Contactless Power Transfer :

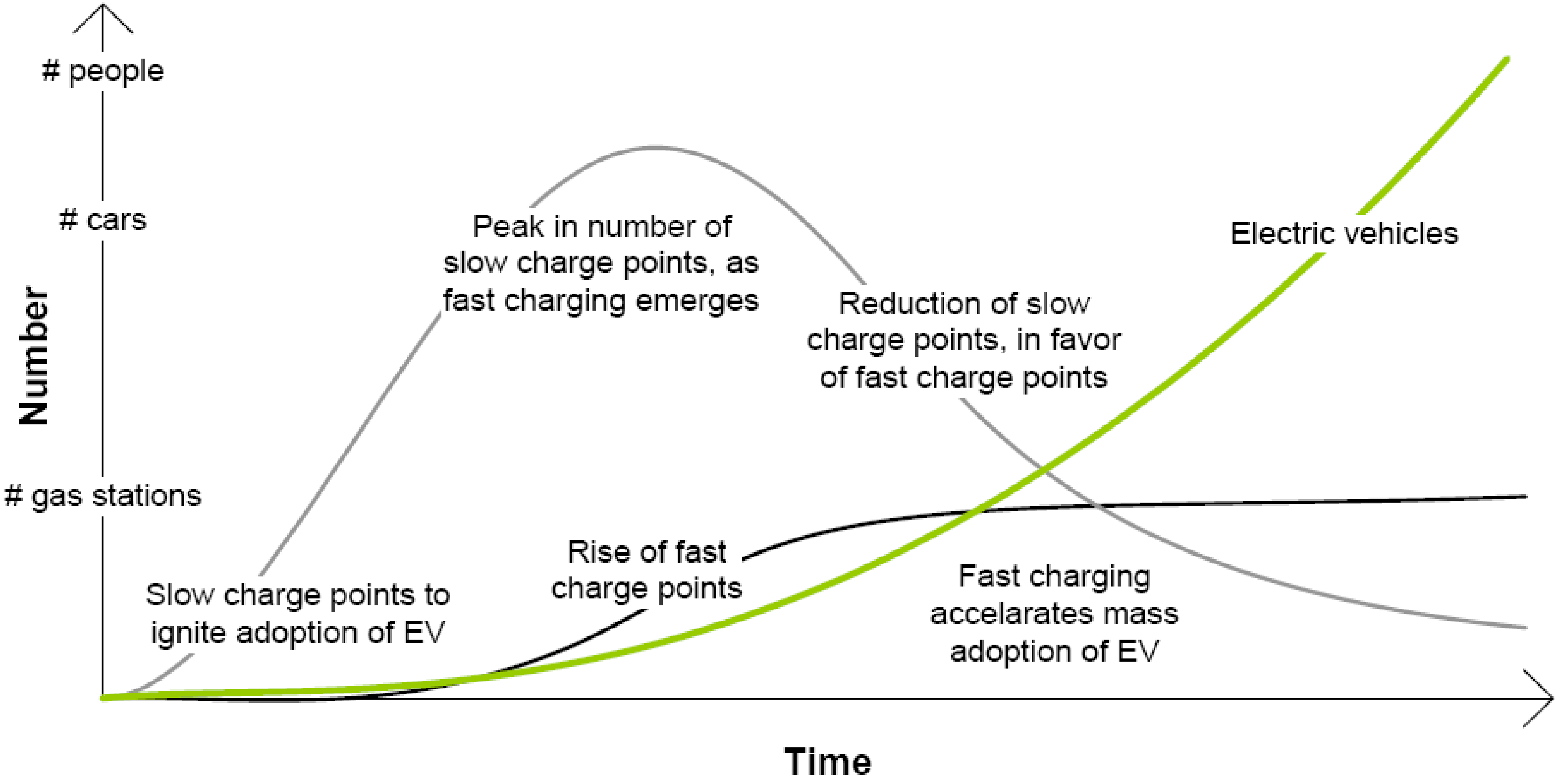
Inductive charging of EV

7-12-2010

P.Bauer

EV have to be charged

“Chicken and egg” problem

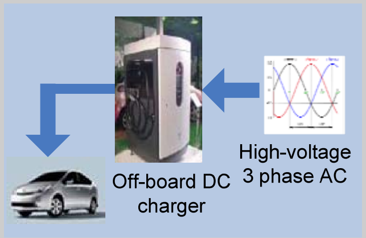


p1

Charging Modes

kVA *Charging Time*

180 - 400 5 – 15 min



Fast

Battery exchange station

10 - 25 1 – 3 h

Medium/Semi-fast

- 3 Phase AC
- 230V
- 32 or 63 A

1 - 5 6 h

Normal/Slow

- 1 Phase AC
- 230V
- 16 or 32 A

p1 Standard charging for EV’s use a charging power of 3.3 kW, corresponding to a socket- outlet of 230 V, 16A. This type of charger is the most extended in Europe and is a single phase an AC charger. This type of charging is dedicated to a normal charging of 6 to 8 hours. It’s generally an onboard charger (located inside the vehicle). Due to its simplicity and low cost, Mode 1 is the preferred mode for all charging operations at a private location, such as a household or workplace. However, Mode 1 has a number of safety problems: its safety depends on a residual current device (RCD) on the supply side. The installation of such device is now enforced by national codes in most countries.

3.1.3.2 SEMI-FAST CHARGING (MODE 3, 2HOURS< CHARGING TIME < 6 HOURS)

Semi-fast charging is defined as a power level of 7 to 22 kW, corresponding to either a 1-phase 32A outlet or a 3-phase 16A outlet. This allows double the available power. A semi-fast charging infrastructure allows a charging time of between 2h and 6 h, for a 30kWh battery. This type of infrastructure corresponds to Mode 3, which is directly connected to an AC supply network. The connector is equipped with a control pilot conductor to protect user and equipment. The concept of the control pilot used is detailed in European standards [Appendix D].

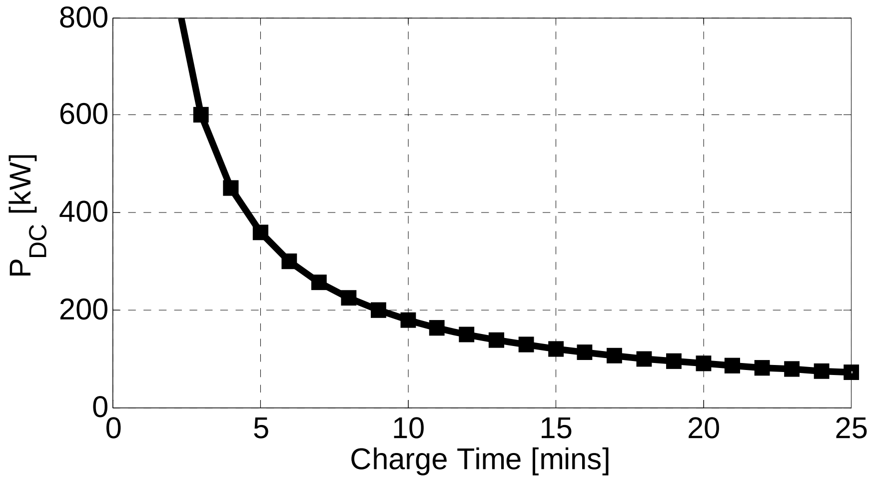
3.1.3.3 FAST CHARGING (MODE 4, CHARGING TIME < 1 HOURS)

In charging Mode 4, the vehicle is charged with a DC current provided by an off-board charger. This solution is most often used for fast charging stations which require a very heavy infrastructure. Different types of fast charger are described:

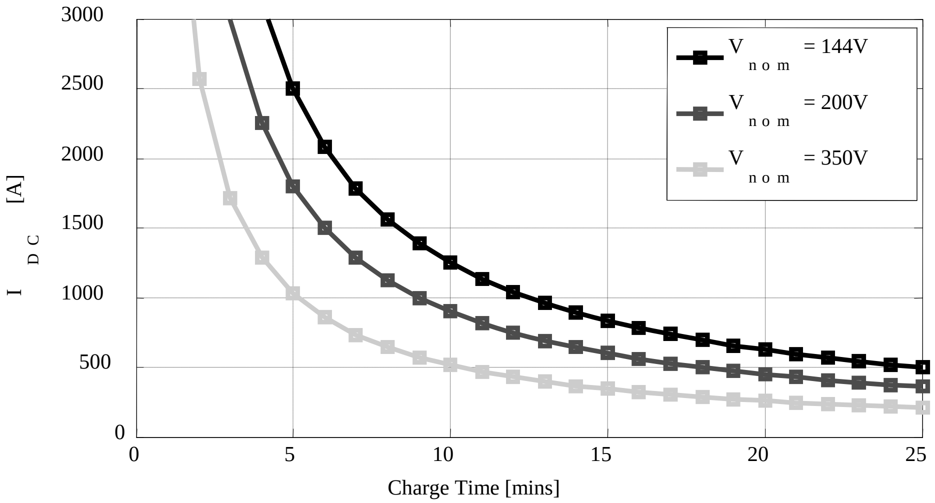
- Fast charger
- Super fast charger
- High AC charger

pbauer; 5-1-2010

Ideal DC Power Supply and Times to Charge 30kWh Battery

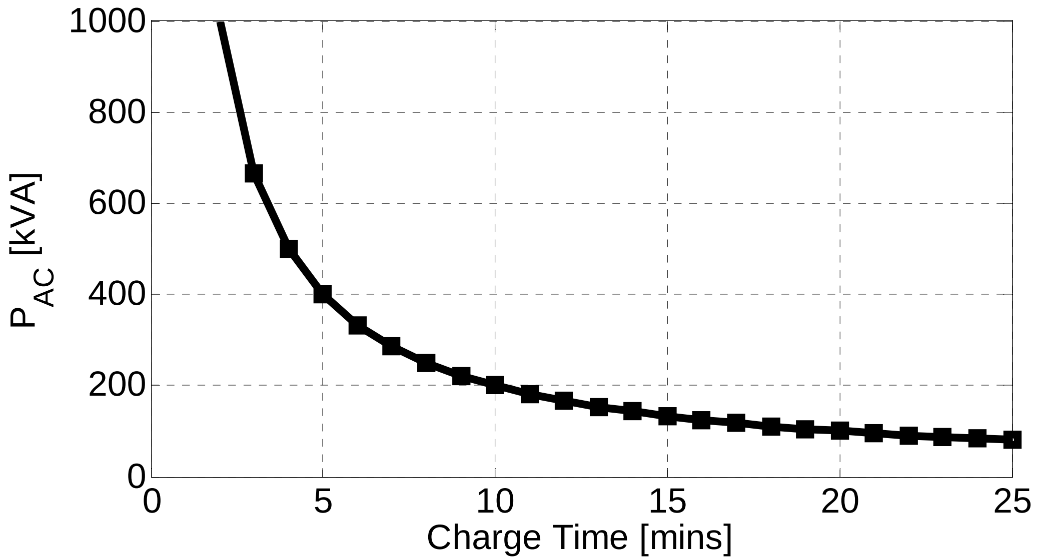


Ideal DC Power Supply and Times to Charge 30kWh Battery



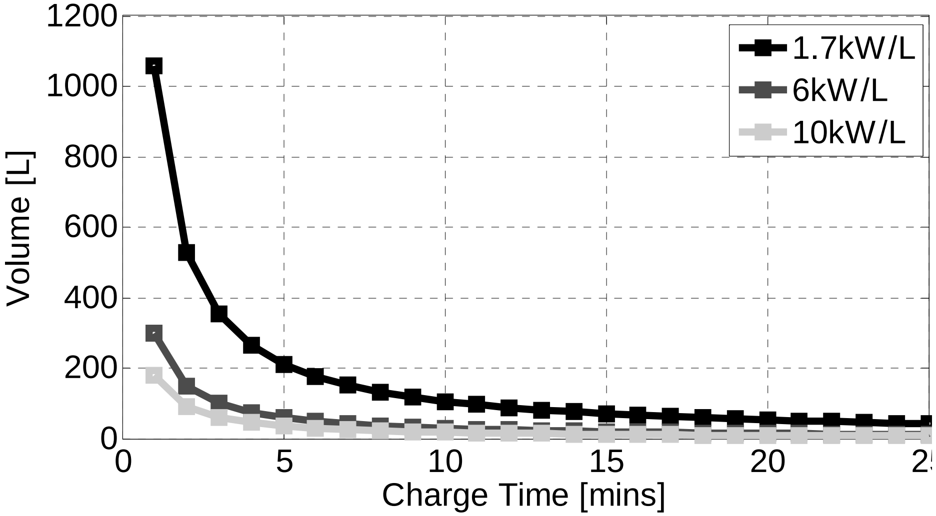
Ideal DC Current and Time to Charge 30kWh Battery

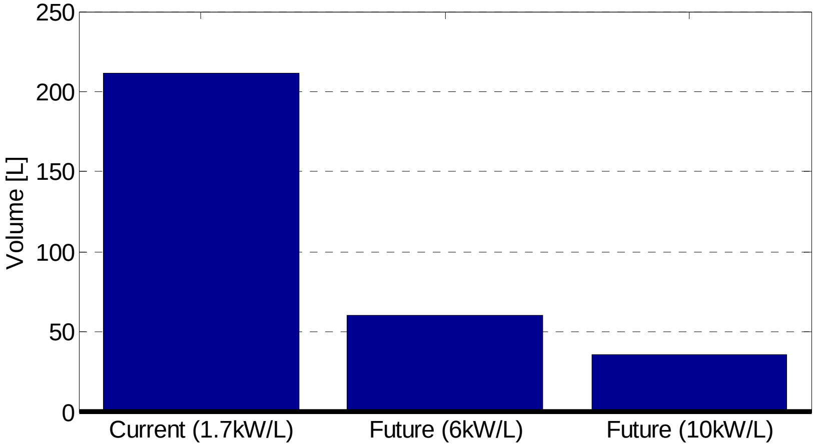
Ideal AC Power Supply to Charge 30kWh Battery



Ideal AC Power Supply and Times to Charge 30kWh Battery

Fast chargers volume for different power densities

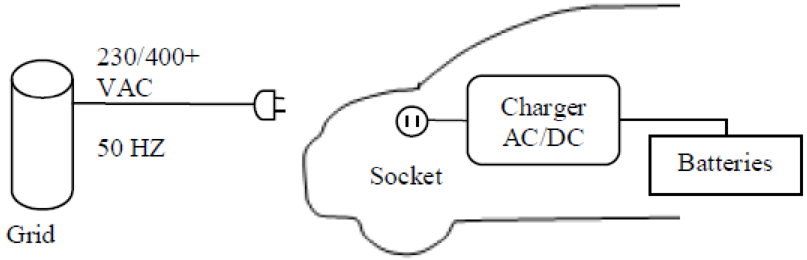


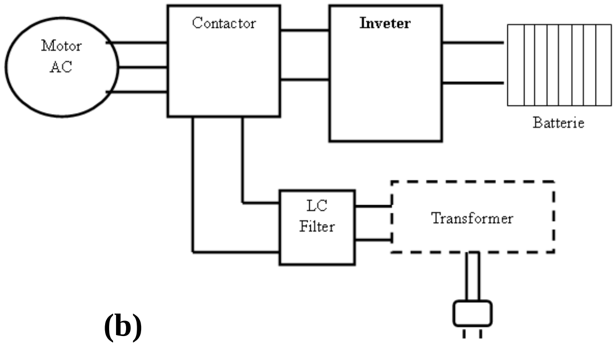


p2

On board charger

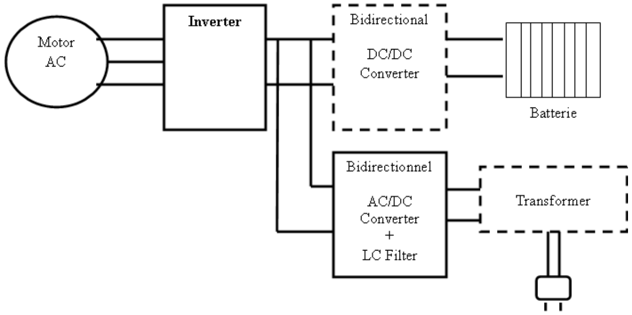
- **(a)**





(b)

(c)



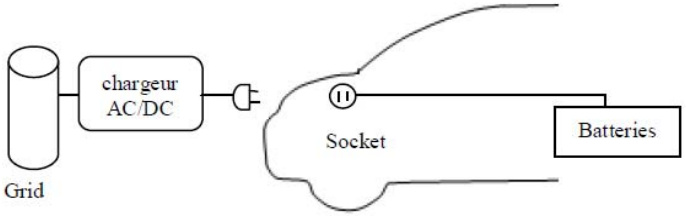
Slide 8

p2 The on-board charger is located inside the vehicle, as shown in Figure 3.3(a). It is designed with a low charging rate and is dedicated to charge the battery for a long period of time. The on-board charger needs to be light (typically less than 5 Kg) and compact due to the limitation of allowable payload and space in the EV and the PHEV. The advantages of this charger are that the battery can be recharged anywhere there is a standard electrical outlet. It can easily communicate with the BMS thanks to the internal wiring network. This effect leads to a higher performance and lower cost. On the other hand, this solution is suitable to the PHEV application in which the specific energy is lower. The drawback of this charger is the limitation of the power output because of size and weight restrictions. There are two methods for designing the bidirectional AC-DC converter: one is that the bidirectional converter separates from the driving system, which is referred to as independent circuit topology and is shown in Figure 3.3(b). The other one is to combine the motor driving with the converter. Commonly this is named combination circuit topology and is shown in Figure 3.3(c). Generally, a battery charger includes not only a bidirectional AC-DC converter, but also an isolation transformer and associated control unit. In this section, the focus is on the AC-DC bi-directional topology. In addition, several bidirectional converter topologies exist and can be used as the PHEV charger. This type of charger is also discussed in [78].

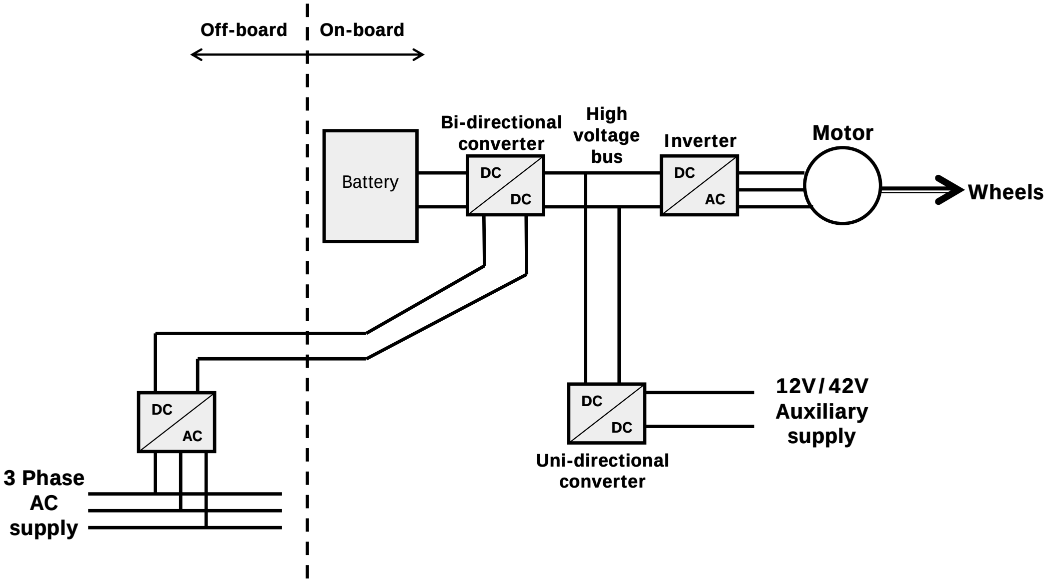
pbauer; 5-1-2010

p3

Off board charger



- **(a)**



p3 The off-board battery charger is separated from vehicle, as shown in Figure 3.4. It can be designed with either a high or low charging rate, and is not limited in its weight and size. The off-board charger is suitable to charge the vehicle during the night with a long charging time or for the public station with a faster charging time (more than 1 hour). In contrast, the high power off-board charger is a fast charger which is designed for commercial applications. This solution is suitable for high power designs, because the power output of fast charges is limited only by the ability of the batteries to accept the charge. The charging time of fast charger is less 1 hour. Even if the EV owner can shorten the time, it means to recharge the batteries with a fast charger. However the availability of this method is restricted due to limitations with the supply network. Since the off-board chargers and the BMS are physically separated, reliable communication is important to ensure correct charging conditions. Depending on the battery’s type, voltage, temperature and SOC supplied by BMS, the off-board charger will adopt a proper charging method

pbauer; 5-1-2010

p7

Renewable energy

p7 Inductively coupled power transfer is based on the principle of electromagnetic induction at high frequency. Whilst the on-board charger and the off-board charger are based on connecting an AC power source to the EV, inductive coupling is based on energy transfer from the power supply to the EV via magnetic induction coupling. A possible solution for an inductive charger is shown in Figure 3.6. A soft-switched converter (high or low parallel resonant) is used for this application. This solution is not sensitive to the parasitic inductance of the cables and the inductance leakage of the transformer. Although the conductive charger has a lot of definitive advantages such as simplicity and high efficiency, the inductive charger is easy to use and is suitable for all-weather conditions. The main drawbacks of this charger are the high investment cost and inevitable induction loss. The basic schema of the inductive charger is shown in the Figure 3.6, the principle is based on the magnetic coupling between two windings of a high frequency transformer. One of the windings is installed in the charger terminal while the other is embedded in the EV. Firstly, the main AC supply of frequency 50-60Hz is rectified and converted to a high frequency AC power of <100kHz within the charger station. Then this high frequency power is transferred to the EV side by induction. Finally this high frequency AC power is converted to a DC power for the battery charging.

pbauer; 5-1-2010

Solar energy

- crystalline silicon solar cells have efficiency around 20%
- to 40% efficiency for multi-junction cells used in space applications
- around 15%, priced at €550/m2, which deliver a maximum power of 125 Watts

Nuna 5 of TUDelft, completely solar powered

Toyota Prius Solar Powered Ventilation System, partially solar powered

Solar EV

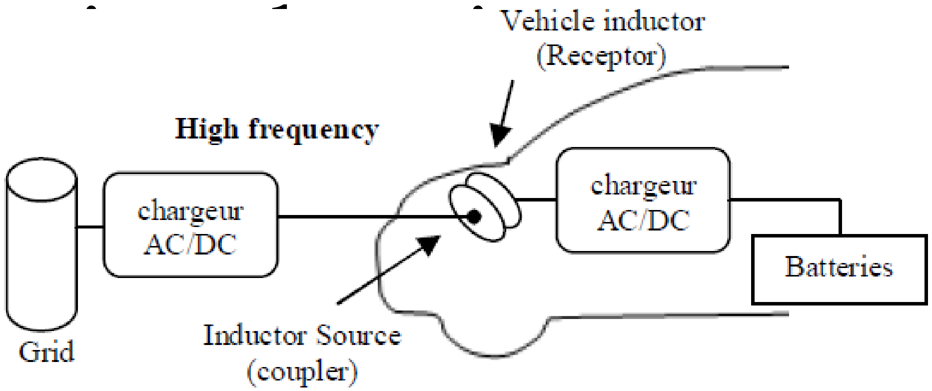
- Examples
- Life-time expectations

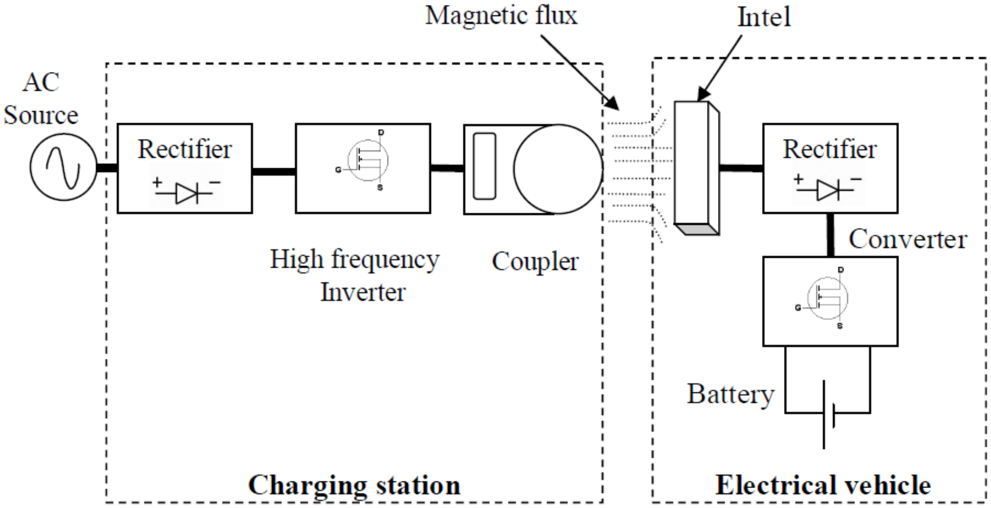
Nuna 5 of TUDelft, completely solar powered

Toyota Prius Solar Powered Ventilation System, partially solar powered

p6

Ind


Vehicle inductor
(Receptor)
High frequency
chargeur
AC/DC
chargeur
AC/DC
Batteries
Grid
Inductor Source
(coupler)


Magnetic flux
Intel
AC
Source
Rectifier
High frequency
Inverter
Coupler
Rectifier
Converter
Battery
Charging station
Electrical vehicle

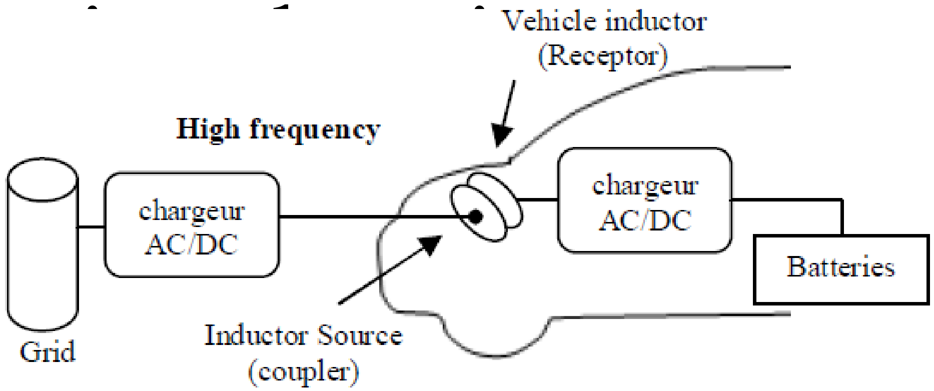
Slide 13

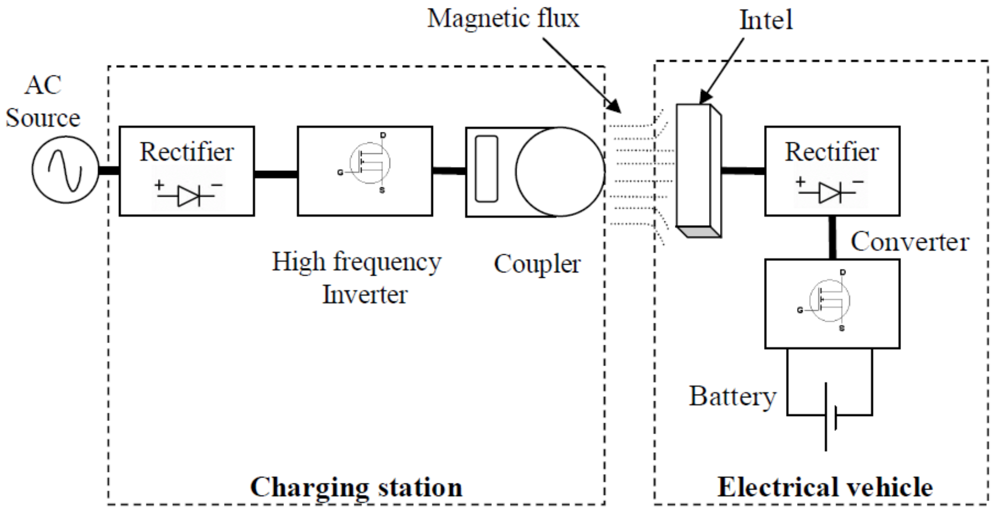
p6 Inductively coupled power transfer is based on the principle of electromagnetic induction at high frequency. Whilst the on-board charger and the off-board charger are based on connecting an AC power source to the EV, inductive coupling is based on energy transfer from the power supply to the EV via magnetic induction coupling. A possible solution for an inductive charger is shown in Figure 3.6. A soft-switched converter (high or low parallel resonant) is used for this application. This solution is not sensitive to the parasitic inductance of the cables and the inductance leakage of the transformer. Although the conductive charger has a lot of definitive advantages such as simplicity and high efficiency, the inductive charger is easy to use and is suitable for all-weather conditions. The main drawbacks of this charger are the high investment cost and inevitable induction loss. The basic schema of the inductive charger is shown in the Figure 3.6, the principle is based on the magnetic coupling between two windings of a high frequency transformer. One of the windings is installed in the charger terminal while the other is embedded in the EV. Firstly, the main AC supply of frequency 50-60Hz is rectified and converted to a high frequency AC power of <100kHz within the charger station. Then this high frequency power is transferred to the EV side by induction. Finally this high frequency AC power is converted to a DC power for the battery charging.

pbauer; 5-1-2010

p4

Ind


Vehicle inductor
(Receptor)
High frequency
chargeur
AC/DC
chargeur
AC/DC
Batteries
Grid
Inductor Source
(coupler)


Magnetic flux
Intel
AC
Source
Rectifier
Rectifier
High frequency
Inverter
Coupler
Converter
Battery
Charging station
Electrical vehicle

Slide 14

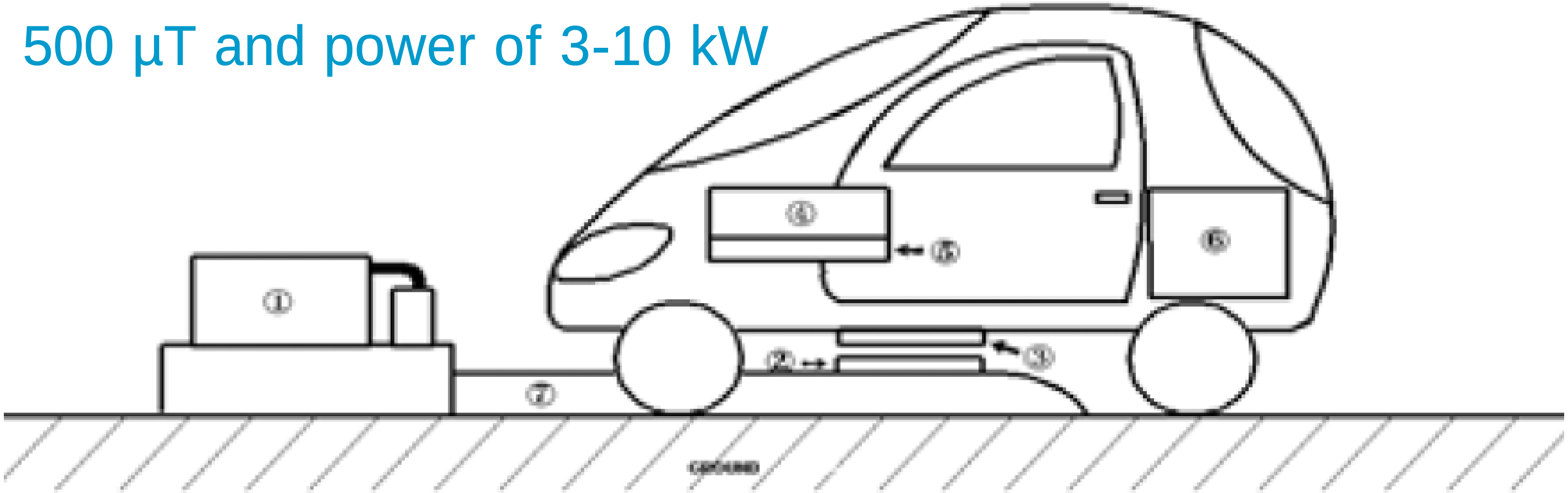
p4 Inductively coupled power transfer is based on the principle of electromagnetic induction at high frequency. Whilst the on-board charger and the off-board charger are based on connecting an AC power source to the EV, inductive coupling is based on energy transfer from the power supply to the EV via magnetic induction coupling. A possible solution for an inductive charger is shown in Figure 3.6. A soft-switched converter (high or low parallel resonant) is used for this application. This solution is not sensitive to the parasitic inductance of the cables and the inductance leakage of the transformer. Although the conductive charger has a lot of definitive advantages such as simplicity and high efficiency, the inductive charger is easy to use and is suitable for all-weather conditions. The main drawbacks of this charger are the high investment cost and inevitable induction loss. The basic schema of the inductive charger is shown in the Figure 3.6, the principle is based on the magnetic coupling between two windings of a high frequency transformer. One of the windings is installed in the charger terminal while the other is embedded in the EV. Firstly, the main AC supply of frequency 50-60Hz is rectified and converted to a high frequency AC power of <100kHz within the charger station. Then this high frequency power is transferred to the EV side by induction. Finally this high frequency AC power is converted to a DC power for the battery charging.

pbauer; 5-1-2010

Inductive charging during parking or at the stoplights

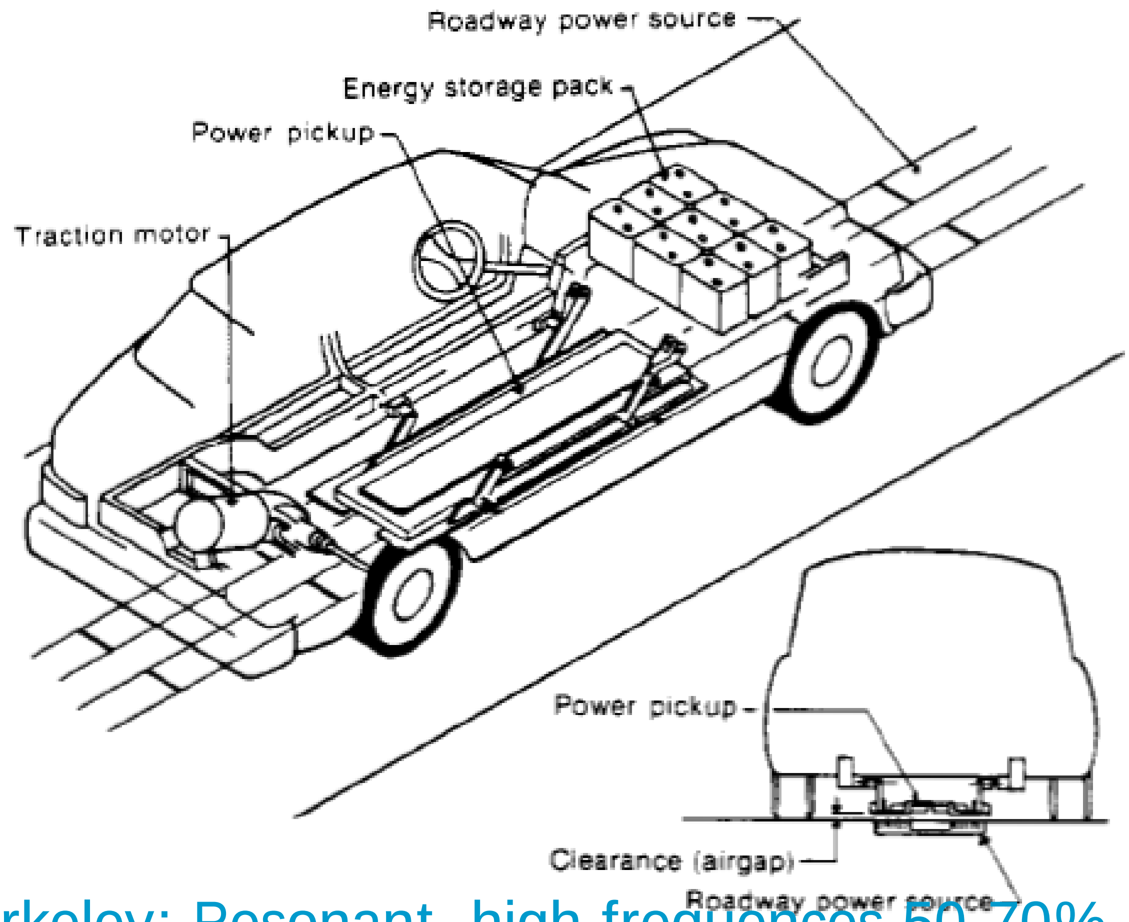
- insertion, proximity and chained-ring

500 µT and power of 3-10 kW



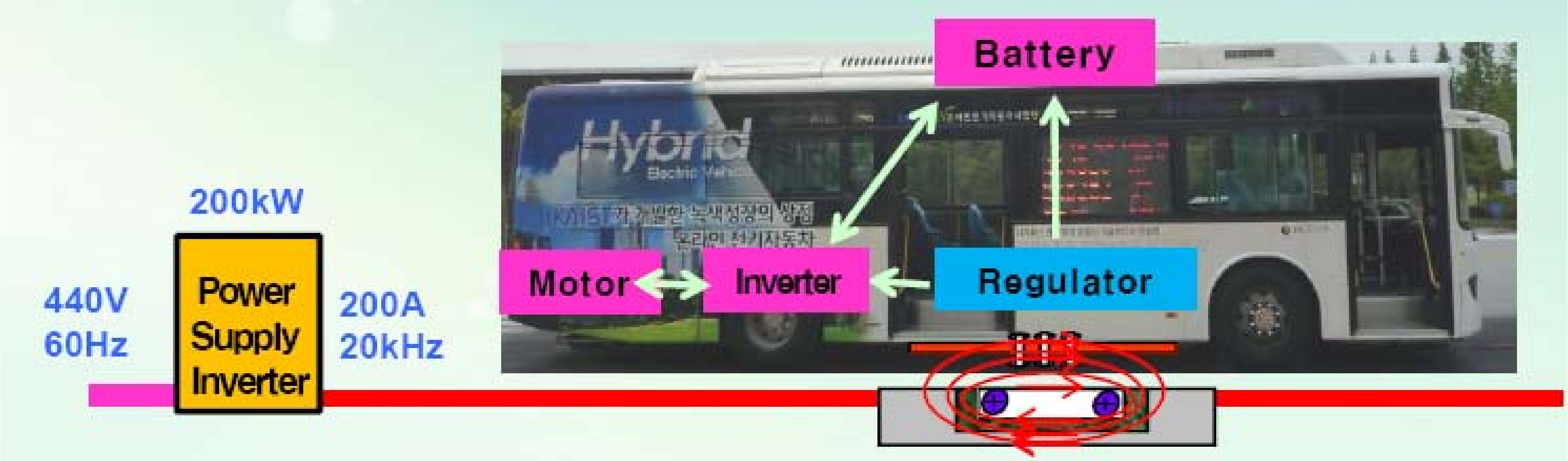
① Outboard charger: primary system ② Primary coil: inductor ③ Secondary coil
④ & ⑤ Onboard charger: secondary system ⑥ Battery ⑦ Wheels guide sidewalk

Inductive charging while driving



Berkeley: Resonant, high frequences 50-70%

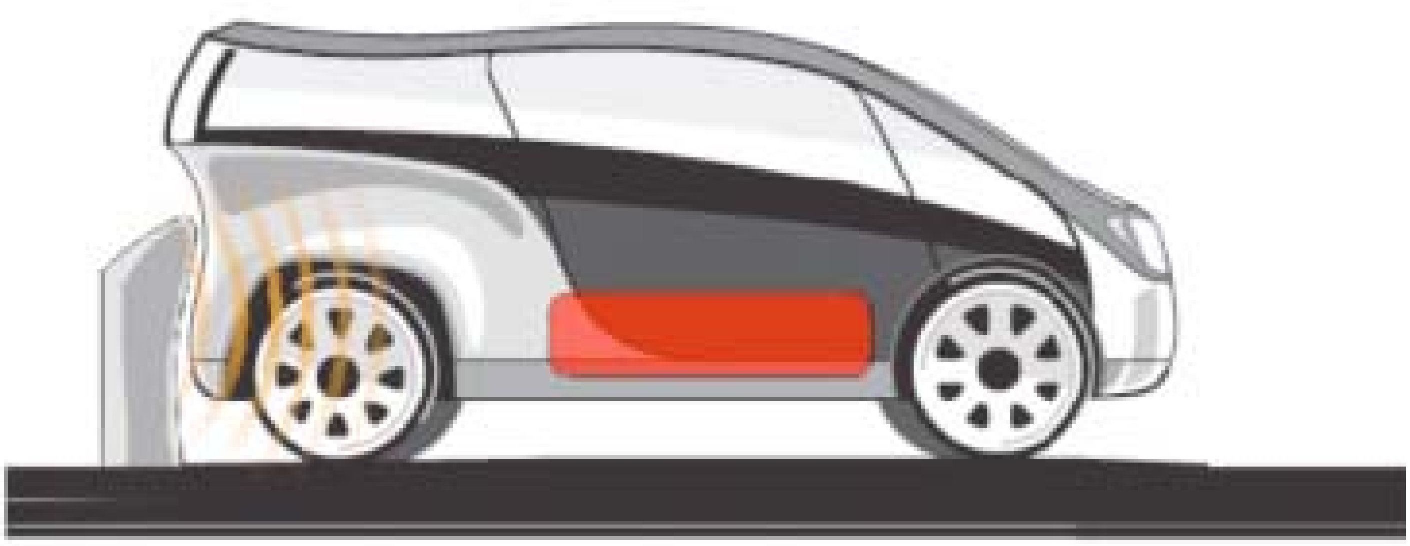
KAIST



OLEV system of KAIST for an electric bus

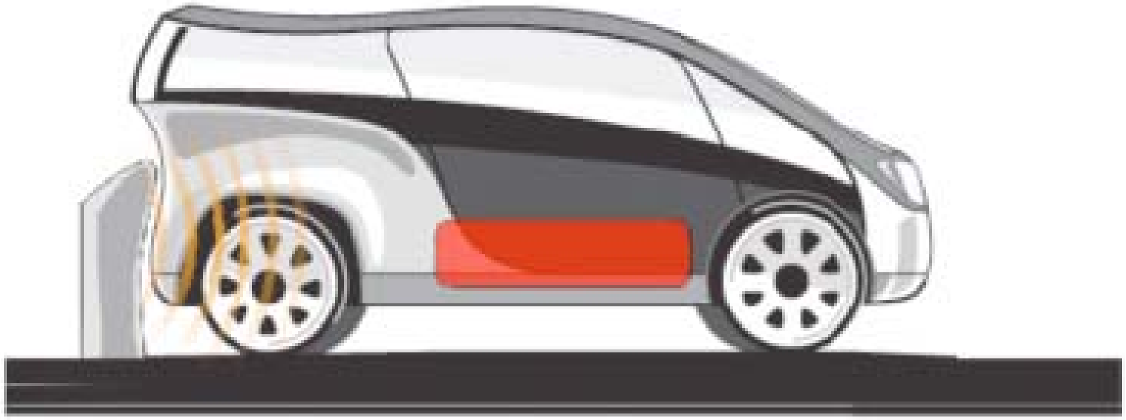
Issues and Questions

- Efficiency
- Cost
- Safety
- Power



Case Study

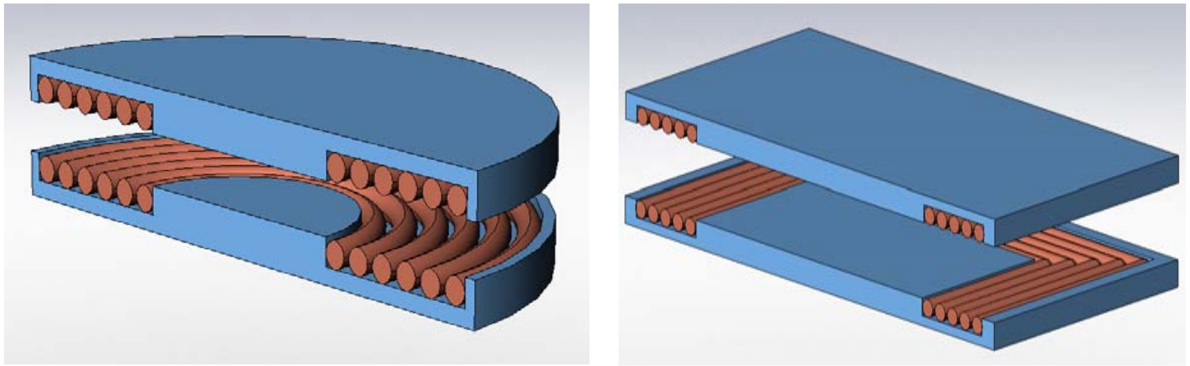
- Design of an contactless charger
- Distance 10 cm



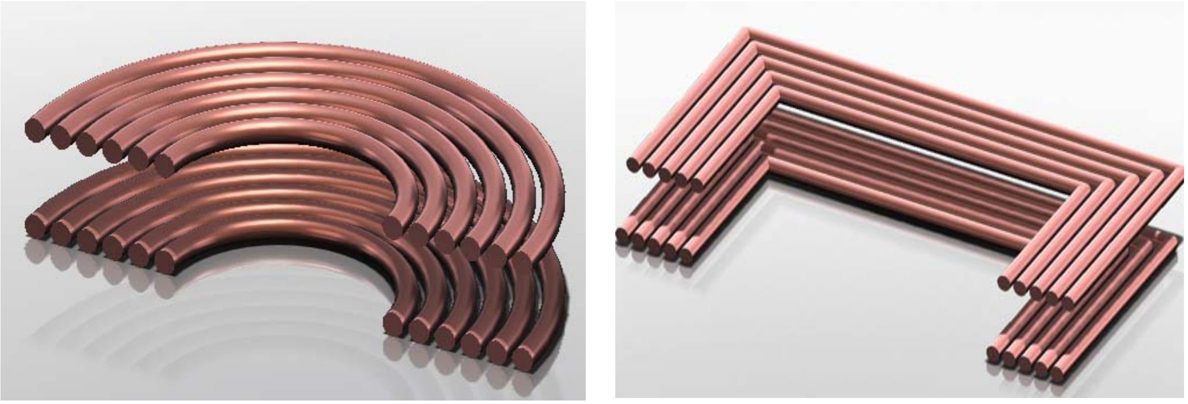
CPT Transformer

Configurations

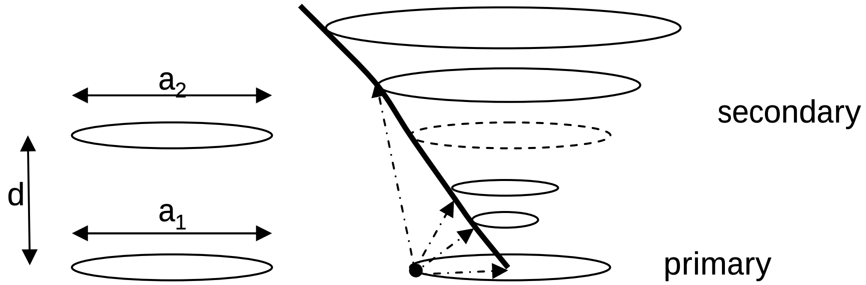
Magnetic Core



Air Core



TU Delft



$$M_{filamentary}\left(a_1,a_2,d\right)=f_{table}(k'^2)\cdot\sqrt{a_1\cdot a_2}$$

$$k'^2=\frac{\left(a_1-a_2\right)^2+d^2}{\left(a_1+a_2\right)^2+d^2}$$

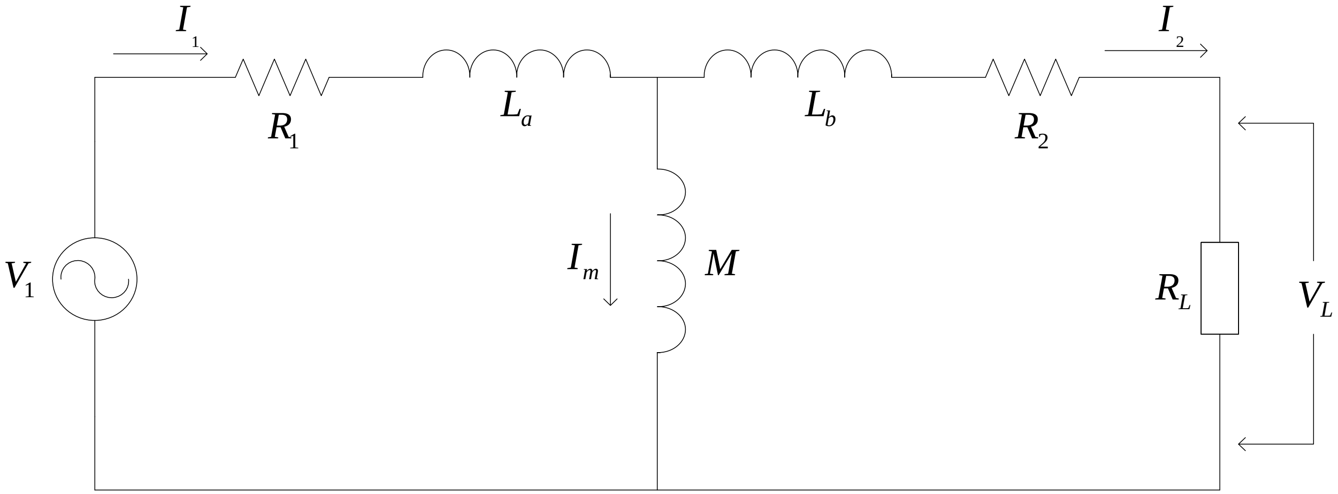
- F.van de Pijl, P.Bauer, J.A.Ferreira: An adaptive controlling method, an adaptive controller and a computer program product, patent application OCT-08-066
- F.van de Pijl, P.Bauer, J.A.Ferreira: Contactless energy transfer, patent application OCT-08-066

Losses in CPT transformer

- Iron losses (eddy current and hysteresis losses)
  - Present only in case of transformer with magnetic core

- Copper losses (I^2R losses)
  - Frequency dependent behavior of resistance of the windings
  - Non-uniform distribution of current density in conductors at high frequencies
  - Eddy current effects: Skin effect and Proximity effect

Equivalent CPT air core transformer model



$$\eta = \frac{\left|\overline{I_2}\right|^2 R_L}{\left|\overline{I_2}\right|^2 R_L + \left|\overline{I_2}\right|^2 R_2 + \left|\overline{I_1}\right|^2 R_1}$$

$$pf = \cos\left(\tan^{-1}\left[\frac{\mathrm{Im}(\overline{V_1}\,\overline{I_1}^*)}{\mathrm{Re}(\overline{V_1}\,\overline{I_1}^*)}\right]\right)$$

$$\eta_{\max} = \frac{R_L}{R_L + R_2 + R_1\left(\frac{L_b + M}{M}\right)^2}$$

Self inductance of primary winding *L_1* [H]	112×10^{-6}
Self inductance of secondary winding *L_2* [H]	15.8×10^{-6}
Mutual inductance *M* [H]	5.7×10^{-6}

Copper Losses

Skin effect and Proximity effect

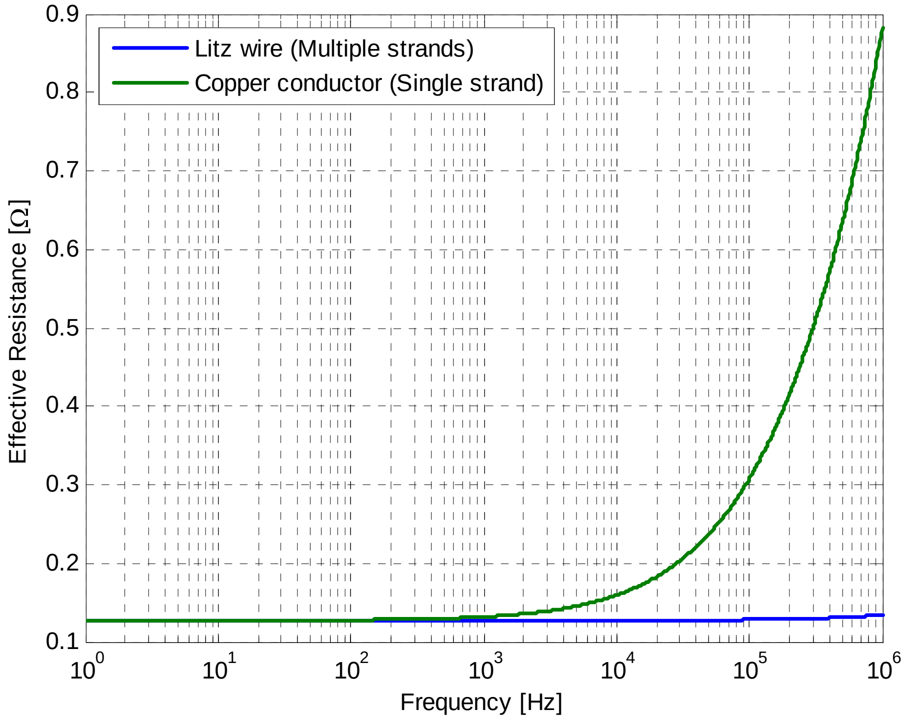
- Skin effect
  - Arises from time varying current flowing in same conductor

$$R_{eff} = \frac{\rho}{\pi \cdot \delta \cdot (1 - e^{\frac{-r}{\delta}}) \cdot (2r - \delta \cdot (1 - e^{\frac{-r}{\delta}}))} [\Omega \cdot m]$$

Where ρ is resistivity of the material of the

Conductor, r is the radius of the round conductor,

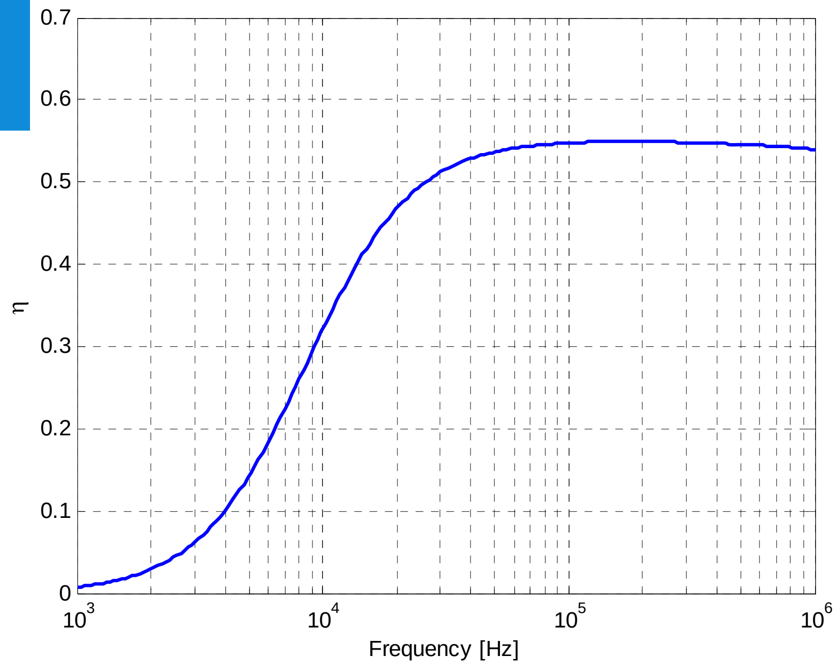
δ is the skin depth

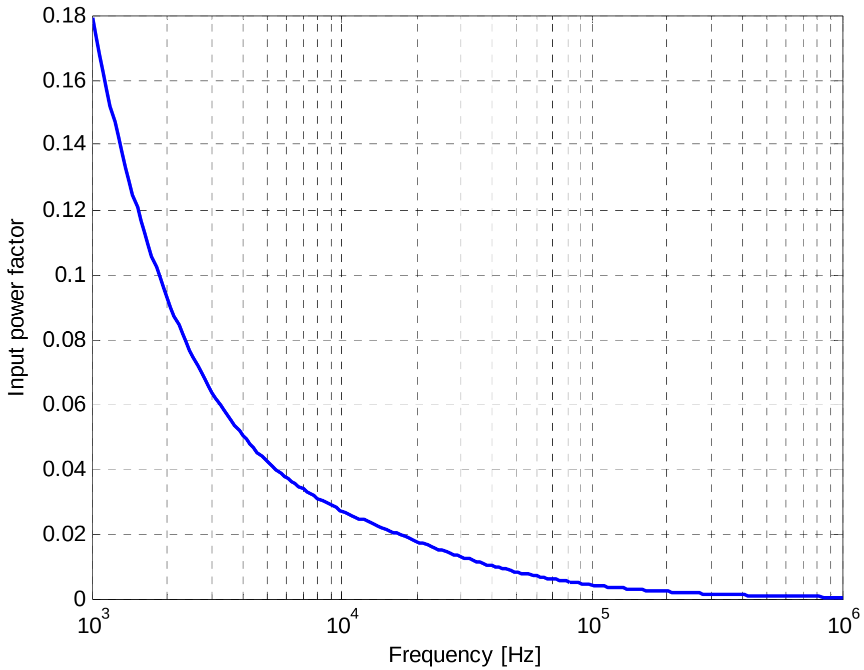


- Proximity effect
  - Arises from time varying current flowing in adjacent conductors

Litz wire designed specifically to minimize skin and proximity effect

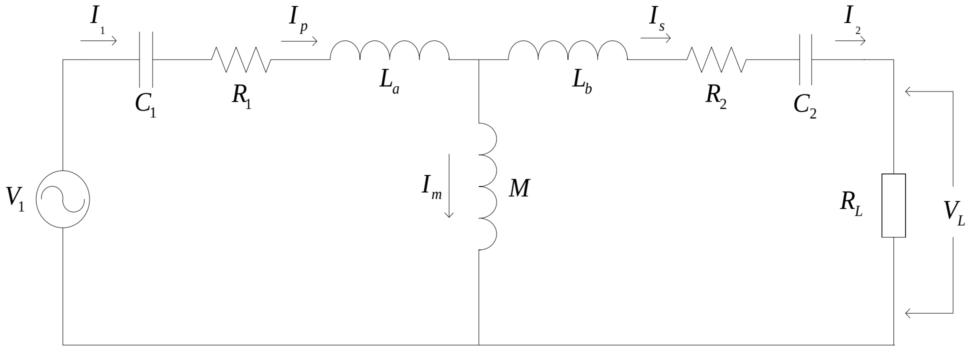
Power transfer capability



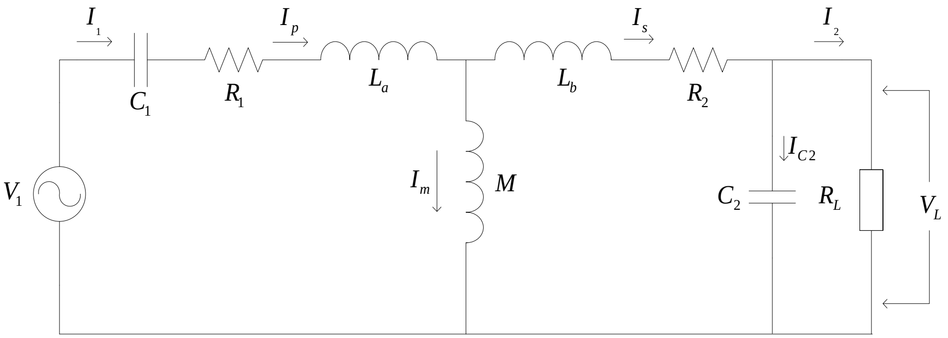


- Power transfer capability of the CPT system is rather poor
- Input power factor is low which implies large VA rating of the source

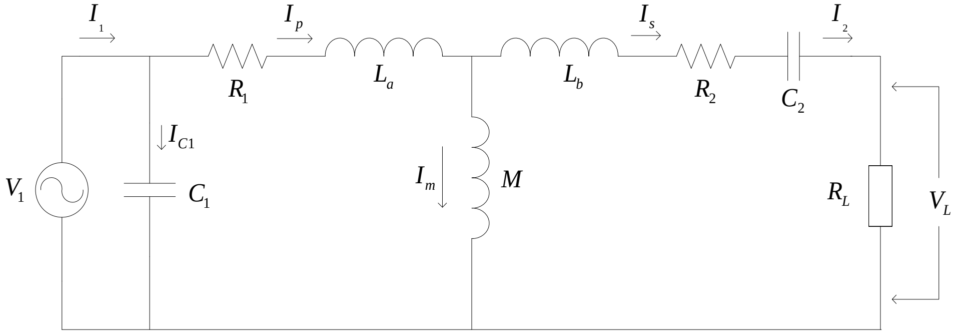
Compensation



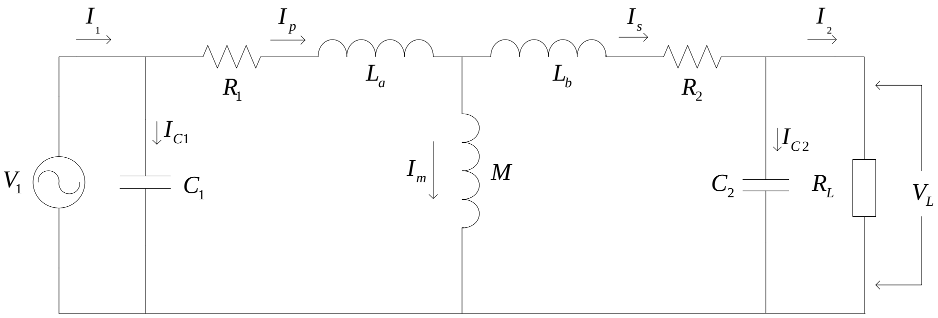
SS



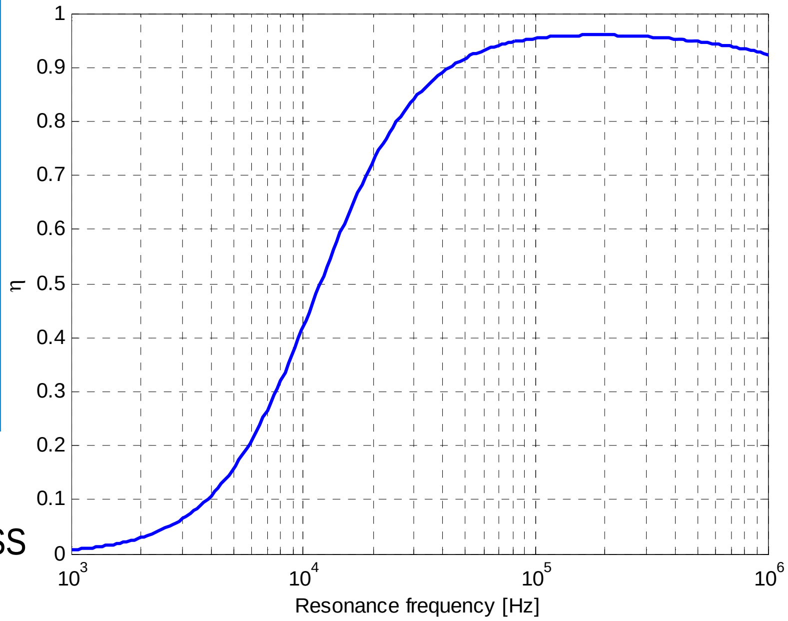
SP



PS

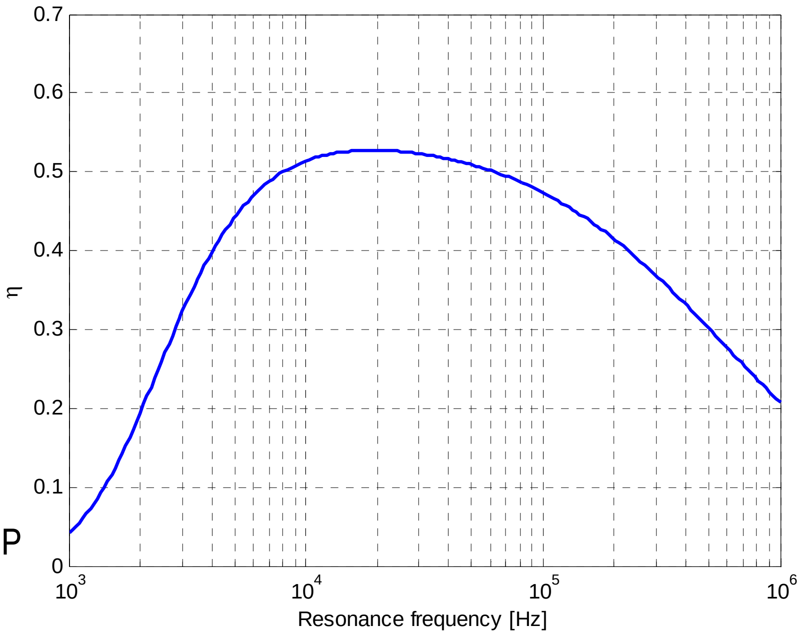


PP



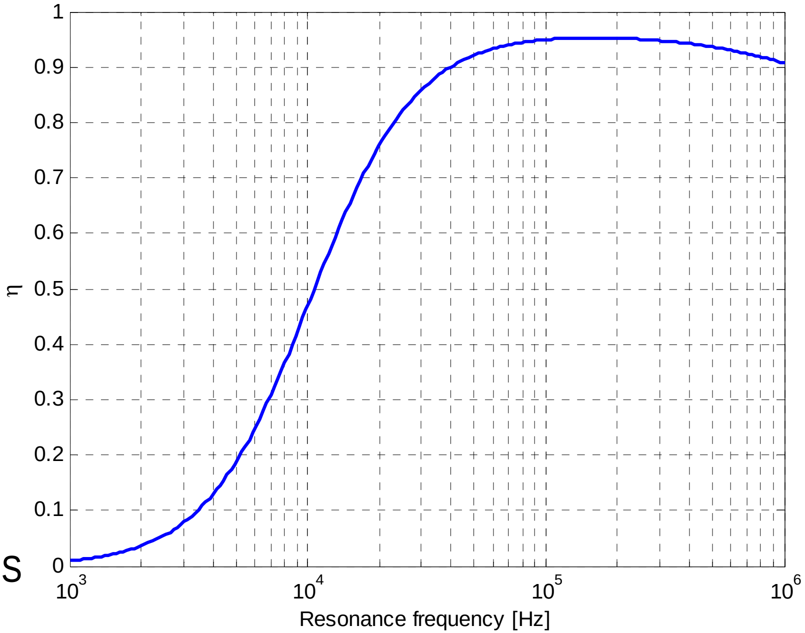
SS

η
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^3
10^4
10^5
10^6
Resonance frequency [Hz]



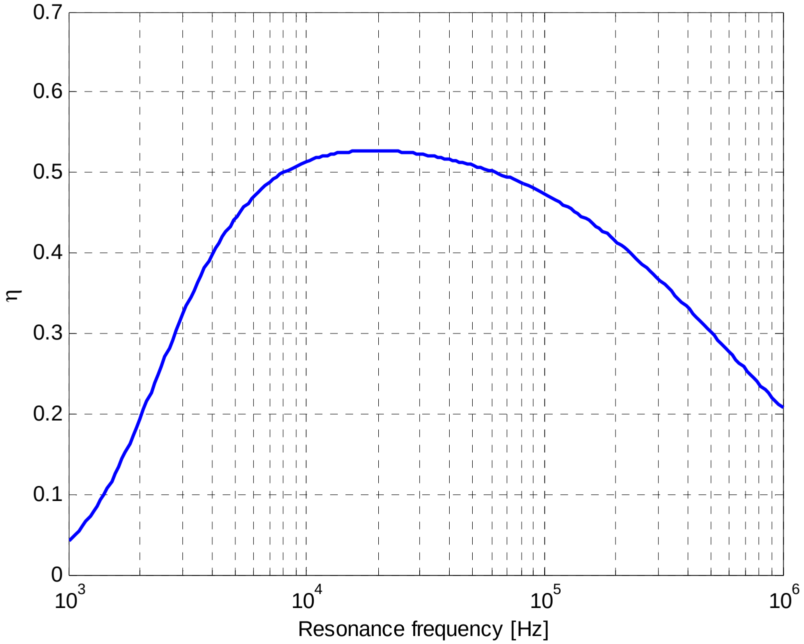
SP

η
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10^3
10^4
10^5
10^6
Resonance frequency [Hz]



PS

η
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^3
10^4
10^5
10^6
Resonance frequency [Hz]



PP

η
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
10^3
10^4
10^5
10^6
Resonance frequency [Hz]

System Configuration