Modeling, Design, and Control of Hybrid Energy Systems and Wireless Power Transfer systems

Chengbin Ma, Ph.D.
Assistant Professor
Univ. of Michigan-SJTU Joint Institute,
Shanghai Jiao Tong University (SJTU),
Shanghai, P. R. China

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Outline

- Introduction
- Quantitative Analysis of HESS
- Energy Management of HESS
- Control/Design of WPT Systems
- Conclusions
1. Battery / Energy Management
2. Wireless Power Transfer
3. Electric Vehicle Dynamics
4. Motion/Motor Control
New Challenges

Control of

- Speed
- Precision
- Efficiency

Synergy
Flexibility
Scalability
Reliability

Control of Motion

Energy

DC System
- Wind power generator
- Solar panel
- Solar collector
- Inveter
- Converter
- Electrolysis
- Heat
- Hydrogen
- Super Capacitor
- Battery

AC Grid
- Fuel Cell
- Fuel Cell EV
- Plug-in EV
- Converter
- AC Grid

Power density (W/kg)

10 hours
10
1 hour
1 second

Energy density (Wh/kg)

0.01
1000
100
10

Conventional battery
1000
0.03 second

 Ultracapacitors
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Battery-Ultracapacitor Test System
ESR-based Efficiency Analysis

- Equivalent-Series-Resistance circuit Model:

\[
R_d^* = \frac{P_{loss,d}}{i_d^2} \\
R_b^* = \frac{P_{loss,b}}{i_d^2} \approx \frac{i_b^2 R_s}{1 - d_s} \\
R_u^* = \frac{P_{loss,u}}{i_u^2} \approx R_{sc}
\]
Even for a high energy efficiency, ultracapacitors should provide most of dynamic load current.

\[
E_{loss} = -I_{l, dp}I_{l, dn}(R_b^* + R_{d, r}^* + R_u^*)
= -I_{l, dp}I_{l, dn}R_u^* T + I_{l, a}^2 (R_b^* + R_{d, r}^*) T + I_{l, a}V_F T,
\]

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

Efficiencies of Four Systems

a) Battery-only System

\[ \eta_{ba} = 1 - \frac{I_{l,a}^2 R_{b1} + I_{l,dp} I_{l,dn} R_{b1}}{V_{o,b1} I_{l,a}} \]

b) Passive HESS

\[ \eta_{ps} = 1 - \frac{I_{l,a}^2 R_{b1} + I_{l,dp} I_{l,dn} R_{p}^*}{V_{o,b1} I_{l,a}} \]

c) Battery Semi-active HESS

\[ \eta_{bs} = \frac{\int_0^T (V_{o,u1} - i_{u,bs} R_{u1}) i_l dt}{\int_0^T (V_{o,u1} i_{u,bs} + V_{o,b2} i_{b,bs}) dt} \]

d) Capacitor Semi-active System

\[ \eta_{cs} = \frac{\int_0^T (V_{o,b1} - i_{b,cs} R_{b1}) i_l dt}{\int_0^T (V_{o,u2} i_{u,cs} + V_{o,b1} i_{b,cs}) dt} \]

Comparison of Efficiencies

- Under various average and dynamic load currents ($I_{l,d}$, $I_{l,dp}$, $I_{l,dn}$), battery SOC ($SOC_b$) and efficiencies of dc-dc converter ($\eta_d$).

## Expectation and Standard Deviation of Efficiencies.

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<tr>
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<tr>
<td>$E(y)$</td>
<td>0.8980</td>
<td>0.9419</td>
<td>0.8897</td>
<td>0.9146</td>
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<tr>
<td>$\sigma(y)$</td>
<td>0.0377</td>
<td>0.0150</td>
<td>0.0335</td>
<td>0.0265</td>
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</tbody>
</table>

First order Sobol’ indice

Second order Sobol’ indice
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

60% SOC

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Experimental Setup

Four battery cells inside the environment chamber

LabVIEW program to control and record data

Three sets of power supply and electronic load.

Environment chamber
**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 ultracapacitors.

- **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 ultracapacitors.

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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)

Dynamic Systems Control Laboratory, UM-SJTU Joint Institute
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-freedom: battery and generator.
The preferences of the engine-generator (EG) unit, the battery and UC packs, are quantified by their respective utility functions.

The currents at the Nash equilibrium provide a solution that balances the different preferences of the players.

**Utility Functions and Nash Equilibrium**

- **EG unit and UC pack**
  \[
  u_{g,c} = w_{g,fuel}[1 - a(i_g - I_{g,opt})^2] \\
  + w_{c,eng}[1 - d(i_c - i_{c,fit})^2],
  \]

- **Bat. and UC packs**
  \[
  u_{b,c} = w_{b,ave}[1 - b(i_b - i_{b,ave})^2] \\
  + w_{b,dif}[1 - c(i_b - i_{b,l})^2] \\
  + w'_{c,eng}[1 - d(i_c - i_{c,fit})^2]
  \]
Test bench

- Host PC
- Power Supply
- Electronic Load
- NI CompactRIO
- Battery Pack
- UC Pack

Power Supply (24 V DC)
DC-DC Converter (Battery)
DC-DC Converter (UC)

While loop (Eng.- Gen. Unit)
- $i_f$
- $i_g, opt$
- $v_c$

While loop (Bat. Pack)
- $i_t$
- $i_{b, ave}$
- $i_{b, 1}$
- $v_c$

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Results under Real Test Cycles

Fault Tolerance in Energy Management

- Game theory-based energy management is expected to be superior in fault tolerance.
- The control strategy can be reconfigured when failure happens.
Other Ongoing Directions

- Battery management system: hardware, states estimation, and control algorithms
- Energy flow modeling and control between electric vehicles and smartgrids.

Modeling
- EV Charging Model and Adaptive Correction
- Distributed Modeling of Energy Flow

Strategy
- Nash Equilibrium among EVs
- Stackelberg Equilibrium between EVs and Grids

Application
- Intelligent and Dynamic Management of Energy Flow
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System-level Optimizations/Control

- Optimal load tracking for high efficiency
- Robust design of system parameters
- Autonomous power distribution and control in multi-receiver systems

Power level: 20 W
System Efficiency: 84% ($k=0.1327$)
Optimal Load for High Efficiency

Optimal loads

PA → Pf → Lm → Rectifier → DC/DC converter → P_L → Load R_L
Improved Charging Efficiency

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

![Graph 1](image1)

**Terminal voltage (V)**

- **Without DC/DC:** η = 54.2%
- **With DC/DC:** η = 72.2%

**Time (s)**

**18% ↑**

![Graph 2](image2)

**Terminal voltage (V)**

- **Without DC/DC:** η = 28.1%
- **With DC/DC:** η = 71.5%

**Time (s)**

**43.4% ↑**

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

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

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 $R_f$.

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

Instead of active control, the system parameters are optimized to improve the robustness against a varying operating condition.

Robust Optimization and Design

$max \eta_{sys}^{nom}(x)

s.t. \alpha_{sys}(x) \leq \alpha_{sys}^{max},

max |D(x, P_{con}, P_{var}) - 0.5| \leq \beta_{D}^{max}. 

Robustness Index

\alpha_{sys}(x) = \max_{P_{var}} \left| \frac{\eta_{sys}(x, P_{var}) - \eta_{sys}^{nom}(x)}{\eta_{sys}^{nom}(x)} \right|
Experimental Results

Variation in coil distance

Load=15 Ohm

Load=30 Ohm

Load=45 Ohm

Variation in load

d=15 cm

d=30 cm

d=45 cm

Multiple-Receiver WPT System

[Image of a multiple-receiver wireless power transfer system setup]

Diagram showing agent models for Transmitter, Receiver No. 1, Receiver No. 2, and Receiver No. 3. Each agent has a utility function (preference) and a physical model (behavior).

- **Transmitter** (leader)
- **Receiver No. 1** (follower)
- **Receiver No. 2** (follower)
- **Receiver No. 3** (follower)

Generalized Nash Equilibrium
- Receiver No. 1 (follower)
- Receiver No. 2 (follower)

Environment
- $p_{1}$
- $p_{2}$
- $p_{total}$
- $p_{1}, p_{2}, p_{3}$

Agent: Transmitter
- Utility Function (Preference)
- Physical Model (Behavior)

Agent: Receiver No. 1
- Utility Function (Preference)
- Physical Model (Behavior)

Agent: Receiver No. 2
- Utility Function (Preference)
- Physical Model (Behavior)

Agent: Receiver No. 3
- Utility Function (Preference)
- Physical Model (Behavior)
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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 of DSC lab:
  - Battery management system: hardware and various algorithms
  - Modeling and control of networked energy systems (hybrid energy systems, alternative energy systems, vehicle-to-grid systems)
  - Optimal design and control of WPT systems (new sensor, tunable components, control and design methodology)
  - Autonomous power distribution among multiple receivers/devices
Thank You

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