Recent Development in High Power Capacitive Wireless Power Transfer

SAN DIEGO STATE UNIVERSITY

Leadership Starts Here

Chris Mi, Ph.D, Fellow IEEE

Professor and Chair, Dept. Electrical and Computer Engineering

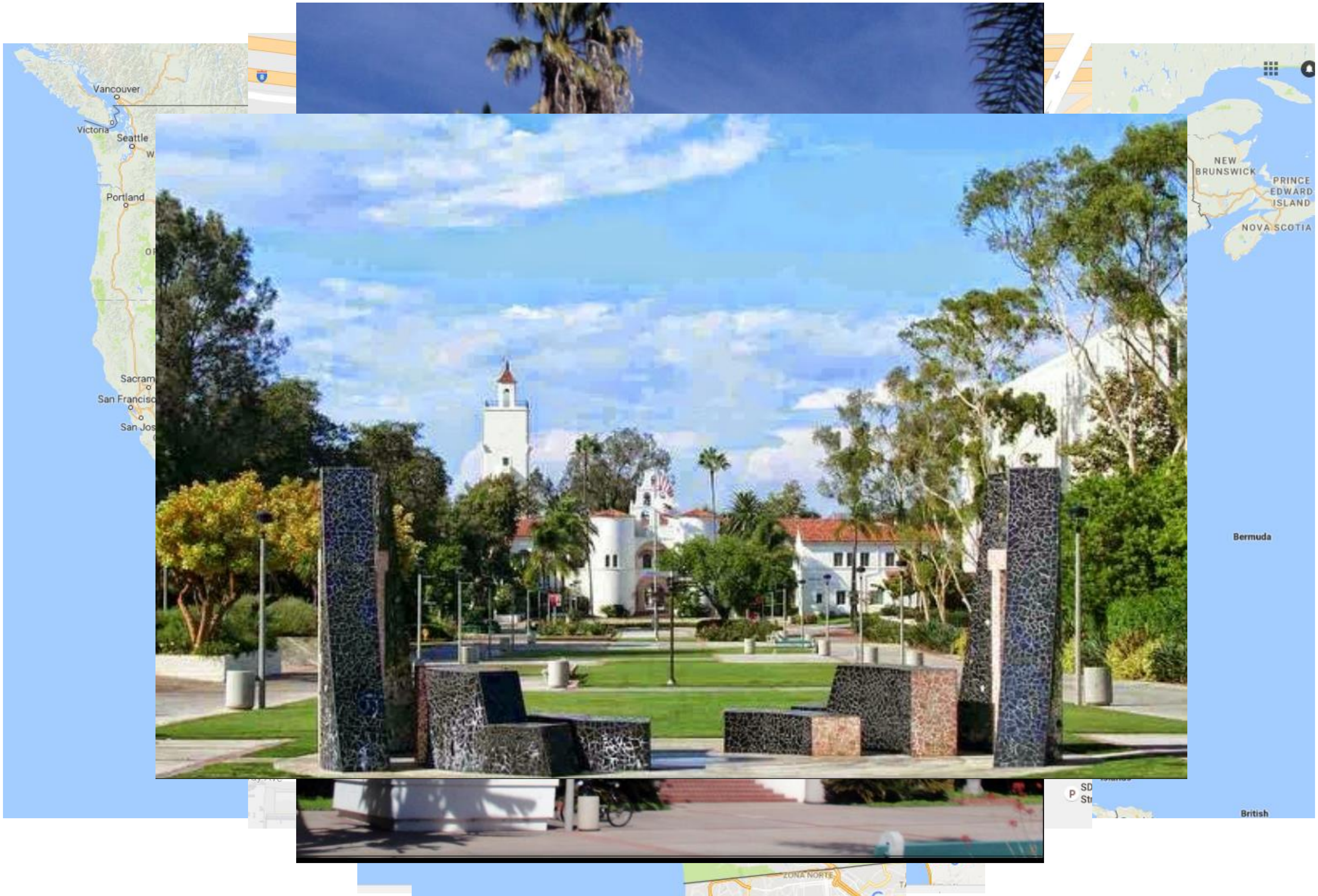
Director, DOE GATE Center for Electric Drive Transportation

San Diego State University, (619)594-3741; mi@ieee.org

Contents

- Introduction to SDSU
- Introduction of Wireless Power Transfer
- Double-sided LCLC Compensation Topology
- Capacitive Coupler Structure
- Prototypes and Experimental Results
- System Improvements
- Conclusion and Future Work

San Diego State University

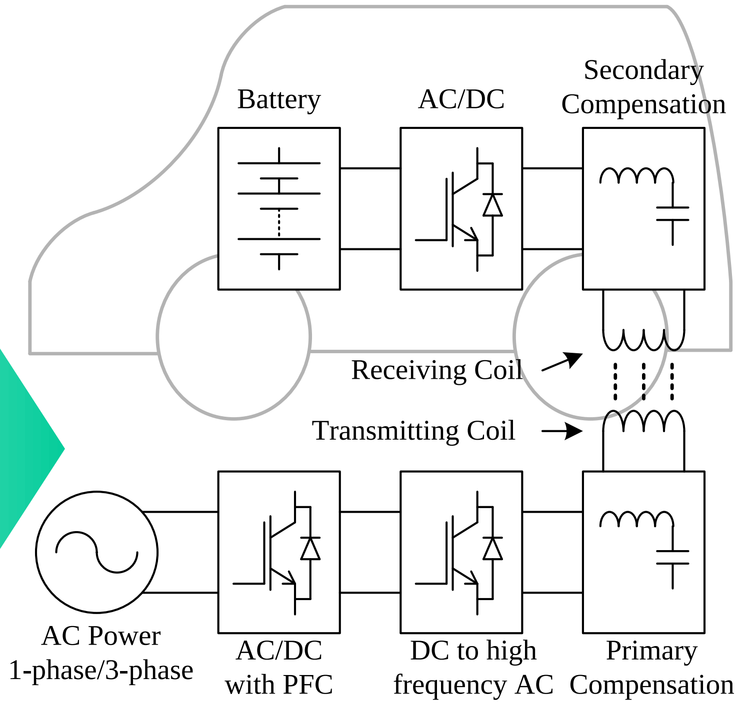


Why WPT: Conductive Charging and Battery Swapping Have Some Issues

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
- 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), KAIST, etc. have developed EV wireless charger prototypes
- 2014: in-motion charging demonstration: Daejoen, Vienna, London

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

Limitations of Current WPT

Safety of magnetic field

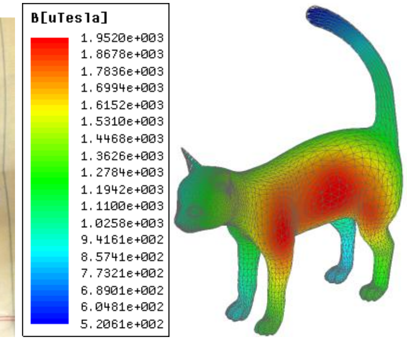
Low efficiency

Sensitive to vehicle alignment

High cost due to litz wire and ferrite

Large size

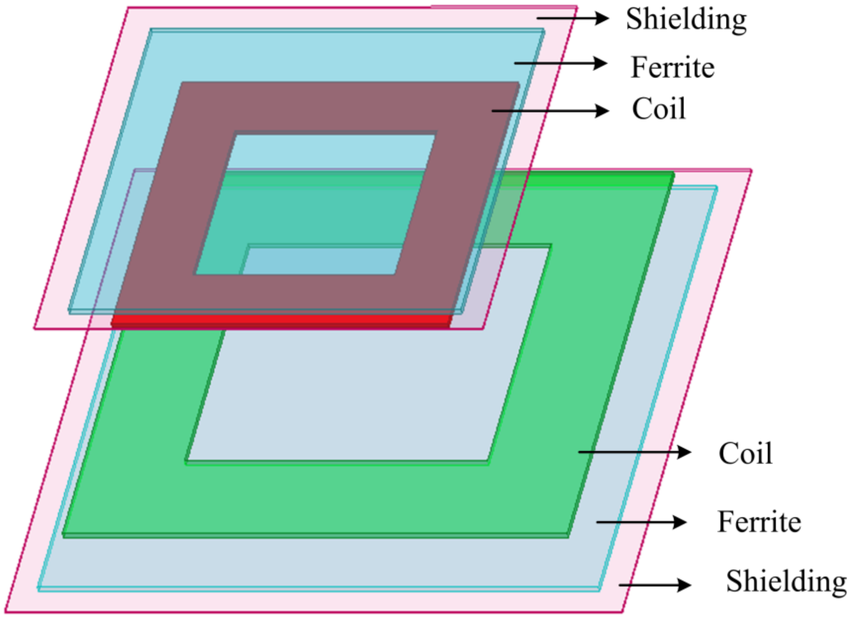
Limited distance



Need of:

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

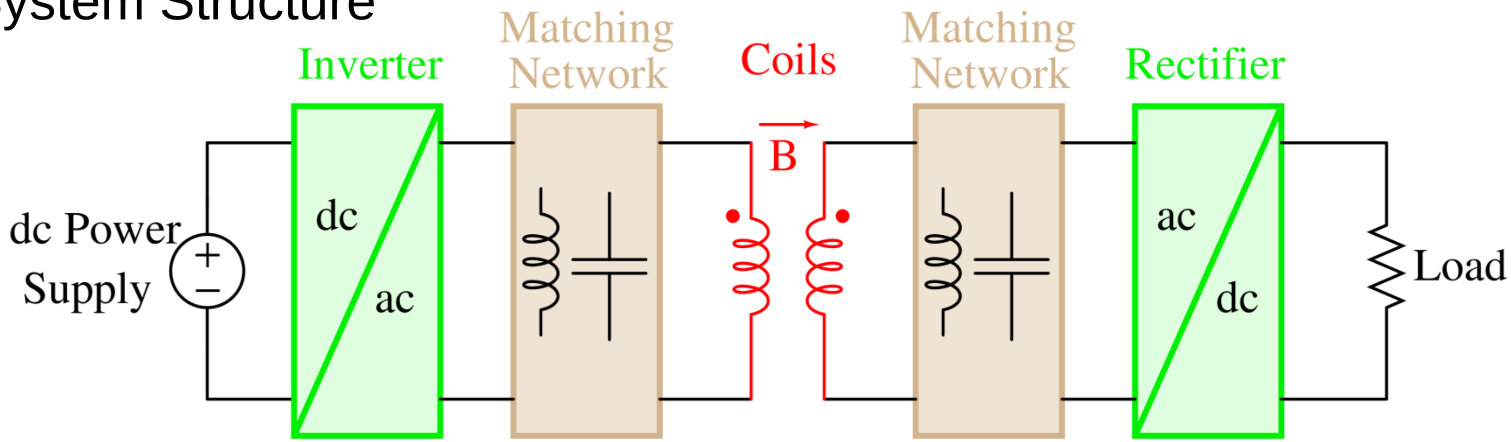
Motivation: Disadvantages of IPT



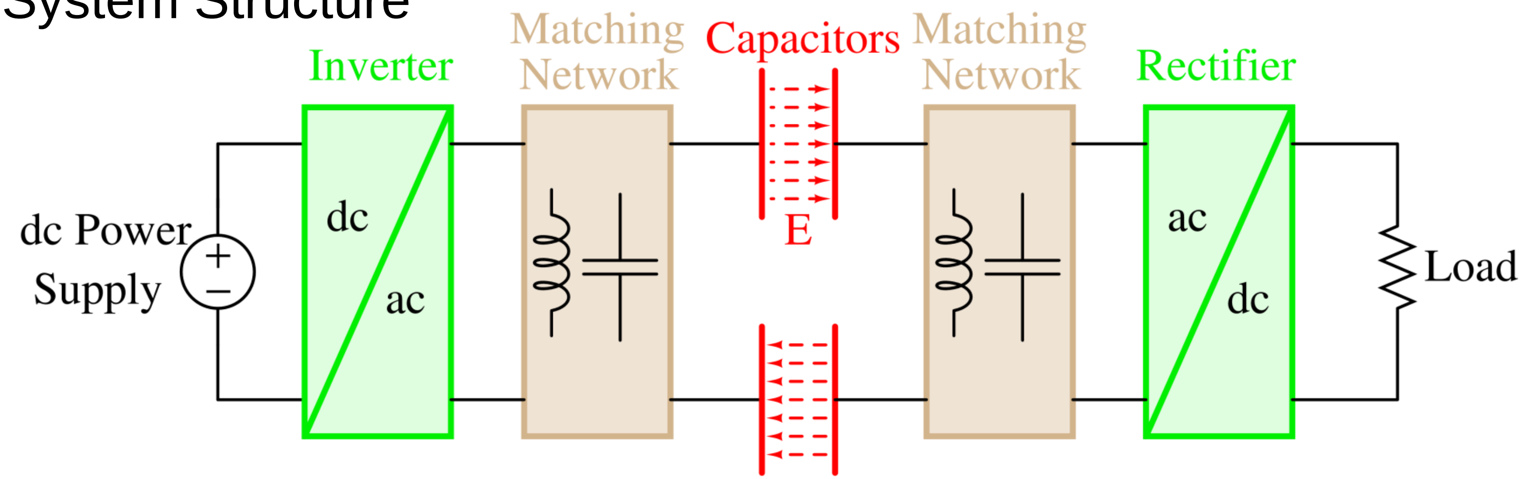
- Cost and Weight
  - Ferrite and Litz-wire are heavy and expensive
- Significant Eddy-Current Loss in Nearby Metals
  - Reduce system efficiency and cause temperature rise
- Misalignment Performance
  - System power drops rapidly with misalignment

Analogy of CPT and IPT

- IPT System Structure



- CPT System Structure

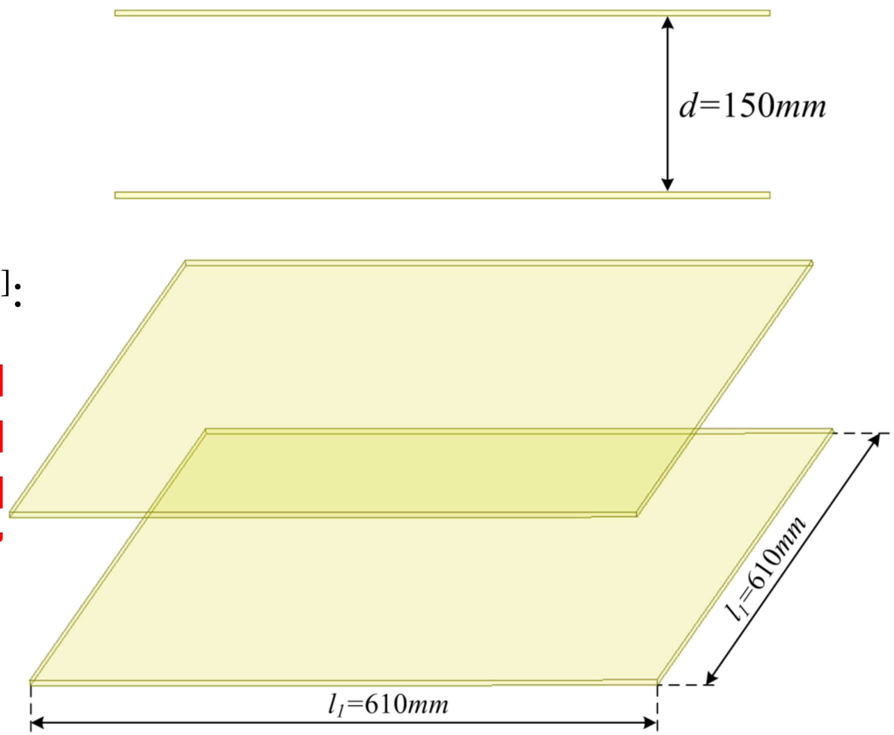


- Electric field is not sensitive to metal material nearby
- Electric field does not generate eddy-current loss in the metal
- CPT coupler uses metal plates, instead of Litz-wire, reduce system cost

Challenges of CPT for EV Charging

- Small Coupling Capacitance
  - An Example:
  - Plates Size l_1=610mm (24in)
  - Distance d=150mm
  - Coupling capacitance of parallel plates is[8]:

$$C_s = [1 + 2.343 \cdot (d / l_1)^{0.891}] \cdot \frac{\varepsilon \cdot l_1^2}{d} = 36.7\text{pF}$$

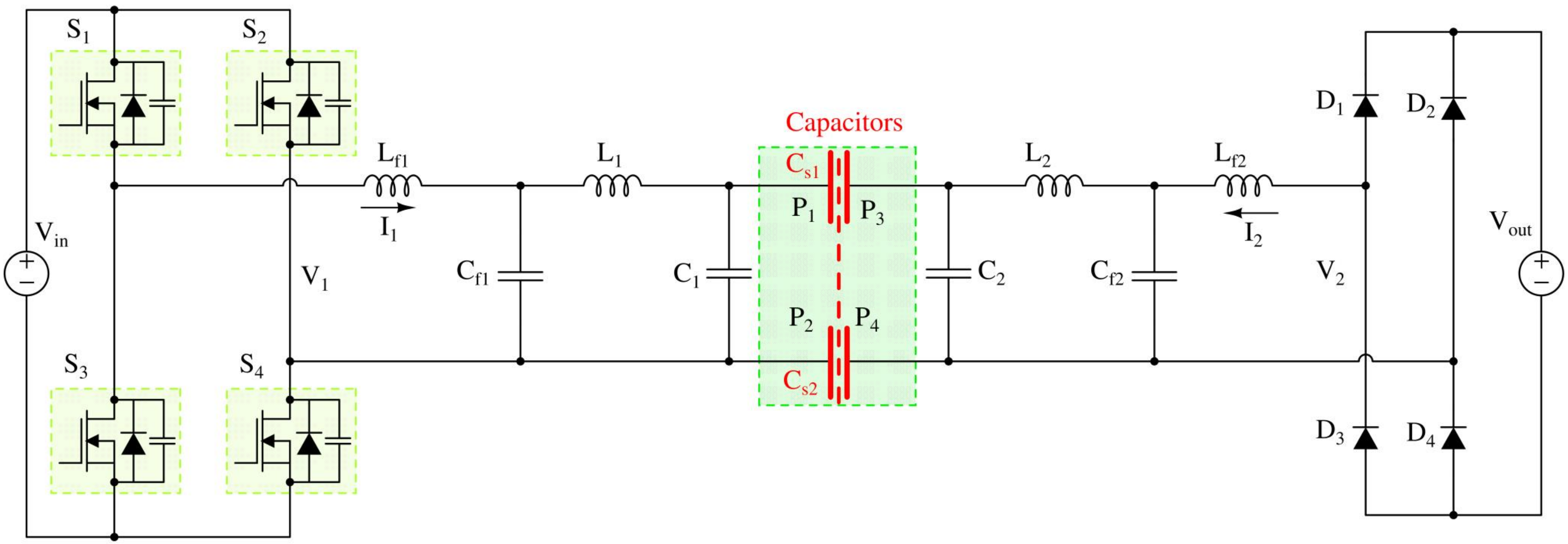


- The former compensation topologies are not suitable to transfer **HIGH** power with so **SMALL** coupling capacitance
  - Series or parallel topology: requires too large inductance or too high switching frequency

NEW Compensation Topology is Required!

[8] H. Nishiyama, M. Nakamura, "Form and Capacitance of Parallel Plate Capacitor," IEEE Transactions on Components, Packing, and Manufacturing Tech-Part A, Vol 17, 1994, 477-484.

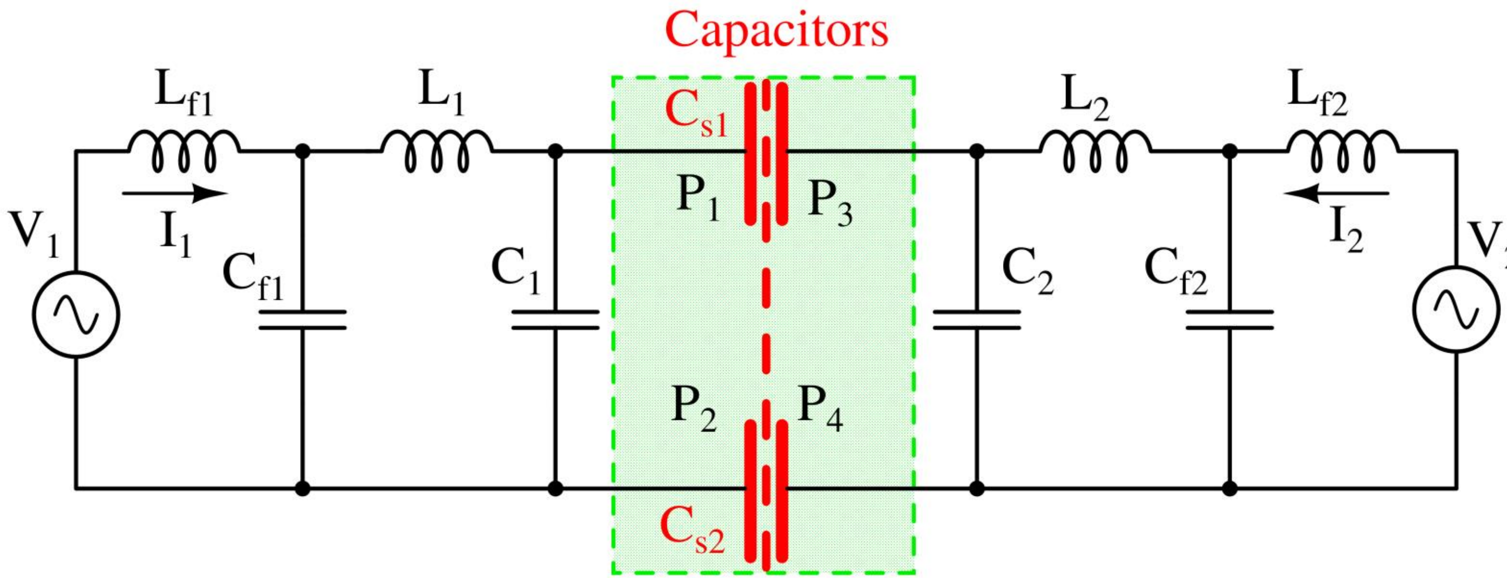
Double-sided LCLC Circuit Topology



- Two inductors and two capacitors are used at each side
- P_1 and P_2 are at the primary side, P_3 and P_4 are at the secondary side
- P_1 and P_3 form a coupling capacitor, P_2 and P_4 form the other capacitor

F. Lu, H. Zhang, H. Hofmann and C. Mi, "A Double-Sided LCLC-Compensated Capacitive Power Transfer System for Electric Vehicle Charging," in *IEEE Transactions on Power Electronics*, vol. 30, no. 11, pp. 6011-6014, Nov. 2015. doi: 10.1109/TPEL.2015.2446891

System Power of FHA Analysis



- At input inverter side, V_1 and I_1 are in phase
- At output rectifier side, V_2 and $(-I_2)$ are in phase
- Neglect passive components losses, the system power is expressed as:

$$P_{in} = P_{out} = \frac{\omega_0 C_s \cdot C_{f1} C_{f2}}{C_1 C_2 + C_1 C_s + C_2 C_s} \cdot V_1 \cdot V_2 = \frac{\omega_0 C_s \cdot C_{f1} C_{f2}}{C_1 C_2 + C_1 C_s + C_2 C_s} \cdot \frac{2\sqrt{2}}{\pi} \cdot V_{in} \cdot \frac{2\sqrt{2}}{\pi} \cdot V_{out}$$

- If there exists $C_{1,2} >> C_s$

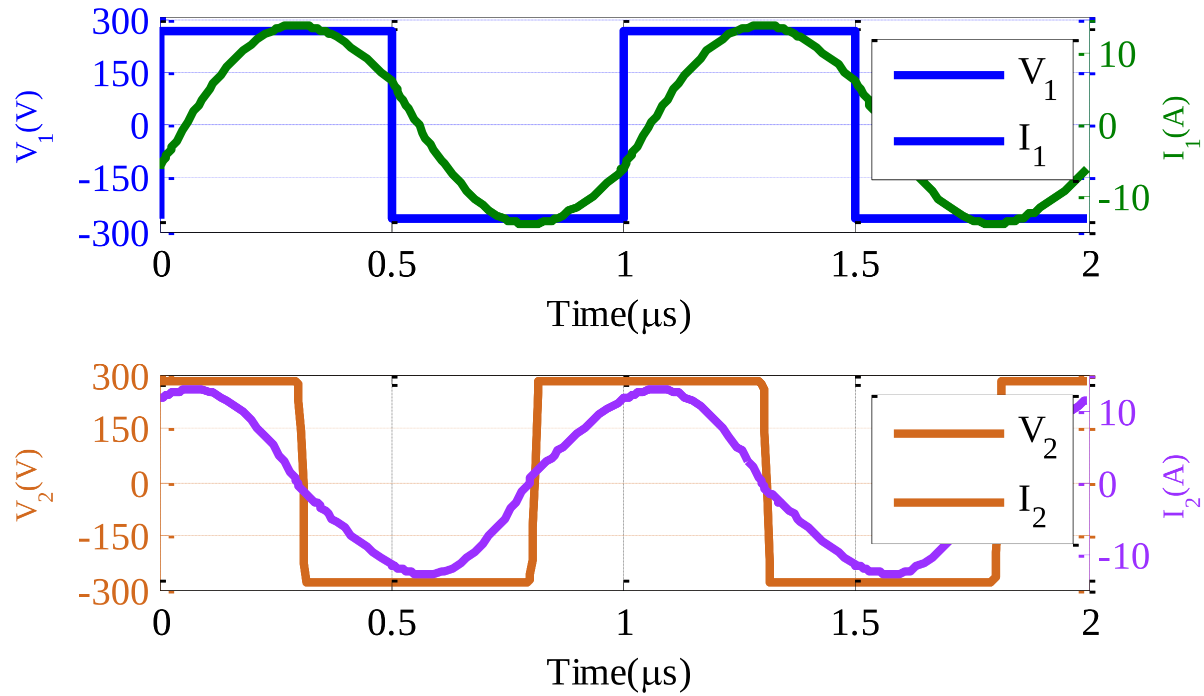
$$P_{in} = P_{out} \approx \omega_0 C_s \cdot \frac{C_{f1} C_{f2}}{C_1 C_2} \cdot \frac{2\sqrt{2}}{\pi} \cdot V_{in} \cdot \frac{2\sqrt{2}}{\pi} \cdot V_{out}$$

Parameter Design and Simulation

- A 2.4kW CPT system is designed with parameters in the following table.

V_{in}	V_{out}	f_{sw}	L_{f1} (L_{f2})	C_{f1} (C_{f2})	C_1 (C_2)	C_{s1}(C_{s2})	L_1	L_2
265V	280V	1MHz	11.6μH	2.18nF	100pF	36.7pF	231μH	242μH

- Circuit simulation is shown below



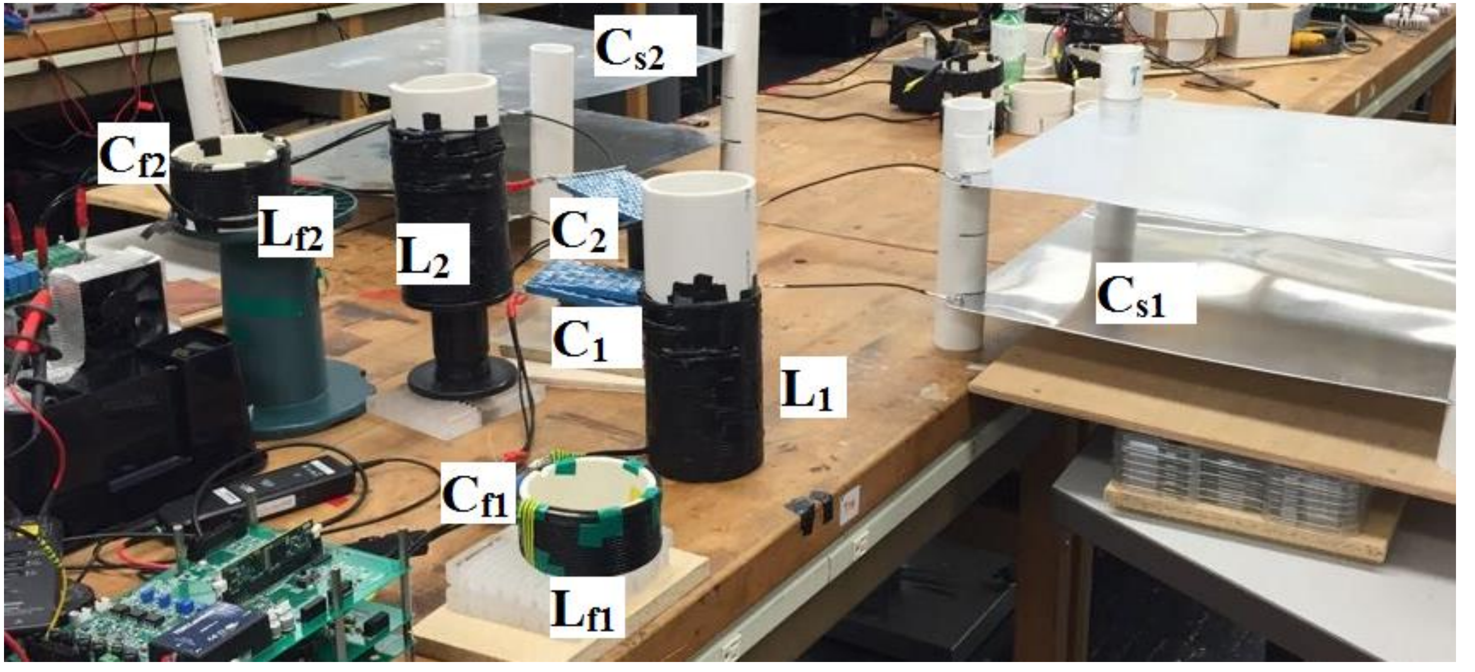
Voltage and Current Stress

- Voltage are current stress are calculated by the previous FHA analysis

Components	L_{f1} (L_{f2})	C_{f1} (C_{f2})	C_1 (C_2)	L_1(L_2)	Plates
Voltage	1.0 kV	1.0 kV	7.2 kV	7.2 kV	3.2 kV
Current	15.5 A	15.0 A	4.8 A	5.2 A	0.7 A

- Inductors are wound with multiple turns to reduce voltage stress between turns
- Multiple capacitors are connected in series to form C_1 and C_2
- Multiple capacitors are connected in parallel to form C_{f1} and C_{f2}
- The electric field in this system is 3.2kV/150mm, and the breakdown field of air is about 3.0kV/mm. Therefore, there is no concern of arcing

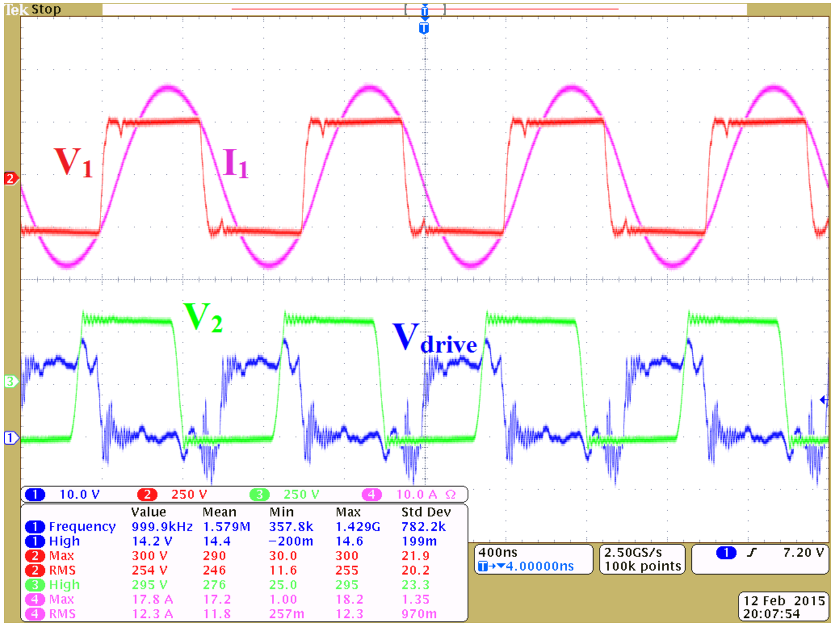
Prototype Design

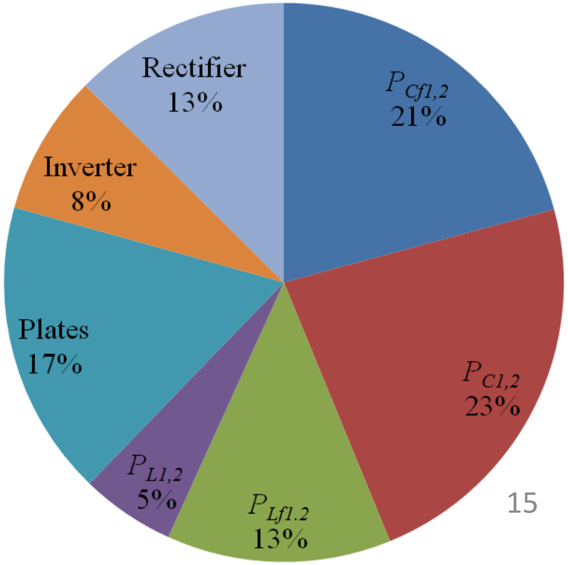


- Plates are made by aluminum sheets
- Inductors are wound by AWG46 Litz-wire without magnetic core
- High-power-frequency thin film capacitors resonate with the inductors
- Silicon Carbide (SiC) MOSFETs C2M0025120D are used in the inverter
- SiC diodes IDW30G65C5 are used in the rectifier

Experimental Results

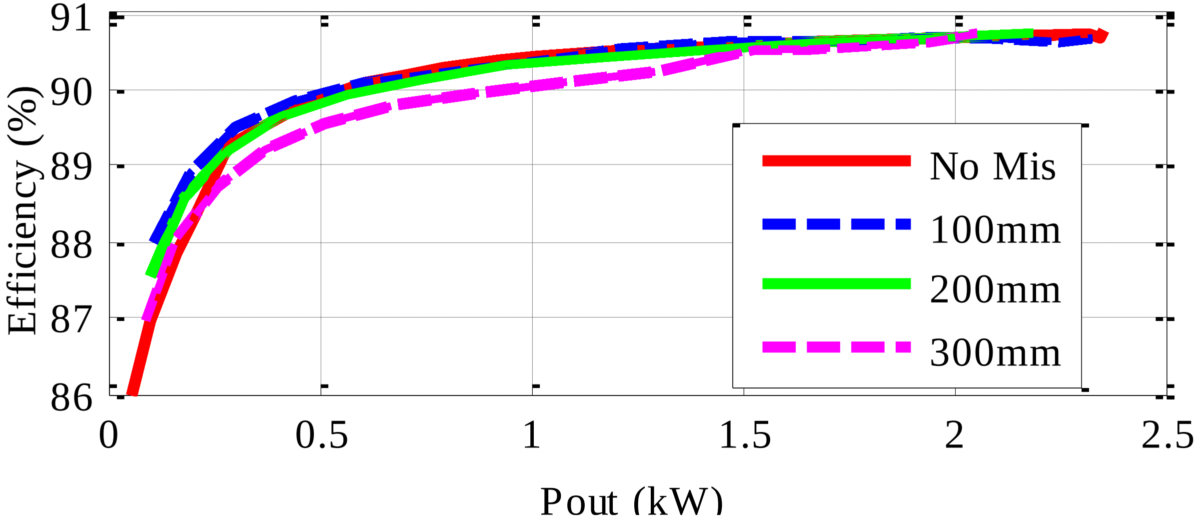
- P_{out}=2.4kW at designed input/output
- The experimental waveform is the same with the simulations
- Soft-switching is achieved
- There is high frequency noise on the driver signal
- Most of the power losses distribute on the capacitors and plates
- If the inductors are wound on magnetic core, the system efficiency will drop 1%-3%.



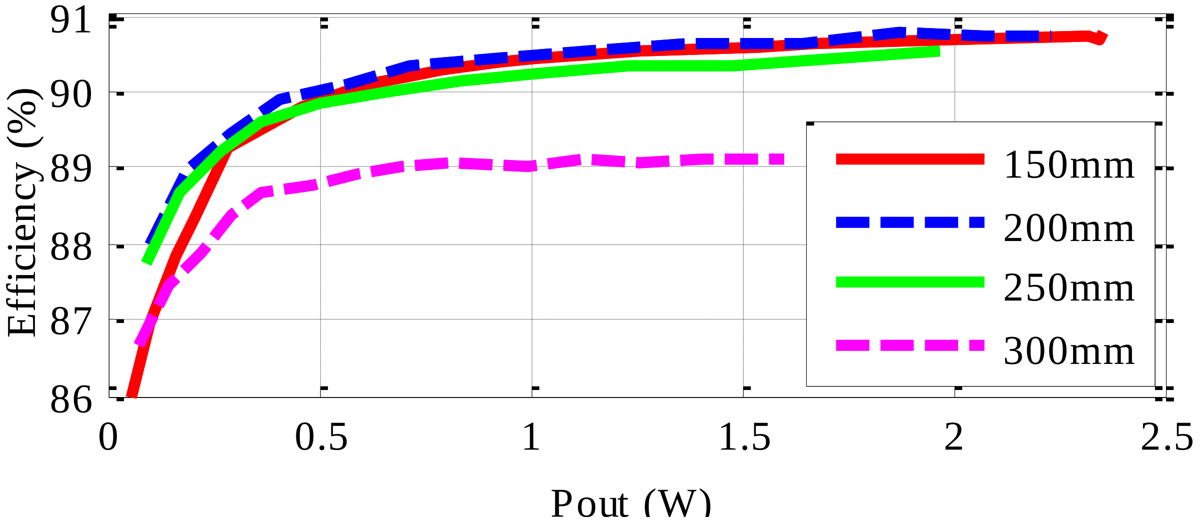


Tolerance to Misalignment and Distance

- Output Power maintains 2.1 kW at 300 mm X axis misalignment

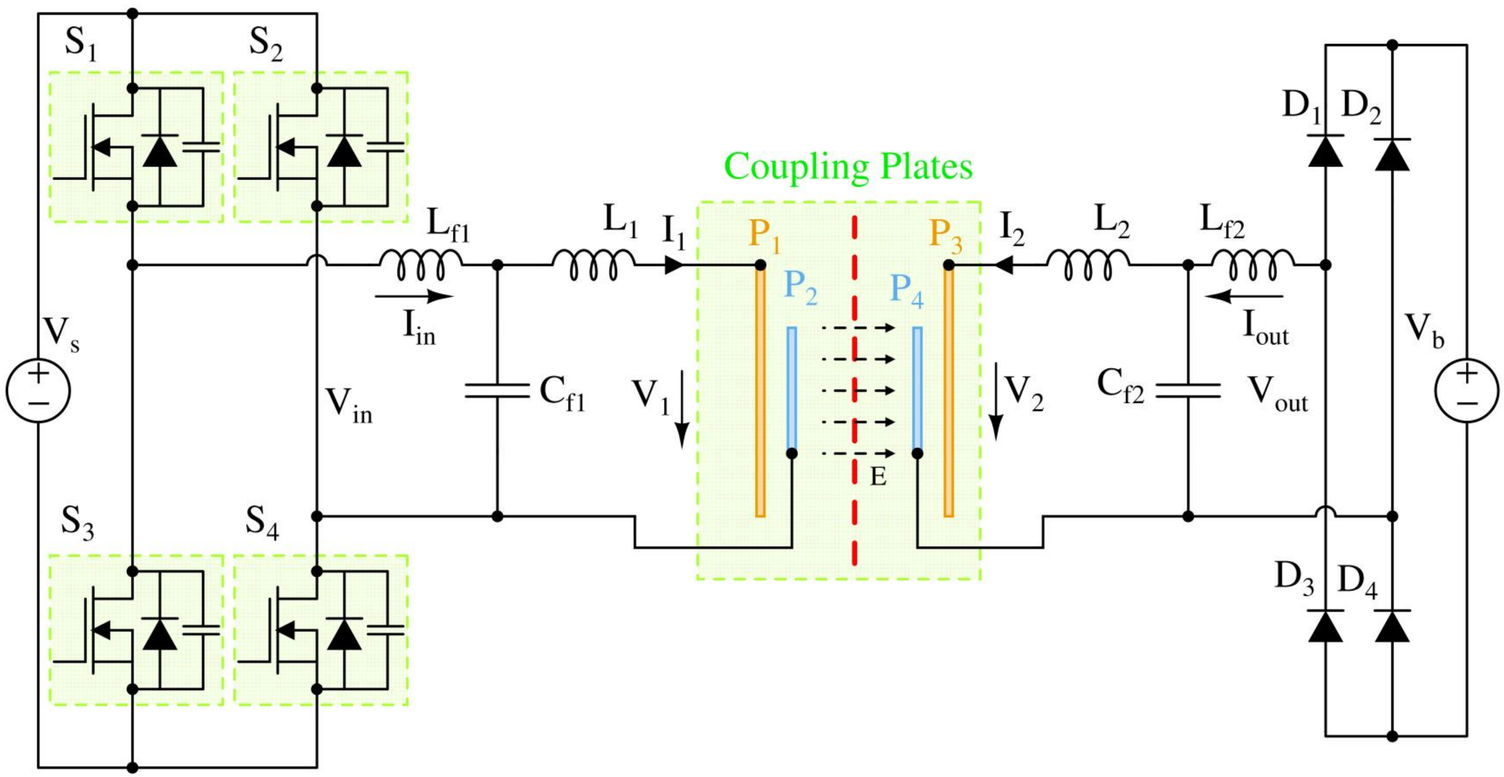


- Output Power maintains 1.7 kW at 300 mm Z axis distance



Potential Improvements

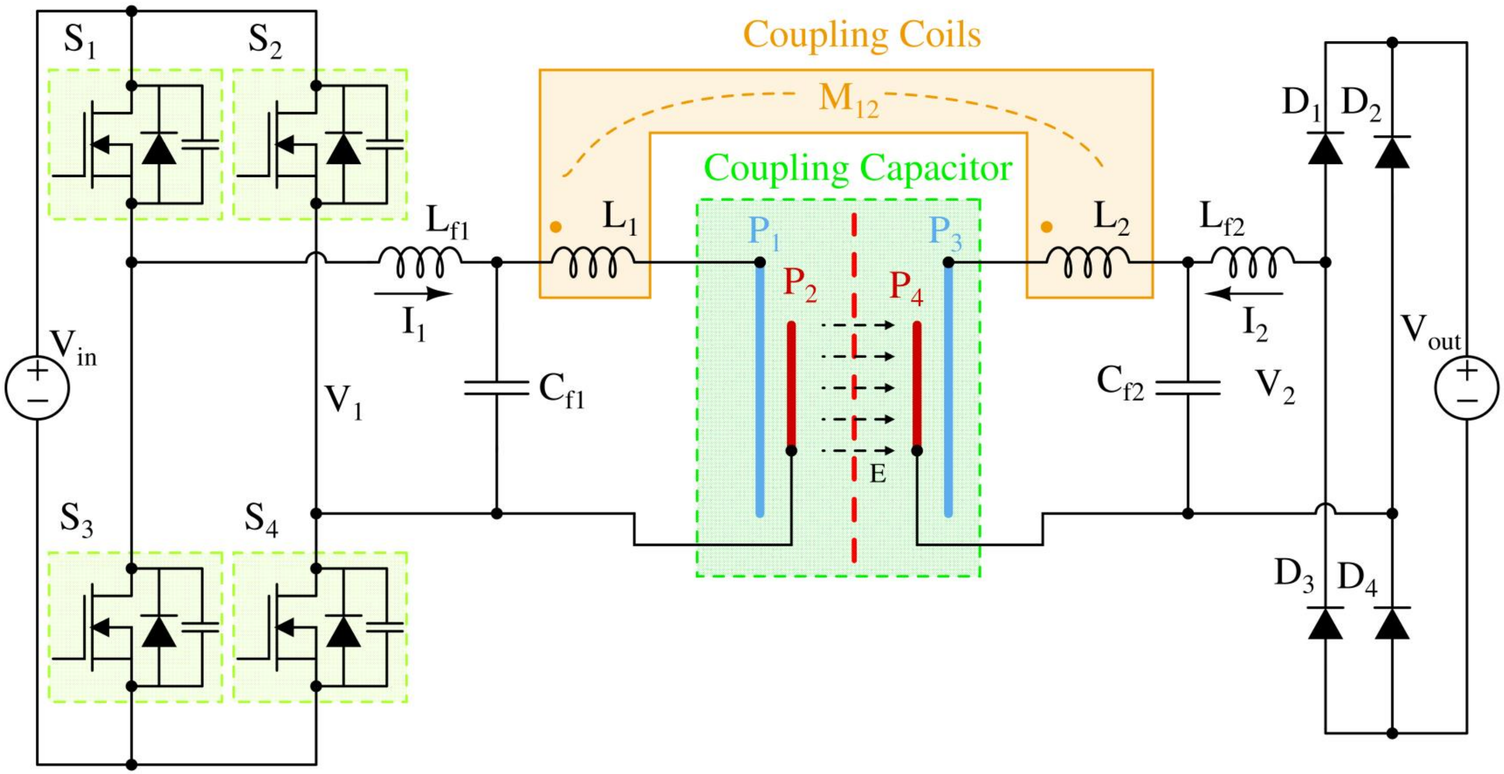
LCL Compensation Topology



➢ Compensation topology is simplified and The LCL compensation circuit is used to resonate with the plates, instead of the LCLC topology

H. Zhang; F. Lu; H. Hofmann; W. Liu; C. Mi, "A 4-Plate Compact Capacitive Coupler Design and LCL-Compensated Topology for Capacitive Power Transfer in Electric Vehicle Charging Applications," in *IEEE Transactions on Power Electronics* , vol.PP, no.99, pp.1-1; doi: 10.1109/TPEL.2016.2520963

IPT+CPT Combined System

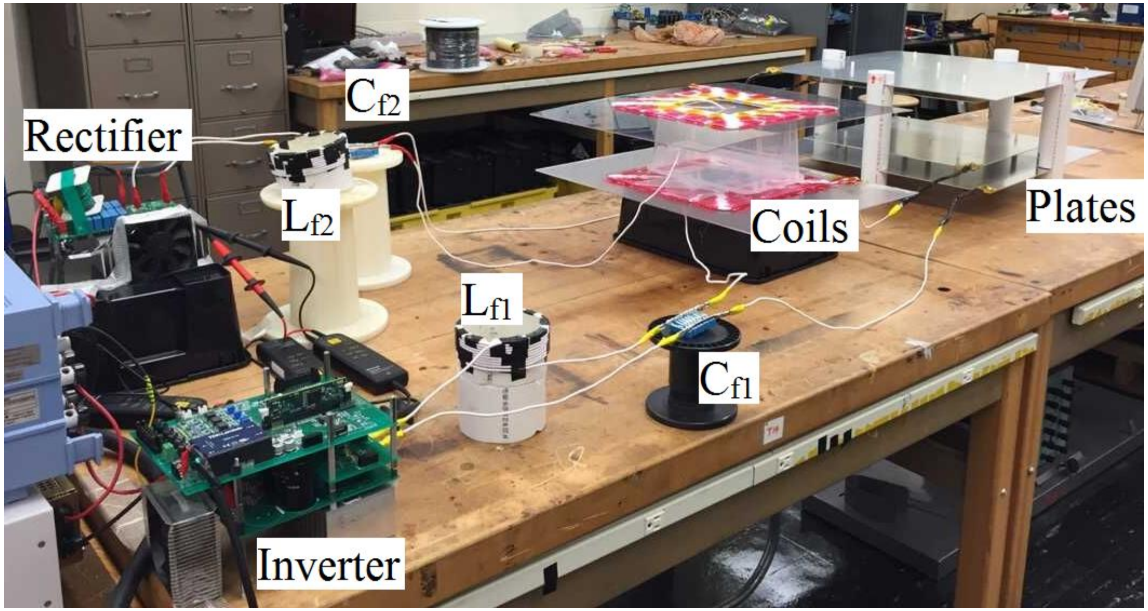


- The two inductors L_1 are L_2 are inductively coupled
- The system utilized both electric and magnetic fields to transfer power

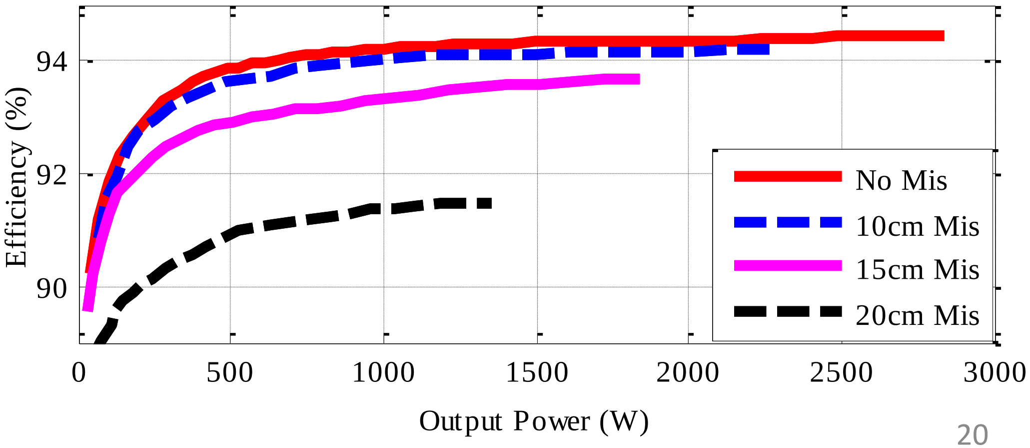
F. Lu; H. Zhang; H. Hofmann; C. Mi, "An Inductive and Capacitive Combined Wireless Power Transfer System with LC-Compensated Topology," in *IEEE Transactions on Power Electronics* , vol.PP, no.99, pp.1-1, doi: 10.1109/TPEL.2016.2519903

Experiments of IPT+CPT Combined System

- Coil size: 320×320mm
- Plate size: 610×610mm
- Only LC compensation network is required at each side



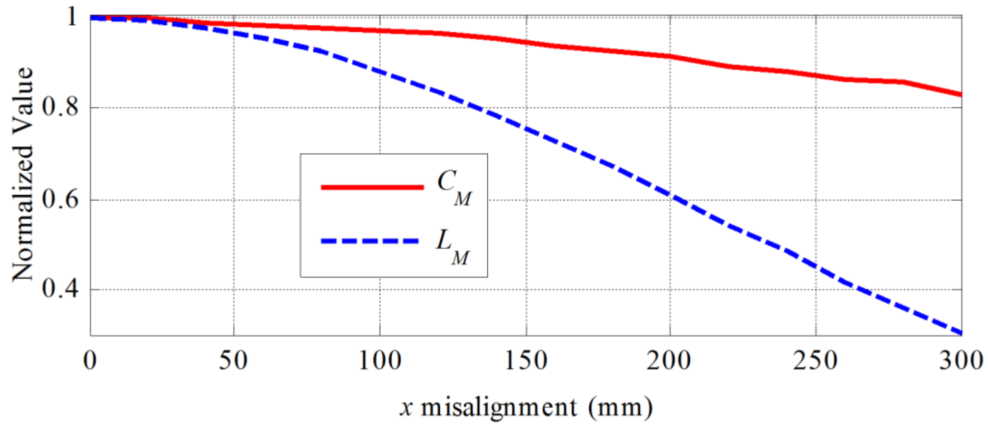
- At nominal input and output condition, P_{IPT}=2000W, and P_{CPT}=800W
- The system also has good misalignment ability



Misalignment Performance

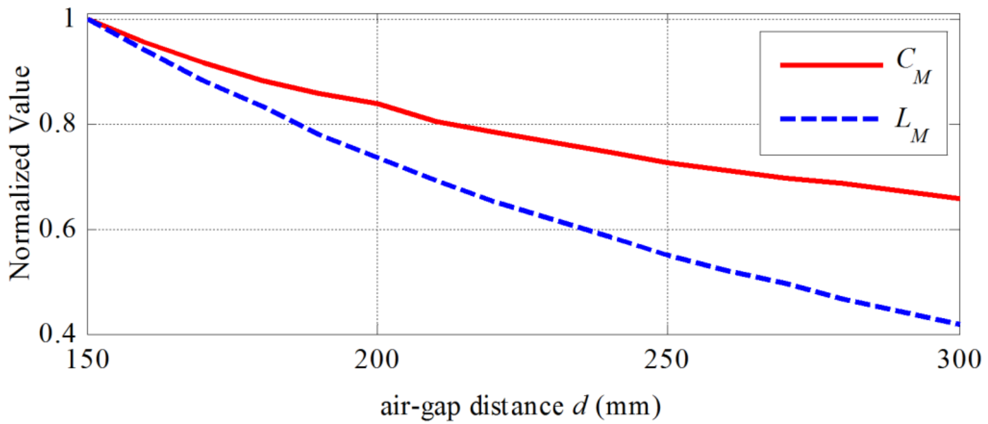
- x Direction Misalignment

Advantage: Better Misalignment Performance



➢ C_M remains 84.2% of the well-aligned value, L_M remains 30% of the well-aligned value

- Air-gap Variation

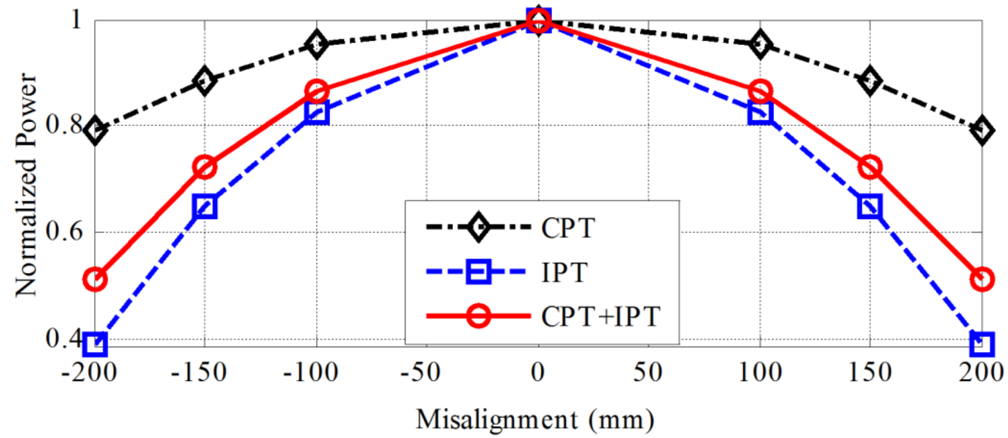


➢ C_M remains 66.5% of the well-aligned value, L_M remains 41% of the well-aligned value

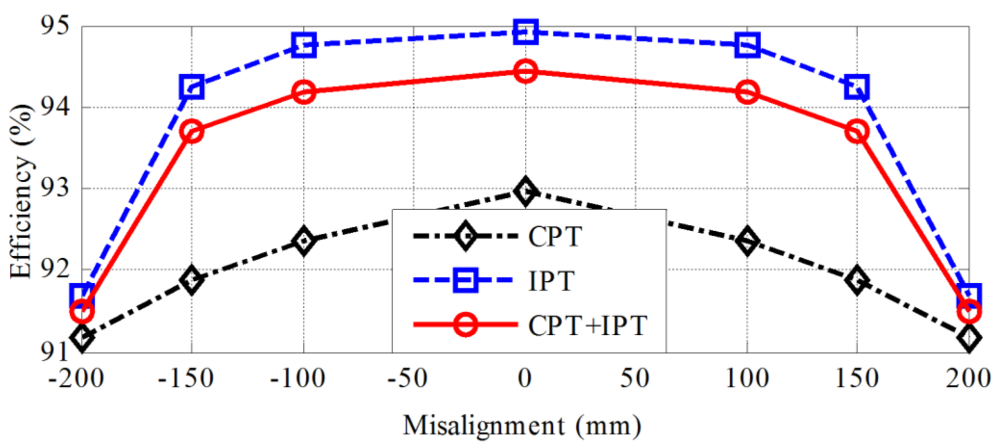
Misalignment Performance

- Output Power

Advantage:
Compared to an IPT system,
misalignment performance is improved



- ➢ Output power drops to 1.35 kW at 200 mm misalignment (47.5% of well-aligned power)

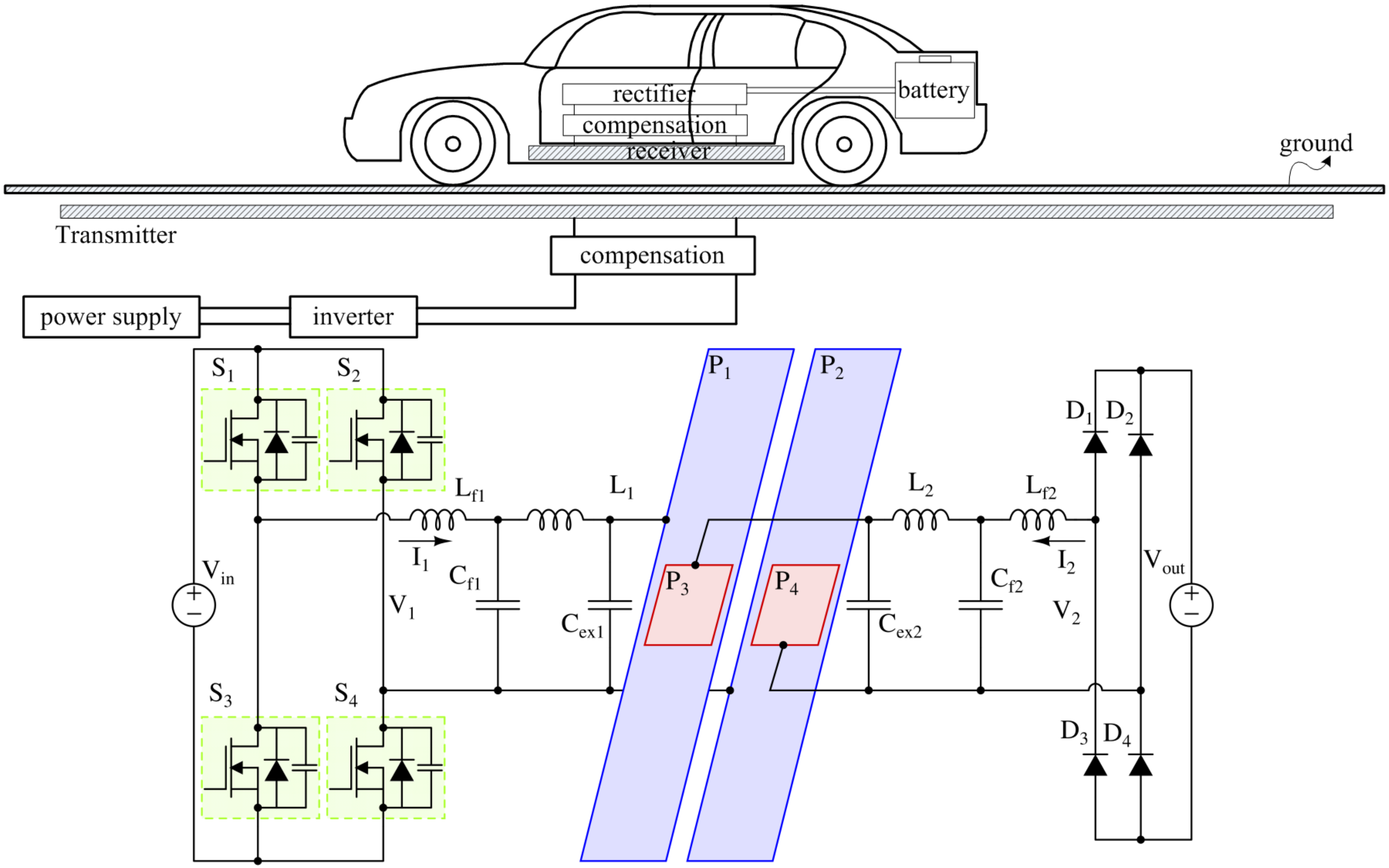


- Efficiency

Advantage:
Compared to a CPT system,
efficiency is improved

- ➢ DC-DC efficiency remains higher than 91.5%

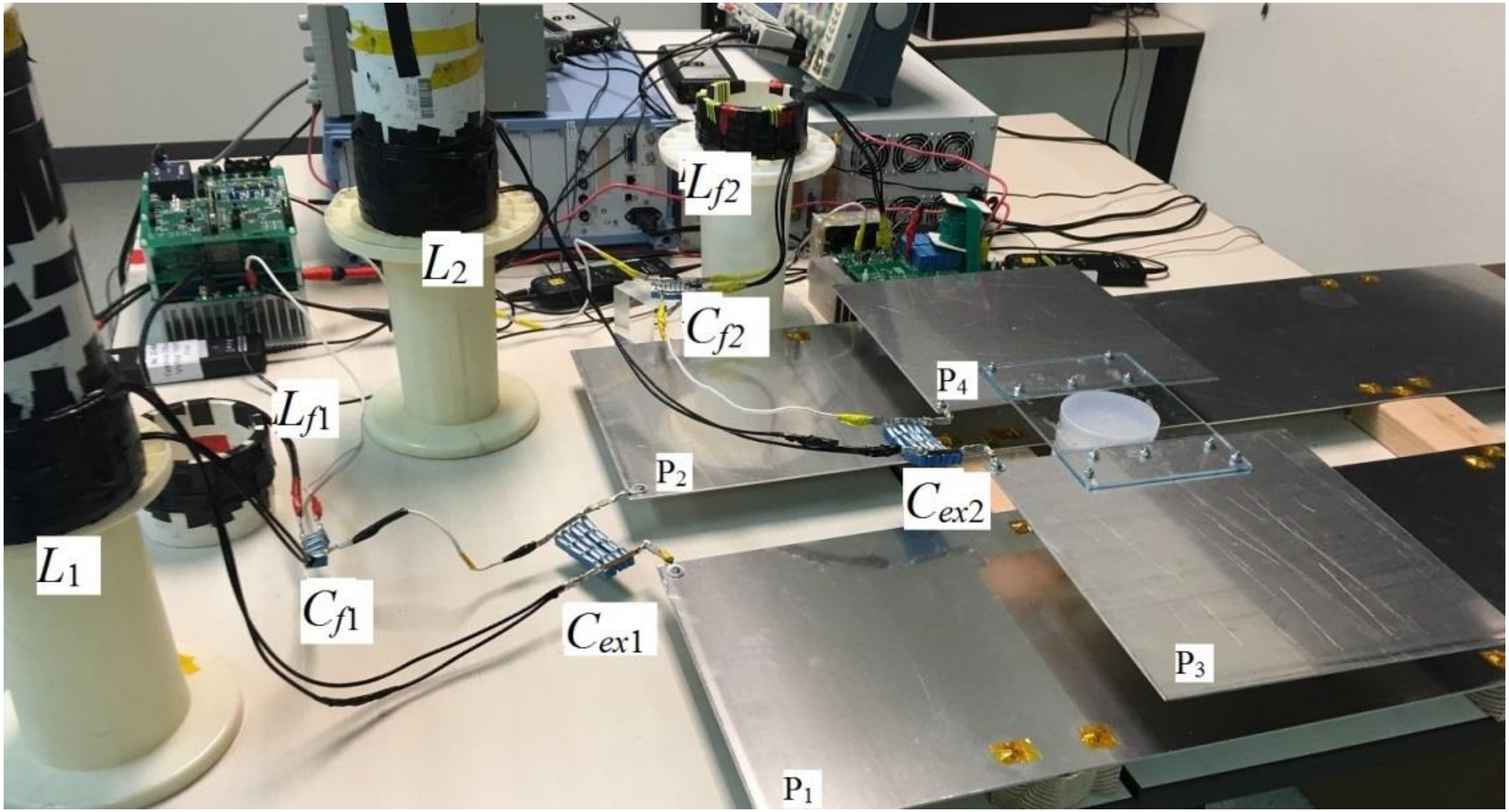
Dynamic Capacitive Power Transfer [11]



- Reduce system cost using metal plates as capacitive couplers
- Reduce stand-by power loss because of small circulating current in the coupler

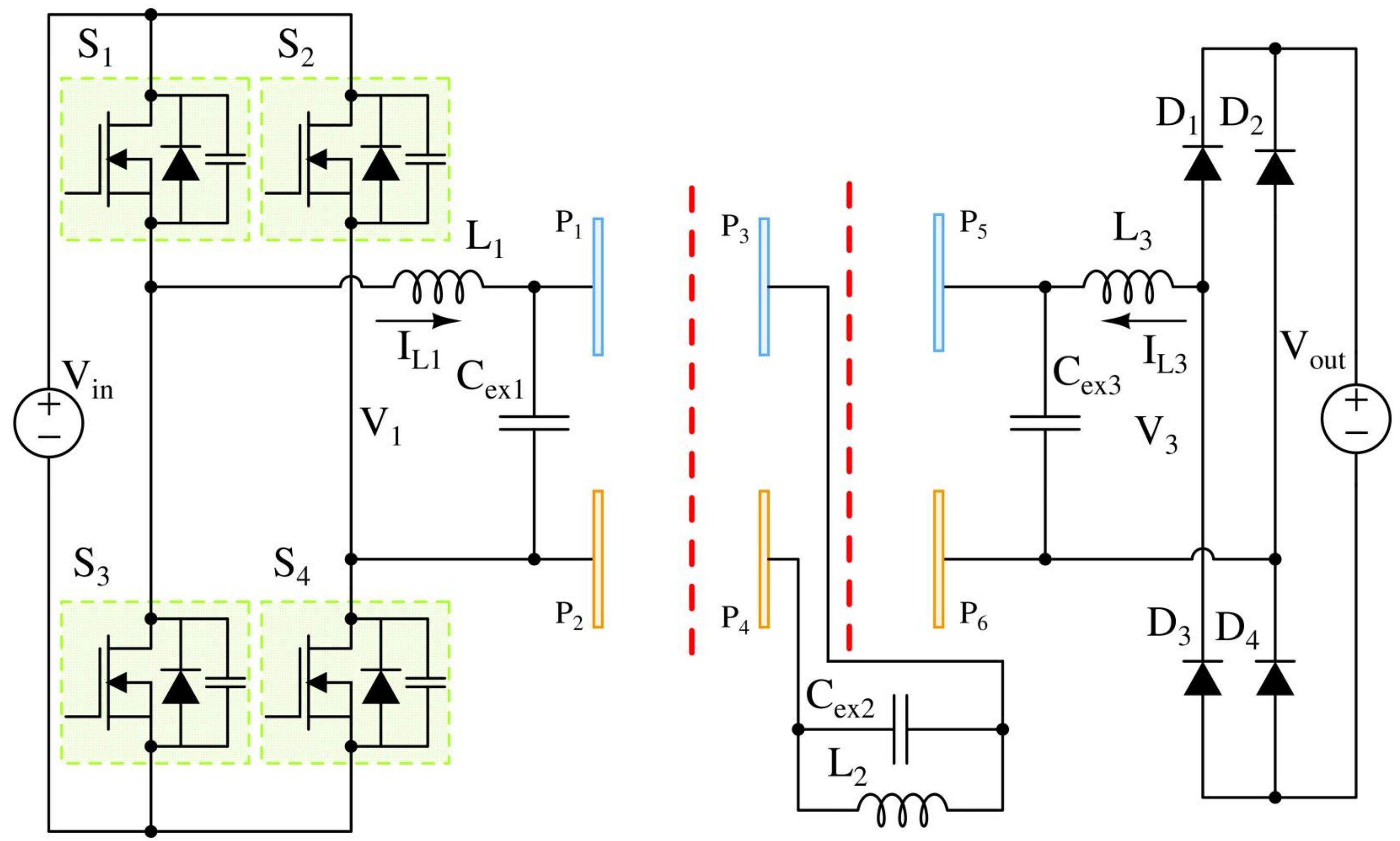
[11] **F. Lu**, H. Zhang, H. Hofmann, Y. Mei, C. Mi, "A Dynamic Capacitive Power Transfer System with Reduced Power Pulsation," Proc. IEEE Workshop Emerg. Tech. Wireless Power Trans. (WoW), pp. 60-64, 2016.

Experimental Prototype



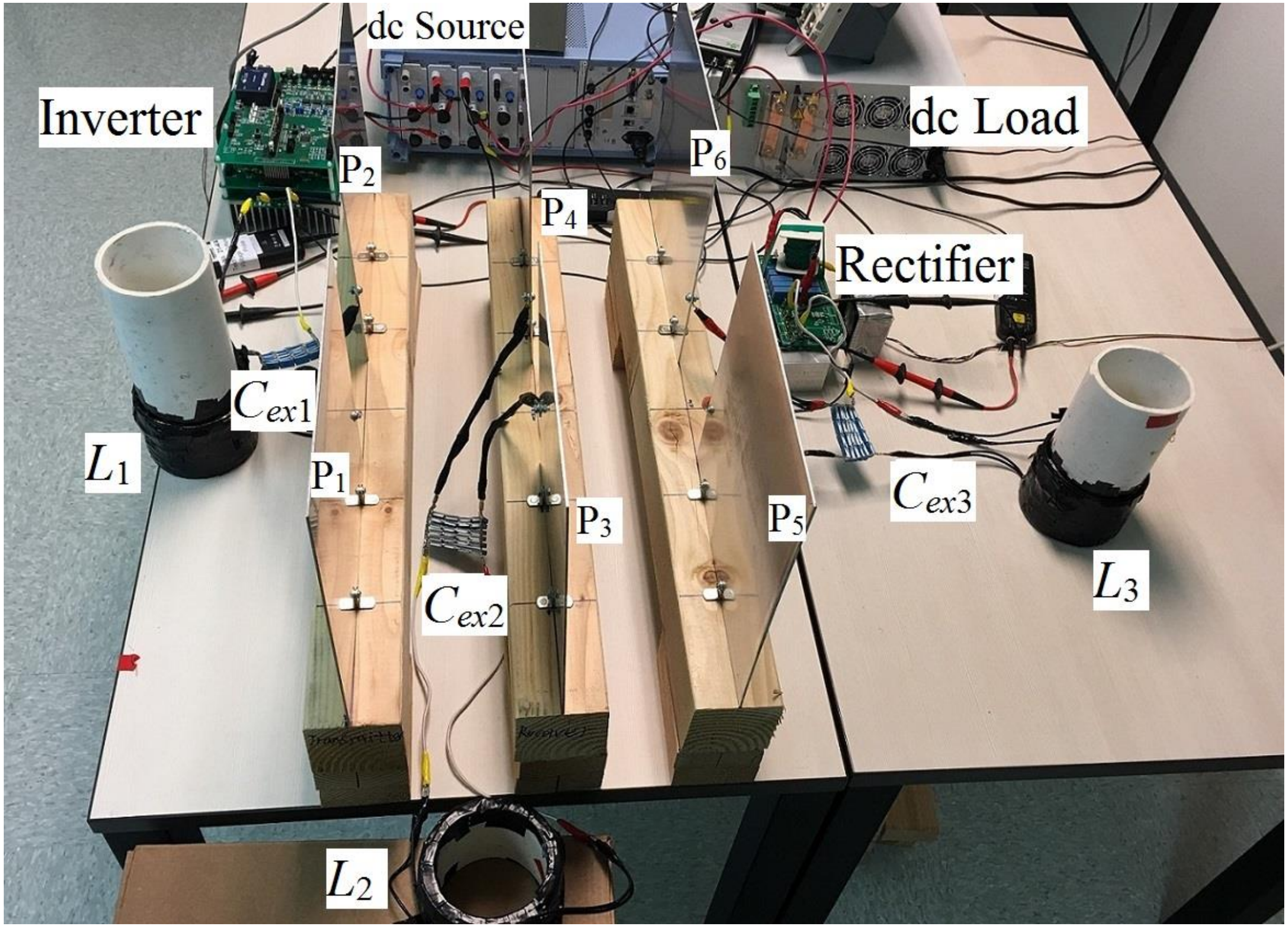
- Transmitter size: 1200mm×300mm
- Receiver size: 300mm×300mm
- Airgap distance: 50mm

LC Compensated CPT Repeater System



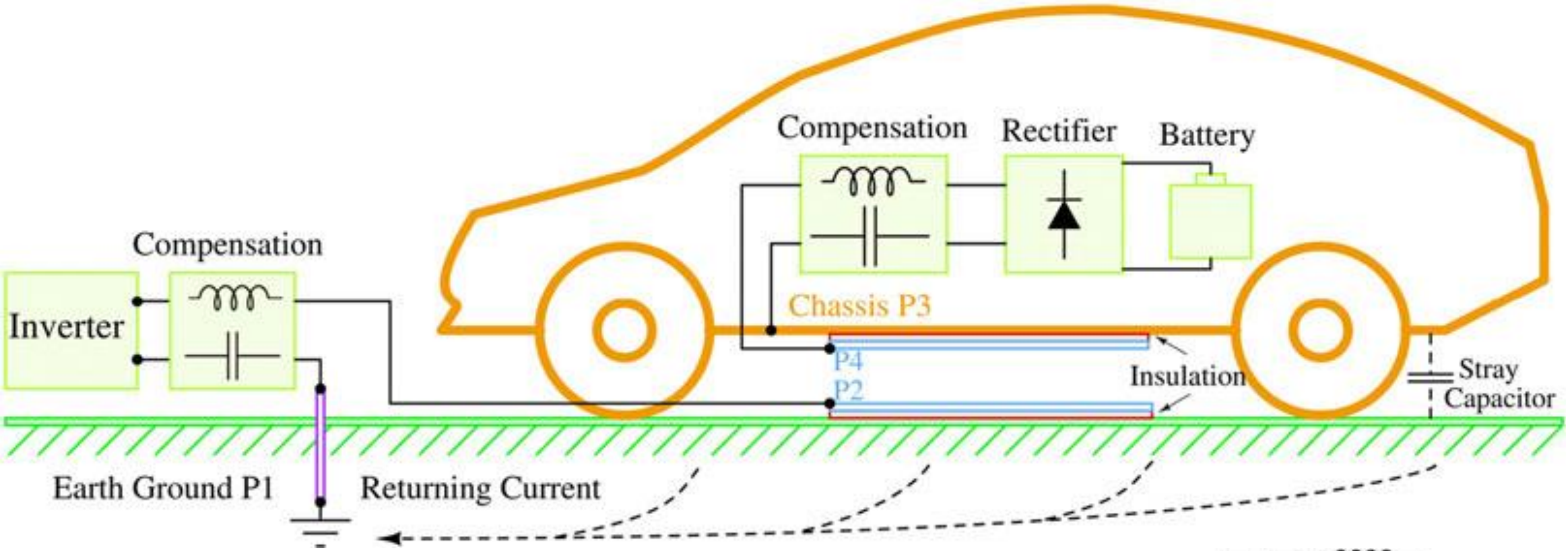
- LC compensation circuitry compensate the capacitive coupler
- Parameters are designed to achieve resonances

100W Prototype

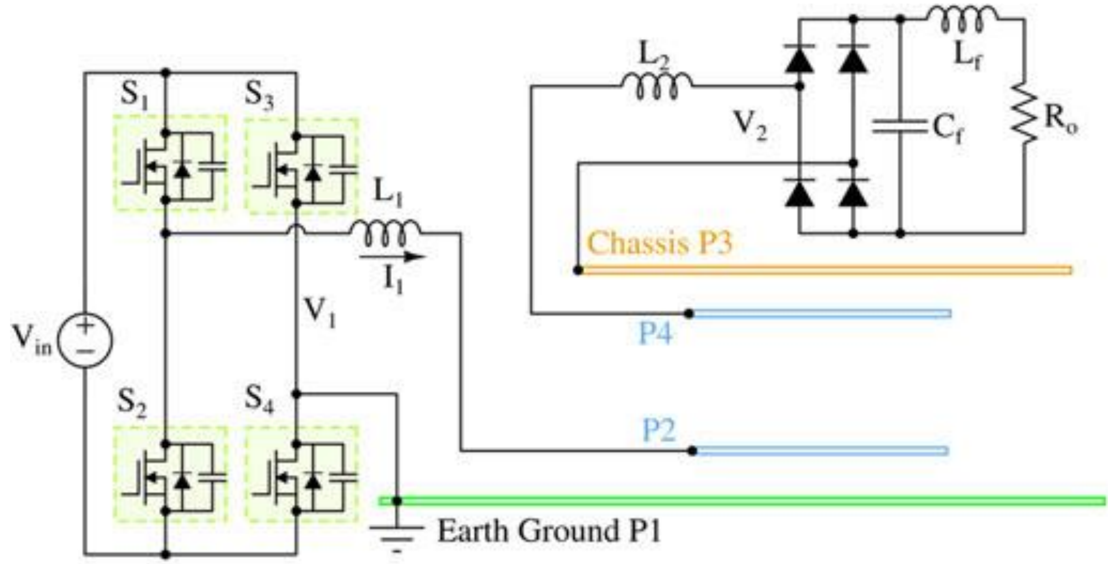


- Aluminum plates are used to make capacitive coupler
- Transfer distance is 180mm + 180mm

Single Ended CPT System

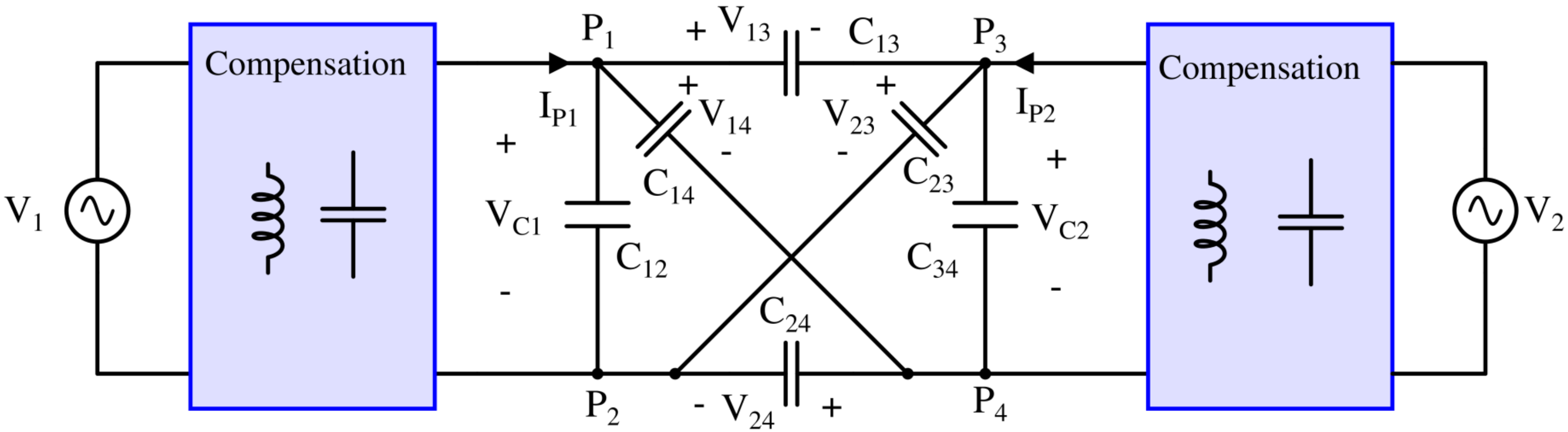


- Two plates only
- Chassis and the earth are the third and forth plates

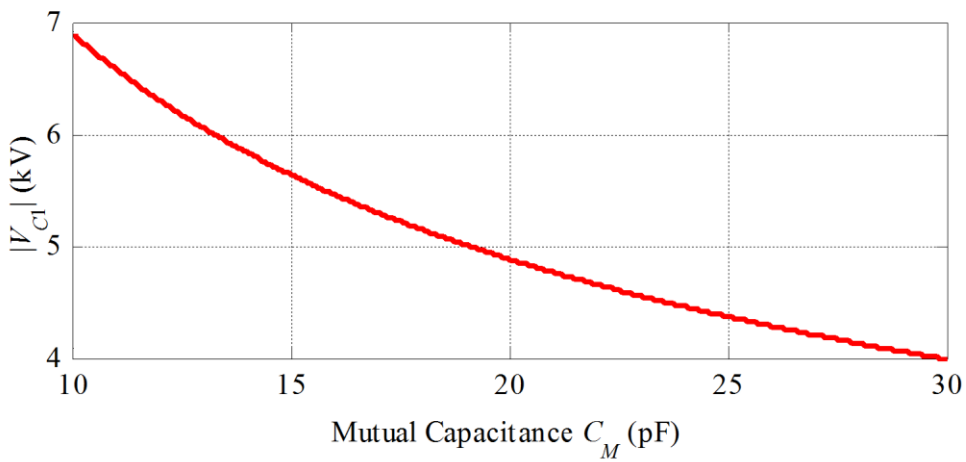


Safety Issue and Impact of Foreign Object

- High voltages on plates



- An example: P_M=3.0kW, f_{sw}=1MHz



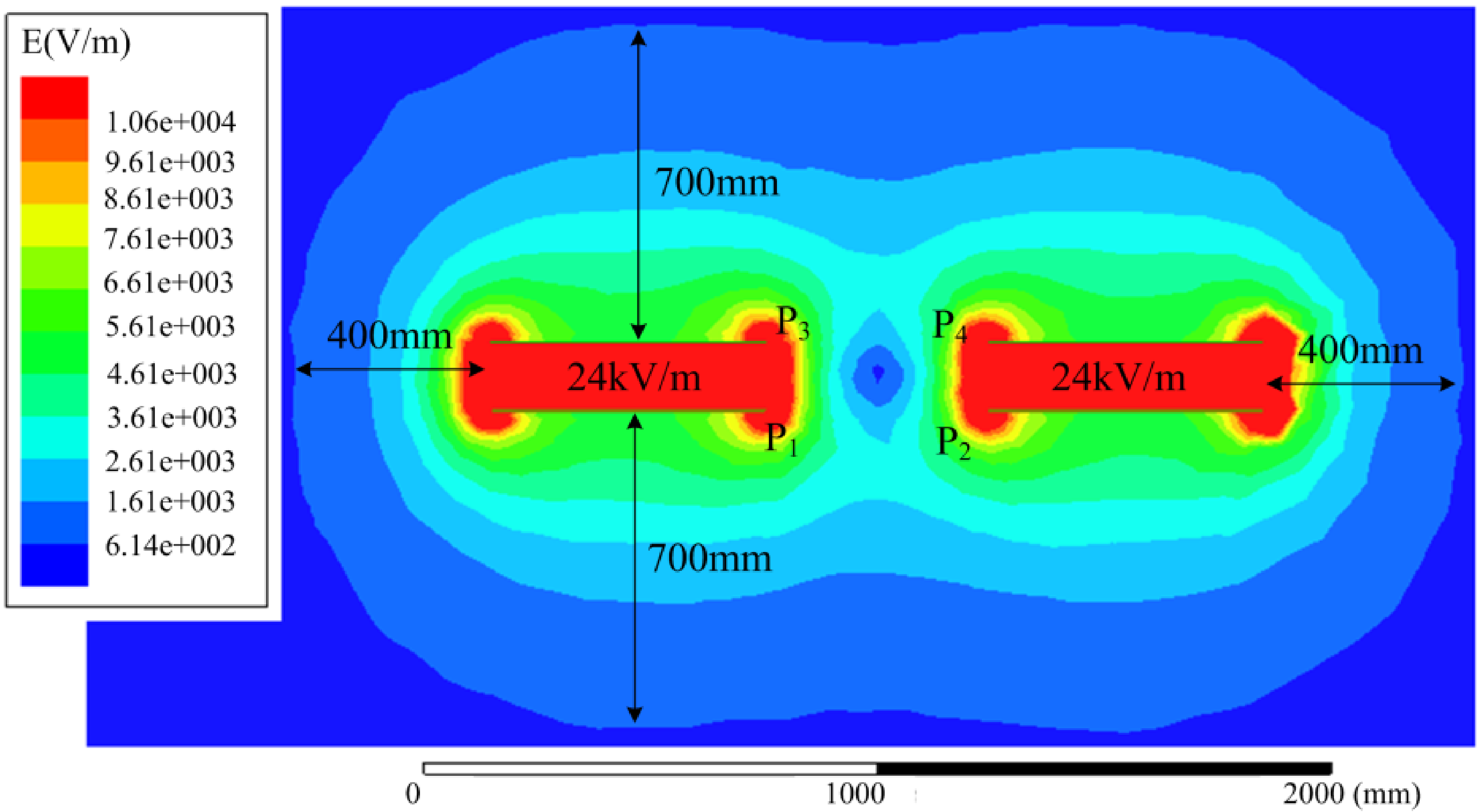
$$P_M = \omega C_M \cdot |V_C|^2$$

$$|V_{C1}| = \sqrt{\frac{P_M}{\omega C_M}}$$

- Voltages are in kV level
- Solution: reliable insulation is required on plate surface

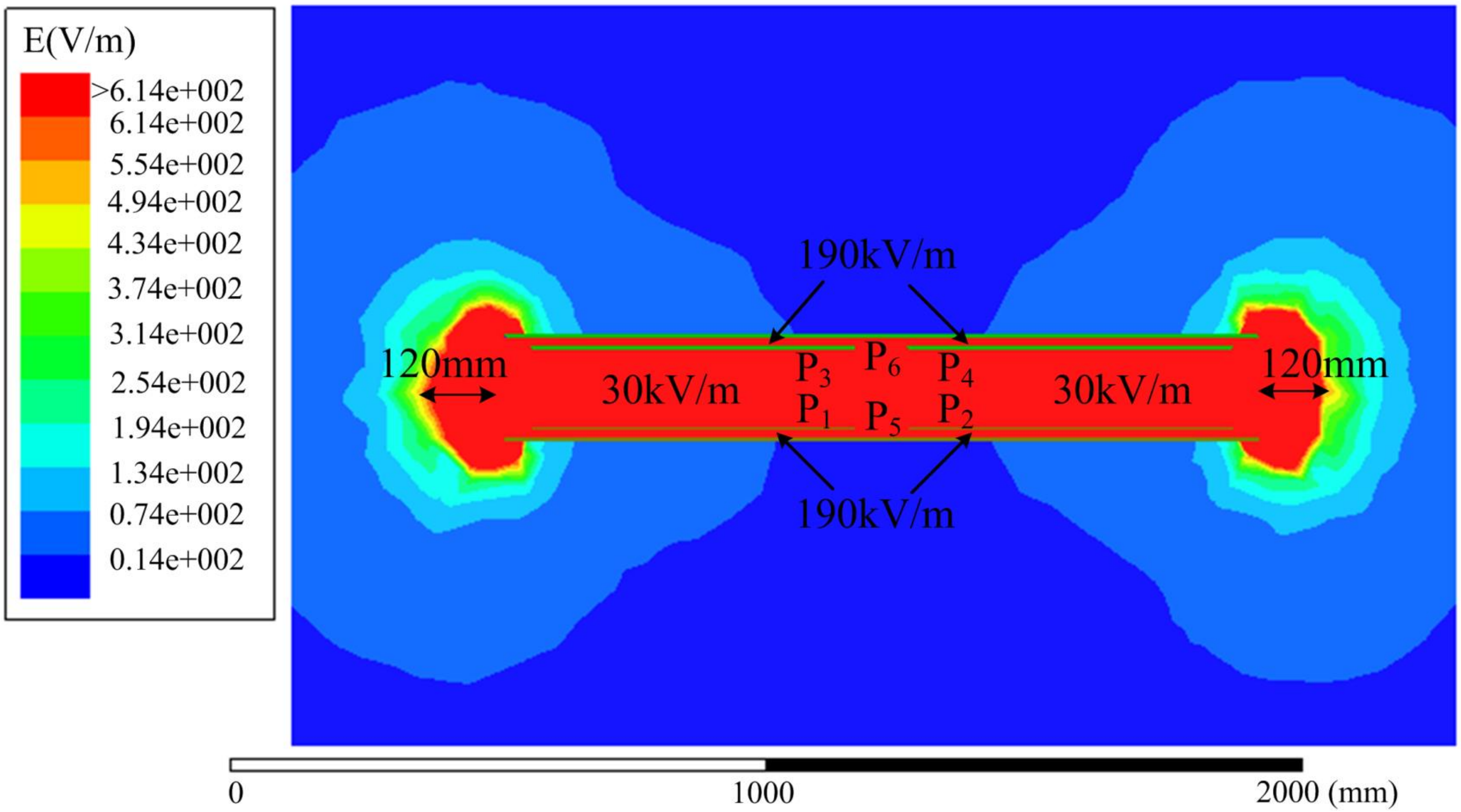
Electric Field Emissions

- $|V_{C1}|=|V_{C2}|=5.2$ kV, $|V_{14}|=|V_{23}|=4.2$ kV, and $|V_{13}|=|V_{24}|=3.1$ kV



➢ Safe range is 700mm from the edge of plates

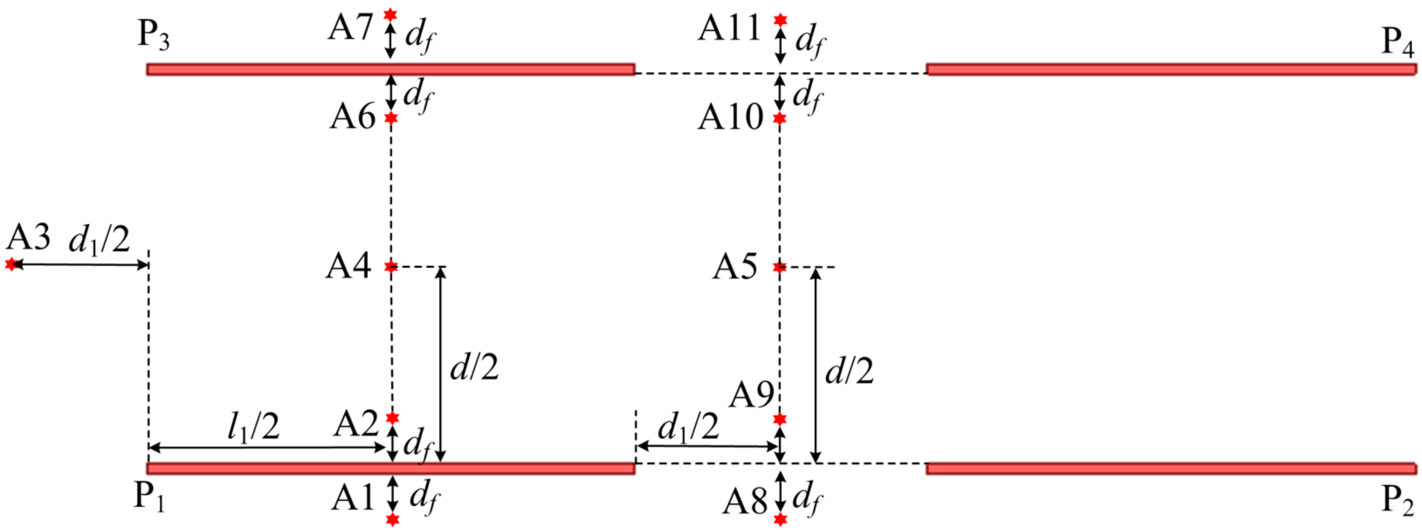
Solution: Six-Plate Coupler[12]

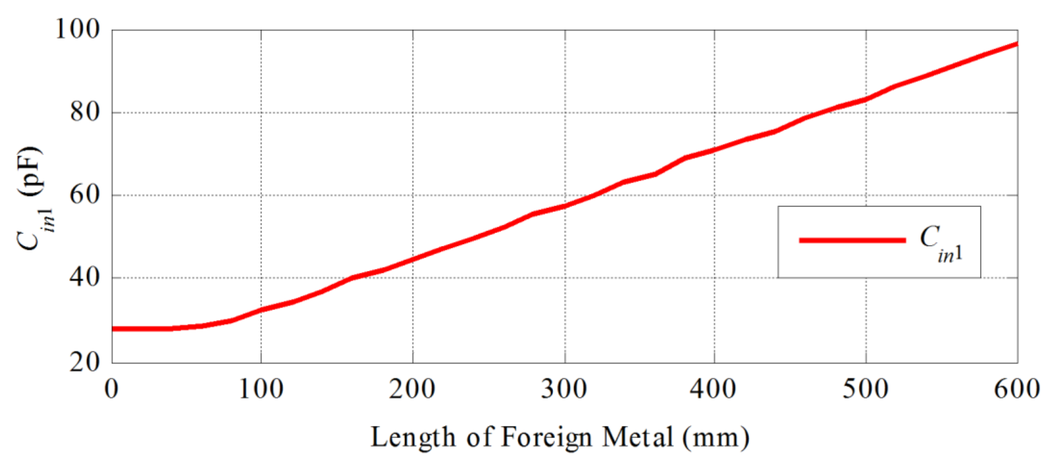


- P5 is grounded, and P6 is equivalently grounded
- Safe range is 120mm from the edge
- Further research shows safe range is 400 mm from the edge with 300mm misalignment

[12] H. Zhang, **F. Lu**, H. Hofmann, C. Mi, "A Six-Plate Capacitive Coupler to Reduce Electric Field Emission in Large Air-gap Capacitive Power Transfer," IEEE Trans. Power Electron., 2017, doi: 10.1109/ TPEL.2017.2662583.

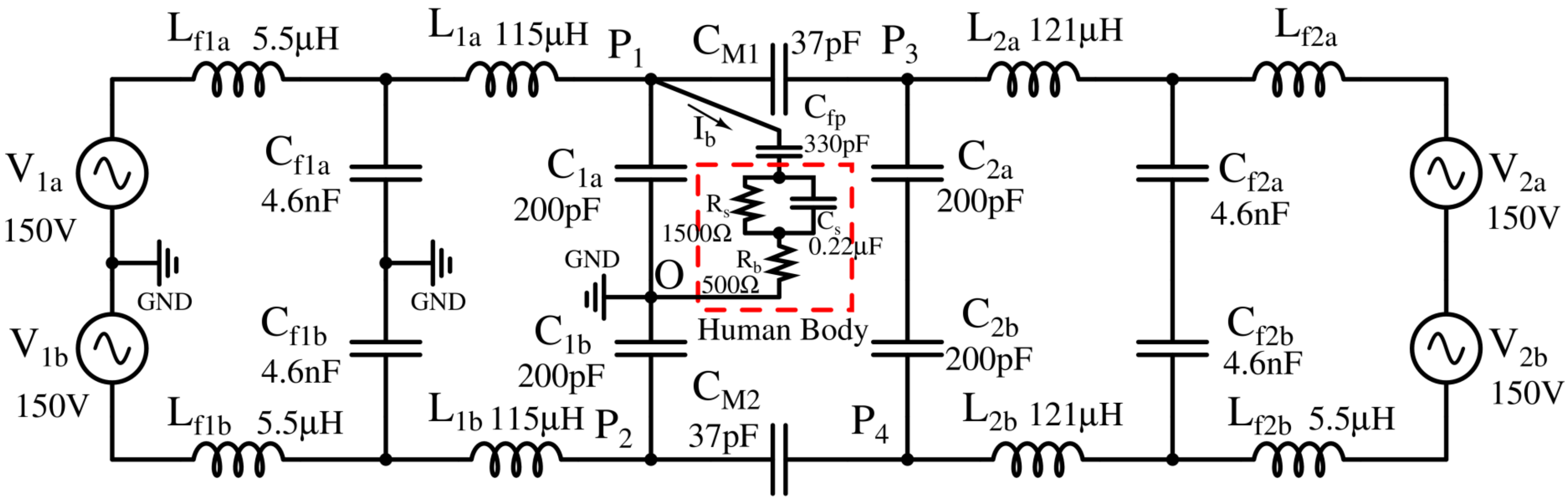
Metallic Foreign Object Influence





- Positions A5, A8, A9, A10, and A11 are sensitive positions
- The influence becomes significant with increasing metal size

Circuit Model of Human Touch



- At high frequency, human model is approximated to be 500Ω resistor (IEC)
- High-frequency (above 100 kHz) current has no neurological and cardiac problem (IEEE 95.1)
- Circuit simulation shows I_b=2.2 A, which may cause heating problem
- IEEE C95.1 requires everage energy density lower than 144J/kg in 6 minutes
- Safe with 100 ms protection mechanism

$$D = \frac{I_b^2 \times R_b \times t}{m} = \frac{2.2^2 \times 500 \times 0.1}{60} = 4.03\, J/kg < 144\, J/kg$$

Final Comparison of CPT and IPT

	IPT	CPT
Switching frequency	85kHz	1MHz
Coupling field	Magnetic	Electric
Foreign objects (metal)	Will generate heat	Will not generate heat
Material	Litz wires, ferrites	Copper/Aluminum plates
Cost	High	Low
Safety	Good	Excellent
Size	Small	Large
Misalignment	Poor	Good
Efficiency	Excellent	Excellent
Voltage stress	Medium	High
Power level	High	Medium
Stationary or dynamic	Better for stationary	Both

We are committed to conduct research to improve performance, efficiency and safety

Proud Sponsors

NSF

arpa·e
CHANGING WHAT'S POSSIBLE

U.S.–CHINA CLEAN ENERGY RESEARCH CENTER
中美清洁能源研究中心

GATE
GRADUATE AUTOMOTIVE TECHNOLOGY EDUCATION

TOYOTA

Skywell
南京金龙
Skywell

Gotion

HUAWEI

LG

STATE GRID CORPORATION OF CHINA
STATE GRID
GEIRI EUROPE
全球能源互联网欧洲研究院

DENSO

United Technologies

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

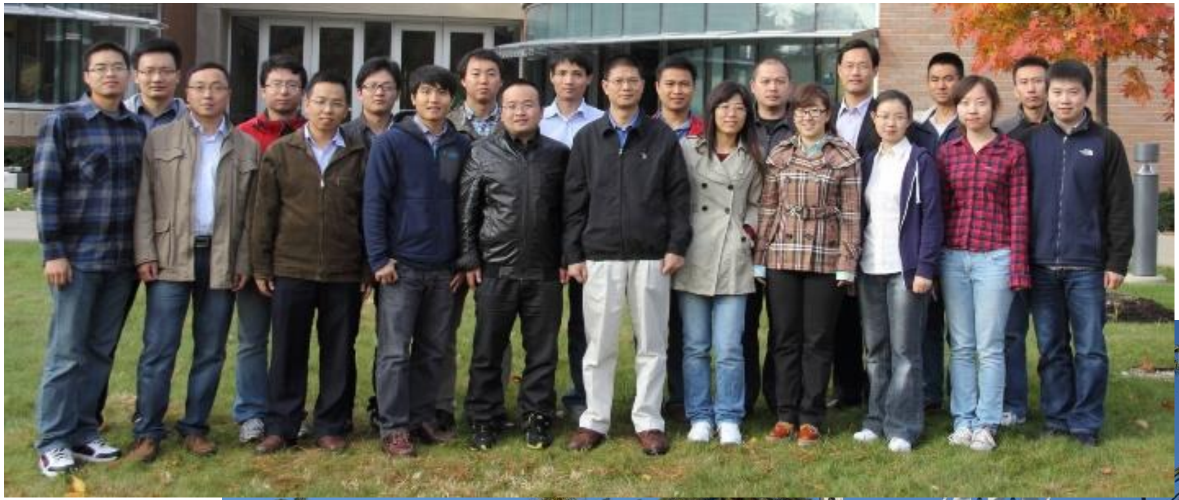
TARDEC

FCA
FIAT CHRYSLER AUTOMOBILES

HONDA

Ford

Hardworking Students!



Q&A

Thanks!