Enabling Extreme Fast Charging with Energy Storage

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Project ID: ELT237

Overview

- Timeline
  - Start: October 1, 2018
  - End: September 30, 2023
  - 35% Complete

- Budget
- Total Budget: $5,831,079
- DOE Share: $2,915,377
- Contractor Share: $2,915,703
- Current Funding: $2,145,722

- 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 Energy Solution: battery mfg (formerly LG Chem Michigan)

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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

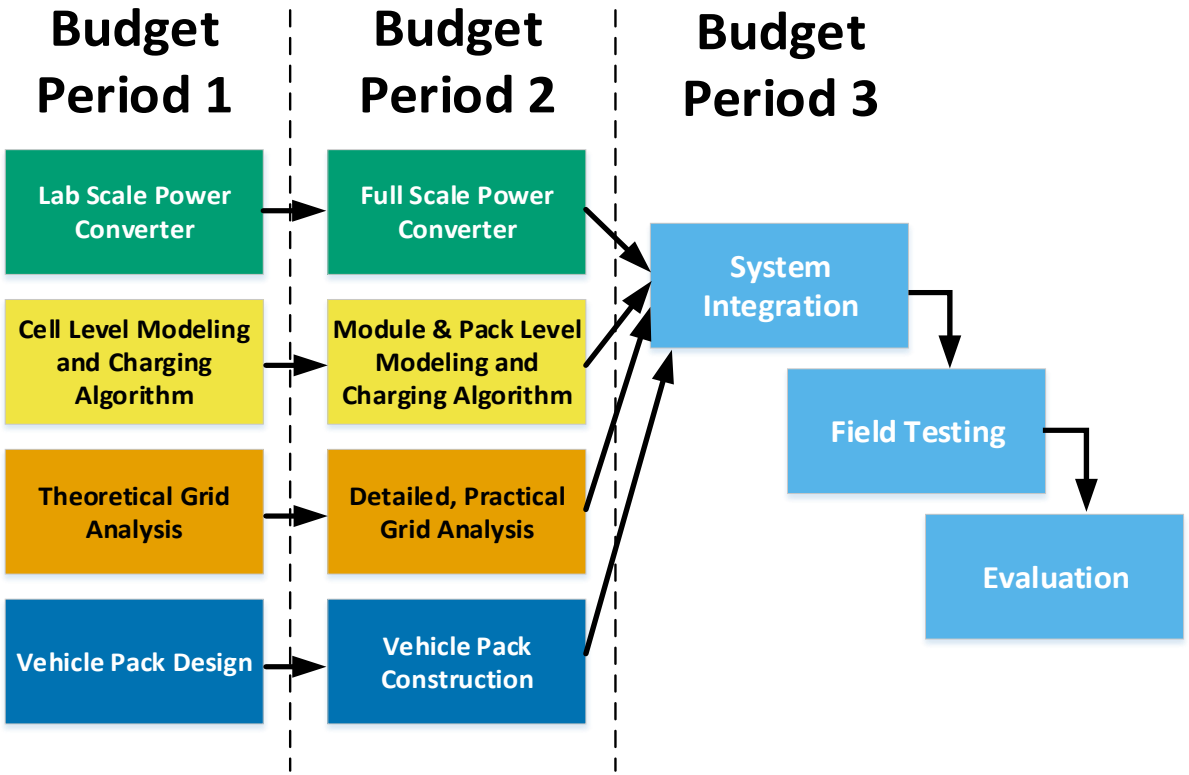
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Milestones for Current Budget Period (BP2)

Milestone	Type	Description
Battery Models Scaled Up	Technical	Battery cell models extended to module and pack level
Subsystems Ready for Integration	Technical	Low-level distributed controller complete; AFE, dc-dc, chargers individually built & tested
Module Tests Complete	Technical	First charge cycling test complete on battery modules to validate charge algorithm and model
Integrated Converter Complete	Technical	All major power converter subsystems integrated and tested
Full-Scale System Go/No-Go	Go/No-Go	Power converter, charging algorithms, ESS, and high-level grid interface control all ready for final integration and field test

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Approach



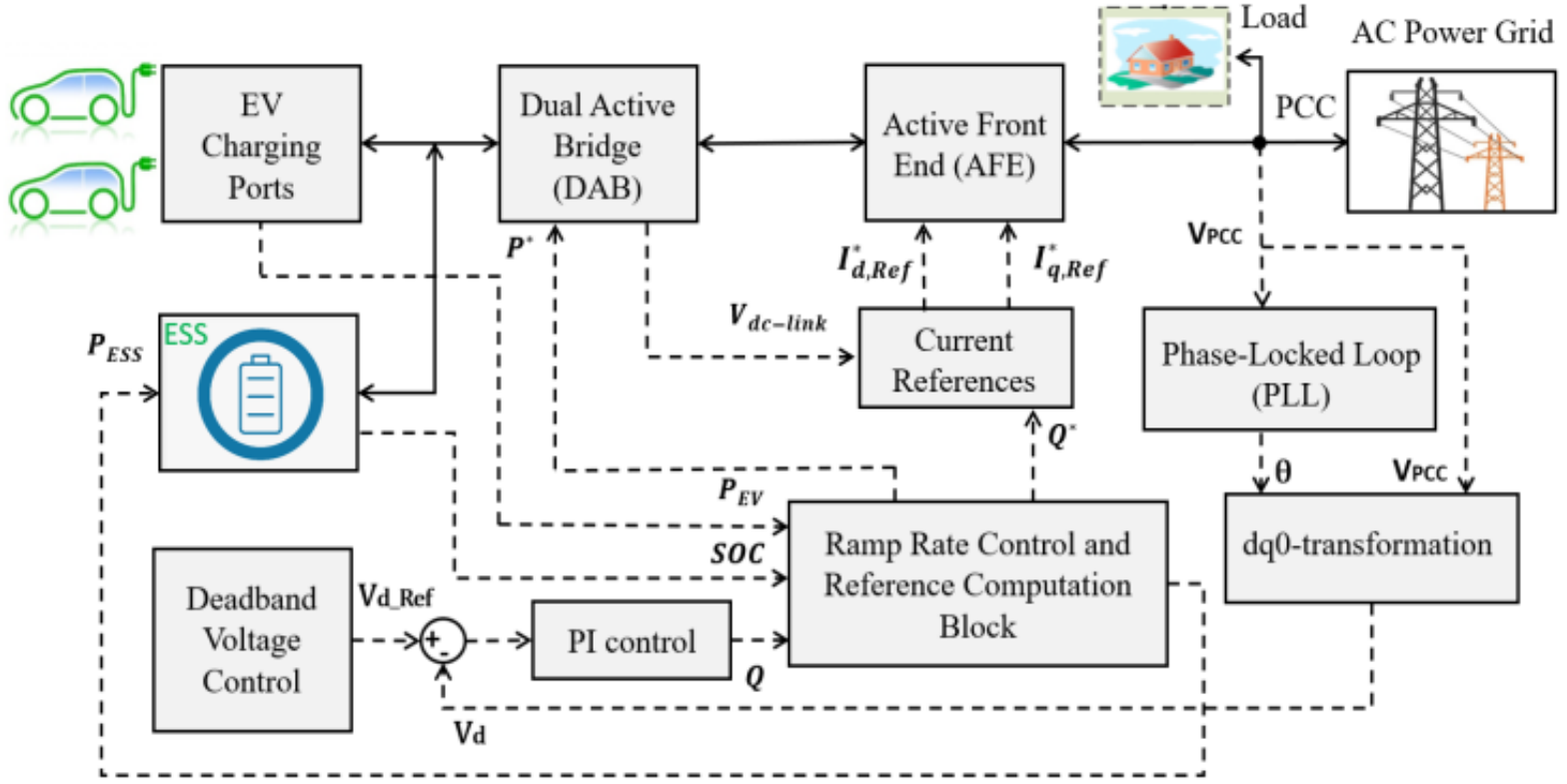
- Budget Period 1 was focused on proof-of-concept, culminated in feasibility go/no-go
- BP2 is focused on reaching full scale, culminates in prototype
- BP3 includes
  - Integration
  - Field Test
  - Evaluation

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

Technical Accomplishments and Progress

- Power Conversion
- Grid Compatibility
- Battery Charging
- Vehicle Pack



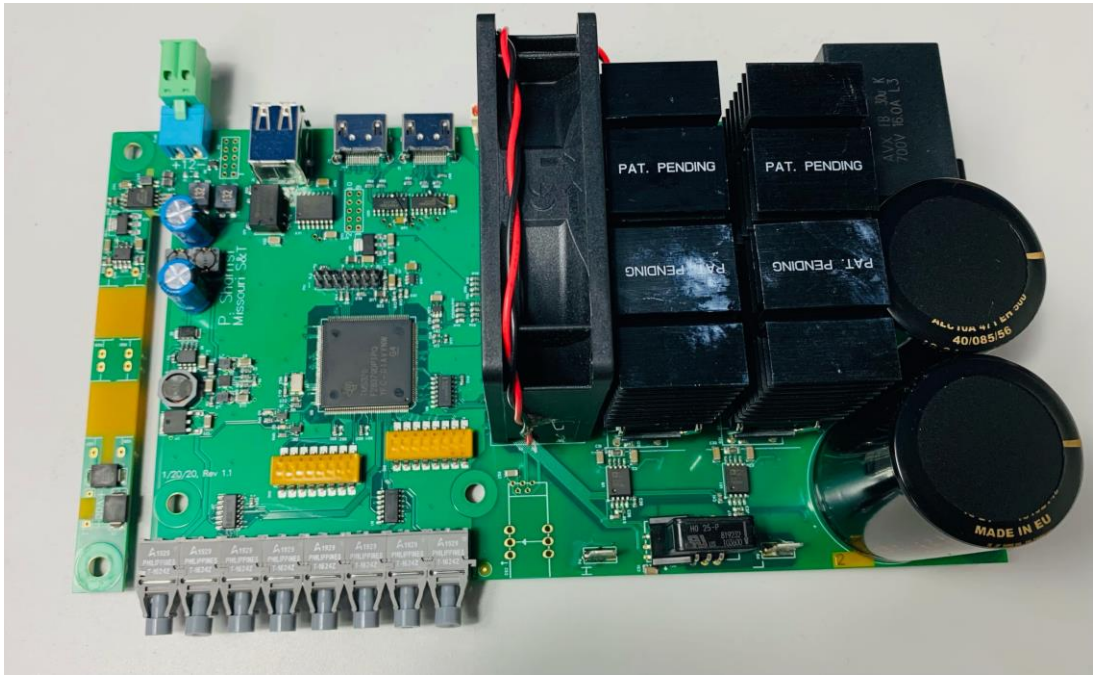
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Low-Voltage Power Converter Prototype Module

Grid Side: Front-end H-bridge Inverter + HF Transformer H-bridge Driver



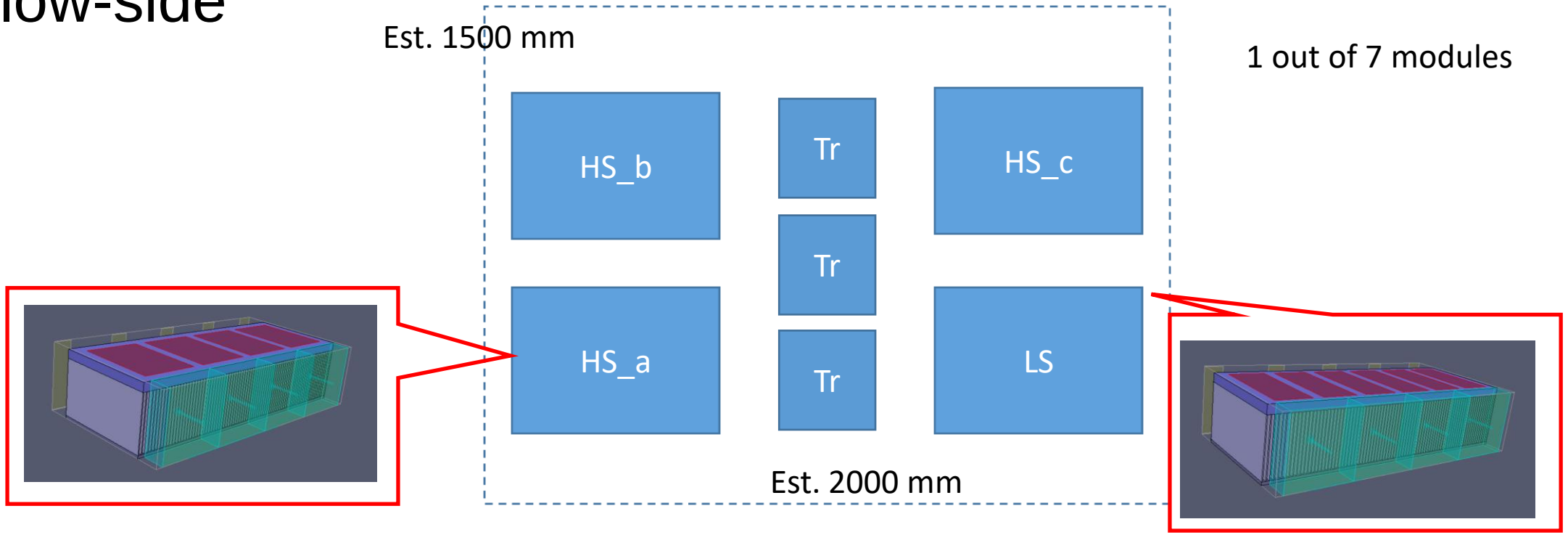
Battery Side: HF Transformer H-bridge Rectifier + Module Controller



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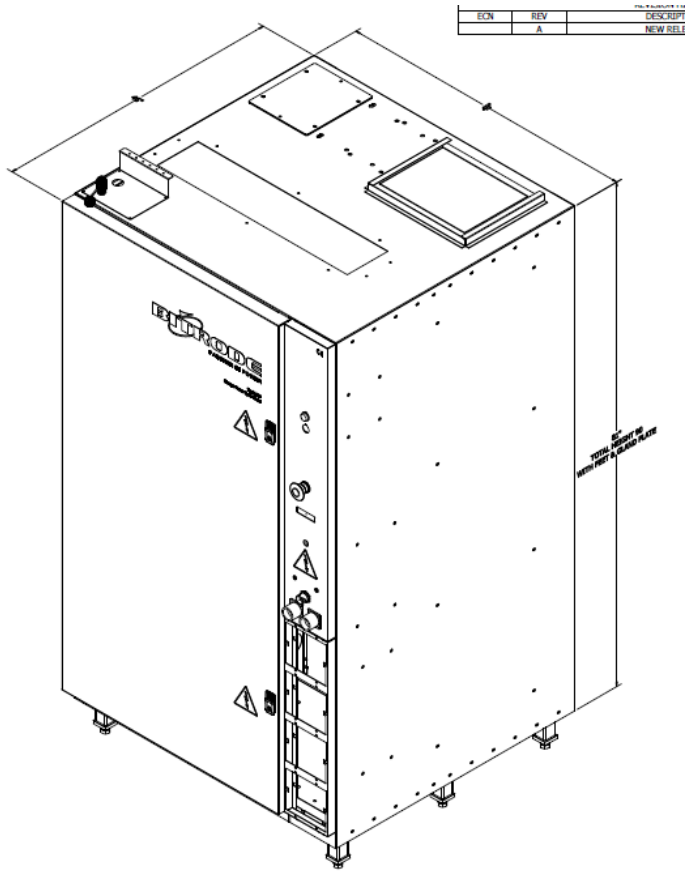
Modular Design of Full-Rated Converter

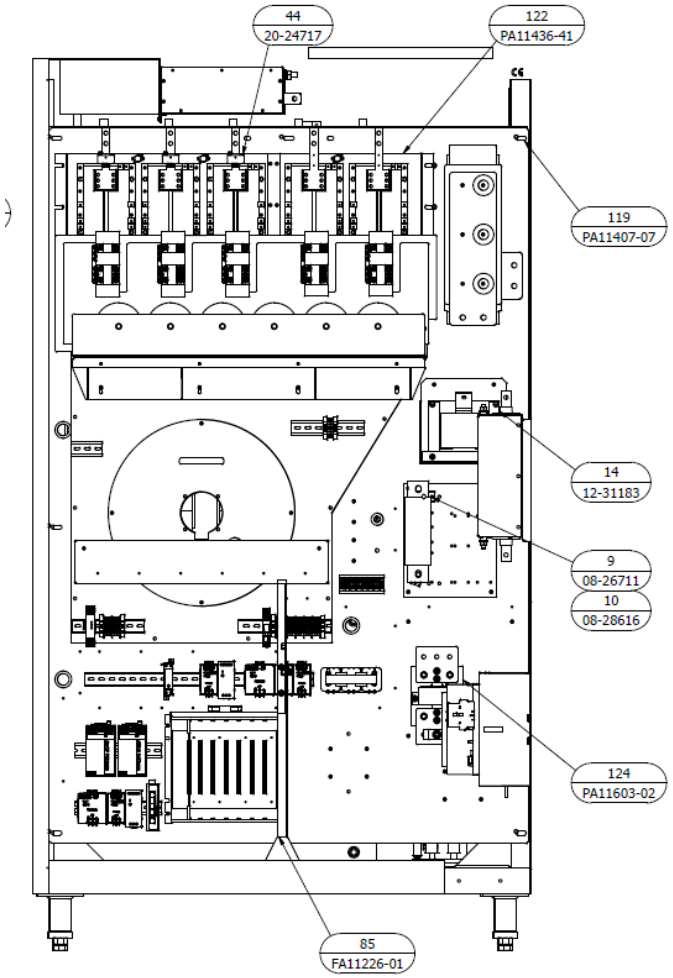
- Each module incorporates three high-side bridges, one low-side



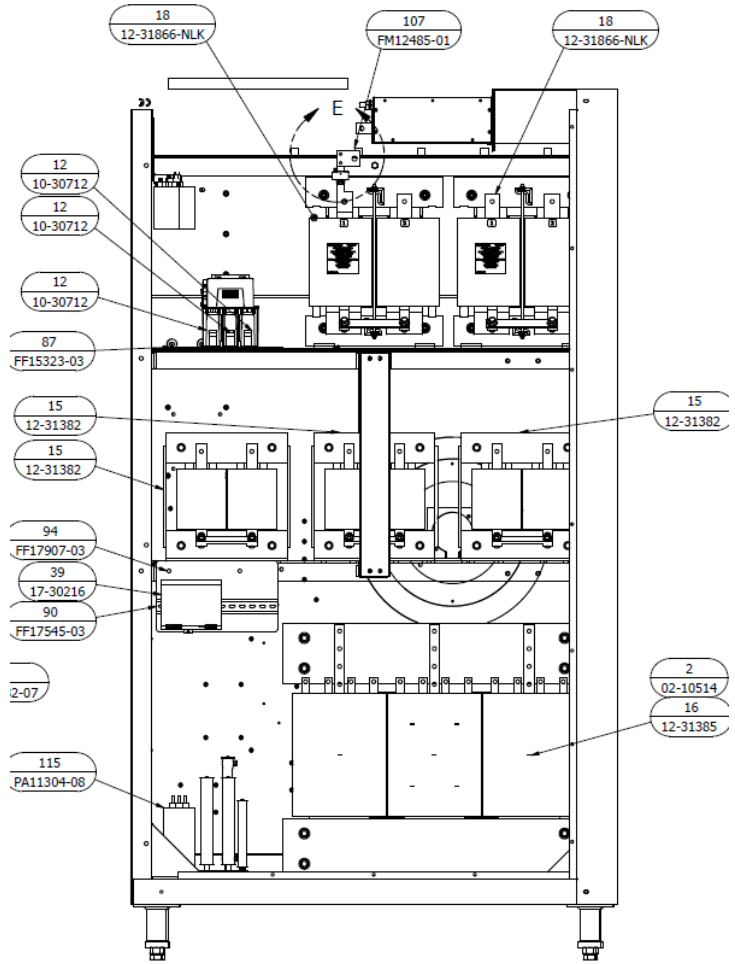
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Design Reuse: Bitrode FTF1-500-1000 Modified for Charger Ports



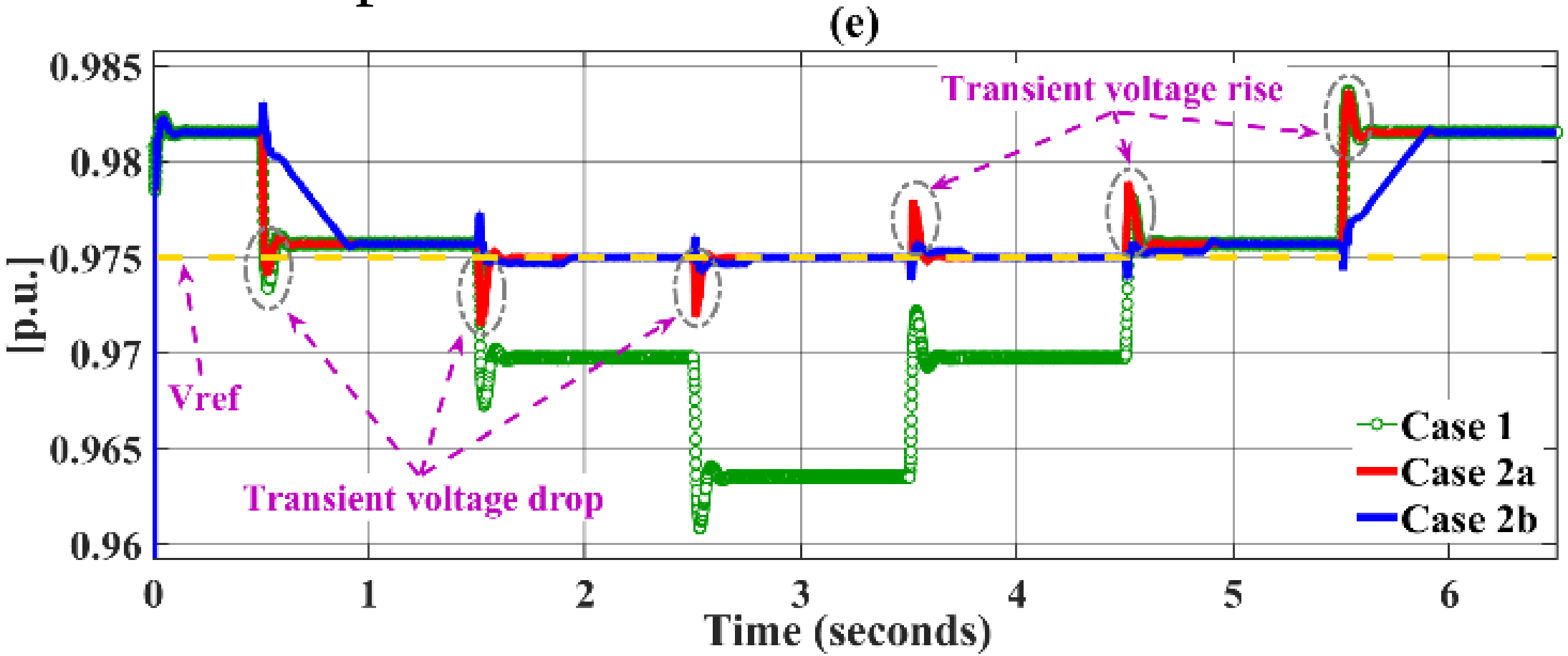


FRONT VIEW



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Grid-Side Control Method: Q injection when possible, ESS charge/discharge when necessary, limited ramp rate for transient control



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Uncertainty Modeling of Charging Demand and PV generation

DETERMINISTIC MILP MODEL (Obj. Func.)

Min. over Decision variables

$$\min_{E_g^{AC},E_{BESS}(t),P_{BESS}^{rated},C_{BESS},DoD,PV^{rated},P_{g,mon}^{max},P_{g,ann}^{max}} \left(\mathrm{SF}^{\mathrm{M}} \times \left(P_{g,mon}^{max} \times \lambda_{MDC}\right) + \left(P_{g,ann}^{max} \times \lambda_{ADC}\right)\right)$$

Demand Charges

BESS Investment

$$+ \left(C_{BESS} \times \left(CE_{BESS}^{capital} + CE_{BESS}^{inst}\right) + P_{BESS}^{rated} \times \left(CP_{BESS}^{capital} + C_{BESS}^{O\&M}\right)\right)$$

PV Investment

$$+ \left(PV^{rated} \times \left(CP_{PV}^{capital} + C_{PV}^{O\&M}\right)\right)$$

XFCS Operation Cost

$$+ \left(\mathrm{SF}^{\mathrm{D}} \times \sum_{t\in\mathcal{T}} \left(E_g^{AC}(t) \times \hat{\lambda}_E(t)\right)\right),$$

Energy balance constraint:

demand Uncertainty

$$E_g^{AC}(t) = \frac{1}{\eta_{AC-DC}} \times \frac{1}{\eta_{DC-DC}} \times \left(\widehat{E_{XFCS}}(t) + E_{BESS}(t) - P_{ac}(t) \times \Delta t\right), \ \forall t \in \mathcal{T}$$

PV Uncertainty

ROBUST COUNTERPART (Obj. Func.) (min-max-min formulation)

$$\min_{E_g^{AC},E_{BESS}(t),P_{BESS}^{rated},C_{BESS},DoD,PV^{rated},P_{g,mon}^{max},P_{g,ann}^{max}} \left(\mathrm{SF}^{\mathrm{M}} \times \left(P_{g,mon}^{max} \times \lambda_{MDC}\right) + \left(P_{g,ann}^{max} \times \lambda_{ADC}\right)\right)$$
$$+ \left(C_{BESS} \times \left(CE_{BESS}^{capital} + CE_{BESS}^{inst}\right)\right.$$
$$\left. + P_{BESS}^{rated} \times \left(CP_{BESS}^{capital} + C_{BESS}^{O\&M}\right)\right)$$
$$+ \left(PV^{rated} \times \left(CP_{PV}^{capital} + C_{PV}^{O\&M}\right)\right)$$
$$+ \max_{m\in U^D, n\in U^{PV}} \min_{E_g^{AC},E_{BESS}(t),P_{BESS}^{rated},C_{BESS},DoD,PV^{rated},P_{g,mon}^{max},P_{g,ann}^{max}} \left(\mathrm{SF}^{\mathrm{D}} \times \sum_{t\in\mathcal{T}} \left(E_g^{AC}(t) \times \hat{\lambda}_E(t)\right)\right), \ \forall t \in \mathcal{T}$$

Uncertainty realization

KKT conditions and duality theorem is used to convert into min. problem

$$U^D = \left\{ \begin{array}{l} E_{XFCS}^m(t) \in R^+ : \underline{\Gamma^D} \le \frac{E_{XFCS}^m(t)}{\widehat{E_{XFCS}}(t)} \le \overline{\Gamma^D} \\ E_{XFCS}^m(t) \in \left[\underline{E_{XFCS}}(t),\ \overline{E_{XFCS}}(t)\right] \\ \overline{E_{XFCS}}(t) = (1+\varrho) \times \widehat{E_{XFCS}}(t) \\ \underline{E_{XFCS}}(t) = (1-\varrho) \times \widehat{E_{XFCS}}(t) \end{array} \right\}, \ \forall t \in \mathcal{T}$$

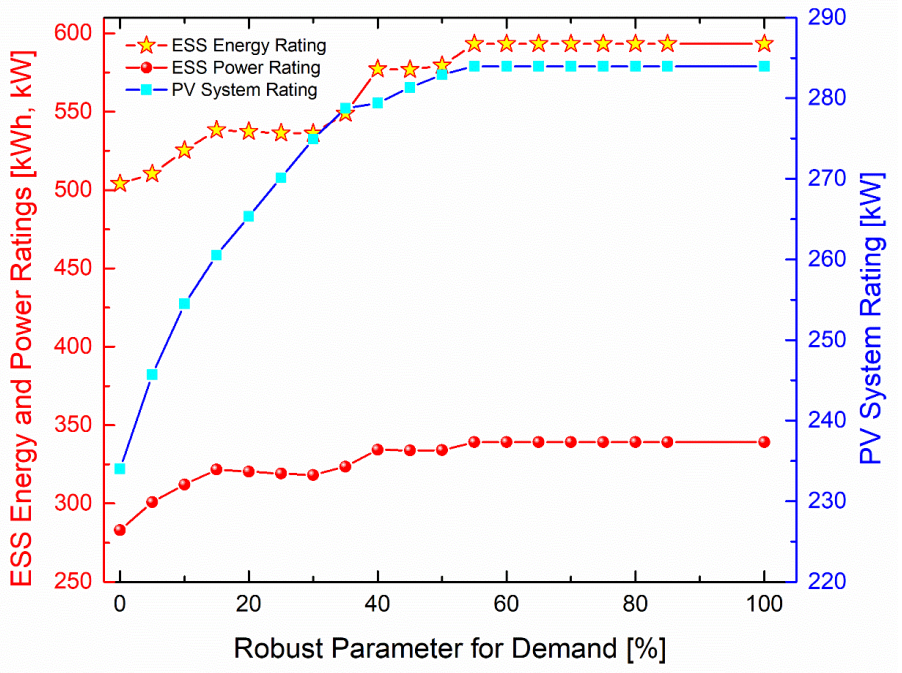
$$U^{PV} = \left\{ \begin{array}{l} PV_G^n(t) \in R^+ : \underline{\Gamma^{PV}} \le \frac{PV_G^n(t)}{\widehat{PV_G}(t)} \le \overline{\Gamma^{PV}} \\ PV_G^n(t) \in \left[\underline{PV_G}(t),\ \overline{PV_G}(t)\right] \\ \overline{PV_G}(t) = (1+\mathcal{E}) \times \widehat{PV_G}(t) \\ \underline{PV_G}(t) = (1-\mathcal{E}) \times \widehat{PV_G}(t) \end{array} \right\}, \ \forall t \in \mathcal{T}$$

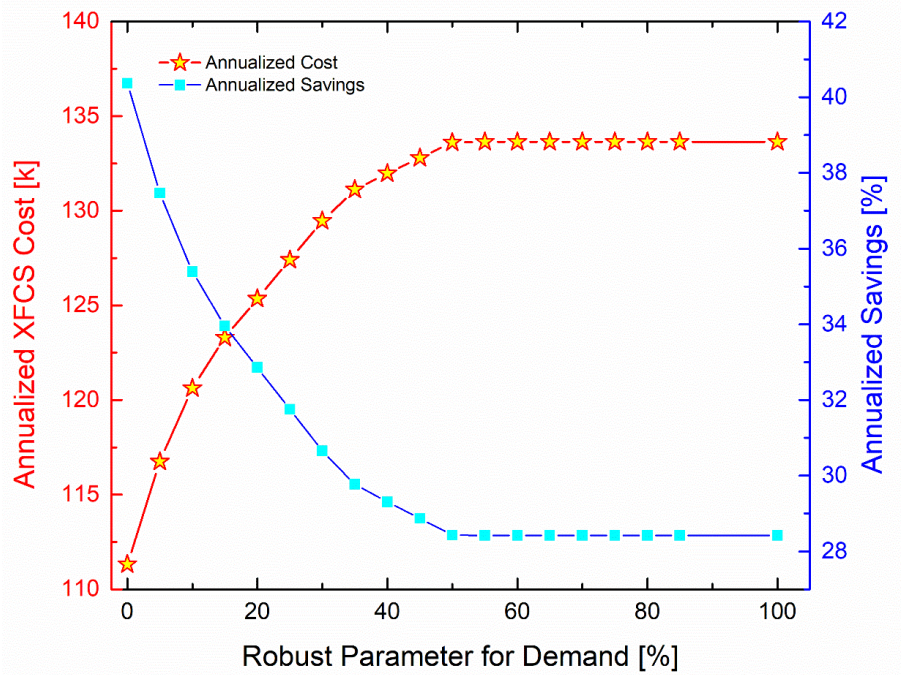
Uncertainty Bounds

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ESS and PV System Sizing with Different Level of Robustness against Charging Demand Uncertainty

- Uncertainty bound 20% around the forecasted XFCS demand
- Γ^D =0% means deterministic case
- Γ^D =100% means extreme conservative solution





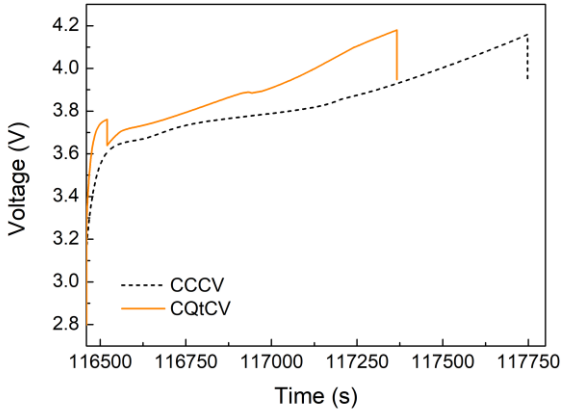
Observations:

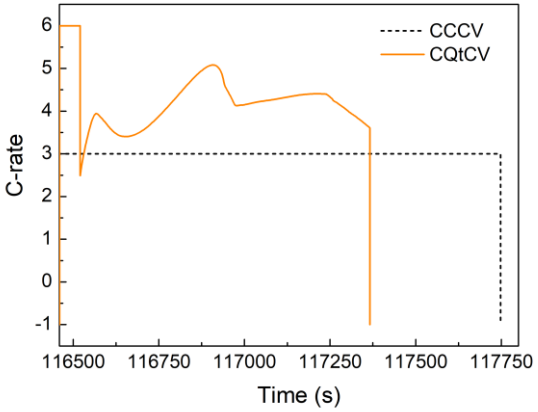
- With increase in robust parameter, sizing of both the ESS and PV system increases until Γ^D=50%; since the charging demand profile is non-zero only about 50% of the day.
- The maximum increase in ESS power and energy ratings is observed to be 20% and 18%, respectively, while PV system's optimal rating increased by 20%.
- Similar trend is observed for increase in total annualized cost. The maximum decrease in annualized savings is about ~12%.

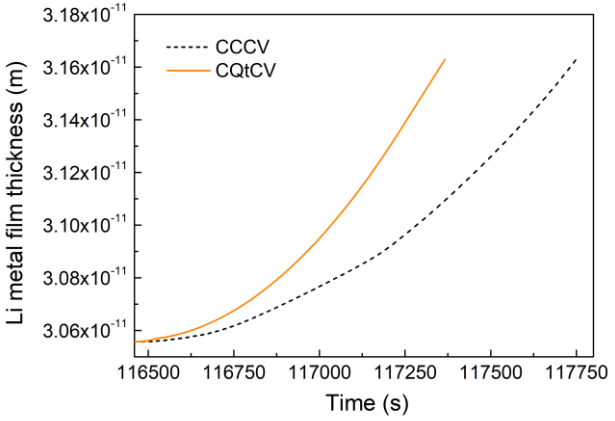
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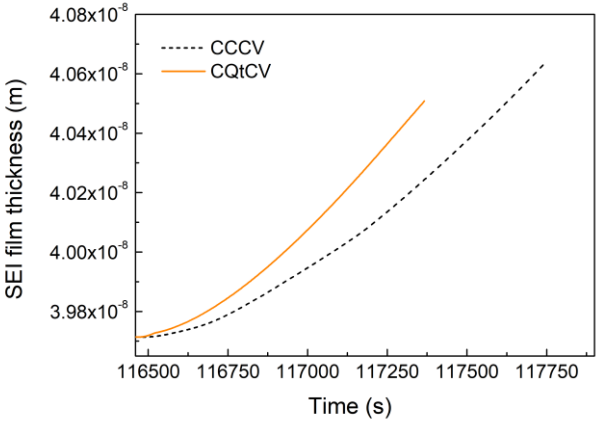
Proposed charging method: CQtCV

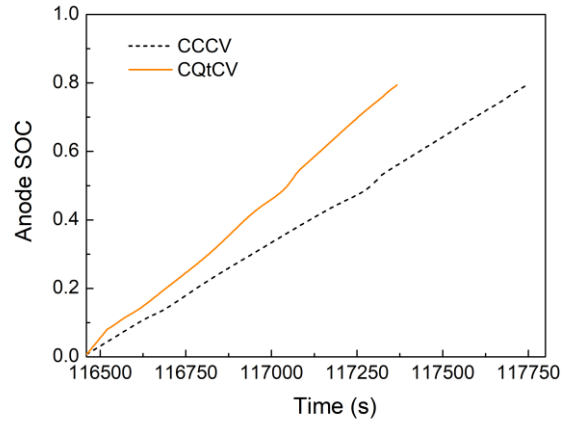
- Constant Current, Constant Voltage: conventional charging
- Constant $\dot{Q}_{Li}$ then Constant Voltage: mitigates degradation due to lithium plating while enabling faster charge rates (by 29%)

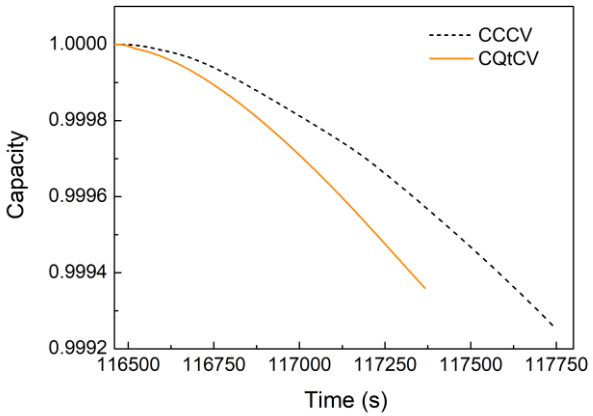








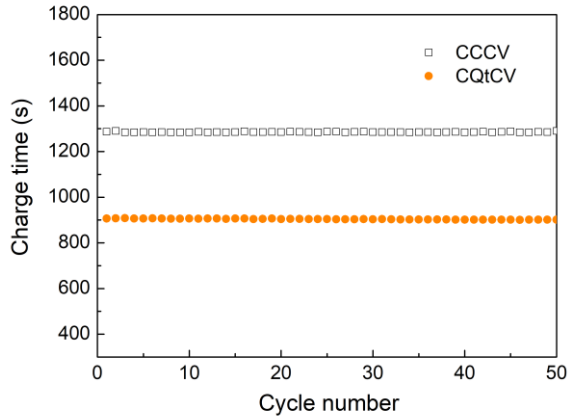


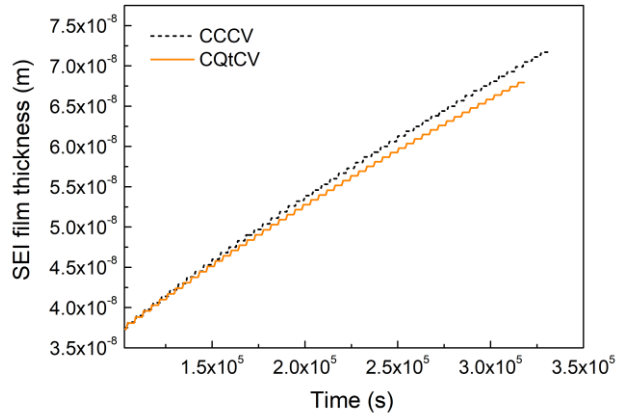


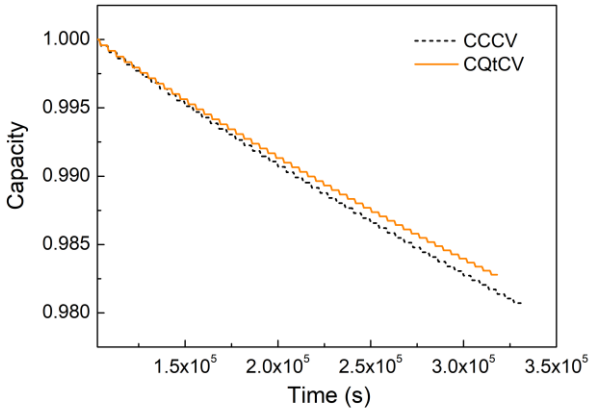
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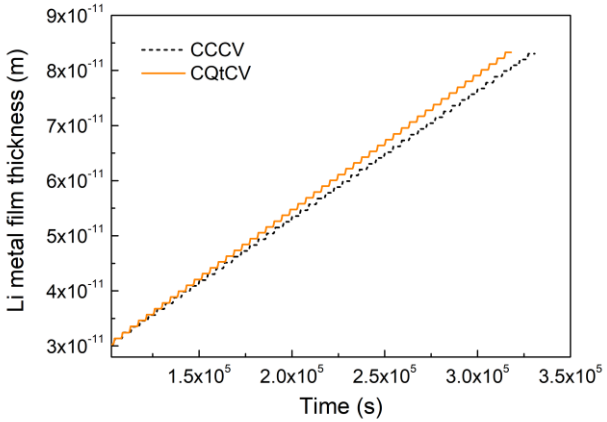
CCCV vs. CQtCV

- The average charge time of 50 cycles is reduced by 29.5% in CQtCV compared with 3C CCCV.
- CQtCV enhances the capacity retention by 0.46% after 50 cycles' test, which is mainly due to the slowed SEI layer growth.





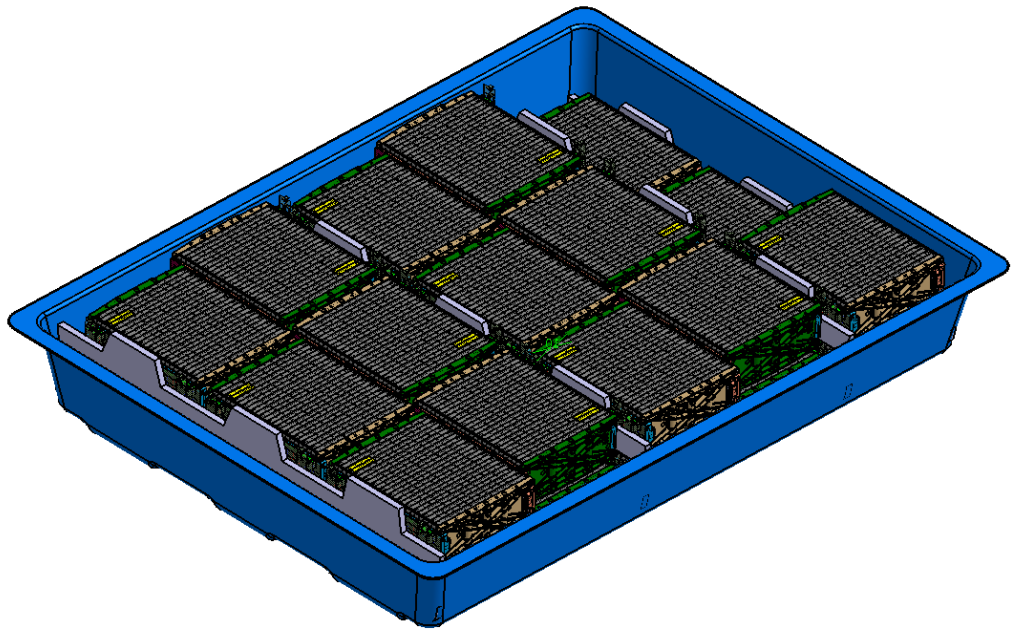




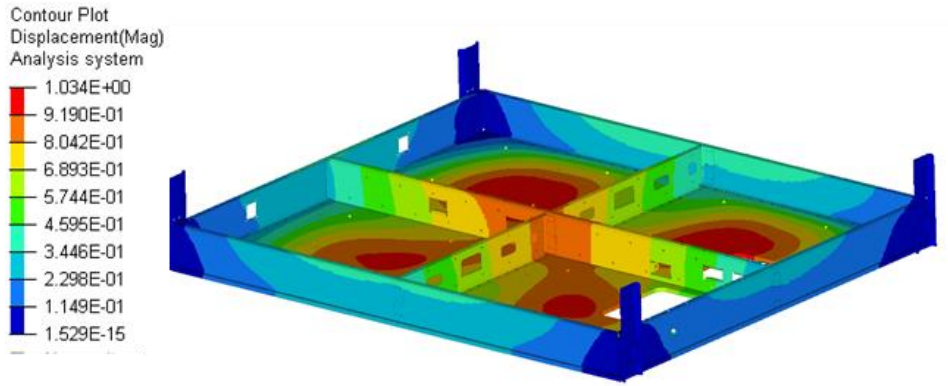
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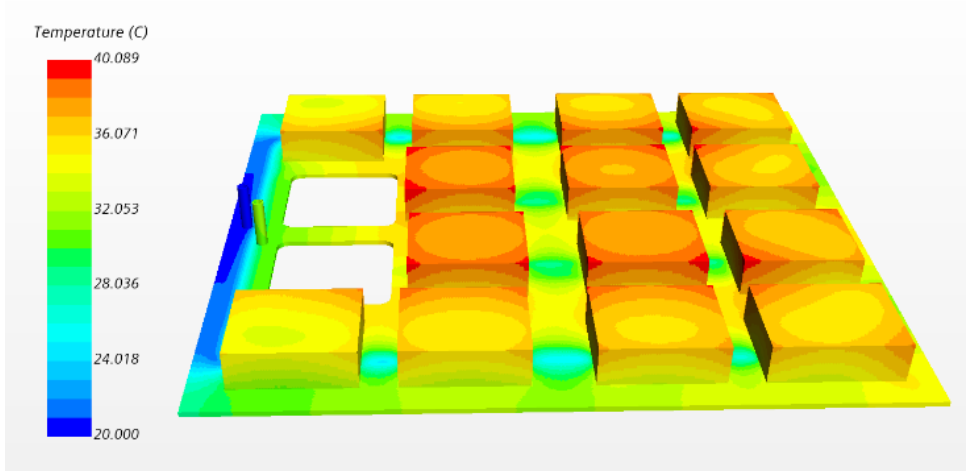
Vehicle Pack Design

Overall Structure: 26 modules, each 8S3P, 160 kWh



Mechanical and Thermal Analysis





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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 Energy Solution (formerly LG Chem) – battery (and pack) manufacturer
  - Battery data; vehicle pack; stationary pack (energy storage system, or ESS)

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Remaining Challenges and Barriers

- Reaching full scale in power converter, including medium-voltage
  - Supply-chain challenges
- System integration
  - Controlling P, Q flow within system and with grid
  - Coordinating large number of modules

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

Proposed Future Research

- Complete subscale development, cell-level modeling, grid initial study → COMPLETE
- 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
- System integration and field testing

BP1

Budget Period 2 (CURRENT)

BP3

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

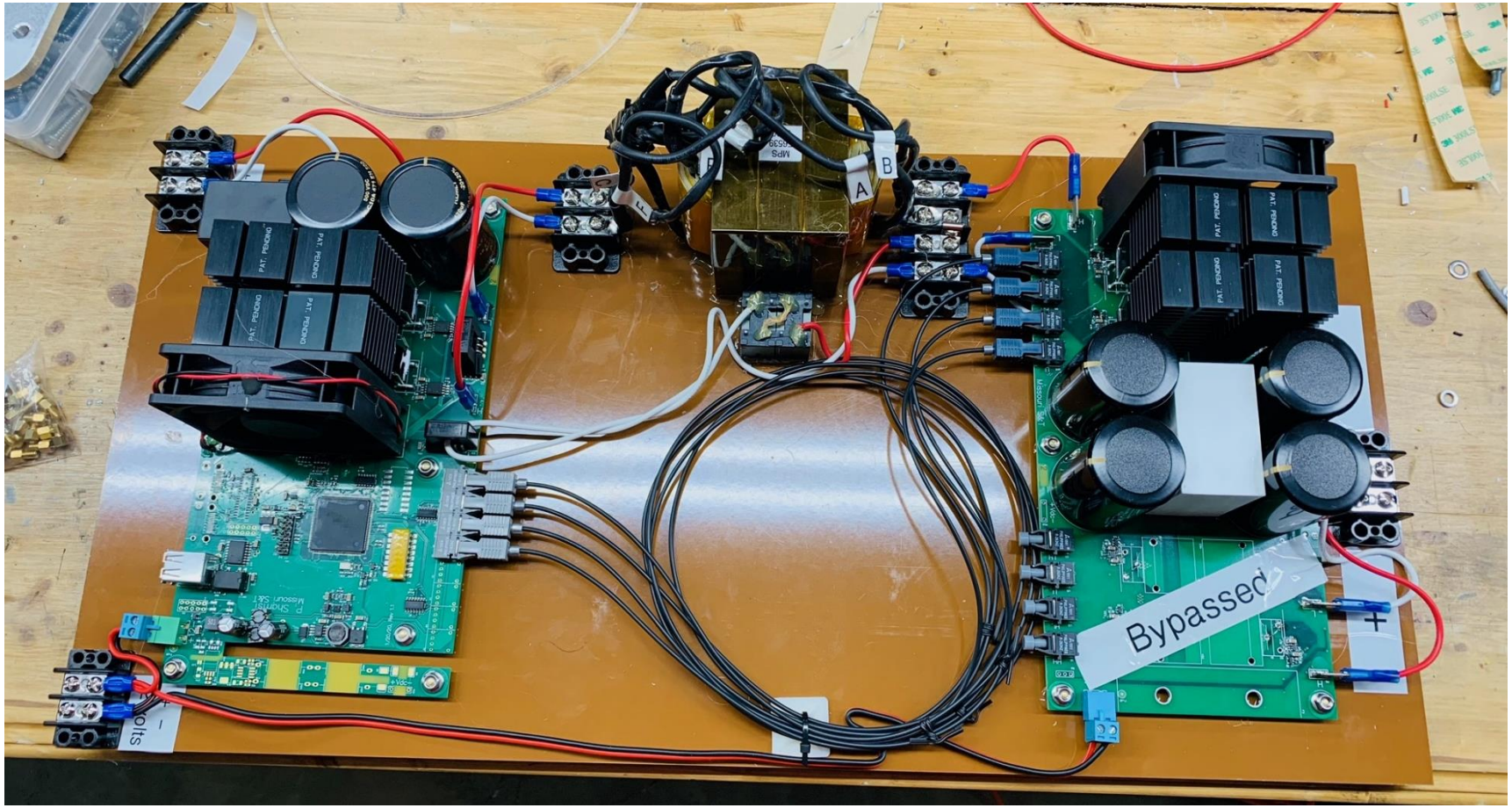
Summary

- 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
- Currently expanding lab-scale to full-scale systems
- Then will integrate and test to demonstrate capabilities

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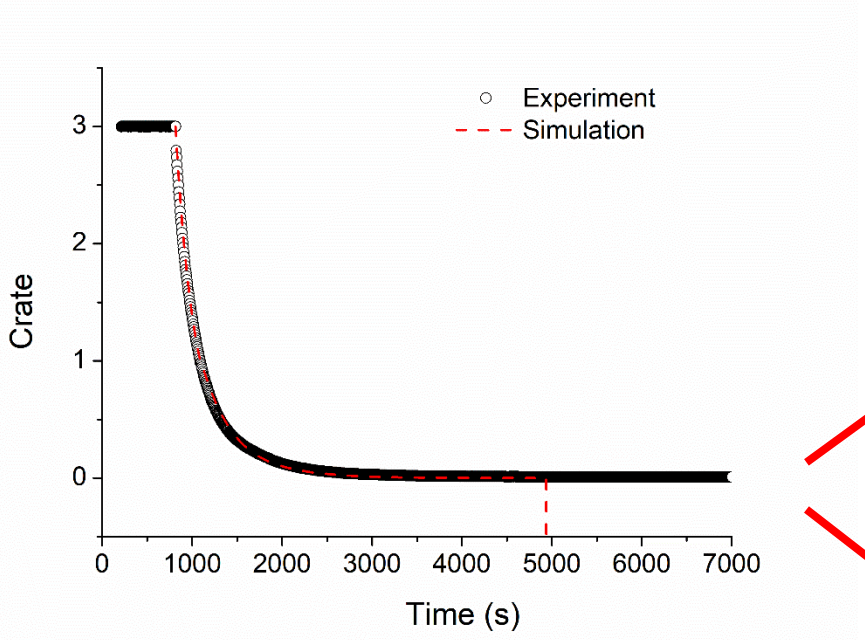
Technical Back-Up Slides

Low-Voltage Prototype

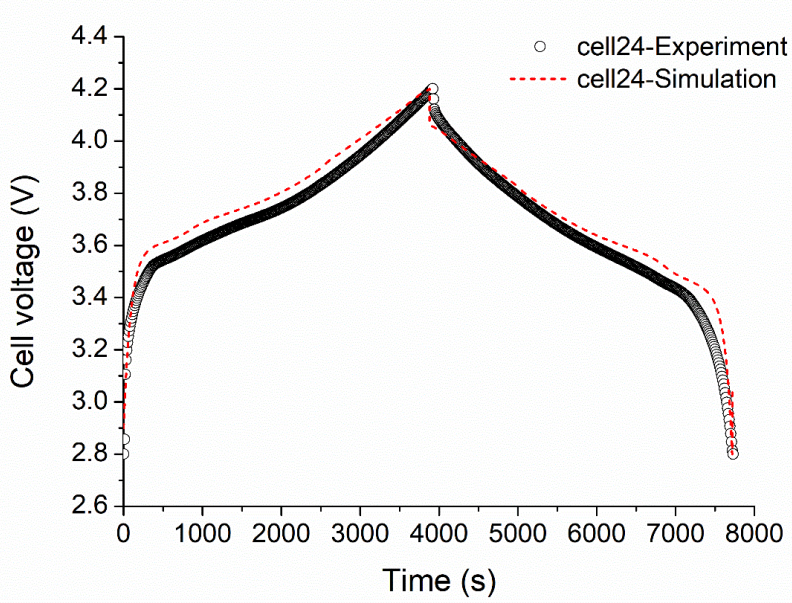


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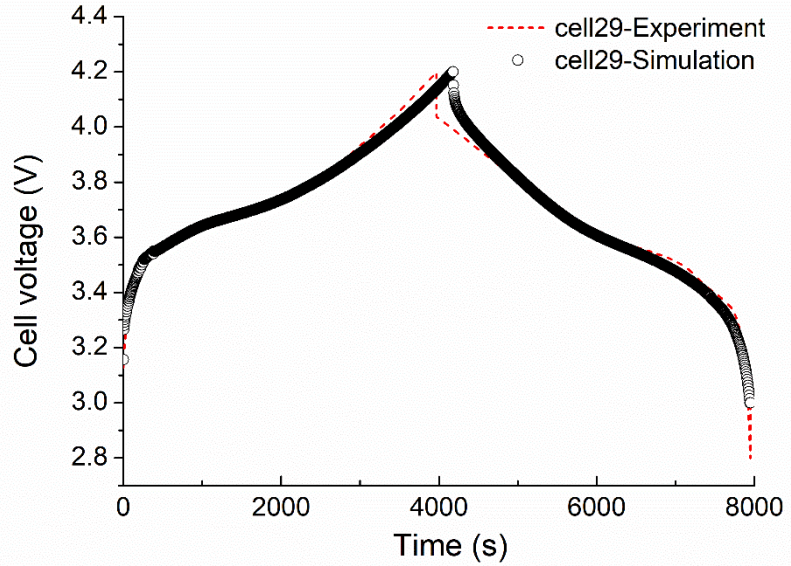
Revalidation of non-degradation parameters



Parameters	Initial value	Fitted value
rn_neg	8.010E-06	5.340E-06
rp_pos	4.016E-06	3.651E-06



Parameters	Cell24
i_1C	5.896
delta_SEI_0	4.563E-09
L_pos	3.453E-05
L_sep	2.589E-05
L_neg	2.888E-05
soc_neg	0.0025
soc_pos	0.87

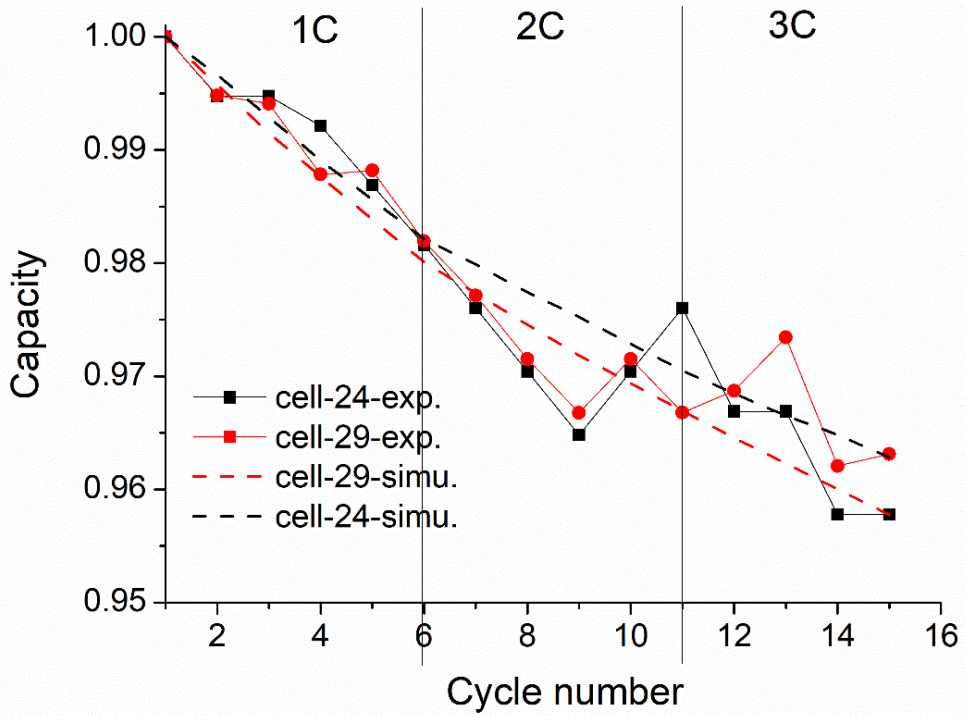


Parameters	Cell29
i_1C	7.605
delta_SEI_0	3.639E-09
L_pos	3.915E-05
L_sep	2.245E-05
L_neg	2.957E-05
soc_neg	0.013
soc_pos	0.95

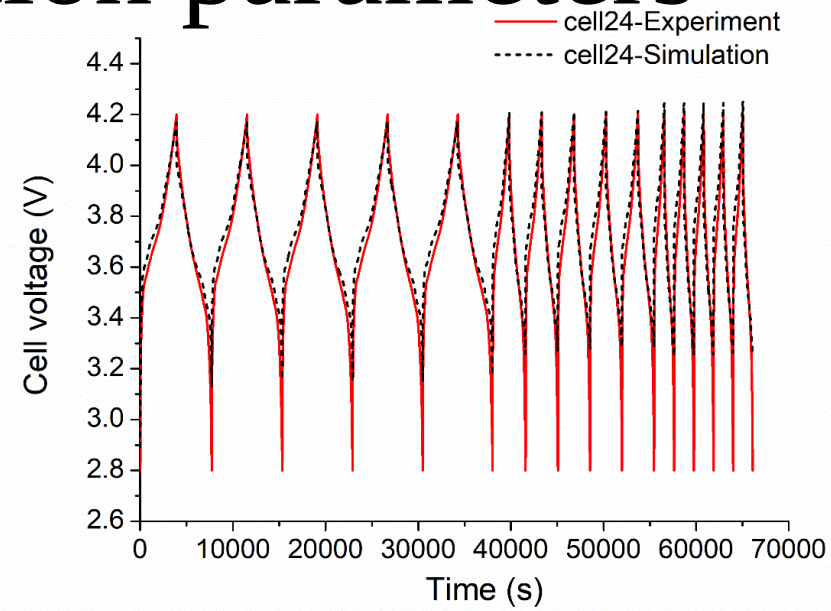
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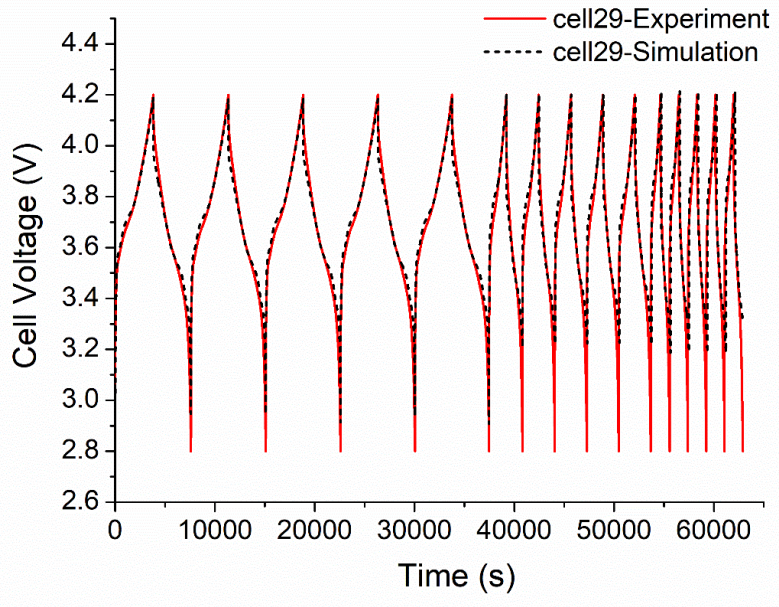
Revalidation of degradation parameters

Relative capacity profile



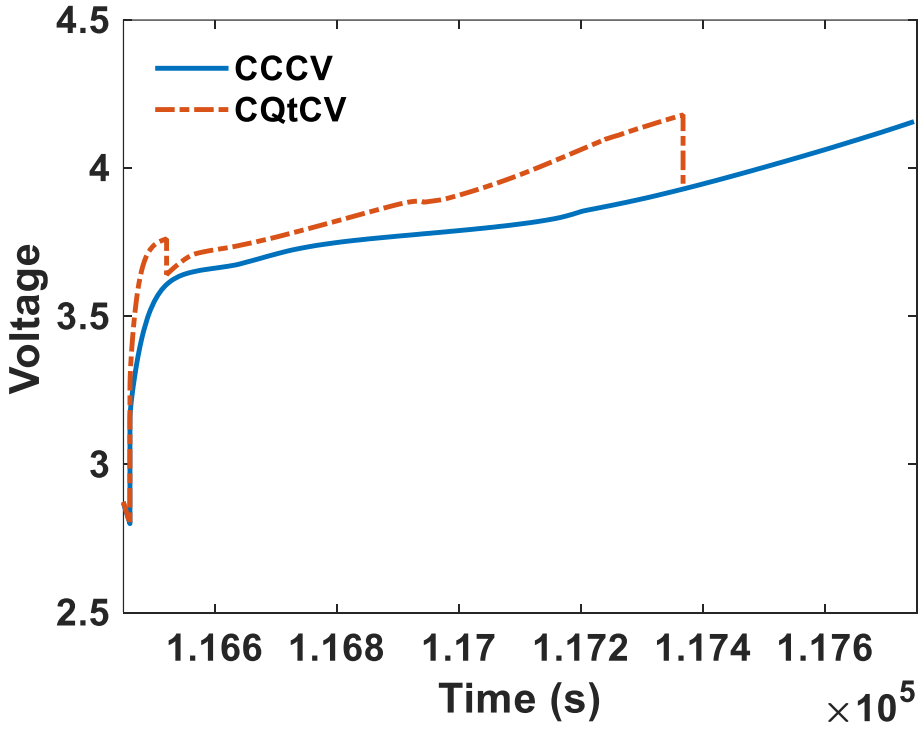
Parameters	Initial value	Fitted value
D_EC	2e-18	2.69e-18
k_SEI	5e-13	2.36e-12
i0_lpl	1e-3	5.01e-3

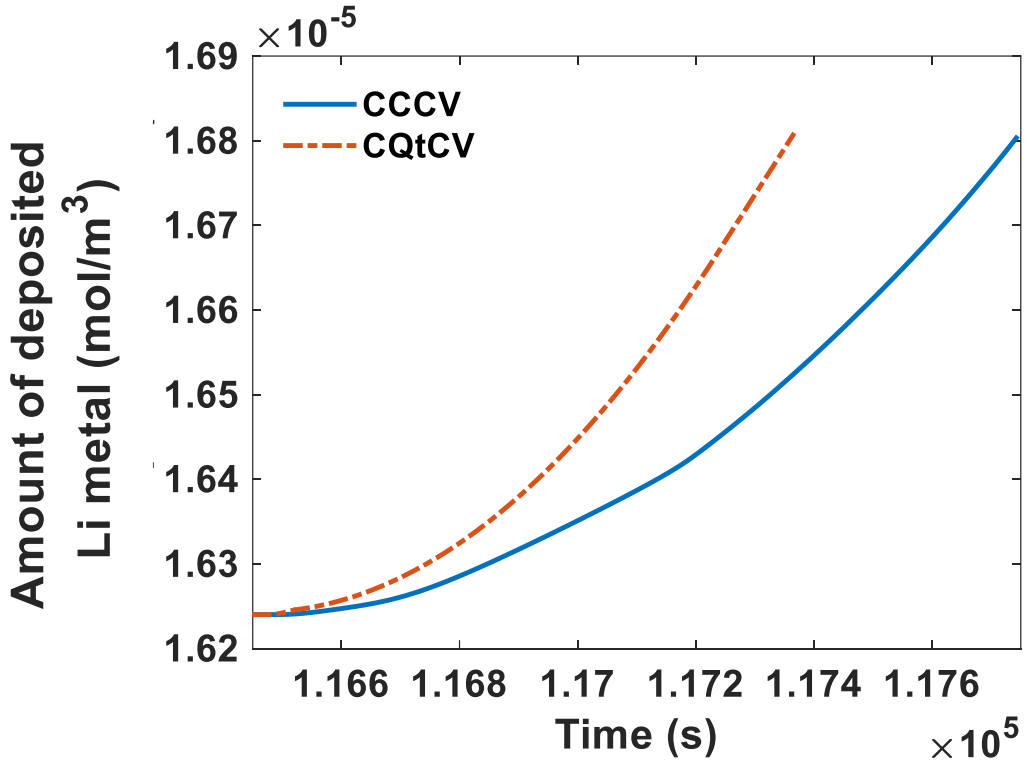




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Optimization result in Cell 1

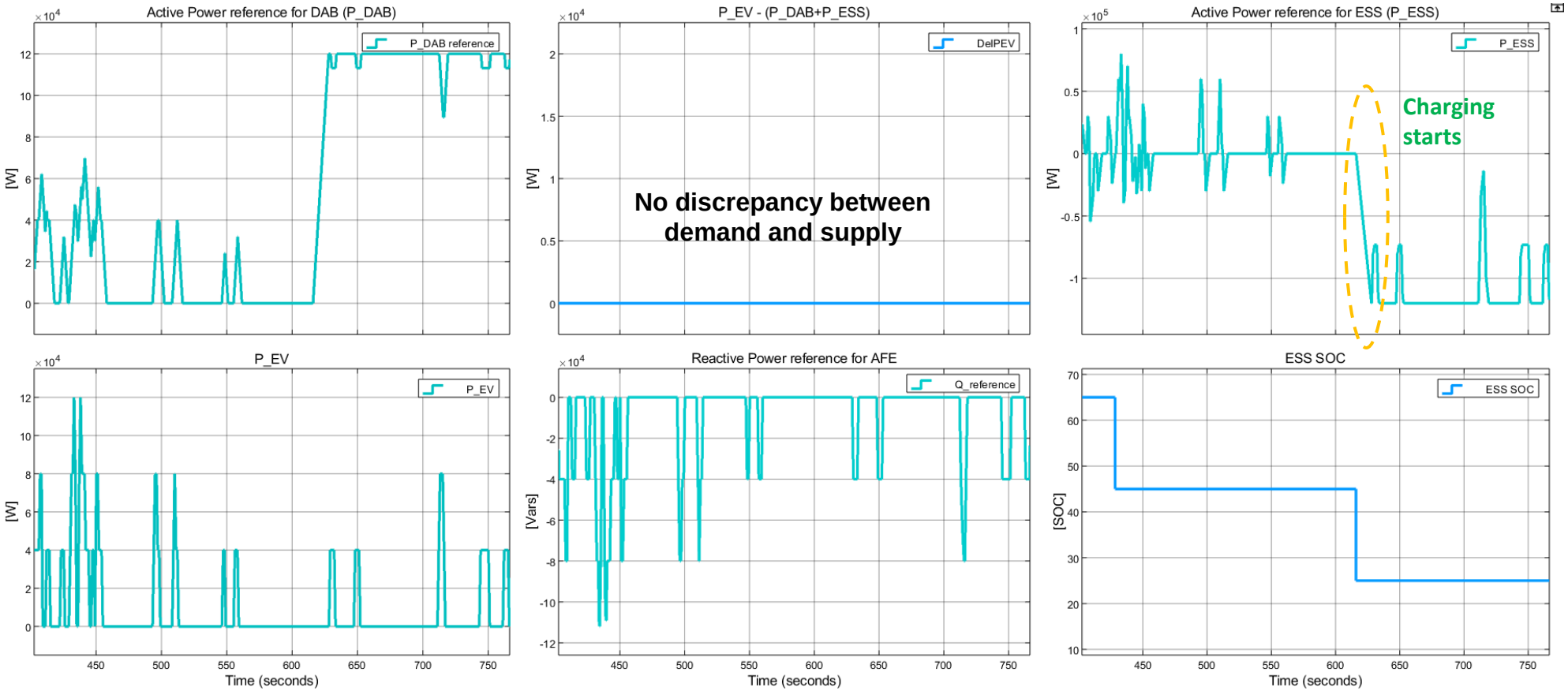




- Slope=1.9609, Threshold=1.2004.
- Compared with CCCV, CQtCV achieved 29% reduction in charge time.

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Testing of Energy Management Algorithm and Power Buffering (example scenario)



- ESS started charging at about 620 sec as SOC<40%.
- Current logic to charge ESS: start charging only if SOC drops below 40% and keep charging until it reaches 60%. If needed, ESS can be used as long as SOC>20%, and usage of ESS is strictly prohibited below 20%. Current logic is proposed to enhance ESS life by keeping SOC between 40-60%, but it can easily be modified based on other applications, e.g., energy arbitrage etc.