Design and Optimization of Megahertz Wireless Power Transfer Systems

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Outline

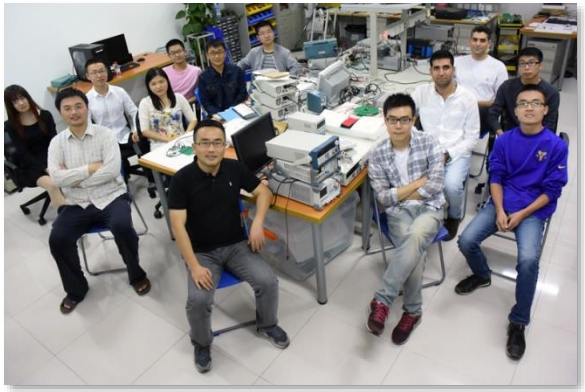
- Introduction
- Parameter Design
- Harmonic Reduction
- Robust Design
- Matching Network Design
- Other Ongoing Activities
- Conclusion

Shanghai Jiao Tong University Dec. 2015

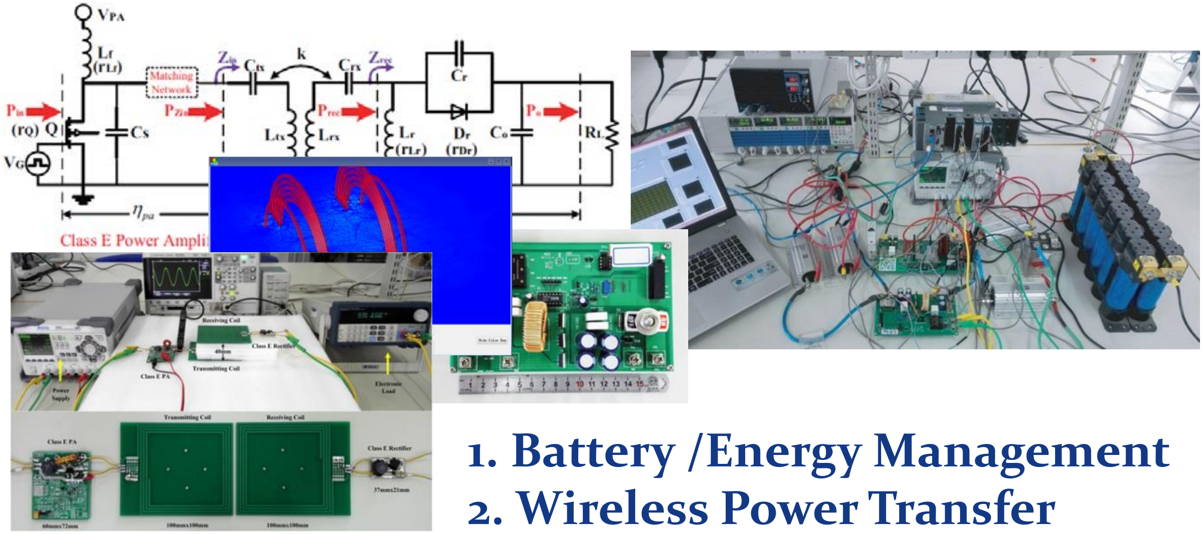
- 28 Schools/Departments
- 13 Affiliated Hospitals
- 16,188 Undergraduates
- 28,842 Graduates (≈64%)
  - 6,506 Ph.D. students
- 2,793 Faculties
  - 890 Professors
- 3.3km² (Minhang Campus)

Dynamic Systems Control Lab (2010~Pre.)

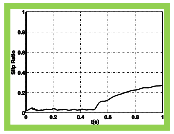
http://umji.sjtu.edu.cn/lab/dsc/

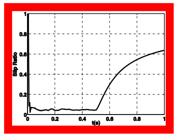


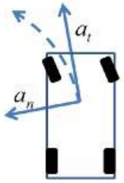
4 Ph.D., 7 M.S. (Oct. 2016)

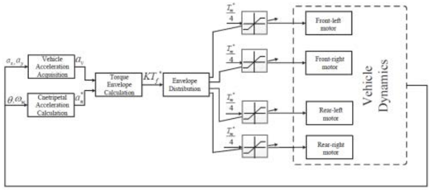


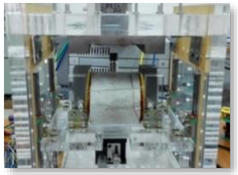
1. Battery /Energy Management
2. Wireless Power Transfer

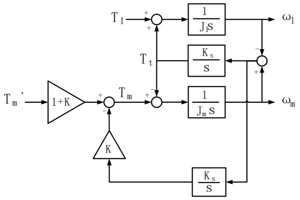








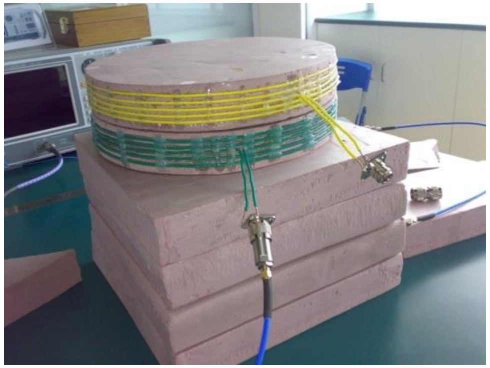




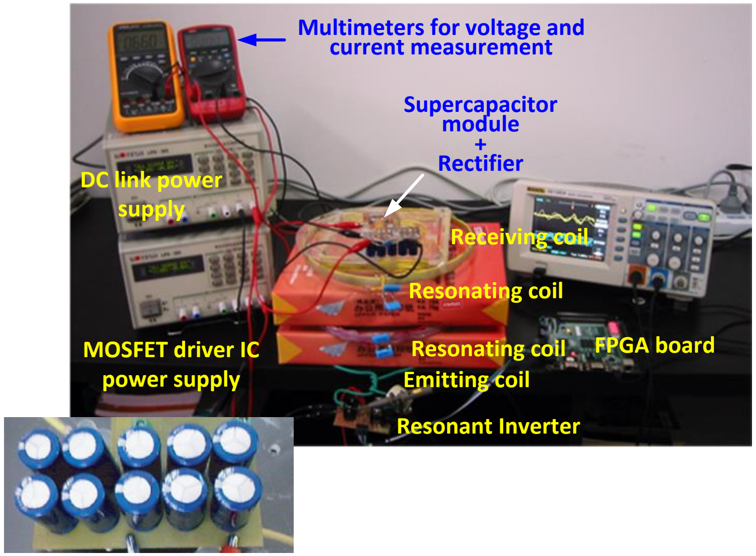
Control of Motion & Energy

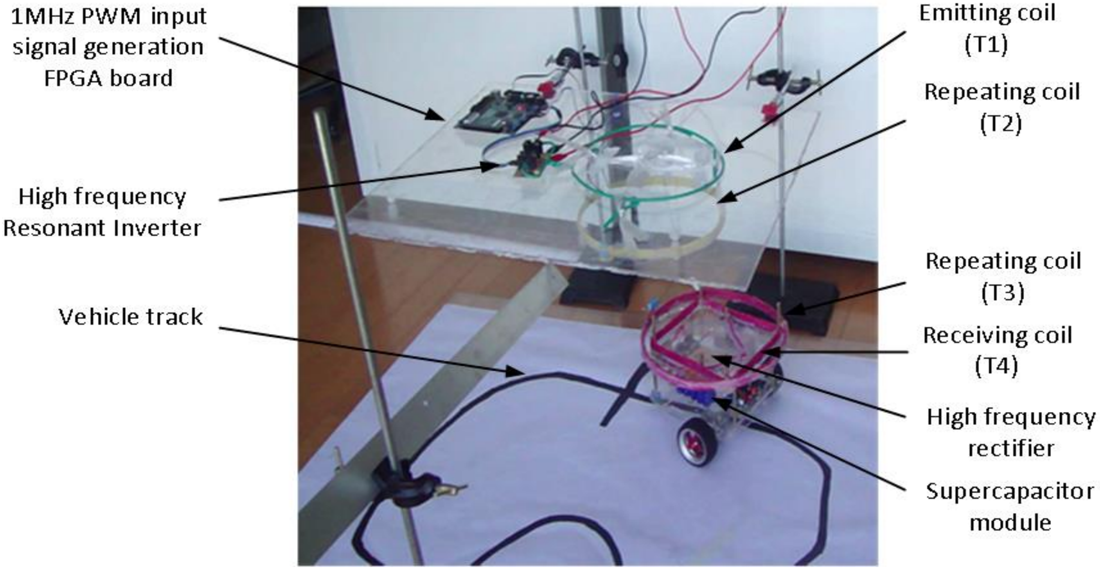
3. Electric Vehicle Dynamics 4. Servo/Motion Control

Initial Efforts Starting from 2010



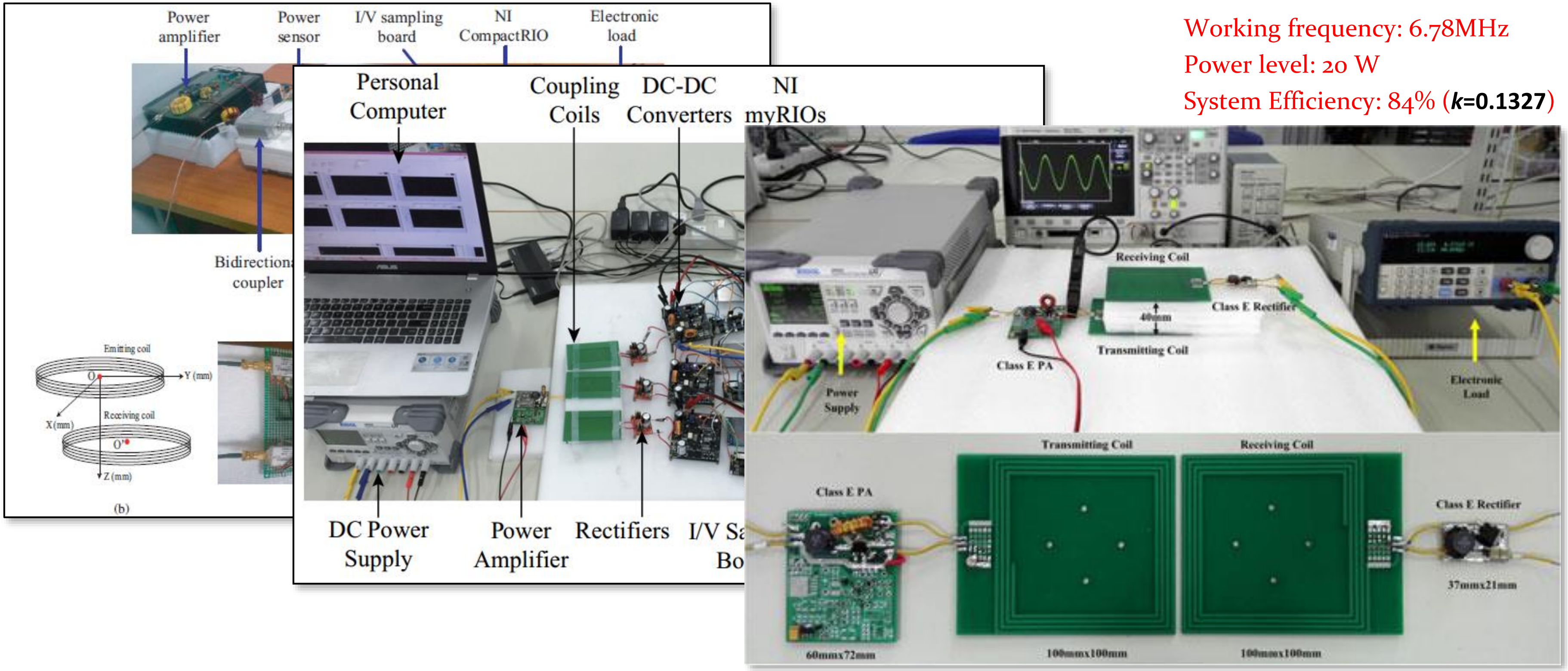
Gap (cm)	5.6	10.1	14.8	19.3	24.1	28
Efficiency (%)	88.84	93.32	**93.69**	92.53	88.07	70.04
F_m (MHz)	13.59	14.74	15.27	15.71	16.11	16.08
F_e (MHz)	19.87	17.85	17.01	16.51	16.11	16.08





System-level Design , Optimization, and Control

- Optimal load analysis and tracking
- Optimal and robust designs of system parameters
- Design and power flow control in multi-receiver systems



Working frequency: 6.78MHz

Power level: 20 W

System Efficiency: 84% (***k*****=0.1327**)

Major Challenges in MHz WPT

- More obvious nonlinearities of the devices and thus non-neglectable reactance
- Potentially higher switching loss and thus lower system **Efficiency**
- More challenging Electromagnetic interference (**EMI**) problem
- **Robustness** again varying operation condition (i.e., coupling and load)

Keywords: MHz wireless power transfer, high efficiency, low-harmonic contents, robustness

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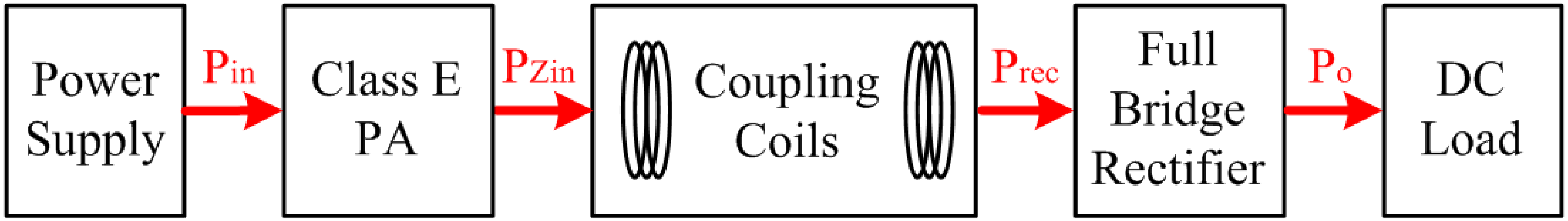
Conventional Design

System Configuration



Conventional Design

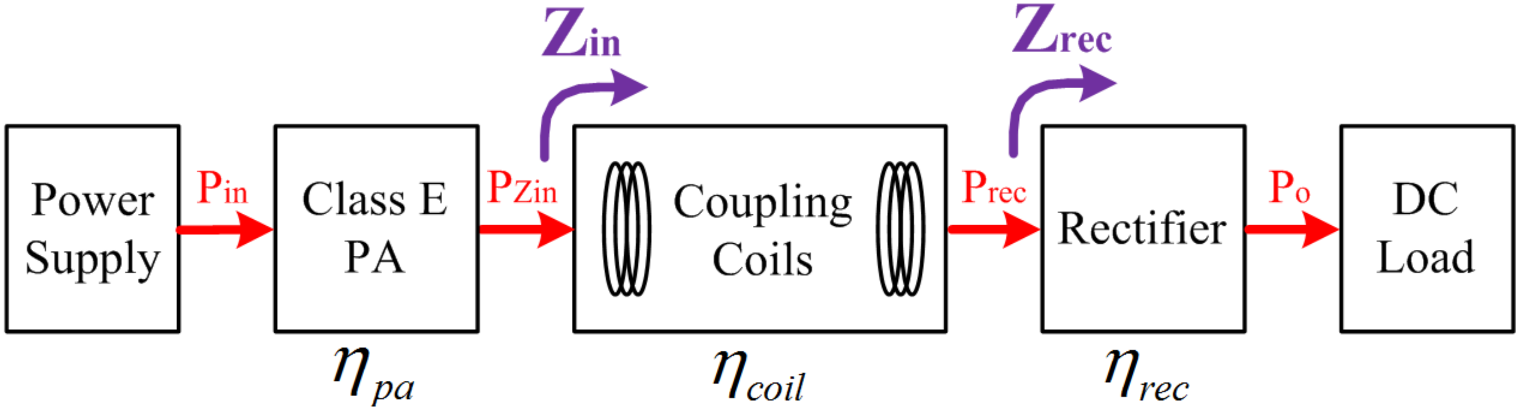
- Input reactance of the full-bridge rectifier is completely neglected;
- The compensation capacitors are designed to resonant with coupling coils;
- The Class E PA is optimized based on the input impedance of coupling coils.

Problems

- Large switching loss on the full-bridge rectifier at MHz;
- Difficult to analytical derive the input reactance of the rectifier ;
- Non-zero rectifier input reactance detunes the coupling coils from resonance;
- It also cause the PA to deviate from its ideal ZVS operation.

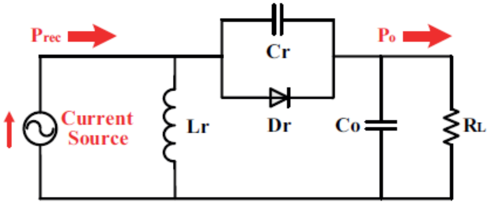
High-efficiency Rectification at MHz

- Select a high-efficiency rectifying circuit;
- Derive an analytical expression of the input impedance of the rectifier;
- Design parameters based on the derived input impedance of the rectifier.

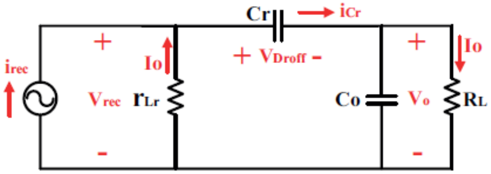


Rectifier Input Impedance

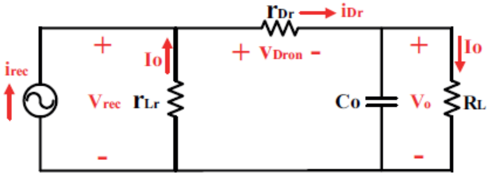
- The analytically derived input impedance of the Class E rectifier and the relationship between C_r and D.



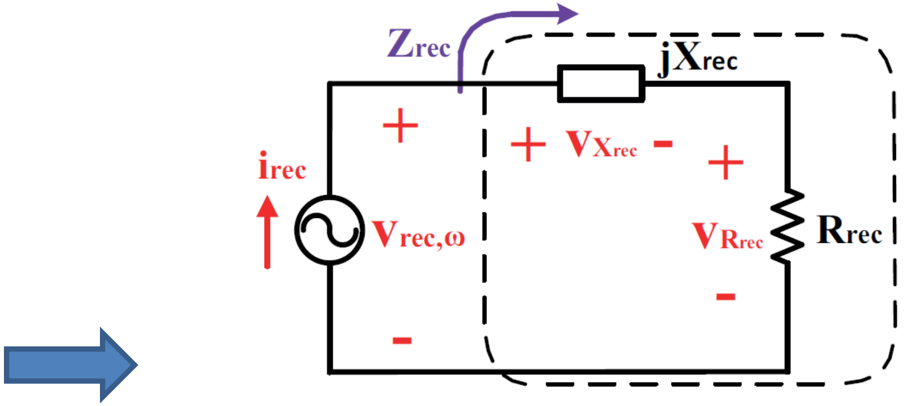
(a)



(b)



(c)



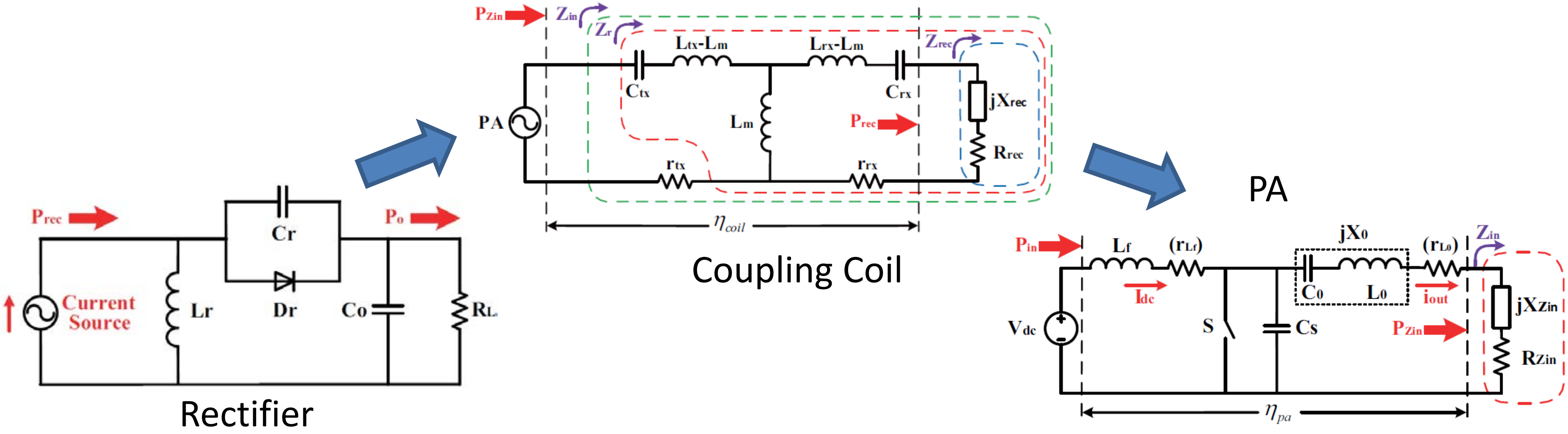
$$X_{rec} = \frac{V_{m,X_{rec}}}{I_m} = -\frac{1}{\pi}\left[\frac{a+b}{\omega C_r} + r_{D_r}(c+d)\right]$$

$$R_{rec} = 2\sin^2\phi_{rec}(R_L + r_{L_r}) + 2er_{D_r}$$

$$C_r = \frac{1 + \frac{[\sin 2\pi D + 2\pi(1-D)]^2}{1-\cos 2\pi D} - 2\pi^2(1-D)^2 - \cos 2\pi D}{2\pi\omega(R_L + r_{L_r} + r_{D_r})}$$

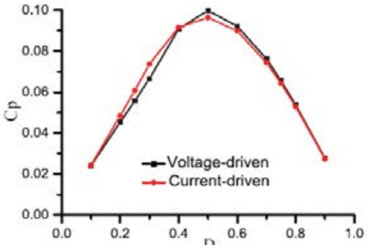
System-Level Optimization

- Rectifier: C_r that enables a 0.5 duty cycle, D;
- Receiving coil: C_{rx} that makes the coupling coils truly resonant;
- PA: C_S that follows the Raab's equations and the load of PA.



Optimized Parameter Design

$$C_{r,opt} = \frac{747.2}{R_L + r_{L_r} + r_{D_r}} \times 10^{-12}$$



$$\eta_{rec} = \frac{R_L}{R_L + r_{L_r} + 1.2337 r_{D_r}}$$

$$C_{rx,opt} = \frac{1}{\omega[\omega L_{rx} - (0.6648(R_L + R_{L_r}) + 0.8484 r_{D_r})]}$$

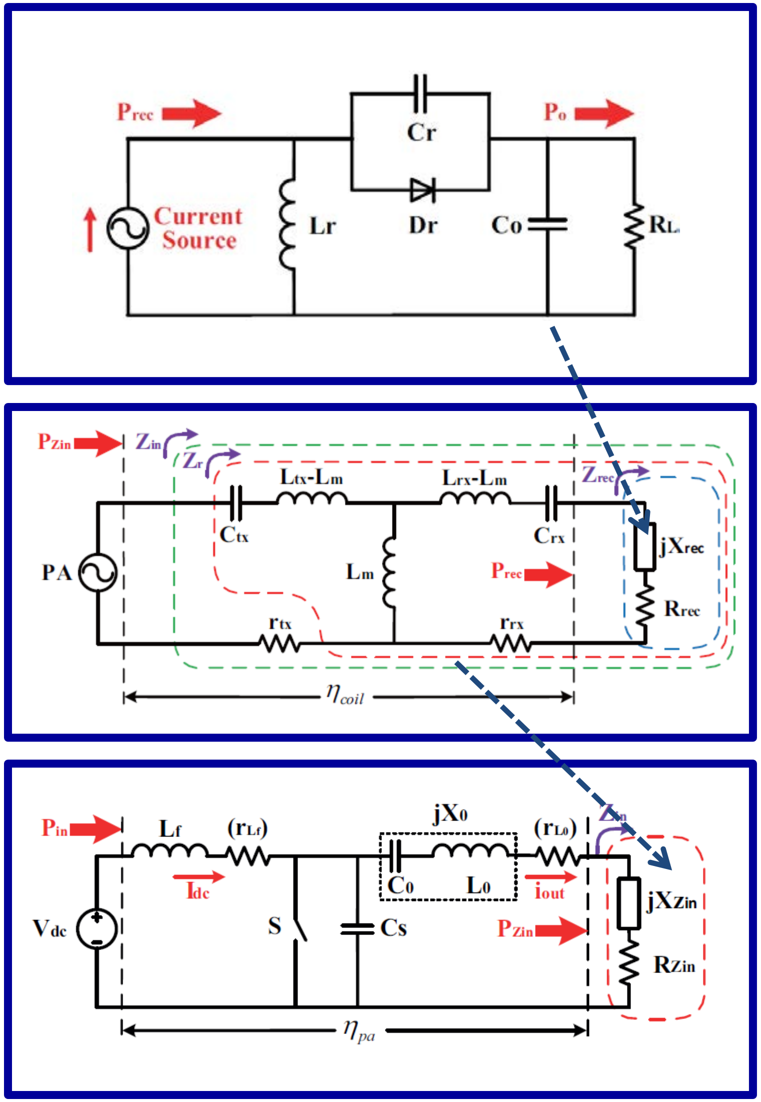
$$\eta_{coil} = \frac{\frac{\omega^2 L^2{}_m [0.5768(R_L + r_{L_r}) + 0.7116 r_{D_r}]}{r_{rx} + 0.5768(R_L + r_{L_r}) + 0.7116 r_{D_r}}}{r_{tx}[r_{rx} + 0.5768(R_L + r_{L_r}) + 0.7116 r_{D_r}] + \omega^2 L^2{}_m}$$

$$C_{S,opt} = \frac{0.1836[r_{rx} + 0.5768(R_L + r_{L_r}) + 0.7116 r_{D_r}]}{\omega r_{tx}[r_{rx} + 0.5768(R_L + r_{L_r}) + 0.7116 r_{D_r}] + \omega^3 L^2{}_m}$$

$$X_{0,opt} = 1.1525 r_{tx} + \frac{1.1525 \omega^2 k^2 L_{tx} L_{rx}}{r_{rx} + 0.5768(R_L + r_{L_r}) + 0.7116 r_{D_r}}$$

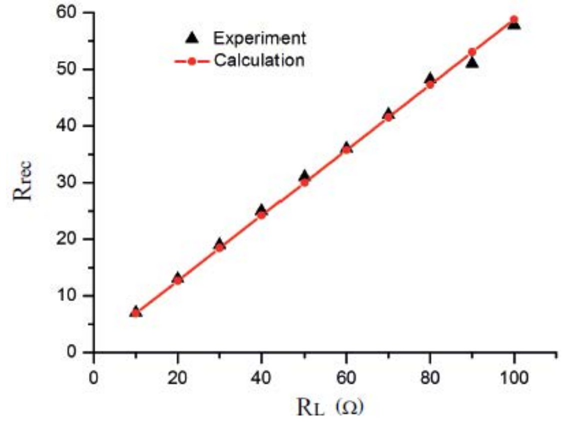
$$\eta_{PA} = \frac{P_{Z_{in}}}{P'_{in}} = \frac{g^2 R_{Z_{in}}}{2R_{dc} + 2r_{L_f} + g^2 r_{L_0}}$$

$$\begin{aligned} g &= \frac{2\pi \sin(\varphi + \phi) + 4cos(\varphi + \phi)}{4 \cos\phi \sin(\varphi + \phi) + \pi \cos\varphi}, \\ \varphi &= arc\tan \frac{X_0}{R_{Z_{in}}}, \\ \phi &= arc\tan \frac{\frac{\pi^2}{2} - 4 - \pi\omega C_S(2R_{Z_{in}} + \pi X_0)}{\pi + \pi^2 \omega C_S R_{Z_{in}} - 2\pi\omega C_S X_0}, \end{aligned}$$

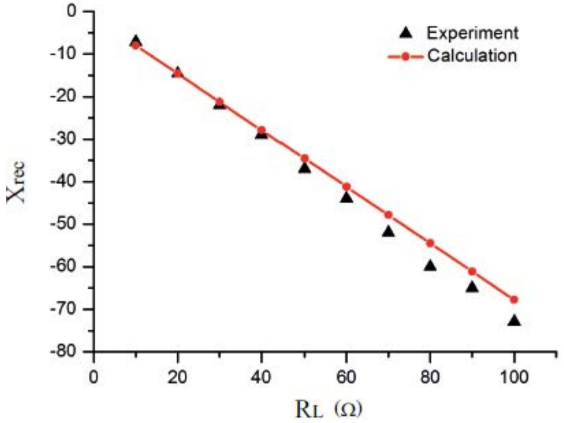


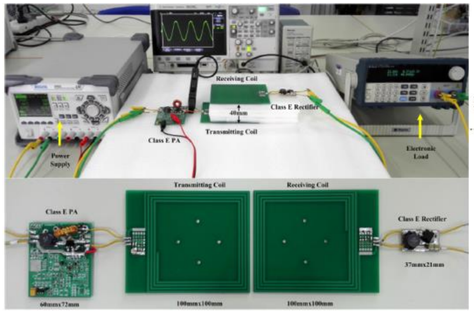
Results (6.78MHz, *k*=0.1327, 84%)

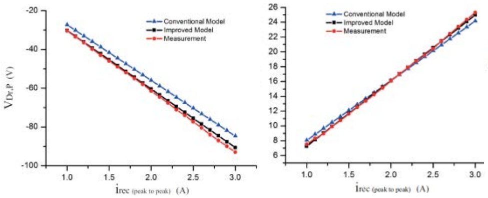
Impedance

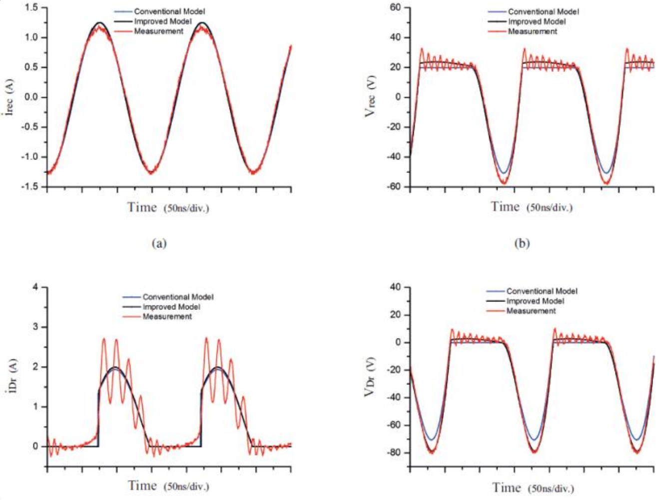


(a)



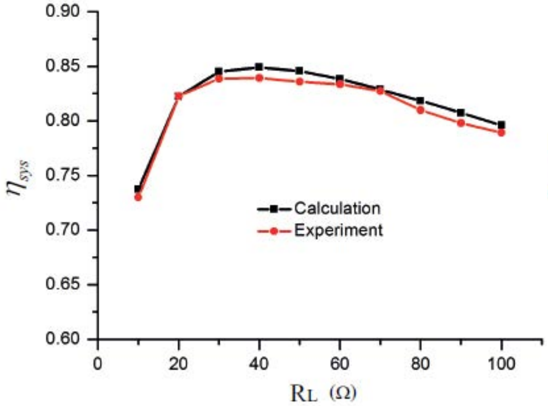


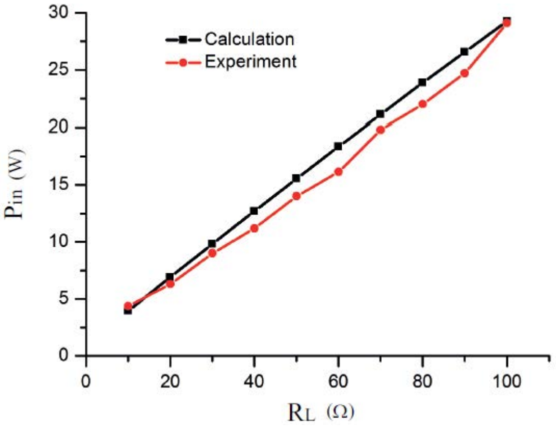




(a) (b)

Efficiency and power





Summary-Parameter Design

- Analytically derived characteristics of the circuits, particularly the input impedance of the rectifier;
- A system-level approach starting from rectifier and being extended to optimize the coupling coils and PA.
- A very high dc-to-dc system efficiency, 84%, is achieved with loosely coupled coils, k=0.1327 (40mm).

- M. Liu, M. Fu, C. Ma: "Parameter Design for A 6.78-MHz Wireless Power Transfer System Based on Analytical Derivation of Class E Current-Driven Rectifier", *IEEE Transactions on Power Electronics*, Vol. 31, No. 6, pp. 4280-4291, June 2016.

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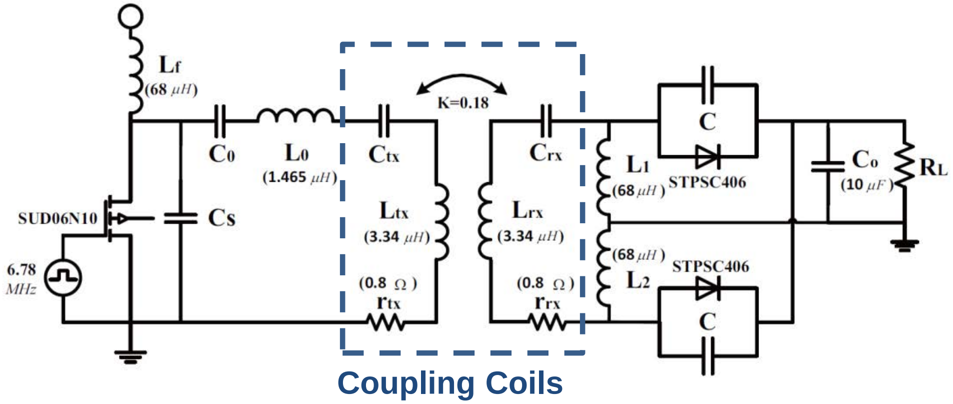
Motivation

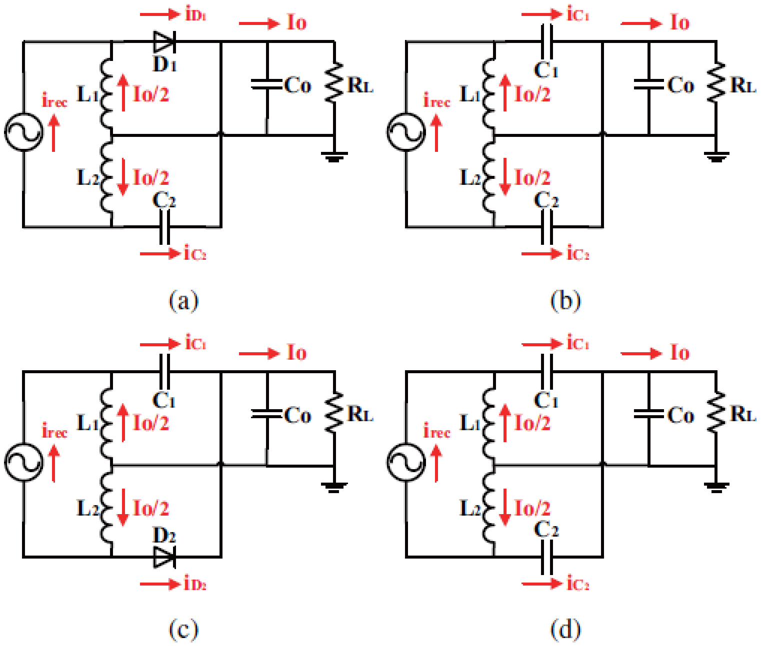
- EMI improvement through optimized design of circuits in a MHz WPT system;
- Reduction of THD of the input/output voltage of coupling coils;
- A high system efficiency at the same time.



Due to the series-series compensation, the input and output currents of the coupling coils are sinusoidal. Thus the THDs of their input/output voltages are criteria to verify the improvement on EMI.

Class-E Full-Wave Rectifier

- A promising candidate because of its sinusoidal input voltage and current.
- A 0.49 duty cycle of the rectifying diodes that avoids the overlapping and maximizes the power output capability of the rectifier.

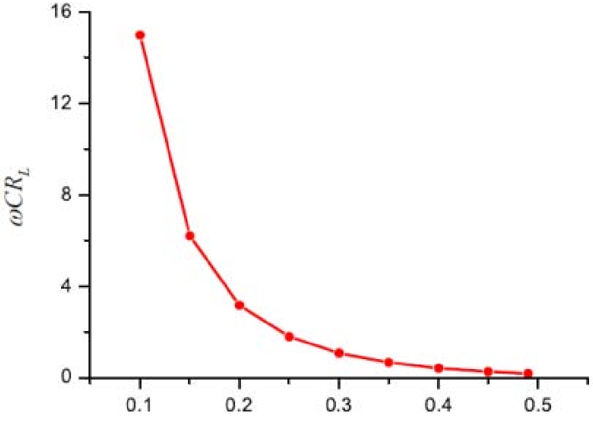


(a) (b)

(c) (d)

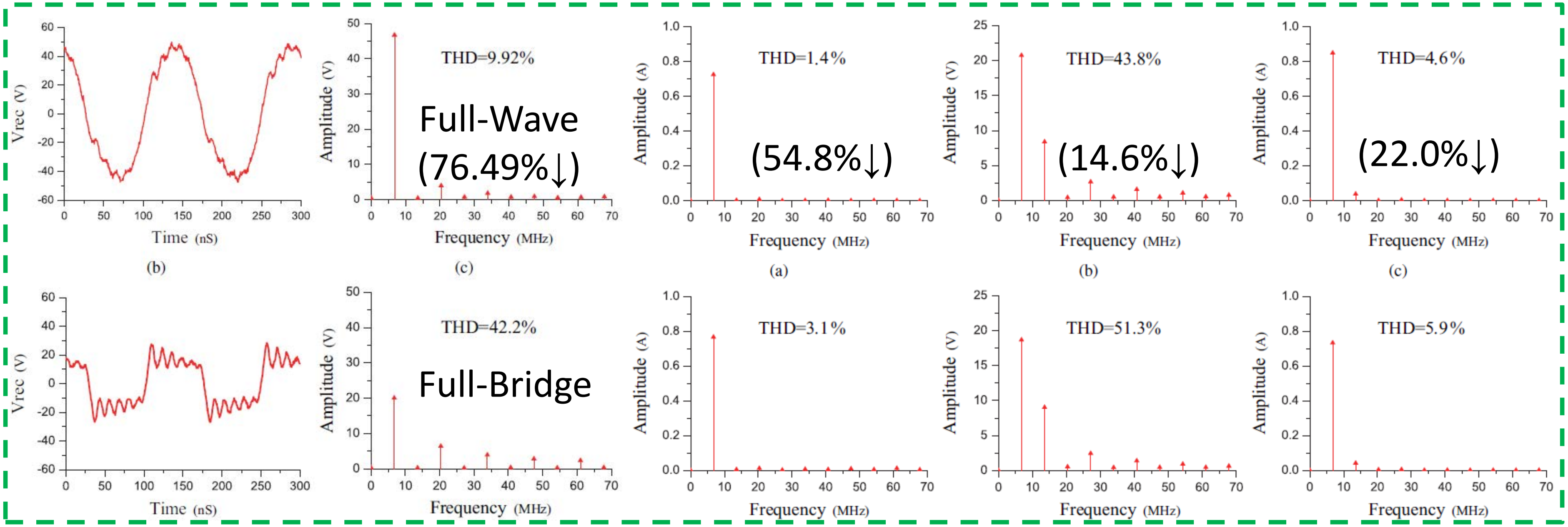
$$C = \frac{1}{\omega R_L}\left[\frac{1}{4\pi} - \frac{\pi}{2}(1-D)^2 + \frac{2\pi(1-D)cos(\phi_{rec}+2\pi D) - sin\phi_{rec}}{4\pi sin(\phi_{rec}+2\pi D)}\right]$$

$$C_{opt} = \frac{0.1756}{\omega R_{L,\min}}$$



Results-THD with D=0.49

- The other parameters are designed following the procedures previously explained.
- The THDs are compared with those of the conventional full-bridge rectifier.



Full-Wave (76.49%↓)

(54.8%↓)

(14.6%↓)

(22.0%↓)

Full-Bridge

Input Voltage Waveform (Rectifier)

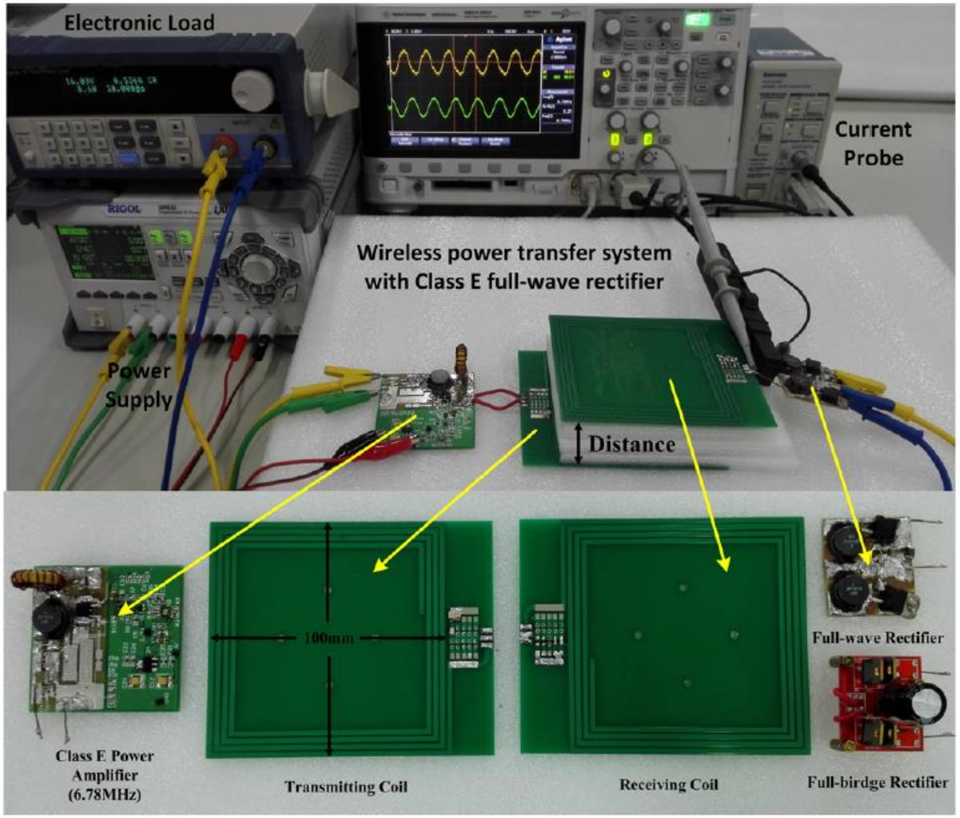
Input Voltage (Rectifier)

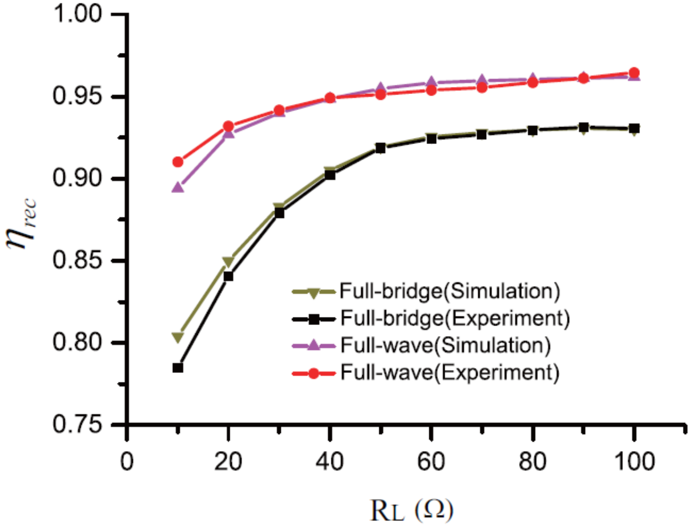
Output Current (Receiving Coil)

Input Voltage (Transmitting coil)

Input Current (Transmitting Coil)

Results-Power Losses





Loss breakdown (10 W, 30 Ω R_L)

Loss	Full-wave Rec.	Full-bridge Rec.
P_{sw}	0.26 W	0.61 W
P_{cd}	0.29 W	0.60 W
P_L	0.03 W	-

$$P_{cd} = \frac{1}{2\pi}\left\{\int_0^{2\pi D}\left[V_F i_{D_1}(\omega t) + r_D i_{D_1}^2(\omega t)\right] d\omega t + \int_{2\pi(1-D)}^{2\pi}\left[V_F i_{D_2}(\omega t) + r_D i_{D_2}^2(\omega t)\right] d\omega t\right\},$$

$$P_L = 2\left(\frac{I_o}{2}\right)^2 r_L$$

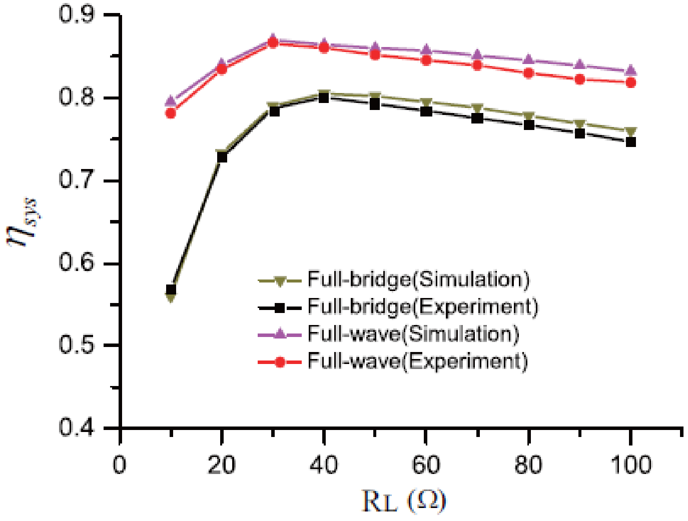
$$P_{sw} = P_{rec} - P_o - P_L - P_{cd}$$

Results-(80% Ave. Efficiency)

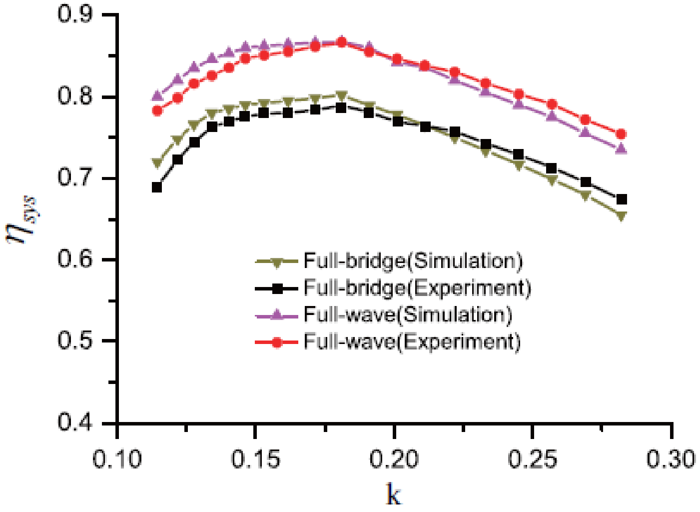
Loss breakdown (10 W system input power, 30 Ω R_L)

Loss	WPT system (Full-wave Rec.)	WPT system (Full-bridge Rec.)
Rectifier	0.55 W	1.06 W
Coupling Coils	0.33 W	0.55 W
PA	0.42 W	0.65 W
Total	1.30 W	2.26 W

Power losses from the rectifiers significantly influence the overall efficiencies (42.48%↓).



Under different loads



Under different coupling

Summary-Harmonic Reduction

- The Class-E full-wave rectifier is proposed to improve the EMI problem;
- A systematic design approach is developed to design the rectifier, coupling coils, and PA;
- Significant THD reduction, 76.49%, in input voltage of the rectifier is achieved comparing with that in the conventional full-bridge rectifier.

- M. Liu, M. Fu, C. Ma: "Low-Harmonic-Contents and High-Efficiency Class E Full-Wave Current-Driven Rectifier for Megahertz Wireless Power Transfer Systems", *IEEE Transactions on Power Electronics*, accepted on Mar. 28th, 2016.

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Motivation-Enhanced Robustness

- Most of existing designs target on a single fixed operating condition, i.e., fixed coil relative position and load.
- However, in real applications changes in the coil relative position and final dc load are common.
- A design methodology, active or passive, is required to optimize the performance over the possible ranges of the coil relative position and load.


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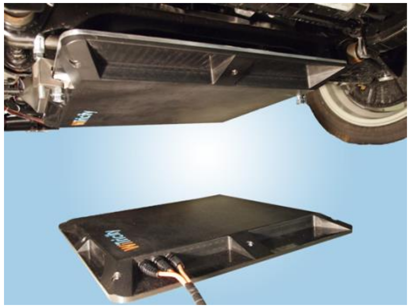
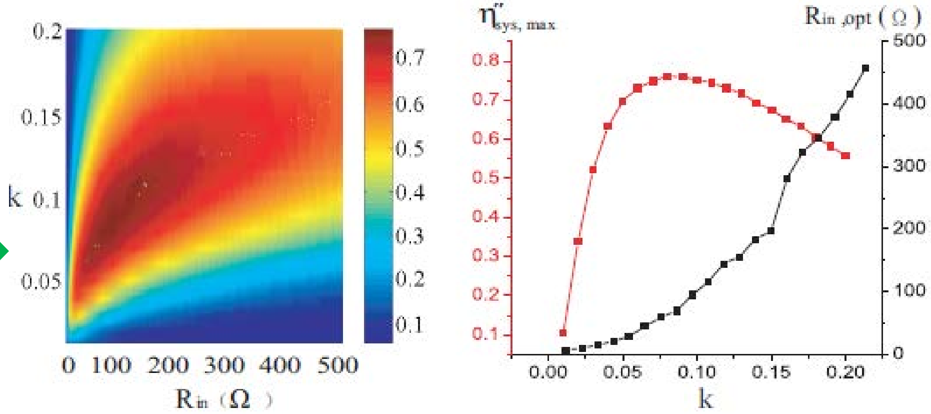
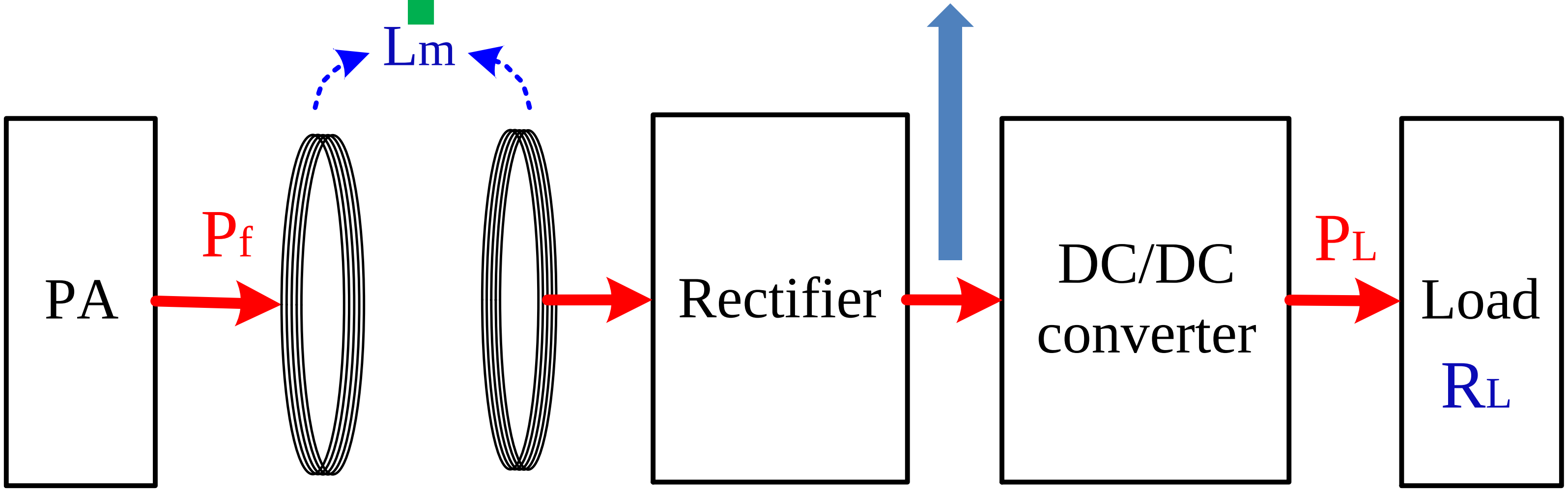
Optimal Load for High Efficiency



Optimal loads





L_m

PA

P_f

Rectifier

DC/DC converter

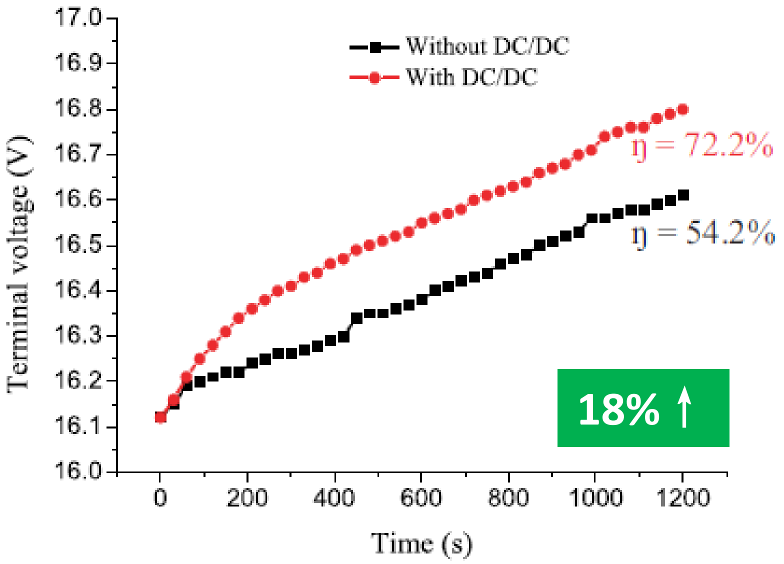
P_L

Load

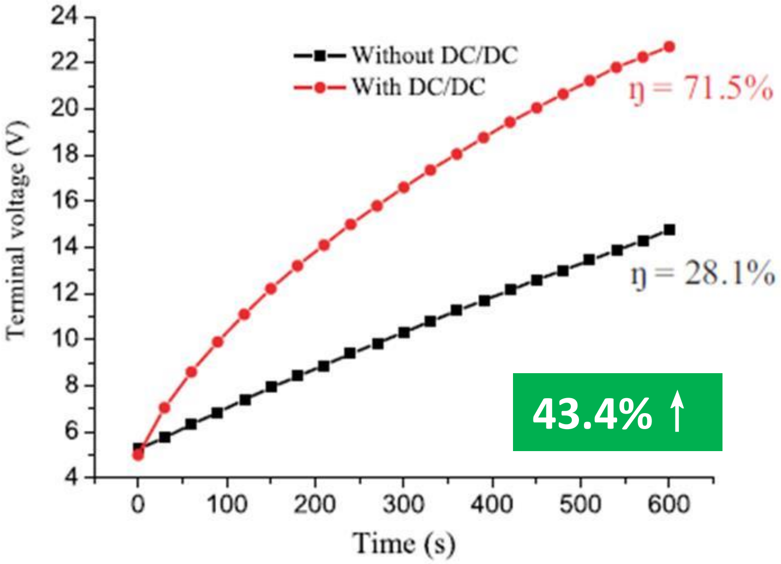
R_L

Improved Charging Efficiency

- Wireless charging efficiency improvement with a fixed coil relative position.



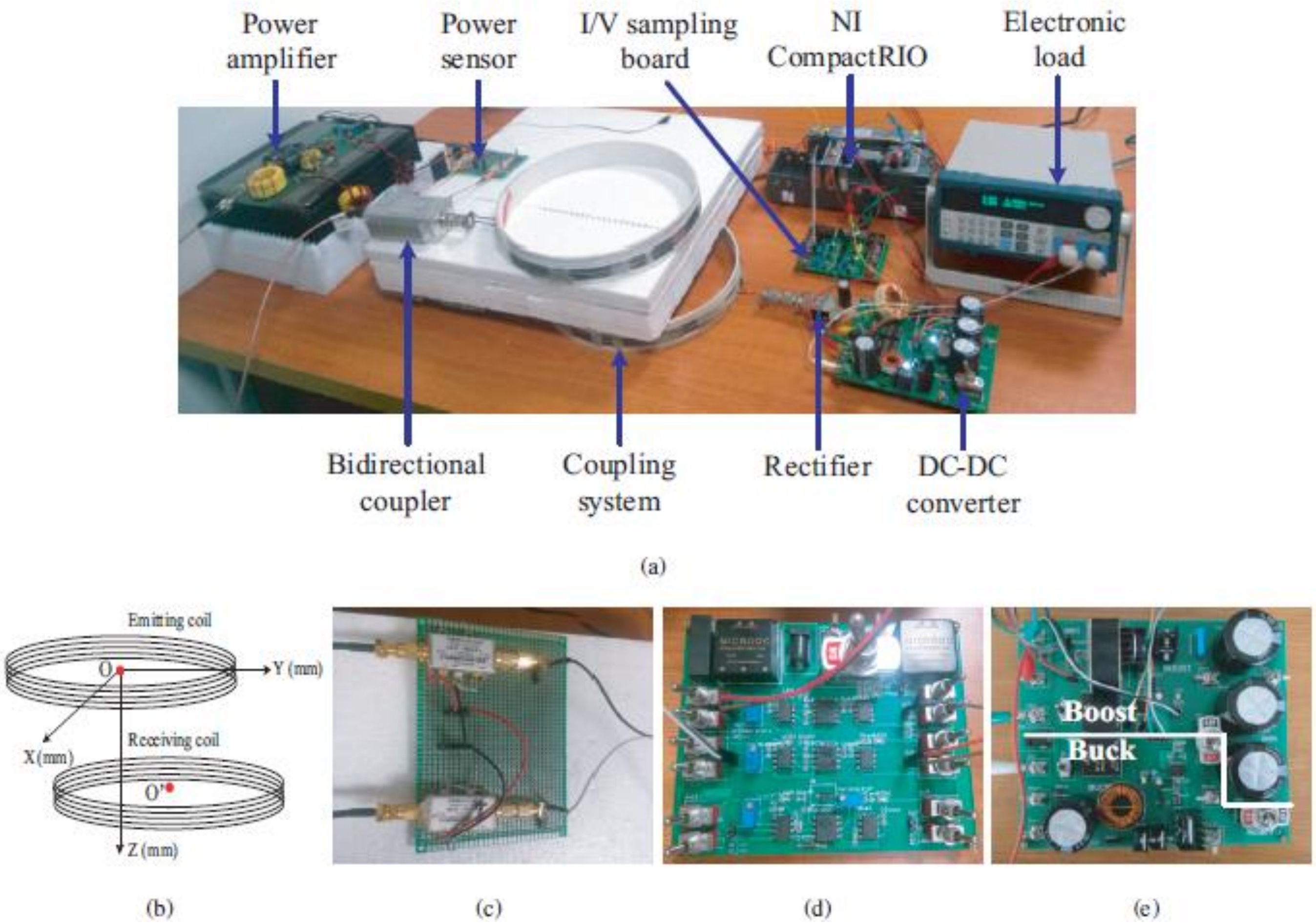
Batteries charging improvement using the cascaded boost-buck DC-DC converter.



Ultracapacitors charging improvement using the cascaded boost-buck DC-DC converter.

- M. Fu, C. Ma, X. Zhu: "A Cascaded Boost-Buck Converter for Load Matching in 13.56MHz Wireless Power Transfer", IEEE Transactions on Industrial Informatics, IEEE Transactions on Industrial Informatics, Vol. 10, No. 3, pp. 1972-1980, Aug. 2014.

Experiment Setup



(a)

(b) (c) (d) (e)

The experimental WPT system. (a) Overall system. (b) Relative position of coils. (c) Power sensor. (d) I/V sampling board. (e) Cascaded DC/DC converter.

Hill-climbing Tracking of Optimal Load

A varying load resistance

A varying coil position

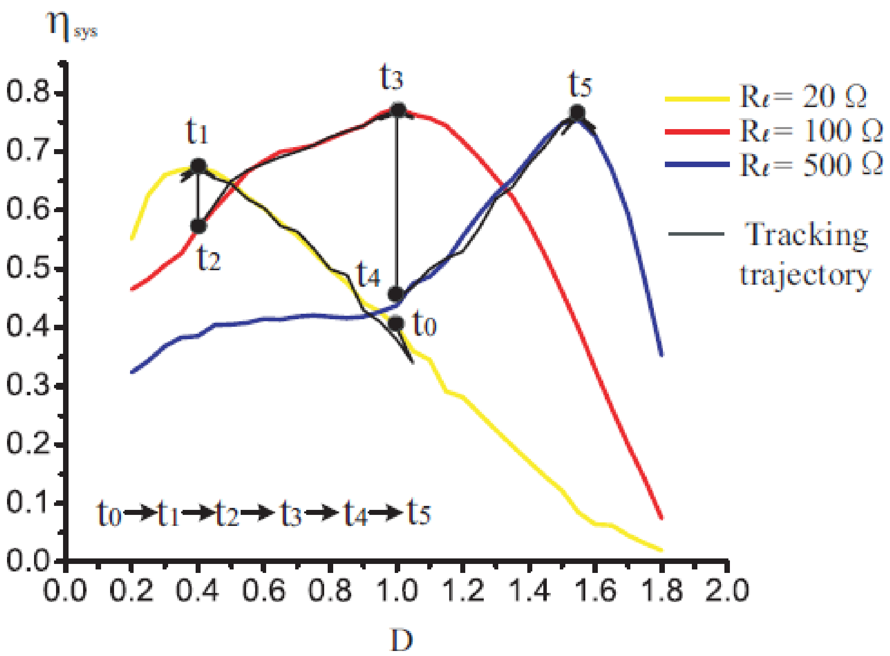


Fig. 1 Tracking of optimal load resistances with a varying R_l.

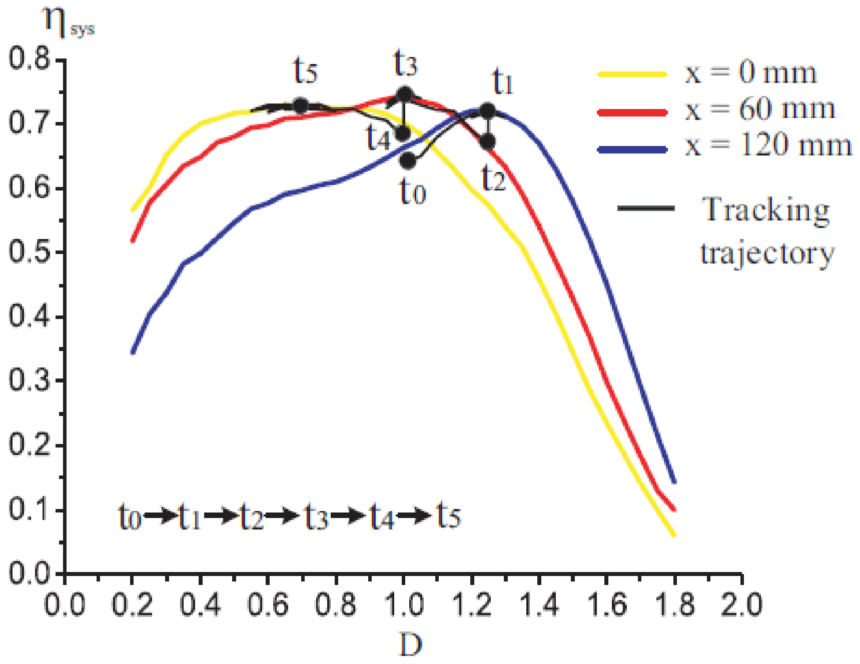
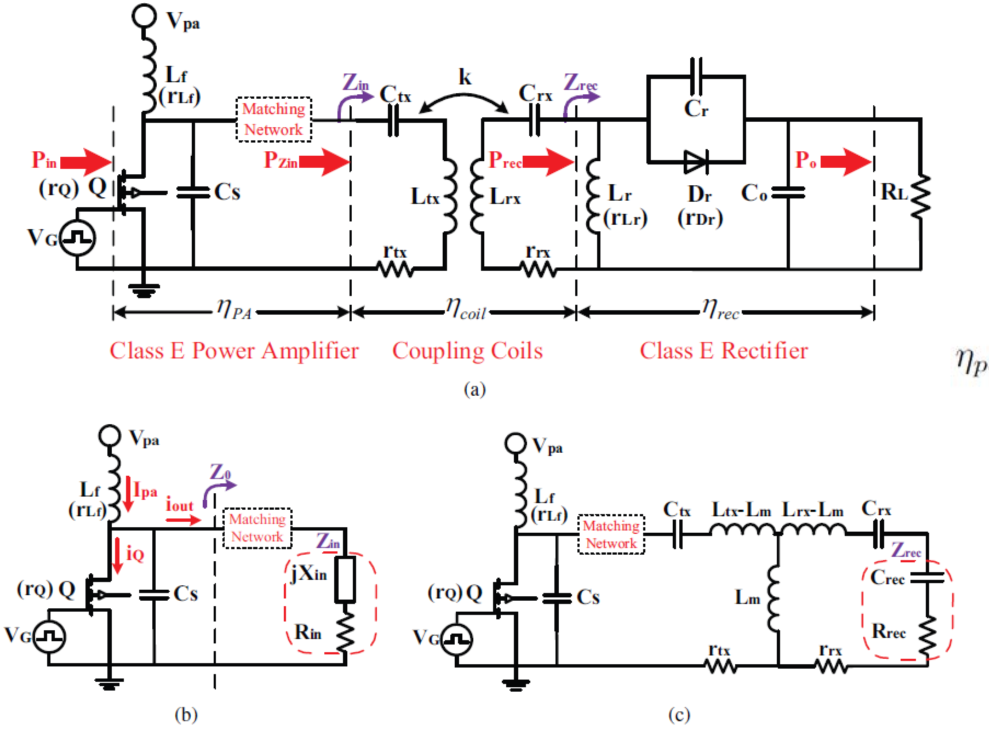


Fig. 2 Tracking of optimal load resistances with a varying *k*.

- M. Fu, H. Yin, X, Zhu, C. Ma: "Analysis and Tracking of Optimal Load in Wireless Power Transfer Systems", IEEE Transactions on Power Electronics, Vol. 30, No. 7, pp. 3952-3963, July 2015.

System Efficiency-Class E² WPT System

- Again, the system efficiency of the MHz Class E² WPT system is analytically derived.



$$\boxed{\eta_{sys} = \eta_{pa} \cdot \eta_{coil} \cdot \eta_{rec} = \frac{P_o}{P_{in}}}$$

$$\eta_{pa} = \frac{P_{Z_{in}}}{P_{in}}, \quad \eta_{coil} = \frac{P_{rec}}{P_{Z_{in}}}, \quad \text{and } \eta_{rec} = \frac{P_o}{P_{rec}}$$

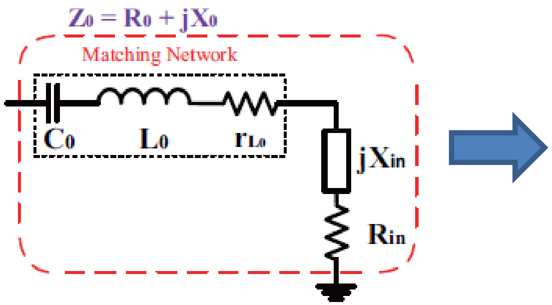
$$\eta_{pa} = \frac{P_{Z_{in}}}{P_{in}} = \frac{a^2(R_0 - r_{L_0})}{2R_{dc} + 2r_{L_f} + a^2 r_{L_0} + (1 + \frac{2a}{\pi} + \frac{a^2}{2})r_Q}$$

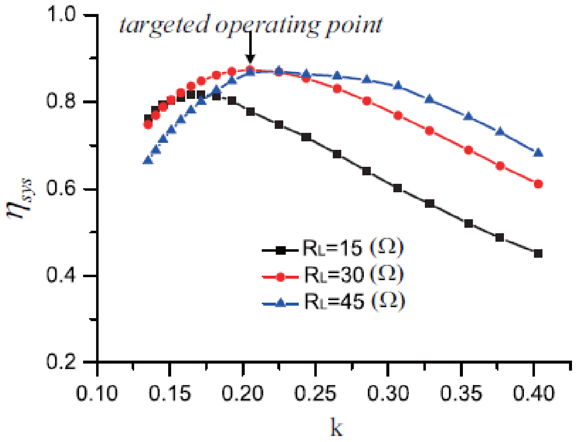
$$\eta_{coil} = \frac{R_{rec}\omega^2 k^2 L_{tx} L_{rx}}{\omega^2 k^2 L_{tx} L_{rx}(R_{rec}+r_{rx}) + r_{tx} b}$$

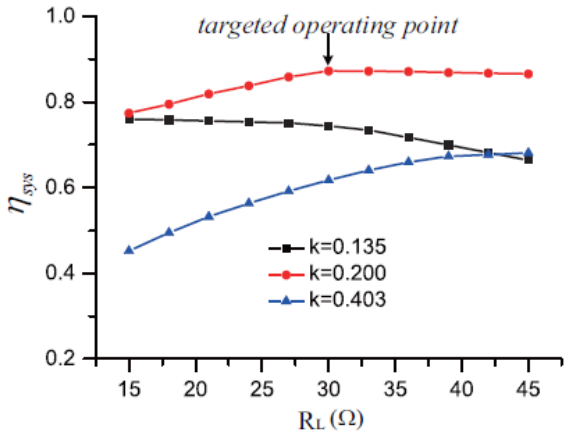
$$\eta_{rec} = \frac{P_o}{P_{rec}} = \frac{R_L}{R_L + r_{L_r} + \frac{c r_{D_r}}{\sin^2\phi_{rec}}}$$

Original PA Matching Network

- Original Class E PA matching network has poor robustness.







Robustness Index

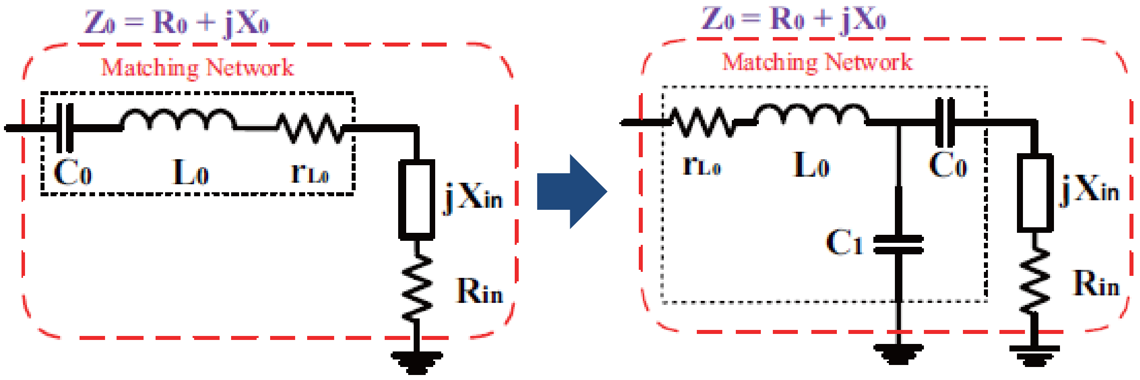
$$\alpha_x = \max \left| \frac{\eta_x(k, R_L) - \eta_x(0.203, 30)}{\eta_x(0.203, 30)} \right|$$

α_{pa}	α_{coil}	α_{rec}	α_{sys}
47.0%	5.3%	4.2%	47.6%

Note: A smaller *α* corresponds to improved robustness.

Modified MN and Design Problem

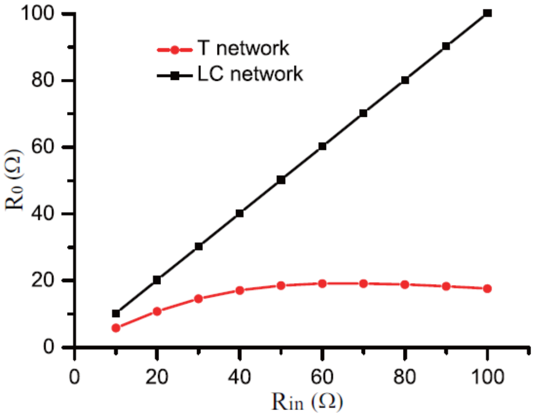
Circuit Improvement

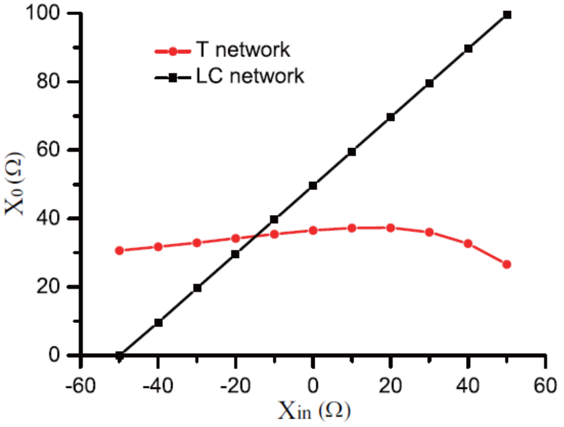


$$R_0 = R_{in} + r_{L_0} \text{ and } X_0 = X_{in} + \omega L_0 - \frac{1}{\omega C_0}.$$

$$R_0 = r_{L_0} + \frac{R_{in}}{\omega^2 {C_1}^2 \left[(\frac{1}{\omega C_0} + \frac{1}{\omega C_1} - X_{in})^2 + {R_{in}}^2 \right]},$$

$$X_0 = \omega L_0 + \frac{(X_{in} - \frac{1}{\omega C_0})(\frac{1}{\omega C_0} + \frac{1}{\omega C_1} - X_{in}) - {R_{in}}^2}{\omega C_1 \left[(\frac{1}{\omega C_0} + \frac{1}{\omega C_1} - X_{in})^2 + {R_{in}}^2 \right]}$$





Robust Optimization

Definitions of Parameters

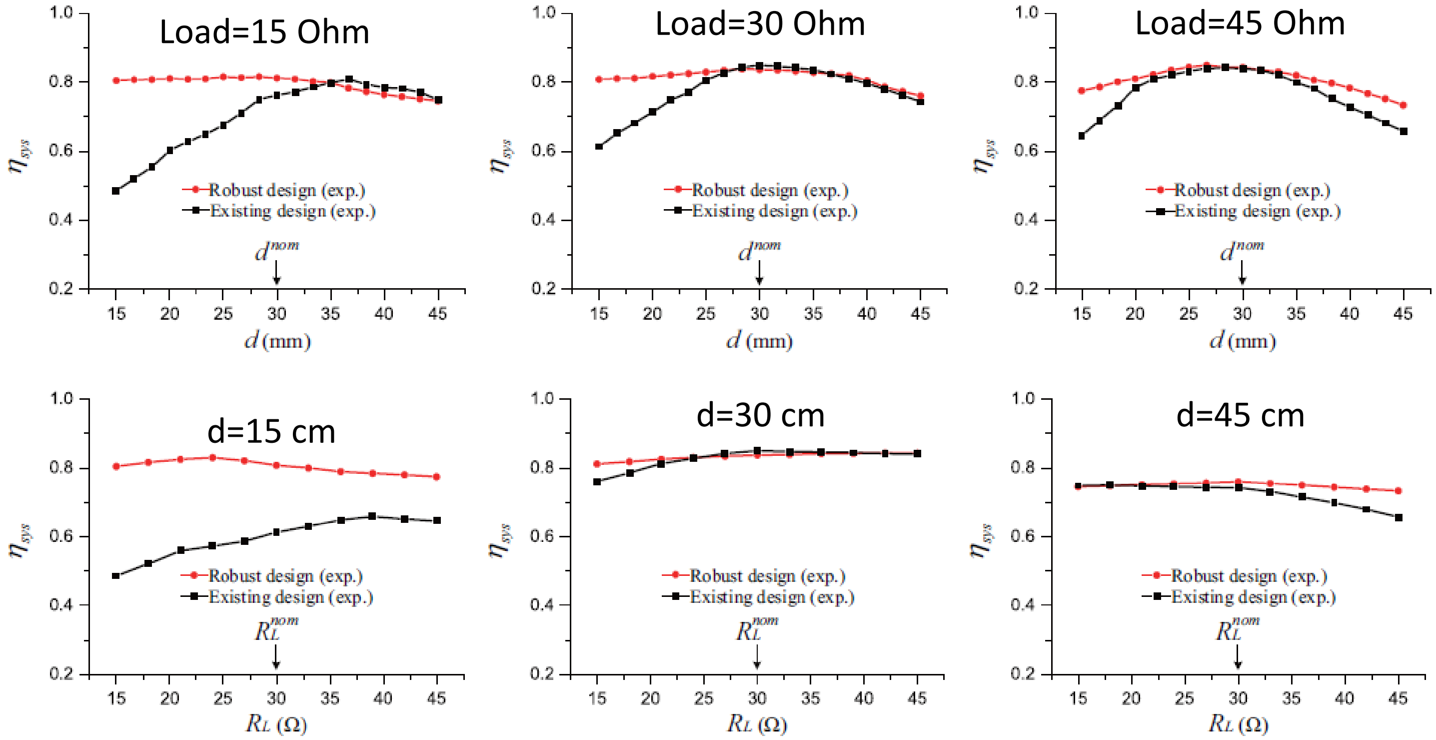
Vector	Components
$\mathbf{x}$	$[C_S,\ C_0,\ C_1,\ C_{rx},\ C_r]_{1\times 5}$
$\mathbf{p_{var}}$	$[k,\ R_L]_{1\times 2}$
$\mathbf{p_{var}^{nom}}$	$[k^{nom},\ R_L^{nom}]_{1\times 2}$
$\mathbf{p_{var}^{lower}}$	$[k^{min},\ R_L^{min}]_{1\times 2}$
$\mathbf{p_{var}^{upper}}$	$[k^{max},\ R_L^{max}]_{1\times 2}$
$\mathbf{p_{con}}$	$[\omega,\ C_{tx},\ L_0,\ L_{tx},\ L_{rx},\ r_Q,\ r_{L_f},\ r_{L_0},\ r_{tx},\ r_{rx},\ r_{L_r},\ r_{D_r}]_{1\times 12}$

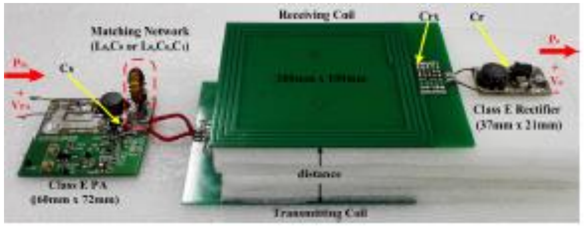
Optimization Problem

$$\begin{aligned} \max_{\mathbf{x}} \quad & \eta_{sys}^{nom}(\mathbf{x}) \\ s.t. \quad & \alpha_{sys}(\mathbf{x}) \le \alpha_{sys}^{max}, \\ & \max_{\mathbf{p_{var}}} |D(\mathbf{x}, \mathbf{p_{con}}, \mathbf{p_{var}}) - 0.5| \le \beta_D^{max} \end{aligned}$$

$$\begin{aligned} \alpha_{sys}(\mathbf{x}) &= \max_{\mathbf{p_{var}}} \left| \frac{\eta_{sys}(\mathbf{x}, \mathbf{p_{var}}) - \eta_{sys}^{nom}(\mathbf{x})}{\eta_{sys}^{nom}(\mathbf{x})} \right| \\ &= \max_{\mathbf{p_{var}}} \left| \frac{f(x, p_{con}, p_{var}) - f(x, p_{con}, p_{var}^{nom})}{f(x, p_{con}, p_{var}^{nom})} \right| \end{aligned}$$

Results





	α_{pa}	α_{coil}	α_{rec}	α_{sys}
Robust design	11.1%	3.3%	3.1%	12.4%
Existing design	43.3%	5.8%	4.2%	44.1%

Summary-Robust Design

- A new circuit design methodology is developed that optimizes the performance over ranges rather than single fixed operating condition.
- The PA matching network is modified to enhance the robustness of the load-sensitive Class E PA.
- The potential of the circuits is maximized through the optimization-based parameter design, i.e., a multi-disciplinary approach.

- M. Liu, Y. Qiao, S. Liu, C. Ma: "Analysis and Design of A Robust Class E^2 DC-DC Converter for Megahertz Wireless Power Transfer", *IEEE Transactions on Power Electronics*, accepted on May 16th, 2016.

Outline

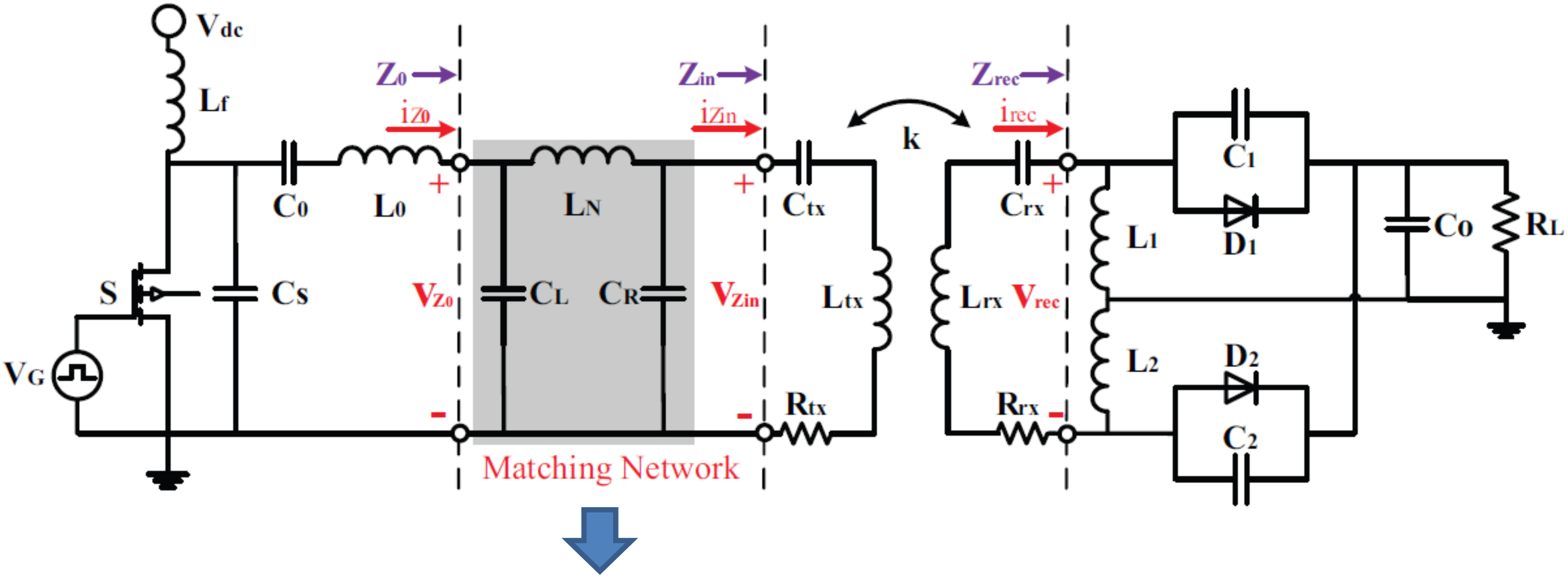
- Introduction
- Parameter Design
- Harmonic Reduction
- Robust Design
- Matching Network Design
- Other Ongoing Activities
- Conclusion

Motivation

- Further reduction of harmonic contents in the input voltage of coupling coils;
- A stable performance under variations in coupling and final load;
- A robust multiple-receiver system driven by a constant-current-mode PA;
- Circuit design methodology to achieve 1) low EMI, 2) high efficiency, and 3) high output power.

Matching Network

- MN is included to transform and thus provide desired impedances as the PA load.



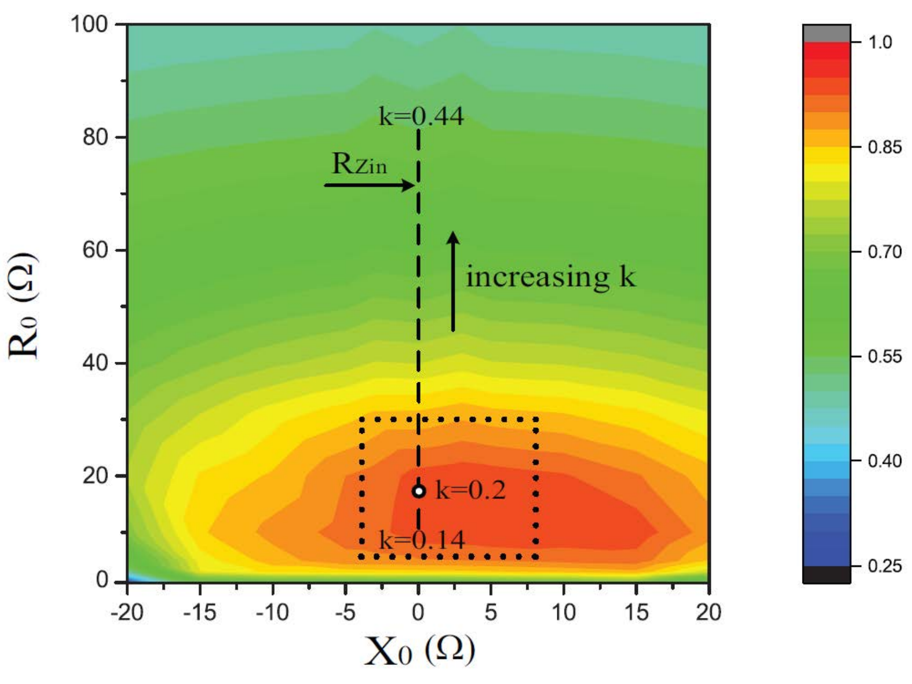
$$R_0 = \frac{\frac{Z_{in}}{\omega^2 C_L C_R}(\omega L_N - \frac{1}{\omega C_L})(\omega L_N - \frac{1}{\omega C_R}) - \frac{\omega L_N Z_{in}}{\omega^2 C_L C_R}(\omega L_N - \frac{1}{\omega C_L} - \frac{1}{\omega C_R})}{(\omega L_N Z_{in} - \frac{Z_{in}}{\omega C_L} - \frac{Z_{in}}{\omega C_R})^2 + (\frac{\omega L_N}{\omega C_R} - \frac{1}{\omega^2 C_L C_R})^2}$$

$$X_0 = -\frac{\frac{{Z_{in}}^2}{\omega C_L}(\omega L_N - \frac{1}{\omega C_R})(\omega L_N - \frac{1}{\omega C_L} - \frac{1}{\omega C_R}) + \frac{\omega L_N}{\omega^3 C_L {C_R}^2}(\omega L_N - \frac{1}{\omega C_L})}{(\omega L_N Z_{in} - \frac{Z_{in}}{\omega C_L} - \frac{Z_{in}}{\omega C_R})^2 + (\frac{\omega L_N}{\omega C_R} - \frac{1}{\omega^2 C_L C_R})^2}$$

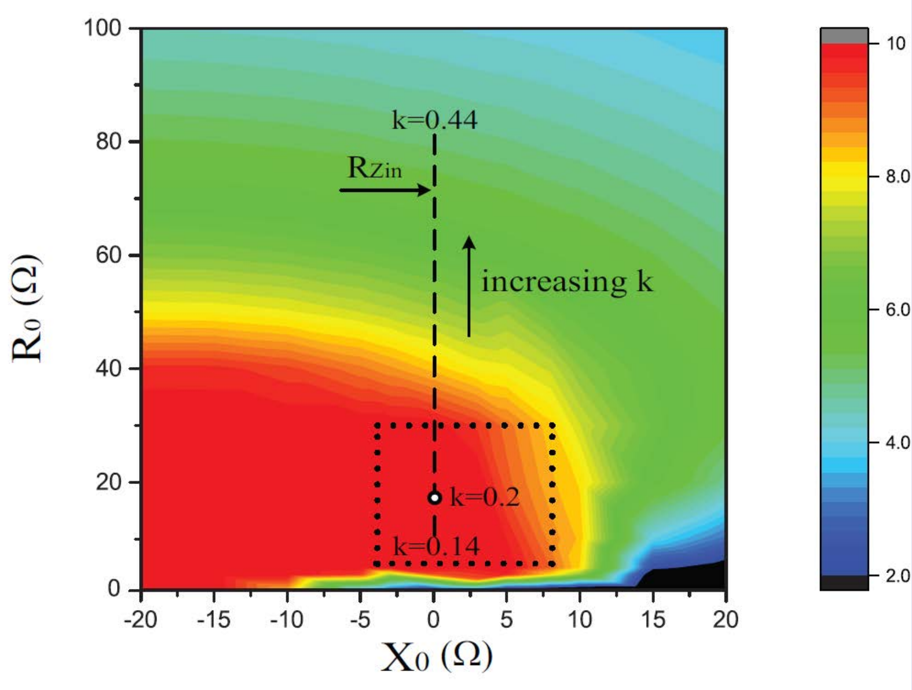
Target Region of PA load

- A common region for both high efficiency and high output power.

PA Efficiency Contours

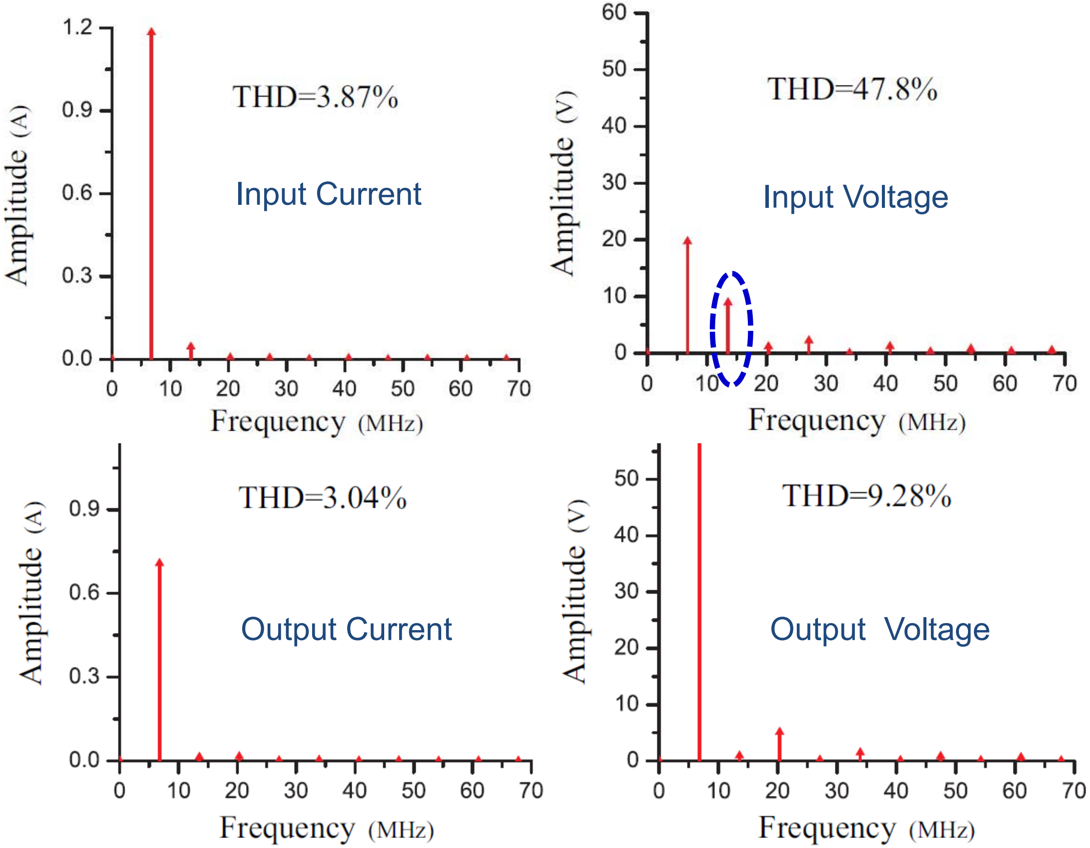


PA Power Contours



THD Analysis

- The high THD of the input voltage of the coupling coils is mostly caused by the 2nd-oder harmonic.



Matching Network Design

Harmonics Suppression

$$V^{(1)}_{Z_{in},m} = \left|Z^{(1)}_{in}\right| I^{(1)}_{Z_{in},m}$$

$$\Downarrow$$

$$\frac{I^{(1)2}_{0,m}}{2} R^{(1)}_0 = \frac{I^{(1)2}_{Z_{in},m}}{2} R^{(1)}_{Z_{in}}$$

$$\Downarrow$$

$$V^{(1)}_{Z_{in},m} = \left|Z^{(1)}_{in}\right| I^{(1)}_{0,m}\sqrt{\frac{R^{(1)}_0}{R^{(1)}_{Z_{in}}}}.$$

$$V^{(2)}_{Z_{in},m} = \left|Z^{(2)}_{in}\right| I^{(2)}_{0,m}\sqrt{\frac{R^{(2)}_0}{R^{(2)}_{Z_{in}}}};$$

$$\Downarrow$$

$$\frac{V^{(2)}_{Z_{in},m}}{V^{(1)}_{Z_{in},m}} = \frac{\left|Z^{(2)}_{in}\right| I^{(2)}_{0,m}\sqrt{R^{(1)}_{Z_{in}}}}{\left|Z^{(1)}_{in}\right| I^{(1)}_{0,m}\sqrt{R^{(2)}_{Z_{in}}}} \cdot \sqrt{\frac{R^{(2)}_0}{R^{(1)}_0}}$$

A smaller ratio of $R_0^{(2)}$ to $R_0^{(1)}$ results in a lower second-order harmonic.

Design Procedure

Define the feasible ranges of C_L and C_R:

$$C_L \in (C_L^{lower}, C_L^{upper})$$

$$C_R \in (C_R^{lower}, C_R^{upper})$$

Define a target region as a constraint:

$$R_0^{lower} \le {R_0}^{(1)}(k, C_L, C_R) \le R_0^{upper}$$

$$X_0^{lower} \le {X_0}^{(1)}(k, C_L, C_R) \le X_0^{upper}$$

Add the 2nd-order harmonic suppression as another constraint:

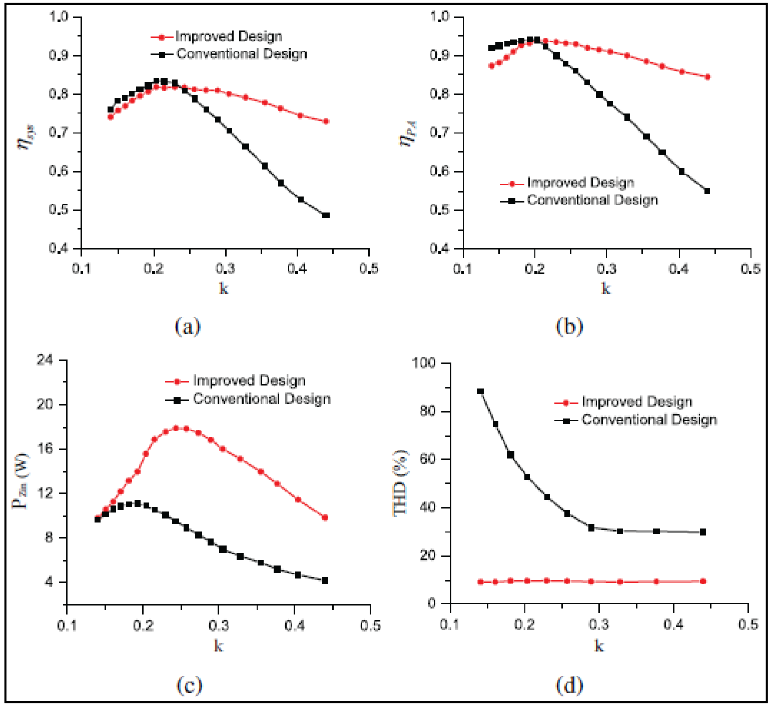
$$R_0^{(2)}(k, C_L, C_R) \le \lambda \cdot {R_0}^{(1)}(k, C_L, C_R)$$

where λ is an index. A smaller λ leads to a smaller 2nd-order harmonic.

The candidate combinations of the two capacitors can be obtained by simply sweeping C_L and C_R within their feasible ranges if the calculated $R_0^{(1)}$, $X_0^{(1)}$, $R_0^{(2)}$ meet the two constraints under the varying k.

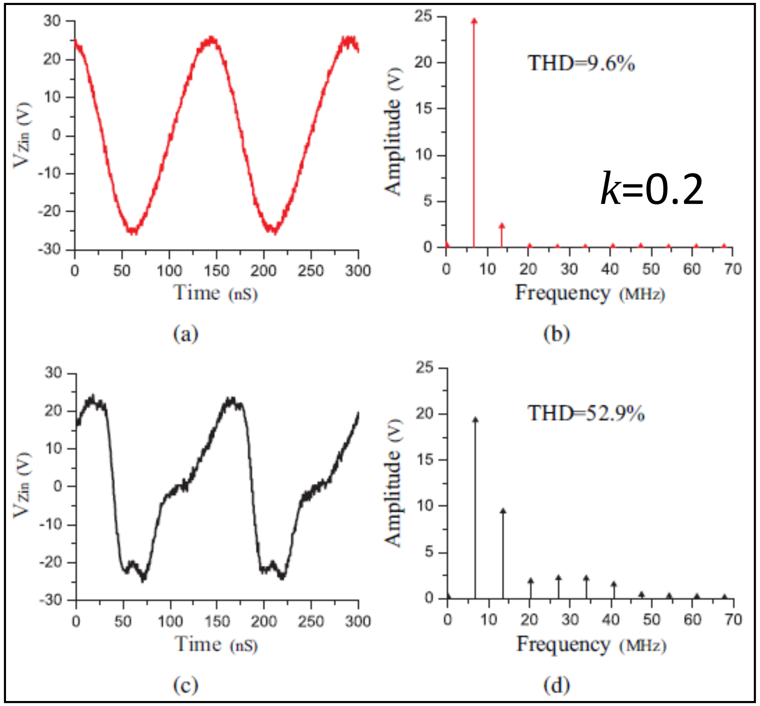
Results

- The efficiency and output power of both the PA and system are significantly improved over a wide range of k;
- The second-order harmonic and THD of the input voltage of coupling coils are obviously reduced, 81.9%.



(a) (b)

(c) (d)



(a) (b)

(c) (d)

Summary-Matching Network Design

- The reduction of harmonic contents in the input voltage of the coupling coils is discussed.
- A matching network is proposed, designed, and implemented.
- A design methodology is developed to perform the parameter design of the circuits at a system level.
- The effort helps to design robust multiple-receiver WPT systems.

- M. Liu, S. Liu, and C. Ma, “A High Efficiency/Output Power and Low Noise Megahertz Wireless Power Transfer System over A Wide Range of Mutual Inductance”, under review.

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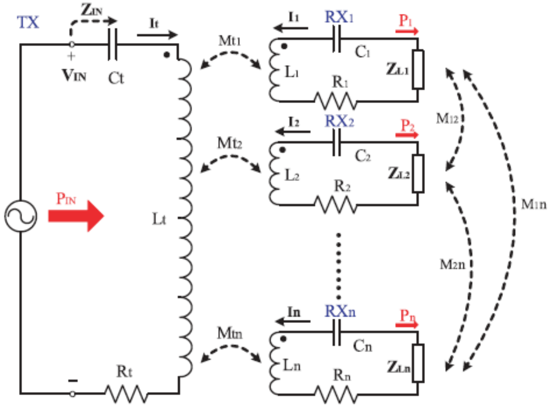
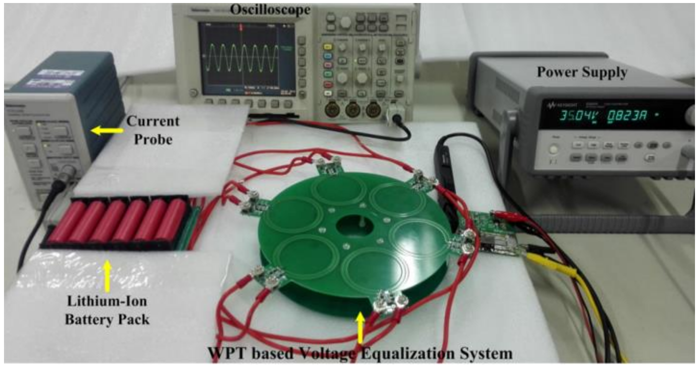
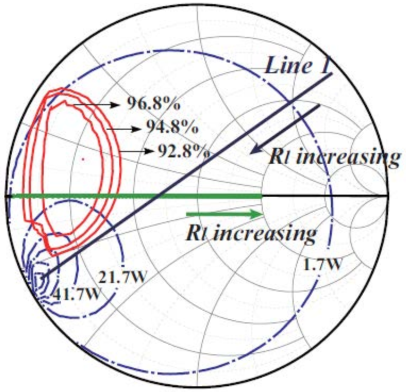
Ongoing Activities

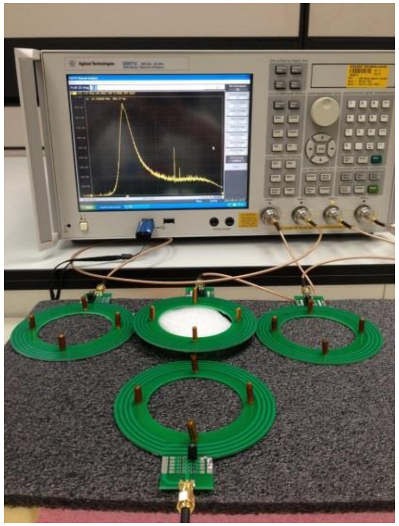


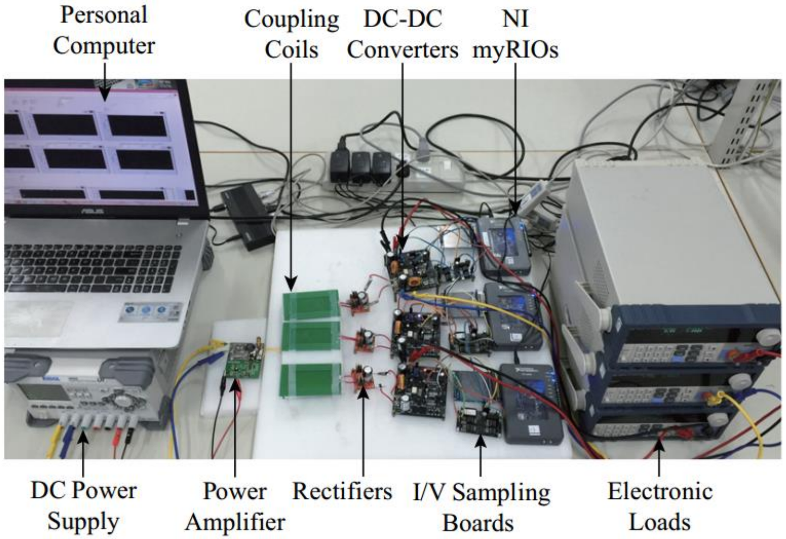


Multiple-receiver MHz WPT system

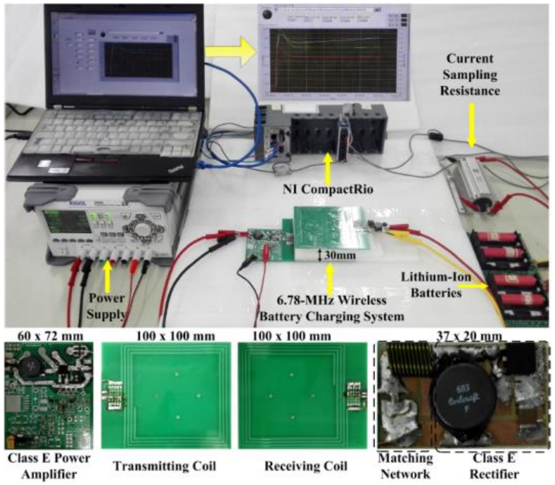


Load pull analysis for CCM Class E PA





Compensation and power distribution in multiple-receiver WPT systems



Charging profile based optimization of MHz wireless battery charger

Publications(2014~Pre.)

1. S. Liu, M. Liu*, S. Yang, C. Ma, X. Zhu: "A Novel Design Methodology for High-Efficiency Current-Mode and Voltage-Mode Class-E Power Amplifiers in Wireless Power Transfer Systems", *IEEE Transactions on Power Electronics*, accepted on August 2nd, 2016.
2. M. Liu*, Y. Qiao*, S. Liu, C. Ma: "Analysis and Design of A Robust Class E^2 DC-DC Converter for Megahertz Wireless Power Transfer", *IEEE Transactions on Power Electronics*, accepted on May 16th, 2016.
3. M. Fu*, H. Yin*, M. Liu*, C. Ma: "Loading and Power Control for A High-Efficiency Class E PA Driven Megahertz WPT System", *IEEE Transactions on Industrial Electronics*, accepted on May 2nd, 2016.
4. M. Liu*, M. Fu*, C. Ma: "Low-Harmonic-Contents and High-Efficiency Class E Full-Wave Current-Driven Rectifier for Megahertz Wireless Power Transfer Systems", *IEEE Transactions on Power Electronics*, accepted on Mar. 28th, 2016.
5. M. Fu*, T. Zhang*, X. Zhu, P. Luk, C. Ma: "Compensation of Cross Coupling in Multiple-Receiver Wireless Power Transfer Systems", *IEEE Transactions on Industrial Informatics*, Vol. 12, No. 2, pp. 474-482, April 2016.
6. M. Liu*, M. Fu*, C. Ma: "Parameter Design for A 6.78-MHz Wireless Power Transfer System Based on Analytical Derivation of Class E Current-Driven Rectifier", *IEEE Transactions on Power Electronics*, Vol. 31, No. 6, pp. 4280-4291, June 2016.
7. M. Fu*, H. Yin*, X. Zhu, C. Ma: "Analysis and Tracking of Optimal Load in Wireless Power Transfer Systems", *IEEE Transactions on Power Electronics*, Vol. 30, No. 7, pp. 3952-3963, July 2015.
8. M. Fu*, T. Zhang*, C. Ma, X. Zhu: "Efficiency and Optimal Loads Analysis for Multiple-Receiver Wireless Power Transfer Systems", *IEEE Transactions on Microwave Theory and Techniques*, Vol. 63, No. 3, pp. 801-812, March 2015.
9. M. Fu*, C. Ma, X. Zhu: "A Cascaded Boost-Buck Converter for High-Efficiency Wireless Power Transfer Systems", *IEEE Transactions on Industrial Informatics*, Vol. 10, No. 3, pp. 1972-1980, August 2014.

Thank You

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