Enabling Extreme Fast Charging with Energy Storage

Jonathan Kimball, Missouri S&T

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Project ID: ELT237

Overview

- Timeline
  - Start: October 1, 2018
  - End: December 31, 2021
  - 25% Complete

- Budget
- Total Budget: $5,831,079
- DOE Share: $2,915,377
- Contractor Share: $2,915,703
- Current Funding: $817,360

- Barriers
  - Power conversion – how to ensure safe, reliable operation on medium-voltage feeder?
  - Battery degradation – how to ensure that high charge rates do not lead to premature wearout or catastrophic failure?
  - Grid interface – how to ensure that the station does not disrupt grid operations? Can we enhance performance?
- Partners
- Lead: Missouri S&T, Kimball
  - Also Bo, Ferdowsi, Landers, Park, Shamsi
- Ameren: utility
- Bitrode: equipment manufacturer
- LG Chem Michigan: battery mfg

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Relevance

- Overall Objectives
  - Charging station connected to 15 kV class, 1 MW
  - Mitigate impact on battery degradation
  - Mitigate impact on the grid
- Objectives This Period
  - Define topology, gather information on grid and battery construction
- Impact
  - Accelerate adoption of electric vehicles
  - Provide economic benefit to charging station owner

Milestones

Milestone	Type	Description
Power Converter Subsystems Verified	Technical	AFE and isolated dc-dc converters designed and verified against models at lab scale
Initial Cell Charging Algorithms Tested	Technical	First attempt at developing innovative charging algorithms tested with cells
Theoretical Grid Analysis Complete for Local Transients	Technical	Local impact on grid analyzed, to begin specifying XFC station requirements
Vehicle Pack Design Complete	Technical	Electrical, mechanical, and thermal designs complete
Feasibility Go/No-Go	Go/No Go	Laboratory results at subscale will be mapped to grid-level requirements; viability of a full-scale XFC station will be established and proven feasible.

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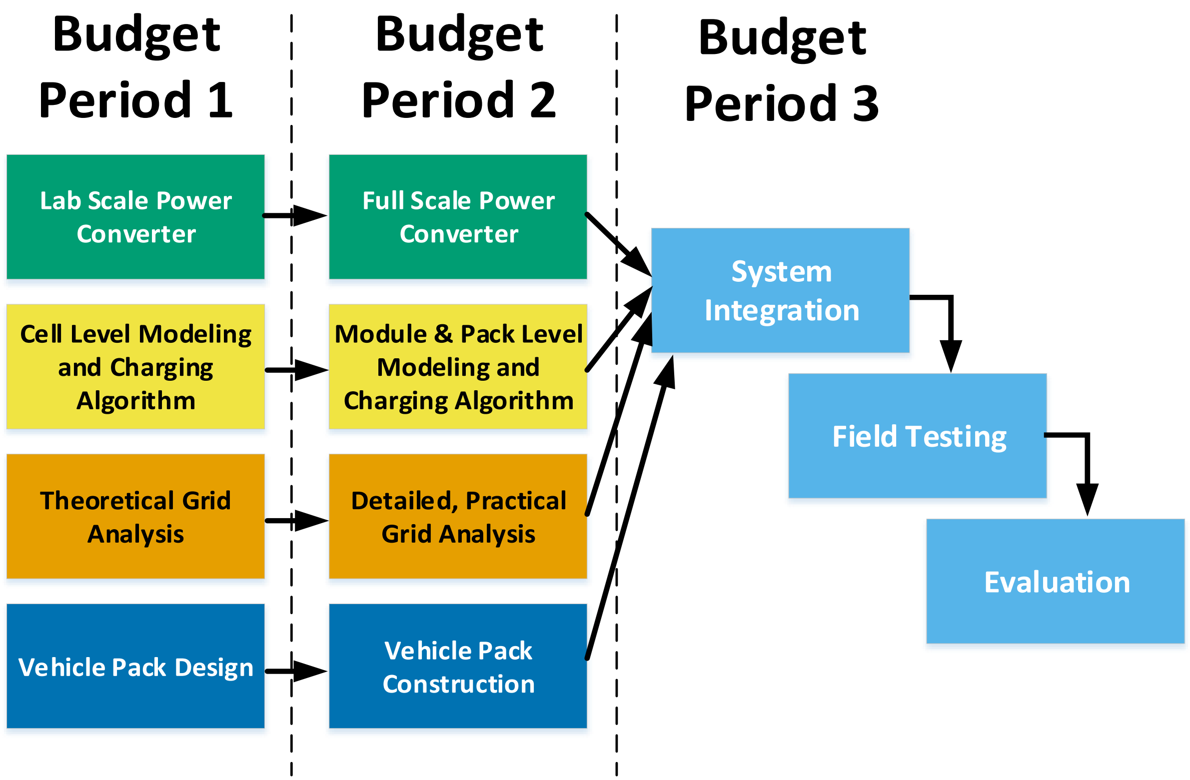
Approach

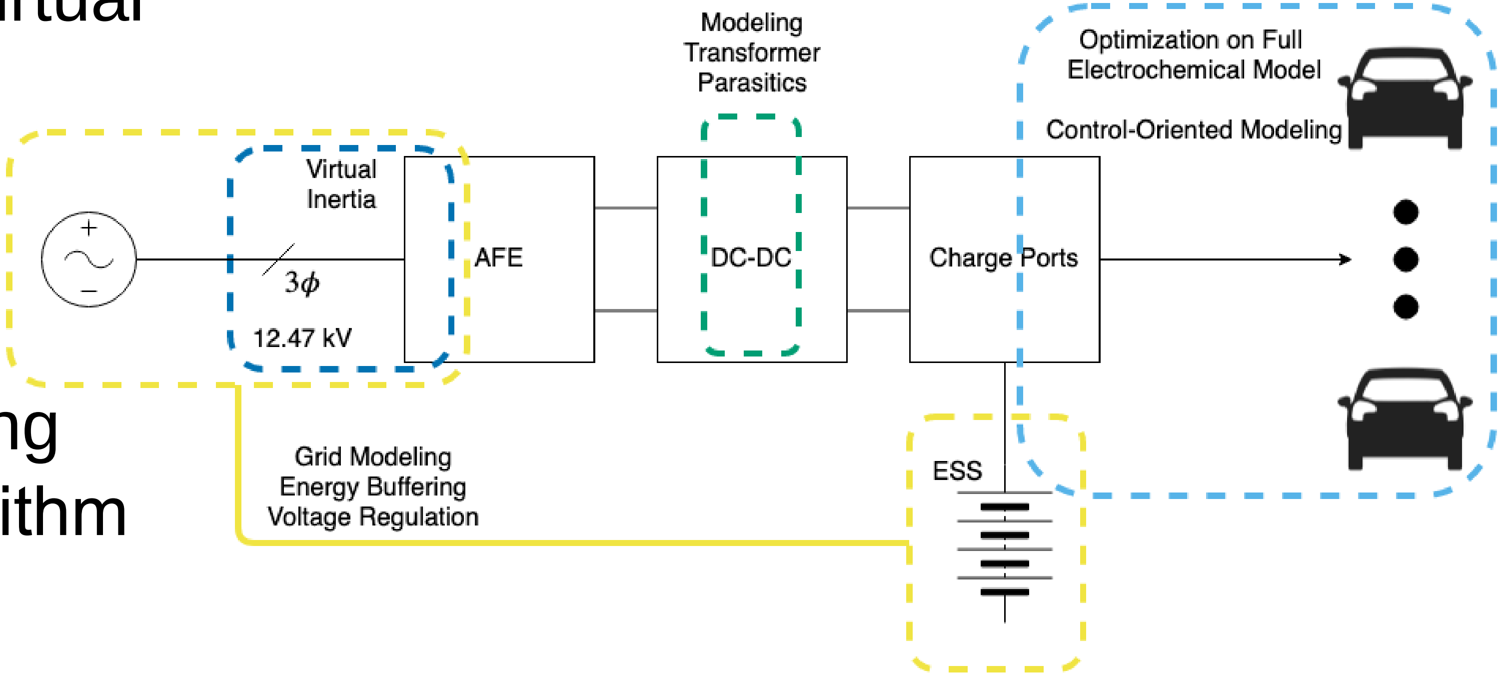


- Budget Period 1 focused on proof-of-concept, culminates in feasibility go/no-go
- BP2 will focus on reaching full scale
- BP3 includes
  - Integration
  - Field Test
  - Evaluation

Any proposed future work is subject to change based on funding levels.

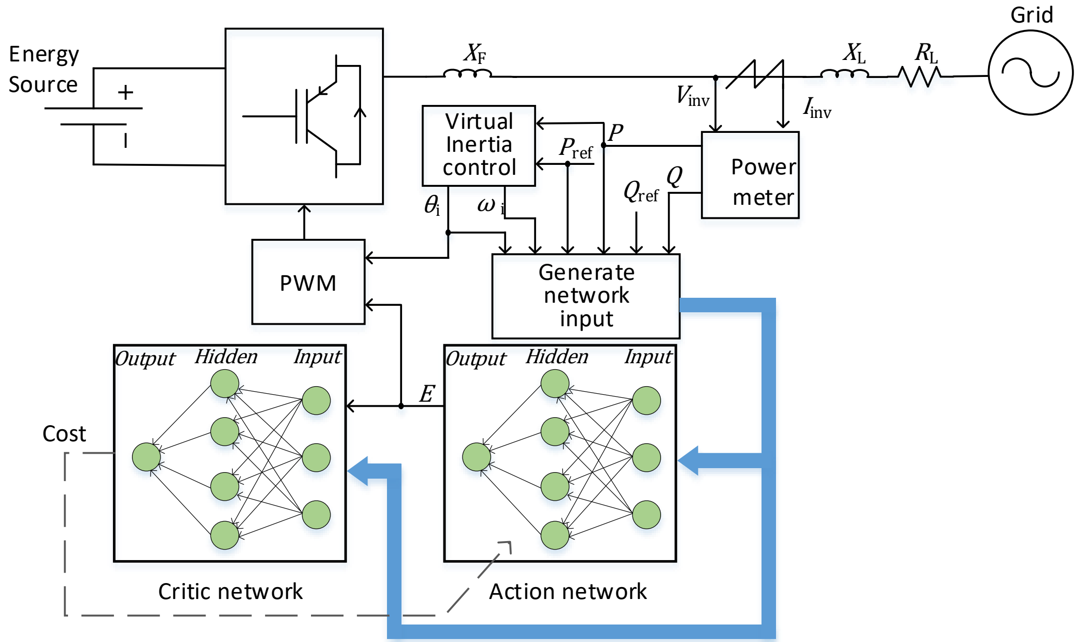
Technical Accomplishments and Progress

- Power Conversion
  - Active front-end (AFE) virtual synchronous generator
  - Transformer modeling & optimization
- Battery Charging
  - Cell degradation modeling
  - “Optimal” charging algorithm
- Grid Compatibility
  - Voltage stabilization



AFE as a Virtual Synchronous Generator

Heuristic Dynamic Programming (HDP) Based VSG

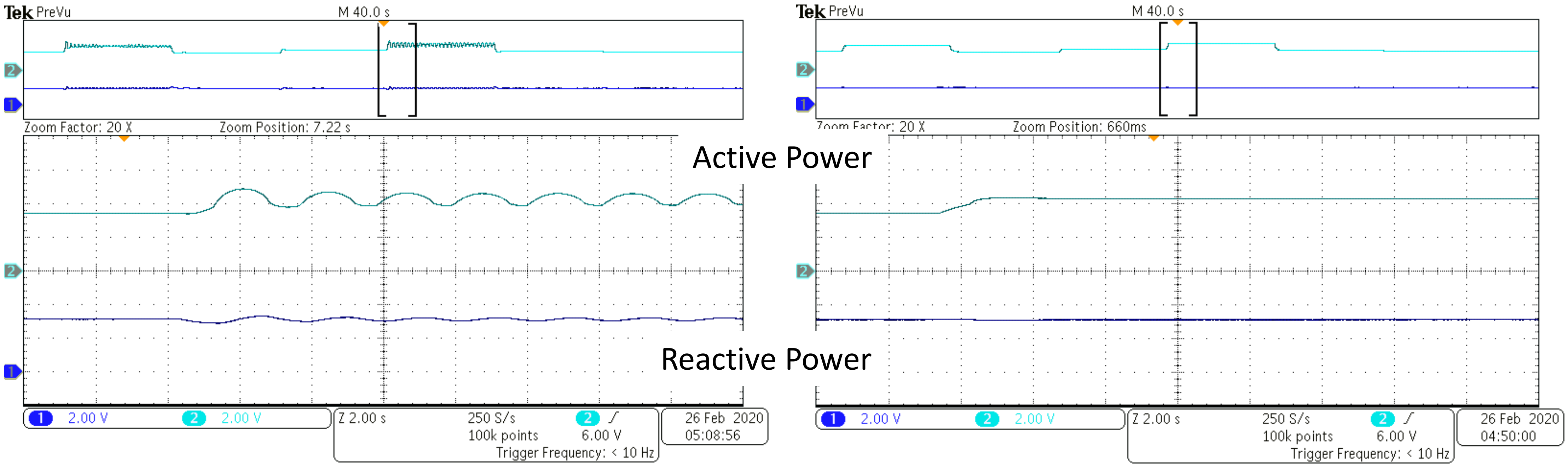


Advantages Over Conventional Approaches

- Current/power control: no inertia
- Typical VSG: linearized control; poor handling of resistive grid
- Neural Network Predictive Controller: needs offline training

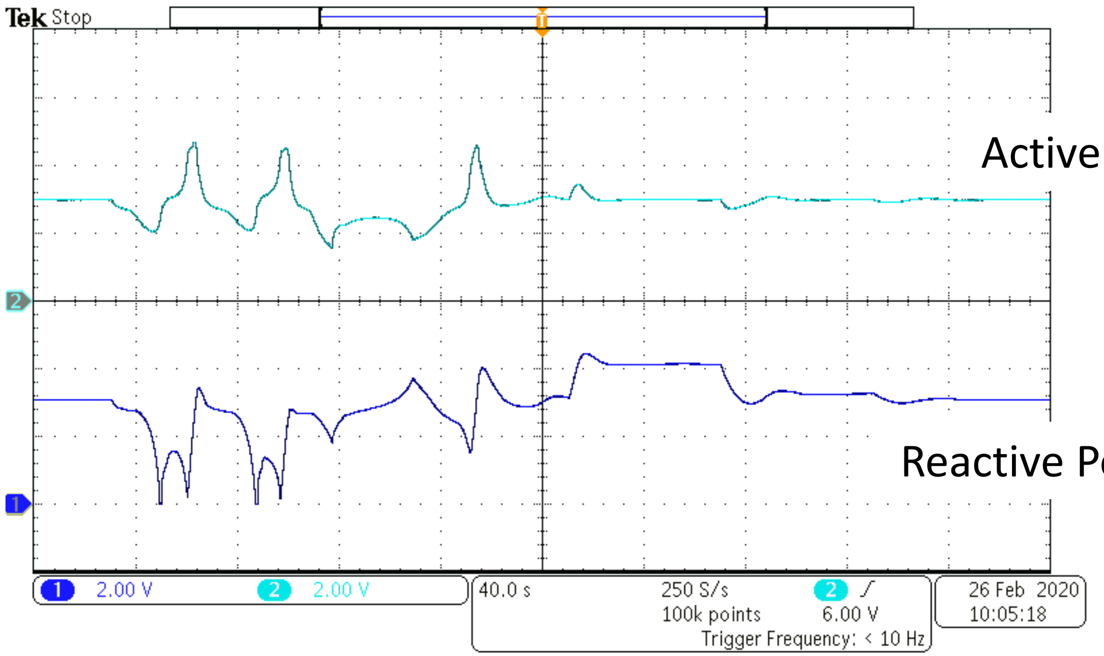
Experimental Results: Active Reference Change

Conventional VSG **HDP-Based VSG**

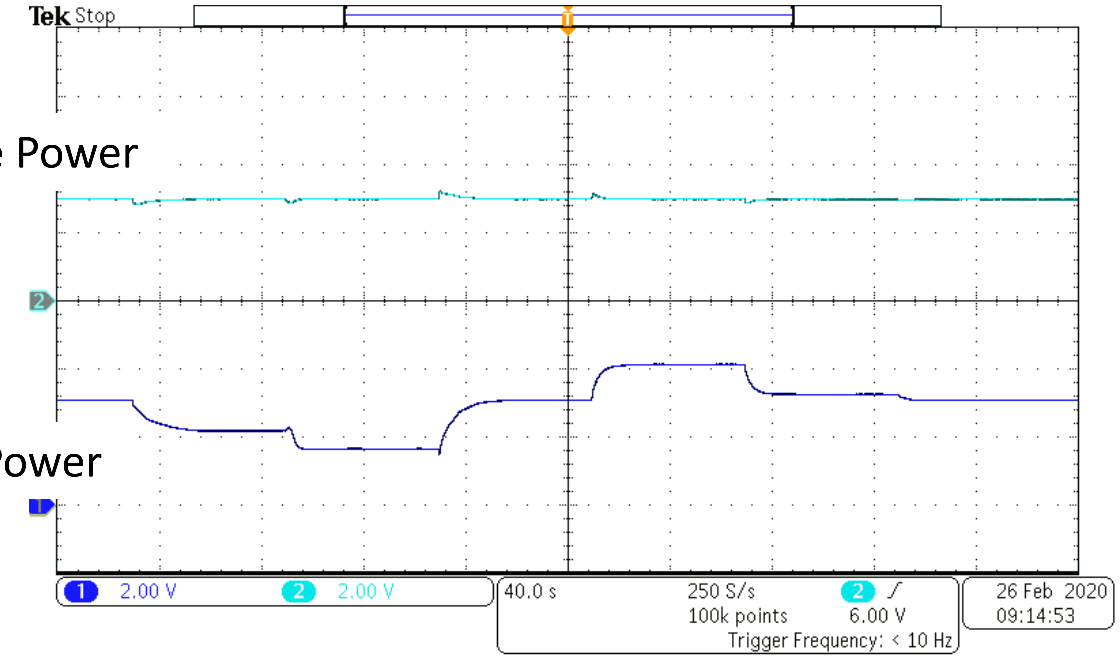


Experimental Results: Reactive Power Change

Conventional VSG

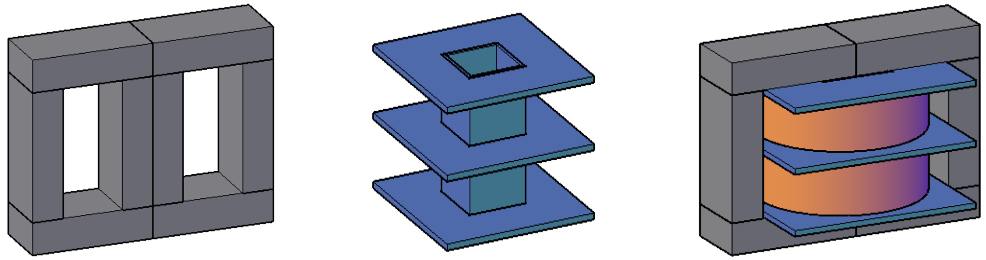


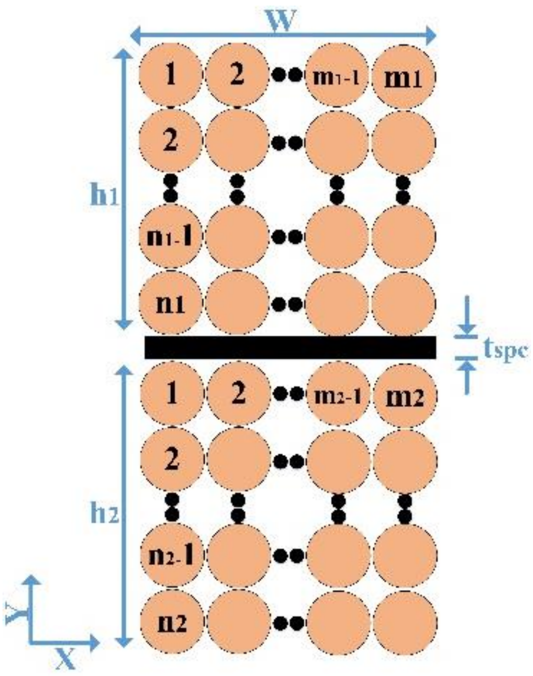
HDP-Based VSG

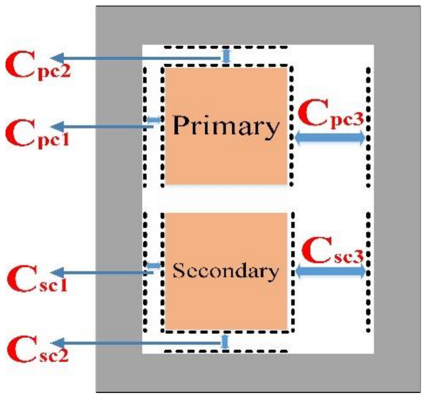


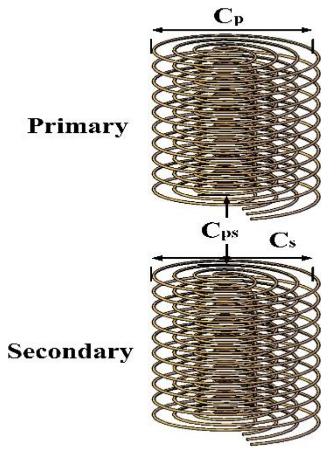
Transformer Modeling & Optimization

- Energy-based models of leakage inductance, parasitic capacitance
- Examined various shapes, chose this EE shape









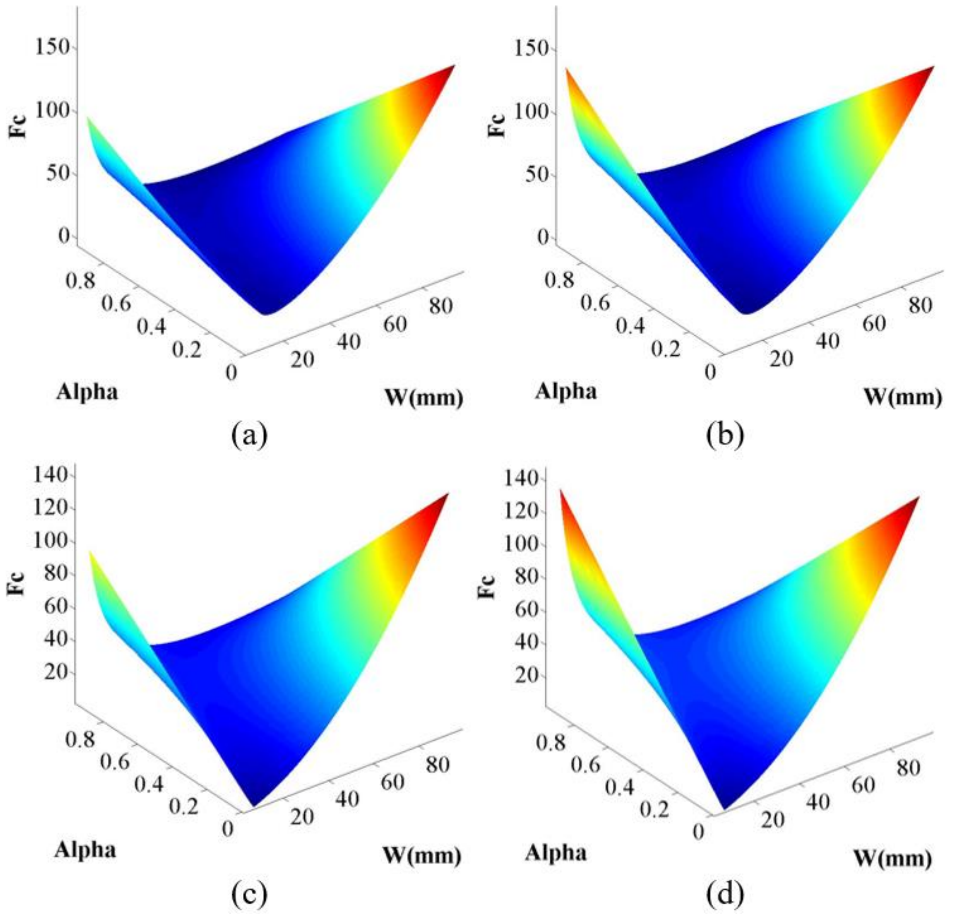
Analytical Models Enable Optimization

$$L_{lk} = 2\frac{E_{ins,p} + E_{ins,s} + E_{spacer} + E_{pri} + E_{sec}}{I_{pri}^2}$$

$$C_{tot} = 2\left[\left(C_{pc1} + C_{pc2} + C_{pc3}\right) \| \left(C_{sc1} + C_{sc2} + C_{sc3}\right)\right] + C_{ps} + C_p + C_s$$

Cost function for different weighting between leakage inductance and parasitic capacitance, vs. window width; fixed window area

(a) Conductive core, 400 turns; (b) conductive core, 450 turns; (c) non-conductive core, 400 turns; (d) non-conductive core, 450 turns



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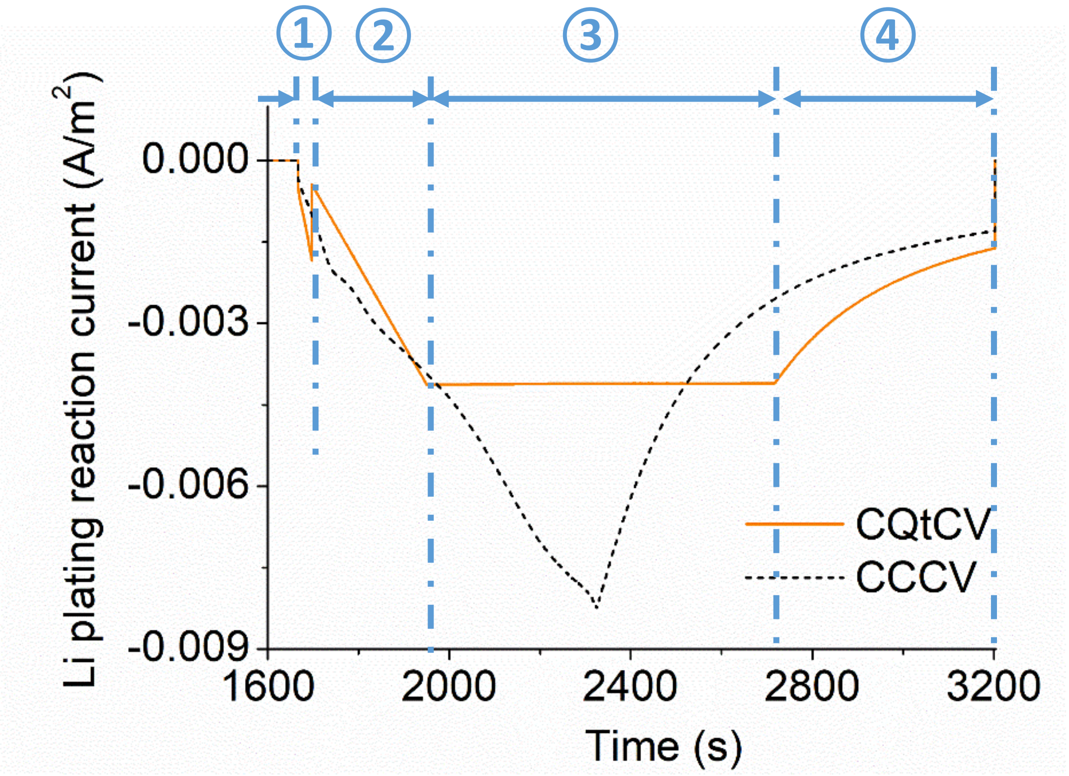
Proposed CQtCV Battery Charge Algorithm

- Electrochemical model with SEI layer growth and Li plating

- CQtCV

① 30s constant current with upper limit
② constant d^2Q_{Li}/dt^2 to certain value of dQ_{Li}/dt
③ constant dQ_{Li}/dt to 4.2 V
④ constant voltage charge to 80% capacity



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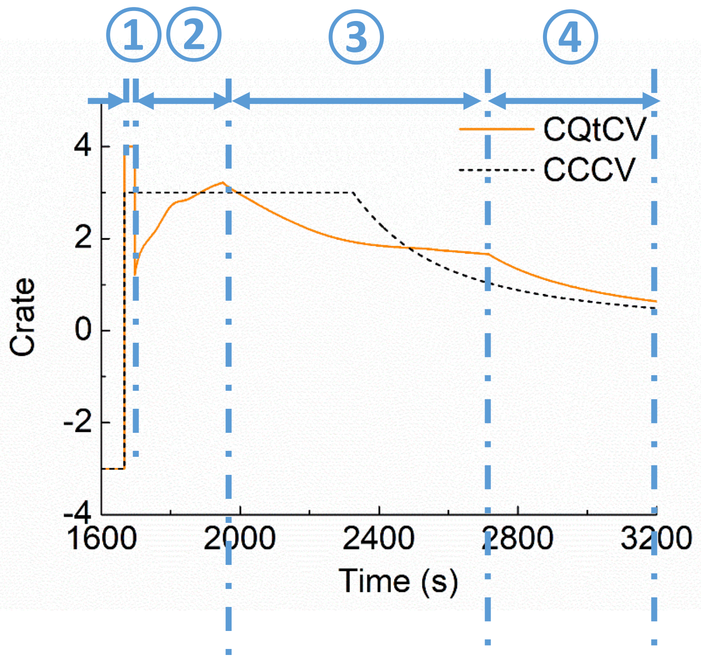
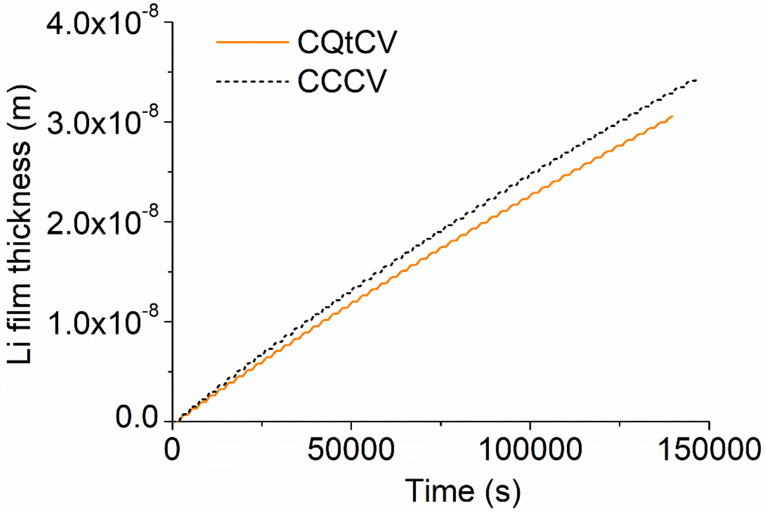
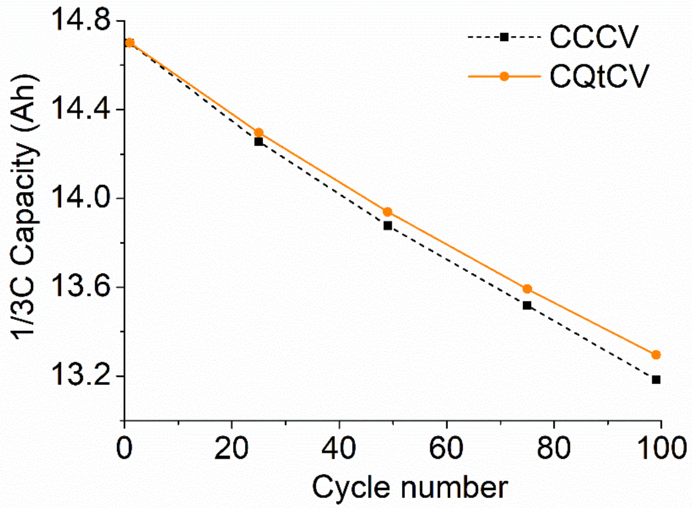
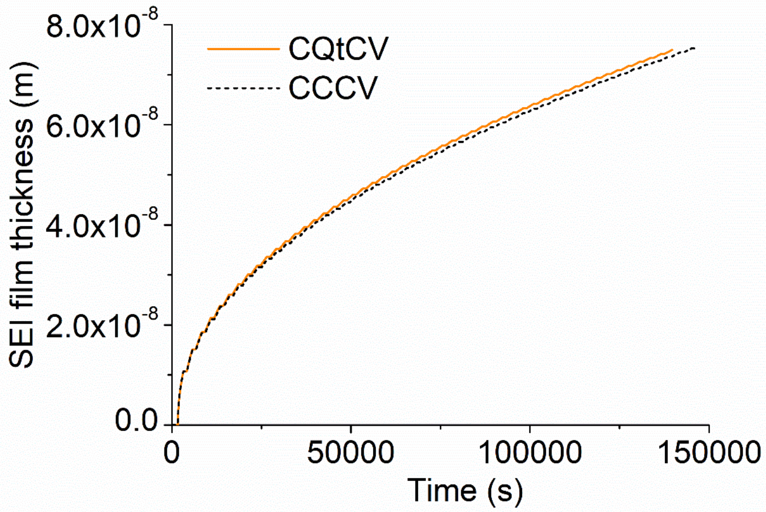
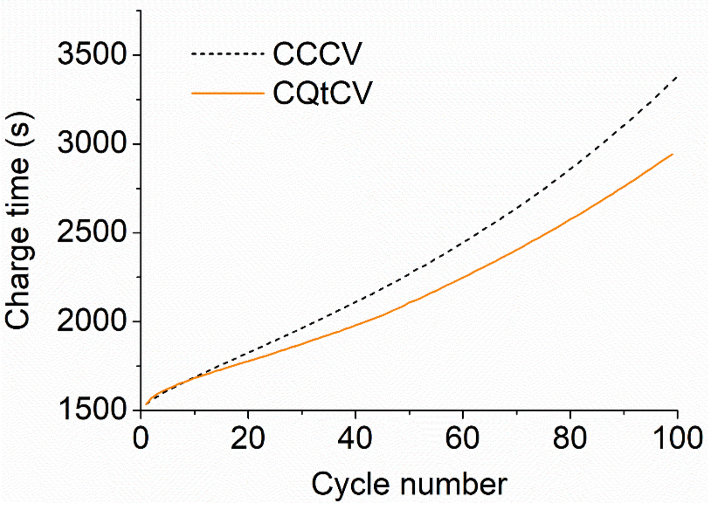
Proposed CQtCV Battery Charge Algorithm





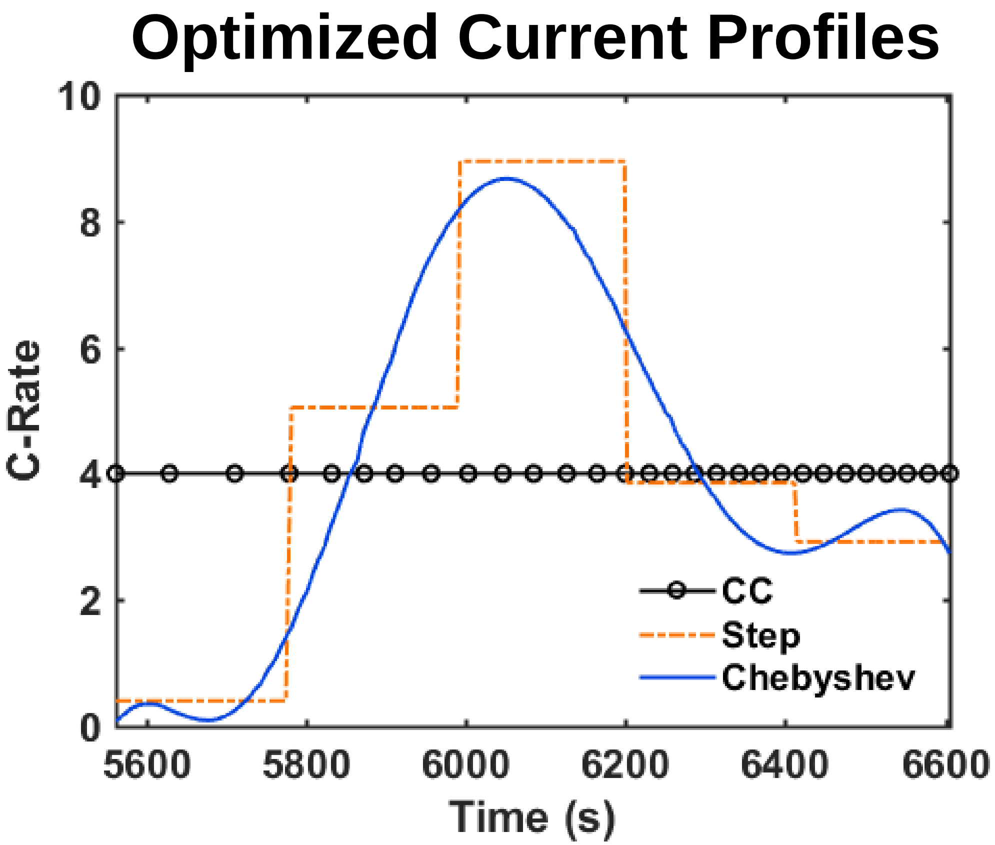




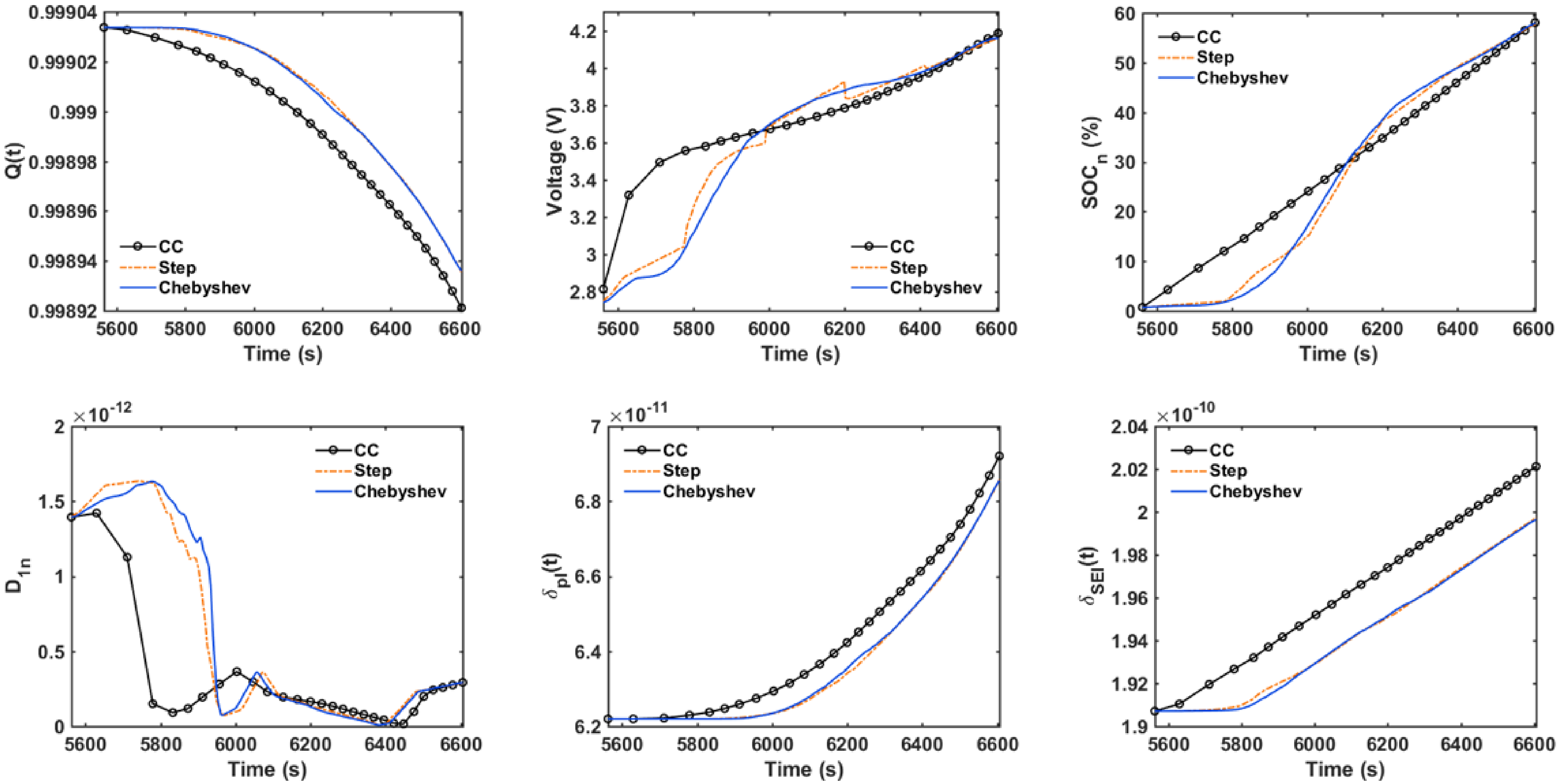


Alternative Approach: Model-Based Optimization

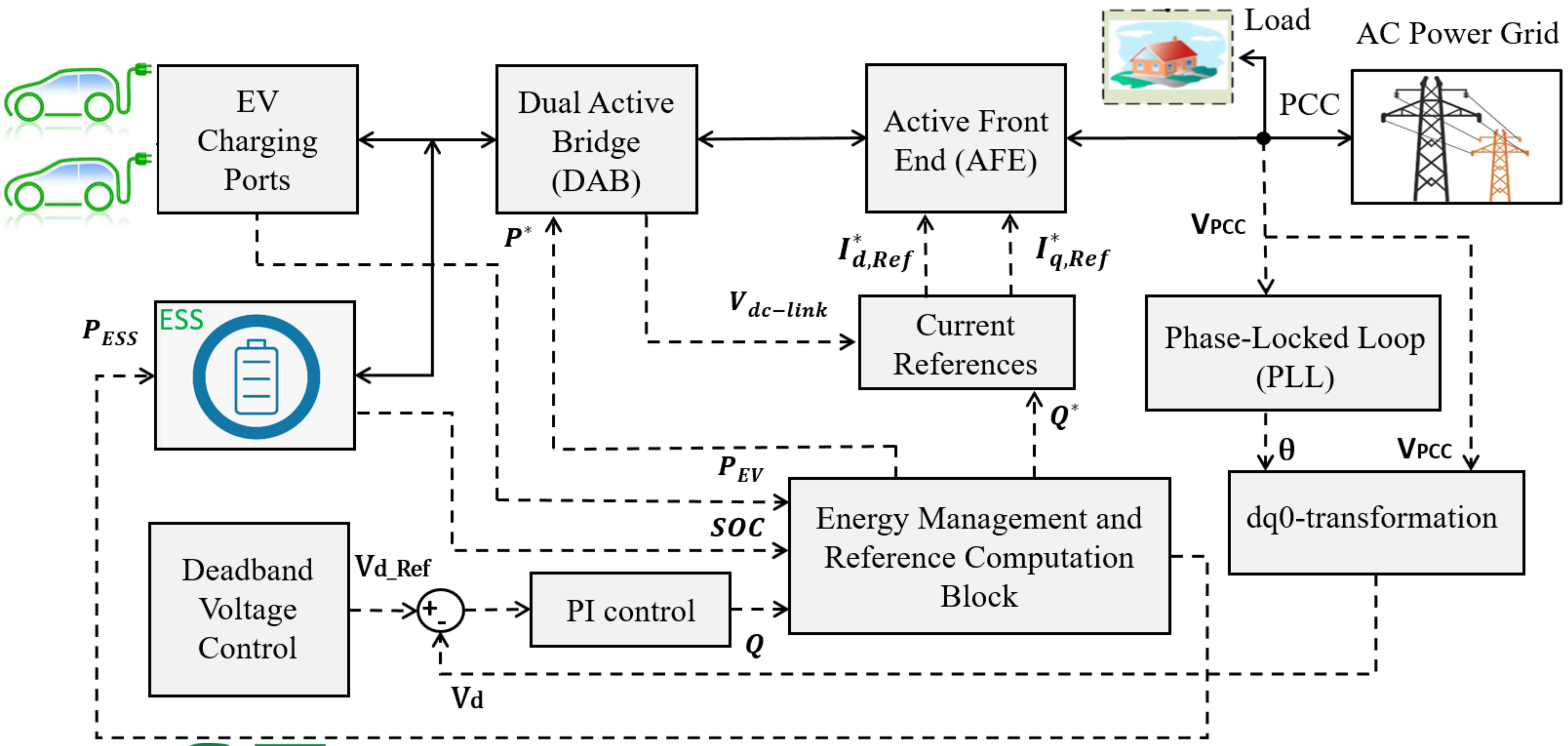
- Apply random constant currents over discrete intervals
- Brute force algorithm obtains near-optimal step profiles
- Chebyshev series is fitted to step profile (smooth, low order)
- Both step and Chebyshev profiles can be optimized
- Minimize capacity fade, meet target SOC and voltage



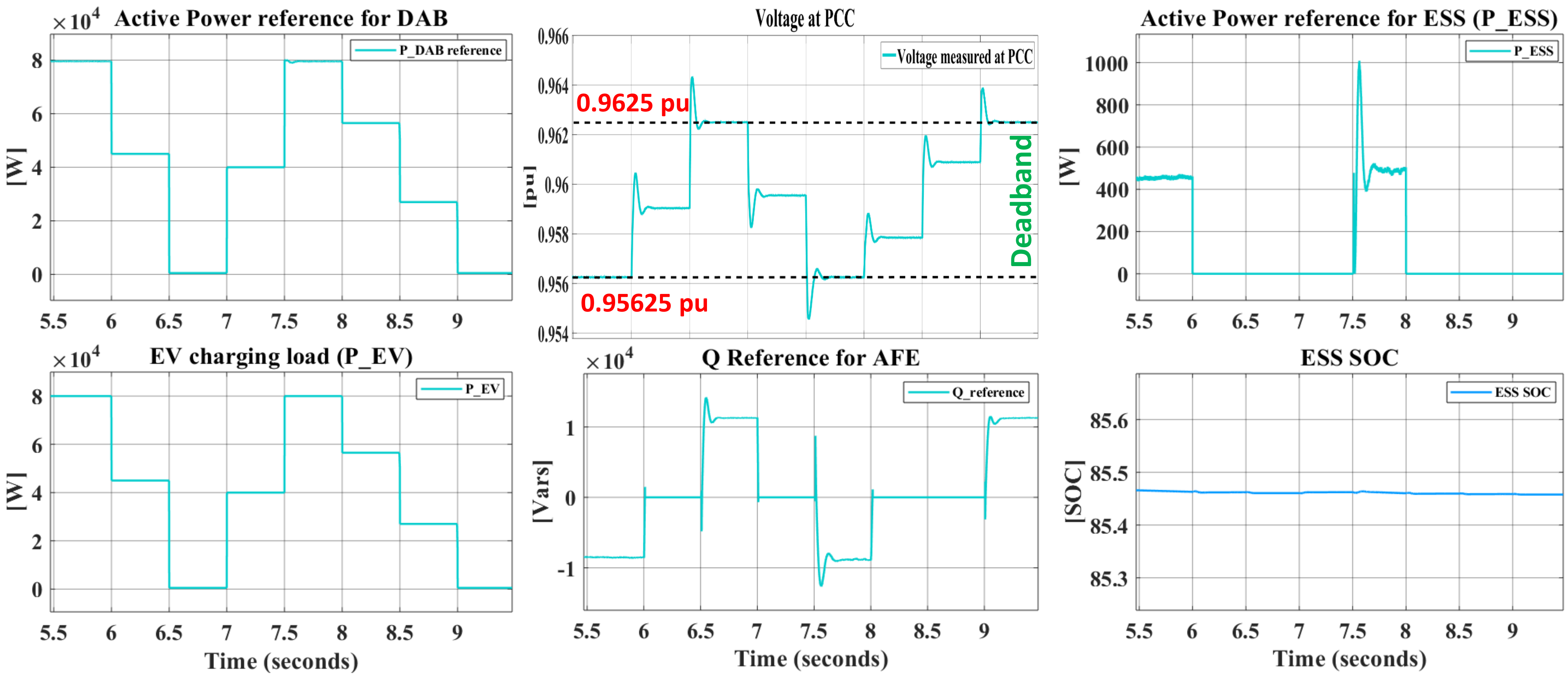
Impact of Optimized Charging Profiles



High-Level Control



Deadband Voltage Control – maintains voltage within limits with minimum of Q



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Collaboration and Coordination with Other Institutions/Organizations

- Ameren – utility in Missouri and Illinois
  - Network data; field testing at Technology Applications Center (TAC)
- Bitrode – battery equipment manufacturer based in St. Louis
  - Will build full-scale prototype
- LG Chem Michigan – battery (and pack) manufacturer
  - Battery data; vehicle pack; stationary pack (energy storage system, or ESS)

Remaining Challenges and Barriers

- Laboratory validation needed for subsystems, cell charging
  - COVID-19 restrictions on campus laboratory access
  - Supply chain challenges for cells

Proposed Future Research

- Complete subscale development, cell-level modeling, grid initial study

Current

- Scale power converter to 12.47 kV, 1 MW
  - Add four battery interface modules
- Develop module- and pack-level charging algorithms
- Complete detailed grid analysis and design controller that mitigates impact, provides revenue
- Vehicle battery pack design and construction

Budget Period 2

- System integration and field testing

BP3

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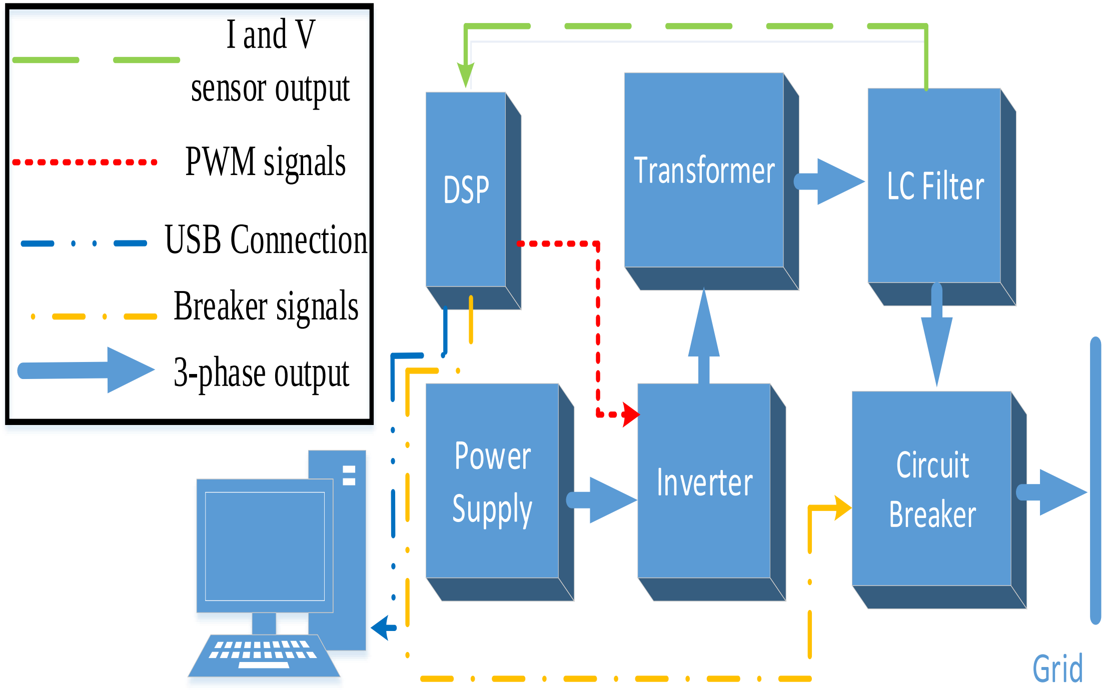
Any proposed future work is subject to change based on funding levels.

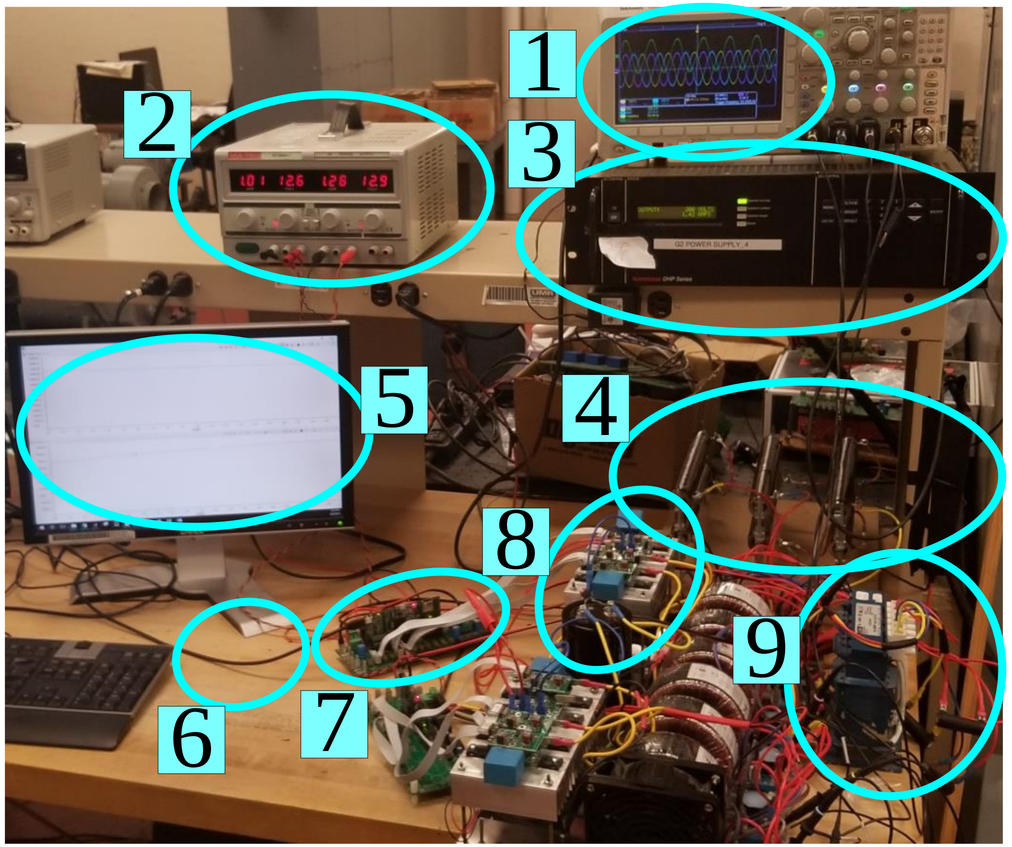
Summary

- Developing an extreme fast charging (XFC) station that connects to 12.47 kV feeder, uses advanced charging algorithms, and incorporates energy storage for grid services
- Subscale development in progress
- Then will scale up, integrate, and test to demonstrate capabilities

Technical Back-Up Slides

VSG Experimental Setup





1. Three-phase output
2. DC supply for Control
3. DC storage for DC side
4. Three-phase load
5. Online monitoring
6. Serial communication
7. TI microprocessor
8. Driver & switching board
9. Emulated resistive line

Experimental testbed parameters

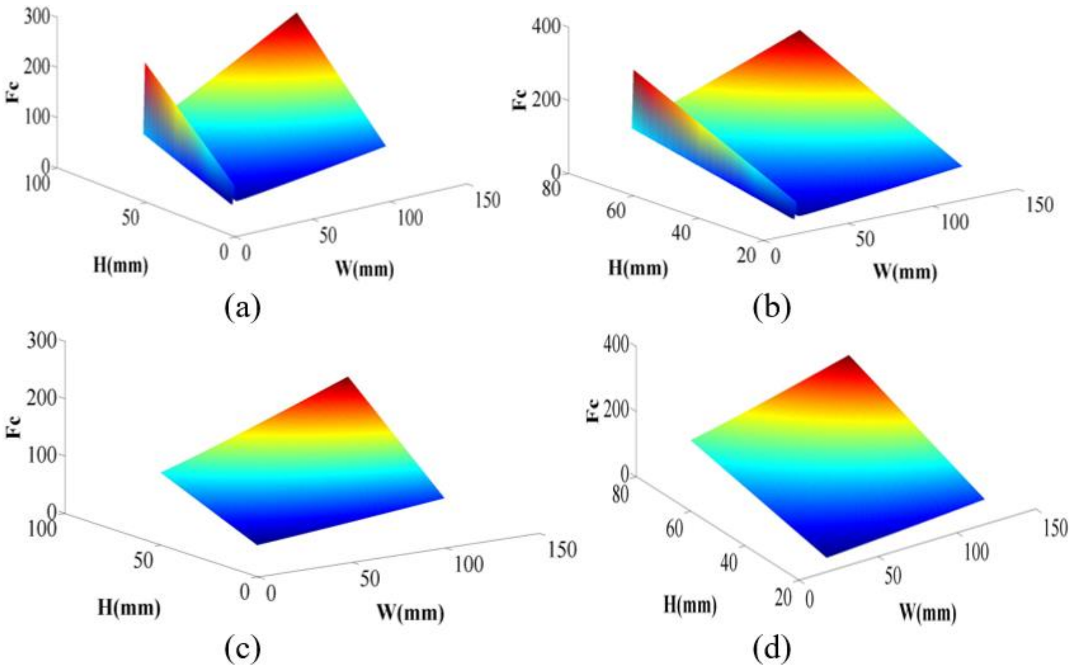
Parameter	Value	Unit
DC Voltage	400	V
AC Line Voltage	110	V
AC Frequency	60	Hz
Moment of Inertia	0.5	kg-m^2
Frequency Droop	4%	
Power Rating	1	kW

Parameter	Value	Unit
Filter Reactance	900	mΩ
Line Reactance	150	mΩ
Line Resistance	1800	mΩ
K_p	0.19	
K_i	40	

Additional Transformer Optimization Plots

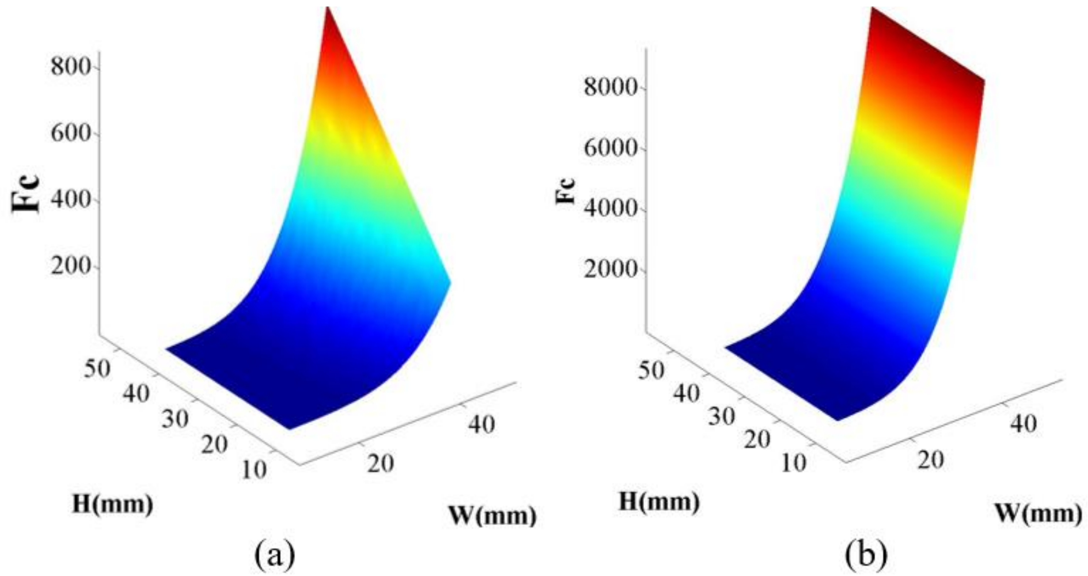
a) Conductive core, *N*=400. b) Conductive core, *N*=450. c) Nonconductive core, *N*=400. d) Nonconductive core, *N*=450.

Fixed turns while window area changes.



f_c-*w*- h graphs. a) Conductive core. b) Nonconductive core.

Fixed Utilization Factor



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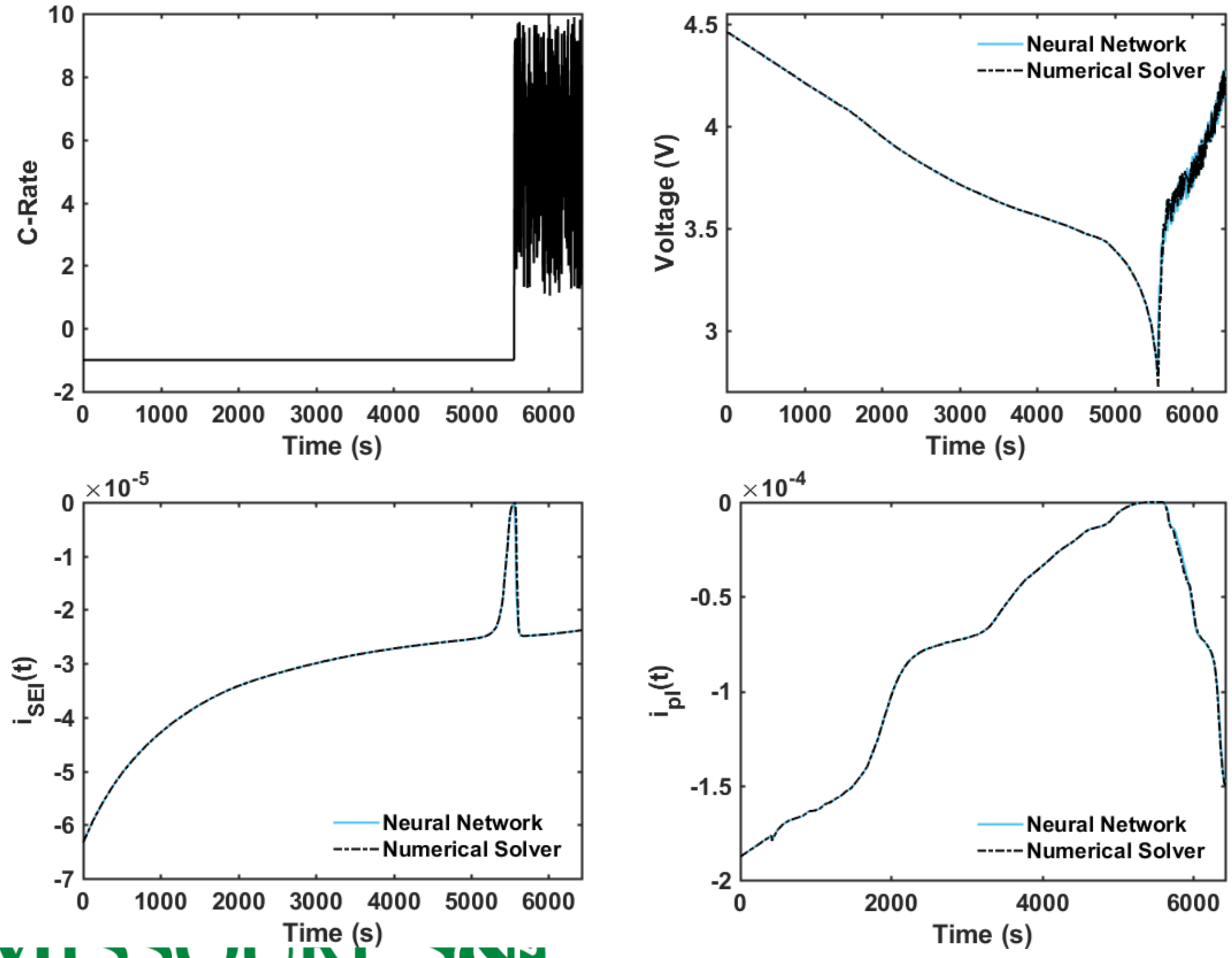
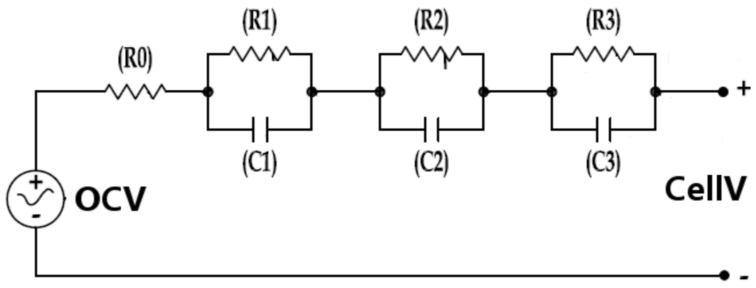
Neural Network Cell Modeling: Implementation

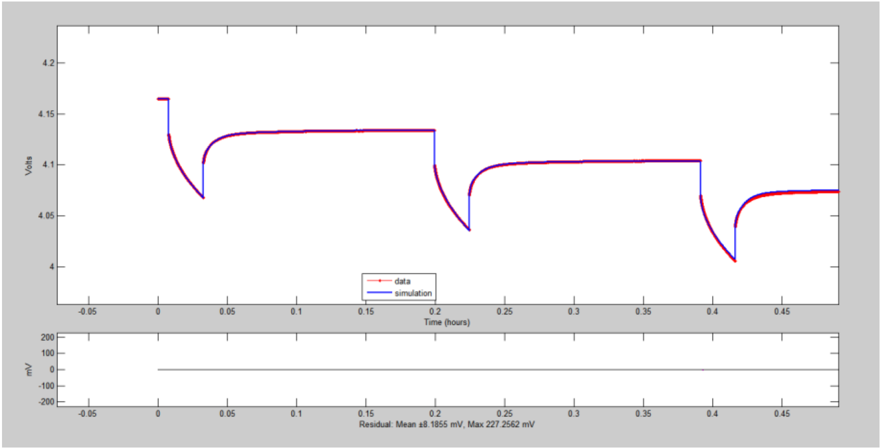


- Demonstrated for 1C discharge, then charge uniformly distributed between 1C and 10C
- Voltage has an average error of about 0.1 V
- Predictions for side reaction current densities are very accurate
- Using NN reduces computation time up to 64%, depends on current profile

Battery Pack Modeling

- Equivalent Circuit Model (Ohmic R0 with 3 stage RC pairs)
  - Nonlinear optimization fits model to actual empirical cell pulse tests





OCV[k] = $v[k] + R_0 i[k] + e^{\left(\frac{-\Delta t}{R_1 C_1}\right)} vc[k] + R_1\left(1 - e^{\left(\frac{-\Delta t}{R_1 C_1}\right)}\right) i[k] +$

$$e^{\left(\frac{-\Delta t}{R_2 C_2}\right)} vc[k] + R_2\left(1 - e^{\left(\frac{-\Delta t}{R_2 C_2}\right)}\right) i[k] + e^{\left(\frac{-\Delta t}{R_3 C_3}\right)} vc[k] + R_3\left(1 - e^{\left(\frac{-\Delta t}{R_3 C_3}\right)}\right) i[k]$$