PHEV Distribution Grid Integration and Smart Systems Testing

Cooperative Research and Development Final Report

CRADA Number: CRD-13-00510

NREL Technical Contact: Tony Markel

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5R00-88679
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NOTICE

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Cooperative Research and Development Final Report

Report Date: January 23, 2024

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Toyota Motor Engineering & Manufacturing North America, Inc.

CRADA Number: CRD-13-00510

CRADA Title: PHEV Distribution Grid Integration and Smart Systems Testing

Responsible Technical Contact at Alliance/National Renewable Energy Laboratory (NREL):

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Sponsoring DOE Program Office(s): Office of Energy Efficiency and Renewable Energy (EERE), Vehicle Technologies Office (VTO)

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1 Modification #1, #2	$0.00
Year 2 Modification #3, #4, #5	$0.00
Year 3 Modification #6, #7	$0.00
Year 4 Modification #8	$11,000.00
Year 5 Modification #9	$0.00
Year 6 Modification #10	$11,000.00
TOTALS	$22,000.00

Executive Summary of CRADA Work:

To continue NREL's mission, which includes preparing technologies and markets with "speed and scale," NREL researchers will collaborate with Toyota on plug-in electric vehicle technology. Toyota will provide a collection of plug-in hybrid electric vehicles ("PHEVs [and ultimately including PEVs], collectively, the "Vehicles") to conduct infrastructure interaction testing at NREL facilities. NREL will use available resources in the Vehicle Testing and Integration Facility (VTIF), its staff parking garage with numerous commercial Electric Vehicle Supply Equipment ("EVSEs"), and its Energy Systems Integration Facility (ESIF) to safely execute research experiments that highlight potential distribution system power quality challenges related to plug-in electric vehicles. The expected outcome of this project is a better understanding of the correlation of individual vehicle power quality attributes to a system of vehicles on a distribution network. The data collected and the simulations conducted will be used to guide future experiments and project development that aid in the deployment of plug-in electric vehicles ("PEV").

CRADA benefit to DOE, Participant, and US Taxpayer:

DOE – research and development of plug-in electric vehicle and infrastructure integration supporting the introduction of petroleum saving vehicle technology at minimal cost.

Participant – insights into potential compounding effects of electric vehicles on grids and the extension of data and value extraction from investment in demonstration vehicles.

US Taxpayer – further development of electric vehicle and smart grid technologies for a minimal cost that will ultimately benefit the country and the environment.

Summary of Research Results:

The original 5 tasks of this CRADA were a joint work of U.S. Department of Energy and Toyota Motor Engineering & Manufacturing North America, Inc. under CRD-13-510 originally started on 3/1/2013. The final report for this project describes the full scope of the project and The National Renewable Energy Laboratory's role of providing expertise in grid integration of electric vehicles. NREL successfully performed this project and met the CRADA agreements. Below is a summary of NREL's achievement in this project for each of the original 5 CRADA tasks.

The objective Task 1 is to provide preliminary data on Toyota PEVs from a grid integration perspective. The research leads to a goal of highlighting and resolving any grid challenges and upgrades necessary to accommodate future vehicle adoption. The period of performance for Task 1 was from 3/1/2013 through 5/30/2013.

TASK 1.0.0: Preliminary PHV Testing

Summary of Research: NREL built a J1772 junction box to connect an oscilloscope for monitoring and performed preliminary Plug-in Hybrid Vehicle (PHV) testing with a grid simulator and a level 2 EVSE. Each vehicle was tested to characterize how it operates with the level 2 EVSE.

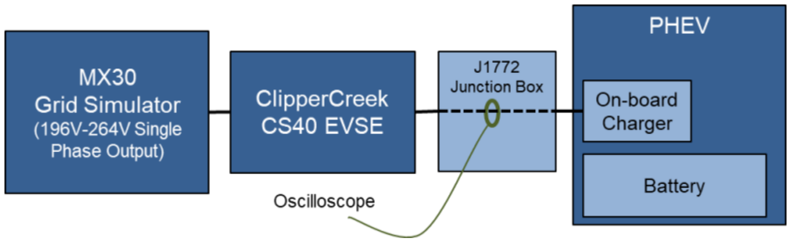


Figure 1: Prototype PHV test setup

Subtask 1.1.0: Vehicle Delivery

Subtask 1.1.1: Equipment Inspection and Acceptance

Vehicle delivery occurred as planned and NREL successfully completed the equipment inspection and acceptance. Over the project duration, vehicles including the prototype Toyota Prius plug-in hybrid electric vehicle and the prototype Toyota Scion iQ EV were provided by Toyota as loaned property for the purposes of conducting the planned testing activities.

TASK 1.2.0: PHEV PQ Testing

Subtask 1.2.1: Grid Sim Test 3-5 Vehicles.

Task Description: NREL will use a grid simulator at the DERFT/VTIF to measure harmonics of individual vehicles.

Summary of Research: NREL performed power quality testing with an MX30 grid simulator by determining basic Power Quality (PQ) limits of a vehicle charging operation. Frequency of the input voltage was swept from 59.5 Hz to 60.5 Hz to find Prius charger cutoff limits for each vehicle. Voltage and current harmonic waveforms were captured to calculate maximum total harmonic distortion (THD).

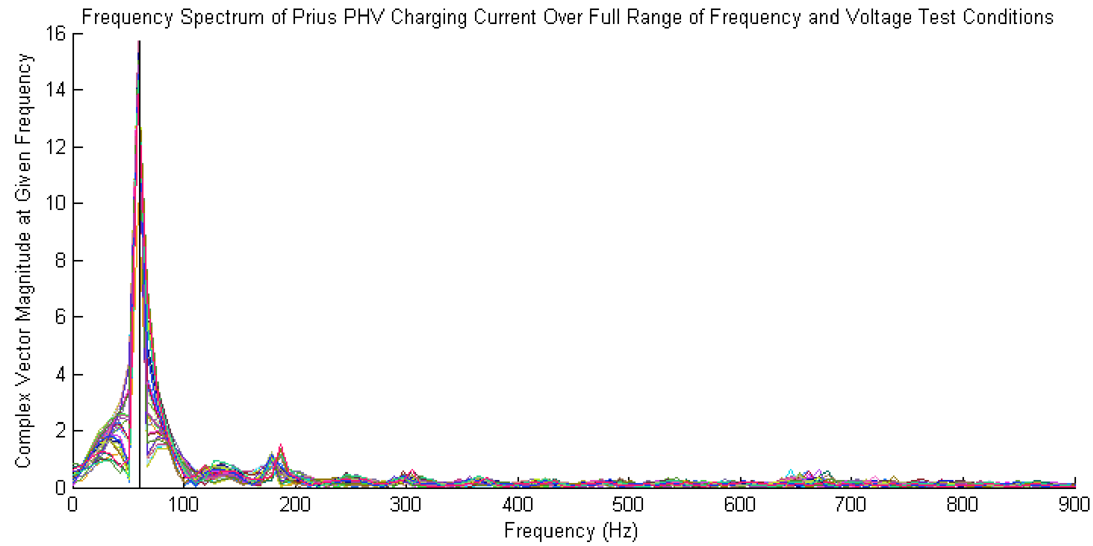


Figure 2: Frequency spectrum of Prius charging current over full range of frequency and voltage test conditions

Subtask 1.2.2: Test EVSE Charge Manage PQ

Task Description: Characteristics with and without EVSE control

Summary of Research: NREL performed tests and characterized the power quality by controlling state-of-charge (SOC) level of the PHEV. Tests showed that current harmonic distortion was high when PHEVs were at high SOC and consuming power at a low rate (below 1 kW) and the largest current THD values were observed at very high voltages (> 250 V), near 60.00 Hz, and at low power consumption. Both the current and voltage THD was lowest when a supply voltage is around 240 Vrms.

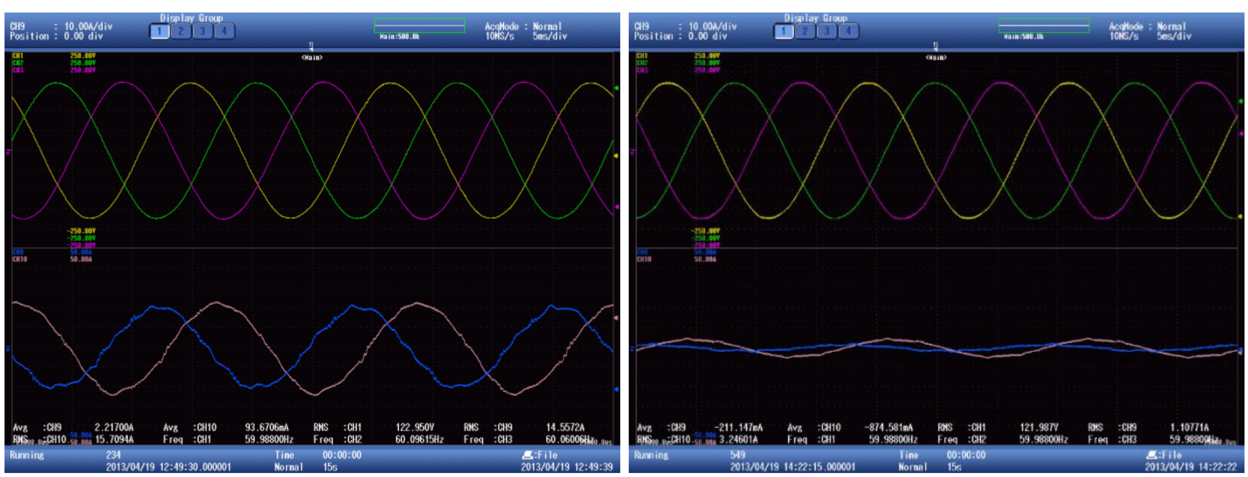


Figure 3: Oscilloscope capture when the PHEV fleet is charging at a mid-level SOC (THD Phase A=9.9%) [left] and at a high-level SOC and many of the PHEVs have entered voltage-sustaining mode (THD Phase A = 57.3%) [right]

TASK 1.3.0: Parking Garage Testing

Subtask 1.3.1: PQ Instrument in Garage

Task Description: Power quality instrumentation of parking garage infrastructure

Summary of Research: NREL set up power quality instrumentation at the NREL parking garage with 36 level 2 EVSEs. An oscilloscope was connected for instrumentation between the distribution panel and the 300 kVA transformer (480V/208V 3 phase).

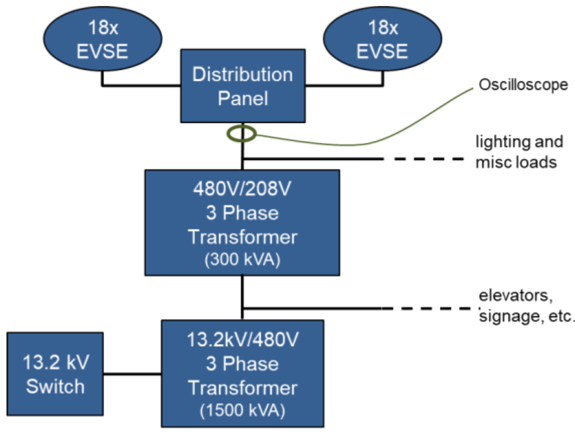


Figure 4: NREL parking garage test setup diagram

Subtask 1.3.2: Test Phase Combos of PHVs

Task Description: Testing combinations of vehicles on a distribution network

Summary of Research: NREL performed tests with combinations of PHVs on a distribution network. EVSEs on each phase were used for tests and total harmonic distortion on each phase were measured for power quality analysis. When operated at the designed full-power load, current harmonic distortion is around 9%. It is suspected that both constructive and destructive interference interactions result in a flat THD profile throughout the course of the test.

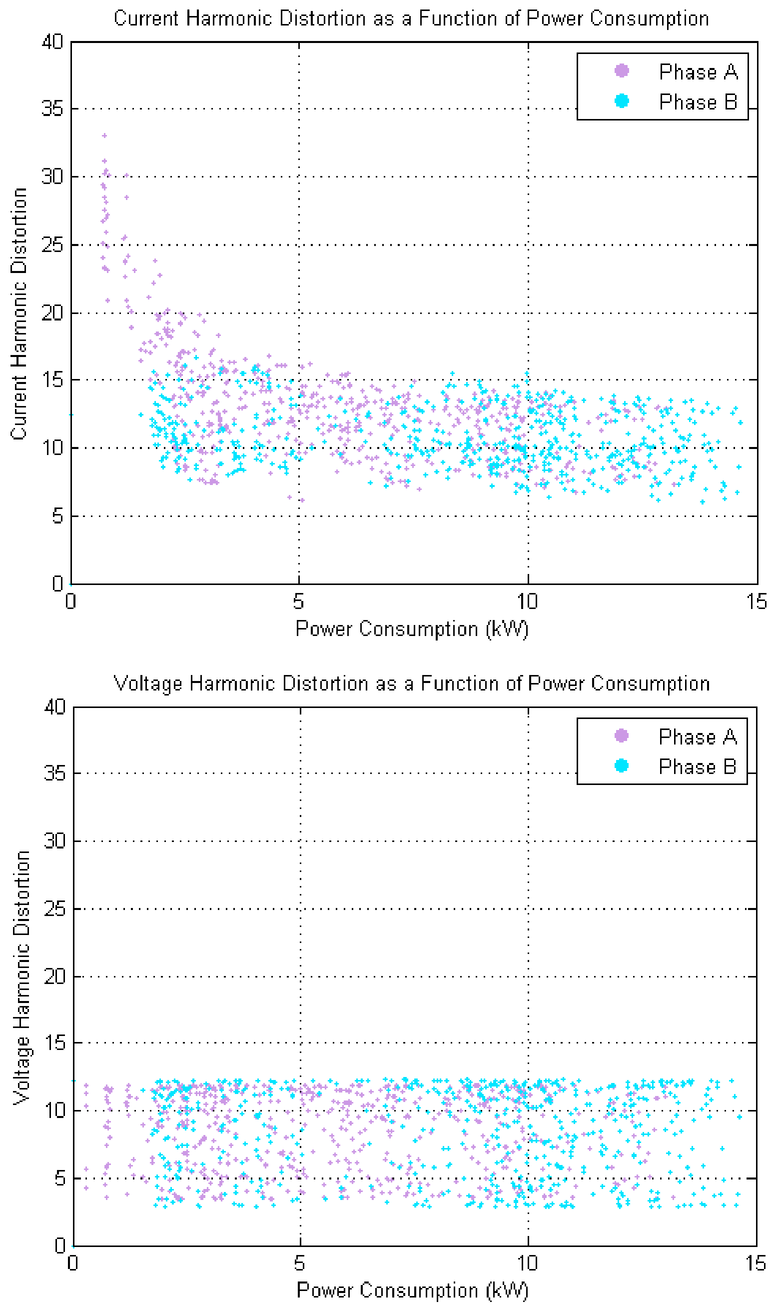


Figure 5: Scatter plot of THD as a function of power consumption for all 567 test points measured as part of the Parking Garage Test; Left represents current THD; Right represents voltage THD

TASK 1.4.0: Preliminary Test Report

Task Description: All preliminary data collected and test scenarios conducted will be summarized in a project task report to be delivered at the end of the period of performance. The report content is expected to draw conclusions from preliminary observations that will guide execution of future focused research collaboration to address identified challenges and opportunities.

Summary of Research: NREL submitted a report to Toyota with summary of the collected data from the test scenarios described in TASK 1.3.0. The report also included conclusions from preliminary observations that will guide execution of future focused research collaboration to address identified challenges and opportunities.

TASK 1.5.0: PHV Distribution System Modeling

Task Description: Integration of PHEV test data into Distribution Grid model

Summary of Research: Combining the lessons learned from the test data collected in TASK 1.3.0, procedures developed, and initial test results, NREL set up a testing environment in the Energy Systems Integration Facility (ESIF) with a grid simulator for the next phase of testing.

TASK 2.0.0: PEV Transformer integration Impacts Testing

The objective of Task 2 is to develop the capability to test and evaluate potential distribution grid impacts of high penetration of PEVs in a distribution network observed at a transformer. Modeling results to date suggest that the greatest impact of PEVs to the grid will occur at the transformer and to the loads connected to a heavily loaded transformer. The period of performance for Task 2 was through 3/28/2014.

Summary of Research: NREL identified six test scenarios of interest regarding the degradation and performance of residential transformers. Each scenario included a sub-set of measurements at different vehicle adoption levels as each vehicle was added to the total distribution circuit load. The test network included a 25kVA residential transformer delivering 240V power from a 13.2kV campus electrical distribution system.

TASK 2.1.0: Test System Design and Develop

Task Description: Design and create a testing system at NREL for evaluating PHV and associated load impact

Summary of Research: A test electrical network was developed at NREL's Medium Voltage Outside Test Area (MVOTA) in Energy System Integration Facility (ESIF) for evaluating PHV and associated load impact. The transformer under test was instrumented with 6 temperature probes and was continuously monitored by power quality meters. The low voltage (secondary) side of the transformer fed a variety of level 2 EVSEs as well as a LOADTEC 250kW load bank connected through a common bus.

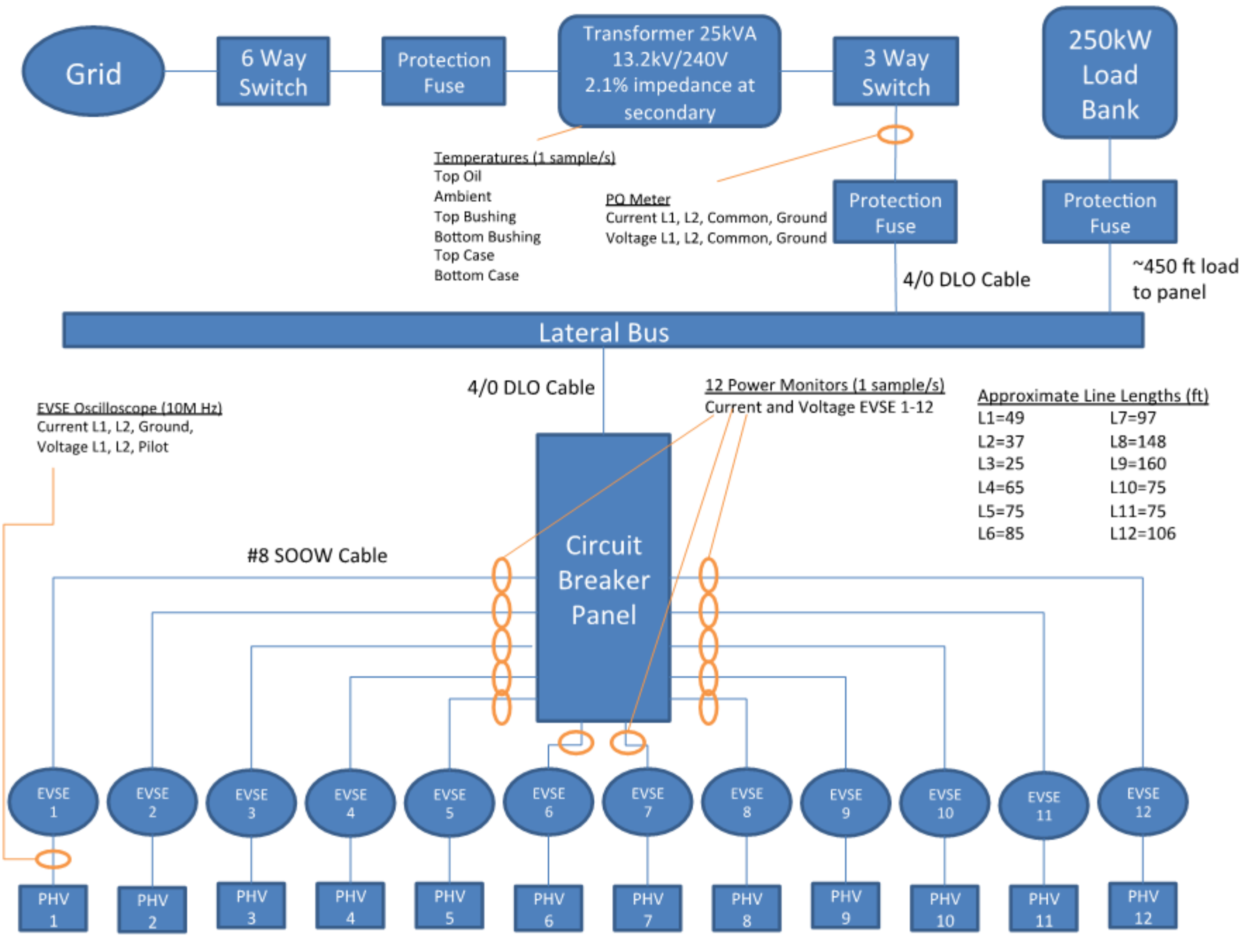


Figure 6: Configuration of PHV power quality network impacts test system

TASK 2.2.0: Test PHV Distribution System Impact

Task Description: Conduct tests with distribution network under which several levels of PHV penetration indicate impact on grid

Summary of Research: NREL performed tests with a distributed network with several levels of PHV penetration. Tests showed that the total harmonic distortion of voltage (including the first 100 orders) increased, relative to the number of the PHVs charging from the same transformer. A similar trend was found in the current distortion.

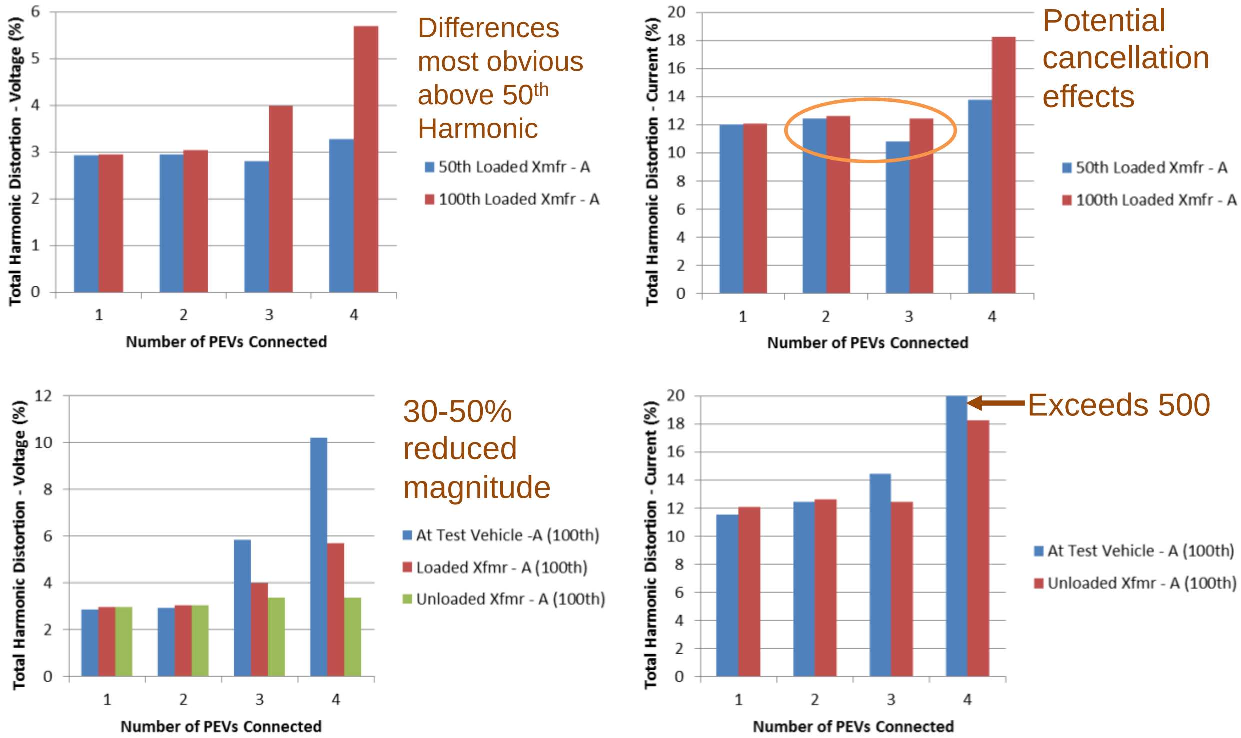


Figure 7: Total harmonic distortion measured at 3 metering locations with respect to the number of PEVs connected

The objective of Task 3 is to generate information on the potential impacts on an electrical distribution network of high PEV market penetration through the development of a unique test system with multiple transformers and PHEVs through the execution of key tests using real vehicles. Modeling results to date suggest that the greatest impact of PEVs to the grid will occur at the low voltage transformer and to the loads connected to a heavily loaded transformer. The period of performance for Task 3 was through 2/28/2015.

TASK 3.0.0: Expanded Network PEV Integration Testing

Summary of Research: NREL set up a test system composed of three laboratories including Medium Voltage Outside Test Area (MVOTA), Energy Storage Laboratory (ESL), and Smart Power Laboratory (SPL). The Research Electrical Distribution Bus (REDB) connects devices in the three labs together as a grid simulator. NREL expanded network PEV integration testing with this combination of three laboratories and performed tests in application of advanced device controls and functionality of residential loads, electrified vehicles, PV, and the grid system at full power.

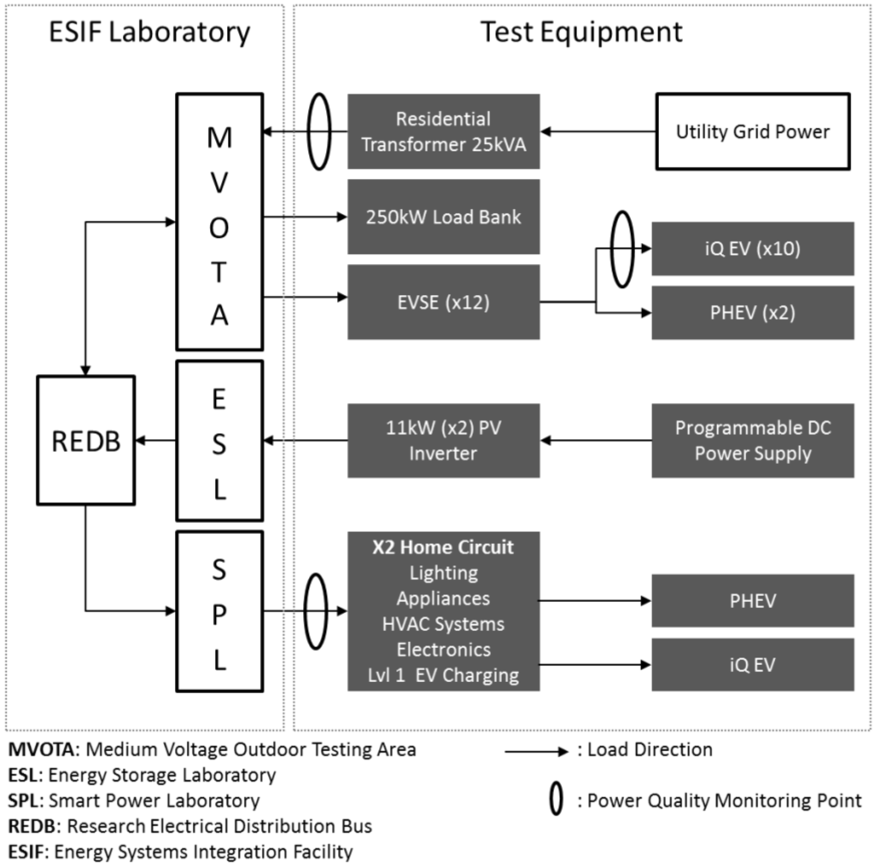
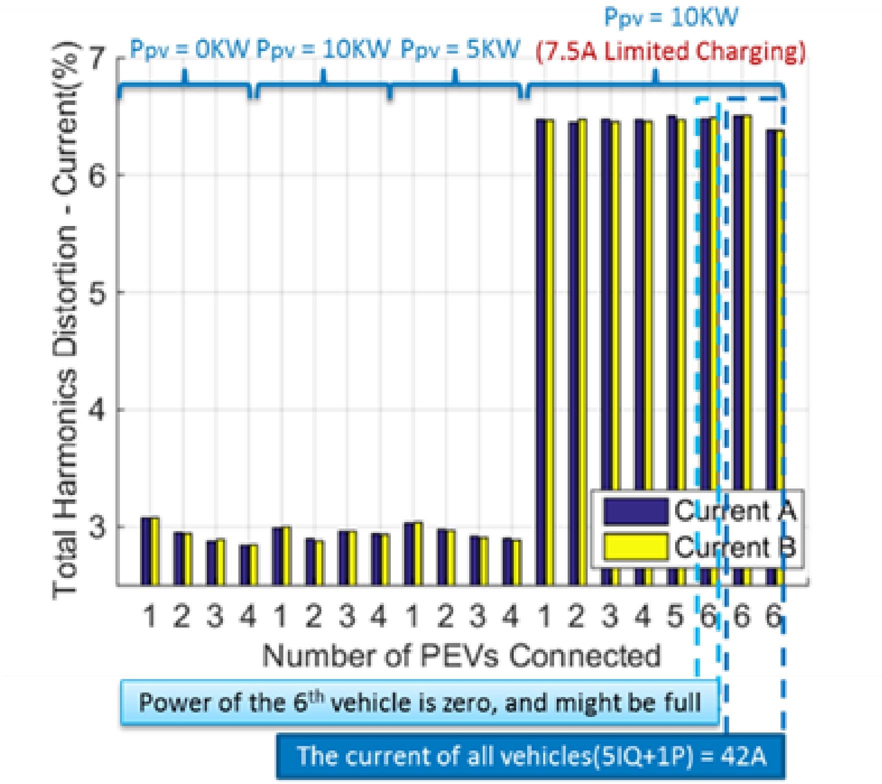


Figure 8: The diagram of the expanded network PEV integration test system

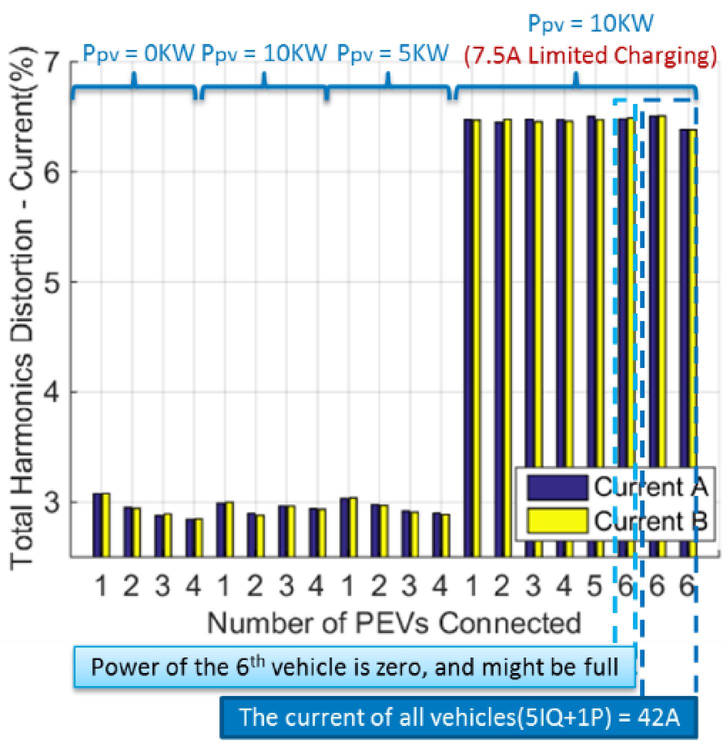
TASK 3.1.0: Simulated Multi-transformer Network Testing

Task Description: Use configuration with multiple transformers, grid simulation, solar generation, and many vehicles to test power quality characteristics

Summary of Research: NREL performed testing of power quality characteristics with the configuration of multiple transformers, a grid simulator, and a PV emulator. Tests showed that vehicle charging and PV integration increases voltage THDs around 0.1% and the net system power has a significant impact on the current THD. The current THD increases with reduced net system load and reaches to peak when the net grid power is approaching to zero.



(a) The THDs of current



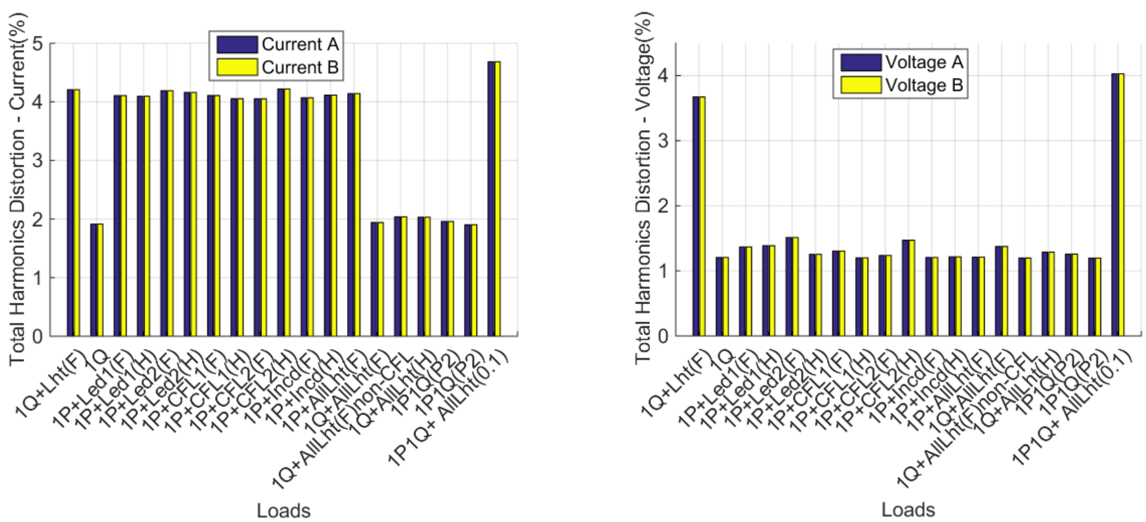
(b) The THDS of voltage

Figure 9: The total harmonics distortion under various PV power and EVSE limits

TASK 3.2.0: Integrated Testing of Vehicles with Smart Homes

Task Description: Leverage Smart Power Lab with many PEVs to test power quality impacts on home devices

Summary of Research: NREL performed integrated testing of vehicles with smart homes. The smart home loads include a water heater, dryers, dishwashers, TV, an LED light bulb array, CFL light bulb array, and incandescent light bulb array. Tests showed that the loads of LED, CFL, and incandescent light bulb arrays cause a high current THD, especially at the dimmed mode. Any high-power home loads such as water heaters, dishwashers, and dryers increase the net grid load and dropped the current harmonics to a low value. The TV load was light and had little impact on the current THD.



(a) The current THD under various home loads (b) The voltage THD under various home loads

Figure 10: The total harmonics distortion under various home loads with PEVs

TASK 3.3.0, 3.3.1, 3.3.2: Reporting

See Task 5 Reporting.

The activities detailed in Task 4 are intended to enhance joint knowledge on potential power quality challenges in future scenarios with many vehicles responding to grid demands in concert with each other. The objective is to find ways that value is generated without adverse distribution system power quality impacts. The period of performance for Task 4 was through 2/28/2016.

TASK 4.0.0: Expanded Managed Charging Power Quality Research

Summary of Research: NREL combined MVOTA and ESL as a system to optimize the active power for voltage control. Six AeroVironment EVSEs in MVOTA and three Leviton EVSEs in ESL provide full rate and on/off control capability to adjust the charge currents of 9 prototype iQ EVs provided by Toyota.

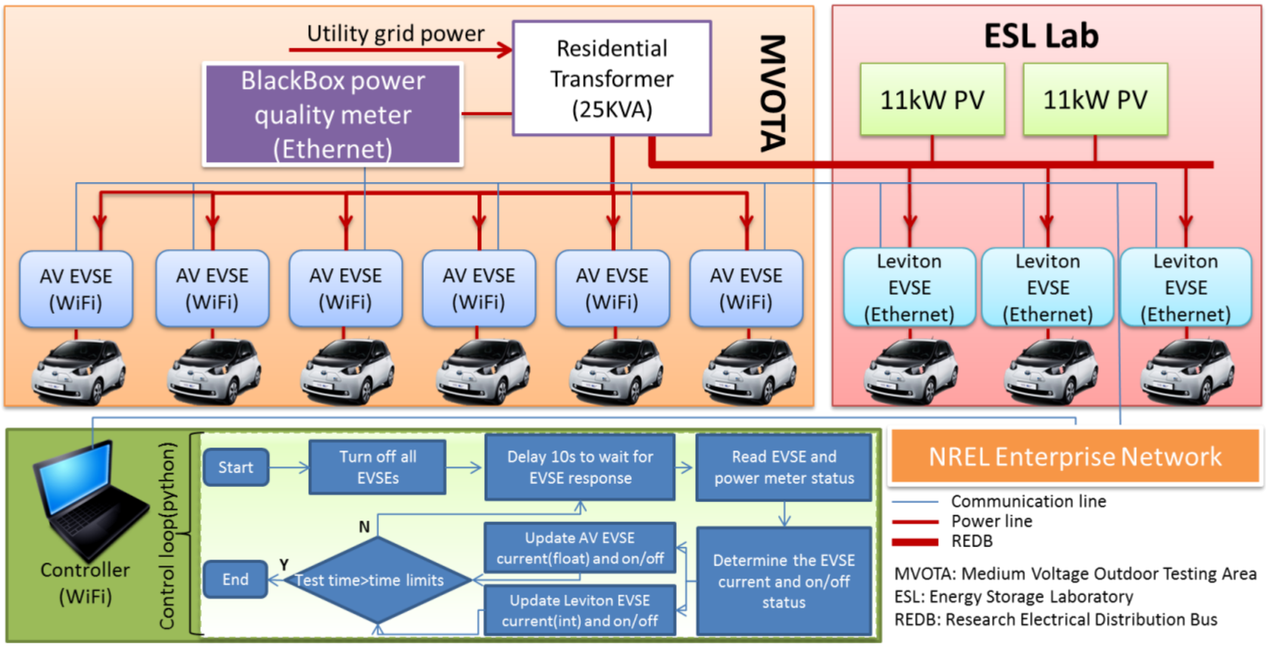


Figure 11: The system architecture for expanded managed charging power quality research

TASK 4.1.0: Plan Equipment Implementation and Scenario

Task Description: Utilize vehicles and design a test strategy using available controllable EVSEs

Summary of Research: Rate based, and an on/off control methods algorithm were developed to provide the required charging power to PEV's. For testing, the 9 prototype iQ EVs provided by Toyota were utilized. The BLACKBOX power quality meter was used to measure the power quality of the transformer output. The voltage control algorithm controlled EVSEs with TCP protocols according to queried power quality information from BLACKBOX power meter by the https requests.

TASK 4.2.0: Charge Management Test Execution

Task Description: Utilize vehicles and controllable EVSEs to evaluate grid power quality results

Summary of Research: NREL executed charge management tests by utilizing vehicles and controllable EVSEs to evaluate grid power quality. Tests showed that both rate-based control method and on/off control method can effectively stabilize the output voltage of the transformer. The rate-based control method was also shown to provide a higher resolution for power control than the on/off control method. To fully utilize the PV generation, a Kalman filter-based method was applied to match the EV charging power with PV power. The matched PV and EV power results in high THDs of current and voltage. THD does not reflect the real impact of the harmonic content of the charger on the grid.

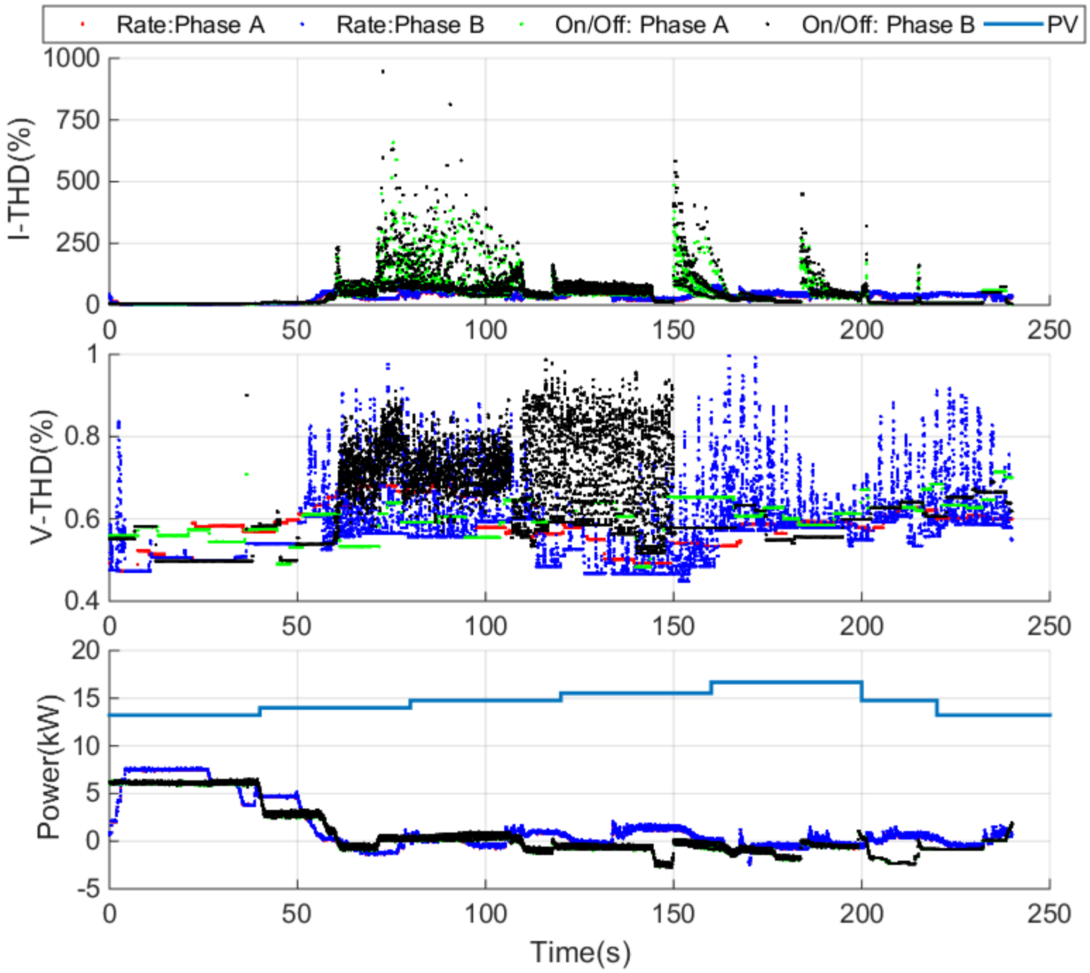


Figure 12: Current and voltage THDs at zero transformer output power

The objective of Task 5 was to address the considerable uncertainty regarding the degree to which PEVs can provide grid services and mutually benefit the electric utilities, PEV owners, and auto manufacturers. This project will investigate the potential benefits of PEV grid services by leveraging capabilities of multiple national laboratories with vehicle/grid integration (VGI) to perform hardware-in-the-loop (HIL) studies that integrate communication and control system hardware with simulation and analysis activities. The period of performance for Task 4 was through 2/28/2019.

TASK 5.0.0: Toyota PEVs Application to Grid Modernization Research Plan

Summary of Research: NREL utilized the Toyota Scion iQ PEV's for DOE Grid Modernization-Systems Research Supporting Standards project. The iQ vehicles were used as a controlled load in the experiments. The EVSEs in the system were used to control the load of each PEV using either a Phoenix Contact Modbus enabled controller or a Raspberry Pi that has been interfaced with an AeroVironment EVSE-RS.

Figure 13: Prototype Toyota Scion iQ PEVs charging from the grid emulator

TASK 5.1.0: PEV Grid Scenario Testing

Subtask 5.1.1: PEV Grid Scenario Testing II

Task Description: Real-time optimization and control of next generation distribution infrastructure

Summary of Research: NREL performed tests for DOE Grid Modernization project in collaboration with INL, ANL, and PNNL and utilized Toyota iQ PEV's in the tests. The NREL aggregator controls the total building load by controlling the EVSE load integrated with the uncontrollable building load. It adjusts EVSE load for total building load not to exceed the value of energy setpoint sent from the INL aggregator.

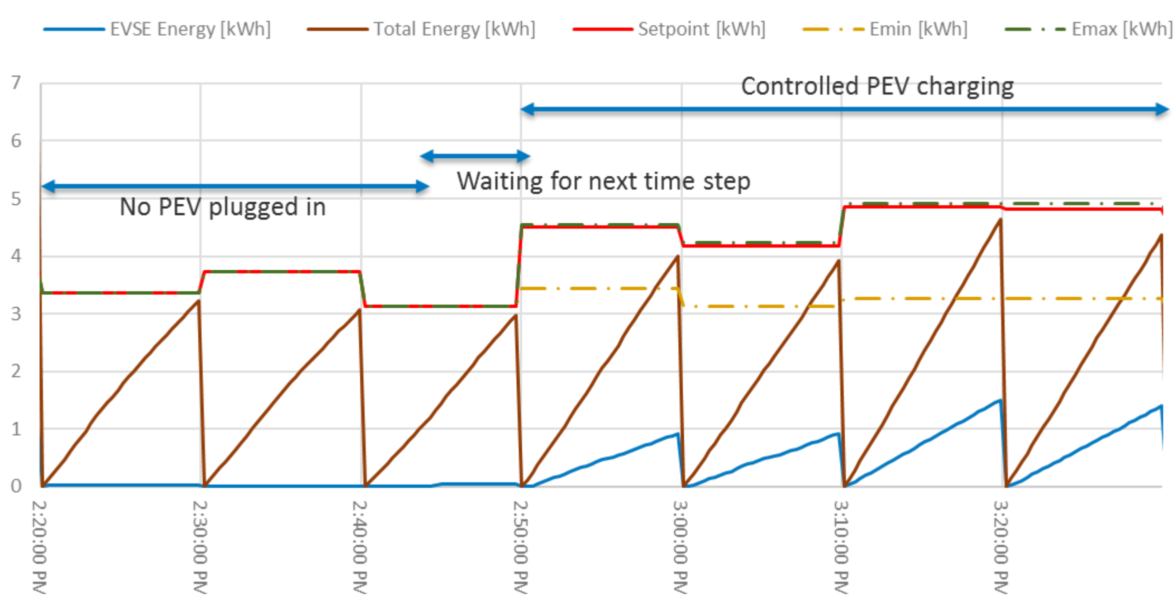


Figure 14. Test results of building control with Scion iQ's

NREL also utilized the Toyota Scion iQ PEVs as a controlled charging load in the Network Optimized Distributed Energy Systems (NODES) project. The Toyota Scion iQ PEVs were controlled through the controllable EVSEs and incorporated with the other distributed energy resource (DERs) under control by the NODES system.

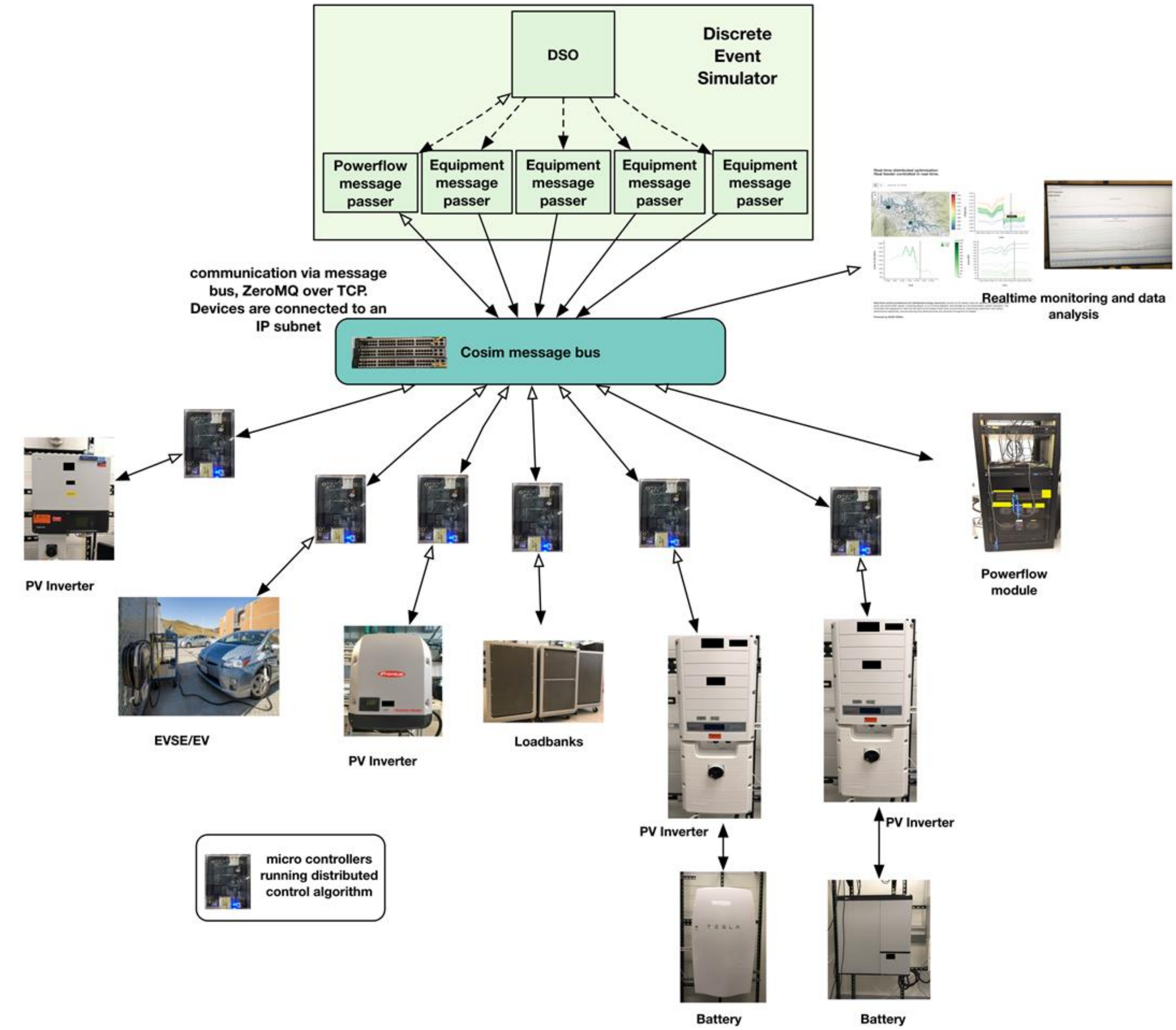


Figure 15: Overview of PHIL platform with Toyota Scion iQ PEVs

TASK 5.2.0, 5.2.1, 5.2.2, 5.2.3: PEV Grid Modernization Activity Report

Task description: Periodically provide updates on vehicle status and develop a final report summarizing vehicle applications to Grid Modernization research.

Summary of Research: NREL provided updates on vehicle status and submitted final reports summarizing vehicle usages January 2017, January 2018, and January 2019.

Subject Inventions Listing:

None

ROI #:

None