# VII.C.3 Dynamic Modeling and Validation of Electrolyzers in Real-Time Grid Simulation

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Project End Date: September 30, 2017

## Overall Objectives

- Validate the benefits of hydrogen electrolyzers through grid services and hydrogen sale to fuel cell vehicles in full-scale deployment.
- Characterize potential and highest economic value based on the needs of multiple stakeholders for specific grid regions.
- Demonstrate reliable, fast-reacting performance of hydrogen-producing electrolyzers as at-scale energy storage devices.
- Verify communications and controls needed for successful participation in electricity markets and Demand Response (DR) programs.

## Fiscal Year (FY) 2017 Objectives

- Expand the utility network (Pacific Gas and Electric [PG&E]) in the digital real-time simulation platform, to accommodate futuristic hydrogen refueling stations. This platform will be used to assess the value of electrolyzers under existing and futuristic DR programs and any other grid services using historic energy and ancillary service prices.
- Implement the front end controller (FEC), which interprets sample utility signals and safely controls the operation of the hydrogen refueling station. Test the control signals generated by the FEC for the lower level controller to respond to different utility signals, hence participate in DR and ancillary service programs.
- Perform real-time simulation within which a future hydrogen refueling station is controlled by the FEC to provide local fast loop support and macro grid level slow loop support.
- Test and validate the performance of single and multiple electrolyzers in providing local voltage and frequency support when integrated with the FEC.
- Test the performance of FEC in driving electrolyzer participation in demand response operated by multiple utility companies.

## Technical Barriers

This project addresses the following technical barriers from Technology Validation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

(B) Lack of Data on Stationary Fuel Cells in Real-World Operation

(G) Hydrogen from Renewable Resources

(H) Hydrogen and Electricity Co-Production

## Contribution to Achievement of DOE Technology Validation Milestones

This project will contribute to achievement of the following DOE milestone from the Technology Validation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

- Milestone 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).

## FY 2017 Accomplishments

- Demonstrated real-time connectivity between the simulators and electrolyzer at the two labs.

- Implemented first version of the FEC as a hardware at INL.
- Multiple utility demand response signal profiles were tested. Test results showed that the FEC can rapidly and precisely drive the electrolyzer set points to follow the command.
- Completed the baseline assessment (without hydrogen refueling stations) of the notional PG&E network, based on typical faults and the disturbances due to them.
- Performed wider range of scenarios on the expanded PG&E network that included hydrogen refueling stations, based on typical faults and the disturbances due to them.
- Compared real-time simulations to the baseline results, to assess the local voltage and frequency benefits due to hydrogen refueling stations integrated with FECs.

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## INTRODUCTION

This project aims to quantify the value of hydrogen refueling stations (electrolyzers) from a grid integration perspective. The anticipated value of electrolyzers stems from the fact that they are a controllable load with fast response. They are typically coupled with hydrogen energy storage, dispensers, and compressor units to form the hydrogen refueling stations. They provide the flexibility to meet hydrogen demand with stored hydrogen when responding to the grid demand, and store more hydrogen when the grid power demand is low. The input resource for electrolyzers is electricity and hence allows flexible co-placement of electrolyzers with other distributed energy sources in a power system network, leading to an optimal value of the objective function.

The test set-up involves real-time simulations of power systems at INL with hardware-in-the-loop (HIL) of a 250 kW electrolyzer, along with the supplementary systems representing the hydrogen refueling station. This project leverages the existing work at both INL and NREL in the areas of power systems, electrolyzers, power markets, and control systems. The FEC developed in this research helps integrate the operations of the electrolyzer with the grid management systems and adds flexibility. This flexibility can be utilized to assimilate renewable energy, manage distribution loads, and provide grid support. The adoption of the FEC developed and tested in this project will drive down the cost of generating hydrogen, while maintaining requisite reserves for demands.

## APPROACH

In FY 2017, INL and NREL performed an aggregate of over 500 hours of testing of the 250 kW electrolyzer stack. The tests primarily included stack characterization and FEC functionality tests. Stack characterization was repeated for the newly upgraded electrolyzer stack rated at 250 kW, which was 120 kW for the FY 2016 tasks. This re-characterization was essential as the project direction hinged on the basic controllability of the electrolyzer stack. The FEC controlling the operation of the electrolyzer in response to utility demand was experimentally verified and the optimal location and sizing of the electrolyzer was analyzed. Several other grid scenarios related to grid dynamics and transients were also simulated in real-time to assess the coordinated operation of FEC and electrolyzers. For these cases, the FEC and electrolyzer were observed to demonstrate voltage and frequency support to the grid. Being capable of participating in demand response programs is key for electrolyzers providing support to the macro-level transmission grid. This functionality was rigorously tested under several utility conditions across the United States. Eleven different utility-based demand response profiles utilizing diverse tariffs, with both baseloads and flexible operation, were tested based on varying conditions. The key takeaway is that the optimal location and sizing of the electrolyzer can greatly affect the performance of the electrolyzer in providing local support.

## RESULTS

Distributed real-time simulations and power HIL were performed, utilizing the 250 kW electrolyzer stack and a hardware implementation of the FEC. The functionalities of the electrolyzer stack responding to control signals from the FEC was verified for applications including grid services within required time resolutions. Representation of the PG&E network in real-time environment was created to understand and assess the performance of the integrated FEC and electrolyzer stack, as shown in Figure 1. Figure 2 shows the functional role of a FEC in a typical grid management related infrastructure. The FEC has two major functional modules represented by two control loops – slow and fast loops. The slow loop is associated with primarily the cost optimization of hydrogen, whereas the fast loop deals with the provision of grid services by the stack. Both these loops and their respective functionalities were verified through 500 hours of testing. Figures 3 and 4 show the performance of the electrolyzers integrated with the FEC that were tested in real-time simulations to confirm voltage and frequency regulations.

The distributed real-time simulations between INL and NREL initially involved controlling the electrolyzer hardware stack using the FEC implemented on the PI-card (a processor card), in order to verify the communication between them. The data transmission for controlling the stack power

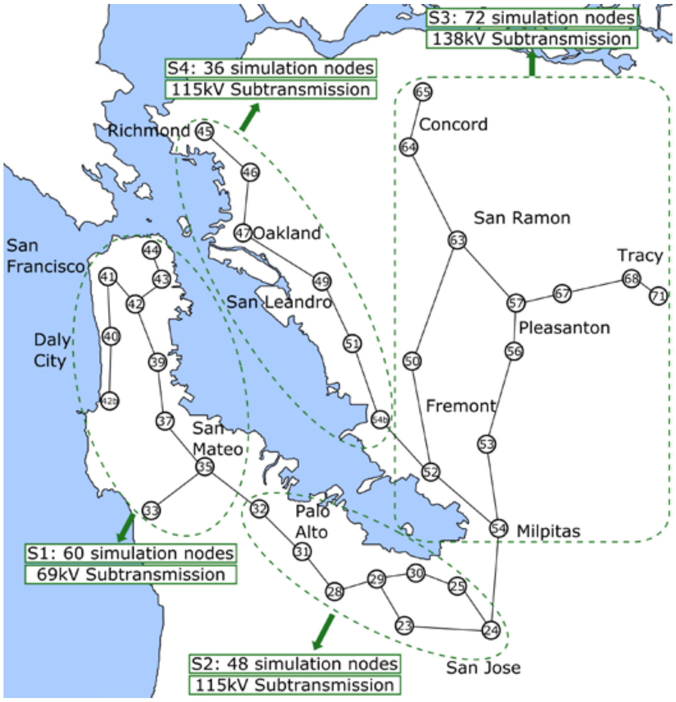


**FIGURE 1.** Real-time model of the PG&E electric grid to study response of hydrogen refueling stations

consumption was 100 Hz. The next phase of testing involved integrating the controller-HIL of the FEC on the PI-card, PG&E sub-transmission real-time model, grid simulator, and the electrolyzer stack. This integrated platform was utilized to test the controllability of electrolyzer stacks based on the functionalities defined in the FEC under dynamic grid conditions. The electrolyzer stack controlled via the FEC on the PI-card demonstrated voltage and frequency support to the PG&E grid based on varying grid conditions.

Test results demonstrated capability of the electrolyzer to provide local grid services and the ability of the FEC as hardware to control the electrolyzer. Economic optimization of the FEC has also been developed and implemented. This allows the FEC to make optimal decisions under different market rates and structures to generate hydrogen at a low cost. The optimization developed for the electrolyzer and implemented in the FEC hardware serves the purpose of striking a balance between providing support to grid operations and increasing the profit of the hydrogen producer.

## CONCLUSIONS AND UPCOMING ACTIVITIES

Capabilities of an electrolyzer as a controllable load and in providing grid services was realized to be significant and was experimentally verified in a real-time environment. The controllability of the electrolyzer was enabled by a vendor-neutral approach termed as the FEC. The FEC ensures an optimal response of the electrolyzer to provide essential grid support in the form of voltage and frequency support. The FEC is a generic controls topology that can be integrated with existing controllers of electrolyzers that are available in the market. The objective of the development of the FECs is demonstration of the immense flexibility that electrolyzers can add to supporting power grid operations and lowerig hydrogen costs. Integrated FEC configurations were tested in both centralized, large electrolyzer plants and smaller distributed ones. Both configurations were observed to perform and provide essential flexibility to the grid under dynamic grid conditions. Additionally, the FEC can drive the hydrogen production cost lower by considering different utility rate structures, participating in DR programs, and interfacing with market signals. A utility-scale network (PG&E distribution network) was modeled in real-time to accommodate the future refueling stations as planned in the San Francisco Bay Area served by PG&E and also assessing the performance of electrolyzers with and without the FEC integration. A cumulative 500-hour test of distributed HIL was performed in FY 2017 and was a significant accomplishment as it was a one of a kind real-

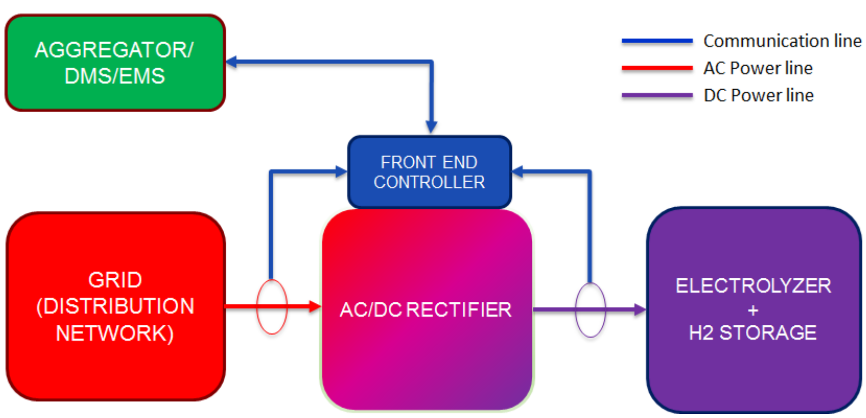


**FIGURE 2.** FEC interfaces hydrogen refueling stations with the grid management systems for providing grid services

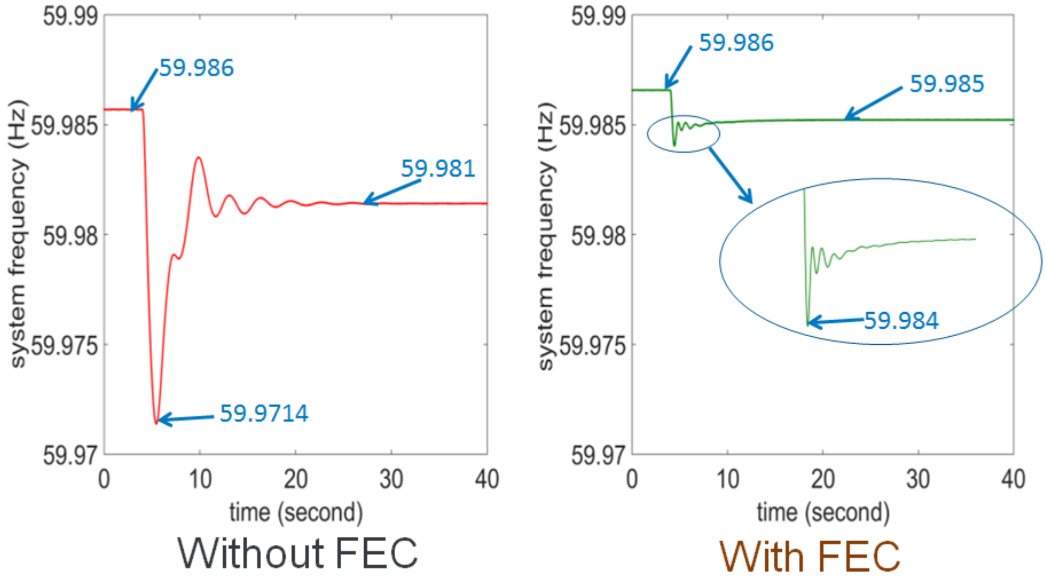


**FIGURE 3.** Frequency response by the integrated FEC and electrolyzers for a grid disturbance

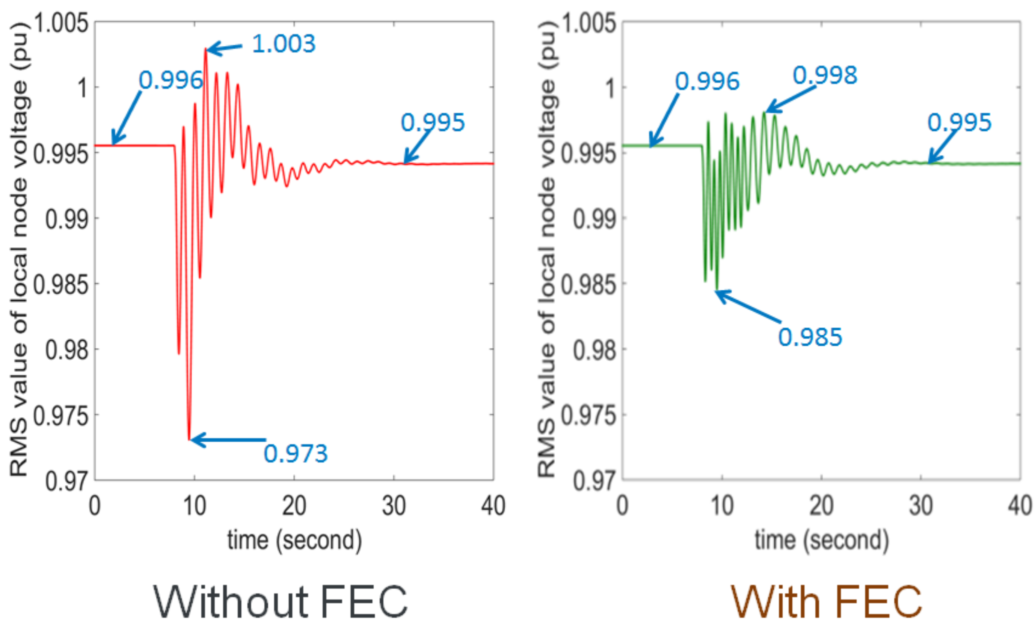


**FIGURE 4.** Voltage response by the integrated FEC and electrolyzers for a grid disturbance

time simulation that yielded accurate results and leveraged laboratory assets. Hardware-based testing in real-time was used to infer and augment the understanding of the role electrolyzers can play in markets for additional revenue. The FEC is now implemented on a hardware controller card and its functionality testing with the electrolyzer stack (250 kW) has also been completed. Performance metrics and acceptable ranges for the FEC with the electrolyzer were established. The final deliverable of the project at the end of FY 2017 is the deployment of this FEC hardware at NREL as an integral part of the existing 250 kW electrolyzer stack.