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SPIDERS Bi-Directional Charging Station Interconnection Testing

M. Simpson
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Technical Report
NREL/TP-5400-60222
October 2013

Contract No. DE-AC36-08GO28308

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Prepared under Task No. DP08.9410

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List of Acronyms

A	amp
AC	alternating current
ADC	amps direct current
DC	direct current
ESIF	Energy Systems Integration Laboratory
EUT	Equipment under Test
EVSE	electric vehicle supply equipment
IEEE	Institute of Electrical and Electronics Engineers
kW	kilowatt
lb	pound
NREL	National Renewable Energy Laboratory
SPIDERS	Smart Power Infrastructure Demonstration for Energy Reliability and Security
THD	total harmonic distortion
V2G	vehicle-to-grid
VAR	volt ampere reactive
Vac	volts alternating current

Abstract

The Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) program is a multi-year Department of Defense – U.S. Department of Energy collaborative effort that will demonstrate renewables integration into island-able microgrids using on-site generation control, demand response, and energy storage with robust security features at multiple installations. Fort Carson will be the initial development and demonstration site for use of plug-in electric vehicles as energy storage (also known as vehicle-to-grid, or V2G).

The National Renewable Energy Laboratory (NREL) has actively participated in the SPIDERS design efforts, helping to formulate the requirements documents, standards, and functional test bed that guided system implementation and reduced risk. In 2013, NREL conducted interconnection tests with the bi-directional charging station purpose-built for use with the five medium-duty Smith electric vehicles currently located at Fort Carson, Colorado. An operational demonstration is scheduled to follow later this year to validate the functionality of interconnected buildings, diesel gensets, on-site solar arrays, and V2G. NREL leveraged funds from the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability to provide un-biased testing.

During testing, NREL engineers discovered that the charging station response to a subset of the abnormal voltage conditions was out of compliance with distributed resource interconnection protocols and took action to further explore the scenarios with the equipment manufacturer. After reviewing the results, the SPIDERS design team decided to accept the unit with the known concerns, having addressed any potential hazard in other systems. The charging station passed all other tests successfully—this report contains the documentation of the equipment's performance in each.

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Objective

In large (or "stiff") grids, small fluctuations in generation or demand have relatively little impact to the overall system power quality. In a much smaller microgrid, impacts from a handful of assets (including seemingly random loads from plug-in electric vehicles or the intermittency of solar arrays) can create much more abnormal conditions. As the newest, least-understood component in the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) microgrid at Fort Carson, Colorado, bi-directional vehicle charging posed the greatest risk to the operational demonstration of the microgrid.

The U.S. Army Corps of Engineers—which is managing the U.S. Department of Defense effort—determined the need early in the design process for a third-party validation of the electric vehicle supply equipment (EVSE) grid interconnection compliance, safety, and reliability as a distributed generation asset. The tests described in this report serve to characterize the basic functionality of the charger and compare its response to abnormal grid conditions possible in the microgrid with those recommended for generic distributed generation by the Institute of Electrical and Electronics Engineers (IEEE).

Equipment Under Test

Coritech manufactured the electric vehicle supply equipment (EVSE)—a 60-kilowatt (kW) "fast" direct current (DC) charging/discharging unit—utilizing on a bi-directional grid-tied inverter. Detailed information regarding the equipment can be found in Table 1.

Table 1: Coritech EVSE Specifications

Electrical Specifications	
Continuous AC power	100 kW
AC connection to grid	3-phase (no neutral)
Nominal AC voltage	480 Vac
Maximum fault current contribution (to grid)	1700 A for 3 ms
Maximum continuous AC current	133 A
AC voltage operating range	480 Vac ± 10%
Frequency range	57.0 – 60.5 Hz
Maximum DC fault current	600 Adc
Maximum operating DC current	285 Adc
Physical Specifications	
Weight	2,450 lbs
Dimensions	48" W x 36" D x 100" H
Environmental/Cooling Specification	
Cooling type	Closed loop air conditioning

AC = alternating current

The National Renewable Energy Laboratory (NREL) observed and characterized the basic performance, interconnection compliance, and reactive power control functionality of this equipment.

Figure 1: Coritech bi-directional EVSE in the Energy Storage Laboratory (left, NREL PIX 26442) EVSE touchscreen user interface (right, NREL PIX 26450)

Test Protocols

A total of seven different studies were conducted with the Coritech EVSE, consisting of over 170 tests based upon vehicle-to-grid (V2G)-specific protocols established by NREL.[1] These procedures utilize methods developed as a part of IEEE 1547.1, a series of interconnection conformance tests for distributed grid resources.

Focused on the protection of electric power system infrastructure and electrical workers, the tests were designed to establish the performance of an interconnected device, such as the combined system of a Coritech EVSE and plug-in electric vehicle (or DC power source). Each of the tests performed during this study falls into one of two categories: interconnection compliance, or power quality characterization. The interconnection compliance tests capture the reaction of the equipment under test (EUT) during abnormal grid conditions, typically measure as a "clearing time" of the EUT in response to a threshold of the parameter under test. The limits and respective clearing time goals are defined in IEEE 1547.

Test Procedure

During June 2013, NREL conducted the following tests with the Coritech EVSE:

Table 2: Interconnection Test Procedures Conducted with Coritech Bi-directional Charger

Item	Test / Procedure	Action
1	Shakedown Charge Cycle	Power on/initialize Ramp power supply up in increments of 10 kW to DC supply/sink. Peak at 60 kW charge and sustain level for 2 minutes.
2	Shakedown Discharge Cycle	Power on/initialize Ramp power draw down in increments of -10 kW to DC supply/sink. Peak at 60 kW discharge and sustain level for 2 minutes.

[1] Chakraborty, S.; Kramer, W.; Kroposki, B.; Martin, G.; McNutt, P.; Kuss, M.; Markel, T.; Hoke, A.(2011). Interim Test Procedures for Evaluating Electrical Performance and Grid Integration of Vehicle-to-Grid Applications. 29 pp.; NREL Report No. TP-5500-51001.

Item	Test / Procedure	Action
3	Review Measurements and Revise Tests	[data processing / analysis]
4	Response to Abnormal Voltages	Power on/initialize Discharge at 60 kW At each setting, conduct ramp test. Capture EVSE trip. Conduct step test. Capture time delay at each trip point.
5	Response to Abnormal Frequencies	Power on/initialize Discharge at 60 kW At each setting, conduct ramp test. Capture EVSE trip. Conduct step test. Capture time delay at each trip point.
6	Synchronization	Power on/initialize Initiate discharge at 60 kW. Trip EVSE in abnormal condition. Capture startup current when engaging discharge after 5 min wait period.
7	Unintentional Islanding	Power on/initialize Discharge at 60 kW Connect load bank in parallel. Tune load bank (R, L, C) so that power from the grid simulator is near 0 kW. Disconnect of grid simulator. Capture time delay at each trip point.
8	Open Phase	Power on/initialize Discharge at 60 kW Step phase voltage to 0 V. Capture time delay at each trip point.
9	Harmonics and Conversion Efficiency	Power on/initialize. Discharge at 60 kW. Capture data at high sample rate for post processing of harmonics/efficiencies.

Exclusions from the Recommended Test Procedure

Due to the unique setup of this test, the test team modified the procedure originally spelled out in NREL's V2G interim test procedures.[2] The following revisions were made:

1. Any bulk vehicle charge and discharge were excluded because no vehicle was readily available with the necessary communications. A programmable DC power supply was used, which has the ability to source or sink DC power indefinitely, unlike a battery. For the same reason, no "loss of control circuit" test was performed.
2. Due to the reduced time frame that the EVSE was available, most abnormal condition tests were only performed once or twice, rather than the five times suggested in IEEE 1547.1. Also, several tests were conducted in charge mode as spot checks, but a complete

[2] Chakraborty, S.; Kramer, W.; Kroposki, B.; Martin, G.; McNutt, P.; Kuss, M.; Markel, T.; Hoke, A.(2011). Interim Test Procedures for Evaluating Electrical Performance and Grid Integration of Vehicle-to-Grid Applications. 29 pp.; NREL Report No. TP-5500-51001.

set of tests was only run for discharge scenarios because distributed generation is of more concern to the microgrid protection than distributed loads.

3. DC current injection tests were foregone because the EVSE installation includes an isolation transformer.
4. The optional output overload and short circuit tests were also foregone due to time restriction and an incompatibility with the laboratory test setup as a part of the accelerated schedule.

Test Configuration

Testing of the Coritech bi-directional vehicle charger took place in the NREL Energy Systems Integration Laboratory (ESIF).[3] The charger was installed in the Energy Storage Laboratory, next to an AV-900 programmable DC bi-directional power supply (used in place of a vehicle battery). Connection to the DC power supply was made via a J1772 “combo” connector as shown in the “Junction Interface” box in Figure 2.

The alternating current (AC) side of the charger was connected to the 250A AC ESIF research electric distribution bus[4] through an AC bus plug. The plug contained a LSI circuit breaker rated at 175A. Testing utilized one 250-kW module of the AC grid simulator and one 250-kW module of the programmable load bank.

Figure 2: SAE J1772 DC junction box (NREL PIX 26445)

Voltage and current probes were placed on each of the three AC power phases as well as on the DC connection outside of the charger. A Yokogawa DL850 scope-corder was used to monitor and capture measurements on all tests. The schematic in Figure 3 contains details of the test configuration. A Yokogawa PZ400 (not shown) was also employed specifically for spot checks of the Harmonics characterization (procedure 9 in Table 1).

All tests were conducted at room temperature at approximately 1800-m altitude. All post-processing was completed using routines sourced from and built in MATLAB.

[3] Energy Systems Integration Facility, http://www.nrel.gov/esi/esif.html

[4] The research electric distribution bus (REDB) connects each lab in ESIF (as well as fixed equipment, including grid simulators and load banks) to common power buses controlled via the Supervisory Control and Data Acquisition system.

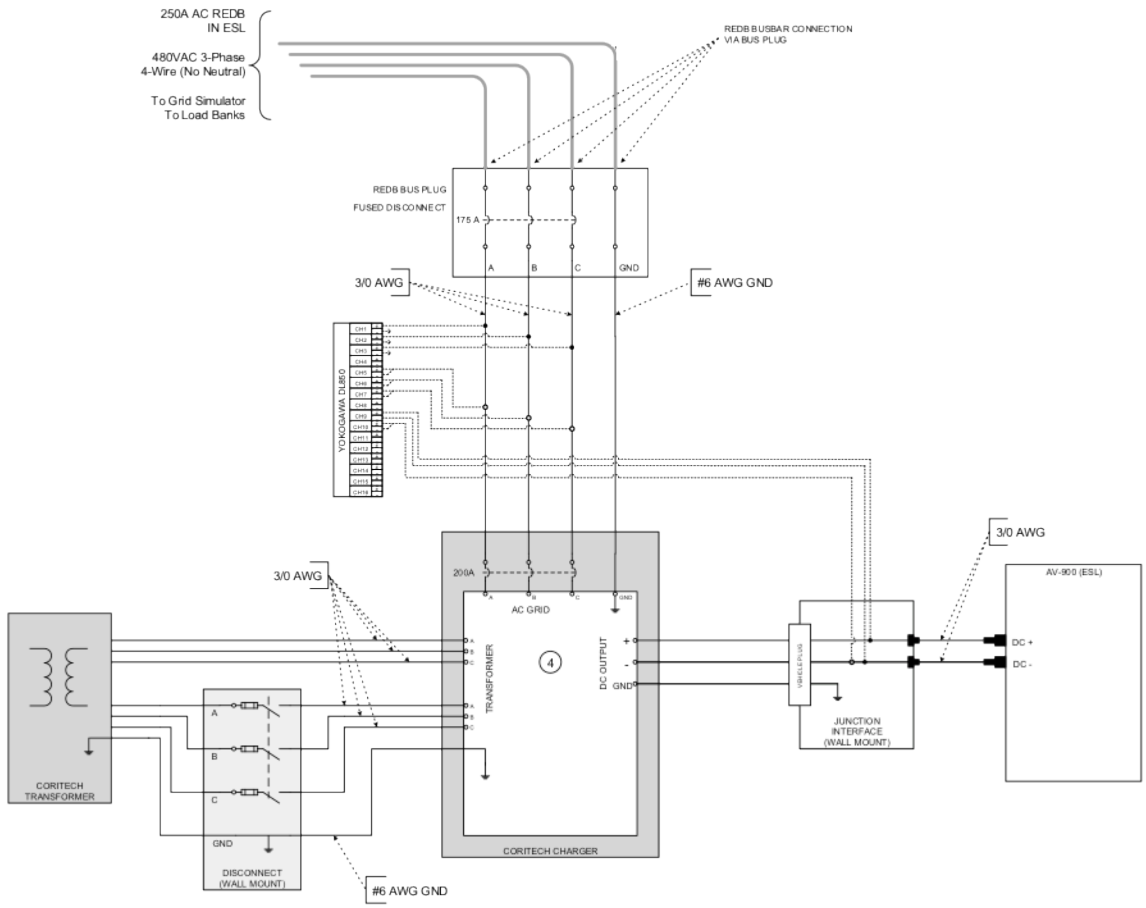

Figure 3: EVSE installation at NREL's ESIF Energy Storage Laboratory

NREL staff employed ESIF Supervisory Control And Data Acquisition systems to configure and connect the experiment with laboratory equipment. Remote operating interfaces for the grid simulator, load bank, and DC power supply control were accessed through the Supervisory Control and Data Acquisition system. Equipment operating limits were set to:

- Grid simulator: current limit to 150 A AC, maximum 500 V AC, maximum 63 Hz.
- Load bank: not to be configured for more than 120 kW.
- AV-900: current limit to 250 A DC, voltage limit to 600 V DC.

Results

The following sections detail the results of each of the seven interconnection tests conducted with the Coritech bi-directional vehicle charger.

Response to Abnormal Voltages

IEEE 1547 defines four thresholds beyond which a distributed generation asset must "trip" or shut down within a defined "clearing time." For example, at a setting between 110% and 120% of the rated voltage, the standard sets the goal for the EUT to trip within 1 second, the "slow-trip" goal. A "fast-trip" at 0.16 s is designated for the more extreme voltages (at or above 120%).

In Table 3 below, the "PUT" denotes the parameter under test, namely voltage, on one or all of the AC power phases. The "setting" indicates the RMS voltage magnitude—defined as the line-to-neutral voltage in a three-phase system—beyond which a trip should occur. "Cutoff" designates the measured voltage at which the unit actually tripped in the IEEE 1547.1 "ramp" test, whereas the "Avg Trip Time" marks the mean "clearing time" during one or more IEEE 1547.1 "step" tests, stepping 10% beyond the measured cutoff during the "ramp."

Table 3: Abnormal Voltage Tests Conducted While in Discharge Mode (Ramp: Left, Step: Right)

Test ID	PUT	Setting (%)	Setting (V)	Ramp Cutoff (V)
1	V_A	88%	243.76	206.0
2	V_B	88%	243.76	205.0
3	V_C	88%	243.76	207.0
4	V_A	50%	138.5	123.2
5	V_B	50%	138.5	123.0
6	V_C	50%	138.5	122.5
7	V_A	110%	304.7	326.7
8	V_B	110%	304.7	n/a
9	V_C	110%	304.7	n/a
10	V_A	120%	332.4	0.0
11	V_B	120%	332.4	0.0
12	V_C	120%	332.4	0.0
13	V_{ABC}	88%	243.76	238.8
14	V_{ABC}	50%	138.5	149.0
15	V_{ABC}	110%	304.7	300.6
16	V_{ABC}	120%	332.4	0.0

Test ID	PUT	Clearing Time Goal(s)	Avg Trip Time	Grade
1	V_A	2.000	1.727	pass
2	V_B	2.000	1.700	pass
3	V_C	2.000	1.733	pass
4	V_A	0.160	no trip	fail
5	V_B	0.160	no trip	fail
6	V_C	0.160	no trip	fail
7	V_A	1.000	1.119	fail
8	V_B	1.000	no trip	fail
9	V_C	1.000	no trip	fail
10	V_A	0.160	no trip	fail
11	V_B	0.160	no trip	fail
12	V_C	0.160	no trip	fail
13	V_{ABC}	2.000	1.716	pass
14	V_{ABC}	0.160	0.004	pass
15	V_{ABC}	1.000	0.725	pass
16	V_{ABC}	0.160	0.152	pass

The EVSE passed each of the three-phase abnormal voltage tests, but failed several of the single-phase tests. Although several attempts were made, the EUT continued to operate nominally through the voltage condition lasting twice the allotted clearing time.[5] The failures occurred specifically during the single-phase fast-trip under-voltage and both slow- and fast-trip over-voltage conditions.

Upon confirming the non-compliance, NREL reported the condition to the manufacturer and the SPIDERS team. Subsequently, the researchers retested the unit under a few of these tests and found that trip times of 2 s (as recommended for the slow-trip under-voltage tests) generally held true in the failed test scenarios.

Response to Abnormal Frequencies

Similar to the suite of abnormal voltage tests, a series of abnormal frequency tests were conducted. The EVSE passed all of the frequency tests sufficiently. Because the under-frequency

[5] As recommended in IEEE 1547.1, NREL held voltage from the grid simulator during abnormal condition tests for twice the clearing time goal to capture any system inaccuracies.

ramp tests yielded fast-trips at the slow-trip frequencies (representing a more conservative design),[6] NREL did not conduct slow-trip under-frequency step tests.

Table 4: Abnormal Frequency Tests Conducted While in Discharge Mode (Ramp: Left, Step: Right)

Test ID	PUT	Setting (Hz)	Ramp Cutoff (Hz)
1	f_A	60.5	60.68
2	f_B	60.5	60.53
3	f_C	60.5	60.46
4	f_A	57	58.93
5	f_B	57	59.38
6	f_C	57	59.52
7	f_{ABC}	60.5	59.03
8	f_{ABC}	57	59.59

Test ID	PUT	Clearing Time Goal(s)	Avg Trip Time(s)	Grade
1	f_A	0.160	0.008	pass
2	f_B	0.160	0.009	pass
3	f_C	0.160	0.005	pass
4	f_A	0.160	0.053	pass
5	f_B	0.160	0.044	pass
6	f_C	0.160	0.054	pass
7	f_{ABC}	0.160	0.005	pass
8	f_{ABC}	0.160	0.048	pass

Synchronization

Results gathered during synchronization tests illustrate a spike, or surge, in the AC current as the EVSE starts up once the grid returns after an outage. The EVSE draws between 108A and 117A on each phase before settling into a steady state, as shown in Figure 4. No fuses were blown or breakers tripped during these tests. This may be the magnetizing current of the external isolation transformer.

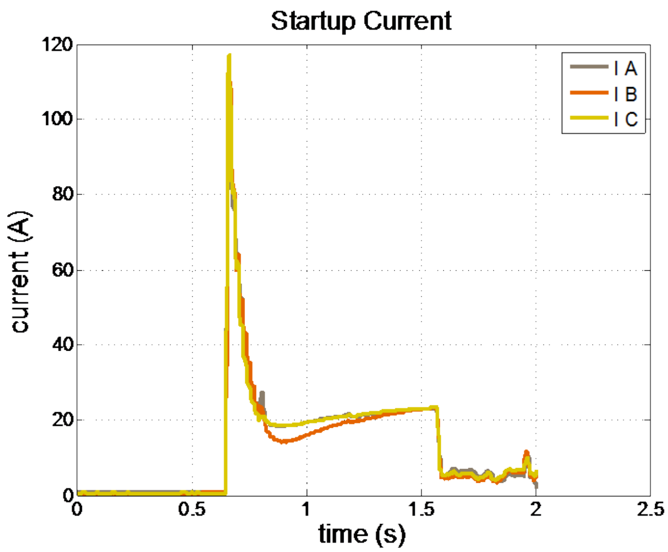

Figure 4: Example of individual phase current during EVSE startup

Unintentional Islanding

Three attempts were made to island the EVSE during discharge events (at 60 kW), feeding the grid in parallel with a load tuned to settings described in Table 5. Though the load almost entirely balanced the EVSE output during each test, the internal controls drove the system out of equilibrium within less than 0.5 seconds, thus passing the test.

[6] IEEE 1547 allows for adjustable trip times during the slow-trip under frequency scenarios.

Table 5: Load Settings and Trip Delay for Three Unintentional Islanding Tests

	Load Bank Settings (kW)				Clearing Time
Test 1	A	B	C	Total	
Resistance	17.3	17.2	17	51.5	0.358 sec
Inductance	20	20.2	20.2	60.4	pass
Capacitance	20.5	20	20	60.5	
Test 2	A	B	C	Total	
Resistance	17.5	17.45	17.1	52.05	0.394 sec
Inductance	20.55	20.2	20.2	60.95	pass
Capacitance	23	20	21	64	
Test 3	A	B	C	Total	
Resistance	17.5	17.5	17.1	52.1	0.44 sec
Inductance	20.26	20.2	20.5	60.96	pass
Capacitance	22.2	20	21	63.2	

Figure 5 contains data from one of the unintentional islanding tests. Initially, the load and EVSE were balanced, drawing very little power from the grid. At approximately 2.73 s into the data acquisition, the researcher opened the relay on the grid simulator, islanding the EVSE and load for nearly 0.36 s before the unit tripped. During the islanded operations, AC frequency on each phase rose exponentially.

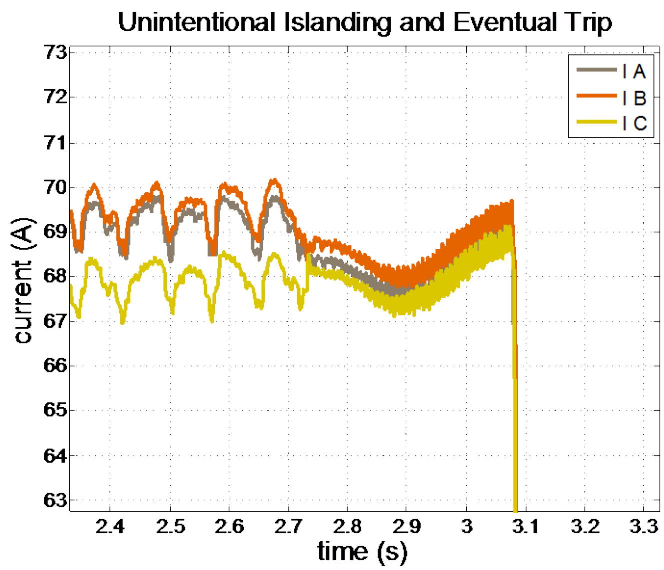

Figure 5: Example of unintentional islanding test

Open Phase

Researchers conducted open phase tests on each AC phase individually during discharge events at -60 kW. All tests caused the EVSE to trip in less than one cycle (averaging 8 ms).

Harmonics Characterization

A series of short duration recordings were collected at varying steady states from charge at maximum power to discharge at maximum power. Taken at high resolution, the data was analyzed to extract total harmonic distortion (THD). As shown in Figure 6, though the relative THD increases slightly during discharge mode, it remains well below the 5% threshold listed in IEEE 1547.

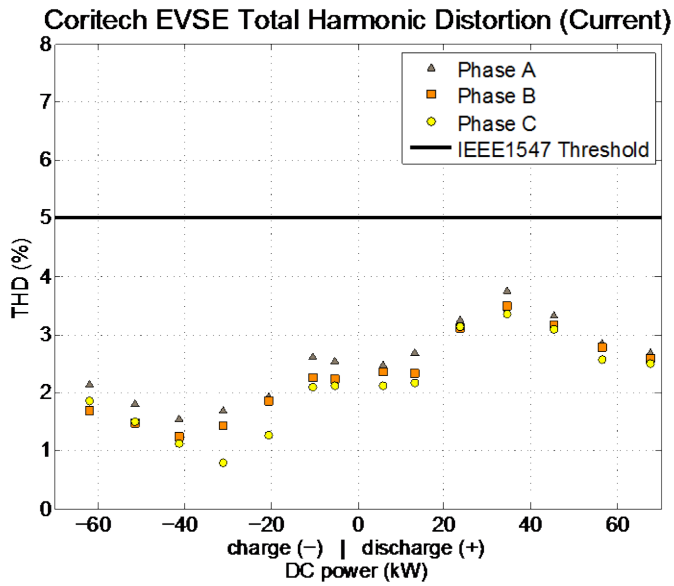

Figure 6: Total harmonic distortion (current) produced by the EVSE at various operating points

It should be noted that IEEE 1547 defines THD in terms of total rated-current distortion, "the greater of the test load current demand or the rated current capacity of the [distributed resource] unit." The THD relative to test load is found in Appendix A: Additional Results.

Conversion Efficiency

Efficiency measurements were taken at the same operating steady states as THD measurements. Figure 7 contains the results, indicating a minimum of 56% efficiency at low rates of discharge, which rose to over 90% at high rates. Charging efficiencies exceeded 97%.

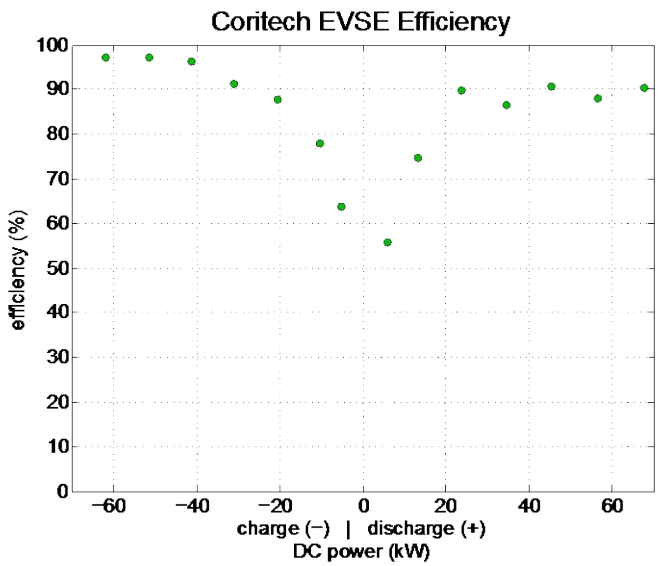

Figure 7: EVSE power conversion efficiency measurements at various operating points

Volt Ampere Reactive Control

NREL concluded testing by exploring the EVSE's volt ampere reactive (VAR) control functionality (Table 6) at the request of the Fort Carson SPIDERS microgrid design team, though outside the IEEE 1547 interconnection compliance test regime. Results, which were captured by a Yokogawa PZ400 power quality meter, confirmed the appropriate magnitude of VAR control during discharge tests up to ±75 kVAR (output accurate within approximately 7% of the command in "manual mode").

Table 6: VAR Control Functionality Test Results

Command	Phase		A	B	C	Sum
55 kW discharge 0 kVAR	Vrms	V	278.5	278.4	278.5	-
	Irms	A	66.82	66.87	66.9	-
	P	kW	-18.6	-18.6	-18.62	-55.34
	S	kVA	18.6	18.6	18.62	55.44
	Q	kVAR	-0.18	0.48	-0.2	3.3
	PF	%	-100%	-99.97%	99.99%	-
	Vthd	%	0.47%	0.48%	0.46%	-
	Ithd	%	4.11%	4.48%	4.10%	-
55 kW discharge 75 kVAR	Vrms	V	279.7	279.7	279.70	-
	Irms	A	114.02	113.96	113.96	-
	P	kW	-18.06	-18.13	-18.09	-53.57
	S	kVA	31.88	31.86	31.86	95.91
	Q	kVAR	-26.27	-26.2	-26.23	-79.55
	PF	%	-56.66%	-56.90%	-56.76%	-
	Vthd	%	0.35%	0.34%	0.35%	-
	Ithd	%	2.91%	2.93%	2.89%	-
55 kW discharge -75 kVAR	Vrms	V	277.3	277.3	277.3	-
	Irms	A	110.59	111.68	110.83	-
	P	kW	-18.4	-18.46	-18.5	-54.65
	S	kVA	30.65	30.95	30.72	88.58
	Q	kVAR	24.49	24.84	24.53	69.46
	PF	%	-60.15%	-59.64%	-60.21%	-
	Vthd	%	0.26%	0.25%	0.26%	-
	Ithd	%	2.88%	2.80%	2.67%	-

Conclusions

NREL successfully completed interconnection compliance testing of the Coritech EVSE on time with a compressed schedule in June of 2013 at the ESIF. This marked the first test of the full 60 kW discharge capability and the full ±75 kVAR capability of the charging station. Vehicle availability limited NREL's ability to test the most critical function of the EVSE – communicating successfully with a plug-in electric vehicle. However, testing of this functionality was completed in parallel at the manufacturer's facility.

The EVSE successfully passed all of the abnormal voltage, abnormal frequency, phase-loss, and unintentional islanding ("trip") tests, with the exception of three abnormal voltage conditions:

- Single-phase fast-trip under-voltage ($V < 138.5\ V_{LN}$ AC)
- Single-phase slow-trip over-voltage ($304.7\ V_{LN}$ AC $< V < 332.4\ V_{LN}$ AC)
- Single-phase fast-trip over-voltage ($V \geq 332.4\ V_{LN}$ AC)

These three failed conditions were confirmed, explored further, and reported to the manufacturer and SPIDERS design team. Researchers found that the slow-trip under-voltage clearing time setting (2 s) seemed to hold true for all abnormal single-phase voltage conditions.

After learning of this, the SPIDERS microgrid design-build contractor expressed no concern and agreed to incorporate this information into its operations. NREL recommends that microgrid controls incorporate considerations for the extended trip times to avoid system-level hazards.

The Coritech EVSE exhibited expected performance during start-up and steady-state conditions. Though conversion efficiencies were low at low operating points, the unit performed at over 90% during the scenarios that simulated the vast majority of its intended operations.

NREL would like to thank the following organizations who helped keep this testing productive and on-schedule:

- Coritech Services, Inc. (EUT manufacturer, technical support)
- Burns and McDonnell (SPIDERS Design Team Lead)
- Southwest Research Institute (SPIDERS Design Team, test planning support)
- U.S. Department of Energy Office of Electricity Delivery and Energy Reliability
- ESIF Operations Team

Appendix A: Additional Results

Abnormal Voltage Tests during Charge Mode

The following results were collected under abnormal voltage conditions during 60-kW charge scenarios.

Table 7: Abnormal Voltage Tests Completed While in Charge Mode

Test ID	PUT	Setting (%)	Setting (V)	Ramp Cutoff (V)
1	V_A	88%	243.8	209.0
2	V_B	88%	243.8	-
3	V_C	88%	243.8	212.0
4	V_A	50%	138.5	123.2
5	V_B	50%	138.5	123.0
6	V_C	50%	138.5	122.5
7	V_A	110%	304.7	n/a
8	V_B	110%	304.7	n/a
9	V_C	110%	304.7	n/a
10	V_A	120%	332.4	n/a
11	V_B	120%	332.4	n/a
12	V_C	120%	332.4	n/a
13	V_{ABC}	88%	243.8	-
14	V_{ABC}	50%	138.5	-
15	V_{ABC}	110%	304.7	300.8
16	V_{ABC}	120%	332.4	0.0

Test ID	PUT	Clearing Time Goal (s)	Avg Trip Time	Grade
1	V_A	2.000	1.730	pass
2	V_B	-	-	*no test*
3	V_C	2.000	1.730	pass
4	V_A	0.160	0.071	pass
5	V_B	0.160	0.078	pass
6	V_C	0.160	0.080	pass
7	V_A	1.000	no trip	fail
8	V_B	1.000	no trip	fail
9	V_C	1.000	no trip	fail
10	V_A	0.160	no trip	fail
11	V_B	0.160	no trip	fail
12	V_C	0.160	no trip	fail
13	V_{ABC}	-	-	*no test*
14	V_{ABC}	-	-	*no test*
15	V_{ABC}	1.000	0.726	pass
16	V_{ABC}	0.160	0.003	pass

Total Harmonic Distortion Relative to Test Load

The same data presented in Figure 6 is shown in Figure 8 as a percent of the respective test load, rather than rated load of the EUT. THD increased sharply at lower power levels, but settled to within the IEEE 1547-recommended values as the rate of charge or discharge increased.

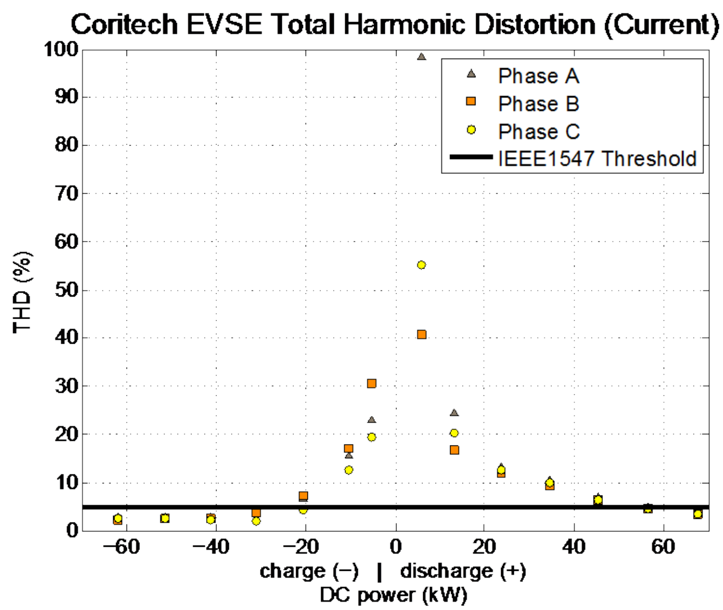

Figure 8: Total harmonic distortion as a percent of the respective test load