Research Introduction
- Motion Control and Energy Management

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JOINT INSTITUTE
交大密西根学院

Outline

- Overview
- Motion Control
- Hybrid Energy System
- 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
- 3.3km^2 (Minhang Campus)

UM-SJTU Joint Institute (1)

UM-SJTU Joint Institute (2)

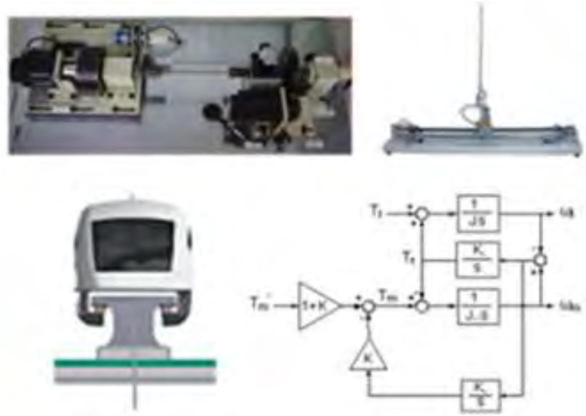
- Serve as a major base to facilitate the growing trend of global education and to reform Chinese higher education.
- Curriculum integrated with that of UM, World-class faculty, International education environment.
- 80% of JI's graduates went to the graduate schools in the USA, among which average 40%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

Chengbin Ma

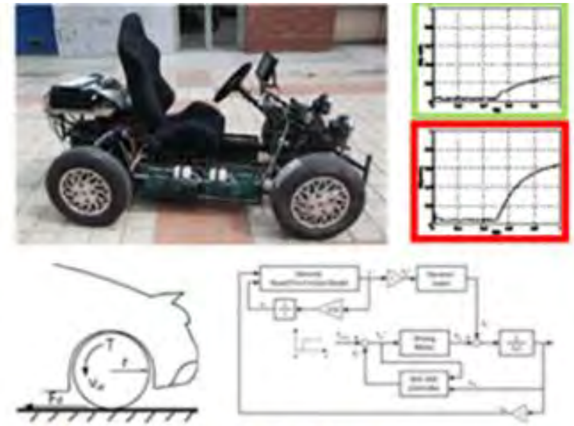
- Background: Systems, Control and Mechatronics
- Research Interests:
  - Motion control, factory automation, electric vehicles, alternative energy systems, wireless power transfer, etc.
- Employment:
  - Aug. 2008-Pre: Assistant Prof., Univ. of Michigan-SJTU Joint Institute; Joint Faculty Position in M. E. School, SJTU
  - 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. S., Dept. of E. E., Univ. of Tokyo, Japan
  - July. 1997: B. S., Dept. of Industrial Automation, East China Univ. of Science and Technology, Shanghai, China

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

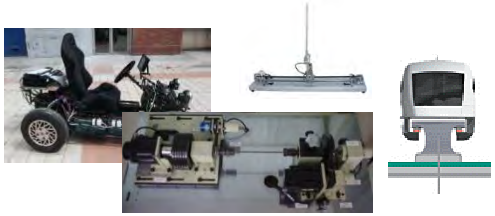
Control of Motion & Energy

Students and Laboratory (2010~Pre.)

From "Motion" to "Energy"

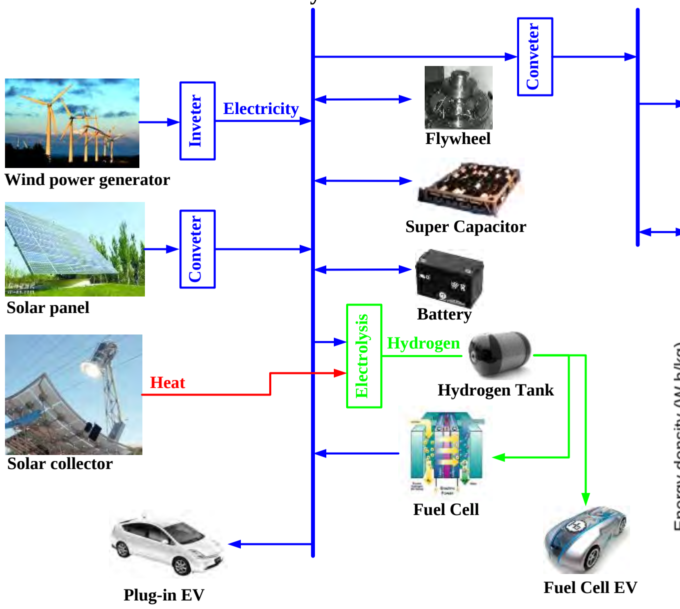
Control of

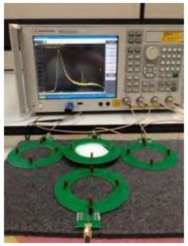
Motion

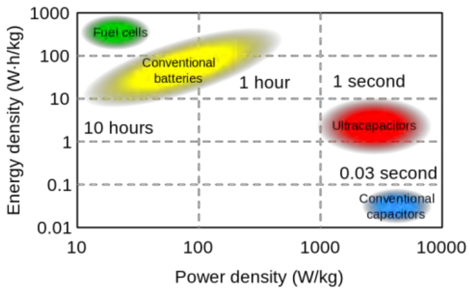


- Speed
- Precision
- Efficiency

Energy







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

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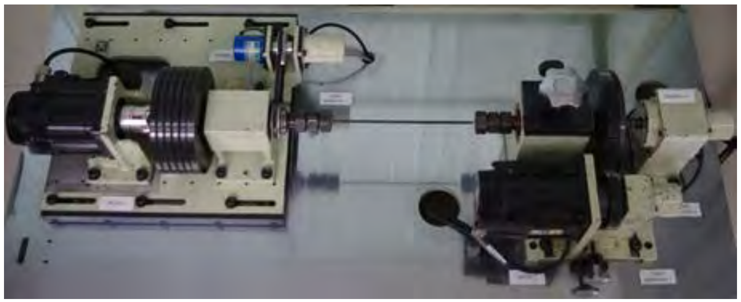
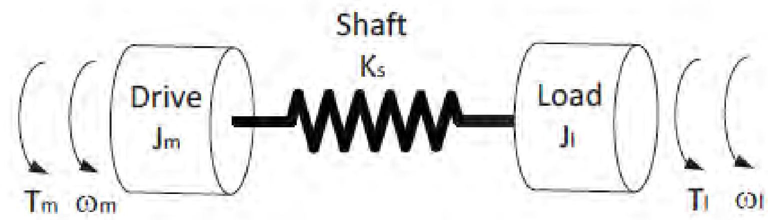
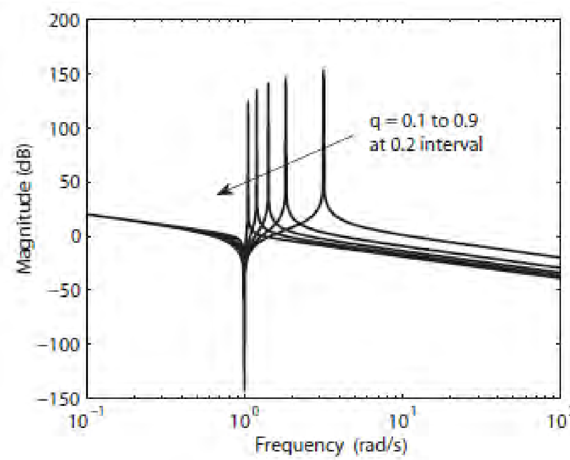
Laboratory Torsion Bench





$$P(s) = \frac{s^2 + \omega_a^2}{J_m s(s^2 + \omega_r^2)}, \xrightarrow{s^* = s/\omega_a} P_n(s^*) = \frac{s^{*2} + 1}{q s^{*3} + s^*},$$



damping versus robustness

Low-Order Controller Design

- The polynomial method could be a general approach that directly targets on the closed-loop transient responses.
- Tradeoff relationship between damping and robustness are explicitly represented by the interaction between γ_i's and τ.

Its characteristic polynomial

$$P(s) = a_n s^n + a_{n-1} s^{n-1} + \dots + a_1 s + a_0$$

$$\gamma_1 = \frac{a_1^2}{a_0 a_2}, \quad \gamma_2 = \frac{a_2^2}{a_3 a_1}, \dots, \gamma_{n-1} = \frac{a_{n-1}^2}{a_{n-2} a_n},$$

$$\tau = \frac{a_1}{a_0},$$

γ_i: characteristic ratios

τ: generalized time constant

$$\frac{1}{\gamma_{n-1}\gamma_{n-2}^2 \cdots \gamma_1^{n-1}}(\tau s)^n + \dots + \frac{1}{\gamma_1}(\tau s)^2 + (\tau s) + 1,$$

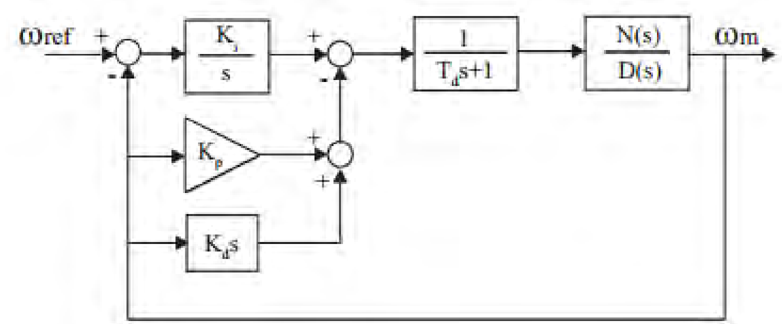
Assignments of γ_i and τ

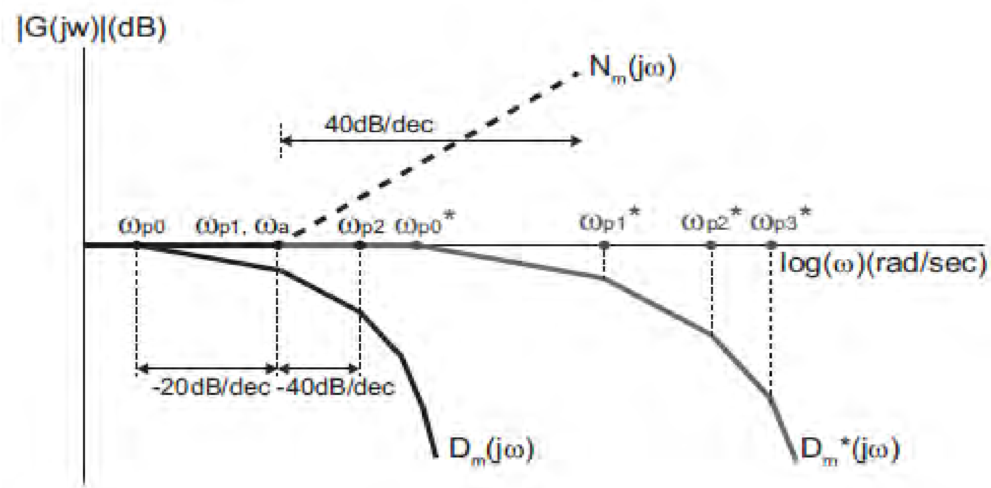
- In polynomial method, γ_i and τ directly relate to damping (overshoot) and the speed of response, respectively.
- Topics under discussion
  - Nominal assignment of γ_i's
  - Assignment of τ for non-all-pole systems
  - Optimized assignments of γ_i's and τ for high-order systems(ongoing)
  - Auto-tuning of low-order controllers(ongoing)

[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 Control064503-1, Vol. 136, November 2014.
[3] Y. Qiao, C. Ma: "The Assignment of Generalized Time Constant for A Non-All-Pole System", IEEE Transactions on Industrial Electronics, accepted on Dec. 16th, 2014.
[Download]: http://umji.sjtu.edu.cn/lab/dsc/

An Example (1)

- Nominal assignment of τ considering pole-zero interaction:





$$\tau \geq \tau_c = \frac{\omega_{p2}^{*}}{\omega_a}$$

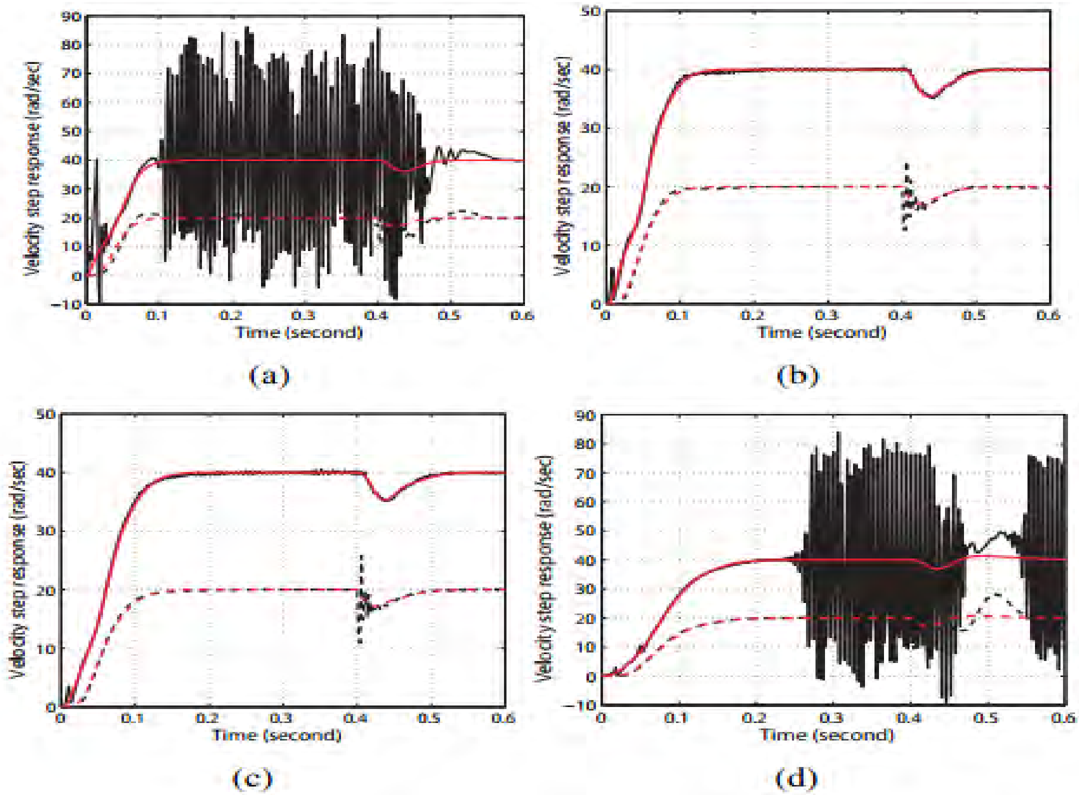
$$\tau_{min} = \frac{\gamma_1}{\omega_a}\sqrt{\gamma_2}$$

$$\tau_{max} = \frac{\gamma_1 \gamma_2}{\omega_a}\sqrt{\frac{1+\sqrt{1-\frac{4}{\gamma_3 \gamma_2^2 \gamma_1}}}{2}\gamma_3}$$

[1] Y. Qiao, C. Ma: “The Assignment of Generalized Time Constant for A Non-All-Pole System", IEEE Transactions on Industrial Electronics, accepted on Dec. 16th, 2014.

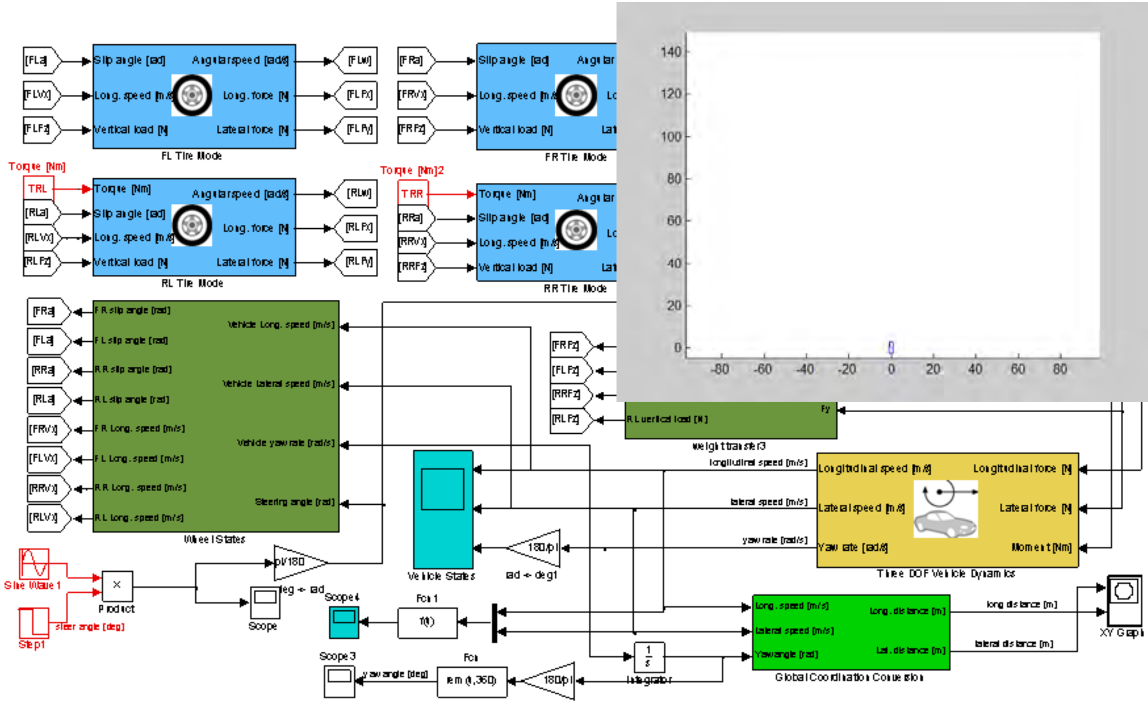
An Example (2)

- ±0.6 deg. gear backlash and 5N·m load disturbance torque from 0.4 second.
- (a) τ=0.0431 s, (b) τ=0.0531 s, (c) τ=0.0631 s, (d) τ=0.0837 s

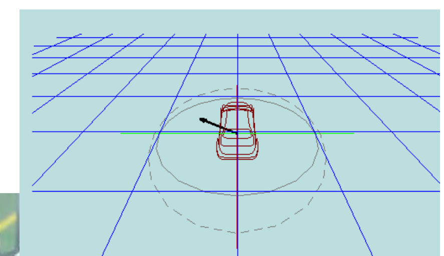


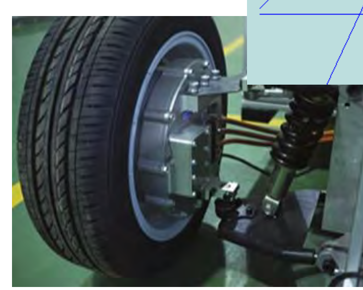
Electric Vehicle Dynamics

- Electric motor (fast and accurate torque control)
  - Serve as driver, actuator, and sensor simultaneously
  - Torque envelope control specified for EVs



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





Example-Longitudinal Dynamics

Without control

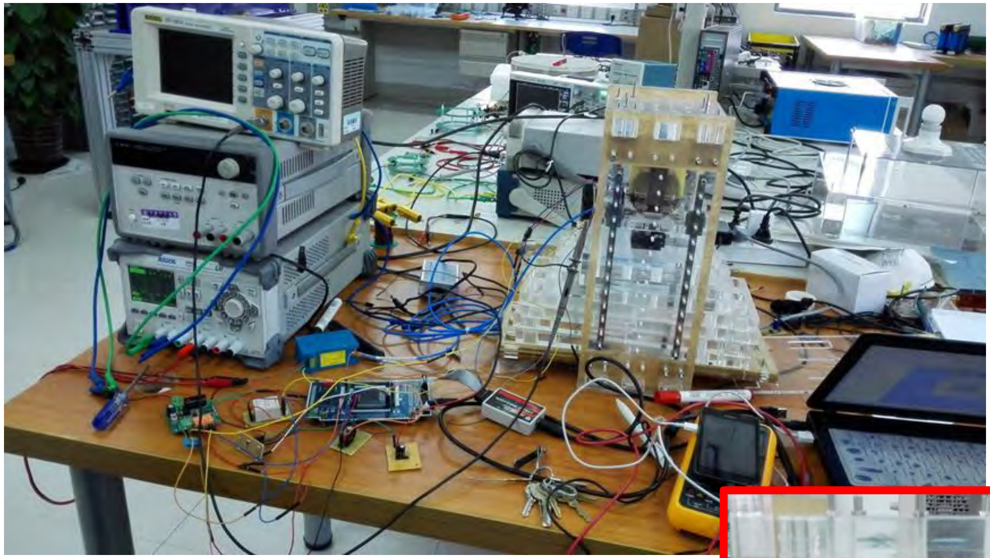
Specifications	Details
Size (m)	$2.5 \times 1.6 \times 1.4$
Weight (kg)	350
Tire	165/70 R14
Traction motor	Four in-wheel motors (4 kW each)
Motor resolver	1024 pulses/rev
Battery	96 V Li-ion battery
Controller	dSPACE/MicroAutoBox
Optical encoder	1024 pulses/rev

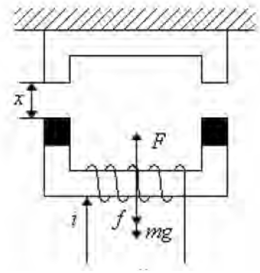
With control

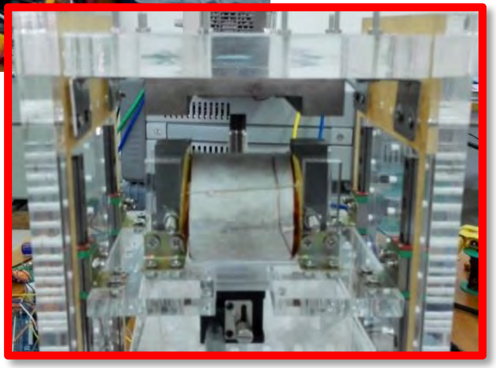
[1] X. Wu, C. Ma, M. Xu, Q. Zhao, Z. Cai: "Single-Parameter Skidding Detection and Control Specified for Electric Vehicles", Journal of the Franklin Institute (Elsevier), Vol. 352, pp. 724-743, 2015.

Electro-Magnetic Suspension

- Control of electro-magnetic suspension for low-speed maglev trains.







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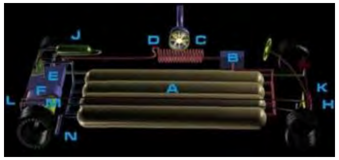
Diversity of Renewable Energy Systems

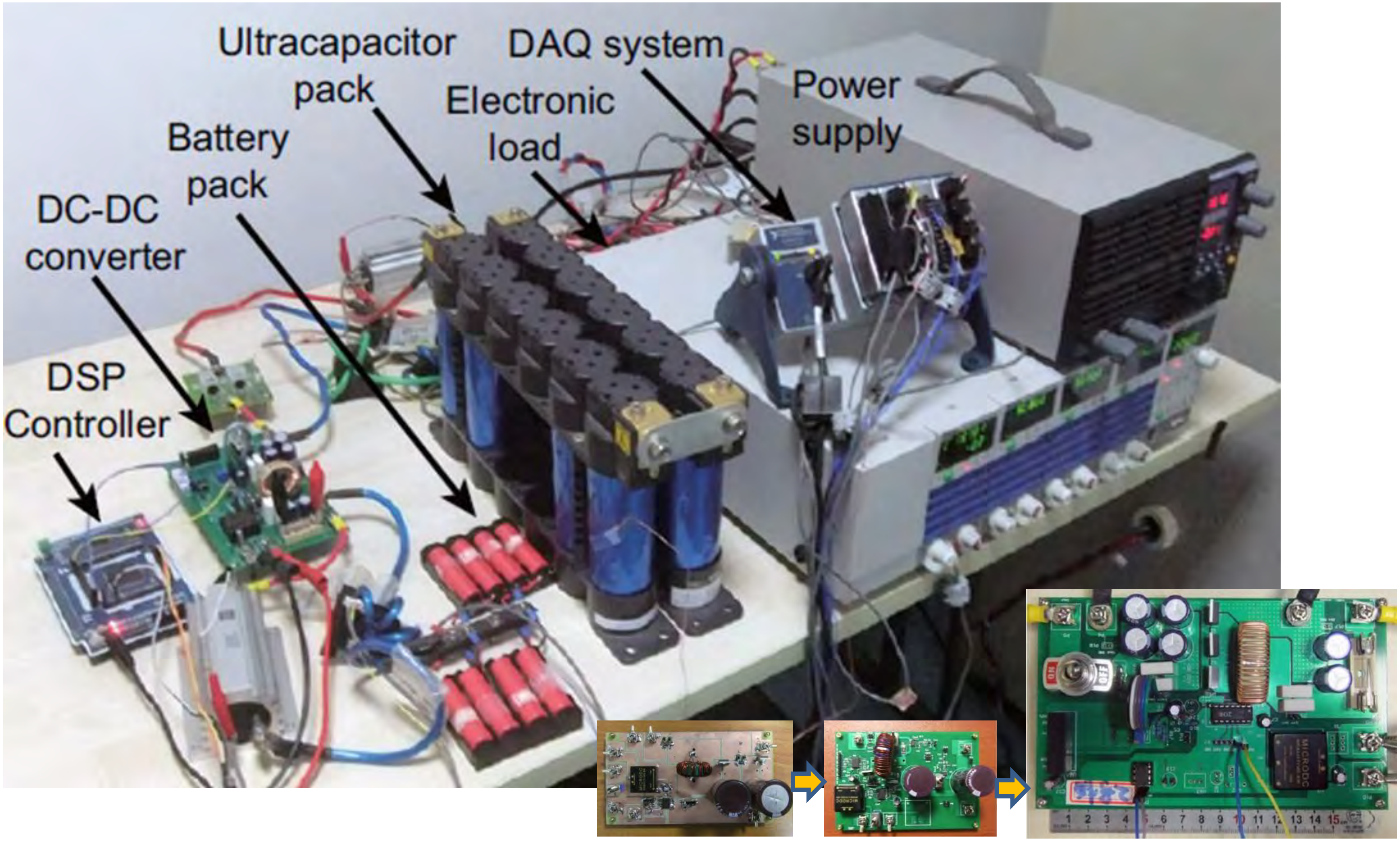
- Energy sources with different dynamics
  - Wind, Solar, Regenerative Energy, etc.
- Immature electricity mass storage technology
  - The energy density of petrol (12000Wh/kg) is hundreds of times as that of a mass market battery (20~200Wh/kg).
  - Combination of multiple energy storage devices/systems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



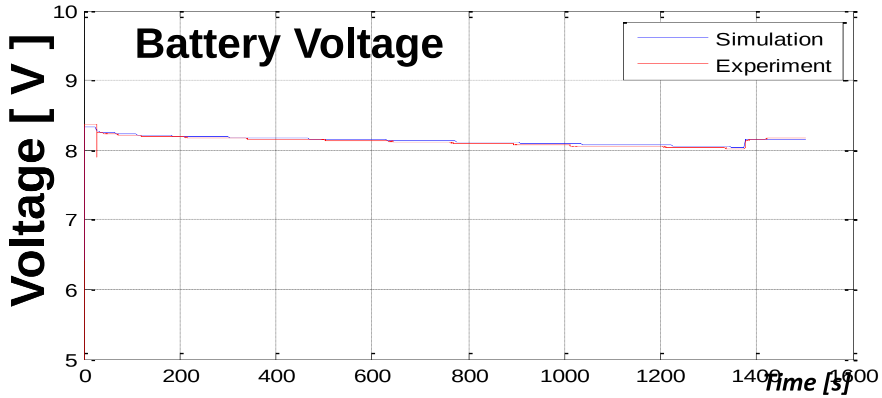


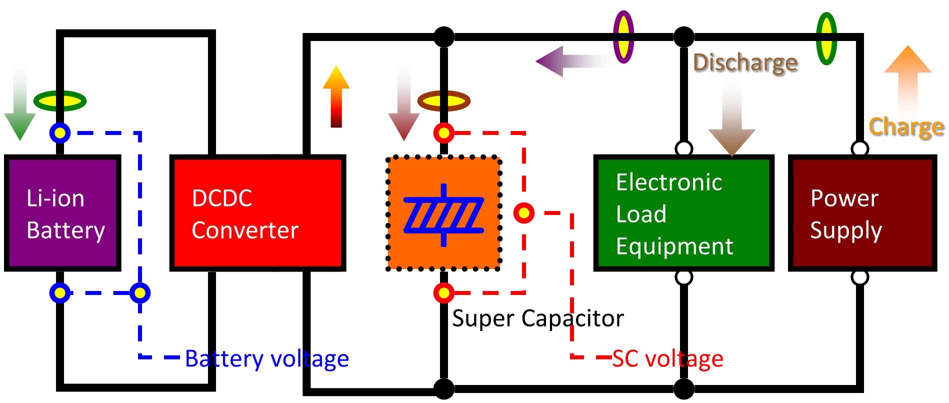
Battery-Ultracapacitor Test System



High-Accuracy Dynamic Modeling

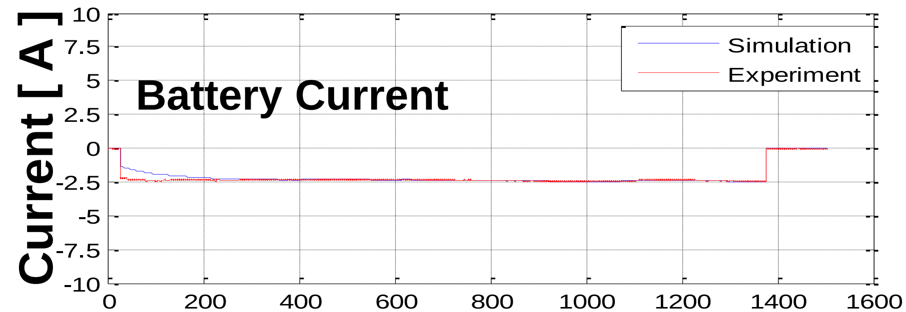
Initial Battery SOC: 1.0(@16.8V)
Regeneration Velocity Constrains: V>20km/h

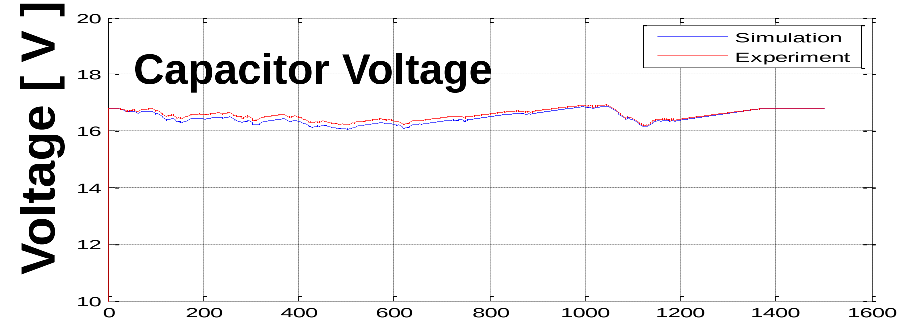


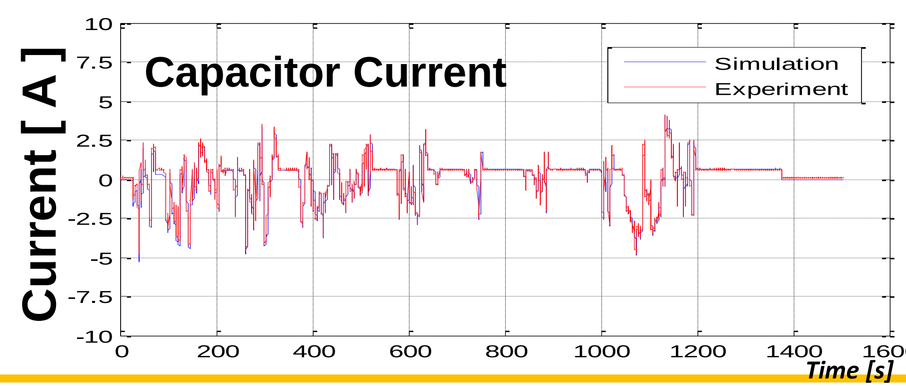


7.4V 10Ah
(2S4P)

Current Converter System







Comparative Study

- The hybrid system works best with energy-type batteries (large internal resistance).

Hybrid Energy System

Peak_Current	5A	10A	15A
Initial_Capacitor_Voltage	14.8V	14.8V	14.8V
Initial_Battery_SOC	0.5(@7.4V)	0.5(@7.4V)	0.5(@7.4[illegible]
End_of_SOC	0.4532	0.4051	0.35[illegible]
Energy_Efficiency[%]	91.05	89.12	87.84

Battery-alone System

Peak_Current	5A	10A	15A
Initial_Battery_SOC	0.5(@14.8V)	0.5(@14.8V)	[illegible](@14.8V)
End_of_SOC	0.4514	0.3946	0.[illegible]24
Energy_Efficiency[%]	89.13	82.67	74.01

13% improvement

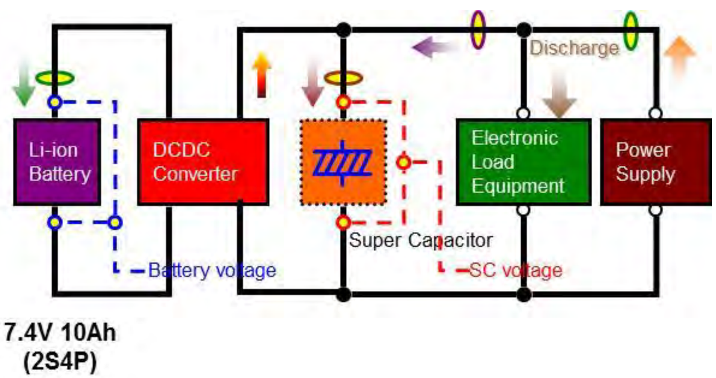
Battery Resistance Amplification Coefficient K	1	2	3
Initial_Capacitor_Voltage	14.8V	14.8V	14.8V
Initial_Battery_SOC	0.5(@7.4V)	0.5(@7.4V)	0.5(@7.4V)
End_of_SOC	0.4532	0.4523	0.451[illegible]
Energy_Efficiency[%]	91.05	89.45	88.52

Battery Resistance Amplification Coefficient K	1	2	3
Initial_Battery_SOC	0.5(@14.8V)	0.5(@14.8[illegible]	[illegible]5(@14.8V)
End_of_SOC	0.4514	0.4480	[illegible]4432
Energy_Efficiency[%]	89.13	83.31	76.41

12% improvement

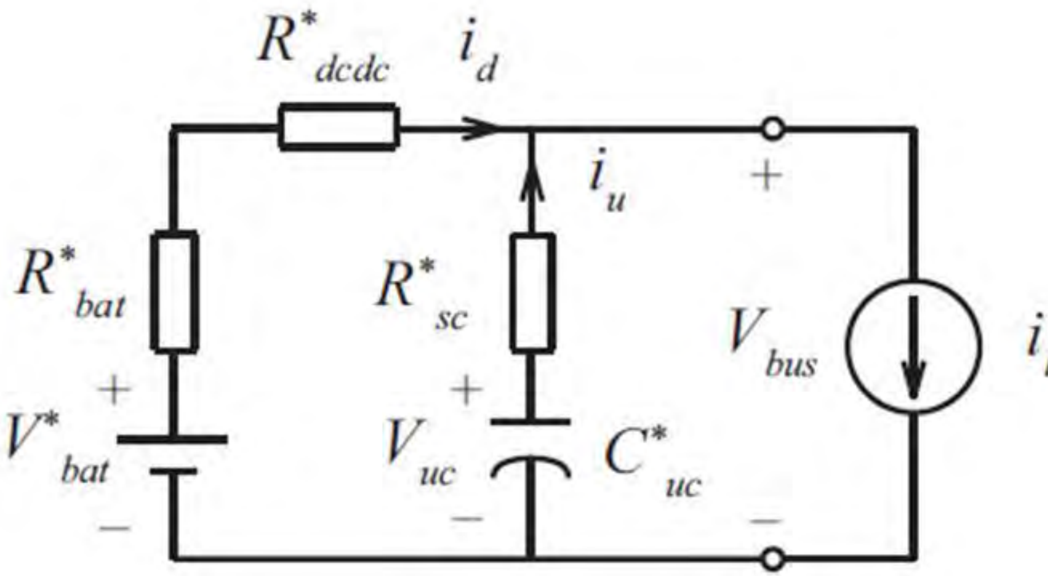
ESR-based Efficiency Analysis

- Equivalent-Series-Resistance circuit Model:



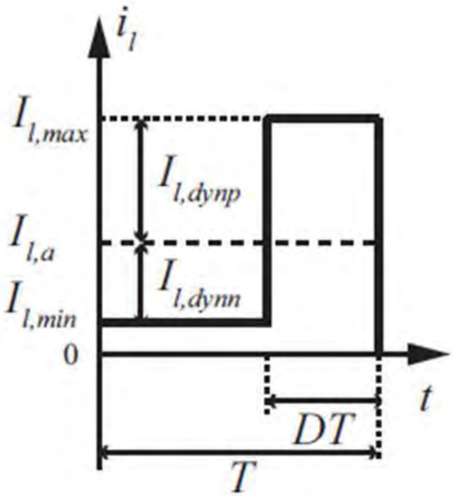
$$
\begin{aligned}
R_d^* &= \frac{P_{loss,d}}{i_d^2} \\
&\approx \frac{R_L + d_s R_{on}}{(1-d_s)^2} + R_b + \frac{V_F}{i_d} \\
&= R_{d,r}^* + \frac{V_F}{i_d},
\end{aligned}
$$

$$
\begin{aligned}
R_b^* &= \frac{P_{loss,b}}{i_d^2} \\
&\approx \frac{i_b^2 R_s}{i_d^2} = \frac{R_s}{(1-d_s)^2}, \\
R_u^* &= \frac{P_{loss,u}}{i_u^2} \approx R_{sc},
\end{aligned}
$$



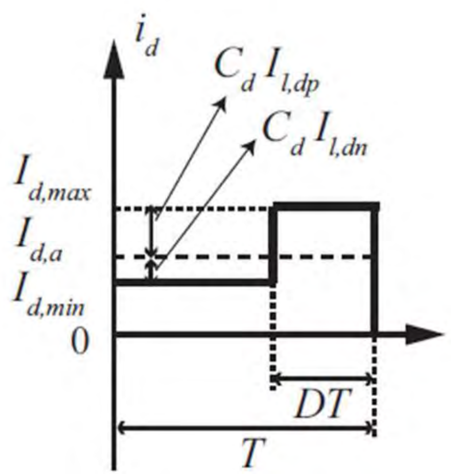
Optimal Current Distribution

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

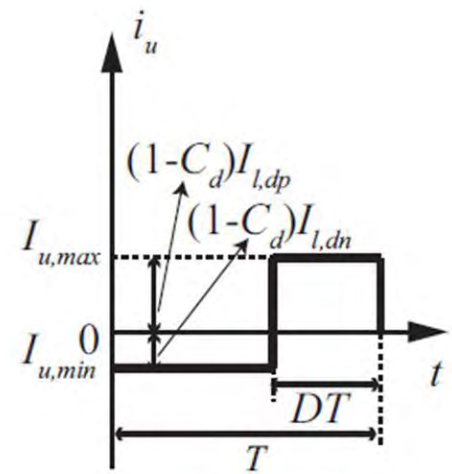


$$E_{loss} = -I_{l,dp}I_{l,dn}(R_b^* + R_{d,r}^* + R_u^*)\left(C_d - \frac{1}{1+K}\right)^2 T - I_{l,dp}I_{l,dn}R_p^* T + I_{l,a}^2(R_b^* + R_{d,r}^*)T + I_{l,a}V_F T,$$

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



Current from DC-DC converter.

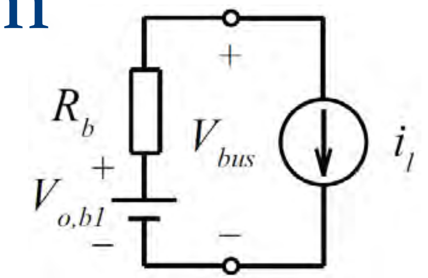


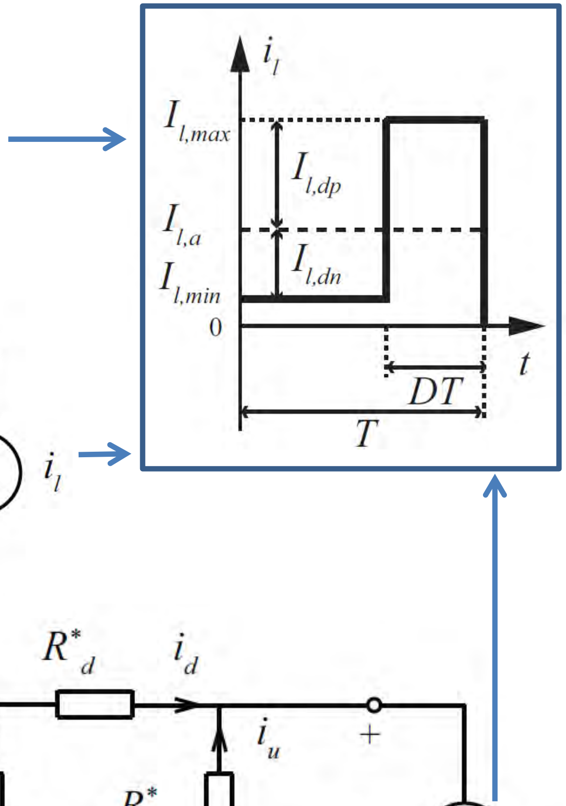
Current from ultracapacitor pack.

Efficiencies of Three Systems

- Battery-only System

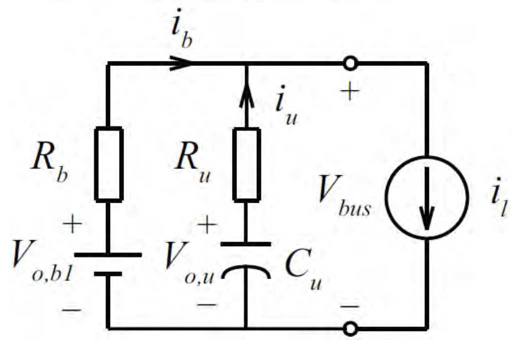
$$\eta_{bo} = 1 - \frac{I_{l,a}^2 R_b + I_{l,dp} I_{l,dn} R_b}{V_{o,b1} I_{l,a}}$$





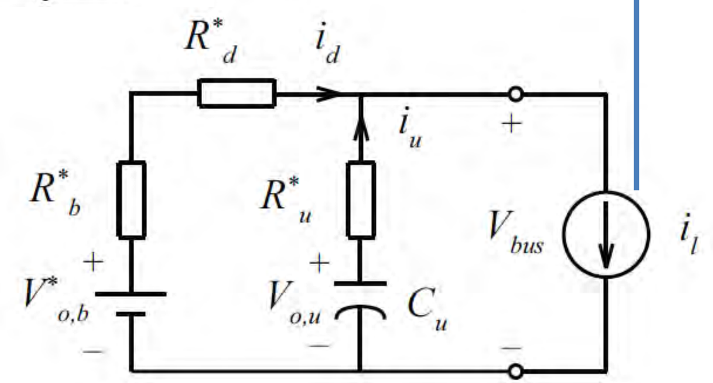
- Passive HESS

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



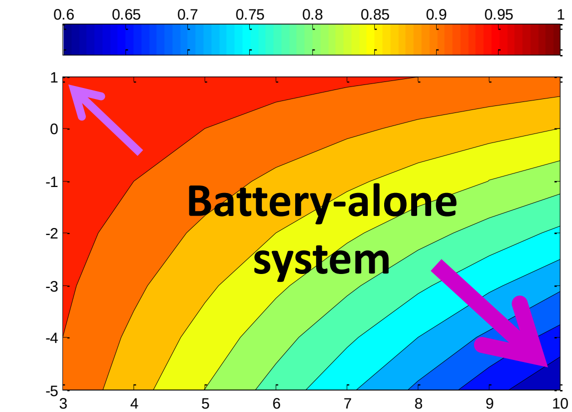
- Battery Semi-active HESS

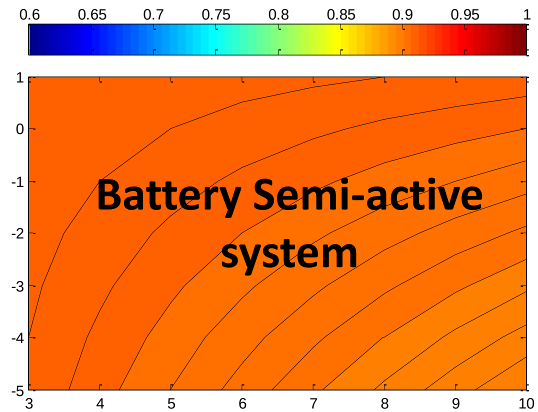
$$\eta_{bs} = 1 - \frac{I_{l,a}^2 (R_b^* + R_d^*) + I_{l,dp} I_{l,dn} R_u^*}{V_{o,u} I_{l,a} + I_{l,a}^2 (R_b^* + R_d^*)}$$



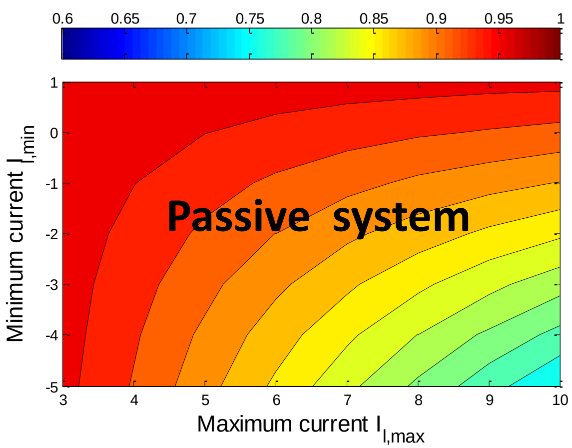
Comparison of Efficiencies

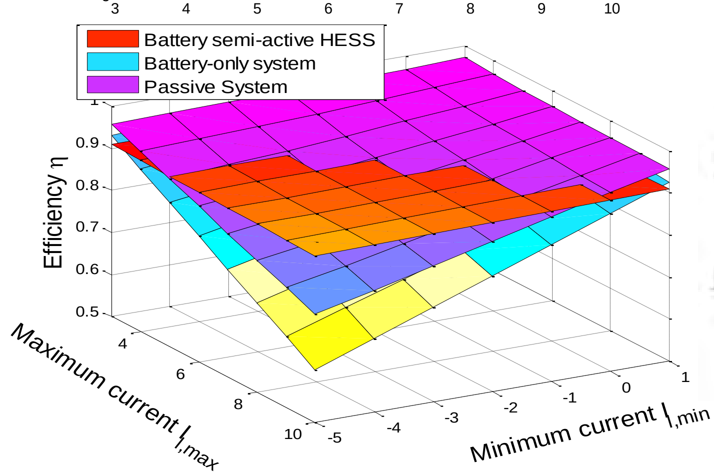
- Pulse load profile: same average current (2A), different I_{max} and I_{min}, and thus a different duty cycle.

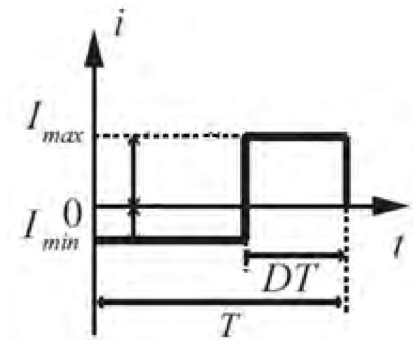




1. Topology
2. Profile dynamics
3. DC-DC efficiency
4. Temperature

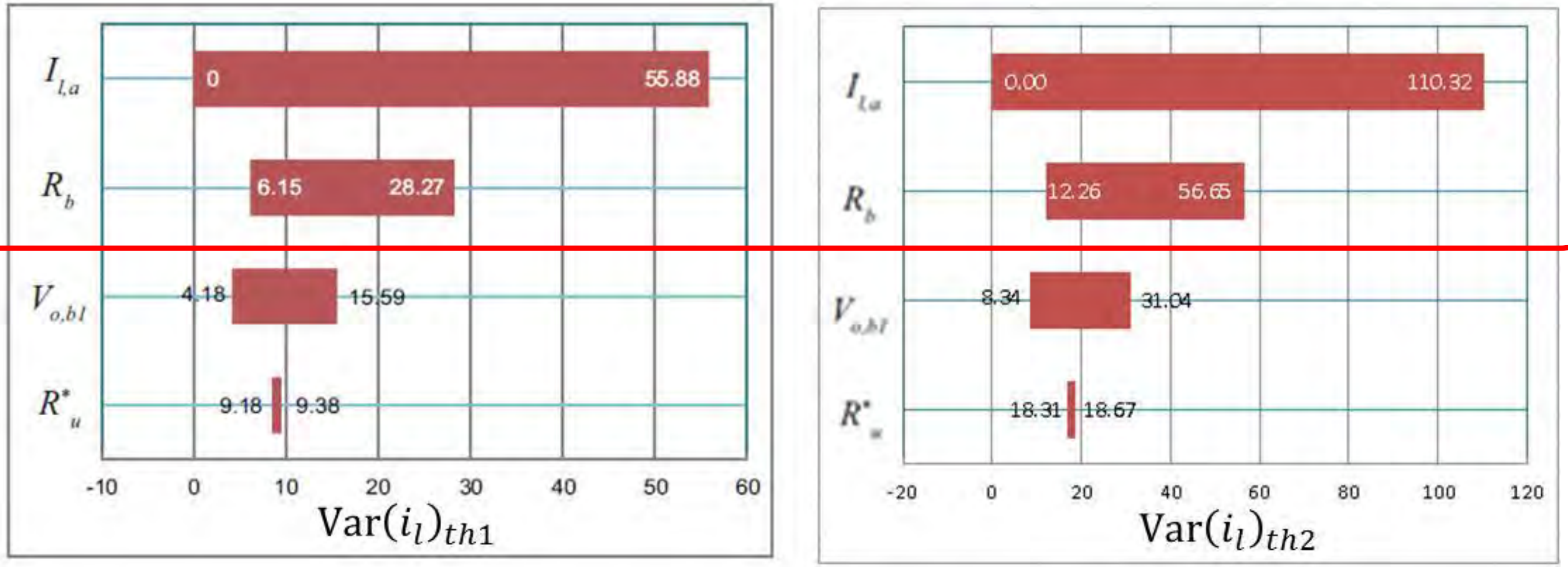






Thresholds and Sensitivity Analysis

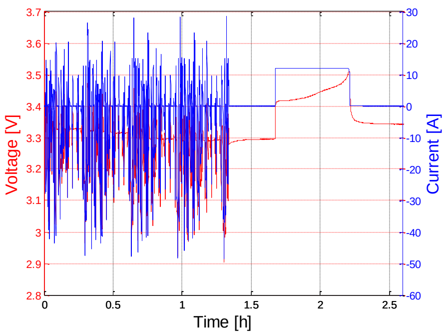
- Thresholds of the variance of the load current can be accurately derived:
  - $\mathrm{Var}(i_l)_{th1}: \eta_{bs} > \eta_{bo}$
  - $\mathrm{Var}(i_l)_{th2}: \eta_{bs} > \eta_{ps}$
- Tornado diagrams for the two thresholds

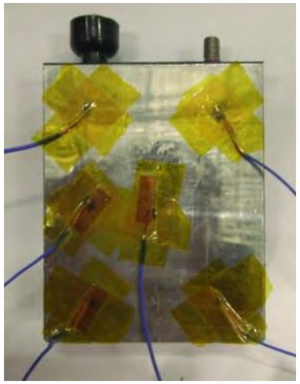


Battery Ageing Test

Temperature: 45 deg.

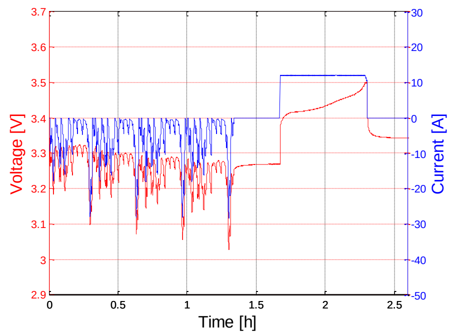
Dynamic Discharging

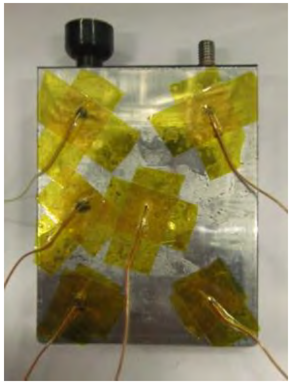




No.1 Cell

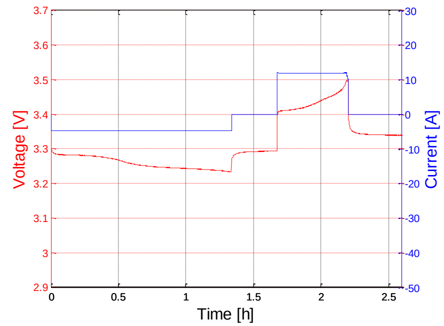
Mod. Constant Discharging

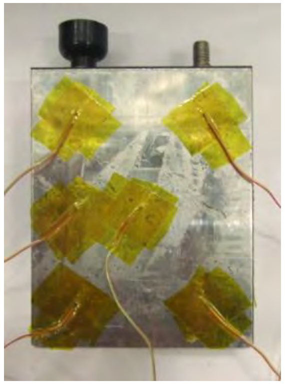




No.2 Cell

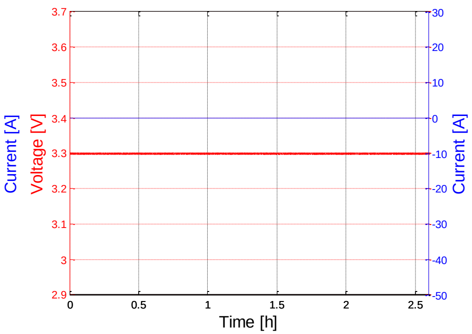
Constant Discharging

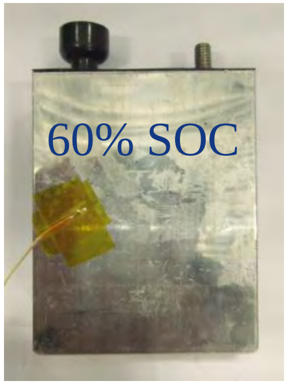




No.3 Cell

Calendar Life

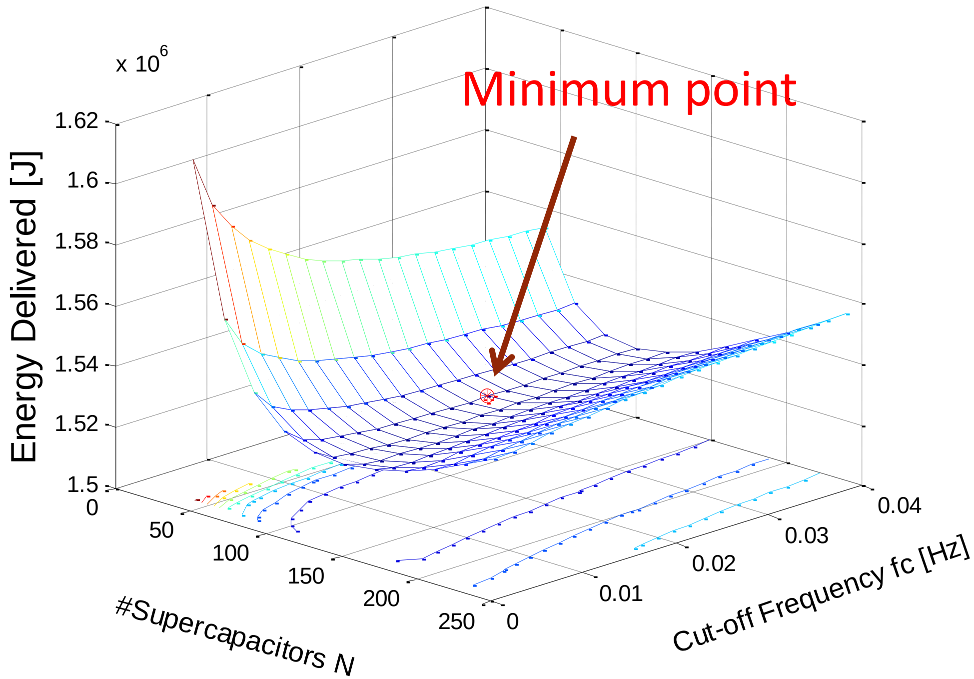


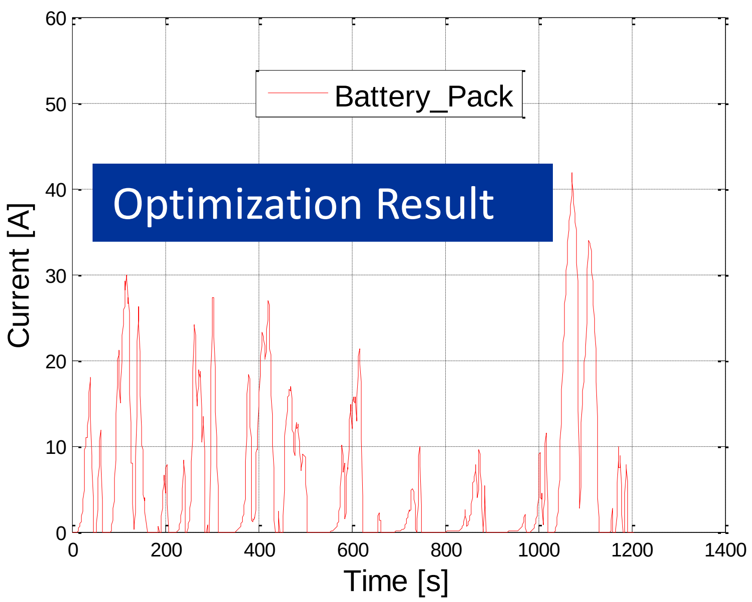


No.4 Cell

Optimized Sizing under JC08 Cycle

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



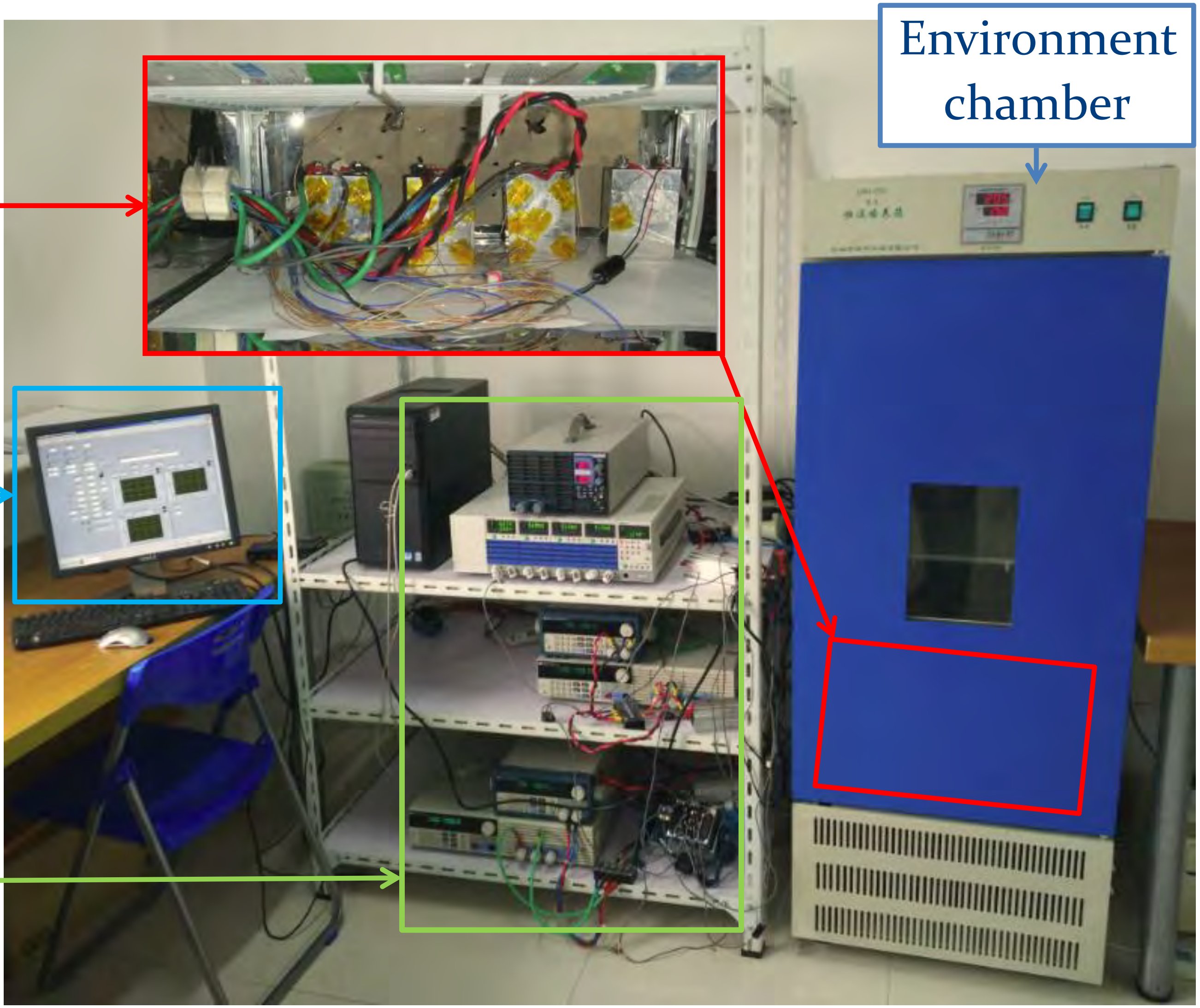


Experimental Setup

Four battery cells inside the environment chamber

LabVIEW program to control and record data

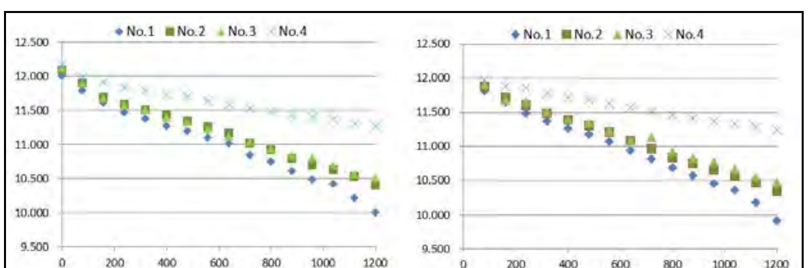
Three sets of power supply and electronic load.

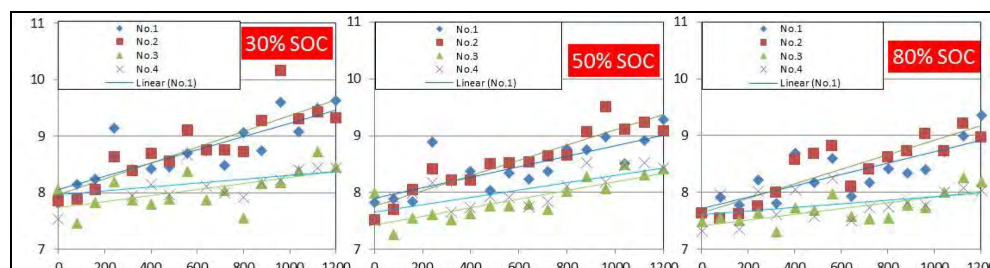


Quantitative Results

- Realistic case with optimized size of SCs
  - The capacity loss of the battery at 1/3 and 1C rate caused by cycling can be reduced by 28.6% and 29.0% respectively, compared with the case with no supercapacitors.

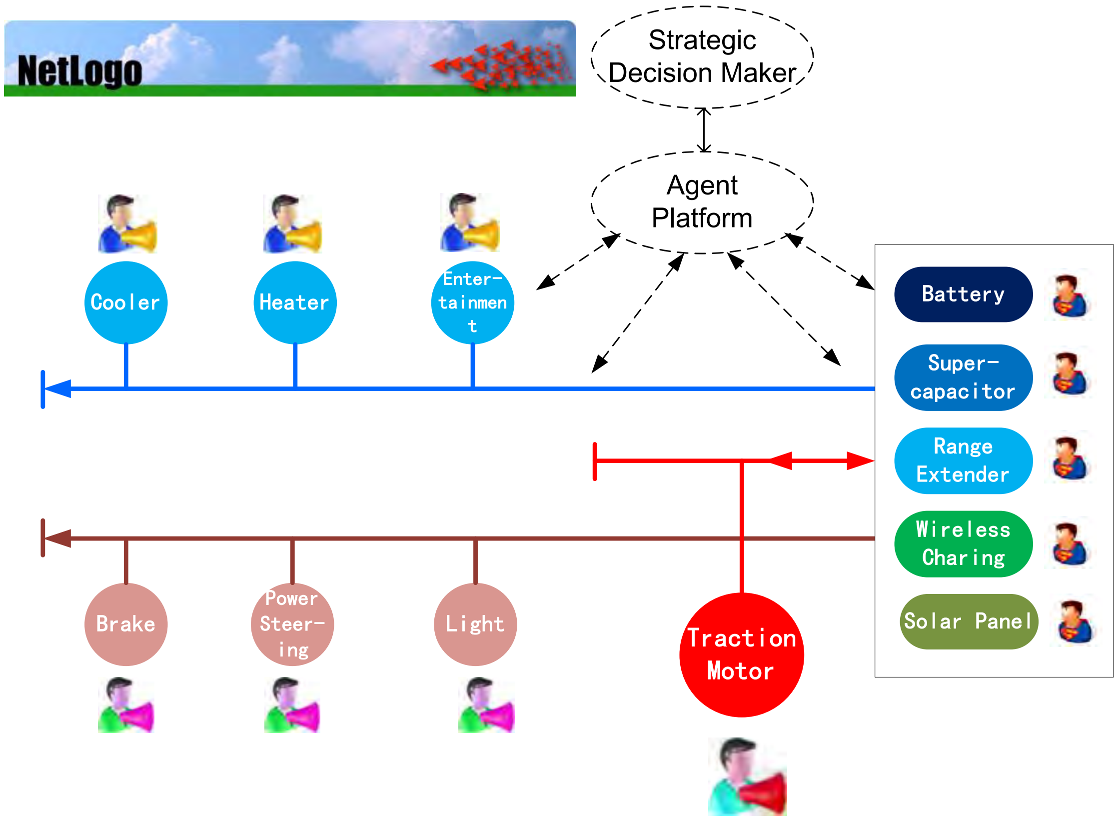
- Ideal case with infinite size of SCs
  - The capacity loss of the battery at 1/3 and 1C rate caused by cycling can be reduced by 36.3% and 39.3 % respectively, compared with the case with no supercapacitors.
  - The resistance increase of the battery can be reduced by at least 50%, compared with the case with no supercapacitors.





Control of Networked Energy Systems

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



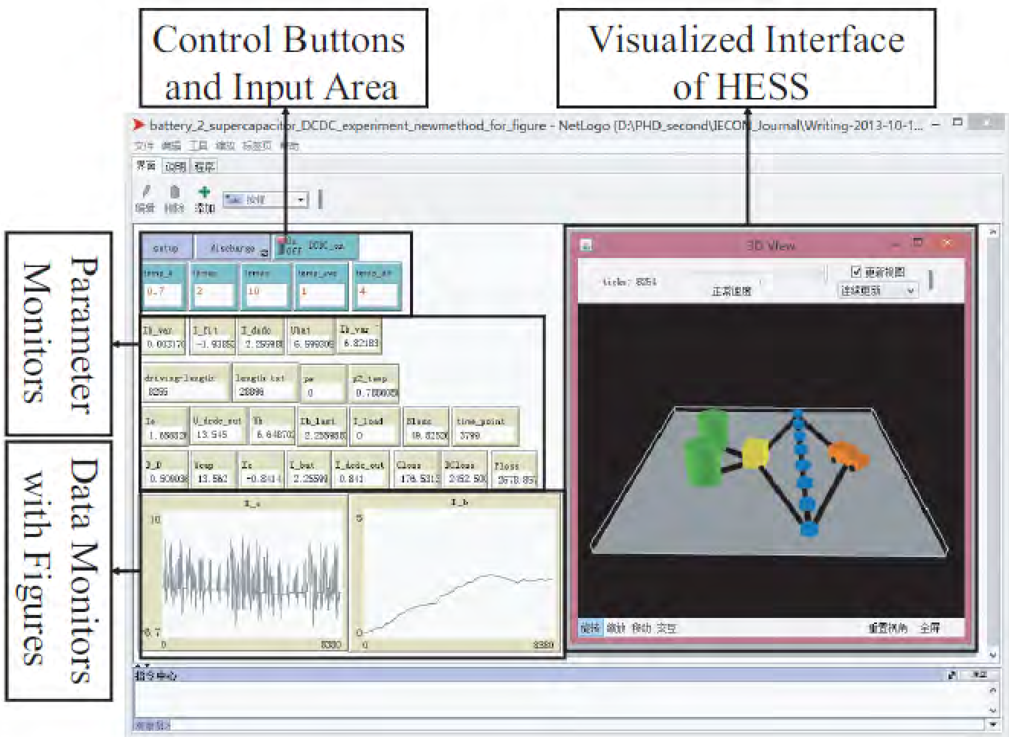
Multi-agent Interaction Modeling

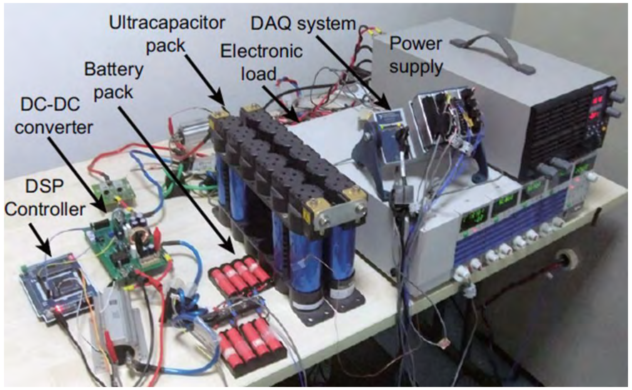
Strategic Interaction Analysis

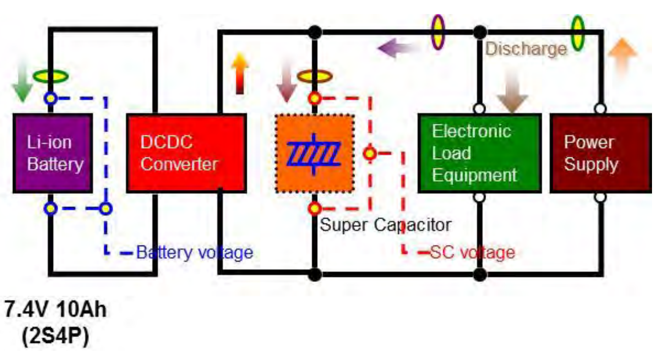
Technical Committee (TC) on "Energy Storage " (TCES)

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

Battery Bank
(**Cycle life**)

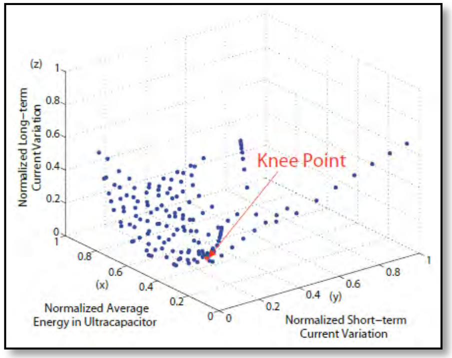
Sensitive

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

Ultracapacitor Bank
(**HESS Performance**)

Robust

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



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

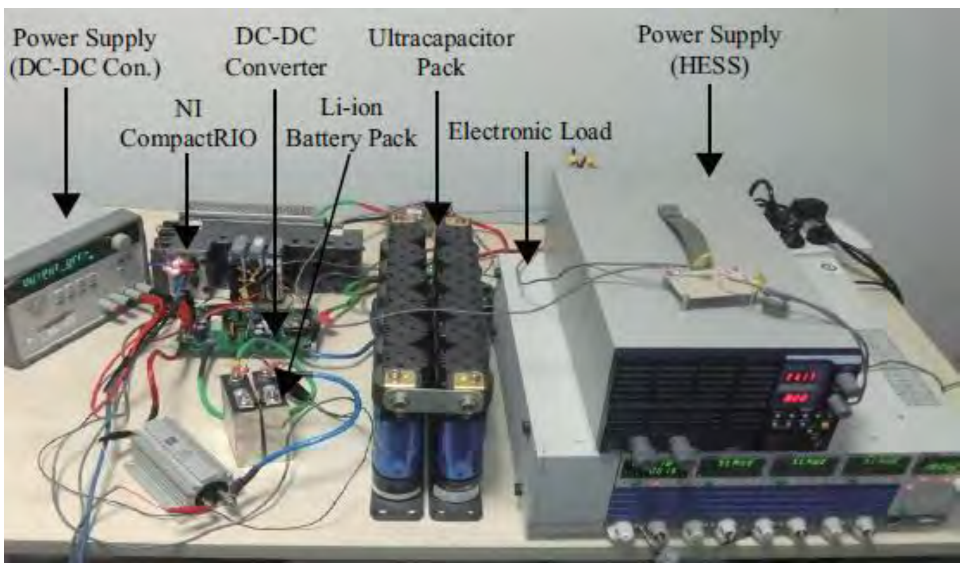
1. The Pareto set is used to determine the weights.
2. The global optimal solution is found by using Karush–Kuhn–Tucker (KKT) conditions.
3. Fast enough for realtime implementation

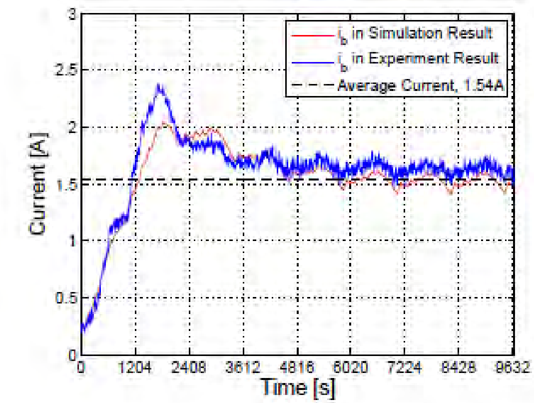
Results under JC08 Cycle

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

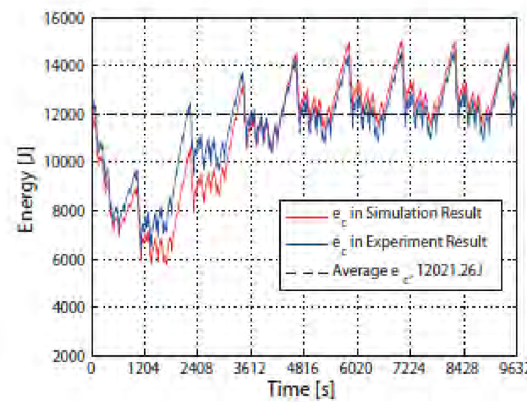
TABLE I
COMPARISON OF SIMULATION RESULTS

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





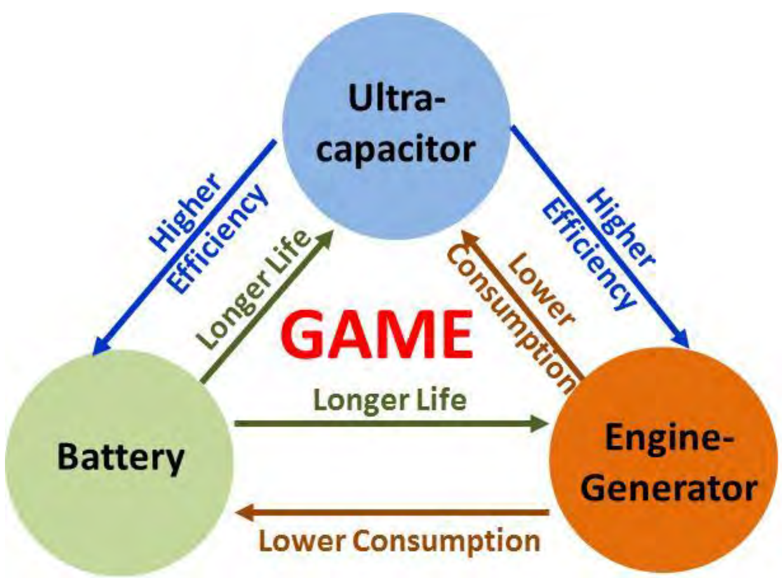
(a)

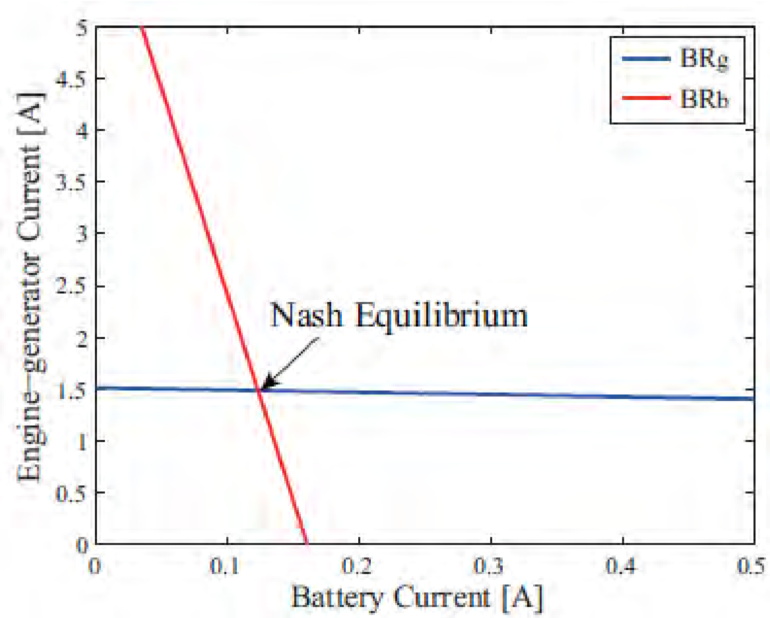


(b)

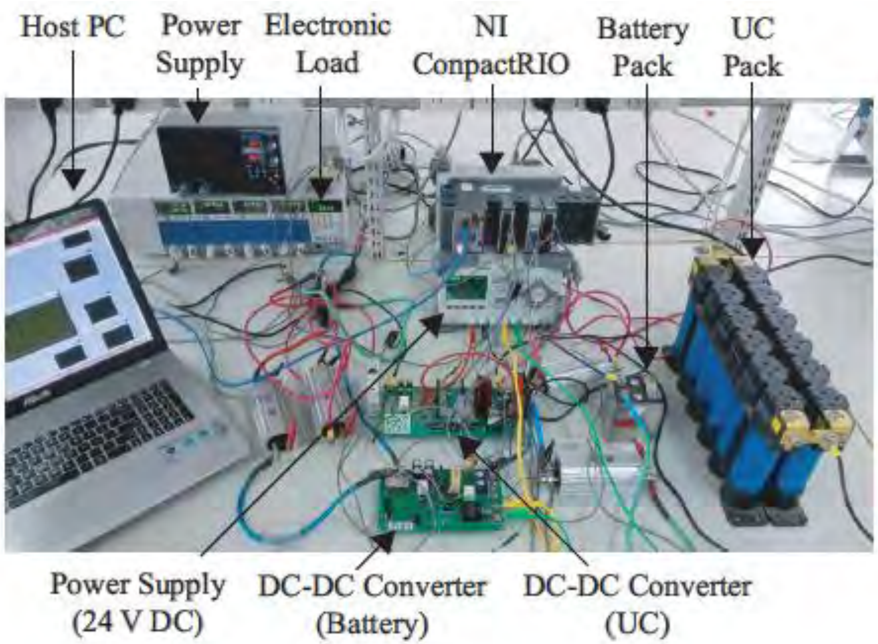
Non-Cooperative Current Control Game

- Three energy devices act as agents to play a game
  - Engine-generator: lower the **fuel consumption**;
  - Battery pack: extend the **cycle-life**;
  - UC pack: maintain the **charge/discharge capability**.
- Ultracapacitor is an assistive energy storage device.
- Two degree-of-freedoms: battery and generator





Results under Three Test Cycles



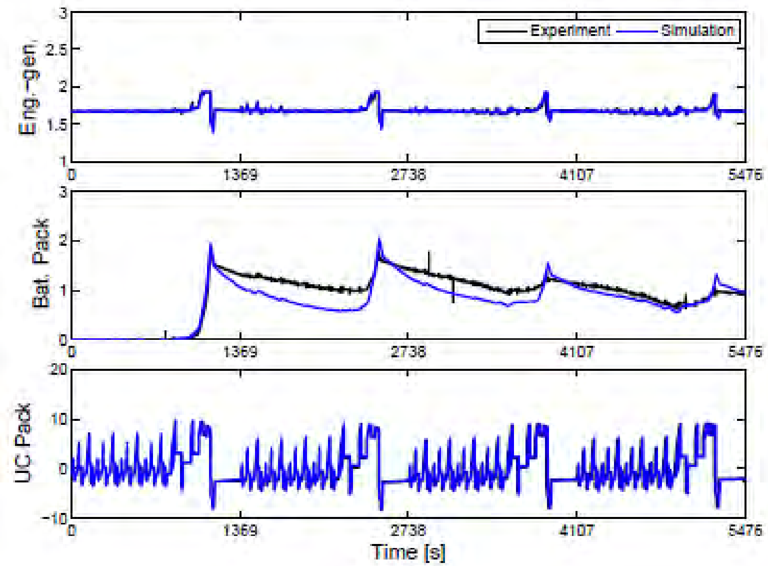
(a)

(b)

(c)

COMPARISON ON VALUES OF CRITERIA

Control Method (GT/ALD-based)	$C_{g,ave}$ (g/kWh)	$I_{b,ave}$ (A)	$I_{b,var}$ (A)	$E_{c,ave}$ (J)
[NEDC]:				
GT-based	248.92	2.27	0.0015	5314.78
ALD-based	247.92	2.46	0	7595.85
[UDDS]:				
GT-based	248.48	2.53	0.0007	5012.43
ALD-based	247.92	2.58	0	4963.78
[JC08]:				
GT-based	248.04	0.62	0.0006	6058.06
ALD-based	247.92	0.86	0	5941.42

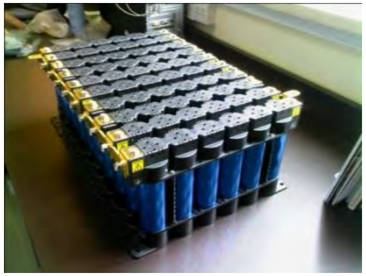


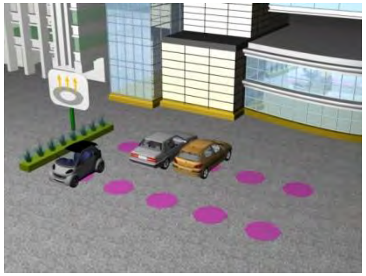
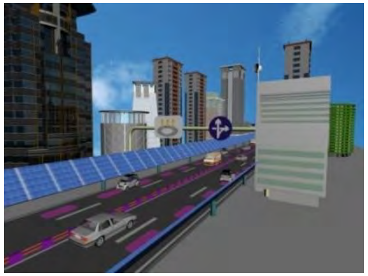
Outline

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

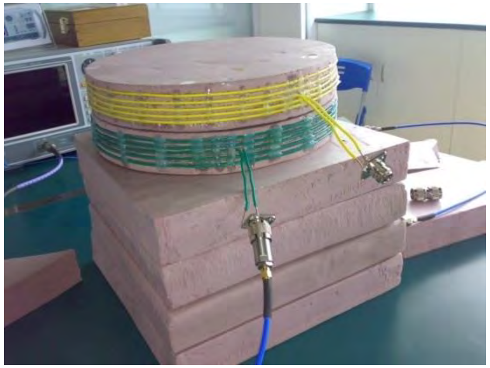
Battery-Free Mobile Energy System

- 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.

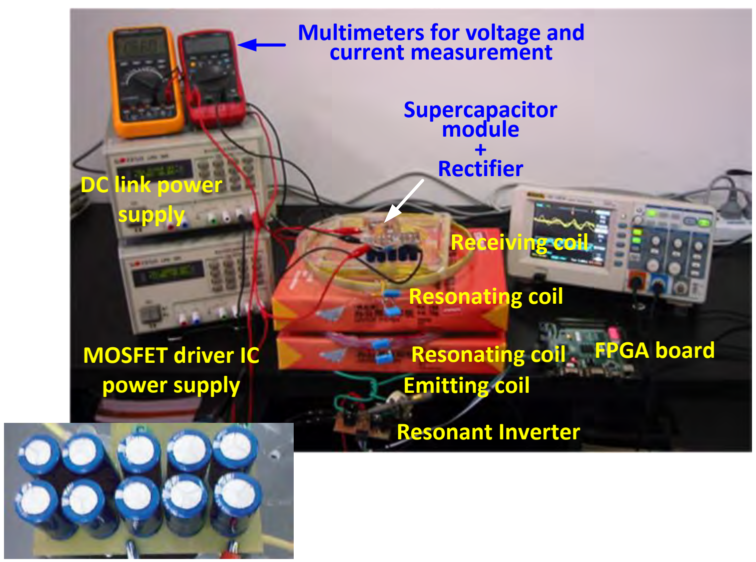


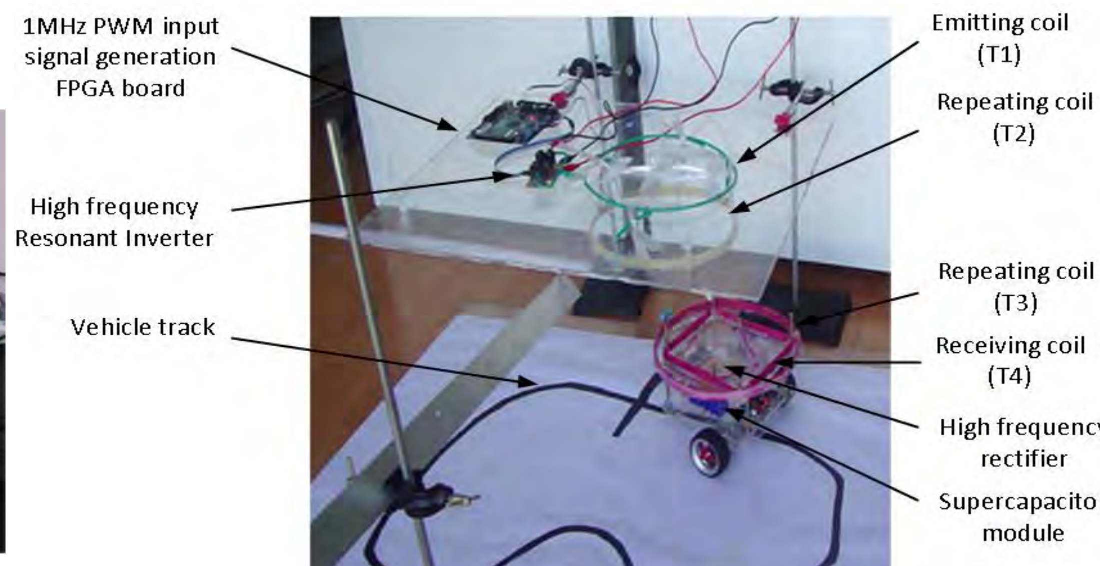



Initial Efforts Starting from 2010



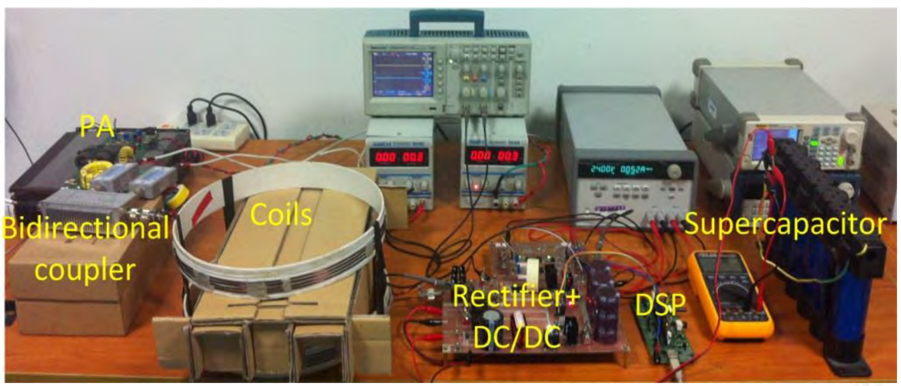
Gap (cm)	5.6	10.1	14.8	19.3	24.1	28
Efficiency (%)	88.84	93.32	**93.69**	92.53	88.07	70.04
F_m (MHz)	13.59	14.74	15.27	15.71	16.11	16.08
F_e (MHz)	19.87	17.85	17.01	16.51	16.11	16.08

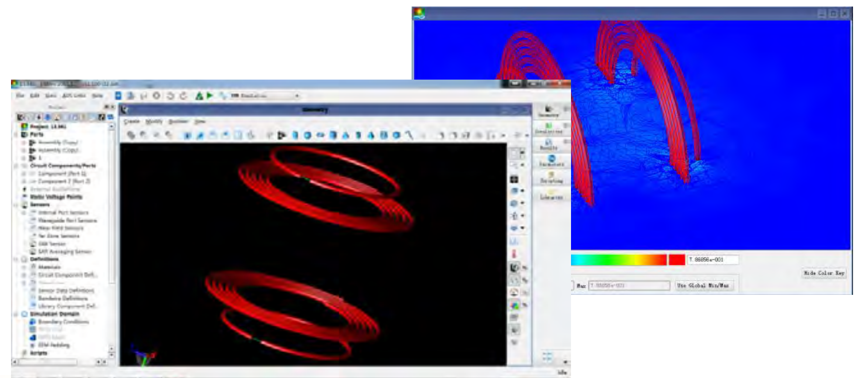


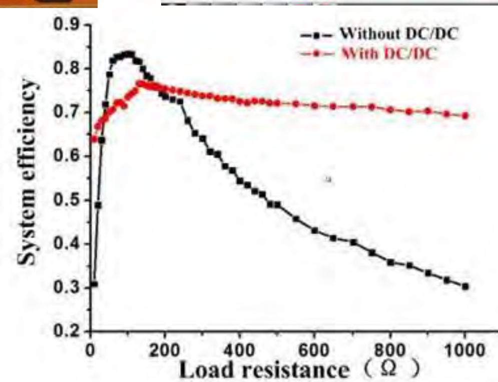


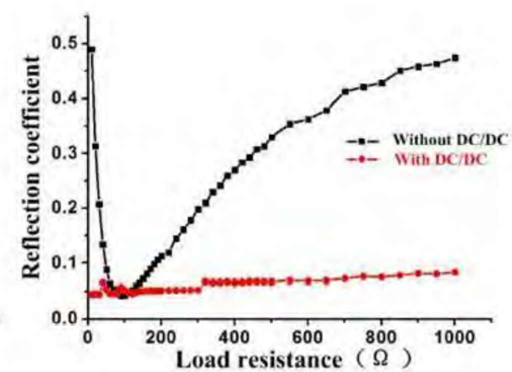
A System-level Optimization/Control

- 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





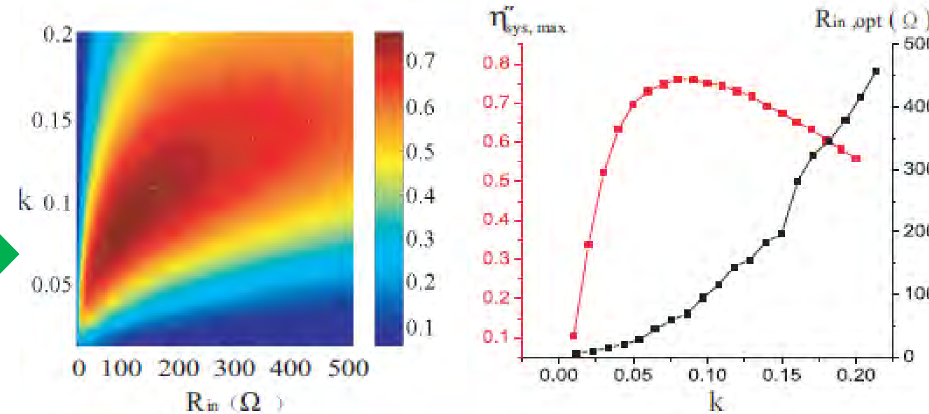


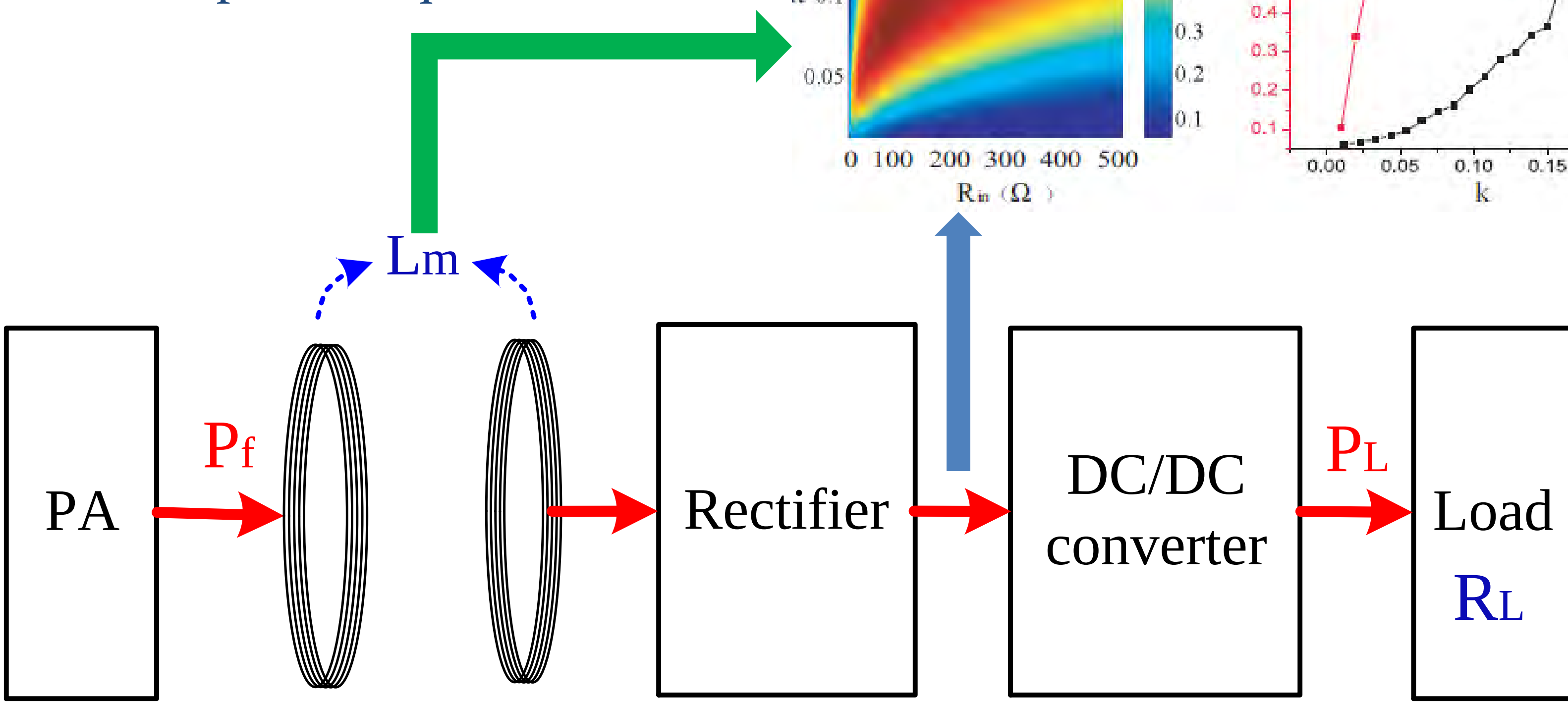


Optimal Load in WPT systems (1)

- 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.

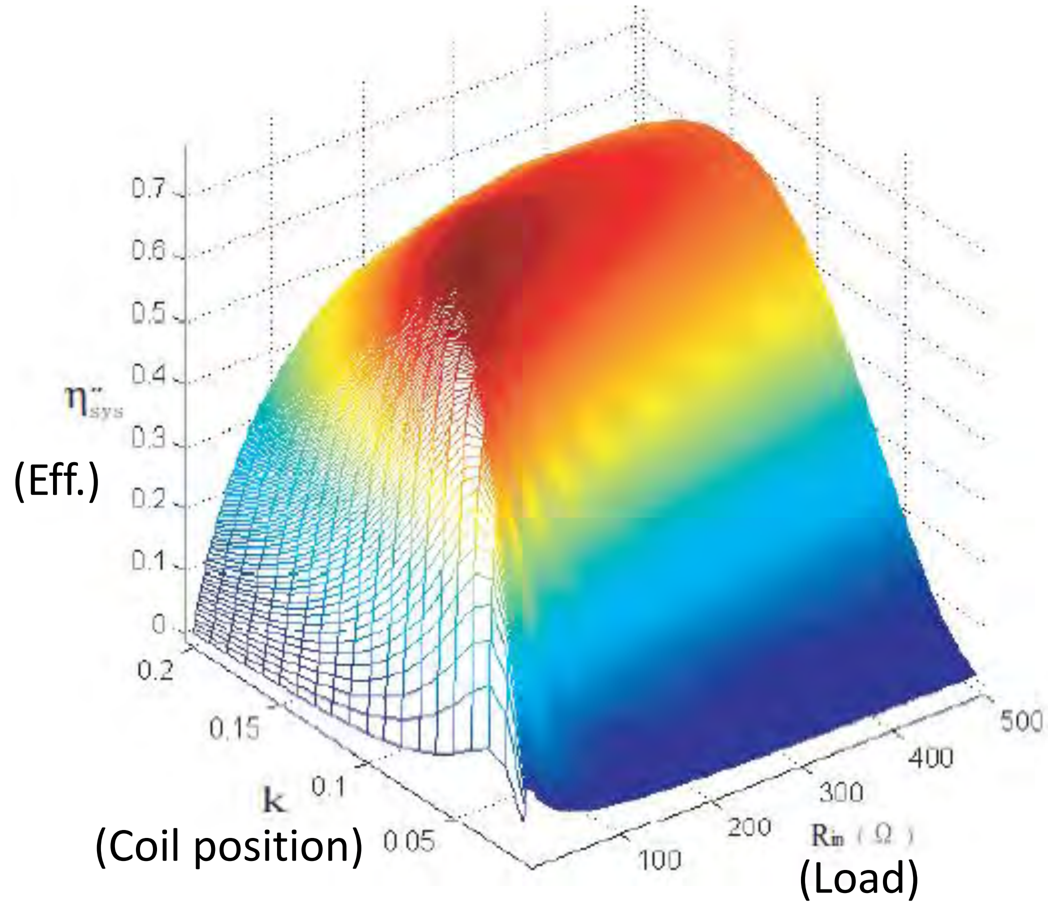
Optimal loads



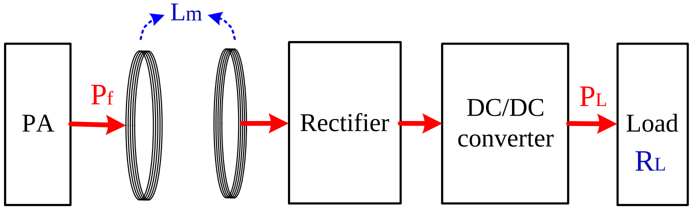


Optimal Load in WPT systems (2)

- 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.

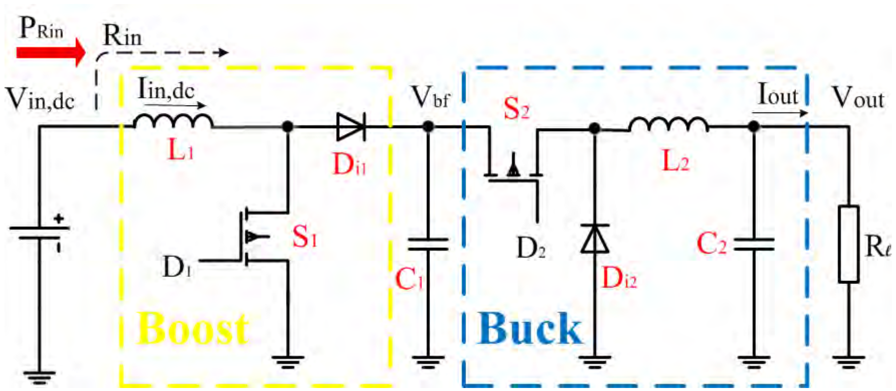


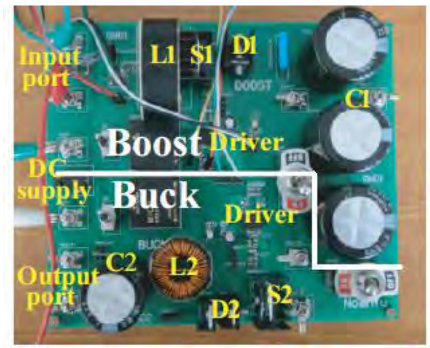
Cascaded Boost-buck Converter

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

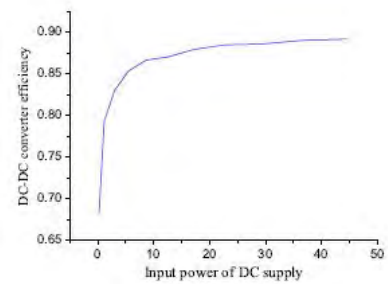
COMPARISON OF THE BASIC DC-DC CONVERTERS

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)

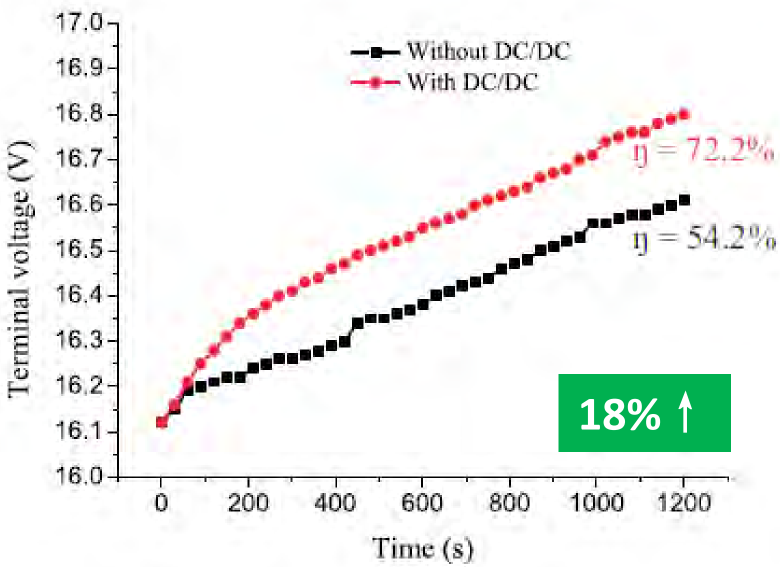


(b)

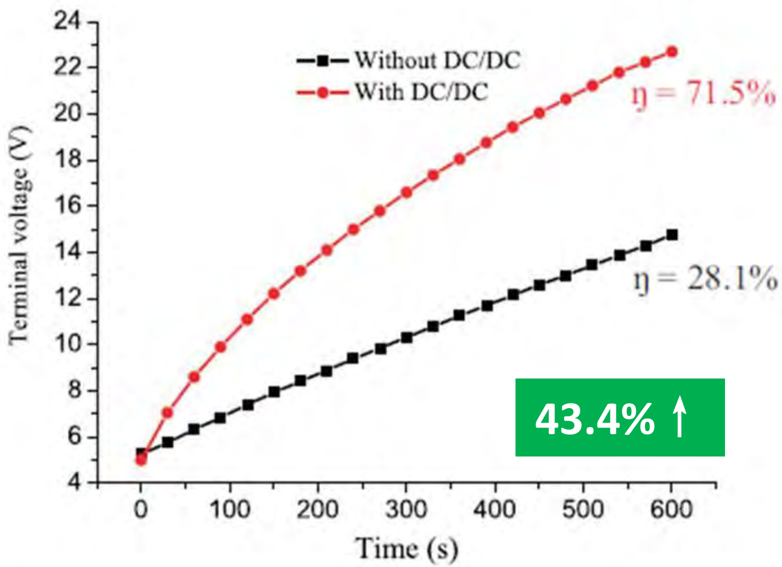
Cascade boost-buck converter. (a) Circuit board. (b) Efficiency.

13.56MHz Charging of Ultracapacitors

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



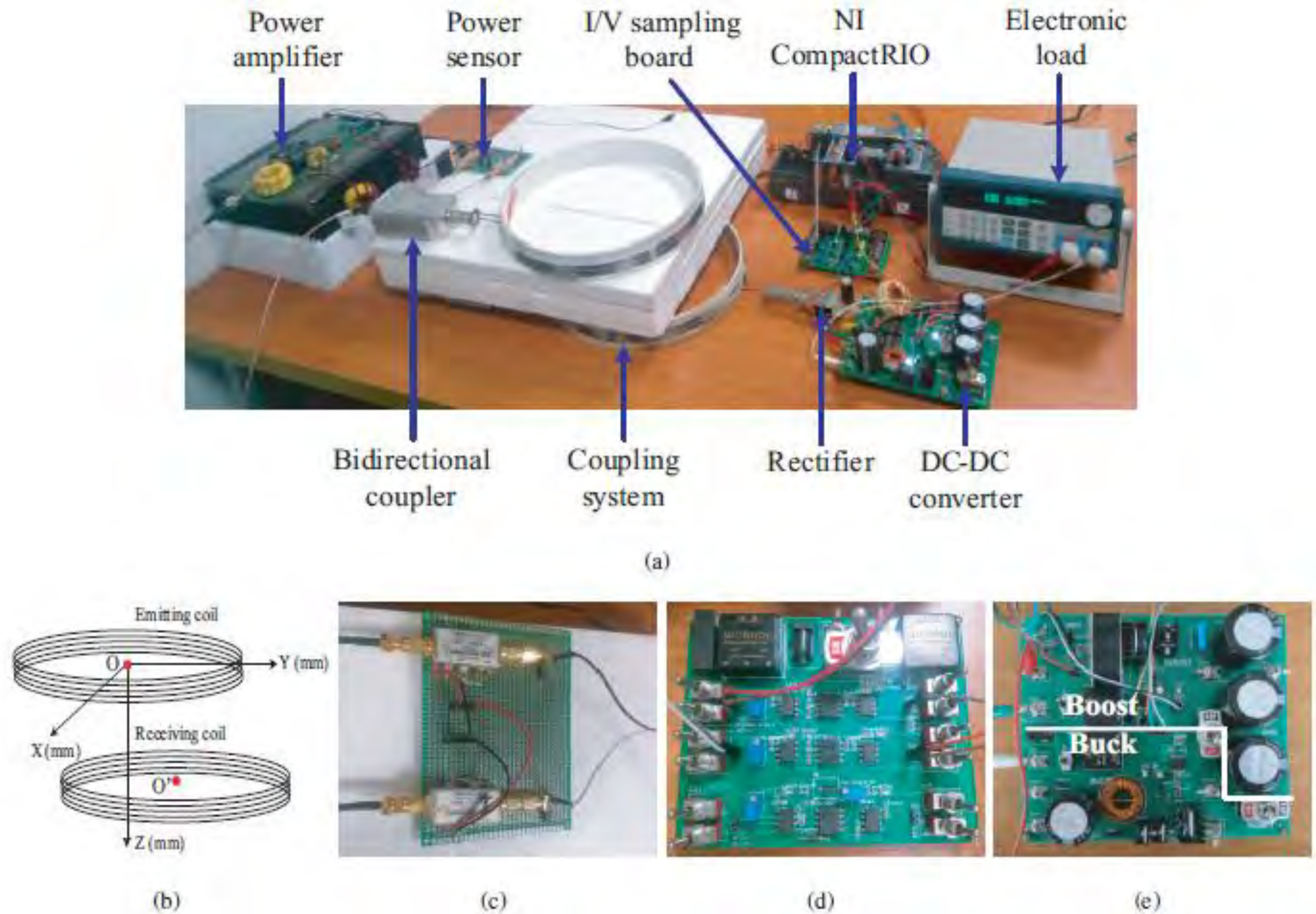
Batteries charging improvement using the cascaded boost-buck DC-DC converter.



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

[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.

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

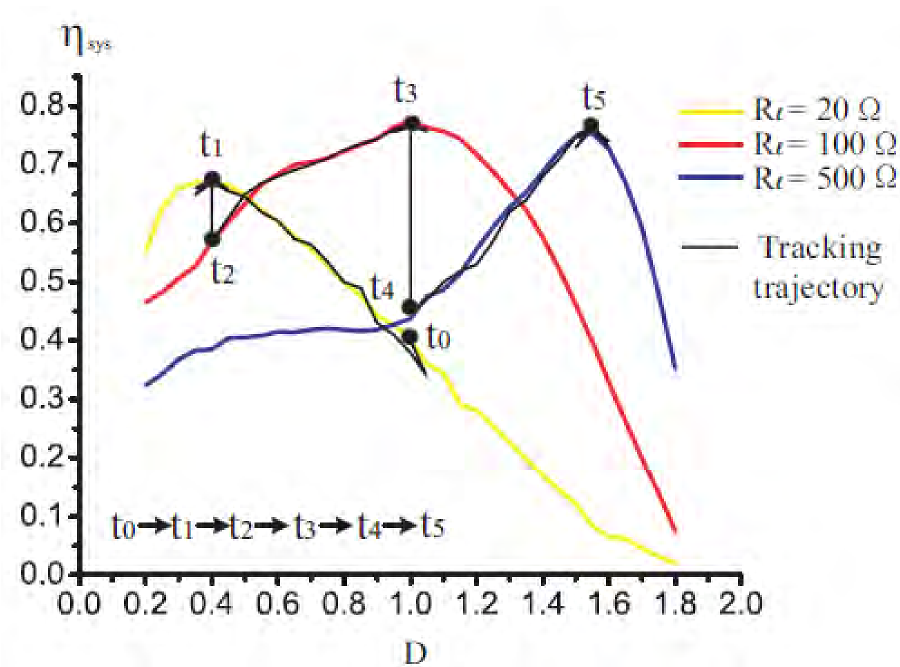


Fig. 1 Tracking of optimal load resistances with a varying R_l.

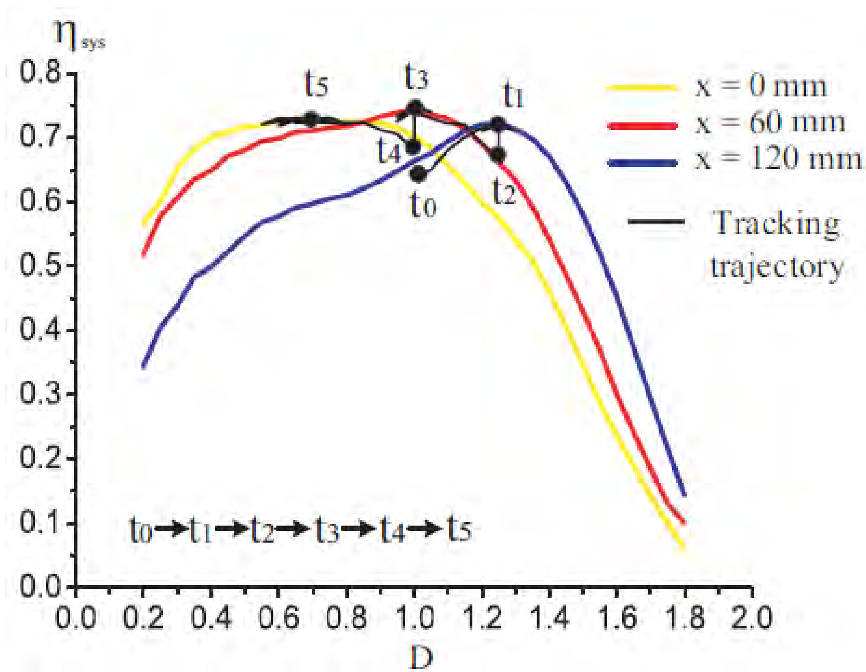
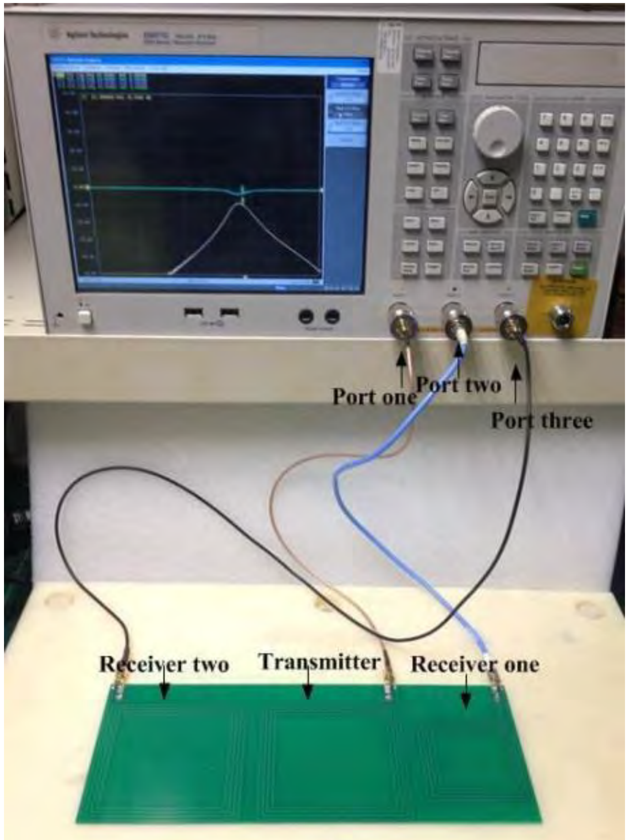
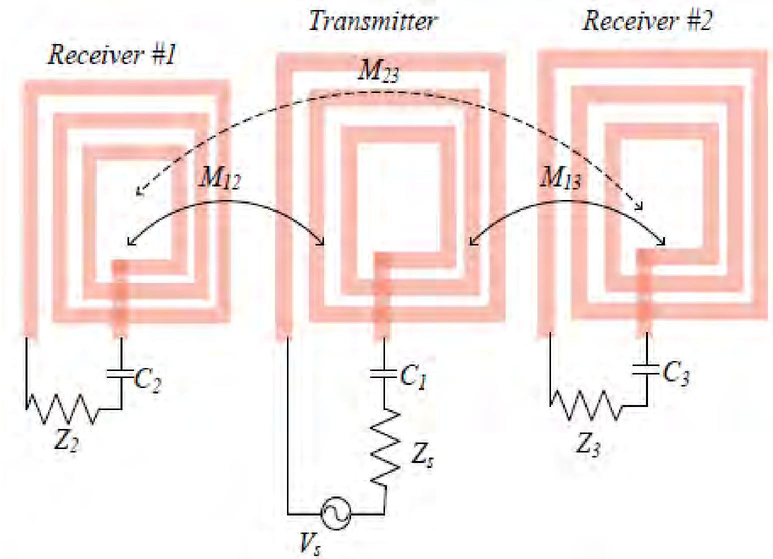


Fig. 2 Tracking of optimal load resistances with a varying *k*.

[1] 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





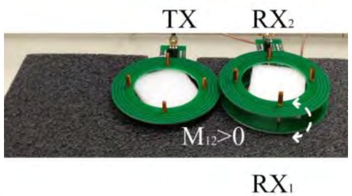
$$Z_{inopt} : Z_{2opt} : Z_{3opt} = R_1 : R_2 : R_3$$

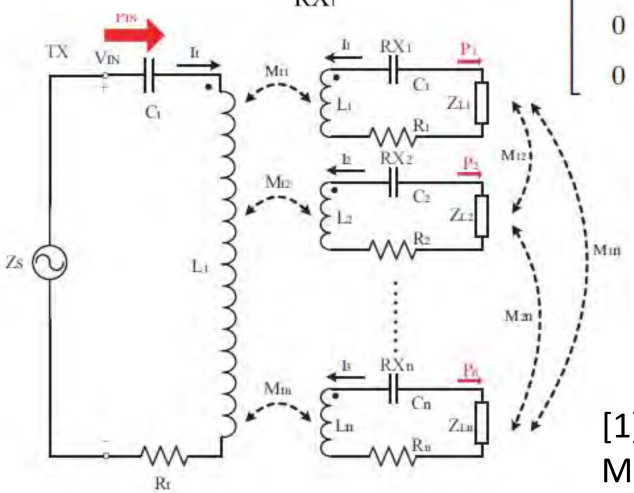
[1] T. Zhang, M. Fu, C. Ma, X. Zhu: "Efficiency and Optimal Loads Analysis for Multiple-Receiver Wireless Power Transfer Systems", IEEE Transactioins on Microwave Theory and Techniques, Vol. 63, No. 3, pp. 801-812, March 2015

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.



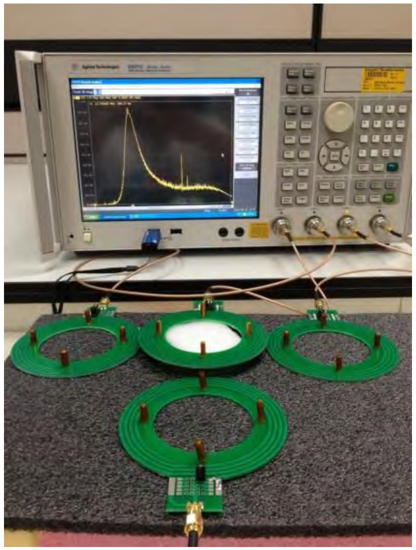


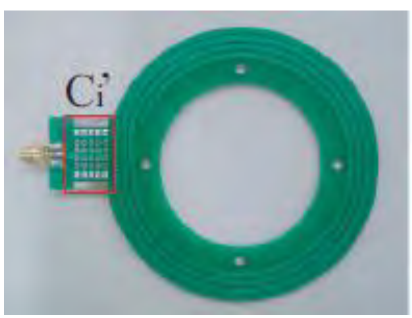
$$\begin{bmatrix} V_{IN} \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_t & j\omega M_{t1} & \cdots & j\omega M_{t(n-1)} & j\omega M_{tn} \\ j\omega M_{t1} & R_1+R_{L1}+jX_{L1} & \cdots & j\omega M_{1(n-1)} & j\omega M_{1n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ j\omega M_{t(n-1)}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

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

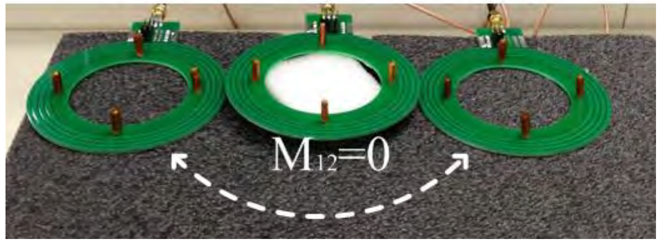
[1] M. Fu, T. Zhang, X, Zhu, P. C. K. Luk, C. Ma: “Compensation of Cross Coupling in Multiple-Receiver Wireless Power Transfer Systems”, (under review)

Experimental Results

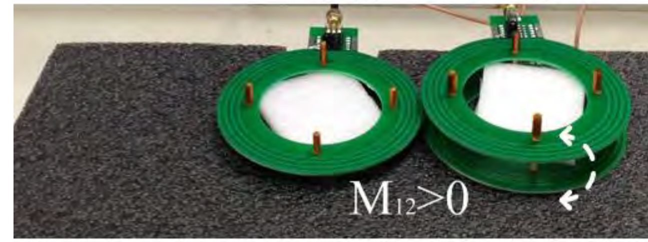




RX2 TX RX1



TX RX2



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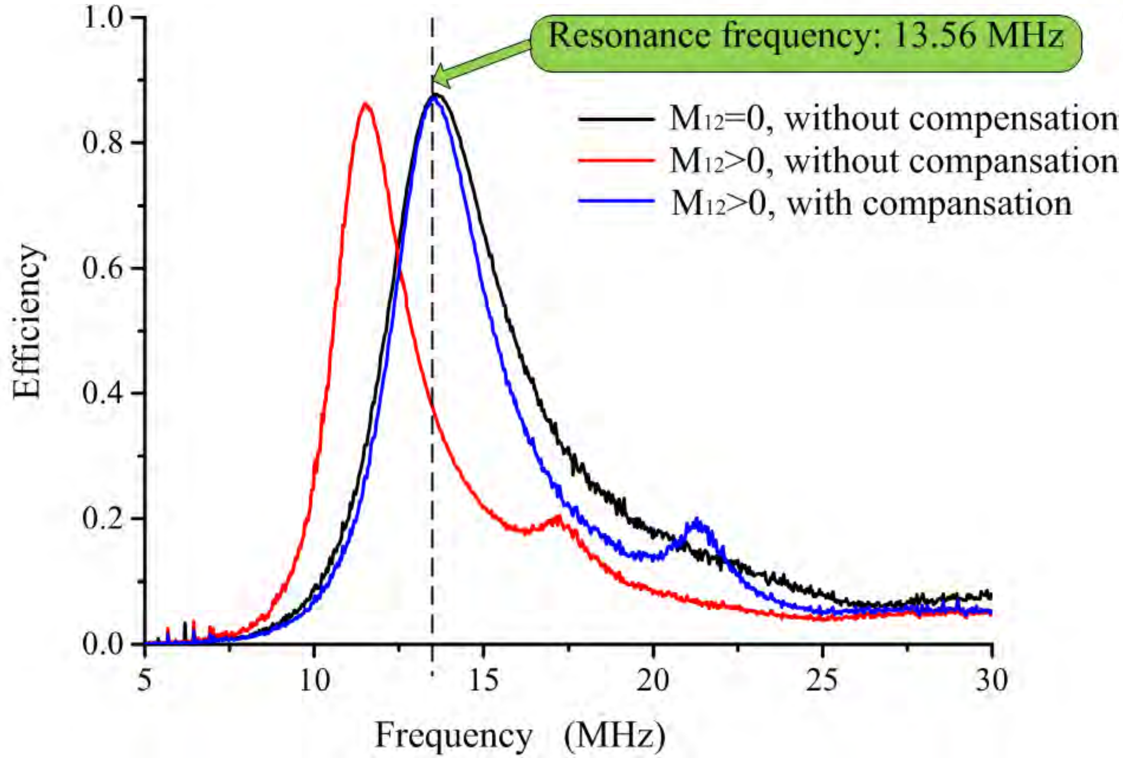
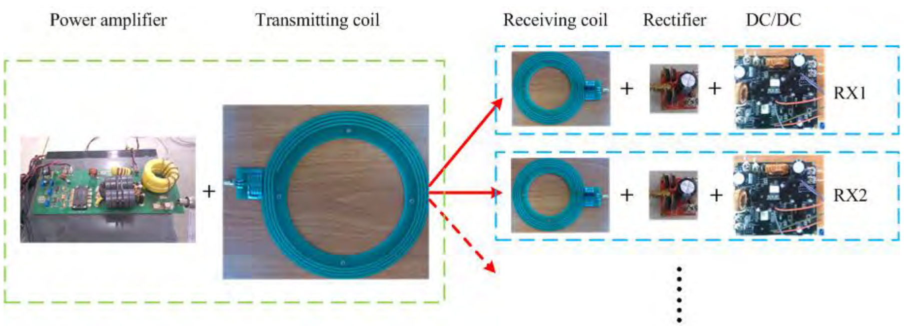
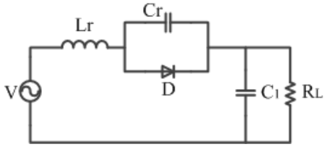
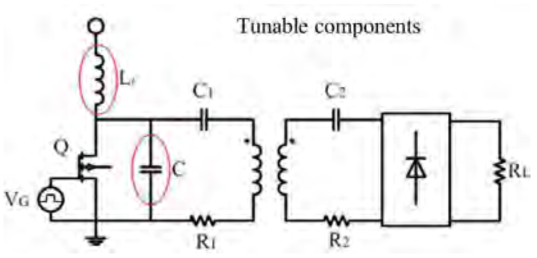


Ongoing Investigations

- Optimal power distribution among multiple receivers;
- Megahertz rectification such as using resonance Class-E rectifier;
- Megahertz waveform detection;
- Tunable Class-E power amplifier.

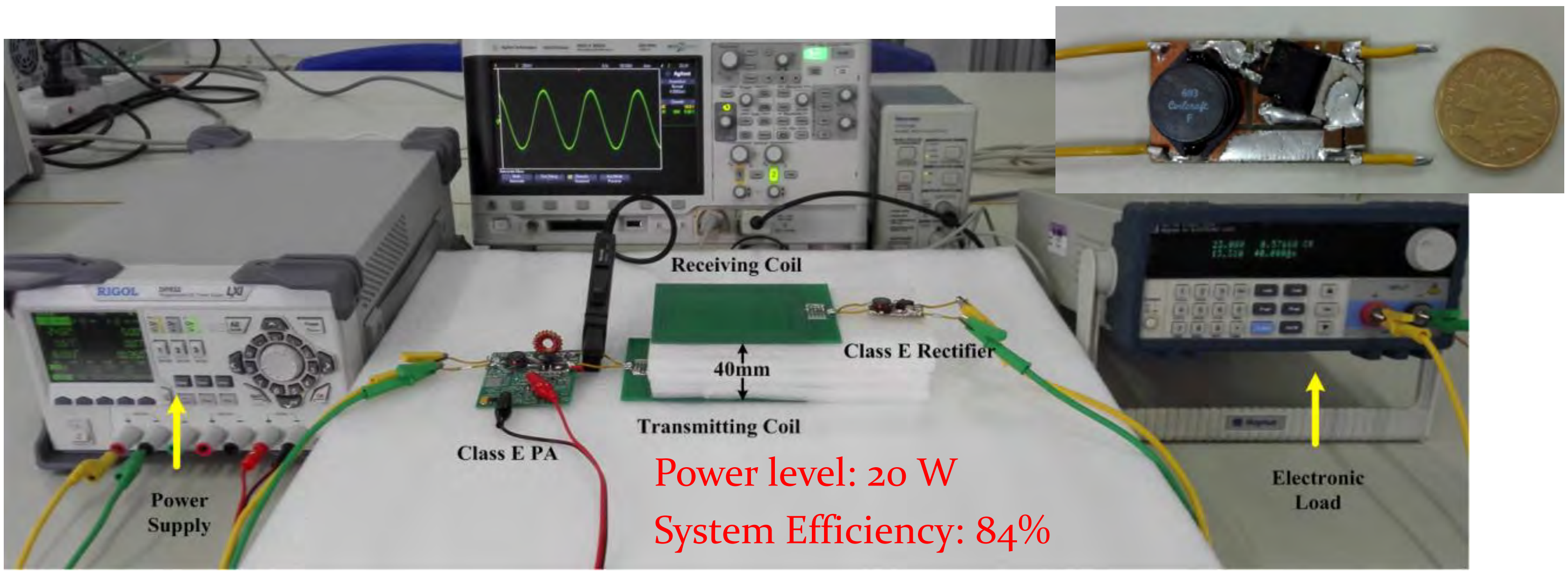






Class E Current-driven Rectifier

- High efficiency, low EMI, suitable for medium power transmission and high frequency rectification.
- Input impedance is analytically derived, for the first time, that guides the optimized parameter design of WPT systems.



[1] 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", (under review)

Outline

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

Conclusions

- A fundamental transition is occurring from control of "motion" to control of "energy".
- System-level analysis, optimization, and implementation of control are crucial.
- Major interests now:
  – Modeling and control of networked energy systems (battery, ultracapacitor, flywheel, fuel cell, solar panel, wind turbine, EV, home, etc.)
  – Closed-loop control of WPT systems (new sensor, tunable components such as PA, control methodology)
  – Autonomous power distribution among multiple receivers using game theory
  – Auto-tuning of controllers through polynomial method

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Thank You

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