磁共振式MHz无线电能传输的基础研究与前景展望

研究生：傅旻帆（博士生）、张统（硕士生）
导师：马澄斌*、朱欣恩

动态系统控制实验室
上海交通大学密西根学院
http://umji.sjtu.edu.cn/lab/dsc/

于无线电能传输技术与应用学术国际会议
南京市，江苏省

10:15AM-10:30AM, 2014年11月16日

JOINT INSTITUTE
交大密西根学院

概要

- 研究团队
- 最优负载控制 (单线圈系统)
  - ✓ 最优负载分析
  - ✓ 静态与动态优化控制
- 多线圈系统
  - ✓ 零耦合下的最优负载分析
  - ✓ 非零耦合的最优补偿
- 最新研究成果与课题
  - ✓ 论文发表小结
  - ✓ 多线圈系统优化控制
  - ✓ 高频整流电路
  - ✓ MHz波形检测
  - ✓ 可调式功率放大器
- 结论

上海交大密西根学院研究团队

Chengbin Ma 马澄斌

Assistant Professor

Office 219

Tel +86-21-34206209

Fax +86-21-34206525

Email chbma@sjtu.edu.cn

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

Education

Ph.D.	Electrical Engineering, The University of Tokyo (2004)
M.S.	Electrical Engineering, The University of Tokyo (2001)
B.S.	Industrial Automation, East China University of Science and Technology (1997)

Xinen (Alfred) Zhu 朱欣恩

Assistant Professor

Office 223

Tel +86-21-34206733

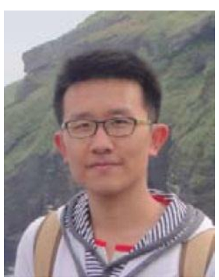
Fax +86-21-34206525

Email zhuxinen@sjtu.edu.cn

Education

Ph.D.	Electrical Engineering, University of Michigan (2009)
M.Sc.	Electrical Engineering, University of Michigan (2005)
B.Eng.(Honor)	Electronic and Communication Engineering, City University of Hong Kong (2003)

研究生 (博士生4名，硕士生2名):



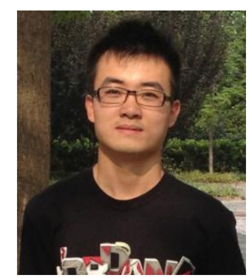
傅旻帆，D5
fuminfan@sjtu.edu.cn

张统，M3
zhangtong@sjtu.edu.cn

尹赫，D3
yyy@sjtu.edu.cn

刘双可，D2
liushuangke@sjtu.edu.cn

刘明，D1
mikeliu@sjtu.edu.cn

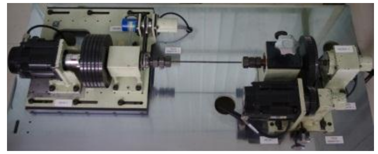


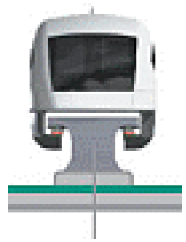
唐泽帆，M1
zftang@sjtu.edu.cn

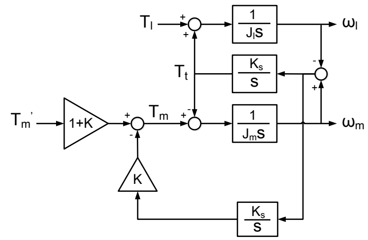
动态系统控制实验室

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

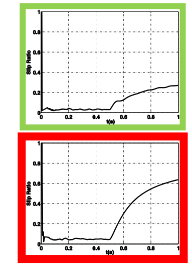
5 博士, 4 硕士

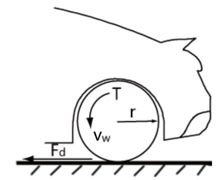


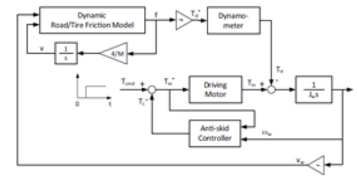




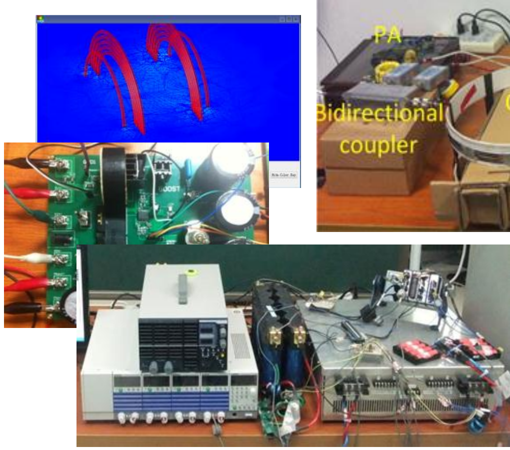
1. 运动与电机控制







2. 电动汽车动力学

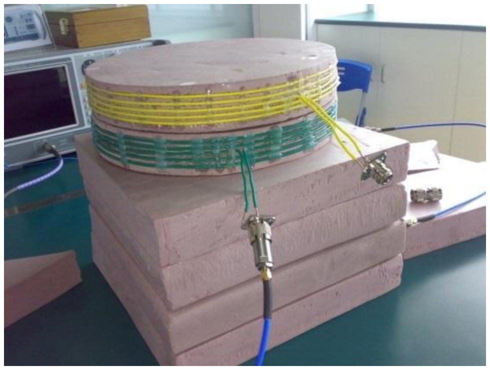


3. 混合能源系统

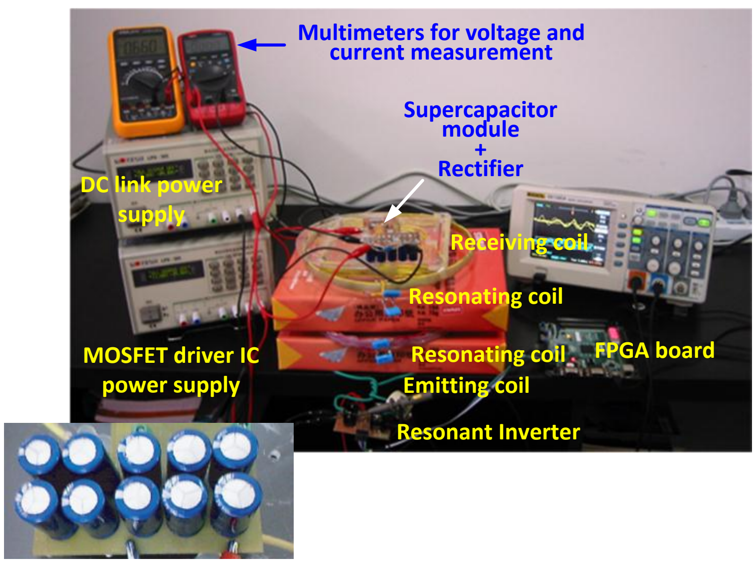
4. MHz无线电能传输系统

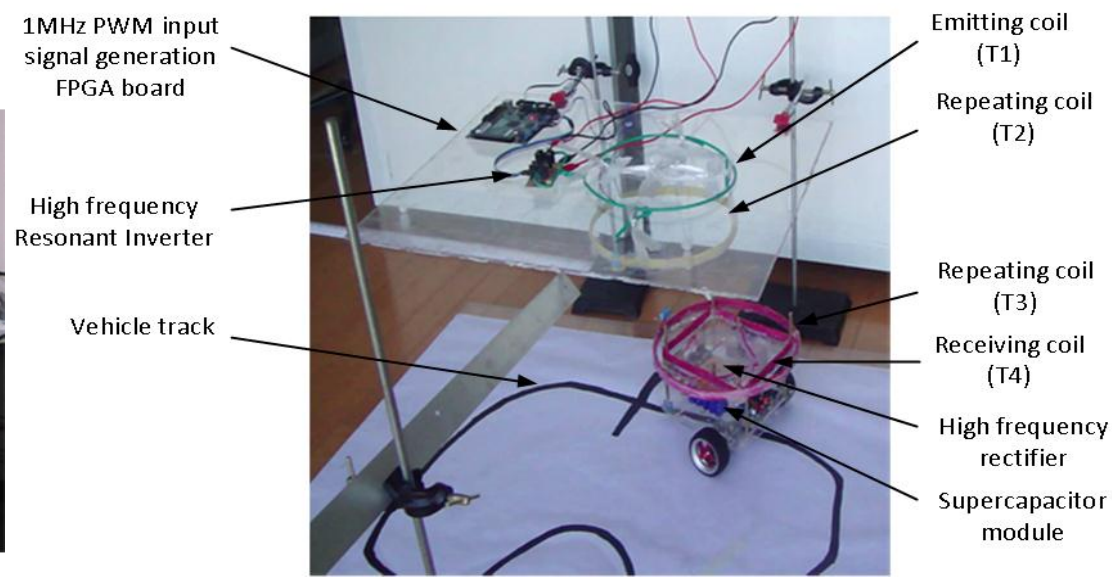
运动与能源的控制

2010年起的初期研究探索



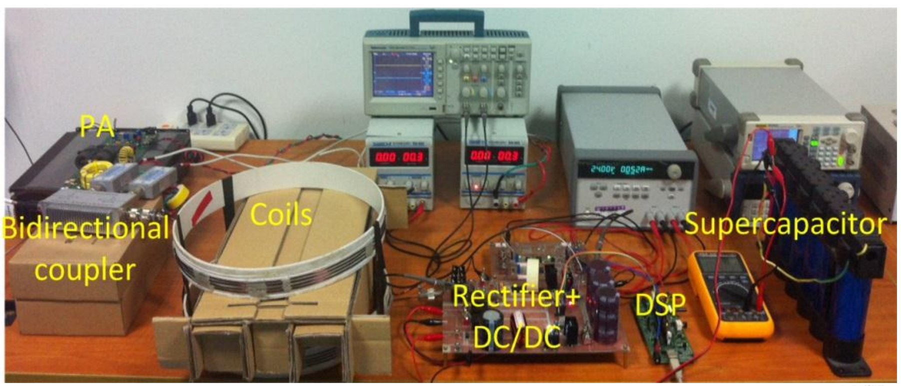
Gap (cm)	5.6	10.1	14.8	19.3	24.1	28
Efficiency (%)	88.84	93.32	**93.69**	92.53	88.07	70.04
F_m (MHz)	13.59	14.74	15.27	15.71	16.11	16.08
F_e (MHz)	19.87	17.85	17.01	16.51	16.11	16.08

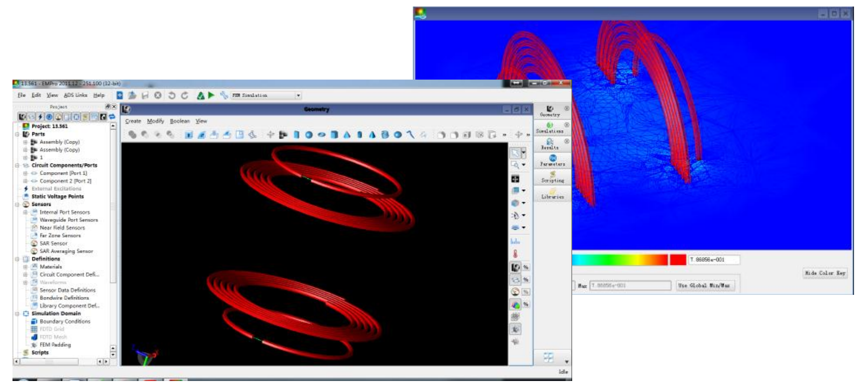


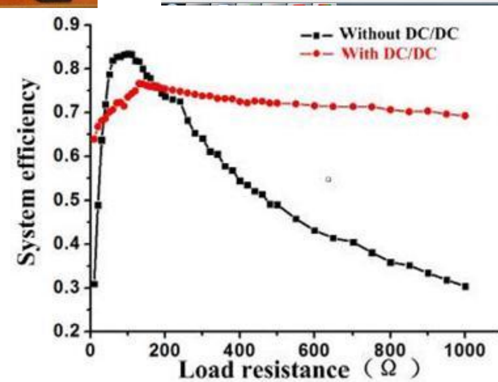


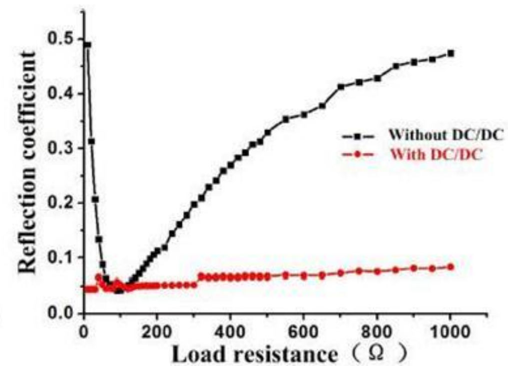
系统层次的优化分析与控制

- 13.56MHz无线电能传输系统 (< 40 watts, 70%)
  - 最优负载分析与静态/动态控制
  - 负载优化控制的电路
  - 实现多线圈系统的能量流优化控制



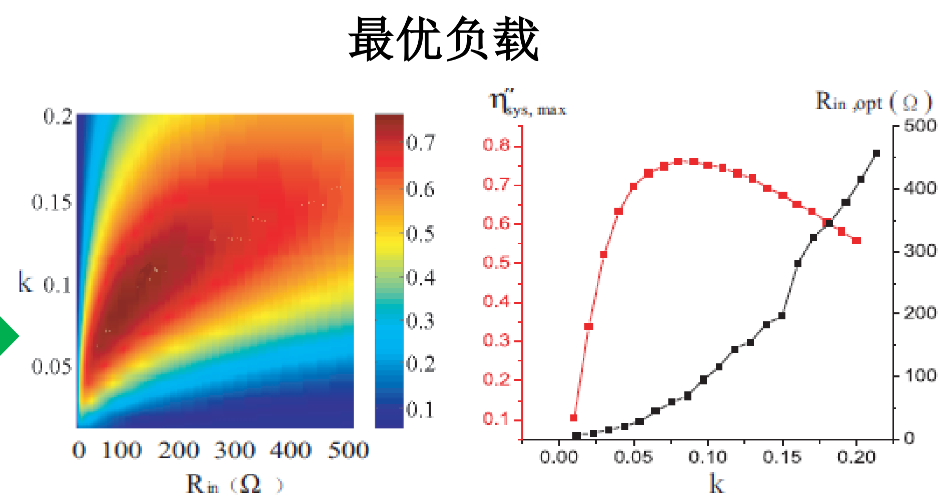


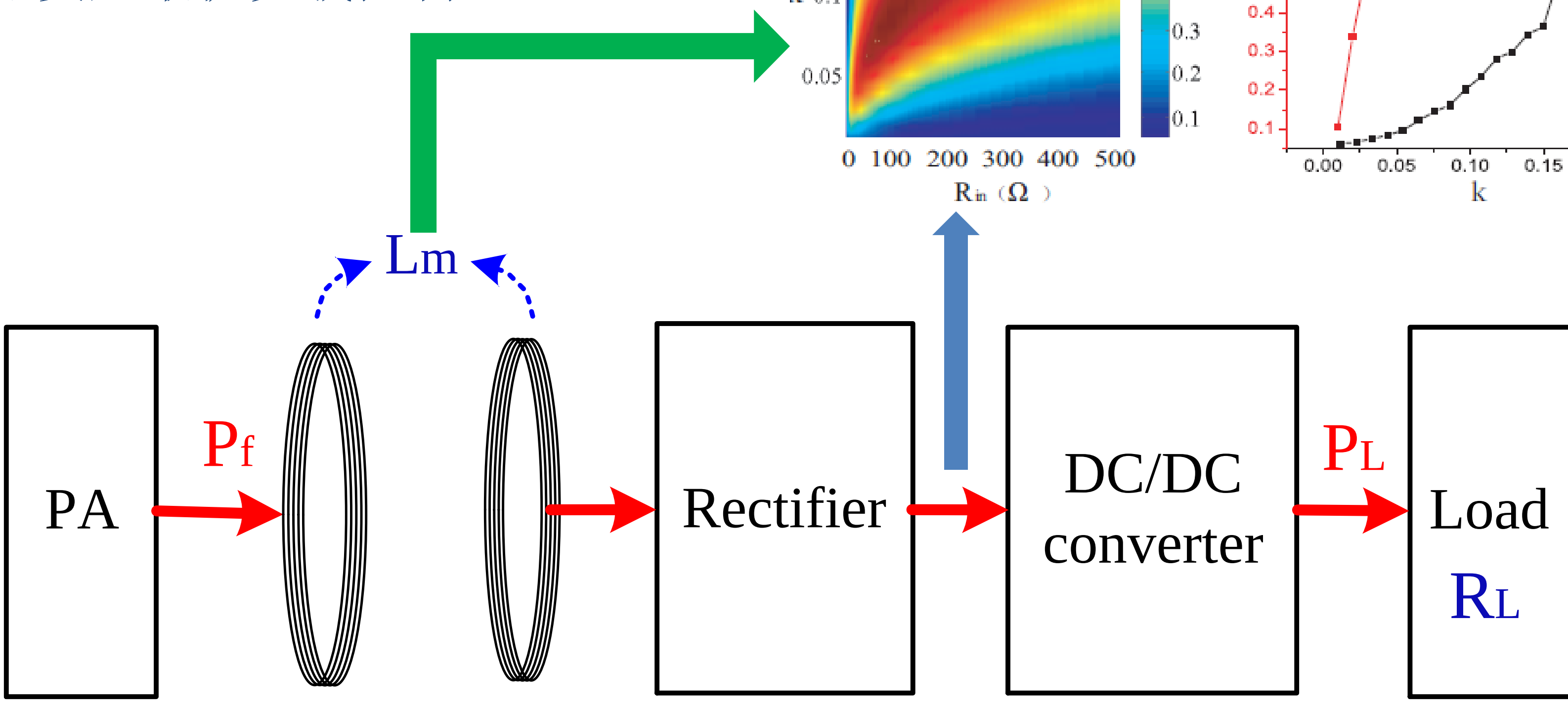




最优负载分析(1)

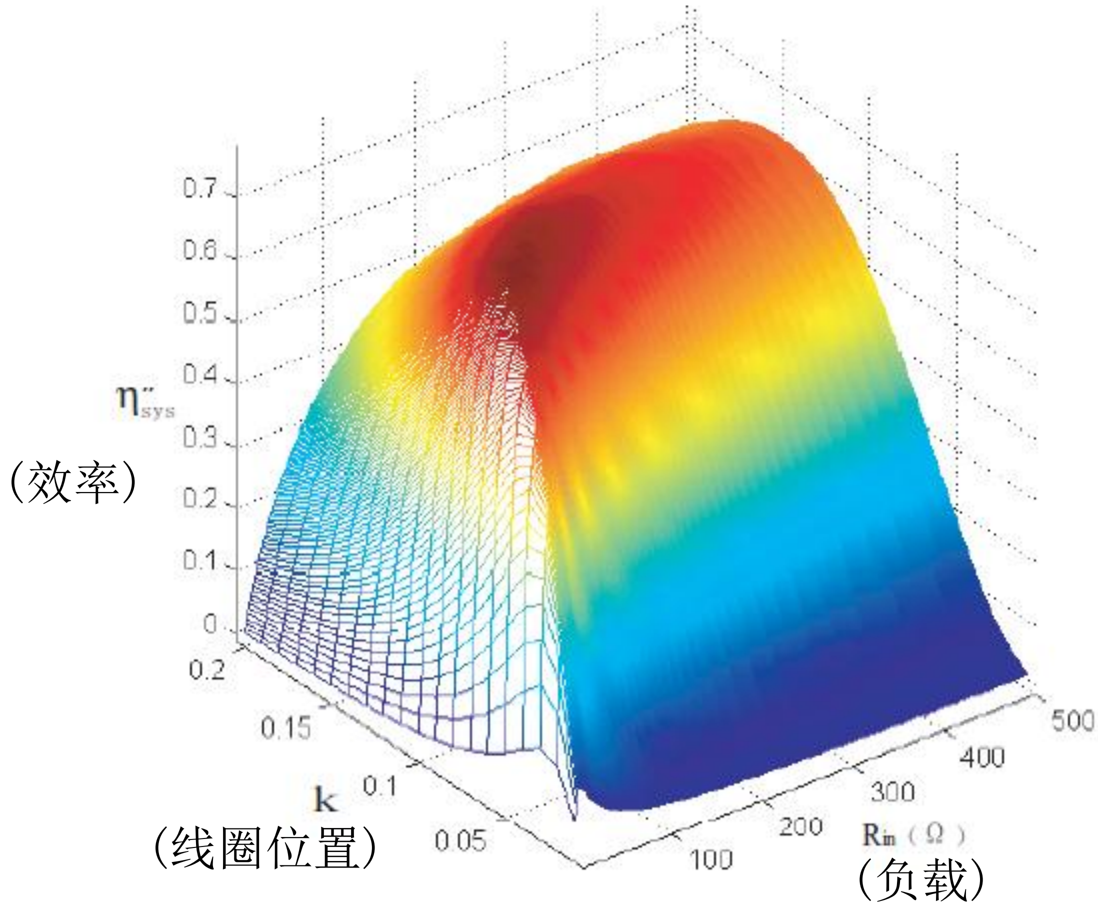
- 最大化 PL/Pf;
- 每个线圈位置（L_m）对应了唯一的从整流器看过去的最优负载值（R_{in}）；
- 提出了新型的boost-buck DC/DC 变换器实施最优负载控制。





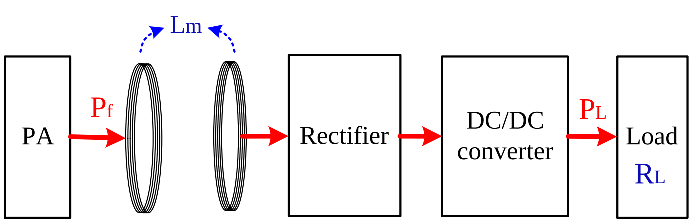
最优负载分析(2)

- 3-D视图



（基本思路）

- K，即线圈位置，由具体应用决定，一般不具有可控性；
- Rin，即整流器看过去的负载值，则可以通过引入新的变换电路来控制。

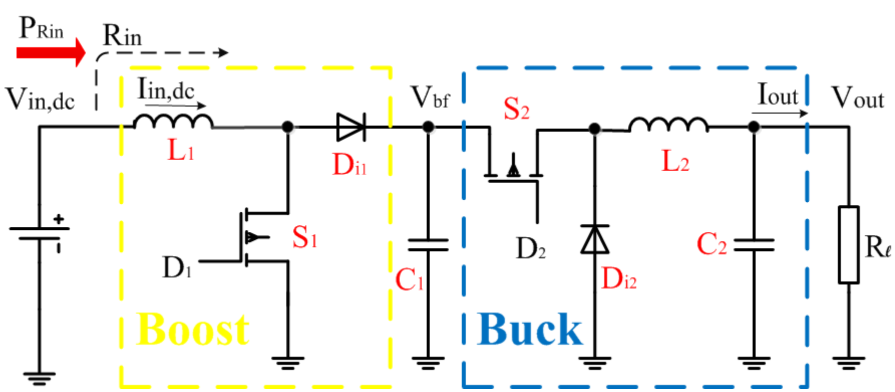


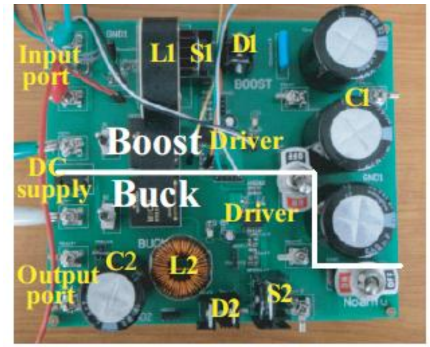
新型级联式Boost-buck变换器

- 该级联式组合可以实现0至+∞的等价负载调节。

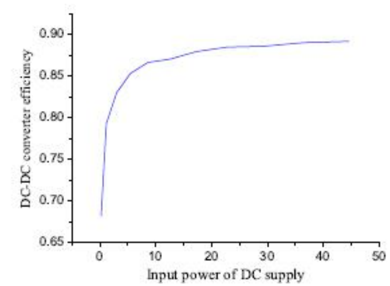
COMPARISON OF THE BASIC DC-DC CONVERTERS

Topology	V_{out}	R_{in}	R_{in} (range)	I_{in}
Buck	DV_{in}	$\frac{R_L}{D^2}$	$R_L \sim +\infty$	Discontinuous
Boost	$\frac{1}{1-D}V_{in}$	$(1-D)^2 R_L$	$0 \sim R_L$	Continuous
Buck-boost	$\frac{D}{1-D}V_{in}$	$\frac{(1-D)^2}{D^2}R_L$	$0 \sim +\infty$	Discontinuous
Ćuk	$\frac{-D}{1-D}V_{in}$	$\frac{(1-D)^2}{D^2}R_L$	$0 \sim +\infty$	Continuous
SEPIC	$\frac{D}{1-D}V_{in}$	$\frac{(1-D)^2}{D^2}R_L$	$0 \sim +\infty$	Continuous
Zeta	$\frac{D}{1-D}V_{in}$	$\frac{(1-D)^2}{D^2}R_L$	$0 \sim +\infty$	Discontinuous





(a)

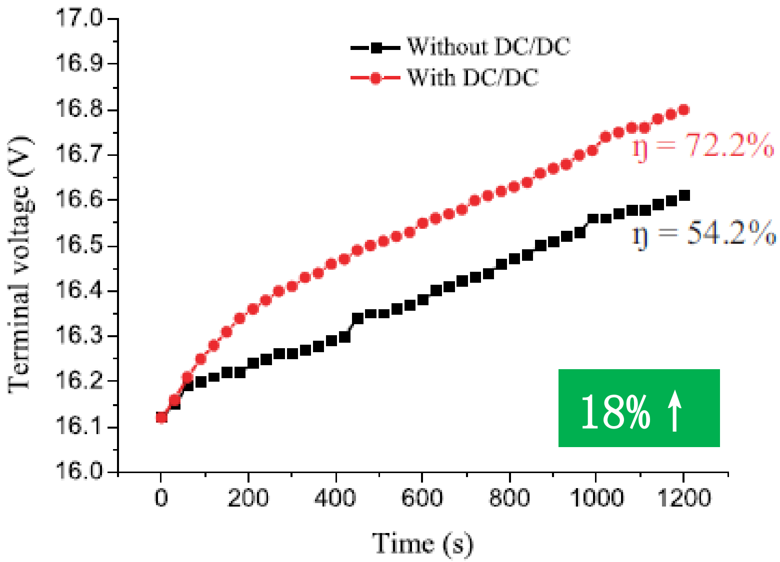


(b)

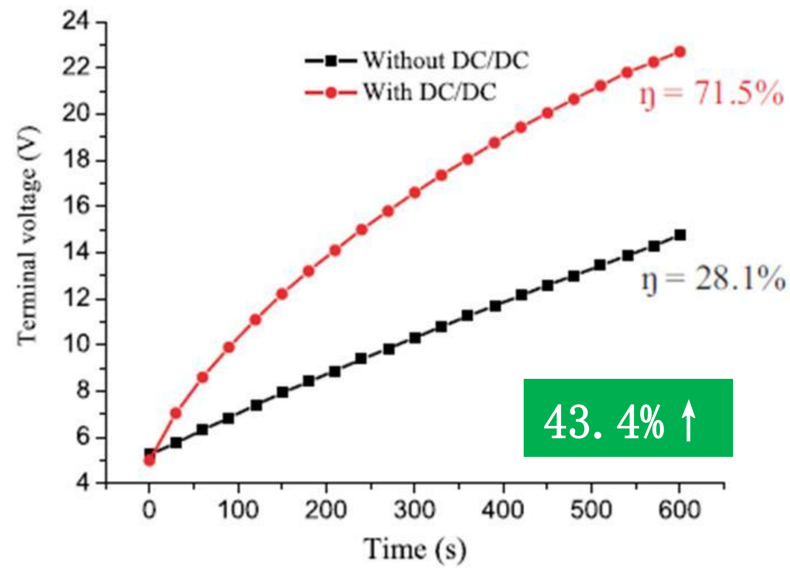
级联式boost-buck 变换器
(a) 电路 (b) 效率

对电池/超级电容的13.56MHz充电

- 在固定线圈位置的情况下充电效率得到了极大的改善。



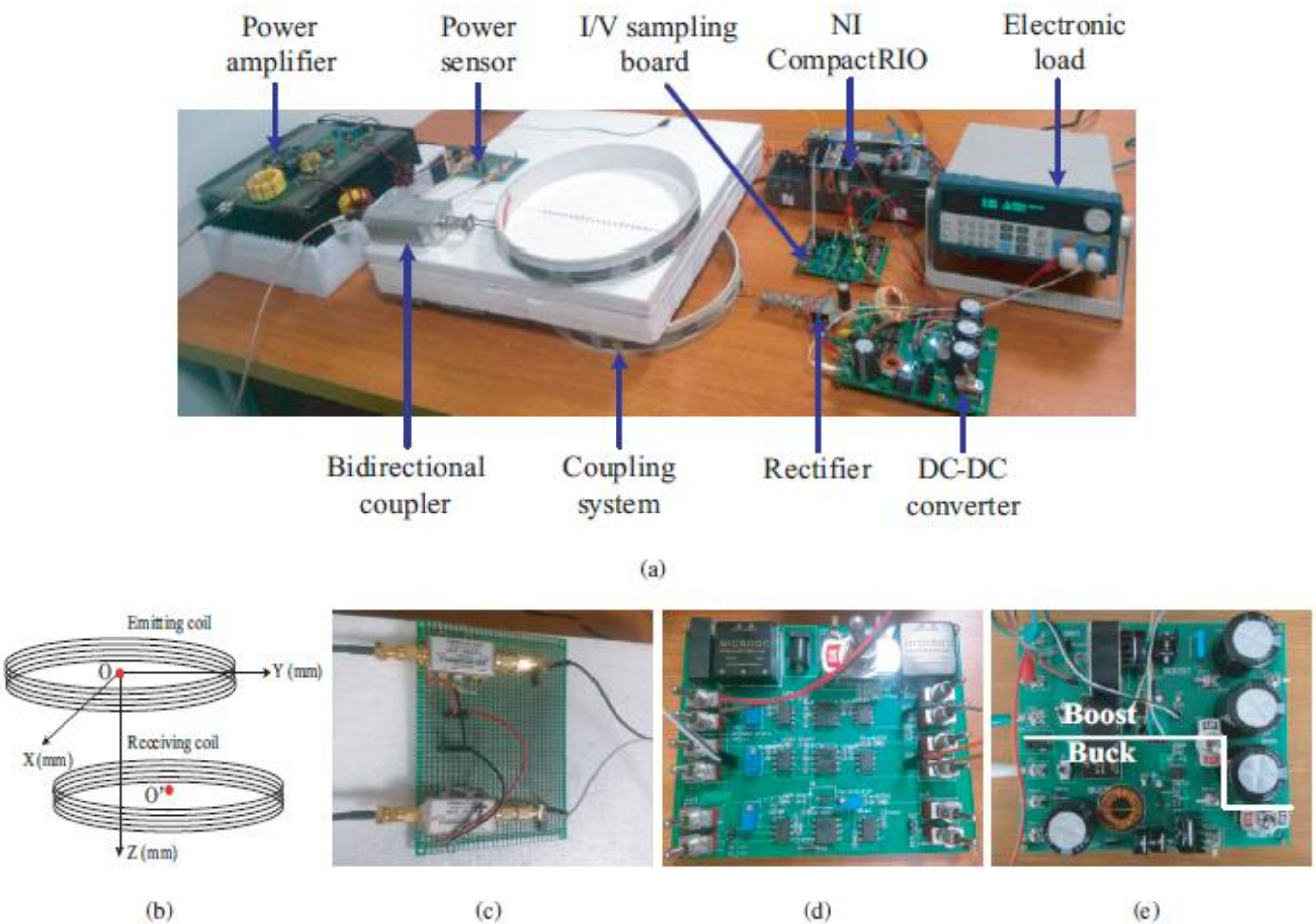
Batteries charging improvement using the cascaded boost-buck DC-DC converter.



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

[1] 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.

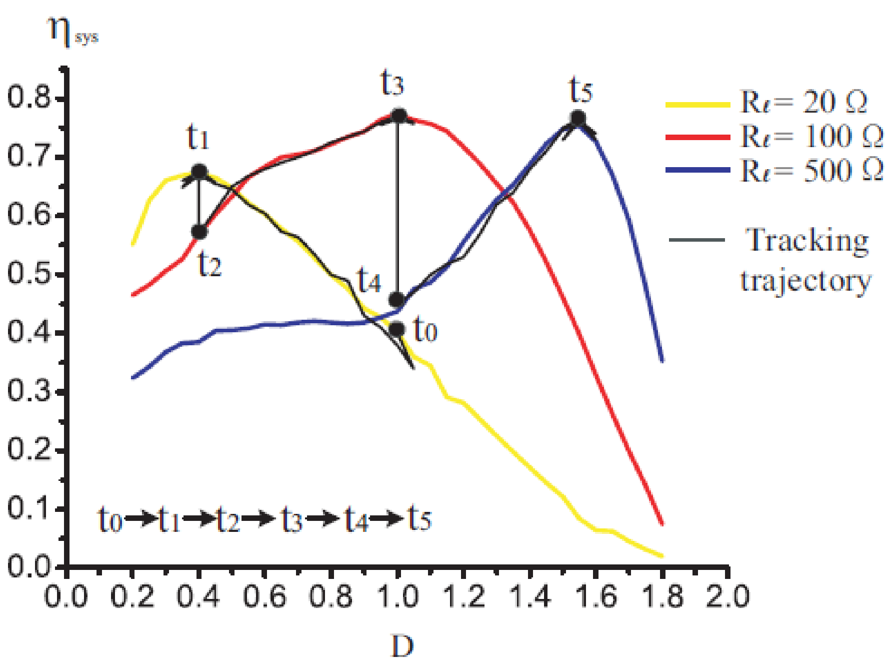
实验系统



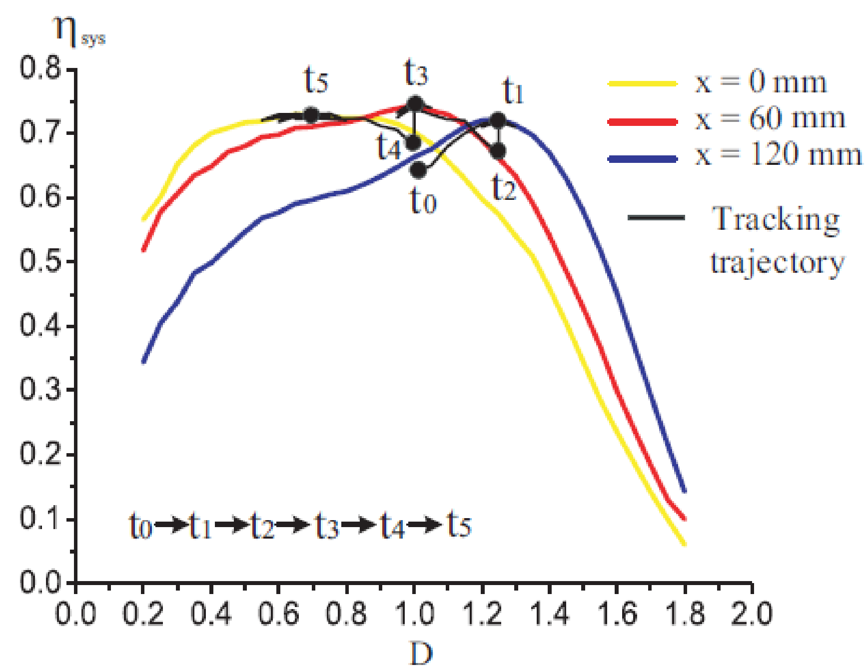
实验无线电能传输系统（a）系统全图（b）线圈相对位置定义
（c）功率传感器（d）I/V采样电路（e）级联式DC/DC变换器

最优负载动态跟踪

负载的变化

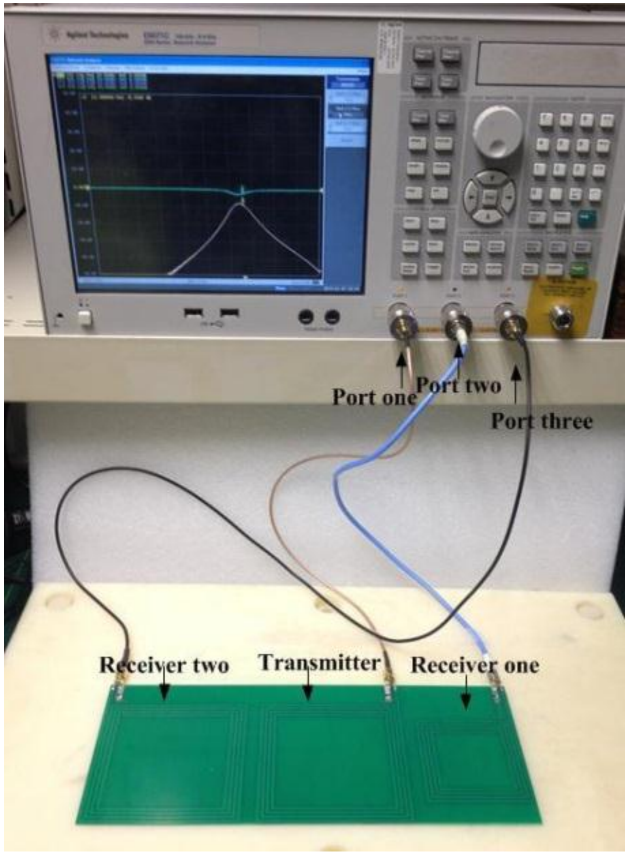


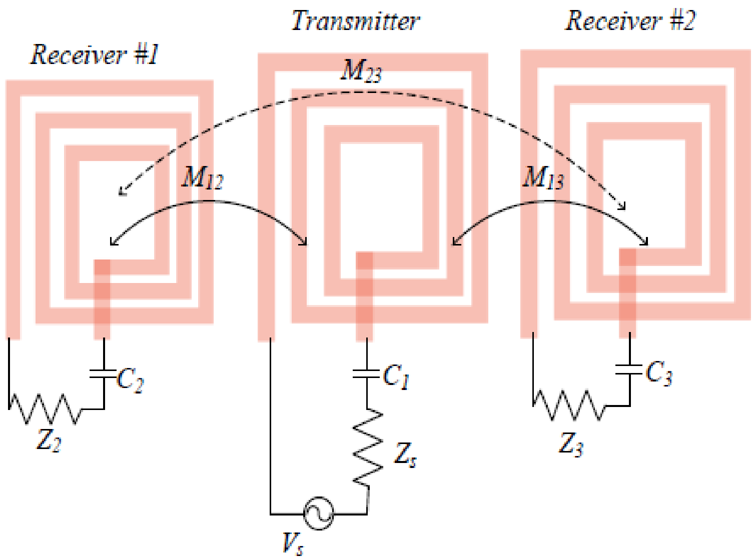
线圈位置的变化



[2] M. Fu, H. Yin, X, Zhu, C. Ma: "Analysis and Tracking of Optimal Load in Wireless Power Transfer Systems", IEEE Transactions on Power Electronics (Accepted on July 29th, 2014)

多接收线圈系统最优负载组合



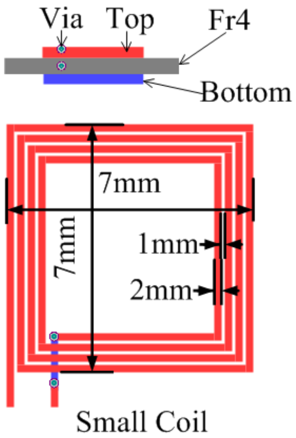


$$Z_{inopt} : Z_{2opt} : Z_{3opt} = R_1 : R_2 : R_3$$

[3] T. Zhang, M. Fu, X. Zhu, C. Ma: "Optimal Load Analysis for a Two-Receiver Wireless Power Transfer System", IEEE Wireless Power Transfer Conference, May 8-9, 2014, Jeju Island, Korea.

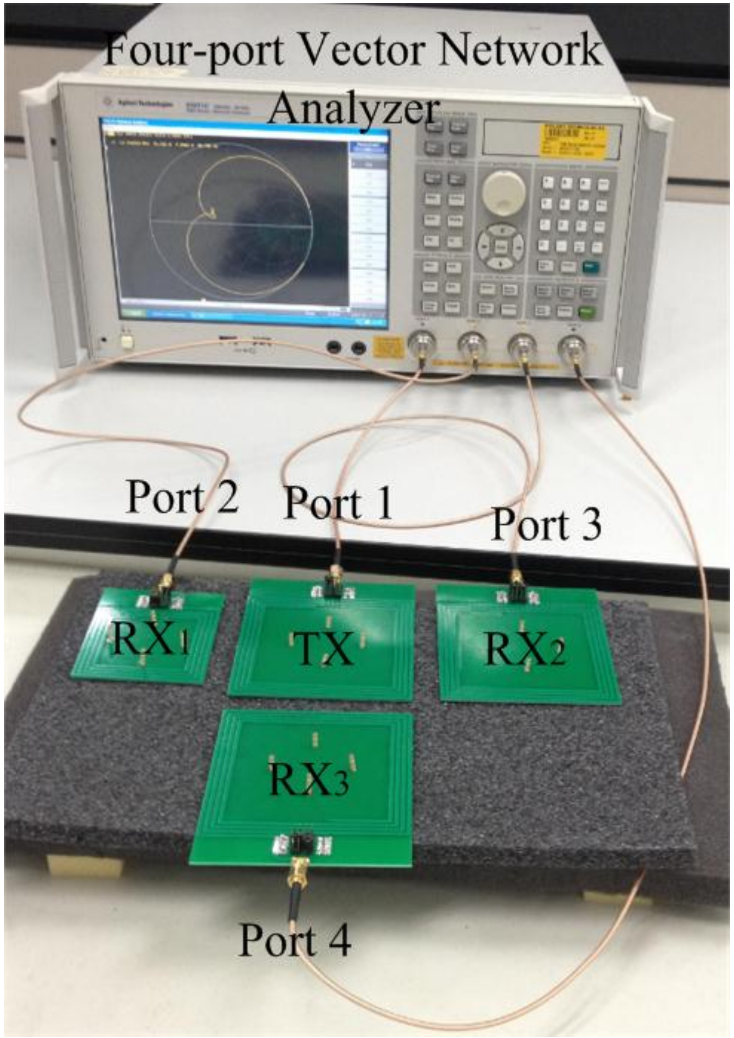
基于博弈理论的优化能量流分配？（实质上是一个新的无线能源网络系统优化控制问题）

实验系统



Coils' layout

参数	大线圈	小线圈
R (Ω)	2.05	1.04
L (uH)	3.93	2.01
C (pF)	37.2	72.5



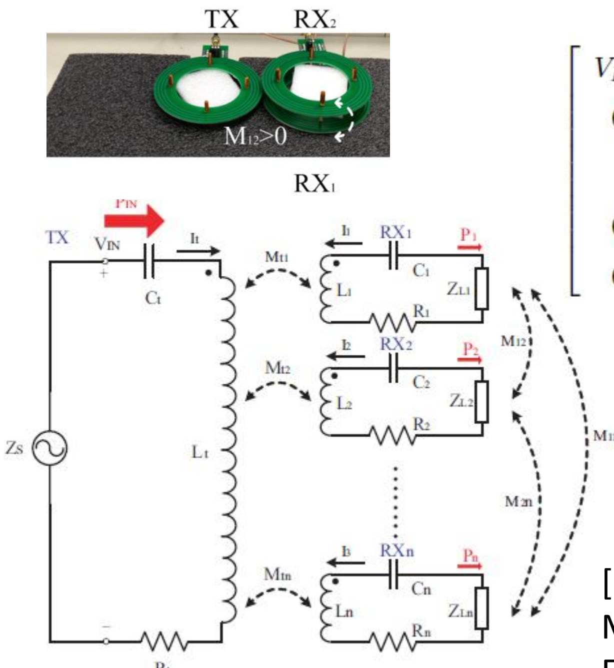
计算与实验结果比较

	Cal	PZC	LC
$Z_{L1,OPT}$	13.58	13.4	13
$Z_{L2,OPT}$	27.84	28.4	28
$Z_{L3,OPT}$	25.13	24.8	25
$Z_{S,OPT}$	27.84	26.4-j3.5	26.6-j2
最优阻值组合 ($Z_{S,OPT}$:$Z_{L1,OPT}$:$Z_{L2,OPT}$:$Z_{L3,OPT}$)	**1 : 0.5 : 1 : 0.9**	**1 : 0.51 : 1.08 : 0.94**	**1:0.49:1.05:0.94**
η	0.8629	0.8537	0.8534

[4] M. Fu, T. Zhang, C. Ma, and X. Zhu, “Efficiency and Optimal Loads Analysis for Multiple-Receiver Wireless Power Transfer Systems,” IEEE Transactions on Microwave Theory and Techniques, submitted.

线圈耦合的补偿

- 理论上可以证明零耦合系统的最优效率产生于所有负载为纯阻性的条件下。
- 假设非耦合系统的最优效率与零耦合系统的效率相等，并进而推导出非耦合系统电抗的最优值。



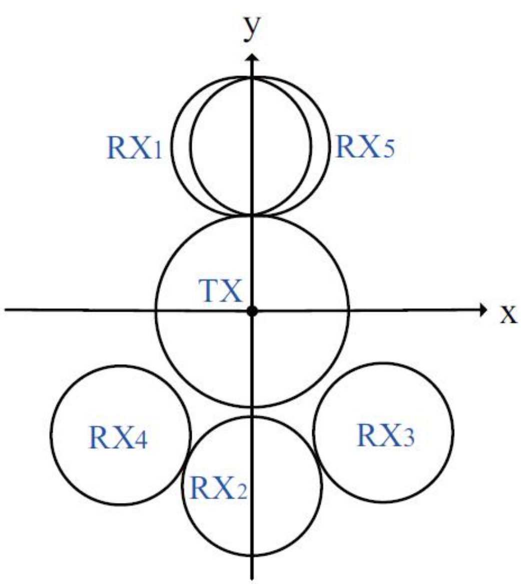
$$\begin{bmatrix} V_{IN} \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_t & j\omega M_{t1} & \cdots & j\omega M_{t(n-1)} & j\omega M_{tn} \\ j\omega M_{t1} & R_1+R_{L1}+jX_{L1} & \cdots & j\omega M_{1(n-1)} & j\omega M_{1n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ j\omega M_{t(n-1)} & j\omega M_{1(n-1)} & \cdots & R_{n-1}+R_{L(n-1)}+jX_{L(n-1)} & j\omega M_{(n-1)n} \\ j\omega M_{tn} & j\omega M_{1n} & \cdots & j\omega M_{(n-1)n} & R_n+R_{Ln}+jX_{Ln} \end{bmatrix} \begin{bmatrix} I_t \\ I_1 \\ \vdots \\ I_{n-1} \\ I_n \end{bmatrix}$$

$$X_{Li}^{*} = -\sum_{k=1,k\neq i}^{n} \frac{\omega M_{ik} M_{tk}(R_i + R_{Li})}{M_{ti}(R_k + R_{Lk})}.$$

[5] M. Fu, T. Zhang, X, Zhu, P. C. K. Luk, C. Ma: “Compensation of Cross Coupling in Multiple-Receiver Wireless Power Transfer Systems”, IEEE Transactions on Power Electronics , submitted

数值仿真的验证

- 五接收线圈系统和四种情形：
  1. 零耦合与纯阻性负载；
  2. 非零耦合与纯阻性负载；
  3. 非零耦合与理论推导出的最优电抗；
  4. 非零耦合与穷举法找出的最优电抗。



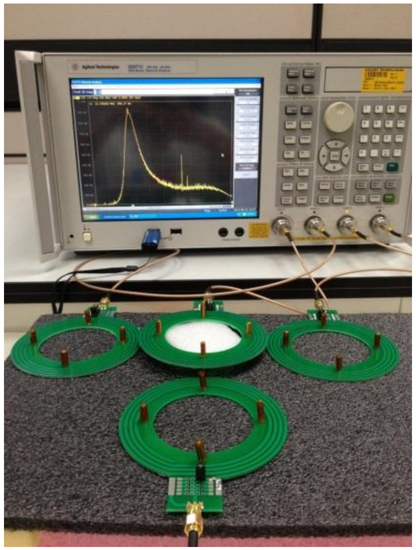
SYSTEM EFFICIENCIES IN CASES 1-4

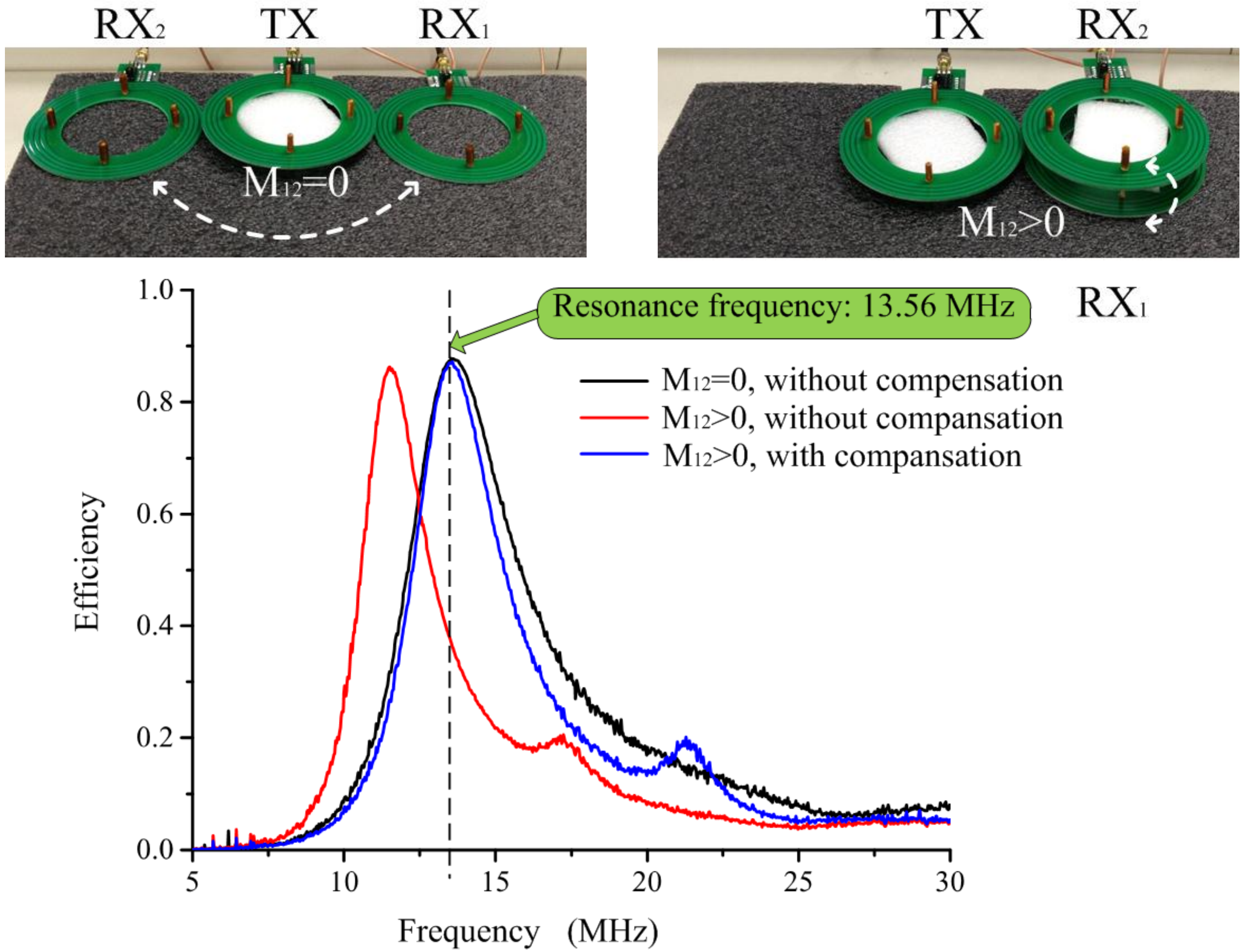
	Case 1	Case 2	Case 3	Case 4
η	89.15 %	82.35 %	89.15 %	89.15 %

COMPARISON OF OPTIMAL LOAD REACTANCES

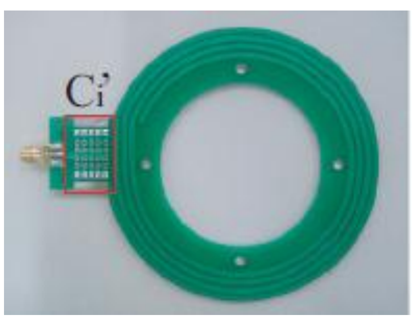
	X_{L1}^*	X_{L2}^*	X_{L3}^*	X_{L4}^*	X_{L5}^*
Case 3	-108.22 Ω	-62.96 Ω	-27.25 Ω	-19.24 Ω	-55.39 Ω
Case 4	-108 Ω	-62 Ω	-28 Ω	-19 Ω	-56 Ω

实验结果





RX2 TX RX1
M12=0
TX RX2
M12>0
RX1
Resonance frequency: 13.56 MHz
M12=0, without compensation
M12>0, without compansation
M12>0, with compansation
Efficiency
1.0
0.8
0.6
0.4
0.2
0.0
5
10
15
20
25
30
Frequency (MHz)



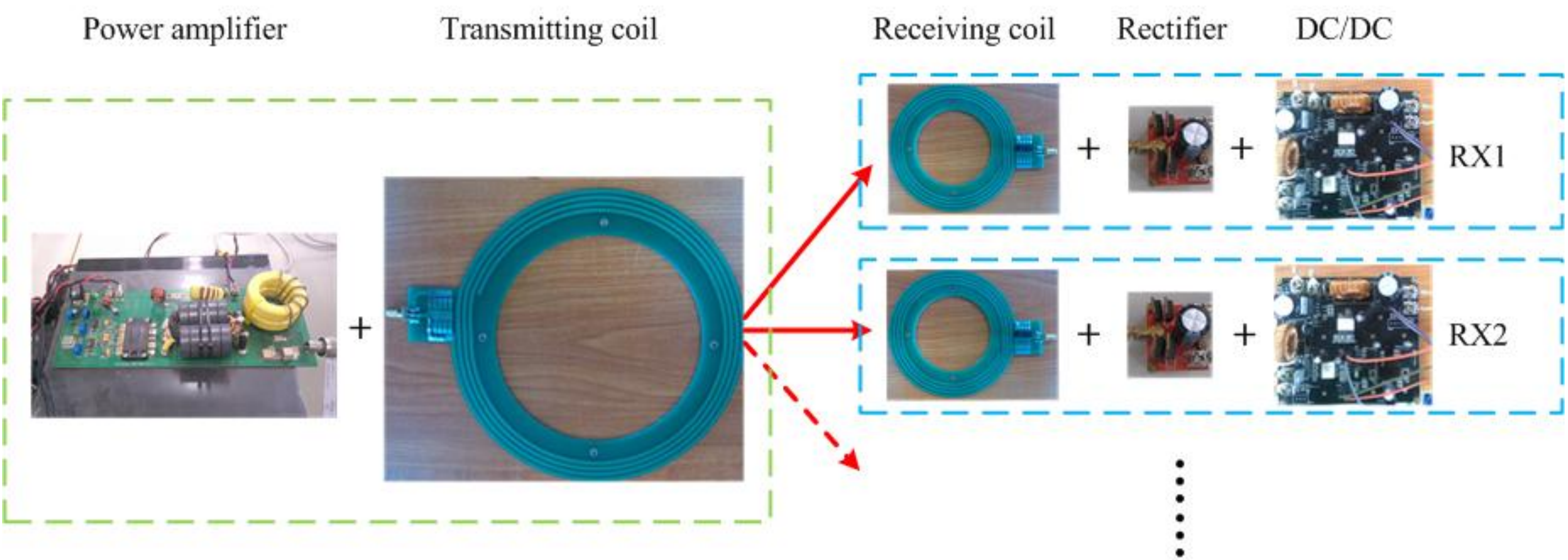
Ci'

目前论文发表情况

- IEEE期刊（录用2篇，投稿2篇）
  1. “Efficiency and Optimal Loads Analysis for Multiple-Receiver Wireless Power Transfer Systems″, IEEE Transactions on Microwave Theory and Techniques (Under the 1st revision).
  2. “Compensation of Cross Coupling in Multiple-Receiver Wireless Power Transfer Systems″, IEEE Transactions on Power Electronics (Under the 1st revision).
  3. M. Fu, H. Yin, X. Zhu, C. Ma: ″Analysis and Tracking of Optimal Load in Wireless Power Transfer Systems″, IEEE Transactions on Power Electronics, accepted on July 29th, 2014
  4. 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, Vol. 10, No. 3, pp. 1972-1980, Aug. 2013.
- 国际会议论文（5篇）
  1. M. Fu, T. Zhang, X. Zhu, C. Ma: “Subsystem-Level Efficiency Analysis of a Wireless Power Transfer System”, IEEE Wireless Power Transfer Conference, May 8-9, 2014, Jeju Island, Korea.
  2. T. Zhang, M. Fu, X. Zhu, C. Ma: “Optimal Load Analysis for a Two-Receiver Wireless Power Transfer System”, IEEE Wireless Power Transfer Conference, May 8-9, 2014, Jeju Island, Korea.
  3. M. Fu, T. Zhang, C. Ma, X. Zhu: “Wireless Charging of A Supercapacitor Model Vehicle Using Magnetic Resonance Coupling”, ASME 2013 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, August 4-7, 2013, Portland, OR, USA.
  4. M. Fu, T. Zhang, X. Zhu, C. Ma: “A 13.56 MHz Wireless Power Transfer System without Impedance Matching Networks”, IEEE Wireless Power Transfer Conference, May 15-16, 2013, Perugia, Italy
  5. C. Ma, X. Zhu, M. Fu: “Wireless Charging of Electric Vehicles: A Review and Experiments″, ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Aug. 28 - Aug. 31, 2011, Washington D. C., USA.

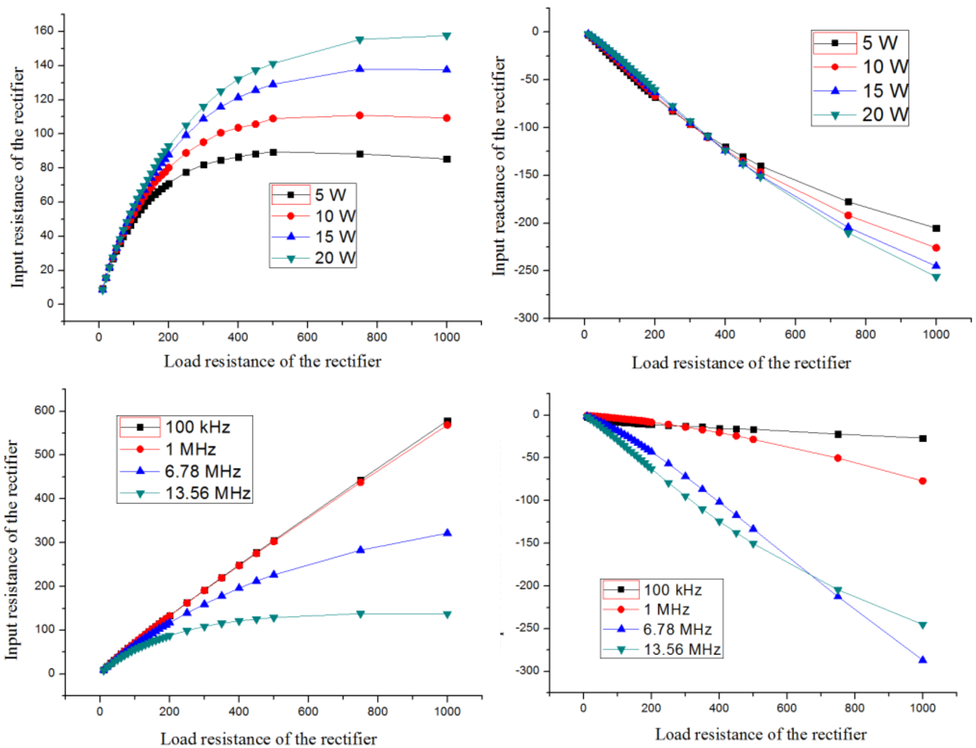
多线圈系统能量流优化控制

- 基于博弈理论的线圈间能量流自主分配
- 基于前述负载优化匹配控制的扩展
- 多线圈系统整体效率与性能的最优化



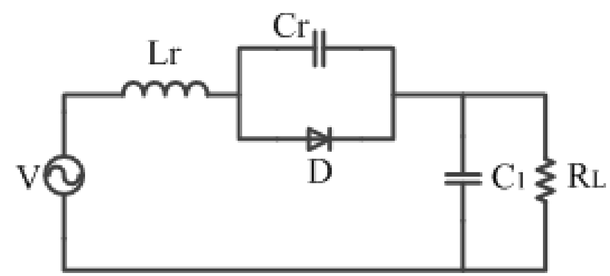
MHz整流电路

1. 全桥整流电路的建模与分析



整流器在不同功率和频率下的输入阻抗

2. 共振Class-E整流器:
实现ZVS或ZCS减小损耗



3. 同步整流:

- 全桥或Class-E结构;
- 提高效率;
- 通过duty cycle控制传递功率（新的控制自由度）

MHz波形的检测

- 各端口AC波形 (幅值与相位)的检测对于实施闭环优化阻抗控制具有重要的意义。

Magnitude

Available in the future

PCB

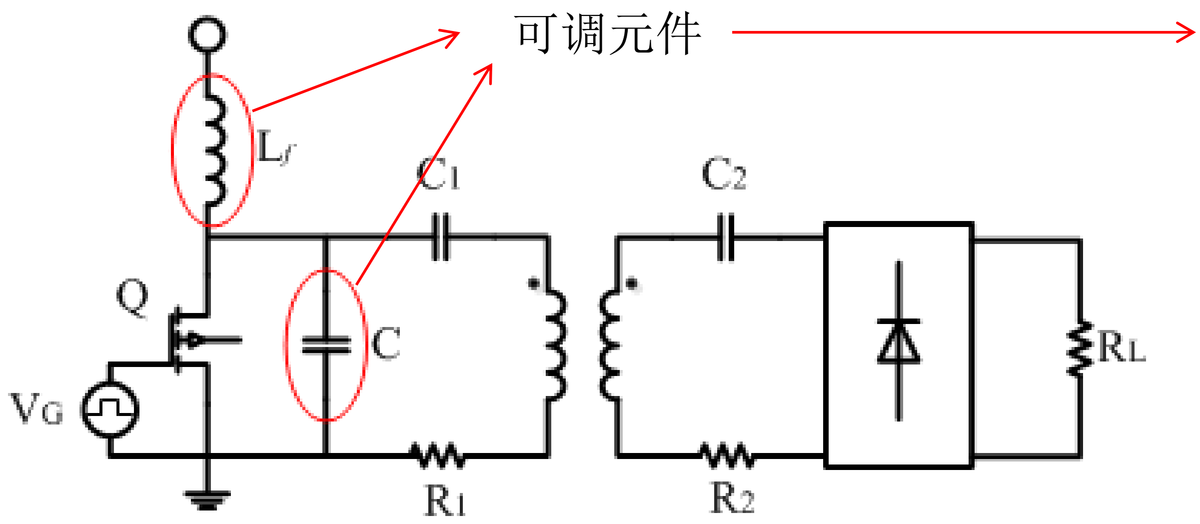
Available in the future

Phase comparison

Available in the future

可调式Class-E功率放大器

- MHz系统功率放大器的效率和输出功率极大地依存于负载的状况，需要基于闭环的反馈控制：
  - 电抗的检测
  - 实时可控电容



微型步进电机

+

可调式电容

结论

- MHz无线电能传输系统各器件间存在着复杂的耦合和交互关系，以及众多的不确定因素，为优化分析与控制的应用提供了很好的研究对象；
- 从系统层面的分析与优化控制出发，上海交大密西根大学团队发现并解决一些初步的原创性课题，包括最优负载的求解与静/动态优化控制、多线圈系统（零/非零耦合）的负载优化分析与实验验证等；
- 今后将进一步深化研究，从单接收线圈系统到多接收线圈系统过渡，通过新型传感装置、可调器件、能量流智能优化分配的研究，并结合多代理人建模与博弈理论等工具，构建多接收线圈系统优化分析与控制的理论构架；
- 进一步深化国际学术交流，和各位同仁一起，力争在国际学术界发出“中国声音。”

无线充电全电化城轨车辆



致谢

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  - 日本贵弥宫公司（2010-至今）
  - 英特尔亚太研发中心 （2013-至今）

  和其他合作单位对我们的鼎力支持！

感谢您的聆听！

动态系统控制实验室

上海交通大学密西根学院

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