Quantitative Analysis, Control, and Wireless Charging of Energy Systems Using Ultracapacitors

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JOINT INSTITUTE
交大密西根学院

Outline

- Overview
- Quantitative Analysis of HESS
- Networked Energy Systems
- Wireless Power Transfer
- Conclusions

Shanghai Jiao Tong University

- 24 Schools/Departments
- 12 Affiliated Hospitals
- 16,802 Undergraduates
- 24,495 Graduates (≈60%)
    - 5,059 Ph.D. students
- 2,979 Faculties
    - 835 Professors
- 3.3km² (Minhang Campus)

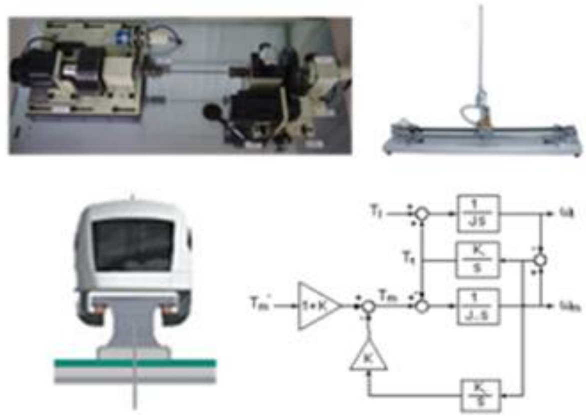
UM-SJTU Joint Institute (1)

UM-SJTU Joint Institute (2)

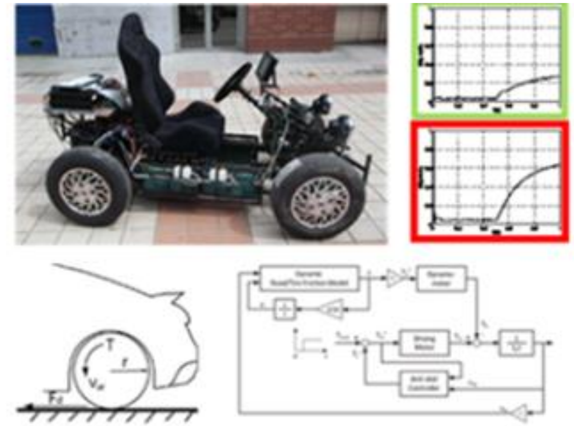
- Serve as a major base to facilitate the growing trend of global education and to reform Chinese higher education.
- Curriculum integrated with that of UM, World-class faculty, International education environment.
- 80% of JI's graduates went to the graduate schools in the USA, among which average 40% were admitted to the Top-10 engineering schools.

Dynamic Systems Control Lab (2010~Pre.)

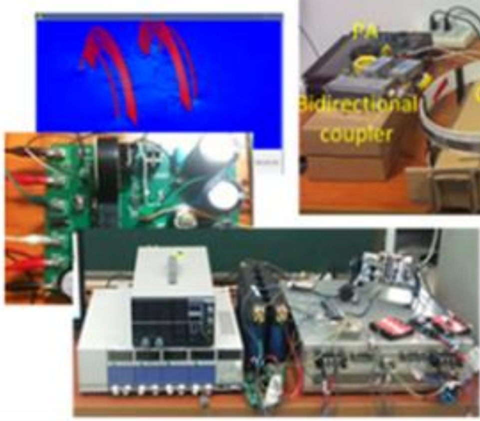
5 Ph.D., 4 Master



1. Motion/Motor Control



2. Electric Vehicle Dynamics



3. Hybrid Energy System
4. MHz Wireless Charging

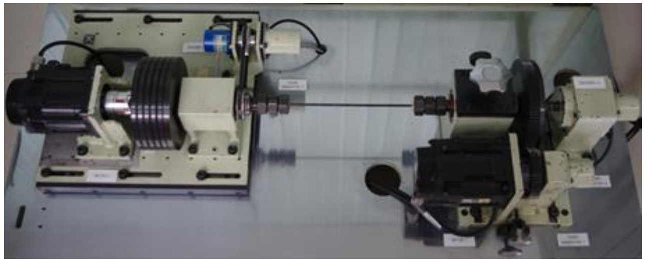
Control of Motion & Energy

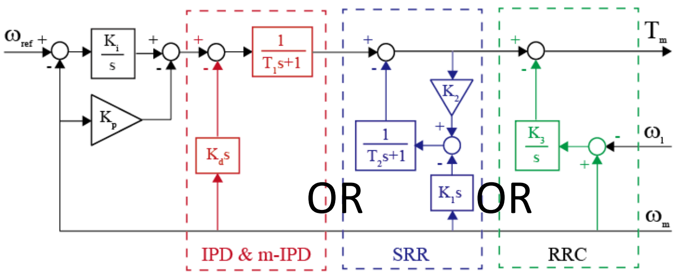
Chengbin Ma

- Background: Systems, Control and Mechatronics
- Research Interests:
  - Networked hybrid energy system, wireless power transfer, electric vehicles, motion control and mechatronics.
- Employment:
  - Aug. 2008-Pre: Assistant Prof., Univ. of Michigan-SJTU Joint Institute, Shanghai, China
  - Nov. 2006-Mar. 2008: Post-doctor, Univ. of California Davis, USA
  - Oct. 2004-Oct. 2006: R&D researcher, FANUC Limited, Japan
- Education:
  - Sep. 2004: PhD, Dept. of E. E., Univ. of Tokyo, Japan
  - Sep. 2001: M. A., Dept. of E. E., Univ. of Tokyo, Japan
  - July. 1997: B. S. (Hons.), Dept. of Industrial Automation, East China Univ. of Science and Technology, Shanghai, China

Students and New Laboratory

Motion Control





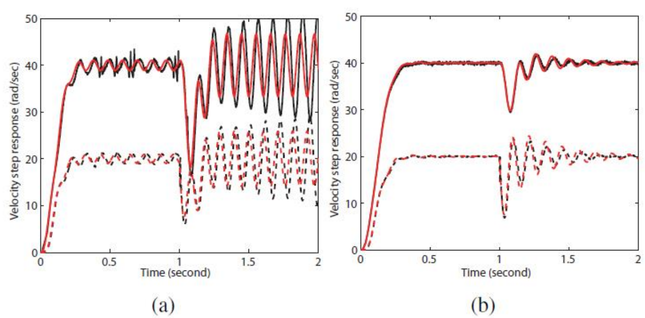


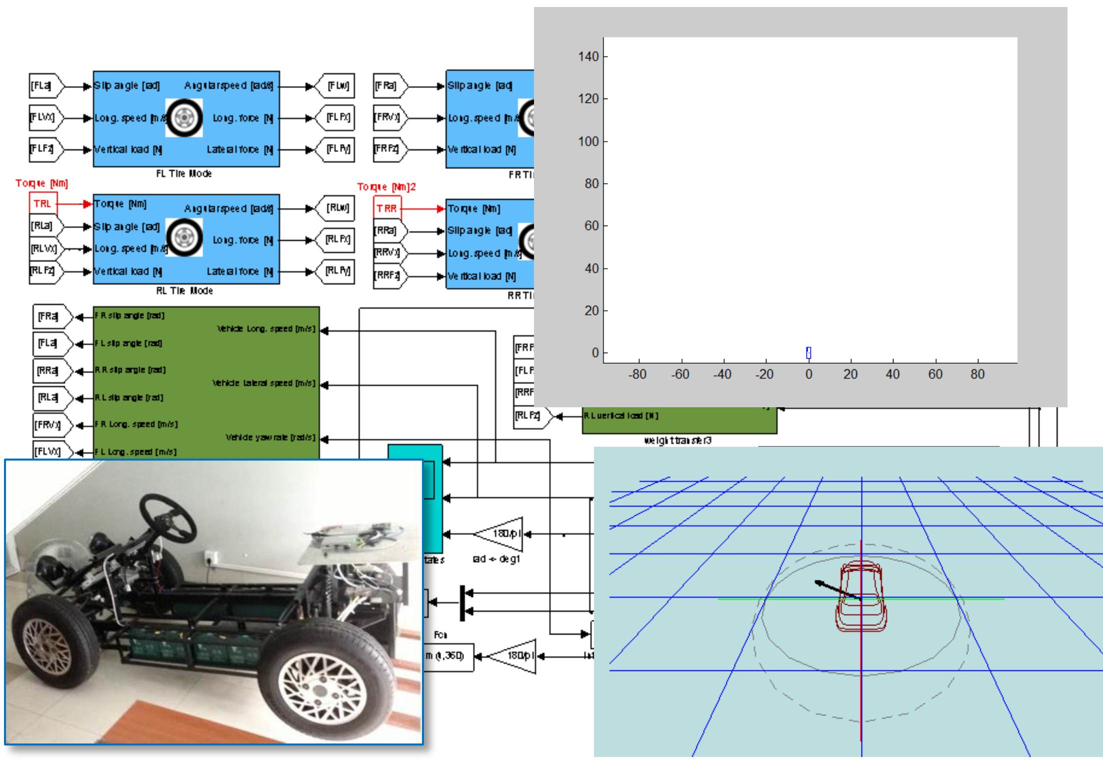
Fig. 12. Velocity step responses under m-IPD control with γ_1=2.48, γ_2=2, γ_3=2 and specified τ's at q=0.80. (a) τ=5.5. (b) τ=6.5.[2]

- The closed-loop-based polynomial method could be a general approach for the control of transient responses.
- Tradeoff relationship between damping and robustness can be explicitly represented by the interaction between γ_i's and τ.
- On-going project: Control of electro-magnetic suspension

[1] C. Ma, J. Cao, Y. Qiao: "Polynomial Method Based Design of Low Order Controllers for Two-Mass System", IEEE Transactions on Industrial Electronics, Vol. 60, No. 3, pp. 969-978, March 2013.
[2] Y. Qiao, J. Cao, C. Ma: "Transient Response Control of Two-Mass System via Polynomial Approach", ASME Journal of Dynamic Systems Measurement and Control, accepted on Apr. 17th, 2014.

Electric Vehicle Dynamics

- Electric motor:
  - Fast and accurate torque control
  - Serve as driver, actuator, and sensor simultaneously



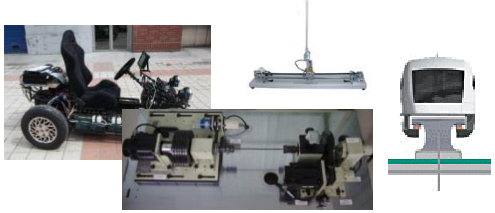
- **Traction Control**
- **Vehicle Stability Control**
- **Assistive Braking Control**
- **Eco-driving Assistance**

[3] X. Wu, C. Ma, M. Xu, Q. Zhao, Z. Cai: "Single-Parameter Skidding Detection and Control Specified for Electric Vehicles", Journal of the Franklin Institute (Elsevier), accepted on July 8th, 2014.

From “Motion” to “Energy”

Control of

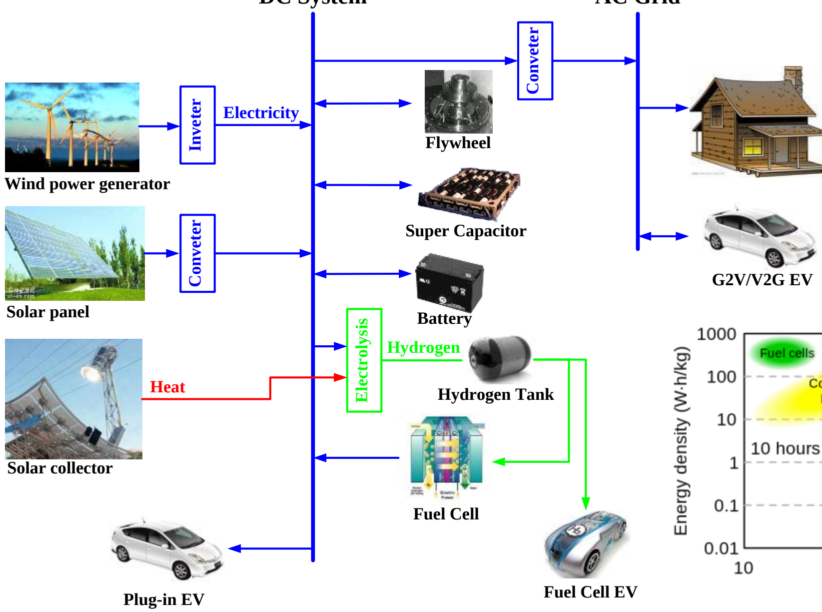
Motion

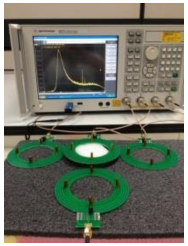


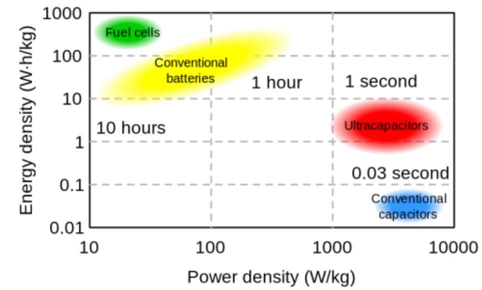
- Speed
- Precision
- Efficiency

Energy

- Synergy
- Flexibility
- Scalability
- Fault-tolerance
- Reliability







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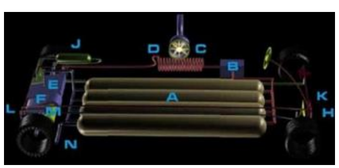
[4] C. Zhao, H. Yin, Y. Noguchi, C. Ma: "Quantitative Analysis on Energy Efficiency of A Batter y-Ultracapacitor Hybrid System", The 23rd IEEE International Symposium on Industrial Electronics, June 1-4, 2014, Istanbul, Turkey.

[5] C. Zhao, H. Yin, Z. Yang, C. Ma: "A Quantitative Study of Efficiency for Battery-ultracapacitor Hybrid Systems", the 40th Annual Conference of the IEEE Industrial Electronics Society, Oc. 29-Nov. 2, 2014, Dallas, TX, USA.

Diversity of Renewable Energy Systems

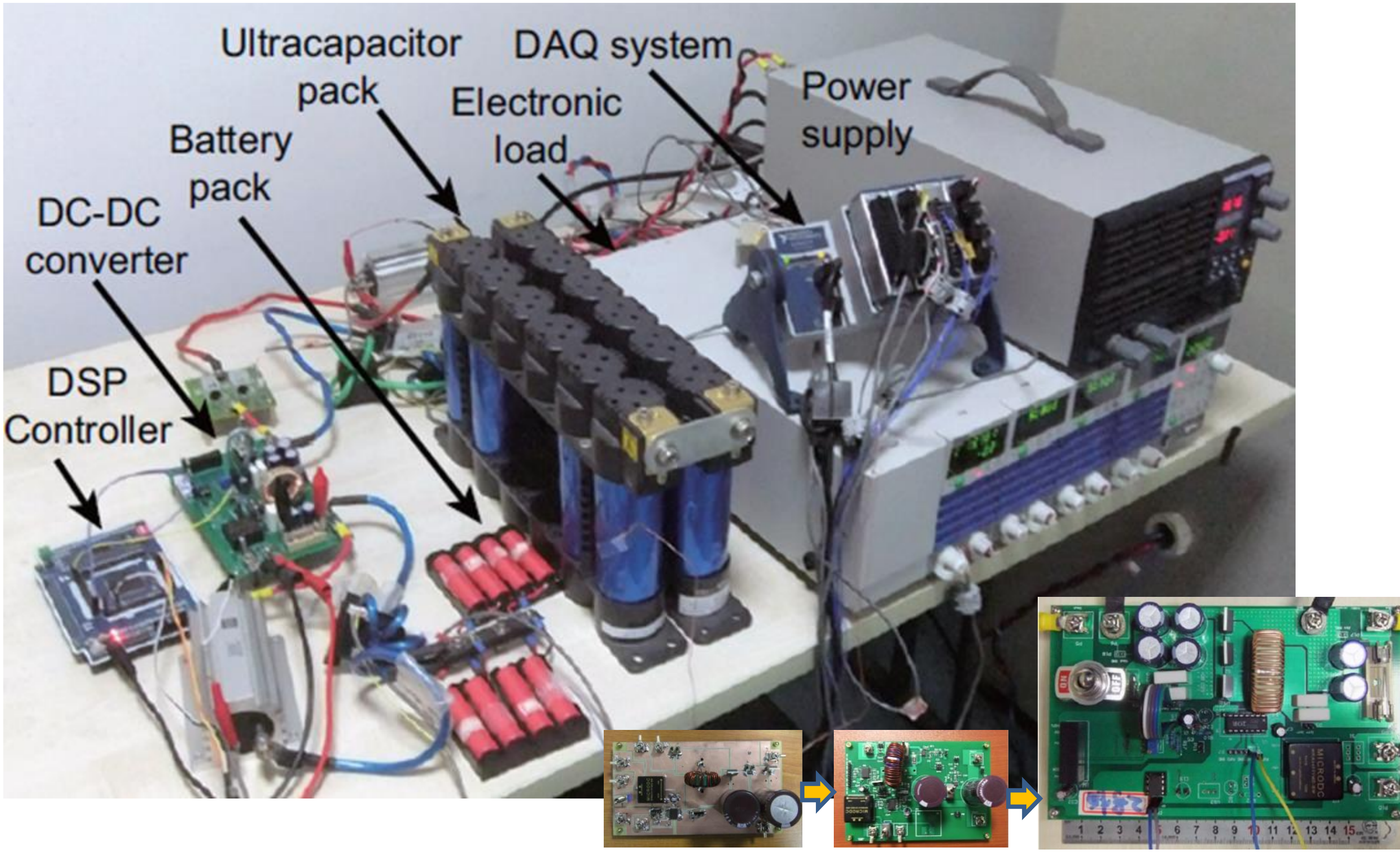
- Energy sources with different dynamics
  - Wind, Solar, Regenerative Energy, etc.
- Immature electricity mass storage technology
  - The energy density of petrol (12000Wh/kg) is hundreds of times as that of a mass market battery (20~200Wh/kg).
  - Combination of multiple energy storage devices/systems with various dynamics are naturally required (e.g. ultracapacitors, flywheels, compressed air tank, wireless power transfer).



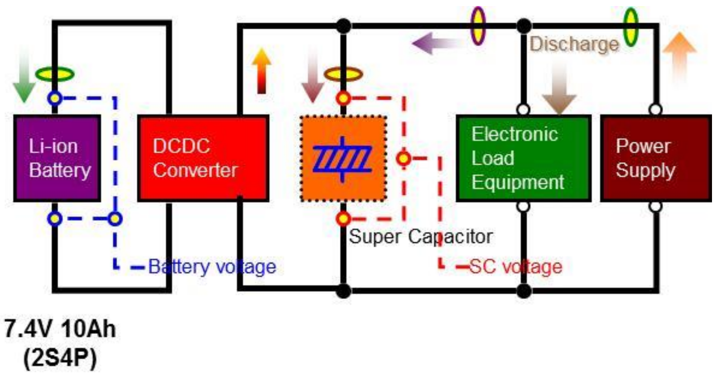


Battery-Ultracapacitor Test System

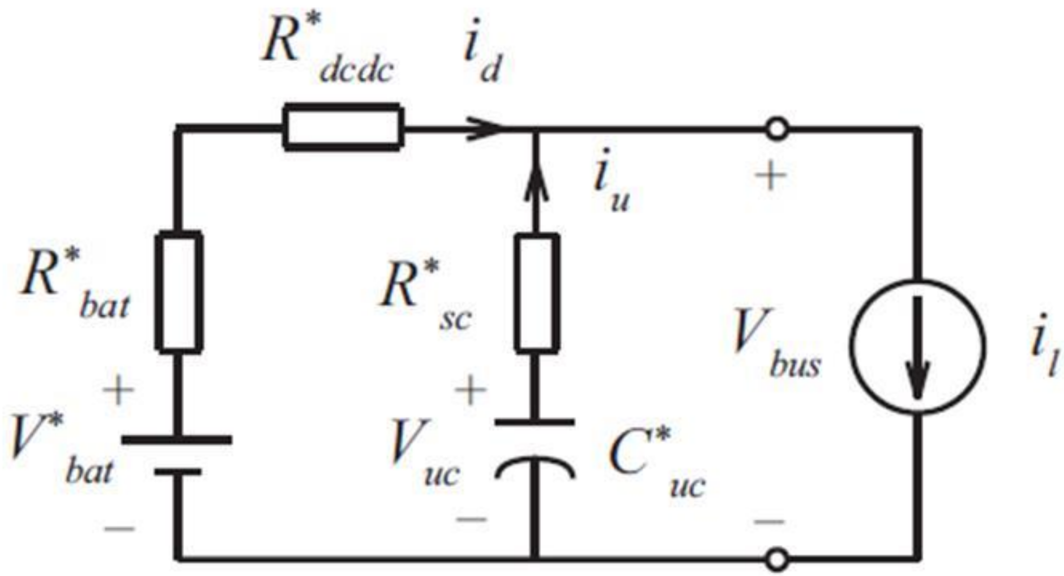


ESR-based Efficiency Analysis

- Equivalent-Series-Resistance circuit Model:



$$R_d^* = \frac{P_{loss,d}}{i_d^2} \approx \frac{R_L + d_s R_{on}}{(1-d_s)^2} + R_b + \frac{V_F}{i_d} = R_{d,r}^* + \frac{V_F}{i_d},$$

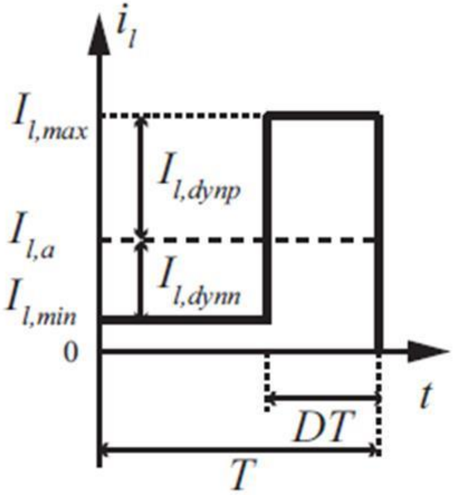


$$R_b^* = \frac{P_{loss,b}}{i_d^2} \approx \frac{i_b^2 R_s}{i_d^2} = \frac{R_s}{(1-d_s)^2},$$

$$R_u^* = \frac{P_{loss,u}}{i_u^2} \approx R_{sc},$$

Optimal Current Distribution

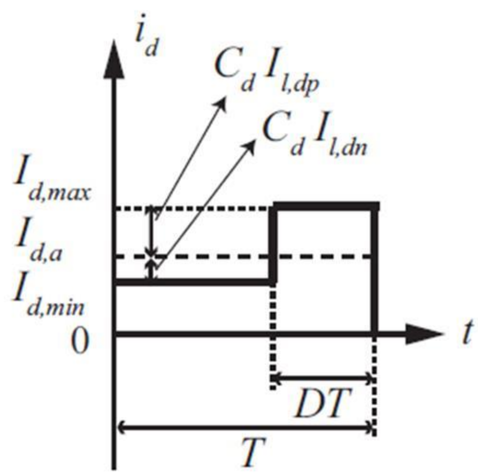
- Even for a high energy efficiency, ultracapacitors should provide most of dynamic load current.



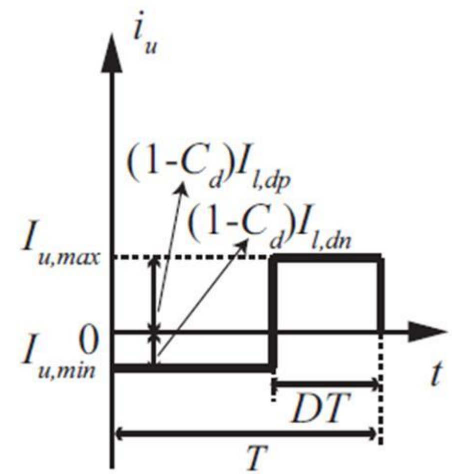
$$E_{loss} = -I_{l,dp}I_{l,dn}(R_b^* + R_{d,r}^* + R_u^*)\left(C_d - \frac{1}{1+K}\right)^2 T - I_{l,dp}I_{l,dn}R_p^* T + I_{l,a}^2(R_b^* + R_{d,r}^*)T + I_{l,a}V_F T,$$

e.g. K=128 and thus Cd*=0.008

$$K = \frac{R_b^* + R_{d,r}^*}{R_u^*},$$



Current from DC-DC converter.

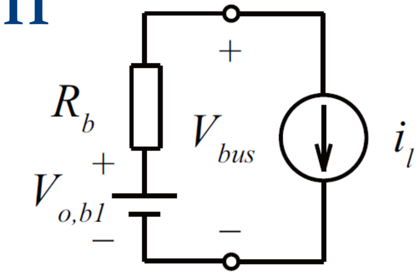


Current from ultracapacitor pack.

Efficiencies of Three Systems

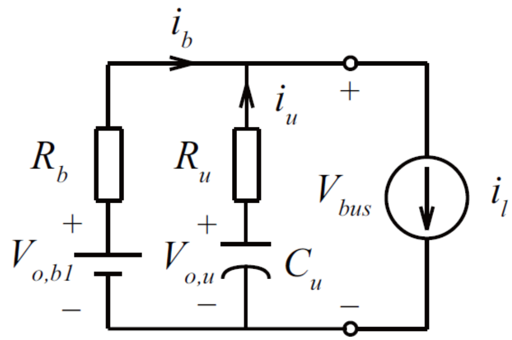
- Battery-only System

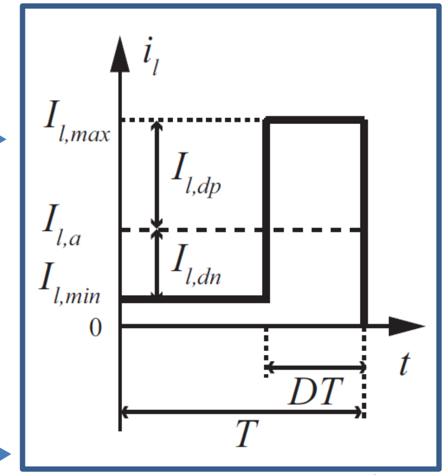
$$\eta_{bo} = 1 - \frac{I_{l,a}^2 R_b + I_{l,dp} I_{l,dn} R_b}{V_{o,b1} I_{l,a}}$$



- Passive HESS

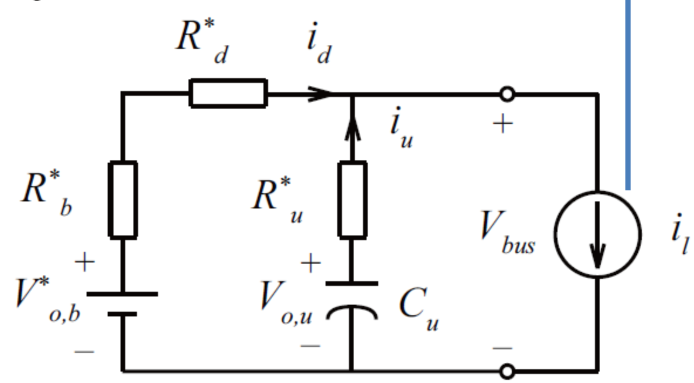
$$\eta_{ps} = 1 - \frac{I_{l,a}^2 R_b + I_{l,dp} I_{l,dn} R_p^*}{V_{o,b1} I_{l,a}}$$





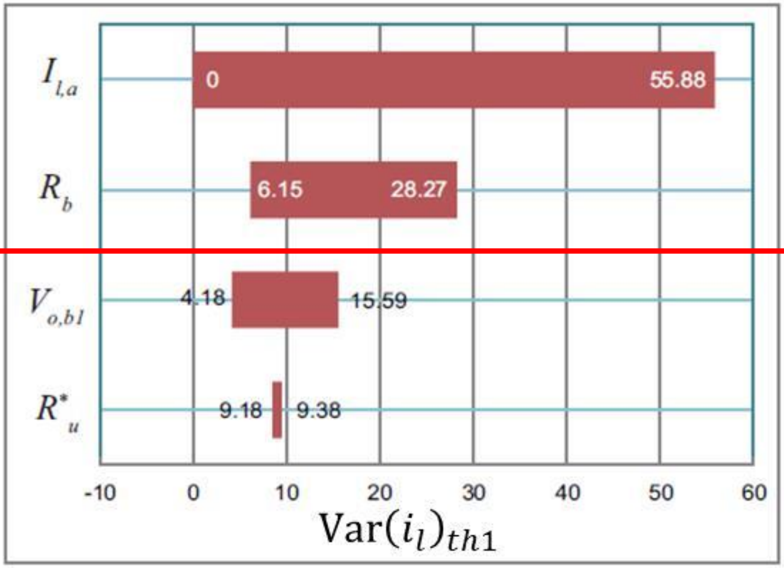
- Battery Semi-active HESS

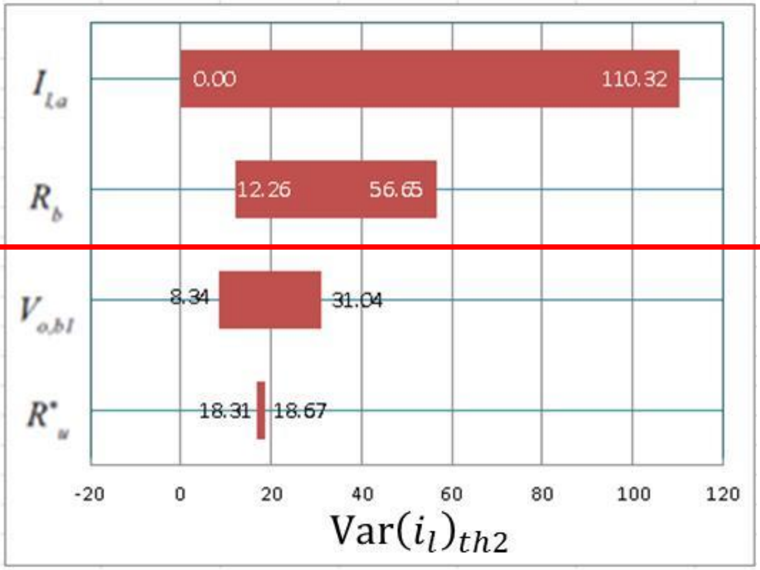
$$\eta_{bs} = 1 - \frac{I_{l,a}^2 (R_b^* + R_d^*) + I_{l,dp} I_{l,dn} R_u^*}{V_{o,u} I_{l,a} + I_{l,a}^2 (R_b^* + R_d^*)}$$



Thresholds and Sensitivity Analysis

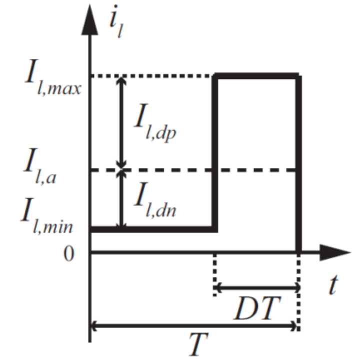
- Thresholds of the variance of the load current can be accurately derived:
  - $\mathrm{Var}(i_l)_{th1}: \eta_{bs} > \eta_{bo}$
  - $\mathrm{Var}(i_l)_{th2}: \eta_{bs} > \eta_{ps}$
- Tornado diagrams for the two thresholds

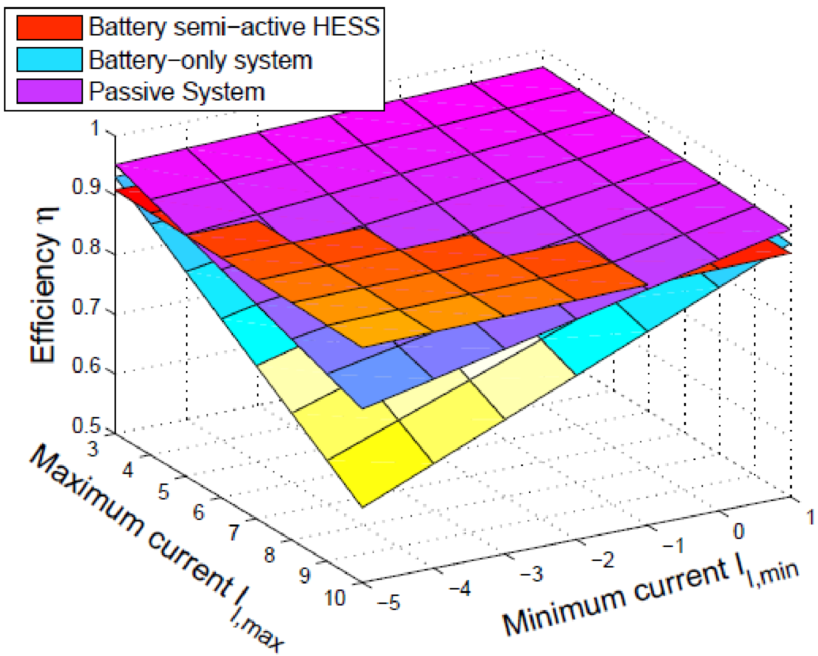


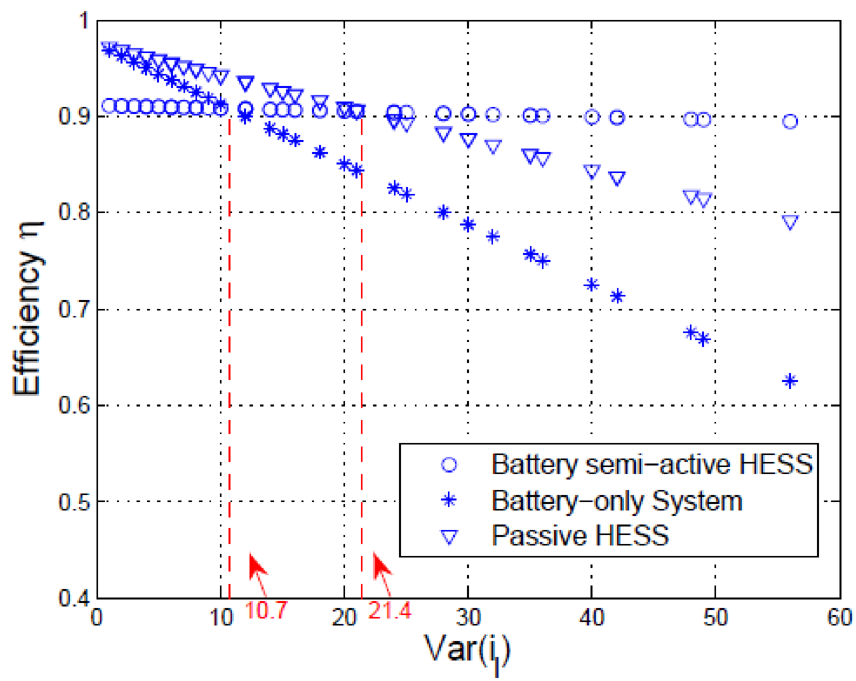


Examples: Ideal pulsed load profile

- $SOC_{bat} = 50\%$, $I_{l,a} = 2A$
- The two thresholds, 10.7 and 21.4, well match the calculation results.

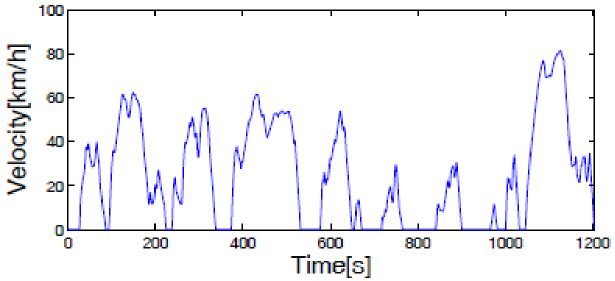


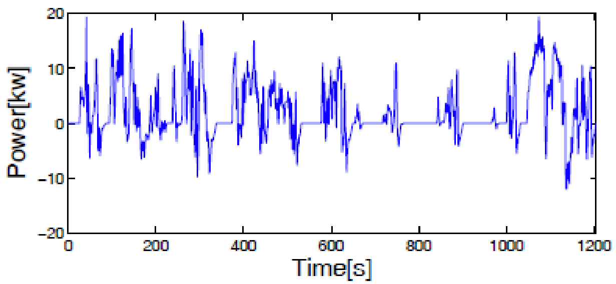




Examples: JCo8 driving cycle

Results under JC08 load	$E_{loss,b}$[J]	$E_{loss,d}$[J]	$E_{loss,u}$[J]	η[%]
Battery-only system	844.95	N/A	N/A	93.1
Passive HESS	188.39	N/A	115.01	97.2
Battery semi-active HESS	165.03	**347.02**	120.87	94.8



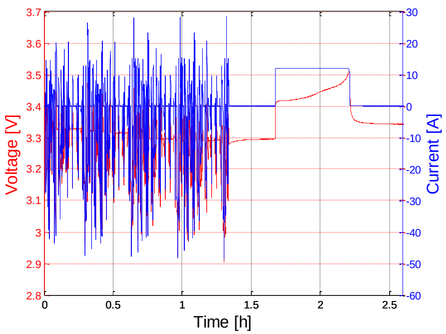


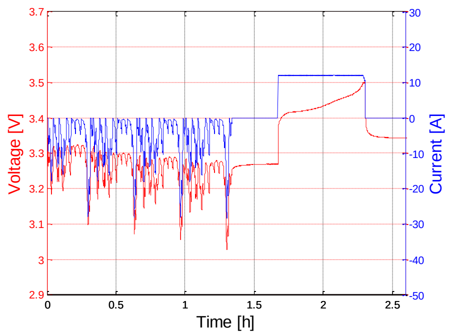
- $\eta_{bs} < \eta_{ps}$
  - $\mathrm{Var}(i_l)(=2.29) > \mathrm{Var}(i_l)_{th1}(=1.11)$
  - $\mathrm{Var}(i_l)(=2.29) < \mathrm{Var}(i_l)_{th2}(=15.53)$
- The efficiency of the battery-ultracapacitor HESS is significantly influenced by the efficiency of DC-DC converter in addition to the added space and weight.

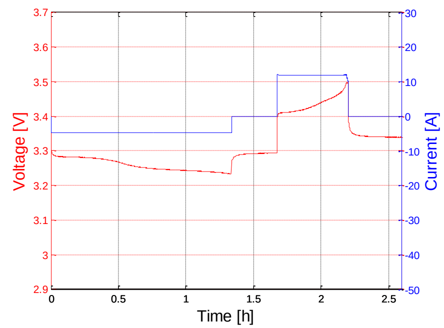
Battery Ageing Test

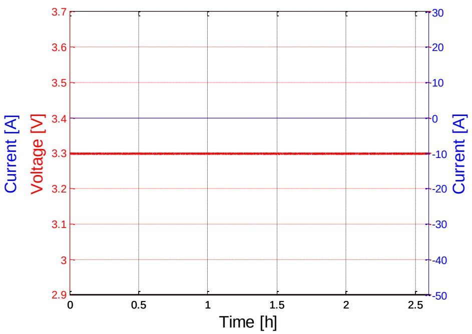
Temperature: 45 deg.

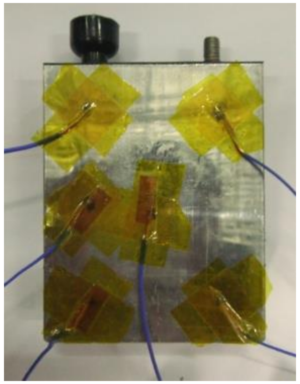
Dynamic Discharging	Mod. Constant Discharging	Constant Discharging	Calendar Life

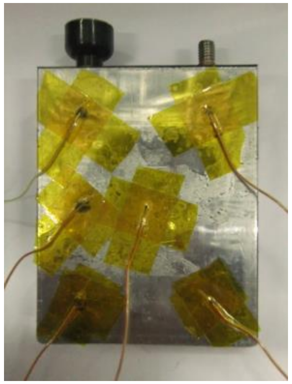


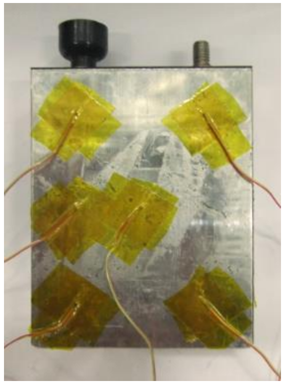


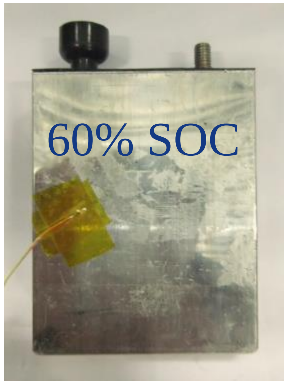






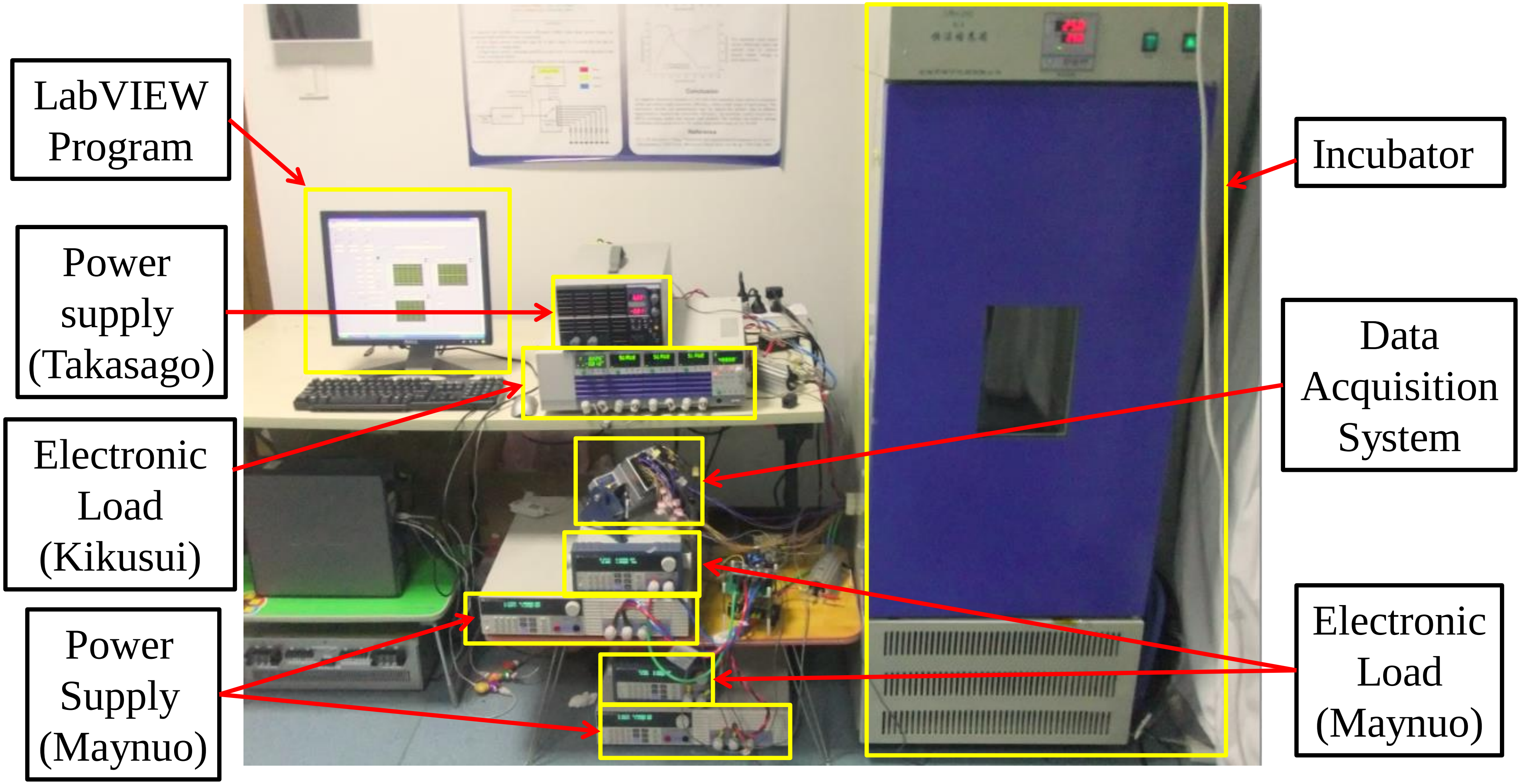






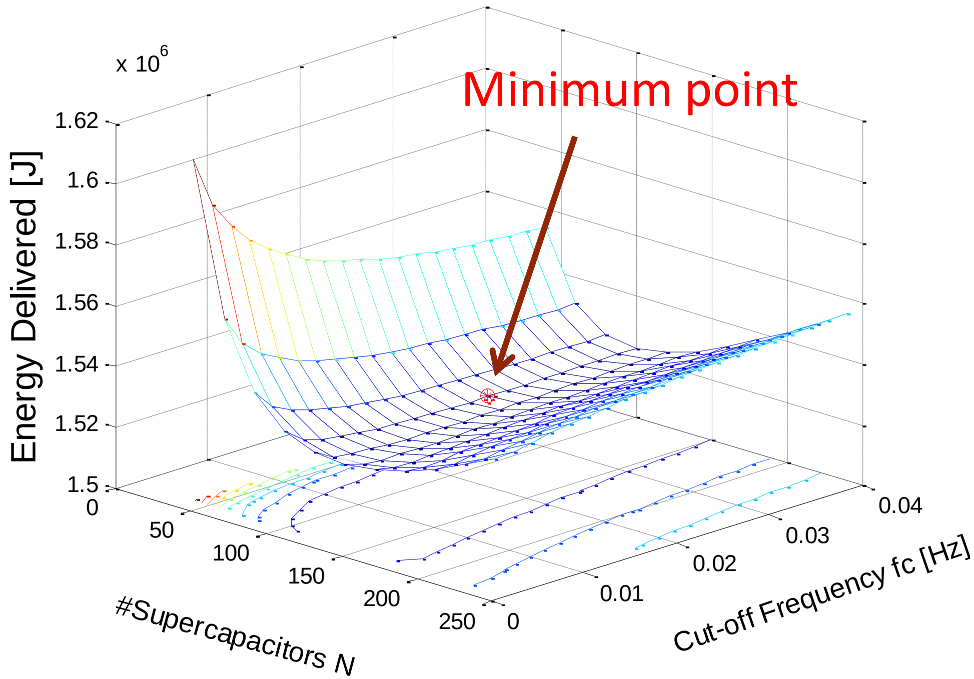
No.1 Cell | No.2 Cell | No.3 Cell | No.4 Cell

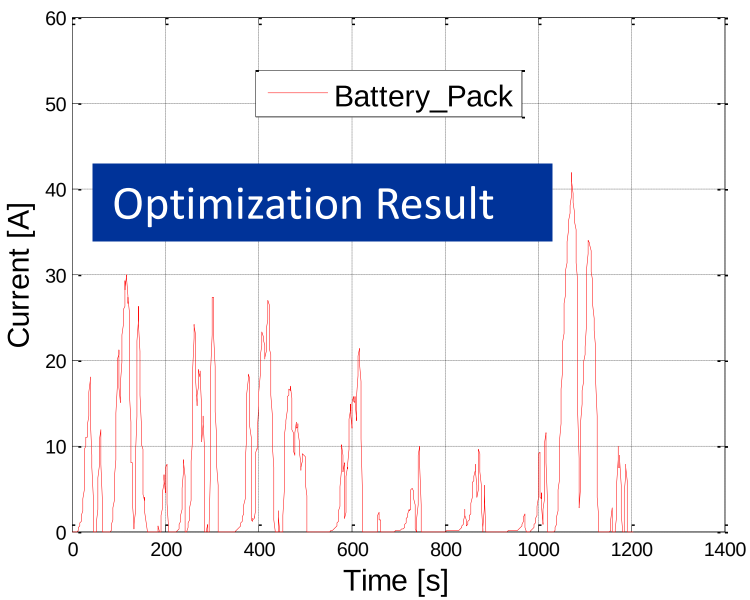
Experiment Setup



Optimized Sizing under JC08 Cycle

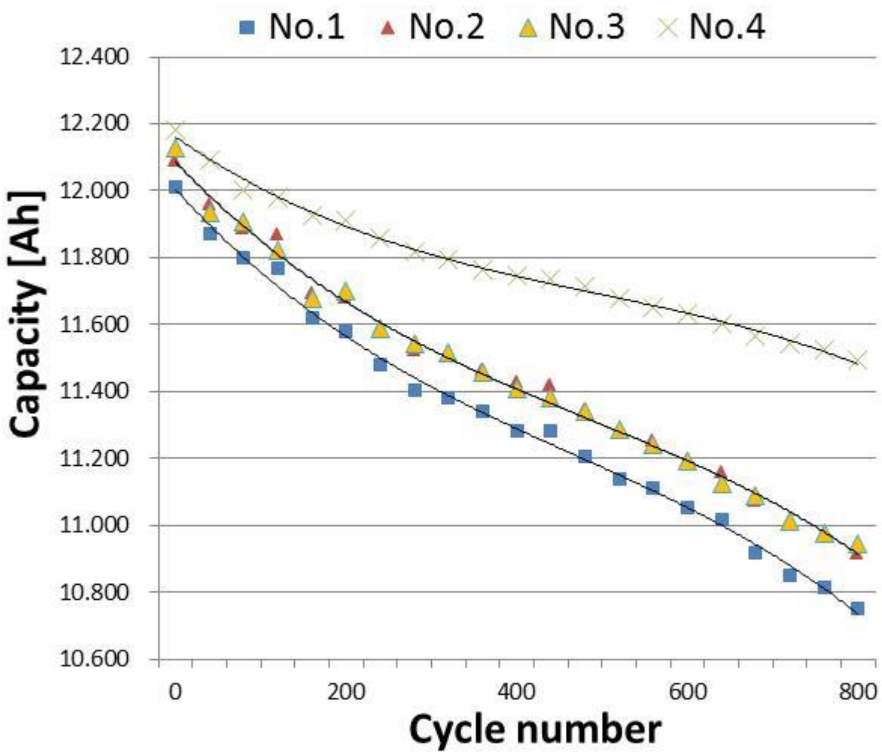
- Two control parameters for the No. 2 cell:
  - number of ultracapacitor cells
  - cut-off frequency for the current distribution





800-Cycle Capacity Test (4A discharge)

- Initial tendency can be observed, but more cycles are needed to further show the variation.



- **No. 1: Dynamic discharging**
- **No. 2: Modified constant current discharging**
- **No. 3: Constant current discharging**
- **No. 4: Calendar life**

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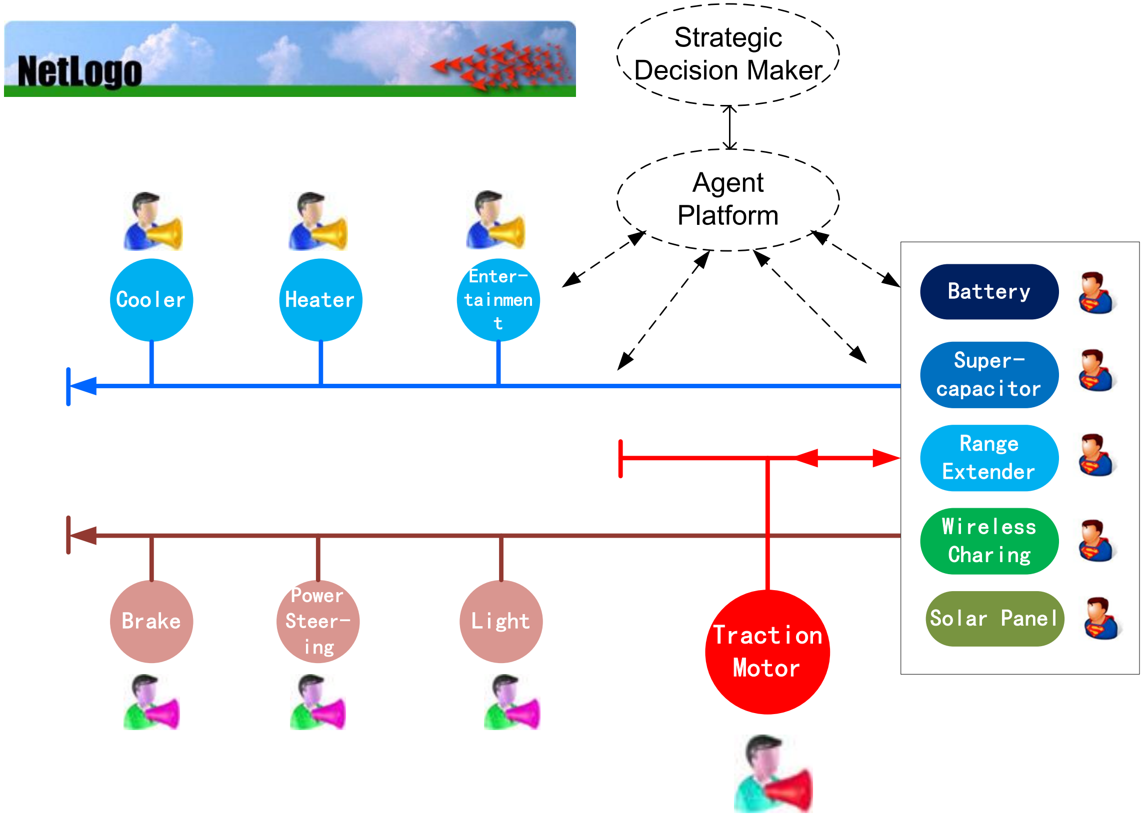
[6] H. Yin, C. Zhao, M. Li, C. Ma: "Utility Function-Based Real-Time Control of A Battery-Ultracapacitor Hybrid Energy System", IEEE Transactions on Industrial Informatics, accepted on Nov. 13th, 2014.

[7] H. Yin, C. Zhao, M. Li, C. Ma: "Control of A Generator-Battery-Ultracapacitor Hybrid Energy System Using Game Theory", the 40th Annual Conference of the IEEE Industrial Electronics Society, Oc. 29-Nov. 2, 2014, Dallas, TX, USA.

Networked Energy Systems

- Flexibility, Fault-tolerance, Scalability, Reliability
- "Plug & Play" in a dynamic environment.

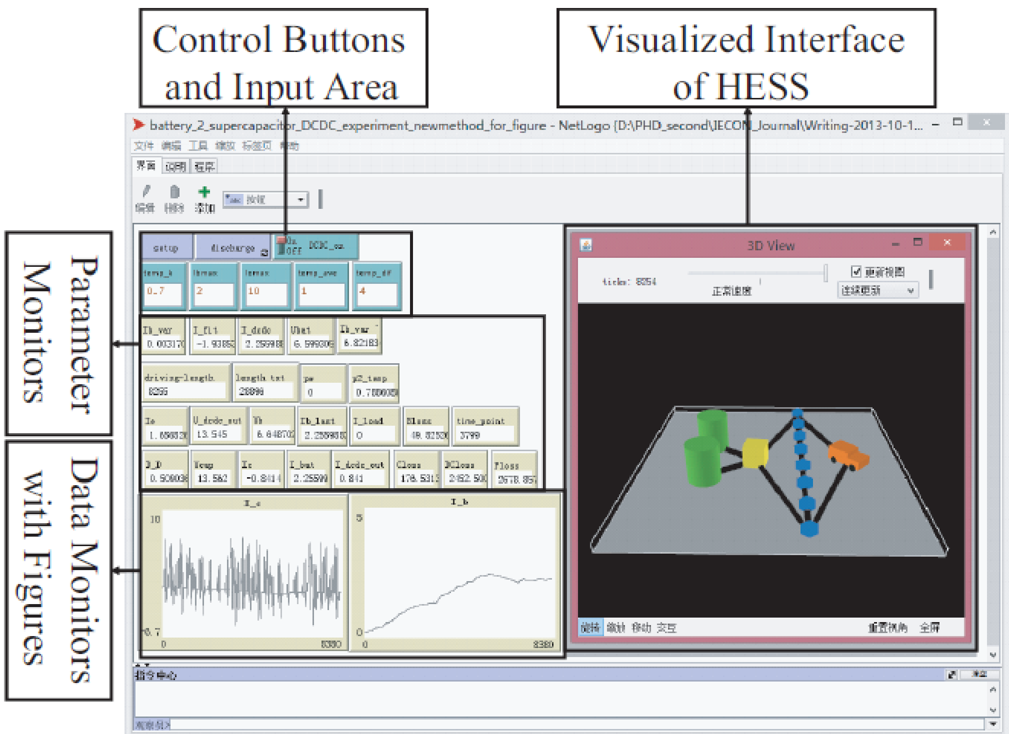


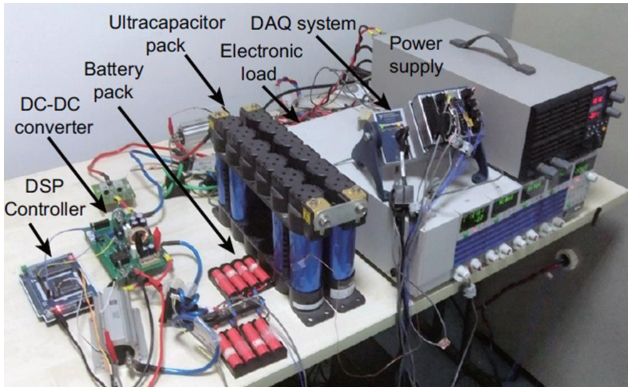
Multi-agent Interaction Modeling (NetLogo)

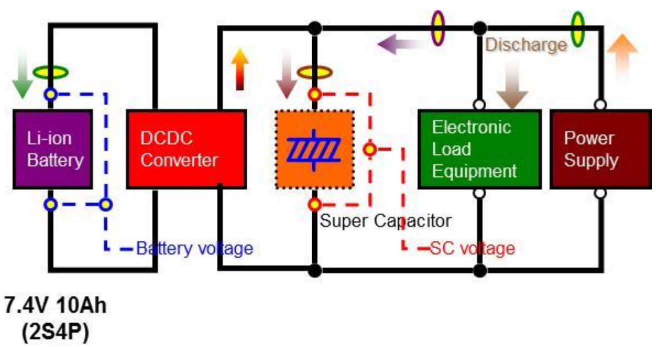
Strategic Interaction Analysis (Game Theory)

Agent-based Modeling

- NetLogo simulation environment: world-widely used for modeling complex systems developing over time.
- The battery-ultracapacitor HESS is used as a simple example.







Utility Function-based Optimization

Sensitive

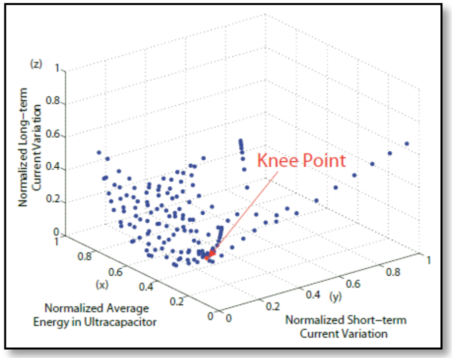
Battery Bank
(**Cycle life**)

$$u_{bat} = u_{life} = w_{ave}u_{ave} + w_{dif}u_{dif}$$
$$u_{ave} = 1 - a(I_{bat} - I_{ave})^2$$
$$u_{dif} = 1 - b(I_{bat} - I_{lbat})^2$$

Robust

Ultracapacitor Bank
(**HESS Performance**)

$$u_{cap} = w_e u_e = w_e[1 - c(I_{cap} - I_{fit})^2]$$
$$c = (I_{cmax} - I_{fit})^{-2}$$
$$I_{fit} = \left(2\frac{U_{cap}^2 - U_{emp}^2}{U_{cmax}^2 - U_{emp}^2} - 1\right)I_{cmax}$$



$$\begin{aligned} OBJ: f_{min(x_1,x_2)} = & -w_{ave}[1 - a(x_1 - I_{ave})^2] \\ & -w_{dif}[1 - b(x_1 - I_{lbat})^2] \\ & -w_e[1 - c(x_2 - I_{fit})^2] \\ S.T.: x_2 + x_1(1-D) - I_{load} &= 0 \\ -x_1 &\le 0 \\ x_1 - 10 &\le 0 \\ -x_2 - 20 &\le 0 \\ x_2 - 20 &\le 0 \\ w_{ave} + w_{dif} + w_e &= 1 \\ 0 \le w_{ave}, w_{dif}, w_e &\le 1 \end{aligned}$$

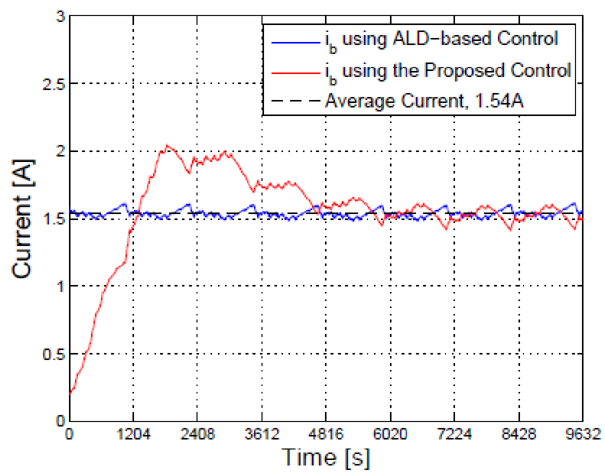
1. The Pareto set is used to determine the weights.
2. The global optimal solution is found by using Karush–Kuhn–Tucker (KKT) conditions.
3. Fast enough for realtime implementation

Results under JC08 Cycle

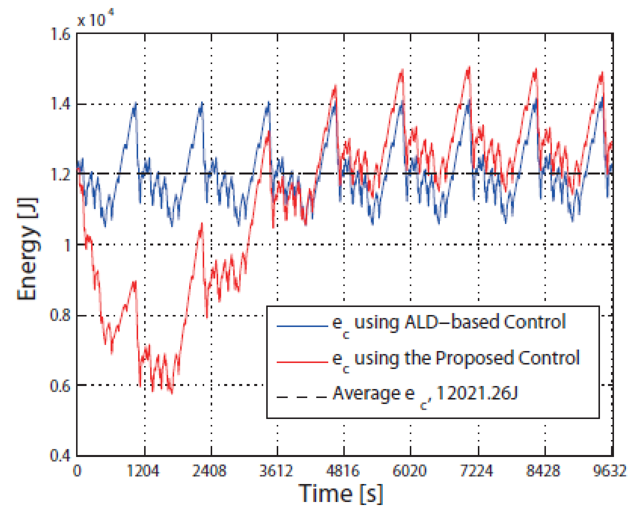
- Comparable performance with the average load demand (ALD) –base control, but need no exact pre-knowledge of the test cycle.

TABLE I
COMPARISON OF SIMULATION RESULTS

Control	$I_{b,ave}$ (A)	$I_{b,rms}$ $(10^{-4}$A)	$E_{c,ave}$ (J)
ALD-based	1.54	1.46	12021.26
Utility fun.-based	1.55	3.52	11270.79



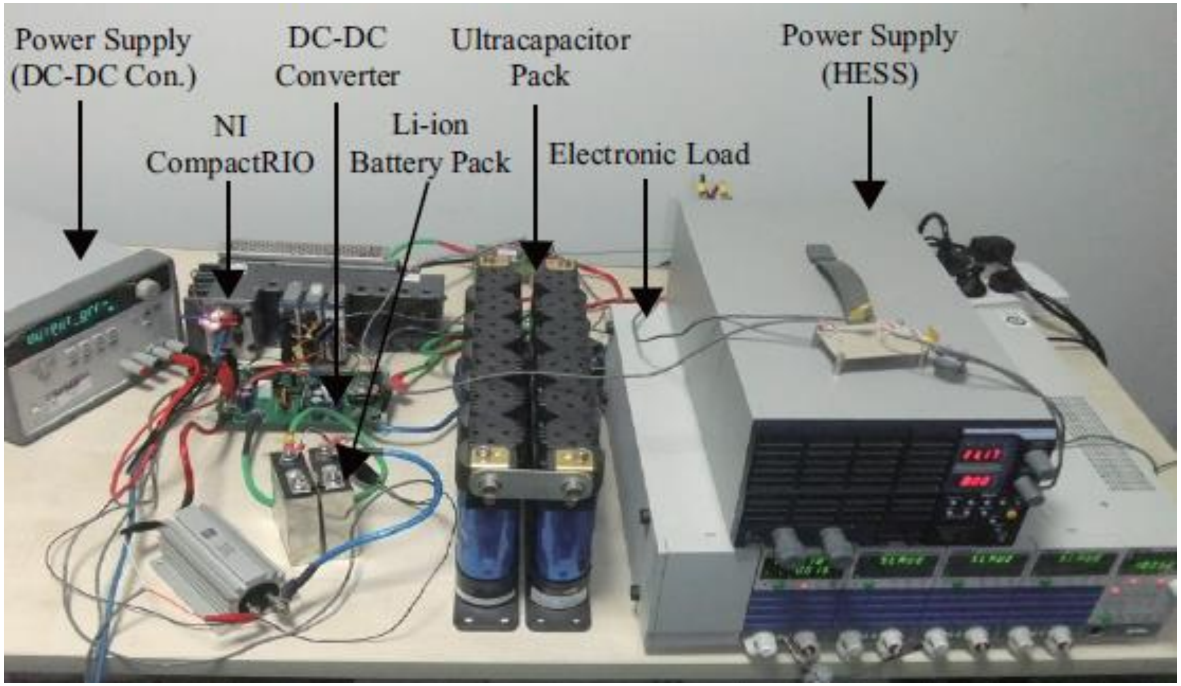
(a)

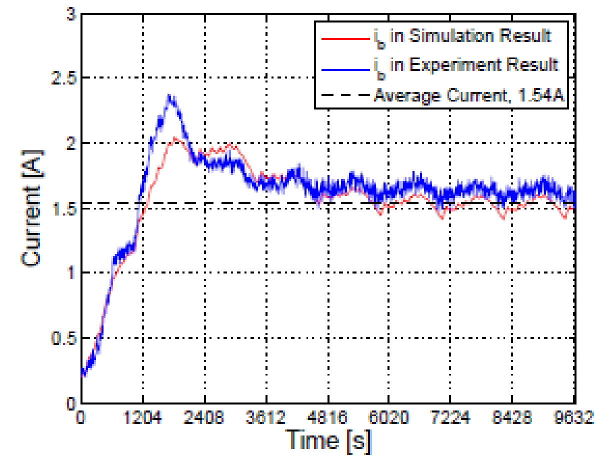


(b)

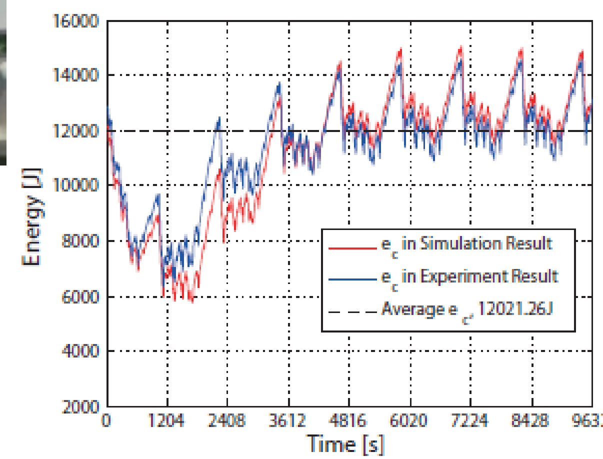
Responses in eight test cycles. (a) Currents of the battery pack. (b) Energy stored in the ultracapacitor pack.

Experimental HESS





(a)

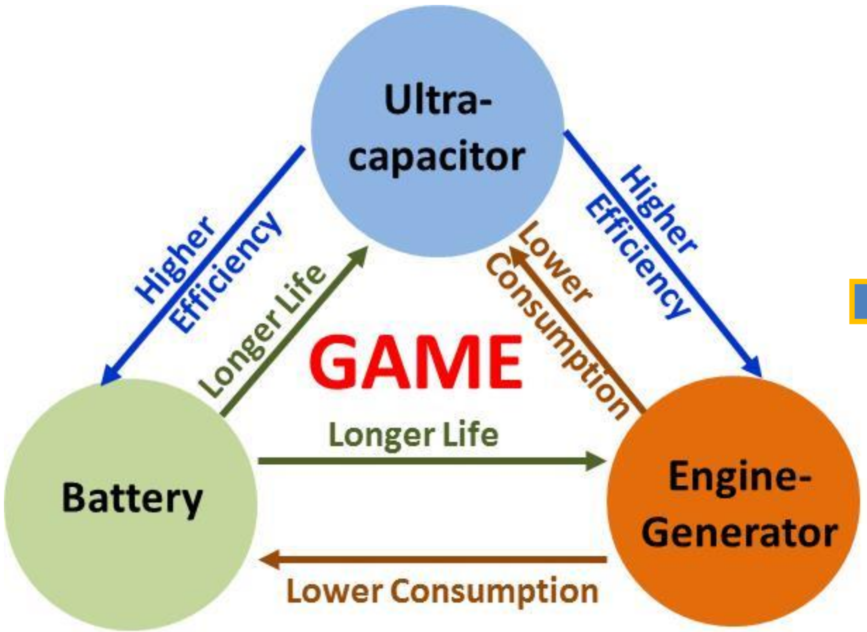


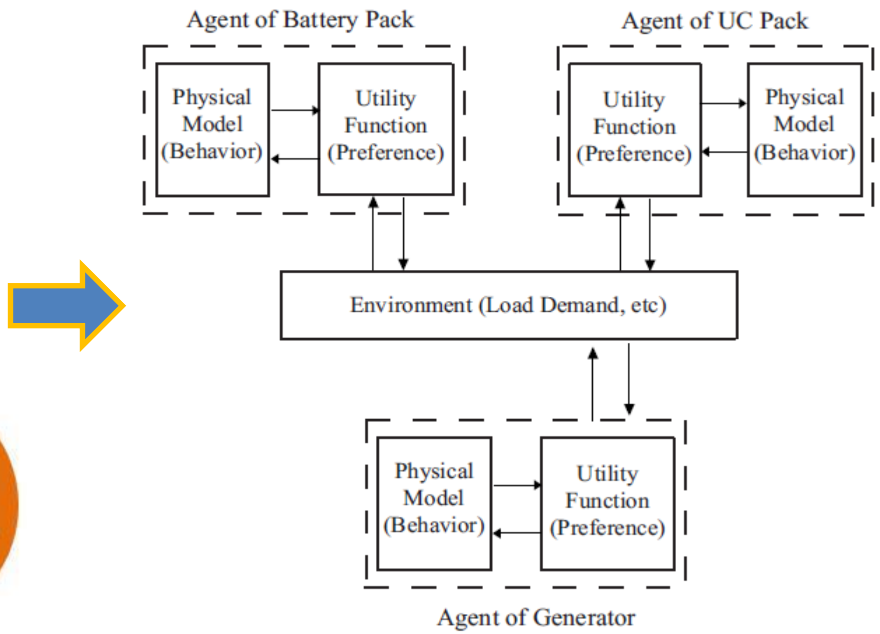
(b)

NOTE: The experimental results match the simulation results closely. This proves the correctness of the realtime implementation of the proposed control.

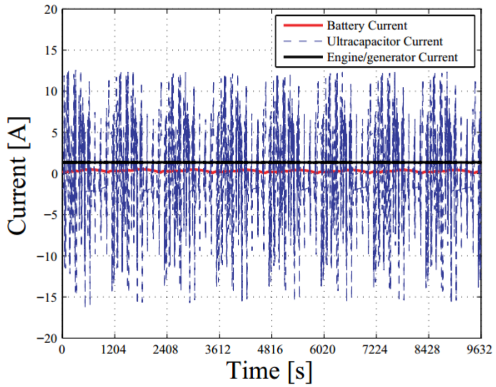
Non-Cooperative Current Control Game

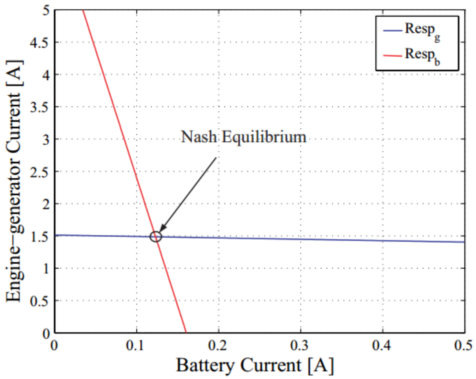
- Three energy devices act as agents to play a game
  - Battery "intends" to prolong its **cycle life**;
  - Engine-generator "prefers" a low **fuel consumption**.
  - Ultracapacitor "works" to improve the **system performance**;
- Ultracapacitor is an assistive energy storage device.
- Two degree-of-freedoms: battery and generator

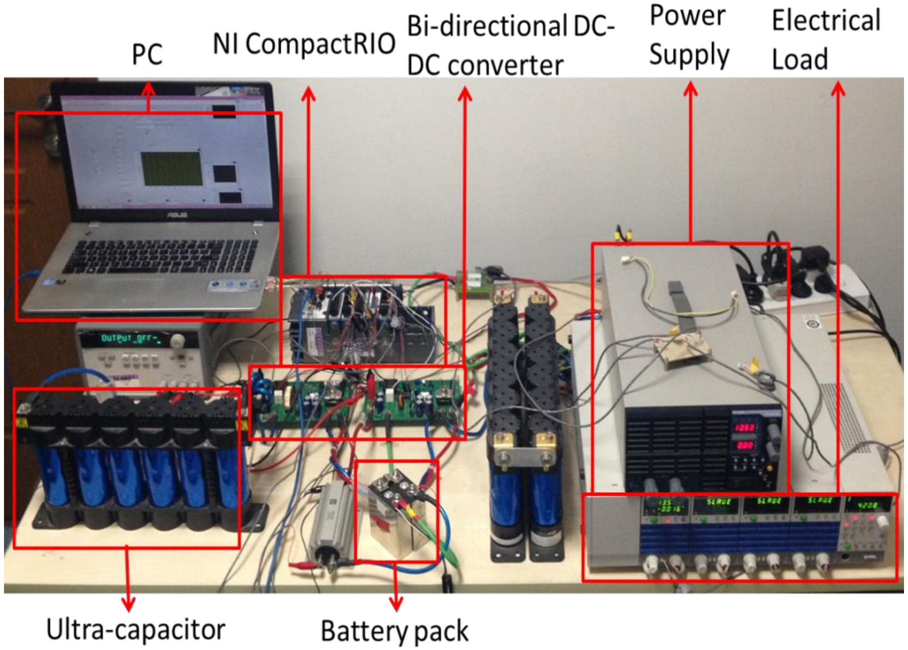




Preliminary Simulation Result







- Balanced Solution among three agents
  - Nash Equilibrium
  - Battery current
    - ✓ Smooth and stable
  - Ultracapacitor current
    - ✓ Dynamic (Energy buffer)
  - Generator current
    - ✓ Almost constant
    - ✓ Fixed engine working point
- Comparable performance with ALD-based control, but again does not need pre-knowledge of the test cycle.

TABLE II
PARAMETERS IN SIMULATION RESULTS

Control Method	$I_{b,ave}$	$I_{b,rms}$	E_{cap}	C_{fuel}
(Battery is not empty)				
Game-Theory-based	0.31 A	0.0453 A	15047.4 J	248.7 g/kwh
ALD-based	0.36 A	0.0003 A	15895.7 J	247.9 g/kwh
(Battery is empty)				
Game-Theory-based	- 1.16 A	0.0450 A	17795.9 J	321.2 g/kwh
ALD-based	-1.25 A	0.0097 A	13797.2 J	322.4 g/kwh

Outline

- Overview
- Motion Control
- Hybrid Energy System
- Wireless Power Transfer
- Conclusions

Battery-Free Mobile Energy System

- With future ubiquitous wireless charging facilities, mobile systems such as electric vehicles may only need to store a reasonable amount of electrical energy for a relatively short period of time.

- Ultracapacitors are suitable for storing and releasing large amounts of electrical energy quickly.

  1) Work electrostatically without reversible chemical reactions involved

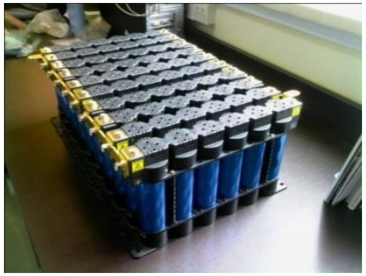
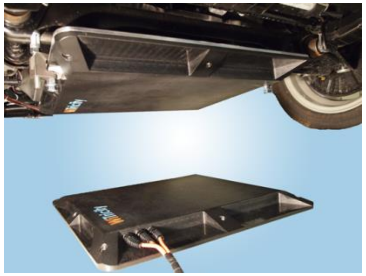
  2) Theoretically unlimited cycle life (can be cycled millions of time)

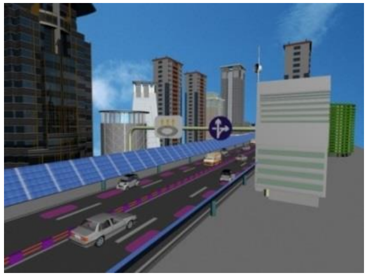
  3) FAST and HIGH EFFICIENT charge/discharge due to small internal resistance (97-98% efficiency is typical)

  4) PRECISE State Of Charge (SOC) measurement (energy stored in capacitors is proportional with the square of charge voltage)

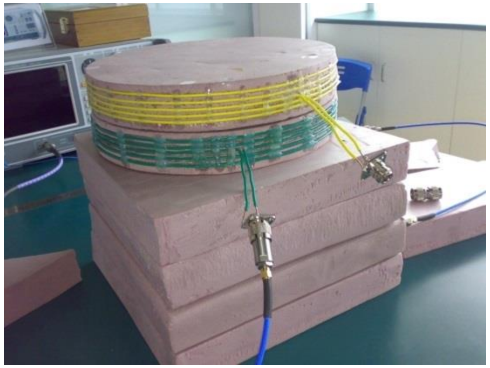
  5) A typical operating temperature range of -40 to +70◦C and small leakage current

  6) Environmentally friendly without using heavy mental for its structure material.

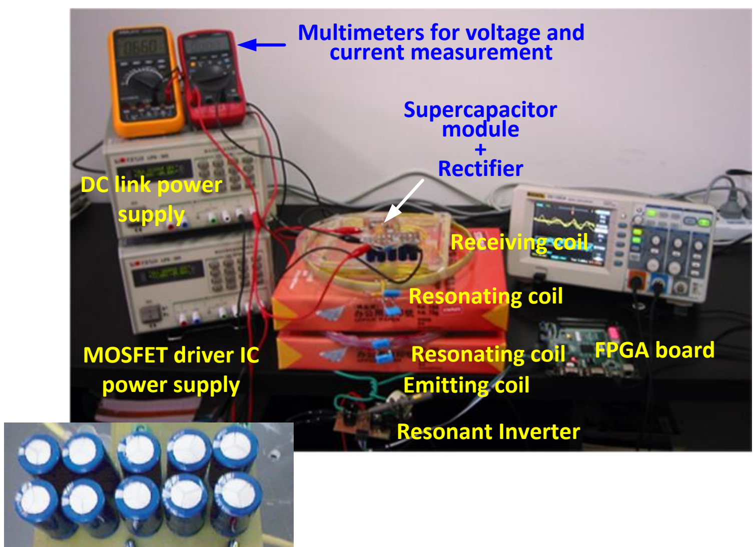



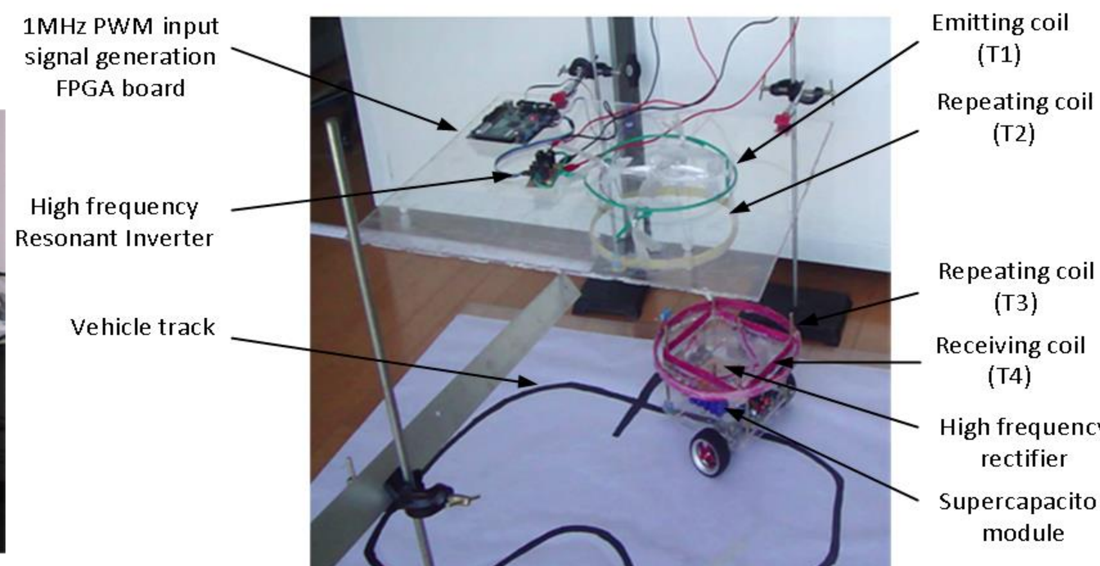


Initial Efforts Starting from 2010



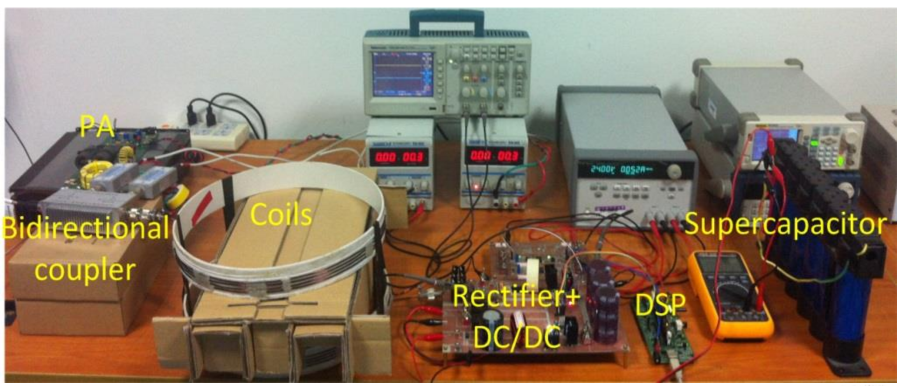
Gap (cm)	5.6	10.1	14.8	19.3	24.1	28
Efficiency (%)	88.84	93.32	**93.69**	92.53	88.07	70.04
F_m (MHz)	13.59	14.74	15.27	15.71	16.11	16.08
F_e (MHz)	19.87	17.85	17.01	16.51	16.11	16.08

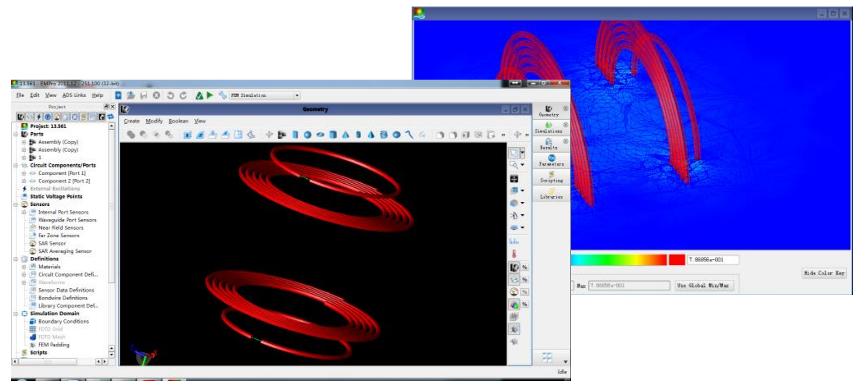


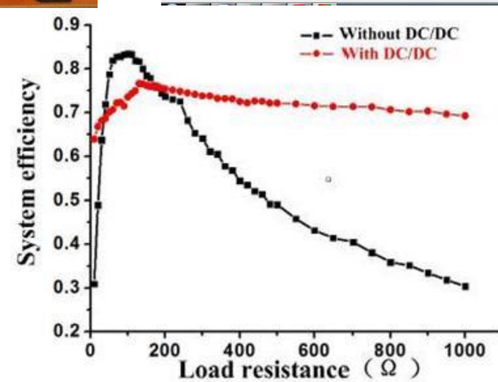


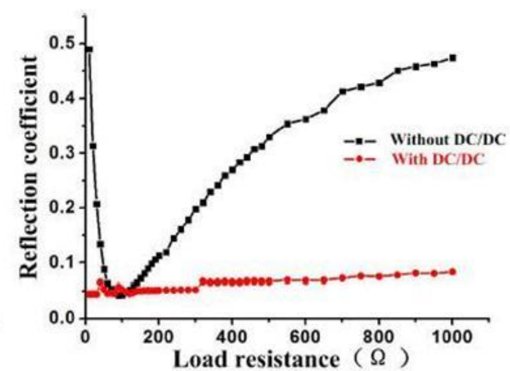
A System-level Optimization/Control

- 13.56MHz Wireless Power Transfer System (< 40 watts, 70%)
  - Optimal load tracking for high efficiency
  - Implementation using cascaded boost-buck converter
  - Optimal power distribution in multi-receiver systems





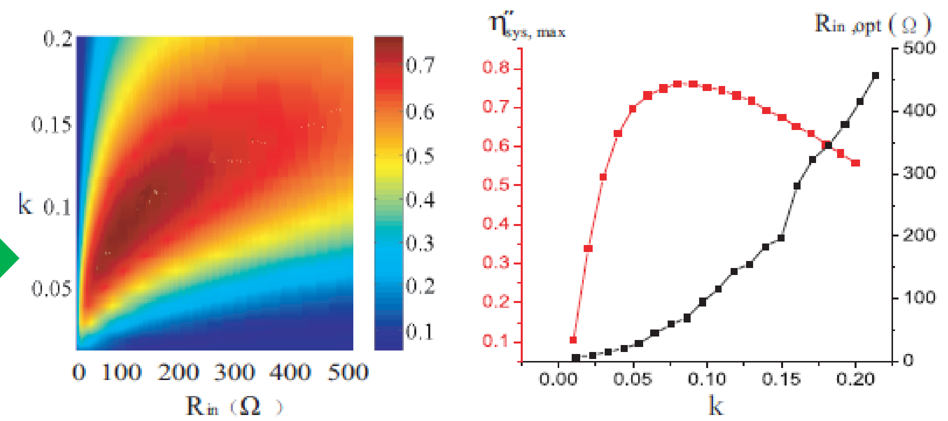


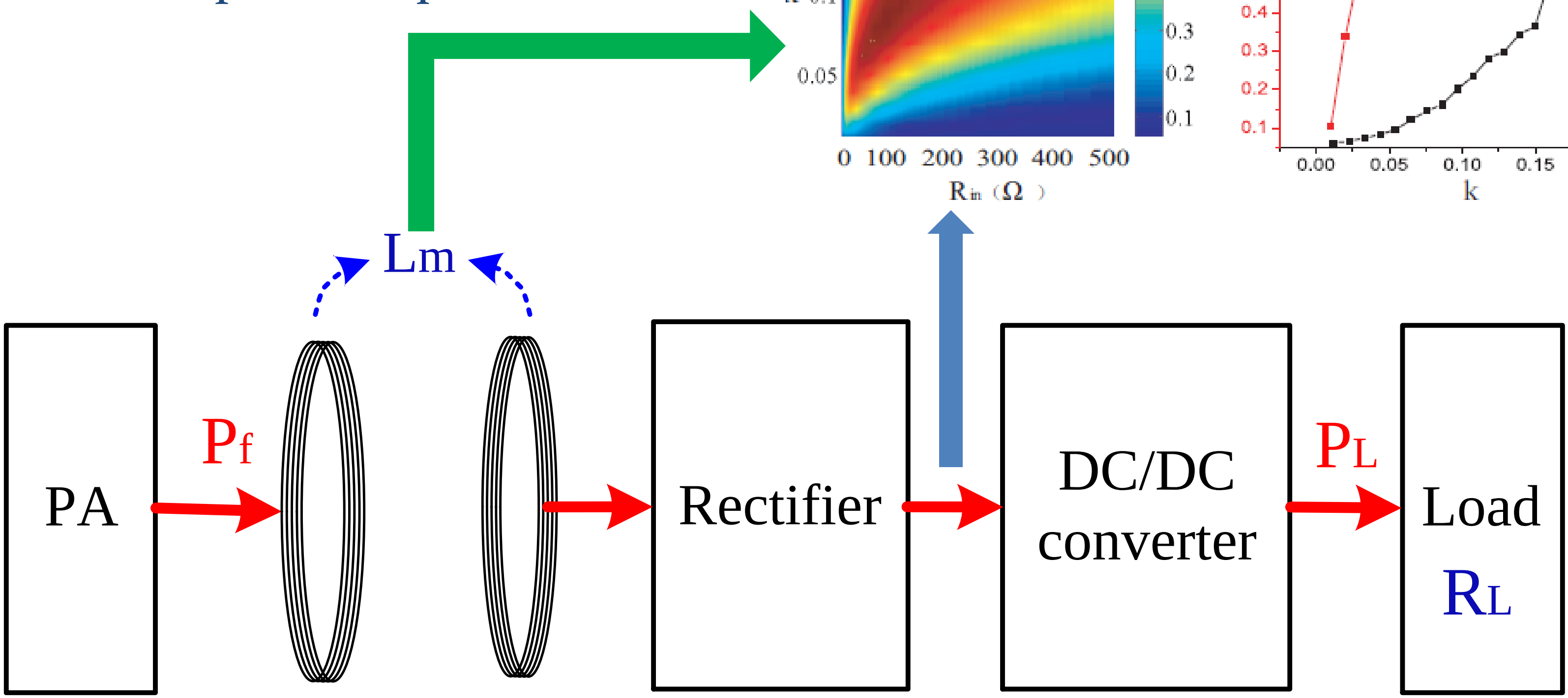


Optimal Load in WPT systems (1)

- Maximize P_L/P_f.
- Each L_m corresponds an optimal load , R_{in}, seen by rectifier.
- Use boost-buck DC/DC converter to provide an optimal equivalent load.

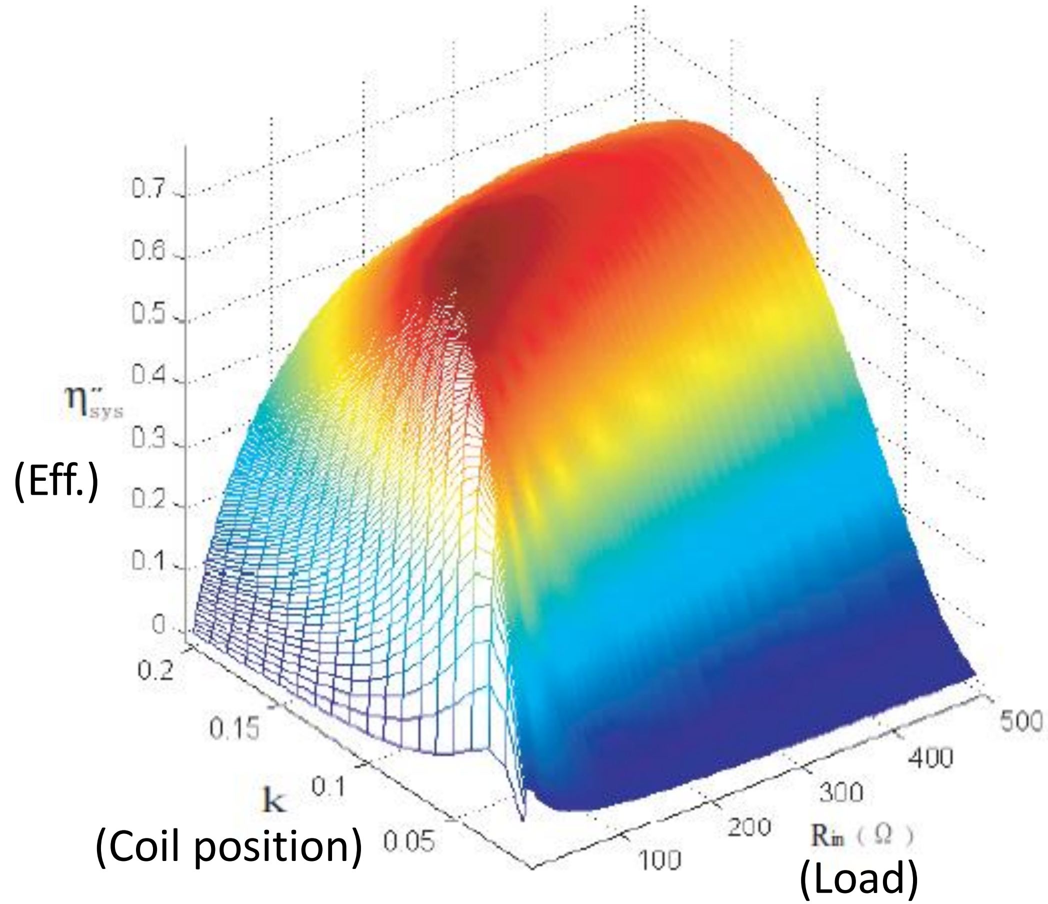
Optimal loads



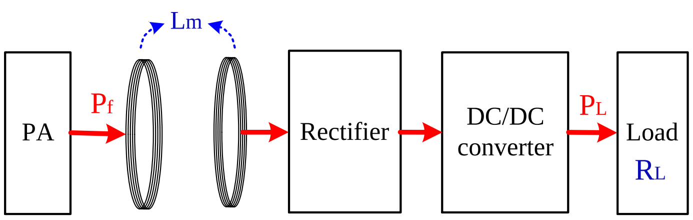


Optimal Load in WPT systems (2)

- A 3-D view



- k is determined by a specific relative coil position.
- Rin can be adjusted by adding a tuning circuit between rectifier and the final load.

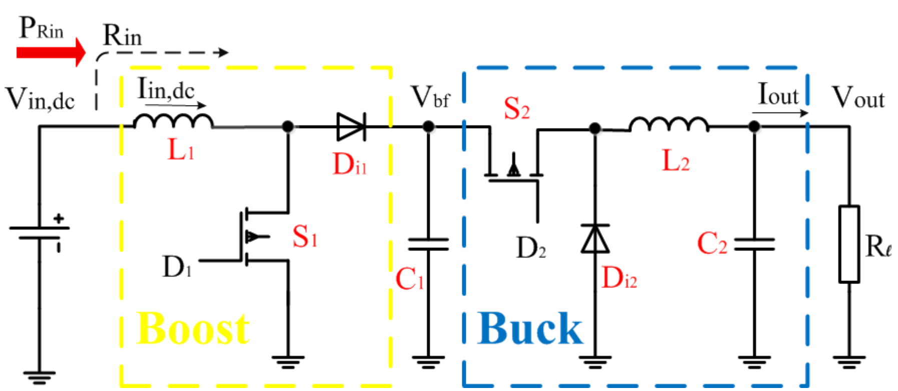


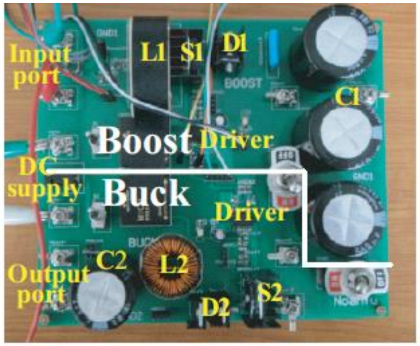
Cascaded Boost-buck Converter

- The cascaded connection provides a general solution to match R_{in} to any specific value from 0 Ω to +∞.

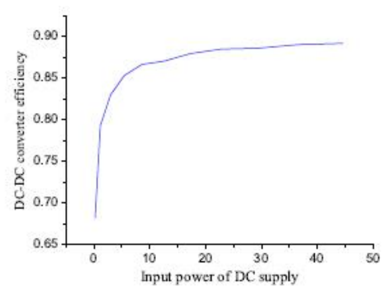
COMPARISON OF THE BASIC DC-DC CONVERTERS

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)

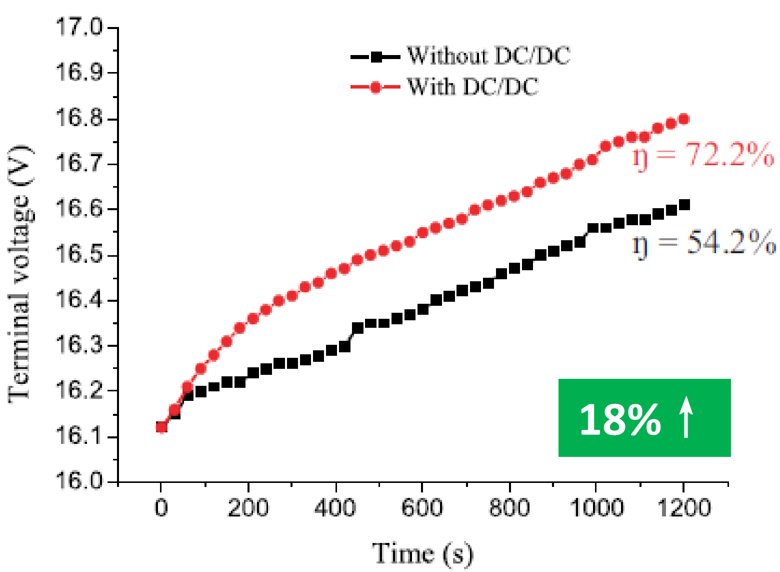


(b)

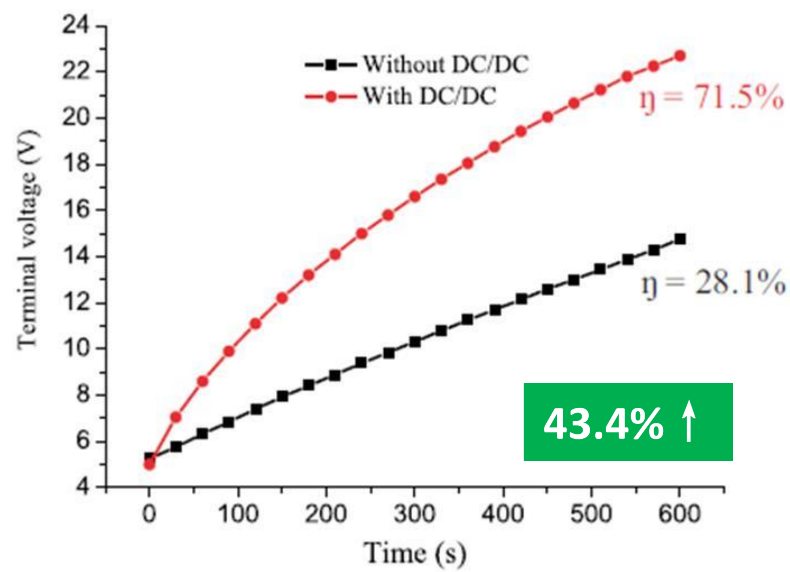
Cascade boost-buck converter.
(a) Circuit board. (b) Efficiency.

13.56MHz Charging of Ultracapacitors

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



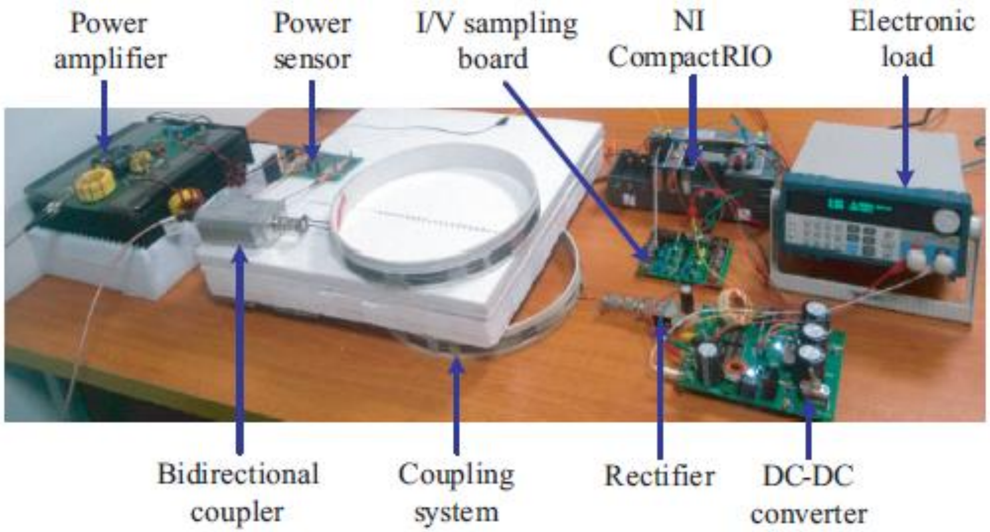
Batteries charging improvement using the cascaded boost-buck DC-DC converter.

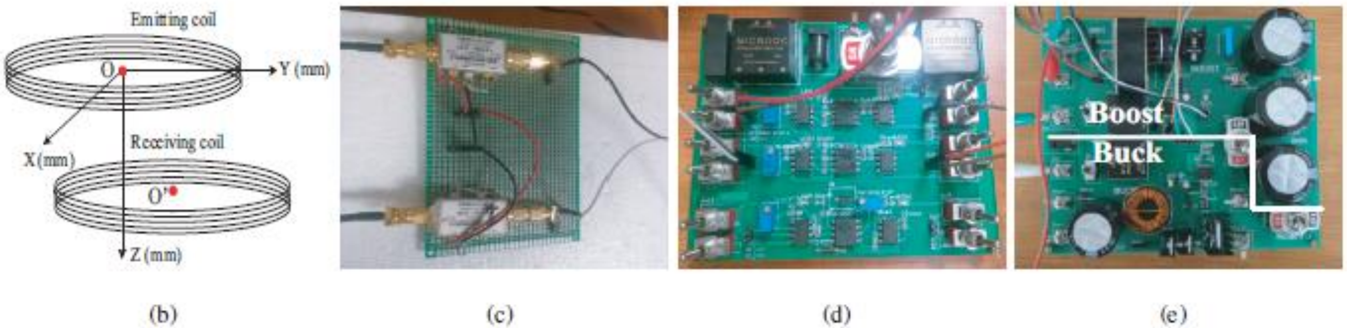


Ultracapacitors charging improvement using the cascaded boost-buck DC-DC converter.

[8] 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

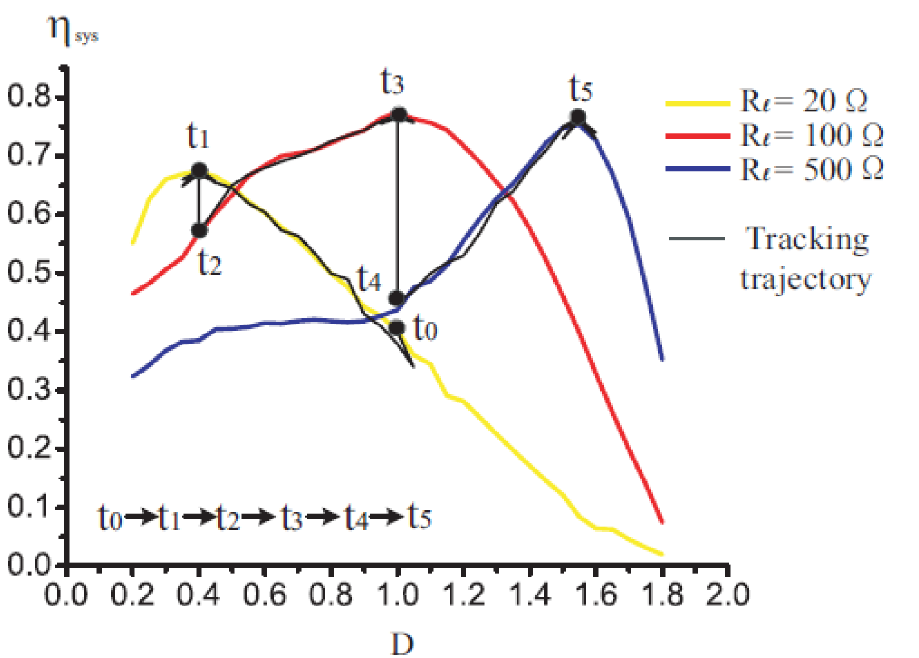


Fig. 1 Tracking of optimal load resistances with a varying R_l.

A varying coil position

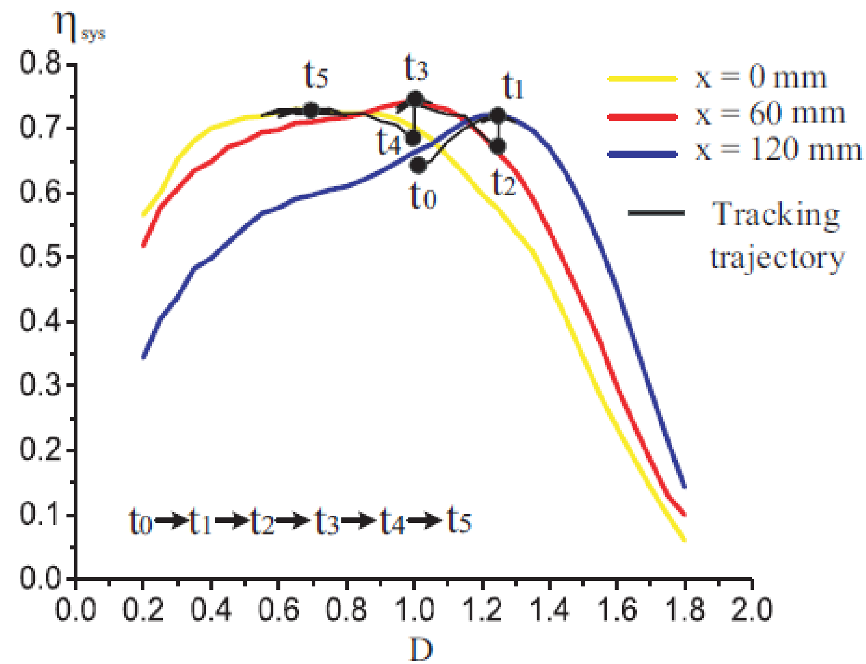
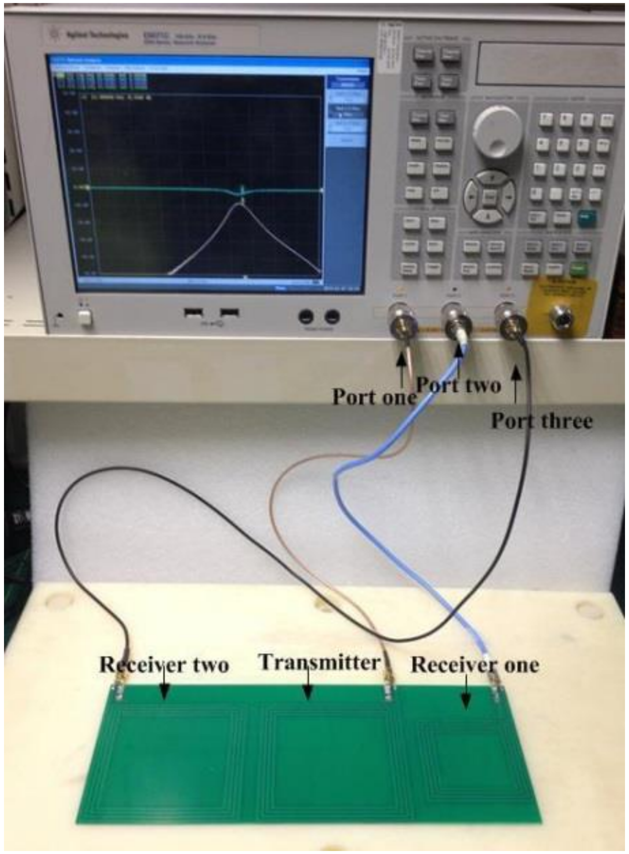
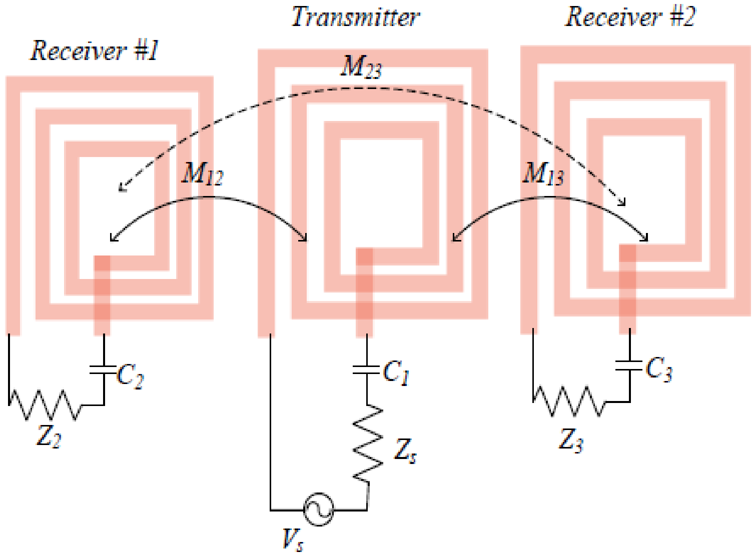


Fig. 2 Tracking of optimal load resistances with a varying k.

[9] 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)

Optimum Load for Multiple Receivers





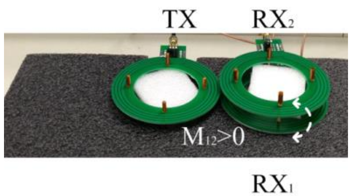
$$Z_{inopt} : Z_{2opt} : Z_{3opt} = R_1 : R_2 : R_3$$

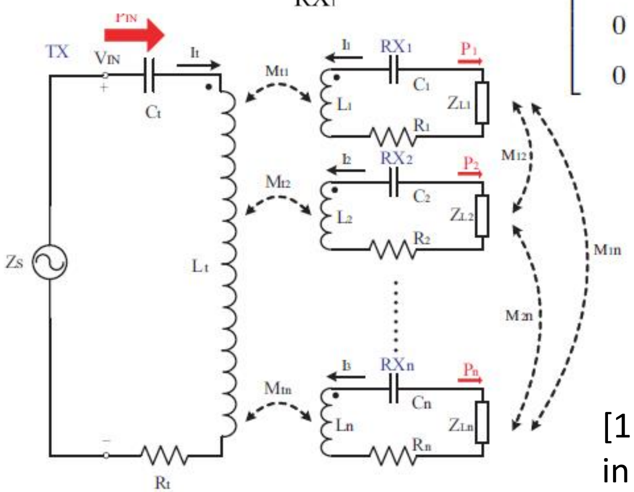
[10] T. Zhang, M. Fu, X. Zhu, C. Ma: "Optimal Load Analysis for a Two-Receiver Wireless Power Transfer System", IEEE Wireless Power Transfer Conference, May 8-9, 2014, Jeju Island, Korea.

Optimal power distribution using game theory (actually a wireless networked energy system)?

Compensation of Cross Coupling

- For zero cross coupling, the maximum efficiency occurs when the loads are all pure resistive.
- Assume the maximum efficiencies for the cases of zero cross coupling and non-zero cross coupling are identical.





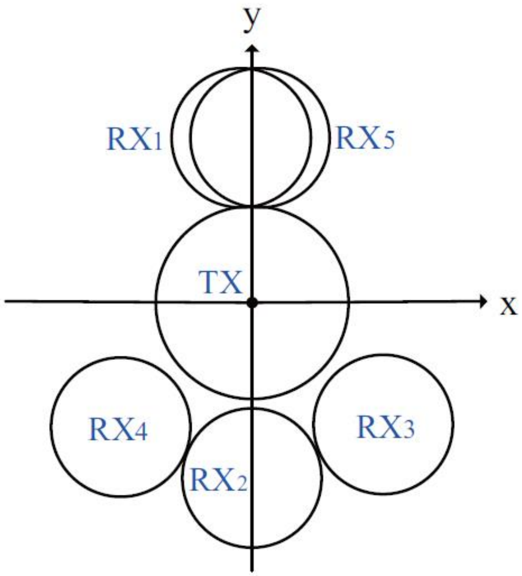
$$\begin{bmatrix} V_{IN} \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_t & j\omega M_{t1} & \cdots & j\omega M_{t(n-1)} & j\omega M_{tn} \\ j\omega M_{t1} & R_1+R_{L1}+jX_{L1} & \cdots & j\omega M_{1(n-1)} & j\omega M_{1n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ j\omega M_{t(n-1)}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

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

[11] M. Fu, T. Zhang, X, Zhu, P. C. K. Luk, C. Ma: “Compensation of Cross Coupling in Multiple-Receiver Wireless Power Transfer Systems”, (under review)

Numerical Validation

- A five-receiver system and four cases:
  1. Zero cross coupling and pure resistive loads
  2. Non-zero cross coupling and pure resistive loads
  3. Non-zero cross coupling and derived optimal load reactances
  4. Non-zero cross coupling and optimal load reactances found by the exhaustive searching



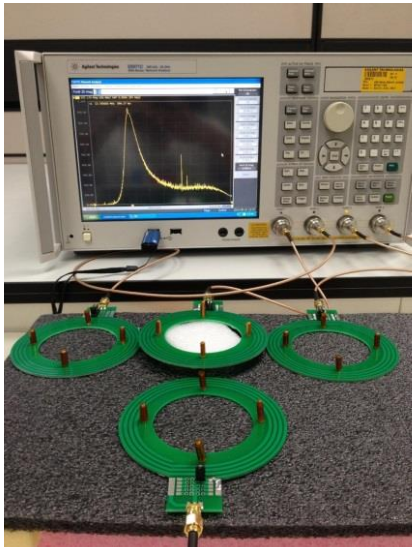
SYSTEM EFFICIENCIES IN CASES 1-4

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

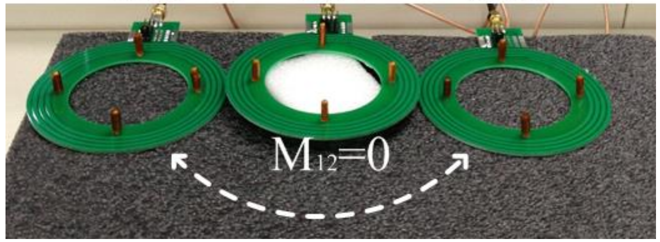
COMPARISON OF OPTIMAL LOAD REACTANCES

	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

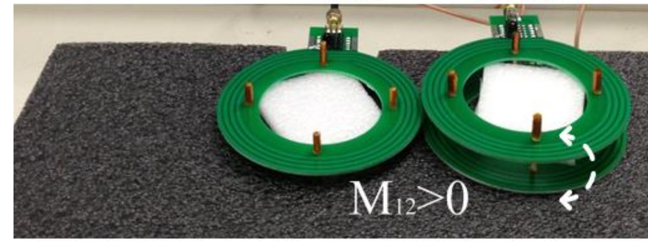
Experimental Results



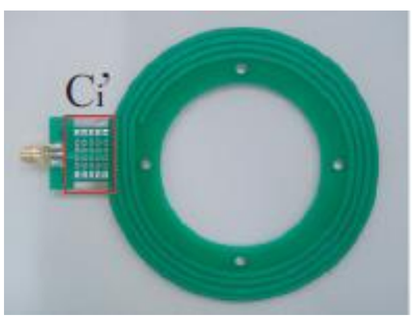
RX2 TX RX1

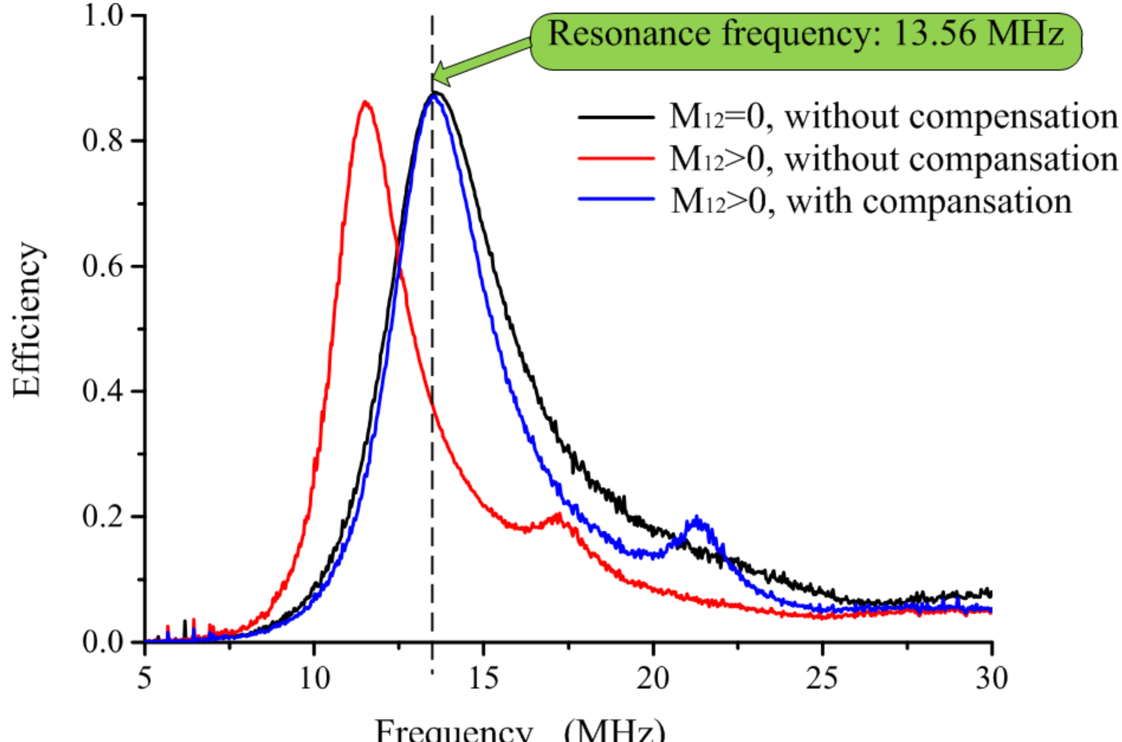


TX RX2



RX1





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Conclusion

- A fundamental transition is occurring from control of "motion" to control of "energy".
- System-level analysis, optimization, and implementation of control are important.
- Major interests now:
  - Modeling and control of networked energy systems (battery, ultracapacitor, solar panel, wind turbine, EV, home, etc)
  - Closed-loop control of WPT systems including PA (new sensor, tunable component, control)
  - Optimized autonomous power distribution among multiple receivers

WPT for (Supercapacitor?) Tram

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  - National Science Foundation of China [grant number 50950110341]
  - Nippon Chemi-con Ltd.
  - Intel Asia-Pacific Research & Development Ltd.

and all the other collaberators for supporting our work.

Thank You

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

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