UNIVERSITY OF MICHIGAN-DEARBORN

Development of an Extremely Efficient Wireless EV Charger

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Outline

- Definitions of wireless power transfer
- Conventional charging methods: limitations
- History and types of wireless power transfer
- Application of wireless power transfer
- State-of-the-art and limitations of current WPT
- Resonant topologies of WPT
- The complete wireless EV Charger system and results
- Other issues: coil selection, safety, object detection
- Application example – wireless power roadway charging of electric bus fleets

Definition of Wireless Power

- Wireless power transfer (WPT)
- Inductive power transfer (IPT)
- Contactless power system (CPS),
- Wireless energy transfer
- Strongly coupled magnetic resonance
- Capacitive wireless power transfer
- The essential principles are the same: given the distances over which the power is coupled is almost always within one quarter of a wavelength and therefore, the fundamental operation of all of these systems can be described by simple coupled models

Ref: Grant Covic and John Boys, “Modern Trends in Inductive Power Transfer for Transportation Applications,” IEEE journal of emerging and selected topics in power electronics, vol. 1, no. 1, march 2013

Electric Vehicle Charging

- EVs offer many advantages such as reduced fossil fuel consumption and emissions from the tailpipe
- But they suffer from short driving range, long charging time, and high cost
- Fast charging can mitigate the above issues but typically compromise battery life, increased cost for the charging stations, and heavy loading for the power grid

	Charging time and Power requirement			
Range	5 minutes	15 minutes	30 minutes	8 hours
100 miles	390 kW	130kW	65kW	4 kW
400 miles	1560kW	520kW	260kW	16kW

Conductive Charging – Regular

Normal charging

AC charging using level 1 or level 2，voltage at 110V, 220V， 4-10 hours per charge.

Charge at home or public space, need large installation of charge stations.

Range anxiety exists due to the slow charging.

"Charging stations in SF City Hall 02 2009 02" by Felix Kramer (CalCars). Image retouched with Photoshop and uploaded by User:Mariordo - Flickr: http://www.flickr.com/photos/56727147@N00/3292024112/in/set-72157614049251389/. Licensed under Creative Commons Attribution-Share Alike 2.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Charging_stations_in_SF_City_Hall_02_2009_02.jpg#mediaviewer/File:Charging_stations_in_SF_City_Hall_02_2009_02.jpg

Conductive Charging – Fast Charging

"Nissan LEAF got thirsty" by evgonetwork (eVgo Network). Original image was trimmed and retouched (lighting and color tones) by User:Mariordo - http://www.flickr.com/photos/evgo/6545153803/. Licensed under Creative Commons Attribution 2.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Nissan_LEAF_got_thirsty.jpg#mediaviewer/File:Nissan_LEAF_got_thirsty.jpg

Fast charging

Charging in 15 to 30 minutes.

For an EV with a 24kWh battery pack, charging in 15 minutes means 96kW. This is way over the power available in private homes.

Fast charging can degrade battery lifetime.

Battery Swapping

Battery swapping

Investment of battery packs; standardization is difficult; swapping stations need a lot investment, space and manpower; safety and reliability is of concern.

Better Place already went to bankruptcy.

"Better Place Charging Station IMG 6670" by Eli Shany שנילי- Own work. Licensed under Creative Commons Attribution-Share Alike 3.0 via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Better_Place_Charging_Station_IMG_6670.jpg #mediaviewer/File:Better_Place_Charging_Station_IMG_6670.jpg

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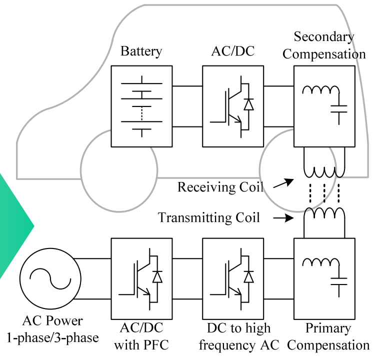
Issues of Conductive Charging and Battery Swapping

Electric safety is of concern: electric shock due to rain, etc.

Charge station, plug and cable can be easily damaged, stolen

Charge/swap station takes a lot of space and affect the views



Possible Solution:

Wireless Charging

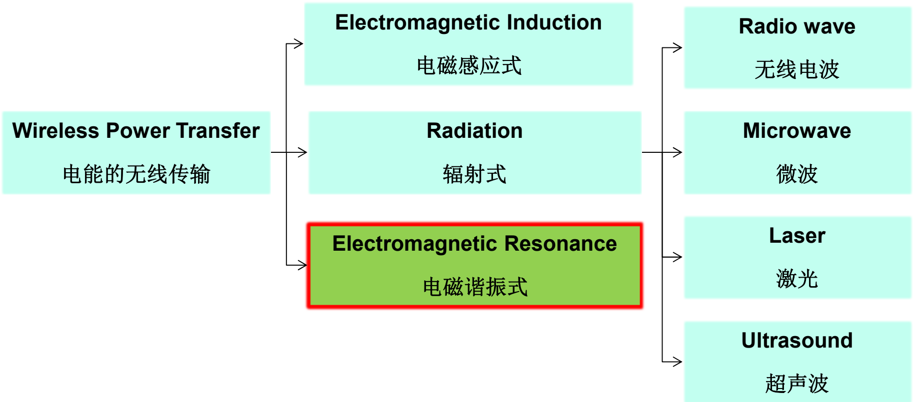
History of Wireless Power Transfer

- 1830’s: Faraday's law of induction
- 1890’s: Tesla had a dream to send energy wirelessly
- 1990’s: GM EV1 used an Inductive charger in the 1990’s
- 2007: MIT demonstrated a system that can transfer 60W of power over 2 m distance at very low efficiency
- 2010: Wireless/inductive chargers are available: electronics, factories, medical
- 2012: Qualcomm, Delphi (Witricity), Plugless Power, KAIST, etc. have developed EV wireless charger prototypes
- 2014: in-motion charging demonstration

"Tesla Broadcast Tower 1904" by Unattributed(Life time: Unattributed) - Original publication: UnknownImmediate source: http://www.sftesla.org/images/Tesla_Broadcast_Tower.JPG. Licensed under Public domain via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Tesla_Broadcast_Tower_1904.jpeg#mediaviewer/File:Tesla_Broadcast_Tower_1904.jpeg

The Predicted Wireless Charging Market: $17 Billion by 2019, including applications in consumer electronics, home appliance, industrial robots, and EV charging

Methods of Wireless Power Transfer



Wireless Power Transfer
电能的无线传输

Electromagnetic Induction
电磁感应式

Radiation
辐射式

Electromagnetic Resonance
电磁谐振式

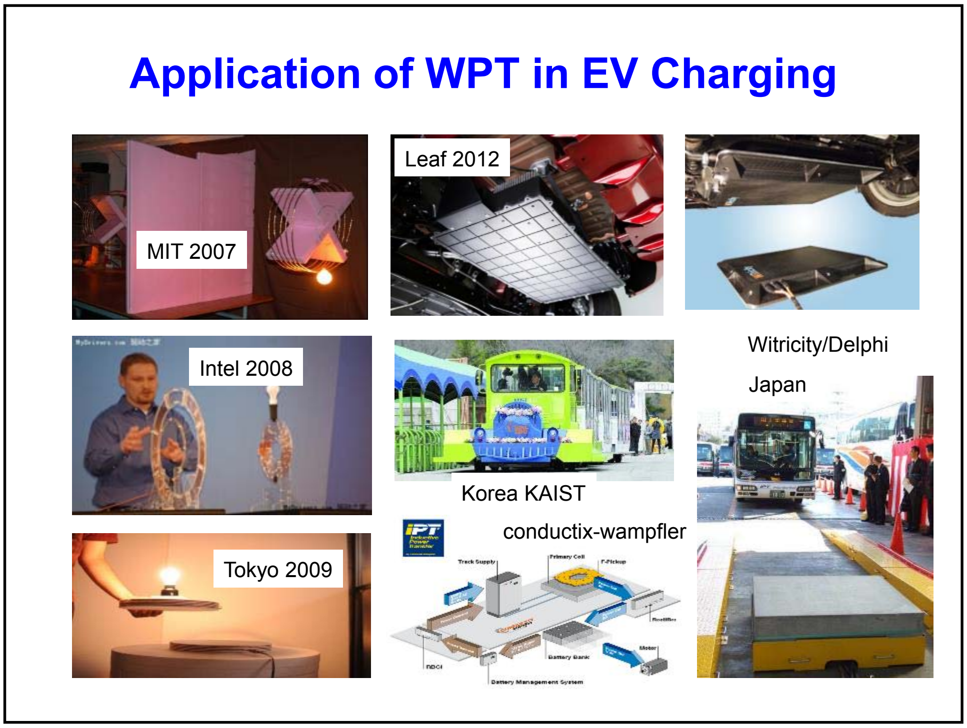
Radio wave
无线电波

Microwave
微波

Laser
激光

Ultrasound
超声波

- Most WPT is to effectively transfer heat
- Microwave has been used in our homes/offices
- Induction heating is popular in industrial applications



Application of WPT in EV Charging

MIT 2007

Leaf 2012

Intel 2008

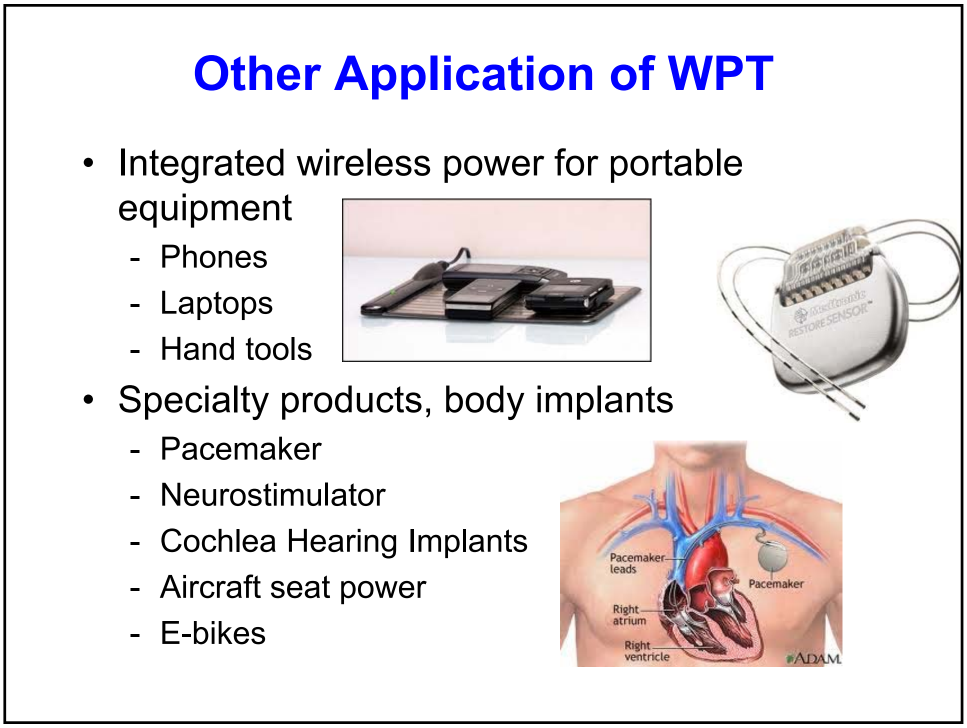
Korea KAIST

Tokyo 2009

conductix-wampfler

Witricity/Delphi

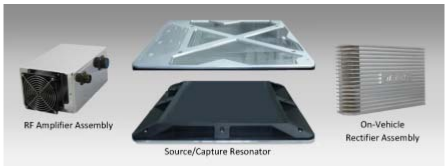
Japan



Other Application of WPT

- Integrated wireless power for portable equipment
  - Phones
  - Laptops
  - Hand tools
- Specialty products, body implants
  - Pacemaker
  - Neurostimulator
  - Cochlea Hearing Implants
  - Aircraft seat power
  - E-bikes

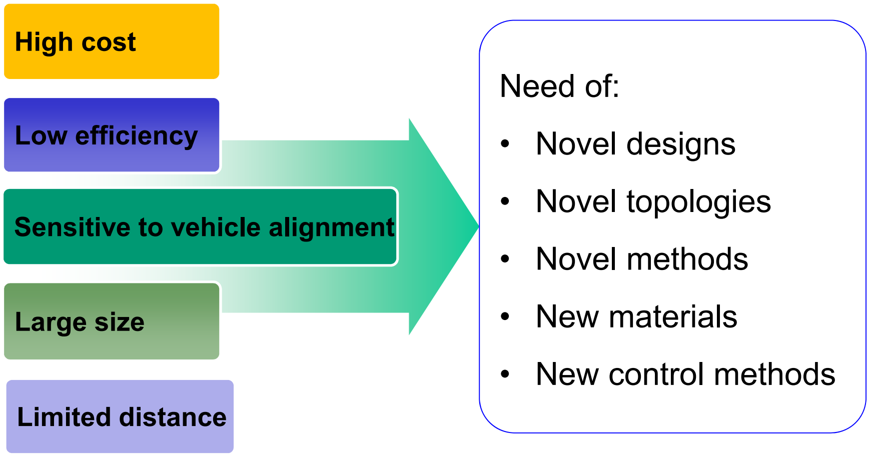
State-of-the-Art Wireless EV Charger



Benchmark：Delphi, Witricity, MIT spinoff company

Attribute	Specifications
Operating Frequency	145 kHz, nominal
Lateral Positional Tolerance	±20 cm in vehicle side to side axis ±10 cm in vehicle bumper to bumper axis
Output Power	DC: 300 watts-3.3 kilowatts, continuously variable
Output Voltage	DC: 350 VDC- 400 VDC at 3.3 kW, 18 cm resonator-resonator distance
Physical Dimensions	
Source Module Enclosure	50 cm x 50 cm x 3.75 cm; 12.5 kg
Capture Module Enclosure	50 cm x 50 cm x 3.75 cm; 12.5 kg
RF Amplifier Assembly	22 cm x 33 cm x 13 cm; 4.2 kg
On-Vehicle Rectifier Assembly	20 cm x 28 cm x 7 cm; 3.6 kg

Limitations of Current WPT



High cost

Low efficiency

Sensitive to vehicle alignment

Large size

Limited distance

Need of:

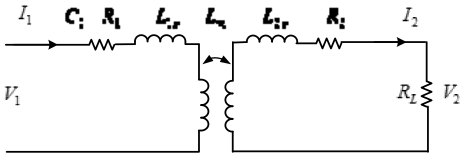
- Novel designs
- Novel topologies
- Novel methods
- New materials
- New control methods

Problems and Difficulties

- Magnetic field is diminishing proportional to1/r^3
- Often the mutual inductance is less than 20% or 10% of the self inductance
- Analytical calculation of coil mutual inductance is almost impossible due to 3D nature, misalignment, etc.
- 3D numerical simulation – magnetostatic may not work due to the high frequency involved
- Further analytical method is needed
- High frequency HFSS instead due to high frequency (20kHz, 85kHz, 150kHz, to MHz)
- Coupled field and lumped parameter simulation is of paramount importance

Transformer Theory

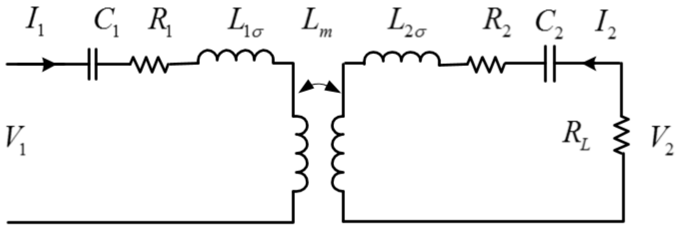
- Inductive WPT systems works like a transformer
- But loosely coupled between the primary and secondary
- Result: mutual coupling coefficient is only 10~20%



- Conventional Transformer
- Leakage is ~2%
- Operate at 50/60Hz

- Wireless less power
- Leakage is >80%
- Operate at KHz ~ MHz

Capacitor Compensation - Resonance



Series-Series Resonance Structure

L_1, L_2 – Self inductance

L_m – Mutual inductance

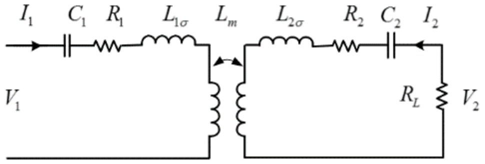
$L_1 = L_{1\sigma} + L_m$; $L_2 = L_{2\sigma} + L_m$

$$\begin{bmatrix} V_1 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j(\omega L_1 - \dfrac{1}{\omega C_1}) & -j\omega L_m \\ -j\omega L_m & R_L + R_2 + j(\omega L_2 - \dfrac{1}{\omega C_2}) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

Series-Series Compensation

- Let

$$Z_1 = R_1 + j(\omega L_1 - \frac{1}{\omega C_1}); \qquad Z_2 = R_2 + R_L + j(\omega L_2 - \frac{1}{\omega C_2})$$



$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \frac{1}{Z_1 Z_2 + (\omega L_m)^2} \begin{bmatrix} Z_2 & -j\omega L_m \\ -j\omega L_m & Z_1 \end{bmatrix} \begin{bmatrix} V_1 \\ 0 \end{bmatrix}$$

Power Transferred

- Power of output side

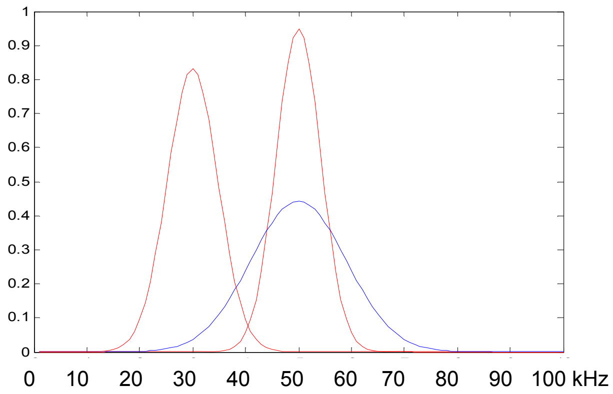
$$P_2 = |I_2|^2 R_L = \frac{V_1^2 (\omega L_m)^2 R_L}{|[Z_1 Z_2 + (\omega L_m)^2]^2|}$$

- Power of the input side

$$P_1 = |V_1| \cdot |I_1| \cos\varphi = \frac{V_1^2 |Z_2|}{|Z_1 Z_2 + (\omega L_m)^2|} \cos\varphi$$

Efficiency

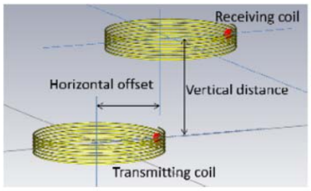
- Efficiency as a function of frequency and circuit parameters

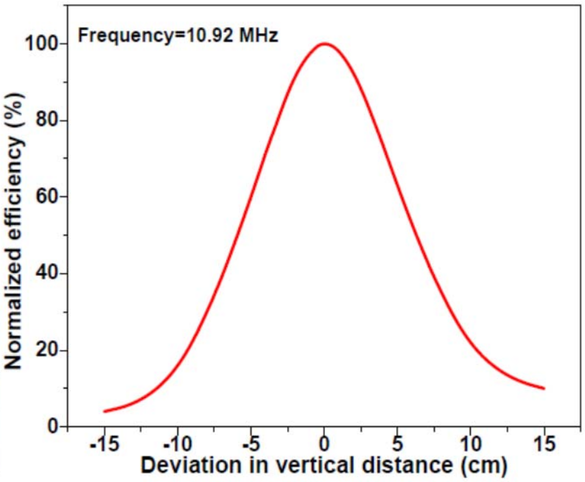


$$\eta = \frac{P_2}{P_1} = \frac{(\omega L_m)^2 R_L}{|Z_2[Z_1 Z_2 + (\omega L_m)^2]| \cos\varphi}$$

Typical Efficiency Curves VS Distance

- Normalized efficiency for deviation in vertical separation from designed value of 25cm





Sivanand Krishnan, Satyanarayan Bhuyan, Vasudevan Pillai Kumar, Wenjiang Wang, Jefnaj Al Afif and Khoon Seong Lim, "Frequency Agile Resonance-Based Wireless Charging System for Electric Vehicles," ECCE 2009

Quality Factor in the Resonance

- High quality factor can increase efficiency at resonance frequency
  - Efficiency drops very quickly when drift away from its resonance
- Definition of quality factor

For series resonance:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{\omega_0 L}{R}; \qquad \omega_0 = \frac{1}{\sqrt{LC}};$$

For parallel resonance:

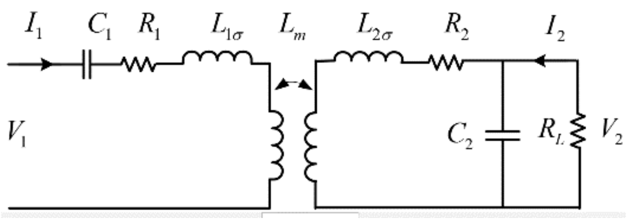
$$Q = \frac{1}{R}\sqrt{\frac{C}{L}} = \frac{R}{\omega_0 L}; \qquad \omega_0 = \frac{1}{\sqrt{LC}}$$

- Typical quality factors are in the hundred

Example: for series resonance:

$$\omega_0 = 2\pi \cdot 80kHz; \qquad L = 30\mu H; \qquad R = 0.1\Omega; \qquad C = 0.132\mu F;\ Q = 150.1$$

Series-Parallel Topology



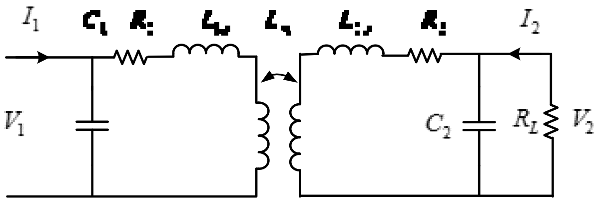
$$Z_1 = R_1 + j(\omega L_1 - \frac{1}{\omega C_1})$$

$$Z_2 = R_2 + j\omega L_2 + \frac{R_L}{1 + j\omega C_2 R_L}$$

Constant current is suitable for battery charging with constant-current

$$\eta = \frac{P_2}{P_1} = \frac{(\omega L_m)^2 R_L}{|Z_2[Z_1 Z_2 + (\omega L_m)^2](1 + j\omega C R_L)^2|}$$

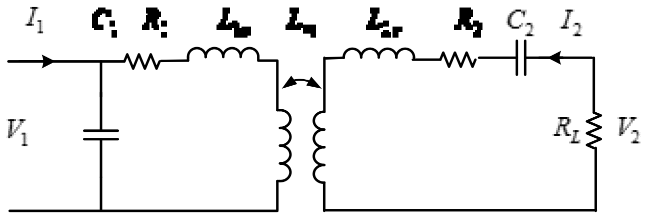
Parallel-Parallel Topology



$$Z_1 = \frac{1}{j\omega C_1} // (R_1 + j\omega L_1)$$

$$Z_2 = R_2 + j\omega L_2 + \frac{R_L}{1 + j\omega C_2 R_L}$$

Parallel-Series Topology



$$Z_1 = R_1 + j(\omega L_1 - \frac{1}{\omega C_1})$$

$$Z_2 = R_2 + j\omega L_2 + R_L + \frac{1}{j\omega C_2 R_L}$$

Compensation Methods

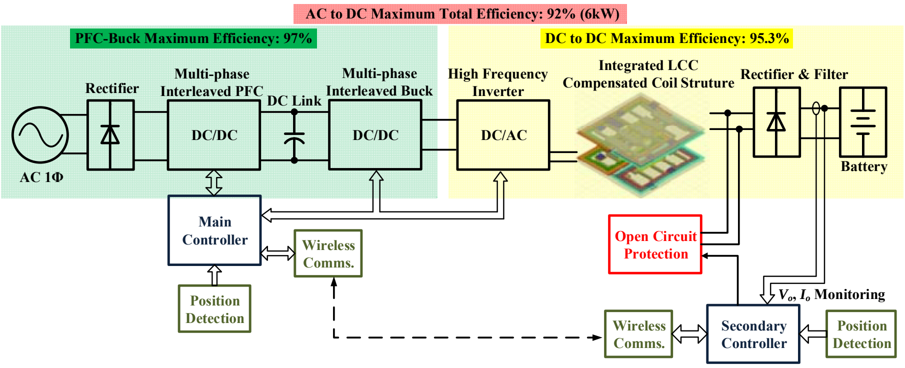
- To resonate with leakage inductance, as position change, leakage inductance will change, Therefore
  - Frequency may need to be tuned for new resonance
  - When circuit resonates, efficiency will dependent on Lm only
  - It is possible that only one coil resonates, which will reduce efficiency
- To resonate with self inductance, L1 and L2 change slightly with alignment
  - Frequency may not need to be tuned

Frequency Selection

- SAE Hybrid J2954 Frequency Selection Task Force is working on the selection of a frequency for EV applications
- 20kHz has been used by KAIST
  - High power (>50kW), IGBT devices
- 80kHz has been used by UM-Dearborn
  - Medium power (10kW), MOSFET
  - For high power, multiple WPT in parallel (>50kW)
- 200kHz has been used to reduce size of WPT
- 2MHz, 13MHz has been used for medical applications
- GHz has been mentioned for ultra small size requirements, for low power applications
  - High frequency cause eddy current in wire, ferrites, and surrounding objects

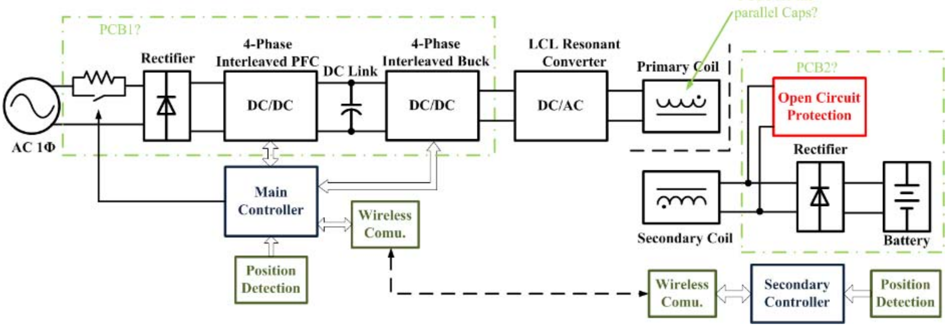
The Complete Wireless EV Charger

- Multistage chargers similar to conductive charger
  - Rectifier + PFC
  - DC-DC converter
  - Resonant inverter
  - Magnetic coupler
  - Rectifier + filter
  - Communications between two coils



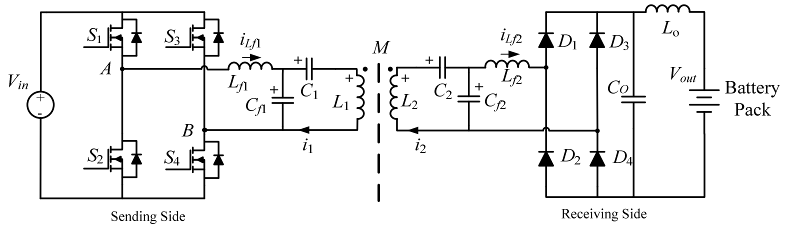
System Topology at UMD

- Key inventions:
  - Optimized multi-coil design for maximum coupling, with bipolar architecture
  - LCC topology for soft switching to further increase efficiency and frequency
  - Distributed circuit parameters to minimize the capacitor size and voltage rating
  - Bidirectional LCL Power factor correction circuit to maximize the front end efficiency and reduce system cost
  - Foreign object detection and electromagnetic field emissions for human and animal safety for the developed system.



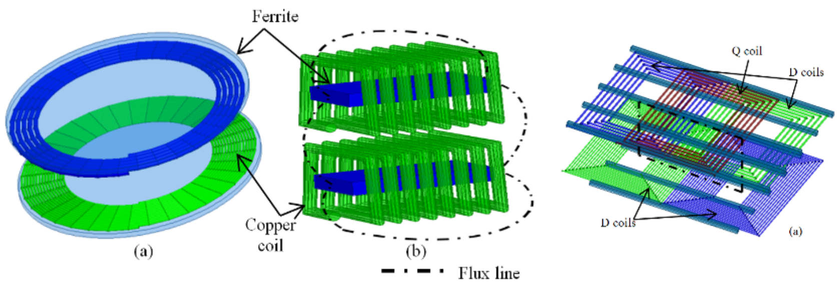
Double-sided LCC Compensated Wireless Power Transfer

- Topology

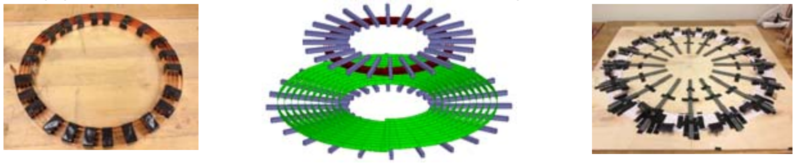


- Important Characteristic:
- The output current at resonant frequency: $I_{Lf2} = I_{Lf2\_1} = \frac{U_m}{\omega_0 L_f} = \frac{L}{\omega_0 L_f^2}\cdot k\cdot U_1$
- The output power can be expressed as: $P = U_2 \cdot I_{Lf2\_1} = \frac{L}{\omega_0 L_f^2}\cdot k\cdot U_1\cdot U_2$

Comparison of Coil Design

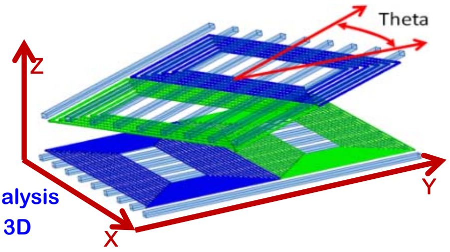


(a) Circular pads, (b) flux-pipe pads (c) DD-DDQ bipolar pads

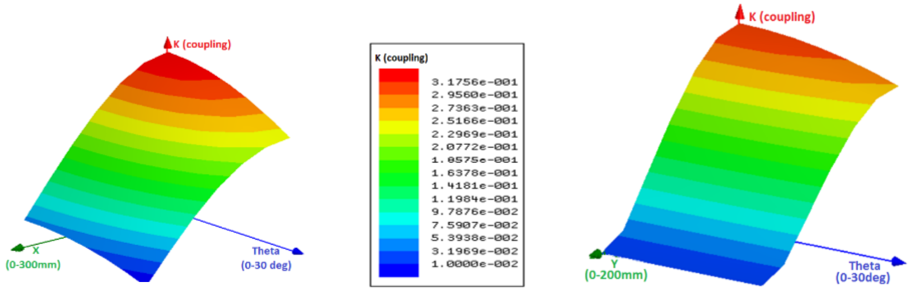


Trong-Duy Nguyen, Siqi Li, Weihan Li, Chunting Chris Mi, Feasibility Study on Bipolar Pads for Efficient Wireless Power Chargers, IEEE Applied Power Electronics Conference, Fort Worth, TX, USA, March16-20, 2014

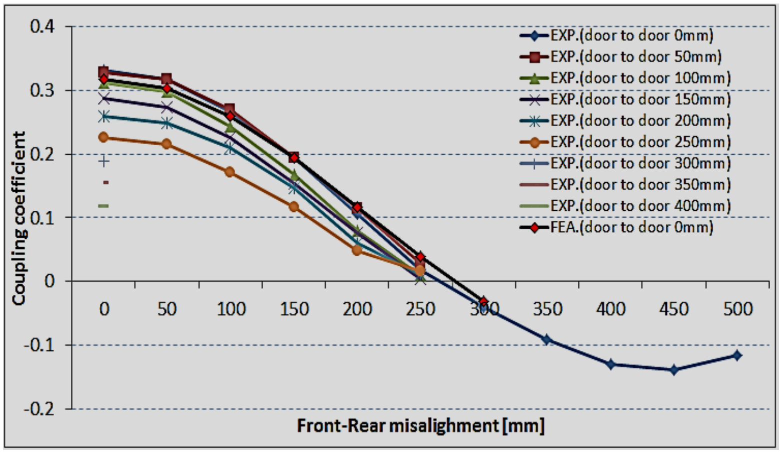
Coupling coefficient vs x, y, theta



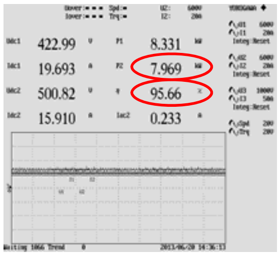
Finite element analysis using Maxwell 3D



Coupling Coefficient Profile versus Door-to-door and Front-to-rear Misalignments

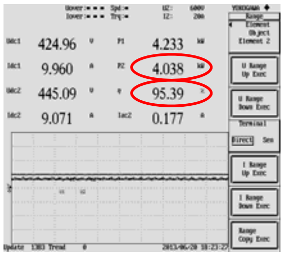


Experiment Results
DC-DC (Battery) Efficiency



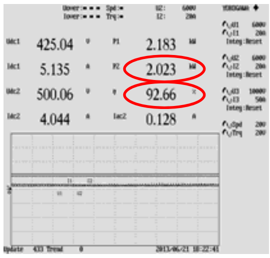
Udc1 422.99 V P1 8.331 kW
Idc1 19.693 A P2 7.969 kW
Udc2 500.82 V η 95.66 %
Idc2 15.910 A Iac2 0.233 A

Xmis=0mm, Gap =200mm



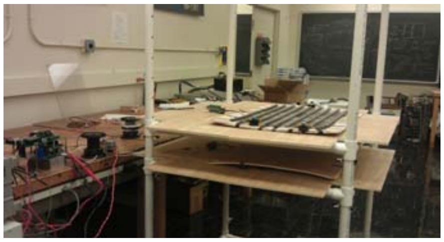
Udc1 424.96 V P1 4.233 kW
Idc1 9.960 A P2 4.038 kW
Udc2 445.09 V η 95.39 %
Idc2 9.071 A Iac2 0.177 A

Xmis=300mm, Gap =200mm

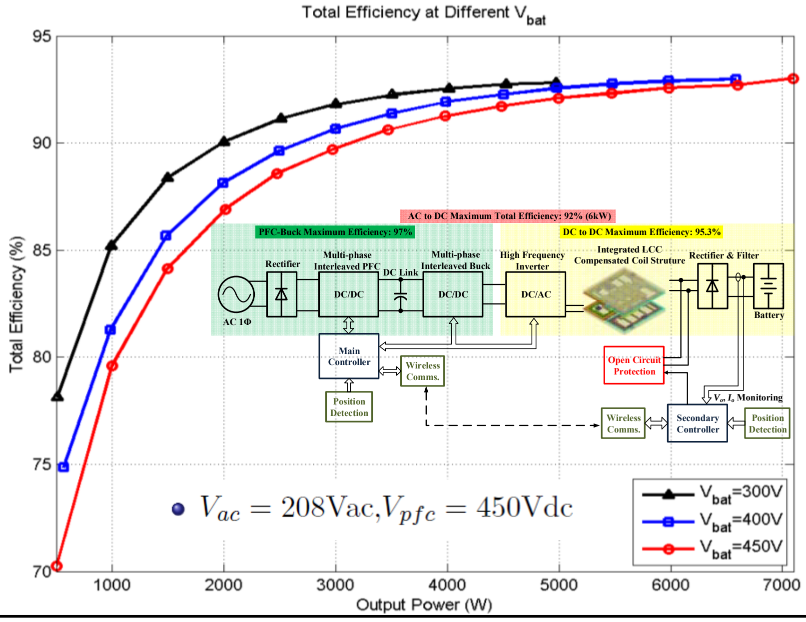


Udc1 425.04 V P1 2.183 kW
Idc1 5.135 A P2 2.023 kW
Udc2 500.06 V η 92.66 %
Idc2 4.044 A Iac2 0.128 A

Xmis=125mm, Gap =400mm



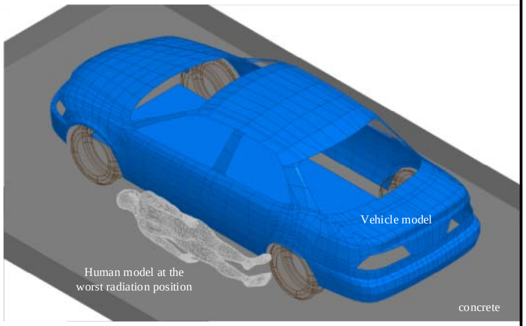
System Efficiency



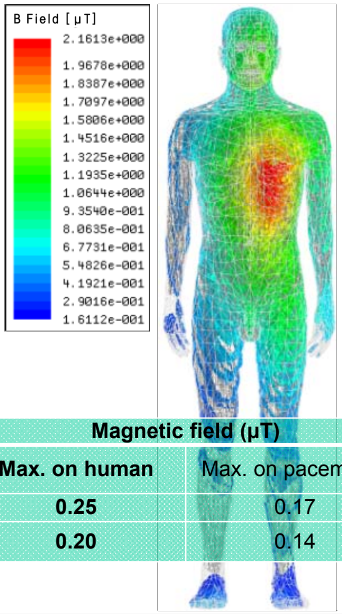
- $V_{ac} = 208\text{Vac}, V_{pfc} = 450\text{Vdc}$

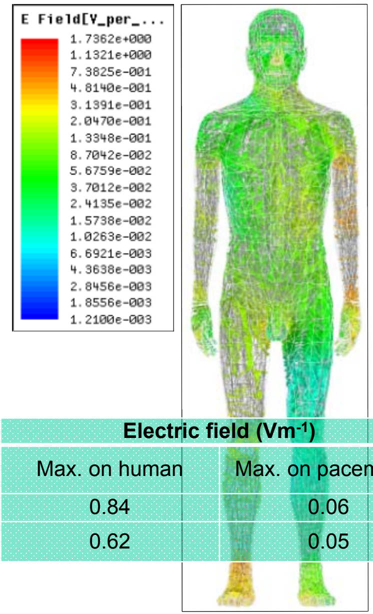
Human Model

- 6.6 kW charging power
- Coil is 500×500 mm
- Worst case is human lay down next to the car and facing the car
- The worst radiation is well below the ICNIRP regulation



Human Model

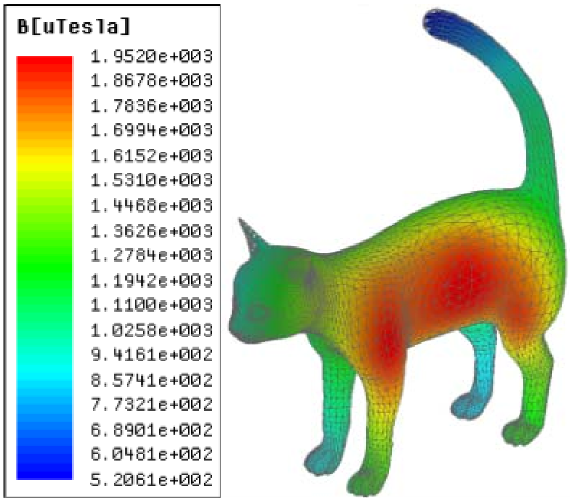




Magnetic field (µT)		**Electric field (Vm^{-1})**	
Max. on human	Max. on pacemaker	Max. on human	Max. on pacemaker
0.25	0.17	0.84	0.06
0.20	0.14	0.62	0.05

Animal Model

- Cat under the car
- 1.95 mT of magnetic field is observed which is not longer safe

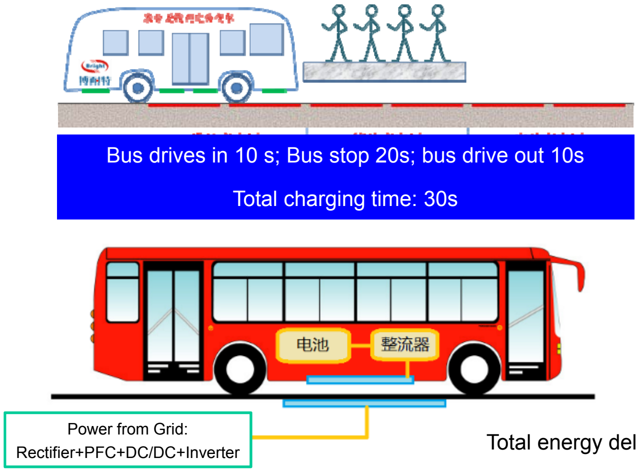


Results of Foreign Object Test #1

Experiment Result: the gum wrapper was burned and there left an imprint, which means the temperature is high.

Electric Bus Project

- Charge points are located in the bus stop area



Bus drives in 10 s; Bus stop 20s; bus drive out 10s

Total charging time: 30s

Power from Grid:
Rectifier+PFC+DC/DC+Inverter

Total energy delivered:

30s/3600s * 80kW = 666Wh ←→0.5 miles

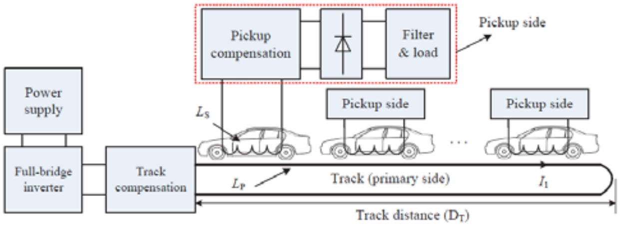
Economics/Benefits of a Bus Project

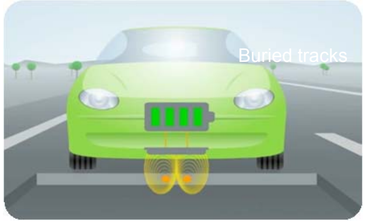
- Saving on board battery
  - Savings of investment of battery: $100k/bus
  - Savings of weight >1 T/bus = 200Wh/mile/bus
- Savings of operating cost
  - Two operators/station is no longer needed: $200k/year
- Increase battery life due to narrow SOC band is used
  - Top off every time at bus stops, no full discharge of the battery
- More reliable; does not have to deal with hundred of amperes of currents, eliminate spark, eliminate electric shock
- Less maintenance: no tear and wear of cable, plug,

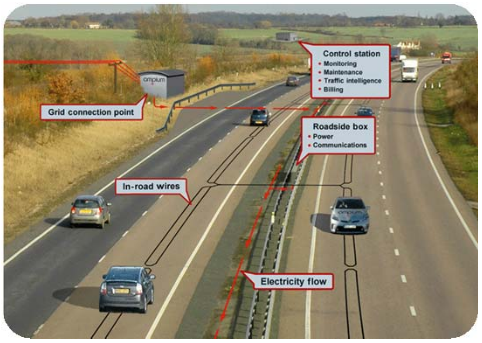
Fleet Savings

- Fleet
  - 12 buses; 30 miles round trip; 10 trips/day-bus
  - Total 300 miles per bus-day
- Total battery savings: $1.2 MM
- Total energy savings: 263 MWh/year-fleet
- Total saving of labor cost: $200k/year
- Using high efficiency charger; 10% more efficient, then savings of 300MWh/year-fleet
- 20 years maintenance-free; further savings

Dynamic In-Motion Charging







IEEE Workshop and TPEL Special Issue on Wireless Power

- 2015 WoW Sponsored by six Societies of IEEE
- PELS, IAS, IES, VTS, MAG, PES
- June 5-6 (Fri.-Sat.), 2015, Daejeon, Korea
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- General Chairs: Dr. Chun Rim, Dr. Chris Mi
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  - IEEE Transactions on Power Electronics
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