IEEE Young Professionals in Circuits and Systems (YPCAS) Forum

華南理工大學
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Optimized Design of Anti-Misalignment Magnetic Coupler for Static and Dynamic Inductive Power Transfer

Dr. Zhicong Huang

zhiconghuang@scut.edu.cn

South China University of Technology,

Guangzhou, China

Outline

- Research Background and Motivation
- Rectangular Solenoidal Pad (RSP)
- Control Free Design for RSP Tx
- Dynamic Tx Track based on RSP

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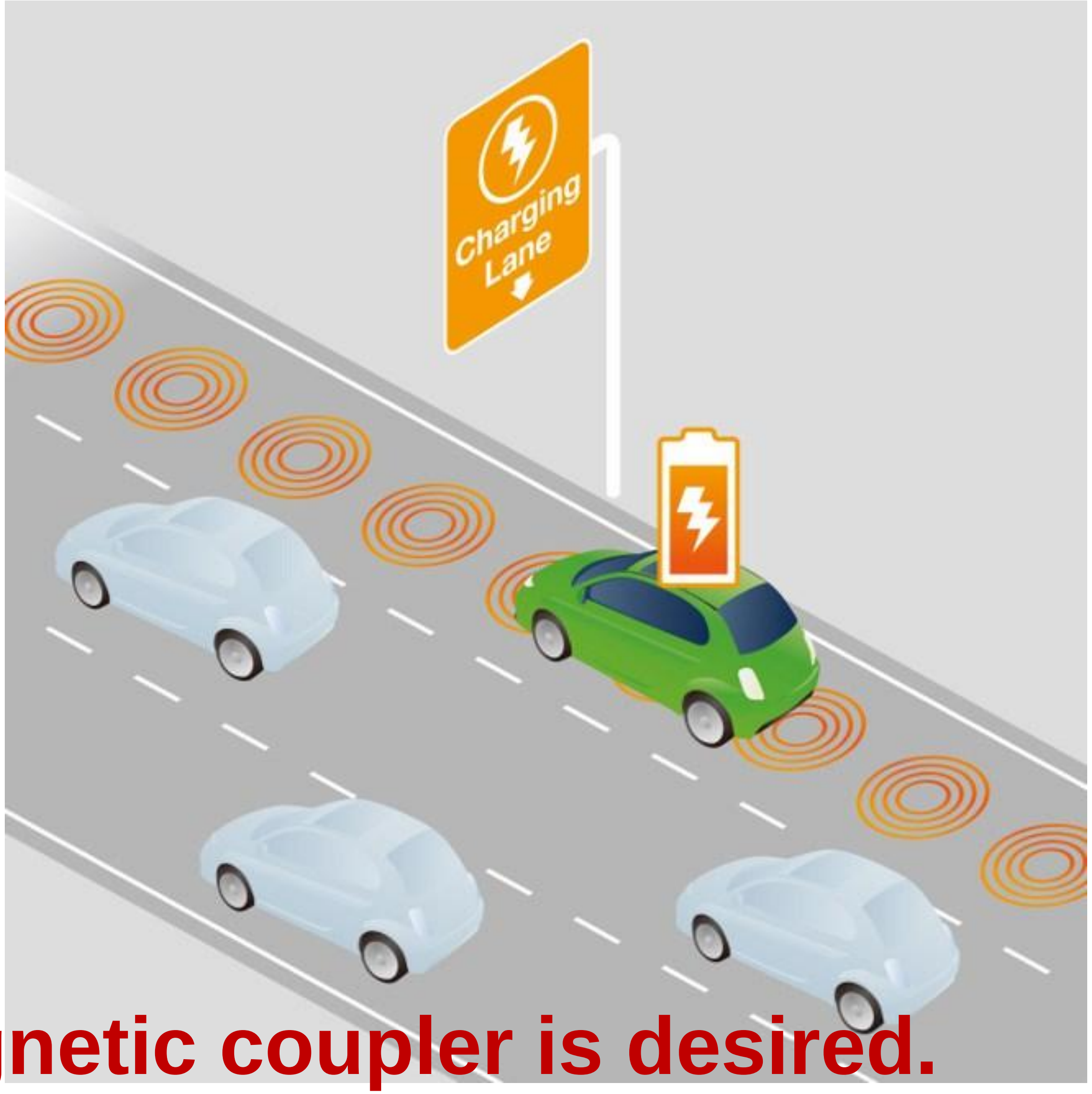
Outline

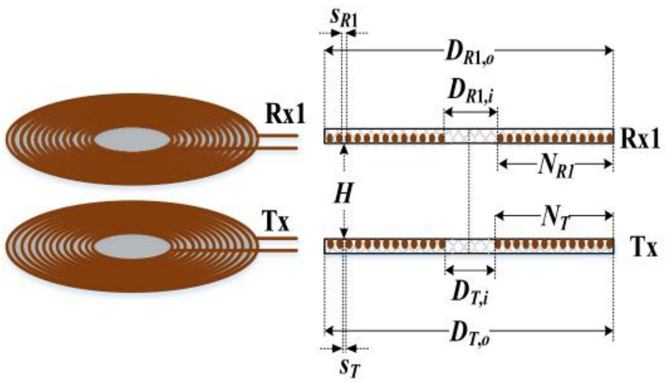
- **Research Background and Motivation**
- **Rectangular Solenoidal Pad (RSP)**
- **Control Free Design for RSP Tx**
- **Dynamic Tx Track based on RSP**

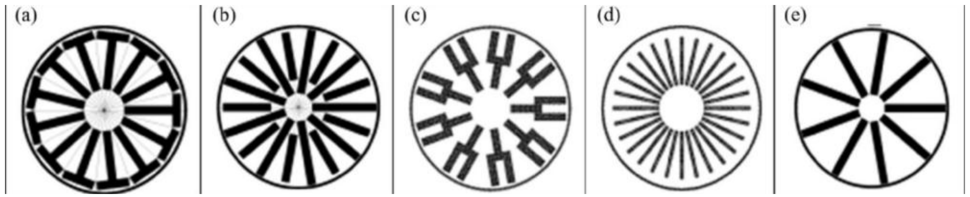
From Static to Dynamic Wireless EV Charging

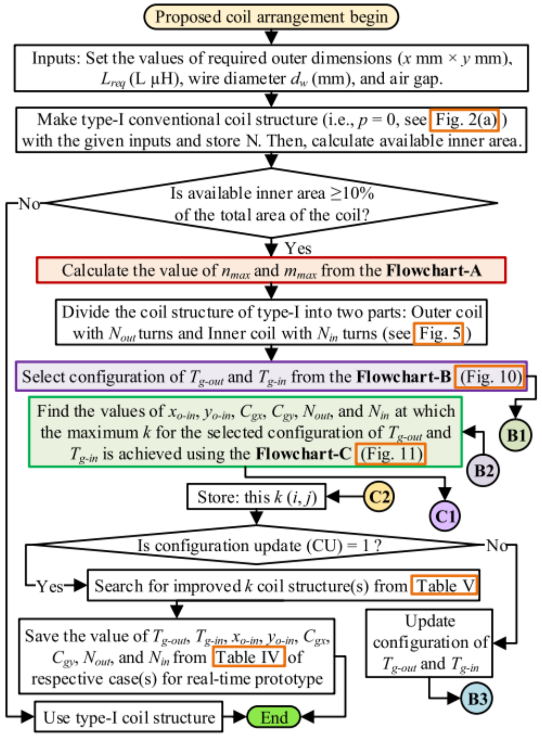


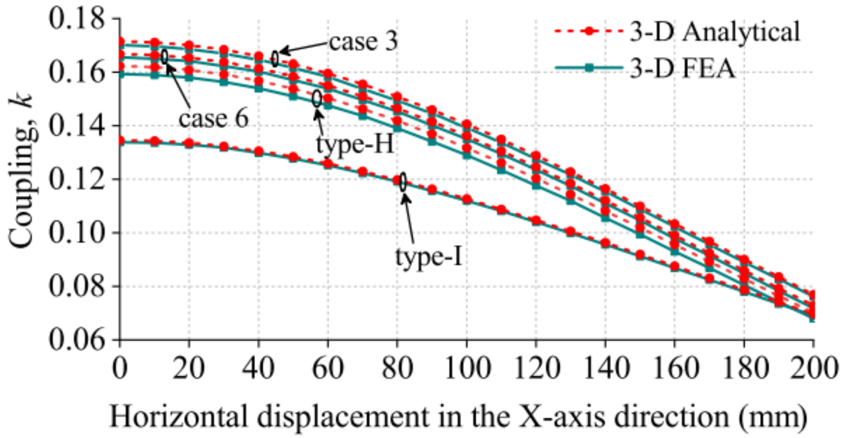
Anti-misalignment magnetic coupler is desired.

Symmetric Design









Coupling coefficient degrades significantly if misalignment occurs.

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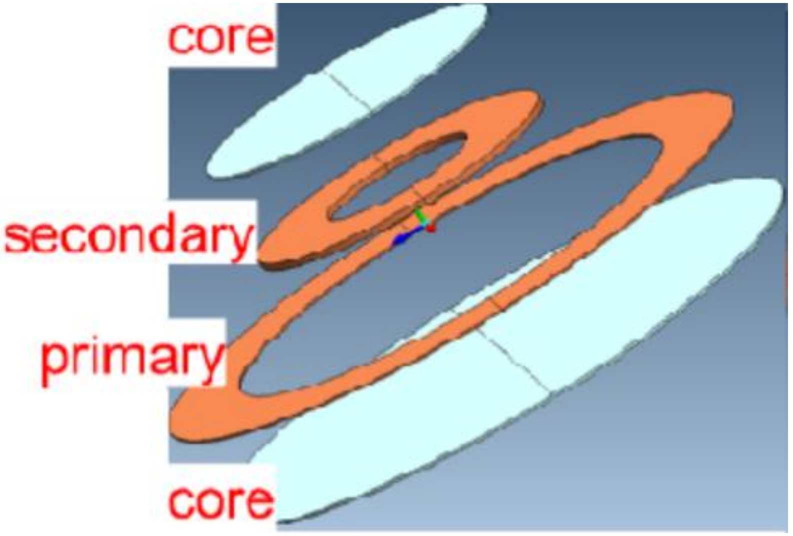
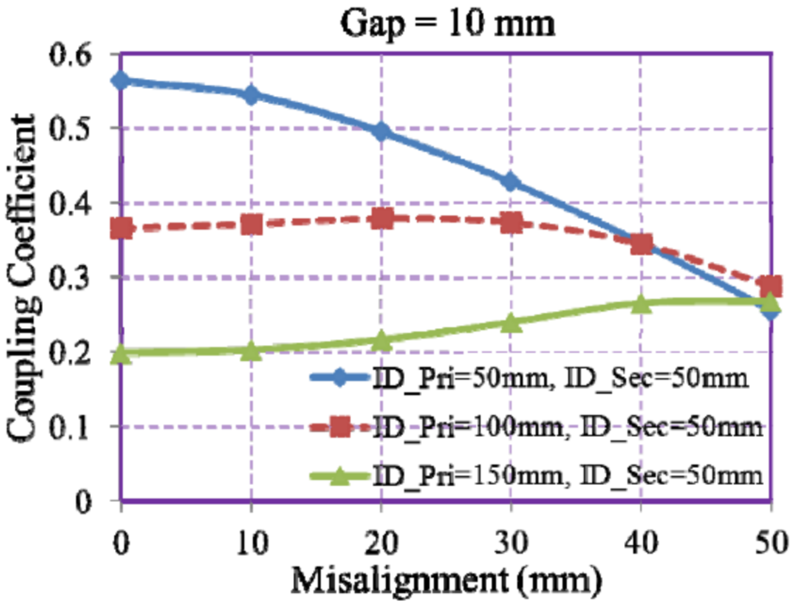
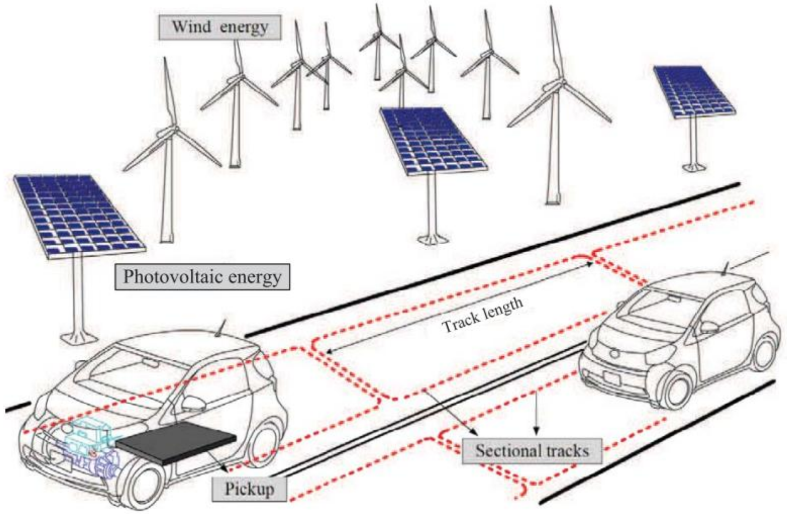
[1] M. Budhia, G. A. Covic and J. T. Boys, "Design and Optimization of Circular Magnetic Structures for Lumped Inductive Power Transfer Systems," in IEEE Transactions on Power Electronics, vol. 26, no. 11, pp. 3096-3108, Nov. 2011.

[2] G. Rituraj, B. K. Kushwaha and P. Kumar, "A Unipolar Coil Arrangement Method for Improving the Coupling Coefficient Without Ferrite Material in Wireless Power Transfer Systems," *IEEE Trans. Transport. Electrific.*, vol. 6, no. 2, pp. 497-509, Jun. 2020.

Asymmetric Design



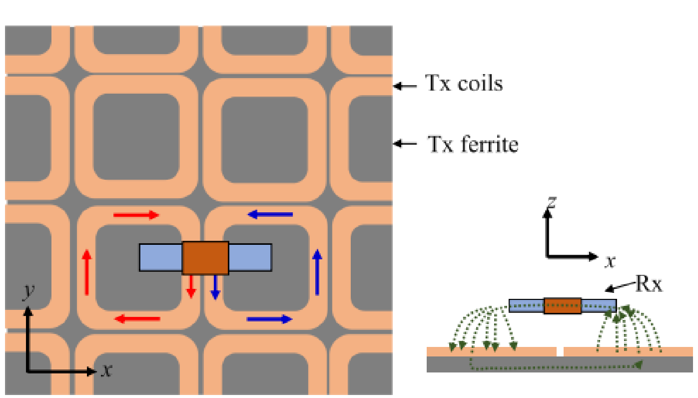


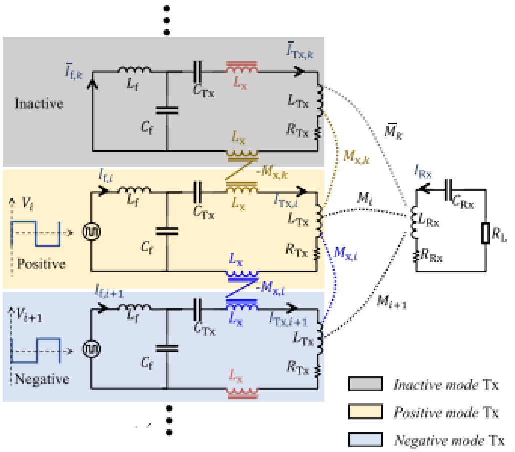


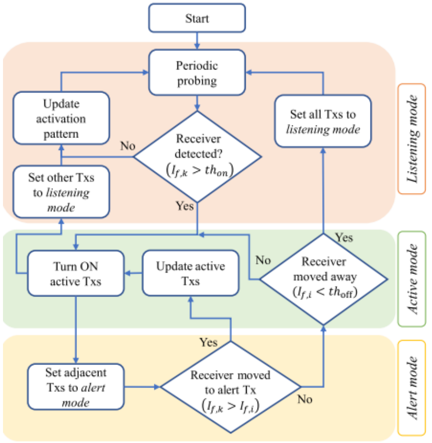
relatively even but poor magnetic coupling due to magnetic leakage

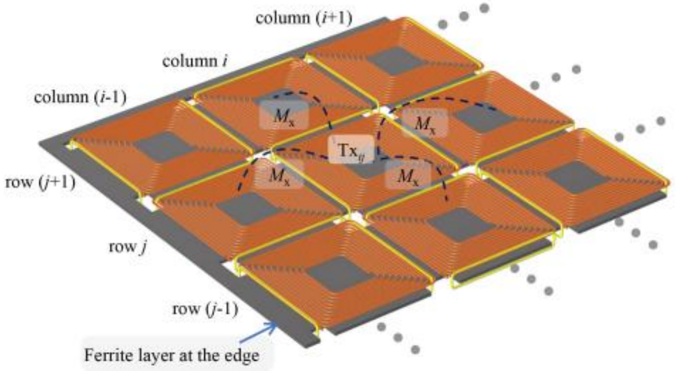
[1] C. Zheng, L. Zhang, X. Zhao, J. Choe and J. -S. Lai, "Asymmetrical loosely coupled transformer for wireless laptop charger with higher misalignment tolerance," 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, Canada, 2015, pp. 3119-3126.
[2] W. Zhang, S. -C. Wong, C. K. Tse and Q. Chen, "An Optimized Track Length in Roadway Inductive Power Transfer Systems," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 2, no. 3, pp. 598-608, Sep. 2014.

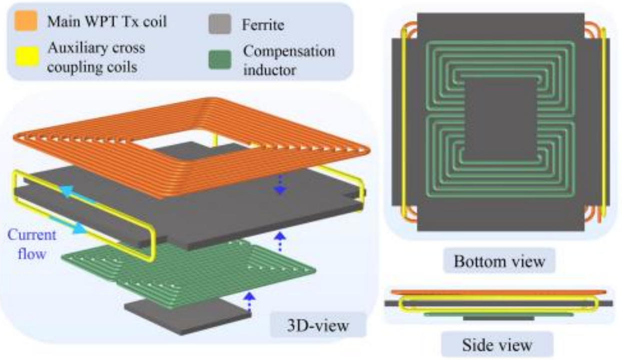
Planar Array Design

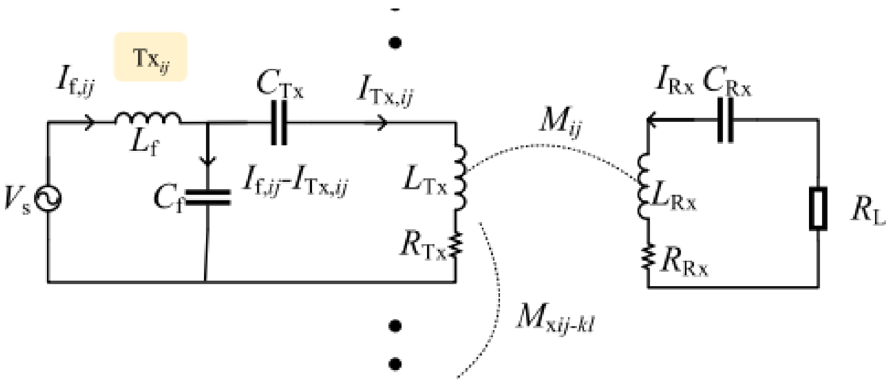








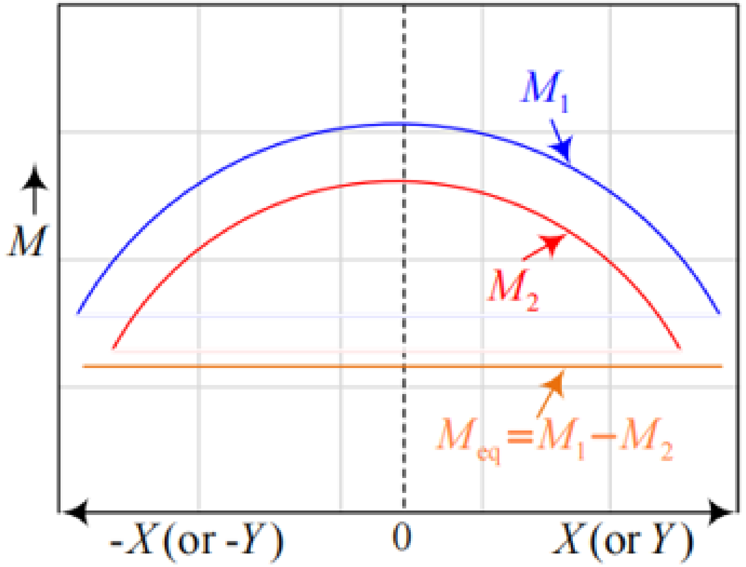


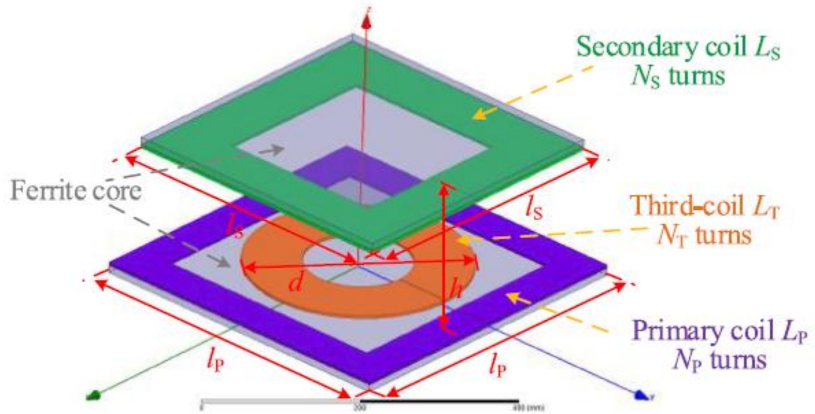


Complex control for activation and cancellation of mutual coupling

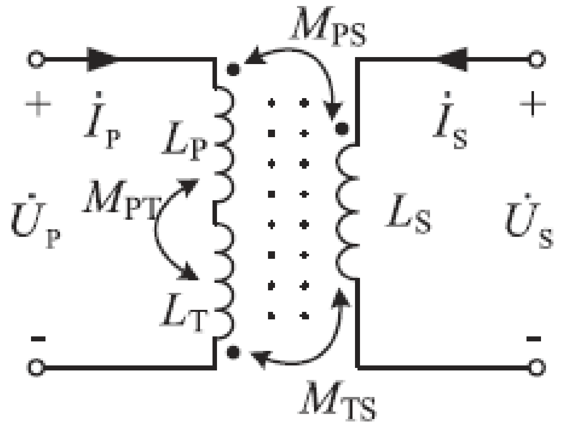
[1] S. A. Al Mahmud, I. Panhwar and P. Jayathurathnage, "Large-Area Free-Positioning Wireless Power Transfer to Movable Receivers," IEEE Trans. Ind. Electron., vol. 69, no. 12, pp. 12807-12816, Dec. 2022.
[2] P. Jayathurathnage, Y. Liu and J. Kyyrä, "Self-Decoupled and Integrated Coils for Modular Multitransmitter Wireless Power Transfer Systems," IEEE Trans.Power Electron., vol. 37, no. 11, pp. 12962-12967, Nov. 2022.

Magnetic Field Cancellation





$$M_{eq}=|M_{PS}|-|M_{TS}|$$



Excessive copper usage, but degraded power transfer capability

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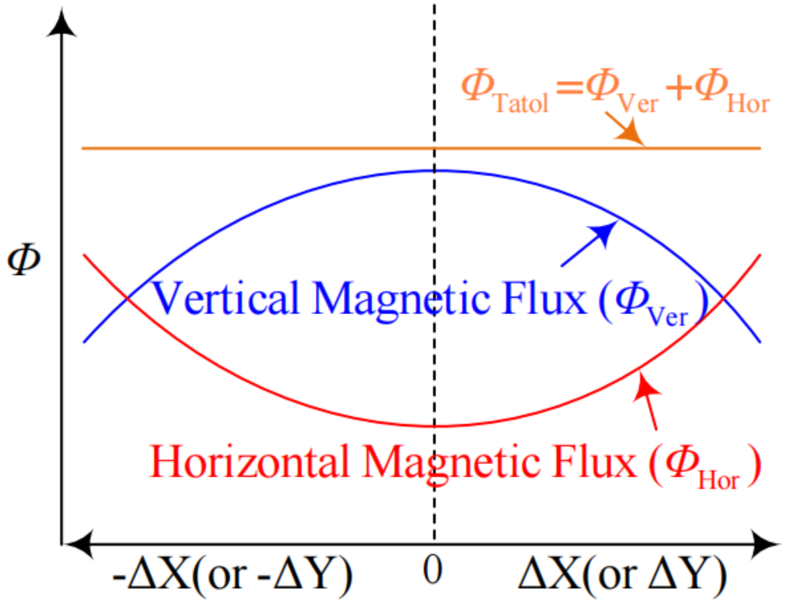
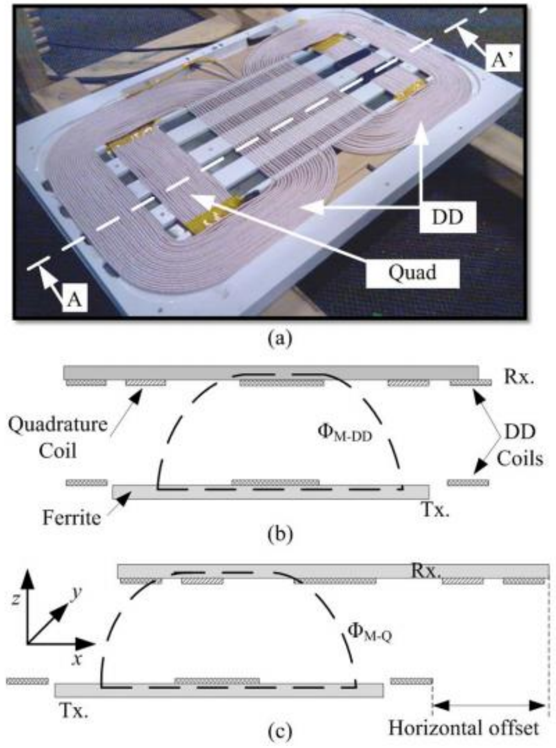
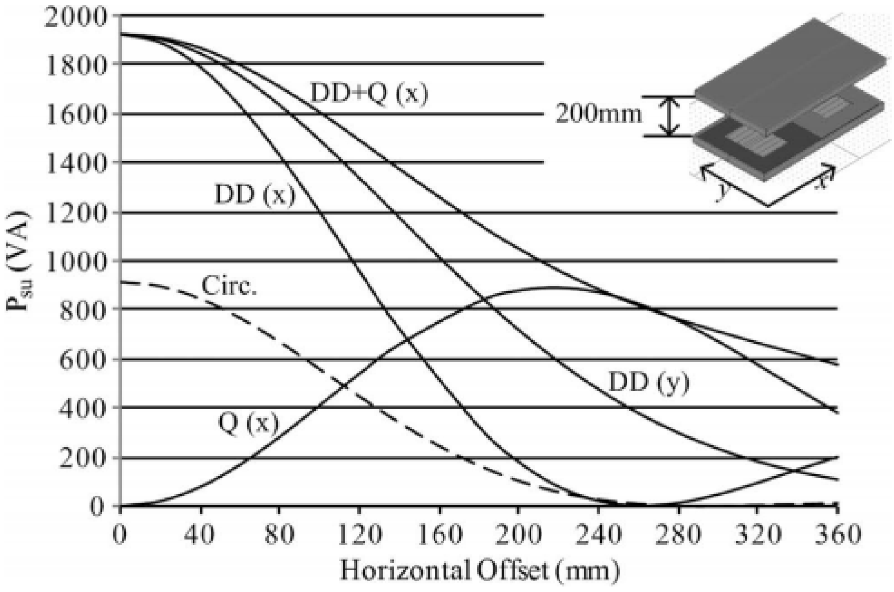
[1] Y. Chen, R. Mai, Y. Zhang, M. Li and Z. He, "Improving Misalignment Tolerance for IPT System Using a Third-Coil," IEEE Trans.Power Electron., vol. 34, no. 4, pp. 3009-3013, Apr. 2019.

Magnetic Field Complementation



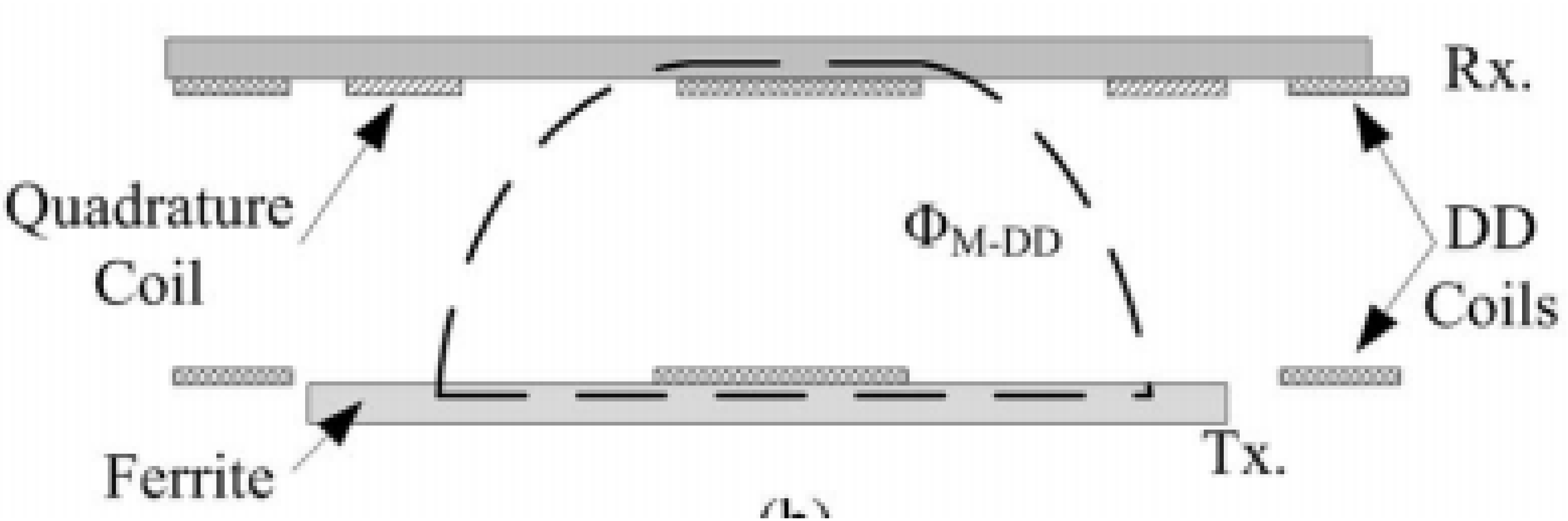


$$M_{eq} = |M_{PS}| + |M_{TS}|$$



DDQP is widely used due to its good anti-misalignment capability.

[1] M. Budhia, J. T. Boys, G. A. Covic, and C. Y. Huang, "Development of a single-sided flux magnetic coupler for electric vehicle IPT charging systems," IEEE Trans. Ind. Electron., vol. 60, no. 1, pp. 318-328, Jan. 2013.



Is the DDQP Good Enough?

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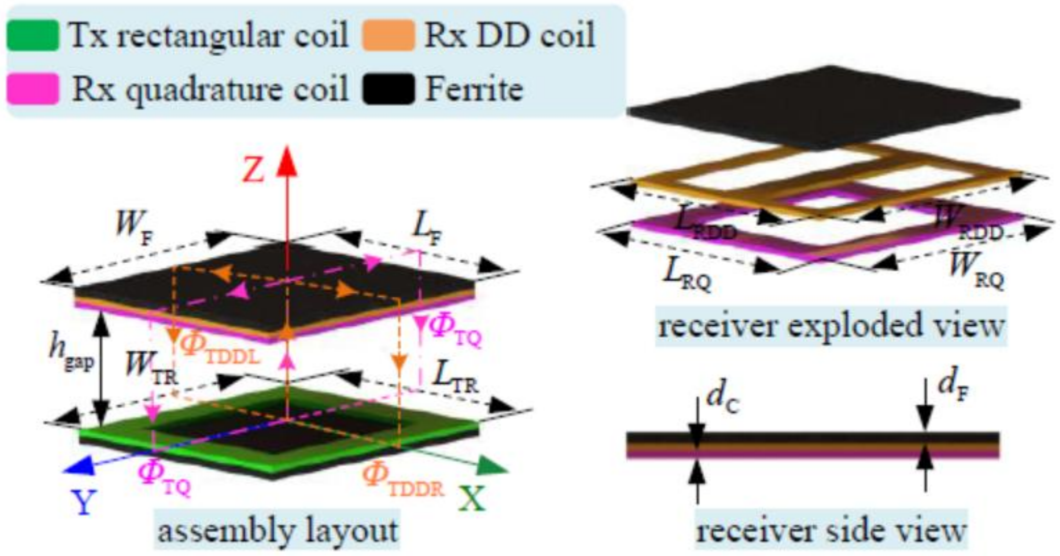
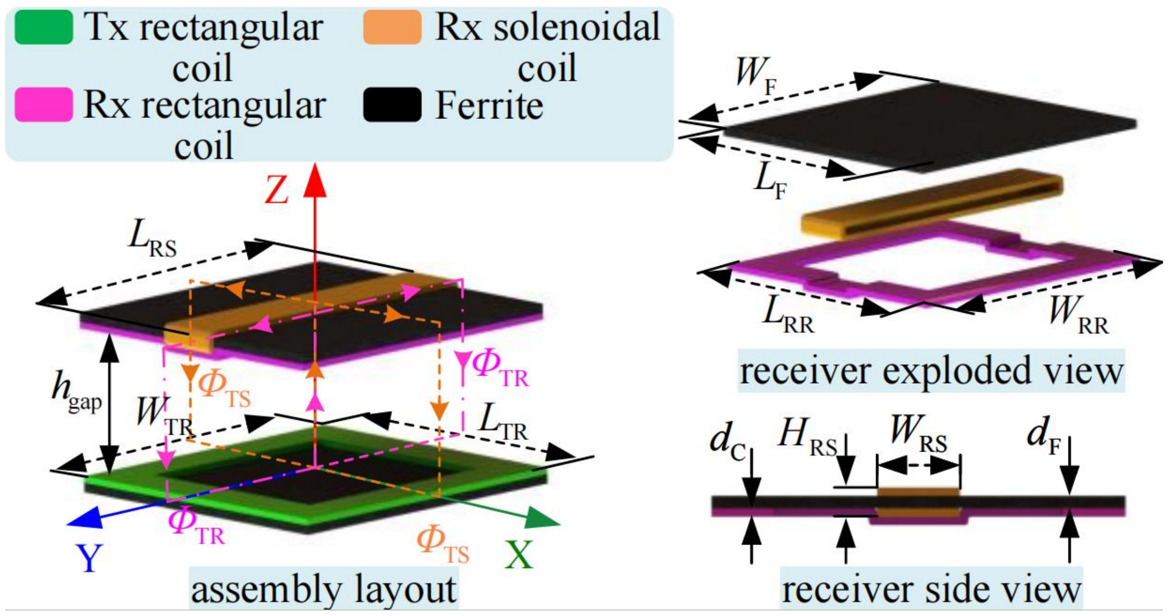
From DD coil to Solenoidal Coil



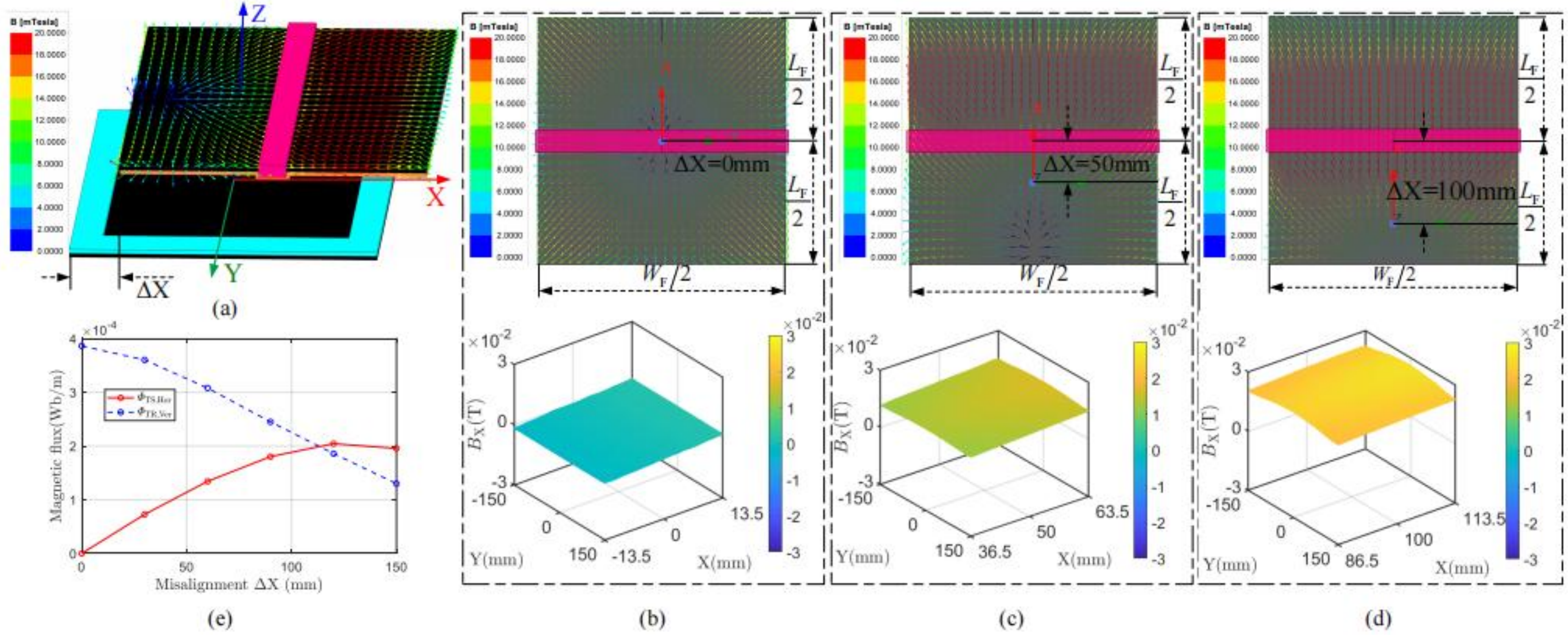
RP-DDQP



RP-RSP

Hai Xu, **Zhicong Huang***, Xiaolu Lucia Li*, and Chi K. Tse, "Misalignment-tolerant IPT coupler with enhanced magnetic flux variation suppression and reduced copper usage," IEEE Transactions on Power Electronics, vol. 39, no. 8, pp. 10506-10517, Aug. 2024.

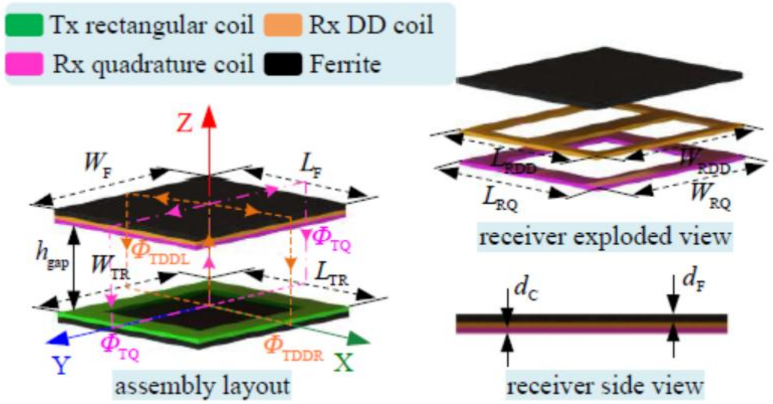
Operating Principle



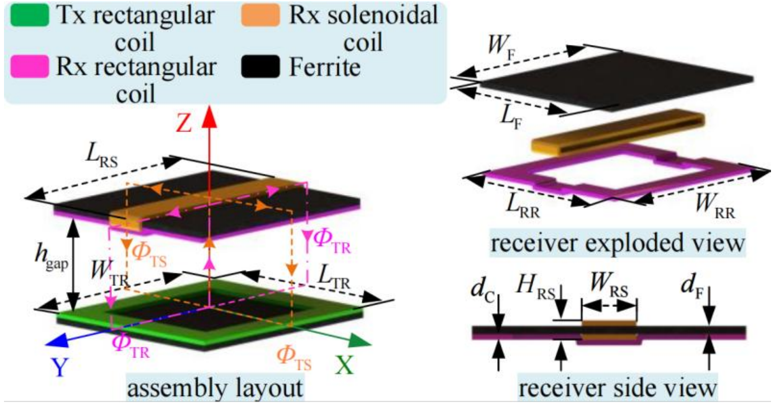
(a) Coordinates. (b) ΔX = 0 mm (fully aligned). (c) ΔX= 50 mm. (d) ΔX= 100 mm. (e) Diagrams of $\Phi_{TR,Ver}$ and $\Phi_{TS,Hor}$

Capture vertical and horizontal magnetic field in a complementary manner for pad misalignment

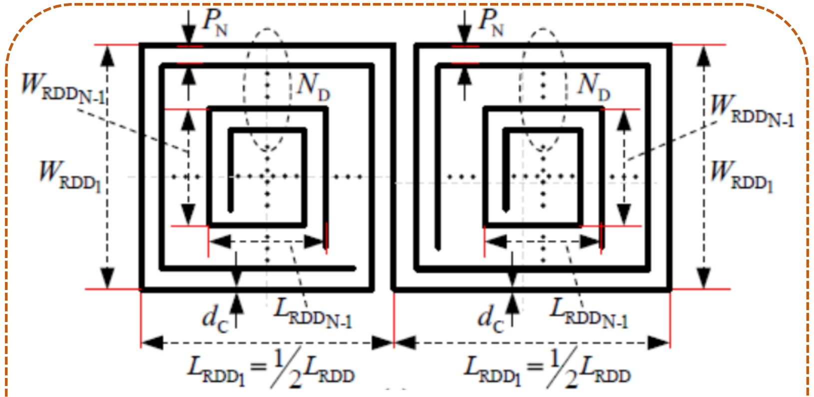
Magnetic Flux Capture Capability



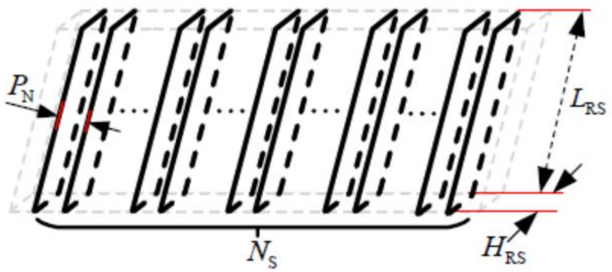
DDQP



Rectangular-Solenoidal Pad（RSP）



Geometries of DD coil



Geometries of solenoidal coil

Effective magnetic flux captured by DD coil with N_D turns

$$\Phi_{TDD} = \int_{S_{L_1}} B_{Z_{L_1}} \cos\alpha dS + \cdots + \int_{S_{L_{N_D}}} B_{Z_{L_{N_D}}} \cos\alpha dS$$
$$(-\int_{S_{R_1}} B_{Z_{R_1}} \cos\alpha dS + \cdots + \int_{S_{R_{N_D}}} B_{Z_{R_{N_D}}} \cos\alpha dS).$$

Make $S_{DD_i}=S_{L_i}=S_{R_i}$.

where

$$S_{DD_1} = \frac{1}{2} L_{RDD} W_{RDD}$$
$$S_{DD_2} = (\frac{1}{2} L_{RDD} - 2(d_C + P_N))(W_{RDD} - 2(d_C + P_N))$$
$$\cdots$$
$$\cdots$$
$$S_{DD_N} = (\frac{1}{2} L_{RDD} - 2(N_D - 1)(d_C + P_N))(W_{RDD} - 2(N_D - 1)(d_C + P_N))$$

Effective magnetic flux captured by solenoidal coil with N_S turns

$$\phi_{TS} = \int_{S_1} B_{X_{S_1}} \cos\alpha dS + \int_{S_2} B_{X_{S_2}} \cos\alpha dS + \cdots + \int_{S_i} B_{X_{S_i}} \cos\alpha dS + \cdots + \int_{S_{N_S}} B_{X_{S_{N_S}}} \cos\alpha dS.$$

$$S_S = S_1 = S_2 = \cdots = S_{N_S} = (L_{RS} - 2d_C)(H_{RS} - 2d_C).$$

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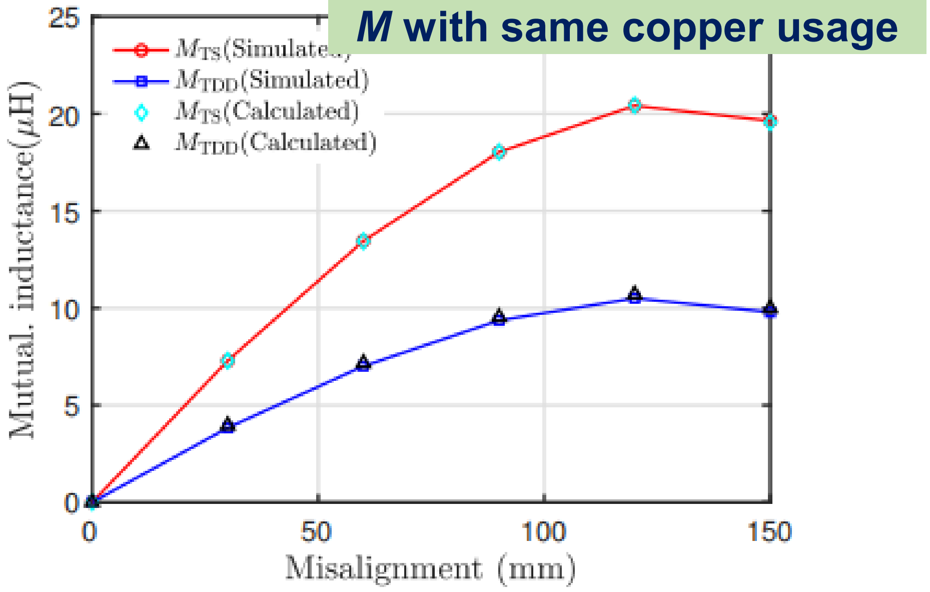
Magnetic Flux Capture Capability

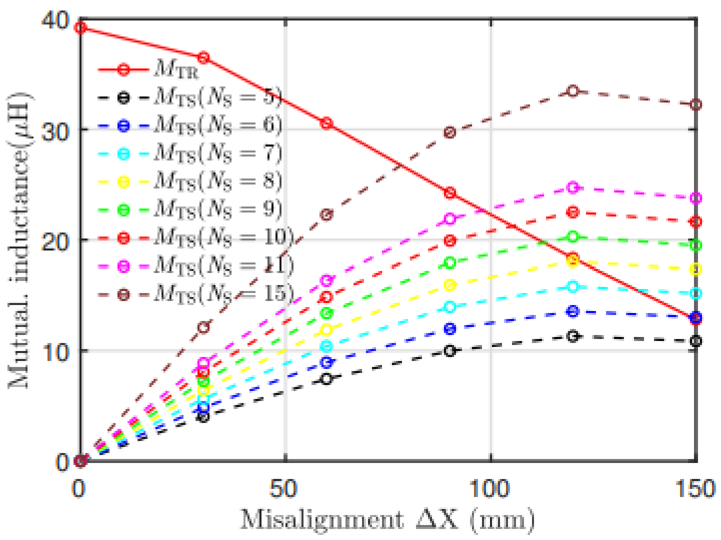
TABLE I
PARAMETERS OF THE COUPLER

Items	Symbols	Parameters	Value(mm)
RSP coupler	L_{RR}	Lenght of Rx rectangular coil	300
	W_{RR}	Width of Rx rectangular coil	300
	L_{RS}	Lenght of Rx solenoidal coil	306
	H_{RS}	Height of Rx solenoidal coil	9
DDQP coupler	L_{RDD}	Lenght of Rx DD coil	300
	W_{RDD}	Width of Rx DD coil	300
	L_{RQ}	Lenght of Rx solenoidal coil	300
	W_{RQ}	Width of Rx quadrature coil	300
Common parameters	L_{TR}	Lenght of Tx rectangular coil	300
	W_{TR}	Width of Tx rectangular coil	300
	$L_{\mathrm{F}}, W_{\mathrm{F}}$	Ferrite dimensions	300,300
	d_{F}		3
	d_{C}	Litz wire diameter of coils	3
	h_{gap}	Power transfer gap distance	60
	N	Turn numbers of unipolar coils	10
	P_{N}	Turn space of coils	0



The solenoidal coil can better capture the horizontal magnetic field using the same amount of copper.

Design of Rectangular Solenoidal Coil



Mutual inductances M_{TR} and M_{TS}

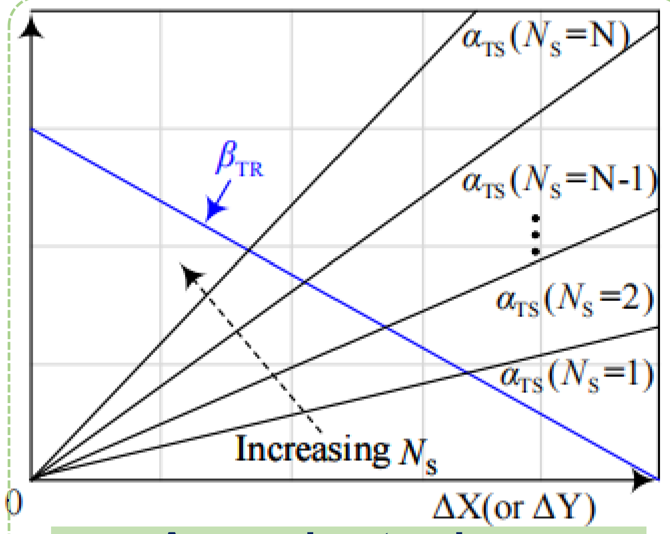
Linearization

$$M_{TS} \approx \alpha_{TS} \Delta X$$

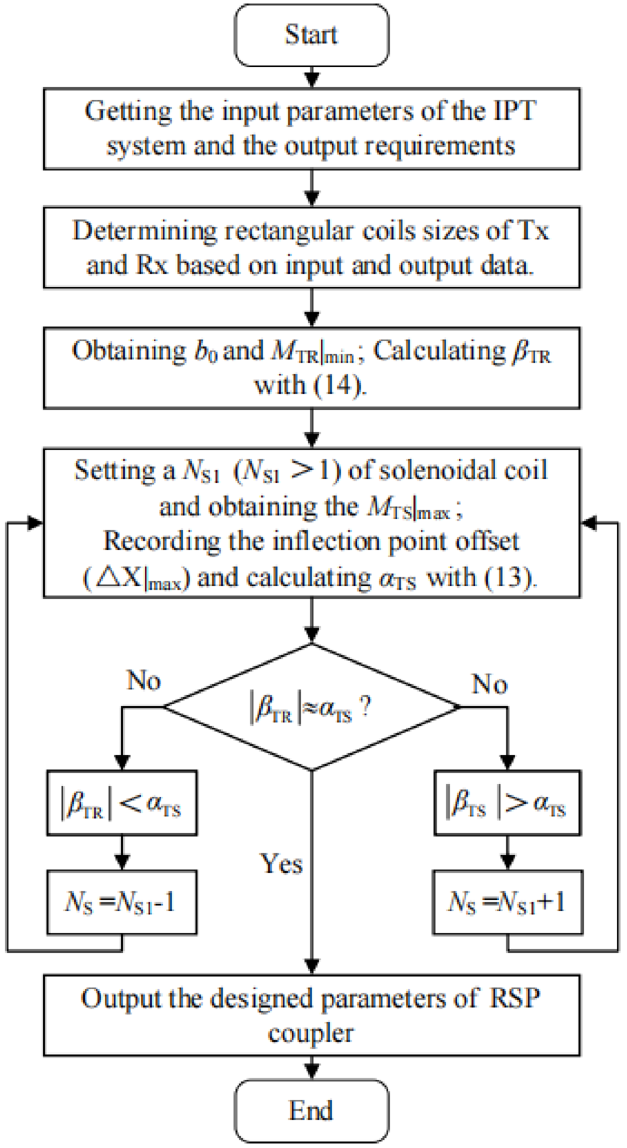
$$M_{TR} \approx \beta_{TR} \Delta X + b_0$$

$$M_{TR} + M_{TS} \approx b_0, \text{ if}$$

$$\alpha_{TS} + \beta_{TR} = 0.$$



Approximate slope matching design principles



Misalignment enhancement design flowchart based on approximate slope prediction of RSP coupler

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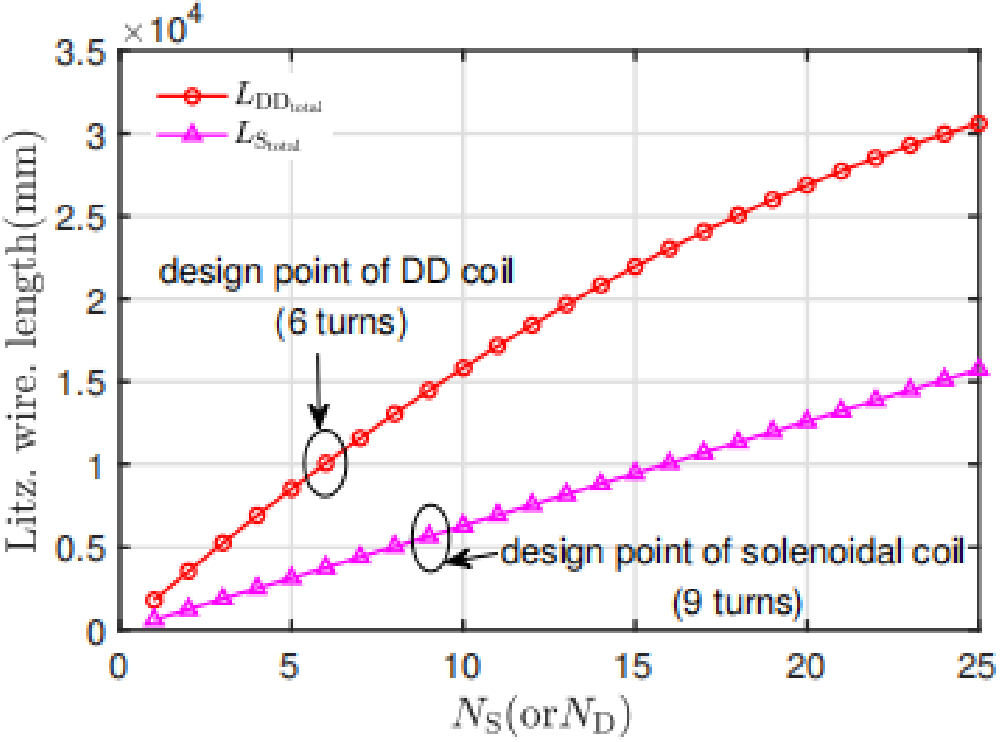
Comparison of Copper Usage

TABLE II
SLOPE AND COPPER CONSUMPTION OF RSP COUPLER AND DDQP COUPLER VERSUS NUMBER OF TURNS

Symbol	Turns number	Slopes	Copper (mm)
Rectangular coil	10	-0.174	
Solenoidal coil	5	0.094	3150
	6	0.113	3780
	7	0.132	4410
	8	0.150	5040
	9	0.169	5670
	10	0.188	6300
	11	0.206	6930
	15	0.279	9450
DD coil	5	0.139	8520
	6	0.163	10080
	7	0.186	11592
	8	0.208	13056
	9	0.228	14472
	10	0.248	15840
	11	0.265	17160
	15	0.320	21960



The proposed solenoidal coil can save **43.73%** litz wire consumption compared with the DD coil for the same anti-misalignment capability.

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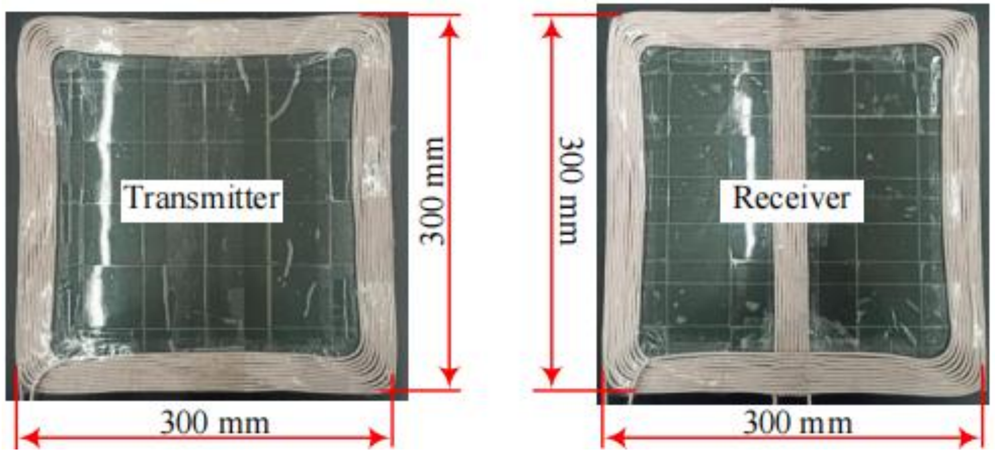
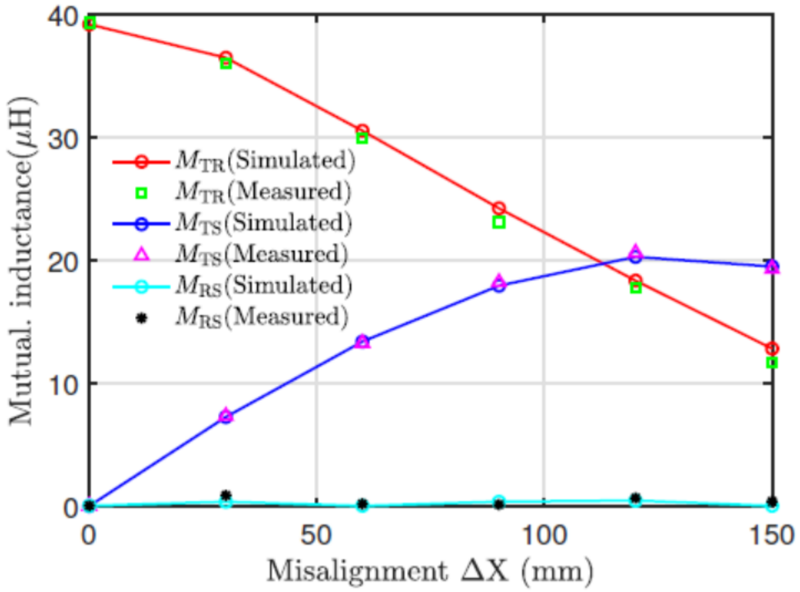
Experimental Validation

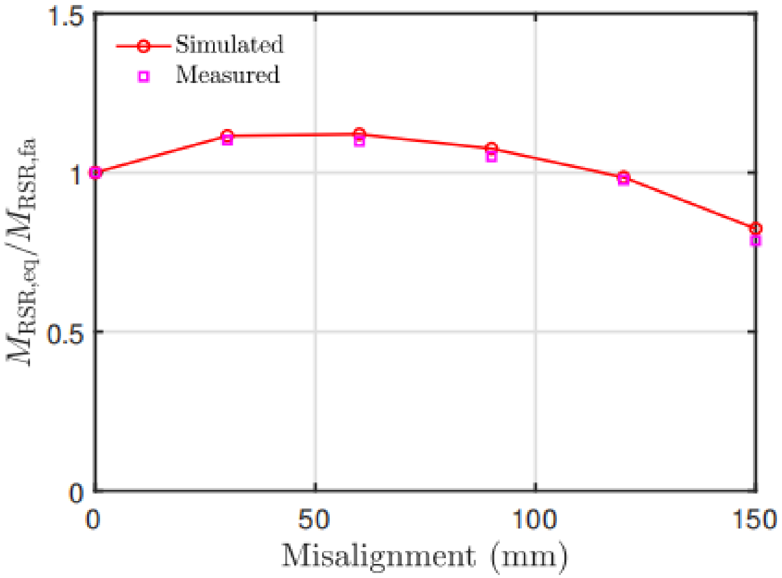
Rectangular Pad –
Rectangular Solenoidal Pad



Mutual inductances



Equivalent mutual inductance



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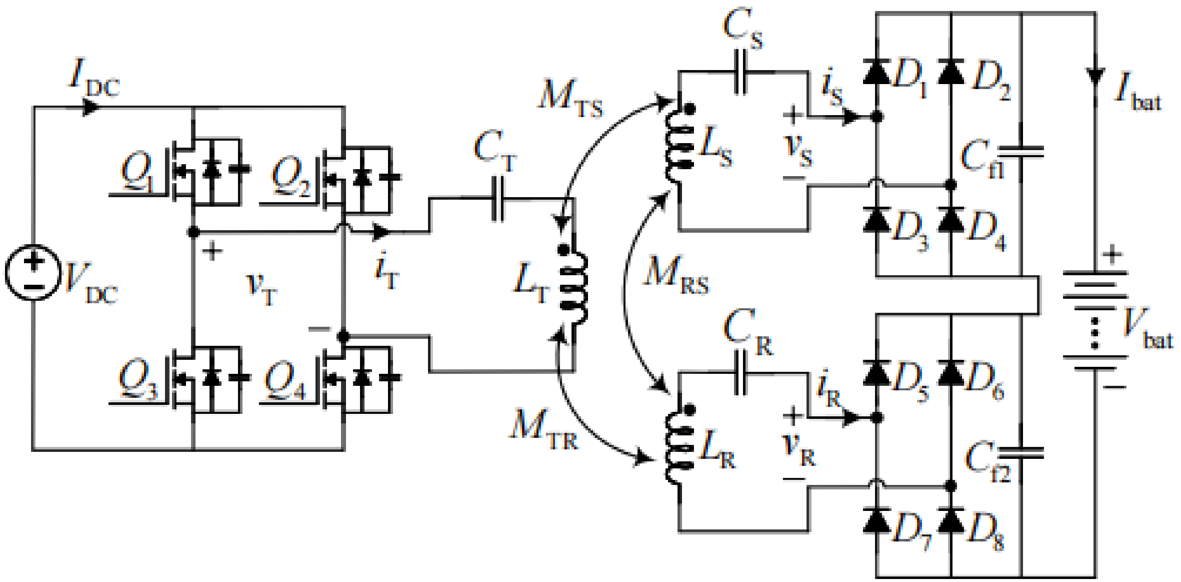
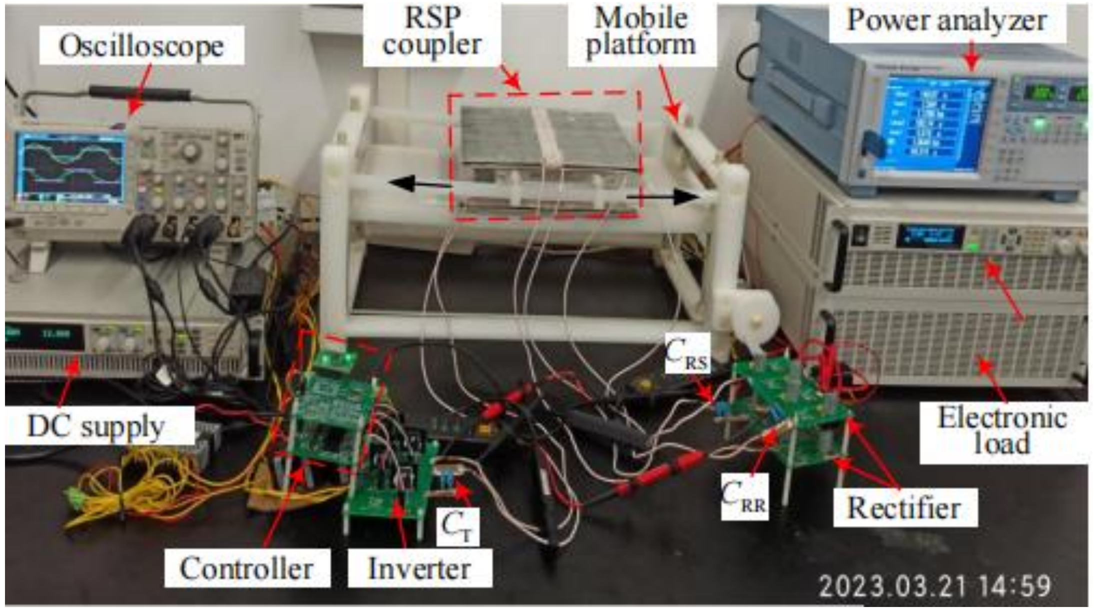
Experimental Validation

IPT system with RSP



Experimental prototype of 1-kW IPT system with RSP



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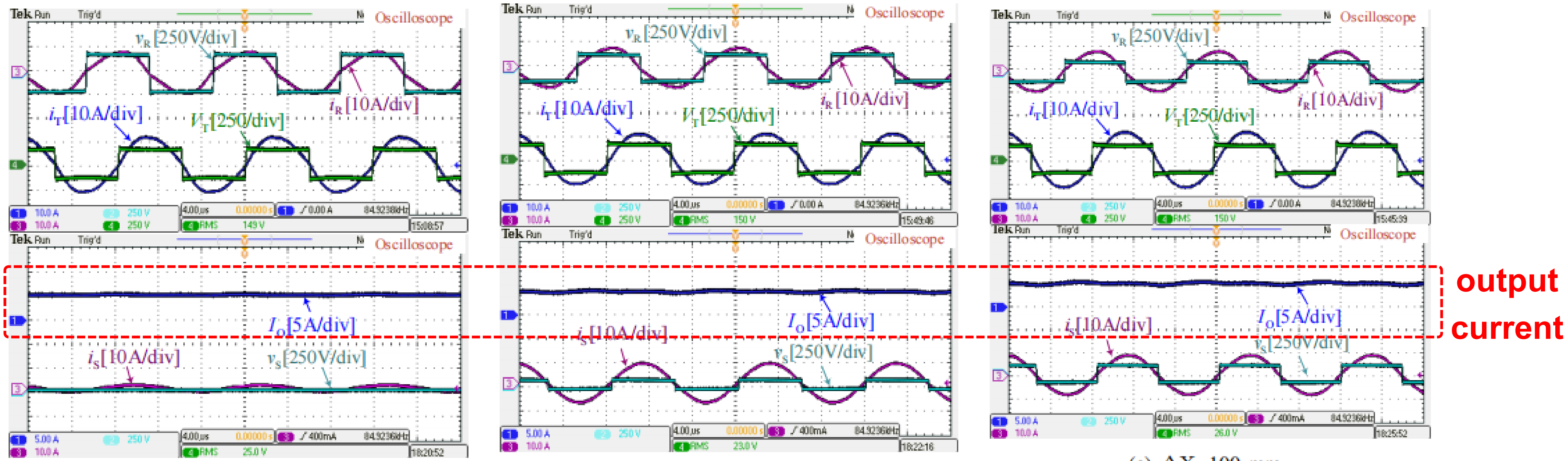
Experimental Validation

Experimental waveforms of the proposed IPT charging system with RSP at various misalignment conditions



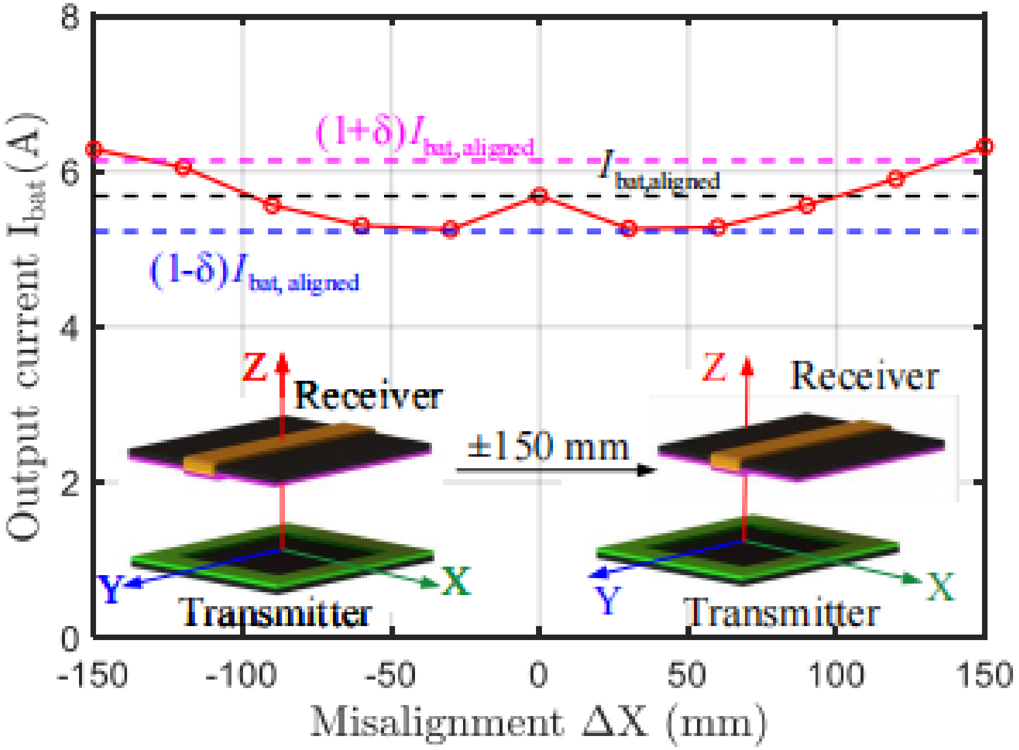
(a) ΔX=0 mm (fully aligned)

(b) ΔX=50 mm

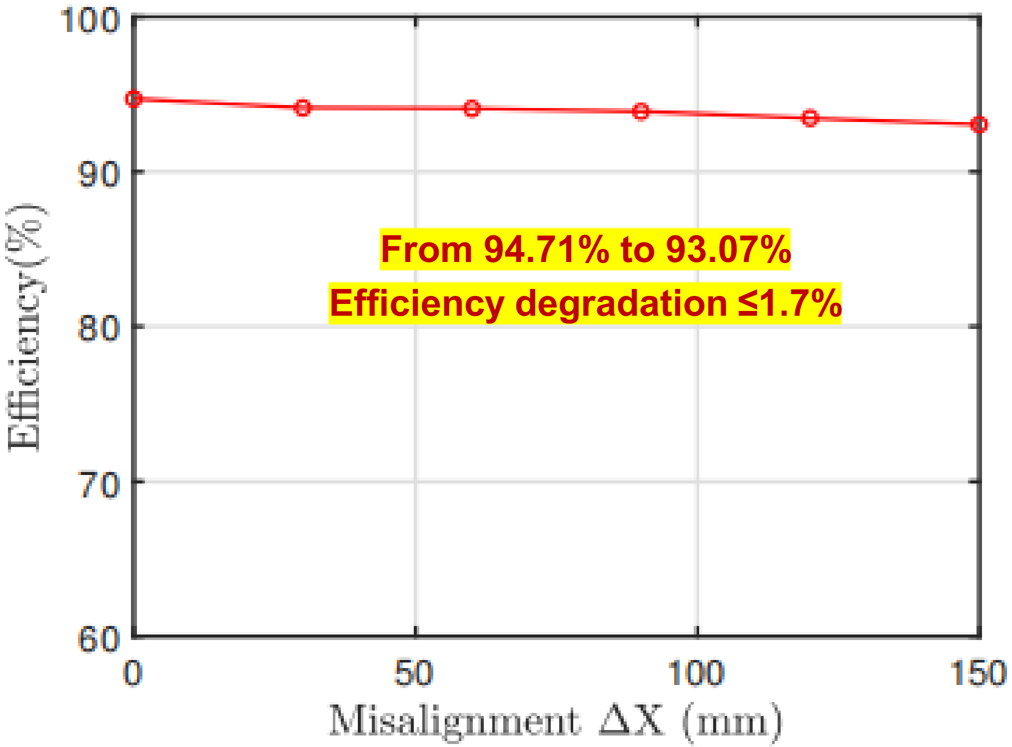
(c) ΔX=100 mm

Experimental Validation

Output current under different misalignments along X-axis



Measured transfer efficiency under different misalignments along the X-axis



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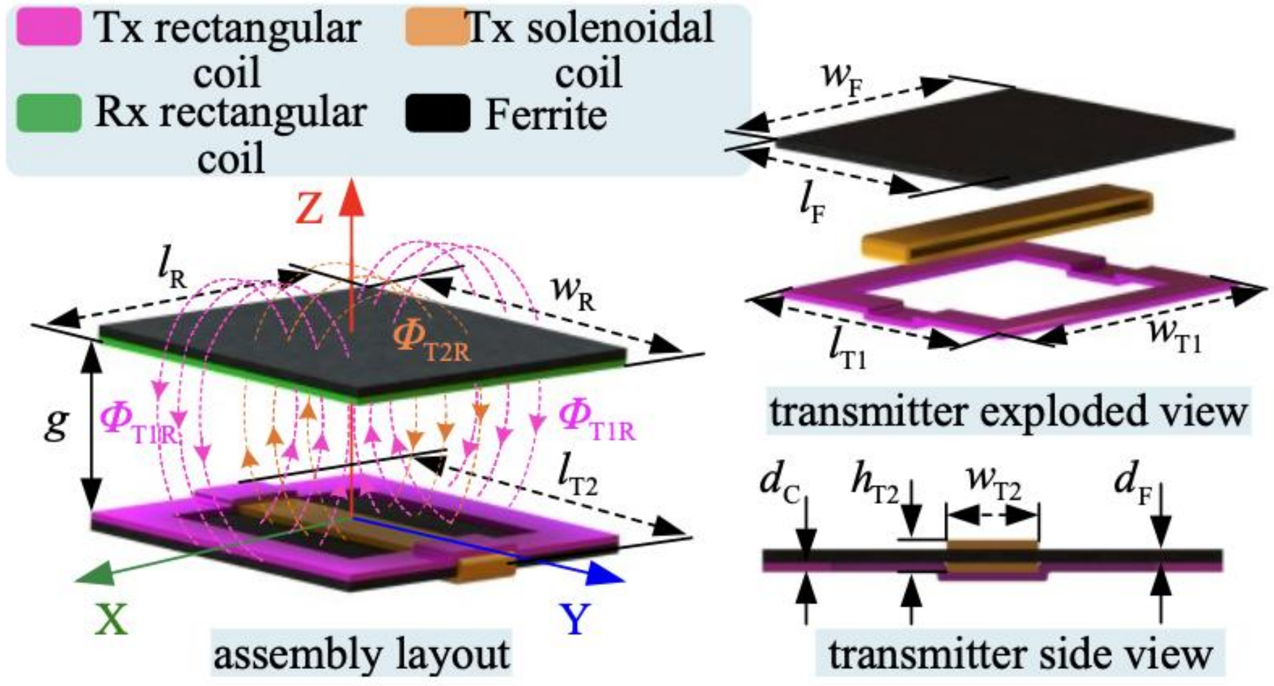
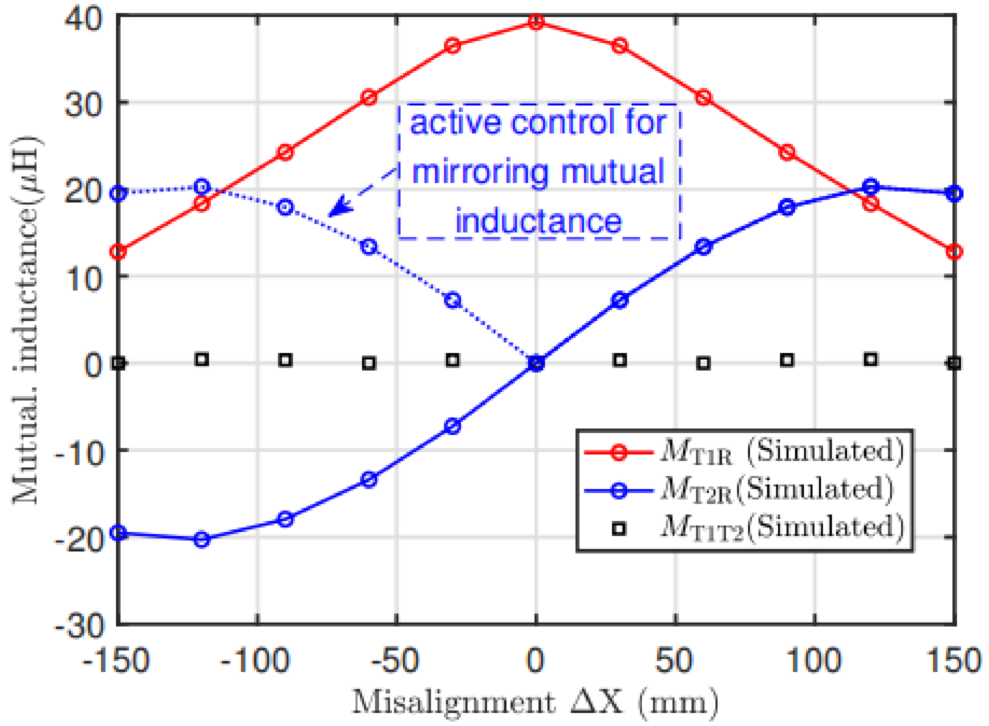
Polarity Reversal Problem

RSP-RP coupler

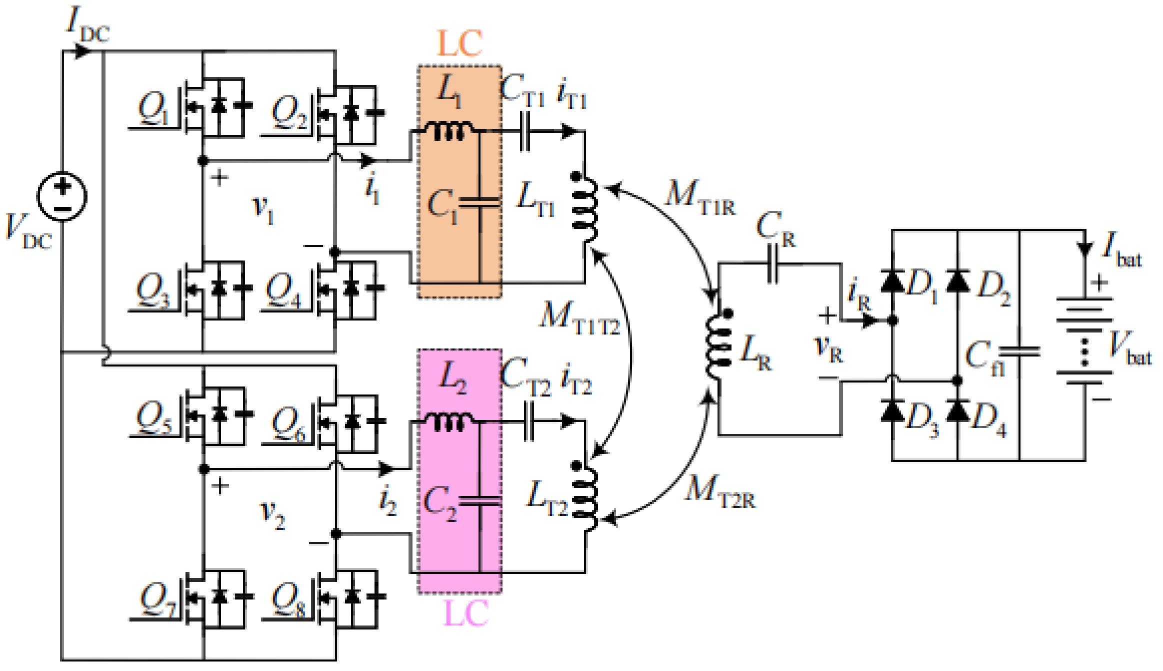


Mutual inductances of RSP-RP versus misalignments along X-axis



Can detection and control be eliminated?

Circuit Modeling



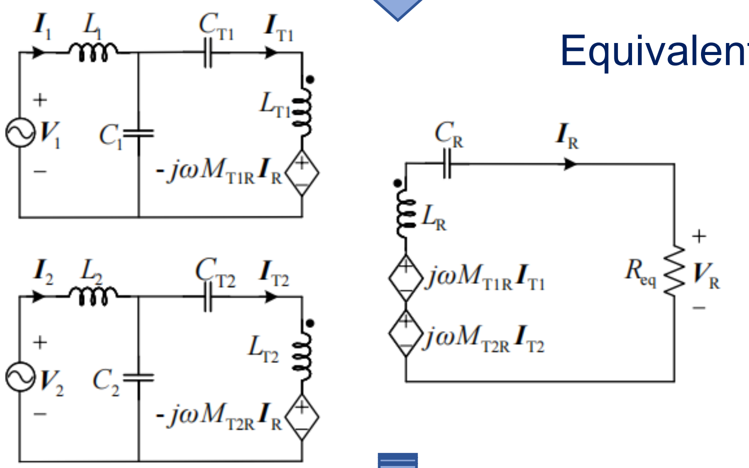
Proposed IPT charging system with RSP-RP coupler

$$\omega L_1 - \frac{1}{\omega C_1} = \omega L_2 - \frac{1}{\omega C_2} = \omega L_R - \frac{1}{\omega C_R} = 0. \quad (4)$$

$$\boldsymbol{I}_{T1} = \frac{\boldsymbol{V}_1}{j\frac{1}{\omega C_1}}, \text{ and} \quad (5)$$

$$\boldsymbol{I}_{T2} = \frac{\boldsymbol{V}_2}{j\frac{1}{\omega C_2}} = \frac{\boldsymbol{V}_1\angle\theta}{j\frac{1}{\omega C_2}}, \quad (6)$$

Equivalent circuit



$$0 = \left(\frac{1}{j\omega C_{T1}} + j\omega L_{T1}\right)\boldsymbol{I}_{T1} - j\omega M_{T1R}\boldsymbol{I}_R,$$
$$0 = \left(\frac{1}{j\omega C_{T2}} + j\omega L_{T2}\right)\boldsymbol{I}_{T2} - j\omega M_{T2R}\boldsymbol{I}_R, \quad (7)$$
$$\boldsymbol{V}_R = R_{eq}\boldsymbol{I}_R = j\omega M_{T1R}\boldsymbol{I}_{T1} + j\omega M_{T2R}\boldsymbol{I}_{T2}.$$

With (7), output voltage $\boldsymbol{V}_R$ is given by

$$\boldsymbol{V}_R = \omega^2 C_1 M_{T1R}\boldsymbol{V}_1 + \omega^2 C_2 M_{T2R}\boldsymbol{V}_1\angle\theta. \quad (8)$$

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Analysis of Output Function

The amplitude of $\boldsymbol{V}_{\mathrm{R}}$ is given by (9).

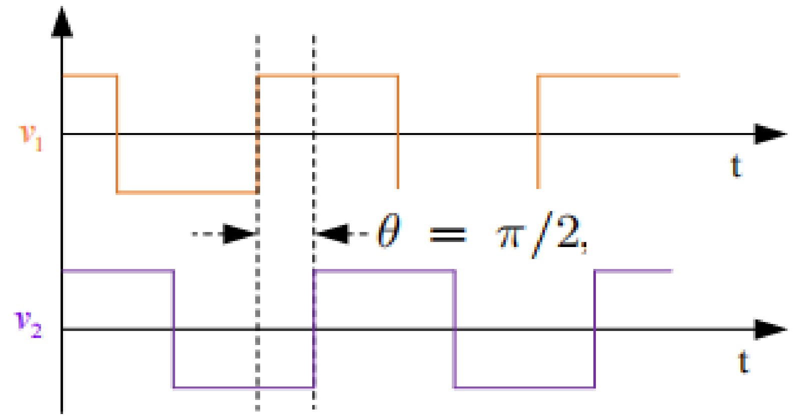
$$|\boldsymbol{V}_{\mathrm{R}}| = \omega^2 C_1 |\boldsymbol{V}_1| \beta, \quad (9)$$

where

$$\beta = \sqrt{\underbrace{\frac{2C_2 M_{\mathrm{T1R}} M_{\mathrm{T2R}} \cos\theta}{C_1}}_{\text{Term ①}} + \underbrace{M_{\mathrm{T1R}}^2 + \frac{C_2^2}{C_1^2} M_{\mathrm{T2R}}^2}_{\text{Term ②}}}. \quad (10)$$

Term ① = 0

Term ② ≈ constant



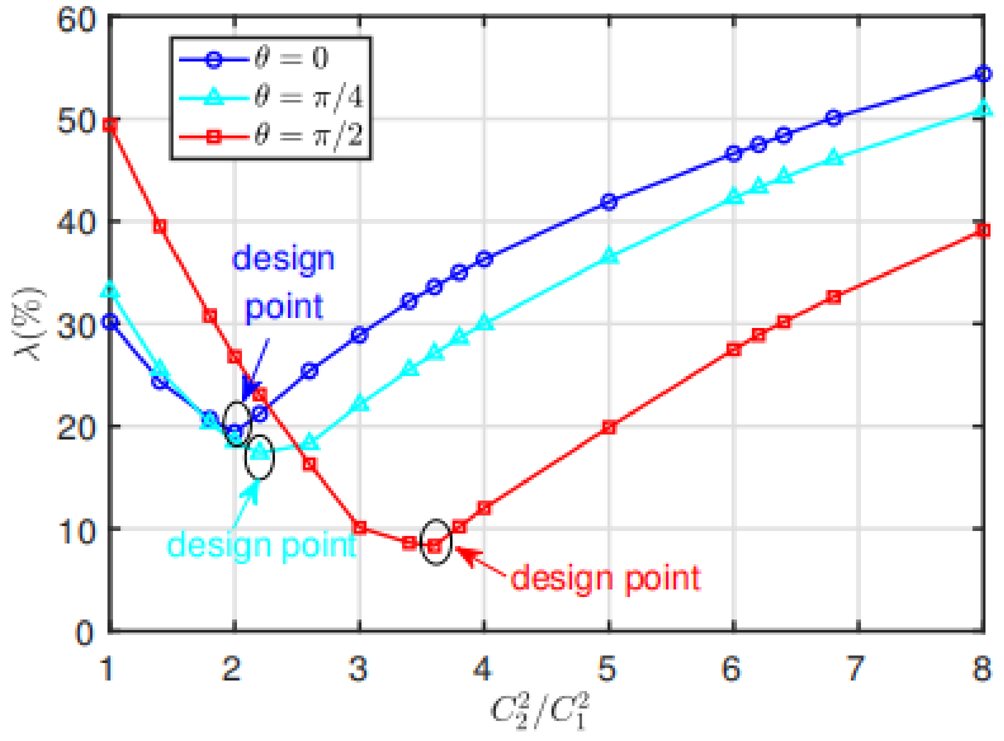
$$V_{\mathrm{O}} = \omega^2 V_{\mathrm{DC}} C_1 \sqrt{M_{\mathrm{T1R}}^2 + \frac{C_2^2}{C_1^2} M_{\mathrm{T2R}}^2}. \quad (11)$$

$$\Delta = M_{\mathrm{T1R}}^2 + \frac{C_2^2}{C_1^2} M_{\mathrm{T2R}}^2. \quad (12)$$

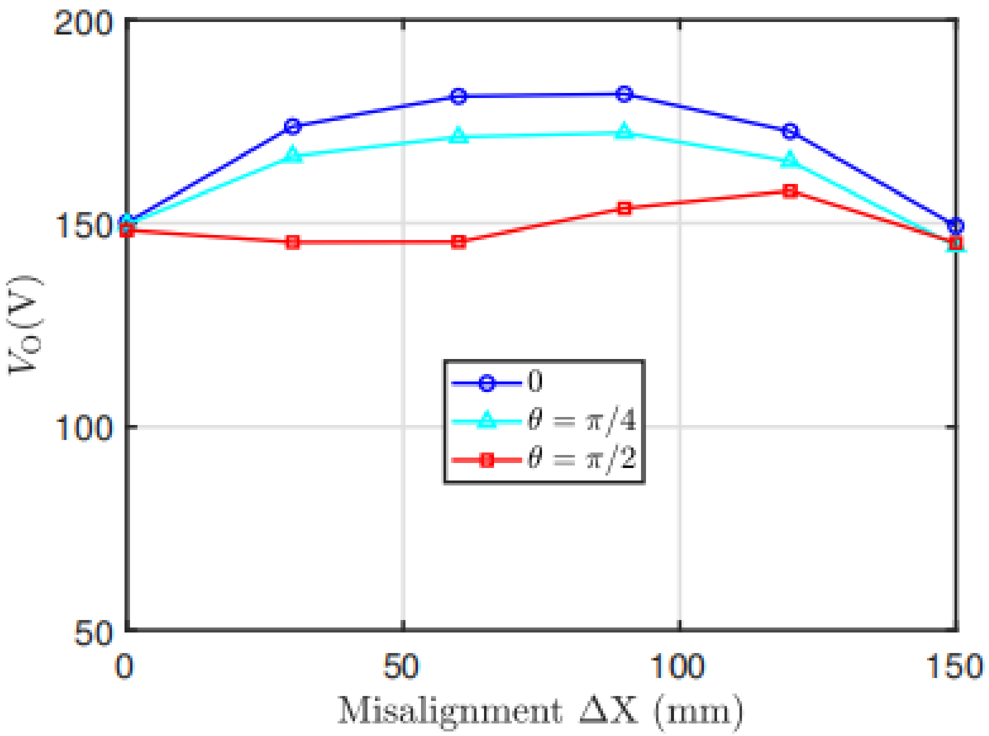
$$\lambda = \frac{\Delta|_{\mathrm{Max}} - \Delta|_{\mathrm{Min}}}{\Delta|_{\mathrm{Max}} + \Delta|_{\mathrm{Min}}} \times 100\%, \quad (13)$$

Orthogonal excitation

Design for Minimal Output Fluctuation

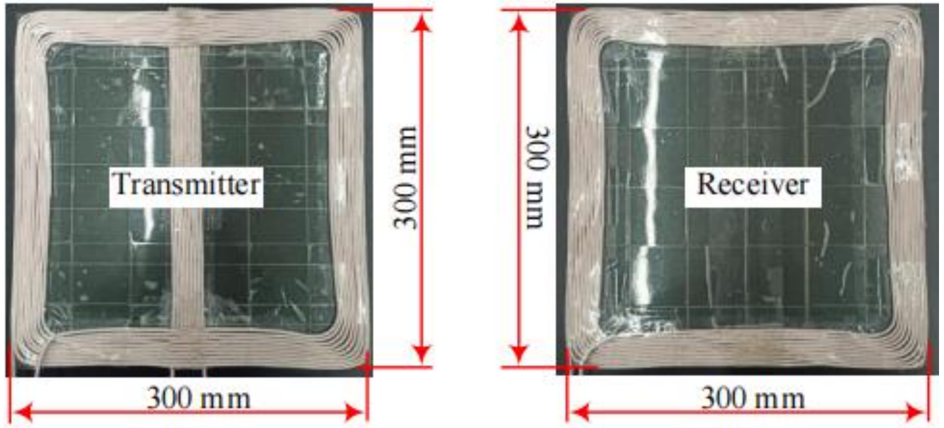


Fluctuation λ versus C_2^2/C_1^2 under different phase difference θ of excitation currents.

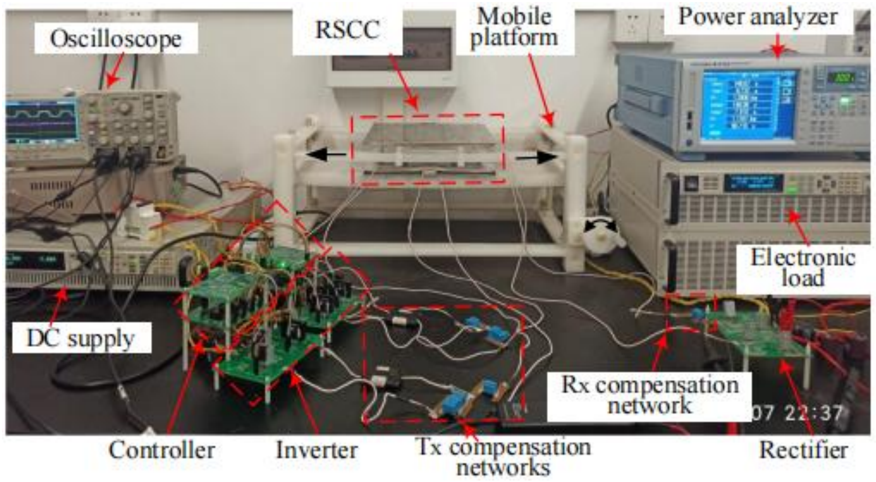


Output voltage versus misalignment along X-axis under different phase difference *θ* of excitation currents.

Experimental Validation



RSP-RP coupler



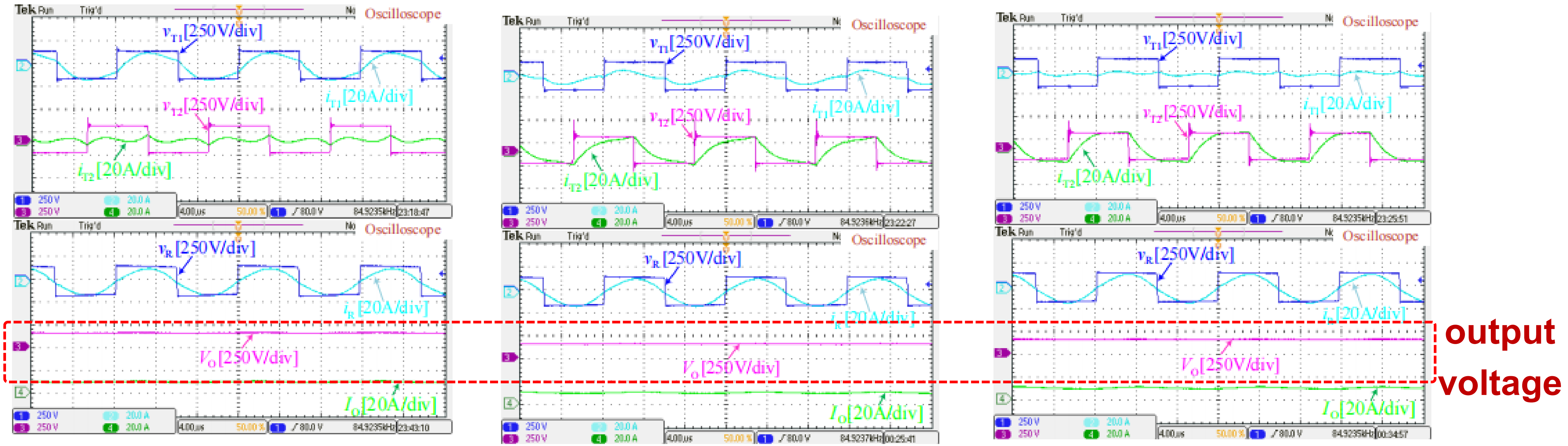
Experimental prototype of 1 kW proposed control-free IPT system

TABLE II
MEASURED PARAMETERS OF THE IPT PROTOTYPE

Coupler parameters		Circuit parameters	
Symbols	Value	Symbols	Value
L_{T1}	101.9 μH	L_1, C_1, C_{T1}	39.57 μH, 88.6 nF, 45.6 nF
L_{T2}	104.5 μH	L_2, C_2, C_{T2}	20.86 μH, 168.1 nF, 40.1 nF
L_R	102.2 μH	C_R	34.4 nF
M_{fa}	39.12 μH	R_L	22.5 Ω
N	10	V_{DC}	150 V
N_S	9	D_1 -D_4	MBR20200CTG
h_{gap}	60mm	Q_1 -Q_8	STC 4050

Measure parameters of IPT prototype

Experimental Validation



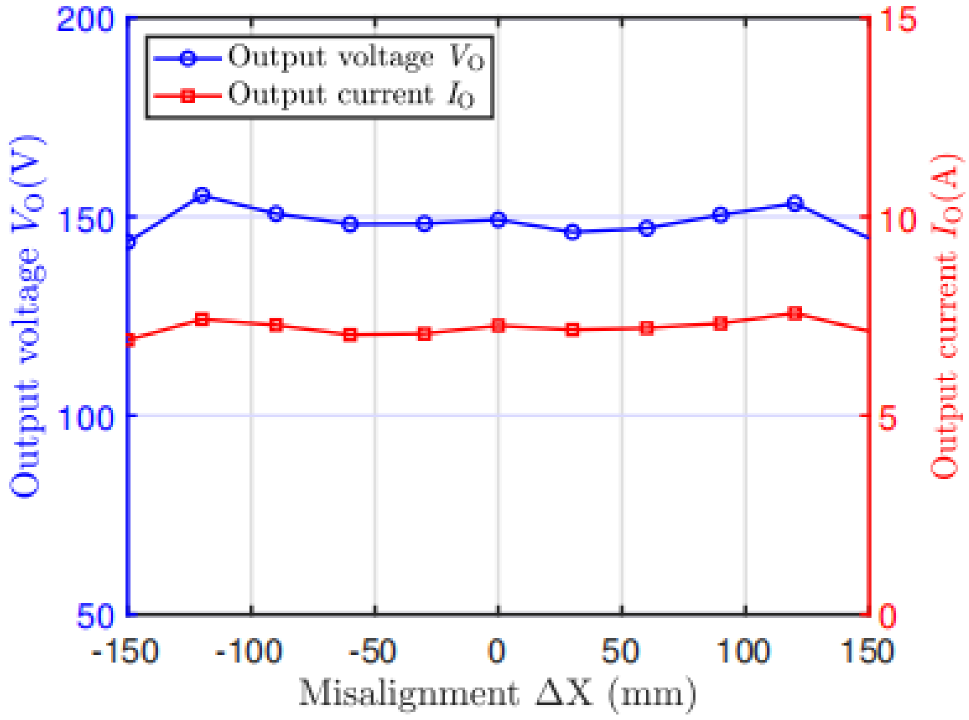
(a) ΔX=0 mm (fully aligned)

(b) ΔX=75 mm

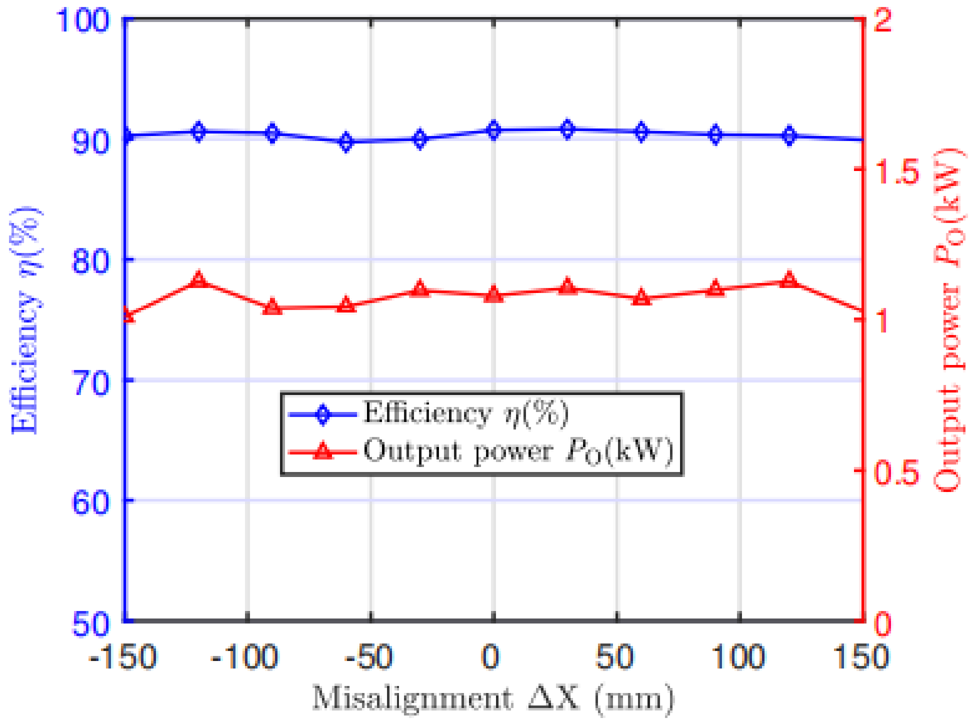
(c) ΔX=150 mm

Experimental waveforms of the proposed control-free IPT system at various misalignment conditions

Experimental Validation



Measured output voltage and current versus misalignment along X-axis

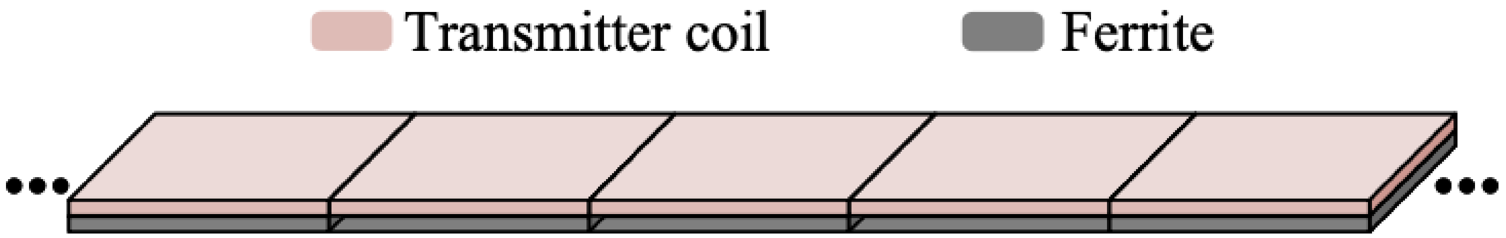


Measured DC-to-DC efficiency and output power versus misalignment along X-axis

Outline

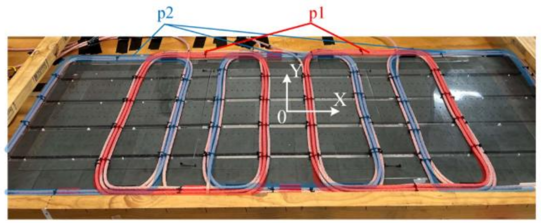
- Research Background and Motivation
- Rectangular Solenoidal Pad (RSP)
- Control Free Design for RSP Tx
- **Dynamic Tx Track based on RSP**

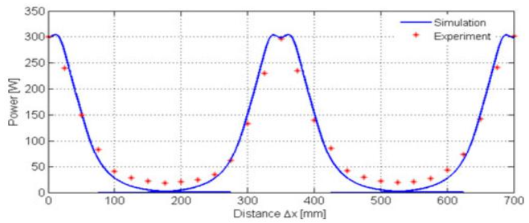
Dynamic Tx Track with Large Spacing Distance



(a) Without spacing distance

(b) With spacing distance





How to effectively mitigate output fluctuation while allowing large spacing distance?

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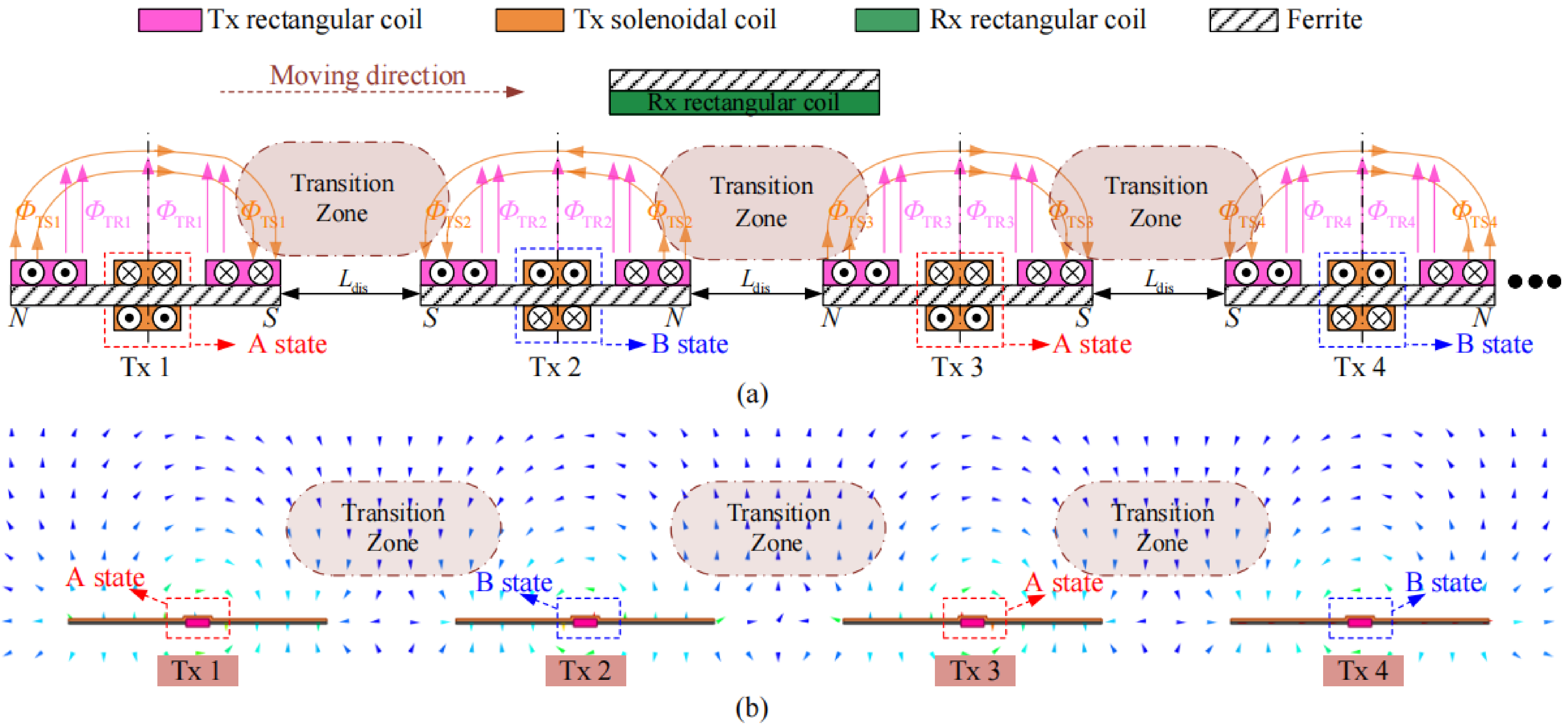
Dr. Zhicong Huang

Hai Xu and **Zhicong Huang***, "Alternately-arranged segmented transmitter pads with magnetic field complementation for suppressing power fluctuation in dynamic wireless power transfer," IEEE Transactions on Power Electronics, vol. 39, no. 10, pp. 14091-14102, Oct. 2024.

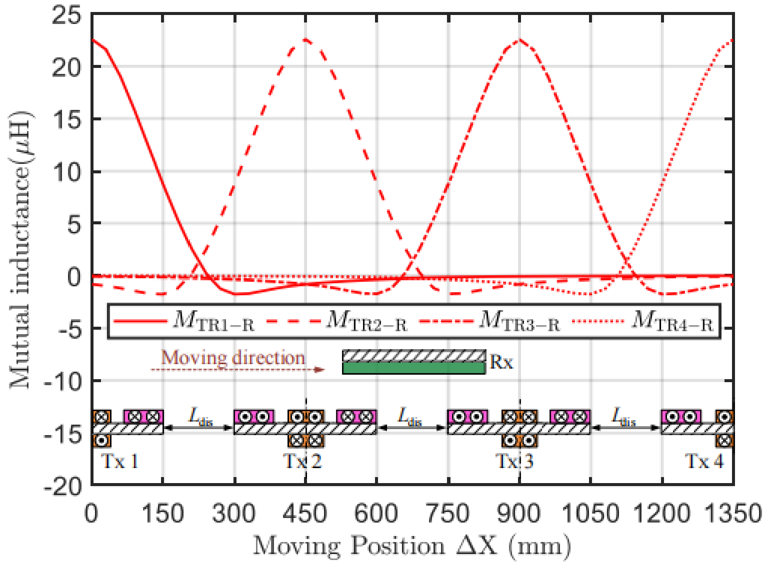
Alternately-Arranged Segmented Transmitter Pads with Magnetic Field Complementation



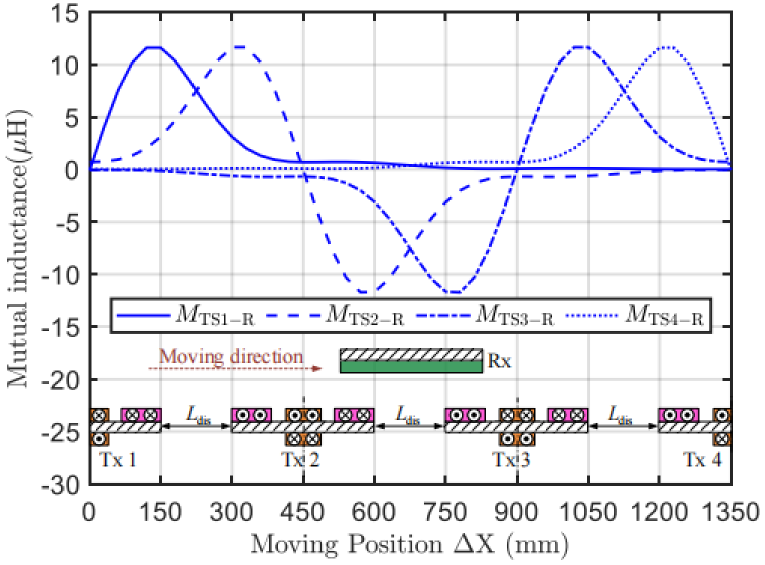
Front view of the proposed DWPT Tx track consisting of
alternately-arranged RSPs with 50% spacing distance

華南理工大學
South China University of Technology
Dr. Zhicong Huang

Operating Principle

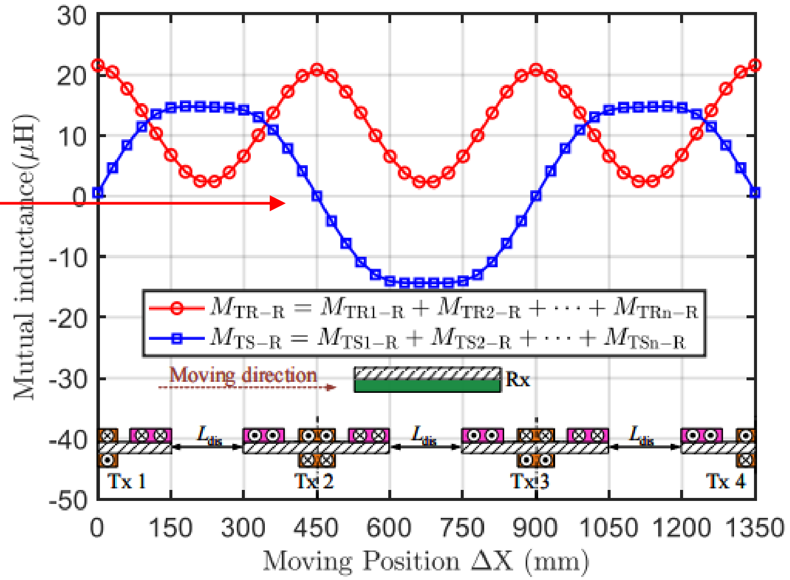


Mutual inductances between Rx RP and individual Tx RP coils



Mutual inductances between Rx RP and individual Tx solenoid coils

Polarity Reversal Problem



Overall rectangular-to-rectangular and solenoid-to-rectangular mutual inductances

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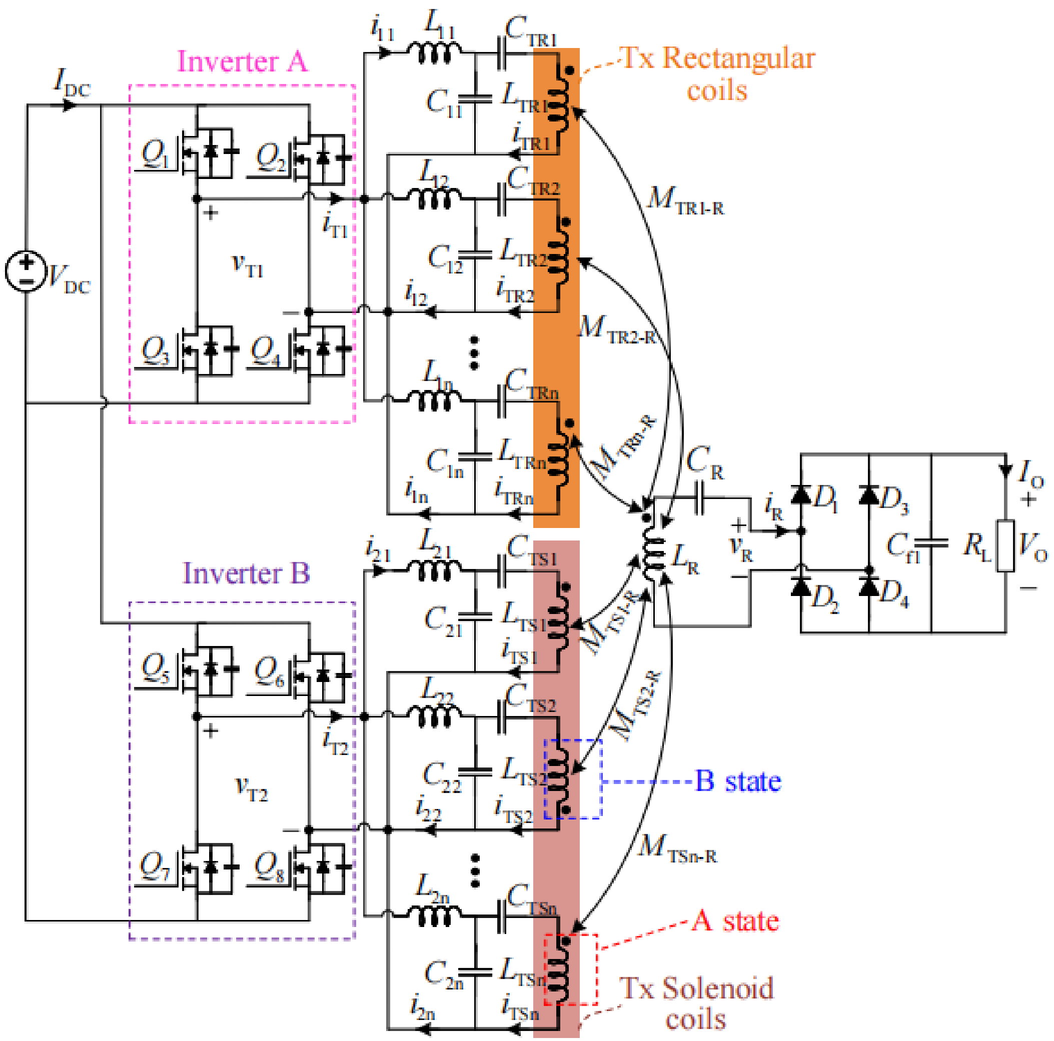
System Schematics and Circuit Modeling



Circuit configuration of proposed DWPT system

$$\begin{aligned} \boldsymbol{V}_{T1} &= \frac{4}{\pi} V_{DC}\angle 0^\circ \\ \boldsymbol{V}_{T2} &= \frac{4}{\pi} V_{DC}\angle \theta^\circ, \end{aligned} \tag{4}$$

$$\begin{aligned} \boldsymbol{V}_{T1} &= X_{11}\boldsymbol{I}_{11} - X'_{11}\boldsymbol{I}_{TR1} \\ 0 &= (X_{TR1} + X'_{11})\boldsymbol{I}_{TR1} - j\omega M_{TR1\text{-}R}\boldsymbol{I}_R - X'_{11}\boldsymbol{I}_{11} \\ \boldsymbol{V}_{T1} &= X_{12}\boldsymbol{I}_{12} - X'_{12}\boldsymbol{I}_{TR2} \\ 0 &= (X_{TR2} + X'_{12})\boldsymbol{I}_{TR2} - j\omega M_{TR2\text{-}R}\boldsymbol{I}_R - X'_{12}\boldsymbol{I}_{12} \\ \boldsymbol{V}_{T2} &= X_{21}\boldsymbol{I}_{21} - X'_{21}\boldsymbol{I}_{TS1} \\ 0 &= (X_{TS1} + X'_{21})\boldsymbol{I}_{TS1} - j\omega M_{TS1\text{-}R}\boldsymbol{I}_R - X'_{21}\boldsymbol{I}_{21} \\ \boldsymbol{V}_{T2} &= X_{22}\boldsymbol{I}_{22} - X'_{22}\boldsymbol{I}_{TS2} \\ 0 &= (X_{TS2} + X'_{22})\boldsymbol{I}_{TS2} - j\omega M_{TS2\text{-}R}\boldsymbol{I}_R - X'_{22}\boldsymbol{I}_{22} \\ &\text{Equations for RSP3} \\ &\ldots \\ &\text{Equations for RSPn} \\ 0 &= X_R\boldsymbol{I}_R - \sum_{i=1}^{n} jX_{TRi\text{-}R}\boldsymbol{I}_{TRi} - \sum_{i=1}^{n} jX_{TSi\text{-}R}\boldsymbol{I}_{TSi} \end{aligned} \tag{5}$$

Analysis of Output Function

$$V_{\mathrm{O}} = \frac{\pi}{4}\left|\boldsymbol{V}_{\mathrm{R}}\right| = \omega^2 V_{\mathrm{DC}} C_1 \sqrt{\alpha + \beta}$$

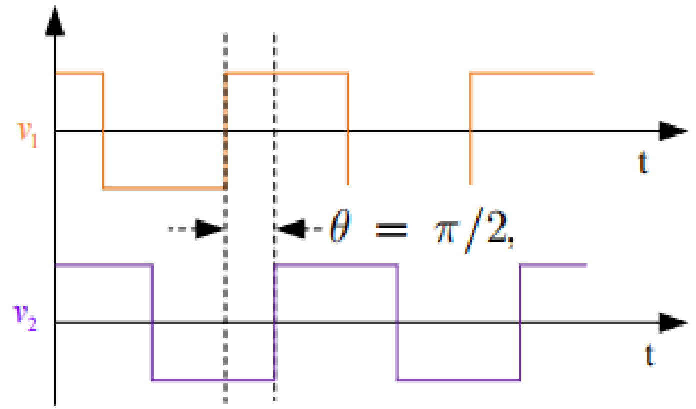
Term ① ≈ constant →

$$\alpha = \left(\sum_{i=1}^{n} M_{\mathrm{TR}i\text{-}\mathrm{R}}\right)^2 + \frac{C_2^2}{C_1^2}\left(\sum_{i=1}^{n} M_{\mathrm{TS}i\text{-}\mathrm{R}}\right)^2$$

$$\beta = \frac{2C_2 \sum_{i=1}^{n} M_{\mathrm{TR}i\text{-}\mathrm{R}} \sum_{i=1}^{n} M_{\mathrm{TS}i\text{-}\mathrm{R}} \cos\theta}{C_1}$$

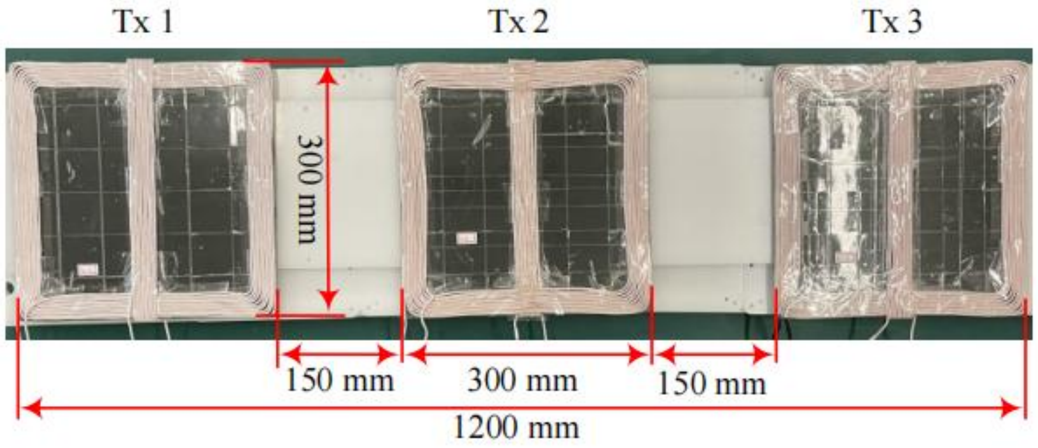
← Term ② = 0

$$\Delta = M_{\mathrm{T1R}}^2 + \frac{C_2^2}{C_1^2} M_{\mathrm{T2R}}^2.$$



Orthogonal excitation

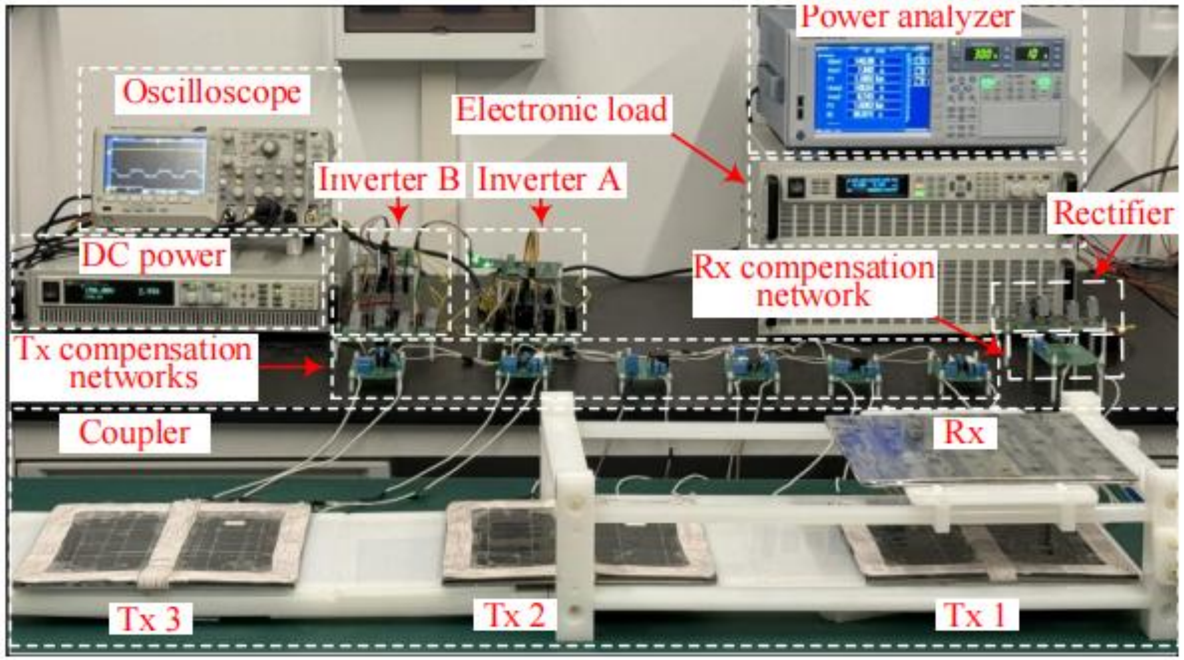
Experimental Validation



Practical structure and dimension of proposed DWPT transmitter

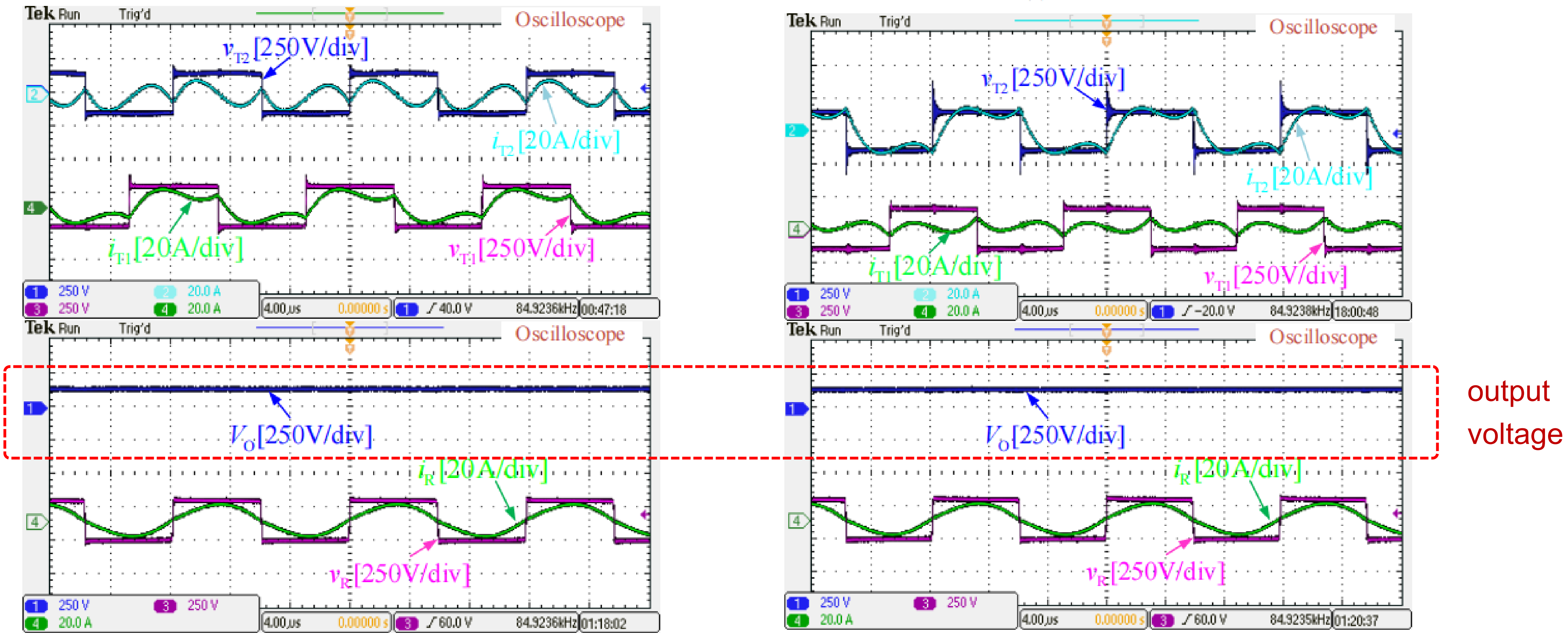
TABLE III
MEASURED PARAMETERS OF THE IPT PROTOTYPE

Coupler parameters		Circuit parameters	
Symbols	Value	Symbols	Value
$L_{\mathrm{TR}i}$ (i=1,2,3)	99.82 μH, 99.56 μH, 99.21 μH	L_1, L_2	21.65 μH, 15.32 μH
$L_{\mathrm{TS}i}$ (i=1,2,3)	101.81 μH, 100.98 μH, 101.36 μH	C_1, C_2	161.9 nF, 228.95 nF
L_{R}	99.86 μH	C_{R}	35.18 nF
h_{gap}	100 mm	C_{TR},C_{TS}	41.96 nF, 42.06 nF
N	10	V_{DC}	150 V
N_{S}	9	D_1 -D_4	MBR20200CTG
d_{C}	3 mm	Q_1 -Q_8	STC 4050



Experimental prototype of 1 kW proposed DWPT system with alternately-arranged segmented transmitters

Experimental Validation



(a) ΔX= 0 mm (b) ΔX= 675 mm

Experimental waveforms of the proposed DWPT system at different moving positions

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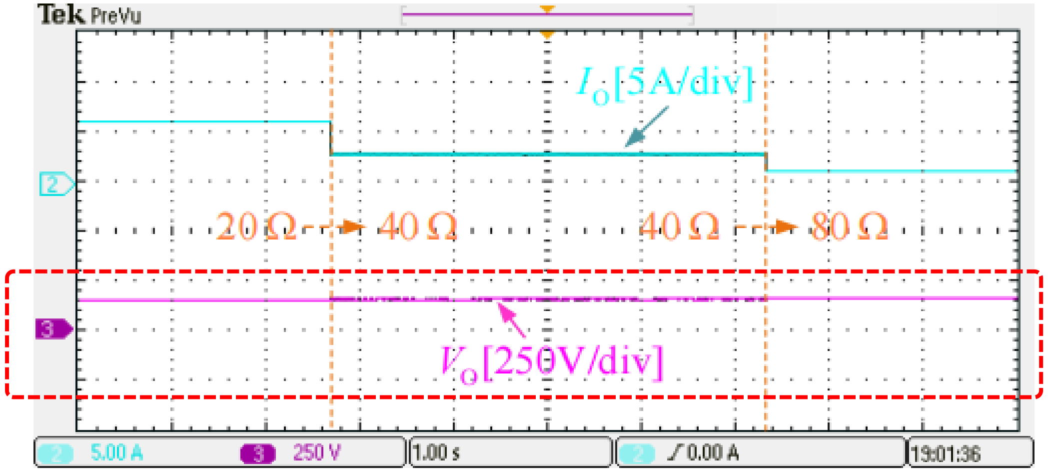
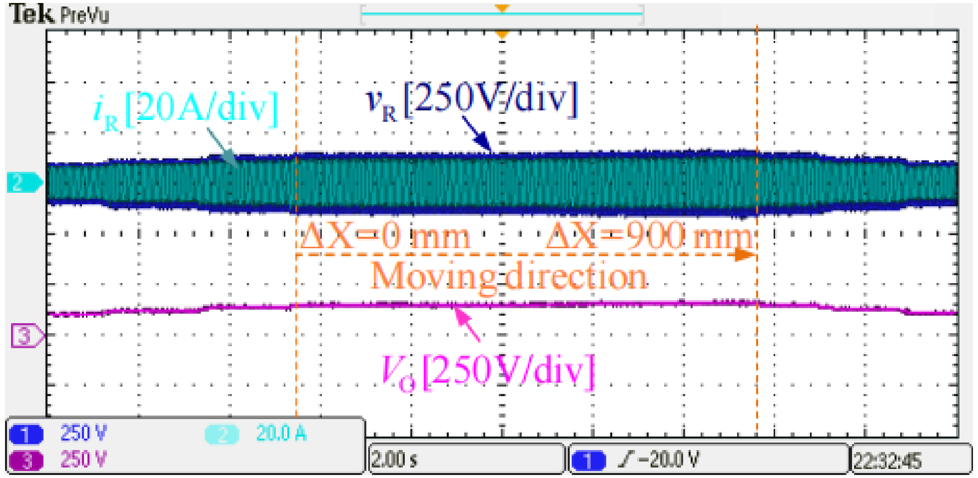
Experimental Validation

Output currents and voltages at different load conditions

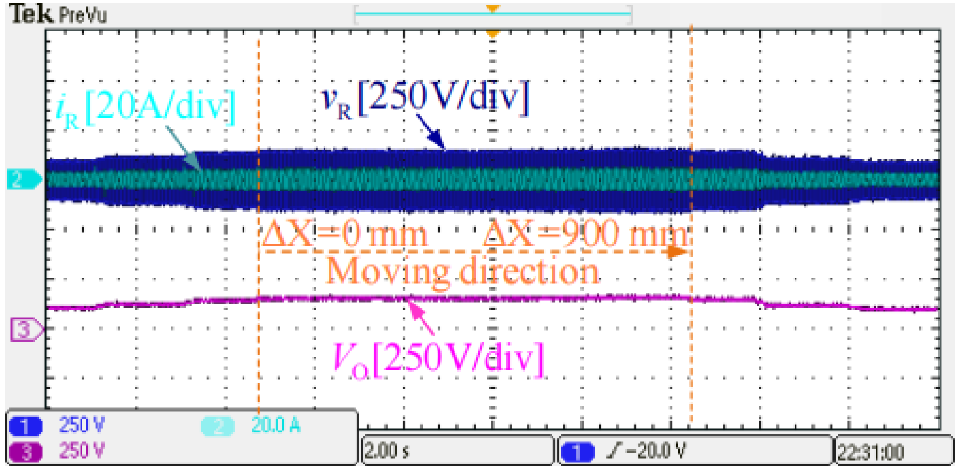


output voltage

Dynamic output currents and voltages at different load conditions

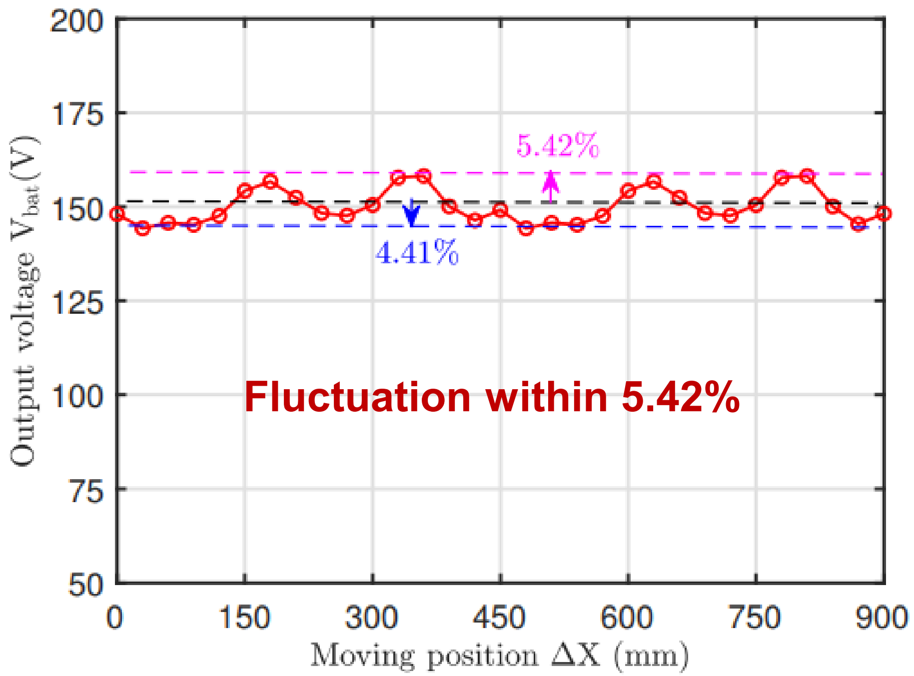


R_L=22.5Ω

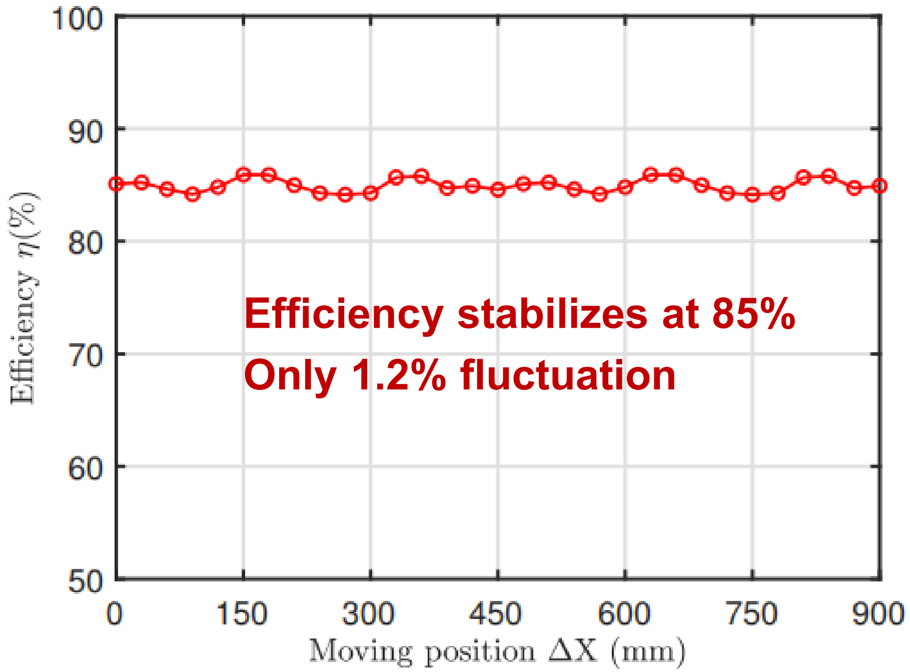


R_L=45Ω

Experimental Validation



Output voltage V_O at full load during moving range ΔX ∈ [0 mm 900 mm]



Measured dc-dc efficiency of proposed DWPT system within moving range ΔX ∈ [0 mm 900 mm] at full load

Conclusion

Our recent works proposed a novel rectangular solenoidal pad (RSP) which is a good approach to misalignment tolerance with reduced copper usage. We also developed a passive scheme to excite the proposed RSP without necessities of detection and control. We furthered extended the proposed RSP from static to dynamic wireless power transfer scenarios.

Acknowledgment

Dr. Hai Xu and Prof. Chi K. Tse

- National Natural Science Foundation of China (52007067)
- Science and Technology Planning Project of Guangdong Province (2023A0505050124)
- Natural Science Foundation of Guangdong Province (2023A1515011623, 2022A1515011581)
- Guangzhou Municipal Science and Technology Bureau (202102020381)