NATIONAL RENEWABLE ENERGY LABORATORY

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Acronyms

DAS	data acquisition system
DERTF	Distributed Energy Resources Test Facility
DUT	device under test
M/G	motor/generator
EMI	electromagnetic interference
LO/TO	lock out/tag out
NREL	National Renewable Energy Laboratory
PCC	point-of-common-coupling
PHEV	plug-in hybrid electric vehicle
PPE	personnel protective equipment
PV	photovoltaic
SOC	state of charge
SOP	safe operating procedures
TRD	total rated-current distortion
V2G	vehicle-to-grid

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1 Overview

Over the past 15 years, energy storage technologies for vehicle traction systems have improved dramatically. This technology is finding its way into commercially viable hybrid, electric and plug-in hybrid vehicles. Vehicle-to-grid (V2G) prototype vehicles are being developed and tested at the National Renewable Energy Laboratory (NREL). Utilizing bi-directional power electronics can allow a vehicle to not only charge its batteries from the electric utility grid during charge but also can provide power back to the grid during discharge. The possible uses of V2G vehicles for distributed energy applications are to provide power to utility/local loads, regulate voltage and frequency, offer spinning reserves, and enable electrical demand management. Electric, plug-in hybrid and V2G vehicles will have the potential to absorb excess electricity produced by renewable energy sources (e.g., wind or photovoltaics) when the grid is operated at low load conditions.

A V2G vehicle provides an electrical connection to the grid resources via an electrical plug-in interface. Such vehicles often also offer a communication and control interface to the utility. Some V2G vehicles may have on-board data acquisition systems to monitor parameters such as power and battery state of charge (SOC). V2G vehicles will utilize a reliable, high-power, high-energy battery pack with bidirectional power electronics and controller. The controller module controls the power electronics to operate in charge, discharge, or standby modes. The first commercial V2G vehicles are expected to use either a nickel metal hydride or a lithium-ion battery pack to obtain high energy density.

The block diagram of a fully electric vehicle (EV) with V2G capability is shown in Figure 1. In this configuration, the utility connection is made using the same power electronics that are used for the motor/generator (M/G), thus eliminating the need for a separate battery charger. Though V2G functionalities are expected to be the same for different vehicles, the specific V2G system configuration can be different depending on the details of the vehicle design, such as fully electric or hybrid; the power electronics topologies; and type of power and control connections. Irrespective of their design, all vehicles with V2G capability must meet IEEE Std. 1547 *Standard for Interconnecting Distributed Resources with Electric Power Systems* (IEEE Std. 1547), which specifies the type, production, and commissioning tests that must be performed to demonstrate that the utility interconnection functions properly.

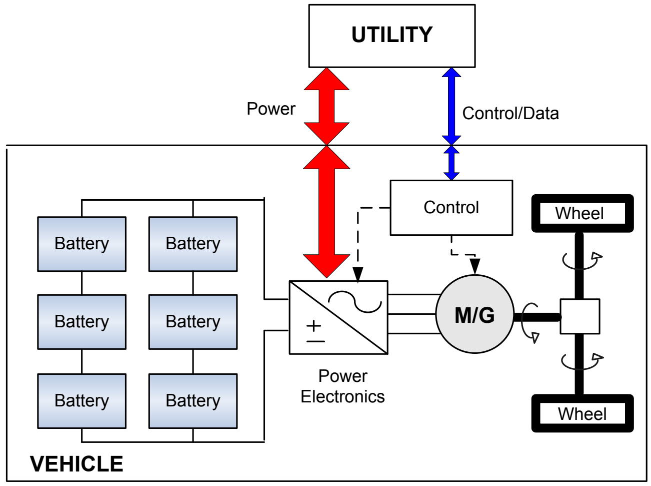

Figure 1. Simple block diagram of an EV with V2G

The objective of this report is to provide an interim test plan for evaluating V2G applications. The test plan is designed to test and evaluate the vehicle's capability to provide power to the grid, and to evaluate the vehicle's ability to connect and disconnect from the utility according to a subset of the IEEE Std. 1547 tests. This test plan does not include all the tests required to meet the 1547 standard due to the uniqueness of the battery-based V2G power electronics that makes some of the IEEE Std. 1547 tests unfeasible or impractical. In exchange, some additional performance tests are included in the test plan to verify the V2G-capable vehicle's continuous output power, efficiency and losses. It is important to note that almost all the tests describe in this document are for V2G modes only, not for modes in which the vehicle is charging its batteries from the grid. A test procedure is included in the test plan to determine the time it takes to charge the vehicle. Also in future various other tests such as transient response test , standby power loss tests etc. will be evaluated and then included in the test plan. The intent of this report is to provide a way to evaluate V2G applications for utility interconnection. Once validated, these procedures could become the basis for testing standards for V2G applications.

2 Test Requirements

2.1 General

Almost all the tests described in this document are for vehicle-to-grid modes. Only one test is provided for grid-to-vehicle, battery charging, and is included to estimate the time it takes to charge the battery based on varying conditions as the amount of time and power required to charge will be of interest to utilities who must provide the infrastructure to provide electricity to PHEV, electric or V2G vehicles.

Implementation of these test procedures shall be conducted in accordance with appropriate safety procedures, sequences, and precautions.

Test result accuracy. The test results shall verify that the V2G Device Under Test (DUT) meets the requirements of IEEE Std. 1547 within the manufacturer's specified accuracy.

Testing environment. The manufacturer shall specify the range of environmental conditions for the V2G (DUT). Therefore, tests shall be conducted in an environment that is within the manufacturer's specified environmental operating conditions.

Measurement accuracy and calibration of the testing equipment. Measurement equipment used to confirm performance of a V2G DUT shall have calibration traceability. The accuracy of the measuring equipment shall be suitable for the test being conducted.

Test reports. The test results shall be documented in a test report. The report shall clearly and unambiguously present all relevant information of the tests (e.g., load conditions, conductor type or routing, functional description, acceptance criteria). Within the test report, test procedures, as performed, shall be detailed; and engineering considerations, including test modifications and exemptions, shall be justified.

The test report shall include sufficient critical operating information to rerun the test and reproduce the results.

Each test method shall be specified; and engineering considerations, including range of operating conditions, shall be justified.

Test equipment. The test equipment such as grid simulator and measurement equipment shall follow the requirements stated in IEEE Std. 1547.1 *Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems* (IEEE Std. 1547-1)*,* Section 4.6.

2.2 Safety Review

Review all safety procedures for the laboratory where the tests are to be conducted. Review all operating manuals for the vehicle provided by the manufacturer.

2.2.1 Purpose

To protect against injury to persons and damage to equipment, a thorough pre-test safety inspection shall be completed. Appropriate documentation, inspection, and approval of the test setup and vehicle-specific procedure shall be completed as required.

2.2.2 Procedure

2.2.2.1 General

Inspect the vehicle under test to determine risk for exposure to moving parts. Specifically, looking for:

- Degree of risk exposure required to perform intended functions
- Sharpness of parts
- Potential for unintentional hazardous contact
- Speed and energy of moving parts

- Potential for a part of the body or clothing to be entangled by a moving part
- Inspect the DUT judging risk for exposure to moving parts.

Inspect the condition of the guards, releases, interlocks, or similar devices to ensure they function as intended. Determine this by conducting a study of the complete DUT, its operating characteristics, and the potential for a risk of injury to persons. The investigation is to include evaluation of the results of a breakdown or malfunction of any one component; however, not more than one component is to be investigated at a time, unless one event contributes to another. When the study shows that malfunction of a component is able to result in a risk of injury to persons, that component is to be investigated for reliability. Furthermore, ensure intended guards are adequate for appropriate safety. Evaluate all hazards and determine if additional guarding is necessary.

Openings in guards that normally enclose moving parts which could pose a risk of injury to personnel shall have minor dimensions less than 1 inch.

All guards, enclosures, frames, knobs, handles, and similar devices shall not be sharp enough to constitute a risk of injury to personnel in normal maintenance and use.

All guards, enclosures, frames, knobs, handles, and similar devices shall be mounted to the assembly so that the part is:

- Unable to be operated with the guard or portion of the enclosure removed
- Secured to the assembly using fasteners requiring a tool for removal
- Provided with an interlock to reduce the risk of contacting the part while hazardous conditions are present.

All rotating parts, such as fan blades, which would result in risk of injury to personnel upon their breakage, shall be enclosed or guarded to reduce the risk of injury to persons. A rotating or moving part that involves a risk of injury to persons when it becomes disengaged shall be provided with a positive means to retain it in place under conditions of use.

When unintentional operation of a switch involves risk of injury to persons, the actuator of the switch shall be located or guarded so that it is inaccessible.

Vehicles containing stored fuel (gasoline) must meet the laboratory requirements where the vehicle is tested. A safety review and inspection shall be conducted prior to any testing.

2.2.2.2 Electrical - General

Ensure the vehicle is provided with an enclosure that houses all current-carrying parts. The enclosure shall protect the various parts of the DUT against mechanical damage from forces external to the DUT.

Uninsulated live parts involving a risk of electric shock or electrical energy-high current levels and a moving part that involves a risk of injury to persons shall be located, guarded, or enclosed to protect against unintentional contact by service personnel adjusting or resetting controls, or similar actions.

Components that require examination, resetting, adjustment, servicing, or maintenance while energized shall be located and mounted with respect to other components and with respect to grounded metal parts to be accessible for electrical service functions without subjecting service personnel to a risk of electric shock, electrical energy-high current levels, or injury to persons by adjacent moving parts.

Ensure access to components is not impeded by other components or wiring.

For an adjustment that is to be made with a screwdriver or similar tool when the DUT is energized, protection shall be provided against inadvertent contact with adjacent un-insulated live parts involving a risk of electric shock. This protection may be provided by:

- Location of the adjustment means away from un-insulated live parts involving a risk of electric shock
- A guard to reduce the potential for the tool contacting un-insulated live parts
- Use of listed rated insulated tools.

Energized or potentially energized metal parts, which may be mistaken for grounded or dead metal, shall be guarded to protect against unintentional contact by personnel. These items may include live heat sinks for a solid-state components, live relay frames, and similar components, involving a risk of electrical shock or high electrical current levels.

A means, such as a bleeder resistor, shall be provided to drain the charge stored in a capacitor so that it does not provide a risk of electric shock or a risk of electrical energy-high current level. Placards or labels must be used to notify personnel of the presence of stored energy in capacitors.

Voltage level labeling shall be included in a plainly visible manner on any and all electrically energized enclosures where uninsulated electrical parts are present.

2.2.2.3 Energy storage systems

Batteries, ultracapacitors, or other energy storage systems shall be contained in a separate enclosure or compartment, or separated using a barrier, from the power conversion portion of an inverter, converter or controller. This barrier or enclosure must protect against the passage of evolved corrosive or flammable gas from the battery area to the area of any electronic components.

Ensure a vented battery, if applicable, includes a flame arrestor to protect against the destruction of the cell, under normal operating conditions, due to ignition of gasses within the cell by an external spark or flame.

The enclosure or compartment housing a vented battery shall be constructed so that spillage or leakage of the electrolyte is contained within the enclosure and not able to:

- Reach the outer surface of the enclosure where contact with personnel is possible
- Contaminate adjacent electrical components or materials
- Bridge the required electrical spacings.

Racks and trays used to support batteries shall be protected against corrosion. Metallic racks and trays shall employ non-conductive members directly supporting the batteries or include a continuous insulating material, other than paint, between conductive support members and the batteries.

2.2.3 Requirements

The V2G DUT shall be free of any problems that may affect the safety of testing personnel or equipment when being tested.

3 Test Setup

3.1 Test Vehicle Characteristics

The manufacturers' specification for the V2G capable vehicle is important in finalizing the test plan and procedures. Depending on the type of vehicle (e.g., electric, hybrid, or fuel cell) most of the following information is required from the manufacturer to be included in the general test plan:

- Type of vehicle propulsion
- Power electronics topology
- Electrical diagram
- Type and size of the batteries
- Battery terminal voltage
- Utility connection voltage level(s) and frequency
- Maximum output power
- Maximum charging rate and time
- Type of power connector
- Charge/discharge control methods
- Data acquisition and display provisions on board the vehicle
- Electrical safety systems.

Based on this information, the test procedures, as performed, shall be detailed; and engineering considerations, including test modifications and exemptions, shall be justified. The test report shall include sufficient critical operating information to rerun the test and reproduce the results.

3.2 Test Equipment and Schematics

A testing facility shall have the proper equipment for conducting the test procedures. The test setup and schematics for the testing should be developed and reviewed. This should include a list of any equipment used for testing including grid simulators, load banks, and data acquisition systems. The model numbers and calibration reports should be verified on all equipment used in testing.

Based on the specifications for the particular V2G capable DUT, the settings for the grid simulator and the load banks will be determined. It is expected that the manufacturer will provide means of disconnecting the battery for laboratory safety reasons. If the battery is integrated into a vehicle by the original equipment manufacturer (OEM) a battery disconnect may not be required or feasible. The manufacturer shall provide the control and monitoring system for the V2G's power electronics and batteries.

An example of a test setup for a V2G-capable electric vehicle is shown in Figure 2. This configuration has a single-phase connection to the utility grid. A programmable AC grid simulator is used to emulate the electric utility. This grid simulator is controlled by a computer and is capable of outputting voltage waveform sequences (required for IEEE Std. 1547 tests). As the grid simulator cannot sink power, a variable load bank is used in parallel. In some cases, the charging and/or discharging of the battery are controlled using cellular signals from the Internet. Also, for safety reasons, a manual disconnect is included in the test system that can disconnect the batteries from the utility connection in case of emergency.

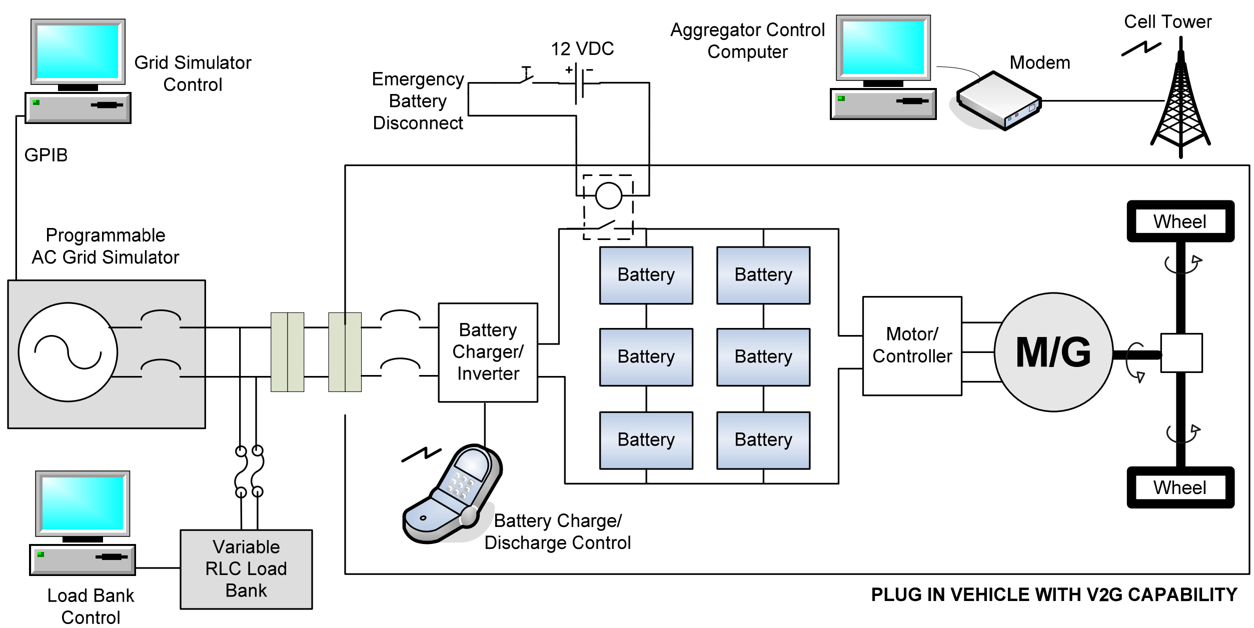

Figure 2. Example of V2G test setup

4 Grid Interconnection Tests

This section contains various tests to determine the safe V2G interconnection to the utility grid. Most of these tests are described based on the IEEE Std. 1547.1 that discusses the conformance test procedures for equipment that interconnect distributed resources with electric power systems. Some of the IEEE Std. 1547.1 tests are unfeasible or redundant for V2G electronics and are discussed as additional tests at the end of this section. The tests described in this section are in the order in which they are suggested in IEEE Std. 1547 (IEEE Std. 1547, Table 4). It is important to note that V2G vehicles may be capable of connecting to the utility at different voltage levels (e.g. 120V, 240V AC rms); therefore, all of the interconnection testing discussed in this report will need to be conducted for all practical utility connection voltages.

4.1 Response to Abnormal Voltages

4.1.1 Purpose

This series of tests will be used to ensure the inverter disconnects from the utility whenever voltage levels go out to the ranges specified in IEEE Std. 1547. The inverter must not only disconnect from the utility when a voltage threshold is reached, but also must do so in a specified amount of time.

4.1.2 Procedure

This procedure uses the ramp and step functions defined in IEEE Std. 1547.1, Annex A. This procedure should be repeated to test for both over- and under-voltage conditions. This procedure has two parts: 1) a magnitude test to determine the grid voltage magnitude at which the inverter disconnects, and 2) a time test to determine the time it takes the inverter to disconnect after the voltage range has been exceeded. The detailed test procedure can be found in IEEE Std. 1547.1, section 5.2. This is a pass/fail test and the V2G DUT shall be considered in compliance if it trips in the voltage magnitude range and time range specified in IEEE Std. 1547.

4.2 Response to Abnormal Frequencies

4.2.1 Purpose

This series of tests will be used to ensure the inverter disconnects from the utility whenever frequency goes out of the ranges specified in IEEE Std. 1547. The inverter must not only disconnect from the utility when a frequency threshold is reached, but also must disconnect in a specified amount of time.

4.2.2 Procedure

This procedure uses the ramp and step functions defined in IEEE Std. 1547.1, Annex A. This procedure should be repeated to test for both over and under frequency conditions. This procedure has two parts: 1) a magnitude test to determine the frequency threshold at which the inverter disconnects, and 2) a time test to determine the time it takes the inverter to disconnect after the frequency threshold has been exceeded. The detailed tests procedure can be found in IEEE Std. 1547.1, section 5.3. This is a pass/fail test and the V2G DUT shall be considered in compliance if it trips in the frequency range specified in IEEE Std. 1547 and also trips with in the specified time range.

4.3 Synchronization and Seamless Transfer

4.3.1 Purpose

To properly interconnect with the utility, V2G power electronics must properly synchronize causing minimal system transients. If the DUT can also supply a load independently of the utility status (i.e., able to run in intentional islanded mode), the voltage and frequency supplied to the load must also be free of significant transients during the transfer process, regardless of the inverter's initial conditions and power exporting status prior to the shift.

4.3.2 Procedure

Two basic test methods are provided in IEEE Std. 1547.1, Section 5.4. If the V2G power electronics can generate a voltage independently of the utility and is thus capable of out-of-phase paralleling (e.g. operating in a stand-alone mode), it has to be tested using Method 1 to verify its synchronizing capability. The V2G power electronics that are not able to supply power independent of the utility must be tested to determine the synchronization current using Method 2. The detailed test procedure can be found in IEEE Std. 1547.1, Section 5.4. This is characterization test; so there are no specific pass/fail criteria except as applied at a specific site.

4.4 Unintentional Islanding

4.4.1 Purpose

The purpose of this test is to verify that the V2G DUT ceases to energize the utility as specified in IEEE Std. 1547 when an unintentional island condition is present. This test determines the trip time for the test conditions and confirms that after the formation of an island, the DUT trips within IEEE Std. 1547 specified limit.

4.4.2 Procedure

This test procedure is designed to be universally applicable to all distributed resources, regardless of output power factor. Any reactive power compensation by the V2G converter should remain on during the test. Where the V2G manufacturer requires an external or separate transformer, the transformer should be connected between the V2G and resistive-inductive-capacitive RLC Load specified in Figure 3 and should be considered part of the product being tested.

The detailed test procedure can be found in IEEE Std. 1547.1, Section 5.7. Note that steps 'n' and 'o' of the anti-islanding tests in IEEE Std. 1547.1 cannot be performed for some V2G DUTs because both the input power from the battery and the output power level are not adjustable. When this is the case, it should be noted clearly in the test report. For the different test conditions specified, each test is successful when the V2G ceases to energize the test load within the timing requirements of IEEE Std. 1547 after switch S3 is opened. If any of these tests results in islanding for longer than the specified time, the DUT fails the test. A single failure of any of these tests is considered a failure of the entire test sequence.

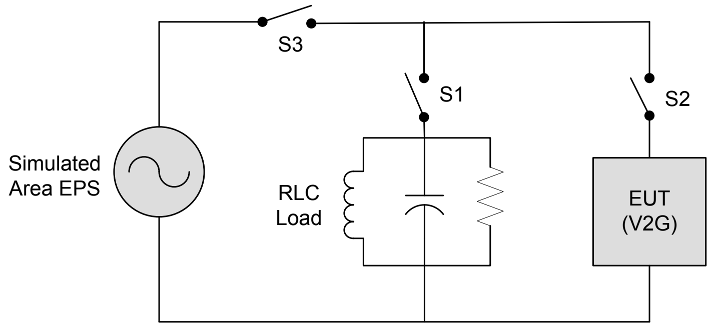

Figure 3. Unintentional islanding test circuit

4.5 Open Phase

4.5.1 Purpose

The purpose of this test is to verify that the V2G DUT ceases to energize the utility upon loss of an individual phase at the point-of-common-coupling (PCC) or at the point of V2G connection.

4.5.2 Procedure

The detailed test procedures can be found in IEEE Std. 1547.1, Section 5.9. This is a pass/fail test and the V2G DUT shall be considered in compliance if after the opening of the disconnect, the V2G DUT ceases to energize all output terminals within the timing requirement of IEEE Std 1547 for unintentional islanding.

4.6 Reconnect Following Abnormal-Condition Disconnect

4.6.1 Purpose

The purpose of this test is to verify the functionality of the V2G interconnection component or system reconnect timer following an abnormal condition disconnect, so that no reconnection takes place until the utility voltage and frequency are in the range specified in IEEE Std. 1547 for the specified time interval.

4.6.2 Procedure

This test may be performed in conjunction with the overvoltage, undervoltage, overfrequency, and underfrequency tests. The detailed test procedure can be found in IEEE Std. 1547.1, Section 5.10. This is a pass/fail test and the V2G DUT shall be considered in compliance if the reconnect time delay meets the requirements of IEEE Std. 1547 within the manufacturer's stated accuracy.

4.7 DC Current Injection

4.7.1 Purpose

The purpose of this test is to verify that the V2G electronics connected to the electric utility grid complies with the DC current injection limit specified in IEEE Std. 1547. This test is only conducted on electronics that connect to the grid without the use of DC-isolation output transformers.

4.7.2 Procedure

The detailed test procedure can be found in IEEE Std. 1547.1, Section 5.6. This test may be conducted as part of the harmonics test. If a simulated electric utility grid is used, the output of the simulated grid should be connected to a dedicated isolation transformer. This is a pass/fail test and the V2G DUT shall be considered in compliance if all calculated percent DC injection currents are within the limit specified in IEEE Std. 1547.

4.8 Harmonics

4.8.1 Purpose

The purpose of this test is to measure the individual current harmonics and total rated-current distortion (TRD) of the V2G DUT under normal operating conditions.

4.8.2 Procedure

The detailed test procedure can be found in IEEE Std. 1547.1, Section 5.11. It is important to take steps to ensure that measured harmonics exceeding the allowable levels in IEEE Std. 1547 are not caused by characteristics of the simulated electrical utility grid. This is a pass/fail test and the V2G DUT shall be considered in compliance if the individual current harmonics and TRD do not exceed the limits specified in IEEE Std. 1547. For a multiphase V2G DUT, each of the phases shall comply with the specified limits.

4.9 Additional IEEE Std. 1547 Tests (optional)

The temperature stability test verifies that the power electronics DUT maintains measurement accuracy of parameters over its specified temperature range. The manufacturer’s protective, monitoring, and control function tests for the V2G power electronics at the specified temperature range can be accepted in lieu of further third-party or owner testing if a temperature-controlled testing environment is not available. The temperature stability test is discussed in IEEE Std. 1547.1, Section 5.1

The reverse power test is performed to characterize the accuracy of the reverse-power protection magnitude setting(s) of the V2G DUT. This test is a variation of the unintentional islanding test and should only be required for V2G power electronics that use reverse or minimum import power-flow protection for disconnecting from the utility when an unintentional island condition is present. Details of the reverse power test procedure can be found in IEEE Std. 1547.1, Section 5.8.

Three tests are included under the interconnection integrity tests category: a test of protection from electromagnetic interference (EMI), a test of surge-withstand performance, and a dielectric test of the paralleling device. In the EMI protection test, V2G power electronics are tested to confirm that the influence of EMI does not result in a change in state or mis-operation of the interconnection functions. The purpose of the surge withstand test is to verify the level of surge withstand protection specified by the manufacturer of the V2G vehicle. The dielectric test determines if the paralleling device (such as a contactor or circuit breaker) of the V2G vehicle, operating at the normal operating temperature, can withstand the application of an AC rms test potential of 1,000 V plus 220% of the nominal AC rms voltage for 1 minute without breakdown. The detailed test procedures and requirements can be found in IEEE Std. 1547.1, Section 5.5. It may be difficult to conduct these tests because of safety concerns, the requirement of special instruments, and the possibility that the V2G DUT could be damaged. In some cases, certified factory test results (i.e. those performed by the manufacturer) may suffice in lieu of further third-party or owner testing.

5 V2G Electrical Performance Tests

This section discusses the performance tests to be conducted on the electronics to determine a vehicle's suitability for V2G applications. These performance tests are designed to verify or establish the relevant converter's operational characteristics. The test results may provide information not generally found on V2G vehicle's specification sheets, or on listing labels or other labels.

5.1 Continuous Output Power

5.1.1 Purpose

The purpose of this test is to establish the continuous output power level that the V2G DUT can maintain for a specified period of time at the specified ambient operating temperature after reaching thermal equilibrium.

5.1.2 Procedure

1. Maintain the ambient air temperature of the test chamber/room within ±3°C of the nominal operating temperature specified in the vehicles information datasheet. Write down the ambient operating temperature in Table 1, first column. If the test facility is not capable of maintaining the required temperature conditions, it shall be clearly stated in the test report that the test is performed "without temperature control".
2. Maintain the vehicle in an environment before testing to ensure that the DUT is relatively warm at the beginning of the test. This will bring the DUT to a stable operating temperature in a reasonably short period of time. If the heat sink temperature cannot be measured or if the V2G battery size does not allow the DUT to operate till thermal equilibrium without significantly discharging the battery, it must be described clearly in the test report as "without thermal equilibrium".
3. Connect the V2G DUT according to the instructions and specifications provided by the manufacturer.
4. Set the simulated utility to provide the nominal AC voltage based on Table 1, Test A.
5. Set (or verify) all V2G DUT parameters to the nominal operating settings.
6. Verify the battery SOC. If the battery SOC is less than 98% (or less than the manufacturer specified upper limit), stop the test and start charging the battery. Once charging is completed, repeat step 3-6.
7. Set the V2G DUT to provide as close as possible to 100% of its rated output power.
8. Record all applicable settings.

9. Measure and record the following values at 5 minute intervals until the end-of-test is reached as described in the following step 10. A continuous sampling at higher data rates and 5-minute averages is preferred for the following values:

   Input voltage (DC and AC)

   Input current (DC and AC)

   Input power (average DC + AC RMS)

   Output voltage (AC)

   Output current (AC)

   Ambient temperature (°C)

   Inverter temperature at heat sink (°C).

10. End test when the DUT output folds back or the DUT shuts down or the battery SOC reaches the manufacturer's recommended minimum value. Record the reason for end-of-test as "Foldback," "Shutdown," or "Low SOC" as appropriate. "Foldback" refers to power curtailment by vehicle controls to protect the V2G DUT. "Shutdown" refers to turn-off of the inverter by controls to protect the V2G DUT. "Low SOC" shall be recorded when the test engineer turns off the inverter to avoid bringing SOC below a minimum value recommended by the vehicle manufacturer.
11. Repeat steps 2-10 for test conditions B and C as shown in Table 1 below. Fill in the table with the minimum of the 5-minute interval power readings for each of the three cases.
12. Repeat steps 1-11 for maximum and minimum allowable ambient temperatures as specified in the vehicle datasheet. Note the ambient operating temperature in Table 1. If the test facility is not capable of maintaining the required temperature conditions, it shall be clearly stated in the test report that the test was performed "without temperature control".

Table 1. Test Conditions for Continuous Power Output

Ambient Temperature (^oC)	Test	V_{AC} (V)	Continuous Power (W)
Nominal	A	V_{nom}	
	B	102% V_{min}	
	C	98% V_{max}	
Maximum	A	V_{nom}	
	B	102% V_{min}	
	C	98% V_{max}	

Minimum	A	V_{nom}	
	B	102% V_{min}	
	C	98% V_{max}	

Note: The response to abnormal voltages test (Section 5.1) must be performed to verify the actual undervoltage and overvoltage trip magnitudes, V_{min} and V_{max}.

5.1.3 Requirements

V2G converters that can connect to utility at multiple nominal AC voltages shall be tested separately for each nominal voltage.

In all test cases, the AC output will be measured on the utility side of any manufacturer-required transformer. If not supplied by the manufacturer, a transformer meeting or exceeding the manufacturer's minimum specifications will be used. Test records shall describe any transformers included in the measurements and state whether such transformers are supplied or required by the manufacturer.

The duration of this test will be determined in most cases by the battery size. The battery should be as close as possible to the 100% SOC (within manufacturer limits) at the beginning of the test. At the end of the test the battery should be at or near the lowest SOC allowed by the controls or by the vehicle manufacturer's specifications as described in the test step 10.

5.1.4 Criteria

This is a performance test; so there are no specific pass/fail criteria. In addition to tabular and graphical representation of the measured data, the test report should include the completed Table 1. The V2G DUT's "Continuous Output Power" at a specific temperature shall be stated as minimum of the three values (A, B, C) at that temperature as recorded in Table 1.

5.2 Conversion Efficiency

5.2.1 Purpose

This evaluation is intended to establish the conversion efficiency of the inverter between the vehicle battery and the AC output as a function of output power level.

5.2.2 Procedure

1. Maintain the ambient air temperature of the test chamber/room within ±3°C of the nominal operating temperature specified in the vehicles information datasheet. Write down the ambient operating temperature in Table 2, first column. If the test facility is not capable of maintaining the required temperature conditions, it shall be clearly stated in the test report that the test is performed "without temperature control".

2. Maintain the vehicle in an environment before testing to ensure that the DUT is relatively warm at the beginning of the test. This will bring the DUT to a stable operating temperature in a reasonably short period of time. If the heat sink temperature cannot be measured or if the V2G battery size does not allow the DUT to operate till thermal equilibrium without significantly discharging the battery, it must be described clearly in the test report as "without thermal equilibrium".
3. Connect the V2G DUT according to the instructions and specifications provided by the manufacturer.
4. Set the simulated utility to provide the nominal AC voltage (Table 2, test A).
5. Set (or verify) all V2G DUT parameters to the nominal operating settings.
6. Verify the battery SOC. If the battery SOC is less than 98% (or less than the manufacturer specified upper limit), stop the test and start charging the battery. Once charging is completed, repeat step 3-6.
7. Set the V2G DUT to provide as close as possible to 100% of its rated output power.
8. Record all applicable settings.
9. Measure and record the following values at 30 second intervals for at least 3 minutes (continuous sampling at higher data rates is preferred):

    Input voltage (DC and AC)

    Input current (DC and AC)

    Input power (average DC + AC RMS)

    Output voltage (AC)

    Output current (AC)

    Ambient temperature (°C)

    Inverter temperature at heat sink.

10. Repeat step 9 for the remaining Test A power levels or similar manufacturer's adjustable power levels as shown in Table 2. If the power levels cannot be adjusted, omit this step.
11. Repeat steps 2-10 for test conditions B through C in Table 2 by changing AC voltage.
12. Repeat steps 1-11 for maximum and minimum allowable ambient temperatures as specified in the vehicle datasheet. Note the ambient operating temperature in Table 2. If the test facility is not capable of maintaining the required temperature conditions, it shall be clearly stated in the test report that the test is performed "without temperature control".

Table 2: Test Conditions for Conversion Efficiency

Ambient Temperature (°C)	Test	V_{AC} (V)	Efficiencies at Inverter AC Output Power Level (%)				
			100%	**75%**	**50%**	**25%**	**10%**
Nominal	A	V_{nom}					
	B	102% V_{min}					
	C	98% V_{max}					
Maximum	A	V_{nom}					
	B	102% V_{min}					
	C	98% V_{max}					
Minimum	A	V_{nom}					
	B	102% V_{min}					
	C	98% V_{max}					

Note: The response to abnormal voltages test (Section 5.1) must be performed to verify the actual undervoltage and overvoltage trip magnitudes, V_{min} and V_{max}.

5.2.3 Requirements

V2G converters that can connect to the utility at multiple nominal AC voltages shall be tested separately for each nominal voltage.

In all cases for the above tests, the AC output will be measured on the utility side of any manufacturer-required transformer. If not supplied by the manufacturer, a transformer meeting or exceeding the manufacturer's minimum specifications will be obtained and used. Test records shall describe any transformers included in the measurements and state whether such transformers are supplied or required by the manufacturer.

If possible, the operation of advanced control strategies should be disabled to reduce the measurement error that would be associated with changes in operating point. If this is not possible, it is important that the monitoring equipment sampling rate must be at least 3-5 times the control systems sample interval. Suitable averaging must then be used to eliminate the influence of the control strategy.

5.2.4 Criteria

This is a performance test; so there are no specific pass/fail criteria. For each power level at each test condition, calculate and report: 1) average DC input power (average of sampled values), 2) average AC output power (average of sampled values), and 3) efficiency = average AC output power/average DC input power. The efficiency values should be entered into Table 2. The DUT's "Peak Efficiency" should be stated as the maximum of the forty-five averaged efficiency values recorded in Table 2. The DUT's "Nominal Average Efficiency" should be stated as the average of the nine efficiency values calculated for the 100%, 75%, and 50% output power levels for all test "A" conditions (designated by the shaded areas in Table 2).

6 Advanced Grid-Support Tests (optional)

Though V2G capable vehicle can provide peak power demand-response, it may not be economical since such a service is needed for just a few hours each year. The most promising markets for V2G are for those services that the electric industry refers to as ancillary services such as frequency regulation and spinning reserve. With today's battery technology, designing a V2G capable vehicle that can provide reserve capability will be easier than designing a vehicle that provides regulation. In this section, a general test procedure is given that is applicable to typical V2G vehicles that desire to provide reserve functions. Additionally another test procedure is developed that determines the charging time for the vehicle. This charging test is important to understand how often one can use the V2G vehicle to support grid reserve. In future, other test procedures will be developed for additional V2G capabilities such as reactive power control, voltage regulation and power quality control based on manufacturer's/customer's request.

6.1 Active Power Reserve

6.1.1 Purpose

The purpose of this test is to evaluate a V2G vehicle's capability to provide active power reserve to the utility using stored energy in vehicle's battery. This test is very similar to the test 5.1 except that the fact that we are measuring the duration for continuous output power at various power levels.

6.1.2 Procedure

1. Maintain the ambient air temperature of the test chamber/room within ±3°C of the nominal operating temperature specified in the vehicles information datasheet. Write down the ambient operating temperature in Table 3, first column. If the test facility is not capable of maintaining the required temperature conditions, it shall be clearly stated in the test report that the test is performed "without temperature control".
2. Maintain the vehicle in an environment before testing to ensure that the DUT is relatively warm at the beginning of the test. This will bring the DUT to a stable operating temperature in a reasonably short period of time. If the heat sink temperature cannot be measured or if the V2G battery size does not allow the DUT to operate till thermal equilibrium without significantly discharging the battery, it must be described clearly in the test report as "without thermal equilibrium".

3. Connect the V2G DUT according to the instructions and specifications provided by the manufacturer.
4. Set the simulated utility to provide the nominal AC voltage (Table 3, test A).
5. Set (or verify) all V2G DUT parameters to the nominal operating settings.
6. Verify the battery SOC. If the battery SOC is less than 98% (or less than the manufacturer specified upper limit), stop the test and start charging the battery. Once charging is completed, repeat step 3-6.
7. Set the V2G DUT to provide as close as possible to 100% of its rated output power.
8. Record all applicable settings.
9. Initiate the external start signal that operates the V2G in the discharging mode.
10. Determine the starting time (T_start) and note it in Table 3. T_start denotes the time between the start signal initiation and when the V2G power generation reaches 90% of the targeted output power level (Figure 4).
11. Measure and record the following values at 10 minute intervals until end-of-test is reached as described in the following step 12. A continuous sampling at higher data rates and 10-minute averages is preferred for the following values:

    Time

    Output voltage (AC)

    Output current (AC)

    Ambient temperature (°C).

12. End test when the DUT output folds back to 90% of the specified power or the DUT shuts down or the battery SOC reaches the manufacturer's recommended minimum value. Record the reason for end-of-test as "Foldback," "Shutdown," or "Low SOC" as appropriate. Note down the time when end-of-test occurs.
13. Repeat steps 2-12 for the remaining Test A power levels or similar manufacturer's adjustable power levels as shown in Table 3. If the power levels cannot be adjusted, omit this step.

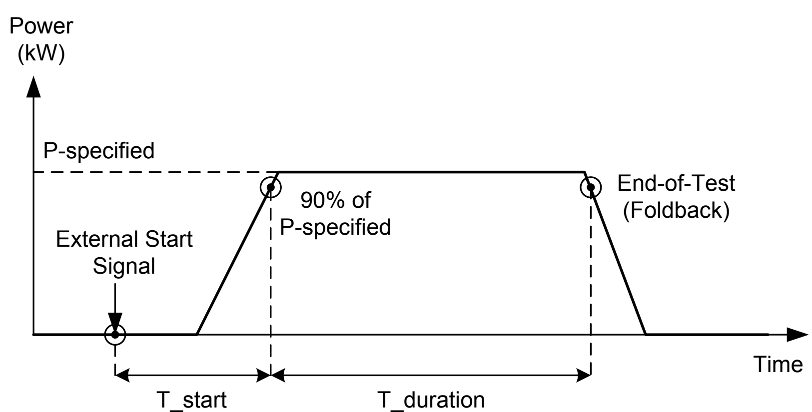

Figure 4. Power profile for a typical V2G converter during test with foldback

14. Repeat steps 2-13 for Test conditions B and C in Table 3 for different AC voltages.

15. Repeat steps 1-14 for maximum and minimum allowable ambient temperatures as specified in the vehicle datasheet. Note the ambient operating temperature in Table 3. If the test facility is not capable of maintaining the required temperature conditions, it shall be clearly stated in the test report that the test is performed "without temperature control".

Table 3. Test Conditions for Active Power Reserve

Ambient Temperature (°C)	Test	V_{AC} (V)	T_start (s)	Duration for Continuous Output Power at Various Power Levels (s)			
				100%	75%	50%	25%
Nominal	A	V_{nom}					
	B	102% V_{min}					
	C	98% V_{max}					
Maximum	A	V_{nom}					
	B	102% V_{min}					
	C	98% V_{max}					
Minimum	A	V_{nom}					
	B	102% V_{min}					
	C	98% V_{max}					

Note: The response to abnormal voltages test (section 5.1) must be performed to verify the actual undervoltage and overvoltage trip magnitudes, V_{min} and V_{max}.

6.1.3 Requirements

V2G converters that can connect to utility at multiple nominal AC voltages shall be tested separately for each nominal voltage.

In all cases for the above tests, the AC output will be measured on the utility side of any manufacturer-required transformer. If not supplied by the manufacturer, a transformer meeting or exceeding the manufacturer's minimum specifications will be obtained and used. Test records shall describe any transformers included in the measurements and state whether such transformers are supplied or required by the manufacturer.

6.1.4 Criteria

This is a performance test; so there are no specific pass/fail criteria. The test report must include completed Table 3, showing the time duration for which the V2G is supplying the specified amount of power. For each test case, this can be calculated from the recorded time between V2G power generation starting time and end-of-test time. For each of the power levels, the minimum of the nine duration times recorded in Table 3 should be stated as “Minimum Active Power Supply Duration” for that particular power level.

6.2 Charging Time

6.2.1 Purpose

The purpose of this test is to determine the time required to fully charge a V2G vehicle using manufacturer recommended charging method from a specified starting state-of-charge at a specified ambient operating temperature.

6.2.2 Procedure

1. Maintain the ambient air temperature of the test chamber/room within ±3°C of the nominal operating temperature specified in the vehicles information datasheet. Write down the ambient operating temperature in Table 4, first column. If the test facility is not capable of maintaining the required temperature conditions, it shall be clearly stated in the test report that the test is performed “without temperature control”.
2. Maintain the vehicle in an environment before testing to ensure that the DUT is relatively warm at the beginning of the test. This will bring the DUT to a stable operating temperature in a reasonably short period of time . If the heat sink temperature cannot be measured or if the V2G battery size does not allow the DUT to operate till thermal equilibrium without significantly changing the battery SOC, it must be described clearly in the test report as “without thermal equilibrium”.
3. Discharge the battery to the lowest SOC possible and note that value in the Table 4.
4. Connect the V2G DUT’s charger according to the instructions and specifications provided by the manufacturer.
5. Set the simulated utility to provide the manufacturer specified AC charging voltage.
6. Set (or verify) all charger parameters to the nominal operating settings.
7. Record all applicable settings.
8. Start the charging and note down the start time.
9. Measure and record the following values at 10 minute intervals until the battery SOC reaches 100%. A continuous sampling at higher data rates and 10-minute averages is preferred for the following values:

    Time

    Input voltage (AC)

    Input current (AC)

    Battery SOC (%)

    Ambient temperature (°C).

10. Repeat steps 2-9 for the remaining test A SOC levels given in Table 4. During step 3, to attain each SOC level either charge the vehicle if the battery SOC is lower or discharge the

vehicle to the grid if the battery SOC is higher. If SOC is not available, battery voltage levels may be used as a proxy (or instead of) for SOC.

11. Repeat steps 1-10 for maximum and minimum allowable ambient temperatures as specified in the vehicle datasheet. Note the ambient operating temperature in Table 4. If the test facility is not capable of maintaining the required temperature conditions, it shall be clearly stated in the test report that the test is performed "without temperature control".

Table 4: Test Conditions for Charging Time

Ambient Temperature (ºC)	**Test**	**Time Taken to Fully Charge Starting from Various SOC (s)**					
		Lowest%	30%	45%	60%	75%	90%
Nominal	A						
Maximum	B						
Minimum	C						

6.2.3 Requirements

V2G chargers that can connect to utility at multiple nominal AC voltages shall be tested separately for each nominal input AC voltages.

6.2.4 Criteria

This is a performance test; so there are no specific pass/fail criteria. The test report must include completed Table 4, showing the time required to fully charge the vehicle from a specific SOC at a certain temperature. Also a family of curves showing the time to charge versus various starting SOCs and various operating temperatures should be developed.

7 V2G Self-Protection Tests (optional)

This section describes tests that are meant to evaluate the V2G power electronics' ability to protect themselves under various abnormal conditions. These tests are obtained from UL Standard 1741 "Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources". If the V2G vehicle comes with power converters that are UL1741 certified, factory test results may suffice in lieu of further third-party or owner testing.

7.1 Output Overload

This procedure ensures the DUT will not become a hazard when subjected to load conditions in excess of its ratings. The details of the test can be found in UL 1741, Section 47.2.

7.2 Short Circuit

The purpose of this test is to characterize the V2G converter's response when subjected to an output-faulted condition. The details of the test can be found in UL 1741, Section 47.3.

7.3 Loss of Control Circuit

The protective utility connect functions become disabled when control power is lost. Under these conditions, a utility interactive converter must cease to export power to the utility upon loss of control circuit power. The details of the test can be found in UL1741, Section 47.8.

8 References

Bower, W; Behnke, M.; Erdman, W.; Whitaker, C (2004). *Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems*, available for download at http://www.bewengineering.com.

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NFPA 70E: Handbook for Electrical Safety in the Workplace (2004). National Fire Protection Association.

NREL Lock Out/ Tag Out Procedures.

UL 1741 (2005), Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources.