Final Report: Open V2X at ESIF

June 2015 – February 2017

Willet Kempton
University of Delaware

Prepared under Subcontract No. NCS-5-42326-05

NREL Technical Monitor: Andrew Hudgins

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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Contractor: University of Delaware
PI: Willett Kempton
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Table of Contents

Acronyms

A/S – Ancillary Services, short duration markets organized by grid operators
CalISO – California ISO, the grid operator for California
CHAdeMO – Charging connector standard used for DC charging
DSO – Distribution System Operator, colloquially called "utilities"
EMS – Energy Management System, used at building level
ENTSO-E – Association of European grid operators to agree on rules
EV – Electric Vehicle
EVSE – Electric Vehicle supply Equipment, colloquially the "charging station"
NORDPOOL – Collection of grid operators for the Nordic countries
PJM – the US grid operator for a 13 state territory in the middle atalntic
PLC-CP – Power Line carrier communicated over control pilot
RTO – regional transmission operator, the FERC term for grid operators in the US
SOC – State of charge of a battery, expressed either in % or in kWh
TSO – Transmission System Operator, the word used worldwide outside the US
V2G – Vehicle to Grid power, the flow of power from an EV to the electric grid
V2X – Like V2G but power flowing to any of: the grid, a local building, or a local load
VSL –Vehicle Smart Link, the embedded controller developed by UD and licensed to several equipment manufacturers

Introduction

Contractor University of Delaware (UD), and their industrial partners, have carried out testing, documentation, and standards development at ESIF. These activities are intended to help meet the objective of NREL's INTEGRATE program, to enable clean energy technologies to increase the hosting capacity of the grid, by providing grid services in a holistic manner using an open source, interoperable platform.

In particular, the "Open V2X at ESIF" project worked to facilitate standardization and interoperability for Electric Vehicle technologies, including battery electric vehicles and plug-in hybrid vehicles (hence EV) to provide grid services. This was done by interconnecting and testing EV and EVSE (charging station) hardware from different manufacturers, by developing standards and test protocols for standards, and by documenting new protocols to be proposed as standards. Contractor-supplied equipment used in the testing included Vehicle Smart Links (VSLs) installed in an EV and School Bus, single-phase and three-phase charging stations, and an optimizing aggregator (software running on a server, hence just "Aggregator"). The Aggregator software was developed by U of Delaware and is now licensed to Nuvve Corp for commercial development, and licensed to NRG/EVgo for demonstrations. The Aggregator monitors capacity and operations of the EVs and EVSEs, dispatches them in response to requests, and reports their operations and metered power flow. In operation, as vehicles move, plug-in and unplug, the aggregator tracks the total capacity available within a defined jurisdiction or RTO (Regional Transmission Organization, synonym for ISO or TSO), and dispatches part or all of that capacity based on market or direct dispatch signals from a grid entity. The VSL is the data acquisition and control module in the resource itself (EVSE or EV), with rich communication between a single Optimizing Aggregator and many VSL (one in each resource). All requests and dispatch events are also logged by the aggregator to make the provision of grid power auditable.

For these tests, the dispatch was typically a recorded signal, the VSL was in the EV or EVSE, and the recording of experimental performance was often carried out by the normal logging functions of the aggregator.

Activities by Contractor at ESIF are summarized in each major section below, each section here representing a summary of a longer report, some with data files. Where appropriate, each major section also has subsections on both "Industry relevance" and "Application and Significance".

Basic Device Characteristics using PJM Performance Scoring (Test 1)

In this test, the PJM performance scoring in order to provide grid services is calculated. Algorithms were developed for testing a combined EVSE and EV as a grid resource, and measuring the PJM Performance score. The test setup was to use the ESIF programmable AC grid simulator to emulate the electric utility grid. The battery charge and discharge are controlled by the aggregator (defined in "Introduction" above) through the VSL in the vehicle and charging station. During the test, the response and requested power are recorded.

The PJM Performance Score is a multipart measurement of the quality of fast-responding resources, such as ancillary services (A/S) resources. The score is made up of three measures—delay, precision, and correlation. Precision includes response times, ramp rates, and minimum and maximum up times. The three are combined to make a single performance score. The performance score is a good general measure of quality of fast response grid resources.

Industry Relevance

As the name "PJM Performance Score" suggests, this is the operational evaluation metric for resource performance used by one of the larger RTOs in the world, PJM Interconnection. Moreover, it is recognized by several other TSOs as a more comprehensive metric for fast response services than is generally available. And more generally, for companies working across RTOs and TSOs, Contractor's use of the

PJM Performance Score is because there is not yet a standardized test available across TSOs, and PJM's is more comprehensive than most.

Application and Significance

Contractor UD, in conjunction with global A/S provider Nuvve, has developed an algorithm to duplicate the PJM performance score, and used it for this test activity to characterize Nissan vehicles with Enel/Endesa CHAdeMO charging stations. As a result of this algorithm's availability, and discusions of evaluation of A/S among Contractor, Nuvve and Danish Technical University, DTU have developed a set of measures of fast-response resources that would be broader and more general than the PJM performance score. Although the DTU set of qualifying measures is not yet quantified like the PJM Performance score, in our judgment it represents a beginning toward a more general, RTO- and TSO-wide, set of standardized tests for fast-response grid resources (Knezović, Marinell et al, 2016).

Standards Based Testing (Test 2)

Testing was carried out with respect to standards IEC61851-1 Ed. 3 Annex D, SAE J3068 (Draft) (SAE 2016), and SAE J3072. Two system types were tested, one (the MiniE and EVSE) using J1772 (PLC-CP) and the other (Transpower bus and EVSE) using CAN/LIN-CP. Background work by contractor included developing the SAE J3068 draft standard itself, for the Society for Automotive Engineers, and work with designers and manufacturers to implement these standards in a single-phase charging station, a three-phase charging station, one light vehicle (MiniE), and a heavy vehicle (Transpower bus).

Industry Relevance

Testing was carried out using digital signaling standards harmonized across single-phase and three-phase connectors, with EVSE and EV from different manufacturers, and testing found that the standard information was successfully transferred. Also, testing was carried out based on the new J3068 (draft) standard for three-phase charging, with NREL's ESIF being the first such testing ever of this standard, the first three-phase standard for North American voltages. Two aspects of J3072 testing were carried out, the signaling of new fields for inverter model and certification (seen in Objective 2 of the Test 2 report). These new fields have not previously existed in any standards and essential for electrical interconnection of on-vehicle bidirectional inverters, and IEEE1547 testing, carried out with EPC and reported as part of test 7.

Application and Significance

This standards testing is of considerable practical significance for three reasons.

First, the current EV charging standard for North America, J1772, only provides for single-phase, nominal 120 or 240 volts and a maximum of 80 Amperes, thus limiting standard charging power to 19.2 kW. The SAE J3068 (draft) standard, harmonized with several IEC standards, provides for three-phase North American voltages up to 480 VAC in the US, and up to 160 Amperes, allowing efficient power transfer to the vehicle up to 133 kW. If adopted by some US states, this would allow high-speed charging at much lower-cost --in our experience, AC charging equipment is about 1/15 the equipment cost of DC charging at the 50 kW level; maintenance of AC chargers appears to also be several times less costly. Thus a high-power AC standard is important to reduce cost of the coming large deployment of public EV charging.

Second, the testing of the IEC61851-1 Ed. 3 Annex D signaling, incorporated with both SAE J1772 and SAE J3068 couplers, and incorporating the SAE J3072 inverter model number and certification, will allow a harmonized digital signaling across connectors, without changing the standard connector pinouts available today.

Third, standard SAE J3072, using Annex D signaling or SEP2 signaling, will provide distribution utilities with assurance that EV "generation" equipment interconnected to the low-voltage side of their grids will provide the safety and power quality they require. This is essential for widespread deployment of EVs to be used for backfeeding power ("Vehicle-to-Grid", or V2G)—surprisingly, despite the widespread discussion (and hype) about V2G (670 peer-reviewed citations to date of Kempton & Tomić 2005), we see no one else addressing the lack of automotive standards for interconnection other than Contractors (UD and eV2g), including Contractors work as part of this ESIF project. Without automotive standards for utility interconnection, we cannot expect widespread V2G based on on-board inverters, which are far more cost-effective than off-board.

Autonomous, local-measurement response to grid conditions (Test 3)

In this test, the ability of the electric vehicle to respond at a requested signal is evaluated. This test uses the direct local-measurement of frequency and creates the electric vehicle's response. A regulation function in the aggregator follows response rules of Energinet.dk for "Primary Reserves", including upward regulation + [MW] and downward regulation - [MW]. The electric vehicle follows the signal for three hours, while the power requested, the response, the frequency, and the stored energy are recorded. Note that a prequalification test is also conducted. The testing was run successfully, demonstrating an EV operating as a grid services resource based on local measurements.

Industry Relevance

Electric system controls may be operated by RTOs, DSOs, and EMSs (individual building Energy Management Systems with intelligent load management). For both

RTOs and DSOs, management of grid resources may be done by centralized control and local control may be done by all three. Local frequency control can be used in RTOs that solicit paid services based on frequency, including, for example, ERCOT in the US and most European countries within both ENTSO-E and NORDPOOL. Using a voltage rather than frequency sensor but the same control regimes, a new service of active voltage control could be created to serve DSOs, although these markets do not yet exist. The TSO services mentioned exist today, making this test immediately applicable to participating in those markets. A future DSO service for active voltage control is currently being discussed as a way to balance distributed resources such as building solar, specifically, to manage voltage fluctuations on distribution feeders.

Application and Significance

Local frequency control was commercially implemented by Nuvve for application in Europe, in parallel with the setup and testing by Contractor UD at ESIF (the same software team, led by Kempton and Vandael did both). This is now in production use in Denmark and the Netherlands, providing Disturbance Reserves for Energinet.dk in Denmark DK-2 zone, and providing Primary Reserves for TenneT in the Netherlands. Thus the testing and development work done under this effort, along with independent work by contractor, is already facilitating commercial deployment

Integrate with solar production (Test 4)

In this test, the viability of combining electric vehicles and solar panels is evaluated through two experiments. In the first experiment, the power transfer of an electric vehicle is controlled to match the power generated by a solar panel, thus leading to a leveling of power output from the device. In the second experiment, the power transfer to an electric vehicle is controlled to reduce the slope in the duck curve, thus targeting the grid-wide generation profile of solar, and preparing for excess generation mid-day and fast ramp in the late afternoon. Both experiments show that, depending on the availability and required SOC, both charging and discharging can be beneficial in supporting the integration of solar generation in the electricity grid.

Industry Relevance

In many jurisdictions, notably including California, solar penetration by 2022 will be sufficient to create problems for management by CalISO, the RTO for California. The CalISO projects generation from distributed solar substantially in excess of load, leading to a dip down around solar noon, and a rapid increase in load not met by solar late afternoon and early evening. The forward projections of the daily load curve resembles a duck in profile, leading the CalISO to name it the “duck curve.” Similar RTO and TSO-wide problems are projected in the near term, for example, in Germany.

The first part of this test demonstrates mitigating solar fluctuations by only local management, essentially making the solar production a more level generation resource within the constraints of the EV battery size and software limits on range of SOC allowed. The second part of this test demonstrates mitigation by targeting the projected duck curve from CalISO, rather than responding only to measurement of local production, thus preparing equipment and control algorithms for use in jurisdictions expected to have problems with the duck curve, even if that curve is not detected locally to one device (e.g. due to local clouds).

Application and Significance

This test generally increases the understanding of these two modes for leveling solar output. As a result of this testing, UD and other participating researchers have an improved understanding of the issues for these two modes of solar balancing. This has in turn improved advising of industry partners regarding the use of EV storage in this way. No specific devices or services have yet resulted from this testing.

Energy efficiency of GIV system (Test 5)

In this test, the electrical losses in the electric vehicle battery and power electronics are measured. This test includes two different experiments: a) Round-trip energy losses (in kW) at set power flow rates, and b) energy mismatch over time (in kWh) while performing grid services. In the first case, two parameters are taken into account: the electric vehicle state of charge (SOC) and the charging or discharging current (Amps). Sixteen different combinations of SOCs and Amps were tested. In the second experiment, the kWh mismatch is calculated for four different SOCs. The results of this test identify the magnitude of losses in both charging and discharging, which are significant. They also provide insight for selecting the optimal parameters of charging level in order to improve efficiency of charging for V2G operation.

Industry Relevance

Given the amount of energy that will be used to fuel an electric vehicle fleet, the energy efficiency of the charging process should be of great practical relevance, for reasons of economic cost, energy supply, and environmental impact. EVs with GIV and V2G capability, for some grid services, may run several time more energy back and forth than would flow for charging only. For V2G, the efficiency of discharging is also of practical relevance for the same reasons as efficiency of charging. Surprisingly, efficiency of charging and discharging has not been deeply investigated.

The findings of this research are that the efficiency of charging and discharging varies significantly. Round-trip losses were found to range between 2.67% and 20.72%.

Application and Significance

The most obvious application of this research is the potential to reduce energy loss, given this test's finding that there is significant energy loss even in simple charging, and more so in back and forth flow (V2G) for grid services. Thus, improvements in efficiency are desirable and would have significant economic payoff. The results of the ESIF testing, combined with testing by the same engineer (Apostolaki-Iosifidou) at the UD EV lab, we expect to be published in the international journal Energy

(Apostolaki-Iosifidou, et al, in review). As noted in the article, the ESIF data was one integral basis for the results. Additionally, based on these efficiency tests (at UD and ESIF), and algorithm revinement by the UD software team, we expect Nuvve to revise the production dispatch algorithms in order to operate EVs and EVSEs at the more efficient ranges, thus reducing the amount of energy losses to provide the same aggregated dispatch services. This is possible in an aggregator model because different EVs can be dispatched at different levels, or sent to “sleep” (very low power mode), as long as the aggregate produces the requested power for the grid operator. If Nuvve continues to expand its operations, this will result in significant energy savings during provision of this service.

Protocol for control of EV and EVSE by aggregator or other remote entities (Test 6)

In this test, the VSL (Vehicle Smart Link) protocol developed at the University of Delaware is documented. The VSL protocol is a byte protocol used between the EV, the EVSE, and the aggregator. This protocol registers the gain and loss of resources as they move and plug in, reports status of those resources, provides continuous meter readings from the resources, and controls the power flow to and from the resources to provide grid services. The testing under this activity—conducted by NREL—was used to validate the documentation of the protocol. NREL software engineers developed an aggregator from the documentation to access vehicles using the VSL. Based on NREL engineers’ feedback, the documentation went through several iterations in order to provide other potential device makers with thorough guidelines for creating devices that can participate in aggregation and other energy services, and for controlling those devices remotely.

Industry Relevance

The UD-developed VSL protocol, to our knowledge, is the only RTO- and TSO-compliant means of communicating all information needed to provide fast-response grid services from EVs and charging stations. Based on the goals of ESIF and the INTEGRATE program, there is a value to documenting the protocol so it can be used by other groups and eventually could be standardized through a formal standards process.

Application and Significance

This task has documented the VSL protocol, making possible more wide use by multiple parties. The ability to do so has been tested via NREL engineers writing access code based on the documentation. Apart from UD software engineering or companies aided by UD, to date additional device makers have not implemented this protocol based on the documentation alone.

Standards Based Testing of TransPower Bus (Test 7)

In this test, the compliance of the electric vehicle and the electric vehicle supply equipment communications is tested. The compliance tests are based on two different standards: IEC 61851-1 Ed. 3 Annex D and SAE J3068 (draft). The tests verify that the electric vehicle and the electric vehicle supply equipment can exchange the data and respect the limits and configuration. For this test, a vehicle with a three phase connector is used.

Industry Relevance

Trucks and large busses, for example those with gross weight over 10,000 pounds (over 4,500 kg), will require significantly larger batteries than to electrify light vehicles. Transpower, for example, has a bus with a 100 kWh battery pack. Transpower had already decided to use AC charging with the on-board motor drive inverter, by far the most economical (versus an offboard DC charger, duplicating all the power electronics). However, the only US AC standard, SAE J1772, provides a maximum charge rate of 19.2 kW, so a minimum charge time of 5 hours for a 100 kWh batterys pack. To solve this problem, prior to involvement with UD and the INTEGRATE project, Transpower was using a non-vehicle plug allowing higher power. However this did not have vehicle safety features such as prox (to prevent driveaway) much less any standard means for the EVSE to signal voltage and current capabilities to the EV inverter. Transpower's bus is only one example, illustrating the significant problems that are confronted by any heavy vehicle manufacturer. These problems are essentially caused by lack of standardized connectors for high-power AC charging.

Thus the industry relevance of both development of the SAE J3068 standard, and testing a heavy vehicle to this standard (this test and test 2), is that it solves a pressing problem for economically electrifying medium- and heavy-vehicles, essentially matching their larger batteries to standardized, economical high charging power. It may be of more general value for economical fast charging in the US, as is already done in Europe for medium power charging, at 400V and up to 63A, thus 43.6 kW.

Application and Significance

The immediate application of this testing is that one heavy vehicle company has now already used the SAE J3068 (draft) standard for connectors and signaling, and is capable of producing these vehicles in the future. Contractor UD is now communicating with other truck manufacturers and helping them to develop this capability. Also, collaborating company Nuvve has begun manufacturing of a UD-designed three-phase AC EVSE (with assembly at First Source Electronics in Baltimore, MD), which now comply with the draft standard, are expected to comply with J3068 when that standard is finalized.

GIV (Grid Integrated Vehicle) cyber security

In this task, an analysis was carried out and a document was written to provide a first vulnerability assessment of cyber security for the GIV (Grid Integrated Vehicle) platform developed at the University of Delaware. To evaluate the cyber security vulnerability, the attack tree formulation was used.

Industry Relevance

Cyber security analysis is a basic requirement of any software to be widely used, including those being used commercially.

Application and Significance

Because the Nuvve/UD aggregator and the VSL in both charging stations and in EVs are in use in multiple countries with the commercial goal of widespread use, this analysis was very helpful for planning to improve security of the particular systems being tested under this Contract.

GIV Interoperability Plan

Through the use of standardized communications protocols, and testing multiple devices against those standards, the Open V2G project furthers the goals of the INTEGRATE program to promote open source and interoperable platforms.

The interoperability plan is part of the overall program for this project. Generally, interoperability determines development of an EV and EVSE industry with both types of devices working together regardless of whether they are made by different manufacturers.

The interoperability plan was used to guide the project. It is not a device or standard in itself that would be applied by industry. Thus, there are neither “Industry relevance” nor “Application and Significance” sections user this heading.

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