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The 27th INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION

BARCELONA

17th-20th November 2013

Experiment of Magnetic Resonant Coupling Three-phase Wireless Power Transfer

THE UNIVERSITY OF TOKYO

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Yoichi Hori

Organized by Fira Barcelona, avele

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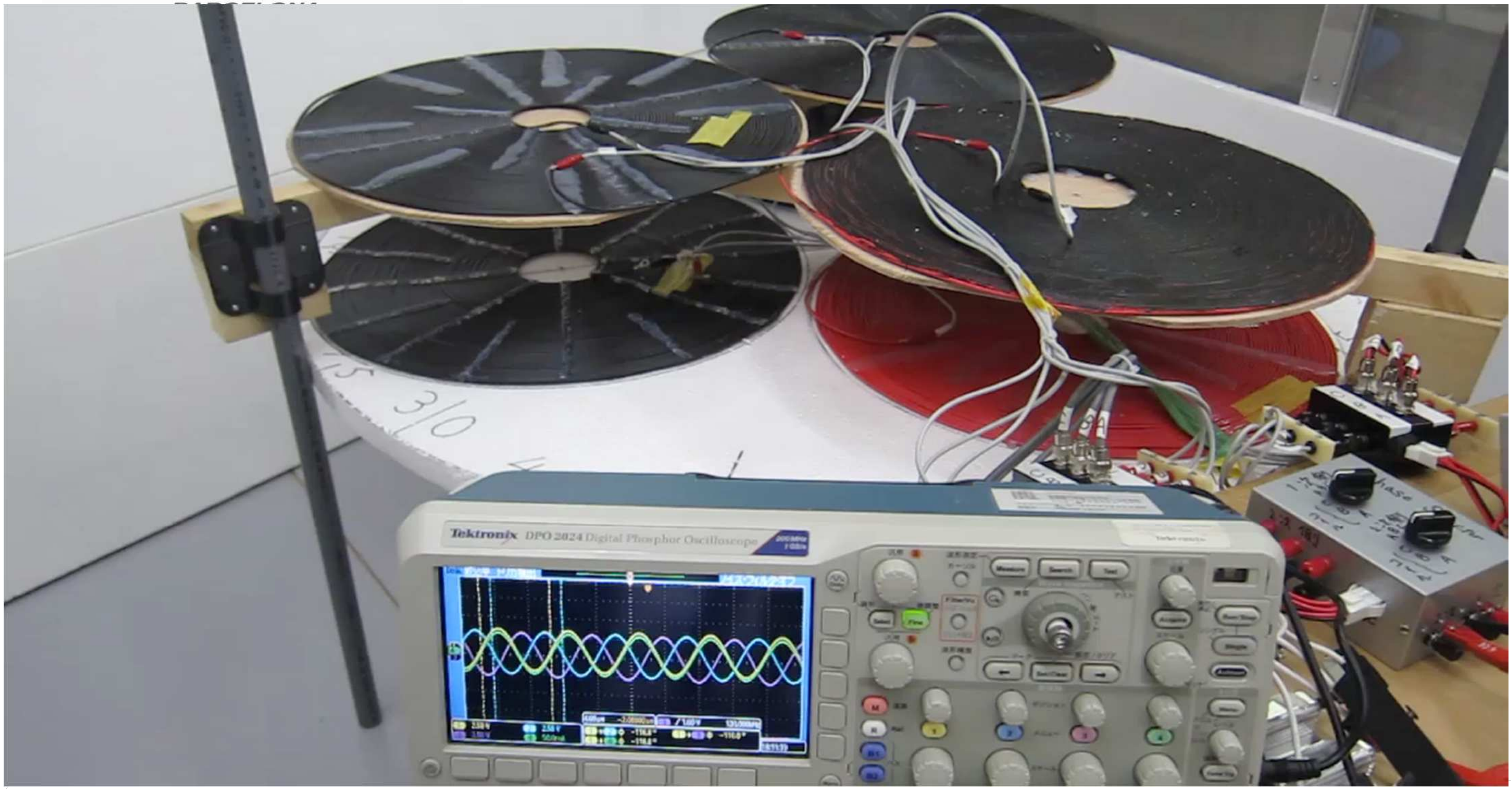
In collaboration with

Supported by European Commission

What is our research?



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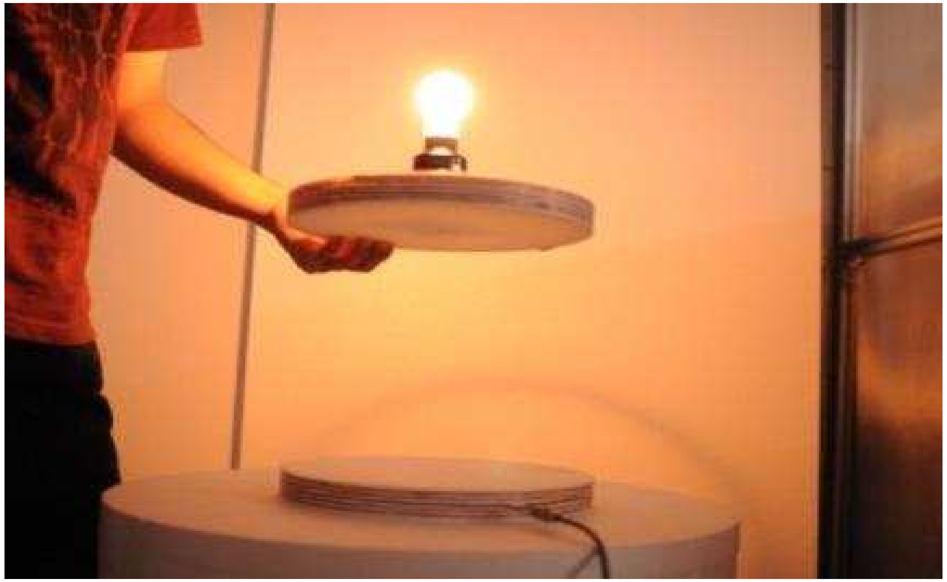

Wireless Power Transfer (WPT)

Applications: **EV**, mobile, and battery charger

Conventional WPT: **Single phase** AC transfer

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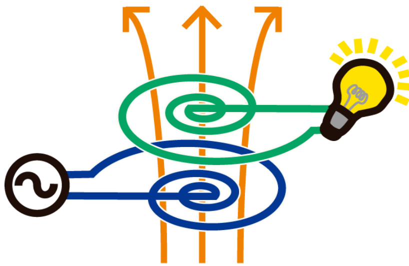
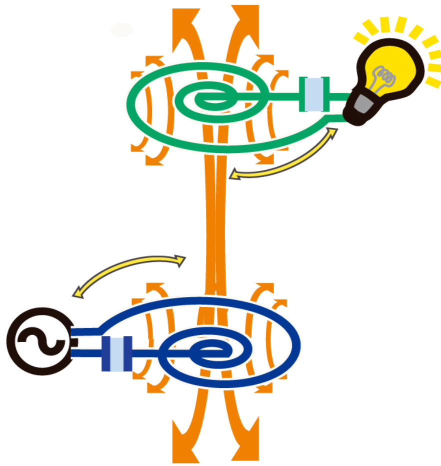
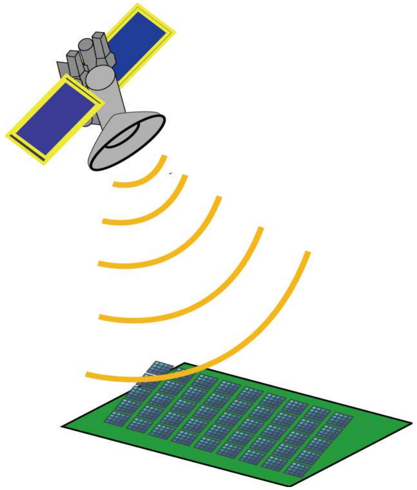
1.1. General info. for WPT 2/3

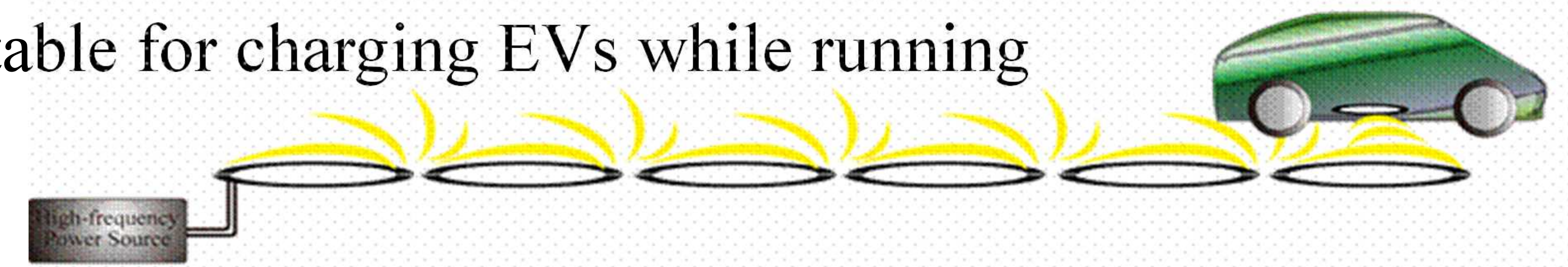
Three methods of WPT technologies

Methods	Magnetic Induction	Magnetic Resonant Coupling	Microwave
Images			
Transfer Gap	Up to 0.2 m	Up to 10 m	A few hundred km
Efficiency	Up to 95%	Up to 97%	Up to 60 %
Robustness for Displacement	Poor	Great	Good

1.1. General info. for WPT 3/3

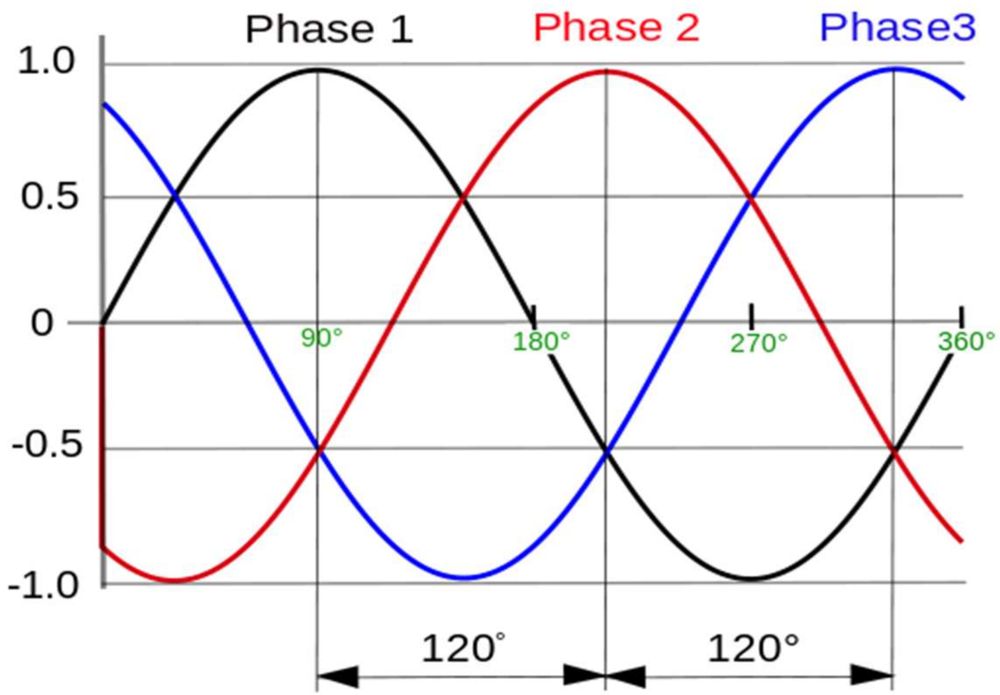
Magnetic Resonant Coupling

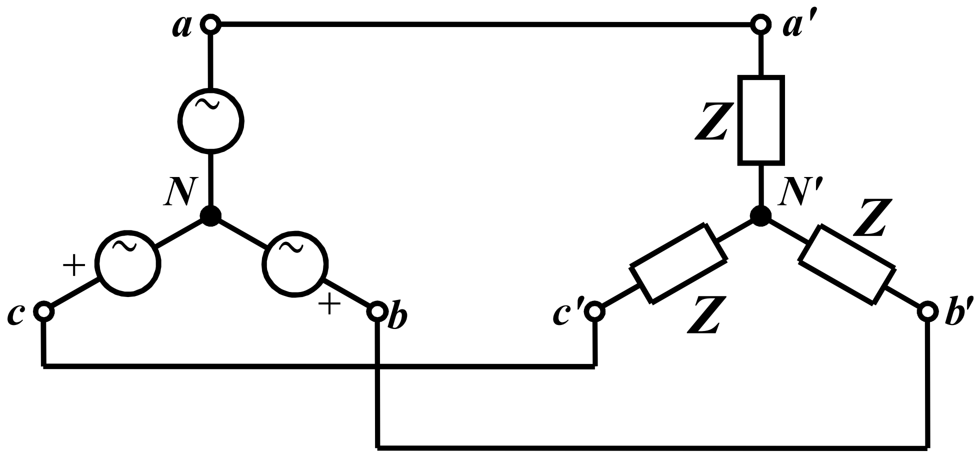
- Transmitter and receiver: LC resonators
- High efficiency (around 90%) at 1 m gap
- Transfer frequency: 100 kHz to 20 MHz
  - Power devices for kHz switching
- Relay resonators (single phase)
  - Suitable for charging EVs while running



1.2. Why three phase? 1/3

1. Advantage for **high power transfer**
2. Suitable characteristics for WPT





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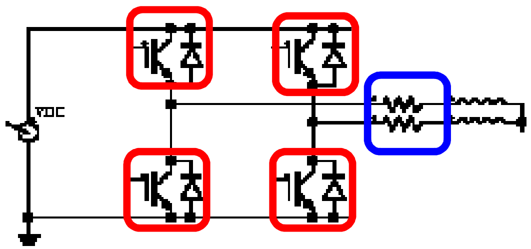
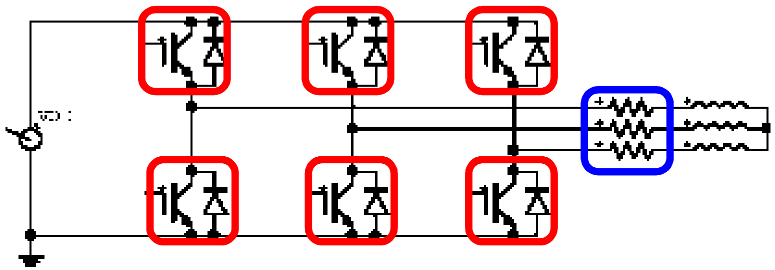
1.2. Why three phase? 2/3

Advantages for high power transfer

- Larger power capacity with same devices
  - Capacity limit: three times of single phase
    (High frequency devices: Low power limit)
- Relatively simple system

	Single phase	**Three phase**
Power limit ratio	1	**3**
Device quantity	2 (4 switches, 2 lines)	**3** (6 switches, 3 lines)
Circuits		

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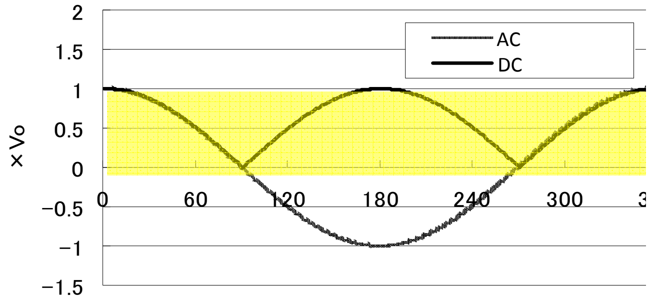
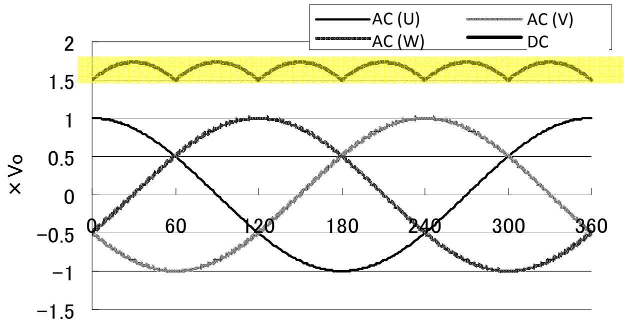
1.2. Why three phase? 3/3

Suitable characteristics for WPT

- Smaller ripples of rectified DC



Single phase



Three phase

- Rotation symmetry: contact-less terminal

Photo ：Wikipedia

Conventional method

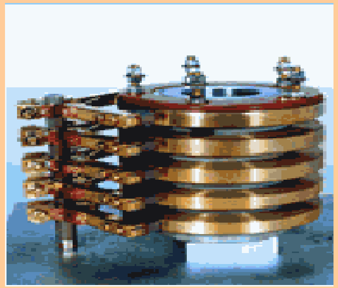


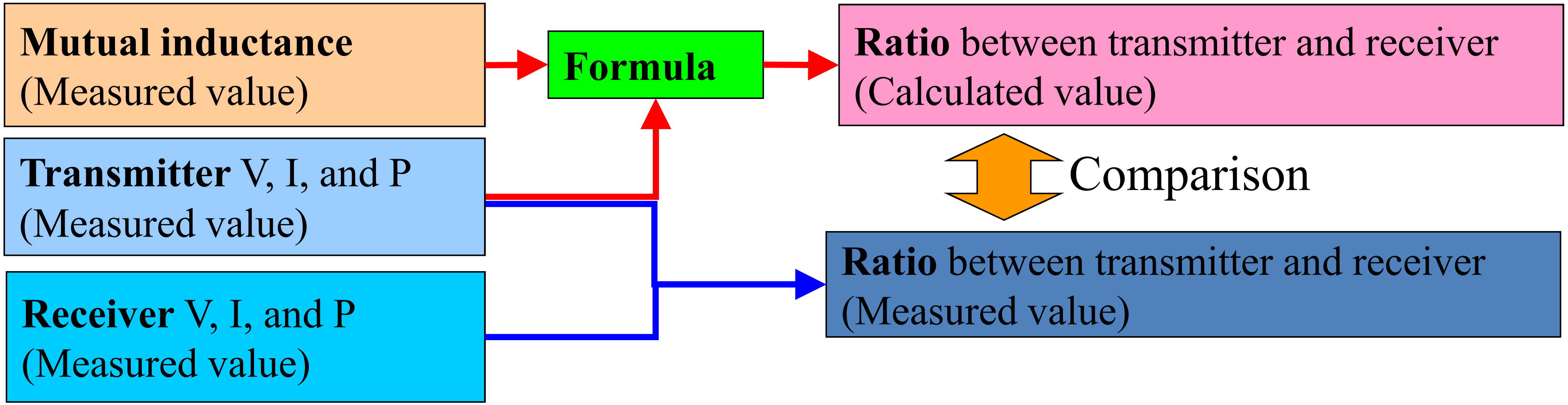
Photo : Toyonaka industry WEB

Contents

2.1. General info. & parameters 1/2

Experiment & analysis of Three-phase WPT

1. Comparison of data and **theoretical formula**
2. Rotation experiment: collection of measured values
   - Each 15 degree from 0 to 360 degree
   - Mutual inductance between resonators
   - Ratio of voltage (V), current (I), and power (P)



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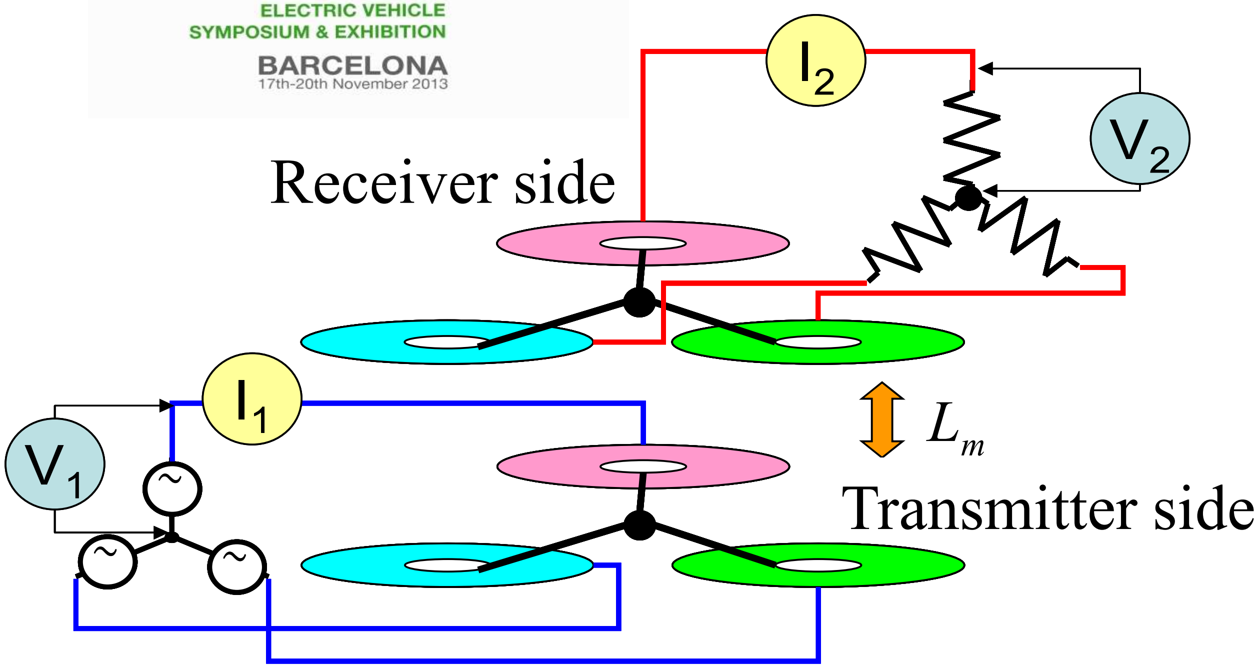
2.1. General info. & parameters 2/2



Voltage ratio

$$A_v = \frac{V_2}{V_1}$$

Current ratio

$$A_i = \frac{I_2}{I_1}$$

Coupling coefficient (nondimensionalized mutual inductance)

$$k = \frac{L_m}{L_1} = \frac{L_m}{L_2} = \frac{L_m}{880\ \mu H}$$

Efficiency (Power ratio)

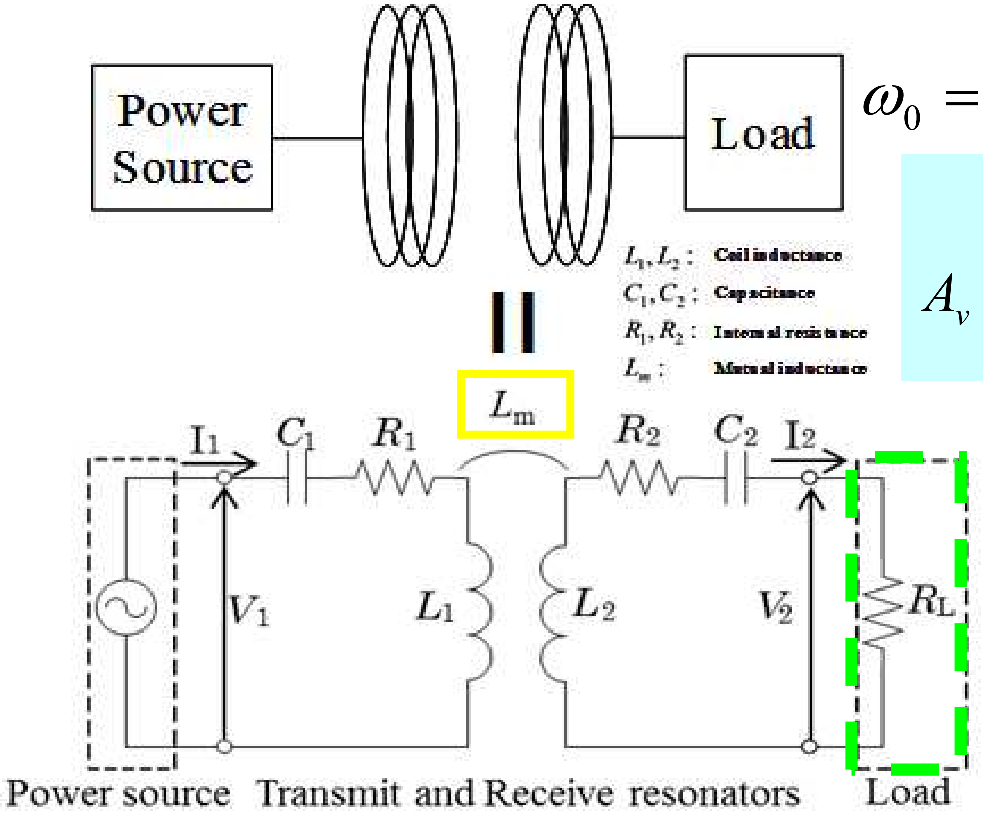
$$\eta = \frac{P_{out}}{P_{in}} = \frac{V_2 \cdot \bar{I}_2}{V_1 \cdot \bar{I}_1} = A_v \cdot \bar{A}_i$$

Power factor = 1.0 (resonant condition)

2.2. Theoretical formula 1/3

Base theoretical formula of single phase

- Resonance: simple formula of mutual inductance L_m and load resistance R_L



Masaki Kato, Takehiro Imura, Yoichi Hori, "The Characteristics when Changing Transmission Distance and Load Value in Wireless Power Transfer via Magnetic Resonance Coupling", The 34th International Telecommunications Energy Conference (INTELEC 34th), 2012

$$\omega_0 = \sqrt{L_1 C_1} = \sqrt{L_2 C_2}$$

At experiment; R_L=50 ohm

- Voltage ratio

$$A_v = \frac{V_2}{V_1} = j\frac{\omega_0 L_m R_L}{R_1 R_L + R_1 R_2 + (\omega_0 L_m)^2} = A_v(L_m, R_L)$$

- Current ratio

$$A_i = \frac{I_2}{I_1} = j\frac{\omega_0 L_m}{(R_L + R_2)} = A_i(L_m, R_L)$$

- Efficiency (Power ratio)

$$\eta = A_v \cdot \overline{A_i} = \frac{(\omega_0 L_m)^2 R_L}{(R_L + R_2)\{R_1 R_L + R_1 R_2 + (\omega_0 L_m)^2\}}$$

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2.2. Theoretical formula 2/3

Modification of formula to three phase

- Three phase; **a lot of mutual inductance values**

  To adapt the single phase formula;

  how to combine the values into **one value**?

- **Combination of trigonometric function**

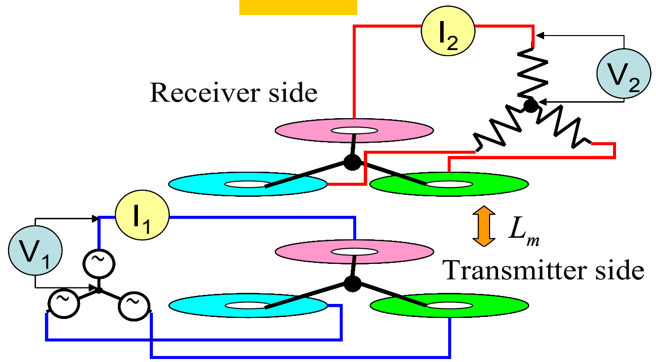
$$\tilde{L}_m = L_{m1}\sin(\omega t) + L_{m2}\sin(\omega t + \frac{\pi}{3}) + L_{m3}\sin(\omega t + \frac{2\pi}{3})$$

$$= \sqrt{(L_{m1}{}^2 + L_{m2}{}^2 + L_{m3}{}^2) - (L_{m1}L_{m2} + L_{m2}L_{m3} + L_{m3}L_{m1})}\,\sin(\omega t + \phi)$$

Phase difference

Combined L_m

$$\begin{cases} \sin\phi = \dfrac{(\sqrt{3}/2)L_{m2} - (\sqrt{3}/2)L_{m3}}{\sqrt{(L_{m1}{}^2 + L_{m2}{}^2 + L_{m3}{}^2) - (L_{m1}L_{m2} + L_{m2}L_{m3} + L_{m3}L_{m1})}} \\ \cos\phi = \dfrac{L_{m1} - (L_{m2}/2) - (L_{m3}/2)}{\sqrt{(L_{m1}{}^2 + L_{m2}{}^2 + L_{m3}{}^2) - (L_{m1}L_{m2} + L_{m2}L_{m3} + L_{m3}L_{m1})}} \end{cases}$$



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2.2. Theoretical formula 3/3

Optimal load for efficient maximization

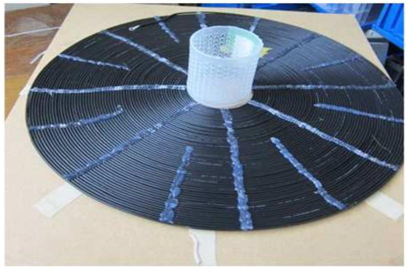
- Efficient formula: function of load resistance

$$\eta = A_v \cdot \overline{A_i} = \frac{\omega_0 (L_m R_L)^2}{(R_L + R_2)\{R_1 R_L + R_1 R_2 + (\omega_0 L_m)^2\}}$$

- Optimal value of load resistance

$$R_L = \sqrt{{R_2}^2 + \frac{R_2}{R_1}(\omega_0 L_m)^2}$$

2.3. Experiment 1/7 (Setting)



- Resonant frequency: 120 kHz
- Cable: Y connection
  - Rotation symmetry
  - 50 ohm load resistance
- Resonators

Cable: 2 mm^2
Diameter: 1.7 mm
Pitch of coil: 2.5 mm

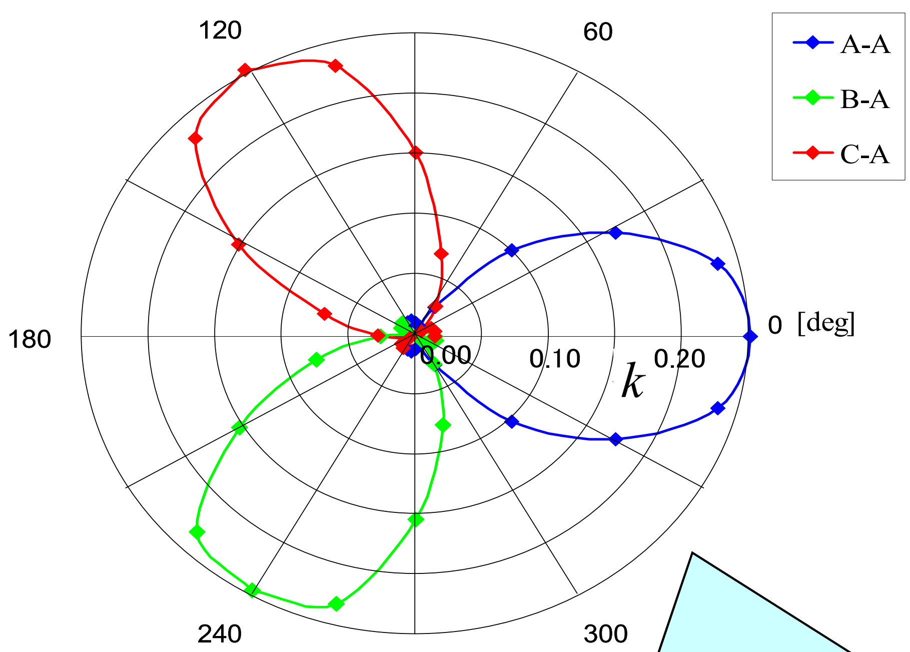
Capacitor: 2000 pF

		Phase a	Phase b	Phase c
Transmitter	Self inductance [μH]	8.73×10^2	8.68×10^2	8.69×10^2
	Internal resistance [Ω]	1.21	1.23	1.12
	Resonant capacitance [pF]	2.04×10^3	2.09×10^3	2.04×10^3
	Quality factor	5.46×10^2	5.36×10^2	5.89×10^2
	Resonant frequency [kHz]	1.19×10^2	1.19×10^2	1.20×10^2
Receiver	Self inductance [μH]	8.67×10^2	8.69×10^2	8.69×10^2
	Internal resistance [Ω]	1.17	1.23	1.20
	Resonant capacitance [pF]	2.07×10^3	2.03×10^3	2.04×10^3
	Quality factor	5.63×10^2	5.36×10^2	5.49×10^2
	Resonant frequency [kHz]	1.19×10^2	1.20×10^2	1.20×10^2

2.3. Experiment 2/7 (Result 1/6)

Mutual inductance L_m

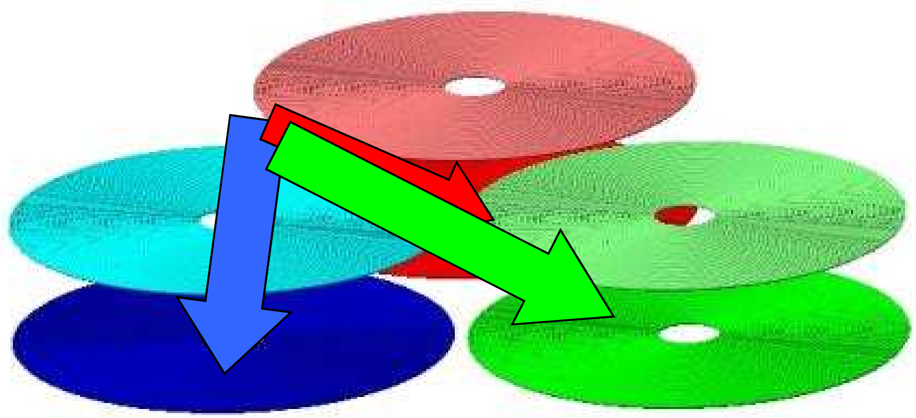
(Coupling coefficient k)



Close position: small rotation angle
Strong coupling

Combined mutual inductance;
calculated from measured values

$$k = \frac{L_m}{L_1} = \frac{L_m}{L_2} = \frac{L_m}{880\ \mu H}$$



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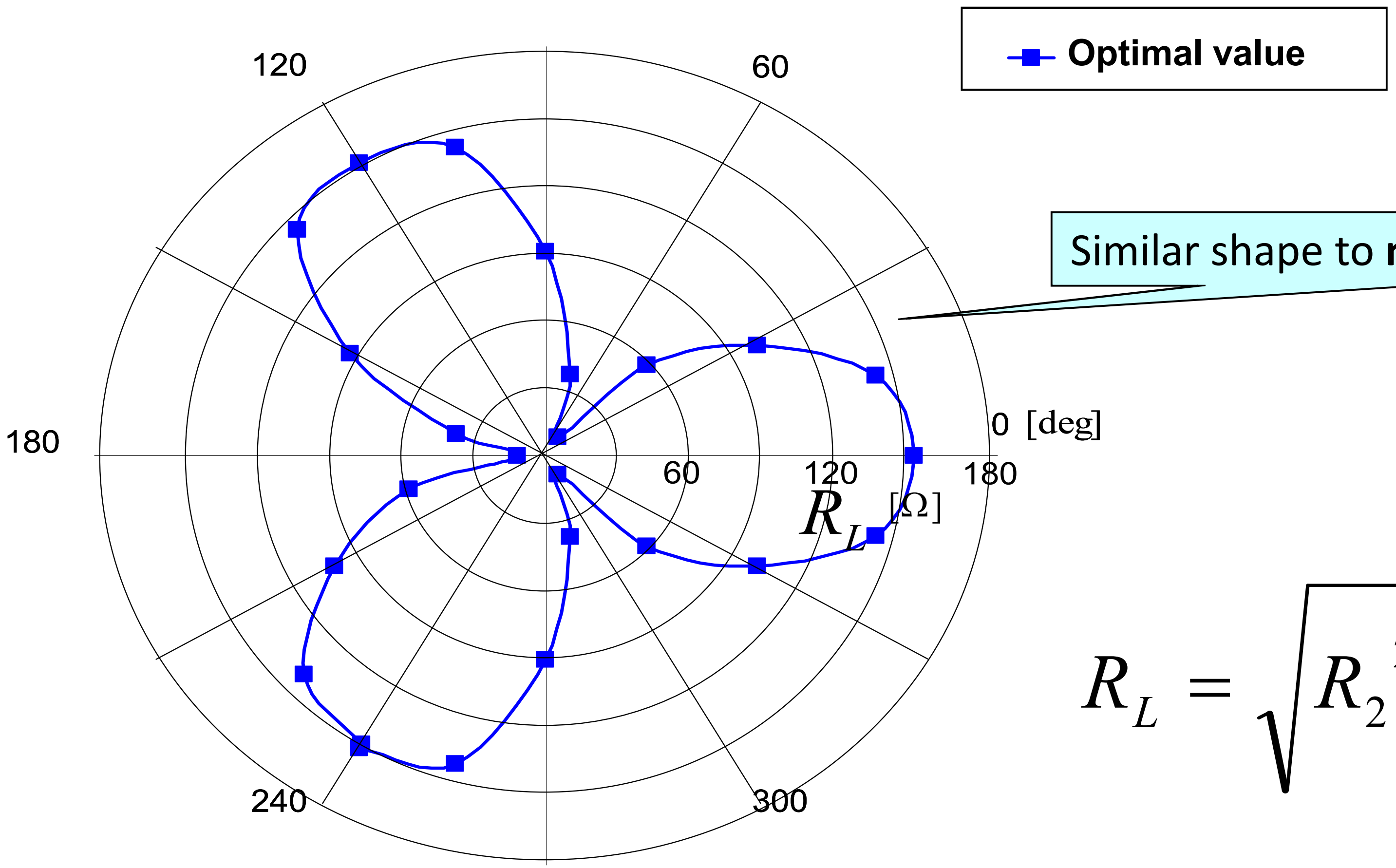
2.3. Experiment 3/7 (Result 2/6)

Optimal load resistance Z_L

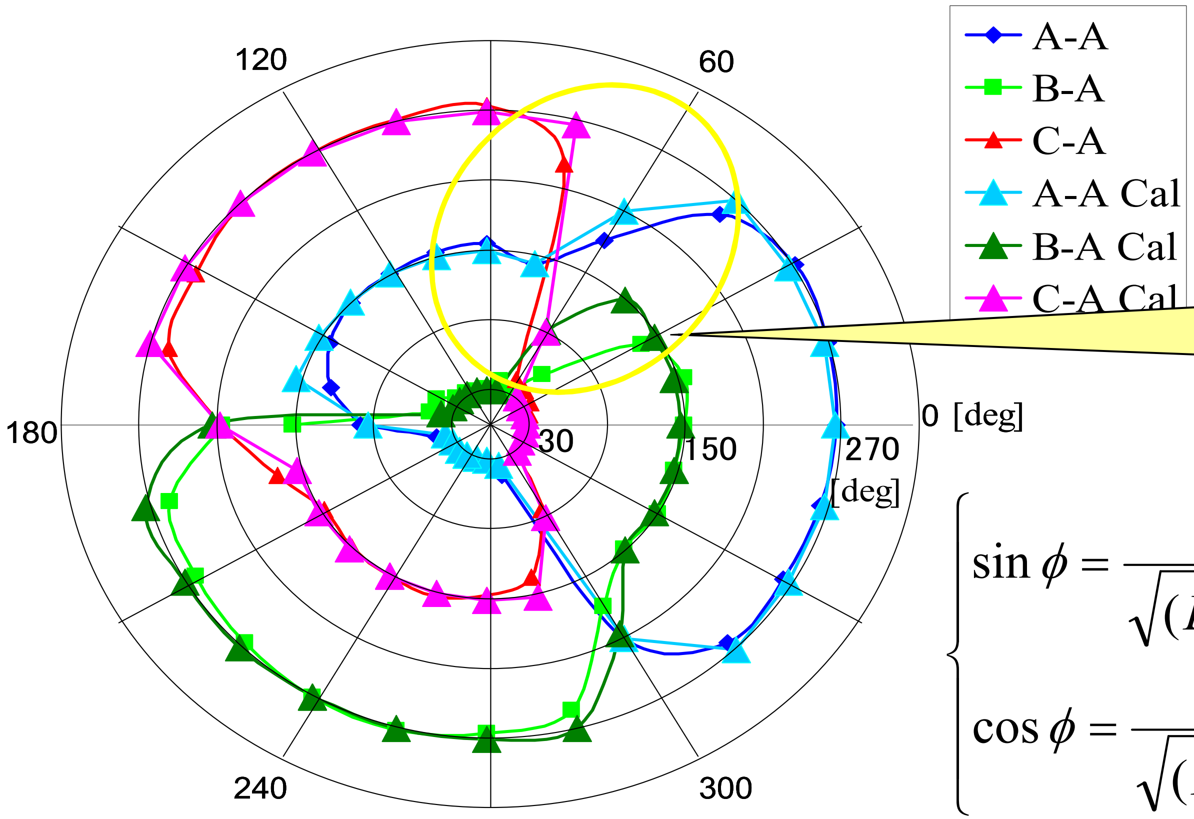


Similar shape to **mutual inductance**

$$R_L = \sqrt{R_2^{\ 2} + \frac{R_2}{R_1}(\omega_0 L_m)^2}$$

2.3. Experiment 4/7 (Result 3/6)

Phase difference ϕf voltage



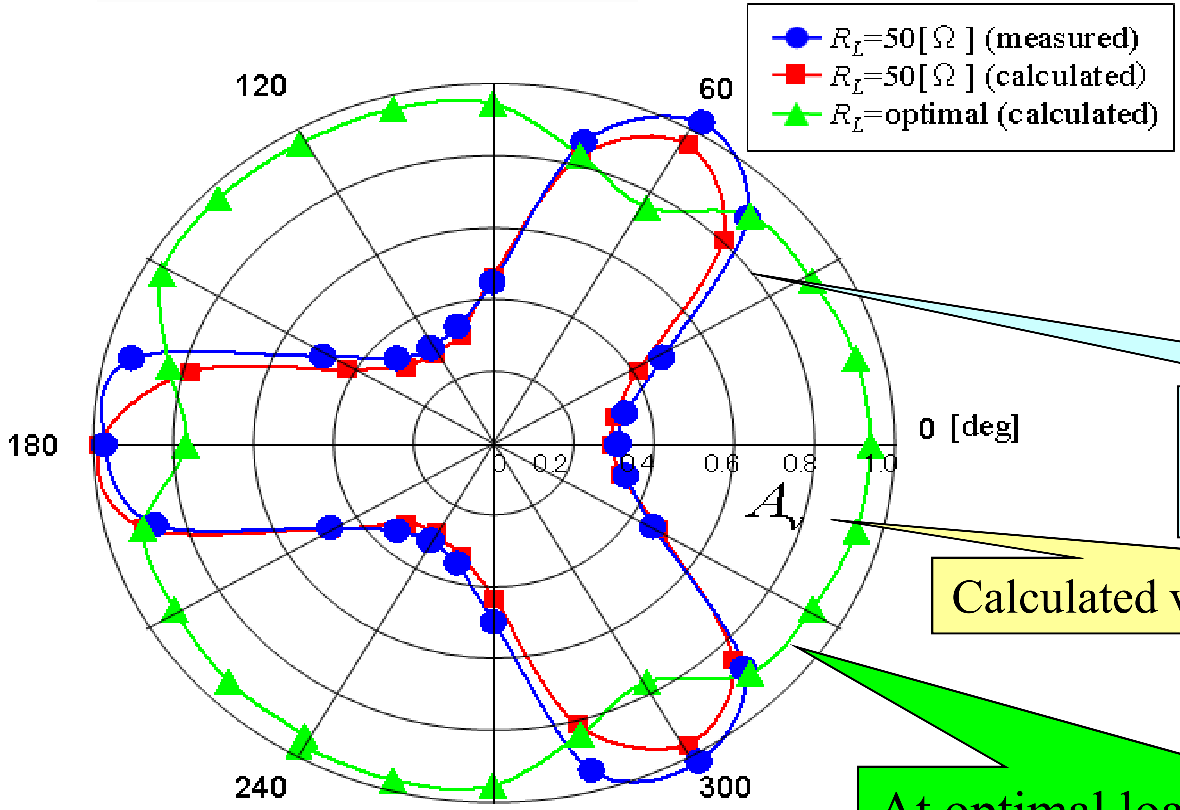
0-45 degree; phase = -90 degree
60 degree; phase = 180 degree
75-120degree; phase = 150degree
=−120−90+360 degree

Precise shape
Between calculation and
measured value

$$\begin{cases} \sin\phi = \dfrac{(\sqrt{3}/2)A_2 - (\sqrt{3}/2)L_3}{\sqrt{(L_1{}^2 + L_2{}^2 + L_3{}^2) - (L_1L_2 + L_2L_3 + L_3L_1)}} \\ \cos\phi = \dfrac{L_1 - (L_2/2) - (L_3/2)}{\sqrt{(L_1{}^2 + L_2{}^2 + L_3{}^2) - (L_1L_2 + L_2L_3 + L_3L_1)}} \end{cases}$$

2.3. Experiment 5/7 (Result 4/6)

Voltage ratio A_v



$$A_v = j\frac{\omega_0 L_m R_L}{R_1 R_L + R_1 R_2 + (\omega_0 L_m)^2}$$

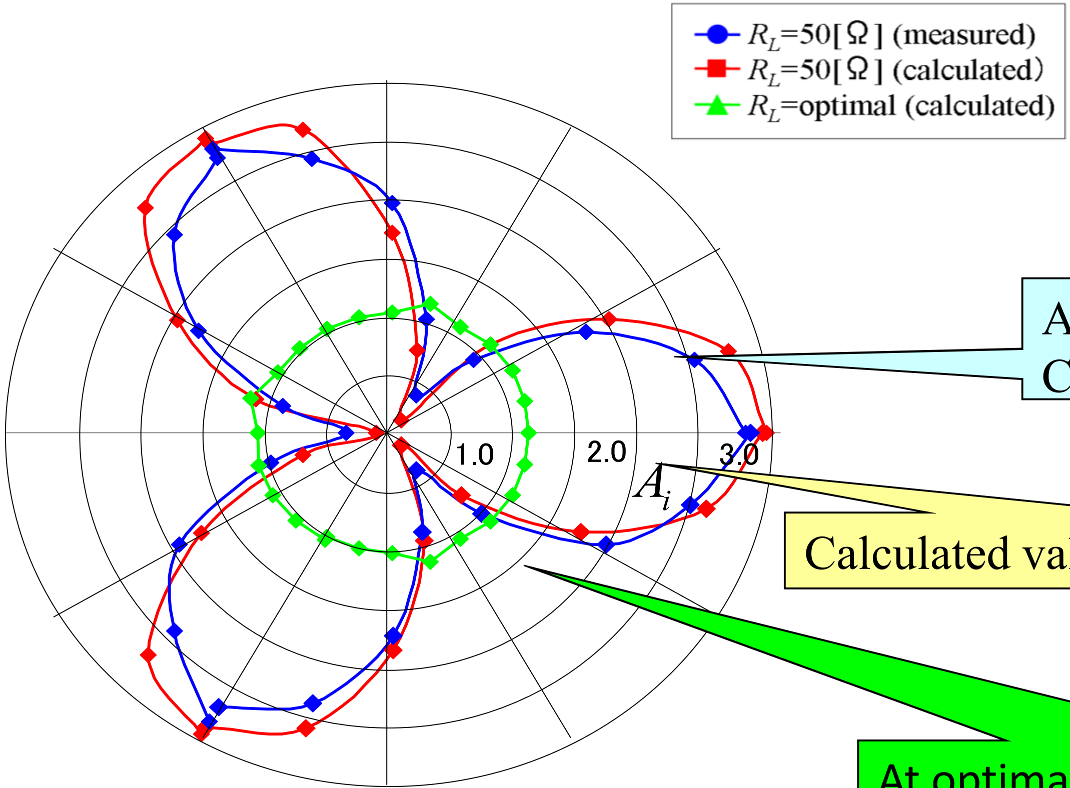
At 60 degree,
Voltage ratio is maximum.

Calculated value < Measured value

At optimal load; circular shape

2.3. Experiment 6/7 (Result 5/6)

Current ratio A_i



$$A_i = j\frac{\omega_0 L_m}{(R_L + R_2)}$$

At 60 degree,
Current ratio is minimum.

Calculated value > Measured value

At optimal load; circular shape

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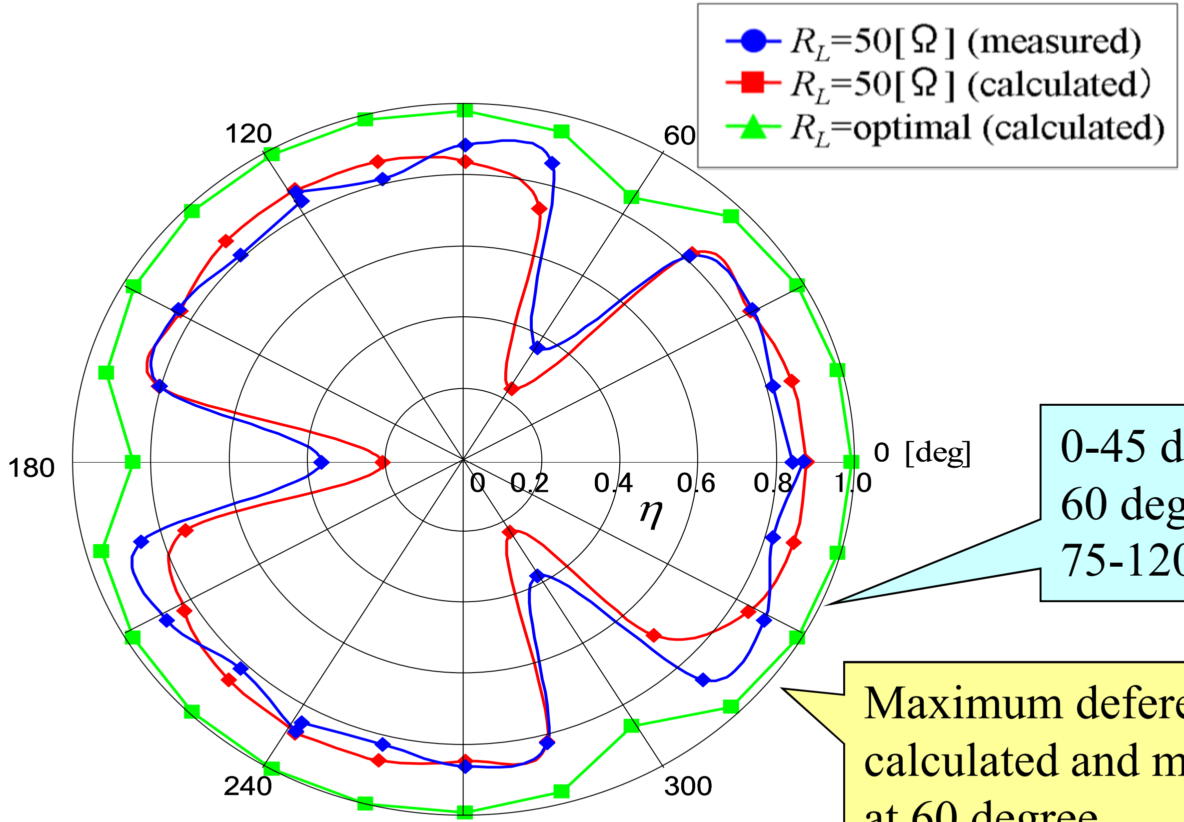
2.3. Experiment 7/7 (Result 6/6)

Efficiency (Power ratio)



0-45 degree: 80%
60 degree: 35%
75-120 degree: 80%

Maximum deference of calculated and measured value; at 60 degree

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Contents

3. Conclusion & future works

- Experiment and analysis of Three-phase WPT
  - 1. Comparison of data and **theoretical formula**

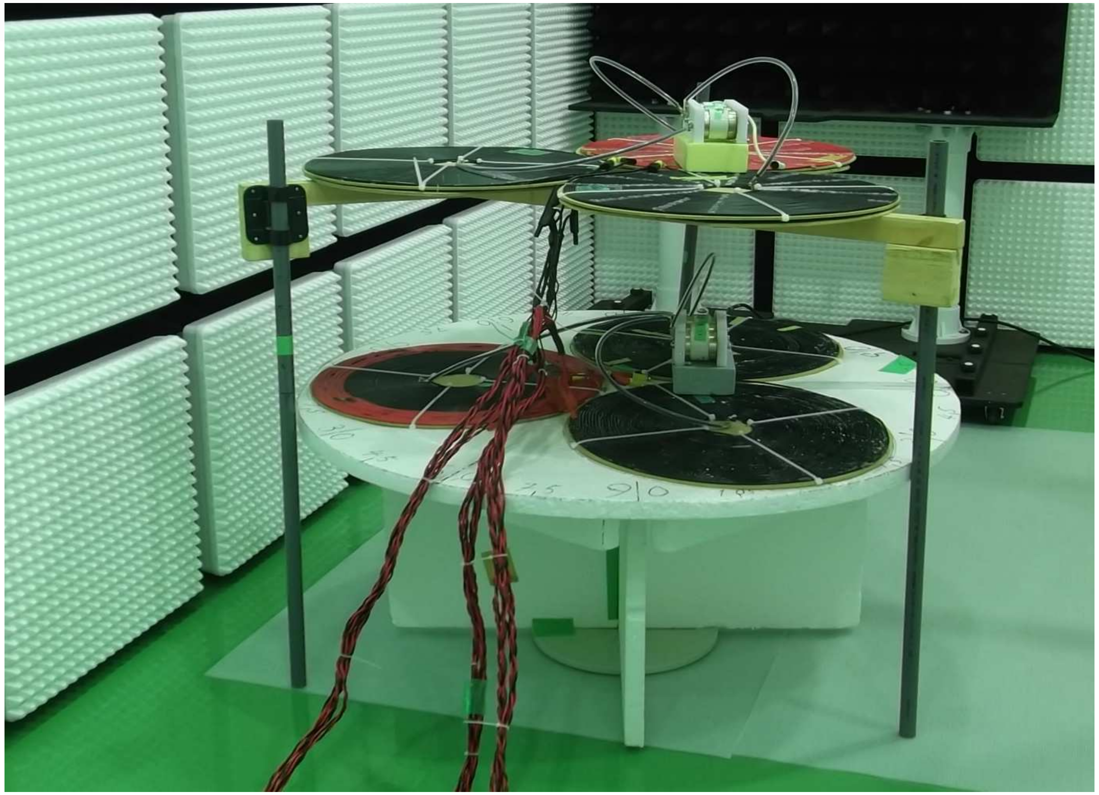
    Each formula draws the similar calculated value as measured value

  - 2. Rotation experiment

    Rotation symmetry of transmitters are shown in experimental result

- Future works
  - High power experiment and analysis
  - Coupling analysis as cross coupling.

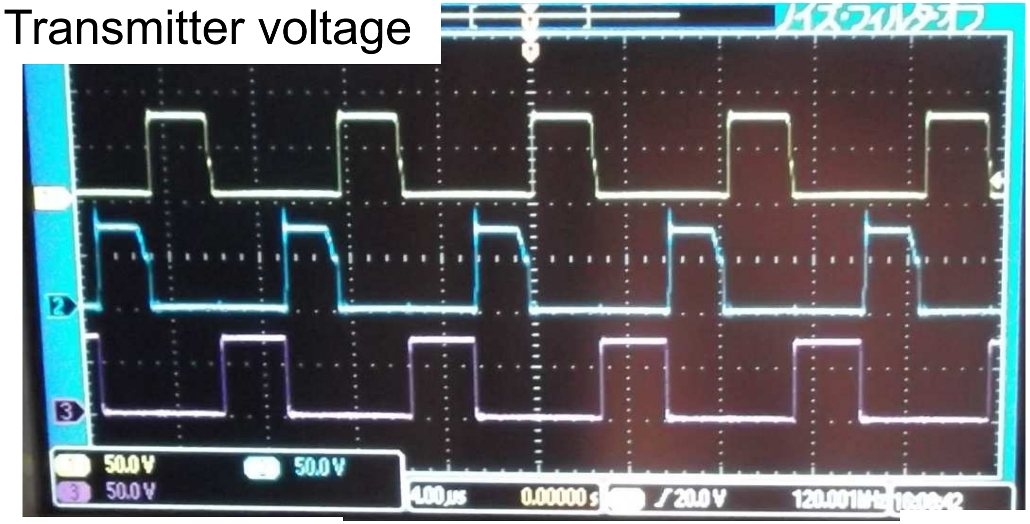
Thank you for listening



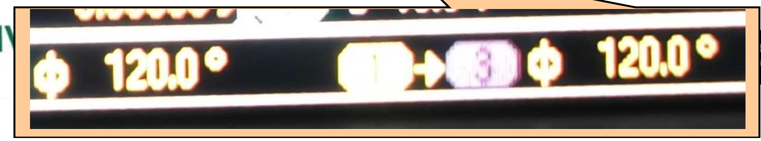
Advanced experiments are undergoing…

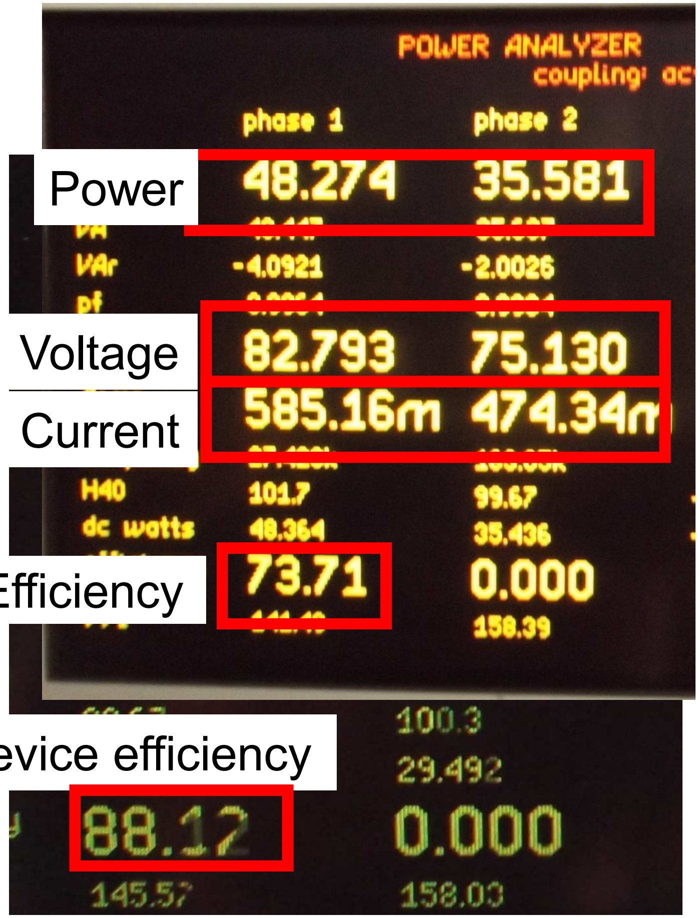
Appendix

Transmitter voltage



Receiver voltage

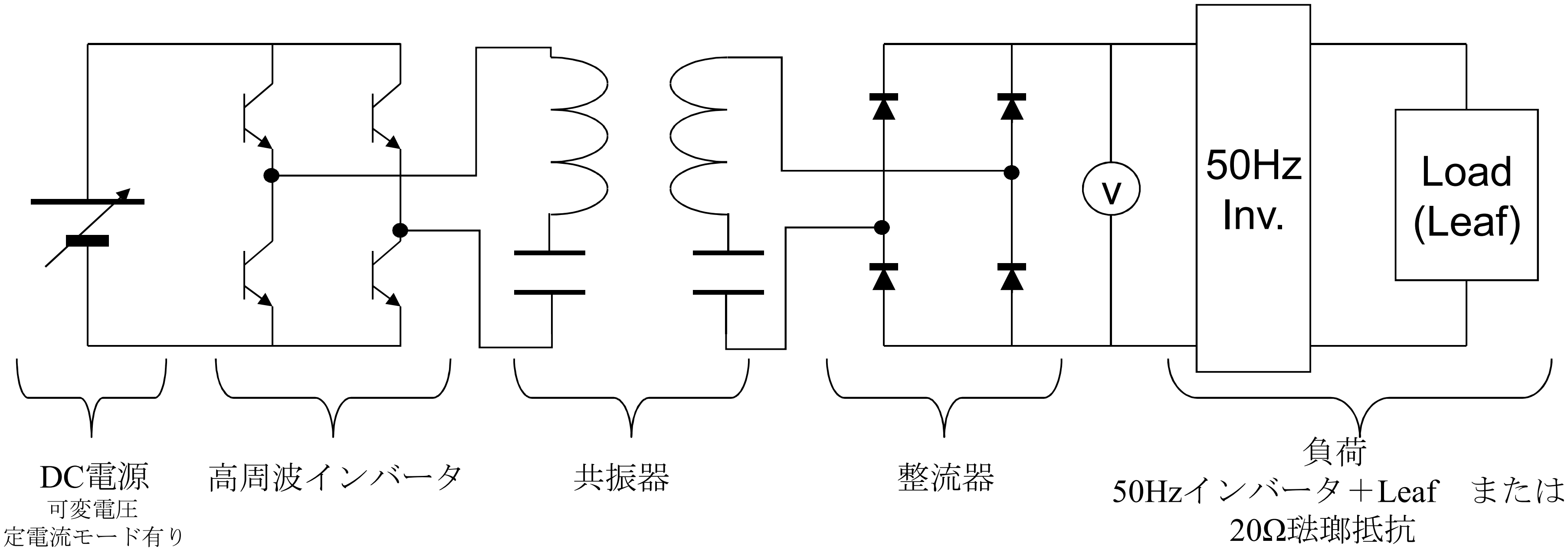


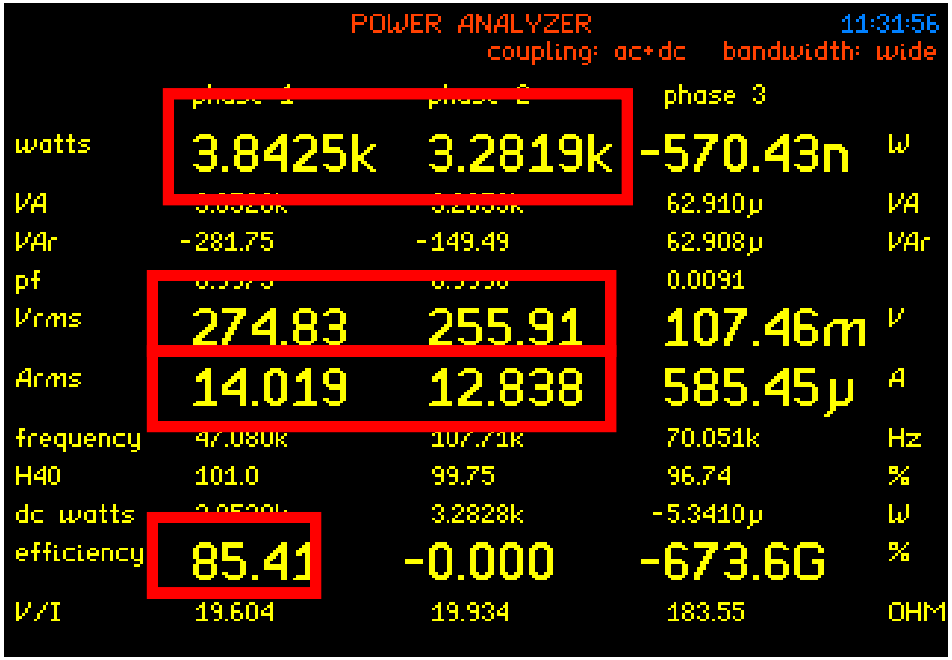


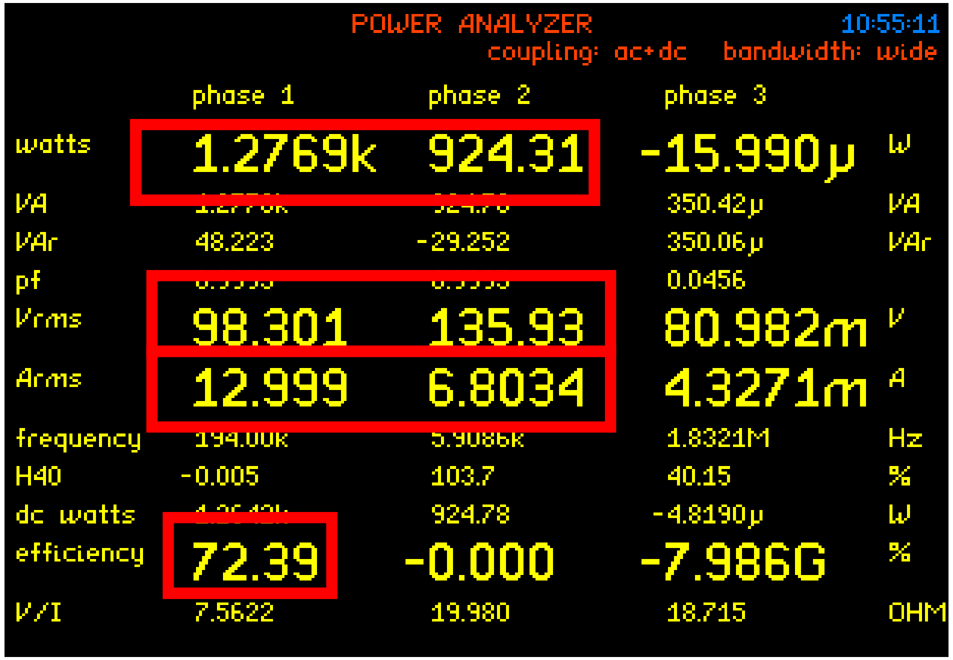
WPT efficiency

$$\eta = \frac{0.737}{0.884} = 0.830 = 83\%$$

回路構成


50Hz
Inv.
V
Load
(Leaf)
DC電源
可変電圧
定電流モード有り
高周波インバータ
共振器
整流器
負荷
50Hzインバータ＋Leaf　または
20Ω琺瑯抵抗


POWER ANALYZER
11:31:56
coupling: ac+dc bandwidth: wide
phase 3
watts
3.8425k
3.2819k
-570.43n
W
VA
62.910µ
VA
VAr
-281.75
-149.49
62.908µ
VAr
pf
0.0091
Vrms
274.83
255.91
107.46m
V
Arms
14.019
12.838
585.45µ
A
frequency
70.051k
Hz
H40
101.0
99.75
96.74
%
dc watts
3.2828k
-5.3410µ
W
efficiency
85.41
-0.000
-673.6G
%
V/I
19.604
19.934
183.55
OHM


POWER ANALYZER
10:55:11
coupling: ac+dc bandwidth: wide
phase 1
phase 2
phase 3
watts
1.2769k
924.31
-15.990µ
W
VA
350.42µ
VA
VAr
48.223
-29.252
350.06µ
VAr
pf
0.0456
Vrms
98.301
135.93
80.982m
V
Arms
12.999
6.8034
4.3271m
A
frequency
1.8321M
Hz
H40
-0.005
103.7
40.15
%
dc watts
924.78
-4.8190µ
W
efficiency
72.39
-0.000
-7.986G
%
V/I
7.5622
19.980
18.715
OHM

$$A_1 \sin(\omega t) + A_2 \sin(\omega t + \frac{\pi}{3}) + A_3 \sin(\omega t + \frac{2\pi}{3})$$

$$= A_1 \sin(\omega t)$$

$$+ A_2 \{\sin(\omega t)\cos\frac{\pi}{3} + \cos(\omega t)\sin\frac{\pi}{3}\}$$

$$+ A_3 \{\sin(\omega t)\cos\frac{2\pi}{3} + \cos(\omega t)\sin\frac{2\pi}{3}\}$$

$$= (A_1 - \frac{A_2}{2} - \frac{A_3}{2})\sin(\omega t) + (\frac{\sqrt{3}}{2}A_2 - \frac{\sqrt{3}}{2}A_3)\cos(\omega t)$$

$$= \sqrt{(A_1 - \frac{A_2}{2} - \frac{A_3}{2})^2 + (\frac{\sqrt{3}}{2}A_2 - \frac{\sqrt{3}}{2}A_3)^2}\ \sin(\omega t + \phi)$$

$$A_1 \sin(\omega t) + A_2 \sin(\omega t + \frac{\pi}{3}) + A_3 \sin(\omega t + \frac{2\pi}{3})$$

線間電圧と相電圧

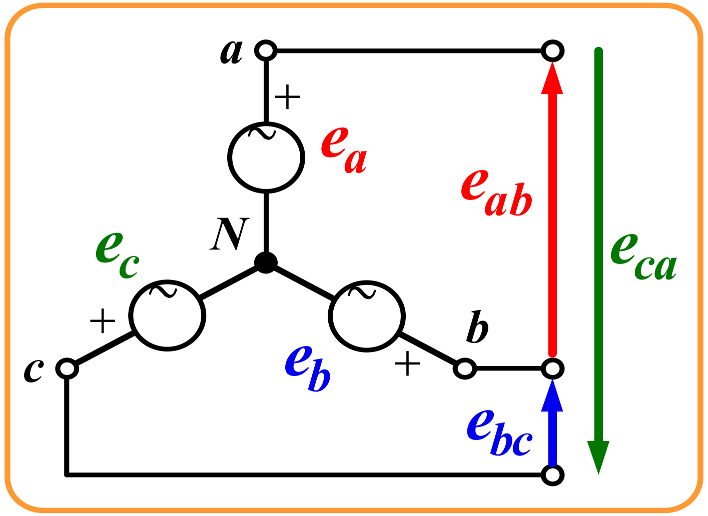
- 対称Y形起電力において

$$e_a = E_{m1}\sin(\omega t - 0°) + E_{m3}\sin 3\omega t + E_{m5}\sin(5\omega t - 0°) + \cdots$$
$$e_b = E_{m1}\sin(\omega t - 120°) + E_{m3}\sin 3\omega t + E_{m5}\sin(5\omega t - 240°) + \cdots$$
$$e_c = E_{m1}\sin(\omega t - 240°) + E_{m3}\sin 3\omega t + E_{m5}\sin(5\omega t - 120°) + \cdots$$

- 各線間電圧は $e_{ab} = e_a - e_b$

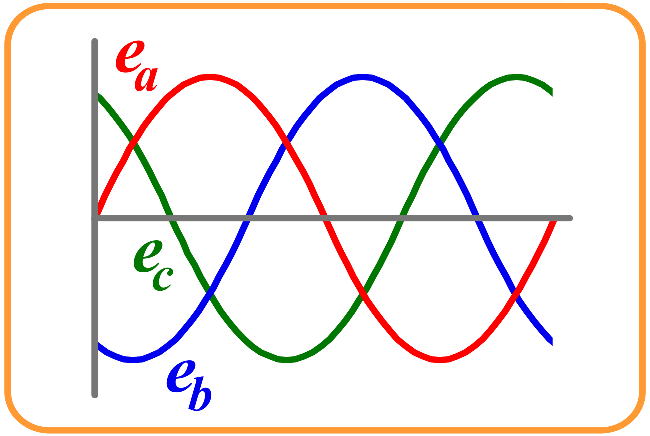
$$= E_{m1}\{\sin\omega t - \sin(\omega t - 120°)\}$$
$$+ E_{m5}\{\sin 5\omega t - \sin(5\omega t - 240°)\} + \cdots$$

線間電圧に三倍次高調波はあらわれない



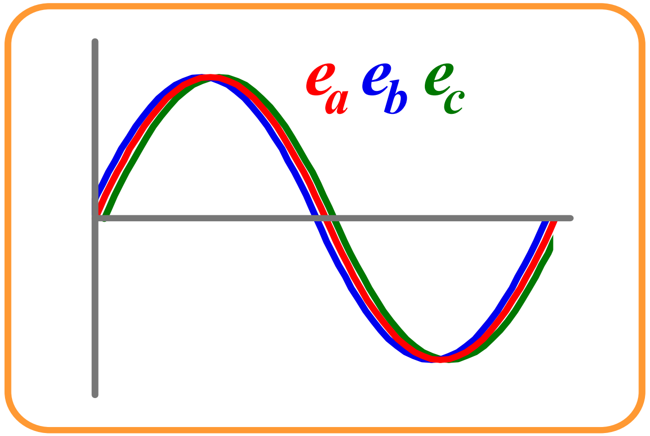
Y形結線における高調波

第1次調波など（正相）



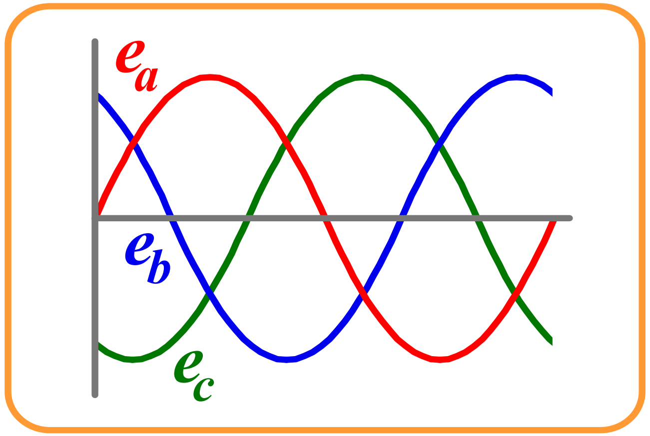
$$e_a+e_b+e_c=0$$

第3次調波など（同相）

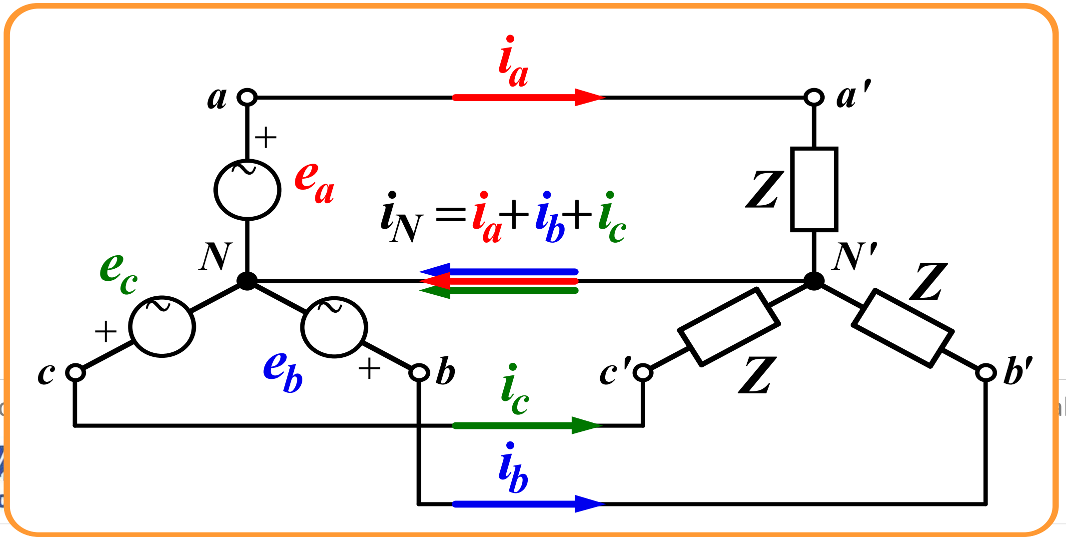


$$e_a+e_b+e_c=3E_{m3}\sin 3\omega t$$

第5次調波など（逆相）



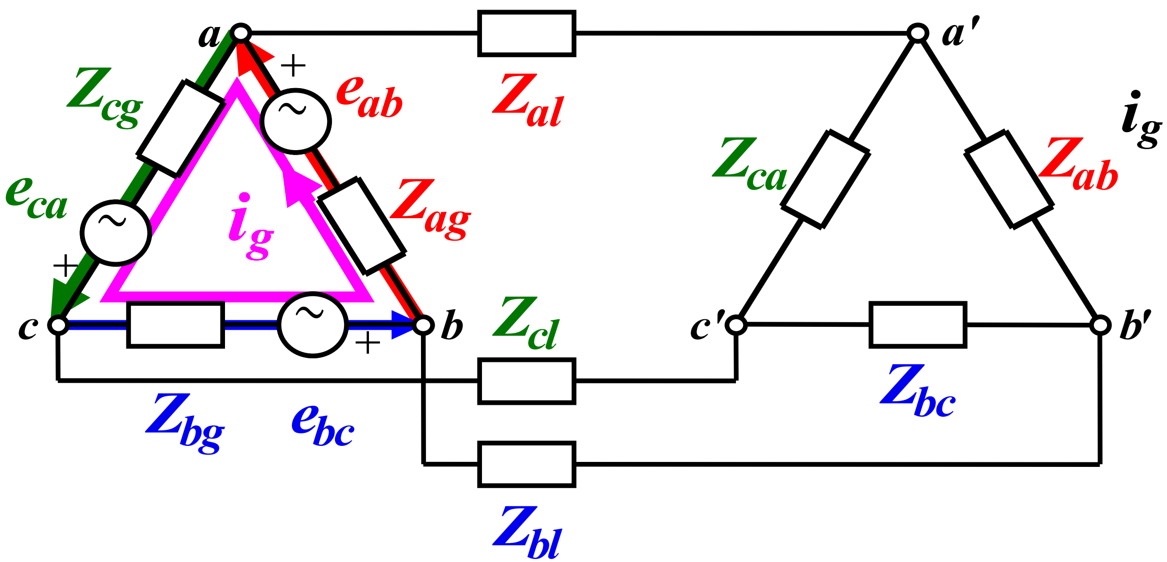
$$e_a+e_b+e_c=0$$



平衡回路でも、同相の高調波があれば中性点間に電流が流れる

Delta connection with harmonic waves

第1次調波など（正相）	第3次調波など（同相）	第5次調波など（逆相）
$e_a+e_b+e_c=0$	$e_a+e_b+e_c=3E_{m3}\sin 3\omega t$	$e_a+e_b+e_c=0$



$$i_g=\frac{e_a+e_b+e_c}{Z_{ag}+Z_{bg}+Z_{cg}}$$

平衡回路でも同相の高調波があれば起電力回路に循環電流が流れる

The 27th INTERNATIONAL ELECTRIC VEHICLE SYMPOSIUM & EXHIBITION
BARCELONA
17th-20th November 2013

0 phase current

$$e_a = e(t) = E_{m1}\sin\omega t + E_{m3}\sin 3\omega t + E_{m5}\sin 5\omega t + \dots$$

$$e_b = e(t - T/3) = E_{m1}\sin\omega(t - T/3) + E_{m3}\sin 3\omega(t - T/3) + E_{m5}\sin 5\omega(t - T/3) + \dots$$

$$= E_{m1}\sin(\omega t - 120^\circ) + E_{m3}\sin(3\omega t) + E_{m5}\sin(5\omega t - 240^\circ) + \dots$$

$$e_c = e(t - 2T/3) = E_{m1}\sin(\omega t - 240^\circ) + E_{m3}\sin(3\omega t) + E_{m5}\sin(5\omega t - 120^\circ) + \dots$$

evs 27
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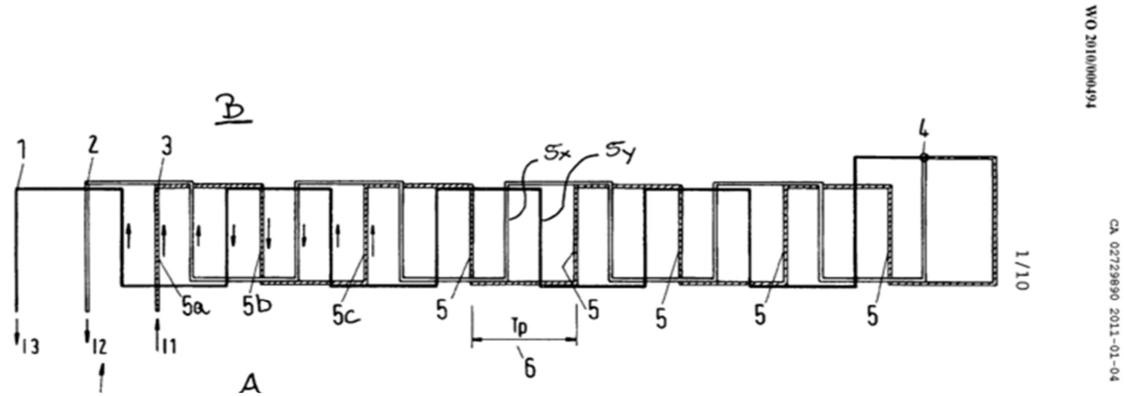
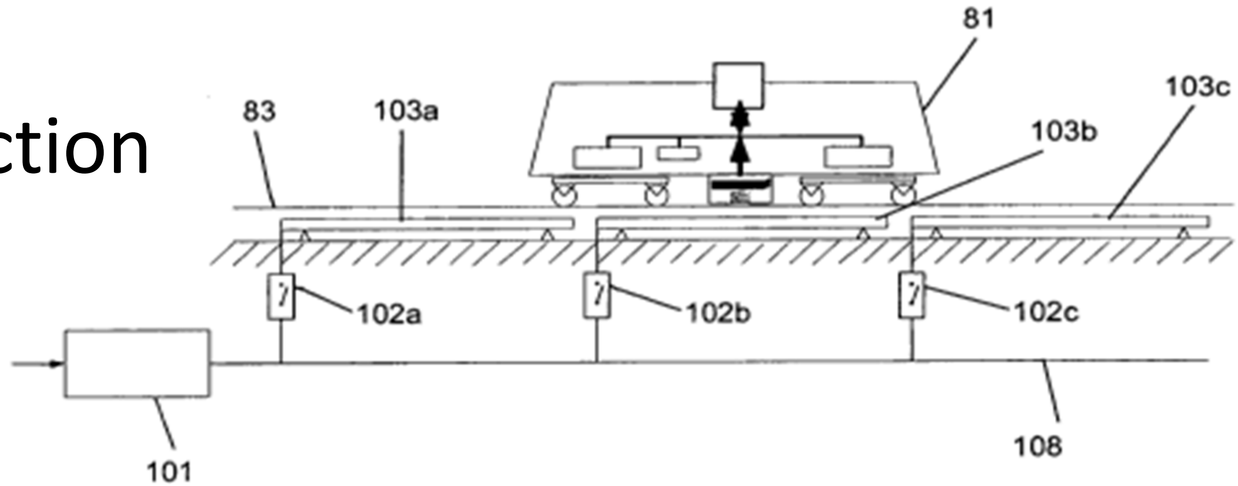
Previous research



- induction



Analysis for previous research

- Induction without magnetic resonant coupling

Ladder coil transmitter for rail transport

  - Small air gap
  - Three phase receivers are original of us
  -