Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation – TV031

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Overview

Timeline

- **Project start date: 06/01/15**
- **Project end date: 09/30/17**

Budget

Total project budget: $3660K

Total recipient share: $2100K(INL), $1560K(NREL)

Total federal share: $3660k

Total DOE funds spent*: **$758.3K**

* As of 3/31/16

Barriers

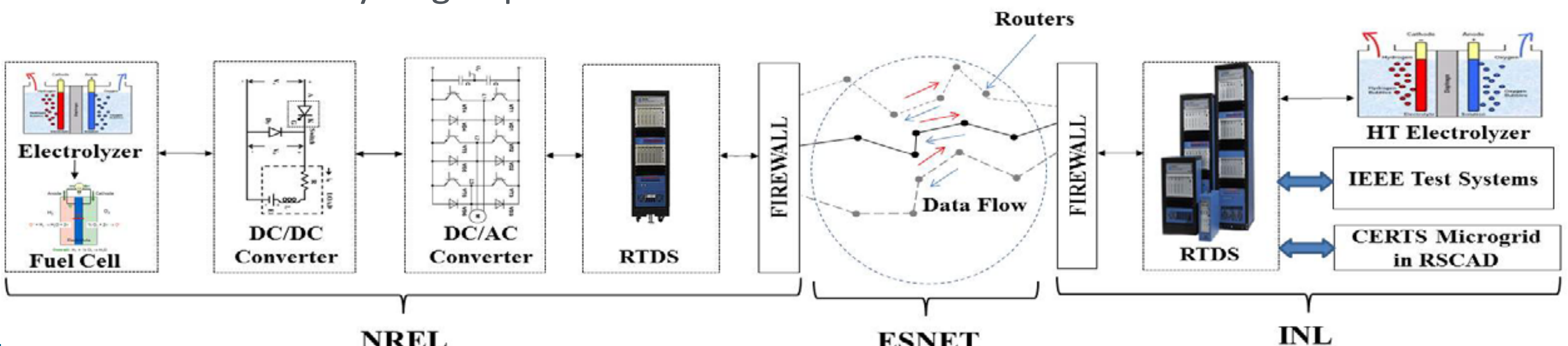
- **Barriers addressed**
  - Lack of Data on Stationary Fuel Cells in Real-World Operation
  - Hydrogen from Renewable Resources
  - Hydrogen and Electricity Co-Production

Partners

- **Funded partners**
  - Idaho National Laboratory and National Renewable Energy Laboratory
- **Collaborators**
  - Utilities: PG&E, CAISO, Xcel Energy, EnerNOC; California Air Resources Board
  - Academic: Humboldt State University, Florida State University

Relevance & Objective

- Relevance: Electrolyzer model validation and simulation in a distributed real time environment that is used for electrolyzer based fueling station business case analysis (California focus)
- Objective: Validate the benefits of hydrogen electrolyzers through grid services and hydrogen sale to fuel cell vehicles for full-scale deployment.
  - Characterization of the potential and highest economic value based on the needs of multiple stakeholders for specific grid regions.
  - Demonstration of the reliable, fast-reacting performance of hydrogen-producing electrolyzers for at-scale energy storage devices.
  - Verification of the communications and controls needed for successful participation in electricity markets and DR programs and ancillary services, leading to additional revenue and reduced hydrogen production cost.



Approach – Electrolyzers, Renewables, and the Grid

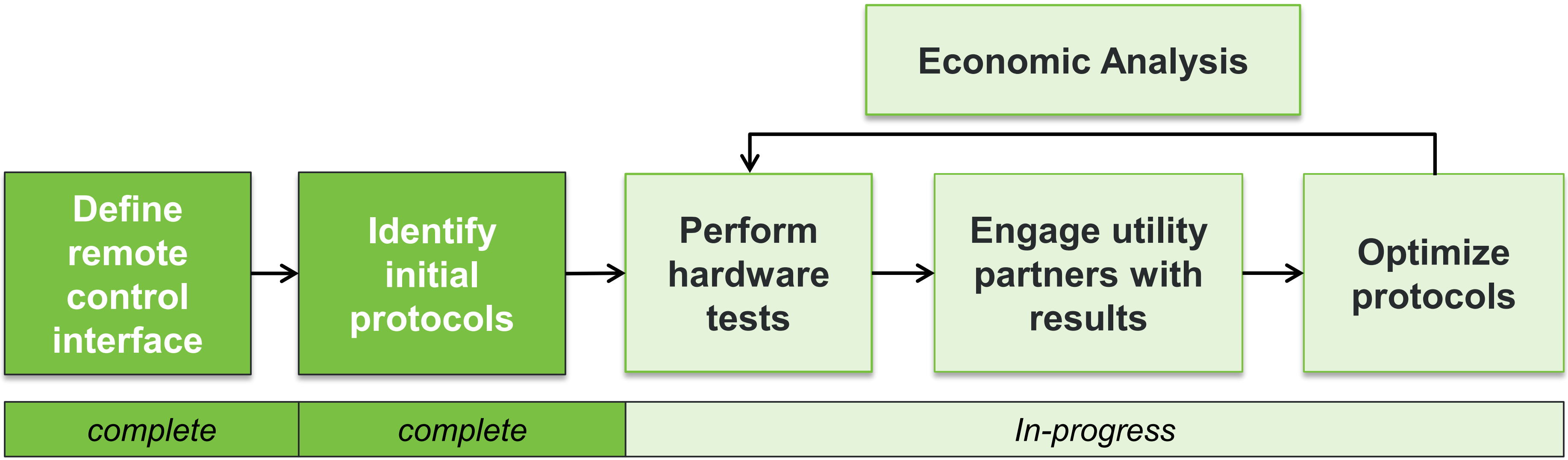
- Grid modeling: Utility distribution network identification and modeling in Real Time Simulator for present case
- Electrolyzer operation: Interface development between electrolyzer and Real Time Simulator to perform Power-Hardware-In-the-Loop (PHIL) model validation
- Utility/Aggregator involvement to provide real world test conditions
- Economic analysis: Operations optimization to calculate maximum revenue
  - Compare revenue to costs to determine competitiveness
  - Based on
    - 2015 Utility rate and/or CAISO nodal price (region, connection, operation strategy)
    - 2015 California renewable profiles (PV or wind)
    - Hydrogen production capacity factor (80, 90, or 95%)

Approach - Electrolyzer Grid Dynamics

Demonstrate that electricity grid markets are additional revenue streams available to electrolyzers to improve their economic competitiveness

- Ancillary services
- Demand response
- Reverse power flow

Characterization and Performance Testing

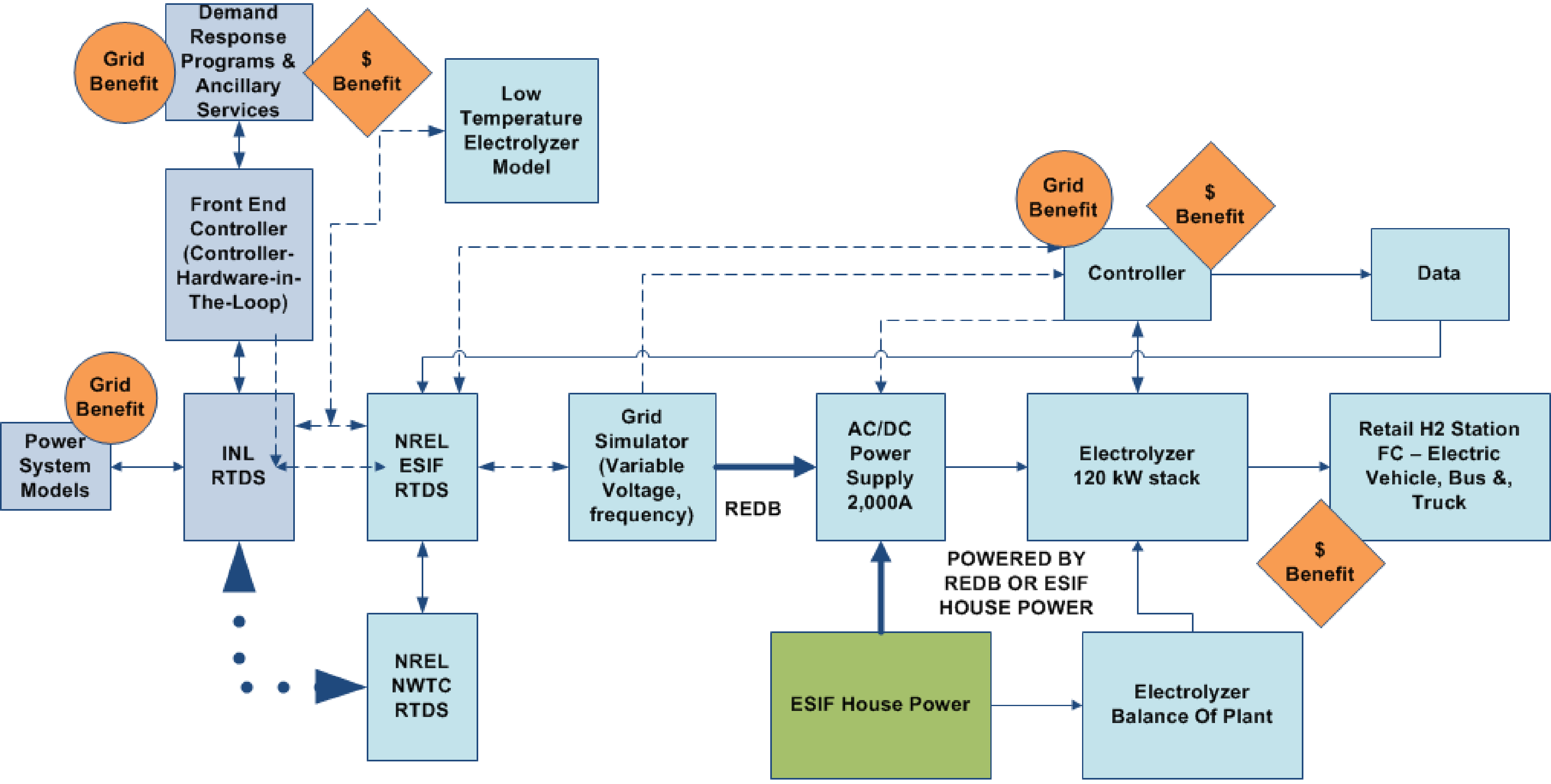


Approach - Electrolyzers and Response Metrics for Grid Services

Time response and level of variation in power consumption of 120 kW stack electrolyzer at NREL

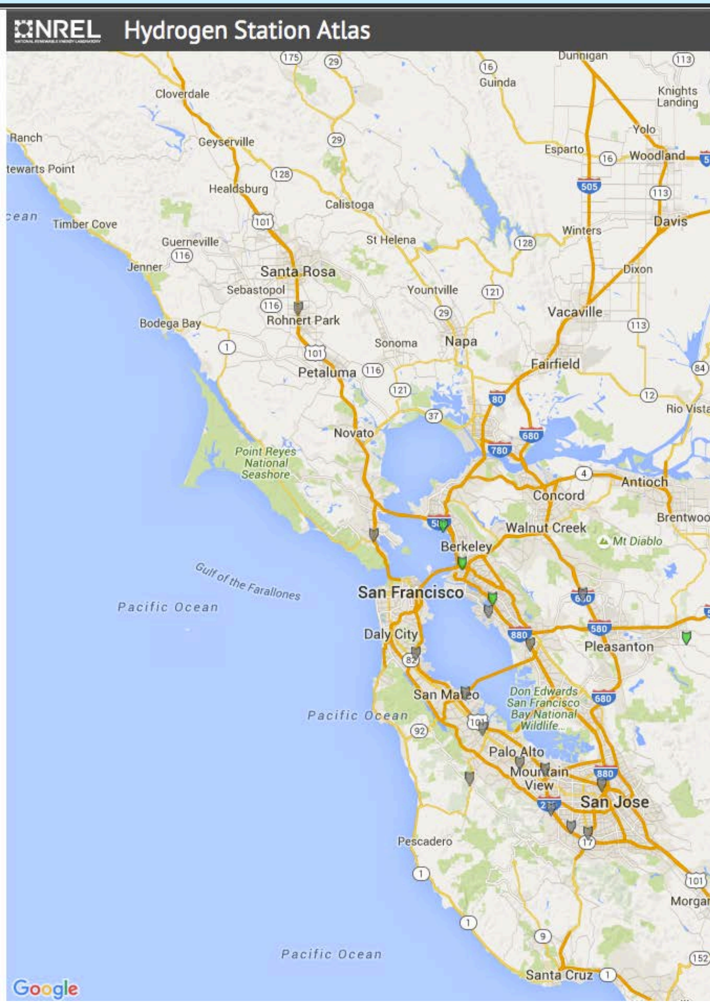
- Response time to a change in power set-point (electrolyzer demonstrated to be milliseconds)
- Settling time after a set-point change (electrolyzer demonstrated to be milliseconds)
- Duration possible for a change in power consumption (electrolyzer demonstrated to be unlimited)
- Turndown level (electrolyzer demonstrated to have a 10:1 turndown capability)
- Startup and shutdown time (electrolyzer demonstrated to start and stop in less than 30 seconds)

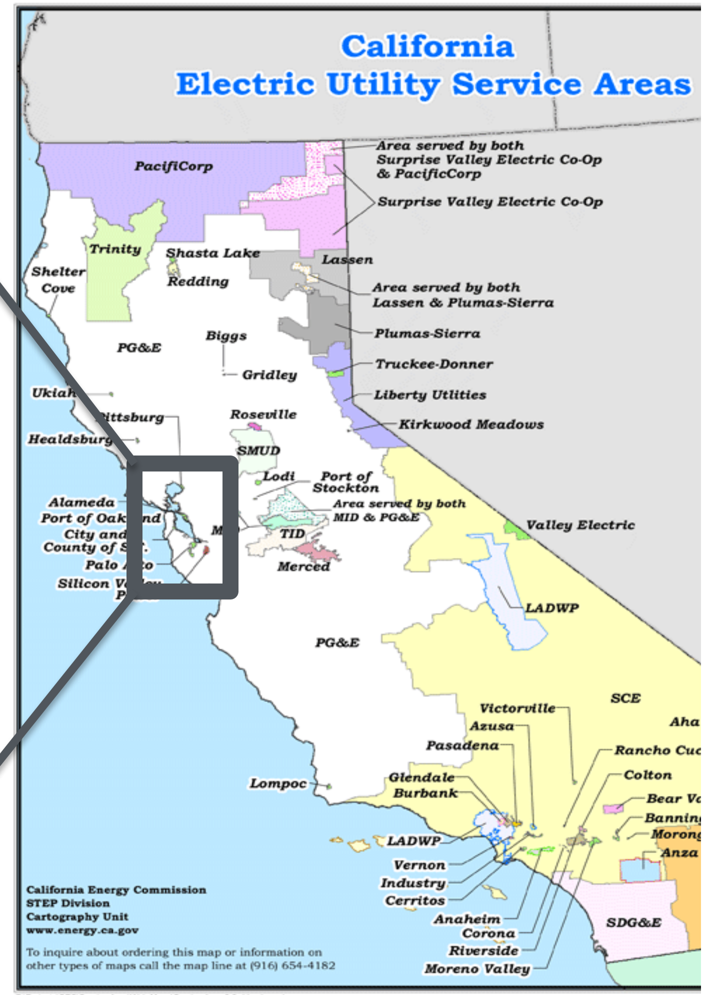
Approach - Simulation Diagram



Approach - Map with Proposed Hydrogen Refueling Stations (Bay Area, California)

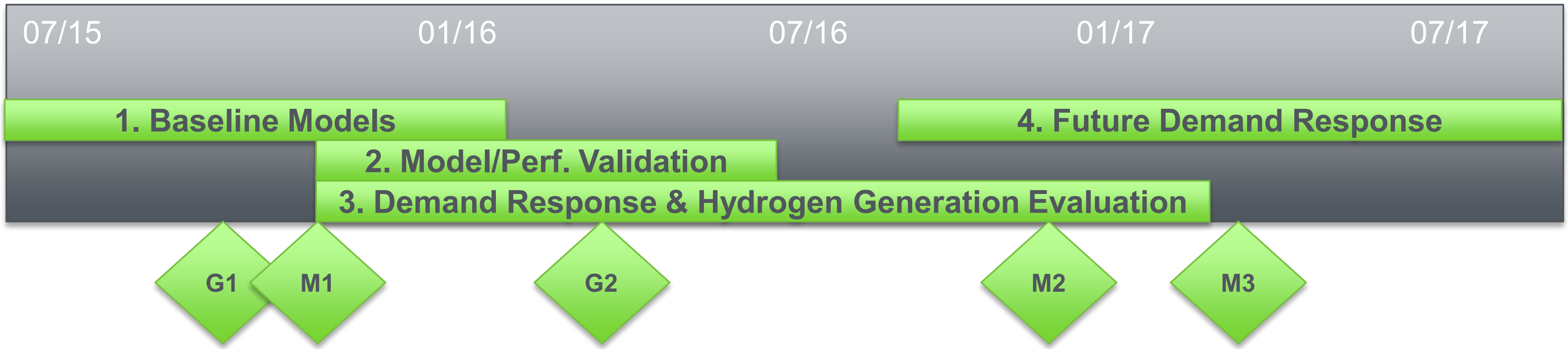
Hydrogen refueling stations used to model the utility system





PG&E Territory (White) & Refueling Stations

Approach – Timeline (Milestones and Go/No-Go decisions)



M1	Demonstrate distributed Real Time Simulation (RTS) with data latency of less than 30 milliseconds during the data transfer between INL and NREL.	September 2015	Completed (100%)
M2	Demonstrate a 250-kW electrolyzer operating (for 500 hours) in 1) the energy market (hydrogen production) and 2) the ancillary service market both for a simulated electricity grid based on real-time pricing signals.	September 2016	Under progress (20%)
G1	1. Furnish a total of 3 utility/system operator support letters summarizing their potential roles in this project - Pacific Gas & Electric, California Independent System Operator, & DR aggregator (e.g., PG&E qualified aggregators for AMP program) 2. Created 3 current and future distribution systems based on PG&E data.	December 2015	Completed (100%)
G2	Demonstrated distributed RT PHIL of 120 kW stack with an efficiency of 60% for 200 hours to test dynamic conditions, demand response, and characterization.	March 2016	Completed (100%)

All milestones and Go/No-Go were completed on schedule

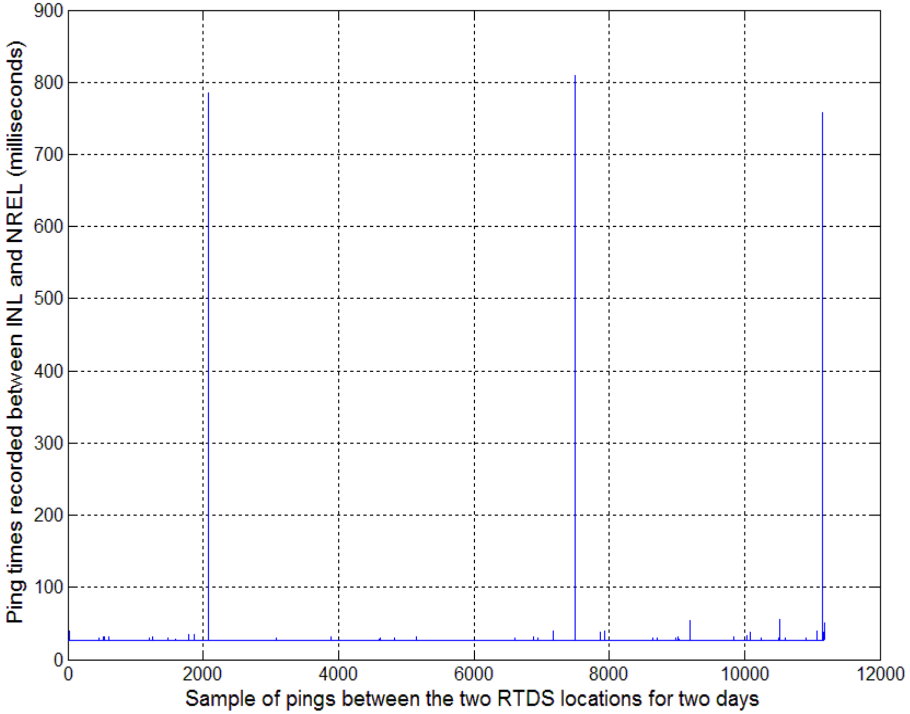
Approach – Deliverables Summary

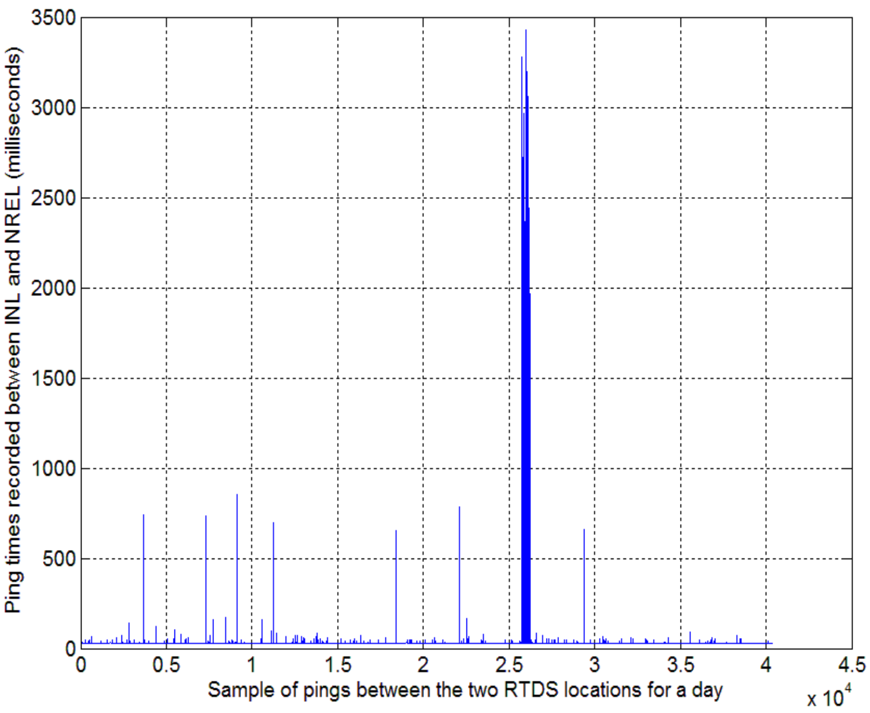
All deliverables are completed on schedule and steady progress towards completing future ones

D1	Electrolyzer model compatible with RTDS® demonstrated and verified through exchanging instantaneous signals between the two.	June 2015 (100%)
D2	Complete the RTDS® models of IEEE 13 node feeder system with electrolyzer. This test system will provide the environment for performing dynamic simulations using the electrolyzer model.	June 2015 (100%)
D3	Assess the economic competitiveness of existing, current and planned electrolytic hydrogen stations, and determine the greenhouse gas emissions impacts for these stations compared with hydrogen station alternatives. Include participation in electricity markets and DR programs.	December 2015 (100%)
D4	Develop and test the 120 kW electrolyzer interface with RTDS® at NREL. Finalize details of the locations that will be simulated and tested within the Bay area served by PG&E.	December 2015 (100%)
D5	Perform distributed RT PHIL on the basis of dynamic conditions described in Appendix B with the electrolyzer connected to the CERTS based microgrid that is modeled as part of FY15 work. The objective of performing this RT PHIL is to characterize the response of the electrolyzer under typical grid conditions to obtain the transient response.	March 2016 (100%)
D6	Develop suitable PG&E distribution network model in RTDS® and dynamic test scenarios under existing DR programs. The dynamic scenarios (hydrogen demand, excess generation, deficit generation, etc.) will be planned such that it leads to DR signals being issued and hence leading to participation of electrolyzers accordingly.	June 2016 (30%)
D7	Modify the PG&E distribution network model (expanded) in RTDS® in order accommodate the future refueling stations as planned in the San Francisco Bay area served by PG&E. (Under progress)	December 2016 (10%)

Accomplishment

Demonstration shows that most data packets took less than 30 milliseconds to travel between INL and NREL (Milestone M1 – 09/2015)





- Maximum = 810 milliseconds
- Minimum = 26 milliseconds
- **Average = 27.2044 milliseconds**
- Data drops = 327

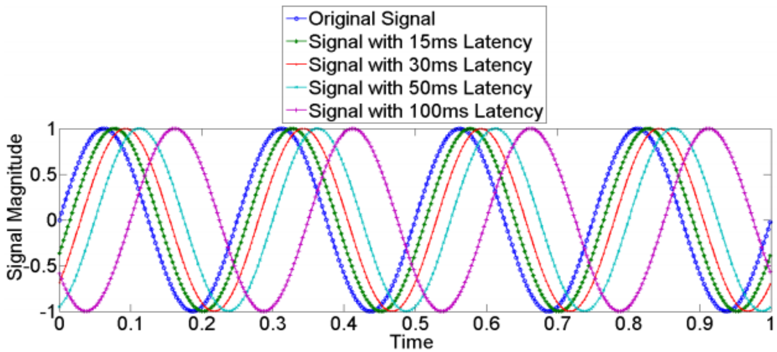
- Maximum = 3433 milliseconds
- Minimum = 26 milliseconds
- **Average = 34.7855 milliseconds**
- Data drops = 43

Accomplishment - Variable Latency in Distributed Real-time Simulations & Solution

NATIONAL RENEWABLE ENERGY LABORATORY

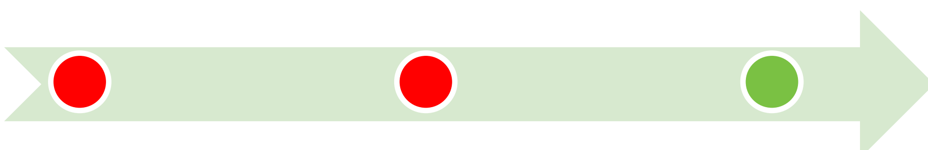
Idaho National Laboratory

Step 1: Identify communication latency issues on distributed real-time simulation



Effect of communication latency on simple sine wave

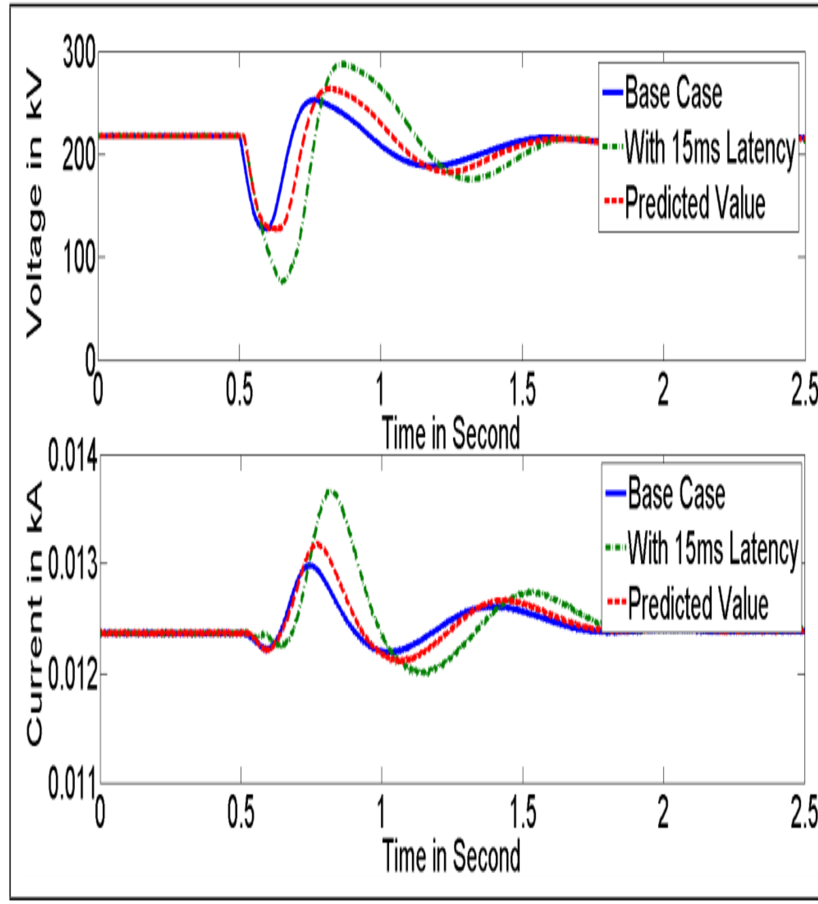
Step 2: Mitigate communication latency issues via Prediction.



N-2

N-1

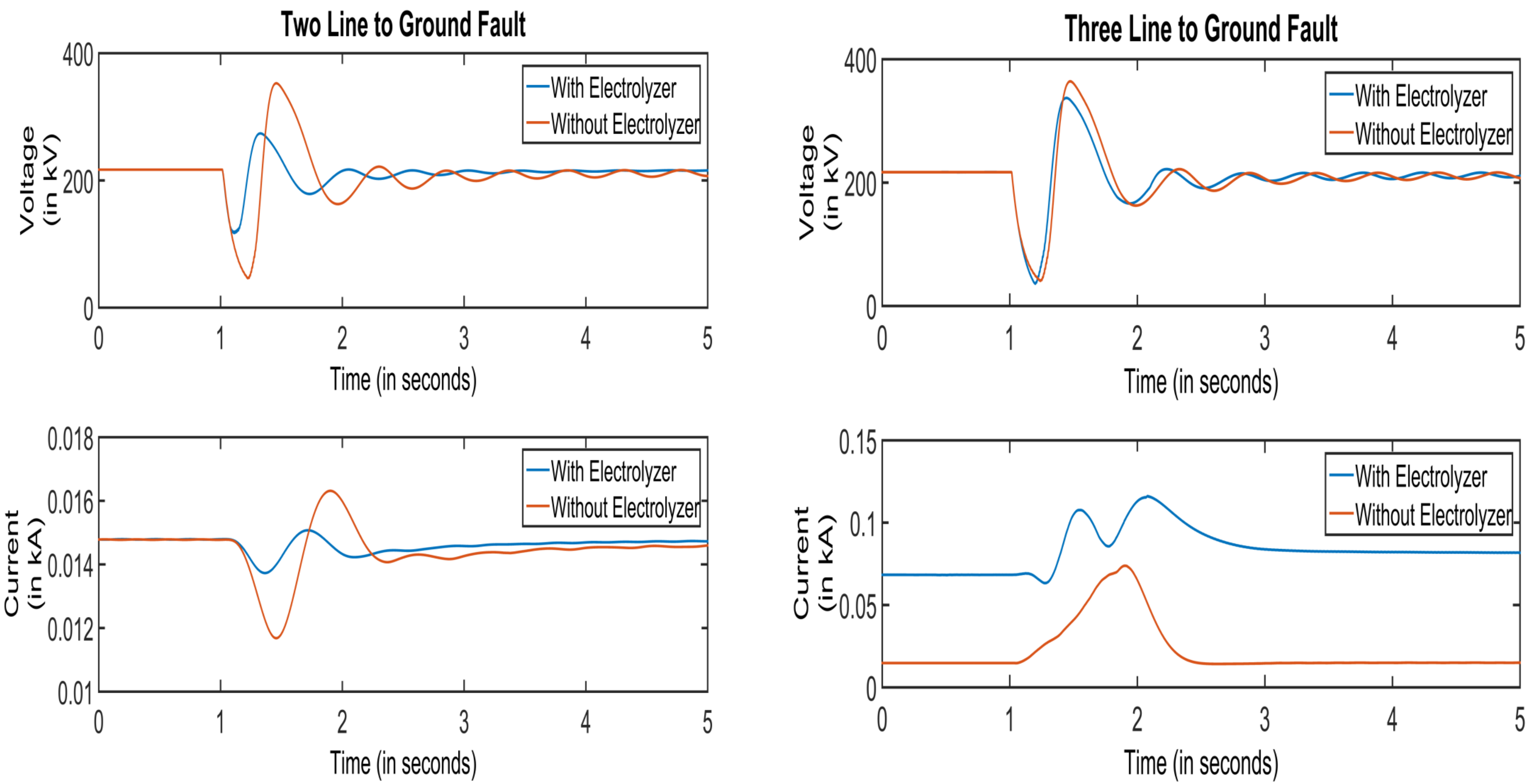
Predicted



Two phase to ground fault with Prediction

Accomplishment - Impacts of Electrolyzer on Power System Transient Stability

Demonstration of reduction in transients created from faults with electrolyzers in the grid



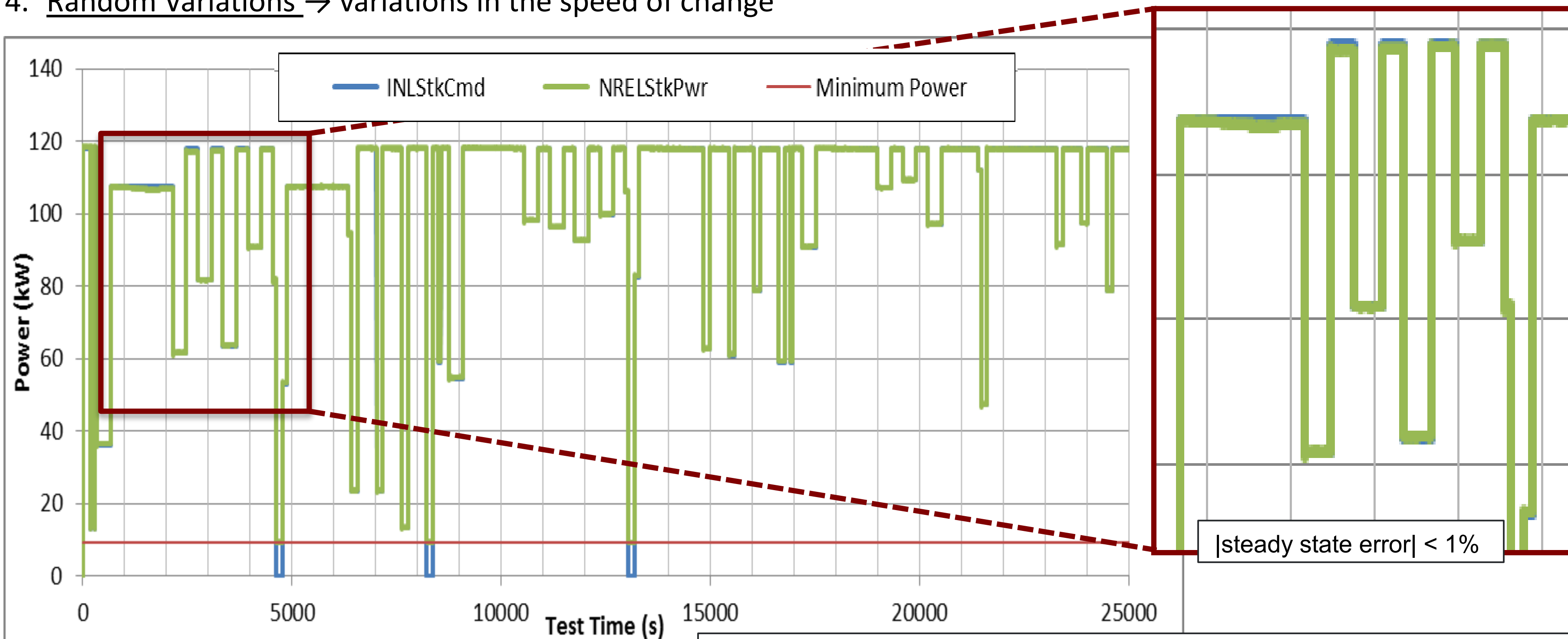
Resistive Capabilities and Impacts on the Grid

Accomplishment - Demand Response Simulations

Remote electrolyzer operation over 200 hour test period shows electrolyzer's ability to participate in grid support market

Four distinct profiles were used to characterize the electrolyzer response to remote commands

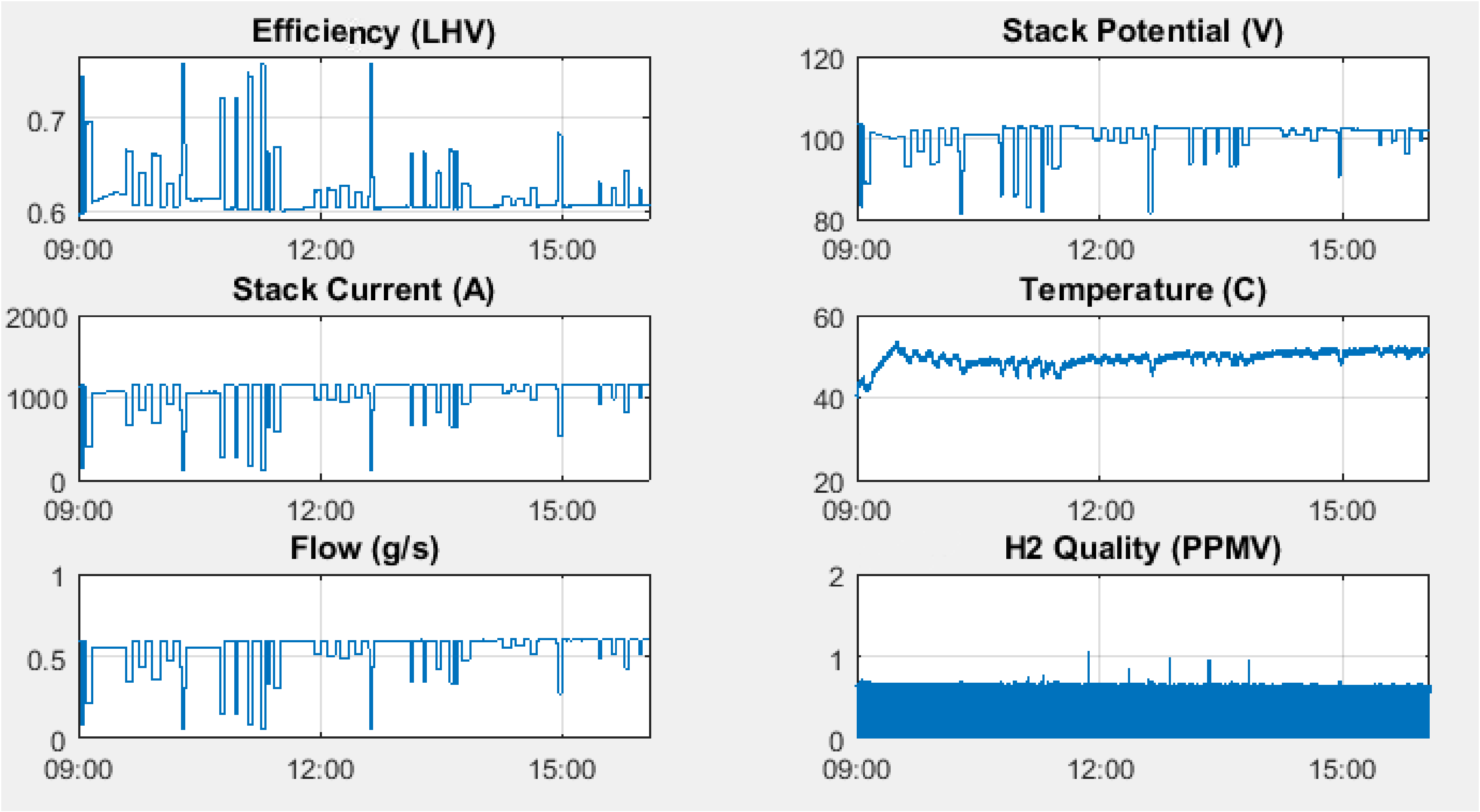
1. Ramp Up, Ramp Down → variations in increasing or decreasing load steps
2. Load Steps → variations in the size of change
3. Utility Demand Response → expected performance of electrolyzer in grid application
4. Random Variations → variations in the speed of change



Sample utility Demand Response time series data (PG&E E-20 profile) used to remotely control the electrolyzer over ~7 hour window 8 March 2016.

Accomplishment - Demand Response Electrolyzer Performance

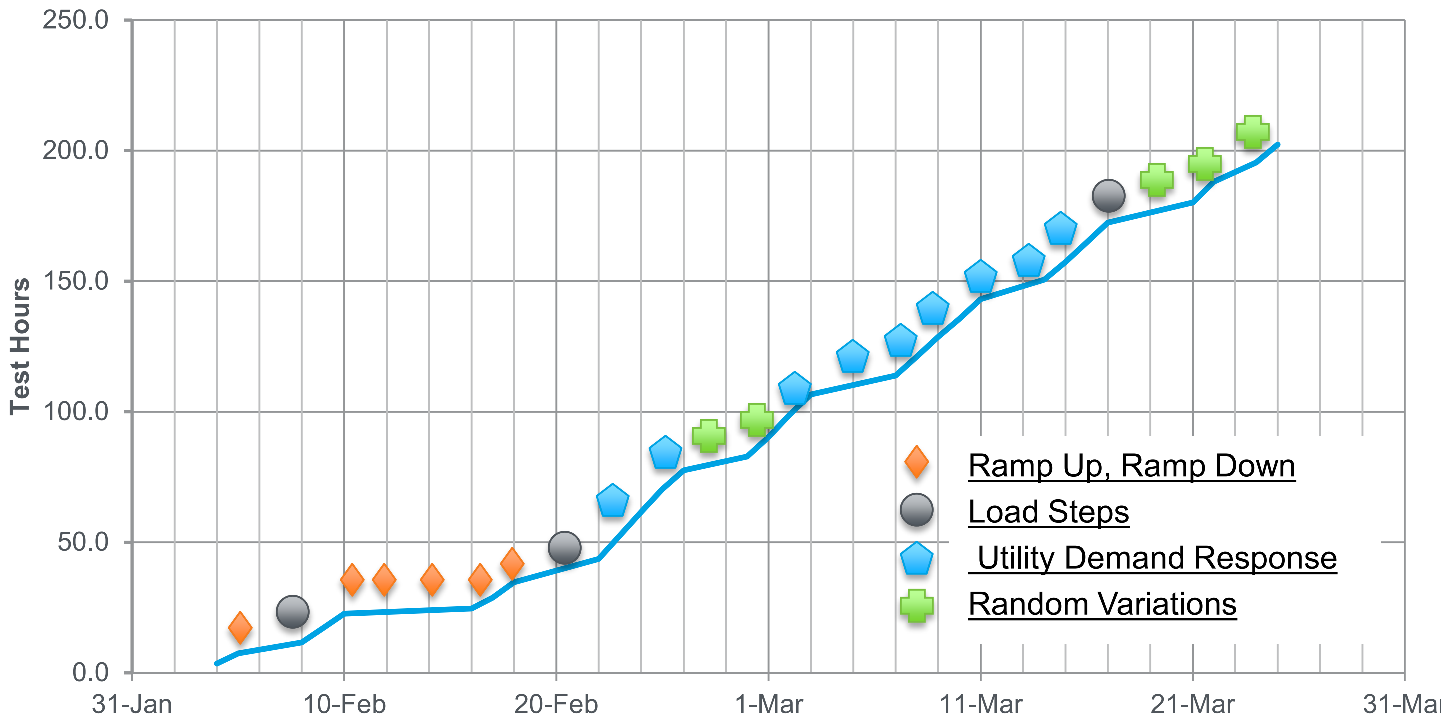
Electrolyzer operated at between 60% - 80% efficiency (LHV) for the duration of the PG&E E-20 Profile



Stack performance data collected by the NREL SCADA system for PG&E E-20 profile

Accomplishment – Electrolyzer Characterization Testing

Types of tests run to achieve 200 hour Go/No-Go



Accomplishment – Electrolyzer Characterization Testing

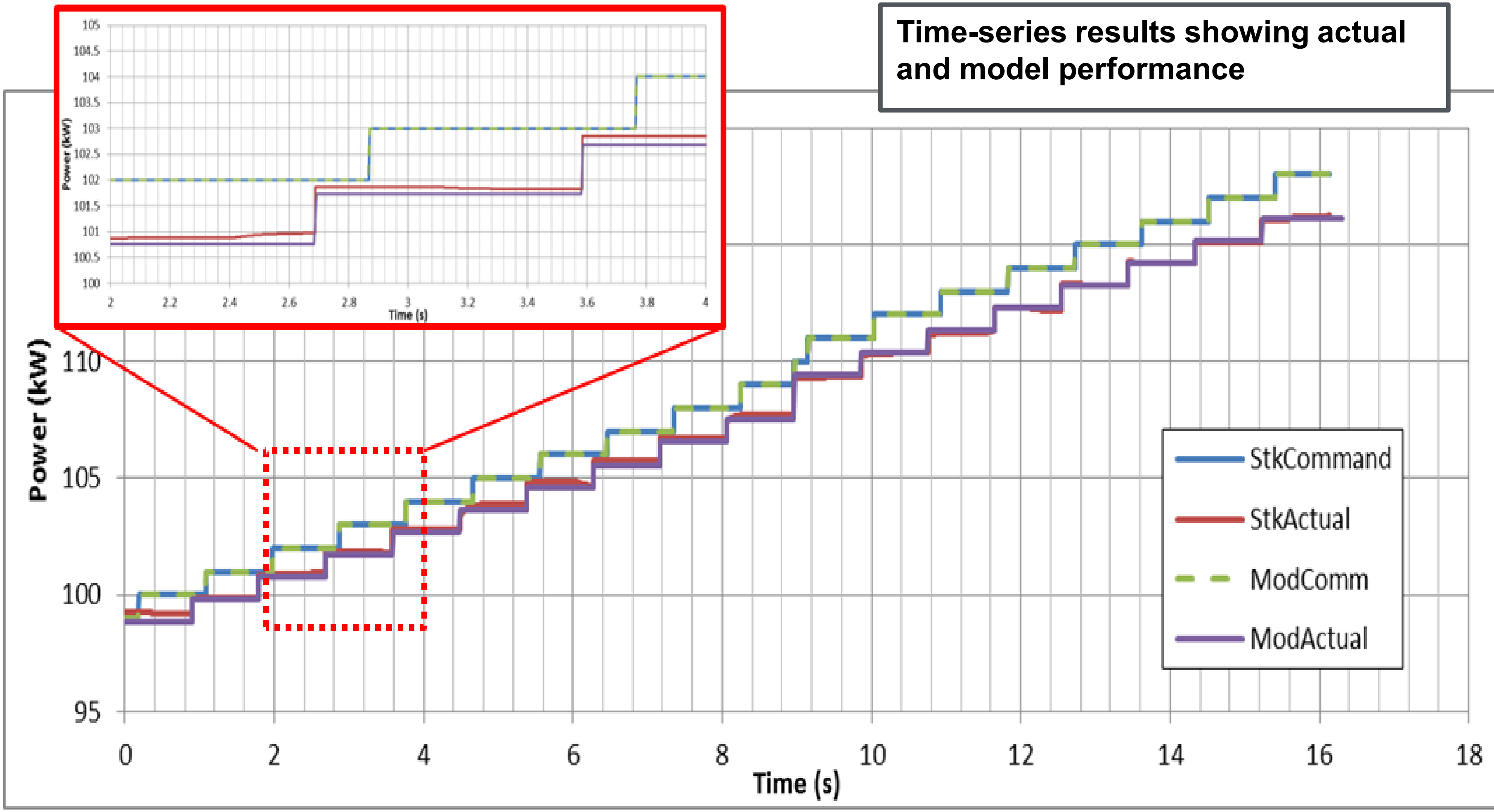
Fast response time & quick slew rate

Performance Metric	Ramp	Load	DR	Random
Response Time	< 1seconds	< 1seconds	< 1seconds	< 1seconds
Settling Time	< 1seconds	< 1seconds	< 1seconds	< 1seconds
Slew Rate	+1 kW/second -1 kW/second (Other rates were 0.5 and 2 kW/second)	Predetermined load values at variable times	10 kW, 20 kW, 30 kW, 40 kW, 50 kW, 118 kW, & E-20 DR (PG&E) at 2, 5, and 10 minutes interval	Random set-points between 13 & 118 kW per second
Operational Limits	13 kW to 118 kW	13 kW to 118 kW	13 kW to 118 kW	13 kW to 118 kW
Startup and Shutdown Time	30 seconds and < 1 second	30 seconds and < 1 second	30 seconds and < 1 second	30 seconds and < 1 second

Accomplishment - Electrolyzer Model

Electrolyzer model developed and validated with 120 kW stack using RTDS simulations

Time-series results showing actual and model performance

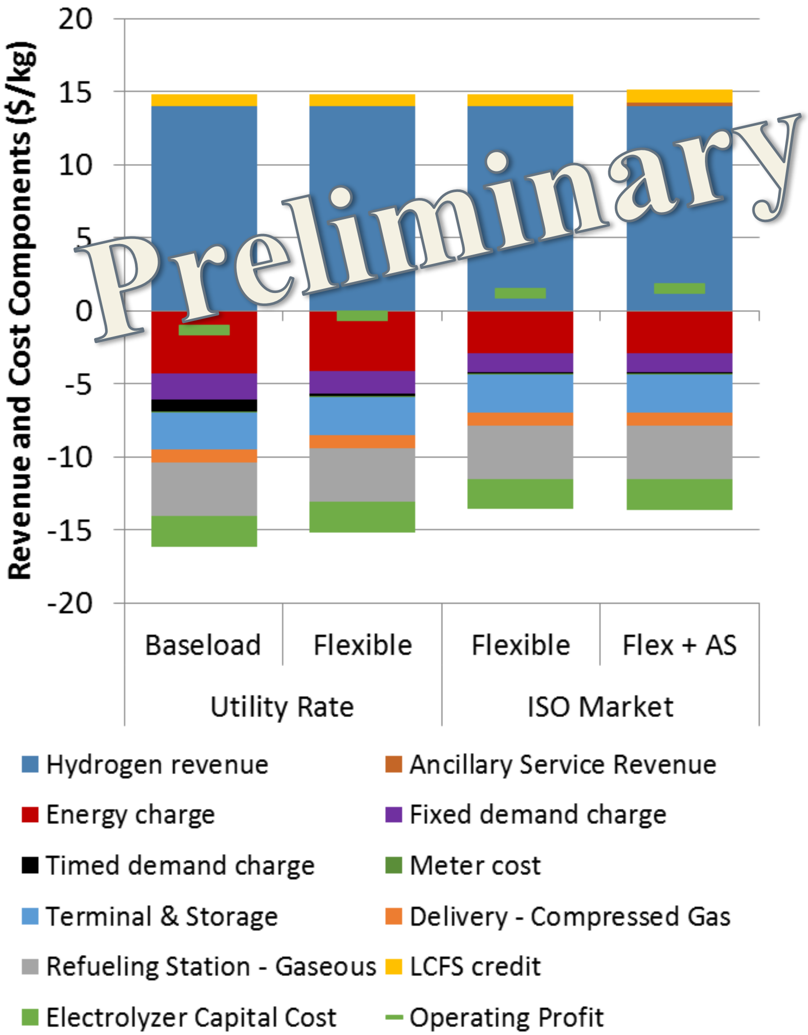


Accomplishment – CA Business Case

"Assess the business case of power-to-gas systems for near-term applications in specific locations in California"

- Selected set of case studies
  1. Southern California hydrogen pipeline
  2. At or near renewable installation (Solar plant, Wind farm)
  3. Natural gas pipeline injection in locations with high fuel heating value (e.g., central valley)
  4. Utility tariffs with utility DR programs
  5. California electricity markets

- **Sample result per case**



Accomplishments

- No prior AMR review on this project; hence no comments from reviewers are addressed (Project started June 2015)

Collaborations

- Idaho National Laboratory and National Renewable Energy Laboratory
  - Prime and jointly funded project partner
  - Laboratory resources will be leveraged for research and development
- Utilities: PG&E, CAISO, Xcel Energy, EnerNOC
  - Real world and market information for direction in research
  - Actual data and system models for case studies, technology evaluation, and demonstrations
- Universities: Humboldt State University, Florida State University
  - Research partners for modeling, simulation, and information dissemination
- California Air Resources Board
  - CA power-to-gas business case evaluation

Remaining Challenges and Barriers

- **Challenge:** Design suitability of the Front End Controller (FEC) that will be used to interface the electrolyzer with the utility (DMS) signals for practical deployment. Typically such a FEC is implemented within the power conversion unit that interfaces any component (such as electrolyzer, PV panel, motors, etc.) to the utility supply.
- **Mitigation:** As a de-risking process, the proposed project involves rapid prototyping approach using Controller-Hardware-In-the-Loop (CHIL) with the RTDS® to verify and validate the functionalities of FEC in real time. This is a high-fidelity and industry accepted process of validating controller designs during development.

Proposed Future Work

- Development of the FEC to interpret utility signals and control the operational controller of the electrolyzer **(December 2016)**
  - Automate the response of electrolyzer to utility signals to provide services
  - Real time implementation of FEC and in the existing simulations
- Engage industry via discussions and data exchange **(September 2017)**
  - Xcel Energy: interested in reverse power flow on three phase systems
  - EnerNOC: quantifying demand response capabilities of electrolyzers
  - PG&E: demand response program information and enhancing grid models
- Upgrading the power supplies to the electrolyzer for AC signal feedback and FEC integration **(December 2016)**
- Implementation of enhanced demand response programs for electrolyzer value quantification **(March 2017 & June 2017)**

Technology Transfer Activities

- Technology Transfer Activities include
  - Publication in peer reviewed journals and conferences
  - Interaction with the utilities in the form of presentations and technical reports

Project Summary

- Verifying and validating the participation of electrolyzers (hydrogen refueling station) under dynamic grid conditions
- First of a kind, distributed real-time simulation with PHIL (electrolyzer) between INL and NREL
  - Electrolyzer transient response on varied time and loading level recorded
  - DR and ancillary service grid conditions imposed
  - Extensive 200 hours completed and an additional 300 hours planned
- Electrolyzer stack efficiency and hydrogen quality is ensured to be acceptable during the whole project
- Improved transient stability observed under grid fault conditions
- Realistic DR conditions and PG&E utility grid data used for real time simulations and PHIL
- **Contributes directly to the DOE Milestone 3.9 related to Systems Analysis & Technology Validation**
  - [From MYRDD 3.9] *Validate large-scale system for grid energy storage that integrates renewable hydrogen generation and storage with fuel cell power generation by operating for more than 10,000 hours with a round-trip efficiency of 40%. (4Q, 2020)*

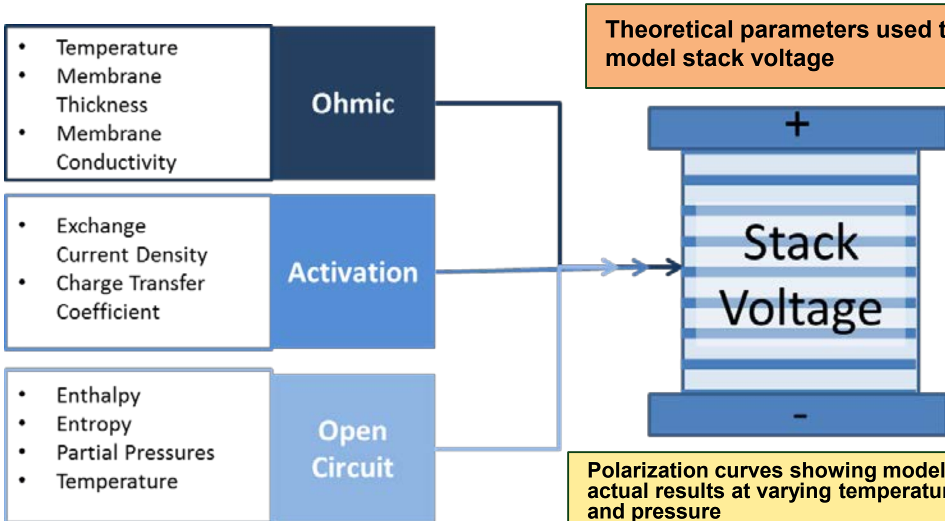
Discussion

Technical Back-Up Slides

Accomplishment - Electrolyzer Model

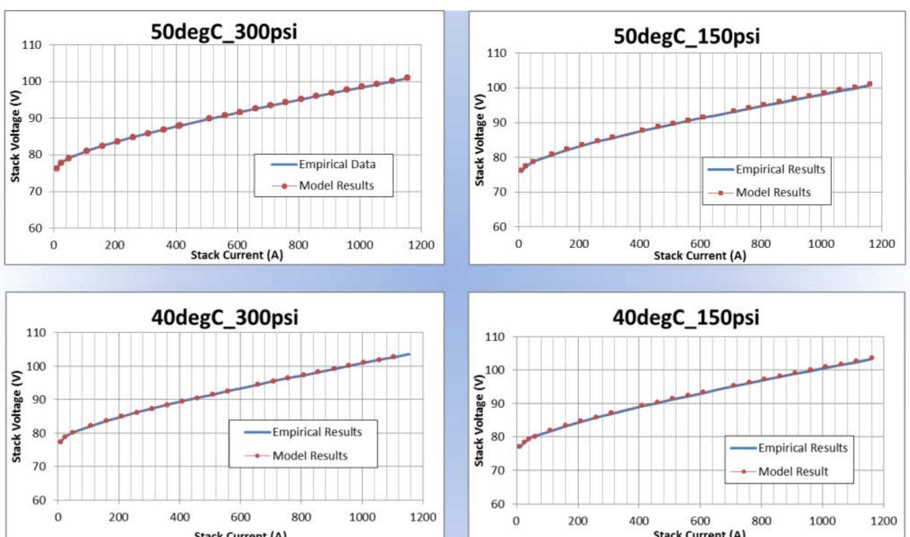
Electrolyzer model developed in RSCAD and validated against 120 kW stack using RTDS simulations

Theoretical parameters used to model stack voltage

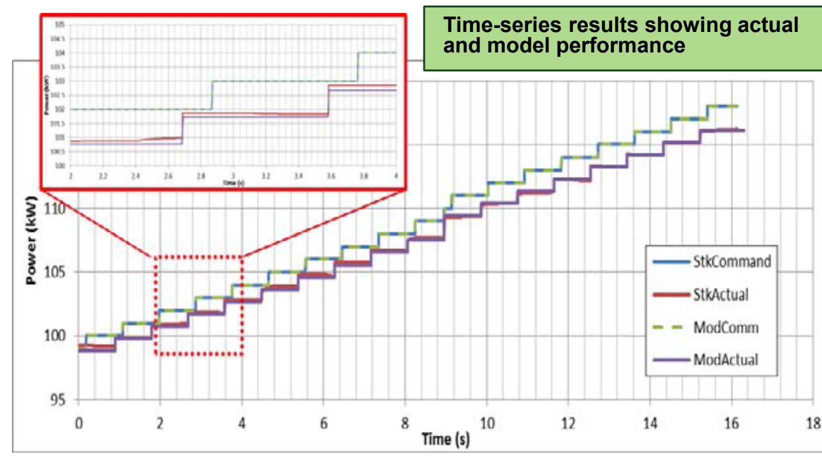


- Collect empirical data on 50-cell PEM stack
- Develop balance of plant model in RSCAD using theoretical equations
- Match empirical and theoretical results using curve fitting to derive parameters
- Compare time-series results from PEM stack and model using INL RTDS test protocol

Polarization curves showing model and actual results at varying temperature and pressure

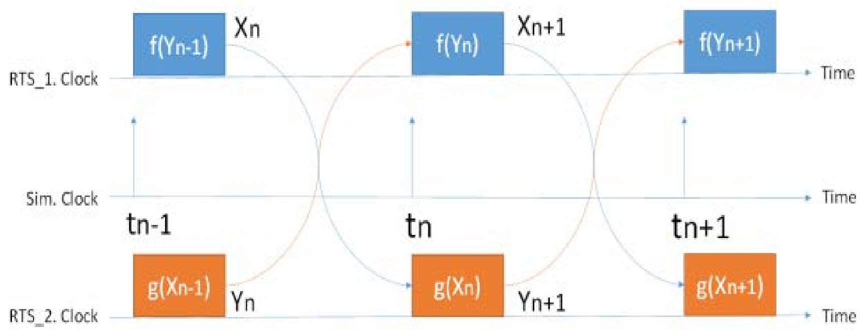


Time-series results showing actual and model performance

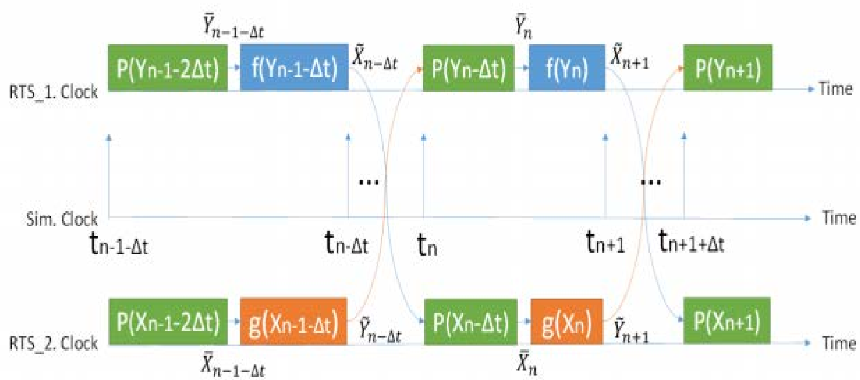


Latency and Distributed Real-Time Simulations

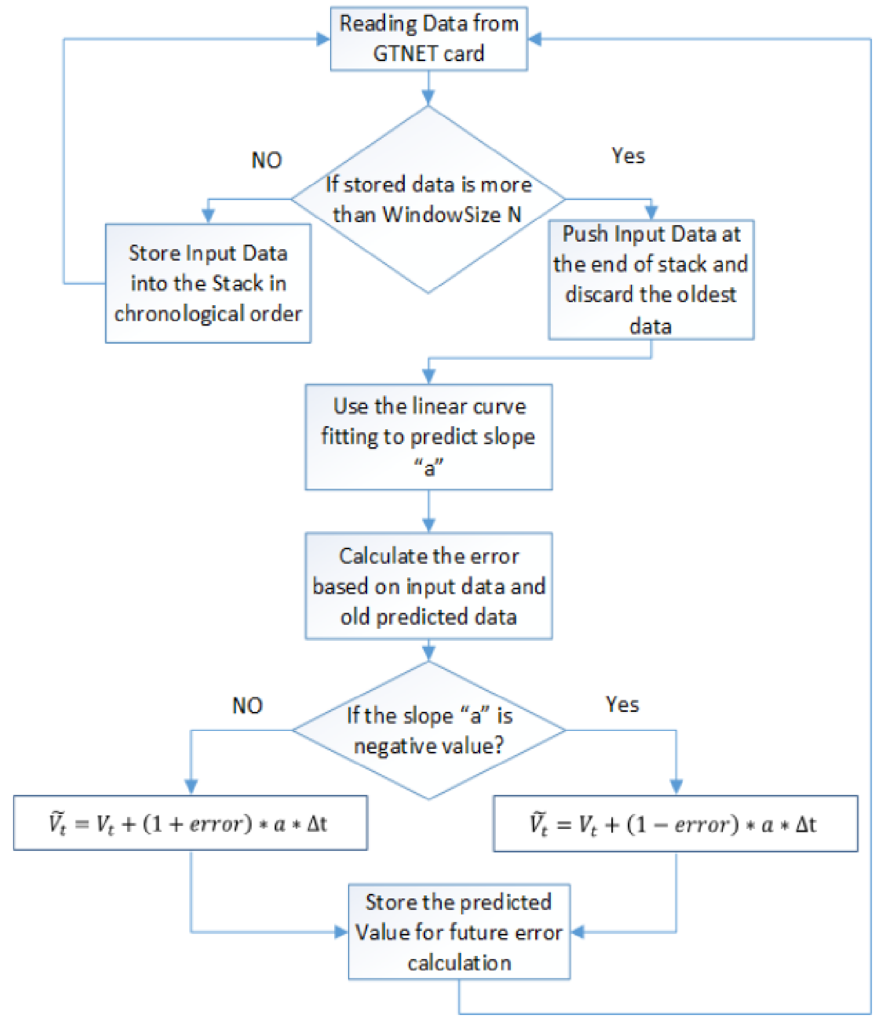
Deterministic latency leads to predictable issues in distributed RTS



4.1 Ideal Condition: There is no communication latency between two simulator



4.2 Prediction Condition: There is Δt communication latency between two simulator



Impacts of Data Latency

- Data exchange simulations tests between INL and NREL indicated some long unexpected delays, loss, and overflow.

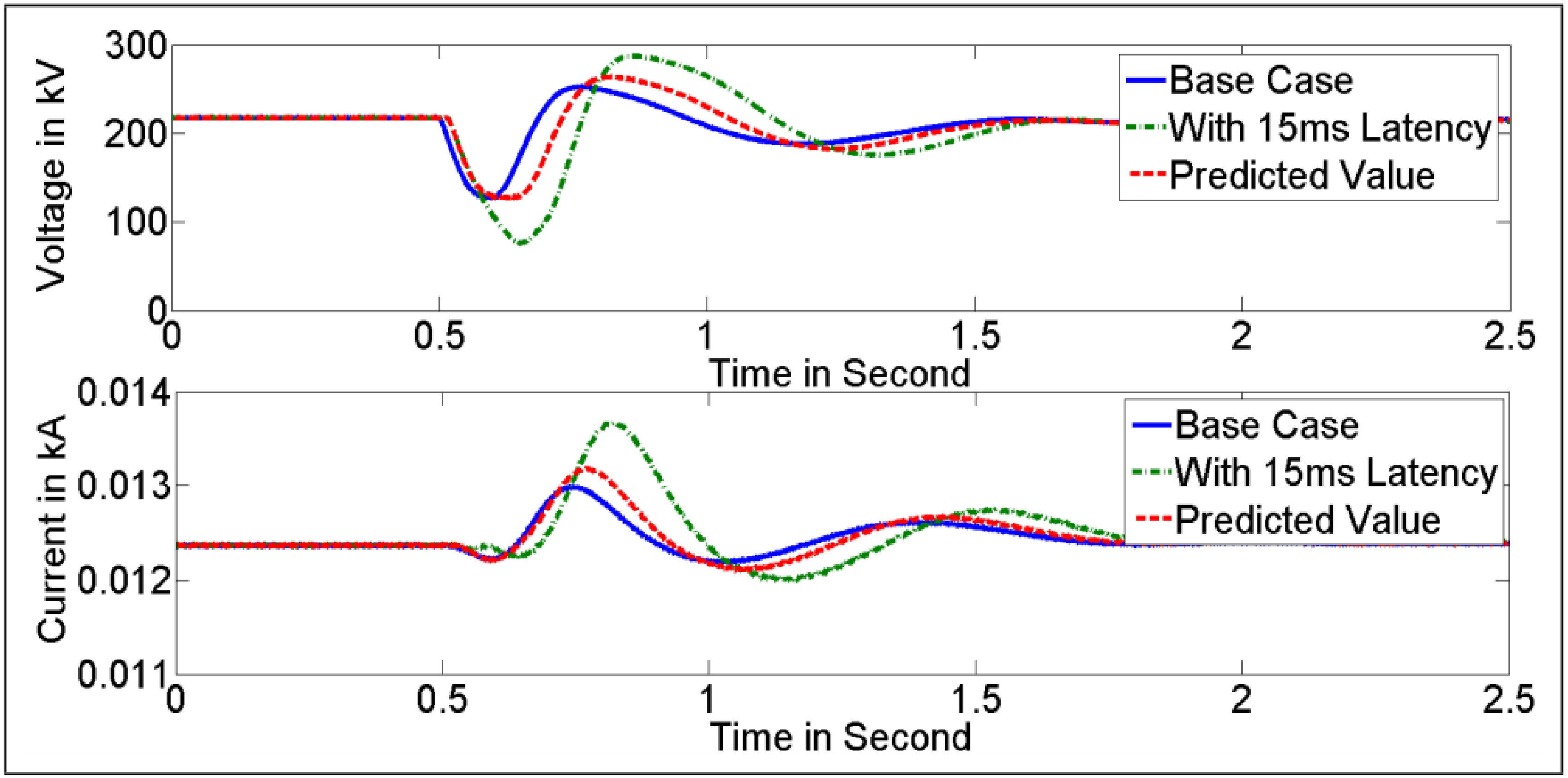
- Wide Area Network (WAN) and firewall upgrades at INL and RTDS hardware upgrades at NREL were performed and significant improvement in the data exchange simulations were observed.

- Overall efficiency and accuracy of the distributed real time simulation was improved.

- Peer-reviewed paper "Role of Linear Prediction in Geographically Distributed Real Time Simulations", investigating communication delays and mitigation using Predictor Approach, is under review.

Predictor Approach & Improvements

Reduction of the impact of variable data latency on the simulation

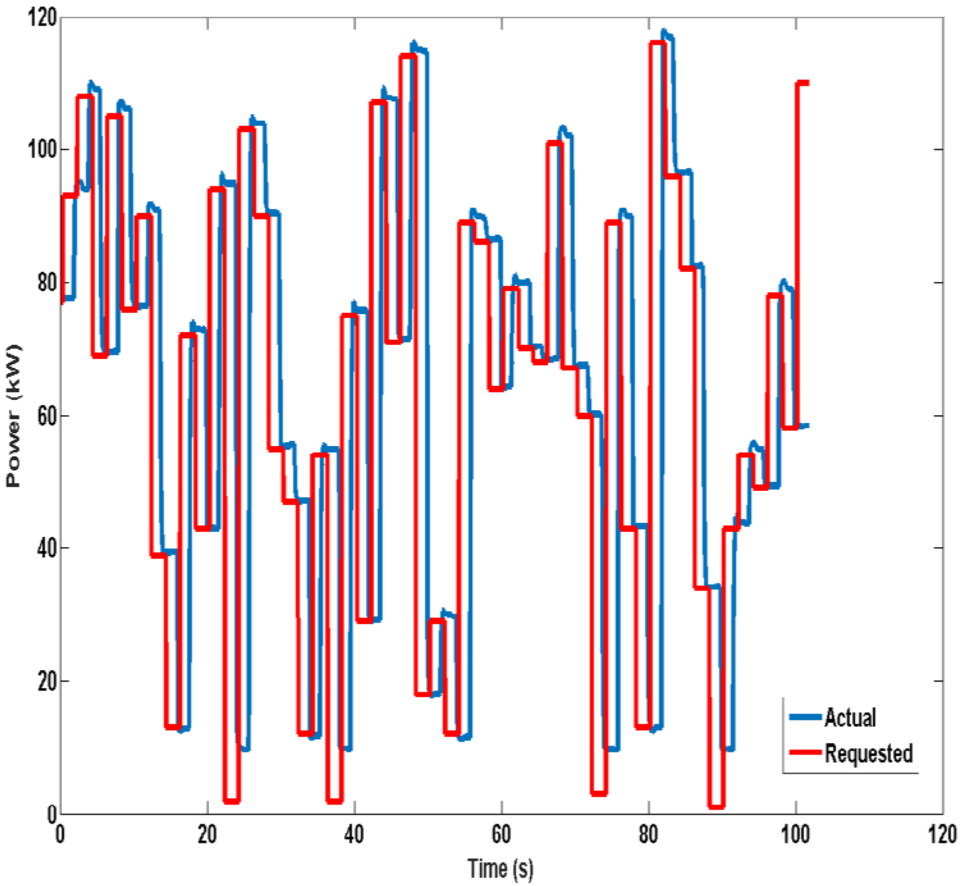


Two phase to ground fault with Prediction

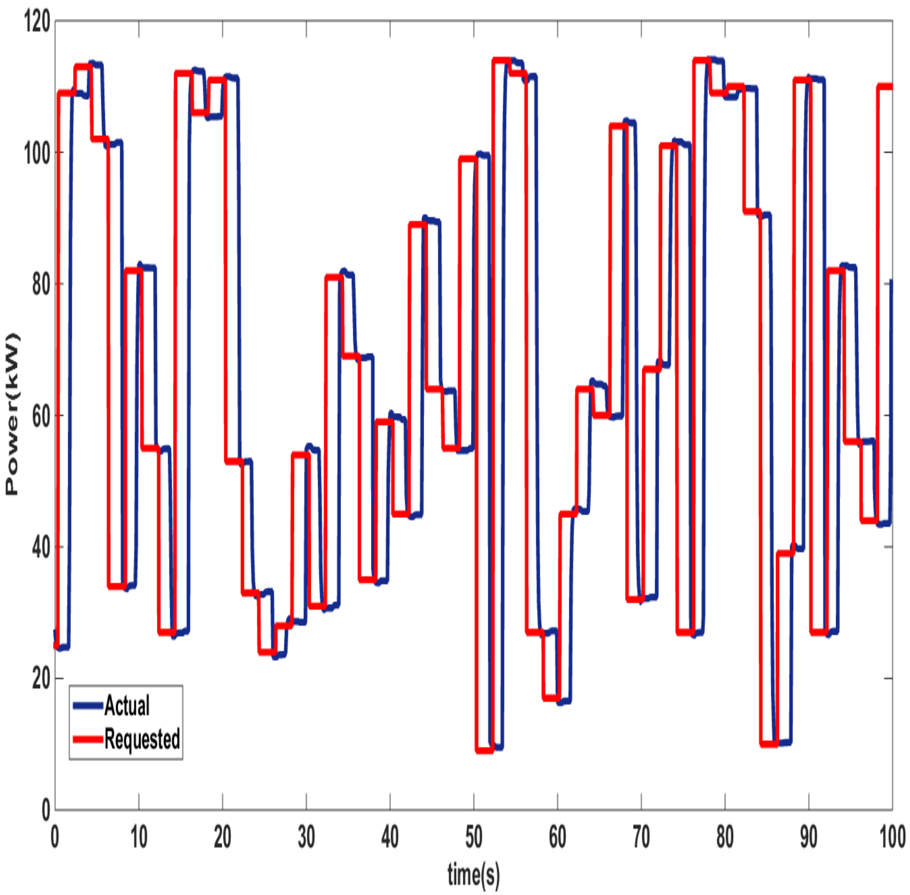
Demand Response Simulations

DR response of electrolyzer at NREL recorded at INL as PHIL
1 second lag is observed due to SCADA limitations and not electrolyzer response

E -20 DR Program (Sample profile)

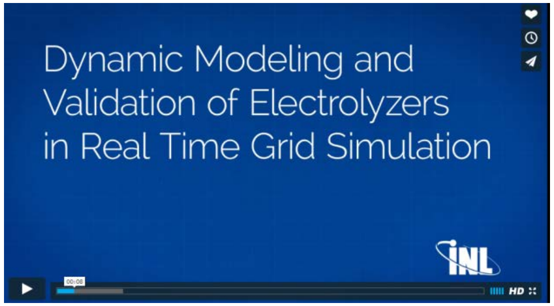


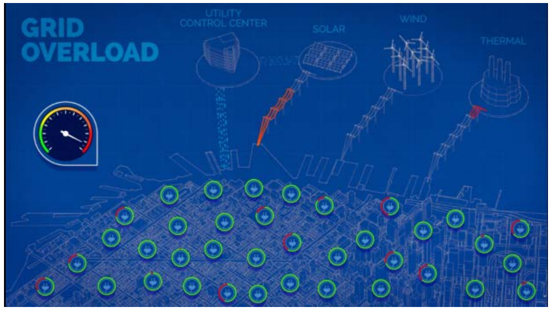
Sample 1 second control



Video Summary of project

A 3 minute summary video of the project to be shown





https://vimeo.com/131805284

password: h2h2h2

Publications

- Publications:
  - R. Liu, M. Mohanpurkar, M. Panwar, R. Hovsapian, A. Srivastava, S. Suryanarayanan,"Role of Linear Prediction in Geographically Distributed Real Time Simulations," International Journal of Electrical Power and Energy Systems, (in review).
  - M. Mohanpurkar, M. Panwar, S. Chanda, M. Stevic, R. Hovsapian, V. Gevorgian, S. Suryanarayanan, A. Monti, "Distributed Real-time Simulations for Power Systems Engineering," Cyber-Physical-Social Systems and Constructs in Electric Power Engineering, The Institution of Engineering and Technology (IET), 2016, pp. 35. (Accepted).