Enhanced Performance in Li-Ion Batteries via Modified Reference Governors

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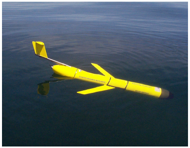
A Golden Era


IS-1
ST. JUDE MEDICAL
Sylmar, CA USA
ACCENT SR RF
PM1210 SSR
IS-1
ST. JUDE MEDICAL
Sylmar, CA USA
ANTHEM RF
PM3212 DDDRV



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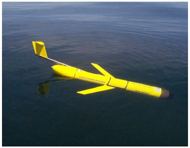

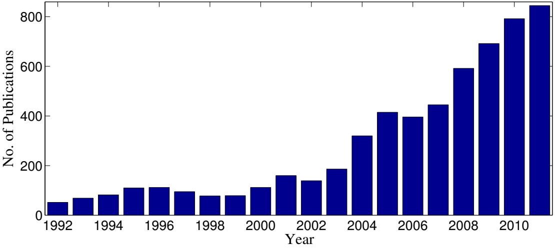

Keyword: "Battery Systems and Control"

The Battery Problem

Needs: Cheap, high energy/power, fast charge, long life

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Some Motivating Facts

EV Batts	1000 USD / kWh (2010)*
	485 USD / kWh (2012)*
	125 USD / kWh for parity to IC engine
	Only 50-80% of available capacity is used
	Range anxiety inhibits adoption
	Lifetime risks caused by fast charging

*Source: MIT Technology Review, "The Electric Car is Here to Stay." (2013)

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Two Solutions

Design better batteries (materials science & chemistry)	Make current batteries better (estimation and control)

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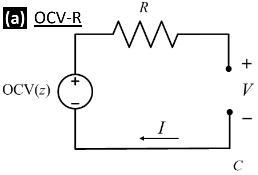
Equivalent Circuit Model

(a) OCV-R



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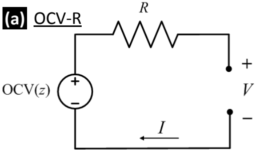
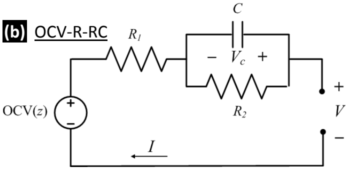
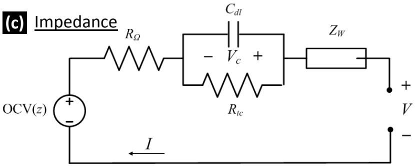


(b) OCV-R-RC



(c) Impedance



Battery Models

Equivalent Circuit Model

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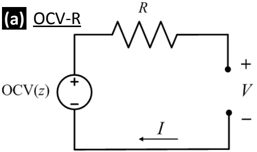

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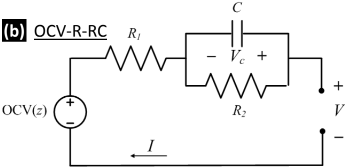

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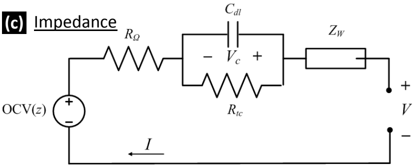
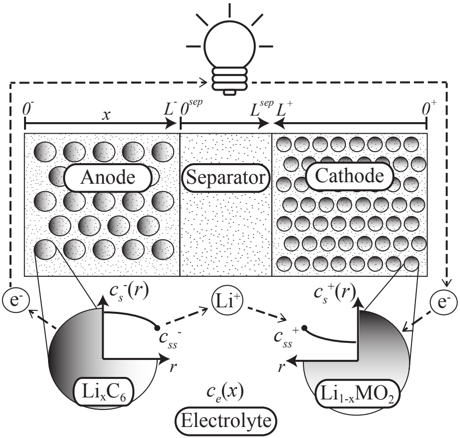
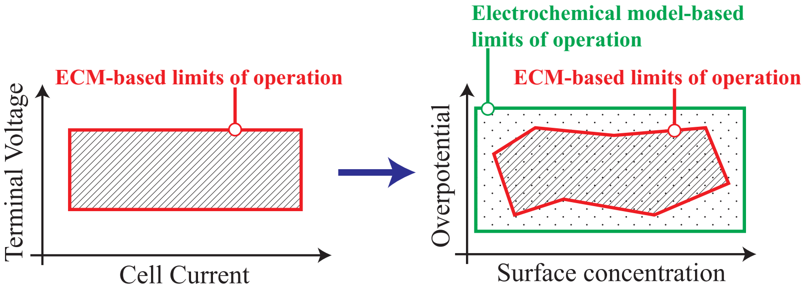


Electrochemical Model



Operate Batteries at their Physical Limits



Electrochemical Model Equations

well, some of them

Description	Equation
Solid phase Li concentration	$\frac{\partial c_s^{\pm}}{\partial t}(x,r,t) = \frac{1}{r^2}\frac{\partial}{\partial r}\left[D_s^{\pm} r^2 \frac{\partial c_s^{\pm}}{\partial r}(x,r,t)\right]$
Electrolyte Li concentration	$\varepsilon_e \frac{\partial c_e}{\partial t}(x,t) = \frac{\partial}{\partial x}\left[\varepsilon_e D_e \frac{\partial c_e}{\partial x}(x,t) + \frac{1-t_c^0}{F} i_e^{\pm}(x,t)\right]$
Solid potential	$\frac{\partial \phi_s^{\pm}}{\partial x}(x,t) = \frac{i_e^{\pm}(x,t) - I(t)}{\sigma^{\pm}}$
Electrolyte potential	$\frac{\partial \phi_e}{\partial x}(x,t) = -\frac{i_e^{\pm}(x,t)}{\kappa} + \frac{2RT}{F}(1-t_c^0)\left(1 + \frac{d \ln f_{c/a}}{d \ln c_e}(x,t)\right)\frac{\partial \ln c_e}{\partial x}(x,t)$
Electrolyte ionic current	$\frac{\partial i_e^{\pm}}{\partial x}(x,t) = a_s F j_n^{\pm}(x,t)$
Molar flux btw phases	$j_n^{\pm}(x,t) = \frac{1}{F} i_0^{\pm}(x,t)\left[e^{\frac{\alpha_a F}{RT}\eta^{\pm}(x,t)} - e^{-\frac{\alpha_c F}{RT}\eta^{\pm}(x,t)}\right]$
Temperature	$\rho c_P \frac{dT}{dt}(t) = h\left[T^0(t) - T(t)\right] + I(t)V(t) - \int_{0^-}^{0^+} a_s F j_n(x,t)\Delta T(x,t)dx$

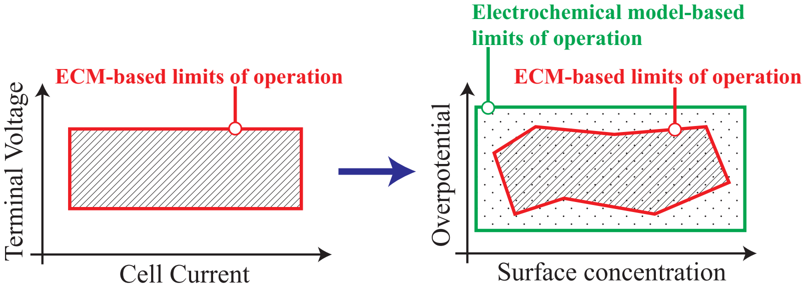
Matlab CODE: github.com/scott-moura/dfn

Animation of Li Ion Evolution

Operate Batteries at their Physical Limits

Problem Statement

Given accurate state estimates*, govern the electric current such that safe operating constraints are satisfied.



* S. J. Moura, N. A. Chaturvedi, M. Krstic, "Adaptive PDE Observer for Battery SOC/SOH Estimation via an Electrochemical Model," *ASME Journal of Dynamic Systems, Measurement, and Control*, 2013.

Literature Background

- Scalar Reference & Command Governors
  Gilbert, Kolmanovsky, Tan '95; Bemporad '98

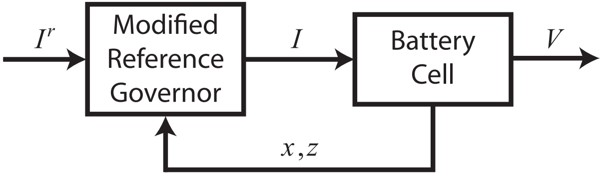
- Electrochemical System Applications
  - Fuel Cells
    Sun, Kolmanovsky '05; Vahidi, Kolmanovsky, Stefanopoulou '07
  - Batteries
    Plett '05; Smith, Rahn, Wang '10; Klein et al. '11 (MPC);
    Suthar et al. '13 (MPC/MHE)

Constraints

Variable	Definition	Constraint
$I(t)$	Current	Power electronics limits
$c_s^{\pm}(x,r,t)$	Li concentration in solid	Saturation/depletion
$\frac{\partial c_s^{\pm}}{\partial r}(x,r,t)$	Li concentration gradient	Diffusion-induced stress
$c_e(x,t)$	Li concentration in electrolyte	Saturation/depletion
$T(t)$	Temperature	High/low temps accel. aging
$\eta_s(x,t)$	Side-rxn overpotential	Li plating, dendrite formation

Each variable, y, must satisfy $y_{\min} \leq y \leq y_{\max}$.

The Algorithm: Modified Reference Governor (MRG)



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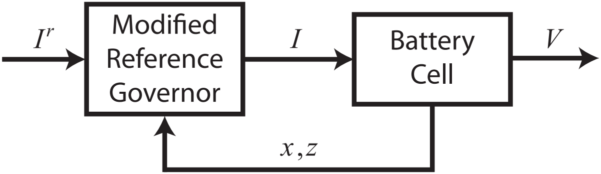

MRG Equations

$$I[k+1] = \beta^*[k] I^r[k], \qquad \beta^* \in [0,1],$$
$$\beta^*[k] = \max \left\{ \beta \in [0,1] : (x(t), z(t)) \in \mathcal{O} \right\}$$

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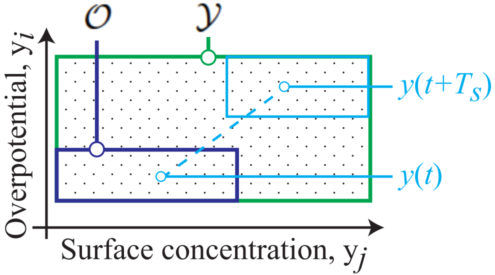

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Admissible Set

$$\mathcal{O} = \left\{(x(t), z(t)) : y(\tau) \in \mathcal{Y}, \forall \tau \in [t, t+T_s]\right\}$$

$$\begin{aligned} \dot{x}(t) &= f(x(t), z(t), \beta I^r) \\ 0 &= g(x(t), z(t), \beta I^r) \\ y(t) &= C_1 x(t) + C_2 z(t) + D \cdot \beta I^r + E \end{aligned}$$

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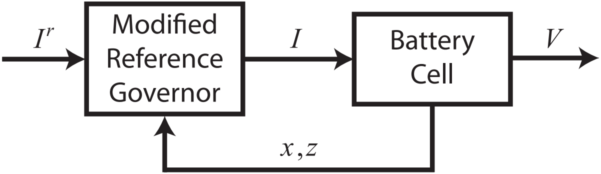

RG Equations $\quad I[k+1] = I[k] + \beta[k]\left(I^r[k] - I[k]\right), \quad \beta \in [0,1],$

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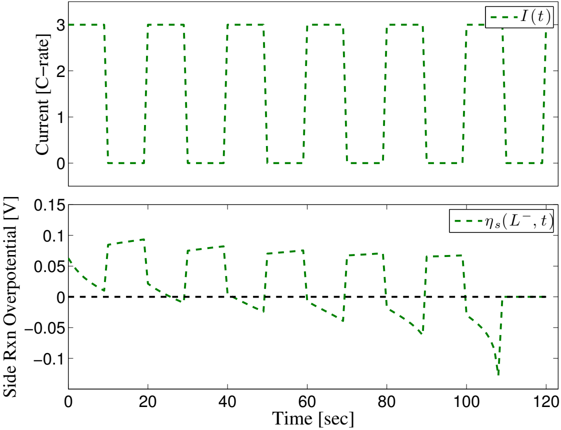
Constrained Control of EChem States



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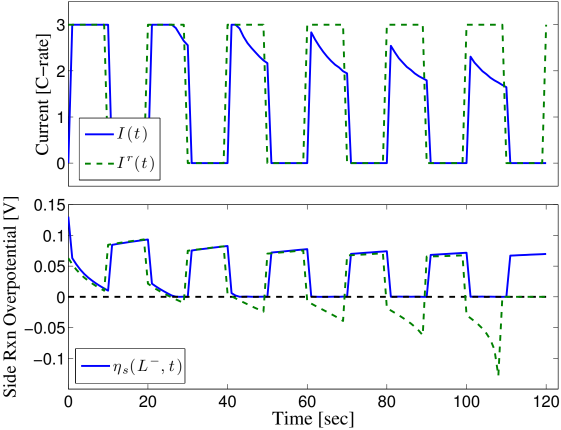
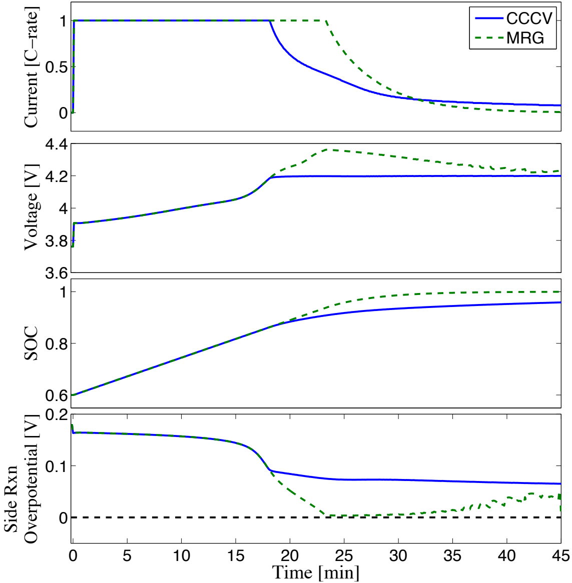


Application to Charging



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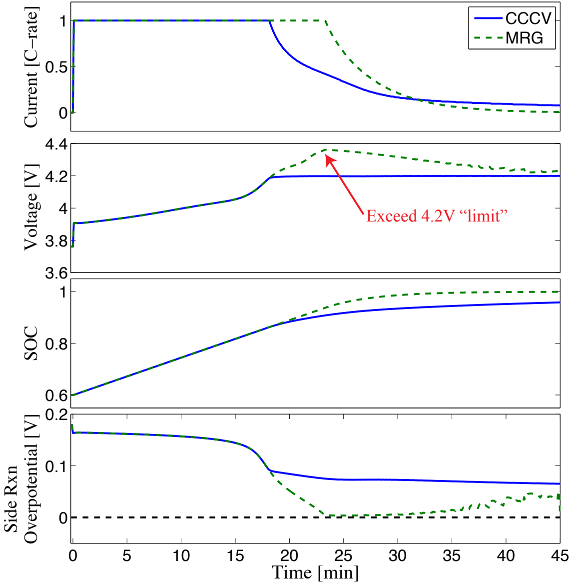

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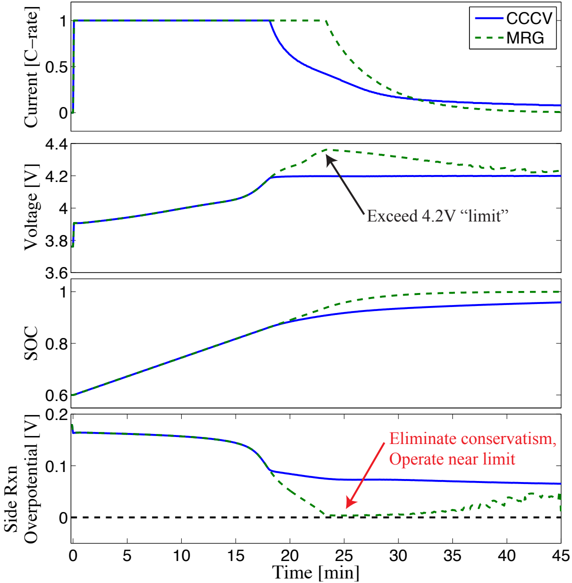

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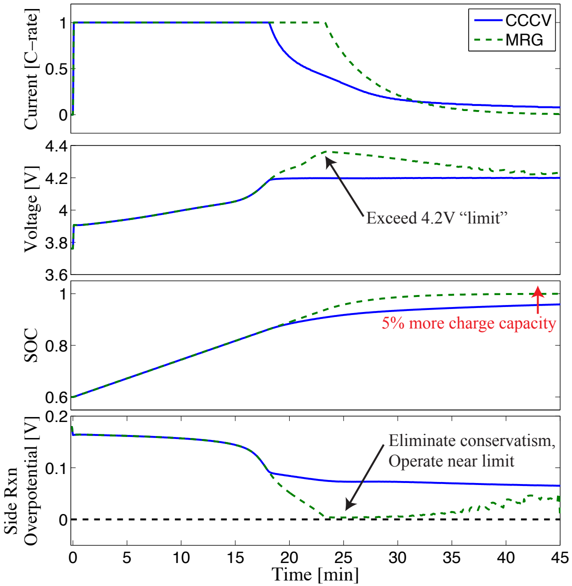

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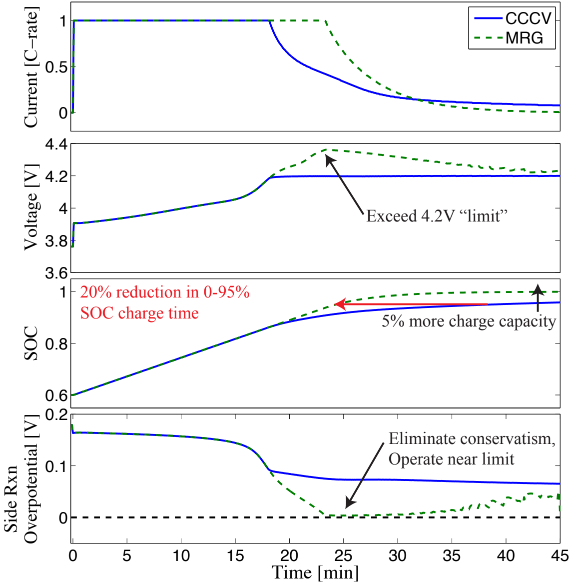
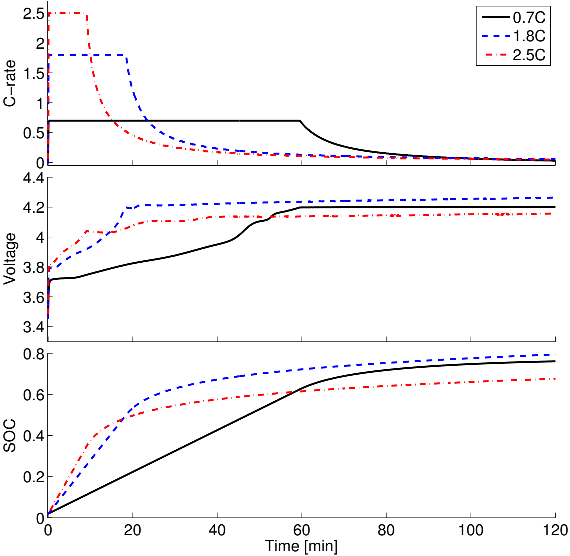


Fast Charging



Fast charge your smartphone/EV while getting coffee

Table: Simulated fast charge times for various C-rates

Charge range	**0.7C** | Traditional	**1.8C** | MRG	**2.5C** | MRG
0-10%	7.92 min	3.17 min	2.33 min
0-20%	17.83 min	7.00 min	5.08 min
0-50%	47.33 min	18.42 min	20.50 min

Linearized MRG Motivation

Remark

MRG requires iterating over nonlinear simulations of discretized PDEs - computationally expensive

Problem Statement

Can we decrease computational complexity at sacrifice of guaranteed constraint satisfaction?

Model Linearization

Linearize around previous time step

$$\begin{aligned}\dot{\tilde{x}} &= A_{11}\tilde{x} + A_{12}\tilde{z} + B_1\tilde{I}, \\ 0 &= A_{21}\tilde{x} + A_{22}\tilde{z} + B_2\tilde{I},\end{aligned}$$

where $\quad \tilde{x} = x - x[k-1], \quad \tilde{z} = z - z[k-1], \quad \tilde{I} = \beta I^r - I[k-1]$
and $\quad A_{11}, A_{12}, A_{21}, A_{22}, B_1, B_2$ are the Jacobian terms

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Reduce DAE to ODE

$\dot{\tilde{x}} = A\tilde{x} + B\tilde{I}$, where $A = A_{11} - A_{12}A_{22}^{-1}A_{21}$ and $B = B_1 - A_{12}A_{22}^{-1}B_2$

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Explicitly compute constrained outputs

$$\begin{aligned}\tilde{x}(t+T_s) &= e^{AT_s}\tilde{x}(t) + \int_t^{t+T_s} e^{A(t+T_s-\tau)}B\tilde{I}d\tau, \\ \tilde{z}(t+T_s) &= -A_{22}^{-1}\left[A_{21}\tilde{x}(t+T_s) + B_2\tilde{I}\right], \\ y(t+T_s) &= C_1\left[x[k-1] + \tilde{x}(t+T_s)\right] + C_2\left[z[k-1] + \tilde{z}(t+T_s)\right] + D \cdot \beta I^r + E \leq 0\end{aligned}$$

Linear MRG

LMRG Equations
$$\max_{\beta \in [0,1]} \quad \beta$$
$$\text{subject to} \quad \beta F \leq G$$

F, G incorporate the constraints, and include $(x[k-1], I[k-1], I^r[k])$

$$\begin{aligned} F &= \left[C_1 L - C_2 A_{22}^{-1}(A_{21} L + B_2) + D\right] I^r[k], \\ G &= -E - C_1 \left[x[k-1] + \Phi(x(t) - x[k-1]) - LI[k-1]\right], \\ &\quad -C_2 \left[z^0 - A_{22}^{-1}\left[A_{21}(\Phi(x(t) - x[k-1]) - B_2 I[k-1]\right]\right], \end{aligned}$$

$$\text{where} \qquad \Phi = e^{AT_s}, \qquad L = \int_t^{t+T_s} e^{A(t+T_s-\tau)} B d\tau.$$

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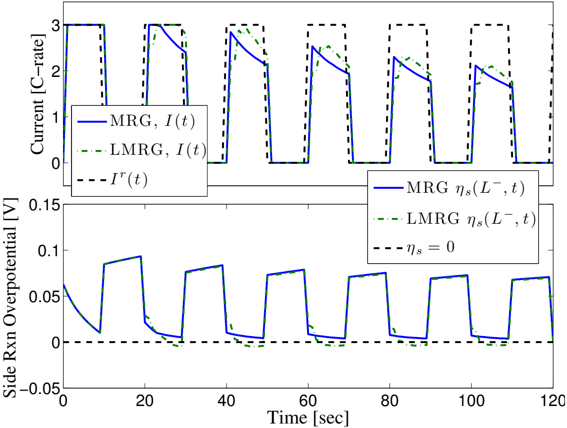
Final Result

One-dimensional LP - can solve explicitly (no iterations over simulations)!

Simulation Example

Modified Reference Governor (MRG) : Simulations
Linearized MRG (LMRG) : Explicit function evaluation



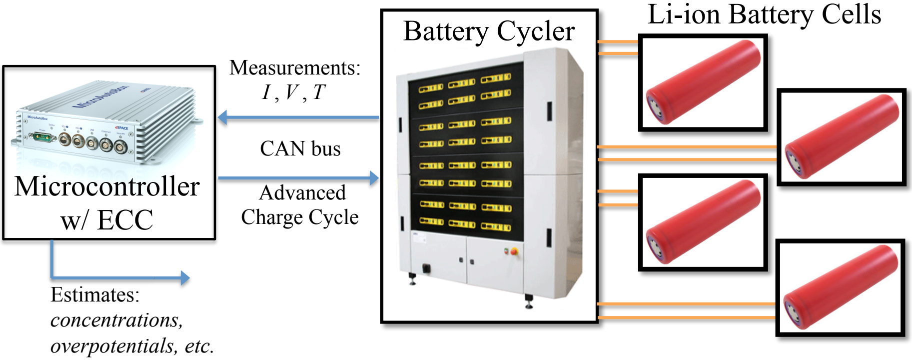
Simulation Example

Modified Reference Governor (MRG) :	Simulations
Linearized MRG (LMRG) :	Explicit function evaluation

Table: Comparison of CPU Time for Nonlinear and Linear MRGs.

Scenario	MRG	Linear MRG
10sec 3C charging	4.27min (100%)	1.03min (24%)
10sec 10C discharging	4.99min (100%)	1.13min (23%)

Battery-in-the-Loop Test Facility



Motivation in Mobile Communication:
6.7B subscription accounts, 5.2B handsets in use,
1.7B sold worldwide in 2012

Constrained control of batteries
via an electrochemical model
and reference governors.

QUESTIONS?

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energy, controls, & applications lab