Design and Optimization of High Efficiency, Low Noise, and Robust Megahertz Wireless Power Transfer Systems

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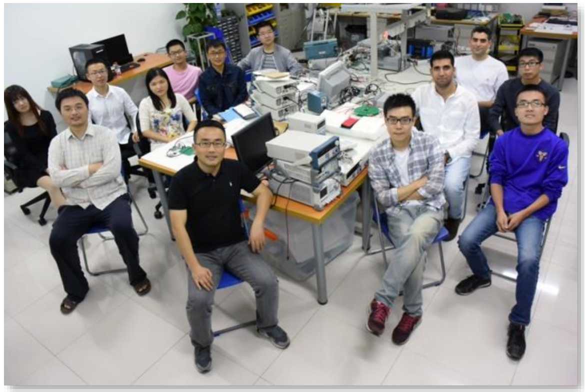
Outline

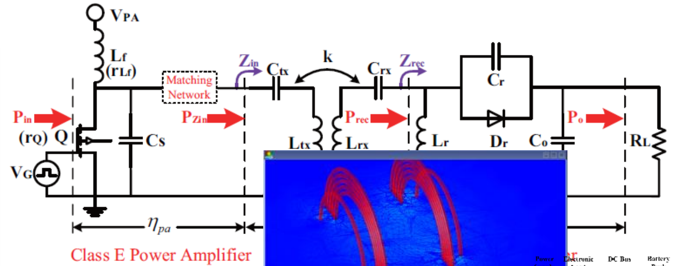
- Introduction
- Parameter Design
- Harmonic Reduction
- Robust Design
- Matching Network Design
- Other Ongoing Activities
- Conclusion

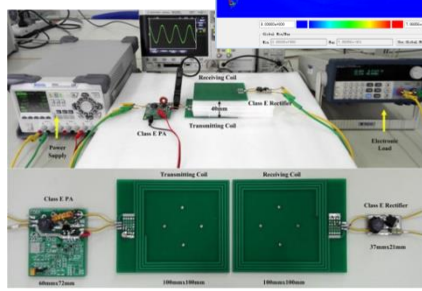
Dynamic Systems Control Lab (2010~Pre.)

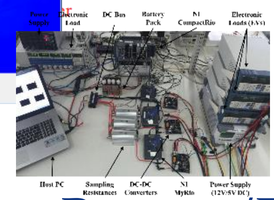
http://umji.sjtu.edu.cn/lab/dsc/

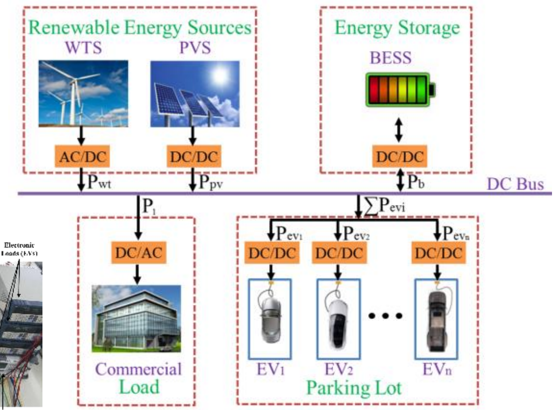


1 Postdoc, 5 Ph.D., 6 M.S.

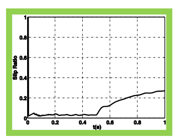


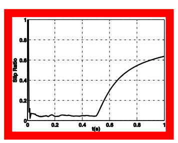


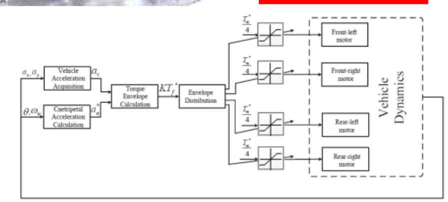


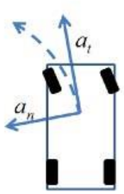


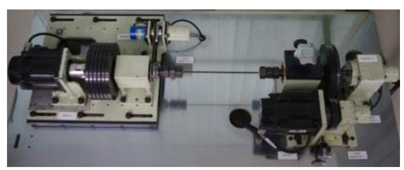
1. Battery /Energy Management
2. Wireless Power Transfer

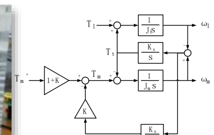


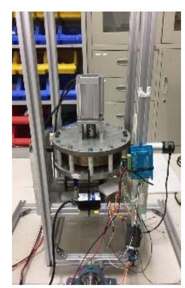










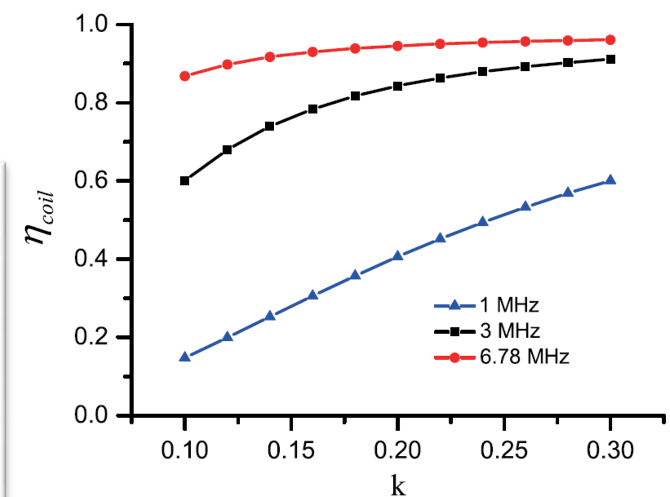


- Control Engr.
- Optimization
- Power Electron.
- Mechatronics

3. Electric Vehicle Dynamics 4. Servo/Motion Control

Automation of Charging

- WPT provides an alternative solution without requiring dramatic improvements in battery technology.
- It enables a totally new direction of management of electric power through automatizing charging of battery-powered systems.
- Spatial freedom can be further improved through a higher operating frequency, such as several megahertz.



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** (dc-dc eff. 84%, Apr. 2015)
- More challenging Electromagnetic interference (**EMI**) problem (e.g. rec. input voltage THD: 42.2% to 9.92%, Sep. 2015)
- **Robustness** against varying operation condition, i.e., coupling and load (e.g. system efficiency variation: 47.5%–85.0% to 73.3%–83.7%, Feb. 2016)

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

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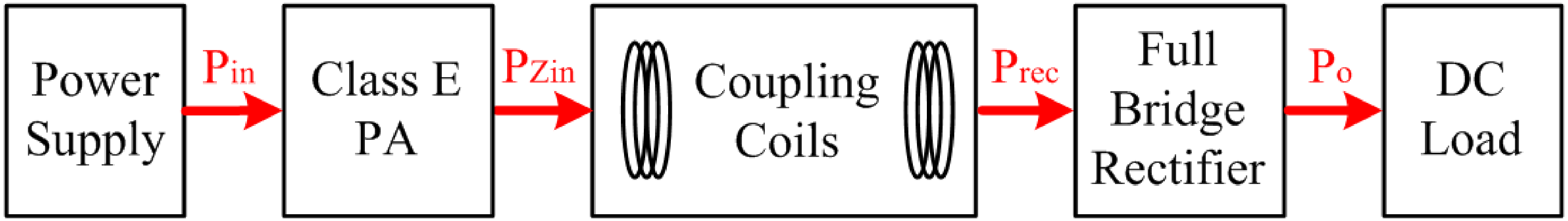
- M. Liu, M. Fu, C. Ma: "Parameter Design for A 6.78-MHz Wireless Power Transfer System Based on Analytical Derivation of Class E Current-Driven Rectifier", *IEEE Transactions on Power Electronics*, Vol. 31, No. 6, pp. 4280-4291, June 2016.

Conventional Design

System Configuration



Conventional Design

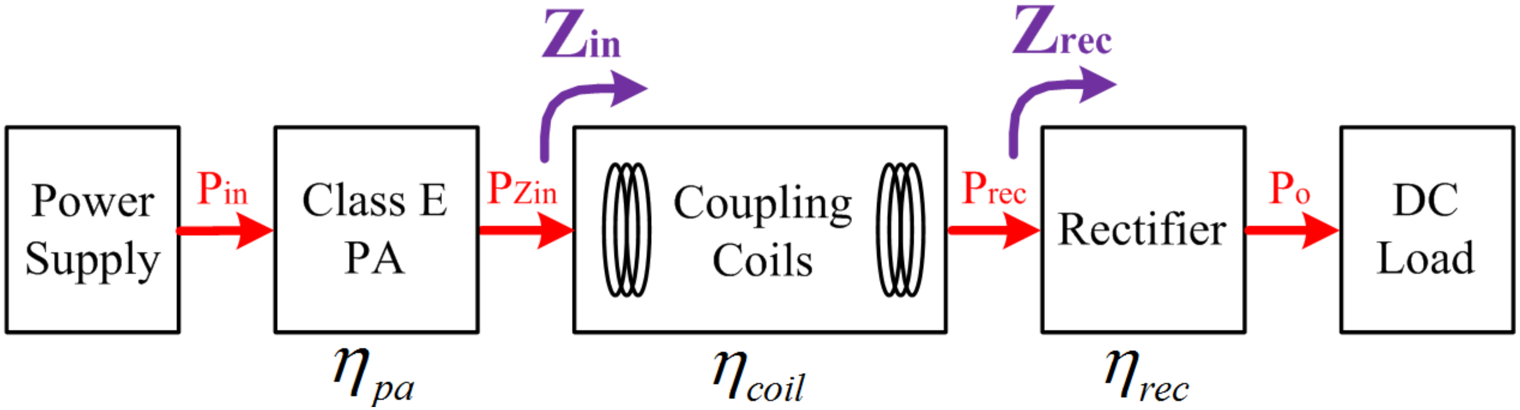
- Input reactance of the full-bridge rectifier is completely neglected;
- The compensation capacitors are designed to resonant with coupling coils;
- The Class E PA is optimized based on the input impedance of coupling coils.

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.

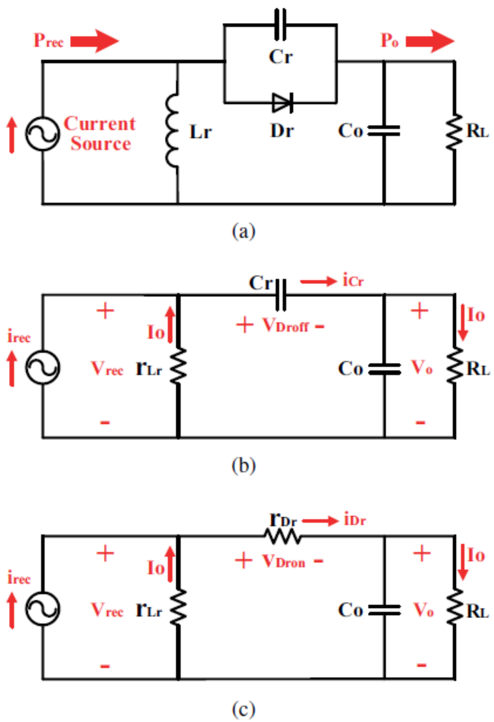
High-efficiency Rectification at MHz

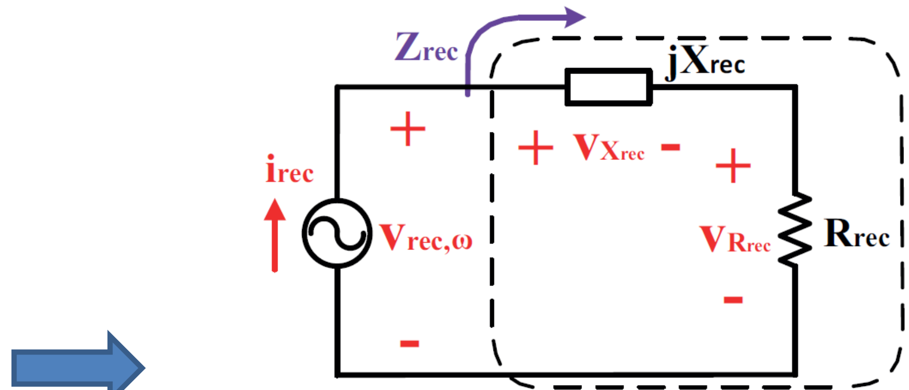
- Select a high-efficiency rectifying circuit;
- Derive an analytical expression of the input impedance of the rectifier;
- Design parameters based on the derived input impedance of the rectifier.



Rectifier Input Impedance

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





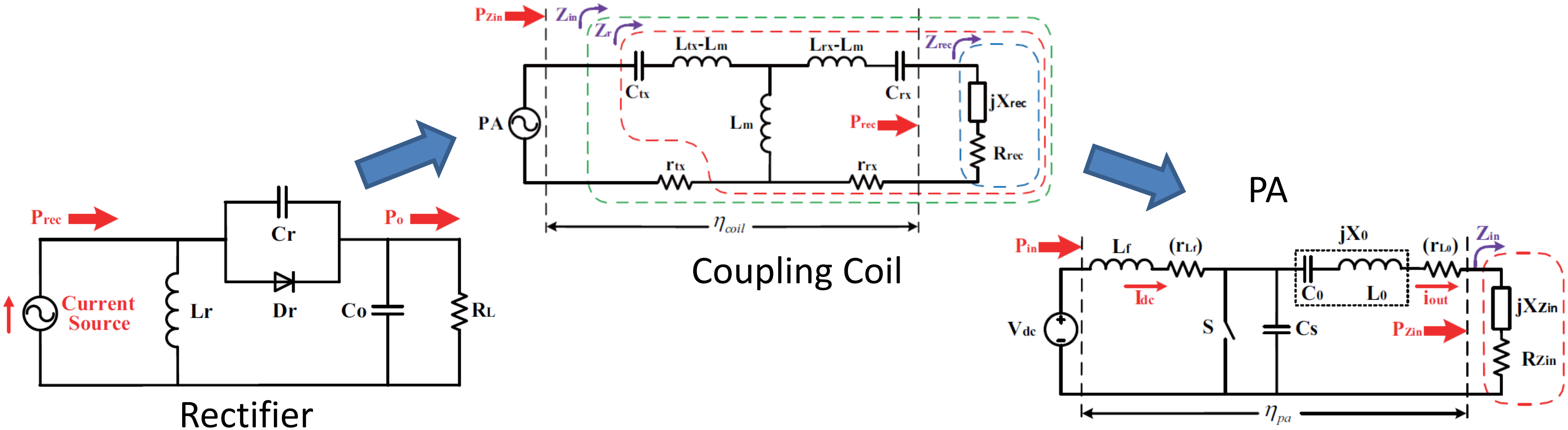
$$X_{rec} = \frac{V_{m,X_{rec}}}{I_m} = -\frac{1}{\pi}\left[\frac{a+b}{\omega C_r} + r_{D_r}(c+d)\right]$$

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

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

System-Level Optimization

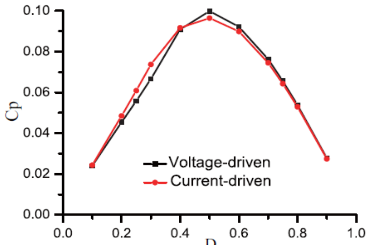
- Rectifier: C_r that enables a 0.5 duty cycle, D;
- Receiving coil: C_{rx} that makes the coupling coils truly resonant;
- PA: C_S that follows the Raab's equations and the load of PA.



Optimized Parameter Design

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

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



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

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

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

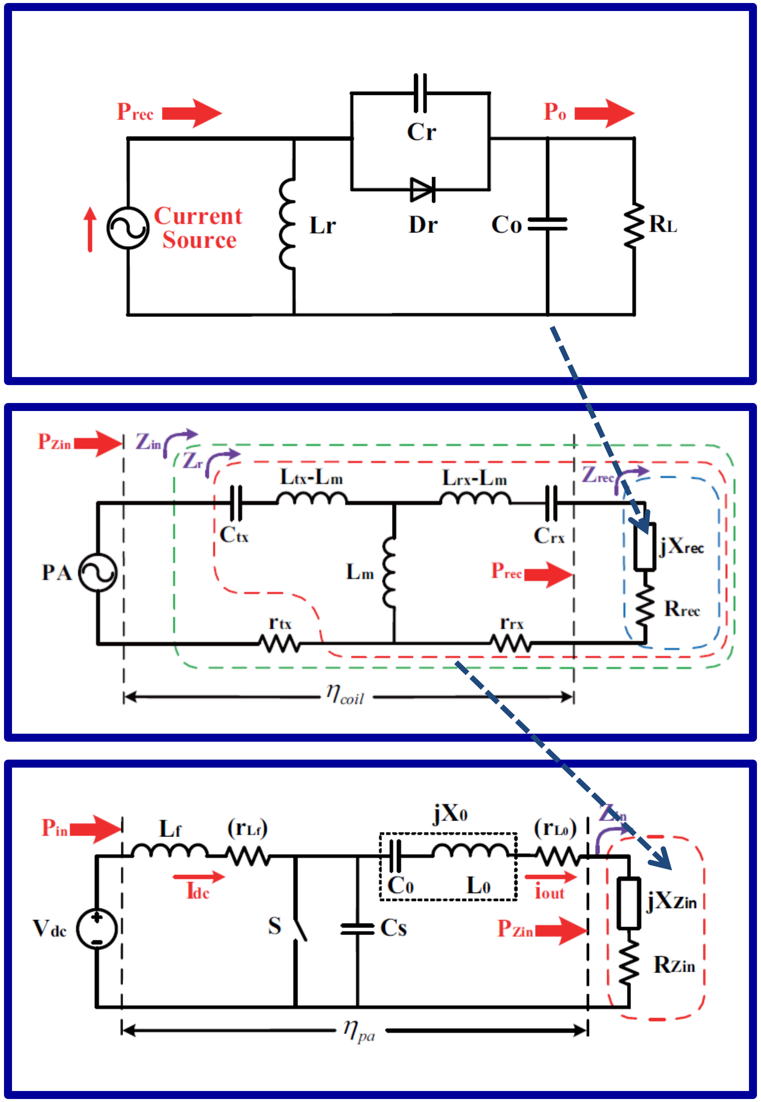
$$X_{0,opt} = 1.1525 r_{tx} + \frac{1.1525 \omega^2 k^2 L_{tx} L_{rx}}{r_{rx} + 0.5768(R_L + r_{L_r}) + 0.7116 r_{D_r}}$$

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

$$g = \frac{2\pi \sin(\varphi + \phi) + 4\cos(\varphi + \phi)}{4 \cos\phi \sin(\varphi + \phi) + \pi \cos\varphi},$$

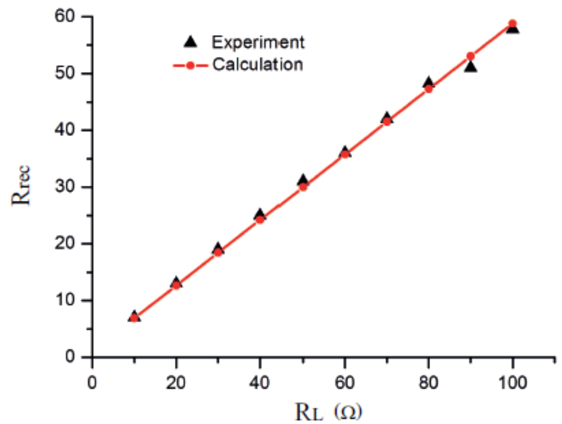
$$\varphi = \arctan \frac{X_0}{R_{Z_{in}}},$$

$$\phi = \arctan \frac{\frac{\pi^2}{2} - 4 - \pi\omega C_S (2R_{Z_{in}} + \pi X_0)}{\pi + \pi^2 \omega C_S R_{Z_{in}} - 2\pi\omega C_S X_0},$$

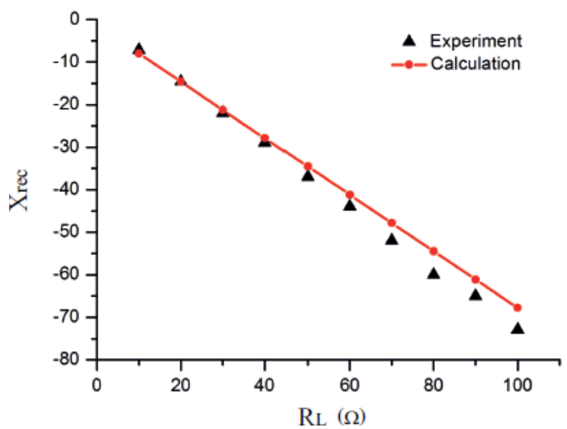


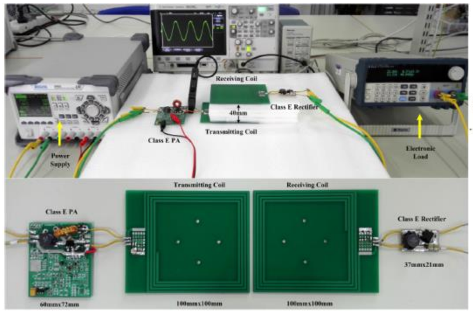
Results (6.78MHz, *k*=0.1327, 84%)

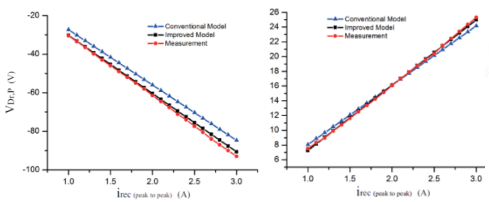
Impedance

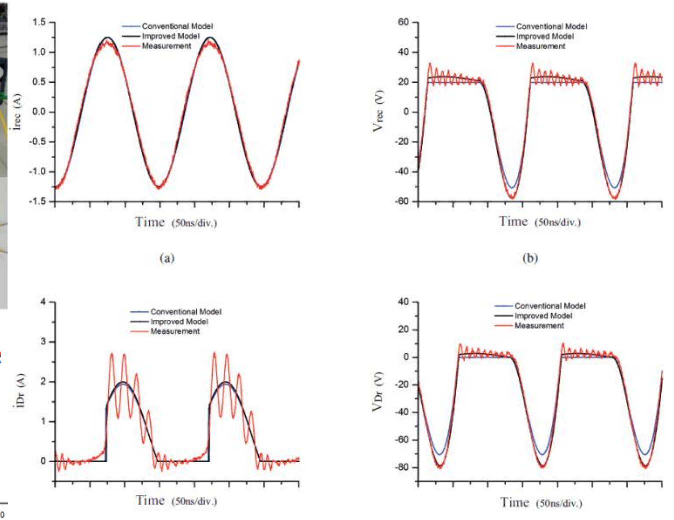


(a)

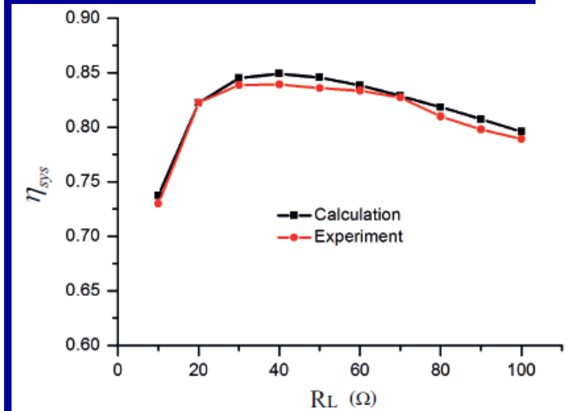


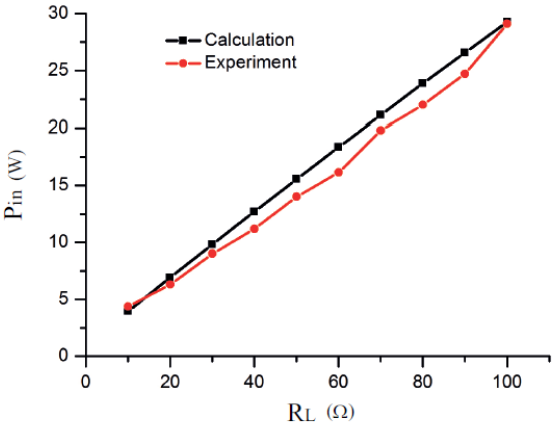






Efficiency and power





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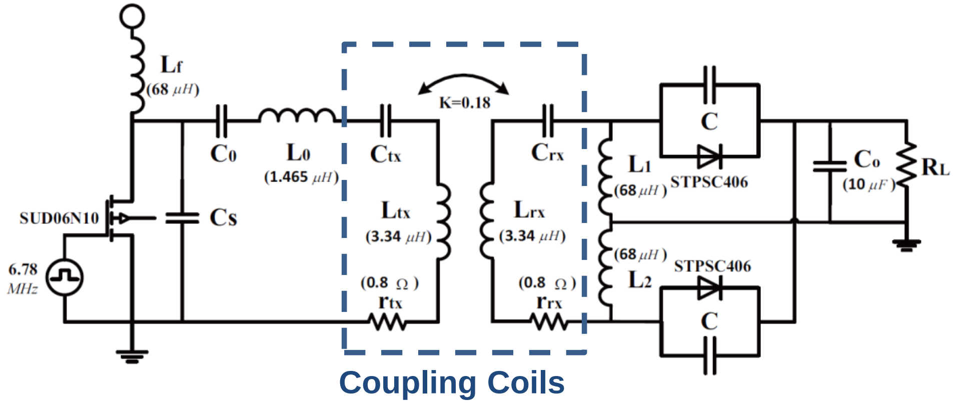
- M. Liu, M. Fu, C. Ma: "Low-Harmonic-Contents and High-Efficiency Class E Full-Wave Current-Driven Rectifier for Megahertz Wireless Power Transfer Systems", *IEEE Transactions on Power Electronics*, Vol. 32, No. 2, pp. 1198-1209, February 2017.

Motivation

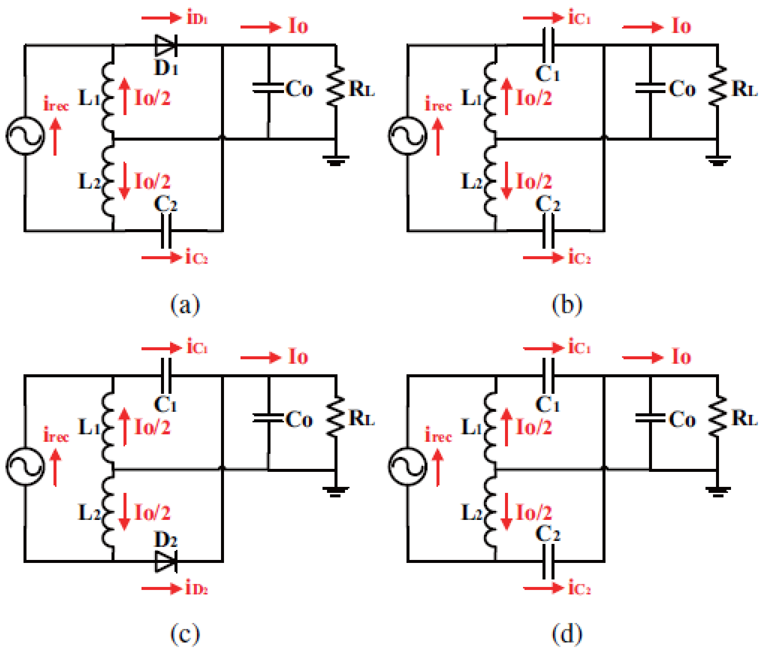
- EMI improvement through optimized design of circuits in a MHz WPT system;
- Reduction of THD of the input/output voltage of coupling coils;
- A high system efficiency at the same time.



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.

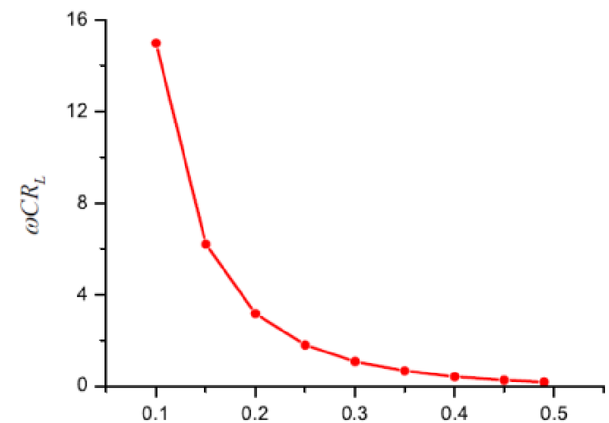
Class-E Full-Wave Rectifier

- 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.



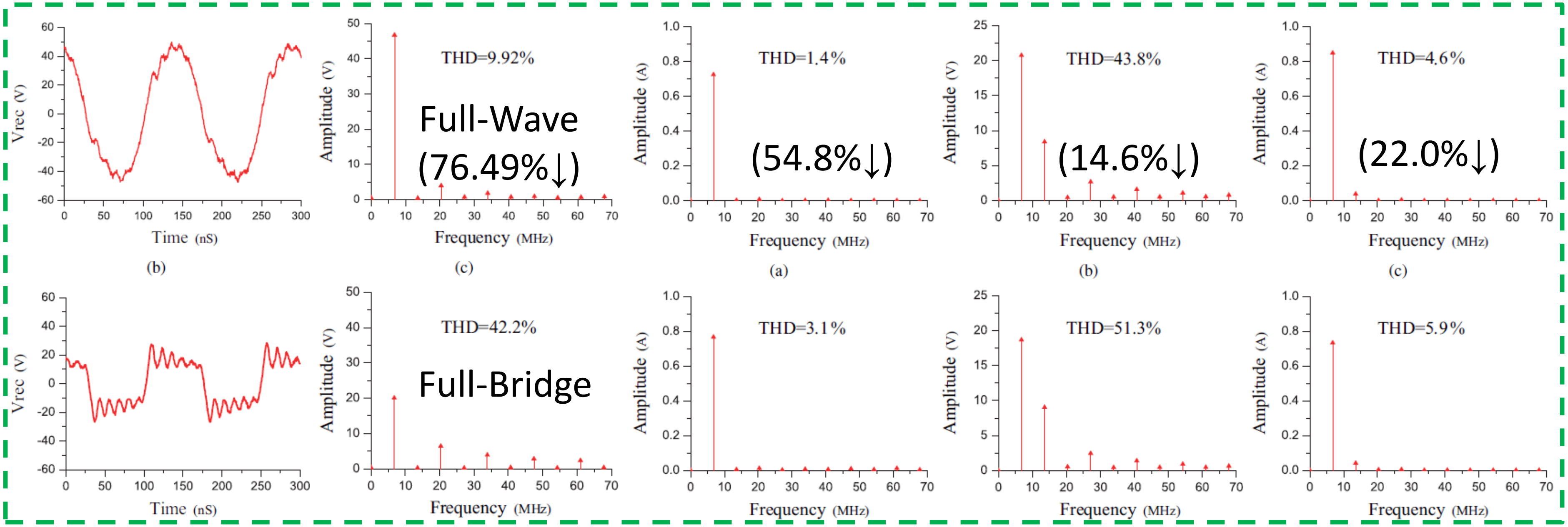
$$C = \frac{1}{\omega R_L}\left[\frac{1}{4\pi} - \frac{\pi}{2}(1-D)^2 + \frac{2\pi(1-D)cos(\phi_{rec}+2\pi D) - sin\phi_{rec}}{4\pi sin(\phi_{rec}+2\pi D)}\right]$$

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



Results-THD with D=0.49

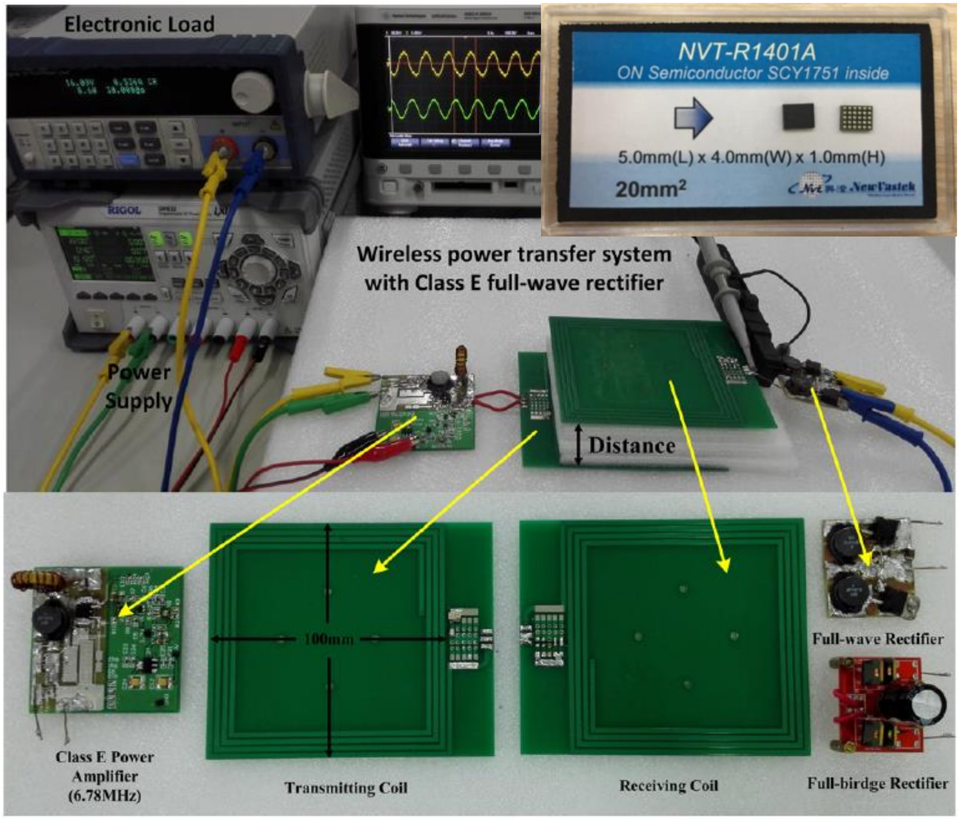
- The other parameters are designed following the procedures previously explained.
- The THDs are compared with those of the conventional full-bridge rectifier.

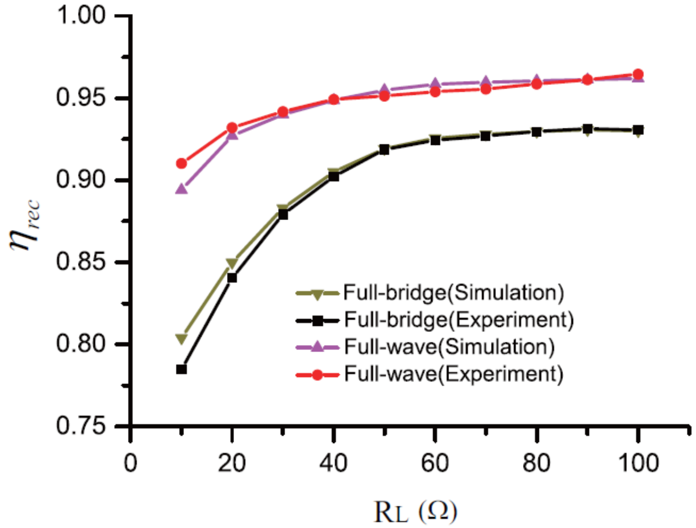


Input Voltage Waveform (Rectifier) | Input Voltage (Rectifier) | Output Current (Receiving Coil) | Input Voltage (Transmitting coil) | Input Current (Transmitting Coil)

Results-Power Losses

10 deg. reduction





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	-

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

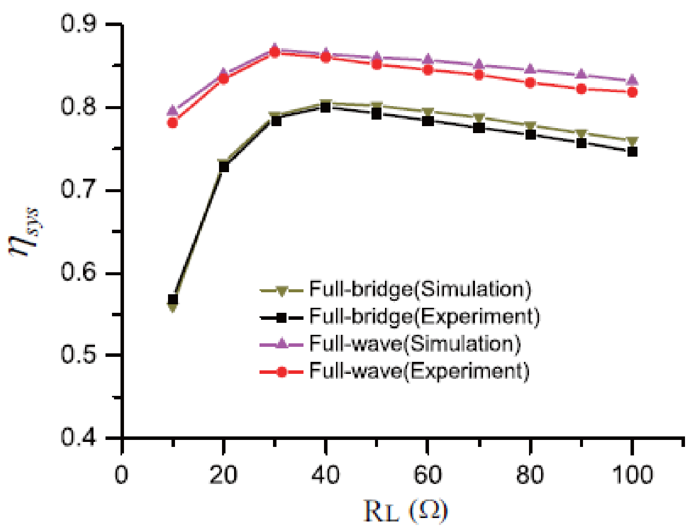
$$P_L = 2\left(\frac{I_o}{2}\right)^2 r_L \qquad P_{sw} = P_{rec} - P_o - P_L - P_{cd}$$

Results-(80% Ave. Efficiency)

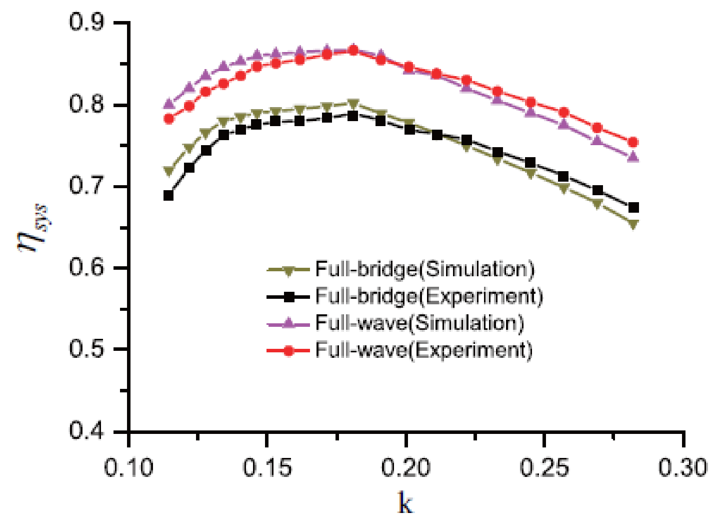
Loss breakdown (10 W system input power, 30 Ω R_L)

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

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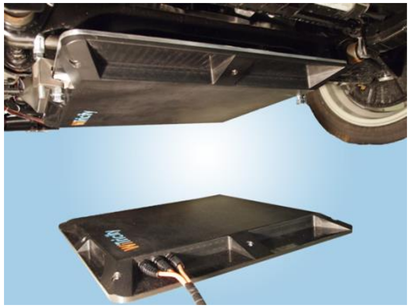
- M. Liu, Y. Qiao, S. Liu, C. Ma: "Analysis and Design of A Robust Class E^2 DC-DC Converter for Megahertz Wireless Power Transfer", *IEEE Transactions on Power Electronics*, Vol. 32, No. 4, pp. 2835-2845, April 2017.

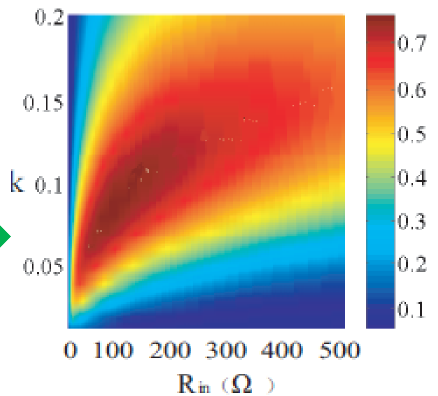
Motivation-Enhanced Robustness

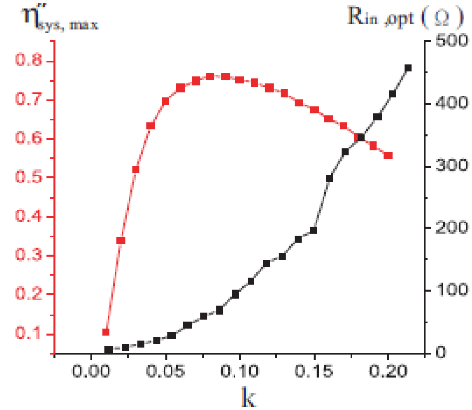
- Most of existing designs target on a single fixed operating condition, i.e., fixed coil relative position and load.
- However, in real applications changes in the coil relative position and final dc load are common.
- A design methodology, active or passive, is required to optimize the performance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

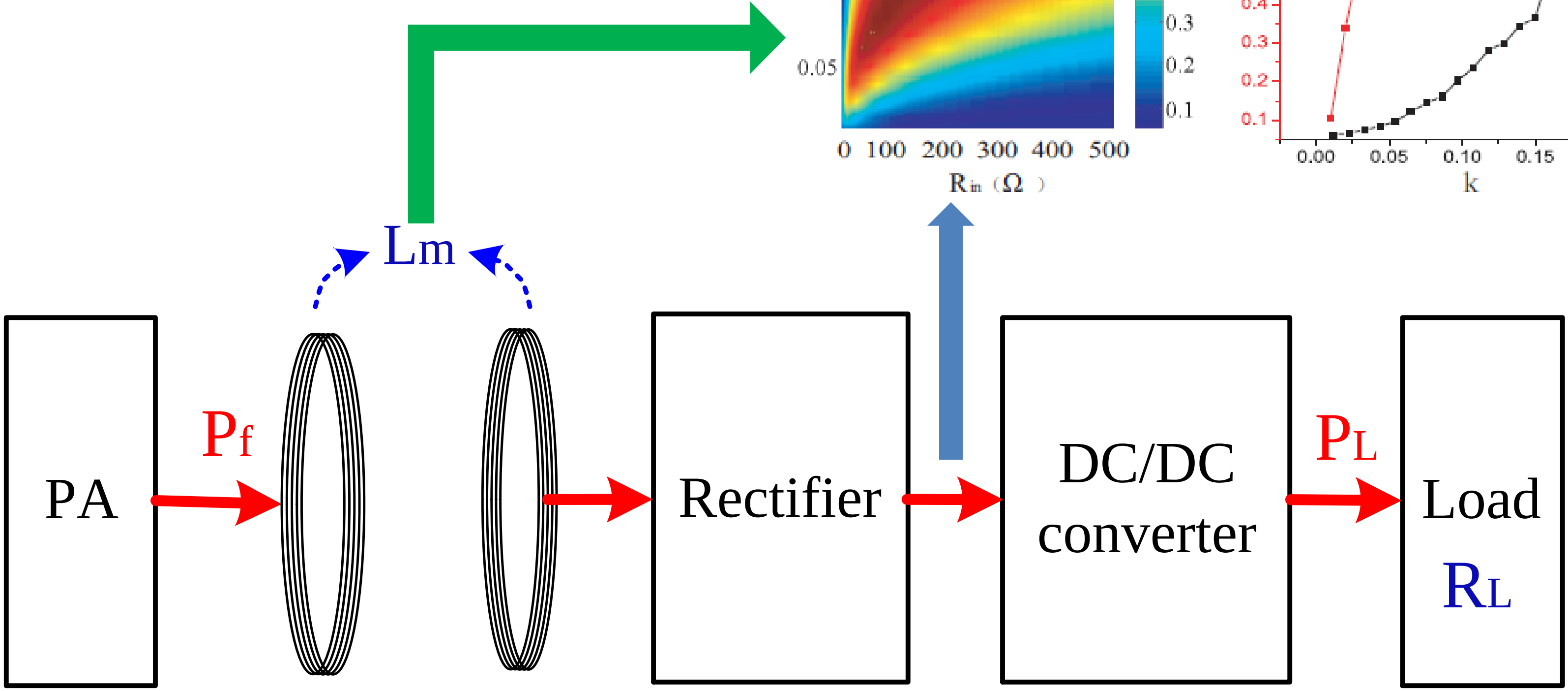
Optimal Load for High Efficiency



Optimal loads

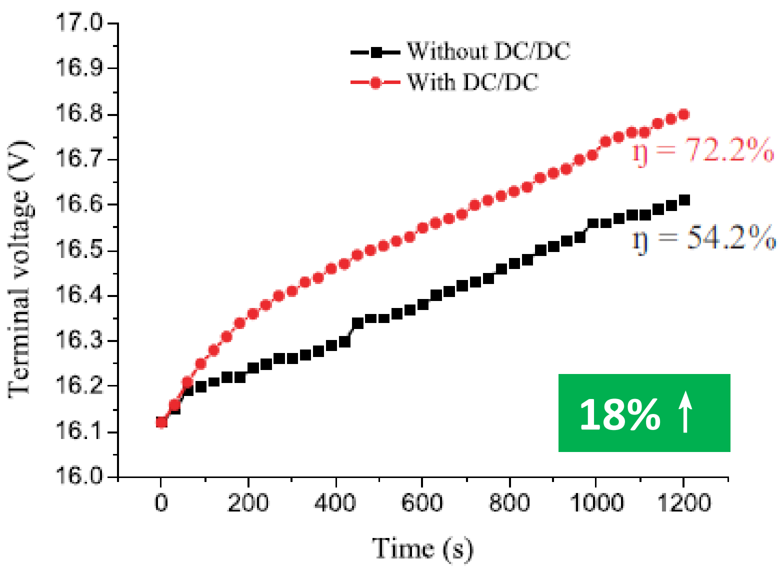




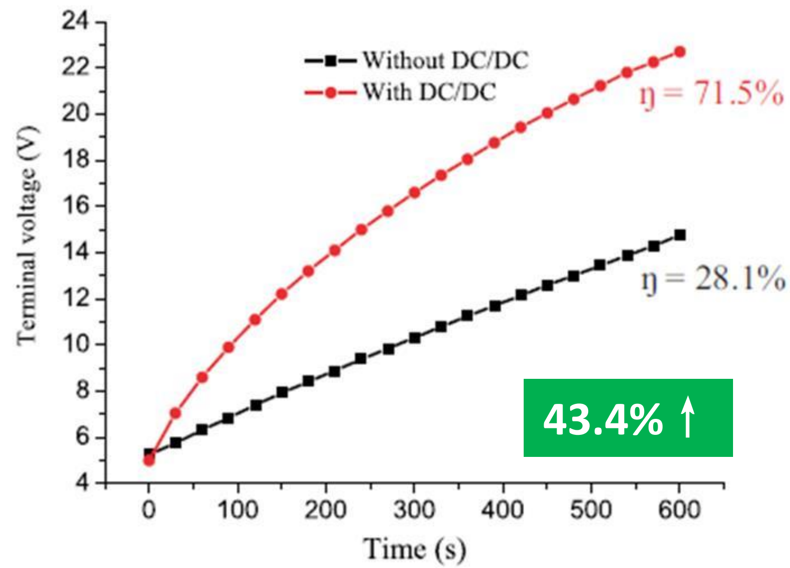


Improved Charging Efficiency

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



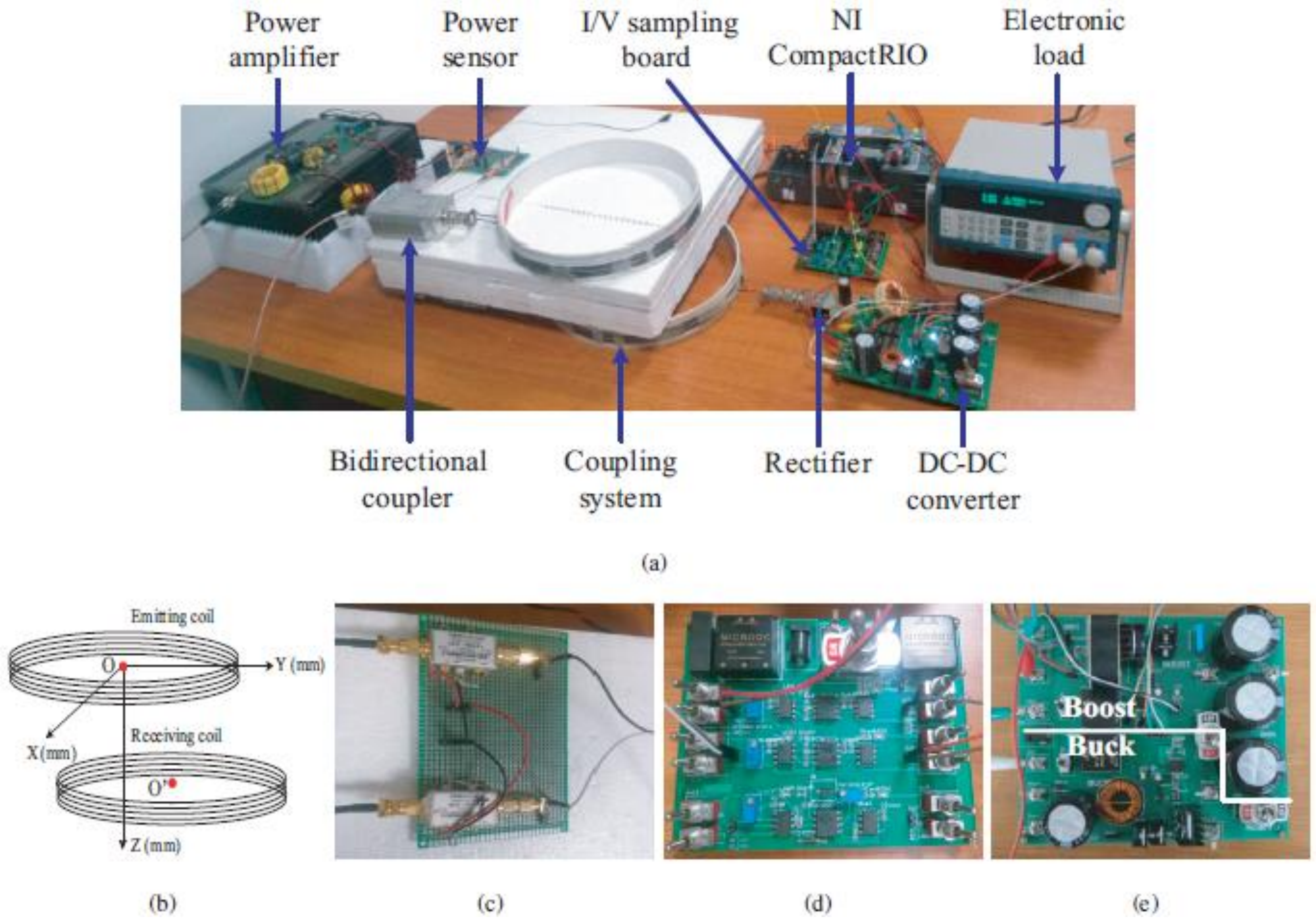
Batteries charging improvement using the cascaded boost-buck DC-DC converter.



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



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

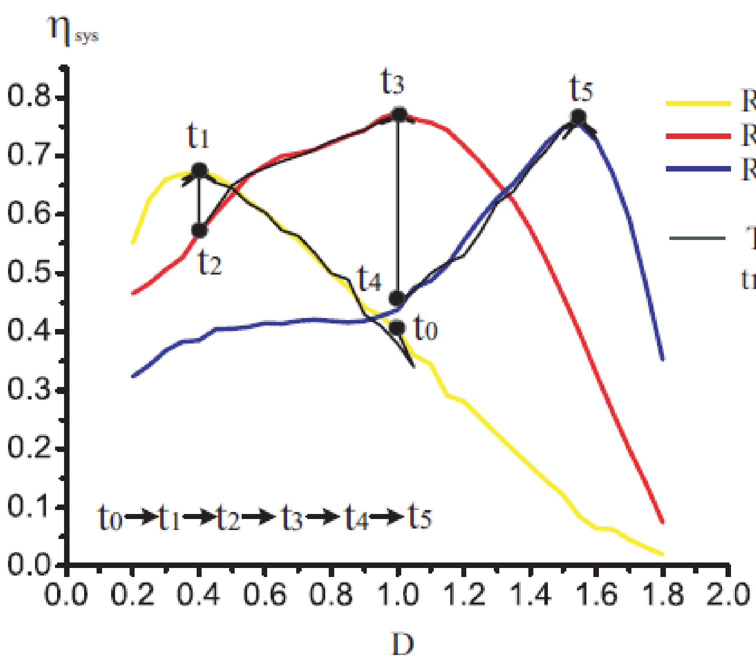


Fig. 1 Tracking of optimal load resistances with a varying R_l.

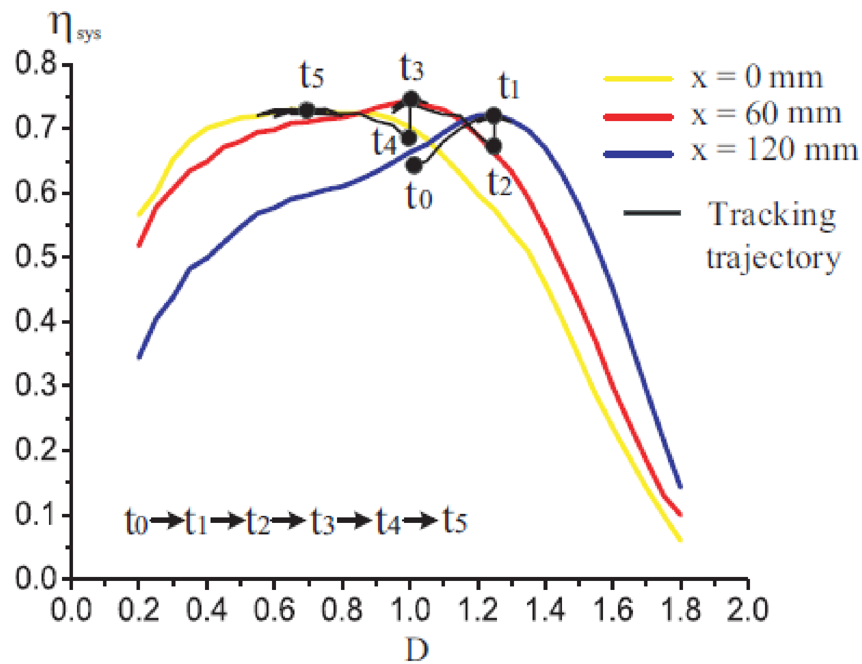
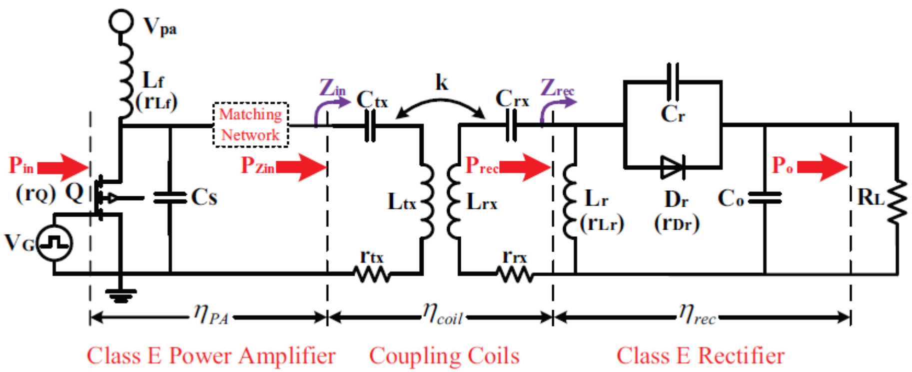


Fig. 2 Tracking of optimal load resistances with a varying k.

- 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.

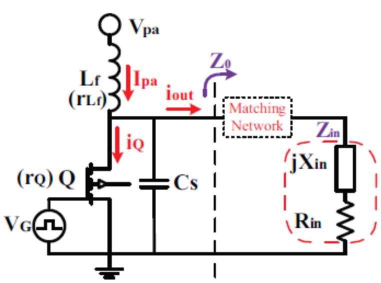


(a)

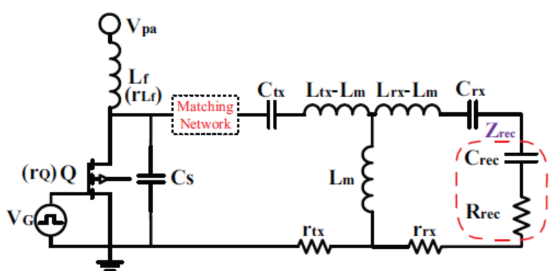
$$\eta_{sys} = \eta_{pa} \cdot \eta_{coil} \cdot \eta_{rec} = \frac{P_o}{P_{in}}$$

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

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



(b)



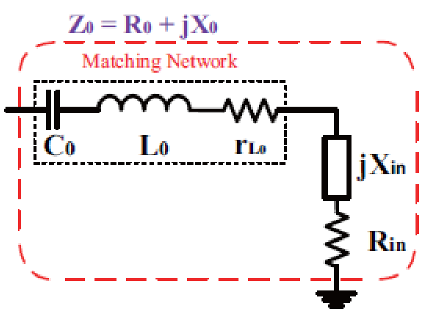
(c)

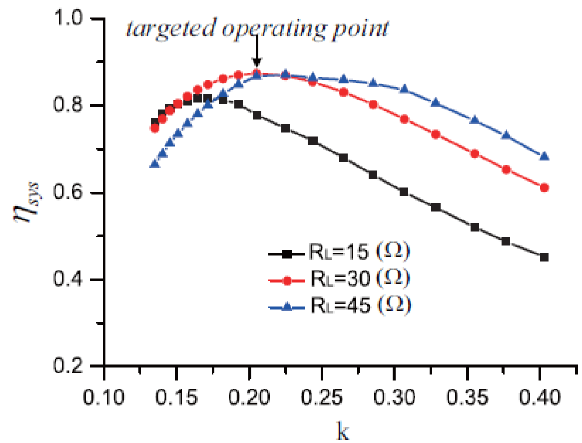
$$\eta_{coil} = \frac{R_{rec}\omega^2 k^2 L_{tx} L_{rx}}{\omega^2 k^2 L_{tx} L_{rx}(R_{rec} + r_{rx}) + r_{tx} b}$$

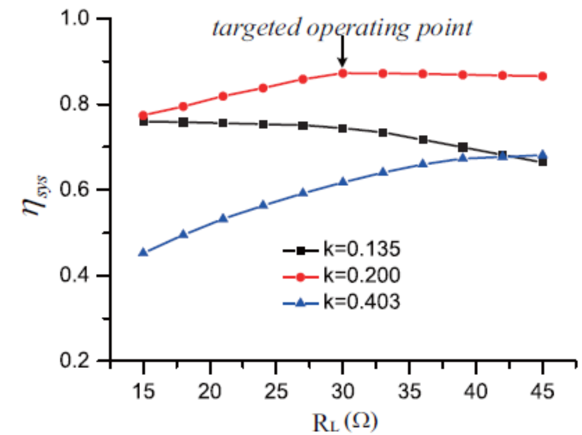
$$\eta_{rec} = \frac{P_o}{P_{rec}} = \frac{R_L}{R_L + r_{L_r} + \frac{c r_{D_r}}{\sin^2 \phi_{rec}}}$$

Original PA Matching Network

- Original Class E PA matching network has poor robustness.







Robustness Index

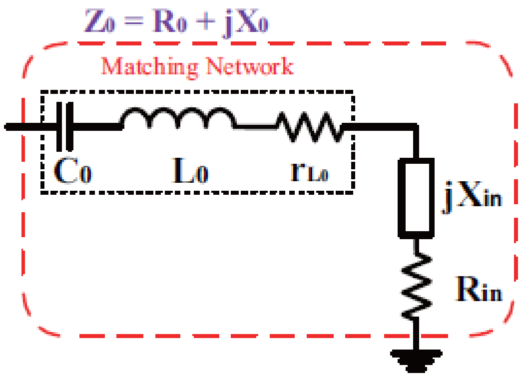
$$\alpha_x = \max \left| \frac{\eta_x(k, R_L) - \eta_x(0.203, 30)}{\eta_x(0.203, 30)} \right|$$

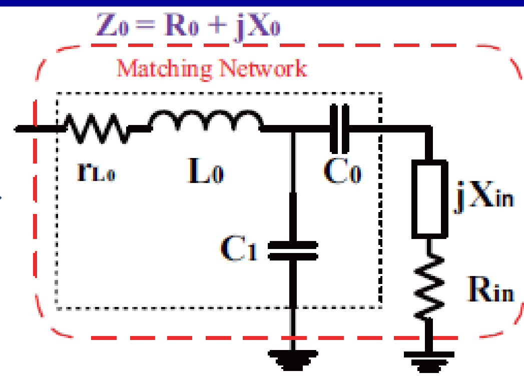
α_{pa}	α_{coil}	α_{rec}	α_{sys}
47.0%	5.3%	4.2%	47.6%

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

Modified MN and Design Problem

Circuit Improvement

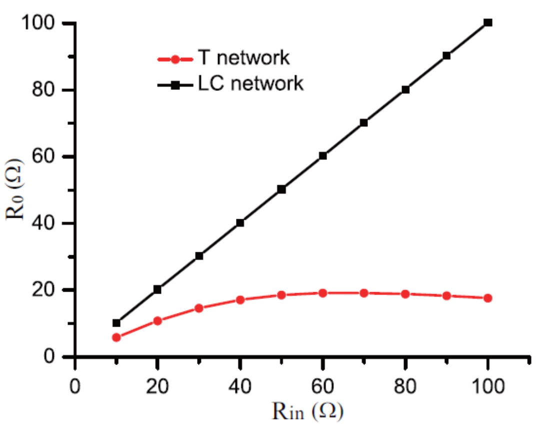


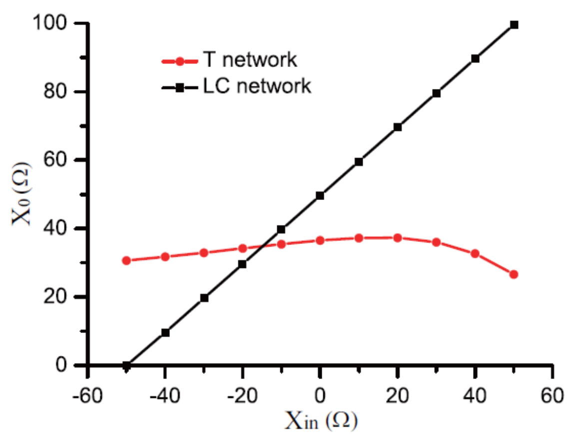


$$R_0 = R_{in} + r_{L_0} \text{ and } X_0 = X_{in} + \omega L_0 - \frac{1}{\omega C_0}.$$

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

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





Robust Optimization

Definitions of Parameters

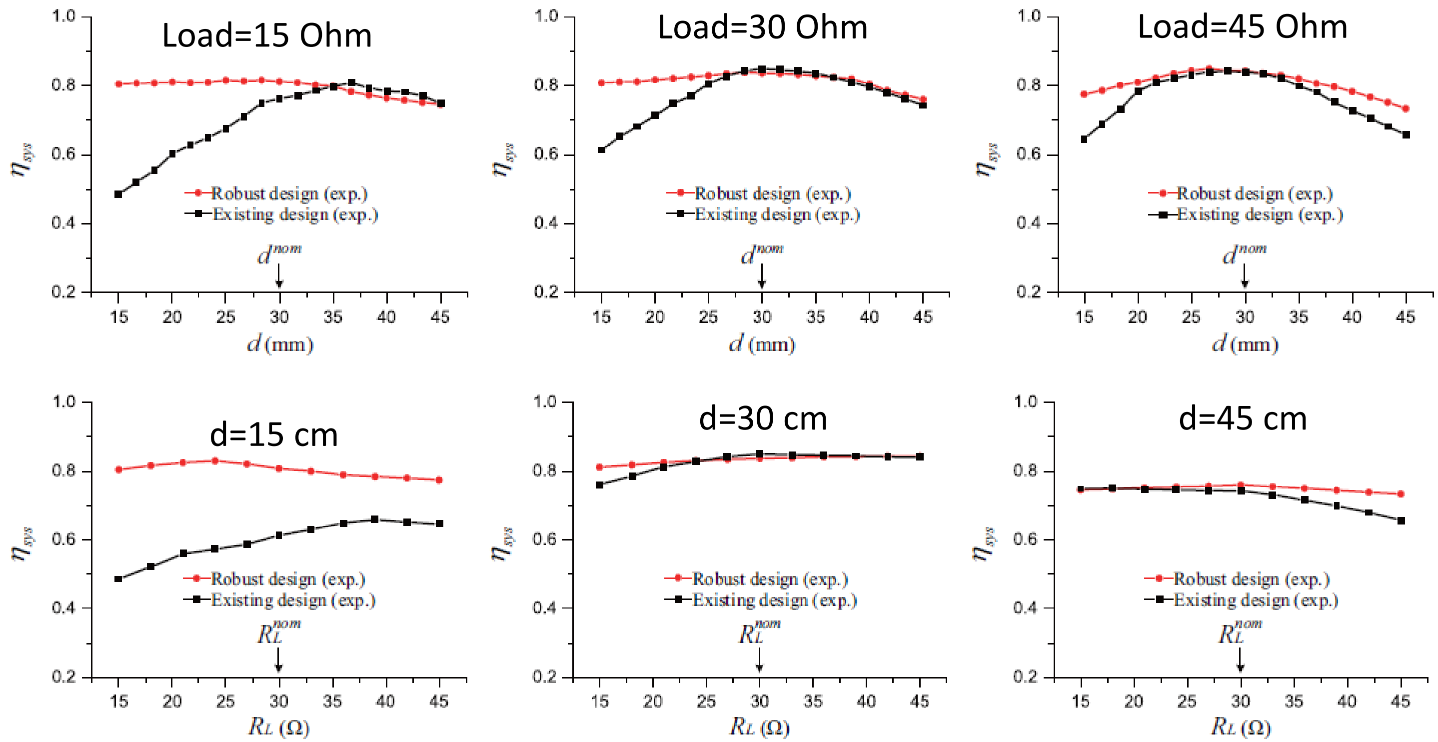
Vector	Components
$\mathbf{x}$	$[C_S,\ C_0,\ C_1,\ C_{rx},\ C_r]_{1\times 5}$
$\mathbf{p_{var}}$	$[k,\ R_L]_{1\times 2}$
$\mathbf{p_{var}^{nom}}$	$[k^{nom},\ R_L^{nom}]_{1\times 2}$
$\mathbf{p_{var}^{lower}}$	$[k^{min},\ R_L^{min}]_{1\times 2}$
$\mathbf{p_{var}^{upper}}$	$[k^{max},\ R_L^{max}]_{1\times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

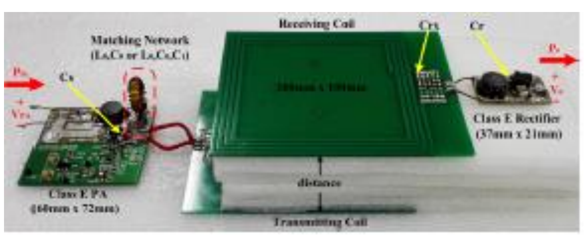
Optimization Problem

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

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

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%

Outline

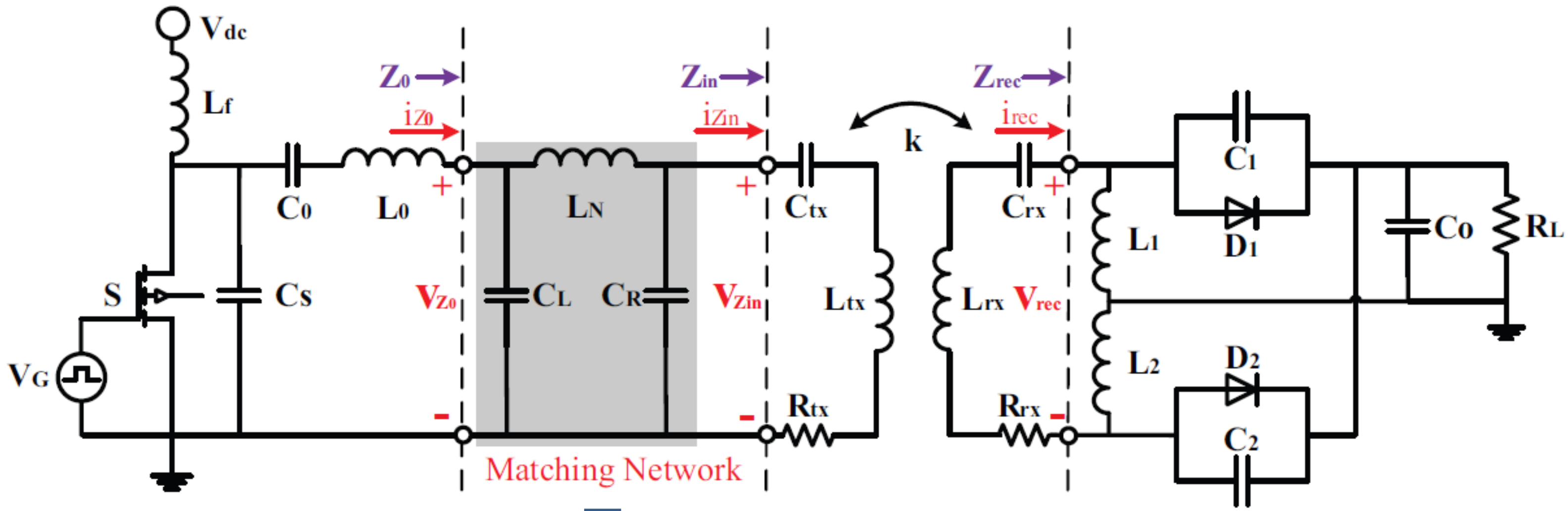
- Introduction
- Parameter Design
- Harmonic Reduction
- Robust Design
- Matching Network Design
- Other Ongoing Activities
- Conclusion

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.



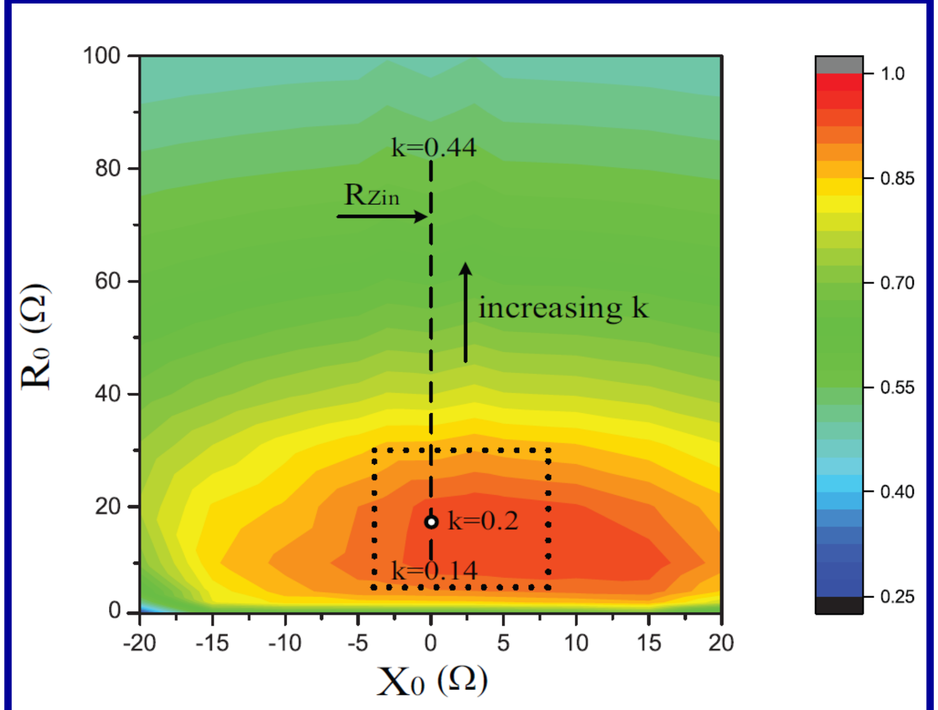
$$R_0 = \frac{\frac{Z_{in}}{\omega^2 C_L C_R}(\omega L_N - \frac{1}{\omega C_L})(\omega L_N - \frac{1}{\omega C_R}) - \frac{\omega L_N Z_{in}}{\omega^2 C_L C_R}(\omega L_N - \frac{1}{\omega C_L} - \frac{1}{\omega C_R})}{(\omega L_N Z_{in} - \frac{Z_{in}}{\omega C_L} - \frac{Z_{in}}{\omega C_R})^2 + (\frac{\omega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

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

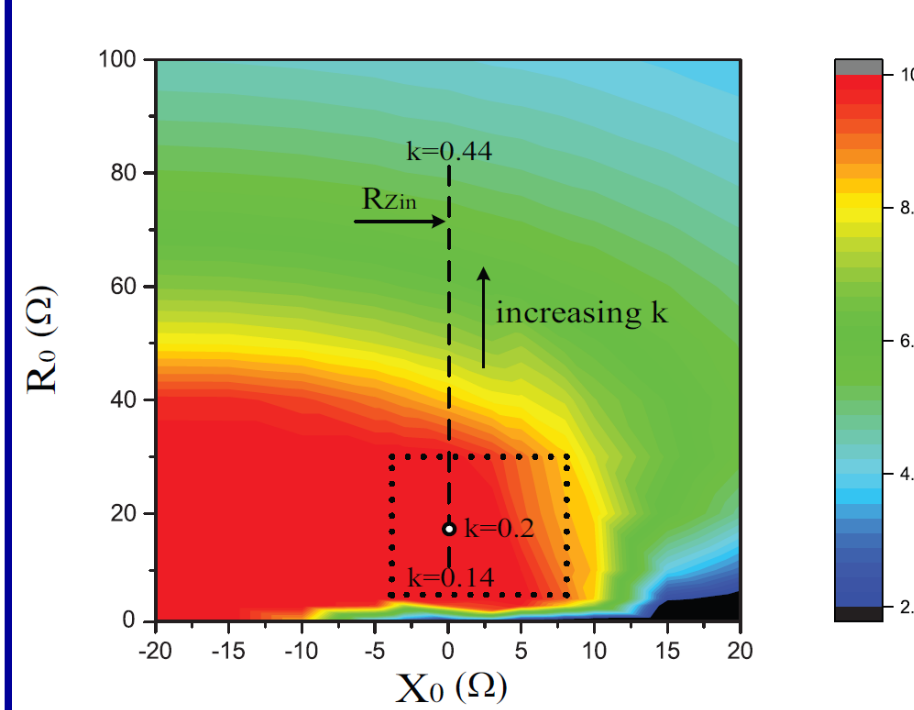
Target Region of PA load

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

PA Efficiency Contours

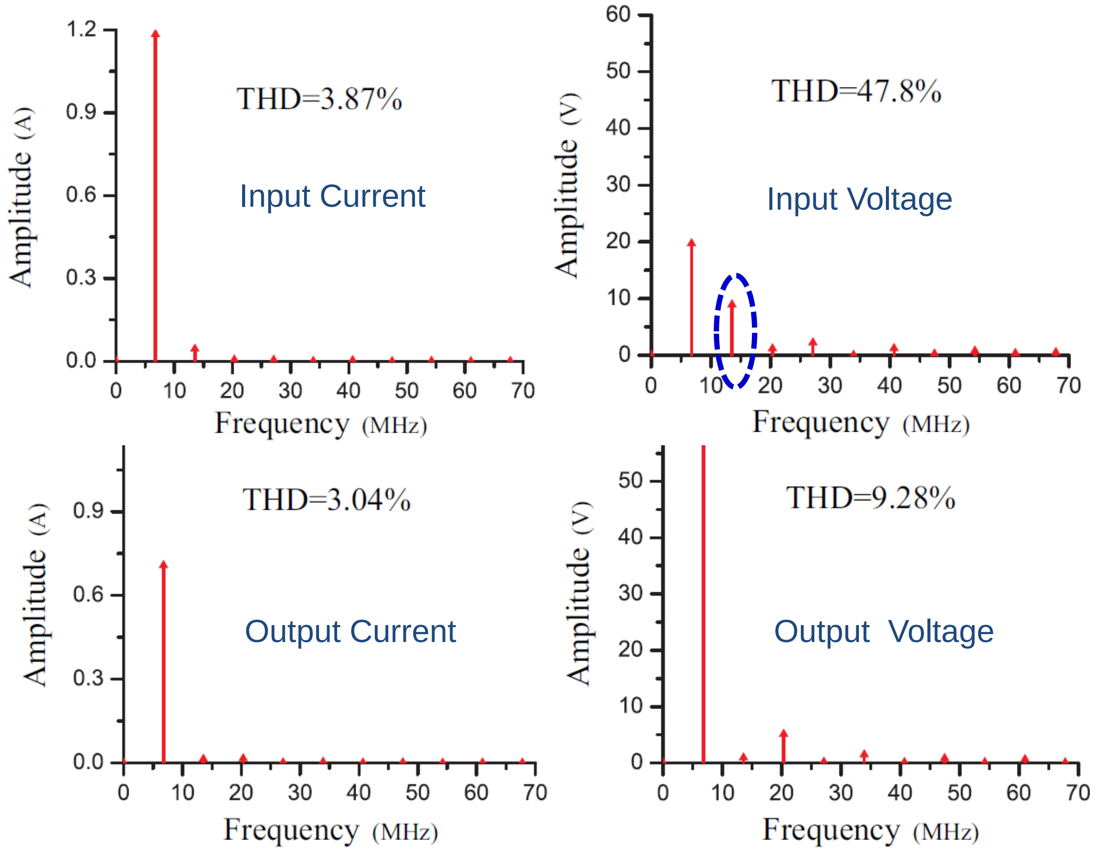


PA Power Contours



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

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

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

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

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

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

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:

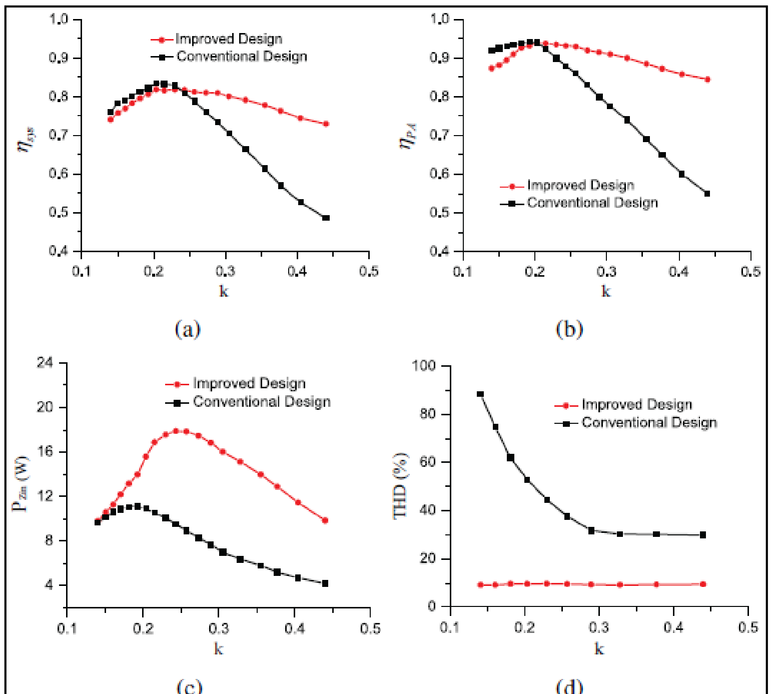
$$R_0^{(2)}(k, C_L, C_R) \le \lambda \cdot R_0{}^{(1)}(k, C_L, C_R)$$

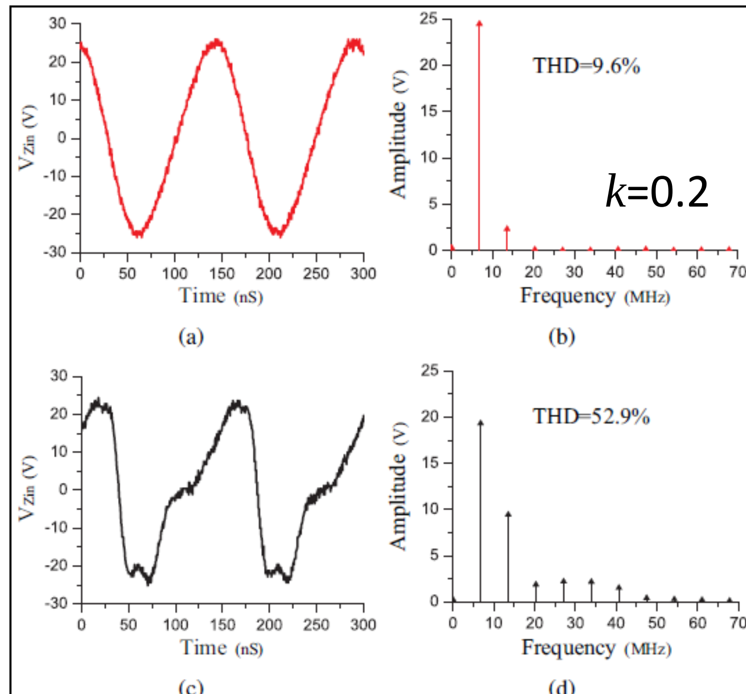
where λ is an index. A smaller λ leads to a smaller 2nd-order harmonic.

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%.





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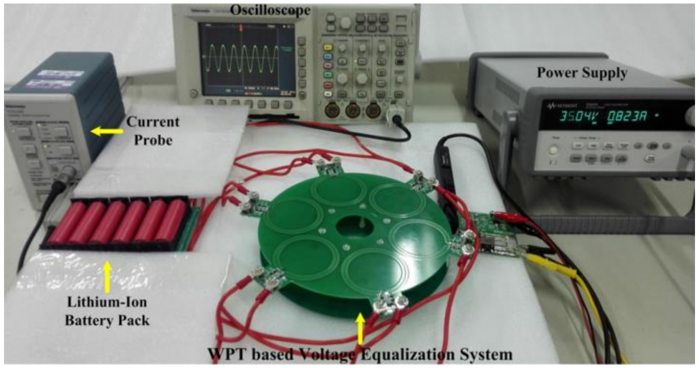
Other Ongoing Activities

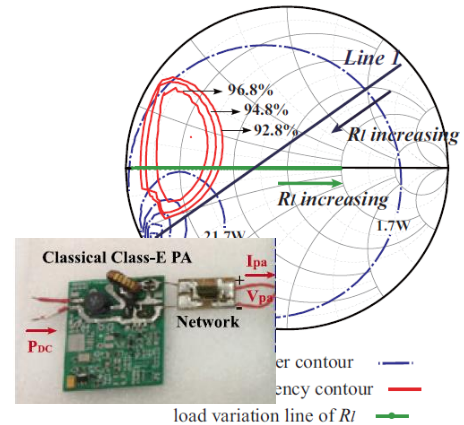


Multi-receiver MHz WPT-based cell equalization

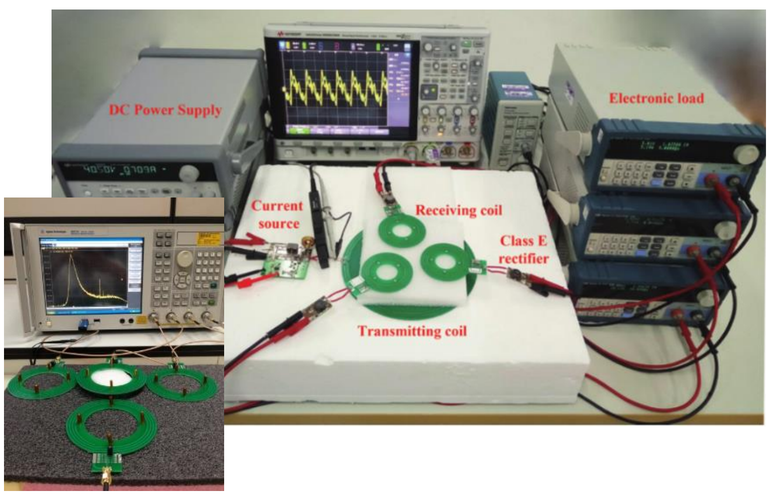
1) Saved weight and space, ease of implementation, and improved safety;

2) The operating principle of the WPT-based equalization is investigated;

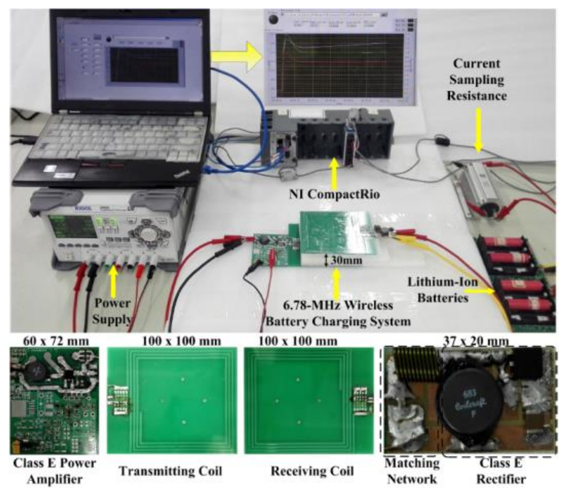
3) A high overall system efficiency (above 71%) when equalizing six li-ion battery cells under loosely coupling (k=0.065).



High Efficiency CCM Class E PA



Compensation and autonomous power distribution in multi-receiver WPT systems



Charging profile based optimization of MHz wireless battery charger

1) Minimization of energy loss during entire charging cycle;

2) A LC matching network to improve the loading conditions;

3) Proposed design achieves a 24.5% reduction of the average power loss.

Conclusion

- Increasing operating frequency to MHz enables **spatial freedom**, the most important advantage of using WPT.
- High efficiency, low noise, and high robust MHz WPT systems are possible through both component-level and particularly **system-level** design and optimization.
- Advancement from "one to one" to "**one-to-multiple**" WPT provides ample opportunities both in research and applications.

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Journal Papers in Megahertz Wireless Power Transfer

- Supervised students are delineated with an asterisk (*).

1. M. Fu*, H. Yin*, M. Liu*, C. Ma: "A 6.78 MHz Multiple-Receiver Wireless Power Transfer System with Constant Output Voltage and Optimum Efficiency", *IEEE Transactions on Power Electronics*, accepted on June 30th, 2017.
2. M. Liu*, M. Fu*, C. Ma: "Battery Cell Equalization via Megahertz Multiple-Receiver Wireless Power Transfer", *IEEE Transactions on Power Electronics*, accepted on May 15th, 2017. [PDF]
3. M. Liu*, S. Liu*, C. Ma: "A High Efficiency/Output Power and Low Noise Megahertz Wireless Power Transfer System over A Wide Range of Mutual Inductance", *IEEE Transactions on Microwave Theory and Techniques*, accepted on March 27th, 2017. [PDF]
4. M. Fu*, H. Yin*, C. Ma: "Megahertz Multiple-Receiver Wireless Power Transfer Systems With Power Flow Management and Maximum Efficiency Point Tracking", *IEEE Transactions on Microwave Theory and Techniques*, accepted on March 6th, 2017. [PDF]
5. M. Liu*, C. Zhao*, C. Ma: "Battery Charging Profile-Based Parameter Design of A 6.78-MHz Class E^2 Wireless Charging System", *IEEE Transactions on Industrial Electronics*, accepted on January 29th, 2017. [PDF]

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  - United Automotive Electronic Systems , Bosch China

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Thank You

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