Session 9 8:55 am - 9:45 am
Advances in Stationary and In-Motion Charging Research

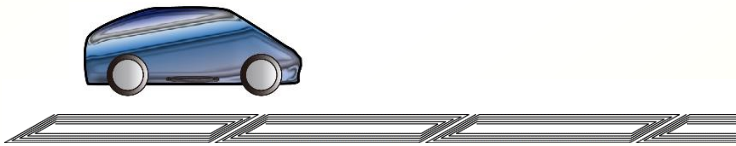
In-Motion Charging Sequence in Sensorless System using Series-Series Topology via Magnetic Resonance Coupling

The University of Tokyo
Hori and Fujimoto lab.

Takehiro Imura

2018.2.27

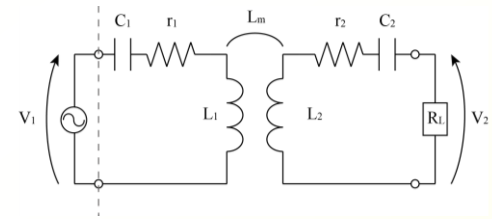
Overview of our system



Coil type

Open type coil
(capacitor-less and ferrite-less)

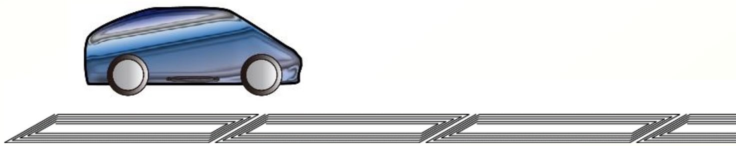
S-S: series-series



Sensorless detection (primary)	detection
Power control by HAR (secondary)	control A type
Maximum efficiency tracking (secondary)	control B type
Simultaneous power and maximum efficiency tracking control (secondary)	control C type
Power off (primary)	power off

Automatic driving using coil sensing

Overview of our system



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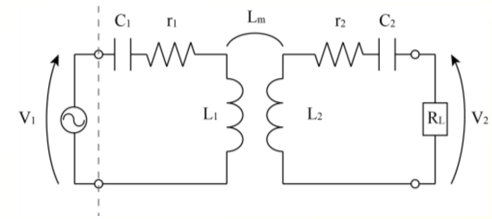

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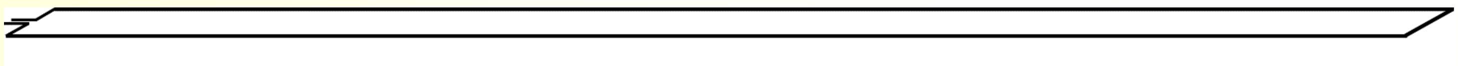
Automatic driving using coil sensing

DWPT（Dynamic WPT）



line type

coil type

At glance, it looks like the line type has a big advantage for charging time and control, but...

advantages coil

efficiency

lower leakage magnetic field

workability

maintenance

advantages line

cost

Overview of our system

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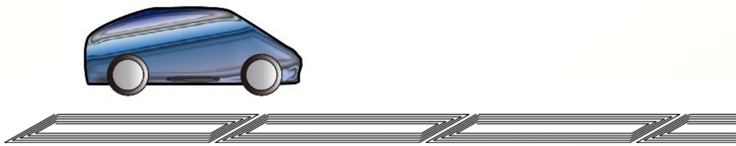

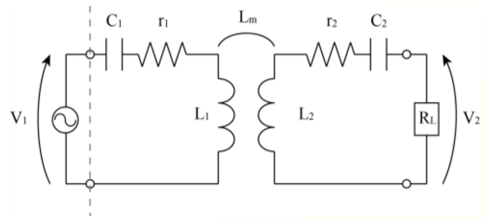

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Automatic driving using coil sensing

Open type coil

<u>**Open end coil for road side**</u>

No need of capacitor or ferrite

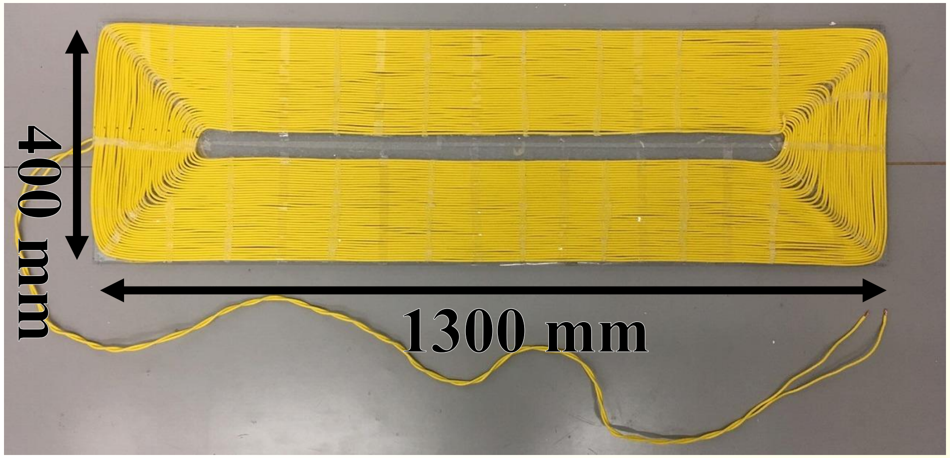
NO capacitor

NO ferrite

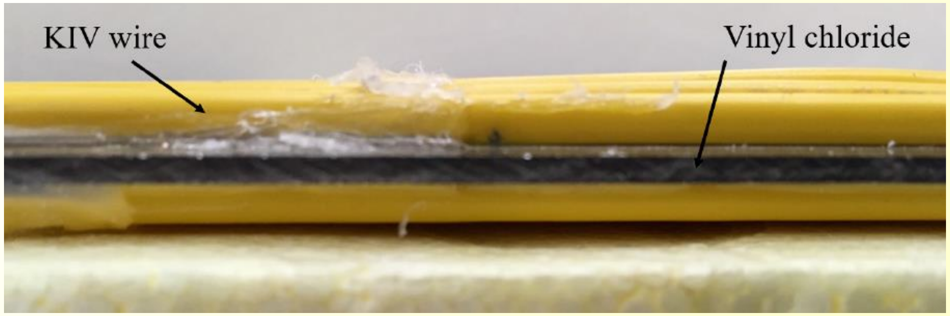
⇒ low cost

<u>**Parameters of actual coil**</u>

Plate size	： 1300 mm × 400 mm
Coil size	： 1280 mm × 380 mm
Wire	： 3.5 mm^2 KIV wire
Layer gap	： 3.6 mm
Wire pitch	： 1.6 mm
No. of turns	： 40.5
Lead-in wire	： 2000 mm



Overview of the actual coil (Top view)



Overview of the actual coil (Side view)

Open type coil

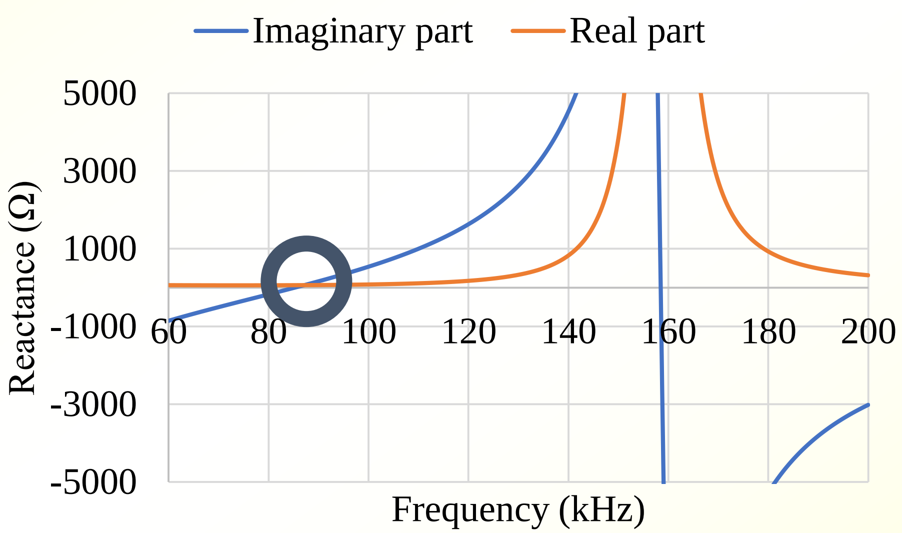
Measured result

The actual coil self-resonates at 85.3 kHz.

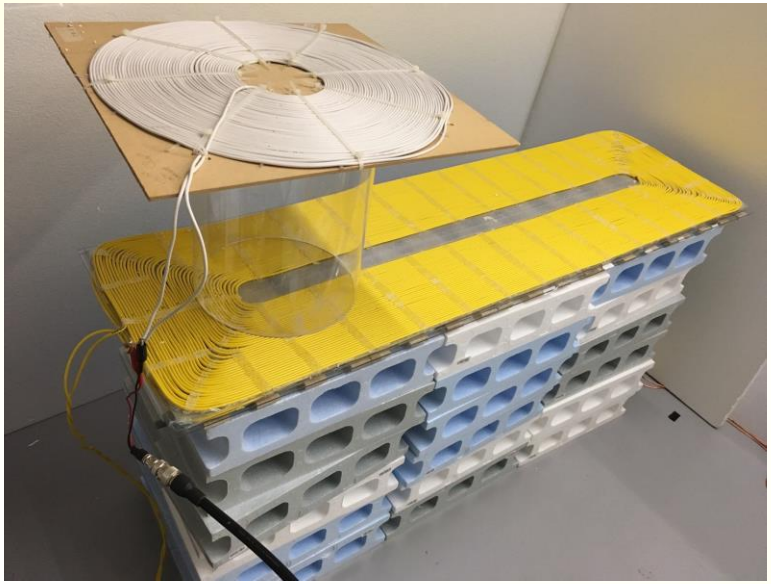
→Feasibility of **85 kHz self-resonant** open end coil is confirmed.

Efficiency

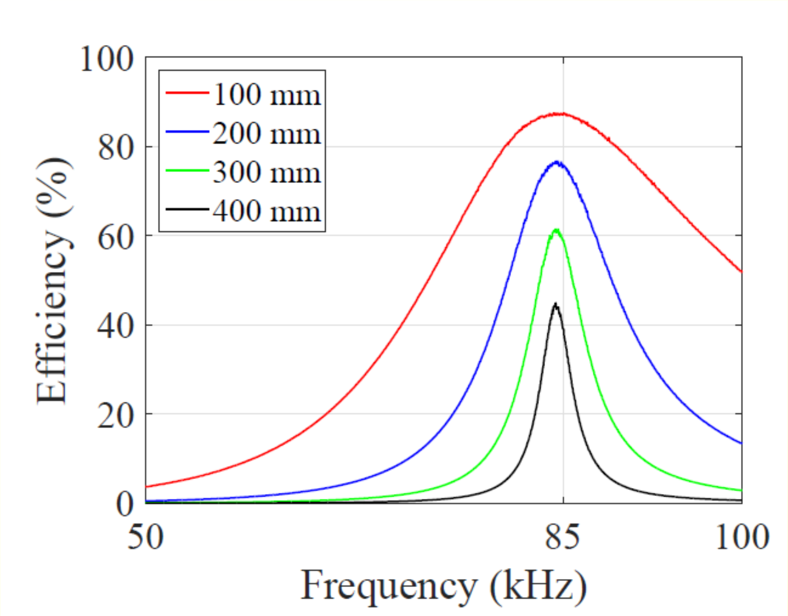
Efficiency is 90% @ 100 mm



Impedance frequency plots



Note: Receiver side is typical short type



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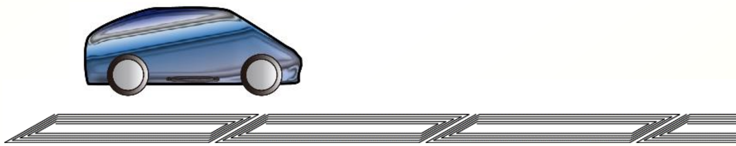

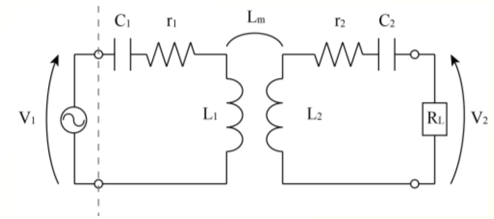

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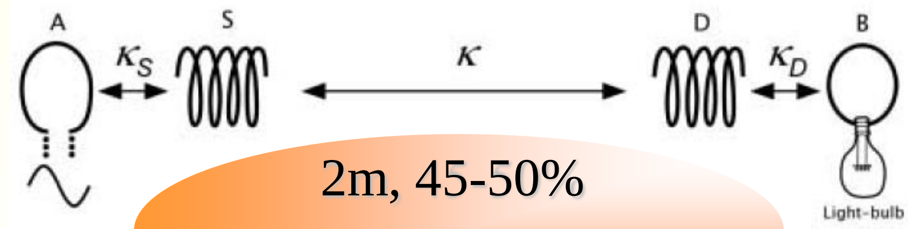
Automatic driving using coil sensing

Magnetic Resonant Coupling (MRC), 2007

10MHz



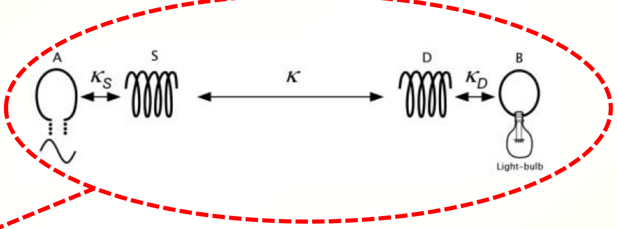
2m, 45-50%

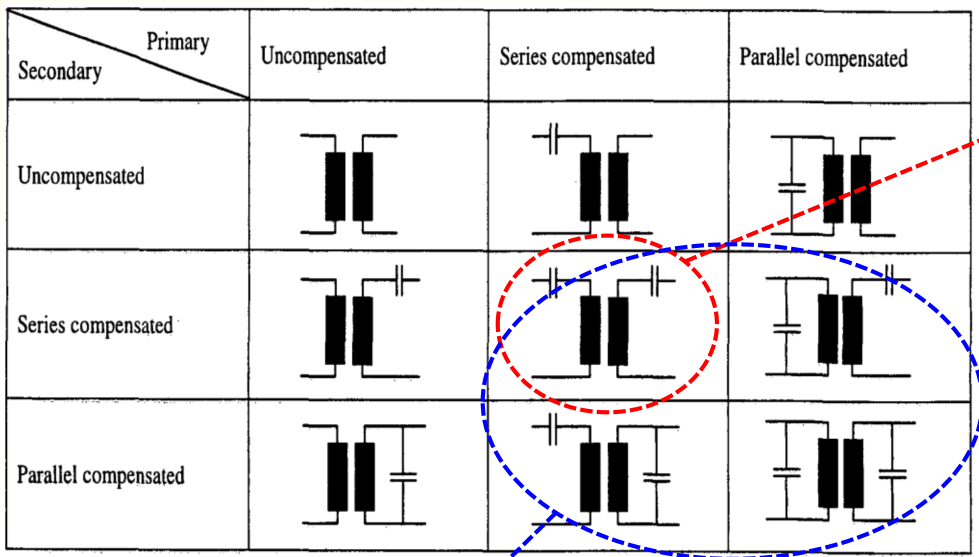
(less 1m, over 90%)

Very large air gap with high efficiency surprised many people.

André Kurs, Aristeidis Karalis, Robert Moffatt, J. D. Joannopoulos, Peter Fisher, Marin Soljačić,
"Wireless Power Transfer via Strongly Coupled Magnetic Resonances," in Science Express on 7 June 2007, Vol. 317. no. 5834, pp. 83 – 86.

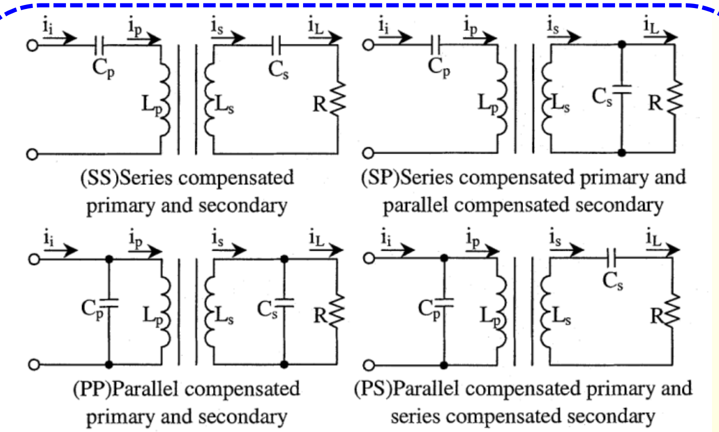
History of IPT, before 2007





O. H. Stielau and G. A. Covic: "Design of loosely coupled inductive power transfer systems", Proc. 2000 Int. Conf. Power System Technology, Vol. 1, pp. 85-90 (2000)

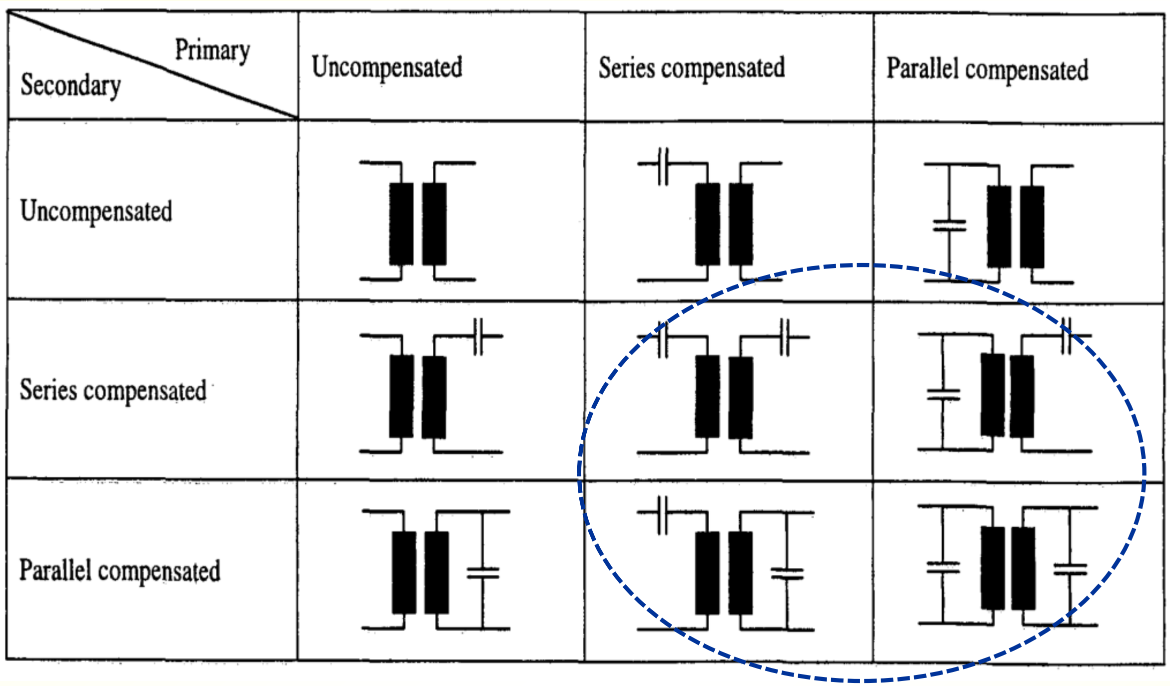
Magnetic resonant coupling (MRC) used electromagnetic induction phenomenon (IPT) and resonance topologies is categorized as S-S compensation.



(a) Basic topologies

W. Chwei-Sen, G. A. Covic, and O. H. Stielau, "Power transfer capability and bifurcation phenomena of loosely coupled inductive power transfer systems," IEEE Trans. Ind. Electron., vol. 51, no. 1, pp. 148–157, Feb. 2004.

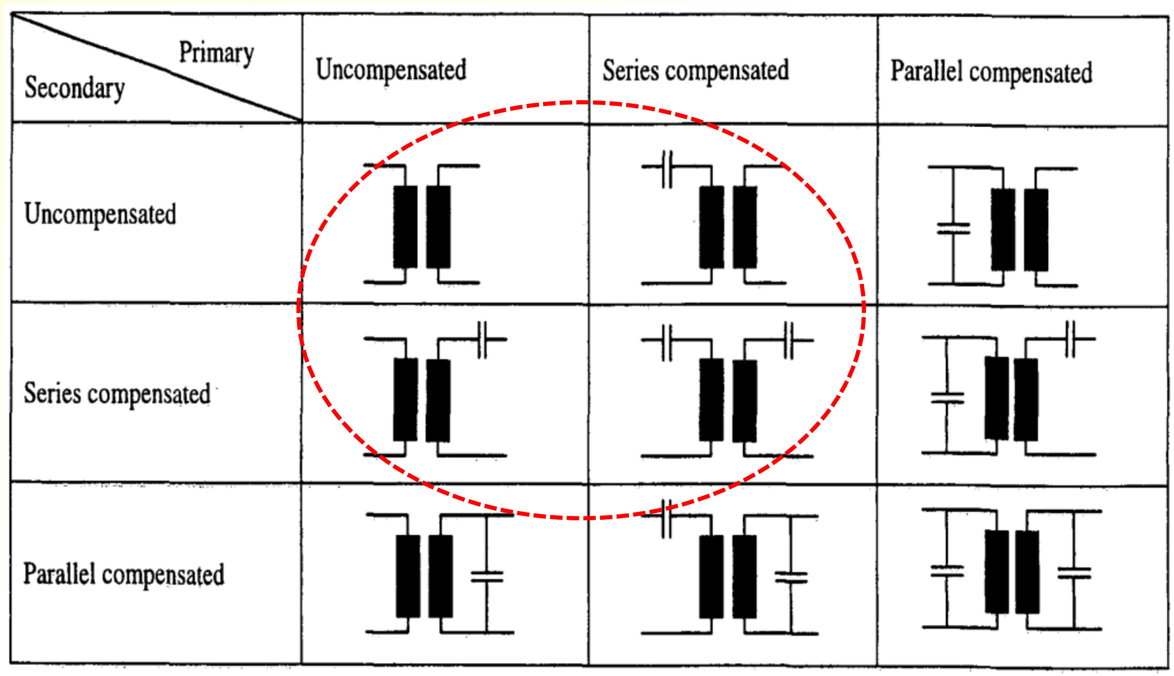
History of IPT, after 2007



There are many paper about resonance topologies.

[1] O. H. Stielau and G. A. Covic: "Design of loosely coupled inductive power transfer systems", Proc. 2000 Int. Conf. Power System Technology, Vol. 1, pp. 85-90 (2000)
[2] C. Wang, G. A. Covic, S. Member, and O. H. Stielau, "Power Transfer Capability and Bifurcation Phenomena of Loosely Coupled Inductive Power Transfer Systems", IEEE Transactions on Power Electronics, 2004
[3] Xun, L., Ng, W.M., Lee, C.K., Hui, S.Y.R. "Optimal Operation of Contactless Transformers with Resonance in Secondary Circuits", In Proceedings of the Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition (APEC 2008).
[4] N. Jamal, "A Study on Performances of Different Compensation Topologies for Loosely Coupled Inductive Power Transfer System", IEEE International Conference on Control System, Computing and Engineering, 2013.
[5] L. V. Ratio, W. Zhang, S. Member, S. Wong, S. Member, C. K. Tse, and Q. Chen, "Analysis and Comparison of Secondary Series- and Parallel-Compensated Inductive Power Transfer Systems Operating for Optimal Efficiency and Load-Independent Voltage-Transfer Ratio", IEEE Transactions on Power Electronics, 2014.
[6] K. Aditya, S. Member, S. S. Williamson, and S. Member, "Comparative Study of Series-Series and Series-Parallel Topology for Long Track EV Charging Application", IEEE Transportation Electrification Conference and Expo (ITEC), 2014.
[7] Y. H. Sohn, B. H. Choi, E. S. Lee, G. C. Lim, G. Cho, and C. T. Rim, "General Unified Analyses of Two-Capacitor Inductive Power Transfer Systems: Equivalence of Current-Source SS and SP Compensations," IEEE Trans. Power Electron., 2015.

History of IPT, after 2007



Seamless transient from S-S to N-N

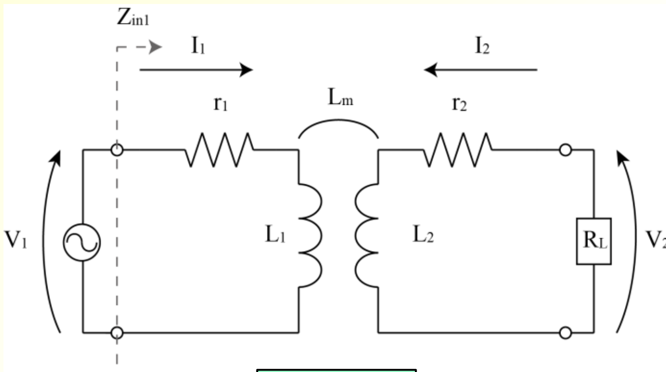
O. H. Stielau and G. A. Covic: "Design of loosely coupled inductive power transfer systems", Proc. 2000 Int. Conf. Power System Technology, Vol. 1, pp. 85-90 (2000)

Comparison of N-N,N-S,S-N,S-S

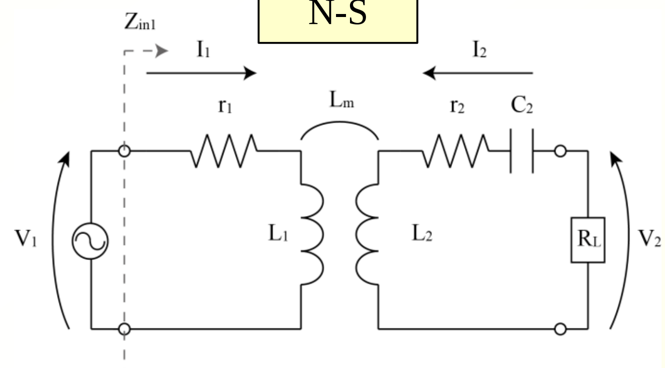
Seamless transient from S-S to N-N

(N: Non-resonant, S: Series)

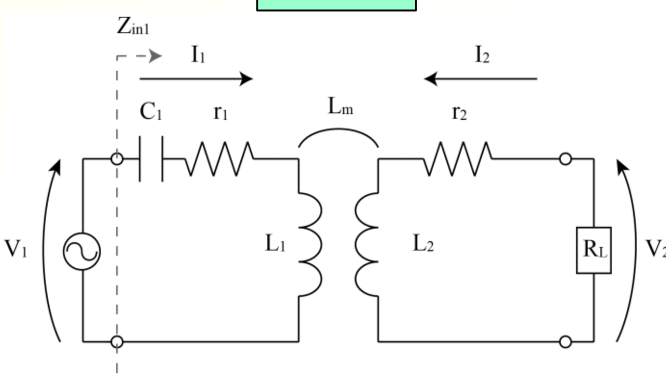
N-N



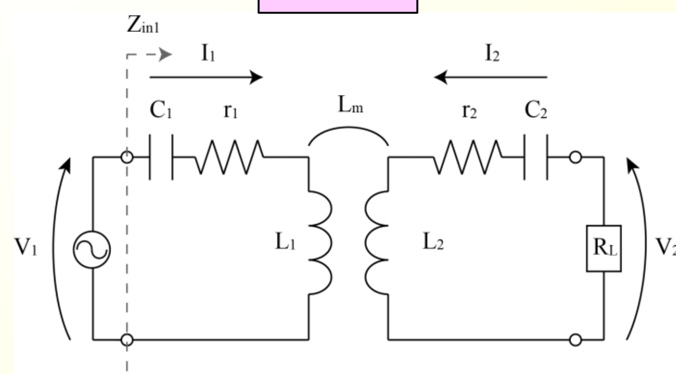
N-S



S-N



S-S



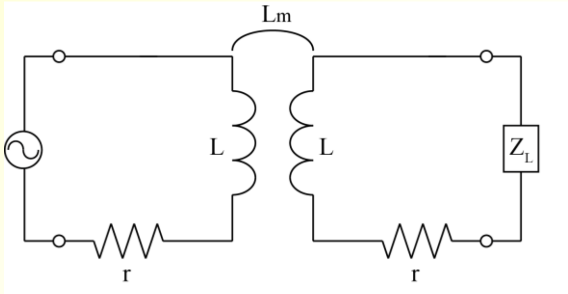
Takehiro Imura, Yoichi Hori, "Superiority of Magnetic Resonant Coupling at Large Air Gap in Wireless Power Transfer", 42nd Annual Conference of the IEEE Industrial Electronics Society (2016).

Voltage source

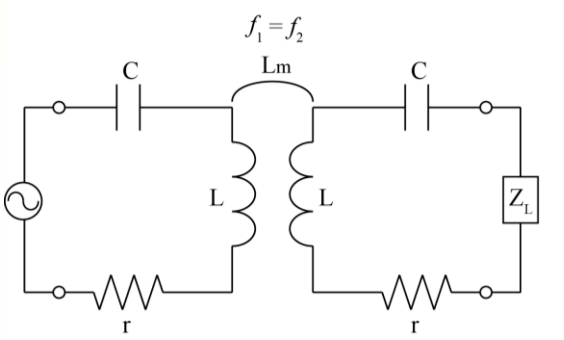
N-N vs. S-S

(N: Non-resonant, S: Series)

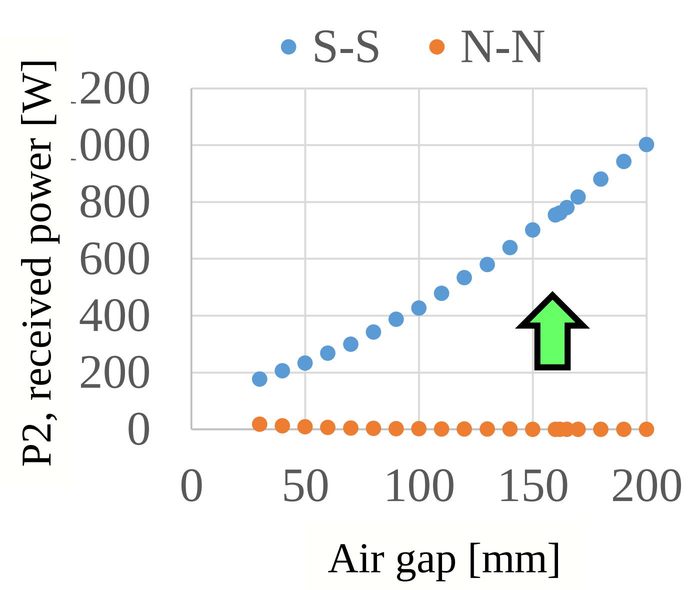
N-N



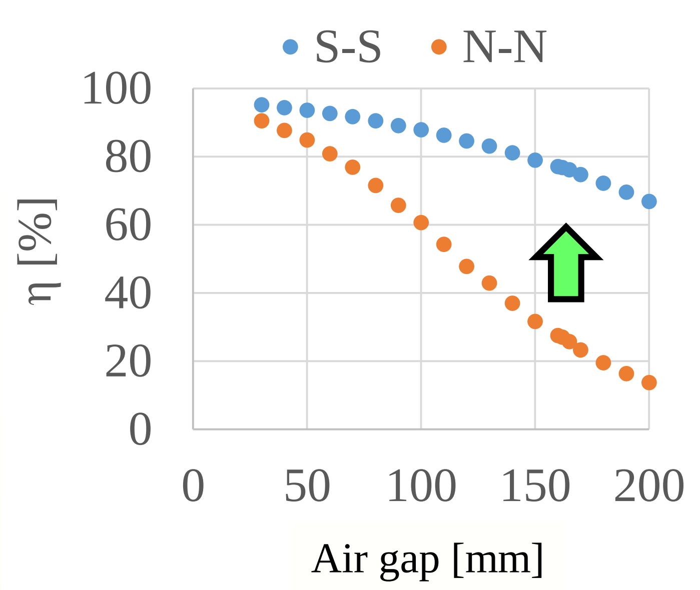
S-S, MRC



High power



High efficiency

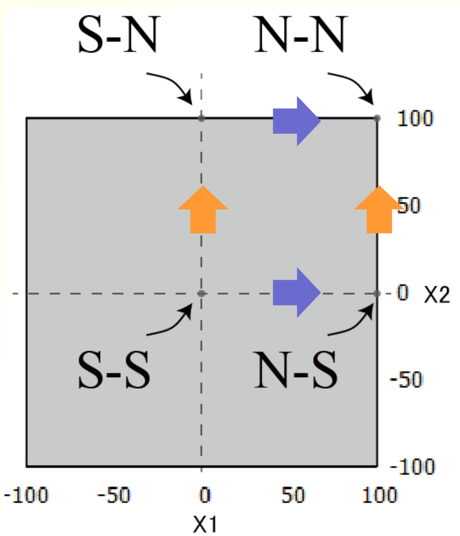


Comparison of N-N,N-S,S-N and S-S: C_1 & C_2

$$\omega L_1 = \omega L_2 = 100\ \Omega$$

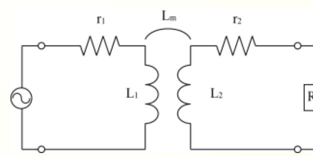
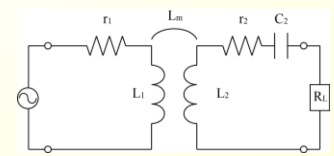
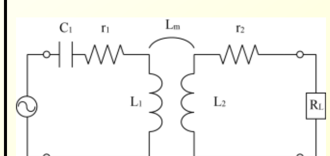
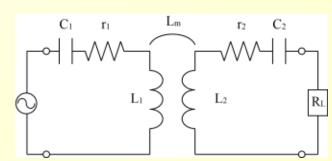
$$X_1 = \omega L_1 - \frac{1}{\omega C_1} = 100 - \frac{1}{\omega C_1}$$

$$X_2 = \omega L_2 - \frac{1}{\omega C_2} = 100 - \frac{1}{\omega C_2}$$



Secondary side

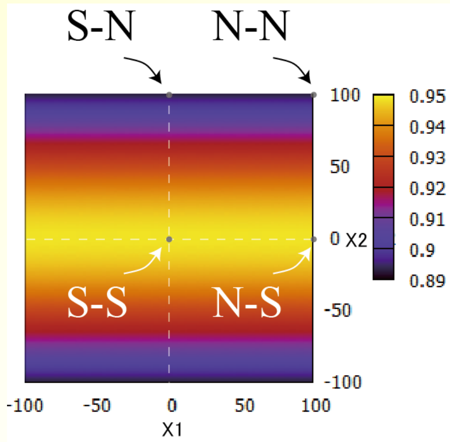
Primary side

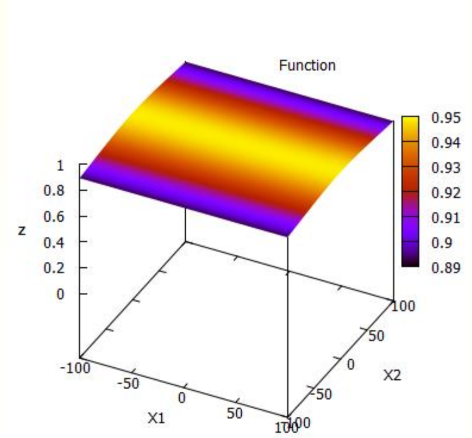
	η (low) w/o C_2 $C_2\to\infty$	η (high) w/ C_2
P (low) w/o C_1 $C_1\to\infty$	N-N 	N-S 
P (high) w/ C_1	S-N 	S-S 

k=0.5

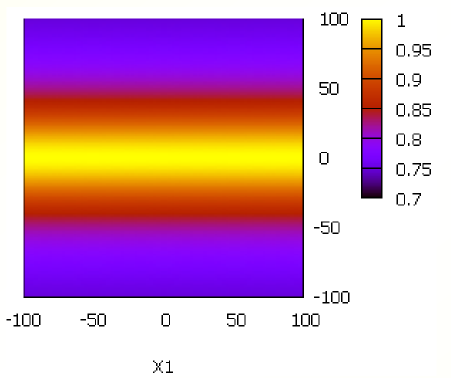
Comparison of N-N,N-S,S-N and S-S

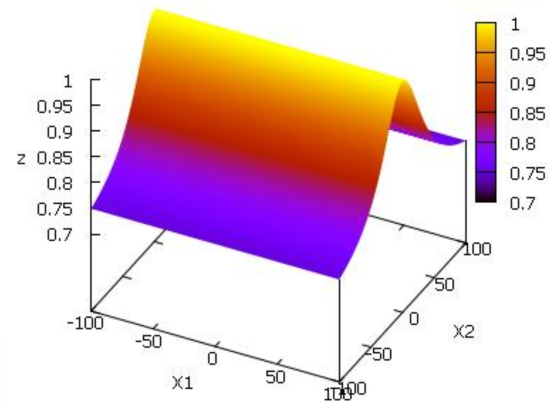
(d) η



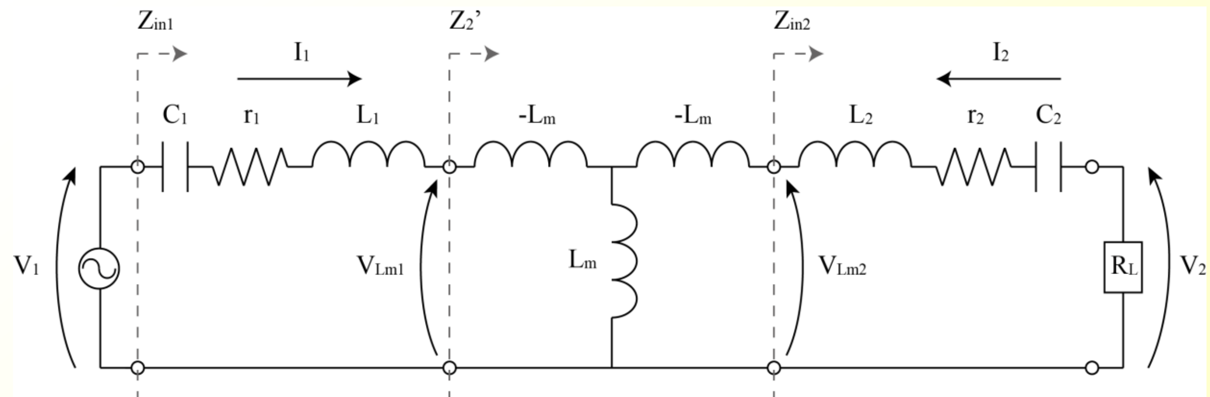


(e) $\cos\theta_{Zin2}$





R_L is optimized to achieve maximum efficiency



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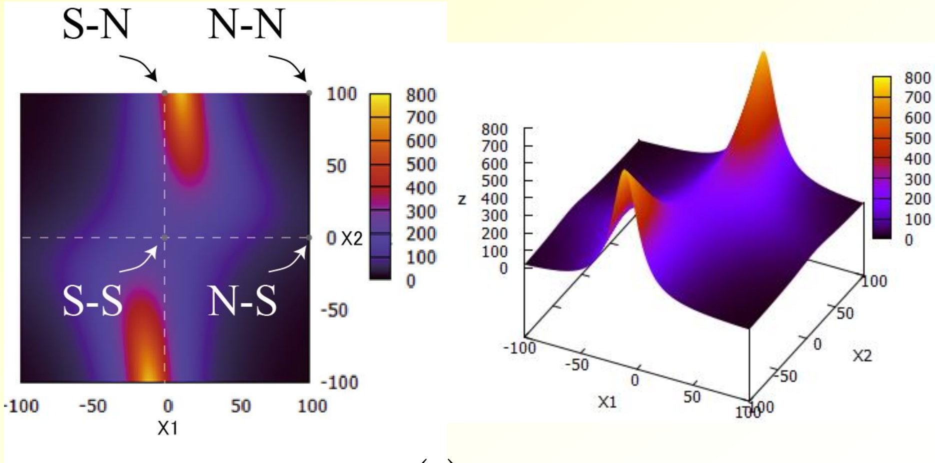
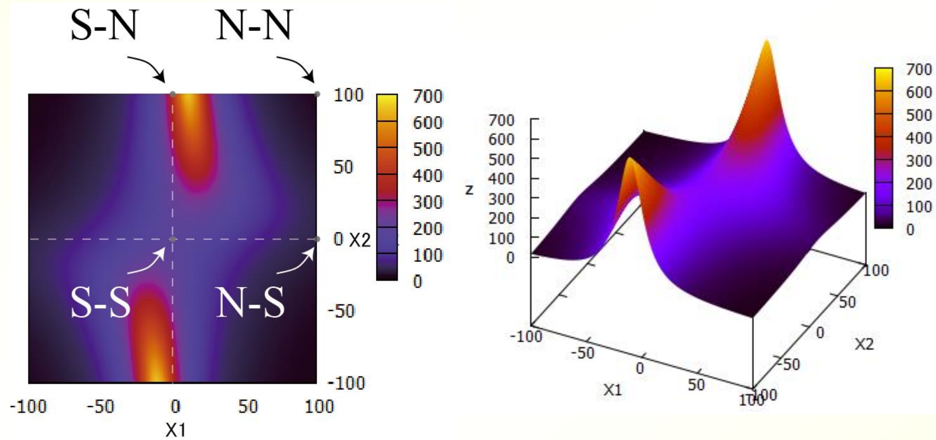
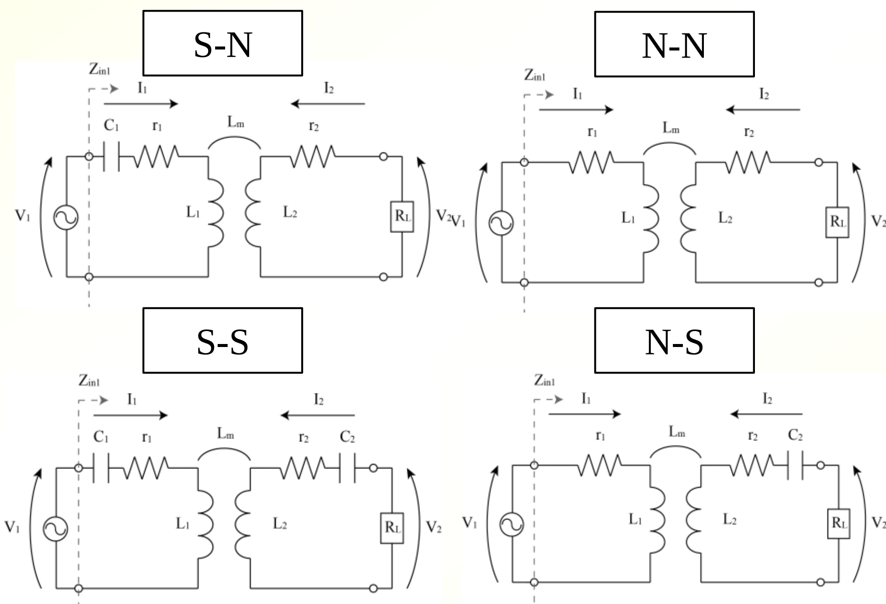


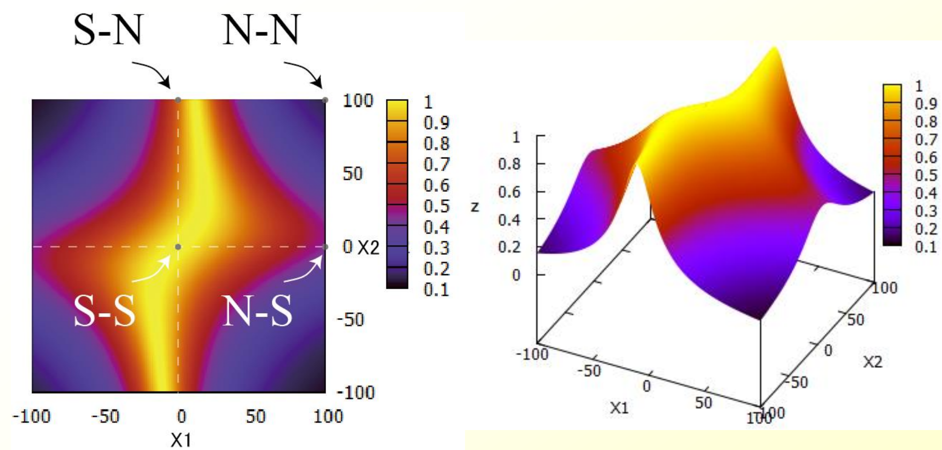
(a) P_1



(b) P_2

$$\omega L_1 = \omega L_2 = 100\ \Omega$$





(c) $\cos\theta_{Zin1}$

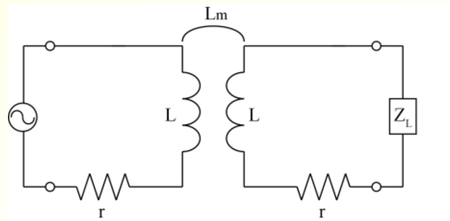
$$X_1 = \omega L_1 - \frac{1}{\omega C_1}$$

$$X_2 = \omega L_2 - \frac{1}{\omega C_2}$$

Picked up at 4 conditions

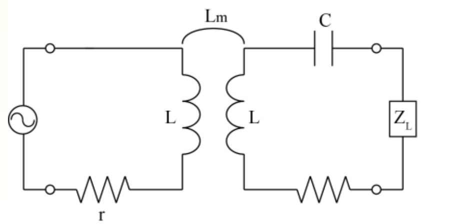
N-N

Efficiency: Low
Power: Low



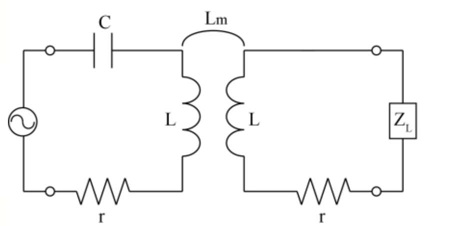
N-S

Efficiency: High
Power: Low



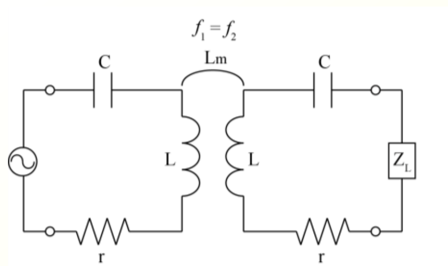
S-N

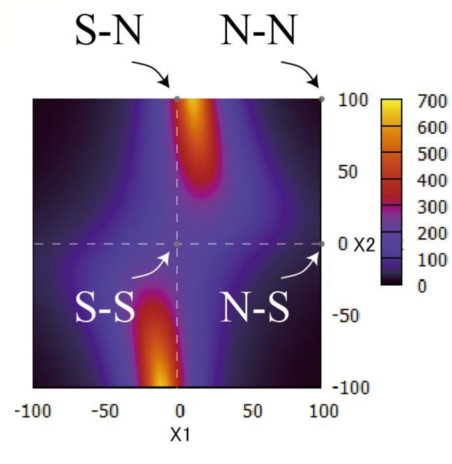
Efficiency: Low
Power: Large



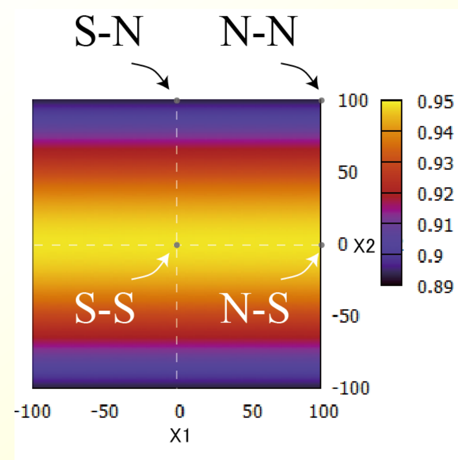
S-S ($f_1 = f_2$)

Efficiency: High
Power: Large





P_2



η

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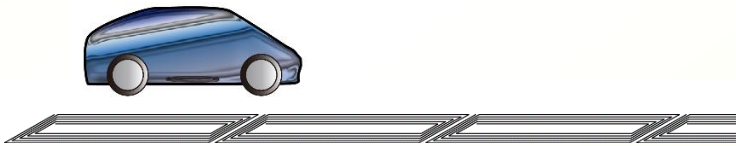

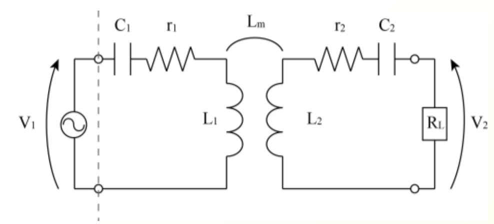

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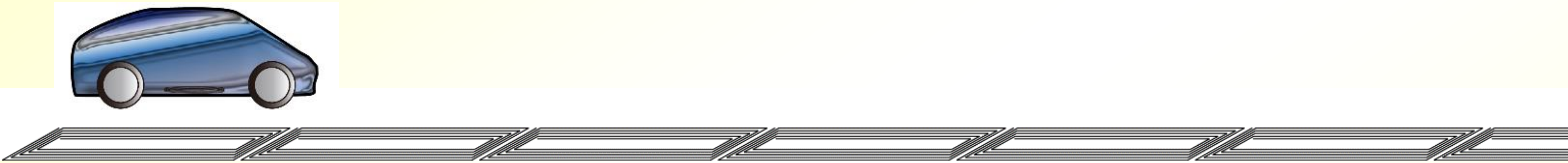
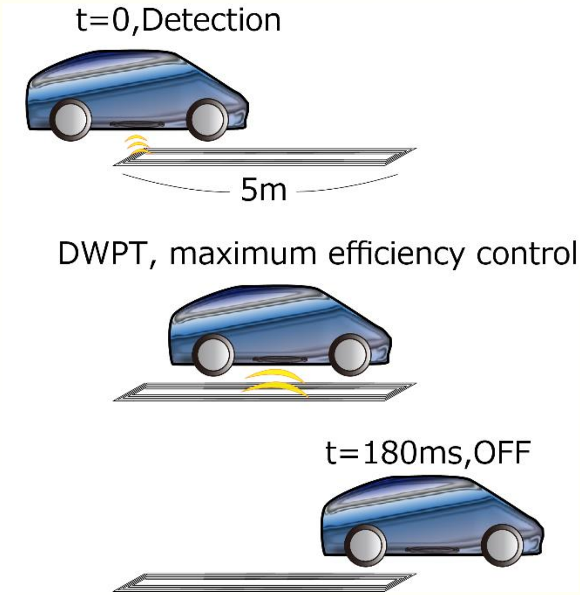
Simultaneous power and maximum efficiency tracking control (secondary) — control C type

Power off (primary) — power off

Automatic driving using coil sensing

Dynamic Wireless Power Transfer: DWPT





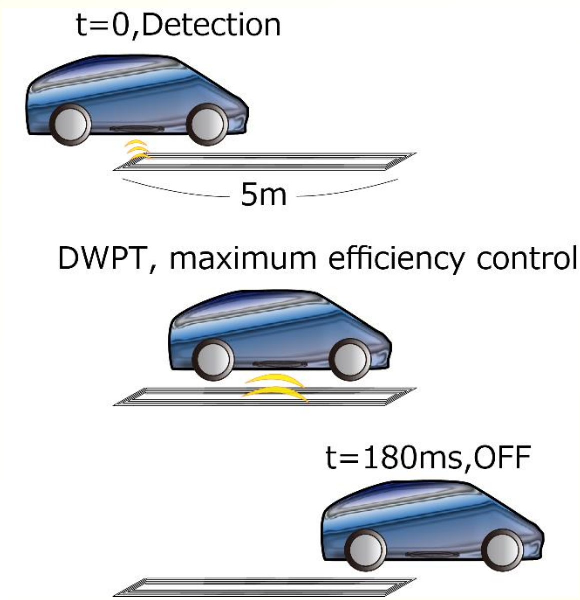
It takes 0.18 sec (180 ms) to pass the 5m transmitting coil when the vehicle speed is 100km/h.

The vehicle moves 27 mm in 1 ms at 100 km/h.

Quick detection and control is necessary.

Dynamic Wireless Power Transfer: DWPT

0.18 sec



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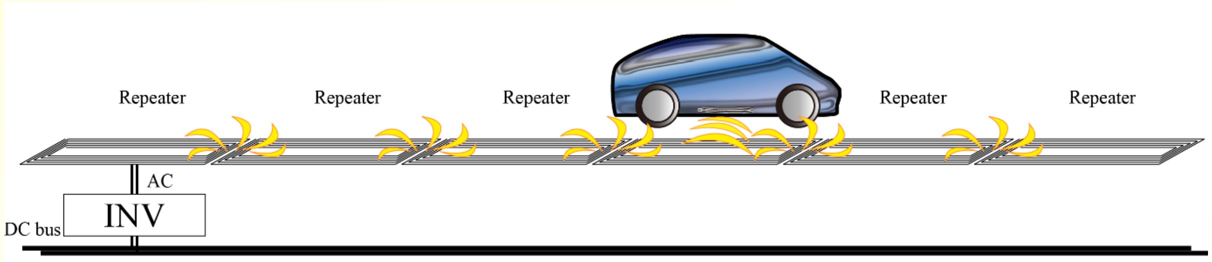
DWPT（Dynamic WPT）

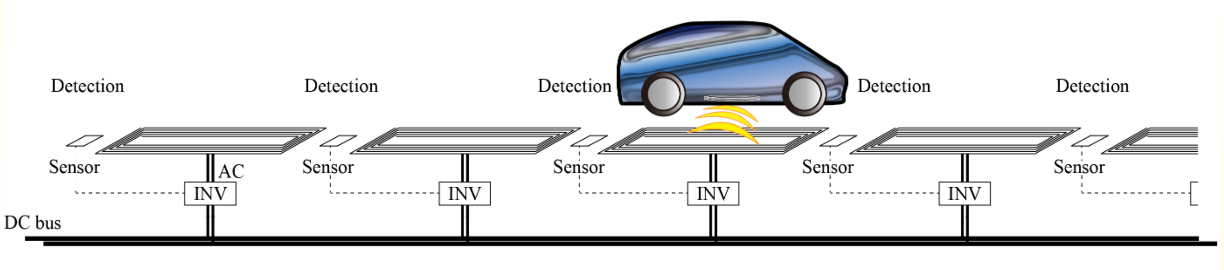
Repeater

Total loss & EMC



Sensor

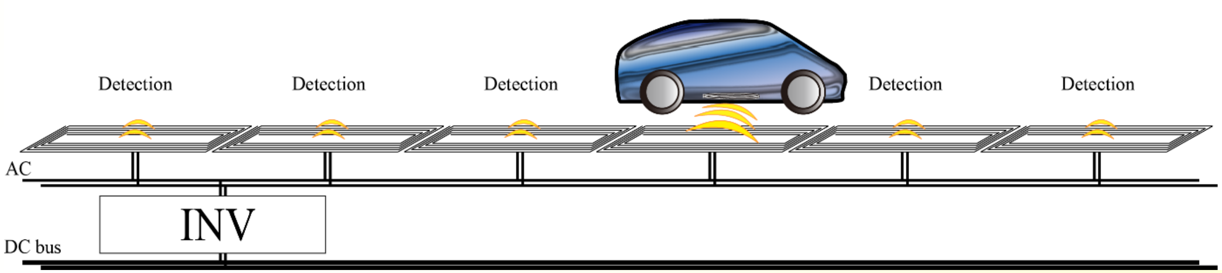
Sensor failure



Sensorless passive

Total loss

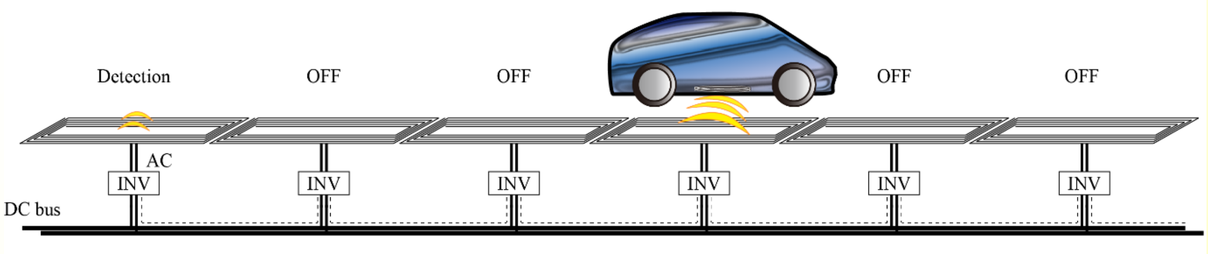
i.e.) P-S



Sensorless Active

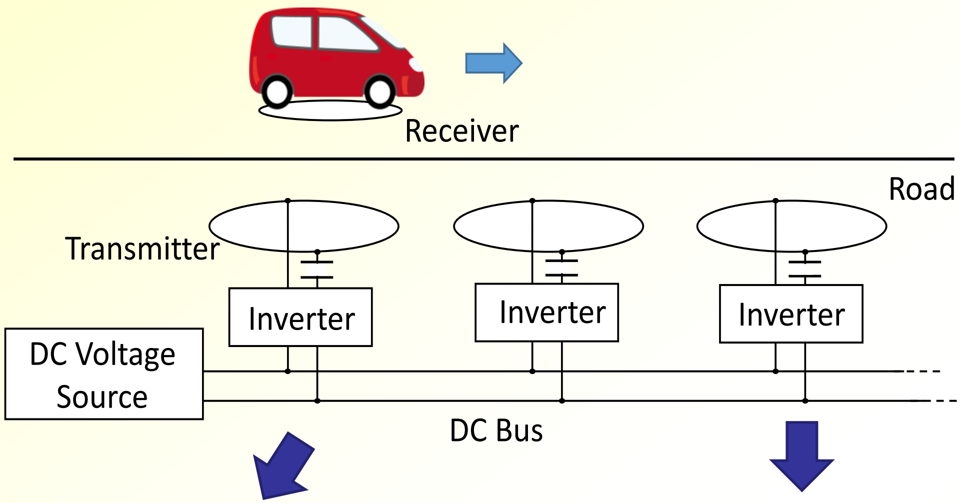
lowest loss

i.e.) S-S



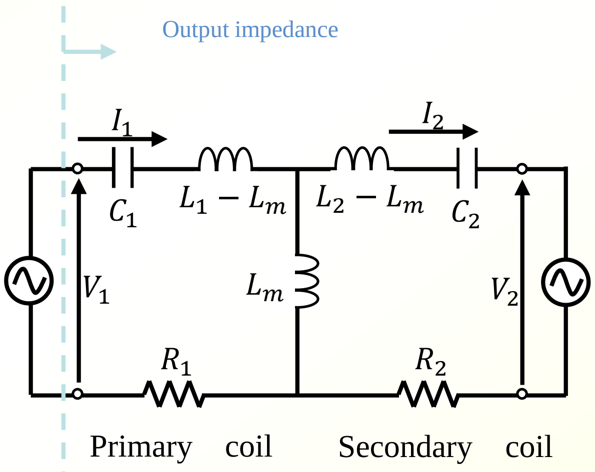
Sensorless Transmitting ON/OFF Switching System

Idea of vehicle detection



High output impedance

Low output impedance



Transmitting current I_1 changes depending on position of a receiver

$$\begin{bmatrix} V_1 \\ jV_2 \end{bmatrix} = \begin{bmatrix} R_1 & -j\omega_0 L_m \\ j\omega_0 L_m & -R_2 \end{bmatrix} \begin{bmatrix} I_1 \\ jI_2 \end{bmatrix}$$

resonance

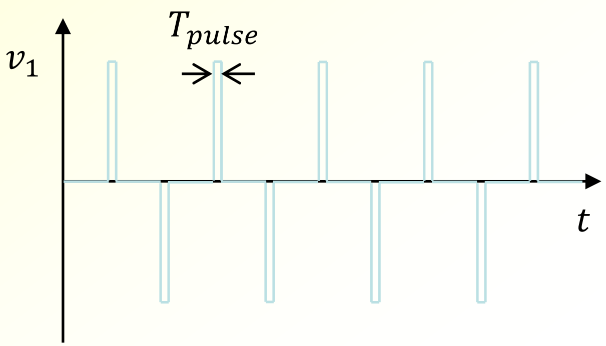
$$I_1 = \frac{R_2 V_1 + \omega_0 L_m V_2}{R_1 R_2 + \omega_0^2 L_m^2}$$

Daita Kobayashi,Katsuhiro Hata,Takehiro Imura,Hiroshi Fujimoto,Yoichi Hori, **Sensorless Vehicle Detection Using Voltage Pulses in Dynamic Wireless Power Transfer System**, *The 29th International Electric Vehicle Symposium and Exhibition*, 2016

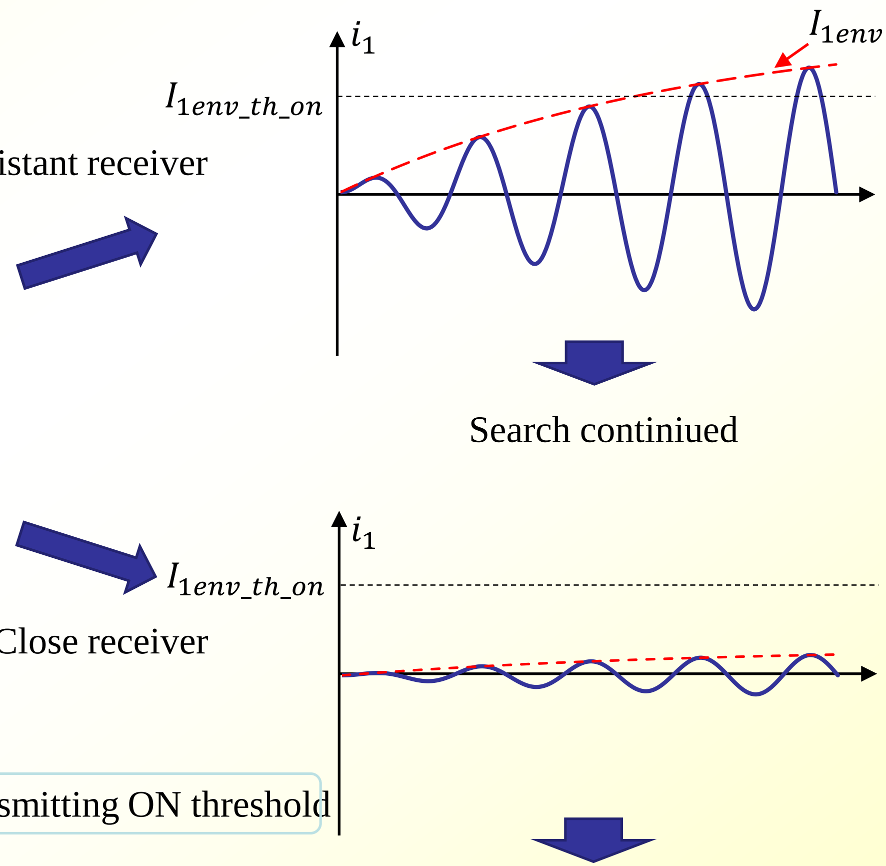
Sensorless Transmitting ON/OFF Switching System

Searching voltage pulses

Envelope of the primary current is used to detect the approach of vehicles



Searching pulse(resonant frequency)



Narrow pulses to reduce standby power

$I_{1env\_th\_on}$: Transmitting ON threshold

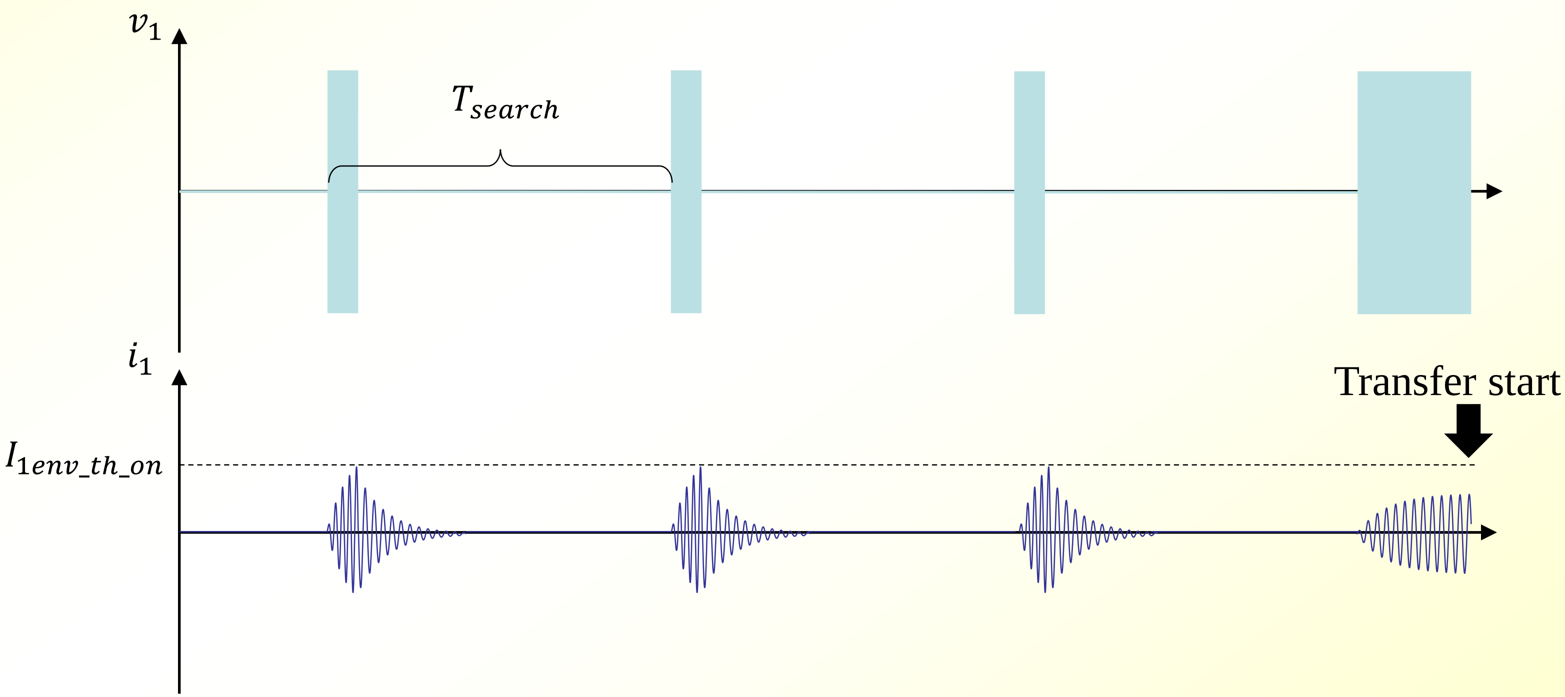
Transmitting start

Daita Kobayashi,Katsuhiro Hata,Takehiro Imura,Hiroshi Fujimoto,Yoichi Hori, **Sensorless Vehicle Detection Using Voltage Pulses in Dynamic Wireless Power Transfer System**, *The 29th International Electric Vehicle Symposium and Exhibition*, 2016

Sensorless Transmitting ON/OFF Switching System

Procedure of the proposed searching method

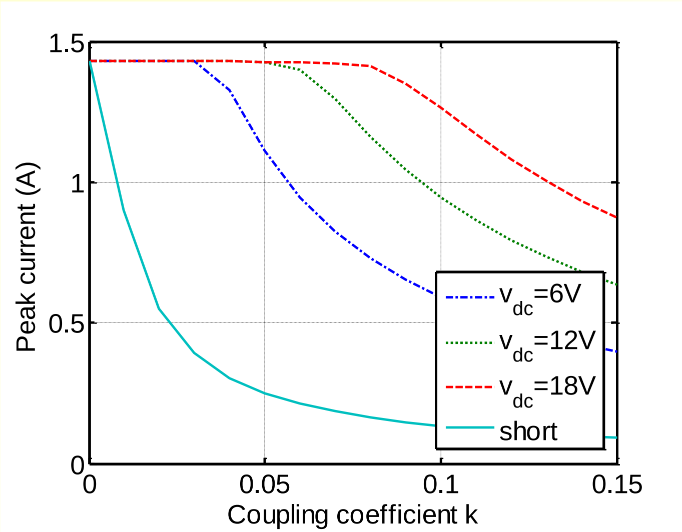
1. Bundles of searching voltages are applied in an interval T_{search}
2. If I_{1env} exceeds $I_{1env\_th\_on}$, searching is stopped and waits until the next period
3. Power transfer starts if I_{1env} does not exceed $I_{1env\_th\_on}$ for certain period



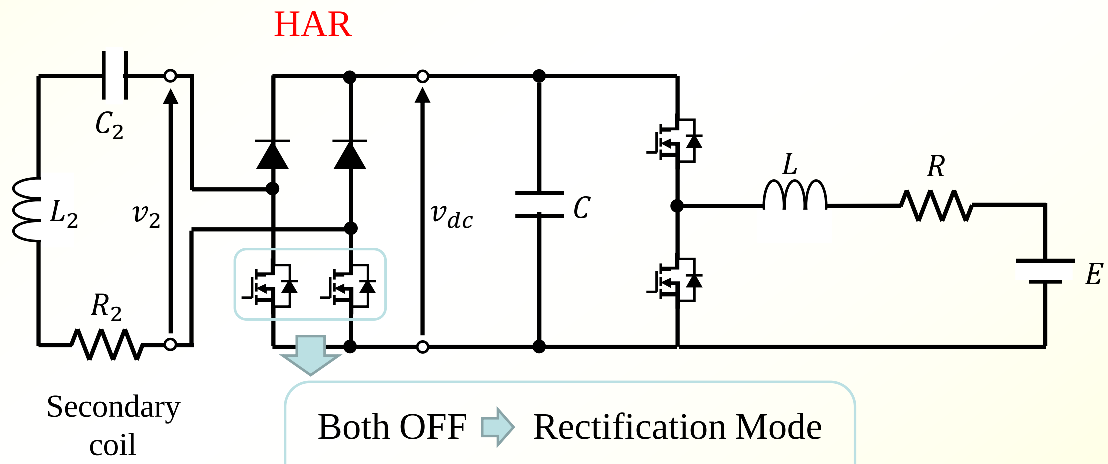
Daita Kobayashi,Katsuhiro Hata,Takehiro Imura,Hiroshi Fujimoto,Yoichi Hori, **Sensorless Vehicle Detection Using Voltage Pulses in Dynamic Wireless Power Transfer System**, *The 29th International Electric Vehicle Symposium and Exhibition*, 2016

Sensorless Transmitting ON/OFF Switching System

Standby method of the secondary circuit (Half Active Rectifier)



Coupling coefficient and the peak value of the primary current
(pulse duty : 0.1, primary voltage : 18 V)



Both OFF ⇨ Rectification Mode

Both ON ⇨ Short Mode

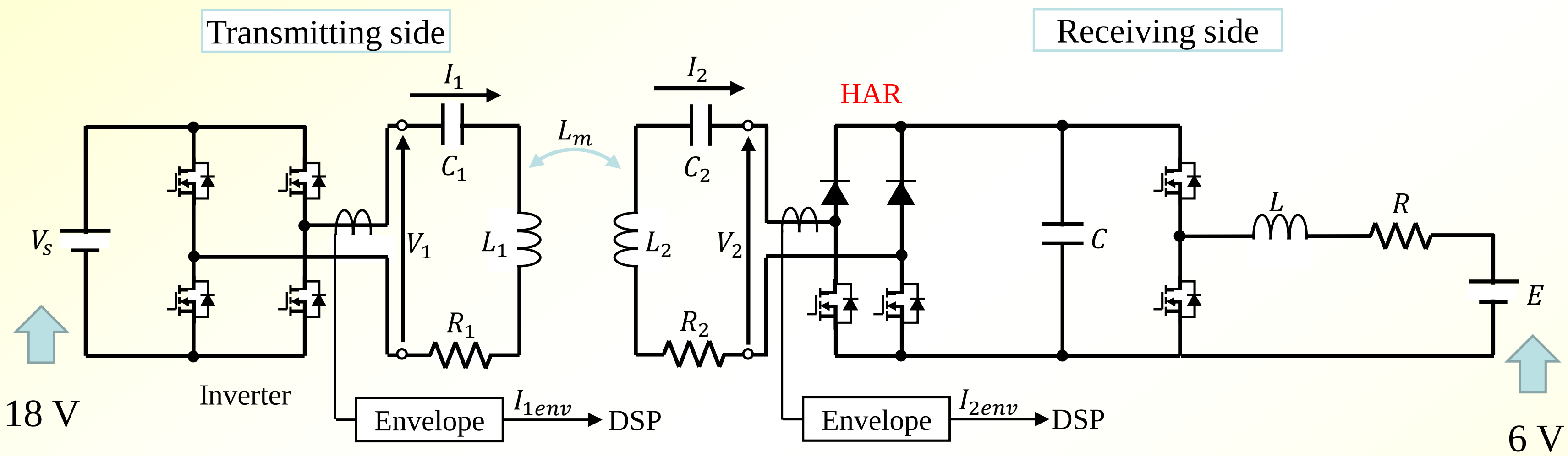
$$I_1 = \frac{R_2 V_1 + \omega_0 L_m V_2}{R_1 R_2 + \omega_0^2 L_m^2}$$

I_1 also depends on V_2

The proposed secondary circuit (Half active rectifier : HAR) turns on two MOSFET and short the circuit (V_2 = 0) during standby mode (Short mode).

Experiment

Experiment



	Primary coil	Secondary coil
L	417.1 μH	208.5 μH
C	6.03 nF	12.15 nF
R	1.83 Ω	1.28 Ω

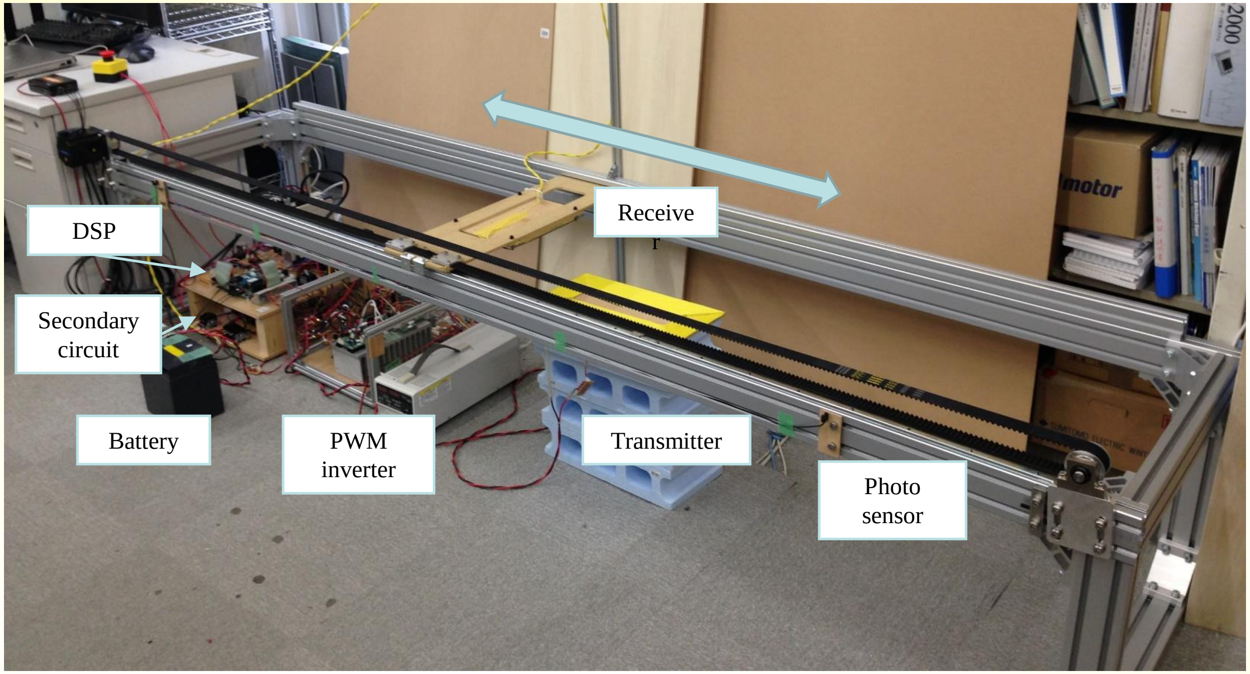
Parameters	Meaning	Value
T_{search}	Searching period	10 ms
T_{pulse}	Pulse width	0.5 μs
$I_{1env\_th\_on}$	ON threshold current	300 mA
$I_{1env\_diff\_th}$	OFF threshold differentiated current	-4000 A/s
k_{off}	OFF threshold coupling coefficient	0.06

Operating frequency : 100 kHz
DC/DC converter frequency : 10 kHz

DC voltage source :18 V
Battery voltage : 6 V

Experiment

1/3 scale DWPT simulation setup



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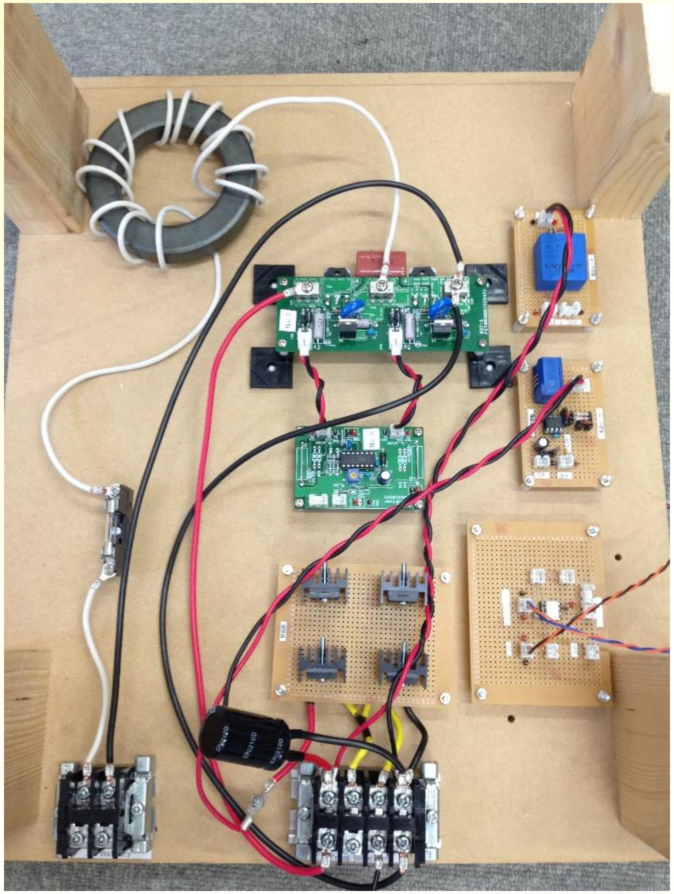
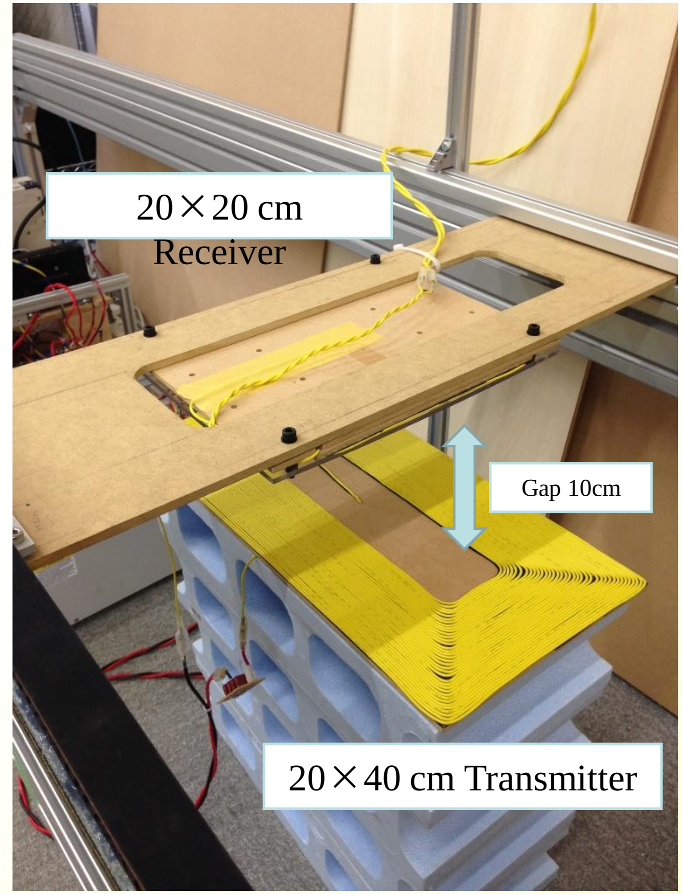


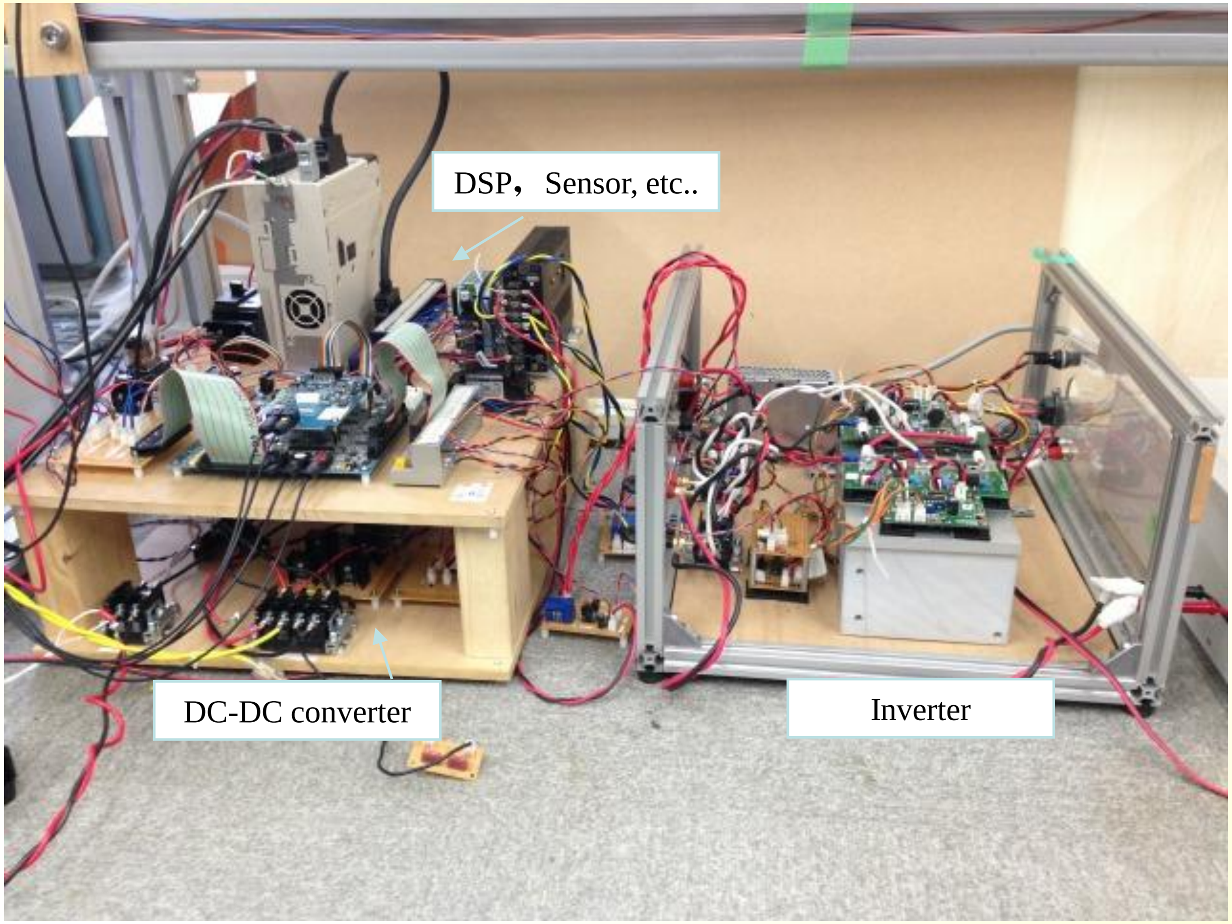
DC/DC converter



Receiver and Transmitter

Daita Kobayashi,Katsuhiro Hata,Takehiro Imura,Hiroshi Fujimoto,Yoichi Hori, **Sensorless Vehicle Detection Using Voltage Pulses in Dynamic Wireless Power Transfer System**, *The 29th International Electric Vehicle Symposium and Exhibition*, 2016

Experiment

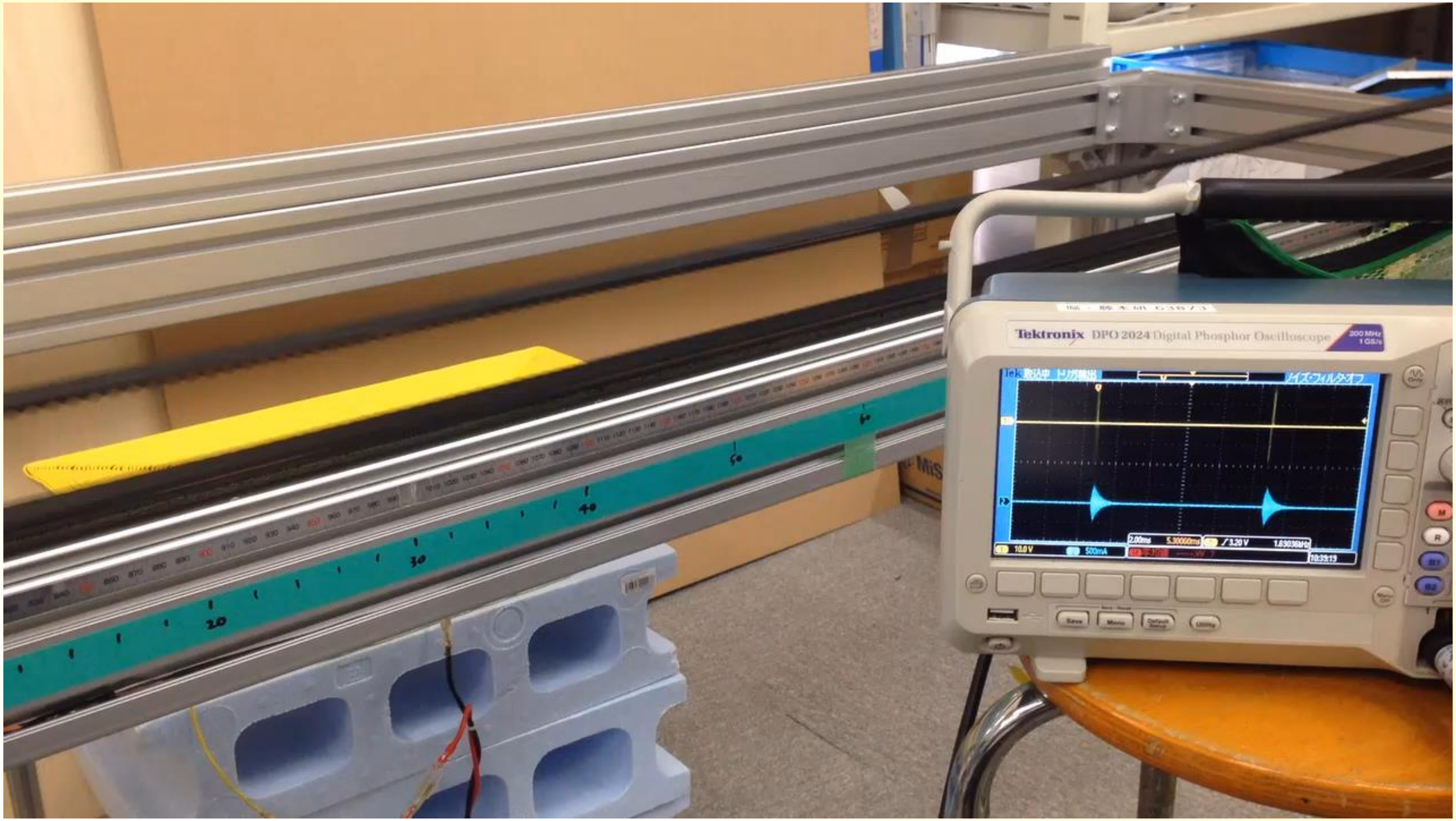


Primary Inverter, DC/DC converter, Controller

Daita Kobayashi,Katsuhiro Hata,Takehiro Imura,Hiroshi Fujimoto,Yoichi Hori, **Sensorless Vehicle Detection Using Voltage Pulses in Dynamic Wireless Power Transfer System**, *The 29th International Electric Vehicle Symposium and Exhibition*, 2016

Experiment

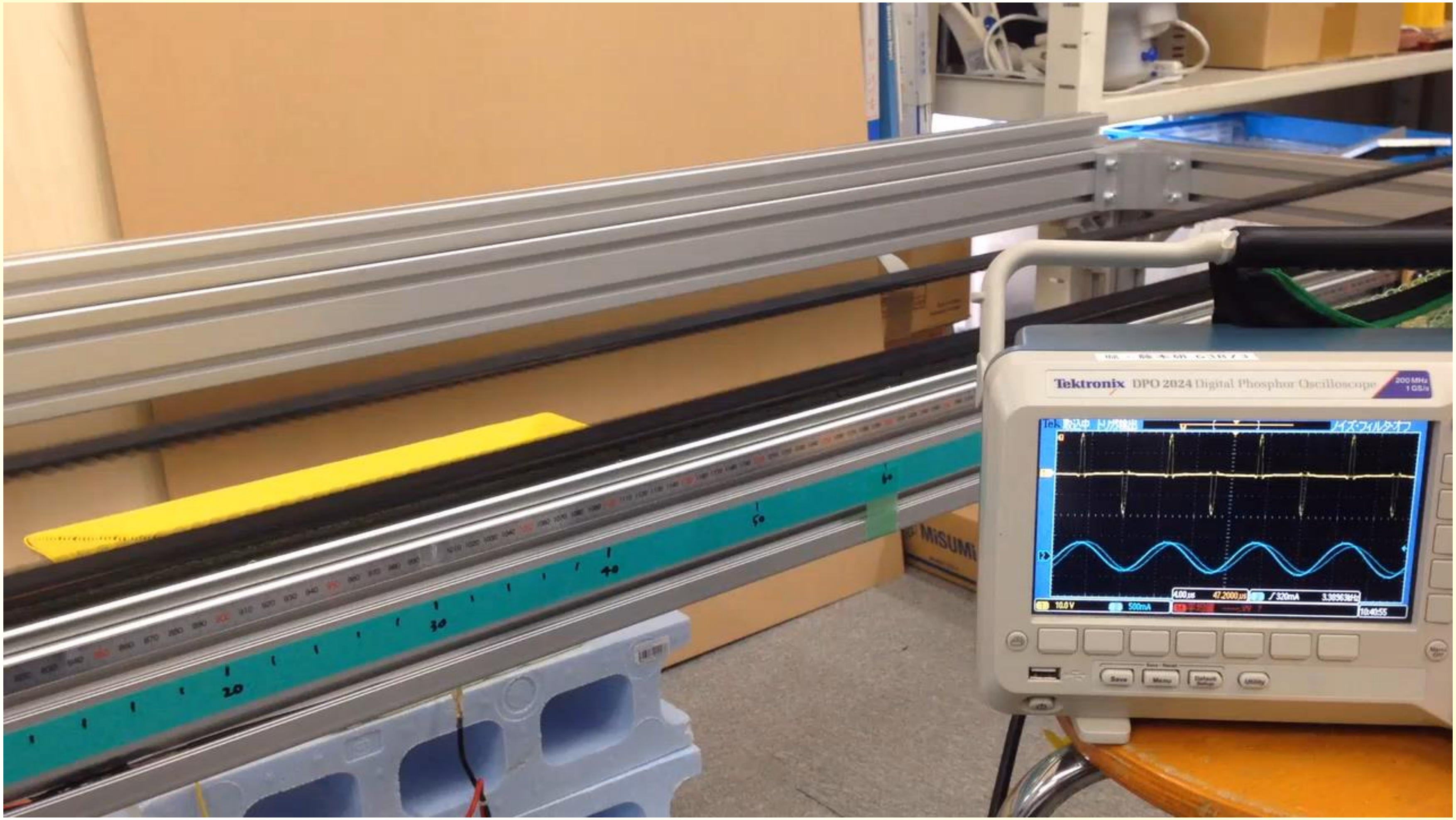
☐ Experimental movie



:primary voltage v_1 : primary current i_1

Experiment

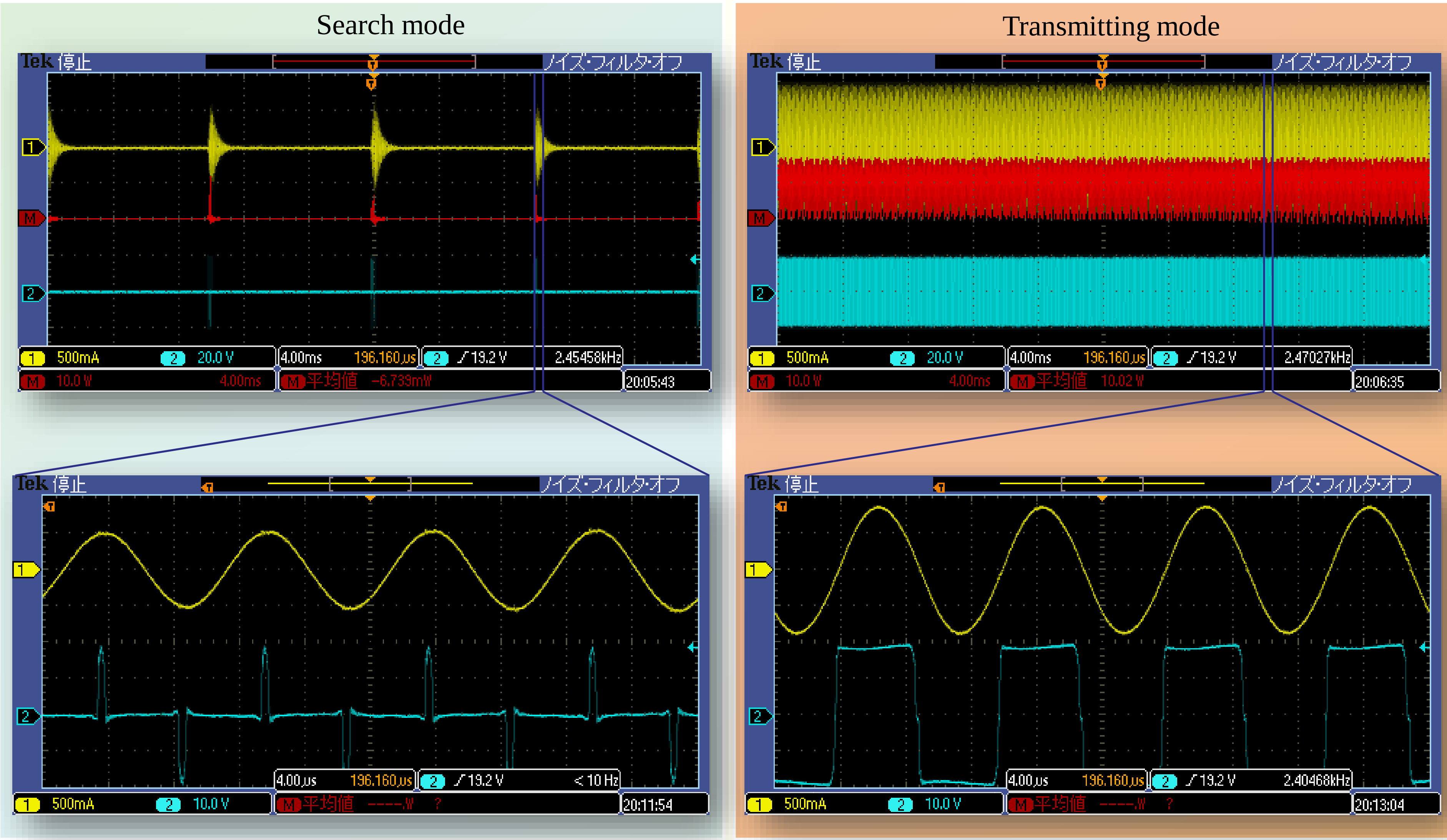
☐ Experimental movie



:primary voltage v_1 : primary current i_1

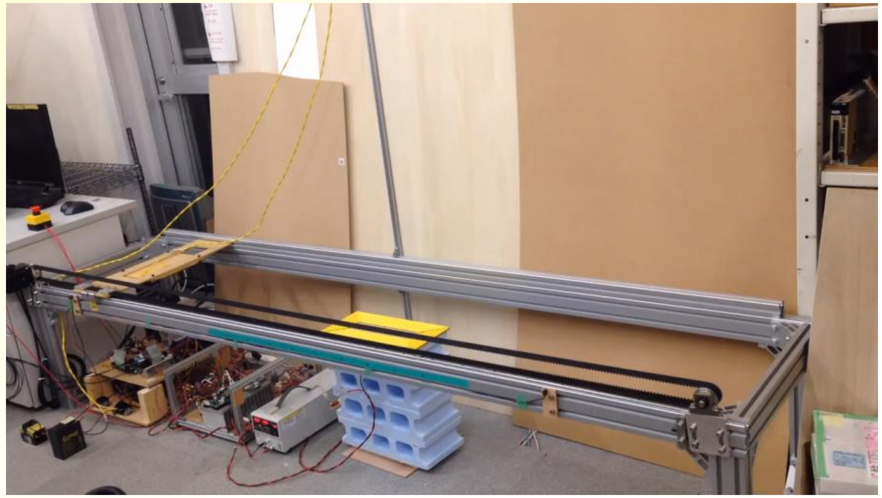
Experiment

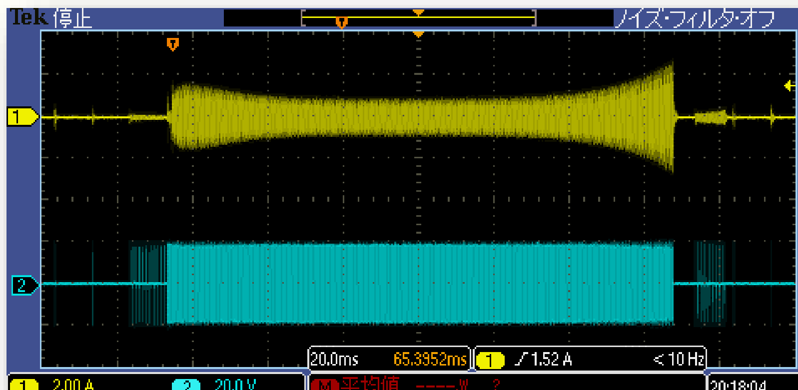
☐ Voltage and current wave form



:primary voltage v_1 : primary current i_1

Experiment





:primary voltage v_1 : primary current i_1

Power transfer automatically switches ON/OFF while 10 km/h driving

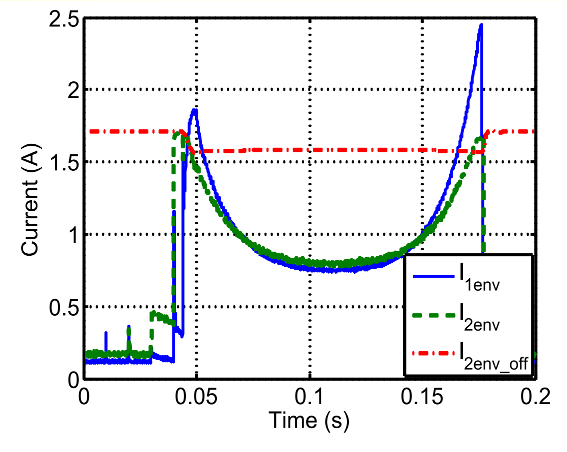
Daita Kobayashi,Katsuhiro Hata,Takehiro Imura,Hiroshi Fujimoto,Yoichi Hori, **Sensorless Vehicle Detection Using Voltage Pulses in Dynamic Wireless Power Transfer System**, *The 29th International Electric Vehicle Symposium and Exhibition*, 2016

Experiment

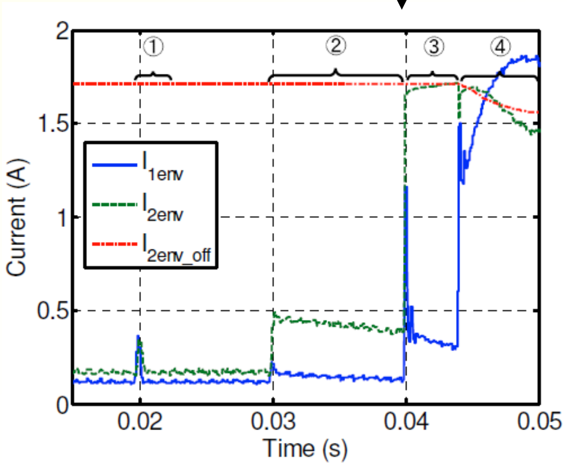
Start

WPT start

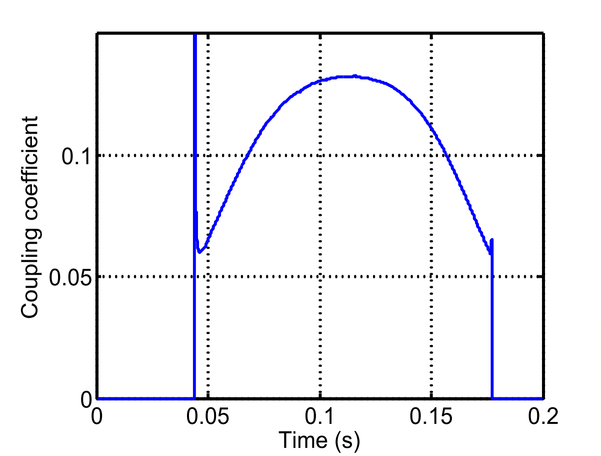
□ 10 km/h



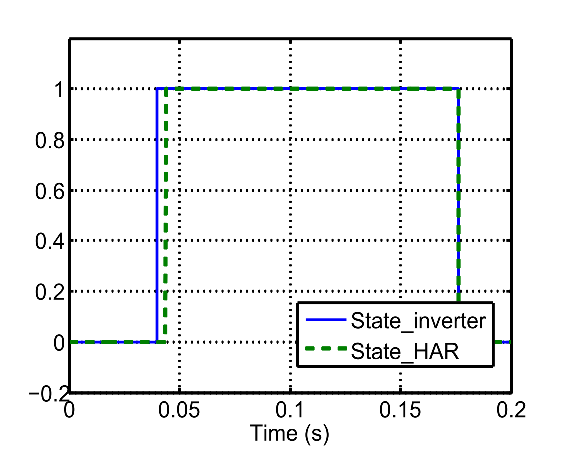
Primary and secondary current



$I_{1env}, I_{2env}, I_{2\_env\_off}$
(at transfer start)



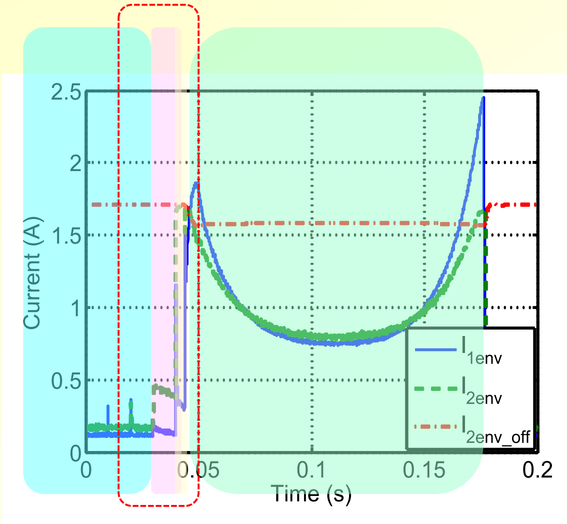
Coupling coefficient (estimated)



Inverter, HAR flags(1 : ON)

Power was successfully transferred only when the two coils are close enough ($k > 0.06$).

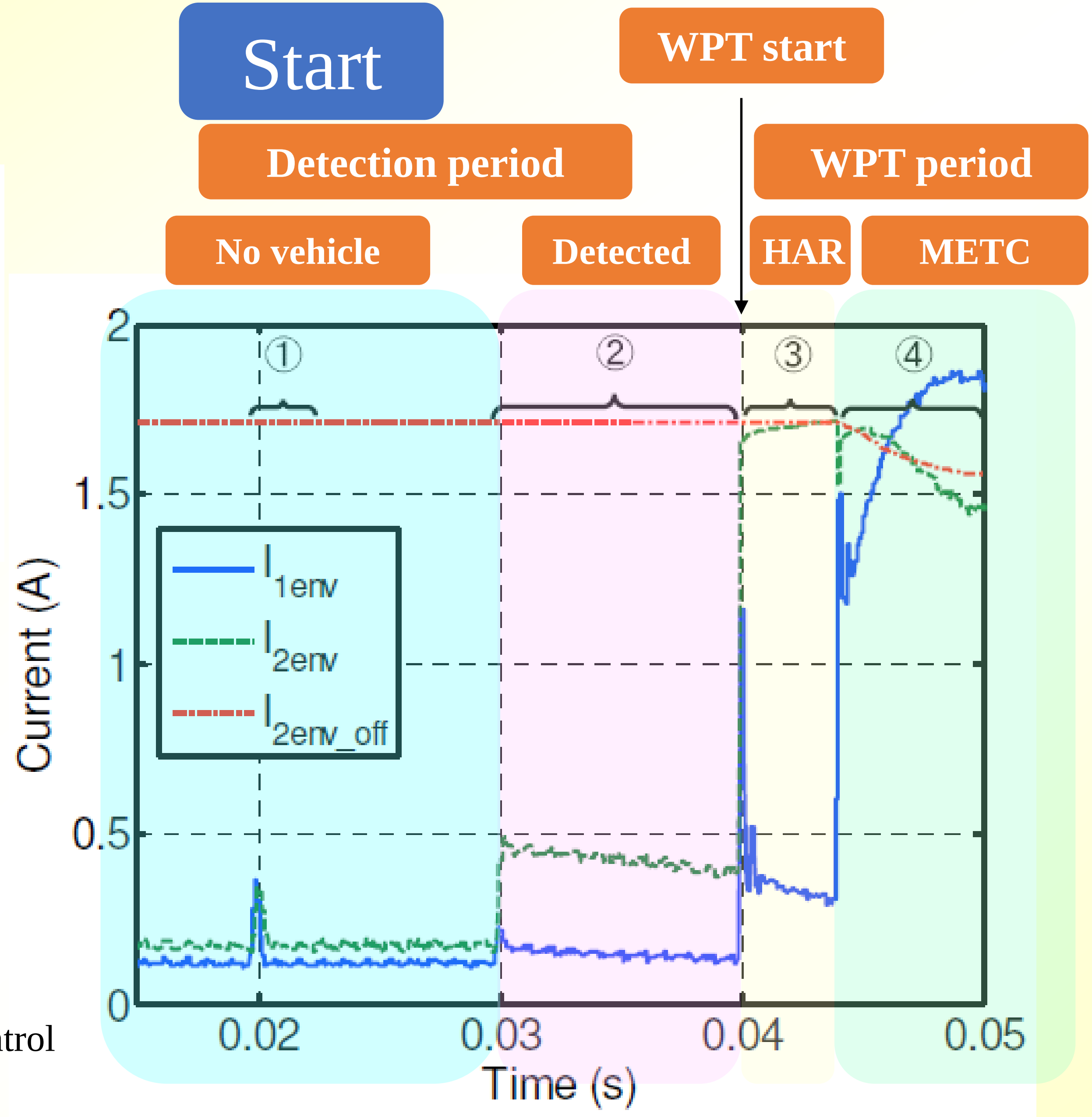
Experiment



Primary and secondary current

HAR: Half Active Rectifier

METC:
Maximum Efficient Tracking Control



$I_{1env}, I_{2env}, I_{2\_env\_off}$ (at transfer start)

Experiment

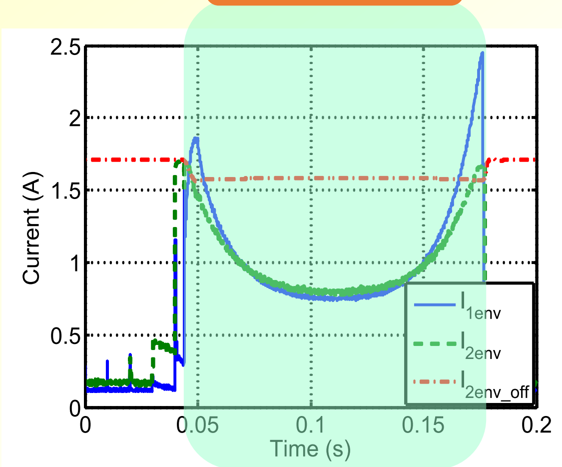
WPT period

METC

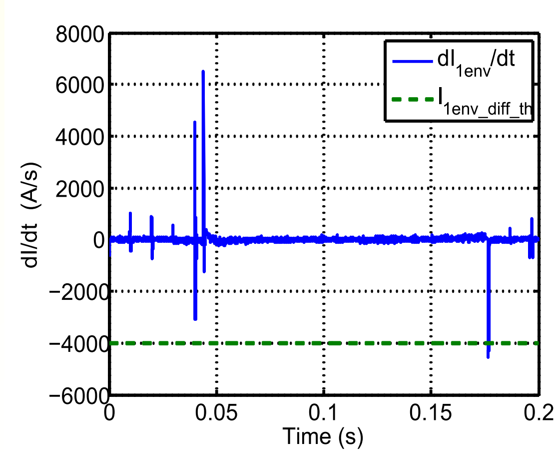
End

10 km/h

METC:
Maximum efficiency tracking control

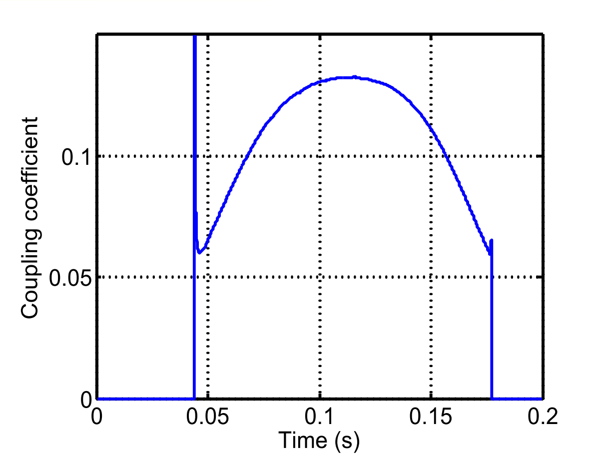


Primary and secondary current

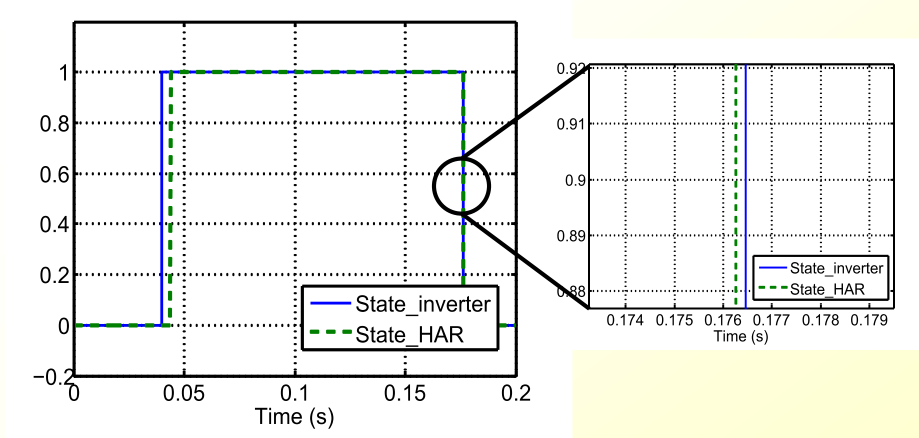


$\frac{d\, I_{1\_env}}{dt}$ (cutoff=100kHz)

0.2ms



Coupling coefficient (estimated)

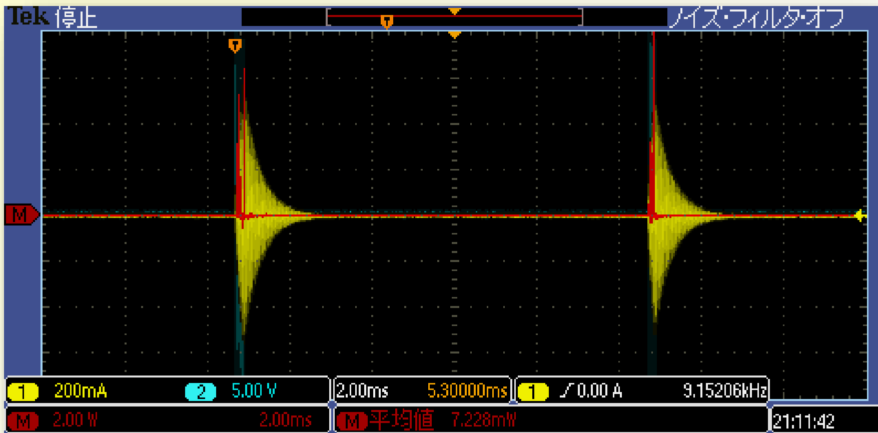


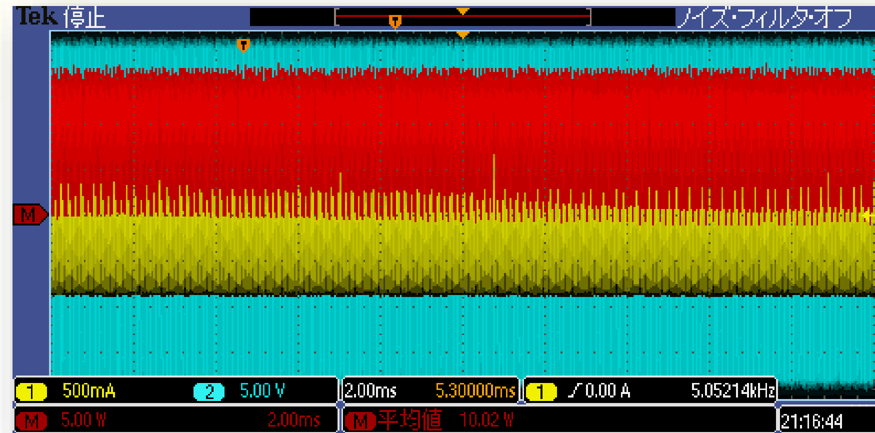
Inverter, HAR flags(1 : ON)

Power was successfully transferred only when the two coils are close enough ($k > 0.06$).

Experiment

☐ standby power





Search mode

Transmitting mode

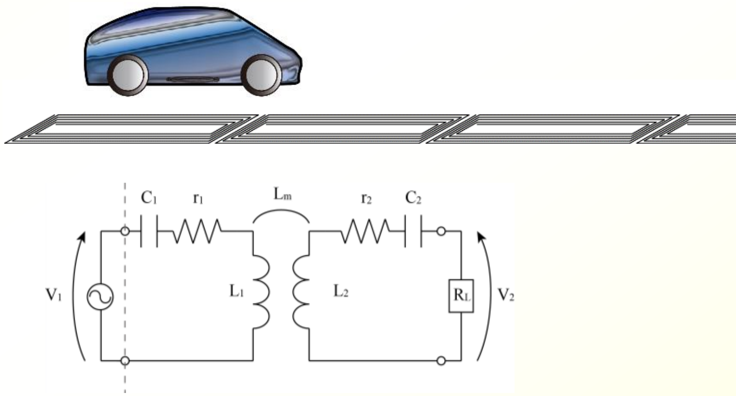
Average power 7.228 mW

Average power 10.02 W

Average power consumption in search mode is less than 1/1000 of transmitting mode

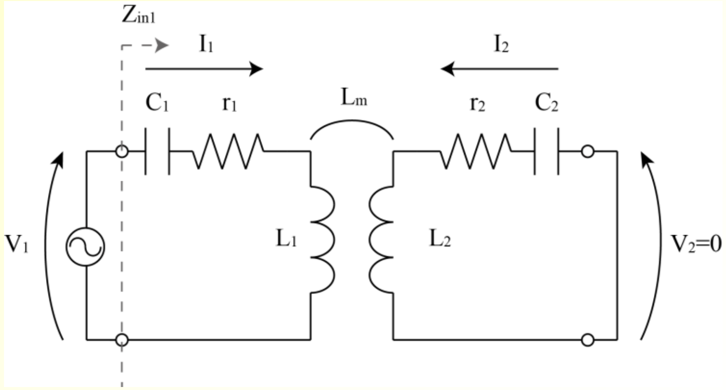
Daita Kobayashi,Katsuhiro Hata,Takehiro Imura,Hiroshi Fujimoto,Yoichi Hori, **Sensorless Vehicle Detection Using Voltage Pulses in Dynamic Wireless Power Transfer System**, *The 29th International Electric Vehicle Symposium and Exhibition*, 2016

Overview of our system

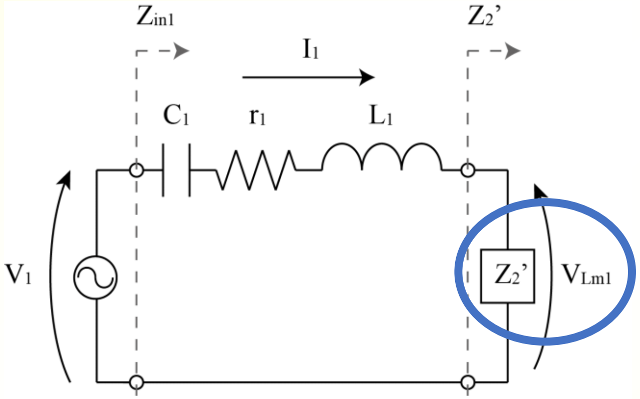


- Coil type
- Open type coil
  (capacitor-less and ferrite-less)
- S-S: series-series
- Sensorless detection (primary) — detection
- Power control by HAR (secondary) — control A type
- Maximum efficiency tracking (secondary) — control B type
- Simultaneous power and maximum efficiency tracking control (secondary) — control C type
- Power off (primary) — power off
- Automatic driving using coil sensing

HAR: half active rectifier



short



$$Z_2^{'} = \frac{(\omega L_m)^2}{r_2} \fallingdotseq \infty$$

$I_1 \fallingdotseq 0$

$P_1 \fallingdotseq 0$

Power shut down, $P_1 \fallingdotseq 0$

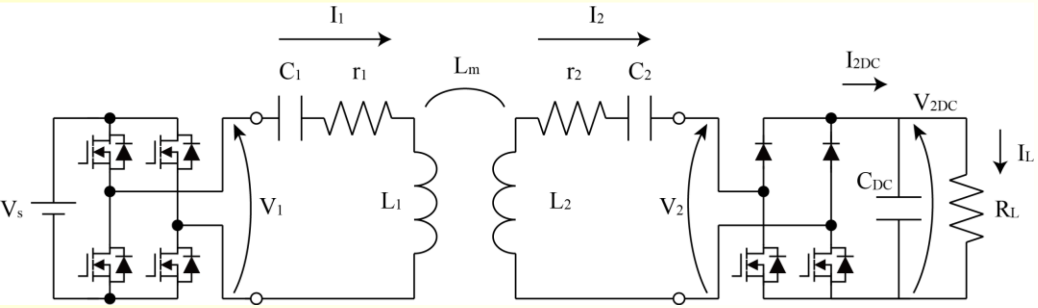
secondary side voltage control

stability of secondary

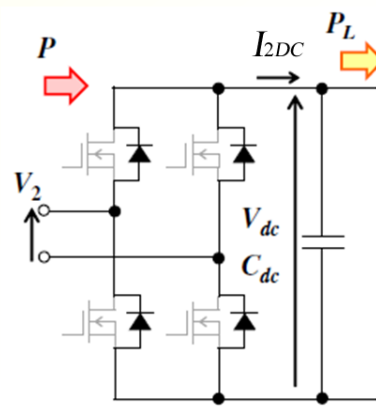
power control by secondary

efficiency control by secondary

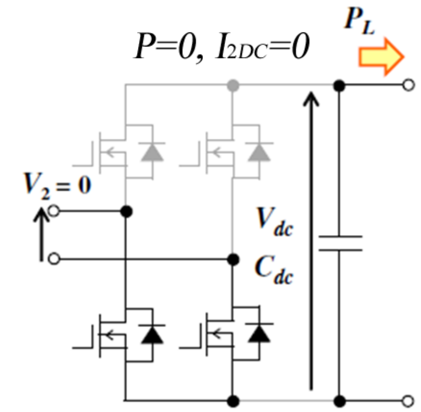
HAR: half active rectifier



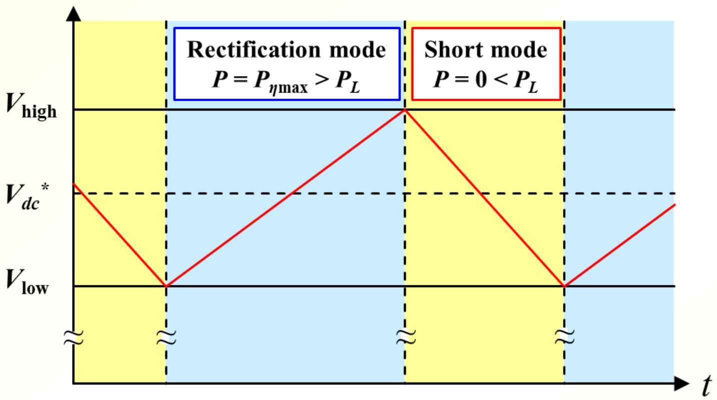
$$V_{\text{high}} = {V_{dc}}^* + \Delta V$$
$$V_{\text{low}} = {V_{dc}}^* - \Delta V$$



rectification mode



short mode



Power shut down, $P_1 \fallingdotseq 0$

secondary side voltage control

stability of secondary

power control by secondary

efficiency control by secondary

Overview of our system

Coil type

Open type coil
(capacitor-less and ferrite-less)

S-S: series-series

Sensorless detection (primary)

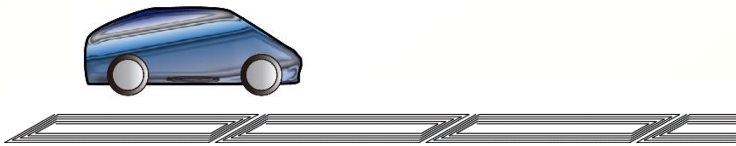
Power control by HAR (secondary)

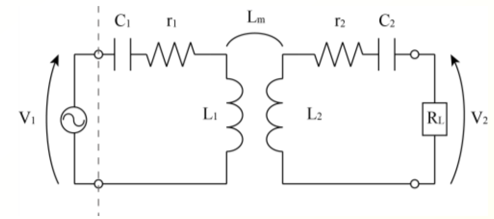
Maximum efficiency tracking (secondary)

Simultaneous power and maximum efficiency tracking control (secondary)

Power off (primary)

Automatic driving using coil sensing





detection

control A type

control B type

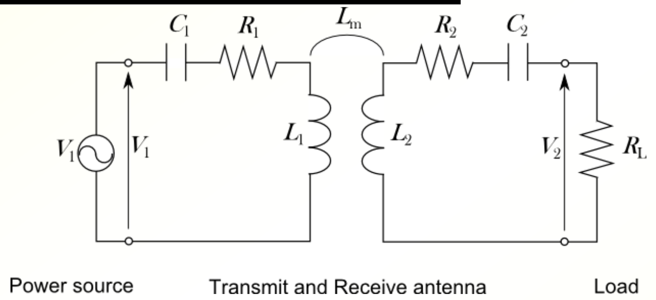
control C type

power off

Maximum efficiency tracking

Maximum-efficiency load

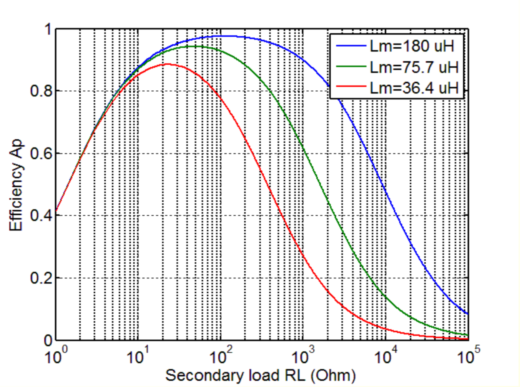
There is a maximum-efficiency load $R_{L\eta max}$
on the circuit of magnetic resonance coupling



Equivalent circuit of magnetic resonant coupling

Efficiency $\eta = \dfrac{\left(\omega_0 k\sqrt{L_1 L_2}\right)^2 R_L}{(R_L + R_2)\left\{R_1 R_L + R_1 R_2 + \left(\omega_0 k\sqrt{L_1 L_2}\right)^2\right\}}$

$$R_{L\eta max} = \sqrt{R_2\left(\frac{\left(\omega_0 k\sqrt{L_1 L_2}\right)^2}{R_1} + R_2\right)}$$



Relationship between load R_L and efficiency η

Optimal Secondary side structure

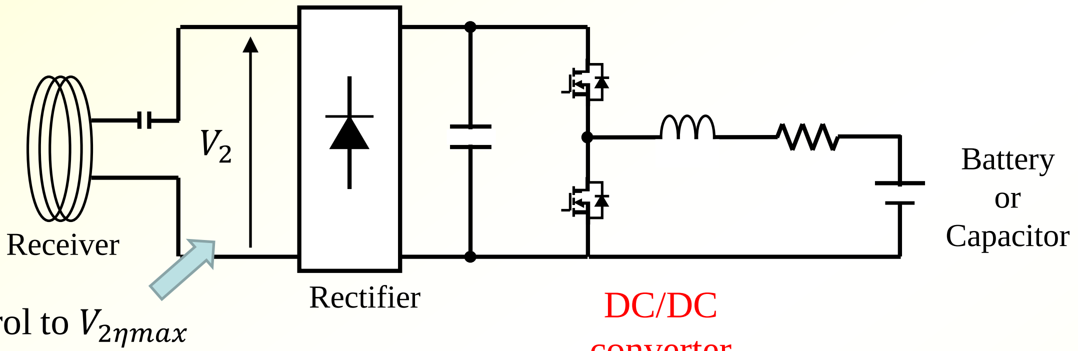
- Controllable secondary side

Normally, secondary storage system determines secondary equivalent load

Need of controllable secondary side to change the secondary equivalent load to $R_{L\eta max}$

Maximum efficiency tracking

- Maximum efficiency control with secondary DC/DC converter



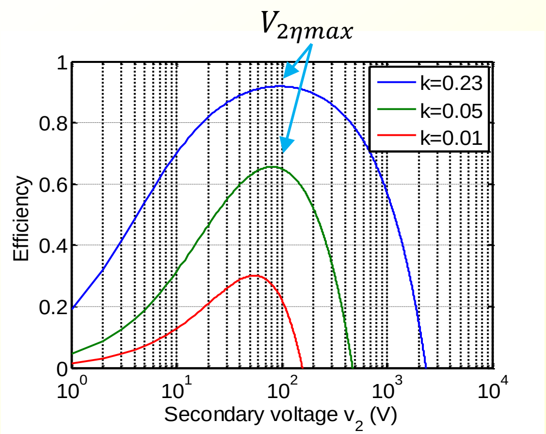
Secondary DC/DC converter controls secondary equivalent load to $R_{L\eta max}$ by controlling V_2

Maximum-efficiency load

$$R_{L\eta max} = \sqrt{R_2 \left(\frac{(\omega_0 k \sqrt{L_1 L_2})^2}{R_1} + R_2 \right)}$$

KVL equation

Maximum-efficiency voltage $V_{2\eta max} = \sqrt{\frac{R_2}{R_1}} \frac{\omega_0 k \sqrt{L_1 L_2}}{\sqrt{R_1 R_2 + (\omega_0 k)^2 L_1 L_2} + \sqrt{R_1 R_2}} V_1$



Relationship between V_2 and efficiency η ($V_1 = 100$ V)

Proposed method

Real-time maximum efficiency control for dynamic wireless power transfer system

Maximum efficiency tracking

Real-time coupling coefficient estimation

$$V_{2\eta max} = \sqrt{\frac{R_2}{R_1}} \frac{\omega_0 k \sqrt{L_1 L_2}}{\sqrt{R_1 R_2 + (\omega_0 k)^2 L_1 L_2} + \sqrt{R_1 R_2}} V_1$$

Need of information of **coupling coefficient *k*** to calculate $V_{2\eta max}$

However..

k is not directly measurable

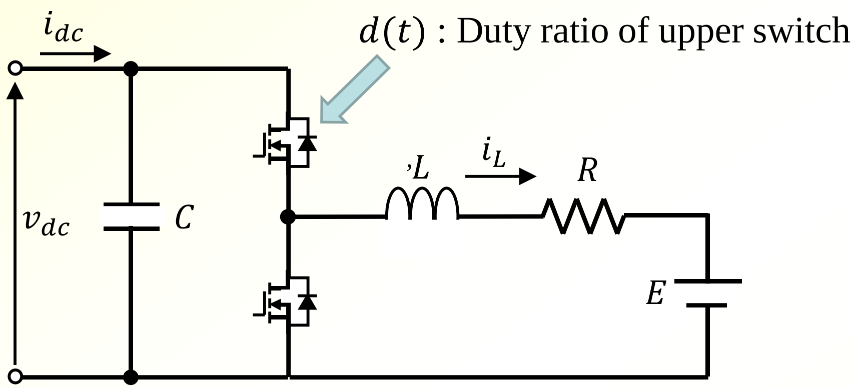
- k estimation only with secondary (EVs') information
  no communication between sides
- k estimation online because k drastically changes in DWPT system.

Real-time k estimation from V_2, I_2

Daita Kobayashi, Takehiro Imura, Yoich Hori, **Real-time Coupling Coefficient Estimation and Maximum Efficiency Control on Dynamic Wireless Power Transfer Using Secondary DC-DC converter**, *41st Annual Conference of the IEEE Industrial Electronics Society* , pp. 4650-4655, 2015

Maximum efficiency tracking

Modeling and control of DC/DC converter with state space averaging method



State space model of DC/DC converter

$$\frac{d}{dt}\boldsymbol{x}(t) = \boldsymbol{A}(d(t))\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t) \qquad v_{dc}(t) = \boldsymbol{c}\boldsymbol{x}(t)$$

$$\boldsymbol{A} = \begin{bmatrix} -\dfrac{R}{L} & \dfrac{d(t)}{L} \\ -\dfrac{d(t)}{C} & 0 \end{bmatrix} \quad \boldsymbol{B} = \begin{bmatrix} -\dfrac{1}{L} & 0 \\ 0 & -\dfrac{1}{C} \end{bmatrix} \quad \boldsymbol{c} = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad \boldsymbol{x}(t) = \begin{bmatrix} i_L(t) \\ v_{dc}(t) \end{bmatrix} \quad \boldsymbol{u}(t) = \begin{bmatrix} E \\ i_{dc}(t) \end{bmatrix}$$

This non-linear model is linearized with a equilibrium point and a small signal model around the point

Daita Kobayashi, Takehiro Imura, Yoich Hori, **Real-time Coupling Coefficient Estimation and Maximum Efficiency Control on Dynamic Wireless Power Transfer Using Secondary DC-DC converter**, *41st Annual Conference of the IEEE Industrial Electronics Society* , pp. 4650-4655, 2015

Maximum efficiency tracking

Linearization of a state space model

At an equilibrium point, $0 = \boldsymbol{A}(d(t))\boldsymbol{x}(t) + \boldsymbol{B}\boldsymbol{u}(t)$ (V_{dc}, I_{dc}, I_L, D : stady state values of v_{dc}, i_{dc}, i_L, d)

$$\Rightarrow \quad V_{dc} = \frac{ED + RI_{dc}}{D^2} \qquad I_L = \frac{I_{dc}}{D} \quad \Rightarrow \quad D = \frac{E + \sqrt{E^2 - 4RV_{dc}I_{dc}}}{2V_{dc}}$$

I_{dc} is determined by WPT characteristics,

$$I_{dc} = \frac{8}{\pi^2}\frac{\omega_0 k\sqrt{L_1L_2}V_s - R_1V_{dc}}{R_1R_2 + (\omega_0 k)^2 L_1L_2} \quad \Rightarrow$$

D at an equilibrium point (maximum efficiency control)

$$D = \frac{E + \sqrt{E^2 - 4RV_{dc\eta\max} I_{dc}\big|_{V_{dc}=V_{dc\eta\max}}}}{2V_{dc\eta\max}}$$

$$\Downarrow$$

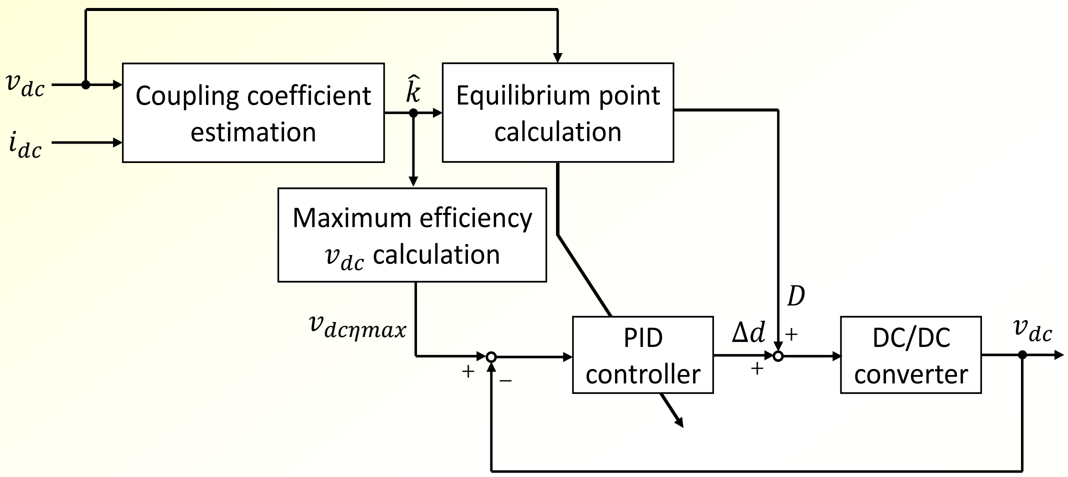
Small signal model

$$\frac{d}{dt}\Delta\boldsymbol{x}(t) = \Delta\boldsymbol{A}\Delta\boldsymbol{x}(t) + \Delta\boldsymbol{B}\Delta\boldsymbol{u}(t) \qquad \Delta v_{dc}(t) = \Delta\boldsymbol{c}\Delta\boldsymbol{x}(t)$$

$$\Delta\boldsymbol{A} = \begin{bmatrix} -\frac{R}{L} & \frac{D}{L} \\ -\frac{D}{C} & -\frac{8}{\pi^2}\frac{R_1}{C\left(R_1R_2 + (\omega_0 k)^2 L_1L_2\right)} \end{bmatrix} \quad \Delta\boldsymbol{c} = \begin{bmatrix} 0 & 1 \end{bmatrix} \quad \Delta\boldsymbol{B} = \begin{bmatrix} \frac{V_{dc}}{L} \\ -\frac{I_L}{C} \end{bmatrix} \quad \Delta\boldsymbol{x}(t) = \begin{bmatrix} \Delta i_L(t) \\ \Delta v_{dc}(t) \end{bmatrix} \quad \Delta\boldsymbol{u} = \Delta d(t)$$

Daita Kobayashi, Takehiro Imura, Yoich Hori, **Real-time Coupling Coefficient Estimation and Maximum Efficiency Control on Dynamic Wireless Power Transfer Using Secondary DC-DC converter**, *41st Annual Conference of the IEEE Industrial Electronics Society* , pp. 4650-4655, 2015

Maximum efficiency tracking



Block diagram of *k* estimation and maximum efficiency control

$\Delta d(s) \rightarrow \Delta v_{dc}(s)$

$$\frac{\Delta v_{dc}}{\Delta d} = \frac{b_1 s + b_0}{s^2 + a_1 s + a_0}$$

$$a_0 = \frac{1}{LC}\left\{D^2 + \frac{8}{\pi^2}\frac{R_1}{R_1 R_2 + (\omega_0 k)^2 L_1 L_2}\right\} \qquad b_0 = -\frac{R I_L + D V_{dc}}{LC}$$

$$a_1 = \frac{R}{L} + \frac{8}{\pi^2}\frac{R_1}{C\{R_1 R_2 + (\omega_0 k)^2 L_1 L_2\}} \qquad b_1 = -\frac{I_L}{C}$$

Designing a PID controller through pole placement

$$C_{PID}(s) = K_P + \frac{K_I}{s} + \frac{K_D s}{\tau_D s + 1}$$

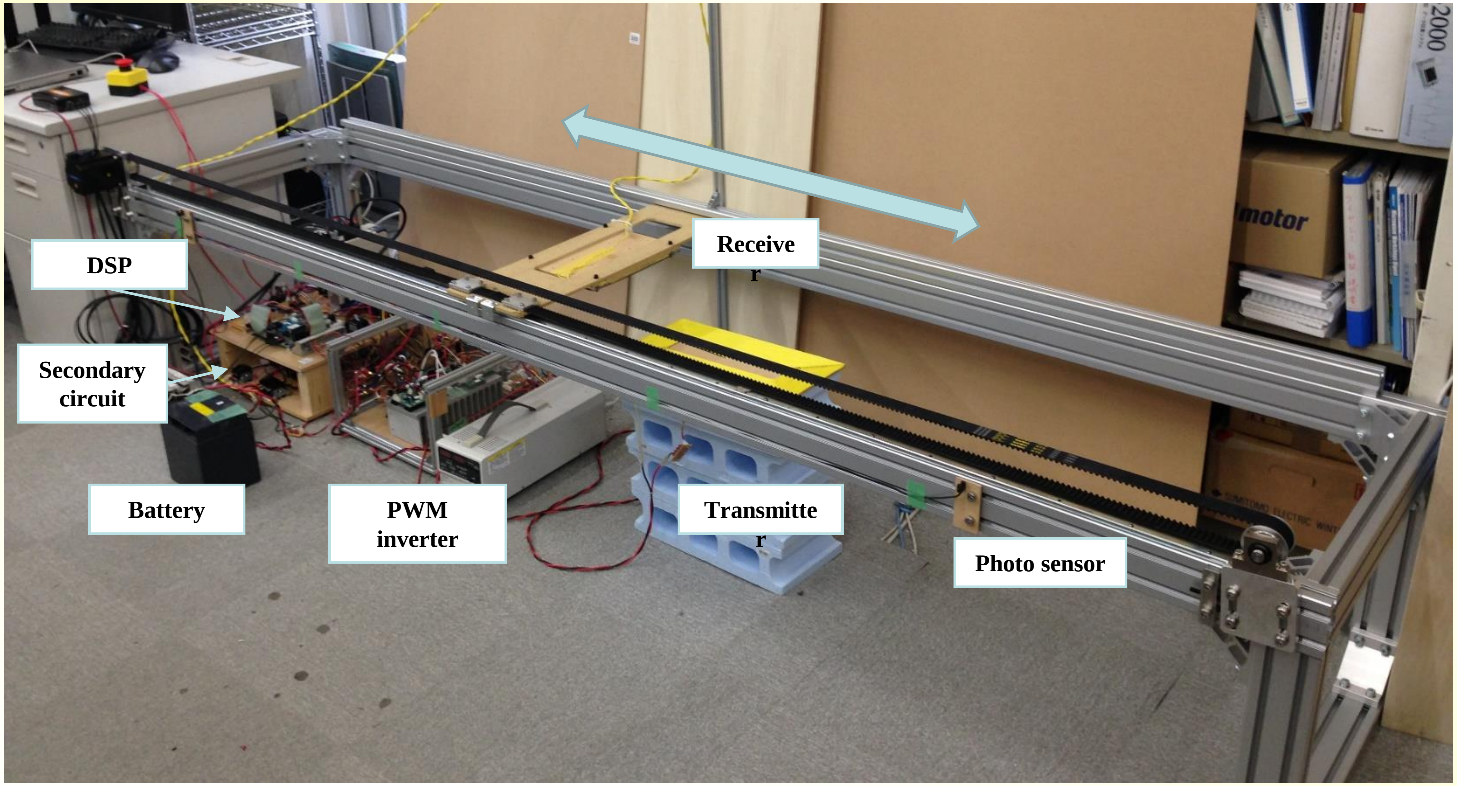
Tustin transformation & Implementation

Daita Kobayashi, Takehiro Imura, Yoich Hori, **Real-time Coupling Coefficient Estimation and Maximum Efficiency Control on Dynamic Wireless Power Transfer Using Secondary DC-DC converter**, *41st Annual Conference of the IEEE Industrial Electronics Society* , pp. 4650-4655, 2015

Maximum efficiency tracking

Experimental setup

1/3 scale DWPT simulation setup



	Primary coil	Secondary coil
L	417.1 μH	208.5 μH
C	6.03 nF	12.15 nF
R	1.83 Ω	1.28 Ω

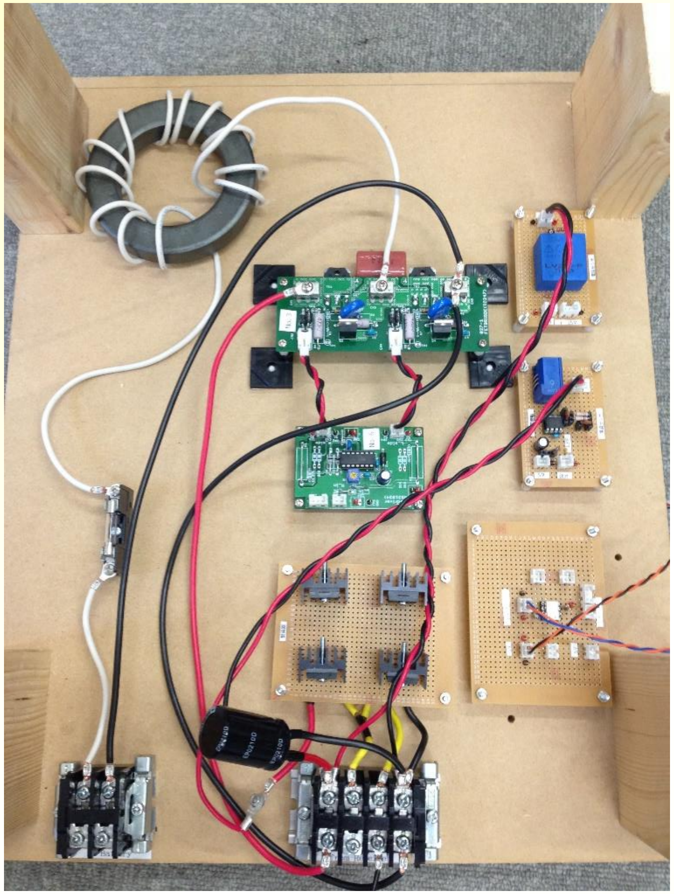
	DC-DC converter
L	1000 μH
C	1000 μF
R	0.2 Ω

Operating frequency : 100 kHz
DC/DC converter frequency : 10 kHz

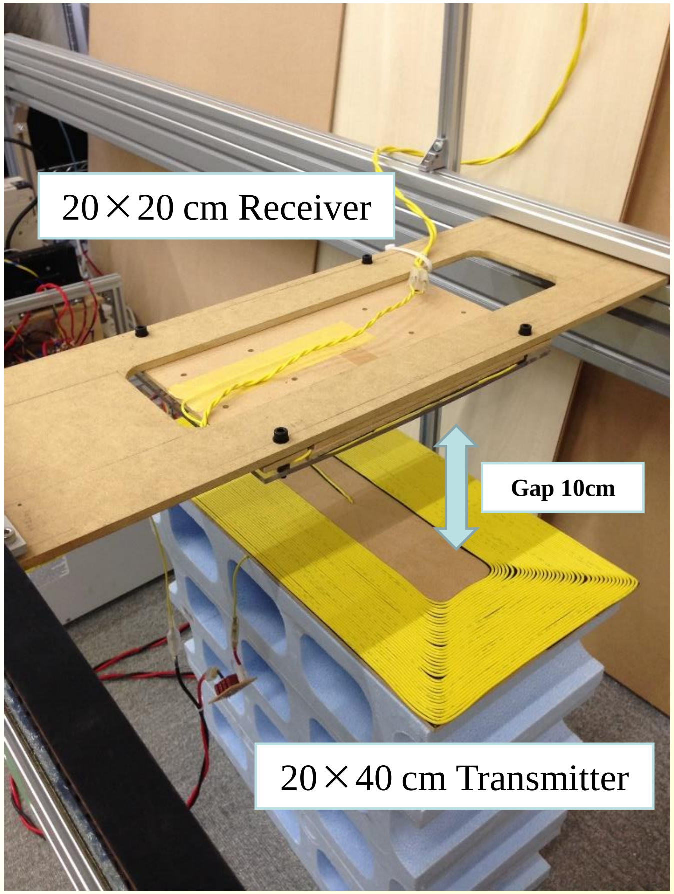
DC voltage source :18 V
Battery voltage : 6 V

Maximum efficiency tracking

Experimental setup



DC/DC converter

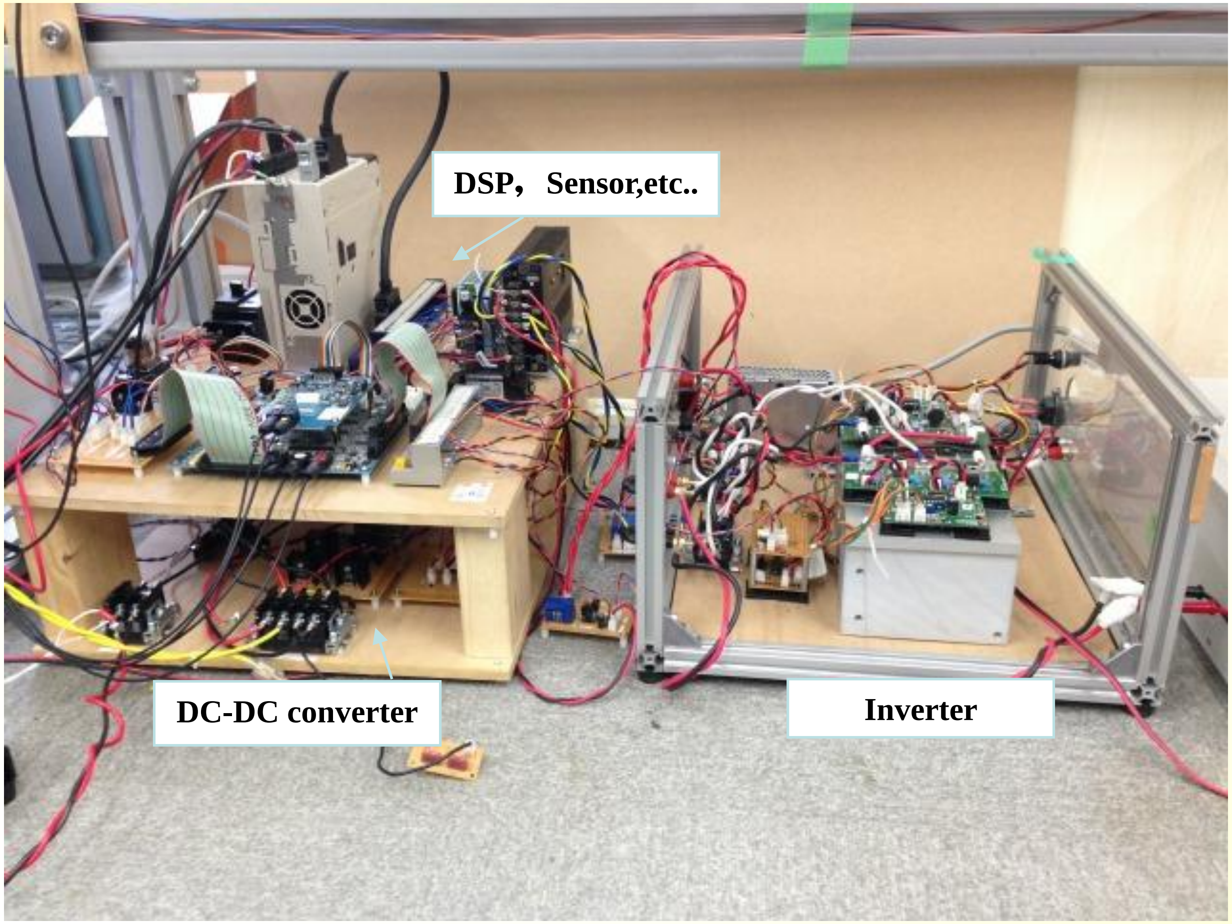


Receiver and Transmitter

Daita Kobayashi, Takehiro Imura, Yoich Hori, **Real-time Coupling Coefficient Estimation and Maximum Efficiency Control on Dynamic Wireless Power Transfer Using Secondary DC-DC converter**, *41st Annual Conference of the IEEE Industrial Electronics Society* , pp. 4650-4655, 2015

Maximum efficiency tracking

Experimental setup

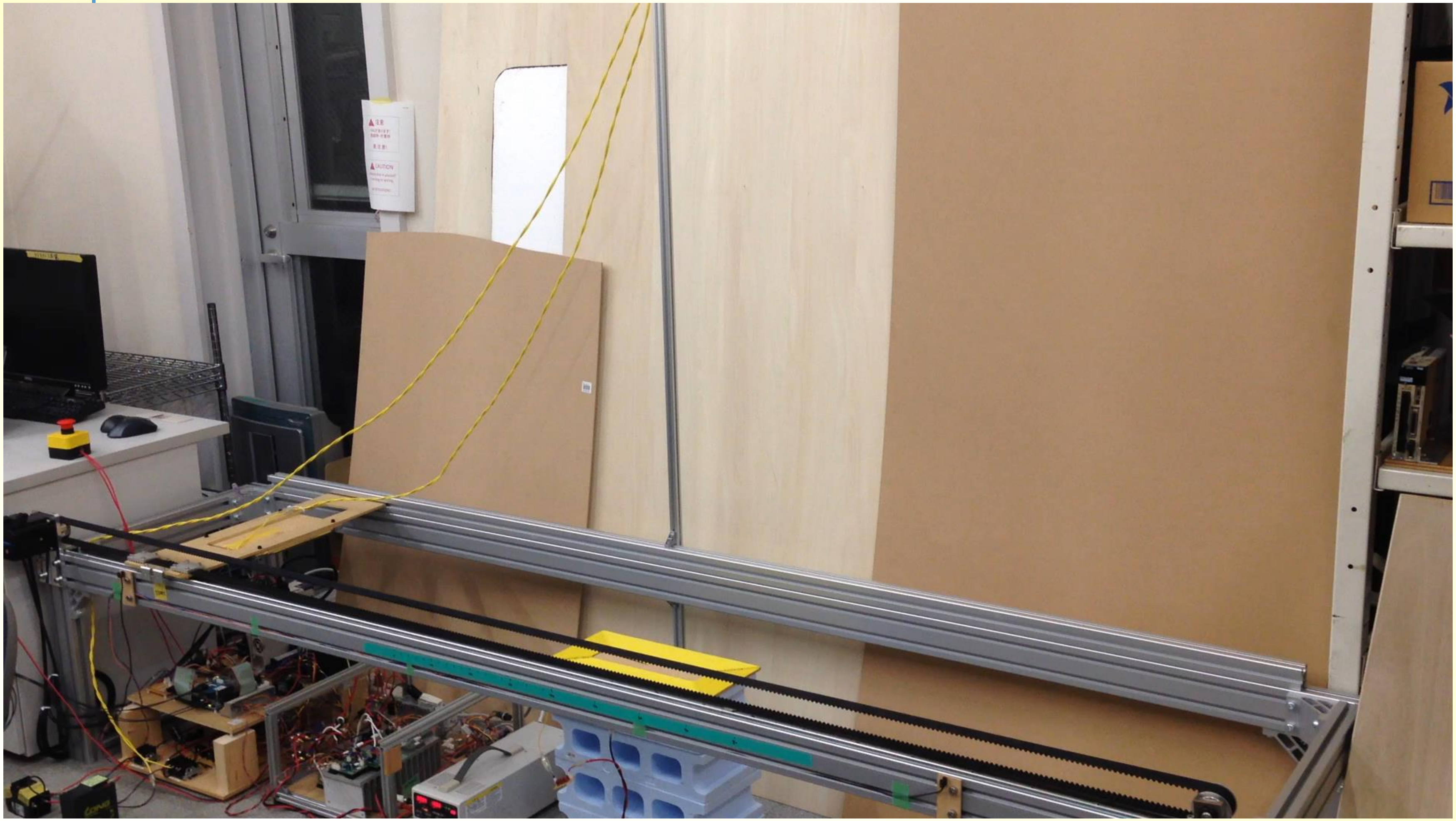


Primary Inverter, DC/DC converter, Controller

Daita Kobayashi, Takehiro Imura, Yoich Hori, **Real-time Coupling Coefficient Estimation and Maximum Efficiency Control on Dynamic Wireless Power Transfer Using Secondary DC-DC converter**, *41st Annual Conference of the IEEE Industrial Electronics Society* , pp. 4650-4655, 2015

Maximum efficiency tracking

Experimental movie



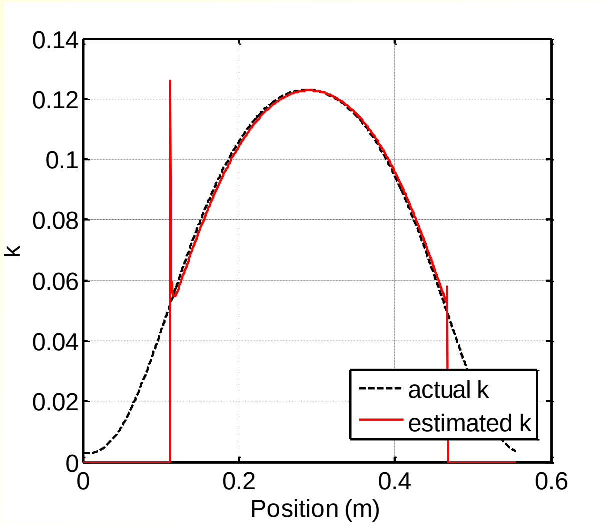
20 km/h

Daita Kobayashi, Takehiro Imura, Yoich Hori, **Real-time Coupling Coefficient Estimation and Maximum Efficiency Control on Dynamic Wireless Power Transfer Using Secondary DC-DC converter**, *41st Annual Conference of the IEEE Industrial Electronics Society* , pp. 4650-4655, 2015

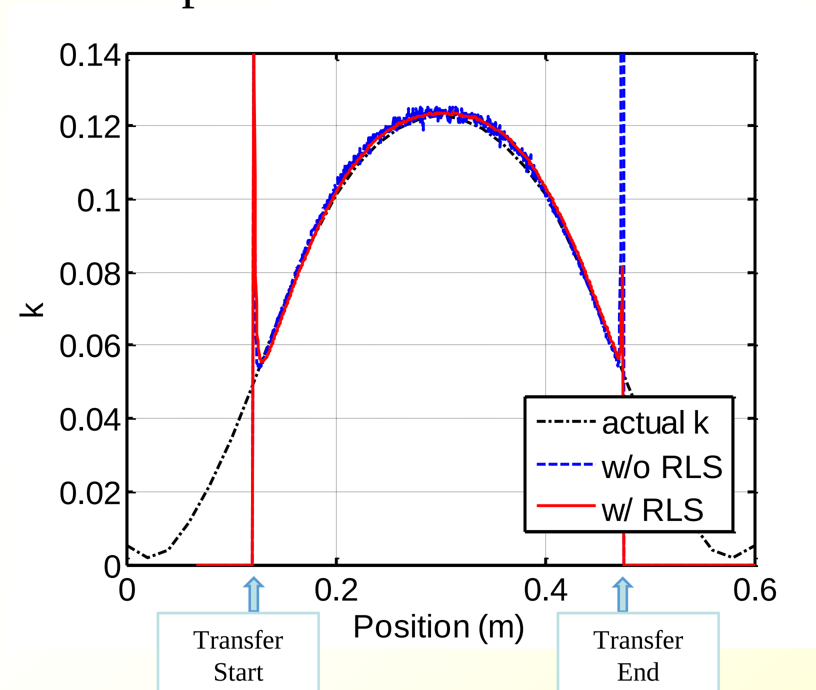
Maximum efficiency tracking

Experimental Result : *k* estimation

- Simulation



- Experiment



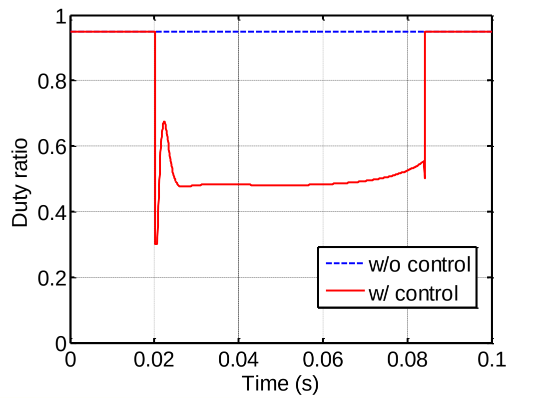
- No estimation delay ⇒ the static *k* estimation equation is applicable
- RLS filter has obvious effect

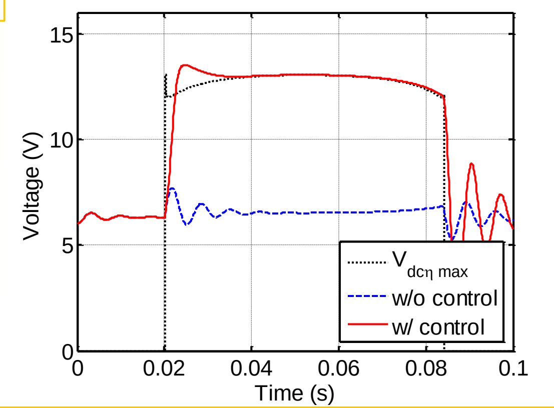
Daita Kobayashi, Takehiro Imura, Yoich Hori, **Real-time Coupling Coefficient Estimation and Maximum Efficiency Control on Dynamic Wireless Power Transfer Using Secondary DC-DC converter**, *41st Annual Conference of the IEEE Industrial Electronics Society* , pp. 4650-4655, 2015

Maximum efficiency tracking

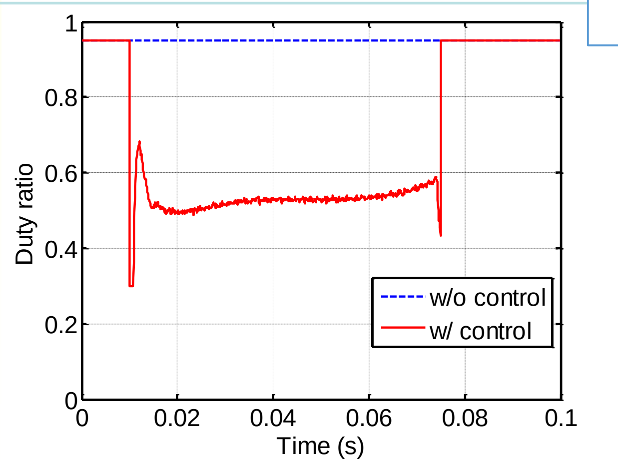
Experimental Result : Secondary voltage v_{dc}

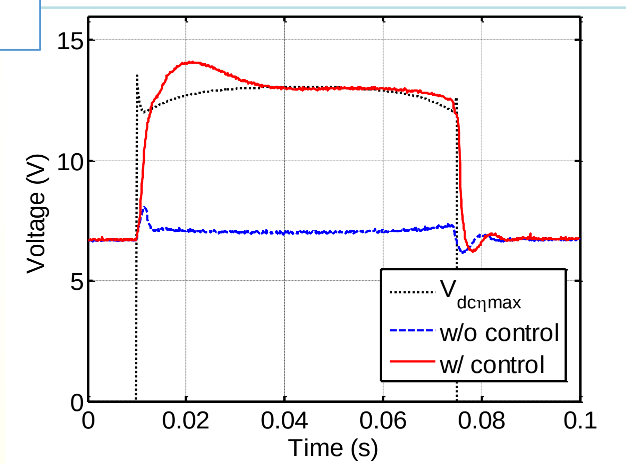
Simulation





Experiment





Upper switch duty ratio $d(t)$

Secondary voltage v_{dc}

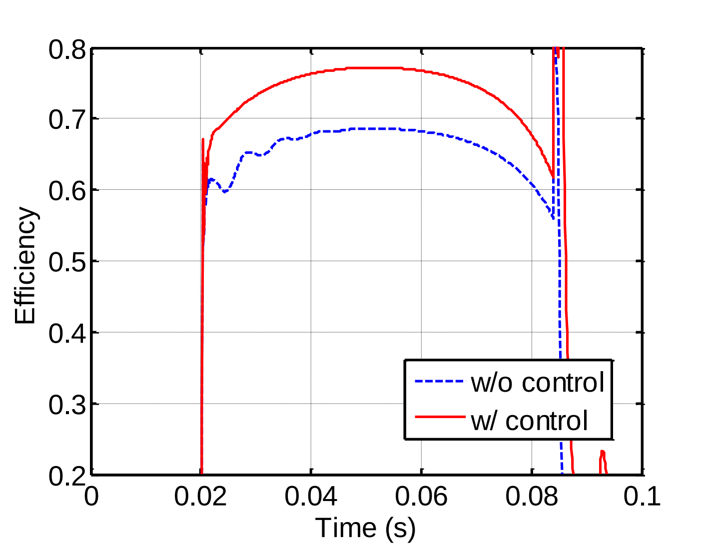
Response can be improved by adjustment of DC-link capacitor and the feedback controller gain

Daita Kobayashi, Takehiro Imura, Yoich Hori, **Real-time Coupling Coefficient Estimation and Maximum Efficiency Control on Dynamic Wireless Power Transfer Using Secondary DC-DC converter**, *41st Annual Conference of the IEEE Industrial Electronics Society* , pp. 4650-4655, 2015

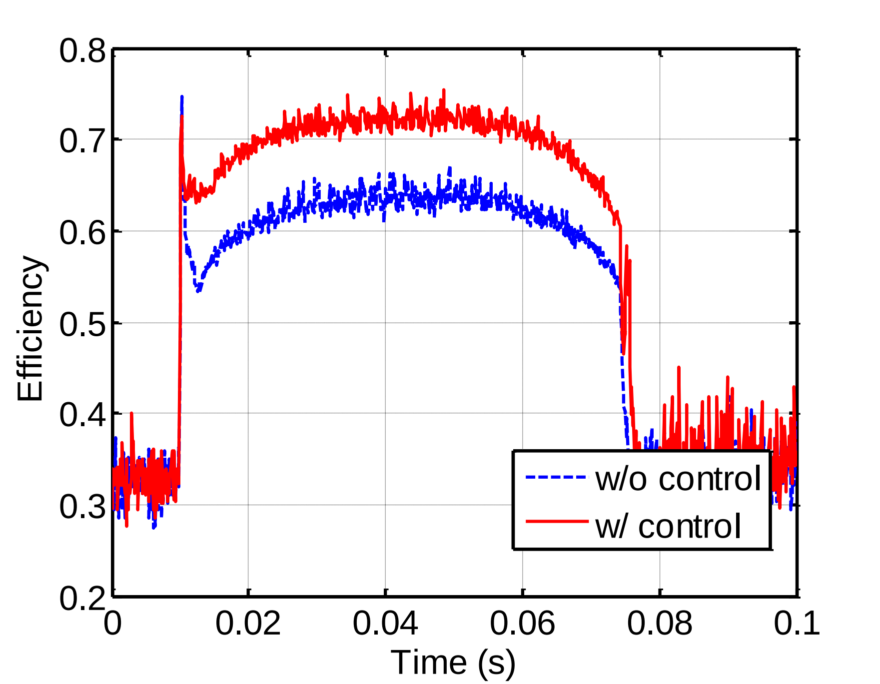
Maximum efficiency tracking

Experimental Result: DC to DC efficiency

- Simulation



- Experiment

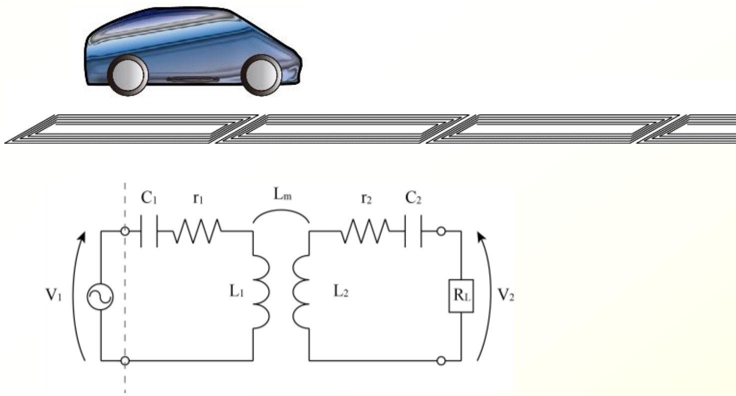


- DC to DC efficiency has improved by 10% at 20 km/h

The proposed real-time control is sufficiently applicable to dynamic wireless power transfer system.

Daita Kobayashi, Takehiro Imura, Yoich Hori, **Real-time Coupling Coefficient Estimation and Maximum Efficiency Control on Dynamic Wireless Power Transfer Using Secondary DC-DC converter**, *41st Annual Conference of the IEEE Industrial Electronics Society*, pp. 4650-4655, 2015

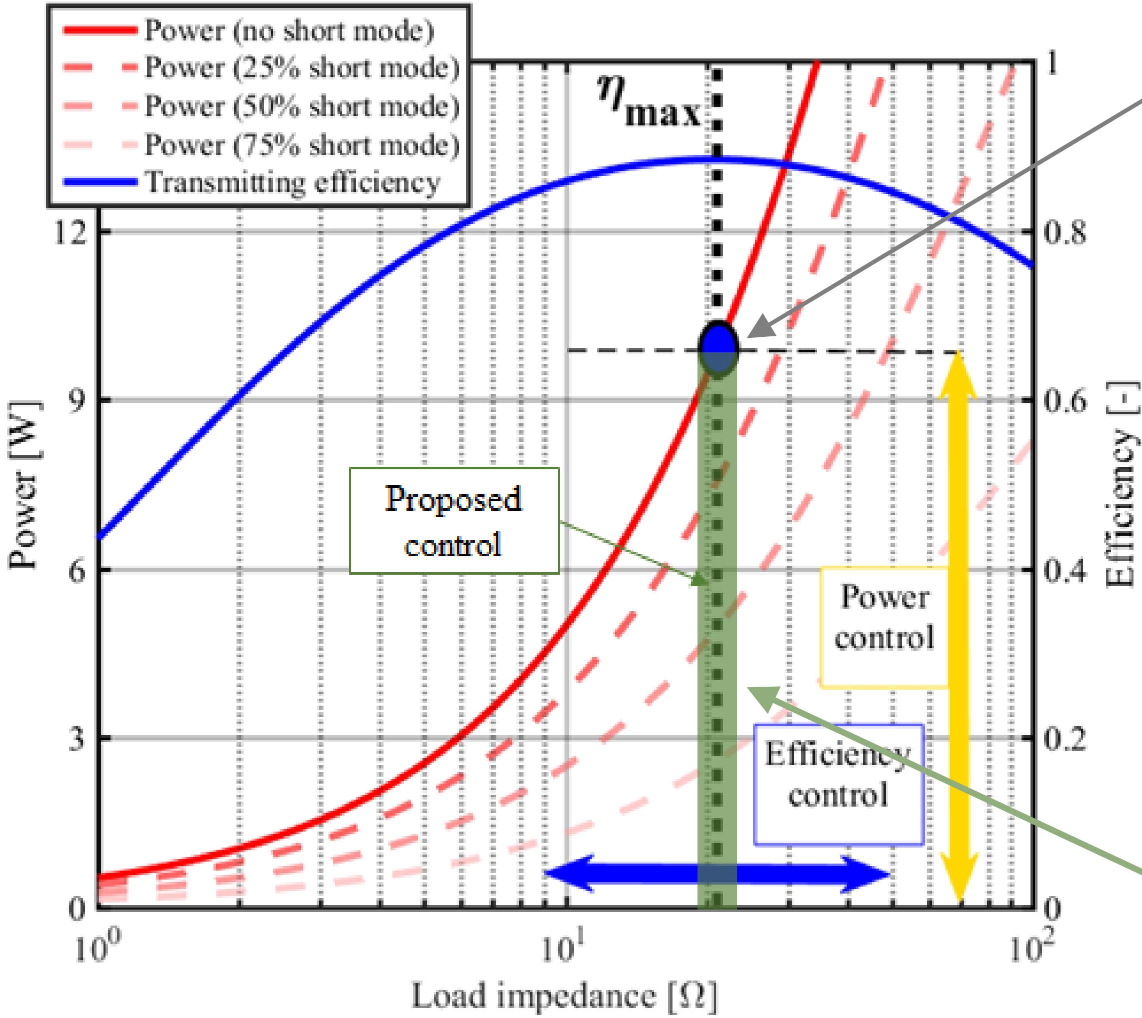
Overview of our system



- Coil type
- Open type coil
(capacitor-less and ferrite-less)
- S-S: series-series
- Sensorless detection (primary) — detection
- Power control by HAR (secondary) — control A type
- Maximum efficiency tracking (secondary) — control B type
- Simultaneous power and maximum efficiency tracking control (secondary) — control C type
- Power off (primary) — power off
- Automatic driving using coil sensing

Simultaneous power and maximum efficiency tracking control

❑ Operation point:



Only secondary control

Typical

Operation point with efficiency control only by secondary

Power is FIXED

Typical solution needs V1 control for power (primary side)

Operation range with proposed control

- maximum efficiency
- power

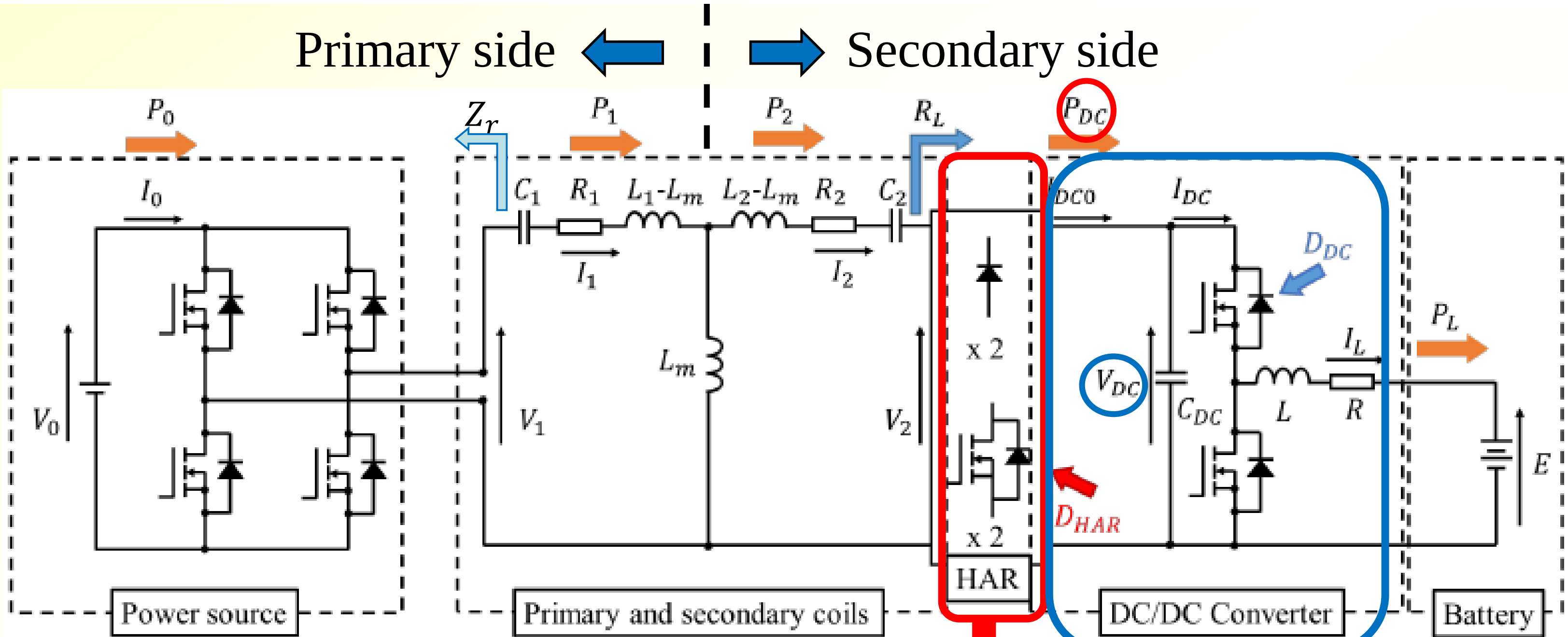
Power is VARIABLE

It was impossible to control power and efficiency simultaneously only secondary side.

Simultaneous power and maximum efficiency tracking control

Only secondary control

❑ <u>Reference circuit:</u> WPT with SS compensation



Power control (HAR)

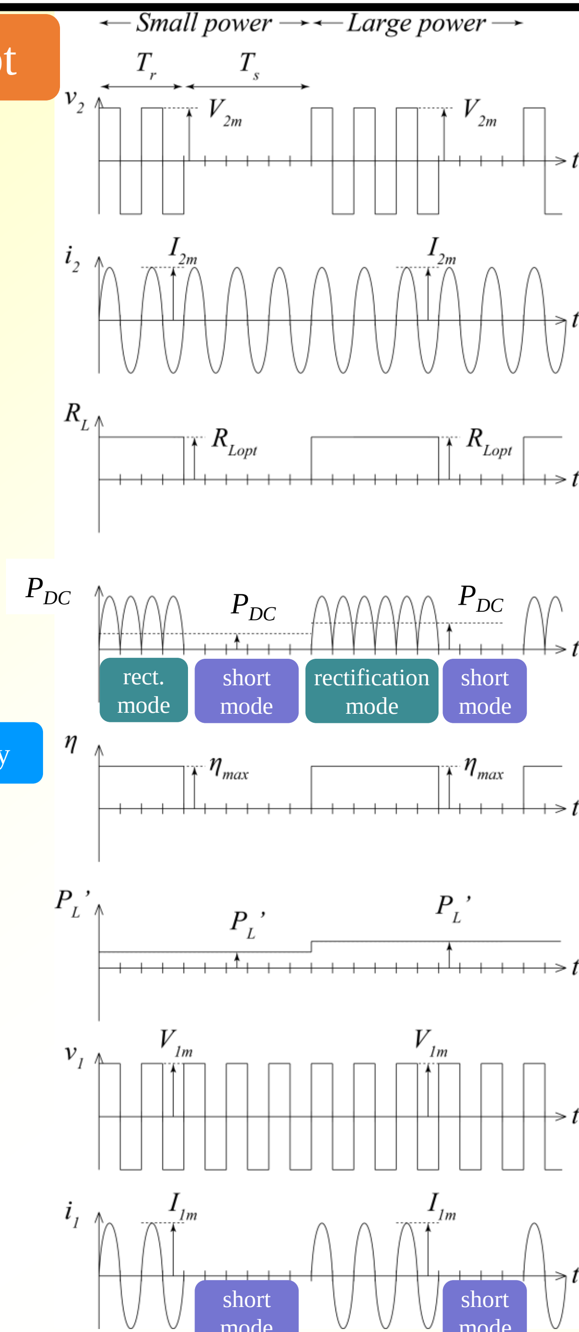
Efficiency control

short mode

Controlled average power is P_{DC} while efficiency controlled by the DC link voltage V_{DC}. The half active rectifier (HAR) is used for power control and the buck converter is used for efficiency control.

Simultaneous power and maximum efficiency tracking control

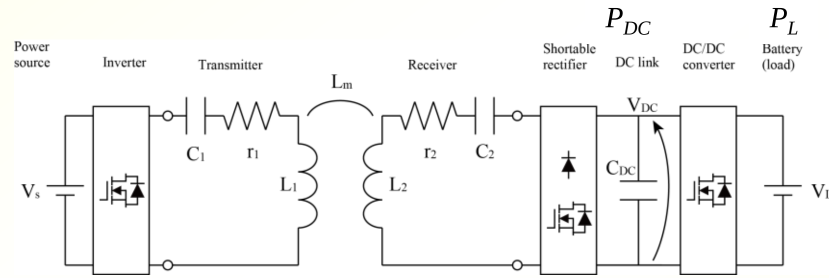
Concept



efficiency

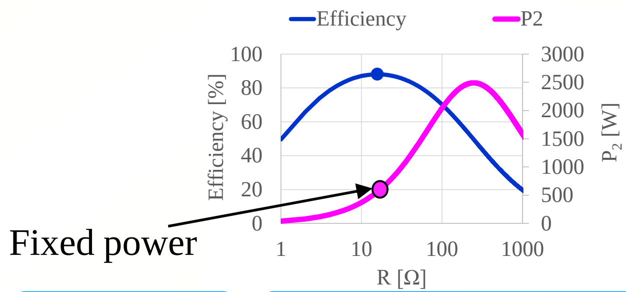
Power

Only secondary control



Typical

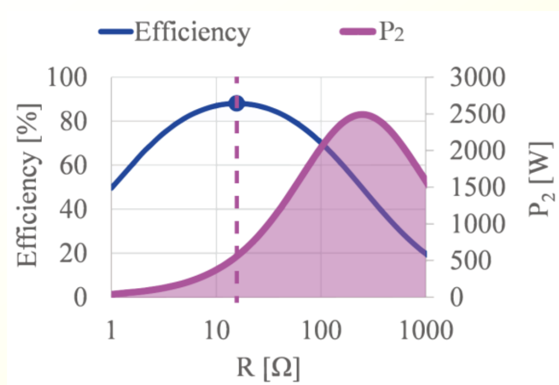
Only efficiency or power control

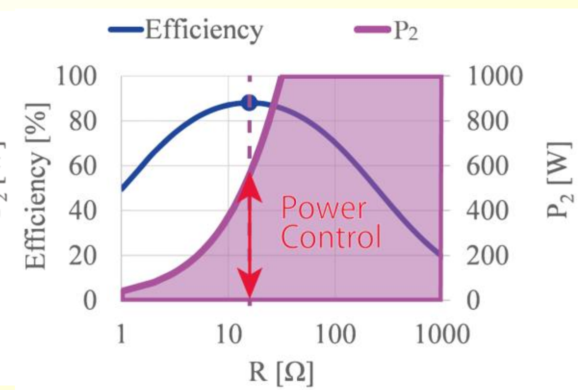


Here, only efficiency is controlled.
power can not be controlled.

Proposal

Maximum efficiency and power control

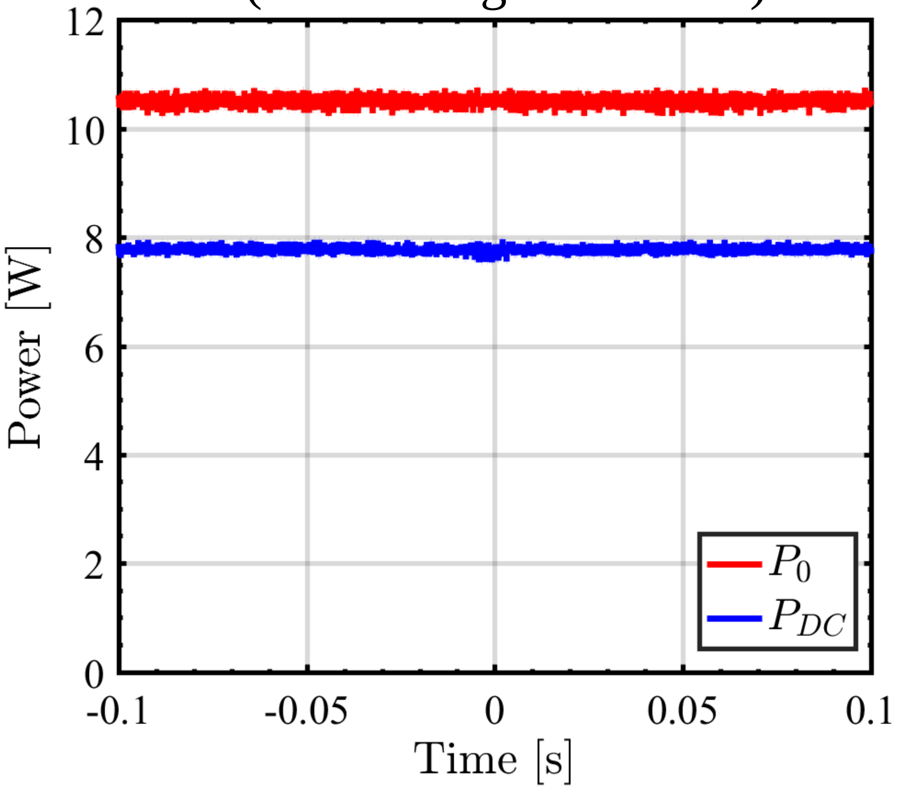




❑ Experimental results: secondary power

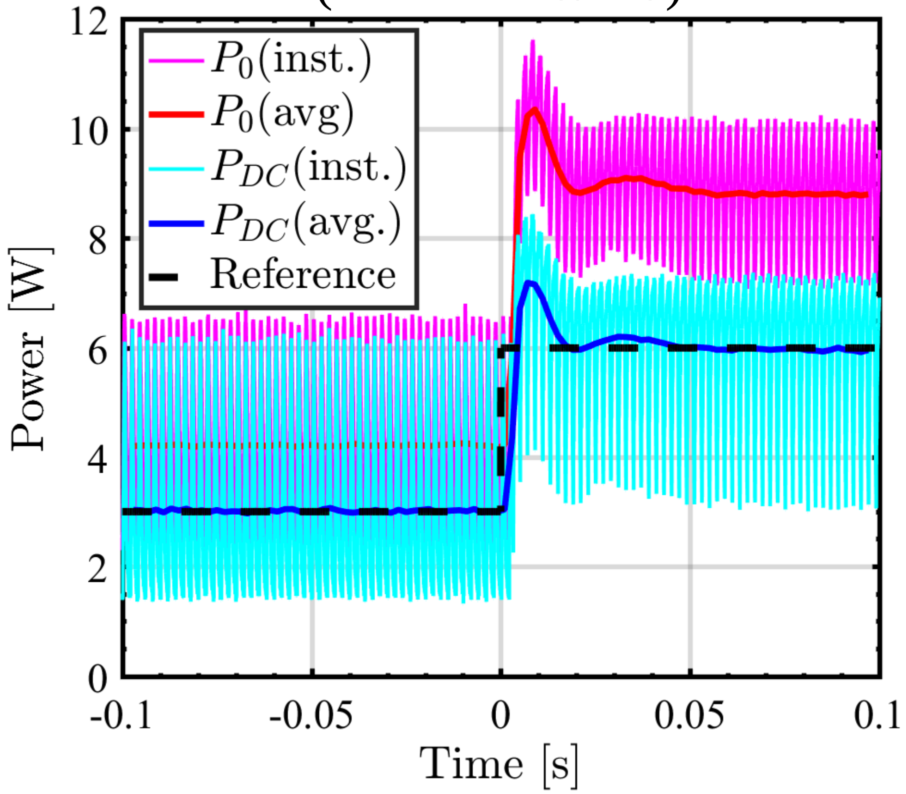
V1 is fixed

Efficiency only control
(diode bridge + DC/DC)



Power cannot be controlled due to diode bridge, max efficiency condition

Proposed control (efficiency & power)
(HAR + DC/DC)



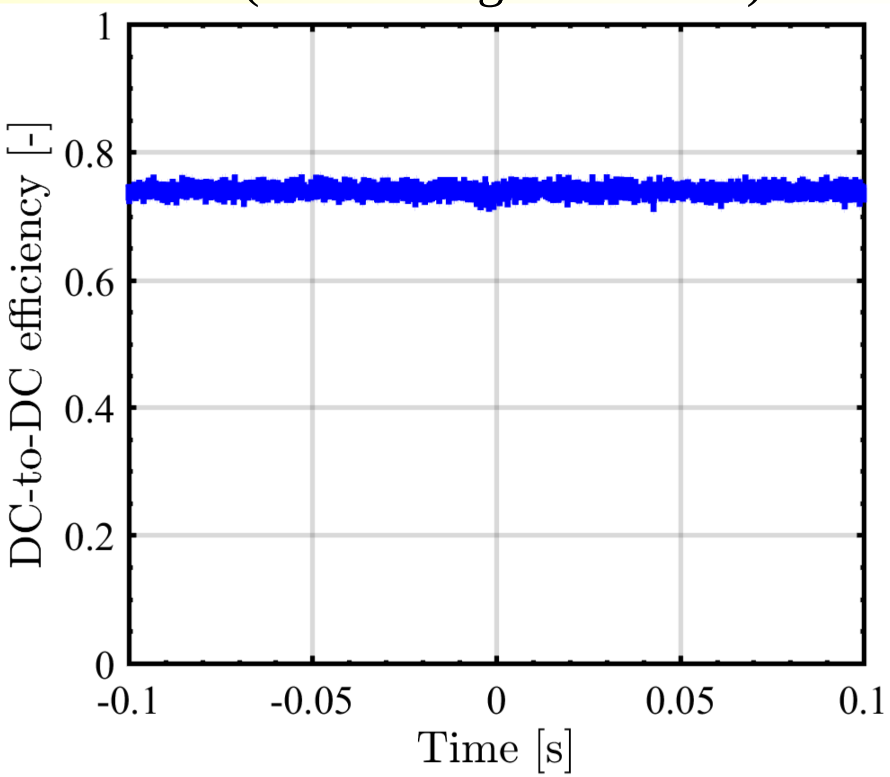
Average power controlled, robustness to power step

Giorgio Lovison, Takehiro Imura, Yoichi Hori, **Secondary-side-only Simultaneous Power and Efficiency Control by Online Mutual Inductance Estimation for Dynamic Wireless Power Transfer**, *42nd Annual Conference of the IEEE Industrial Electronics Society* , pp. 4553-4558, 2016

❑ Experimental results: DC-to-DC efficiency

Typical

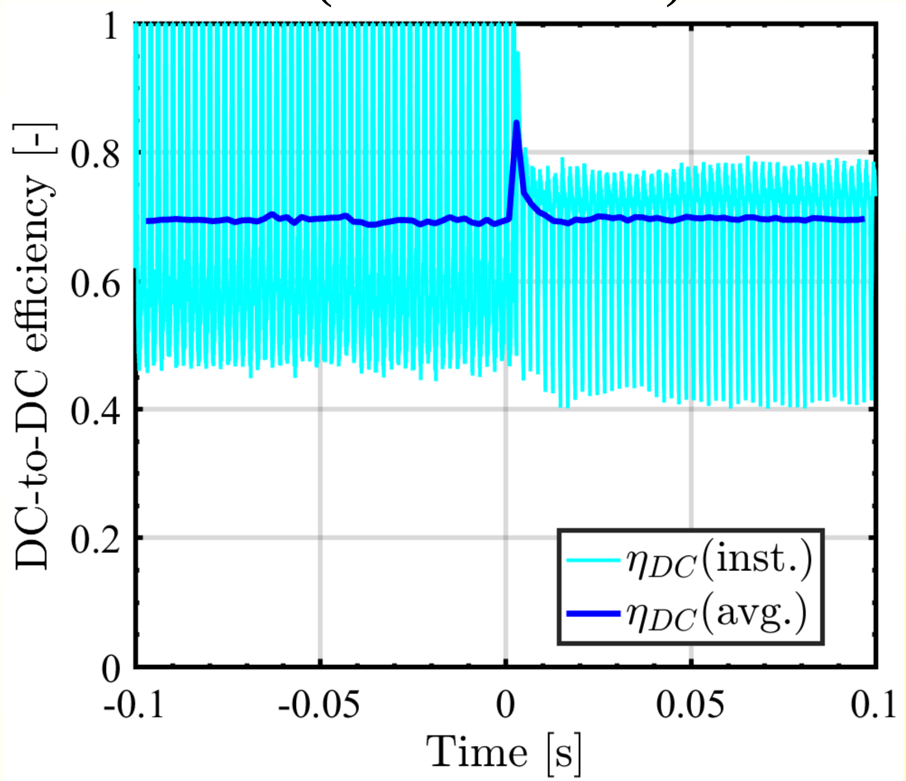
Efficiency only control
(diode bridge + DC/DC)



Max efficiency condition

Almost maximum efficiency is achieved

Proposed control (efficiency & power)
(HAR + DC/DC)



Average efficiency 4% lower than max,
unchanged with power step

Giorgio Lovison, Takehiro Imura, Yoichi Hori, **Secondary-side-only Simultaneous Power and Efficiency Control by Online Mutual Inductance Estimation for Dynamic Wireless Power Transfer**, *42nd Annual Conference of the IEEE Industrial Electronics Society* , pp. 4553-4558, 2016

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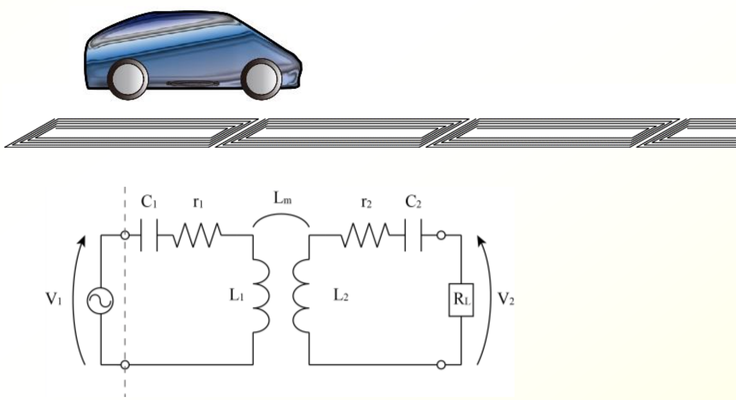
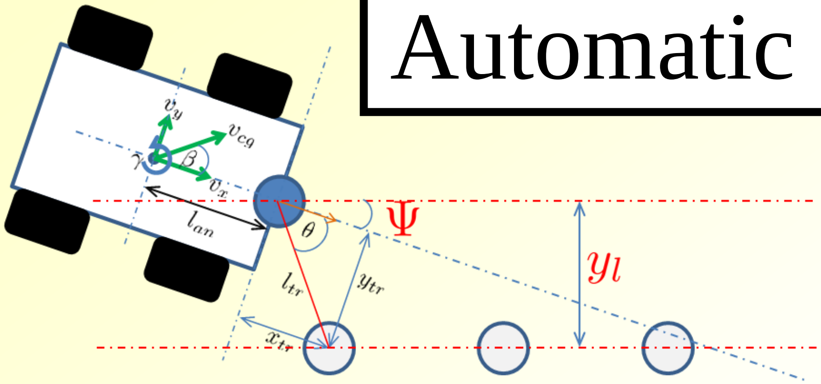
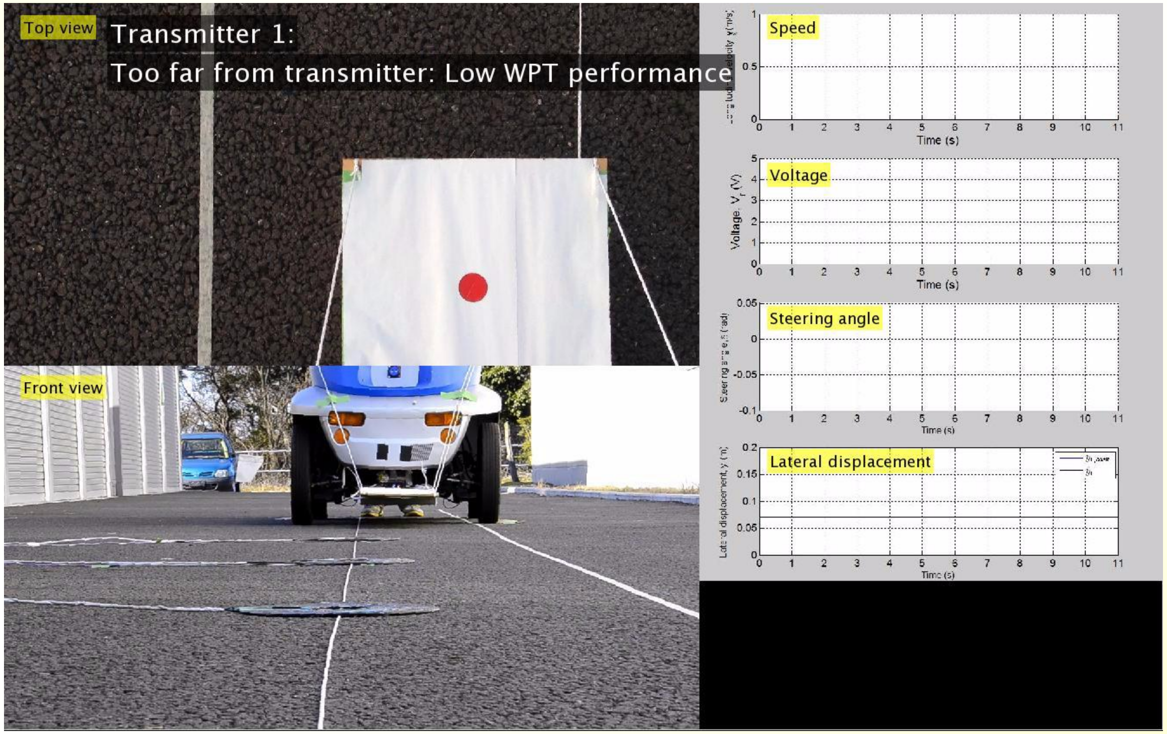
Automatic driving using coil sensing



Automatic driving using coil sensing



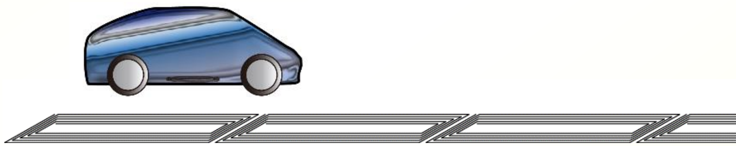
Lane Following Control

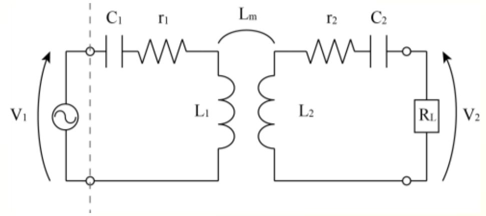


Master thesis: Pakorn SUKPRASERT , " Estimation and Control of Lateral Displacement of Electric Vehicle Using Wireless Power ransfer Information", 2015.3

Real vehicle

Our first in-motion system using real vehicle





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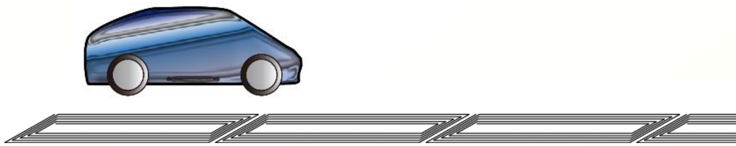
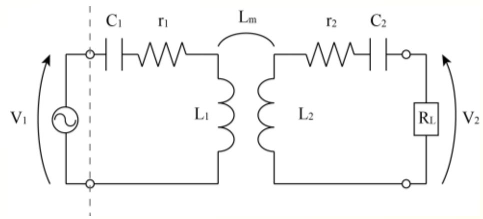
Automatic driving using coil sensing	

Our first in-motion system using real vehicle





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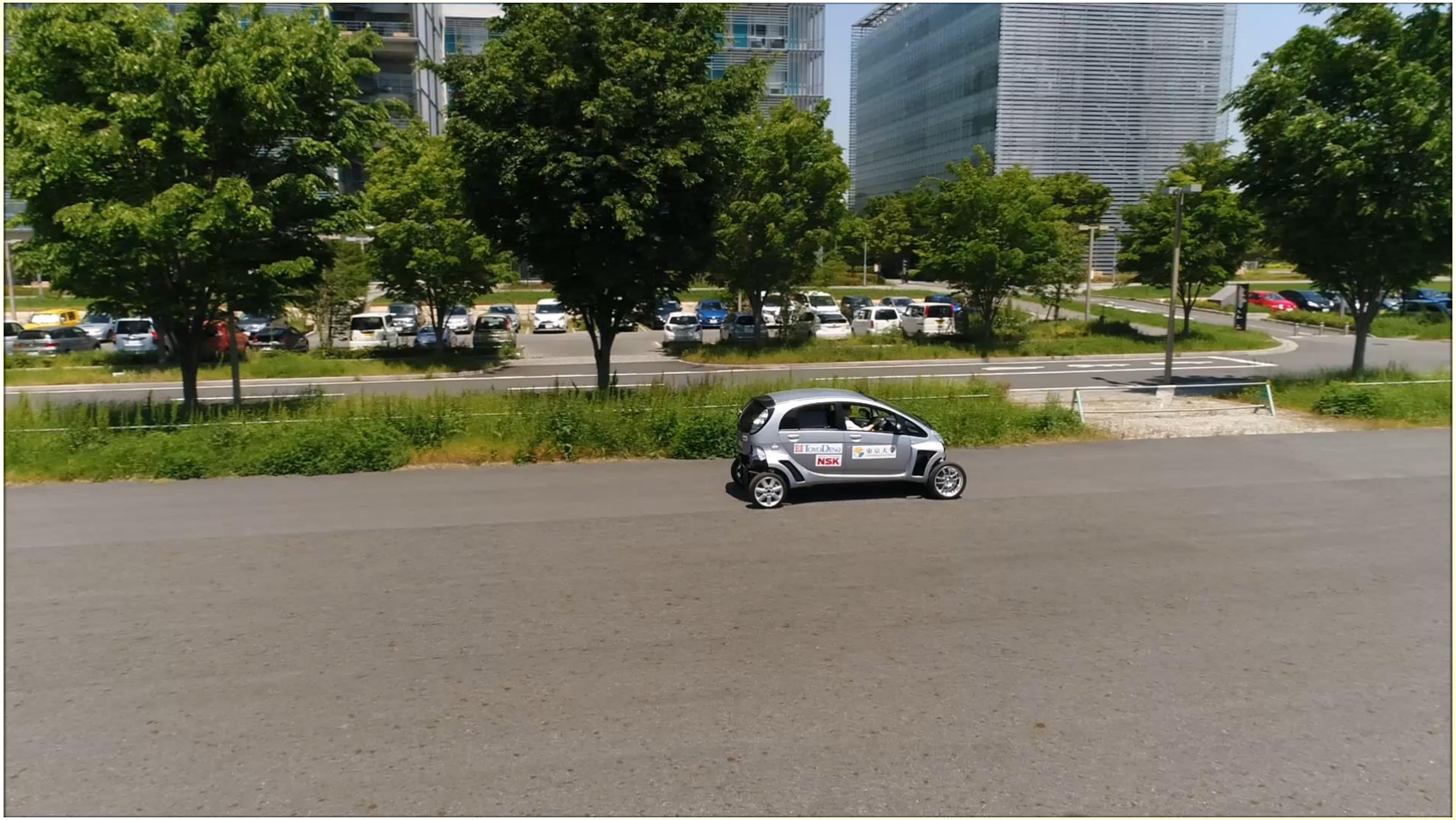
Automatic driving using coil sensing

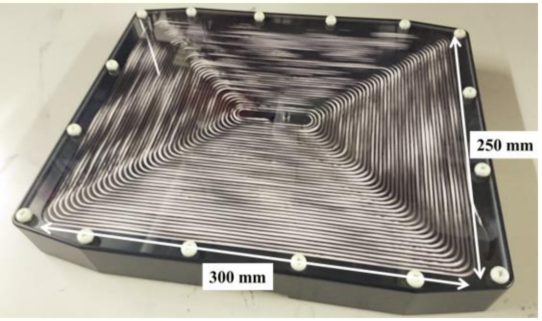
In-motion charging

Wireless in-wheel moter project
The University of Tokyo
Toyodenki Seizo K.K.
NSK Ltd.



T.Takeuchi, T.Imura, H.Fujimoto and Y.Hori, "**Power Management on Wireless In-Wheel Motor with Dynamic Wireless Power Transfer",** EVS30, 2017

Experiments



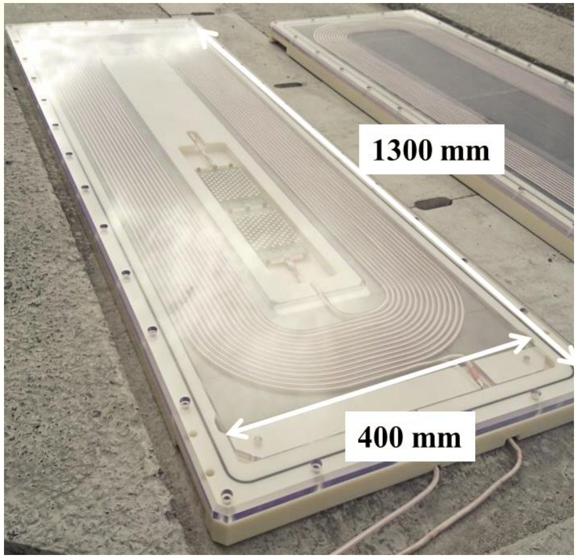
☐Efficiency measurement

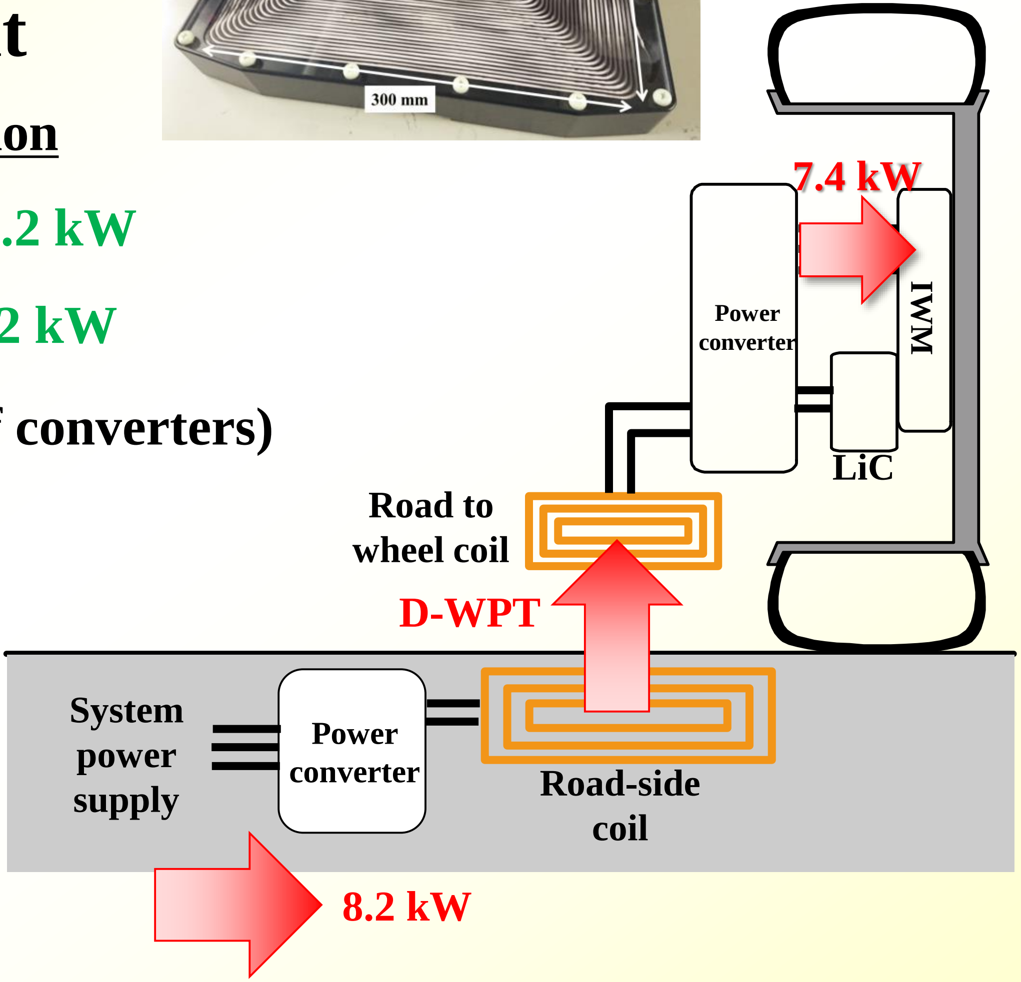
Road to Wheel power transmission

Road-side input power is 8.2 kW

Input power of IWM is 7.2 kW

Total efficiency (including loss of converters) reached 90.24 %





Total efficiency is 90.24 %

T.Takeuchi, T.Imura, H.Fujimoto and Y.Hori, "**Power Management on Wireless In-Wheel Motor with Dynamic Wireless Power Transfer**", EVS30, 2017

Conclusion

In-motion charging project at our laboratory is shown.

We use S-S topology and sensorless detection technology.

HAR is important to control power at secondary.

Low cost open end coil is one option for our system.

Simultaneous power and efficiency control is another option.