Modular Electric Vehicle and The Control Technology

Chengbin Ma (马澄斌), PhD
Assistant Professor
Univ. of Michigan-SJTU Joint Institute
Shanghai Jiao Tong University
Shanghai, China

At The 3rd China New Energy Vehicle Forum, Shenzhen, China
Nov. 25-26th, 2013

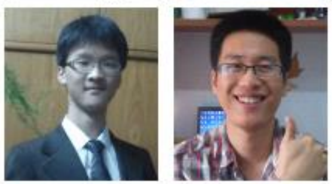
JOINT INSTITUTE
交大密西根学院

Outline

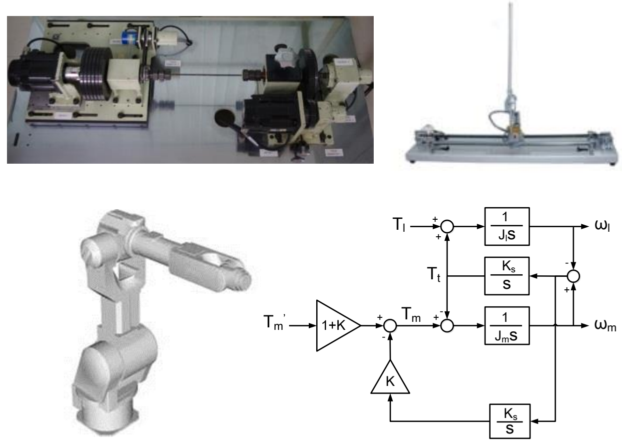
- Introduction
- Modular EV
- EV Dynamics
- Hybrid Energy System
- Wireless Charging
- Conclusion

Dynamic Systems Control Lab

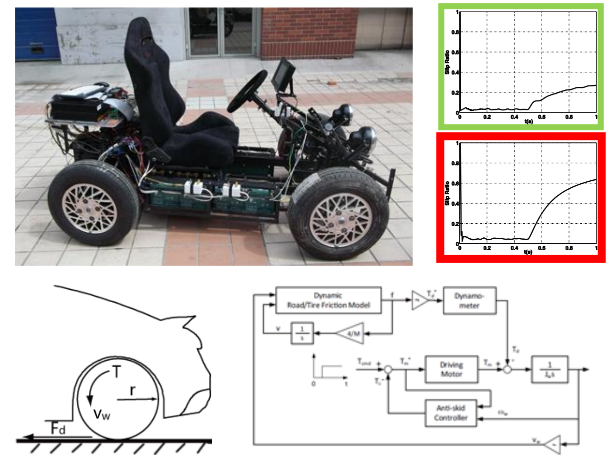
UNIVERSITY OF MICHIGAN



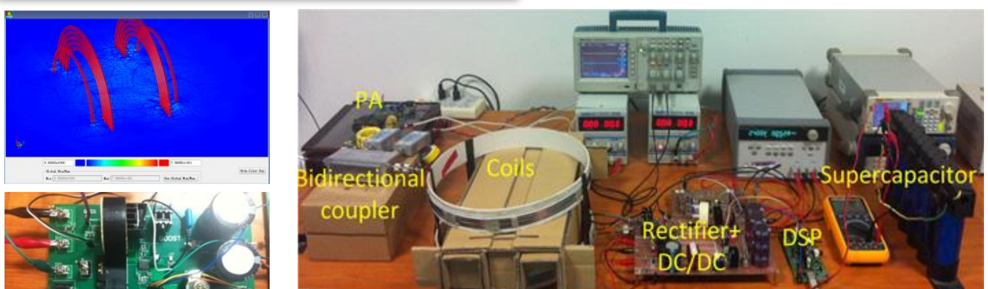
4 Ph.D.
4 M. S.

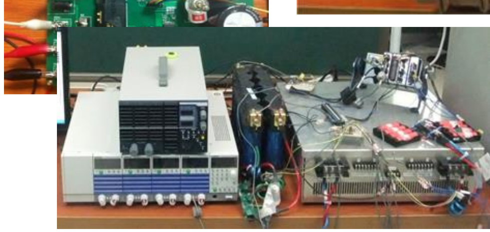


1. Motion/Motor Control



2. EV Dynamics Control





3. Hybrid Energy System

4. MHz Wireless Charging

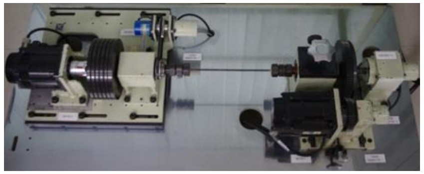
Control of Motion & Energy

General Interests

Control of

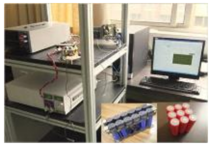
Motion



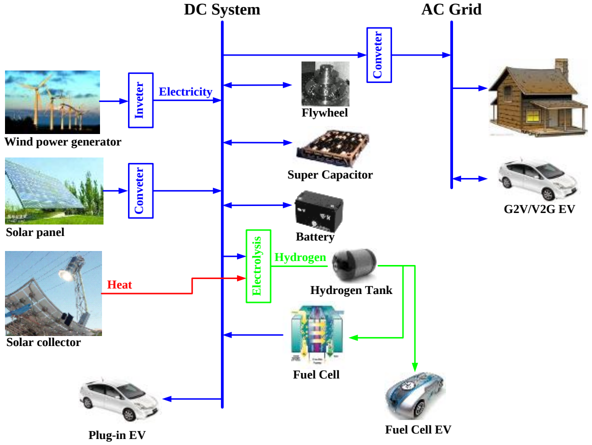



- Speed
- Precision
- Efficiency

Energy




- **Secure**
- **Flexible**
- **Caring**
- **Invigorating**



Various Plans

	10^{th} 5-years: 2001-2005	11^{th} 5-years: 2006-2010		12^{th} 5-years: 2011-2015	
Focus	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell	Fuel Cell
	HEV	HEV	HEV	HEV	HEV
	BEV	BEV	BEV	BEV/PHEV	BEV/PHEV

Goals	(2005) 5-10% share in 2010 50% share in 2030	(2008) 10% share in 2012	(2009) 500K production 5% share in 2011	(2010-2011) 1 Million EVs in 2015 5 Million EVs in 2020

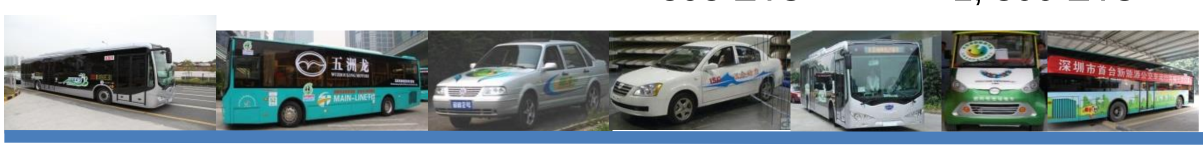
Similar with the goals of DOE, USA

Reality

Beijing Olympic
595 EVs

Shanghai EXPO
1, 300 EVs

Production: 12,784
Model: 361
Company: 75
⇒ **36/model**
170/company



Demonstration

2011

High End versus Low End

BYD

JAC

SAIC

ZOTYE

SHIFENG

Roewe E50
Price: 234,900RMB ($37,887)
Subsidy: 106,900RMB ($17,242)
Range: 180Km
Max speed: 130Km/hr
Battery: 18kWh

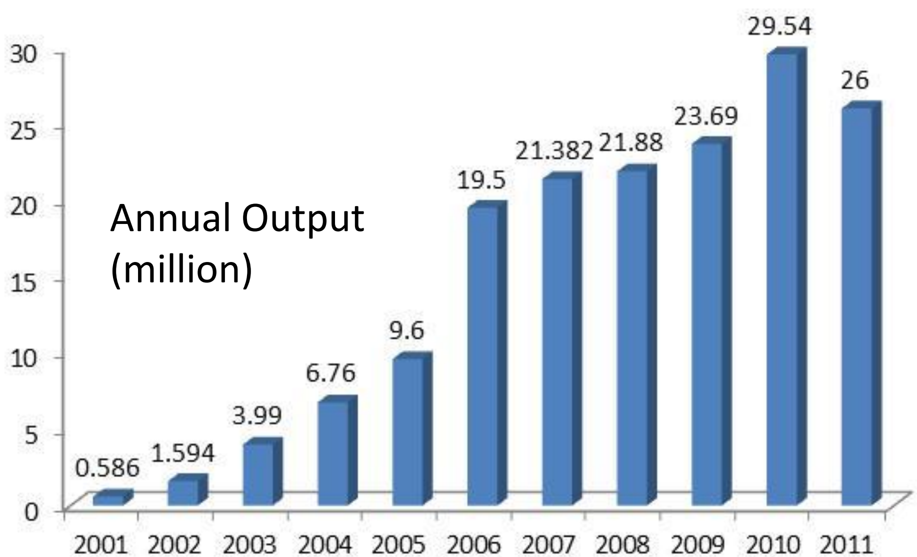
Price: 31,800RMB ($5,129)
Range: 180Km
Max speed: 55Km/hr
Battery: Lead-acid

83,300 low-speed electric vehicles were sold in Shandong Province in 2012.

Significant Success of e-Bike Industry

- In 2011, over 26 million e-bikes were produced.
- A unique highly modularized industry

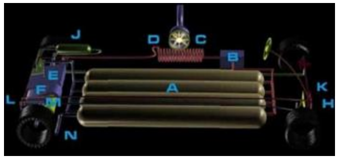
≈ $300



Battery Bottleneck

- Dynamic energy supply and consumption
  - Acceleration/Deceleration, Regenerative braking, 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).
  - Multiple energy storage devices with various dynamics are naturally required: Ultracapacitors, Flywheels, Compressed air tank, etc.

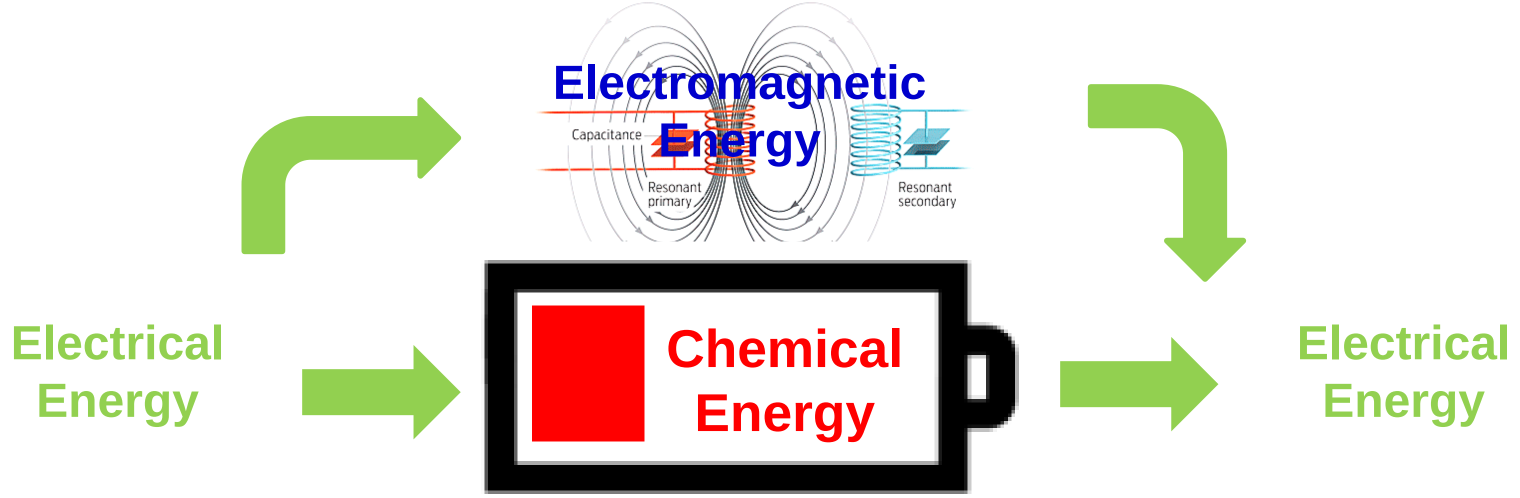




Wireless Charging (1)

- The electrification could extend beyond delivering electrical energy and converting it into chemical energy through batteries.
- It can effectively extend the mileage, lighten the weight, diversify energy sources and reduce our reliance on scarce resources such as lithium.

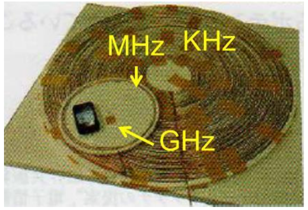


Wireless Charging (2)

Example: 20KHz 30kW wireless charging systems:

Company	Efficiency	Air gap (mm)	Weight of Receiving coil and core (kg)	Size L*W*D (mm)
Conductix-Wampfler	86%	50	**70Kg**	1025*875*61
Showa Air Craft	92%	100	**35Kg**	847*847*33

- Current systems usually operate in kHz range because the state-of-art power electronic devices are available for both power generation and conditioning.
- This low frequency requires a large size coil and heavy ferrite materials, which is not favored by vehicles in terms of payload efficiency.



Outline

- Introduction
- Modular EV
- EV Dynamics
- Hybrid Energy System
- Wireless Charging
- Conclusion

Energy-Inefficient Modern Cars

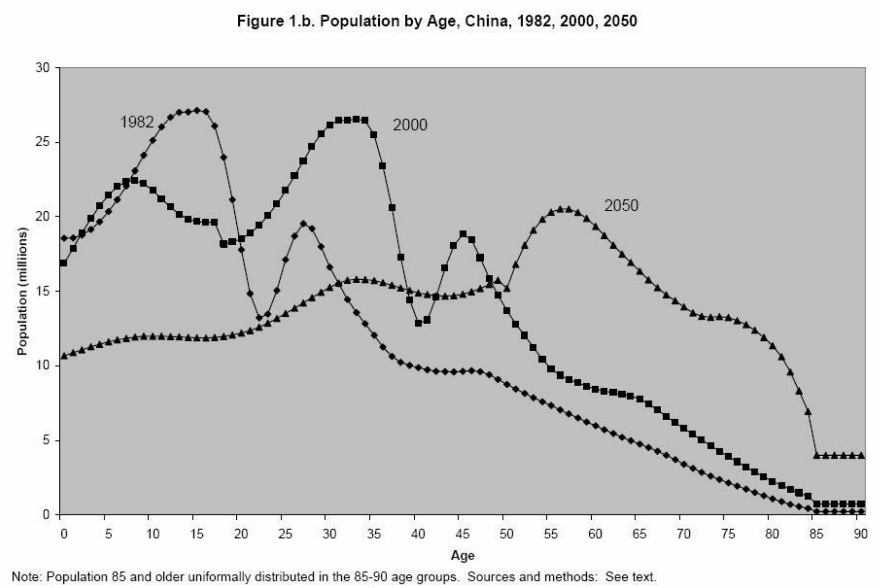
- People use only a tiny portion of its potential for the most of time
- The modern cars are designed to be all things to all the people, which leads to the inefficiencies.

A cautious man carries an umbrella every day…

− seat five
− more than l00mph
− accelerate from 0-60 in about 10 seconds
− easily break 40mpg
− be able to work at more than 50C
− warm passengers/ engines at -30C.
− usually also have big trunks.

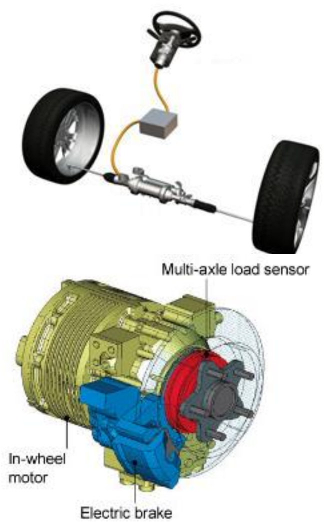
EV-A Consumer Electronics Product

- Consumer electronics products naturally tend to be personalized, portable and small.
- Long-term problem of battery and aging population are the fundamental background.
- There is a need and technological feasible to develop low-speed small EVs.



Nature of Electrical System

- Electric/electronic devices are naturally easy to be modularized.
- The realization of modular EV would improve the market competition and thus significantly reduce the cost.
- The success of Chinese e-bike and low-cost EV industry has proved a unique strength of the modular electric vehicle and the new industrial structure.



Matured Low-Cost Components

- Especially motor, inverter and lead-acid battery are becoming both technological and commercially matured.

Searched on Taobao online shopping site

48V 500W
BLDC Motor
(100RMB, $56.5)

48V 500W
BLDC Controller
(100RMB, $16)

48-72V 350-2000W
E-Drive Set
(680-1,500RMB, $109.68-241.94)

48-84V 2,000W Motor
(1,270RMB, $204.84)

48-72V 4,500W Controller
(1,500RMB, $241.94)

E-bike

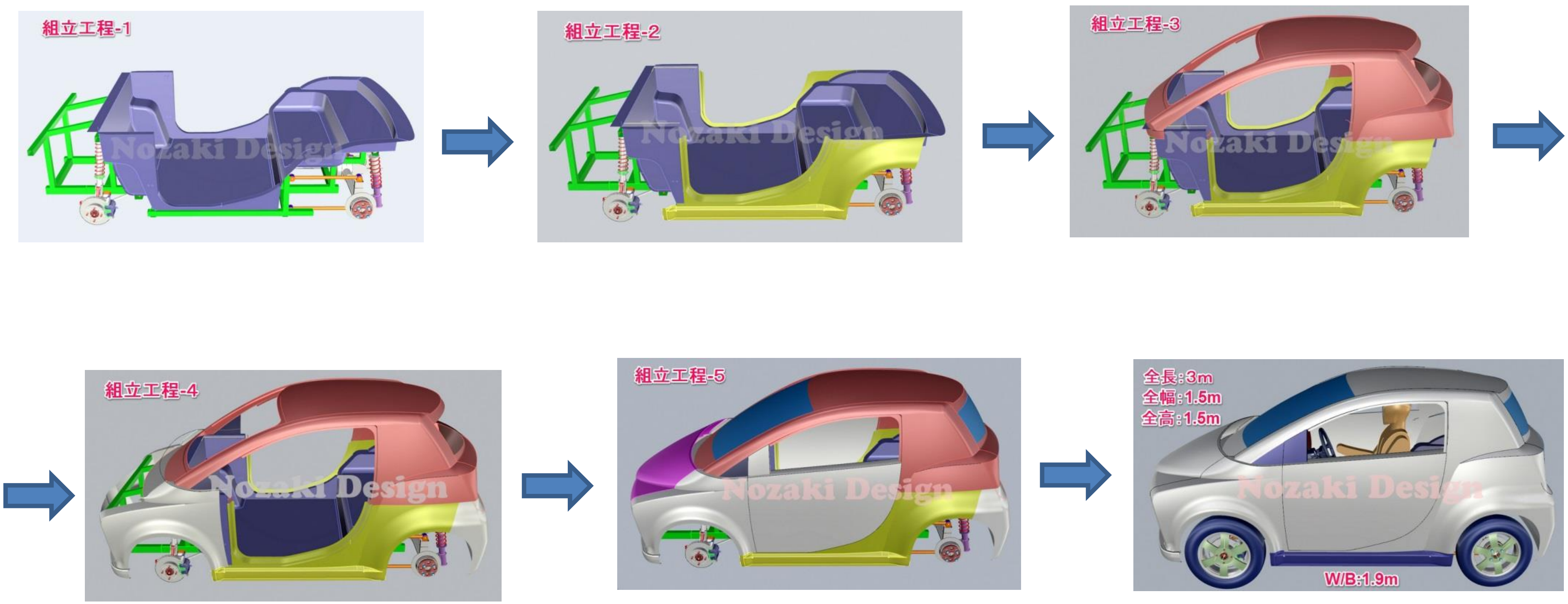
E-scooter

E-motorcycle

E-vehicle?

Our Practice

- Metton: liquid molding resin



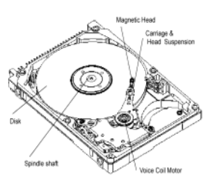
Outline

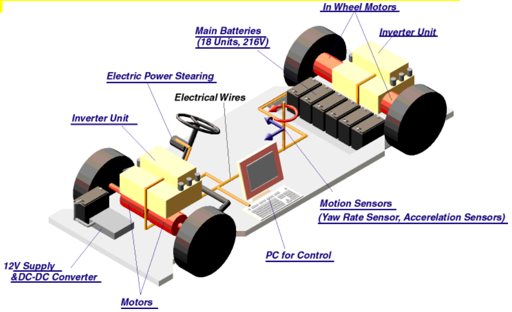
- Introduction
- Modular EV
- EV Dynamics
- Hybrid Energy System
- Wireless Charging
- Conclusion

Advantages of e-Drive

- Fast and accurate torque control
- Simple and accurate dynamic model
- Fast and accurate current/torque feedback
- Capable to generate driving/braking forces
- Easy to implement distributed motor systems

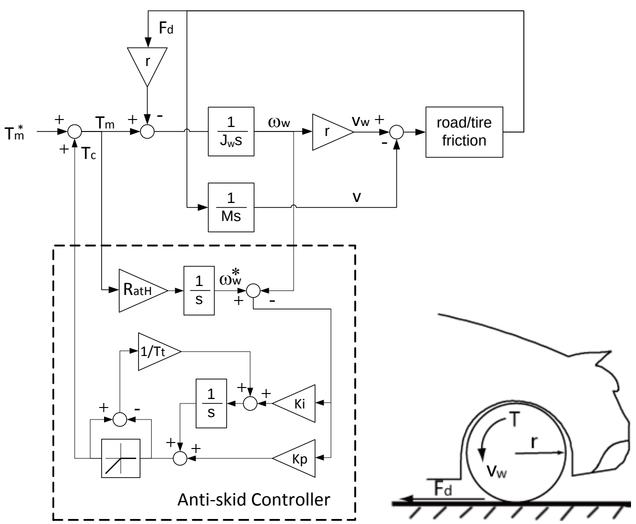
Motors can be utilized not only for propulsion, but also as "actuators" and "sensors".

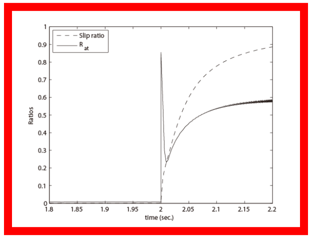


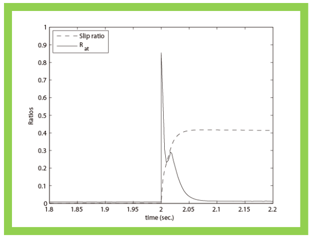


EV Dynamics Control

- EV Motion Control:
  - Traction Control
  - Assistive Braking Control
  - Vehicle Stability Control
  - Eco-driving Assistance

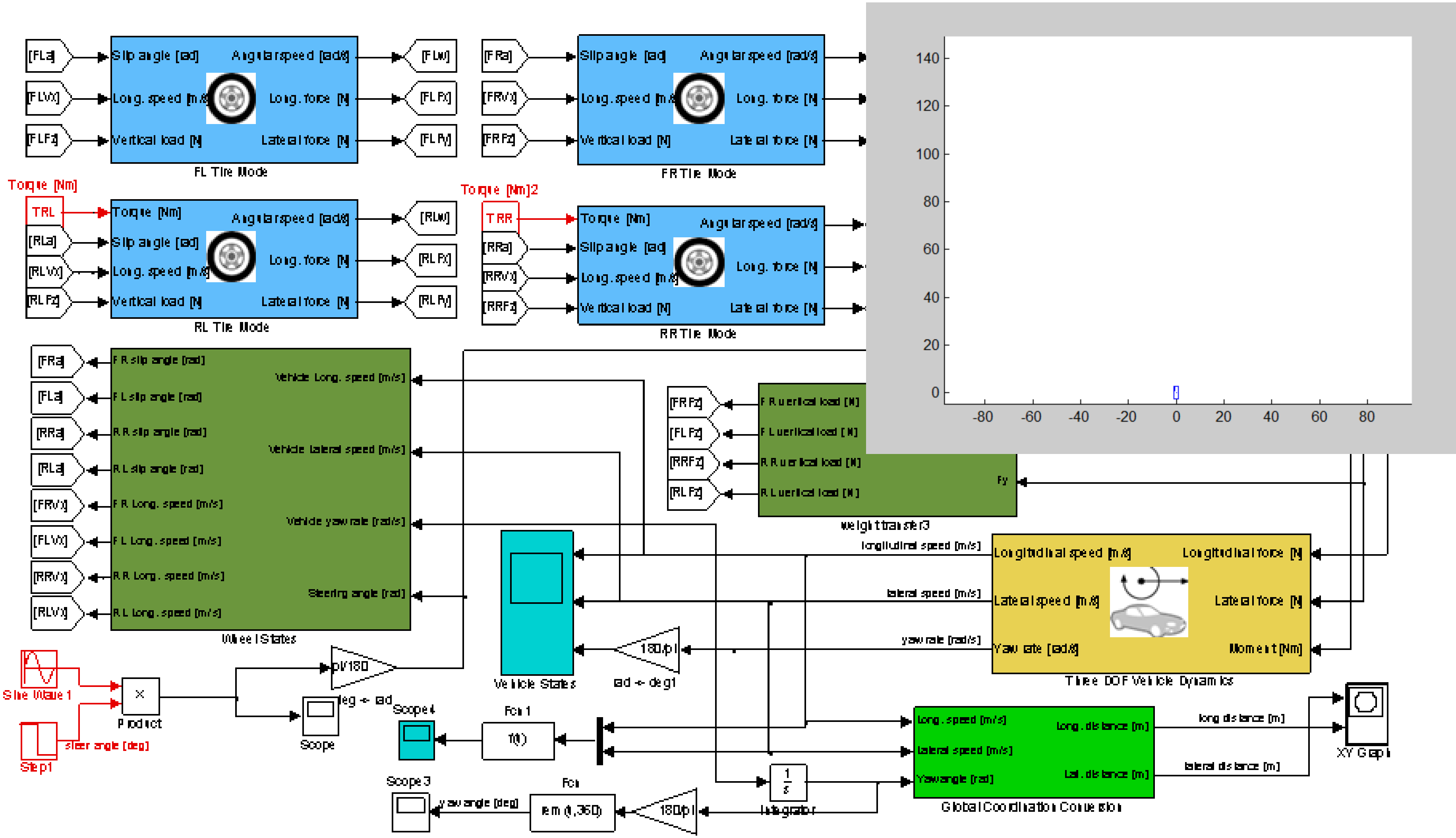






Video

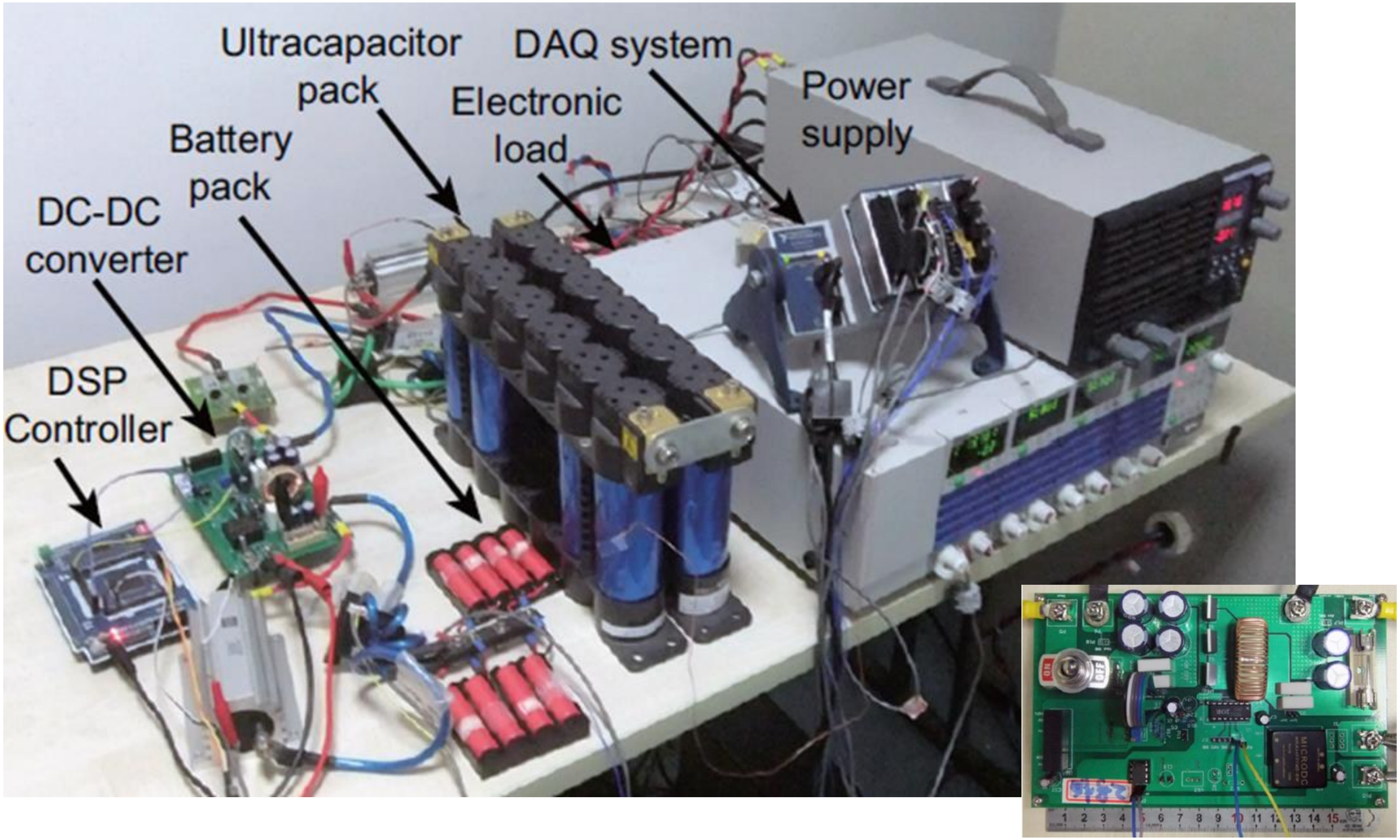
Four WD EV Modeling



Outline

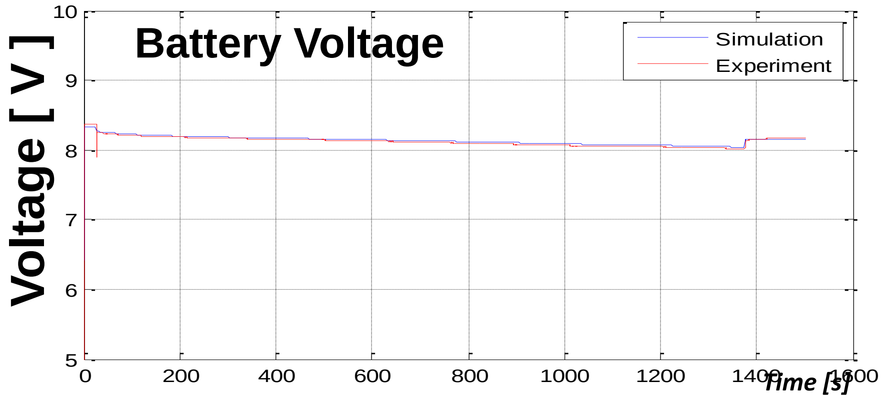
- Introduction
- Modular EV
- EV Dynamics
- Hybrid Energy System
- Wireless Charging
- Conclusion

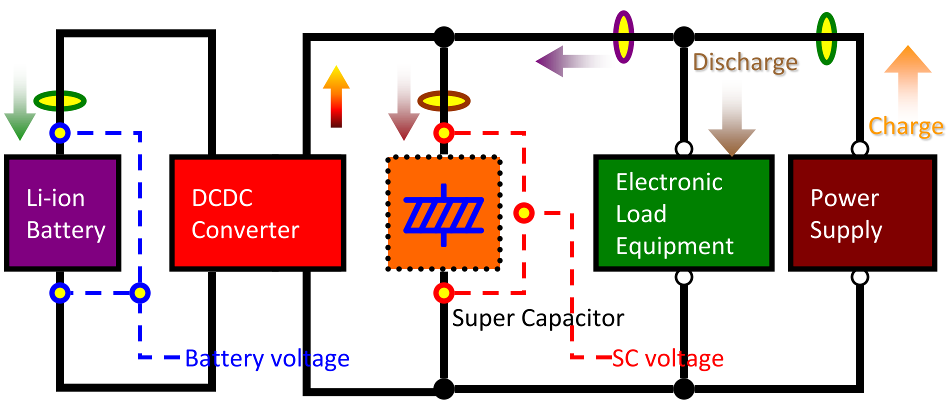
Battery-Ultracapacitor Test System



Dynamic Modeling

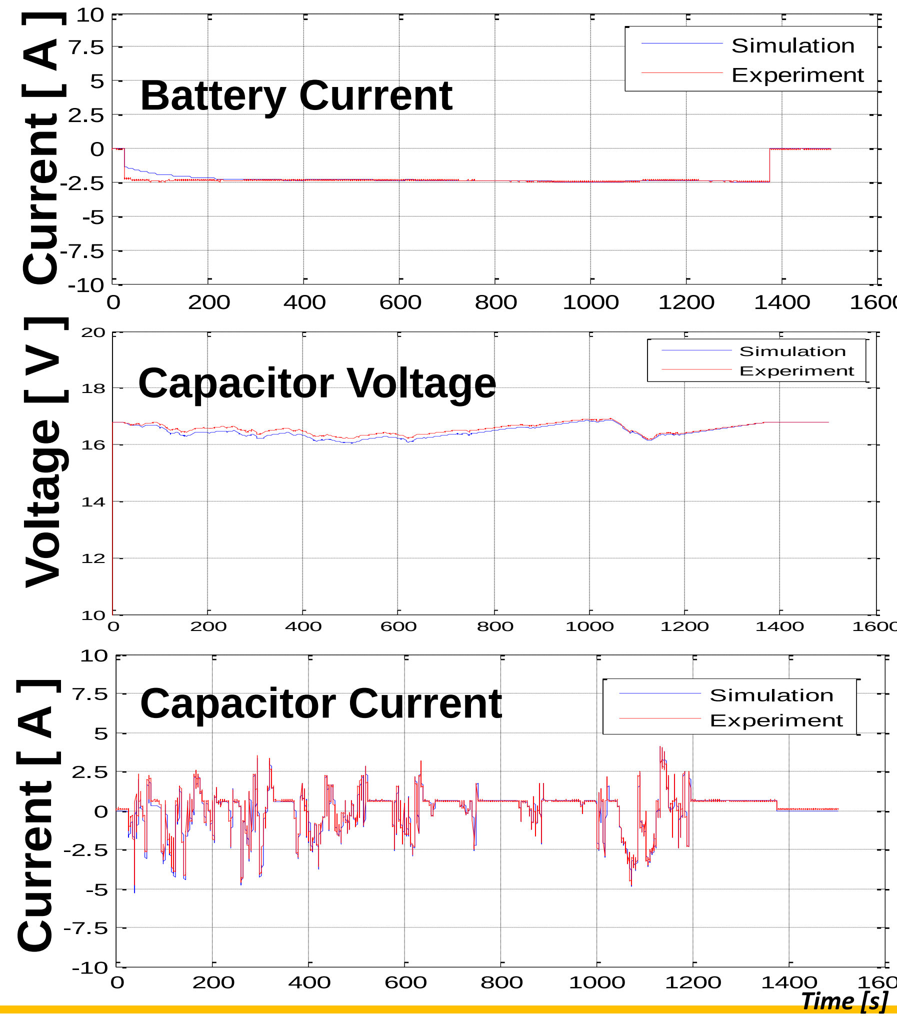
Initial Battery SOC: 1.0(@16.8V)
Regeneration Velocity Constrains: V>20km/h





7.4V 10Ah (2S4P)

Current Converter System



Comparative Study

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

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(@7.4V)
End_of_SOC	0.4532	0.4051	0.3559
Energy_Efficiency[%]	91.05	89.12	87.84

Battery-Only System

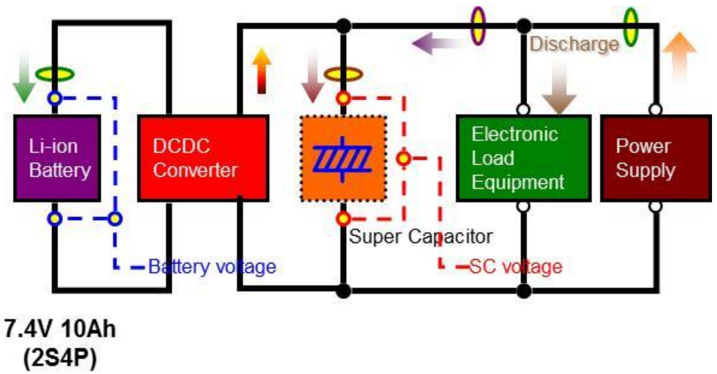
Peak_Current	5A	10A	15A
Initial_Battery_SOC	0.5(@14.8V)	0.5(@14.8V)	0.5(@14.8V)
End_of_SOC	0.4514	0.3946	0.3224
Energy_Efficiency[%]	89.13	82.67	74.01

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	0.4518
Energy_Efficiency[%]	91.05	89.45	88.52

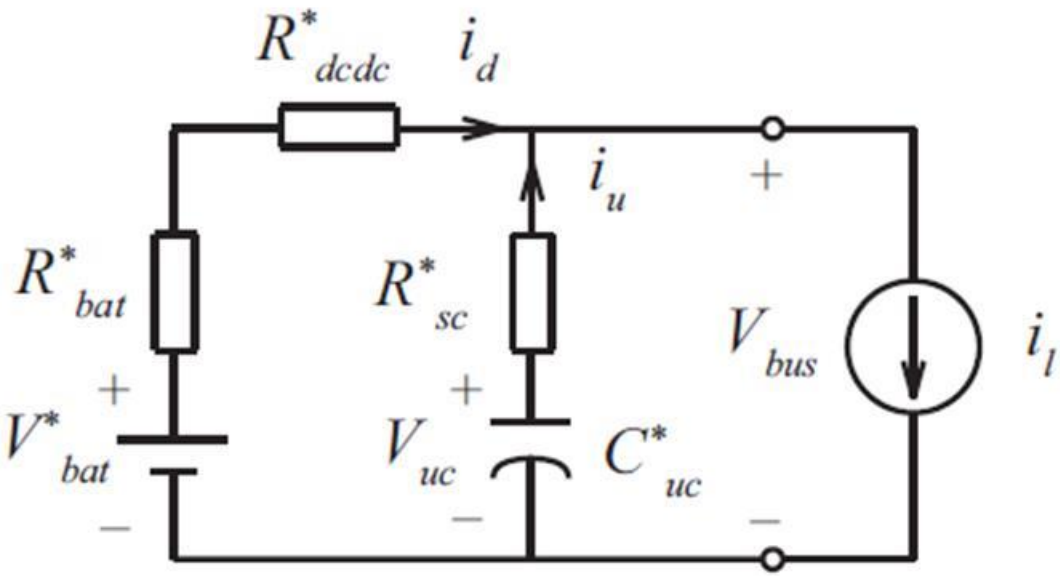
Battery Resistance Amplification Coefficient K	1	2	3
Initial_Battery_SOC	0.5(@14.8V)	0.5(@14.8V)	0.5(@14.8V)
End_of_SOC	0.4514	0.4480	0.4432
Energy_Efficiency[%]	89.13	83.31	76.41

ESR-based Efficiency Analysis

- Equivalent-Series-Resistance circuit Model:



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

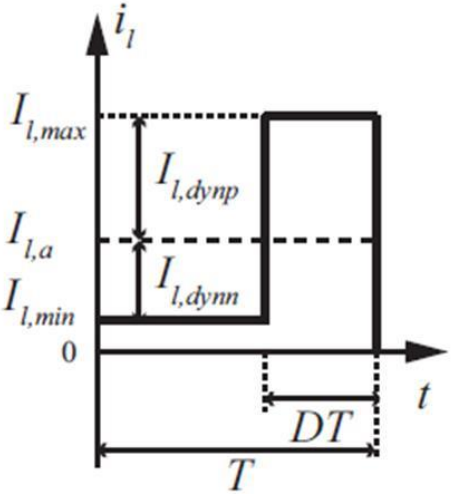


$$R_b^* = \frac{P_{loss,b}}{i_d^2} \approx \frac{i_b^2 R_s}{i_d^2} = \frac{R_s}{(1-d_s)^2},$$

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

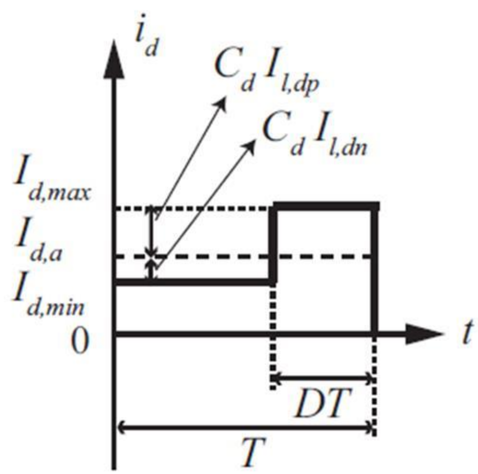
Optimized Current Distribution

- It is theoretically guaranteed that ultracapacitors should provide the most of dynamic load current.

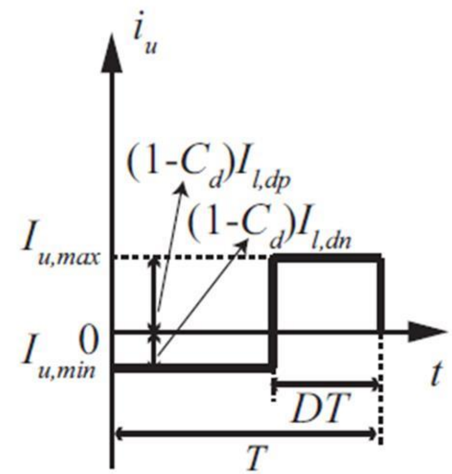


$$\ldots_{loss} = -I_{l,dp}I_{l,dn}(R_b^* + R_{d,r}^* + R_u^*)\left(C_d - \frac{1}{1+K}\right)^2 T - I_{l,dp}I_{l,dn}R_p^* T + I_{l,a}^2(R_b^* + R_{d,r}^*)T + I_{l,a}V_F T,$$

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



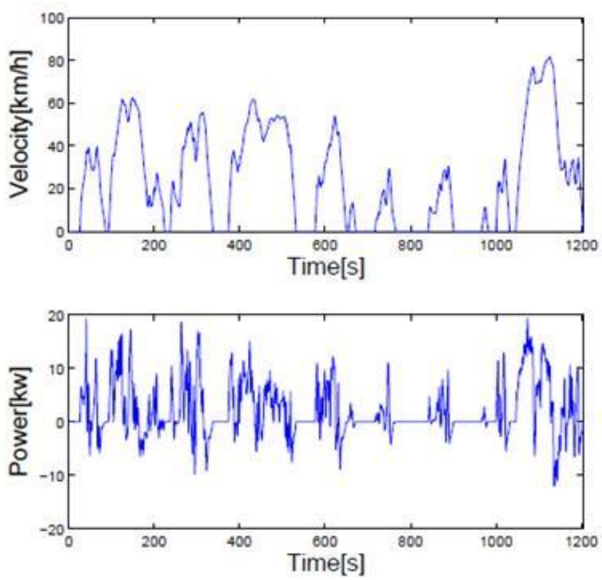
Current from DC-DC converter.

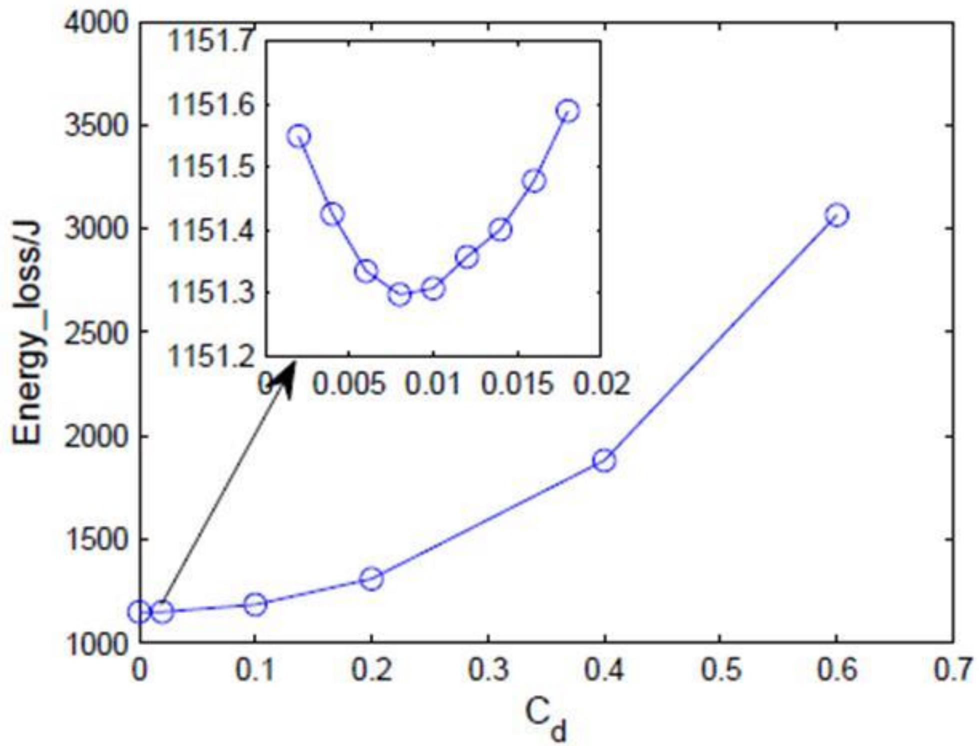


Current from ultracapacitor pack.

Experimental/Simulation Verification

- JC08 driving cycle is applied.





$$K^* = \frac{\frac{R_s}{(1-d_{s,a})^2} + \frac{R_{in} + R_{F1} + R_L + d_{s,a}R_{on}}{(1-d_{s,a})^2} + R_{out} + R_{S1} + R_b}{R_{sc}},$$
$$= 82.$$

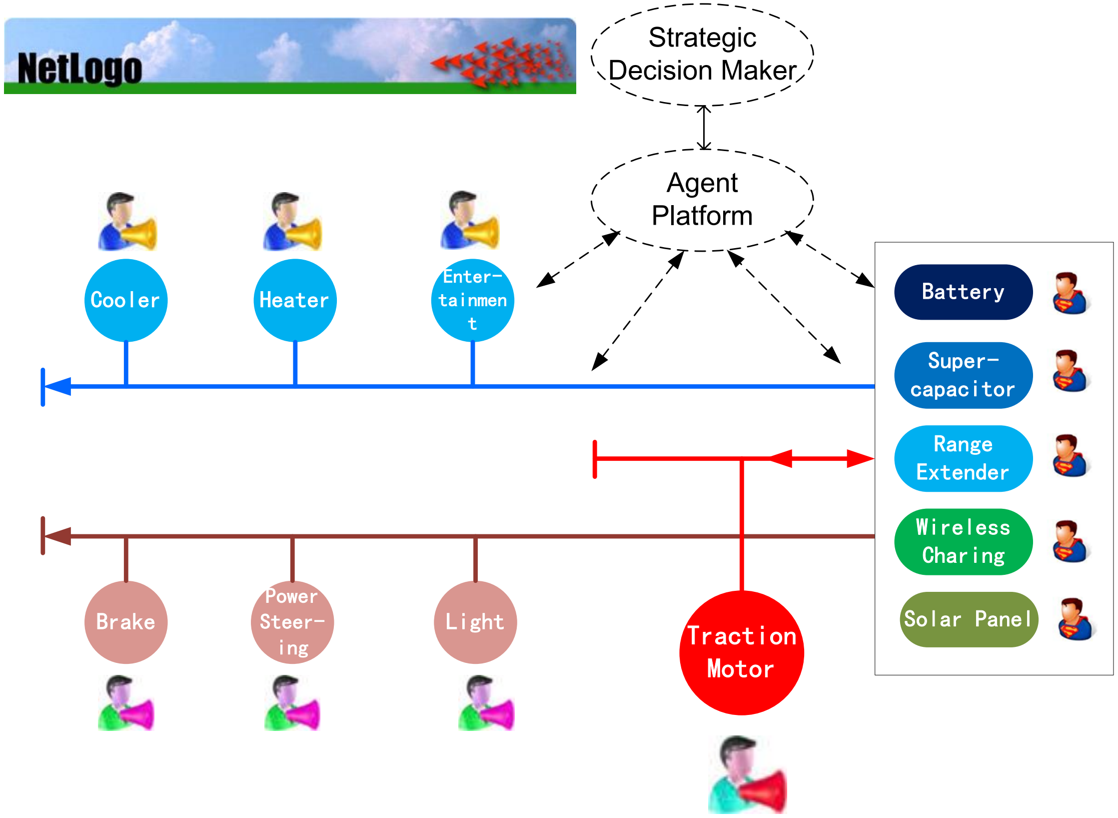
$$C_d = \frac{1}{1+K^*} = 0.012.$$

Ongoing Aging Test

- Test at higher temperature (45 deg.) to accelerate the aging of batteries.
- Four scenarios (3 months):
  1. Battery-only without charging/discharge: calendar life
  2. Battery-only: establishment of a baseline
  3. Ultracapacitor-battery hybrid (No.1): batteries only provide average load current.
  4. Ultracapacitor-battery hybrid (No.2): limited number of ultracapacitors, thus batteries have to supply certain part of dynamic load current.

Control of Networked Energy Systems

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



Multi-agent Interaction Modeling

Strategic Interaction Analysis

Technical Committee (TC) on "Energy Storage Devices and Systems" (ESDS)

Utility-Function based Optimization

- battery cycle life versus. energy efficiency.

Battery Bank

$$u_{bat} = u_{life} = w_{ave}u_{ave} + w_{dif}u_{dif}$$

$$u_{ave} = 1 - a(I_{bat} - I_{ave})^2$$

$$u_{dif} = 1 - b(I_{bat} - I_{lbat})^2$$

Ultracapacitor Bank

$$u_{cap} = w_e u_e = w_e[1 - c(I_{cap} - I_{fit})^2]$$

$$c = (I_{cmax} - I_{fit})^{-2}$$

$$I_{fit} = \left(2\frac{U_{cap}^2 - U_{emp}^2}{U_{cmax}^2 - U_{emp}^2} - 1\right)I_{cmax}$$

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

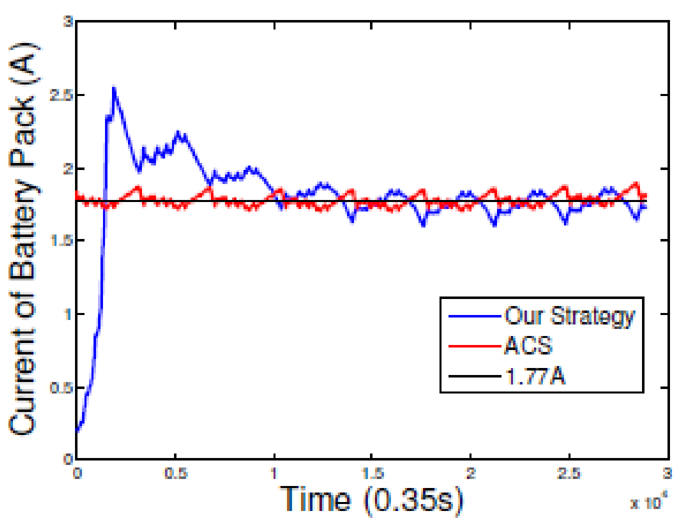
Karush–Kuhn–Tucker (KKT) conditions can be used to solve the problem.

Results using JC08 Cycle

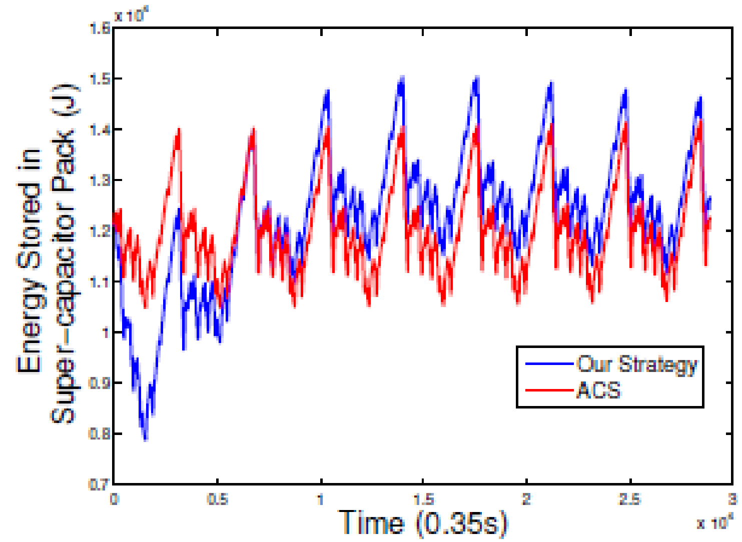
- Similar results with average current control, which needs to know future power demand.

SIMULATION RESULT ANALYSIS

Strategies	I_{bave} (A)	I_{bvar} (A^2)	E_{cap} (J)
ACS	1.325	0.0255	12731.2
Our strategy	1.35	0.0486	12922.9

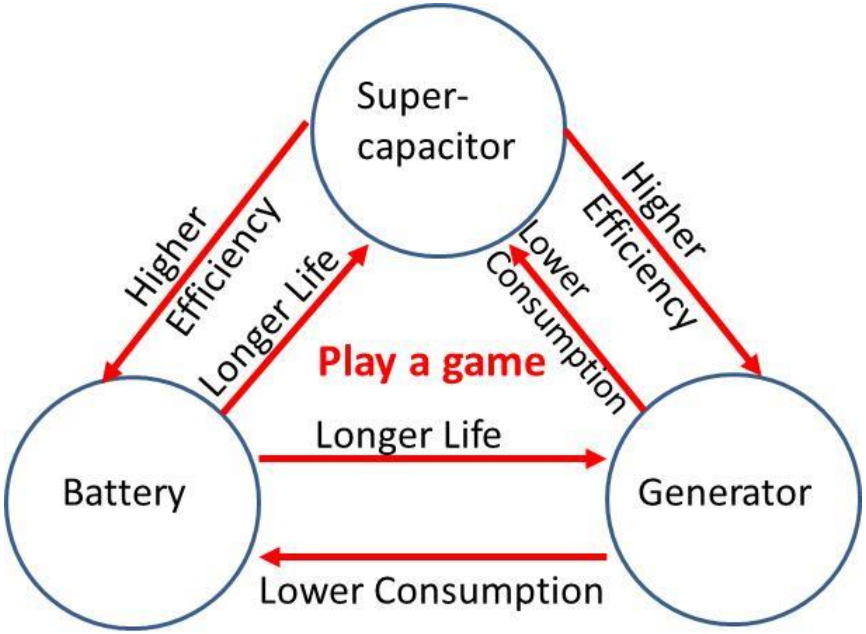


(a) Current of Battery Pack



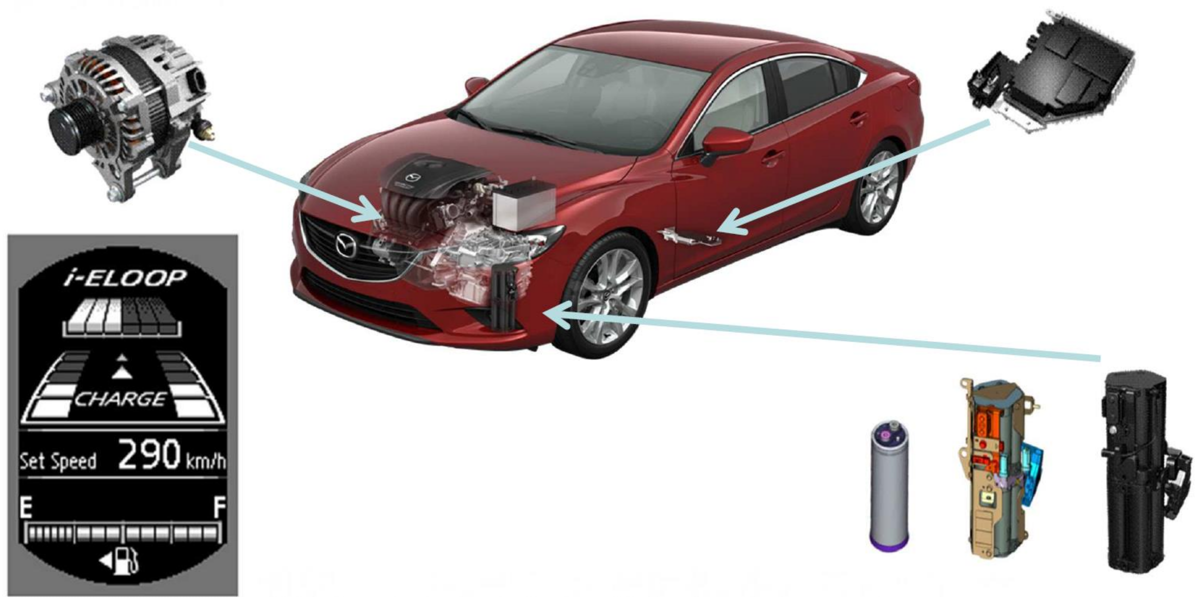
(b) Energy in Super-capacitor Pack

Future work (1)



- Battery, supercapacitor hybrid energy system with an additional generator
- Game theory based control strategy

Future work (2)



Outline

- Introduction
- Modular EV
- EV Dynamics
- Hybrid Energy System
- Wireless Charging
- Conclusion

Battery-Free EV

- With future ubiquitous wireless charging facilities, 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

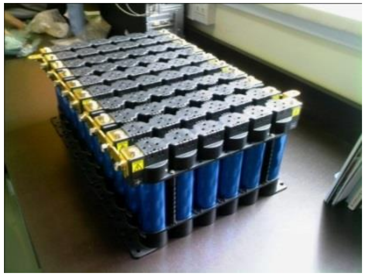
  2) Theoretically unlimited cycle life (can be cycled millions of time)

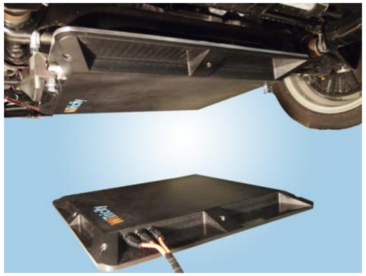
  3) Fast and high efficient charge/discharge due to small internal resistance (97-98% efficiency is typical)

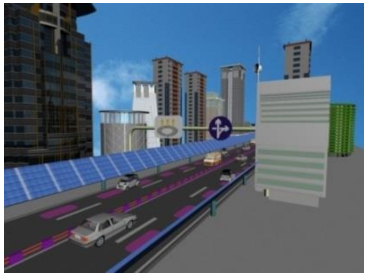
  4) Precise voltage-based State Of Charge (SOC) measurement (energy stored in capacitors is proportional with the square of charge voltage)

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

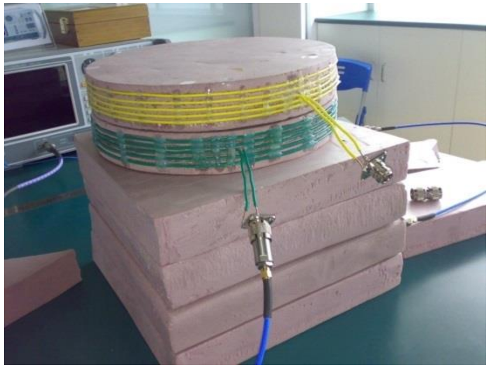
  6) Environmentally friendly without using heavy mental for its structure material.



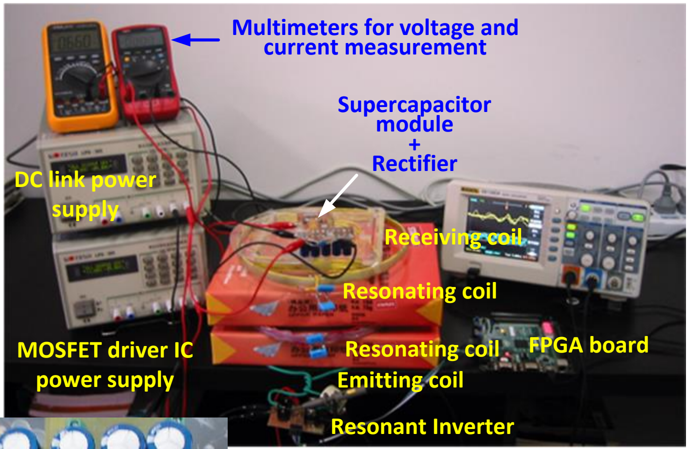


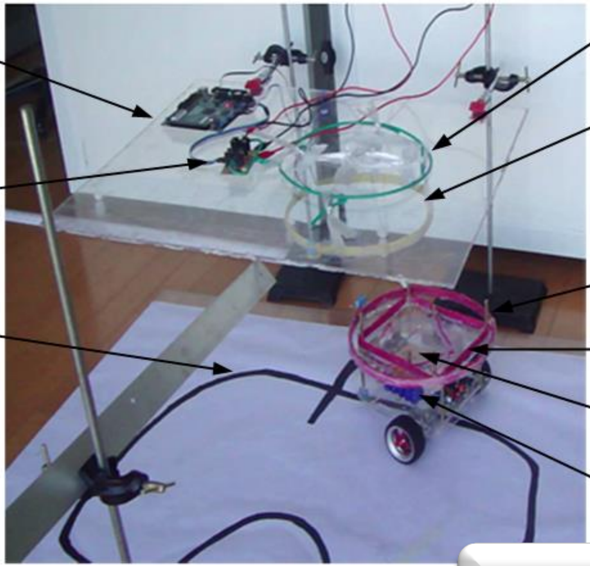


Initial Results



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

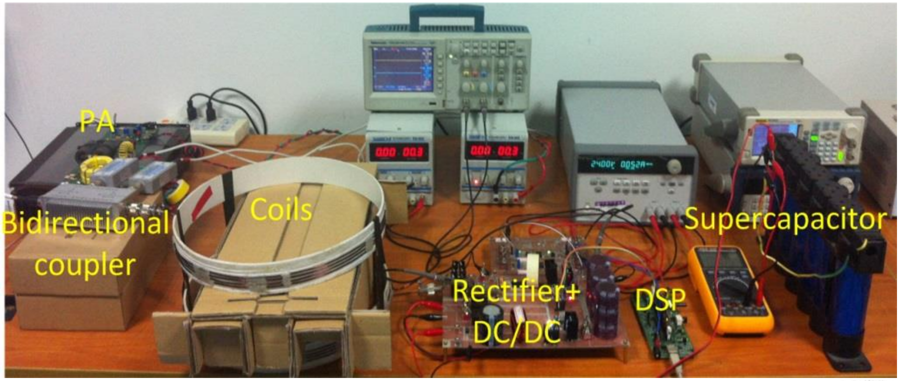


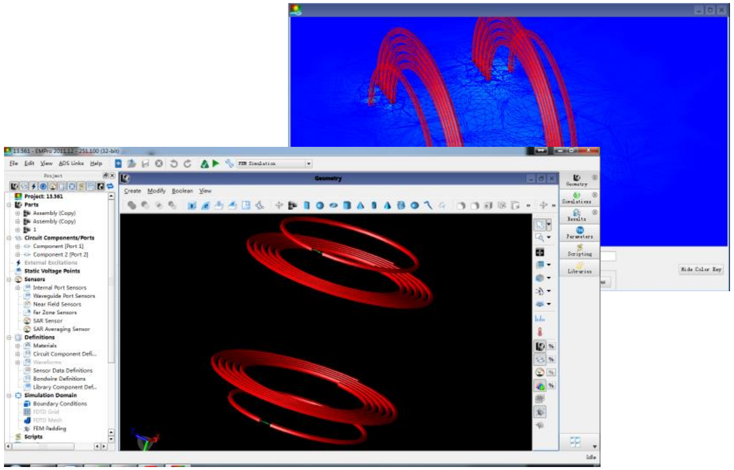


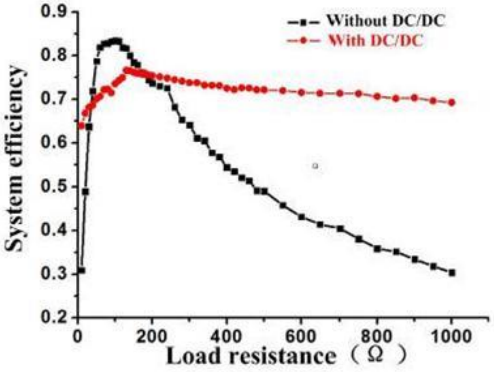
Video

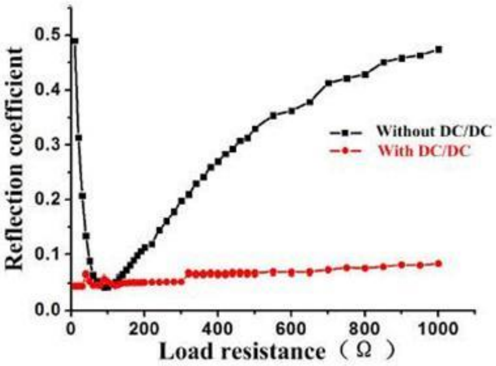
Ongoing Investigations

- 13.56MHz Wireless Power Transfer System
  - Cascaded Boost-buck converter for high efficiency
  - Multi-coil Simulation



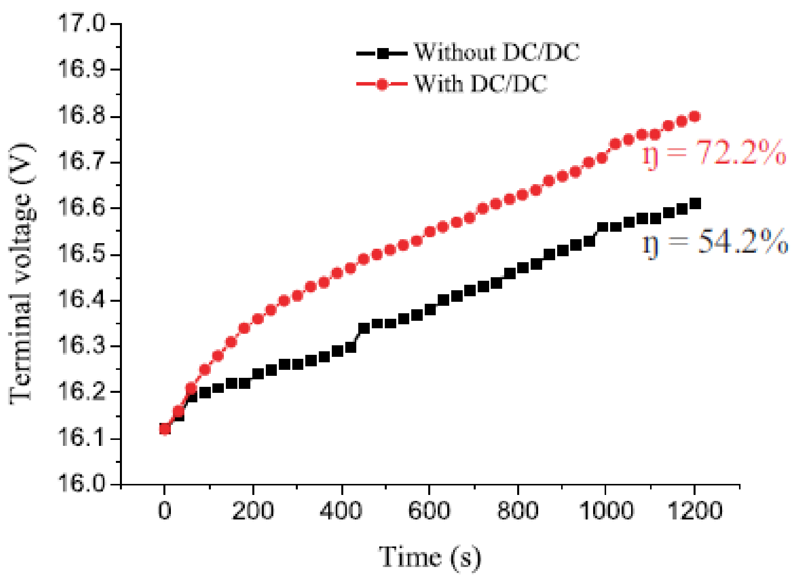




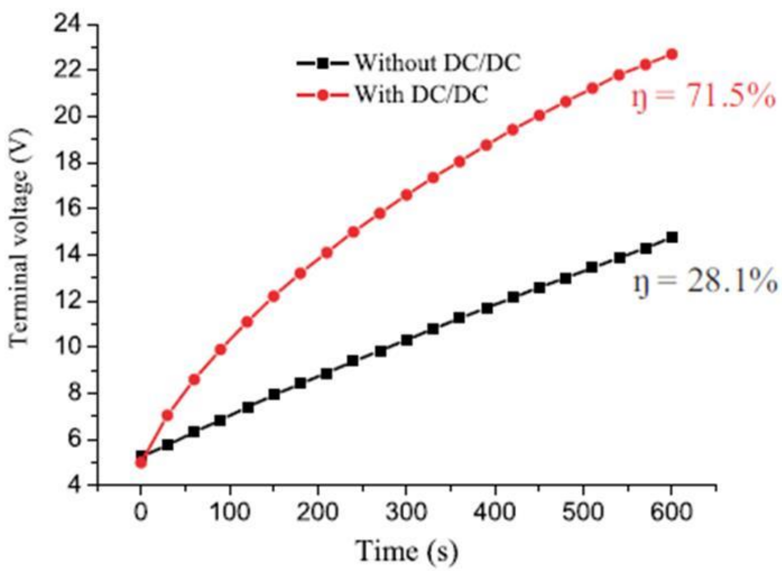


13.56MHz Charging of Supercapacitors

- Wireless charging efficiency improvement by the real time control of the DC-DC converter.



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

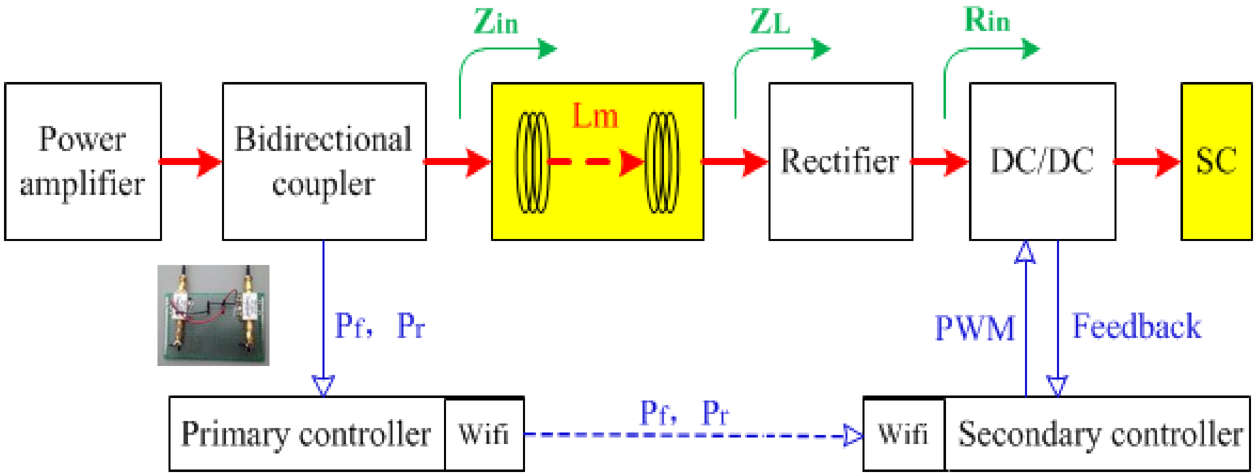


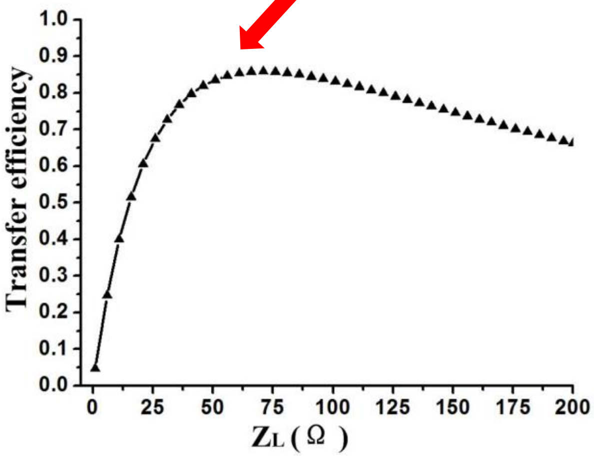
Ultracapacitors charging improvement using the cascaded boost-buck DC-DC converter.

MPPT Control for Wireless Charging

- Maximum power point tracking with variable Lm and load impedance.

$$Z_{L,opt} = \frac{w^2 L_m{}^2}{Z_{in,opt}}$$

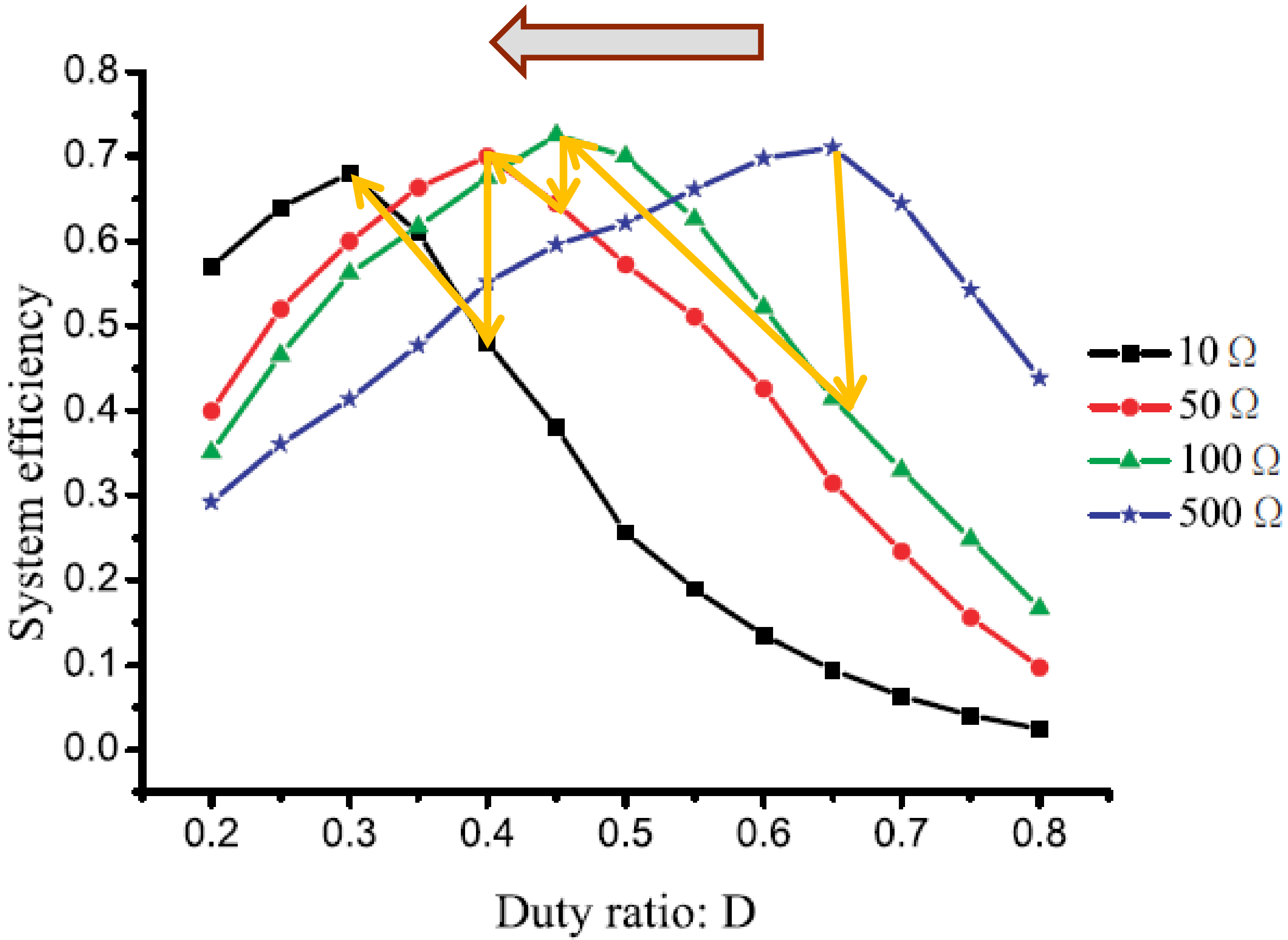




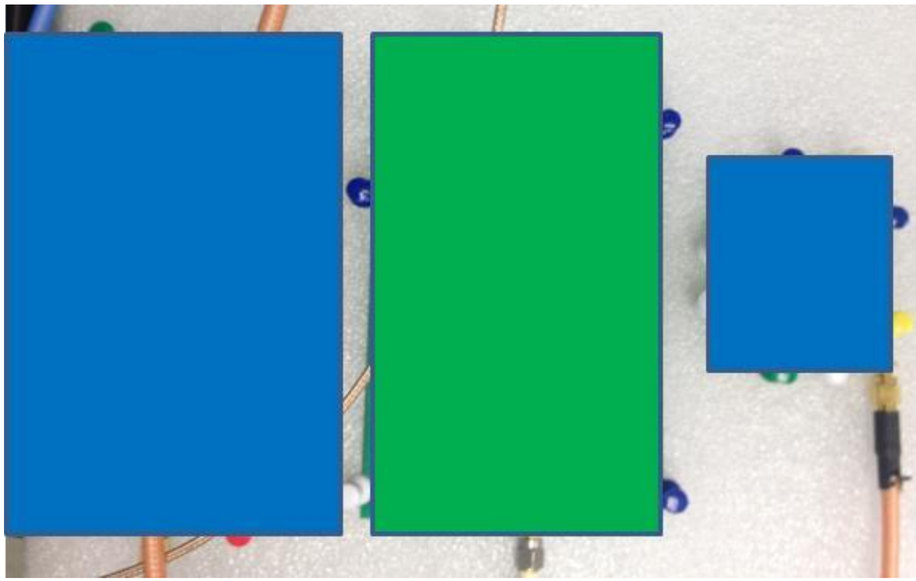
  - Zin,opt is usually fixed (50 ohm).
  - ZL,opt is determined by Lm under resonance for ideal coils.
  - ZL,opt is achieved by well controlling Rin.
  - MPPT method: Minimizing Pr/Pf by controlling Rin to keep track with maximum power point.

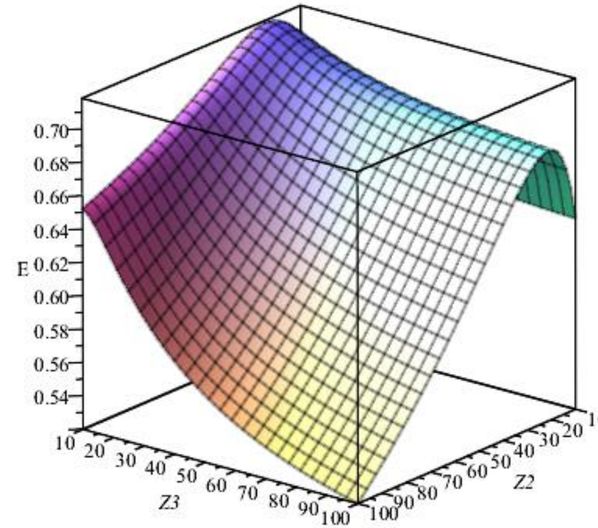
Tracking of Optimum Duty Cycle

Varying load impedance



Optimum Load for Multiple Receiver WPT System





Efficiency has one maximum value

$$Zopt2 := \frac{\sqrt{R1\ R2\ R3\ (R1\ R2\ R3 - R2\ jwM2^2 - R3\ jwM1^2)}}{R1\ R3}$$

$$24.42721532 \qquad (23)$$

$$Zopt3 := \frac{\sqrt{R1\ R2\ R3\ (R1\ R2\ R3 - R2\ jwM2^2 - R3\ jwM1^2)}}{R1\ R2}$$

$$12.21360766 \qquad (24)$$

$$Zinopt := \frac{R1\ R2\ R3 + R1\ R2\ Zopt3 + R1\ R3\ Zopt2 + R1\ Zopt2\ Zopt3 - R2\ jwM2^2 - R3\ jwM1^2 - Zopt2\ jwM2^2 - Zopt3\ jwM1^2}{R2\ R3 + R2\ Zopt3 + R3\ Zopt2 + Zopt2\ Zopt3}$$

$$18.32041148 \qquad (25)$$

$$Effiopt := -\frac{R2^2\ Zopt3\ jwM2^2 + 2\ R2\ Zopt2\ Zopt3\ jwM2^2 + R3^2\ Zopt2\ jwM1^2 + 2\ R3\ Zopt2\ Zopt3\ jwM1^2 + Zopt2^2\ Zopt3\ jwM2^2 + Zopt2\ Zopt3^2\ jwM1^2}{(R2\ R3 + R2\ Zopt3 + R3\ Zopt2 + Zopt2\ Zopt3)\ (R1\ R2\ R3 + R1\ R2\ Zopt3 + R1\ R3\ Zopt2 + R1\ Zopt2\ Zopt3 - R2\ jwM2^2 - R3\ jwM1^2 - Zopt2\ jwM2^2 - Zopt3\ jwM1^2)}$$

$$0.7185795406 \qquad (26)$$

Outline

- Introduction
- Modular EV
- EV Dynamics
- Hybrid Energy System
- Wireless Charging
- Conclusion

Conclusion

- Innovations in technology, market mechanism and industrial structure are needed to breakthrough the traditional mindset that was optimized hundred of years for internal combustion engine cars.
- Especially, the unique advantages brought by the vehicle electrification should be fully utilized.
- EV dynamics, on-board hybrid energy system and wireless charging are the promising research and development areas.

Thank You

Presented by Chengbin Ma
Email: chbma@sjtu.edu.cn
Web: http://umji.sjtu.edu.cn/faculty/chengbin-ma/