Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

AMAA 2014
Smart Systems for Safe, Clean and Automated Vehicles

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Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Agenda

- **Objectives and Requirements**
- **Energy Transfer**
  - Inductive transformer
  - Power electronics
  - Power system integration
- **Additional Functions**
  - Foreign object protection
  - Living object protection
  - Positioning assistance
  - RF system interference
- **Summary**

Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Objectives

Comfort

- Eliminates plug-in and cables
- Park positioning support/assistance

Security

- Cable free, minimizing tampering and preventing hazards
- Elimination of tripping over cables

Availability

- Account for frequent insertions
- Automatic charging, increasing range
- Theft prevention

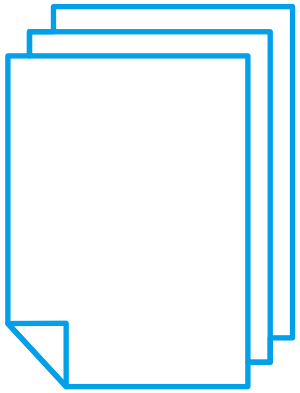
Variants

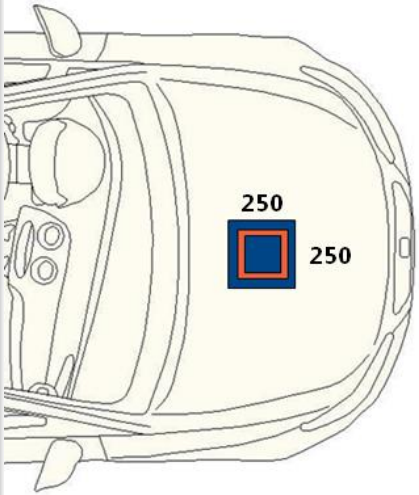
- Stationary parking, including public, residential and during travel
- Dynamic en-route – while driving

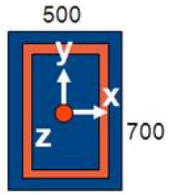
Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Requirements

Input Voltage	230VAC / 50Hz / 60Hz
Input Power	3.7kW ... later: 7.2kW…22kW
Power Factor	>0.98
Efficiency DC_{out}/AC_{in}	>90%
Output Voltage	≤450VDC
Output Current	10A
Energy Transfer Direction	Uni-directional ... Later: Bi-directional
Operating Frequency	85kHz (140kHz)
Air Gap	120mm…150mm…210mm
Tolerance Gap	Dz<50mm
Tolerance X/Y	Dx<100mm; Dy<150mm
Volume (Vehicle Side)	250mm x 250 mm x 20 mm
Flux Density (general vacinity)	<6.25µT (ICNIRP) INTERNATIONAL COMMISSION ON NON-IONIZING RADIATION PROTECTION







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Commercial applications of wireless energy transfer

High power

Industry

Quelle: greenovation.tv

Inductive cooking

Low power

Quelle: WHD

Inductively charged toothbrushes

Quelle: Duracell

Inductively charged portable devices

Features and Functions

- Air gap
- Power
- Efficiency
- Frequency
- Control
- Field Monitoring
- Positioning

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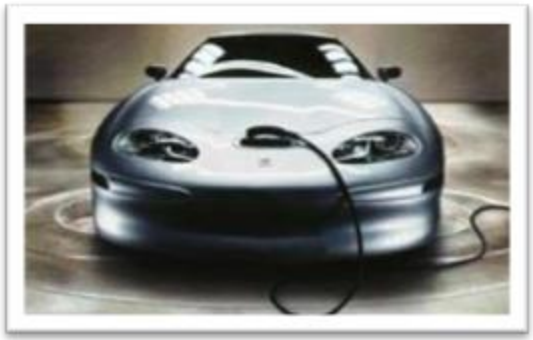
Evolution of inductive car charging

HELLA VAHLE
Inductive charging

VAHLE
licence plate charging



GM EV-1
Delco Electronics

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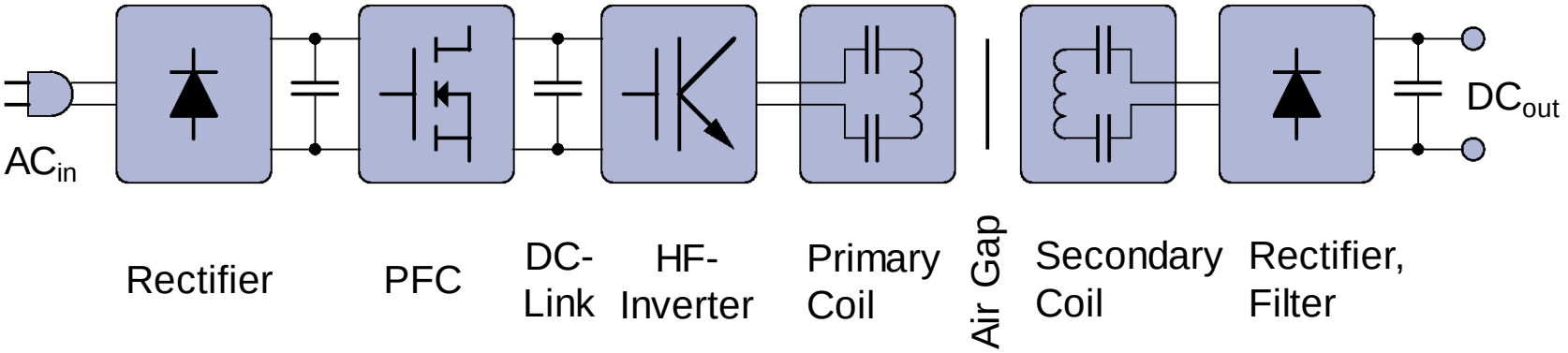
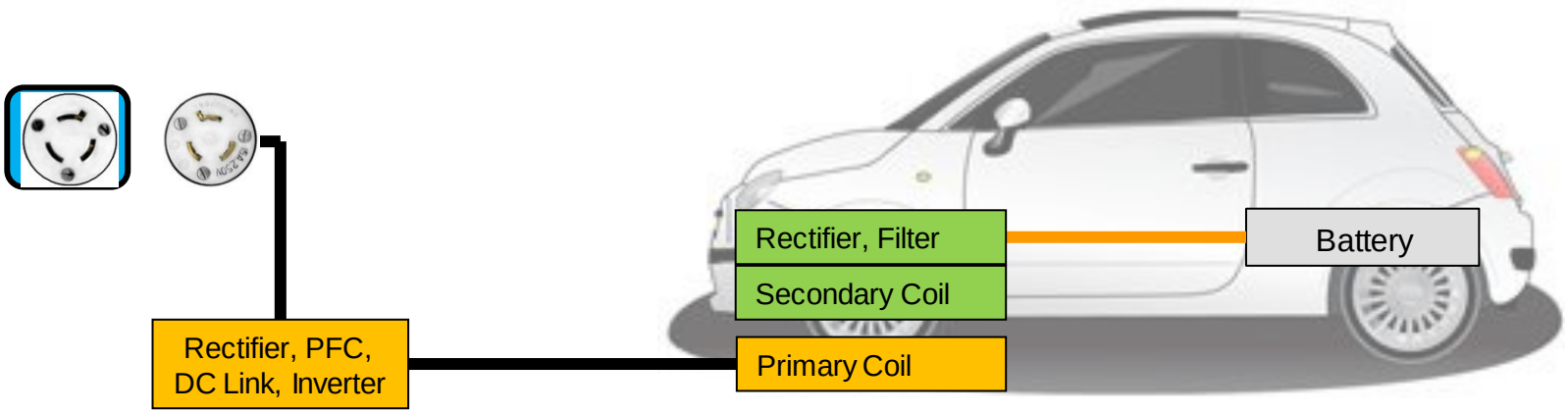
System overview of the energy transfer





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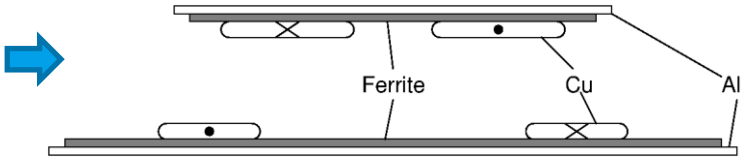
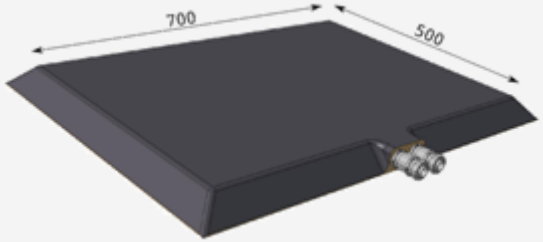
Power Transmission – 3.7kW Demonstration Unit

Cu – Windings: Generate field
Ferrite: Field guide
Al: Aluminum Shielding



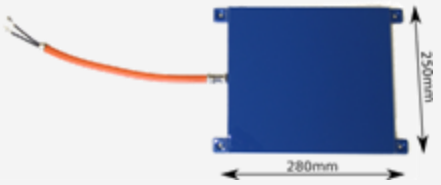
Bottom Plate

- Primary circuit (L,C)
- Can be driven over with vehicle
- Sensors for additional function
- Integrated power electronics [Future]



Pick-up

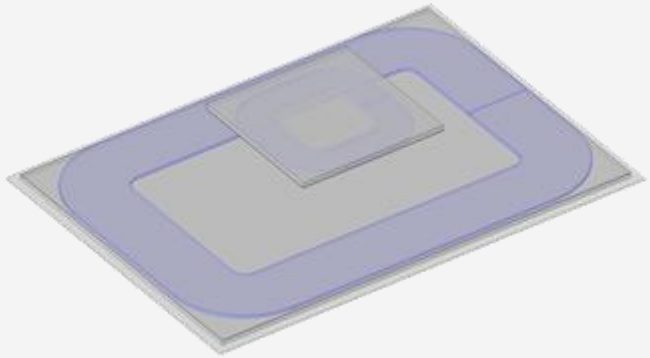
- Secondary circuit (Rectifier)
- Small, lightweight
- Sensors for power transmission and additional functions



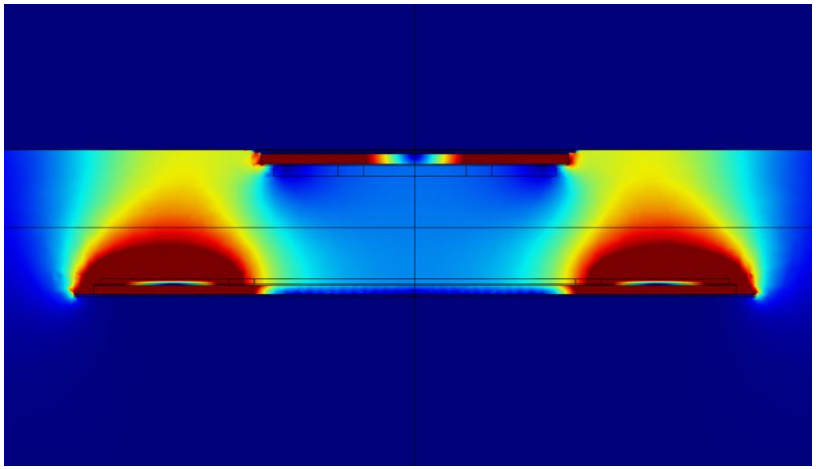
Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

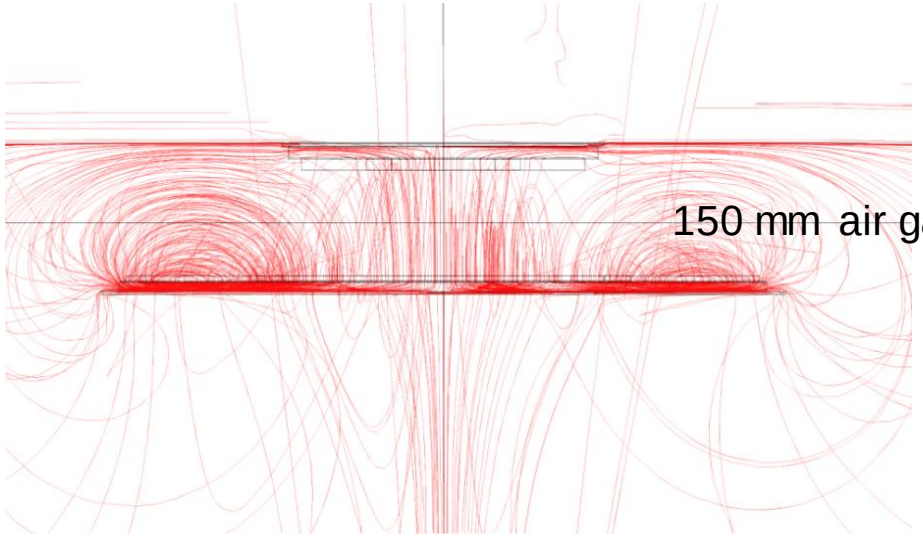
Unipolar Rectangular (3.7kW)

Unipolar rectangular



- Well known and simple design
- Large rotational angle tolerance
- Concentrated central magnetic flux with equal magnetic yoke distribution on outer edges





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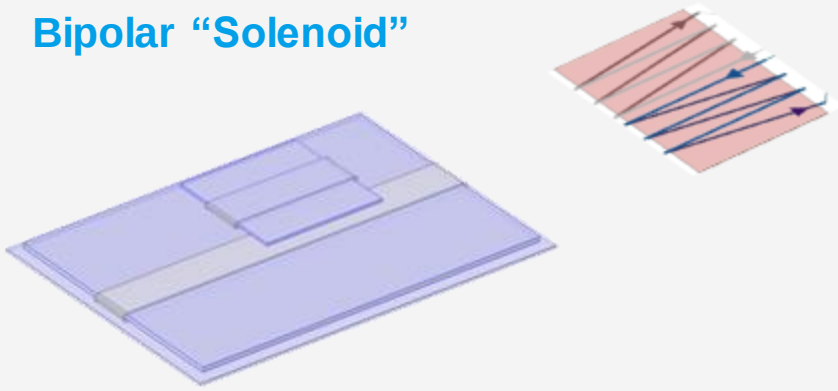
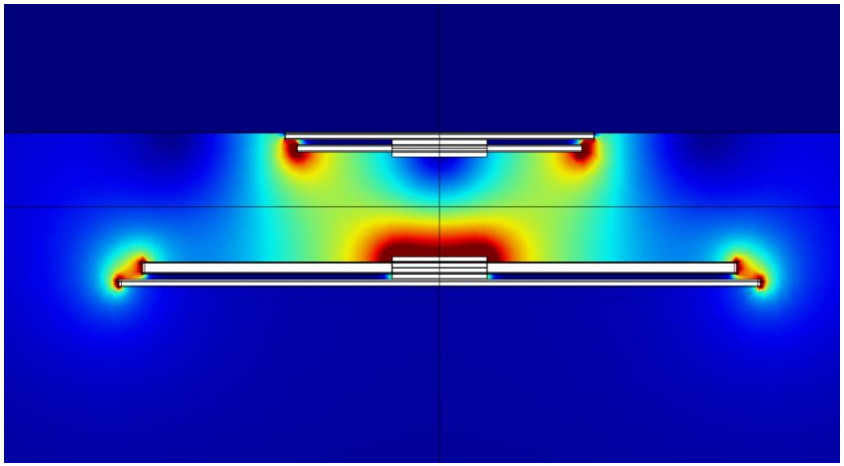
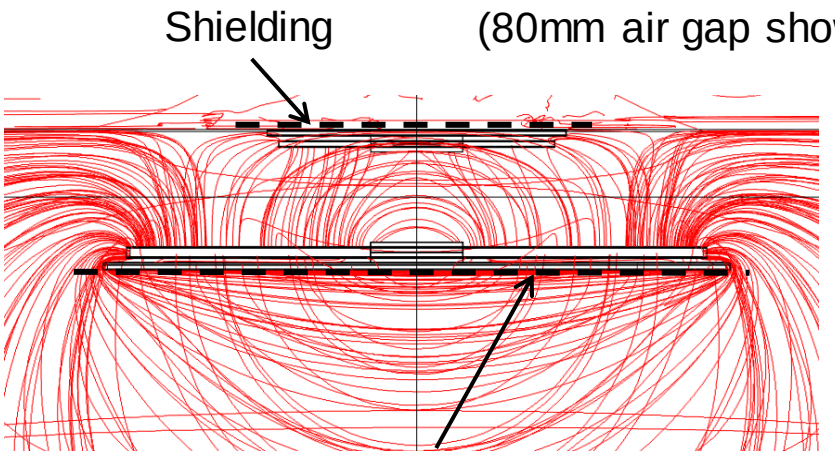
Bipolar Solenoid (3.7kW)

Bipolar "Solenoid"



- Bipolar arrangement with 2 symmetric magnetic poles with opposite flux directions
- Lower rotational angle tolerance
- Flux flow in the outer region of the coil requires shielding on vehicle underbody





Primary Shielding necessary

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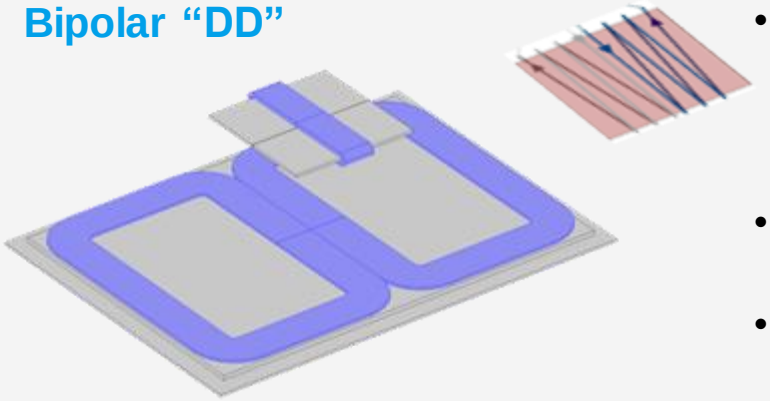
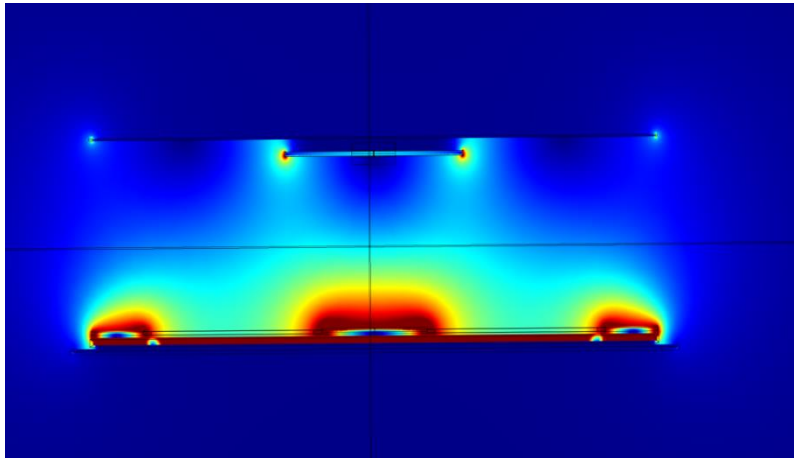
Bipolar Rectangular (3.7kW)

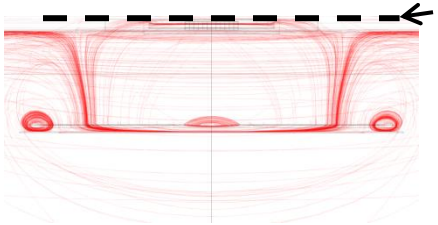
Bipolar "DD"



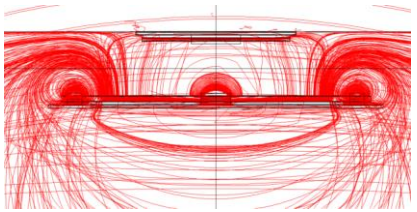
- A bipolar field via 2 planar coils in the primary circuit with different flux flow directions
- Lower rotational angle tolerance
- No windings on the bottom of the primary coil - Reduced shielding requirements, thus less eddy current losses.



150 mm air gap (shown)



150 mm air gap



80 mm air gap

Good efficiency due to high coupling

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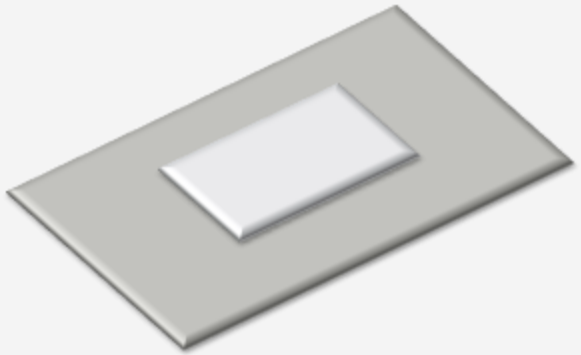
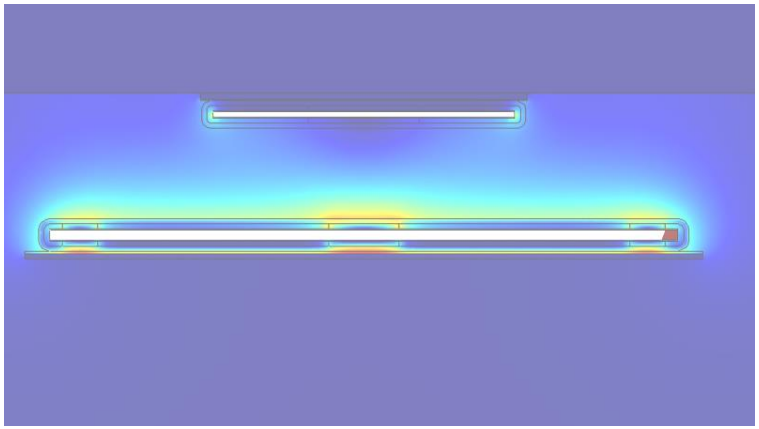
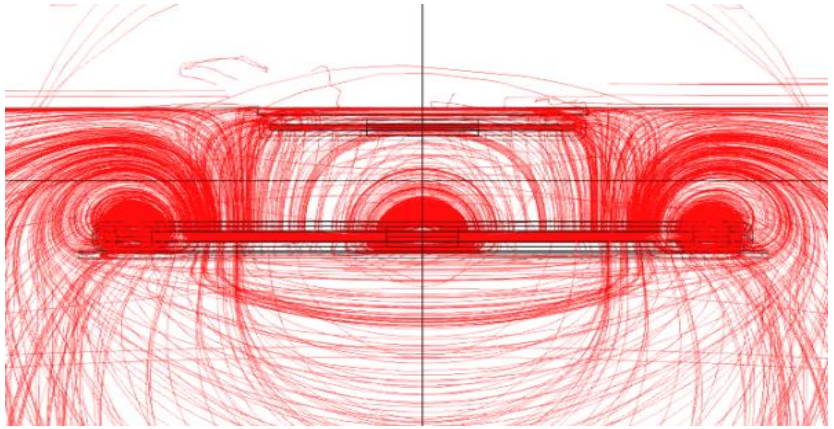
(7.2kW) – (New Development Effort)

HELLA/Vahle Recent developments in coil design allows for higher power at comparable size and at the same frequency (85kHz, 140kHz)



- Almost twice the power density
- High coupling
- High compatibility with other coils at different power levels (I.e. 3.6kW, 7.2kW)



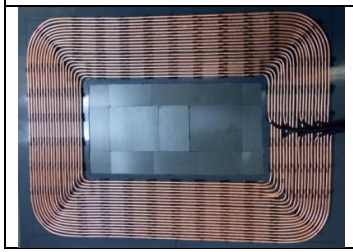


80 mm air gap (shown)

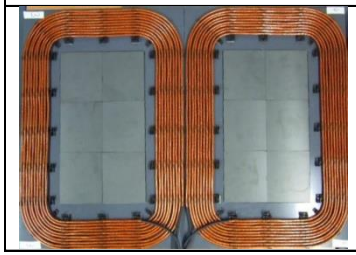
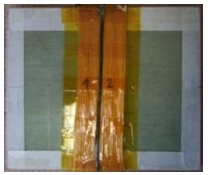
Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Coil Efficiency Summary – 400VDC, 3kW

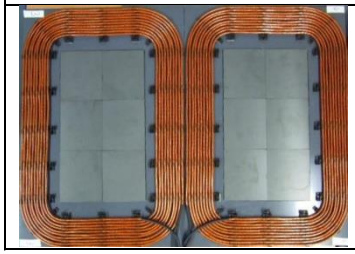
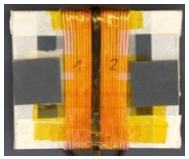
		Planar coil Config #1	Solenoid coil Config #2	Solenoid coil Config #3
Coil Size	[mm]	270 x 310 x13	270 x 310 x 22	185 x 210 x 22
Air gap	[mm]	80 - 160	180 - 250	120 - 140
DC-DC Efficiency	[%]	86 - 91	83 – 93	92 – 94
L	[uH]	205	200	118.2
C	[nF]	6.3	6.3	10.9

Primary	Secondary (vehicle side)
Single Layer Unipolar Planar	Double Layer Bipolar Planar
500mm x 700mm	270mm x 310mm
	

#1

Primary	Secondary (vehicle side)
Single Layer Bipolar Planar	Bipolar Solenoid
700mm x 500mm	270mm x 310mm
	

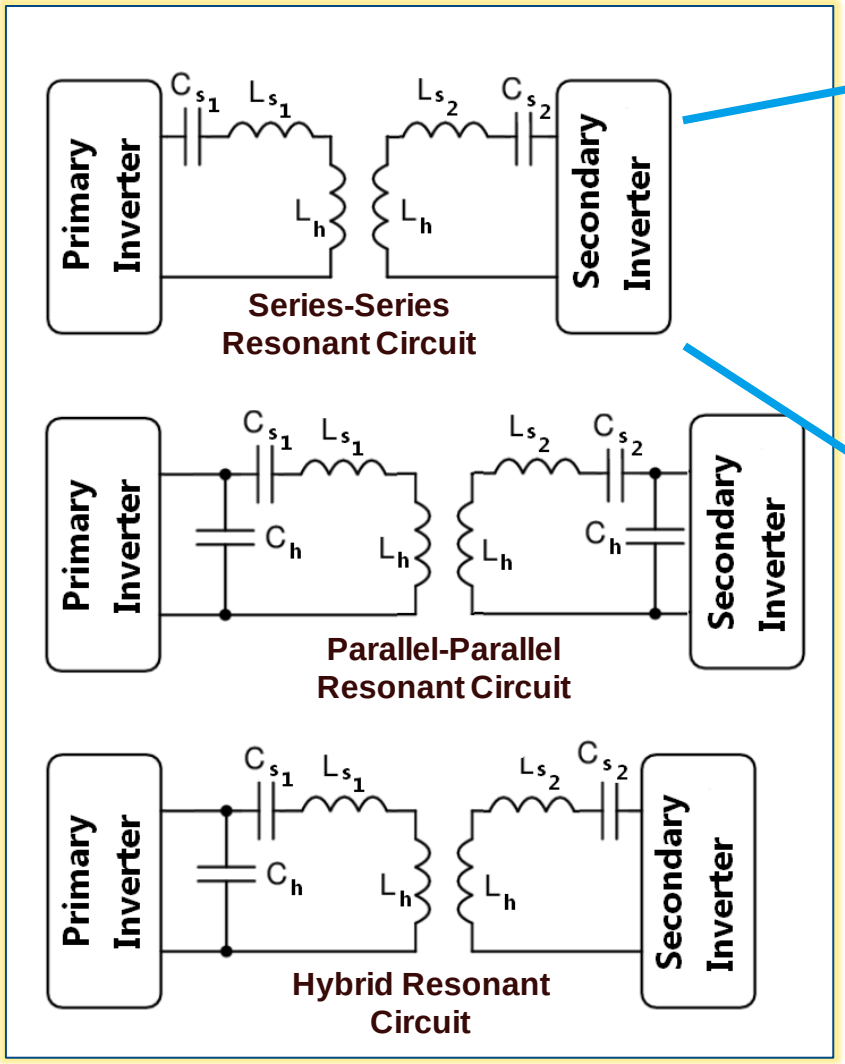
#2

Primary	Secondary (vehicle side)
Single Layer Bipolar Planar	Bipolar Solenoid
700mm x 500mm	185mm x 210mm
	

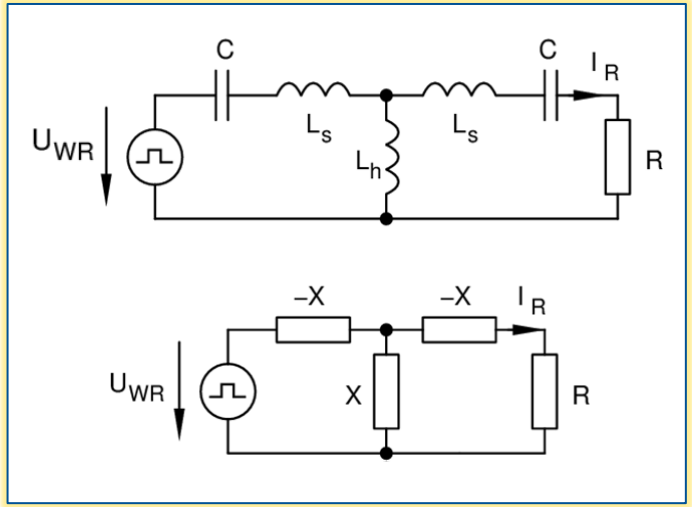
#3

Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Inductive resonant energy transfer



Preferred Topology

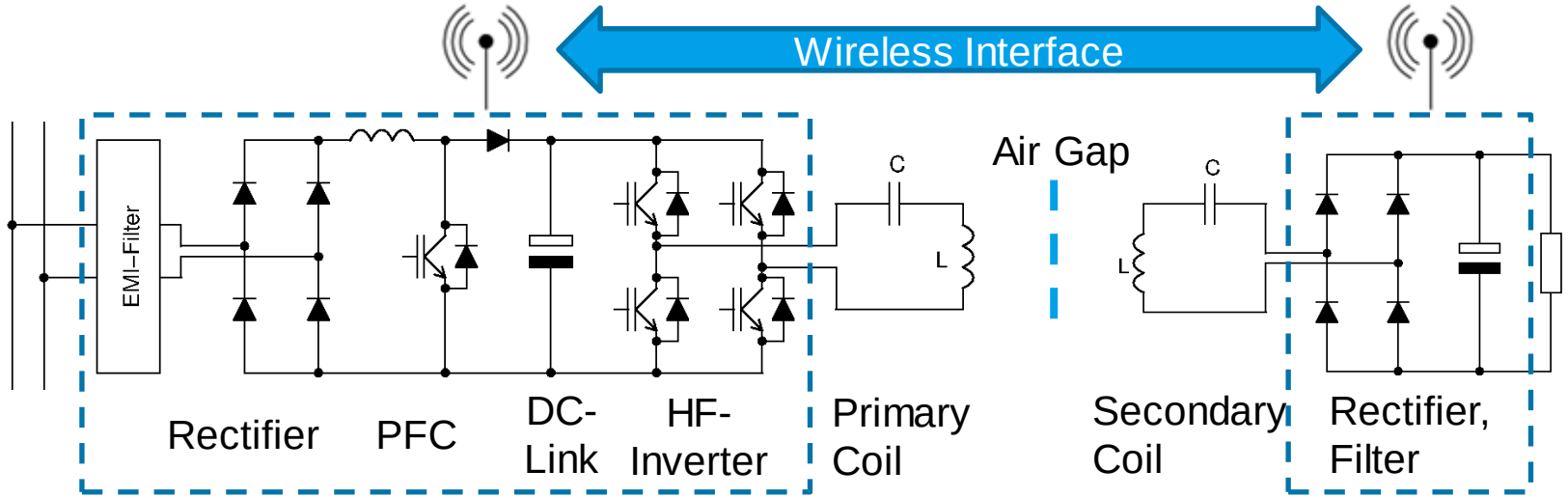


- Large air gap results in high leakage inductance
- Reactive power compensation by means of C leads to resonant circuit.
- Series – Series Transmission Behavior: Gyrator

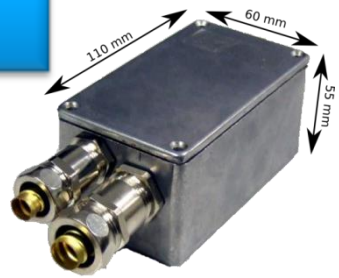
$$I_R = U_{WR} * R \; / \; X^2$$

Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Power Electronics – Uni-directional topology



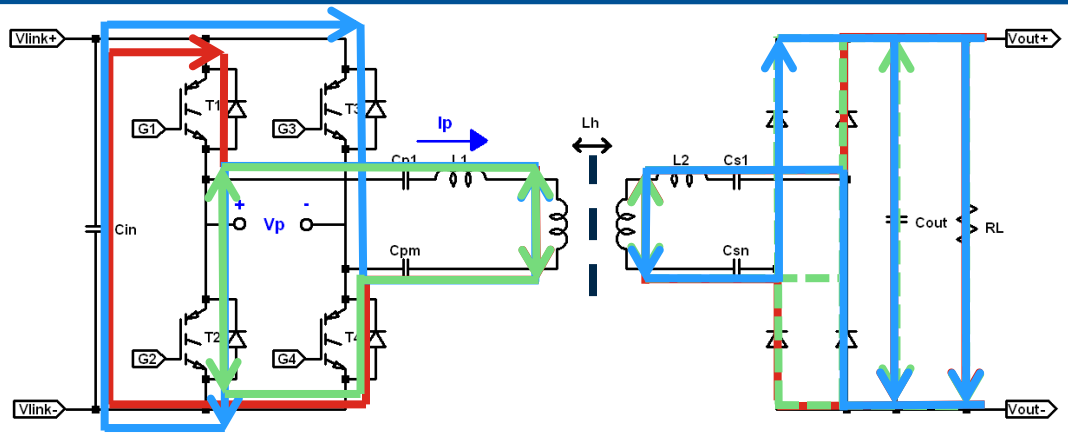
+ No voltage converter necessary in vehicle

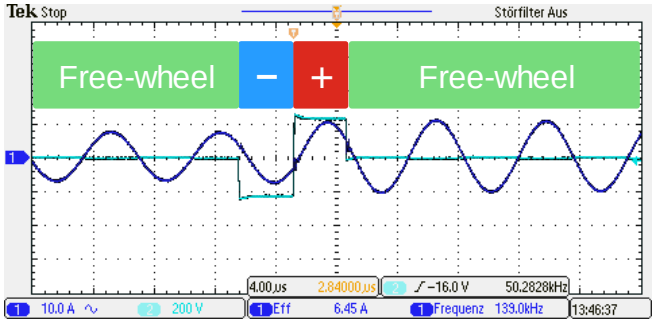


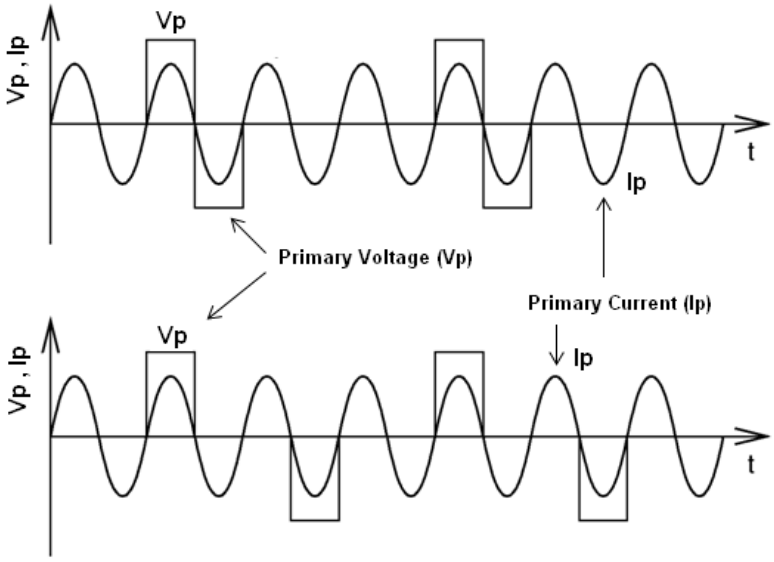
Rectifier, Filter, Current/Voltage Measurements

Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Power Electronics – Inverter Switching Strategy





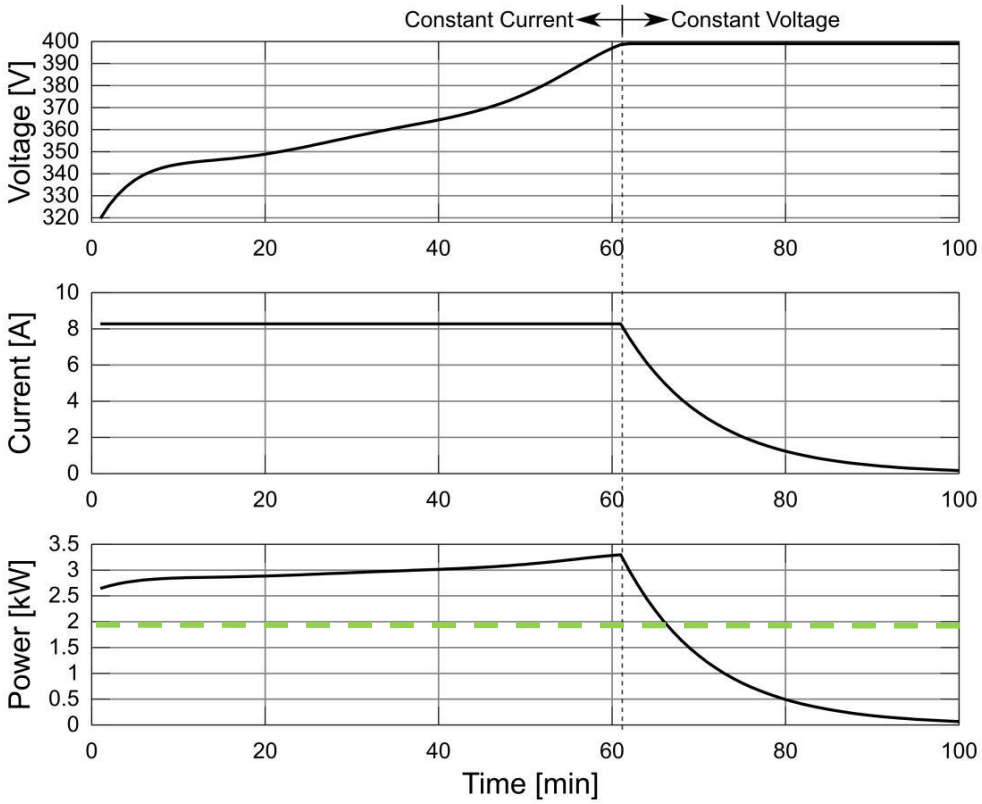


- Soft switching is maintained throughout the load operating region
  - Zero Current Switching (ZCS) [IGBT]
  - Zero Volt Switching (ZVS) [MOSFET's]
- Inverter operates at the resonant frequency which varies with:
  - Coupling factor (k) X / Y / Z positioning variation
  - Compensation capacitance (temperature affects)
- Output Voltage / Current is regulated by pulse skipping in a time symmetric fashion depending on load conditions
  - Half cycles – Reduces output ripple
  - Whole cycles

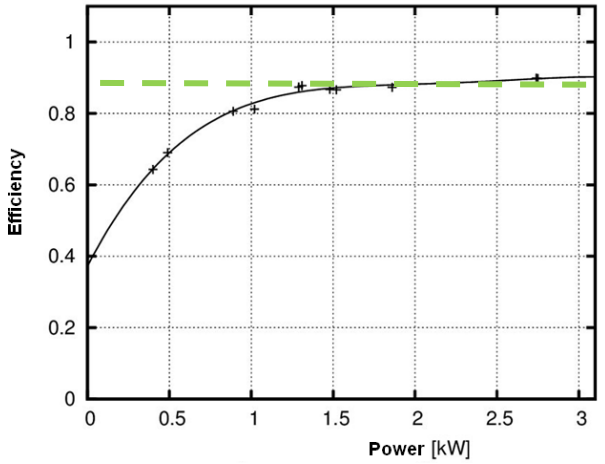
Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Efficiency

Battery State of Charge



Efficiency DC_{out}/AC_{in}



η>90%

- During constant current charging
- Until about 90% SOC

Efficiency DCout / ACin of inductive charging is only slightly lower than that of conductive charging

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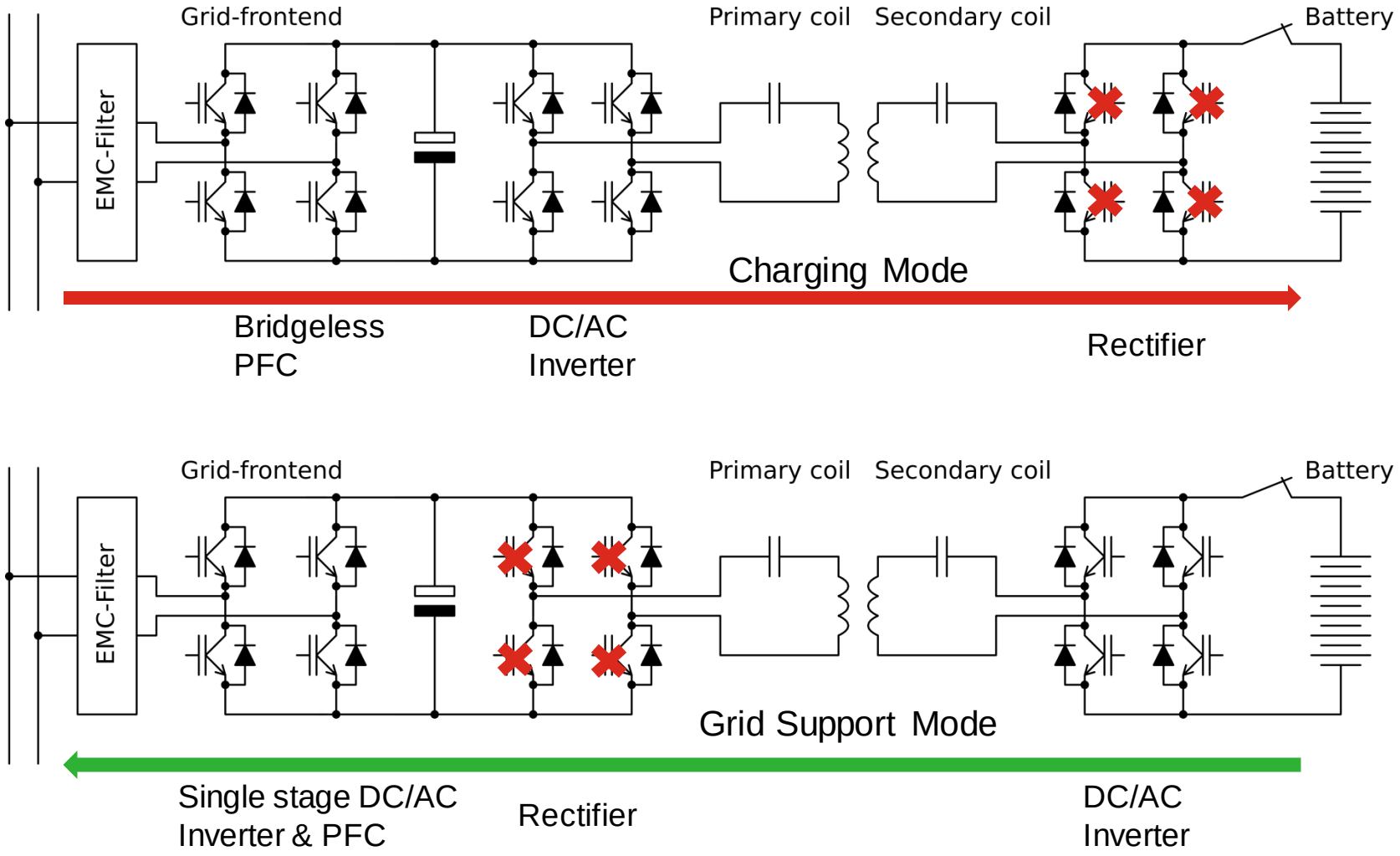
Power Electronics – Bi-directional topology (Charging or Grid Support)



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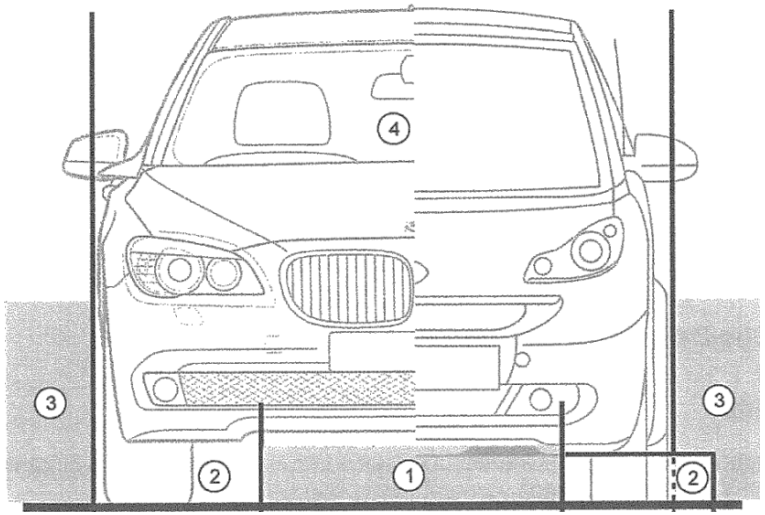
Foreign Object Monitoring (FOD) - Guidelines

VDE-AR-E 2122-4-2

1. Function region ① and transition region ②
   a) Heating @40°C T<80°C (metallic Obj)
      T<90°C (non-metallic Obj)
   b) Inflammation is not permitted

2. Transition - and public area ③④
   Personal protection as ICNIRP guideline, that is, much safer than German 26 BImSchV

- **Compact design = High flux density**
  - ➢ Eddy currents in metallic objects leads to heat / inflammation; required detection (FOD = Foreign Objects Detection).
  - ➢ Compliance permitted for persons flux density (6.25 µT) in the outdoor area is safe; under the vehicle detection of organisms (LOD)
- LOD / FPS: interruption of energy transfer



Richtlinien für die Begrenzung der Exposition durch zeitlich veränderliche elektrische, magnetische und elektromagnetische Felder (bis 300 GHz) · ICNIRP-Richtlinie

Tabelle 7. Referenzwerte für die Exposition der Bevölkerung durch zeitlich veränderliche elektrische und magnetische Felder (ungestörte Effektivwerte)[a]

Frequenzbereich	Elektrische Feldstärke ($V\ m^{-1}$)	Magnetische Feldstärke ($A\ m^{-1}$)	B-Feld (µT)	Äquivalente Leistungsdichte bei ebenen Wellen S_{eq} ($W\ m^{-2}$)
⋮	⋮	⋮		
3-150 kHz	87	5	**6.25µT**	—

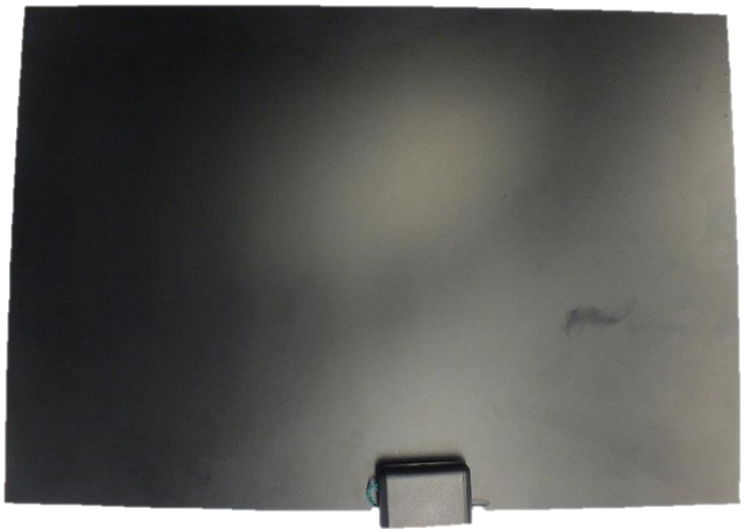
Twenty-sixth regulation
Execution of the Federal Pollution Control Act
(Decree on electromagnetic fields 26 BImSchV) (27µT)

Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

FOD

- Thin plastic sheet on top of primary coil, (secondary coil optional)
- First prototype detects objects on surface
  - 50 cent coin
  - cigarette pack
  - gum wrapper
  - 330 ml beverage can

- Possible increase of detection distance up to 20 mm for larger objects by optimizing internal structure



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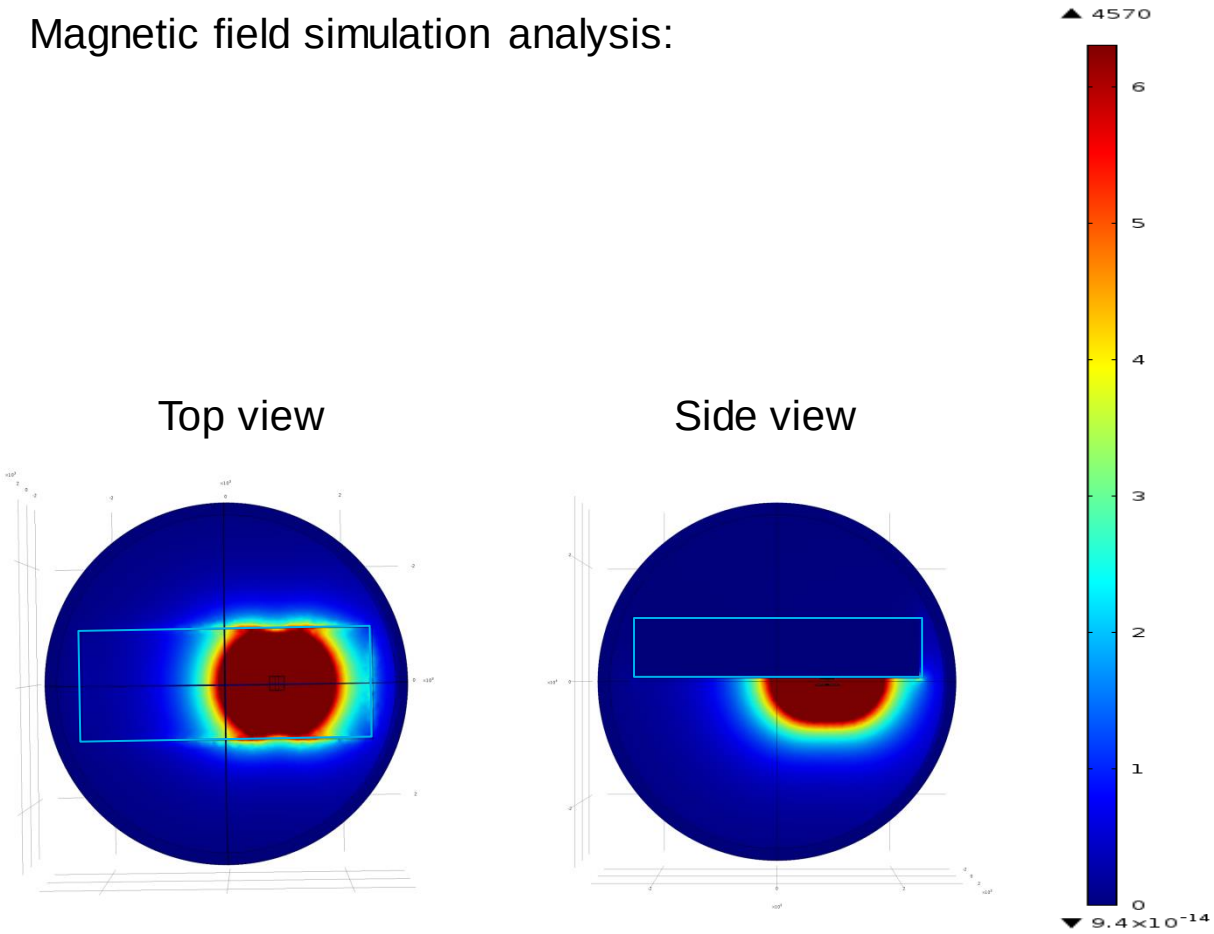
ICNIRP Limits - simulation

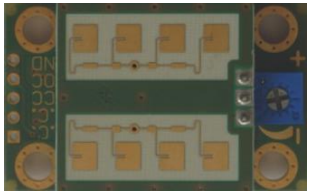
Magnetic field simulation analysis:

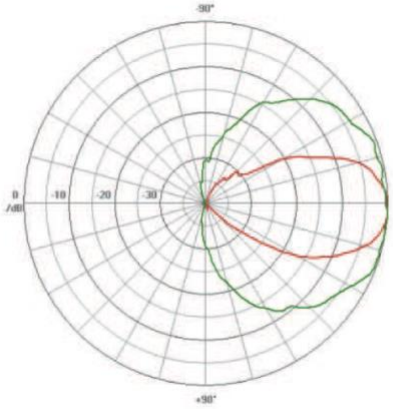


Flux density will be lower than 6.3 µT (colored in dark red) at the borderline of the vehicle

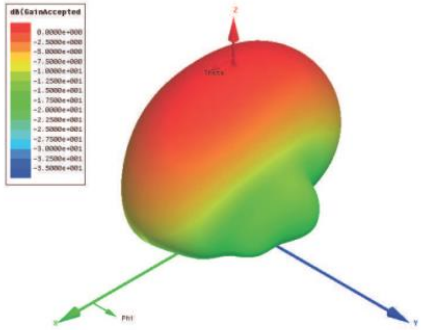
Test with CW Radar Sensor

Integration approach:





system-pattern (measured)



3D-pattern (simulated)

Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Positioning assistance

Support for the driver to position vehicle in optimal charging x/y position

- when approaching, 5-30m
- At close range, ~ 1m
- at end position

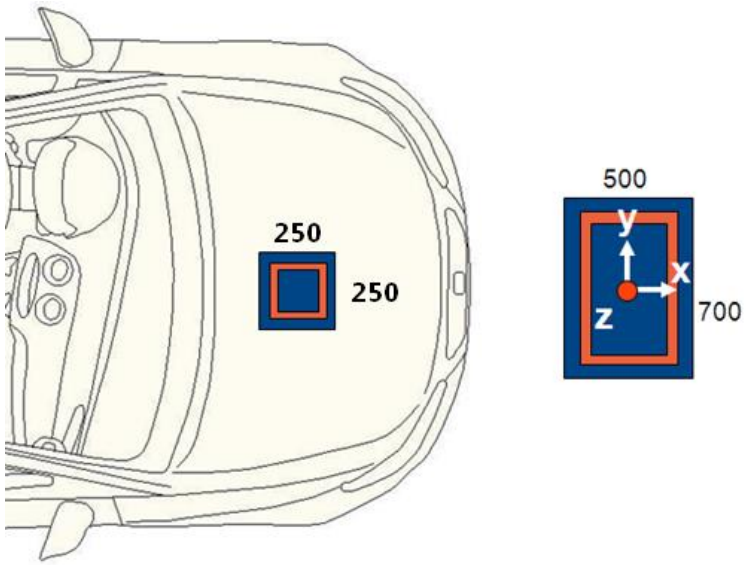
With increasing accuracy

Communication

- Directional and distance information in the cluster or at the stationary charger box
- Virtual top view with guidance
- Perspective automation ~ „Park Assist“

Approaches

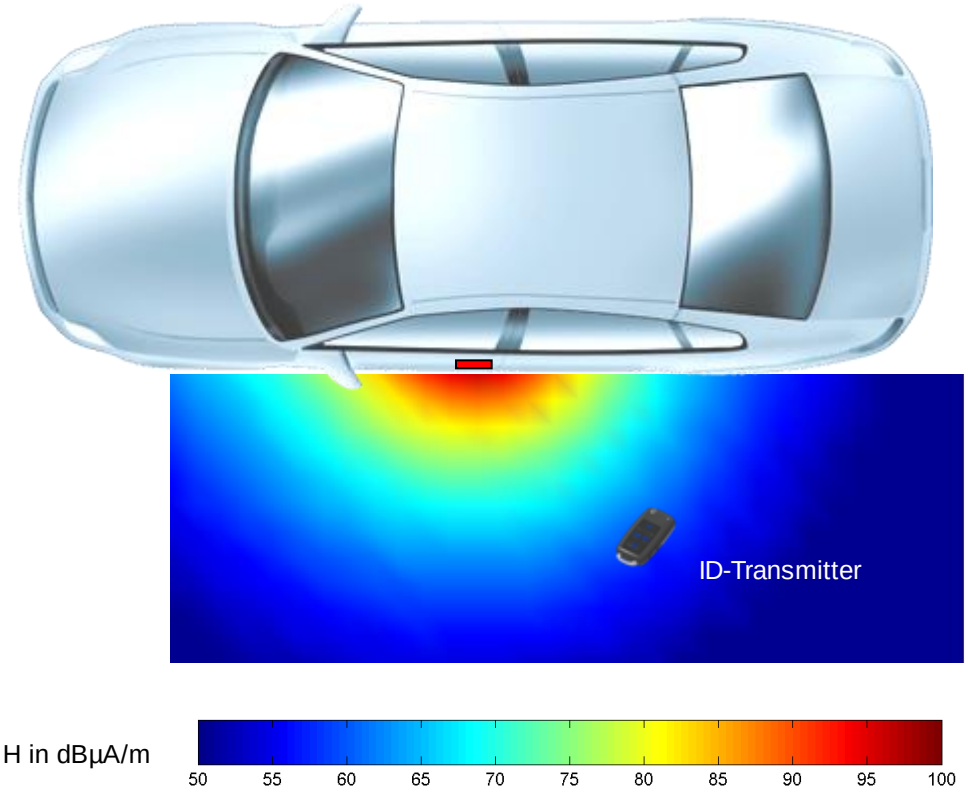
- Optical / camera systems - Visibility
- Radio-based systems
  - RFID
  - Power Transformers



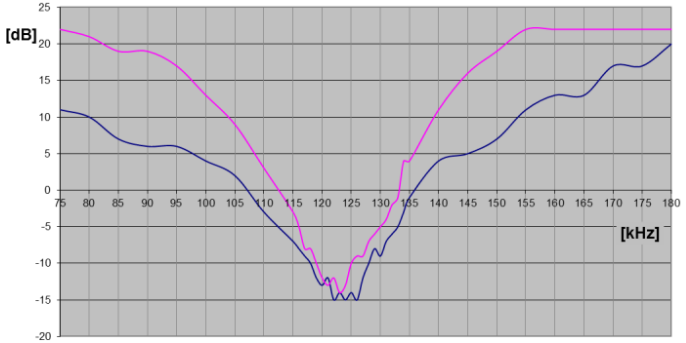
Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

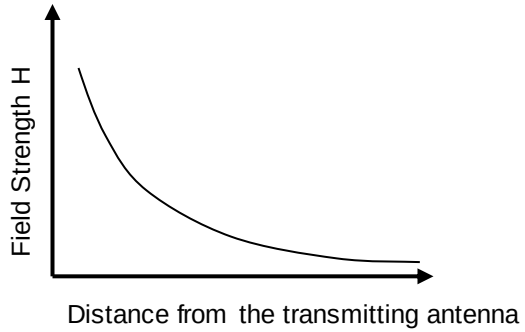
Radio system compatibility - keyless access and drive authorization

Data transmission **from** the vehicle **to** the ID transmitter
Frequency band f = 125kHz (25kHz, 132kHz ...)



Receiver Selectivity

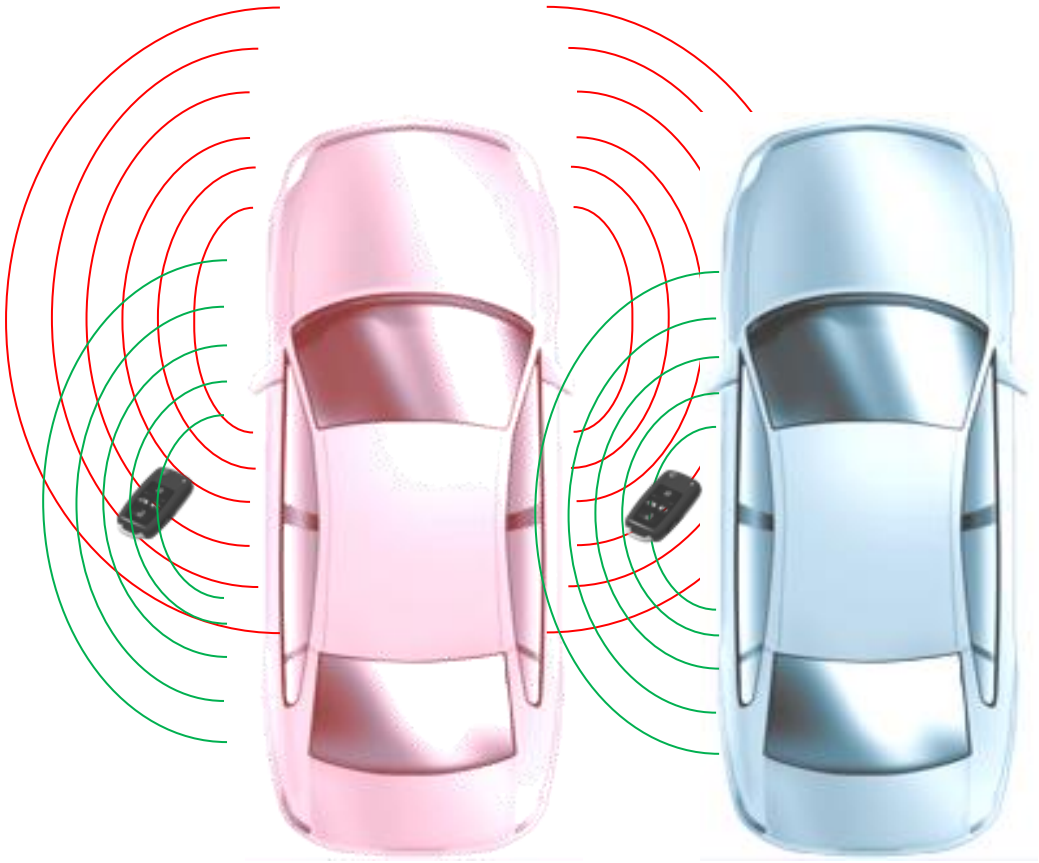




Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Radio system compatibility - keyless access and drive authorization

LF data reception disturbance from strong magnetic fields of charging vehicle hinders the charging vehicle and others nearby



Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Summary

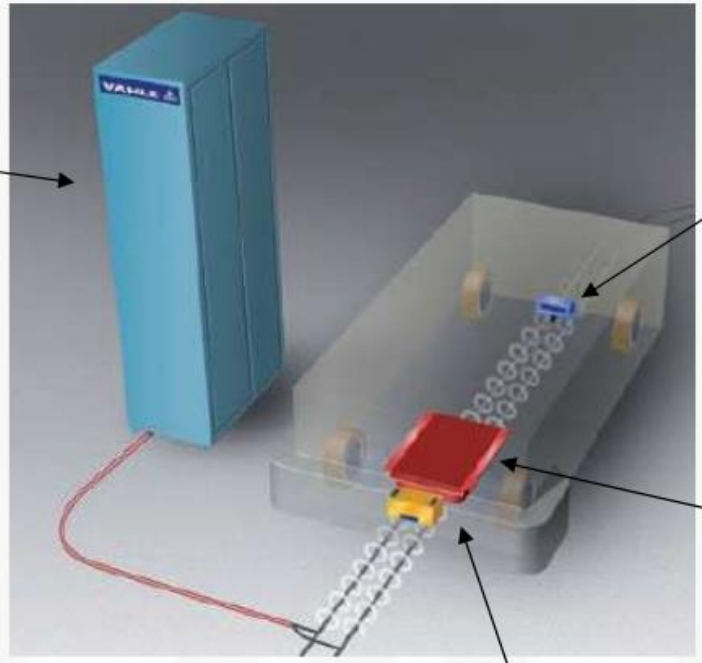
- Based on known technologies in new designs and combination
  → challenging but achievable system
- Allows comfortable and convenient charging
- Precondition for the widespread implementation of electric mobility
- Interoperability between systems and sub-systems of various vehicle and system manufacturers as necessary
- Compatibility with vehicle radio systems and other required radio systems

Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Industrial Application (Vahle)

Inverter

Input Voltage
400V (3~, 50 Hz)
Output:
70…200 A (1..3 ~)
20 kHz, up to 250 kW



Data antenna

Profibus 187,5 kbit/s

Pickup

300 mw … 250 kW
DC voltage output,
stabilized / unstabilized

HF-cable

1…3 ~, up to 4,5 km length

Positioning sensor

mA or mV analog output signal

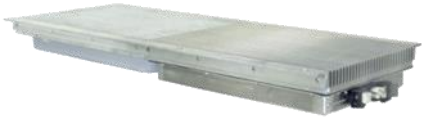
Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Industrial Application (Vahle)

Logistic (Sorter)

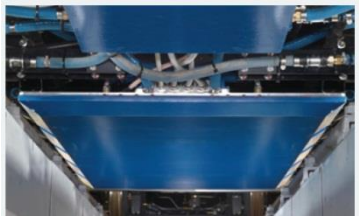
Tool-Machines

Automotive Production



Trams & Buses*

* cooperation with Bombardier



Clean Rooms

… since 1998

Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

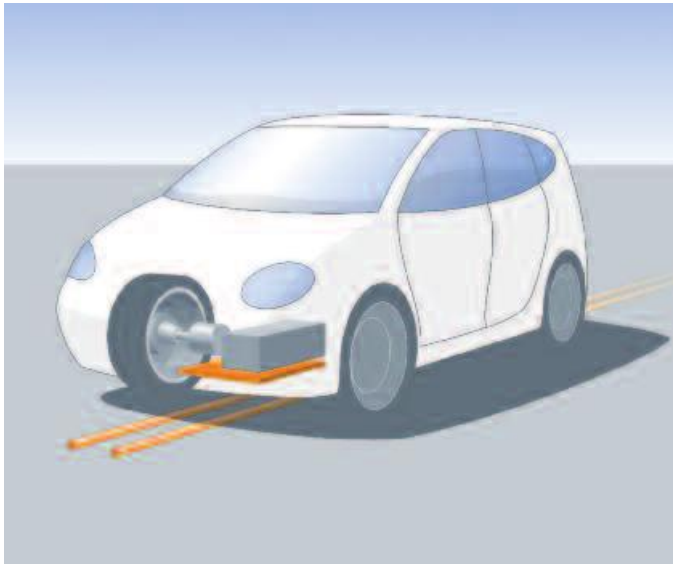
Inductive Power Supply CPS®: AGV-Application

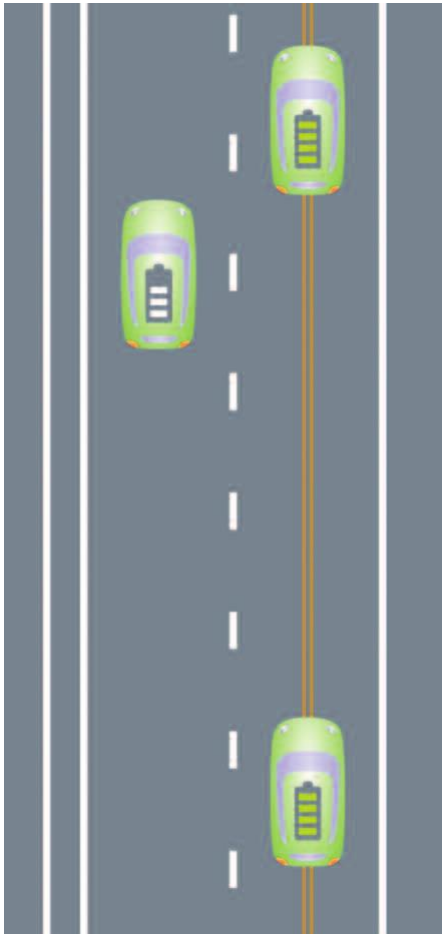
AGV 3 kW SuperCap chargers in Coburg (Kaeser)

1.5 kW AGV-supply with track guiding sensor in Tubos del Mas / Spain

Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Outlook: Dynamic Charging (Vahle / IAV)





Future Challenge:
Safe and inexpensive dynamic charging infrastructure

Thank you for your attention!

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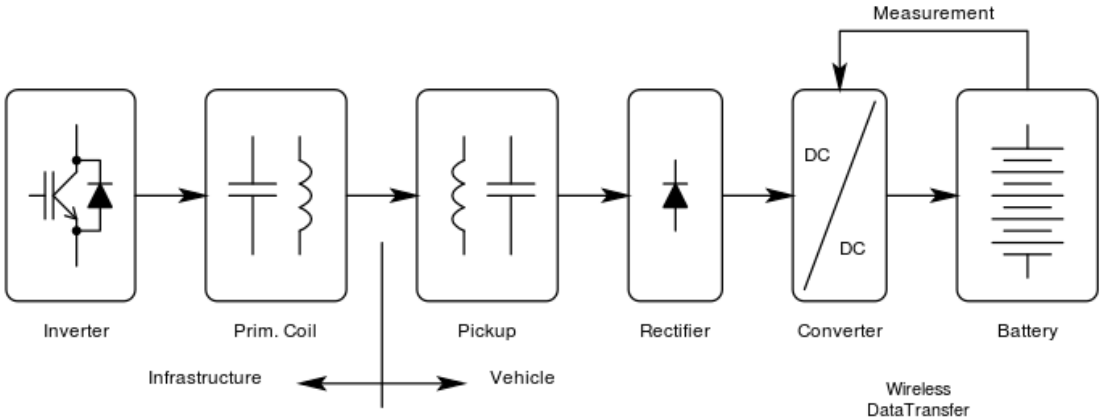
Westicker Str. 52, 59174 Kamen
faical.turki@vahle.de
Tel.: 02307 / 704 271

BACKUP

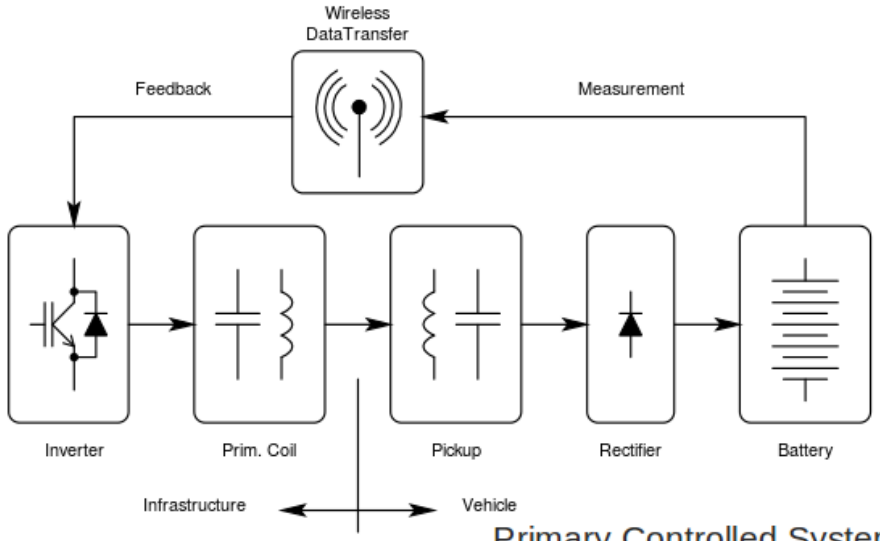
Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Power Control



Secondary Controlled System

+ Self-sufficient power control in the vehicle
- Voltage transformation in vehicle generates losses

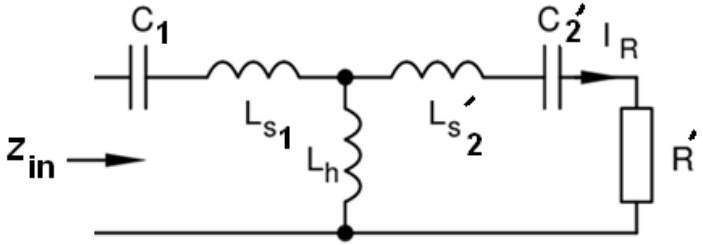


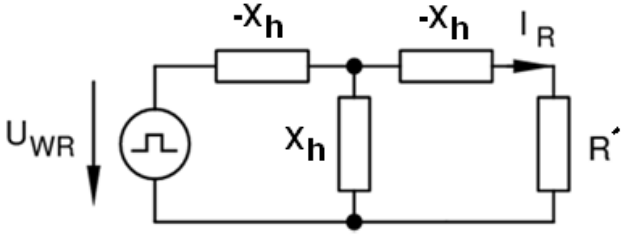
Primary Controlled System

+ No voltage converter necessary in vehicle

Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Inductive Series-Series resonant energy transfer gyrator





U_{WR}=380VDC

The "gyrator" function transforms the primary referred load impedance R' into 1/R' times a constant X_h^2 at resonant frequency f_n

*Impedances (X') referred to primary

$$Z_{in} = XC_1 + XL_1 + XL_h \frac{X_{L2} + XC_2 + R'}{X_{Lh} + XL_2 + X_{C2} + R'}$$

at resonant frequency f_n, C_1 and C_2 compensate Ls_1, Ls_2 and L_h such that:

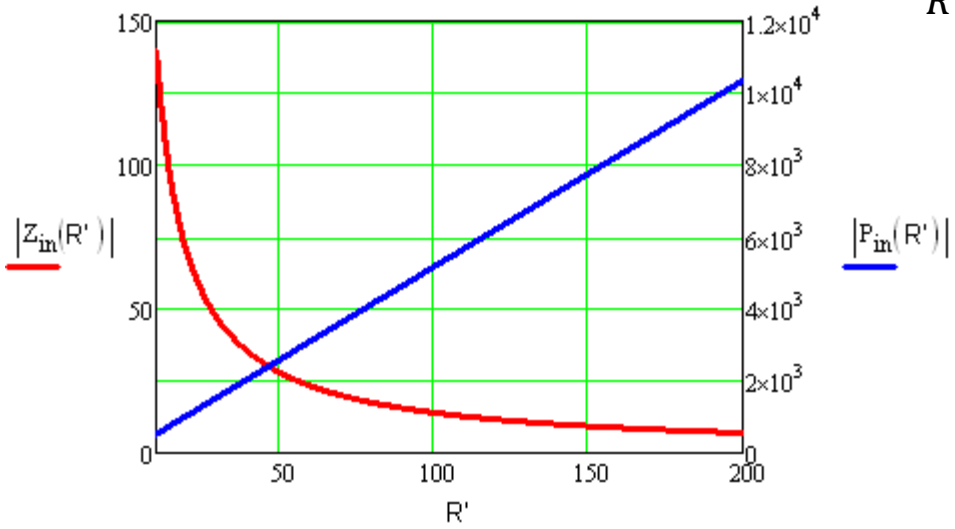
$$X_{C1} + XL_1 + XL_h = 0$$

$$X_{C2} + XL_2 + XL_h = 0$$

$$Z_{in} = \frac{X_{Lh}^2}{R'}$$

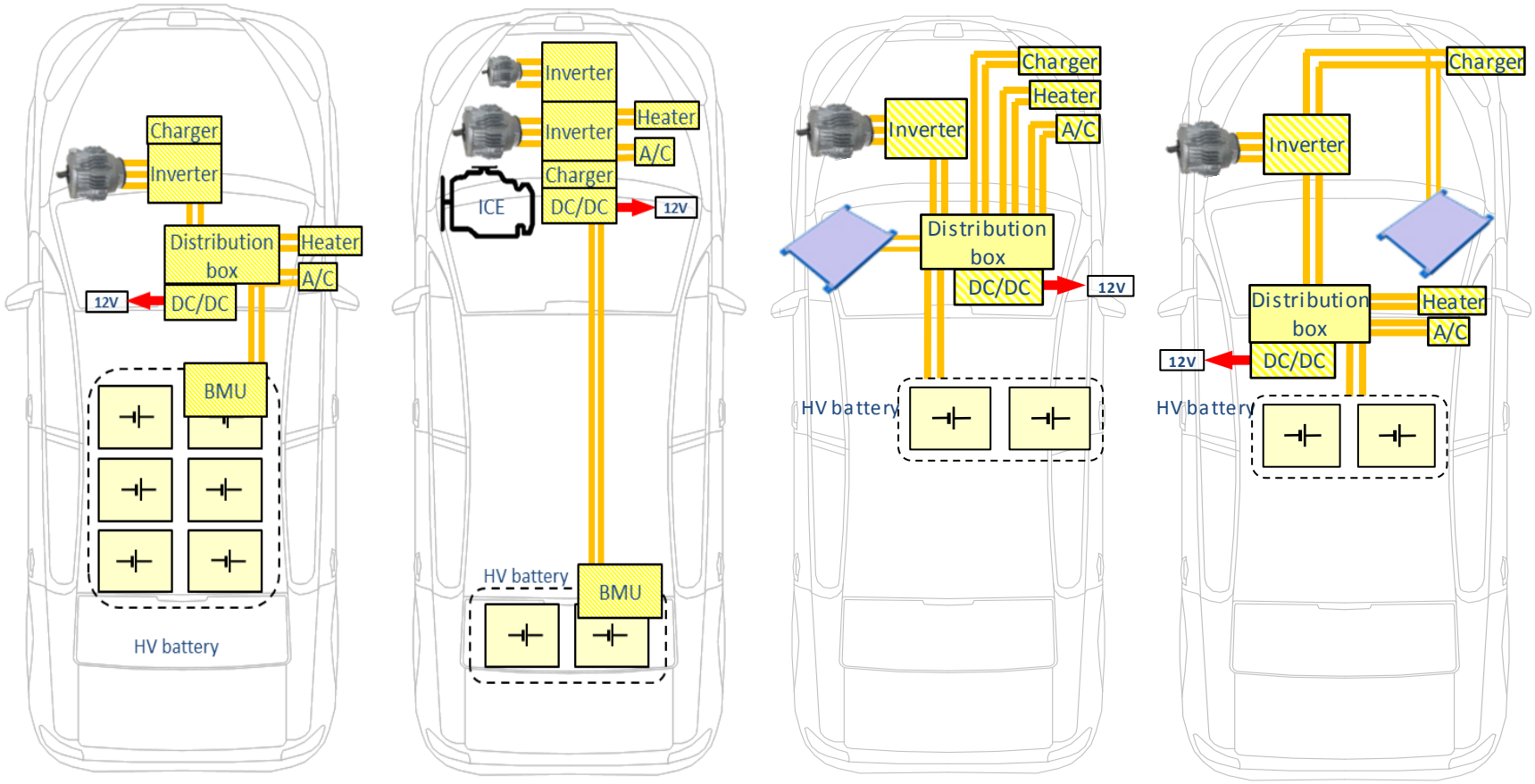
Where:

$$R' = \frac{8}{\pi^2} \acute{R}_L$$



Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

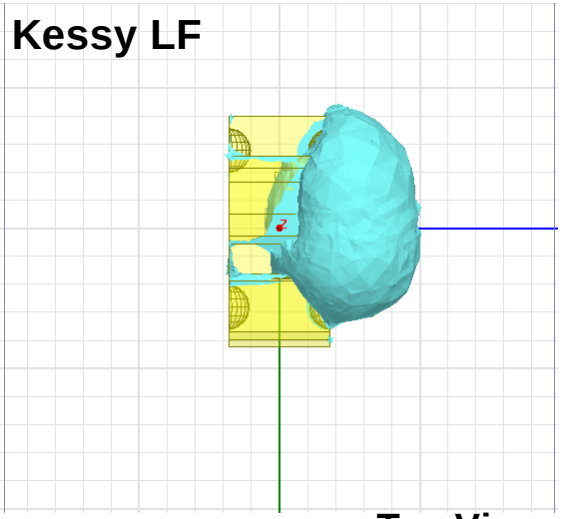
Integration into the HV board network

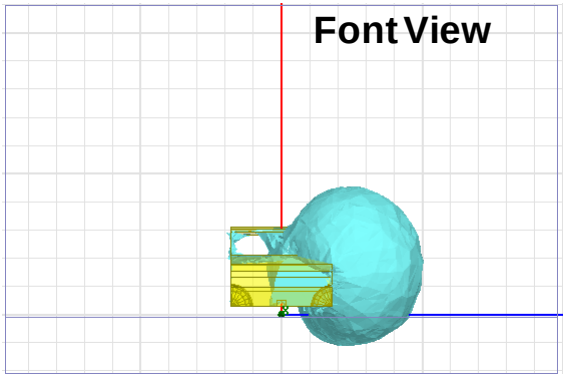


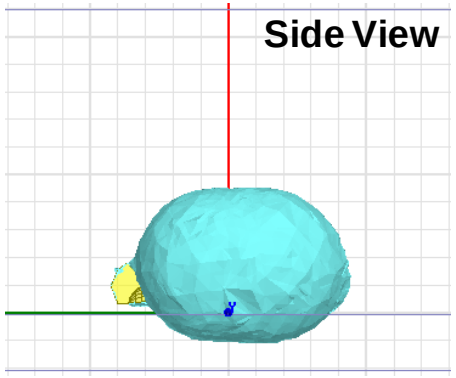
EV Hybrid Plug-in Hybrid with inductive charging

Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

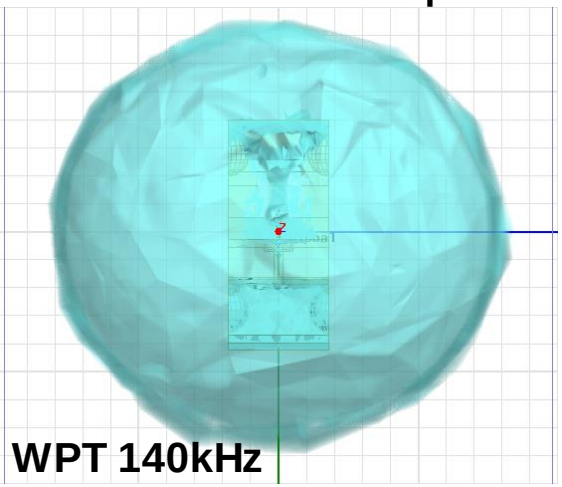
Keyless entry LF compatibility – 70dbµA/m ISO

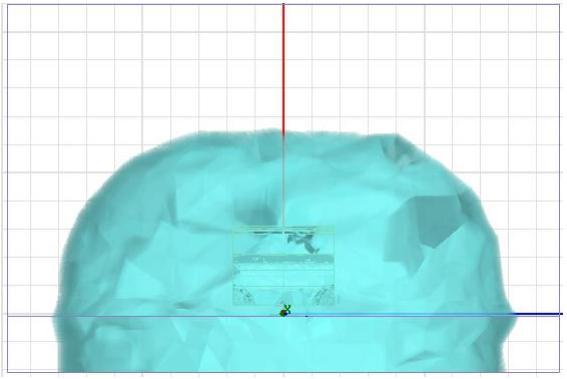


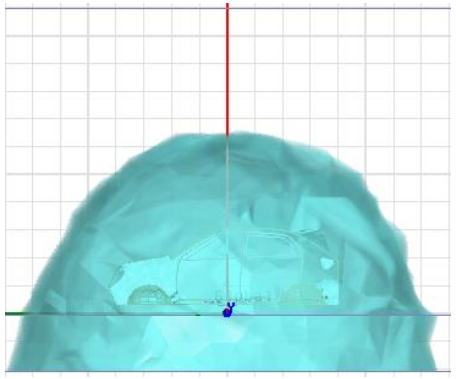




The 70dBµA/m surface with unipolar rectangular WPT includes the keyless entry 70dBµA/m surface. In this flux density no Keyless Entry LF communication is possible

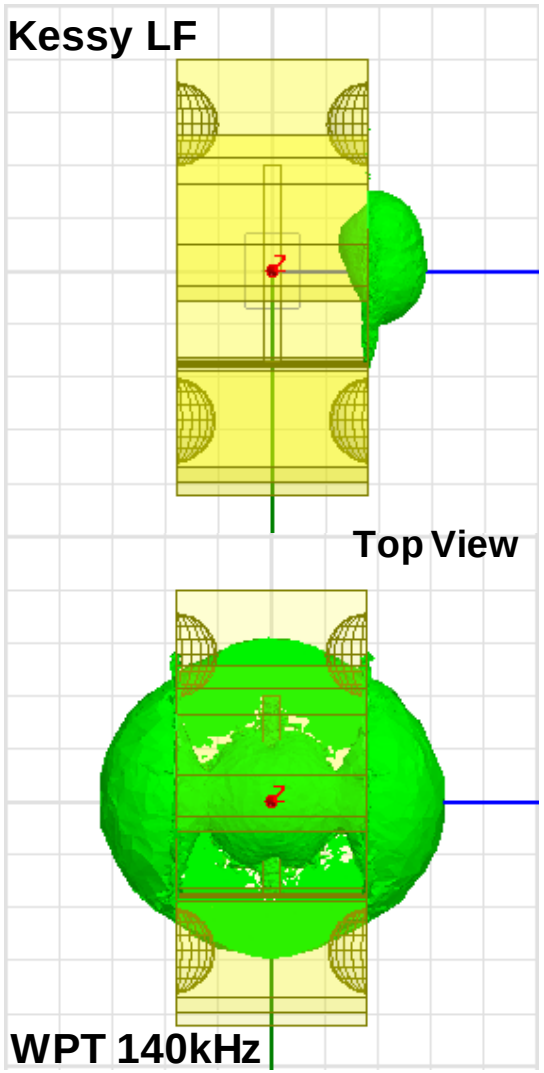


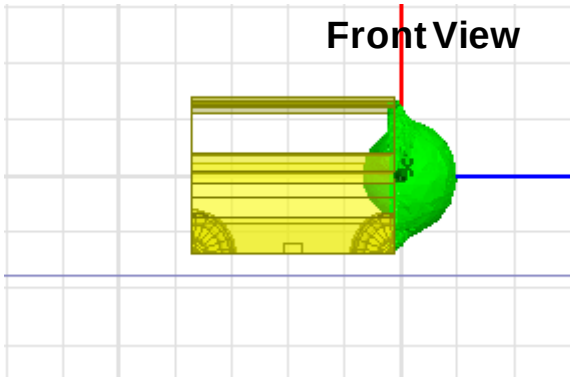


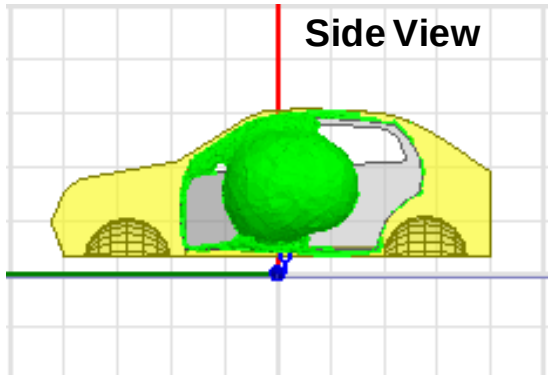


Compact, Safe and Efficient Wireless and Inductive Charging for Plug-In Hybrids and Electric Vehicles

Keyless entry LF compatibility – 100dbµA/m ISO







The 100dBµA/m WPT ISO does not completely enclose the Keyless Entry 100dBµA/m ISO – Keyless Entry LF Communication is possible, depending on location, frequency, receiver and, if necessary, further measures.