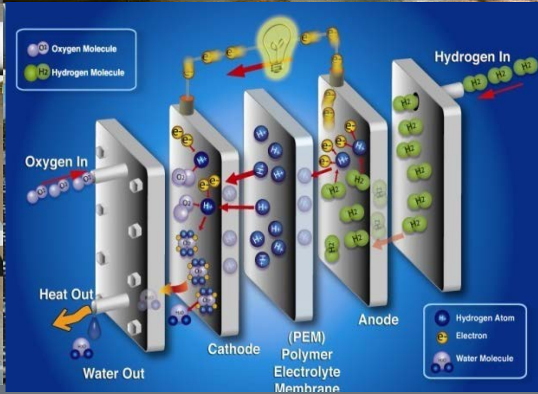
Fuel Cell Technologies Office Webinar

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy





Electrolyzers and Power Grid Integration

04/25/2017

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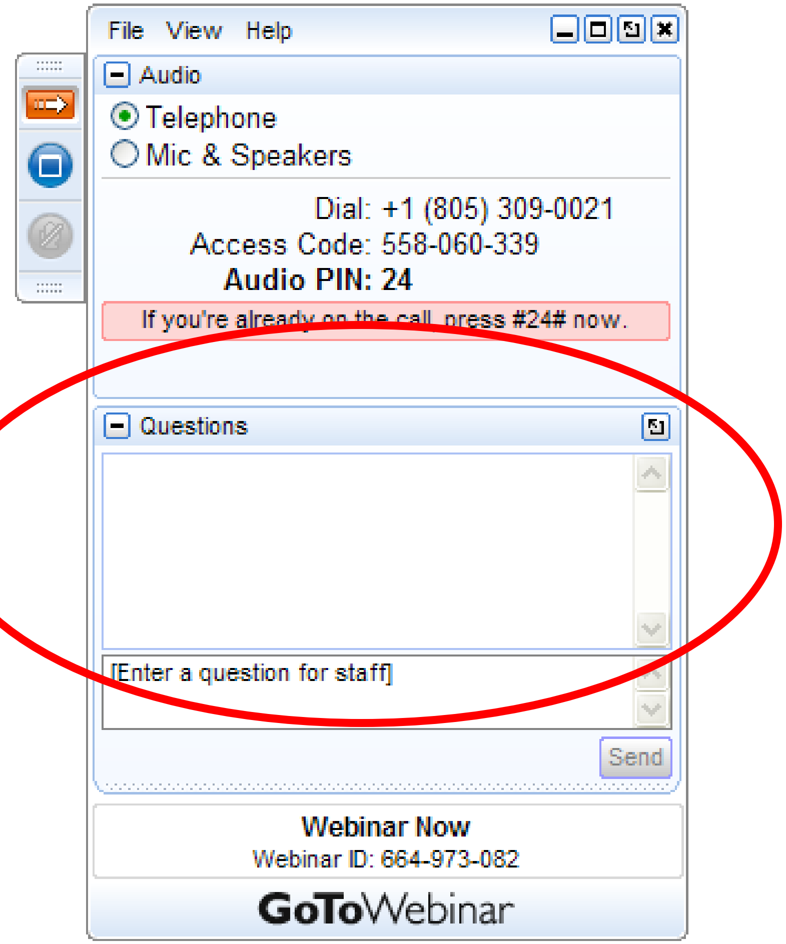
- Please type your questions into the question box



Funding Acknowledgment

- DOE Grid Modernization Laboratory Consortium (GMLC) project 1.4.2 “Definitions, Standards and Test Procedures for Grid Services from Devices”

- DOE Fuel Cell Technologies Office (FCTO) project “Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation”

Webinar Outline

- Introduction to Grid Modernization Laboratory Consortium (GMLC) project 1.4.2 “Definitions, Standards and Test Procedures for Grid Services from Devices”
- Identification and characterization of power grid services potential
- Introduction to Fuel Cell Technologies Office (FCTO) project “Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation”
- Providing power grid services
- Summary
- Q&A

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1.4.2 - Definition and Standards and Test Procedures of Grid Services From Devices

This project is about

- **Enhancing**
- **Empowering**
- **Unlocking**
- **Unleashing**

the value of grid modernization devices everywhere!

Impact:

- ✓ Std. performance, value & impact metrics for devices providing grid services
- ✓ Reward innovation, sell more devices
- ✓ Better decision-making by consumers, utilities, 3rd parties
- ✓ Lower cost, more reliable, cleaner grid

Project Description

Develop characterization test protocol and model-based performance metrics for devices' (DERs') ability to provide a broad range of grid services, i.e., to provide the flexibility required to operate a clean, reliable power grid at reasonable cost.

Expansion Potential:

- ✓ Battery equivalent interface as a modeling standard
- ✓ Allows detailed, state-of-the-art device models to plug & play into planning and operation tools

Classes of Devices and Services

Devices (DERs)

Responsive, flexible end-use loads

- Water heaters
- Refrigerators
- Air conditioners
- Commercial rooftop units (RTUs)
- Commercial refrigeration
- Commercial lighting
- Electric vehicles (charging only)
- Electrolyzers

Storage

- Battery / inverter systems
- Thermal storage systems
- Electric vehicles (full vehicle-to-grid)

Distributed generation

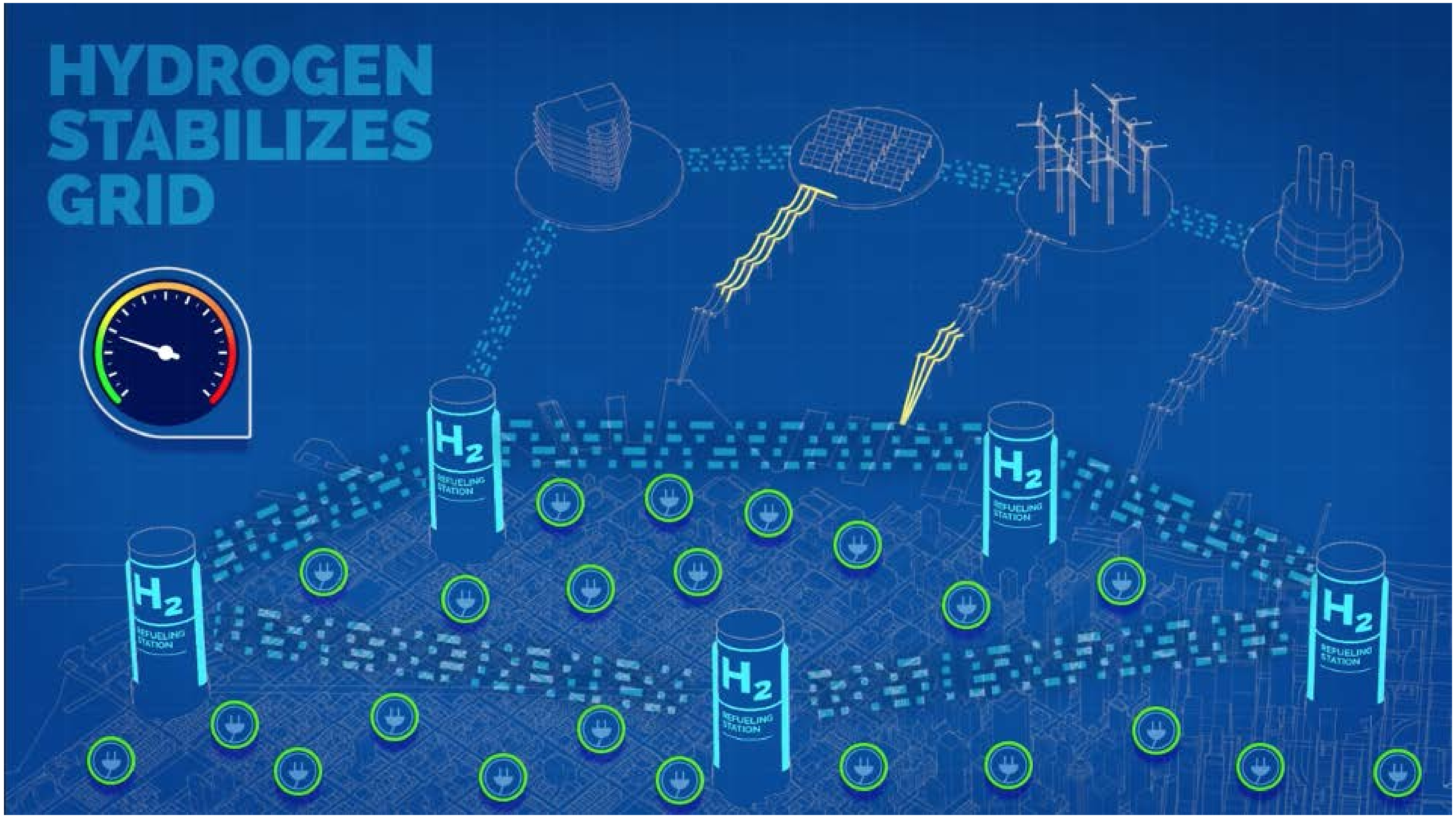
- Photovoltaic solar (PV) / inverter systems
- Fuel cells

Grid Services

- Peak load management (capacity)
- Energy market price response (wholesale energy cost)
- Capacity market dispatch (market value)
- Frequency regulation (market value)
- Spinning reserve (market value)
- Ramping (new)
- Artificial inertia (new)
- Distribution voltage management (new; e.g., PV impacts management)

Motivation

- Hydrogen production and storage during excess generation from renewables or traditional energy sources.
- Hydrogen can provide grid services



Project outcomes

- Develop best practices for testing hydrogen electrolyzer and performance rating to validate the eligibility of providing grid services
- Inform utilities and grid operators about electrolyzer (hydrogen refueling station) capabilities
- Inform H_2 fuel producers about electrolyzer capabilities and accelerate market adoption
- Encourage innovation by device manufacturers and support identification of services and their impact on the operation of an electrolyzer

Approach

- Identify hardware, embedded (low-level) and separate (high-level, front end) controllers, quantify their properties

- Define the minimum control functionality for responding to grid signals, and autonomous response to voltage and frequency

- Characterization protocol that acknowledges operating constraints and provides simple test to identify appropriate grid services

- Performance metrics describe how well an electrolyzer / fleet of electrolyzers can provide each grid service and the coincident impact on:
  - electrolyzer’s energy consumption
  - owner or user
  - device itself

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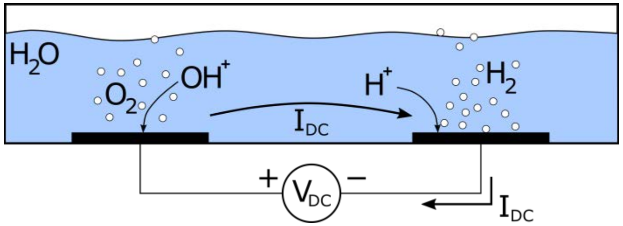
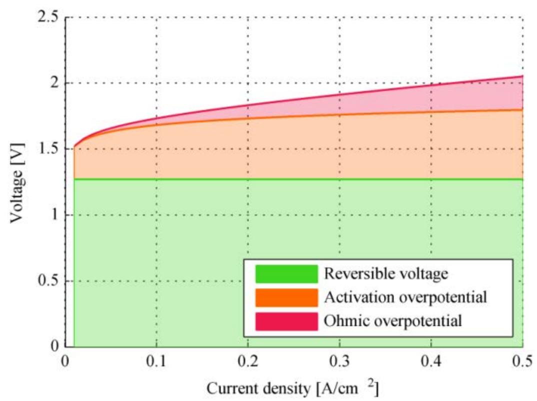
Physical model of electrolyzer

- Electrochemical cell
  - DC current passed through two electrodes
  - at *critical voltage* between the electrodes
    - hydrogen produced at negative electrode
  - amount of produced H_2 produced correlates to the DC current
  - excellent thermal management characteristics
  - Voltage of a electrochemical cell is sum of reversible voltage and additional overvoltages in the cell

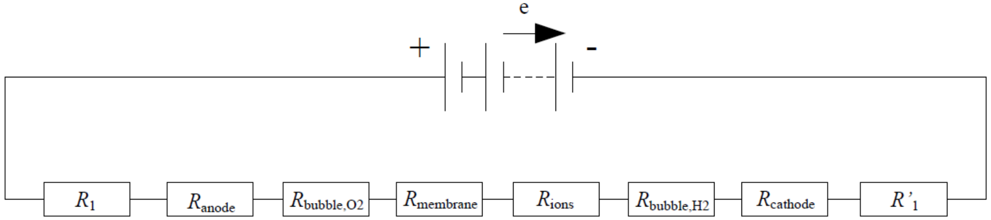


Electrochemical cell

$$U_{cell} = U_{rev} + U_{ohm} + U_{act} + U_{con}$$



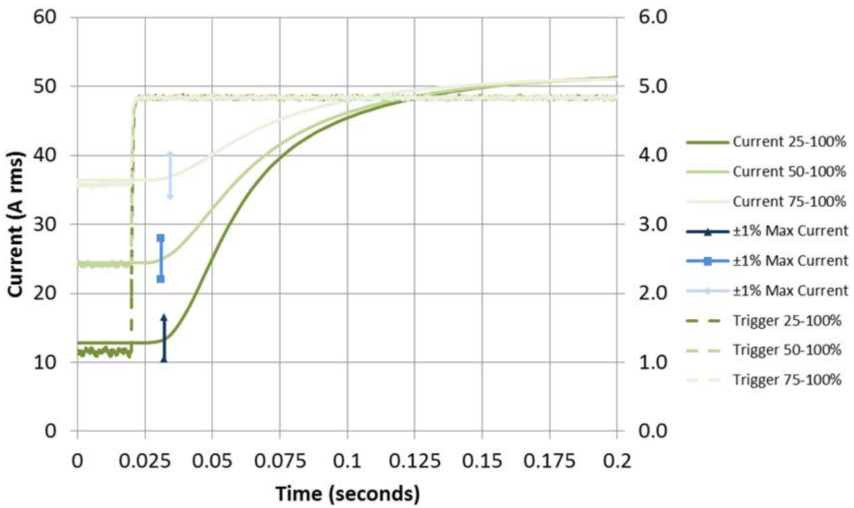
Example of overvoltage share [Ref. 5]

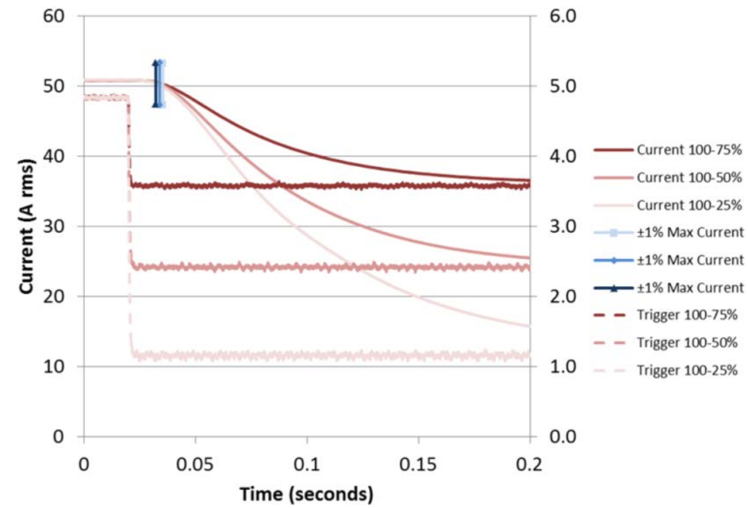


A simplified circuit analogy of a water electrolysis system [Ref. 5]

Dynamic Characteristics: Ramp-up and Ramp-down Test

- Ramp-up Tests
  - from 25% to: 50%, 75% and 100% of rated power
- Ramp-down Tests
  - from 100% to: 75%, 50% and 25% of rated power



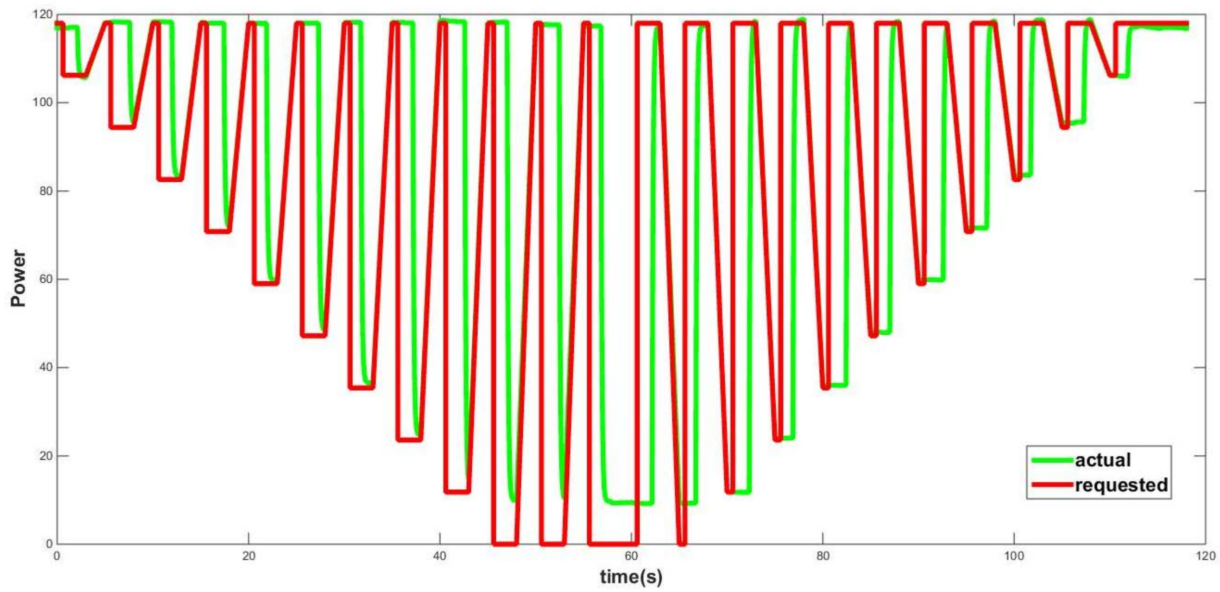


Ramp-up and ramp-down response of a PEM electrolyzer [Ref. 1]

	PEM electrolyzer
Electrical Power	40 kW
Rated Current	155 A per stack
Stack Count	3

Dynamic characteristics – Power Variation

- Power set-point variation to examine Demand Response
  - quantification of rate of rapid load change and demand response
  - tested with SCADA system – inherent delay of 1 second



INL & NREL testing of a 120kW electrolyzer

Identified Grid Services 1

- Peak capacity management
  - deploying fleets of electrolyzers to consistently and reliably reduce critical peak loads within a defined region or location on the grid
- Energy market price response
  - fleets of electrolyzers consume energy when prices are low and defer consumption (set energy free) when prices are high
- Regulation
  - operating point adjustment counteracts short-term changes in electricity use that might affect the stability of the power system
- Spinning Reserve
  - by reducing its power consumption fleets of electrolyzers can support the event when loss of generation unit in the grid occurs

Identified Grid Services 2

- Ramping
  - analogue to generator, fleets of electrolyzers start and stop on command, while the "ramp rate" is the rate at which they can increase or decrease consumption
- Artificial inertia
  - fleets of electrolyzers regulate active power consumption in response rate of change of frequency
- Distribution voltage management
  - upon detecting the voltage deviations (self-sensing and/or receipt of external measurement signals) fleets of electrolyzers adjust the net load in the form of their reactive and/or real power components
- Autonomous grid service responses
  - additional (high-level) controller enables grid services in "stand-alone" mode

Key Capabilities of Electrolyzers

- Purely resistive load, supplied from a DC source (power converter)
- Very high rate of change and flexibility in setting power operating points
- Capable of sensing deviations in power systems, capable of adjusting their operating points to support the grid (fleets of electrolyzers)
- Frequency and voltage support by reducing/increasing power consumption

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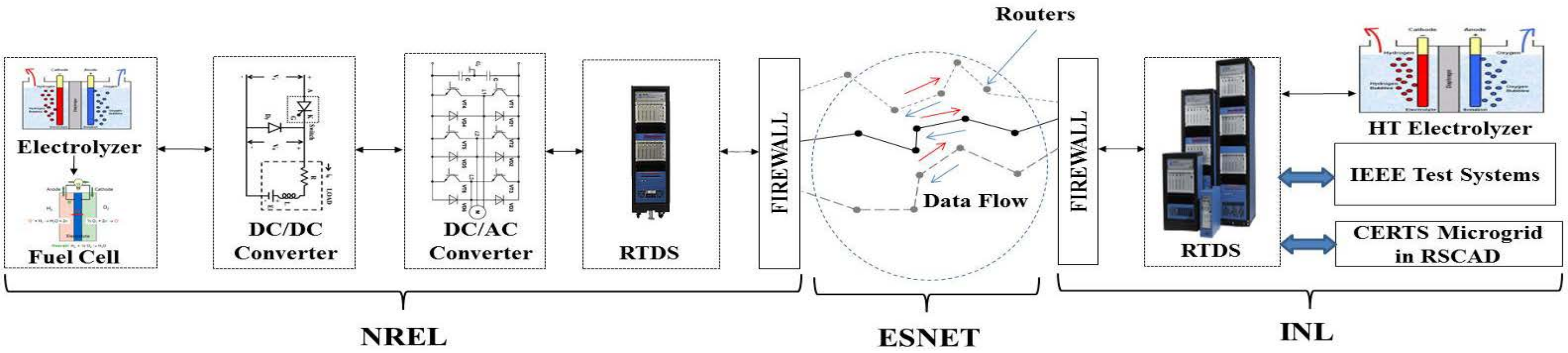
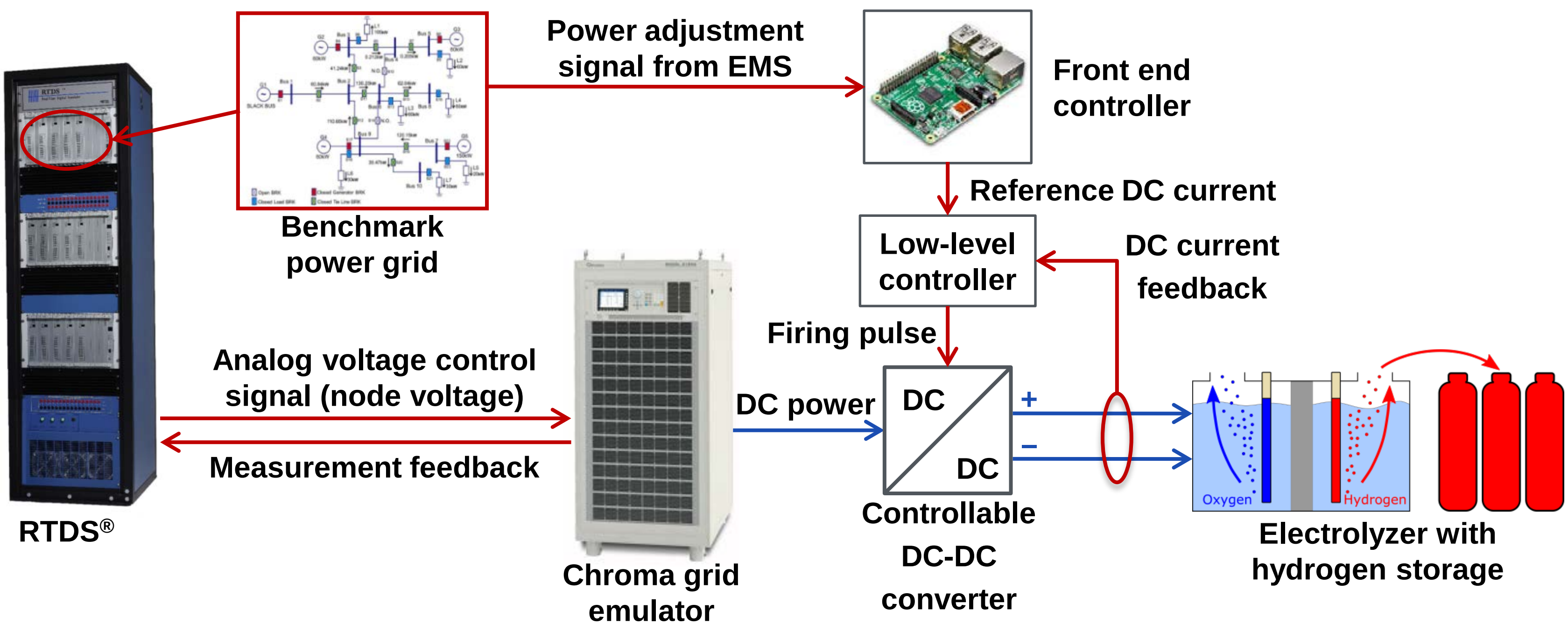
Role of Electrolyzers in Grid Services

- 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



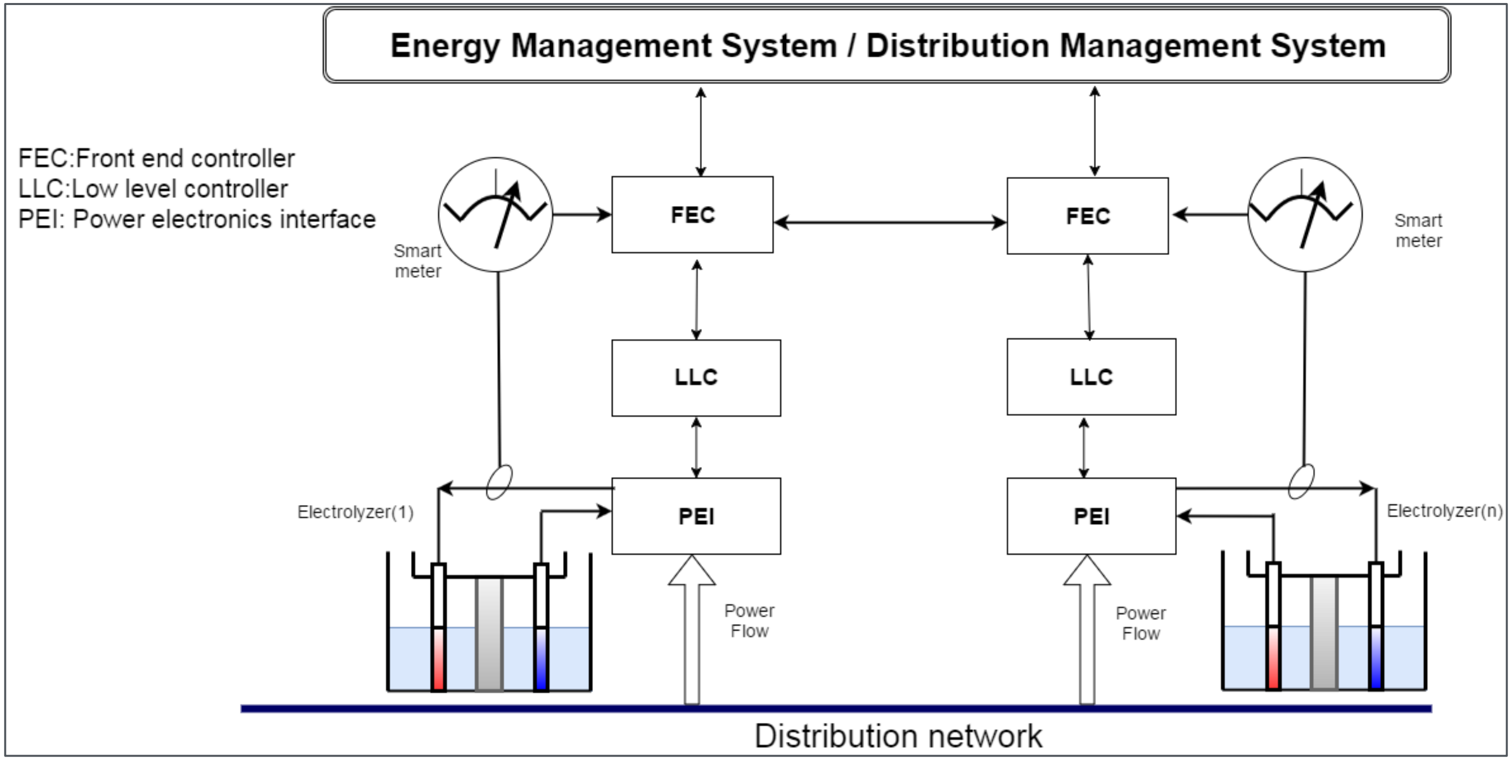
Characterization Protocol

- Eligibility requirements and constraints to response
- Parameters to be characterized
- Adopted and assumed parameters & standard test conditions
- Data to be collected
- Test rig and instrumentation, equipment installation
- Communicating to the device under test
- Characterization Sequence



Controller Requirements

- High-level controller (Front-end controller)
  - applies EMS requirements and supports power quality by varying the electrolyzer's operating point
  - communicates to other FECs to coordinate remedy actions



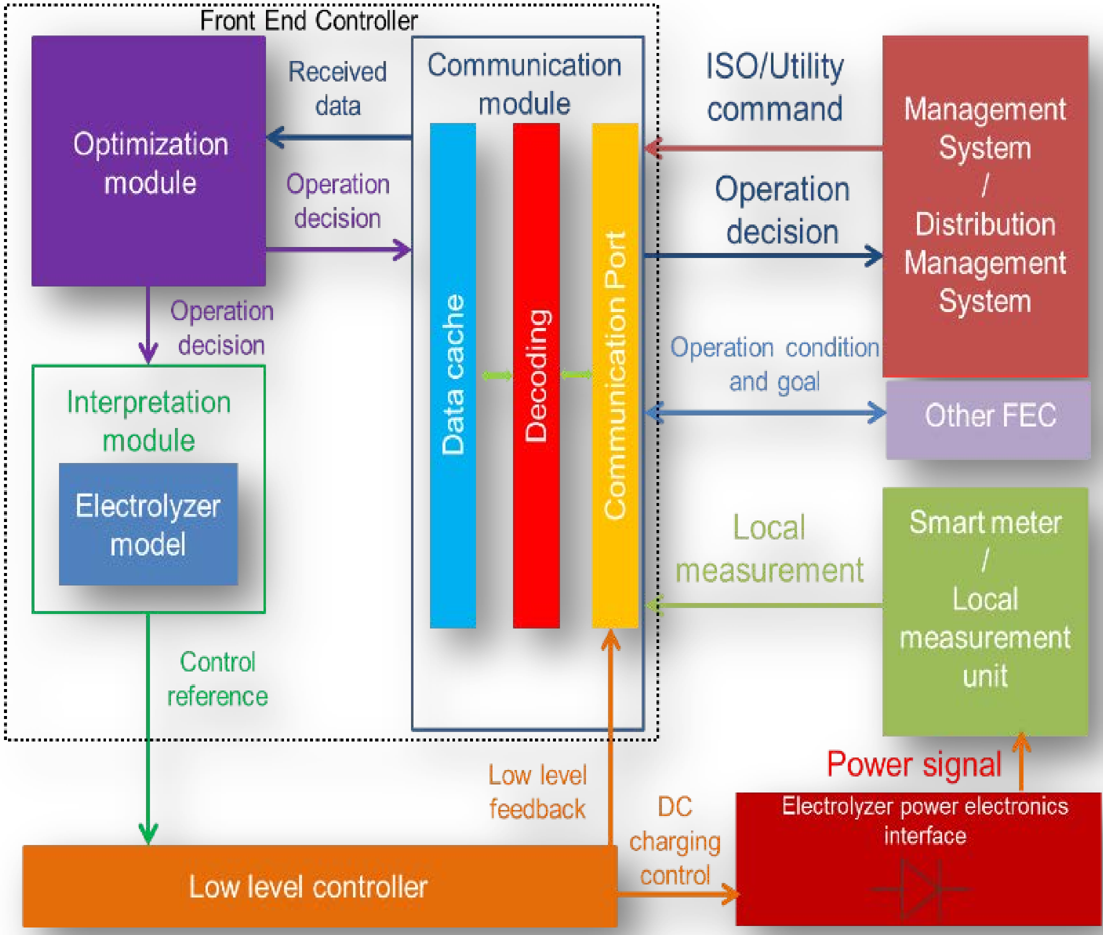
Front-End Controller Architecture 1

FEC consists of three modules:

1. **Communication module**
   Realizes data exchange between FEC, utility, and electrolyzer's low-level controller

2. **Optimization module**
   Computes set point for electrolyzer operation that optimizes the revenue of the hydrogen refueling station

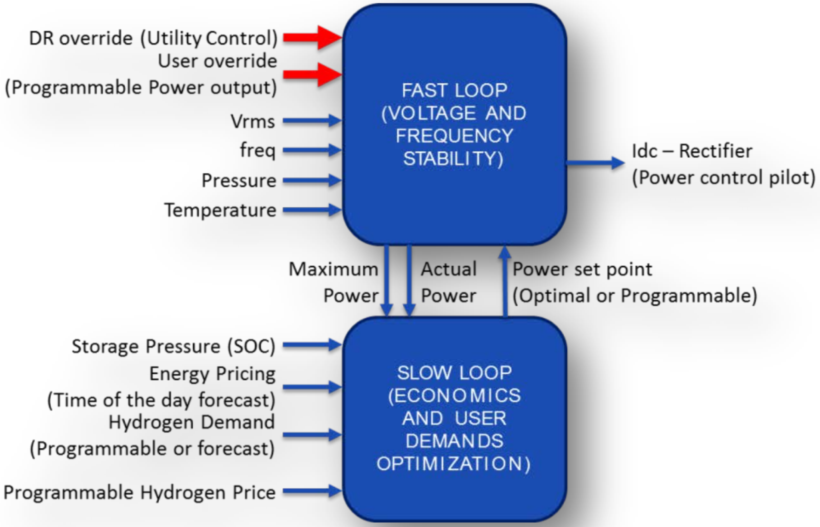
3. **Interpretation module**
   Generates the reference control signal in order to ensure that the low level controller properly integrates with the FEC

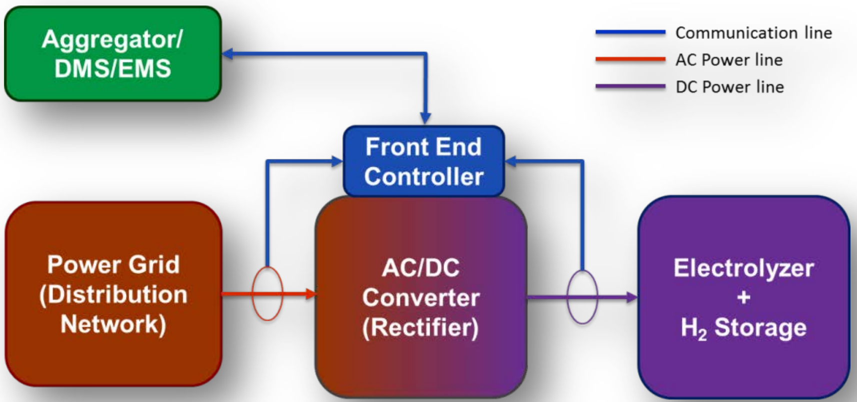


Front-End Controller Architecture 2

- FEC receives numerous information at input, applies optimization algorithm, and generates reference DC current
- Reference is forwarded to the electrolyzer's low level controller

- FEC interfaced with Electrolyzer
- DR Signal received from higher level control (EMS/DMS/Aggregator)
- Local sensing of power quality
- Reference operating point (DC-current) sent to power converter





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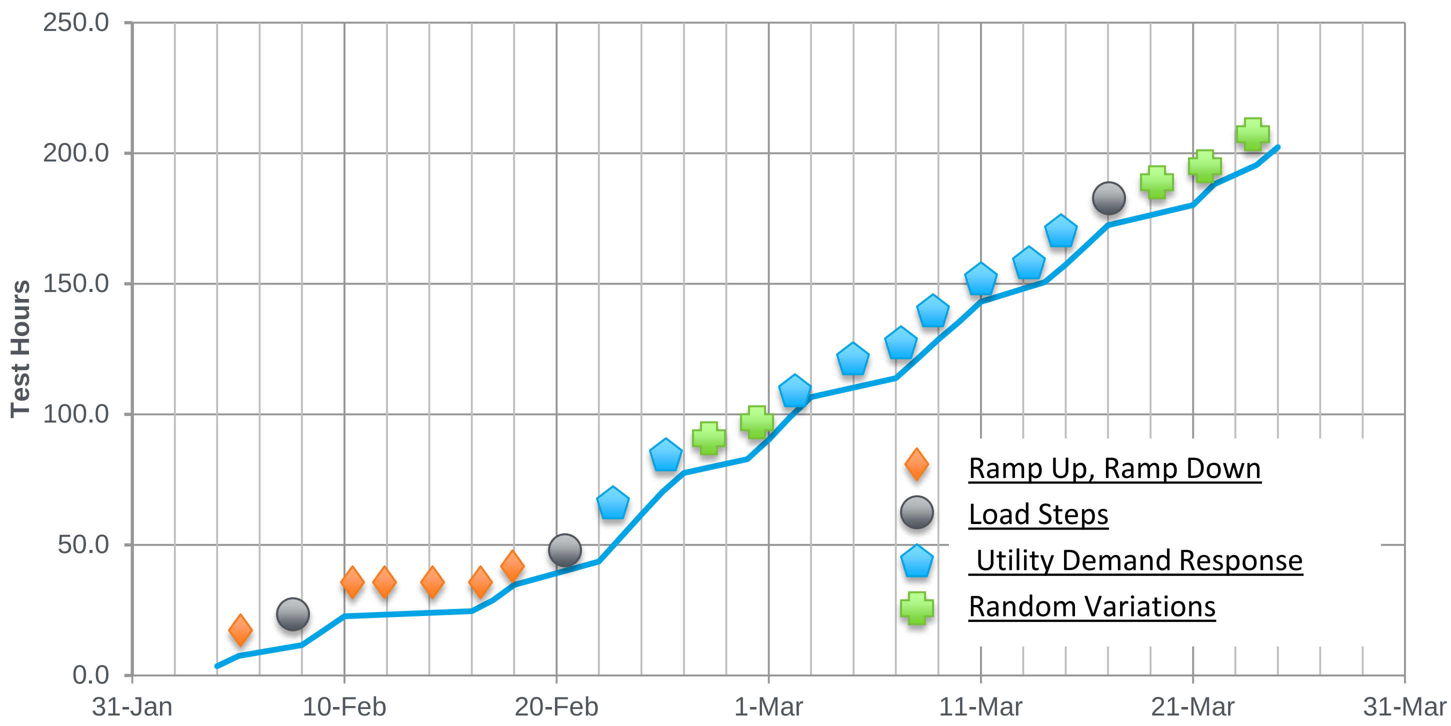
Electrolyzer Characterization Testing

Types of tests run to achieve 200 hour test results



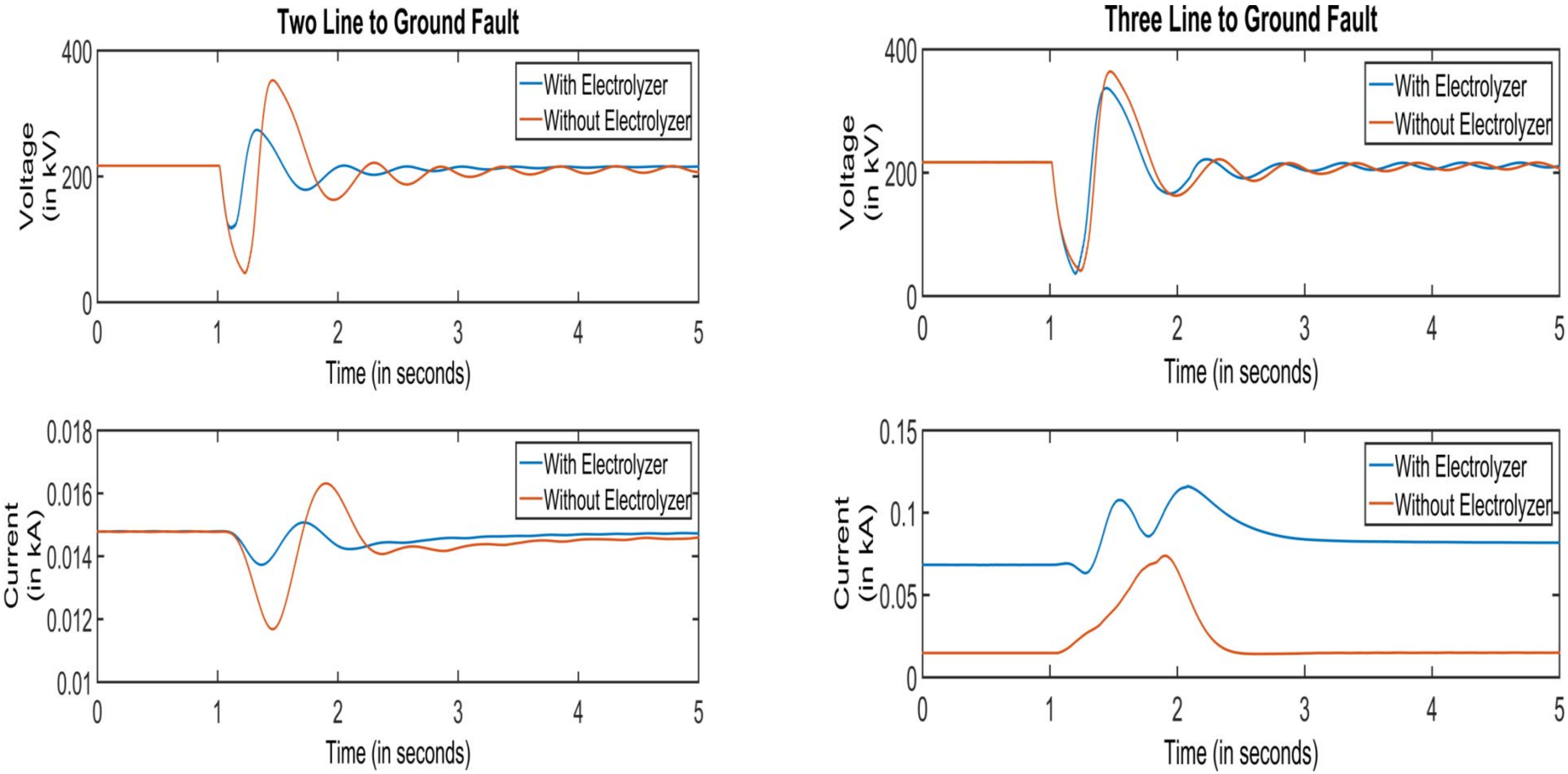
Electrolyzer Characterization Testing: Summary

Fast response time & quick slew rate

Performance Metric	Ramp-up & Ramp-down	Load Steps	DR	Random Variation in Load
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

Impacts on Power System Transient Stability

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

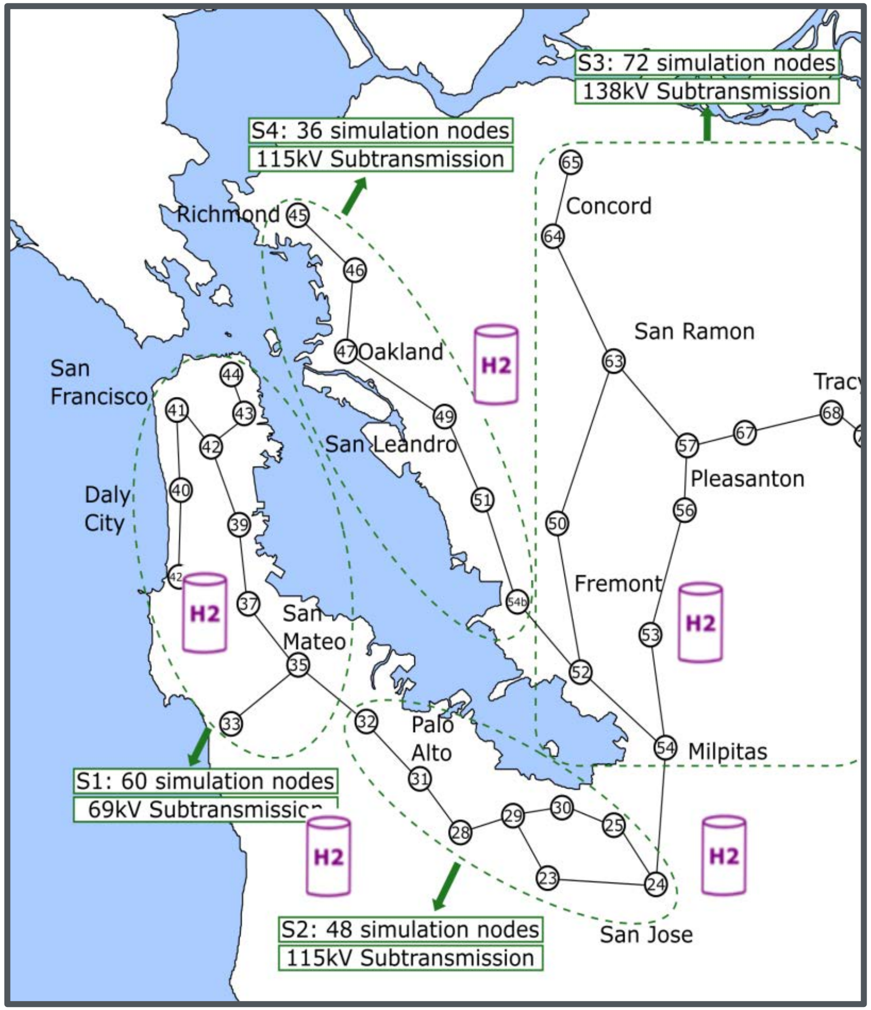


Resistive Capabilities and Impacts on the Grid

Real-Time Model of PG&E Network

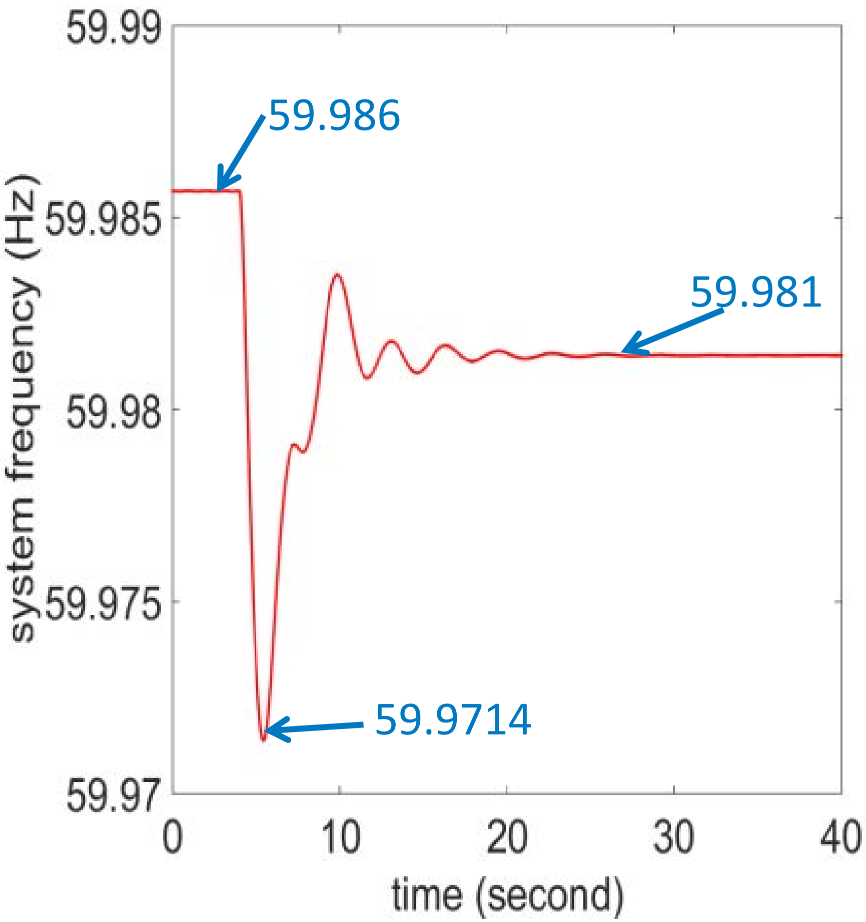
Real-time grid model of Pacific Gas & Electric that covers hydrogen refueling station interconnections

- Network synthesis and modeling in real-time simulator at INL, represents the PG&E infrastructure
- Electrolyzer connected as Hardware-In-the-Loop
- Served as a testbed for testing grid services and stability of connecting electrolyzers
  - Centralized and distributed electrolysis is assessed under varying conditions
  - Fault conditions within the grid
    - Balanced and unbalanced faults
    - Step load changes in the grid
    - Voltage and frequency variations
  - Demand response signals and response of the electrolyzer

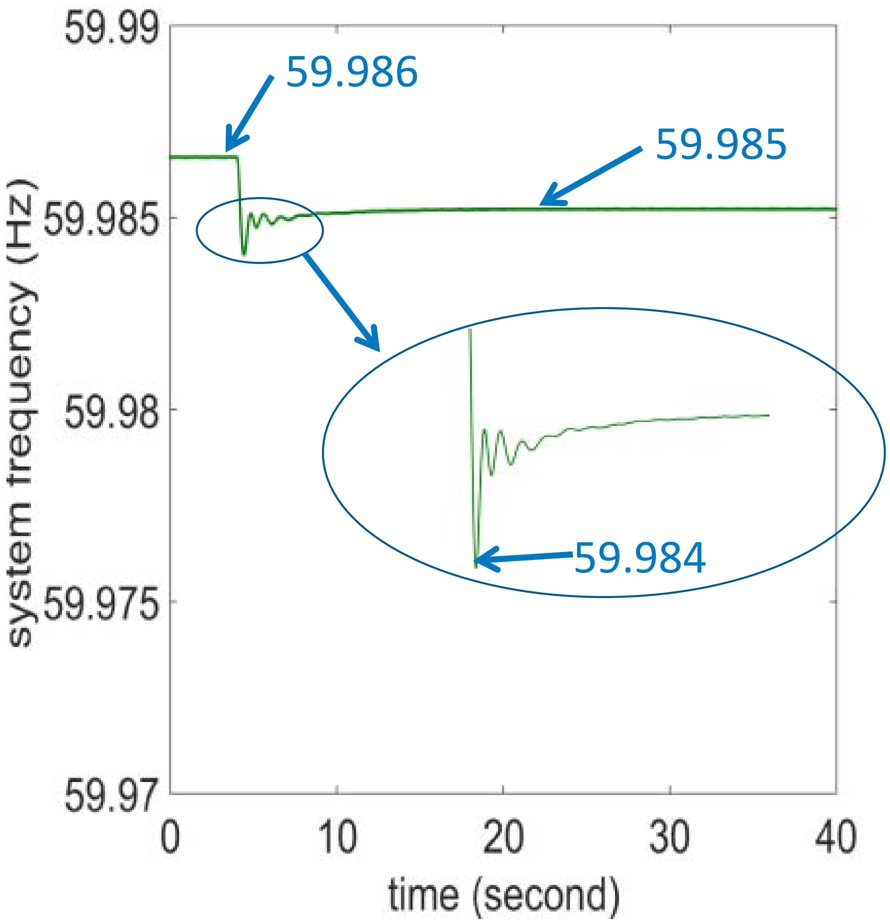


Frequency Support by Centralized Electrolysis

Electrolyzers controlled by FEC can enhance grid stability by limiting frequency excursions



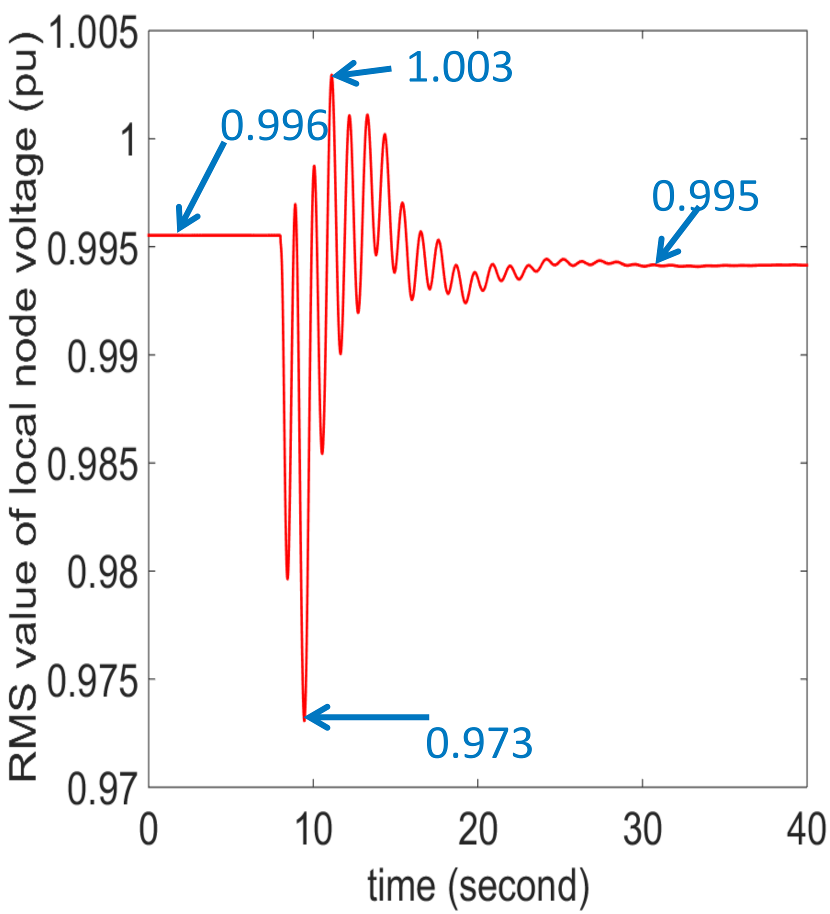
Electrolyzer Response without FEC



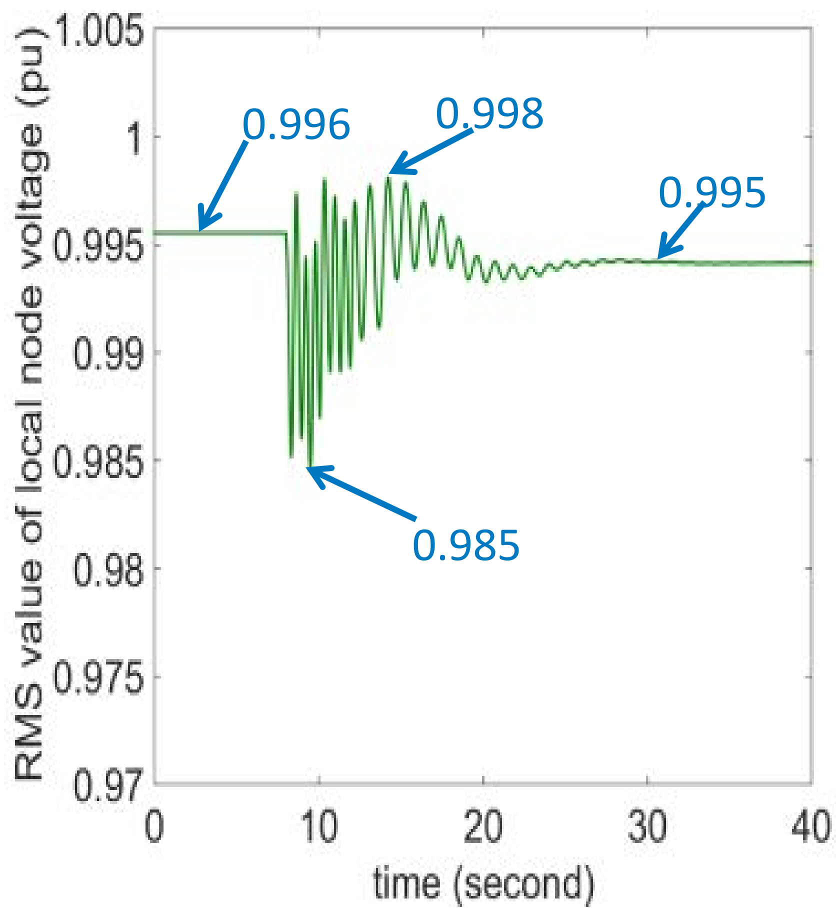
Electrolyzer Response with FEC

Voltage Support by Centralized Electrolysis

Electrolyzers controlled by FEC can enhance grid stability by limiting voltage excursions



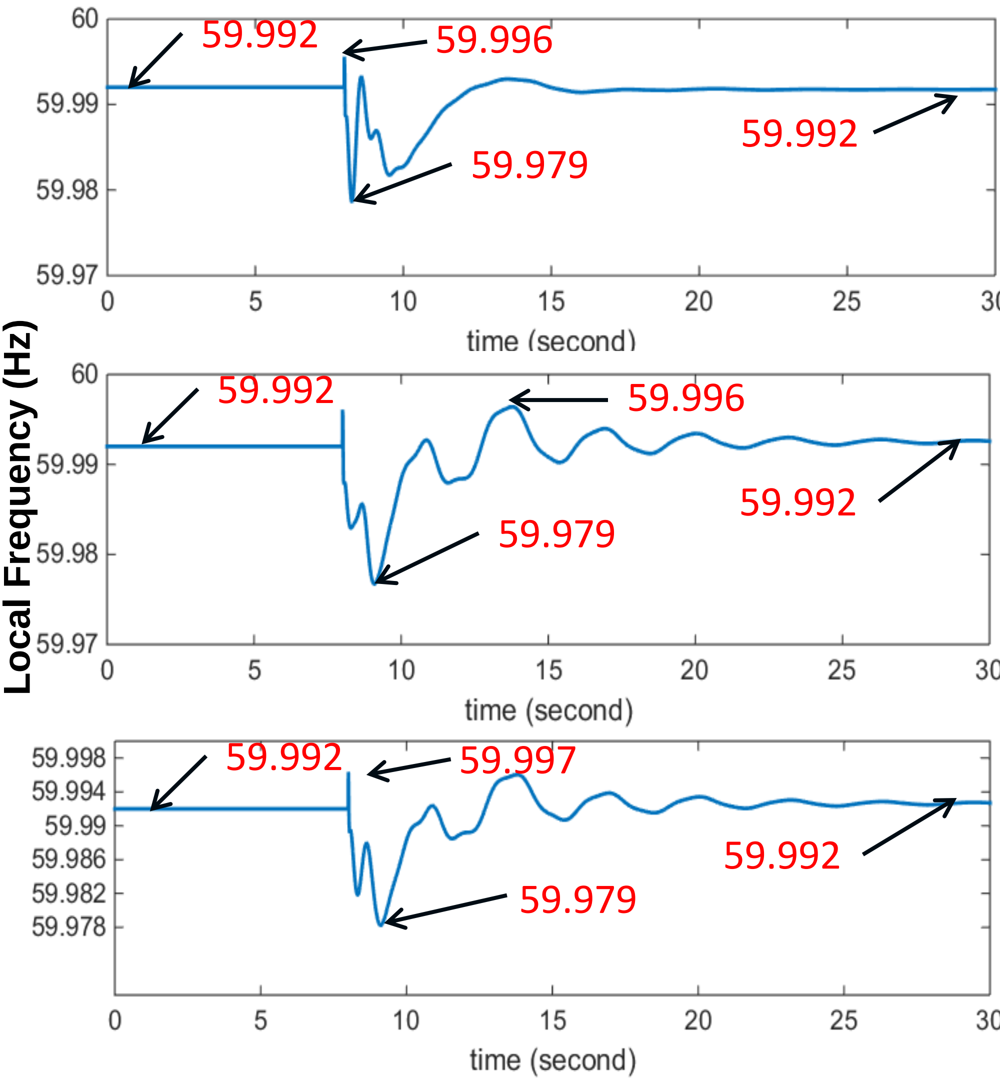
Electrolyzer Response without FEC

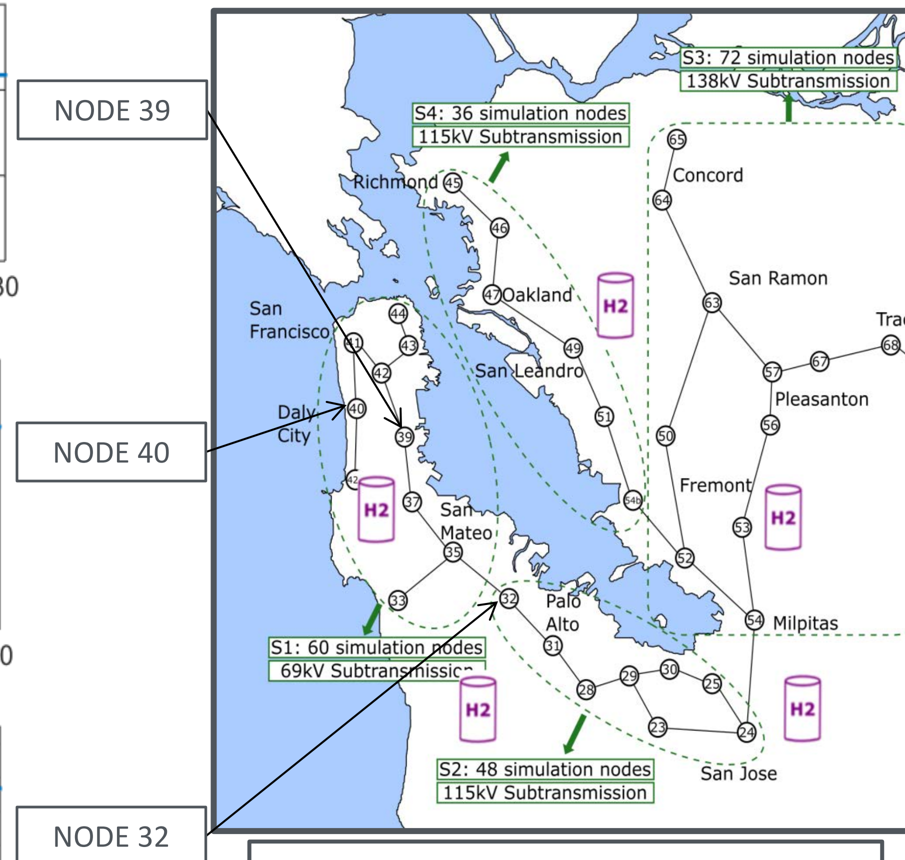


Electrolyzer Response with FEC

Frequency Support by Multiple Electrolyzers with FEC

Multiple electrolyzers controlled by FEC can enhance overall grid stability by limiting frequency excursions

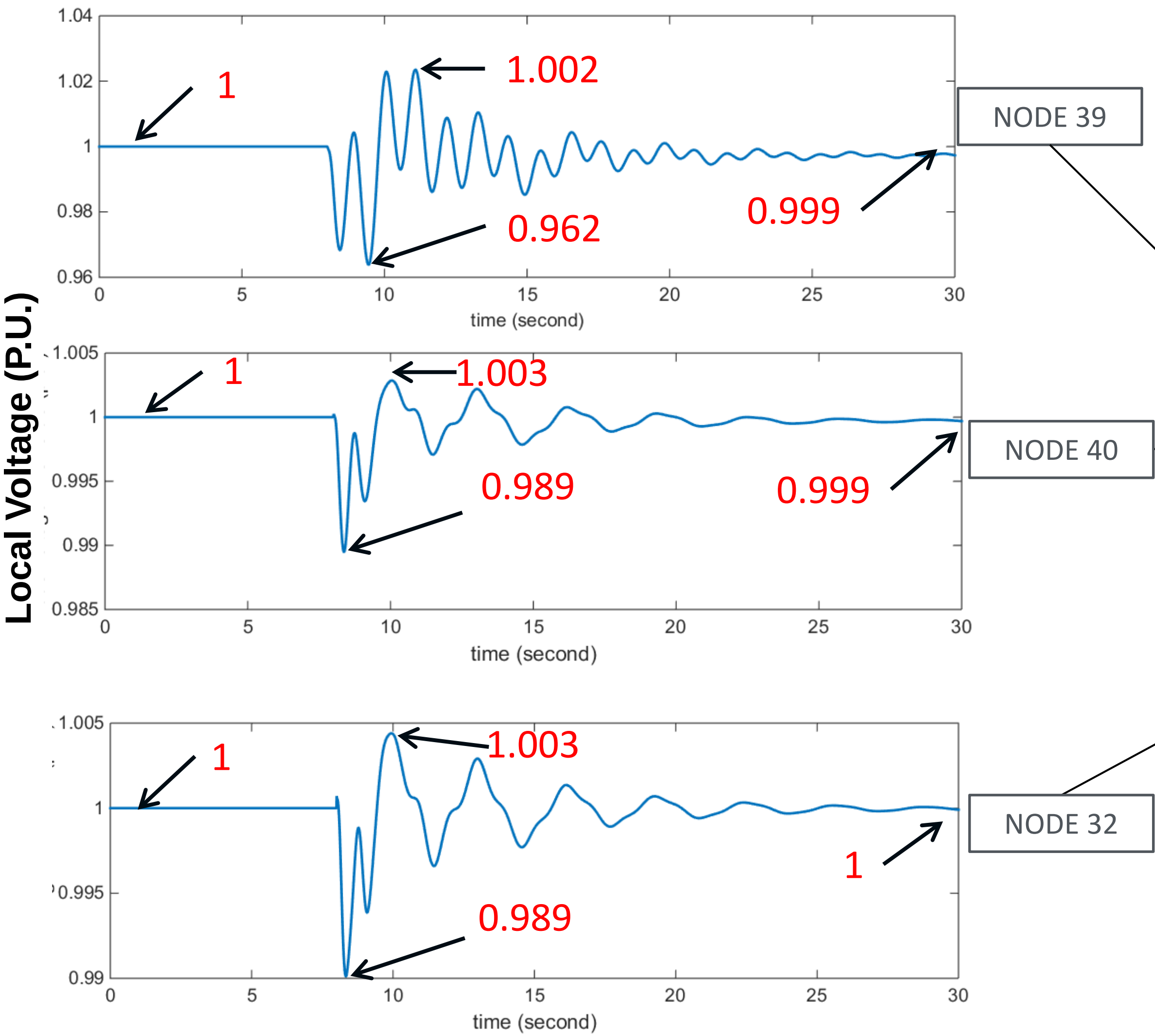


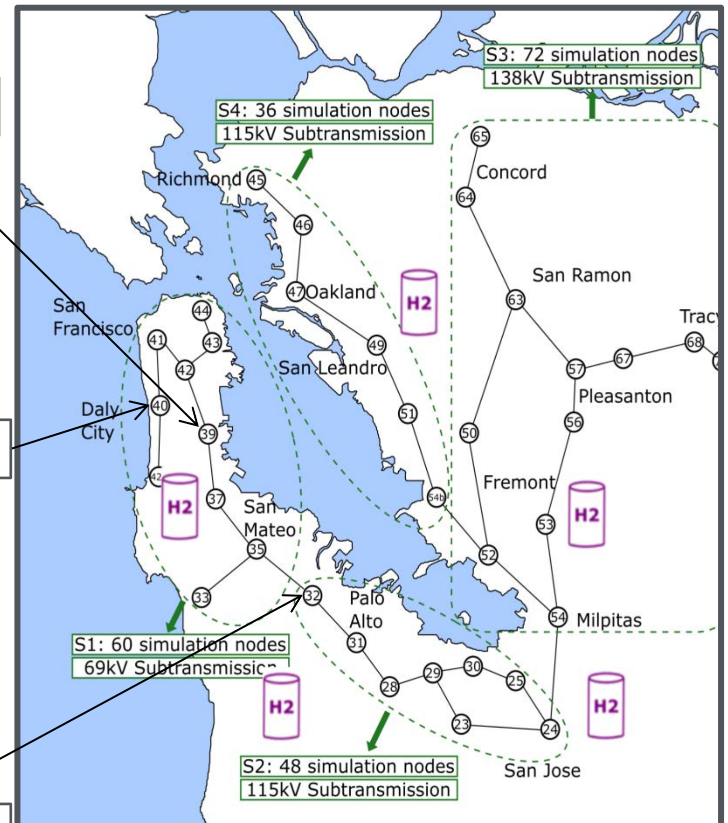


Fault location: Node 39
Fault type: Three phase balance
Fault duration: 0.1 seconds

Voltage Support by Multiple Electrolyzers with FEC

Multiple electrolyzers controlled by FEC can enhance overall grid stability by limiting voltage excursions





Fault location: Node 39
Fault type: Three phase balance
Fault duration: 0.1 seconds

Lessons learned

- Fleets of electrolyzers (hydrogen refueling stations)
  - grid support by reducing voltage and frequency excursions
- Enhanced revenue and reduced H_2 cost of production by participating in power grid services
- FEC
  - is a vendor-neutral controller that is compatible with the existing electrolyzer’s (low level) controllers
  - can receive and interpret communication signals coming from & going to EMS/DMS/Aggregator
  - enhances electrolyzer’s basic purpose to produce hydrogen by providing grid services
  - allows cohesive response of fleets of electrolyzers
  - enables autonomous grid service responses
  - allows H_2 operator choice to participate in grid services (or not to)

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Summary

- Electrolyzer is a very fast responding load and can provide various grid services, thus being essential energy device in a grid with high penetration of renewables

- Capabilities of electrolyzers to coordinately support voltage and frequency by utilizing front end controllers demonstrated using actual hardware in Hardware-In-the-Loop simulations

- The limitations in providing grid services is the size of the hydrogen tank as well as possible degradation of electrolyzer material
  - However: grid services may be economically compensated

- Recommended testing procedure will enable quick and straight-forward testing of an electrolyzer to quantify its ability to provide grid services

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References

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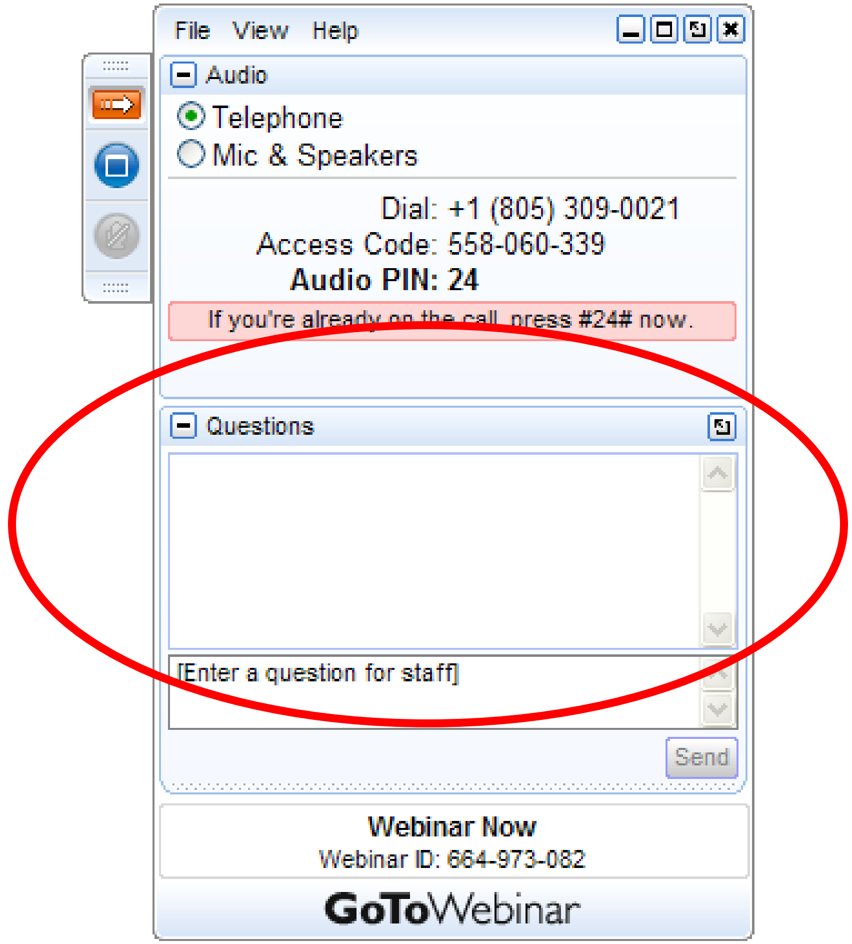
Question and Answer

- Please type your questions into the question box



Thank you

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