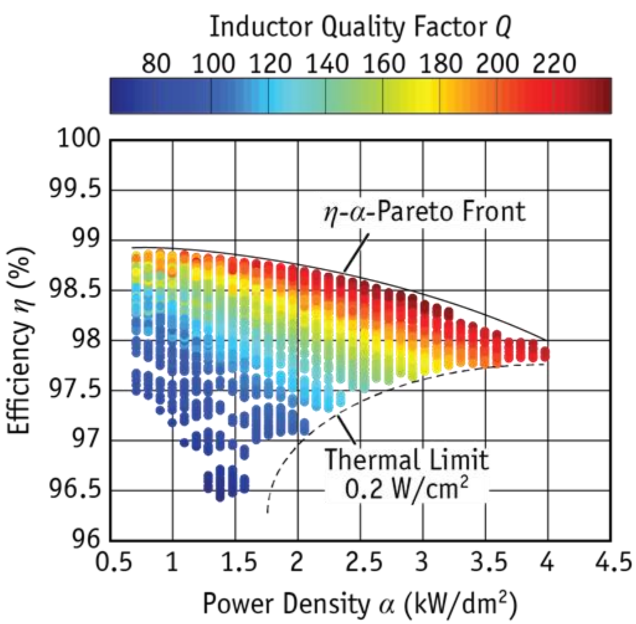
- **η-α-Pareto Front**
  - Physical Performance Limit
  - Clarifies Trade-Off of Coil Size vs. Efficiency

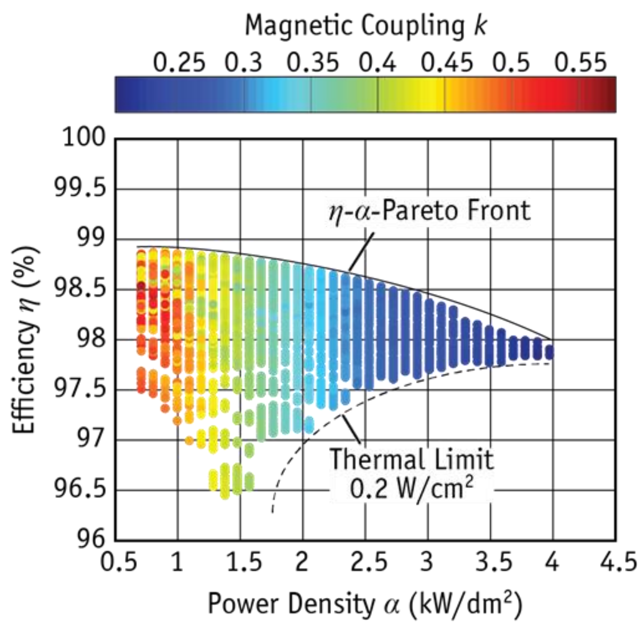
- **Thermal Limit**
  - Limited Power Dissipation Capability for Given Coil Size
  - Lower Limit on Efficiency



▶ η-α-Pareto Coil Optimization: Key Results (1)

■ **Analysis of the Mapping of Key Design Parameters into the Performance Space**
- Confirms Analytical Analysis of the Fundamentals (Figure-of-Merit = $k{\cdot}Q$)
- Identify Key Design Parameters that Impact the System Performance



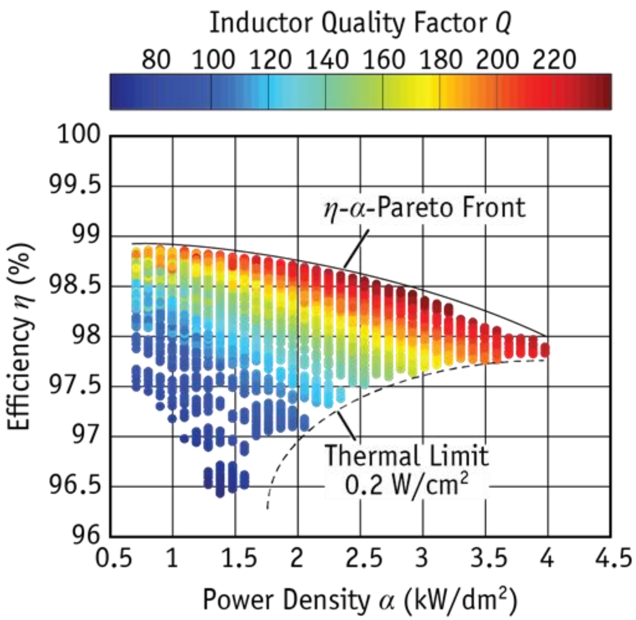


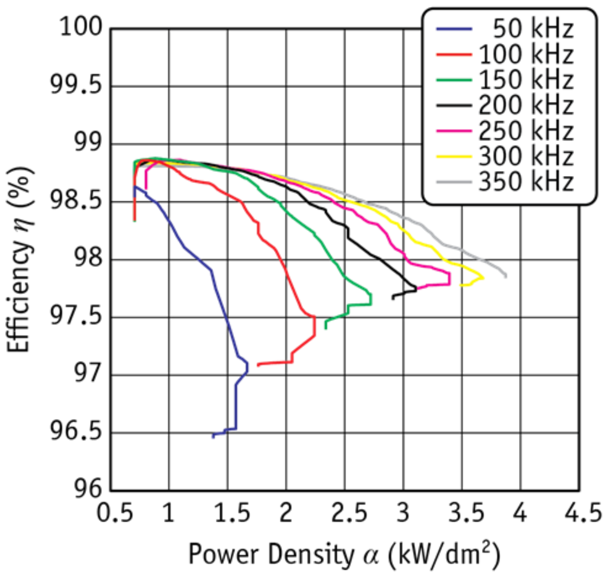
→ **Efficiency depends on *FOM* = $k{\cdot}Q$: Can be High for Low *k*, if *Q* is High Enough (!)**

▶ η-α-Pareto Coil Optimization: Key Results (2)

■ **Analysis of the Mapping of Key Design Parameters into the Performance Space**

- Confirms Analytical Analysis of the Fundamentals (Figure-of-Merit = $k{\cdot}Q$)
- Identify Key Design Parameters that Impact the System Performance

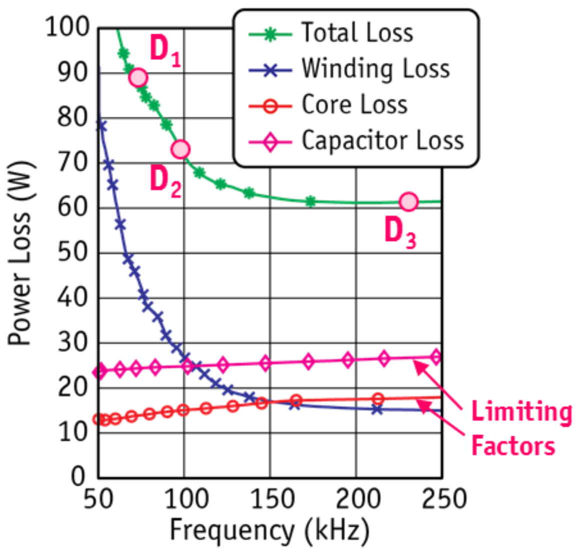


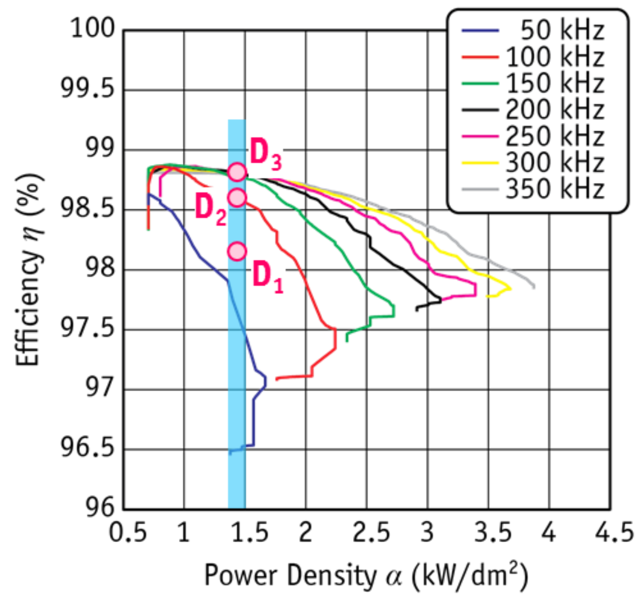


→ **High Transmission Frequency results in High $Q = \omega L / R_{ac}$ - High Efficiency**

Efficiency for High-Frequency Transmission

- **Reduced Winding Losses due to Lower Number of Turns**
  - Design Condition $R_{L,opt} \approx k\omega_0\sqrt{L_1 L_2}$ allows Lower L_1, L_2 at higher ω_0
  - Reduction of Flux Limits Increase of Core Losses
  - Core and Capacitor Losses are Limiting Factors for High-Frequency Operation





- **Power Loss Breakdown @ 1.47 kW/dm²**
- **η-α-Pareto Limits for Const. Sw. Frequency**

High-Frequency Transmission & Stray Field

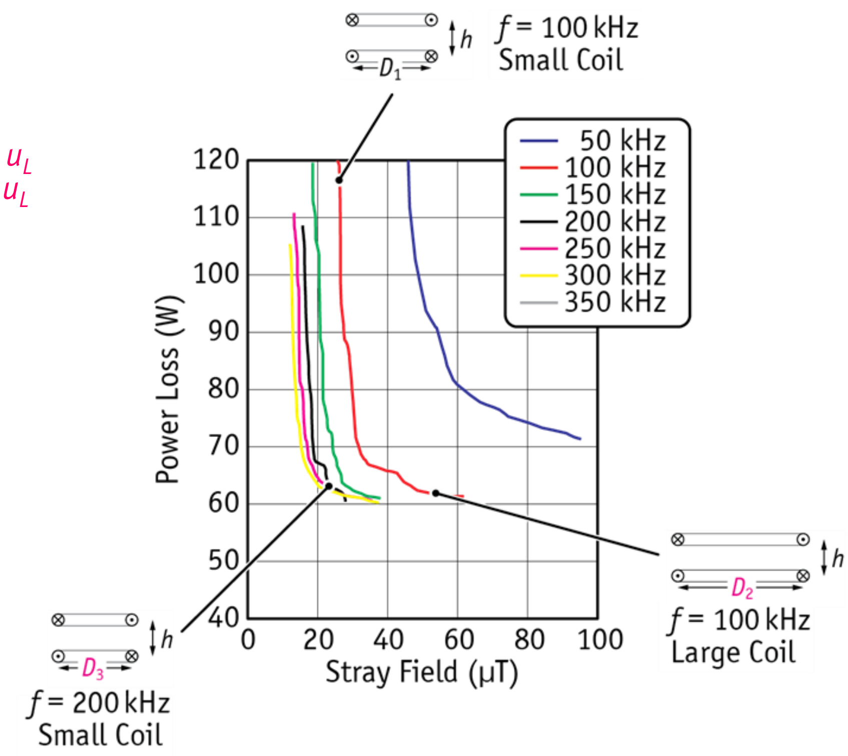
Effects of High Transmission Frequency

- Smaller Coil Area Possible for Same Voltage u_L
- Lower Flux Density Possible for Same Voltage u_L

$$u_L = N\frac{d\Phi}{dt} \propto \omega_0 \hat{B} A_{coil}$$

Encountered Design Trade-Offs

- Coil Size vs. Efficiency
- Coil Size vs. Stray Field
- Frequency vs. Stray Field

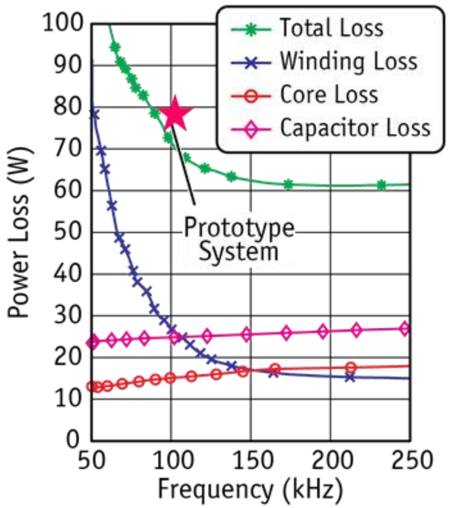


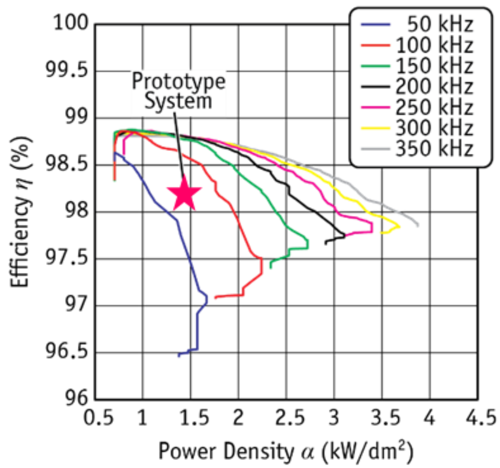
→ **Pareto-Optimization allows to Select of a Coil Design Taking All Aspects into Account**

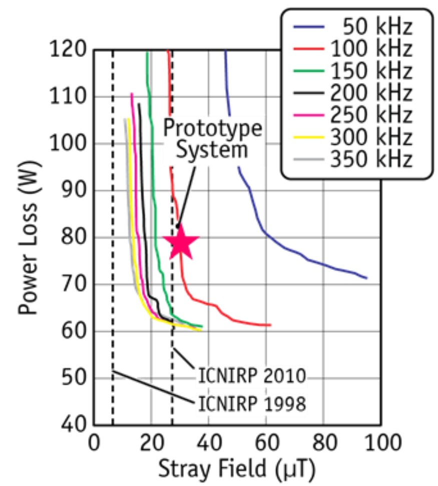
Selected Design for 5kW Prototype

Selection of Transmission Frequency for Prototype System

- Significant Improvement of Sum of Coil/Core/Cap Losses Only up to 100kHz
- Lower Frequency for Standard Litz Wire (630x71µm) & Low Inverter Losses

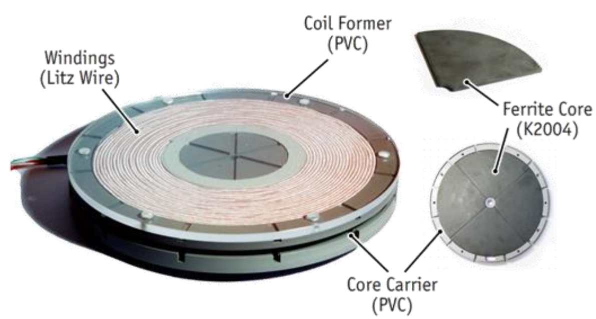






System Specification

- Coil Diameter **210mm**
- Frequency **100kHz**
- Efficiency **98.25% @ 52mm Air Gap**
- Power Density **1.5 kW/dm²**
- Stray Field **26.2 µT**
- Cooling System **Forced-Air**



Optimization of a
50kW Demonstrator System

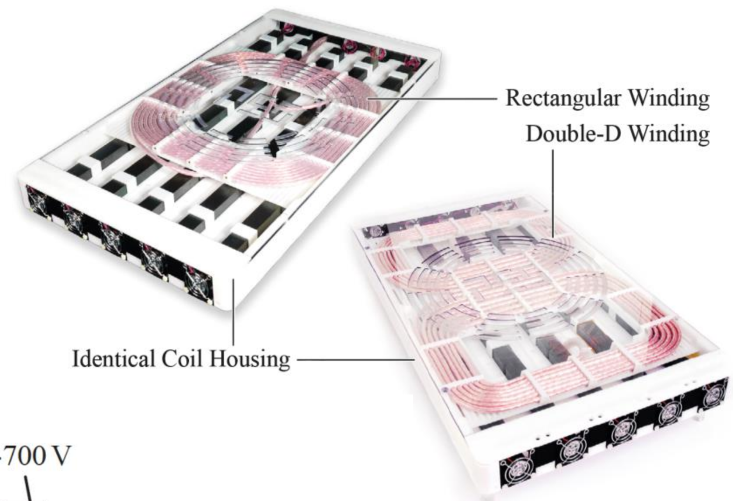
▶ Multi-Objective Optimization of a 50kW Prototype (2)

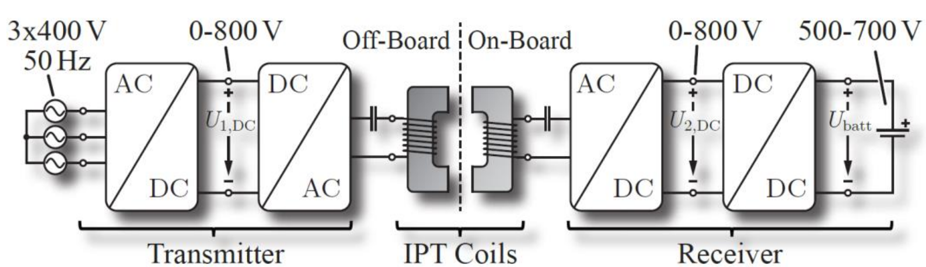
- **Pareto-Optimal Design – Efficiency / Power Density / Stray Field**
- **Comp. Evaluation of Rectangular & Double-D Coil Geometry**

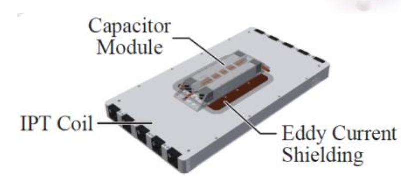
- **System Specification**

- Output Power	50kW
- Battery Voltage	500...700V
- Transmitter Voltage	0...800V
- Receiver Voltage	0...800V
- Air Gap	100...200mm
- Pos. Tolerance	± 150mm
- Operating Frequency	85kHz

- **Power Density Target** 1.6 kW/dm^2







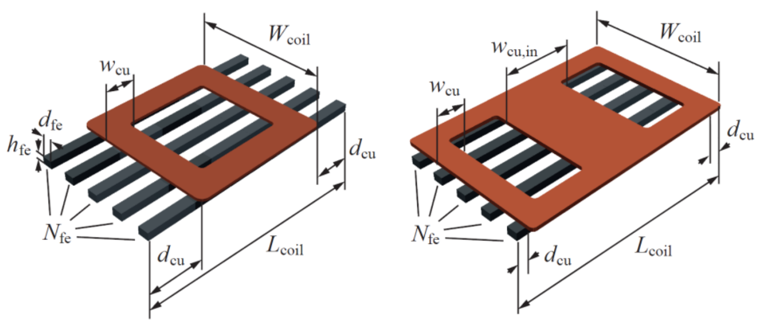
Multi-Objective Optimization of a 50kW Prototype (2)

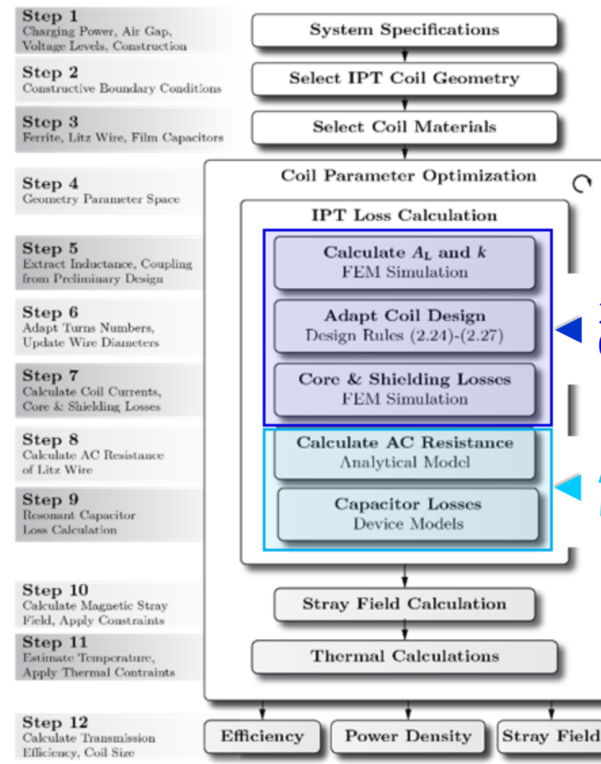
- **Pareto-Optimal Design – Efficiency / Power Density / Stray Field**
- **Comp. Evaluation of Rectangular & Double-D Coil Geometry**

- **Simplifications**
  - Identical Transmitter & Receiver Coils
  - Vehicle Chassis Not Considered

- **Fixed Parameters**
  - Litz Wire 2500 x 0.1mm
  - Core Material Ferrite K2004

- **Degrees of Freedom**
  - Number of Core Rods N_{fe}
  - Width of Copper Winding w_{cu}
  - Overlap of Core Rods d_{cu}
  - Outer Coil Dimensions $(W_{coil} \cdot L_{coil})$





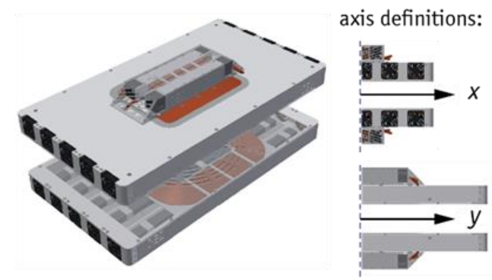
3D FEM Calculations

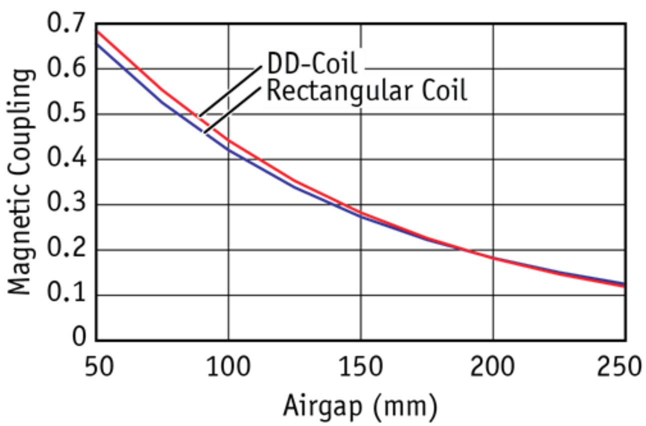
Analytical Models

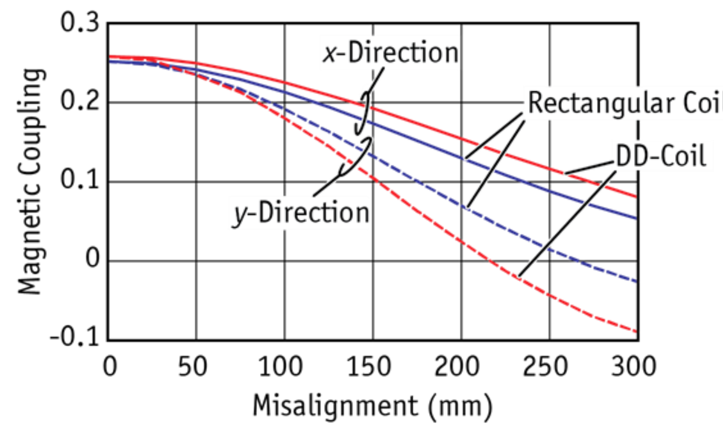
▶ Magnetic Coupling for Rectangular & Double-D Coils

- **Evaluation of Magnetic Coupling for Ideal and Misaligned Coil Positions**
  - 3D-FEM Simulation Results in Frequency Domain

- **Rectangular and Double-D Coil Achieve Equal Coupling for Ideal Positioning**
- **Performance Concerning Misalignment**
  - Double-D Coil → Less Sensitive in x-Direction
  - Rectangular Coil → Less Sensitive y-Direction

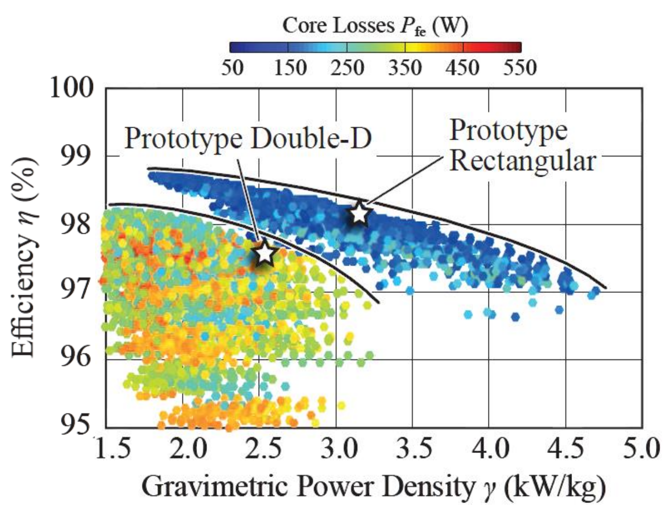




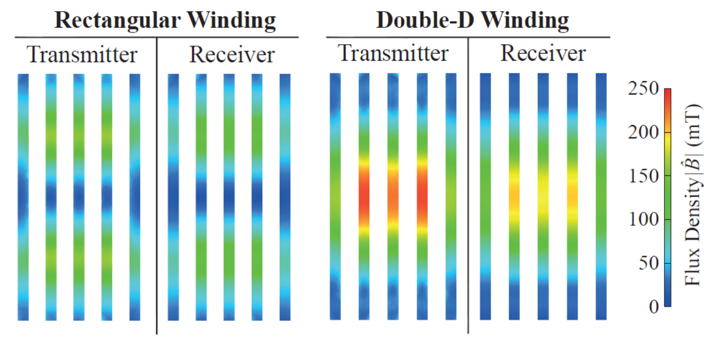


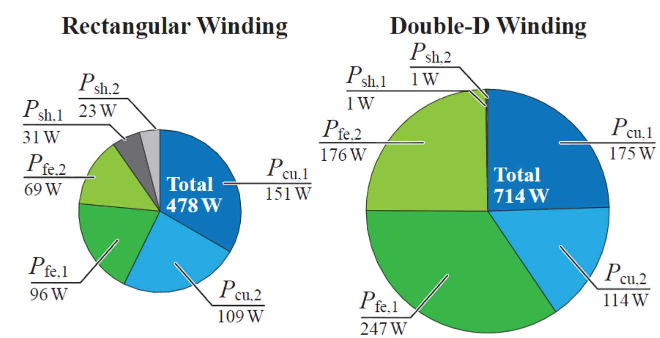
▶ Pareto Fronts for Rectangular & Double-D Coils (1)

- **Rectangular Coil Designs are Lighter & Allow to Reach Higher Efficiencies**
  - Higher Losses Result from High Flux Density in the Central Region of the Double-D Cores



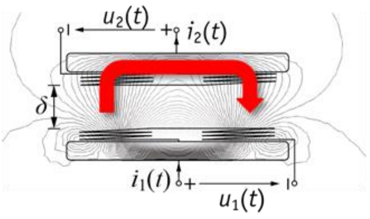
@ 50kW Output
160mm Air Gap



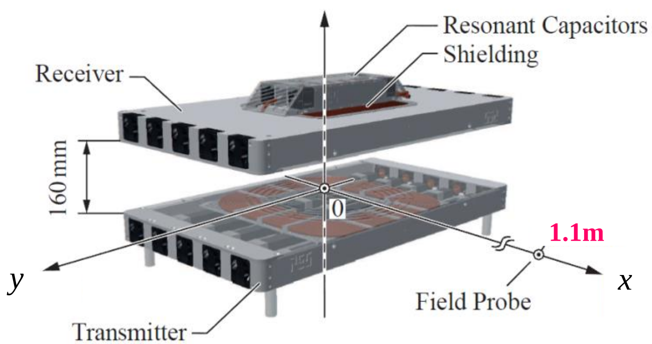


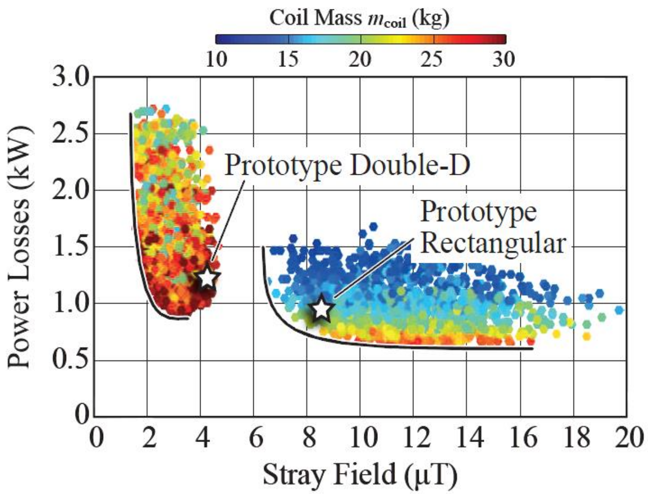
Pareto Fronts for Rectangular & Double-D Coils (2)

- **Double-D Coils show Significantly Lower Stray Field**
  - Integration of Main Flux Return Path into the Main Coil Structure
  - Lower Losses in Eddy Current Shielding



@ 1.1m Distance from Coil Center





Experimental Results of 50kW Demonstrator System

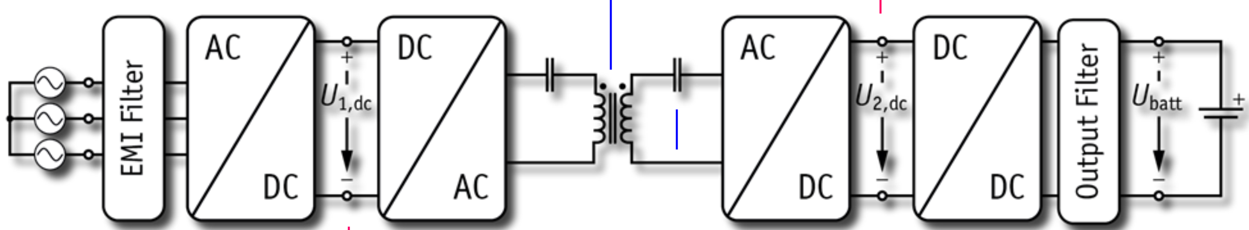
Power Electronics
Efficiency Measurements
Stray Field Measurements

Source:
Wasserstein

▶ System Overview

- **Transmission Coils**
  - Magnetic Design using FEM
  - Winding and Core Losses (FEM)
  - Thermal Model
  - Shielding of Stray Field

- **Receiver-Side Power Electronics**
  - Synchronous Rectification
  - Battery Current Regulation
  - Load Matching

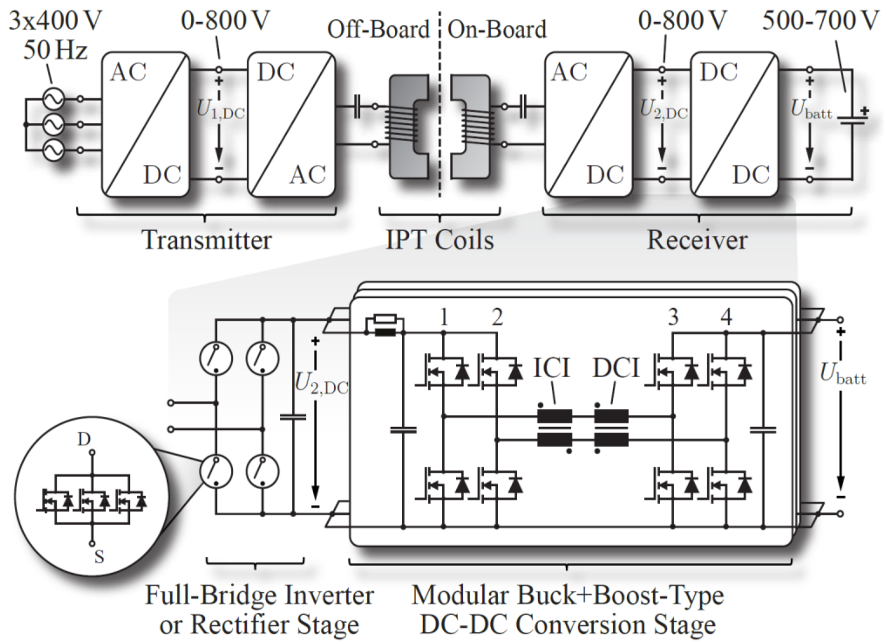


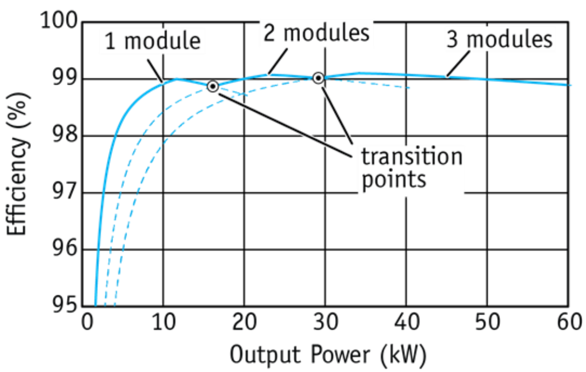
- **Transmitter-Side Power Electronics**
  - 1/3-Phase PFC Mains Interface
  - DC Link Voltage Control
  - High-Frequency ZVS Inv. Stage

- **Resonant Compensation**
  - Voltage and Current Stresses
  - Loss / Lifetime Analysis

► Concept of the 50kW Demonstrator System

- **Single ZVS SiC MOSFET Inverter Stage**
- **Modular SiC MOSFET DC/DC Converter**
  - 3x20kW - Ripple Cancel. by Parallel Interleaving
  - 2 Interleaved Magn. Coupl. Stages per Module
  - Disabling of Stages Ensures High Part-Load Efficiency
  - Ideally Complements High Part Load Efficiency of Coil System achieved by “Load Matching”

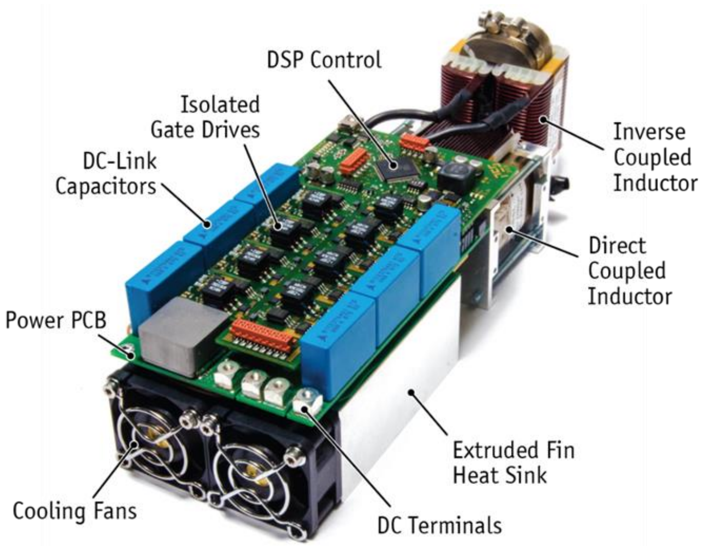


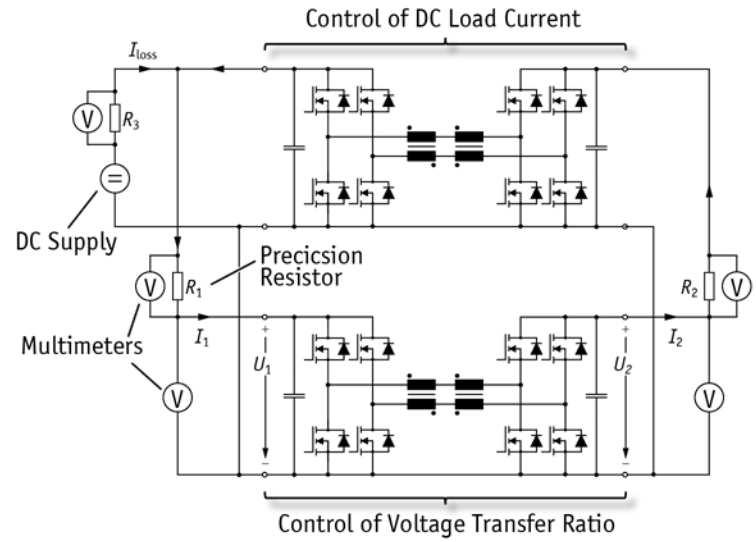


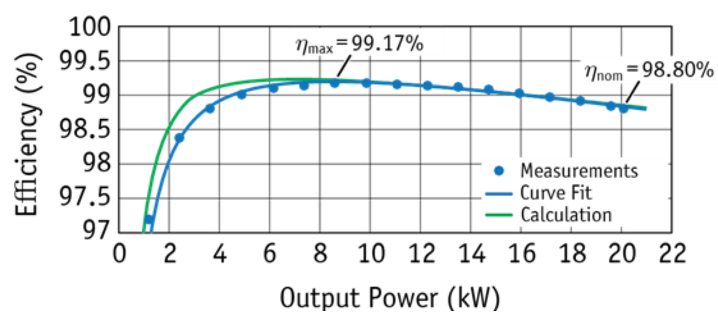
► SiC MOSFET Buck+Boost DC/DC Converter Module

- **Output Power** 20kW / 600…800V
- **Power Density** 12.7kW/dm³
- **DC/DC Efficiency** 98.8% @ Rated Load
- **Sw. Frequency** 50kHz (hard)

- **Efficiency Measurement by Back-to-Back Operation of Two DC/DC Conv. Modules**
  - Allows Direct Power Loss Measurement





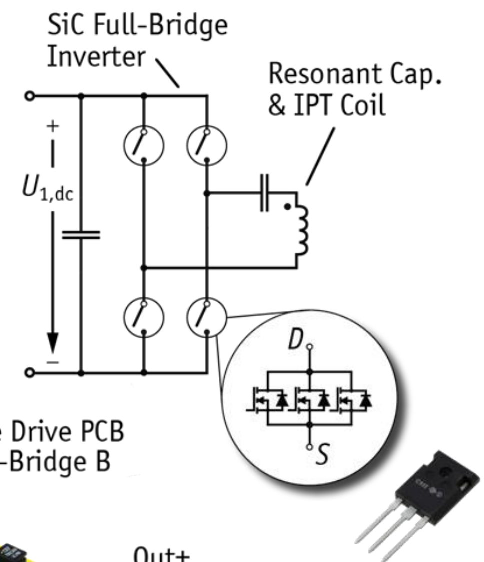


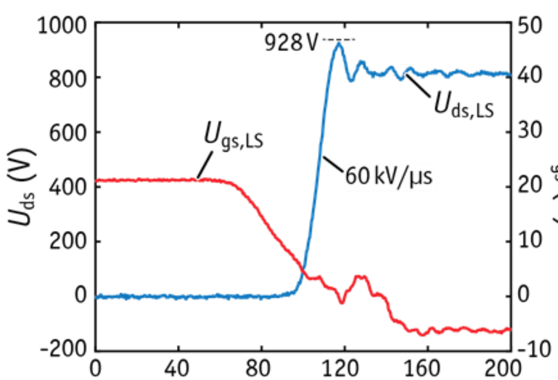
▶ SiC MOSFET ZVS Full-Bridge 60kW Inverter Stage

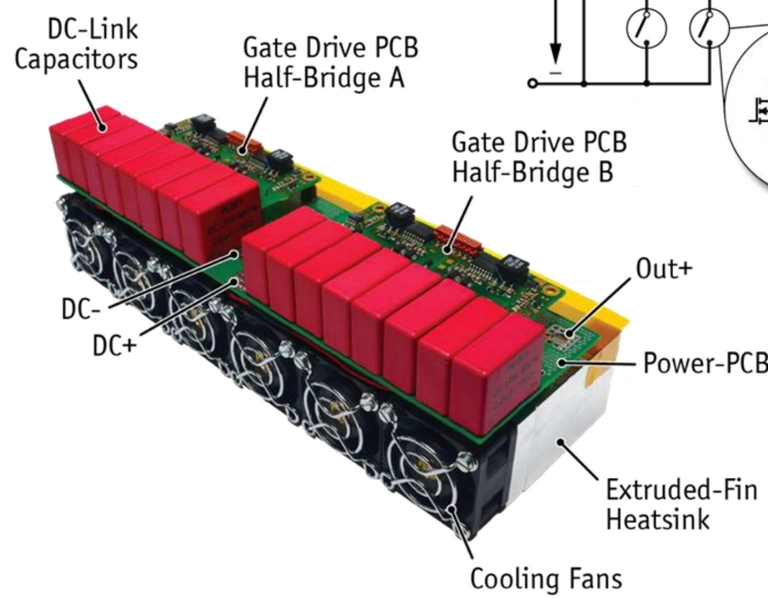
- **Output Power** **60kW @ 800V, 100A$_{rms}$**
- **Power Density** **40kW/dm^3**
- **Sw. Frequency** **85kHz**

- **Realization of Switches / Gate Drive / Circuit Layout**

  - 3x25mΩ 1200V SiC MOSFETs in Parallel
  - Single Gate Driver (3xR_{gate}) for Min. Complexity
  - Power PCB Layout Highly Critical for
    Symm. Current Distribution

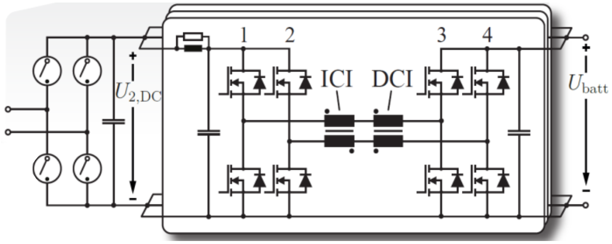


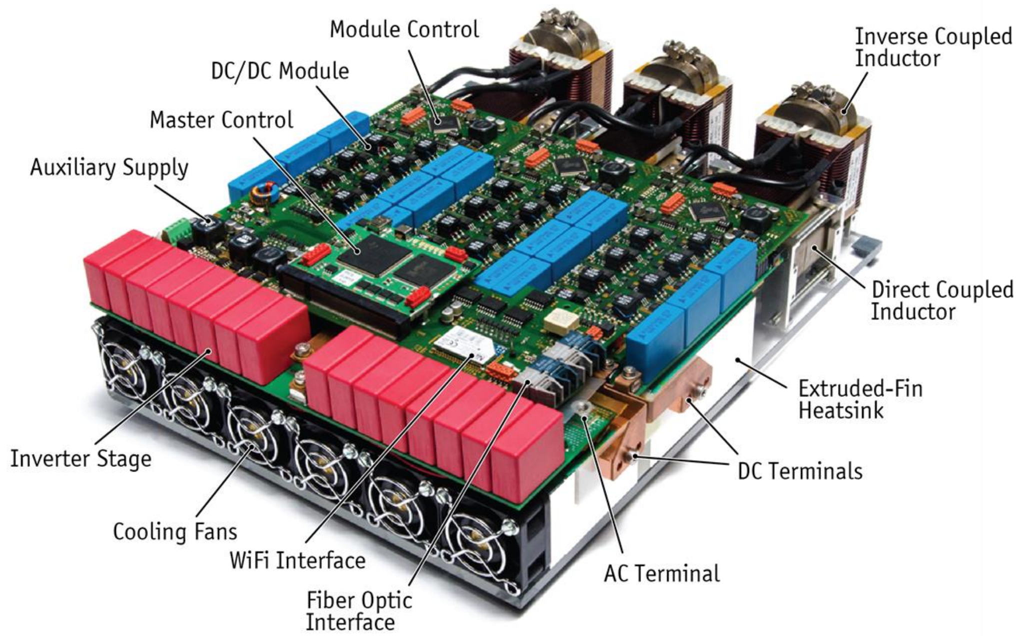




▶ 60kW SiC Inverter & DC/DC Converter

- AC/DC/DC Efficiency 98.6% (calcul.)
- Volum. Power Density 9.5kW/dm³
- Gravim. Power Density 6.8kW/kg
- Forced-Air Cooling
- Wireless Communication Link

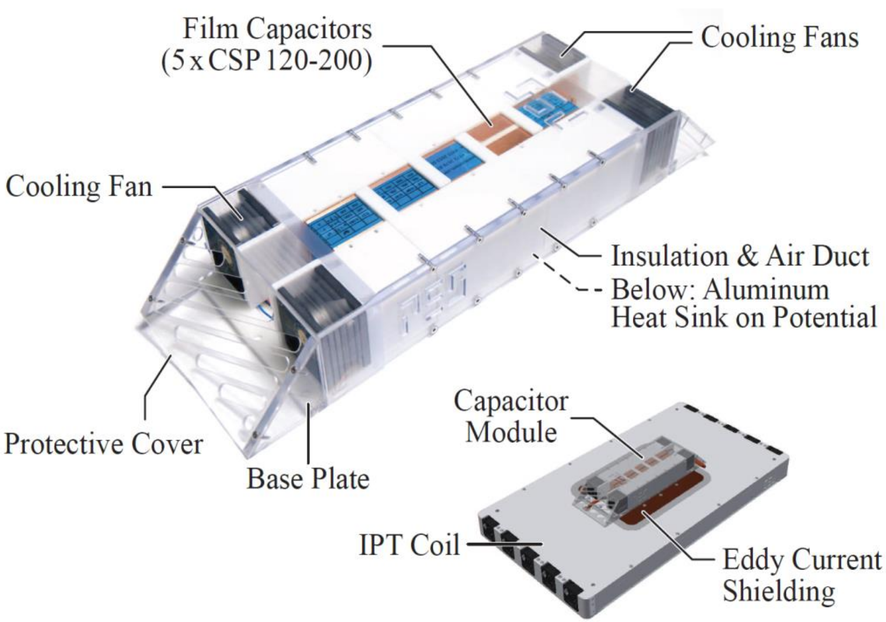


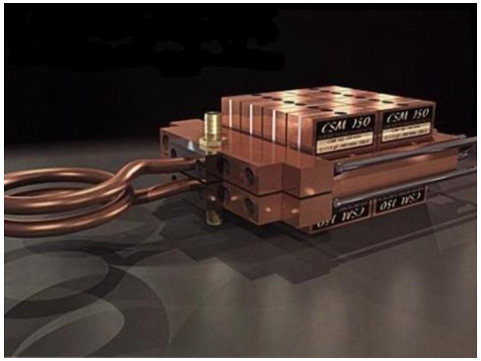


▶ Resonant Capacitor Module for 50kW System

- **Capacitor Requirements** **100A @ 85kHz / 3…4 kV_{rms}**
- **Capacitor Module** **5 x CSP 120-200 in Series**
  - 5 x 12 x 38 cm^3 / 2.6kg
  - 22kW/dm^3, 19kW/kg
  - 98.9% Efficiency @ 50kW

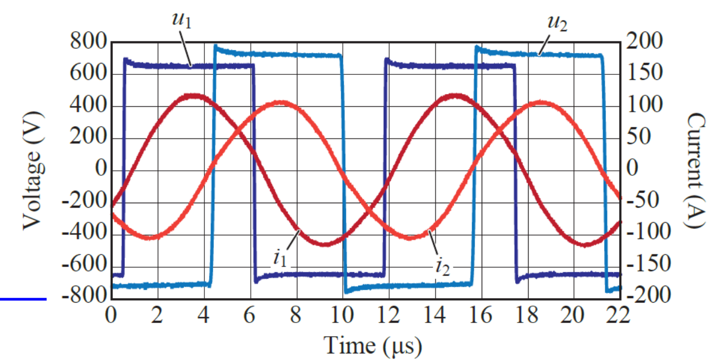
CSP 120-200
1.1 kV_{pk}
$tan(\delta)$ = 1/1000 ... 1/700
1MHz @ Full Power
6 kVA_r/cm^3



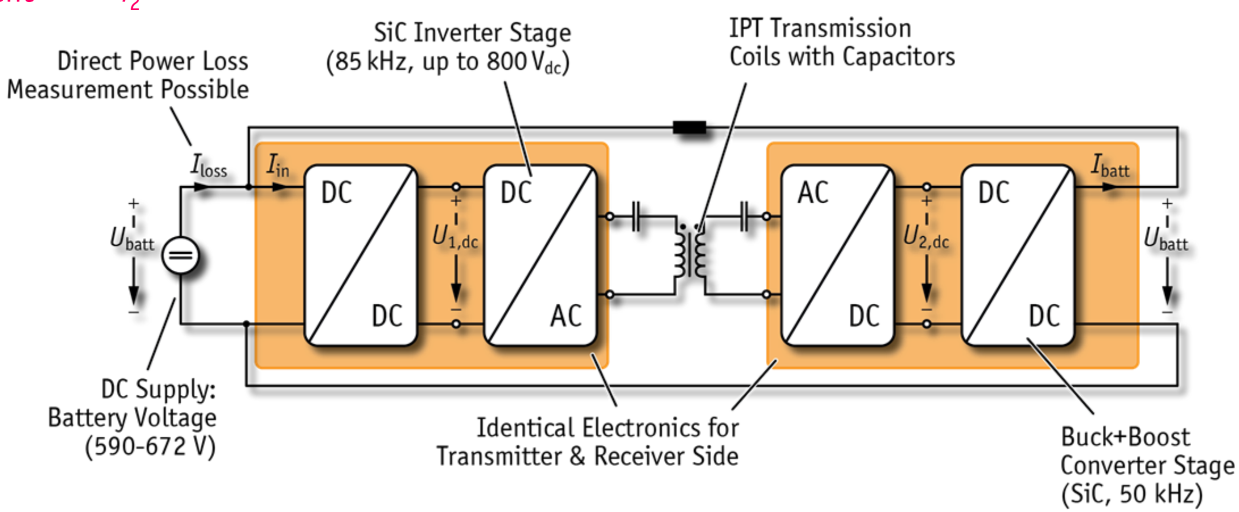


▶ Testing of 50kW System with Energy Circulation

- Direct Power Loss Measurement @ DC Supply Input
- Identical Conv. Stages @ Transmitter & Receiver
- Experim. Evaluation of Different Coil Designs



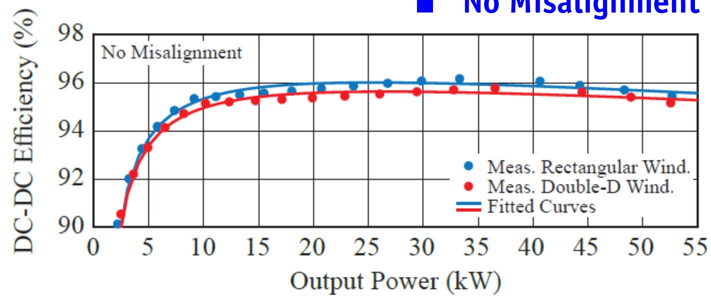
- Transm. Full-Bridge Volt. u_1 — @ 50kW/U_{batt}=600V
- Transmitter Coil Current i_1
- Receiver Rect. Inp. Volt. u_2
- Receiver Coil Current i_2



▶ Results of DC/DC Efficiency Measurements

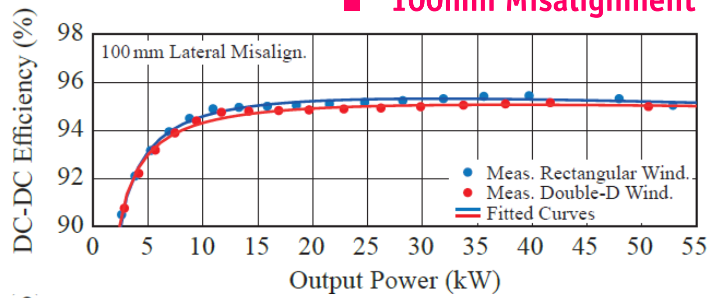
- **Misalignment Results in Lower Efficiency**
- **Lower Eff. of Double-D for Lateral Misalignment**
  - Flat Eff. Curve Due to “Load Matching”
  - Misalignment Results in Lower Coupling
  - Lower Efficiency Figure-of-Merit=*k·Q*

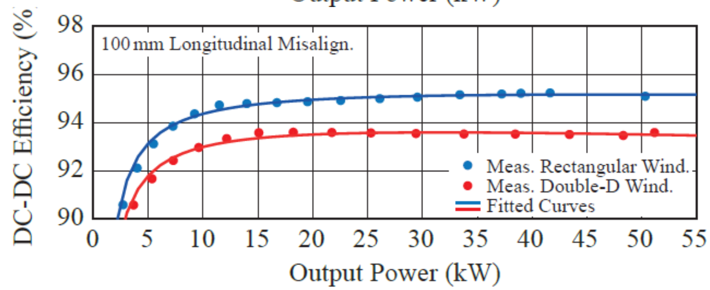
■ No Misalignment



Measurements @
160mm Air Gap

■ 100mm Misalignment

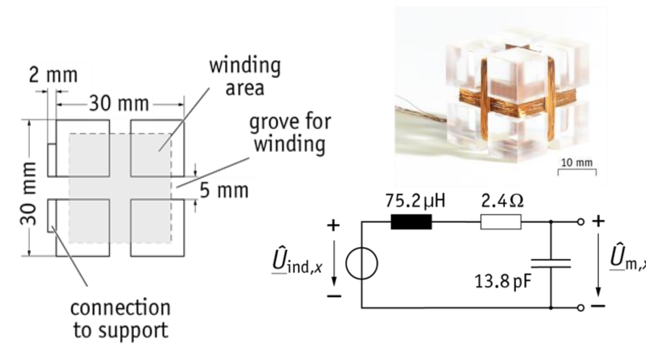


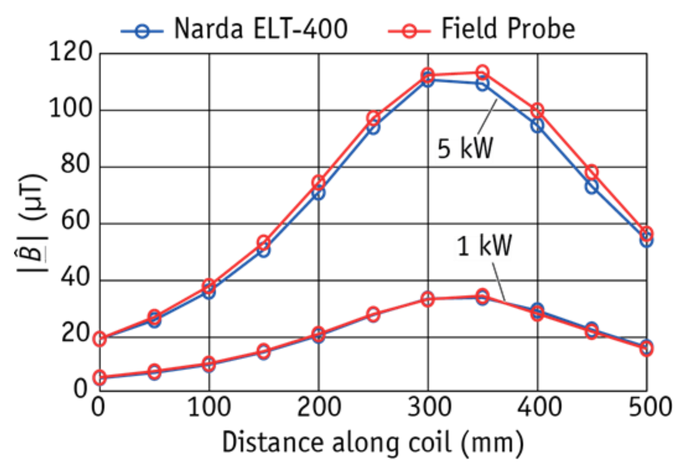


▶ Magnetic Stray Field Measurement

■ **Commercial Field Probe ELT-400 Replaced by Inexpensive Compact Laboratory Field Probe**

- 15mV/µT @ 100kHz
- Allows Precise Point Measurement





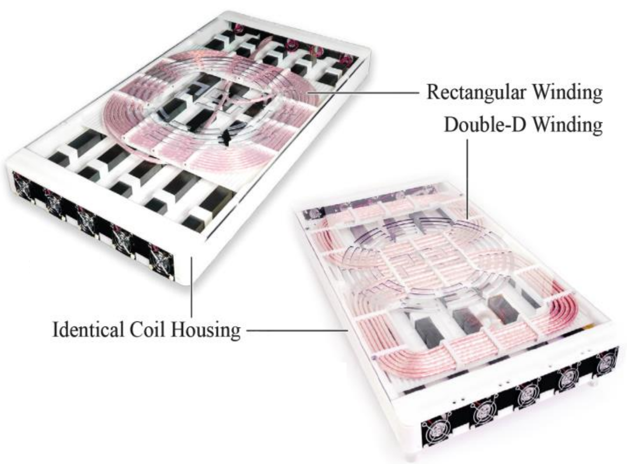
▶ Results of Magnetic Stray Field Measurement

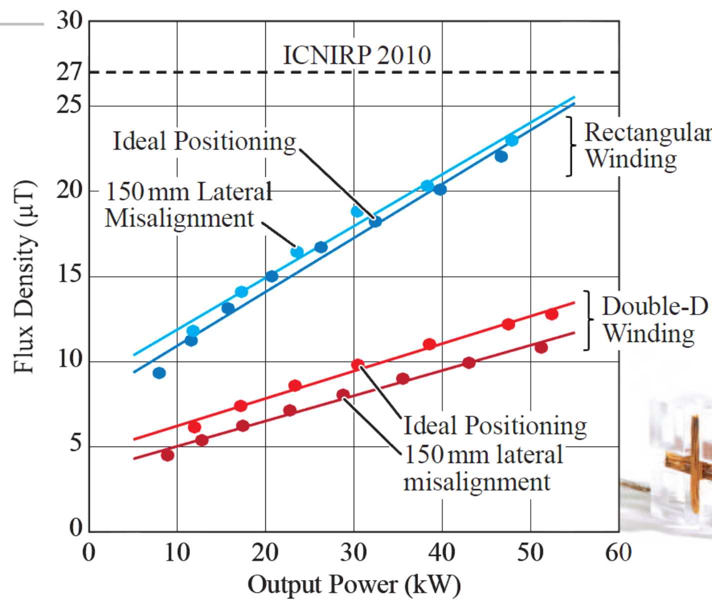
■ **Measurement @ 800 mm (Lateral) Distance from Air Gap Center Point**

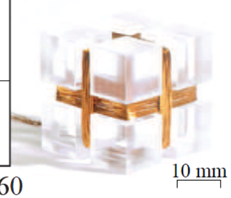
- No Misalignment & 150mm Lateral Misalignment
- Rectangular Coils Still Fulfill ICNRP 2010

Measurements @
160mm Air Gap

**Stray Filed of Double-D Coils
Lower by Factor of 2 (!)**







▶ Realized 50kW Hardware Demonstrator - Summary

- **All-SiC Power Electronics**
  - Rated Power 50kW
  - Battery Voltage 600...800V
  - Power Density 9.5kW/dm^3
  - Sw. Frequency 50kHz/85kHz

- **Inductive Power Transfer Coils**
  - Air Gap 150...220mm
  - Power Density 1.6kW/dm^2
  - Frequency 85kHz

★ η_{DCDC} **= 95.8% @ 50kW / ICNIRP @ 800mm**

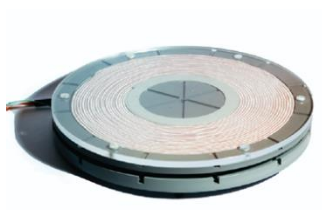
Technological Limitations

Limiting Factors
Competing Technologies

Source: www.rms.nsw.gov.au

Key Figures of Designed Demonstrator Systems

5 kW Prototype System



- Output Power 5 kW@400V, 100kHz
- DC/DC Efficiency 96.5%@53mm (meas.)
- Coil Dimensions 210 mm x 30 mm
- Weight Coil+Cap. 2.3 kg

- Spec. Weight 2.2 kW/kg
- Area-Rel. Power Dens. 1.5 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

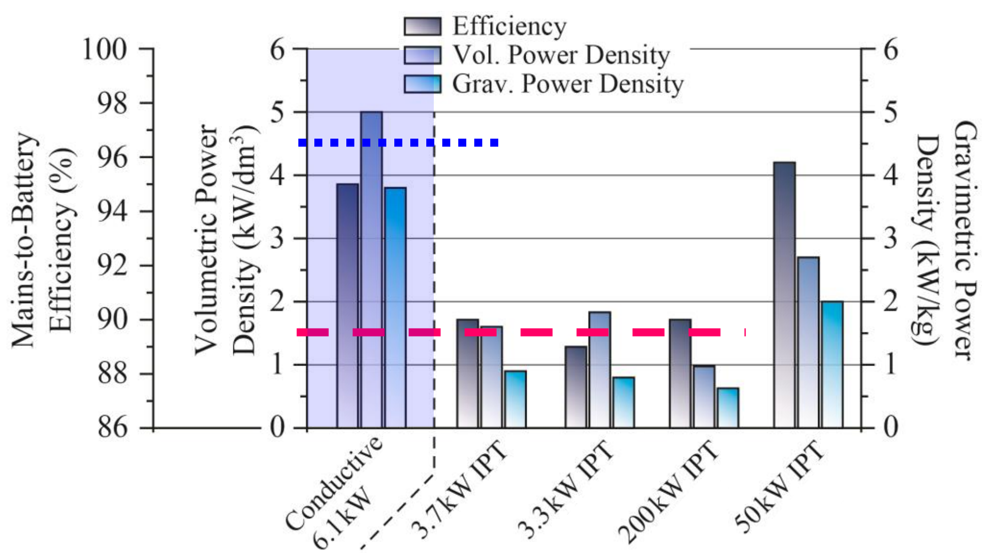
- Output Power 50 kW@800V, 85kHz
- DC/DC Efficiency 95.8%@160mm (meas.)
- Coil Dimensions 41 cm x 76 cm x 6 cm
- Weight Coil+Cap. 24.6 kg

- 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-Cip Area 9.4 mm^2/kW

- **DC/DC Efficiency ≈ 96% (No Misalignment) @ Power Density ≈ 1.5kW/dm²**

▶ Comparative Evaluation of IPT vs. Conductive Chargers

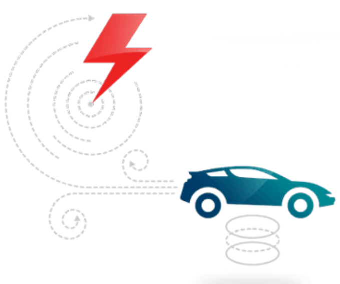
- 3...5% Lower Efficiency → 90% (incl. Misalignment) vs. 95...97% of Cond. Chargers
- Factor 2...3 Lower Power Density → Not incl. Constructional Parts for Mounting

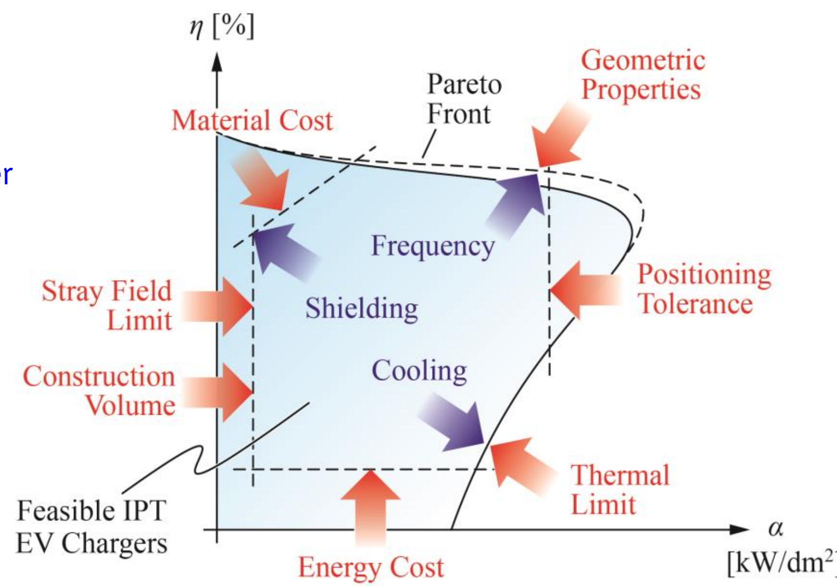


- Infrastructure Costs & Vehicle Integration Costs → Significantly Higher than for Cond. Charging

▶ Limitations of Inductive Power Transfer

- **Lower Efficiency of Compact Systems**
  - Smaller IPT Coils / Large Air Gap of Interoperability / Lower Coupling / Lower *FOM=k·Q* → ***Physical Limitation (!)***
- **Lower Misalignment Tolerance of Compact Systems**
  - Influence of Misalignment def. by IPT Coil Diameter / Larger Red. of Coupl. for Smaller IPT Coils → ***Physical Limitation (!)***
- **Lower Power Capability of Compact Systems**
  - Limited Convection Cooling w/o Metal Heatsinks / Limited Power Transfer per Area → ***Physical Limitation (!)***
- **Magnetic & Electric Stray Fields**
  - Emissions limited by Standards / Limits Power and Voltage Levels / Min. System Size or Distance Required → ***Power Limit (!)***

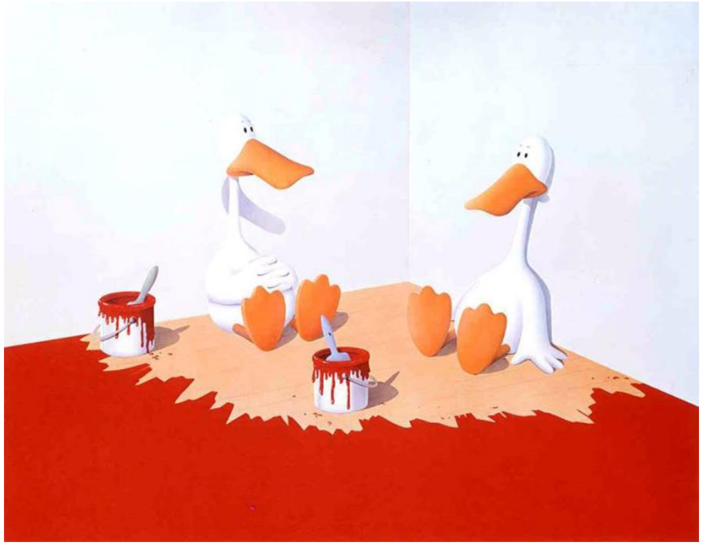


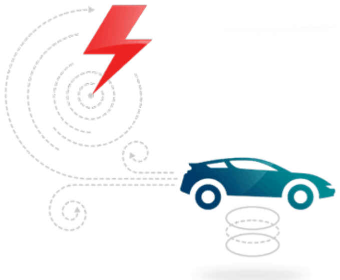


▶ Limitations of Inductive Power Transfer

- Ind. Power Transfer → - *More Convenient*
  - *More Expensive*
  - *Less Efficient* → *Improvement Blocked* by Physical Limits / Material Properties / Interoperability Requirements
  → Standard Restricts Key Design Parameters
    - f = 85 kHz
    - 10…30cm Air Gap etc.

Source: M. Bedard, 1989



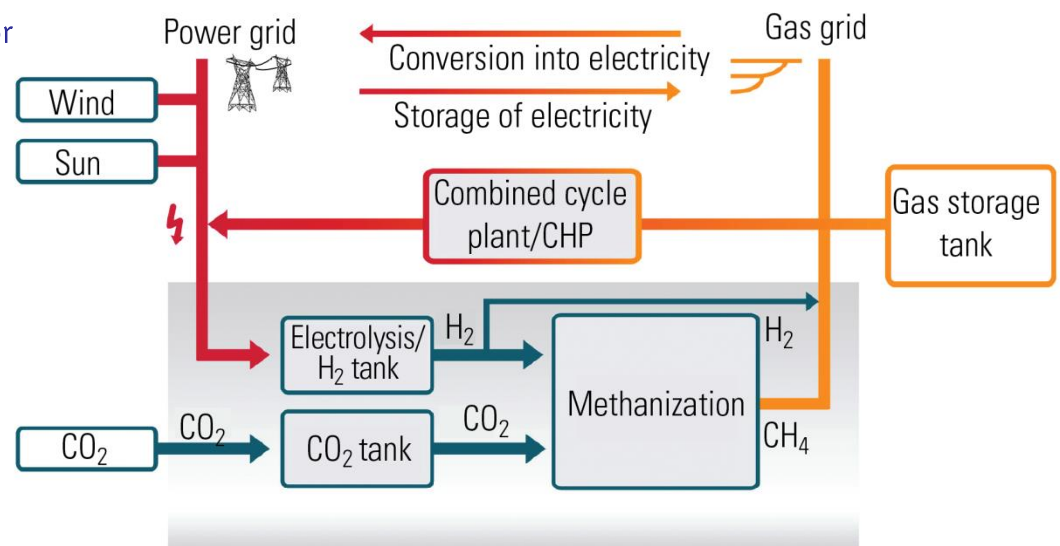


Source: www.qualcomm.com

► Future: H_2 / Fuel Cells Instead of Batteries ? (Power-to-Gas)

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

– Hydrogenics 100 kW H_2-Generator



Source: www.r-e-a.net

- **Future Public Transport could Adopt H_2 partly Utilizing Existing Petrol Station Infrastructure**

Future Research

Technology Advancements & Vehicle Integration

Comp. Full-System Evaluation of Cond./Ind./Cap. Charging incl. Infrastructure Costs

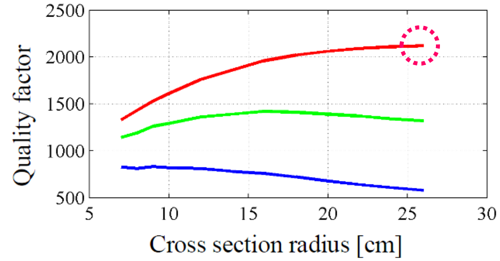
▶ MHz-Frequency Multi-kW Inductive Power Transfer

- Research on (Very)-High Sw. Frequ. Systems → Aiming for Lower Physical Size
- Up to Now Limited by Low Efficiency → IPT Coils ≈95% (Res. Cap. Not incl.) → Inverter ≈96% (Rectifier Not incl.)

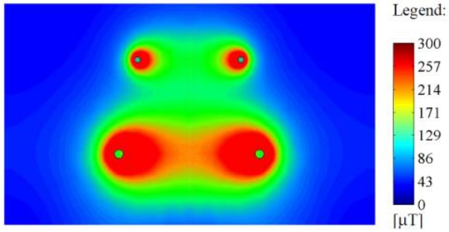
– B. Lorenz (2011)

η = 95%
3kW @ 3.7MHz
46cm Coil Diam.
30cm Air Gap

Loop Radius 10/17/25cm

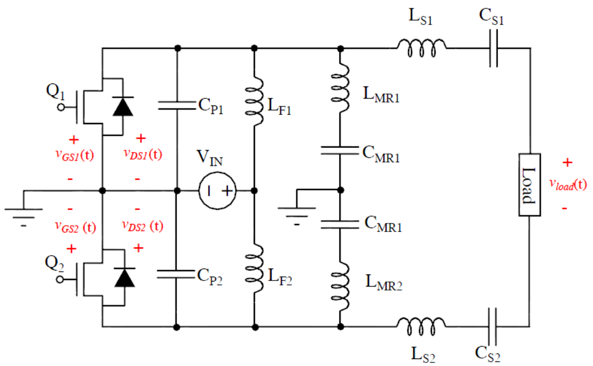


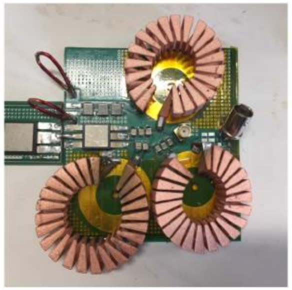
Surface-Spiral Coil

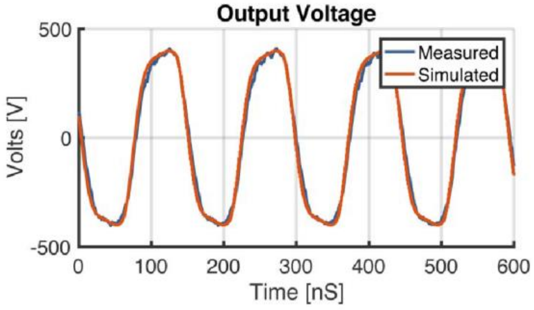


– J. Rivas (2016)

η = 96%
V_{DC} = 200V
650V eGaN FETs
2kW @ 6.78MHz





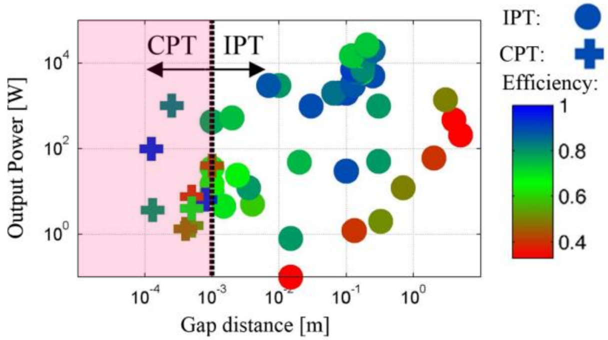


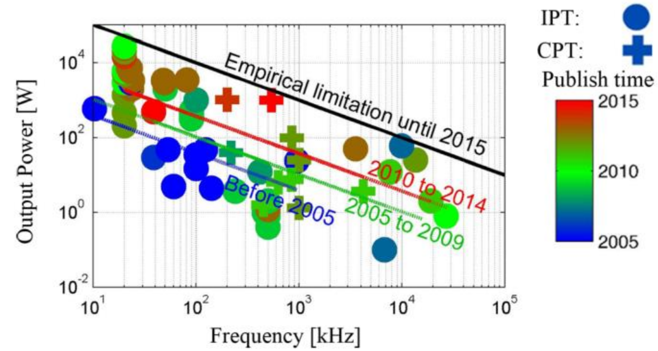
- Next Step – Full-System Design & Pareto-Optimiz. incl. EMI Filter & Shielding (incl. Meta-Materials)

▶ Large Gap High-Power Capacitive Power Transfer

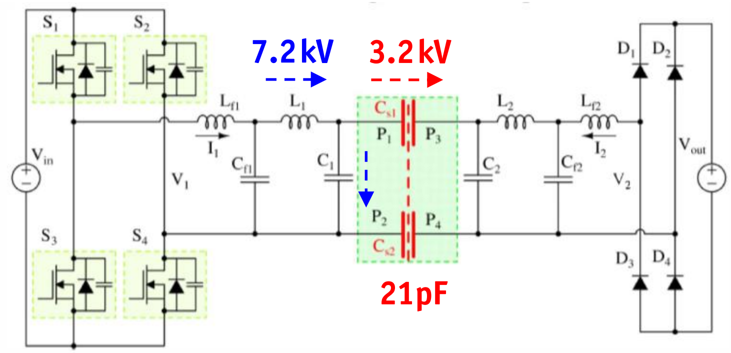
- 1^{st} Demonstrated by N. Tesla in 1891
- Renewed Interest within Last Decade → Recently Demonstrations for Large Gaps

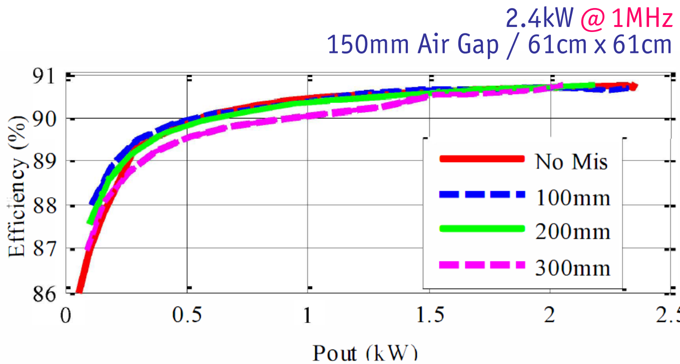
– D. Ludois (2015)





– C. Mi (2015)





- Next Step – Full-Syst. Pareto-Optimiz. incl. Stray Field & Safety / Comparison to IPT

Thank You !

Questions