Inductive EV Battery Charging Systems

Requirements, Basics, Limitations, Future Research

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Outline

► Introduction
► Basic Requirements
► IPT Fundamentals
  * Resonant Compensation
  * Pole Splitting
  * Load Matching
  * Figure-of-Merit
  * Control
► Optimization / Pareto Front
► Physical Limitations
► Future Research

Acknowledgement

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Introduction

E-Mobility
Motivation for Wireless Charging
Requirements
Global Trend Towards E-Mobility

- Key Advantages of Electric Vehicles
  - Smaller CO₂-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

- **Key Advantages of Electric Vehicles**
  - Smaller CO₂-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

Self-Driving will be **THE Main Feature of Future Cars** → Requires Compatible Refueling Concept (!)
Inductive EV Battery Charging – Advantages

- 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
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)

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

  - **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
Source: www.chargepoint.com
Source: www.qualcommhalo.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 $S = E \times H$ 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** ($\text{kW/dm}^2$, kW/kg)
  - High Ratio of Coil Diameter / Air Gap Needed
  - Heavy Shielding & Core Materials Necessary

- **High Efficiency** $\eta$
  - Efficiency Limited by Magnetic Coupling
  - Sensitivity to Coil Misalignment

- **Low Magnetic Stray Field** $B_s < B_{\text{lim}}$
  - 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**
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**
  - $\frac{di}{dt}$ defined by Voltage Levels & Transformer Stray & Magn. Ind.

- **Schematic Converter Waveforms**

- **Realization Example**

Source: D. Jitaru, 2000
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 $C_{s,\text{opt}} = \frac{1}{\omega_s^2 L_0}$ to Match Resonance and Inverter Sw. Frequency

Bode Diagram of $Z_S$ for Different Values $C_s$

- Converter Output Characteristics

Converter Output Characteristics

Bode Diagram of $Z_S$ for Different Values $C_s$
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)**
  - 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

\[ U_{1(1)} = \frac{4}{\pi} U_{1,dc} \]

\[ Z_s = 0 \quad \omega = \omega_s \]

\[ R_{L_{eq}} = \frac{8 U_{2,dc}}{\pi^2 P_2} \]

\[ \omega_s = \frac{1}{\sqrt{1-k^2} L_1 C_s} \]

- 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 \( R_{Leq} = \text{const.} \)
**Series-Series Compensated IPT System (1)**

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

![Circuit Diagram]

- Complete Cancellation of Self-Inductance @ $\omega_0$
- $\varphi_{Zin}=0$ @ $\omega_0$ Independent of $k$ and $R_{L,eq}$

![Graph]

- But: Voltage Gain @ $\omega_0$ Still Coupl. and Load Dependent!

- Voltage Transf. Ratio for $R_{L,eq}=$ const.
Series-Series Compensated IPT System (2)

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

- Complete Cancellation of Self-Inductance @ $\omega_0$
- $\varphi_{Z_{in}}=0$ @ $\omega_0$ Independent of $k$ and $R_{L,eq}$

Voltage Transf. Ratio for $k=const.$

$$\omega_0 = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}}$$

But: Voltage Gain @ $\omega_0$ Still Coupl. and Load Dependent!
**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** \( \omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \)

- **Purely Ohmic Input Impedance for Any Load & Coupling @ \( \omega_0 \)**

\[
Z_{\text{in}} = -j \omega_0 M + \frac{j \omega_0 M \cdot (R_{\text{L,eq}} - j \omega_0 M)}{j \omega_0 M + R_{\text{L,eq}} - j \omega_0 M} \quad \Rightarrow \quad Z_{\text{in}} = \frac{\omega_0^2 M^2}{R_{\text{L,eq}}} \quad \Rightarrow \quad \arg[Z_{\text{in}}] = 0 \quad k = 0 \rightarrow Z_{\text{in}} = 0
\]
\[
R_{\text{L,eq}} = 0 \rightarrow Z_{\text{in}} = \infty
\]
Interesting Properties of Series-Series Compensation (2)

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

- Output Current @ \( \omega_0 \) Independent of Load Resistance \( R_{L,eq} \)

\[
\begin{align*}
\hat{u}_h &= \hat{i}_2 (R_{L,eq} - j\omega_0 M) \\
\hat{i}_h &= \frac{\hat{i}_2}{j\omega_0 M} (R_{L,eq} - j\omega_0 M) \\
\Delta \hat{u} &= -j\omega_0 M (\hat{i}_2 + \hat{i}_h) = -j\omega_0 M \hat{i}_2 - \hat{i}_2 (R_{L,eq} - j\omega_0 M)
\end{align*}
\]

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

\[
\hat{i}_2 = \frac{j\hat{u}_1}{\omega_0 M}
\]
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 $i_1$ and $i_2$ are Displaced by 90°

\[
\hat{i}_1 = \hat{i}_2 \frac{R_{\text{Leq}}}{j\omega_0 M} = \hat{u}_1 \frac{R_{\text{Leq}}}{\omega_0^2 M^2}
\]

- For $\phi = 135°$ a Poynting Vector Analysis Confirms Power Transfer Despite Decoupled Field Lines

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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 (!)
  \[ \frac{P_{loss}}{P_2} = \frac{P_{loss,1}}{P_2} + \frac{P_{loss,2}}{P_2} \]

- **Min. Relative Losses**
  - Min. Loss Factor \( \lambda \)
  \[ \frac{d}{dR_{L,eq}} \left( \frac{P_{loss}}{P_2} \right) = 0 \]

- **Load Resistance for Max. Efficiency**
  \[ R_{L,opt} = \sqrt{\frac{\omega_0^2 M^2}{\lambda} + \frac{R_{ac}^2}{\lambda_1}} \approx k\omega_0 \sqrt{L_1 L_2} \]
  \[ R_1 \approx R_2 = R_{ac} @ \omega_0 \]
**Efficiency Limit & “Figure-of-Merit” (FOM)**

- Maximum Efficiency for Opt. Load Resistance
  \[ R_{\text{L, opt}} \approx k \omega_0 \sqrt{L_1 L_2} \]
  \[ \eta_{\text{max}} = \frac{k^2 Q_1 Q_2}{\left(1 + \sqrt{1 + k^2 Q_1 Q_2}\right)^2} \approx 1 - \frac{2}{k \sqrt{Q_1 Q_2}} \]

\[ \rightarrow \text{Figure-of-Merit} = k \sqrt{Q_1 Q_2} = kQ \]

- Magnetic Coupling
  \[ k = \frac{L_h}{\sqrt{L_1 L_2}} \]
- Coil Quality Factor
  \[ Q = \frac{\omega L}{R_{\text{ac}}} \]

---

**Diagram:***

- Frequency vs. Magnetic Coupling
- Coil Diameter (4 Turns) vs. Air Gap
- Transfer Efficiency (%)
- Figure-of-Merit vs. Frequency

**Values:**
- \( k = 0.25 \) / \( Q = 400 \)
- \( k = 0.1 \) / \( Q = 1000 \)
- \( k = 0.2 \) / \( Q = 100 \)
- \( k = 0.05 \) / \( Q = 400 \)
- \( k = 0.3 \) / \( Q = 10 \)
- \( k = 0.03 \) / \( Q = 100 \)
Maximizing $FOM = \text{Quality Factor} \times \text{Magnetic Coupling}$

- «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)

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

Source: www.witricity.com
Source: www.toyota.com
Efficiency Optimal Control of the System

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

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

\[
\begin{align*}
P_2^* & \quad \text{... reference} \\
\omega_0 & \quad \text{... selected} \\
U_{\text{batt}} & \quad \text{... given} \\
k & \quad \text{... estimated}
\end{align*}
\]

\[R_L^* \approx k\omega_0 L_2 = \frac{8}{\pi^2} \frac{U_{2,\text{dc}}^2}{P_2^*}\]

\[U_{2,\text{dc}}^* = \sqrt{\frac{\pi^2}{8} P_2^* k\omega_0 L_2}\]
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

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

Source: Yokogawa
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

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

- **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
Selection of Transmission Coil Geometry
- **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

- **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

Source: Fraunhofer ISE
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**
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  - Coil Geometry Guides Return of the Flux
  - Relatively Low Stray Field
  - Coupling Strongly Dependent on Diameter/Airgap Ratio
  - Max. Coupling for Certain Core Overlap

Source: G. Covic / J. Boys et al.
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·m²) and 10W/(K·m²))

Exp. Measurement Verifies < 5% Error
0.2W/cm² is a Reasonable Assumption for Forced Convection
Selection of the Resonant Capacitors (1)

- Polypropylene Film Capacitors for Resonant Applications
  - Low $\tan(\delta)$ (Low High-Frequency Losses) and Low ESR
  - Least Affected by Temperature / Frequency / Humidity
    (Could Lead to Changing Resonant Frequency)

Source: EPCOS

Frequency Dependency of $\tan(\delta)$
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 $t_{\text{Life}}$ by Factor of 2!

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

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<th>$\pi_V$</th>
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- **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. [m³]
- Switching Frequency [kHz]

■ System Performance
- Efficiency $\eta = \frac{P_{\text{out}}}{P_{\text{in}}} [%]$
- Power Density $\alpha = \frac{P_{\text{out}}}{A_{\text{coil}}} [\text{kW/dm}^2]$
- Stray Field $\beta = \frac{B_{\text{max}}}{B_{\text{normi}}} [%]$
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

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**Diagram:**
- Desing Specifications $P_L, U_{in,c}, U_{in,d}, I_d, f_0$
- Limitations of Target Application (Coil Size/Weight, Cooling, Stray Fields)
- Select Coil Geometry (Spiral, Rectangular, Double-D, etc.) and Geometry Parameters
- Build FEM Coil Model
- Calc. Equivalent Coil Parameters $L_1, L_2, L_3, k$
- Design Number of Turns to Reach $R_1 = k \omega L_2$
- Calc. Compensation $C_1, C_2$
- & Actual Operating Point $I_1, I_2$
- FEM-Cal. of Actual Operating Point $P_{ coil}, P_{ wind}$
- Selection of a Copper Litz Wire
- Analytical Model for for $R_{1, ac}, R_{2, ac}, P_{ wind}$
- Calculation of Efficiency $η$, Power Density $α/ρ$, Specific Weight $γ$
- Thermal Analysis of Coil Designs
- Calculation of Pareto-Front & Trade-Off Analysis
- Selection of a Design for Prototype

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ies
\( \eta - \alpha \)-Pareto Coil Optimization (2)

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

Component & System Models

Performance Space

![Diagram showing the relationship between efficiency and power density with magnetic coupling as a parameter.](image)

Each Point Represents a Separate Coil Design
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 = $kQ$)
  - 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 = $kQ$)
  - 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 \( R_{L,\text{opt}} \approx \kappa \omega_0 \sqrt{L_1 L_2} \) allows Lower \( L_1, L_2 \) at higher \( \omega_0 \)
  - 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

- \( \eta-\alpha \)-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 $u_L$

  \[ u_L = N \frac{d\Phi}{dt} \propto \omega_0 B A_{\text{coil}} \]

- **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

**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

**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
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/dm²
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

- Coils
- System Specifications
- Select IPT Coil Geometry
- Select Coil Materials
- Coefficient Parameter Space
- Extract Inductances, Coupling from Ordinary Design
- Adapt Turns Numbers, Update Wire Diameter
- Calculate Coil Currents, Core & Shielding Losses
- Calculate AC Resistance of Litz Wire
- Thermal Capacitor Loss Calculation
- Calculate Magnetic Stray Field, Apply Constraints
- Estimate Temperature, Apply/Thermal Constraints
- Calculate Transmission Efficiency, Coil Rin
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
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\textsubscript{rms}
- Power Density: 40kW/dm\textsuperscript{3}
- Sw. Frequency: 85kHz

Realization of Switches / Gate Drive / Circuit Layout
- 3x25mΩ 1200V SiC MOSFETs in Parallel
- Single Gate Driver (3xR\textsubscript{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\text{rms}
  - 5 x CSP 120-200 in Series

- Capacitor Module
  - 5 x 12 x 38 cm\(^3\) / 2.6kg
  - 22kW/dm\(^3\), 19kW/kg
  - 98.9% Efficiency @ 50kW

CSP 120-200
1.1 kV\text{pk}
\tan(\delta) = 1/1000 ... 1/700
1MHz @ Full Power
6 kVA\(_c\)/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 $i_2$

Diagrams and equations are depicted in the figure.
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 = kQ

Measurements @ 160mm Air Gap

Identical Coil Housing

Rectangular Winding
Double-D Winding

No Misalignment

100mm Misalignment

100mm Lateral Misalign.
100mm Longitudinal Misalign.

DC-DC Efficiency (%)
Output Power (kW)
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

Stray Field 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/dm³
  - Sw. Frequency: 50kHz/85kHz

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

\[ \eta_{\text{DC-DC}} = 95.8\% \at 50\text{kW} / \text{ICNIRP} \at 800\text{mm} \]
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/dm²
- Power Density: 4.8 kW/dm³
- 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/dm²
- Power Density: 2.7 kW/dm³
- Spec. Copper Weight: 52 g/kW
- Spec. Ferrite Weight: 160 g/kW
- Spec. SiC-Cip Area: 9.4 mm²/kW

DC/DC Efficiency ≈ 96% (No Misalignment) @ Power Density ≈ 1.5 kW/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 $FOM = k \cdot Q \Rightarrow \text{Physical Limitation (!)}$

- **Lower Misalignment Tolerance of Compact Systems**
  - Influence of Misalignment def. by IPT Coil Diameter / Larger Red. of Coupl. for Smaller IPT Coils $\Rightarrow \text{Physical Limitation (!)}$

- **Lower Power Capability of Compact Systems**
  - Limited Convection Cooling w/o Metal Heatsinks / Limited Power Transfer per Area $\Rightarrow \text{Physical Limitation (!)}$

- **Magnetic & Electric Stray Fields**
  - Emissions limited by Standards / Limits Power and Voltage Levels / Min. System Size or Distance Required $\Rightarrow \text{Power Limit (!)}$

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Source: www.qualcomm.com
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**
- \( f = 85 \text{ kHz} \)
- 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

- 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)

\[ \eta = 95\% \]
3kW @ 3.7MHz
46cm Coil Diam.
30cm Air Gap

- J. Rivas (2016)

\[ \eta = 96\% \]
\[ V_{DC} = 200V \]
650V eGaN FETs
2kW @ 6.78MHz

Large Gap High-Power Capacitive Power Transfer

- 1st 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