ELECTRIC POWER RESEARCH INSTITUTE

Laboratory Evaluation of Grid-Tied Photovoltaic and Energy Storage Systems

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Technical Update, December 2011

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ABSTRACT

Output variability of a PV power plant is an important issue for wide-spread grid integration. Combining energy storage with PV is one way to help manage variability. In prior work EPRI conducted a side by side test regiment on several Distributed Energy Storage Systems (DESS) with grid support capabilities in the 25 to 50 kW and 12.5 to 82 kWh range, reported in 1021935. Two of these battery systems included PV plant support algorithms.

The work discussed here covers further evaluation of energy storage to support PV plant operations and defines PV-specific functionality. To accomplish this, five different PV support functions are defined and evaluated as to their ability to mitigate the variable nature of PV power output. These are time shifting, energy scheduling, smoothing, load following, and ramp rate reduction. The DES systems evaluated for PV support were manufactured by Greensmith and rated at 50 kVA/ 82 kWh and 25 kVA/50 kWh.

This report describes the test procedures, results, and recommended future research related to applying energy storage to support PV. Grid compatibility, energy performance and PV support capabilities are covered. Two control algorithms built-in the DESS were configured in different ways to evaluate the five different PV support functions defined in this technical update report.

Keywords

Solar photovoltaic (PV)
Electrical energy storage
PV intermittency
Solar time shifting
Solar smoothing
Solar energy scheduling
Load following with solar
Solar ramp rate reduction

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1
INTRODUCTION

In 2010, U.S. photovoltaic (PV) installations almost doubled to an estimated 820 MW, up from 435MW in 2009. Grid-connected solar in the US is expected to double again by the end of 2011. Utility are seeing increasing interconnection requests for large numbers and sizes of distributed PV on their power distribution circuit. And utility planners are expected to face many challenges in the grid integration of renewable generation as relative numbers and penetration level increase.

Among other factors, managing the inherent variable nature of photovoltaic (PV) systems is a key challenge. The power output from a grid-connected PV system can drop rapidly due to shading from overhead clouds. Power production can also rise very fast when clouds clear and can even exceed the nominal output of the PV plant due to cloud enhancement. Figure 1-1 shows the AC power production of a 1 MW PV system in East Tennessee on a cloudy day. Figure 1-2 highlights one ramp event from the Figure 1-1 PV output. In this particular example, ramp rates are close to 1.8 MW/min. Ramp rates > 100 MW/min are possible and pose a threat to grid stability at high penetration rates.

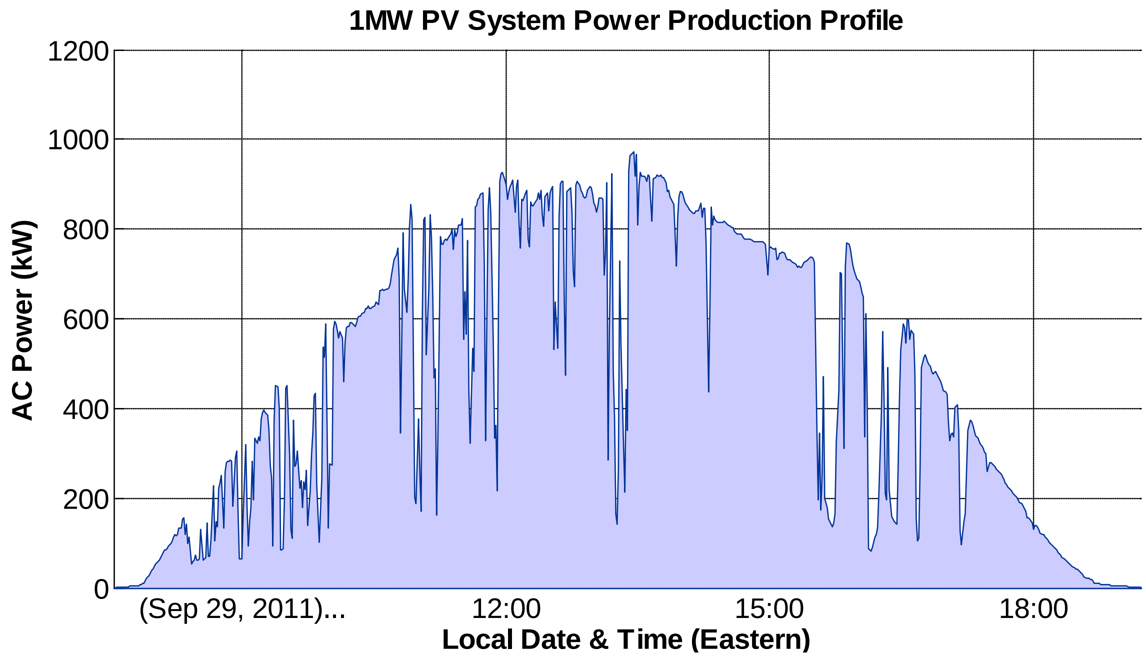

Figure 1-1
Power Production Profile of a 1MW PV Plant on a Cloudy Day in East Tennessee

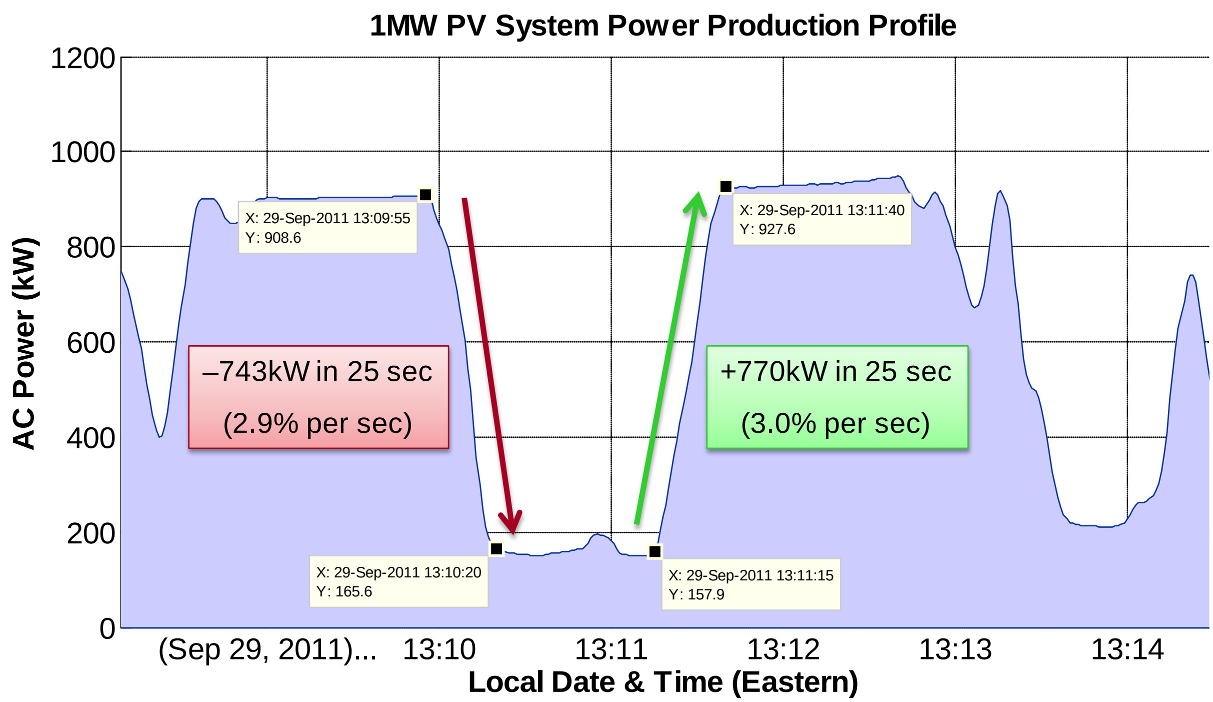

Figure 1-2
1MW PV System's Sample Power Ramp Event Due to Passing Cloud

Step changes in PV plant output can also occur when several inverters trip simultaneously. In some cases, for example when a large PV system is connected to a relatively small grid or at the end of a relatively low capacity, high impedance feeder, rapid power production change can make it difficult to regulate voltage. Complete loss of PV generation due to protection or nuisance tripping events are less likely than cloud induced changes, but more severity. Currently, these trips are expected as inverters are required to shut off when grid voltage and/or frequency deviate from narrow tolerance range. Onsite energy storage can mitigate or at least minimize the wind and PV power fluctuations.

Combining energy storage with PV is one way to help manage variability. A combination of industry drivers – including increased deployment of distributed renewable generation, the high capital cost of managing grid peak demands, and large investments in grid infrastructure for reliability and smart grid initiatives – is creating new interest in electric energy storage systems. An energy storage system typically integrates a battery bank with battery management system, an energy management system, and a power electronics interface for bidirectional four quadrant AC-DC power conversion. The energy storage system is connected to the power grid in a shunt configuration, often in parallel with a renewable power generating facility or critical load.

Onsite energy storage can mitigate or at least minimize the PV power fluctuations. Energy storage can also defer T&D asset investments; supply frequency regulation, spinning reserve, and off-peak wind and PV energy storage; provide load leveling for energy arbitrage opportunities; and mitigate output fluctuations to enable greater usage of solar generating assets. When properly deployed and integrated, these storage systems have the potential to improve the reliability and efficiency of the energy delivery network and pave the way for higher penetration of variable renewable resources onto the grid.

In 2011 EPRI's Energy Storage research program evaluated the following five Distributed Energy Storage Systems (DESS) at in EPRI's Knoxville laboratory:

- 50 kW/46 kWh unit from BYD
- 50 kW/82 kWh unit from Greensmith, Power Vault 80, with International Battery
- 25 kW/48 kWh unit from NEC
- 25 kW/12.5 kWh unit from Beckett Energy Systems and
- 25 kW/50 kWh unit from Greensmith, Power Vault 50, with Boston Power Battery

The two Greensmith systems included built-in control algorithms designed for support photovoltaic integration. They designate these algorithms as "renewable ramp rate control" and "renewable and load following." Both are site configurable. EPRI engineers configured the two algorithms in different ways to demonstrate the use of energy storage to mitigate PV power output variability in five different ways. These were:

1. **Solar Time Shifting:** Energy storage shifts PV output to better match peak load (1-4 hours)
2. **Solar Energy Scheduling:** Storage enables PV output to meet an energy schedule commitment
3. **Solar Smoothing:** Charging or discharging smoothes daytime PV output variations
4. **Load Following with Solar**: Energy storage plus PV output follows a prescribed demand curve
5. **Solar Ramp Rate Reduction:** Storage supports the control of PV ramp rates, both up and down

This report describes the test procedures, results and recommended future research related to applying energy storage to support PV. Chapter 2 describes the system under test. Chapters 3 and 4 cover the grid compatibility and energy performance test results. In chapter 5 energy storage support functions for mitigation of variability are further defined and demonstrated. Conclusions and recommendations for future work are included in chapter 6.

2

DISTRIBUTED ENERGY STORAGE SYSTEM (DESS) UNDER TEST

This chapter provides an overview of the distributed energy storage system (DESS) that was evaluated to demonstrate energy storage support to reduce PV output variability. This DESS, which incorporates some PV integration algorithms, is one of the five systems tested in EPRI's Knoxville laboratory under the 2011 EPRI energy Storage base program.

Greensmith DES System Overview

This section provides a detailed overview of the DES systems provided by Greensmith Energy Management System, LLC. These systems are basically integration of Greensmith energy management controller, a Satcon power conditioning system (PCS), and International Battery (in Power Vault 80) or Boston Power (in Power Vault 50) battery modules. The Greensmith controller manages operation of the full DESS by communicating between PCS and the battery management system. The controller also communicates with users through web based graphical user interface (GUI) and issues charge/discharge commands to the PCS using Modbus protocol. The battery cabinet, which is a NEMA 3 enclosure, is designed for easy access to batteries and components, integrated safety features, and versatility to host a variety of options. Figure 2-1 and Figure 2-2 show the unit as installed in EPRI's Knoxville laboratory outside test bay.

Figure 2-1
Greensmith Power Vault 50 installed in EPRI's Knoxville Laboratory

Figure 2-2
Rear Side of the Greensmith Power Vault 50

Table 2-1 below shows the different manufacturer of the DESS components.

Table 2-1
Greensmith DES System Summary

Scope of Supply	Company, Location	Description
System Integrator	Greensmith Energy Management Systems Bethesda, MD	
Power Conversion System	Satcon Technology Boston, MA	50 kVAR / 50 kW bi-directional PCS (Software limited to 25 kW for Power Gate 50)
Battery in Power Vault 80	International Battery Allentown, PA	Lithium iron phosphate, prismatic format 82kWh (20 X 160Ah, 25.6V modules), Includes Battery Management System
Battery in Power Vault 50	Boston Power (BP) Westborough, MA	Lithium-ion, cylindrical format, 50 kWh

Highlights of the Greensmith DES Systems include:

- Web browser based graphical user interface
- Swappable battery module trays
- Four quadrant operation – DESS can source and sink real power (kW) and reactive power (kVAR)

- Renewable ramp rate control mode – DESS attempts to limit the net ramp rate of the DESS integrated with a PV system to mitigate ramp-related grid impacts
- Renewable and load following mode – DESS attempts to negate any change in PV system output or load

Power Conversion System (PCS)/Inverter

The Satcon Power Gate Plus PCS utilized in the Greensmith DES systems is a commercial unit with UL 1741 certification as a grid-tie PV inverter only, not as a bi-direction converter. Extended grid compatibility testing was considered low priority for this system and was not executed during the 2011 research year. The Greensmith Power Vault 80 has the added capability to provide four quadrant operations. This functionality was demonstrated by Greensmith engineers during a site visit, but not formally tested by EPRI engineers due to the web-based GUI not fully supporting the function during testing.

The Satcon inverter is rated at 50 kW/50 kVA for both AC-to-DC and DC-to-AC operation. It can be commanded to provide or sink reactive power up to 0.8 leading and lagging power factor. Although there is limited control available on the front of the unit, most of the control functions are disabled. Instead, the Greensmith controller sends Modbus commands to the inverter's RS-485 serial interface. There is an indicator light on the front of the inverter to indicate that it is active, and an on/off switch that can activate/deactivate the inverter without opening the input breakers. Figure 2-3 shows the Satcon PCS as installed in EPRI Knoxville laboratory's outdoor test bay. Figure 2-4 shows different key components inside the Satcon inverter.

The Greensmith controller for this system is mounted on the side of the battery cabinet in a NEMA 3 enclosure. The Satcon specifications from its manual are contained in Appendix B as reference. These include the range of AC and DC voltages appropriate for the inverter, as well as information on the fault protection included within the unit. AC power rating of the unit was software limited to 25kW/25kVA for the Greensmith Power Gate 50 unit.

Figure 2-3

Satcon Power Conditioning System

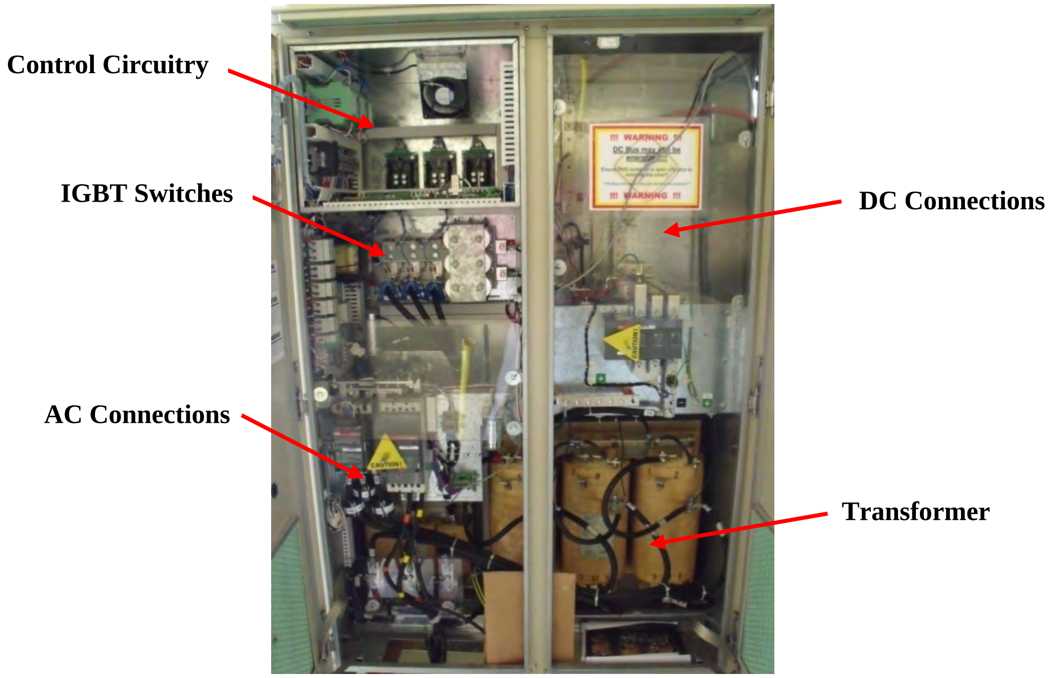

Figure 2-4
Inside View of the Satcon Inverter

Boston Power Battery

The battery used in Power Vault 50 DESS is produced by Boston Power and integrated into the system by Greensmith with the Satcon inverter. Table 2-2 gives a summary of this battery. The system includes a battery connection box containing 500 A DC fuses and battery monitoring systems are integrated into each battery tray. The data from the battery monitoring system feeds into the control box for collection of the individual battery cell parameters.

Table 2-2
Boston Power Battery Specification Summary

Item	Parameter
System Capacity/Energy	50 kWh
Nominal Battery Voltage	not specified
Cell Chemistry	Lithium Iron Phosphate
Nominal Cell Voltage	not specified
Cells per Module	not specified
Modules per System	not specified

International Battery

The battery used in the Power Vault 80 DESS is produced by International Battery (IB) and integrated by Greensmith with the Satcon inverter. Table 2-3 gives a summary of the battery used in this system. This system also includes a battery connection box containing a 500A fuse and a battery monitoring system. The data from the battery monitoring system feeds into the Greensmith box for collection of the individual battery cell parameters.

Table 2-3
International Battery Specifications Summary

Item	Parameter
System Capacity/Energy	160 A-hr/82kWh
Nominal Battery Voltage	not specified
Cell Chemistry	Lithium Iron Phosphate
Nominal Cell Voltage	3.2Vdc
Cells per Module	8
Modules per System	20

Software and Communications

Greensmith provides two remote control options:

- Modbus/ TCP based control interface for real time system integration.
- Web portal based graphical interface for user to remotely monitor and control units over internet using web browsers. This requires username and password.

The Greensmith web portal-based control system is unique in that the control box located at the inverter connection (via an Ethernet connection) to the internet, and accesses the control server periodically to check for start and stop commands. This configuration eliminates the necessity of creating firewall exceptions for incoming communications since the Greensmith box initiates its communications with the control server. It also results in a slight delay between commands and the system's ability to execute them (typically less than 20 seconds).

Since the Greensmith system is controlled through a webpage, it presents the user with many more options and more information than the typical human machine interface. Figure 2-5 shows the home screen of the web interface. A map shows the location of each system available for control or monitoring. Clicking on a system brings up the system nameplate information, as well as energy available, charge capacity, output power, and total energy in and out of the system.

Once a device is selected on the map or the device list at the left of the screen, the "Operation," "Configuration," and "User" tabs at the top of the webpage allows users to navigate to the appropriate pages. The "Operation" page allows the user to schedule charge and discharge events. Note that all events on the Greensmith system must be scheduled, so there are no "Charge" or "Discharge" buttons. Figure 2-6 shows the Operation tab page showing the available events (functions). Clicking on the events within the "Dispatch" tab allows the user to schedule these events. "Summary" tab shows the even log.

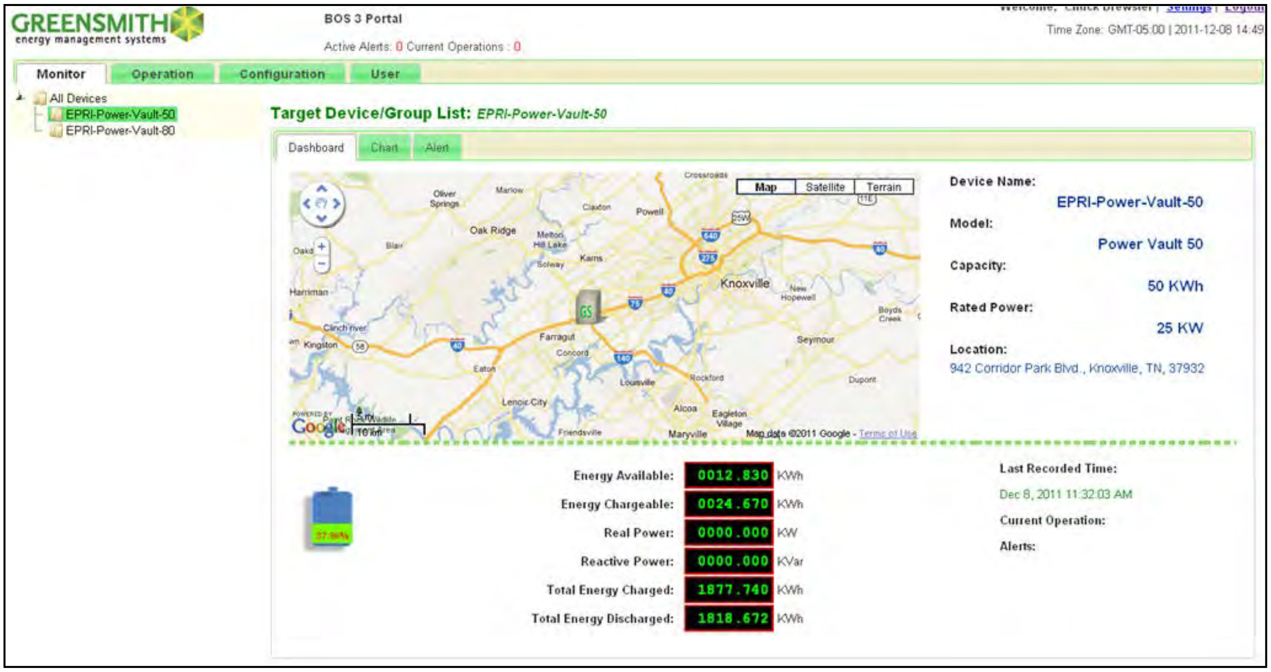

Figure 2-5
Greensmith Web Portal Home Screen

Figure 2-6
Greensmith Event (Function) Options

This report presents the use of the "Renewable Ramp Rate Control" and "Renewable and Load Following" events to demonstrate how storage can be utilized to mitigate PV intermittency issues. For most of PV integration tests Greensmith Power Vault 50 DES unit was used. Detail performance metrics of both the Greensmith DES systems and comparison with other DESS units tested at EPRI is included in a separate report entitled "Testing and Evaluation of Distributed Energy Storage Systems – 2011 Interim Report."[1]

[1] *Testing and Evaluation of Distributed Energy Storage Systems – 2011 Interim Report*. EPRI, Palo Alto, CA: 2011: 1021935

3
DESS BASIC OPERATION AND GRID COMPATIBILITY TESTS

This chapter describes the basic operation and grid compatibility tests that were conducted for the Greensmith DES systems. Test procedures and sample results are shown to better explain each test. Test results specific to the Greensmith DES systems evaluated in EPRI's Knoxville laboratory are also included here.

Basic Commands

The Basic Commands testing verified that the Distributed Energy Storage System will turn on and off when commanded, and shut down properly following the loss of utility voltage. Systems that do not perform consistently during these tests may not be safe to connect to the power grid. Figure 3-1 shows the setup used for the basics commands tests.

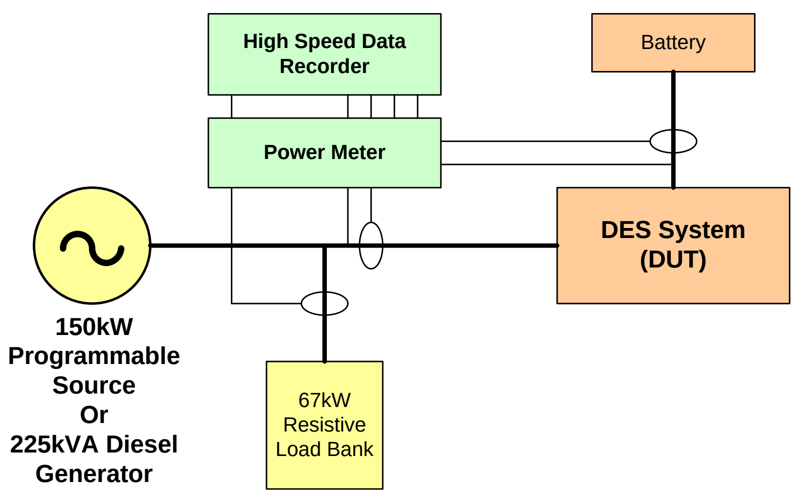

Figure 3-1
Setup for Basic Commands Test

Test Procedure

The following test protocol was executed for the Greensmith system:

1. Connect the device under test (DUT), source, and load as shown in Figure 3-1 above.
2. With the DUT in discharge mode, de-energize the utility bus and verify the system shuts down.
3. With the DUT in charge mode, de-energize the utility bus and verify the system shuts down.
4. With the utility bus energized, command the DUT to turn on and observe its behavior. Repeat this step using any secondary control communication such as a remote interface.

5. With the utility bus de-energized, command the DUT to turn on. Compare the results of this step with the previous and confirm the unit does not energize the utility bus. Repeat using any secondary control communication.
6. With the utility bus energized and the DUT on, command the DUT to turn off and observe its behavior. Repeat this step using any secondary control communication.
7. Confirm the function of any safety disconnects or Emergency Power Off (EPO) features. Also, take note of any protection controls such as an Over-Temperature auto-cutoff.

Utility Failure while in Discharge Mode

This test characterizes the behavior of the system to a utility failure while it is sourcing current in discharge mode. It is important for the system to suspend output power in the event the utility or connected power source suffers a failure in order to prevent damage to connected loads and service personnel. Figure 3-2 illustrates this test and an acceptable result.

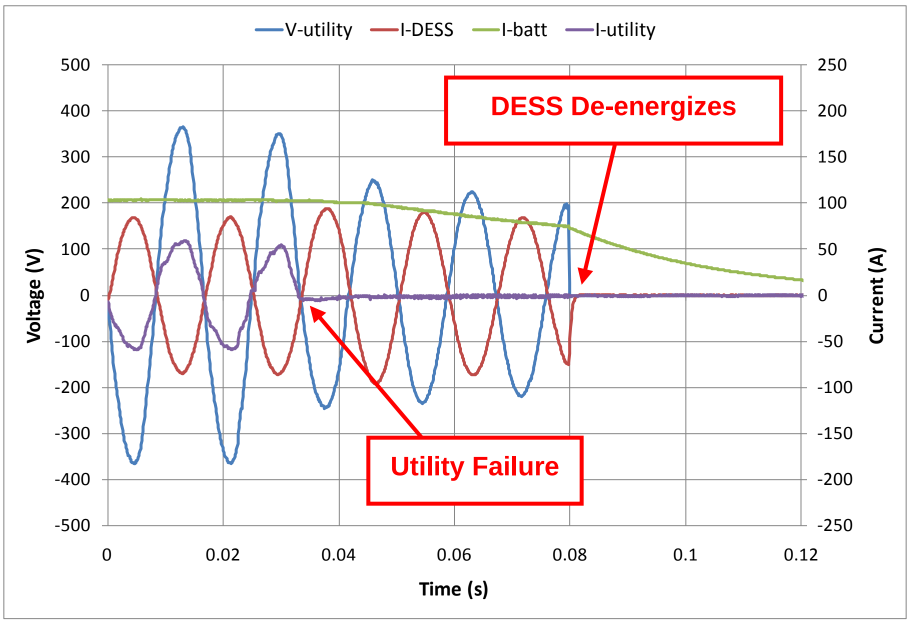

Figure 3-2
Illustration of a DES System De-energizing Following a Utility Failure

Utility Failure while in Charge Mode

This test characterizes the response of the DES system to a utility failure during a charge cycle. This condition is less likely to present a safety hazard than utility failure during discharge since the DES system acts as a load rather than a source. However, it is still important for DES systems to recognize that the local utility grid is no longer present and cease charging in a safe manner. The ideal result of this test is much like the example provided above for a utility failure during discharge with the exception that power flows into the DES system during this test.

Utility Energized Startup

This measures the startup profile of the DES system. The profile is typically the same whether the unit is charging or discharging, and usually consists of a ramp up of charge/discharge current over the course of a few seconds. Figure 3-3 illustrates this behavior during the beginning of a full power discharge.

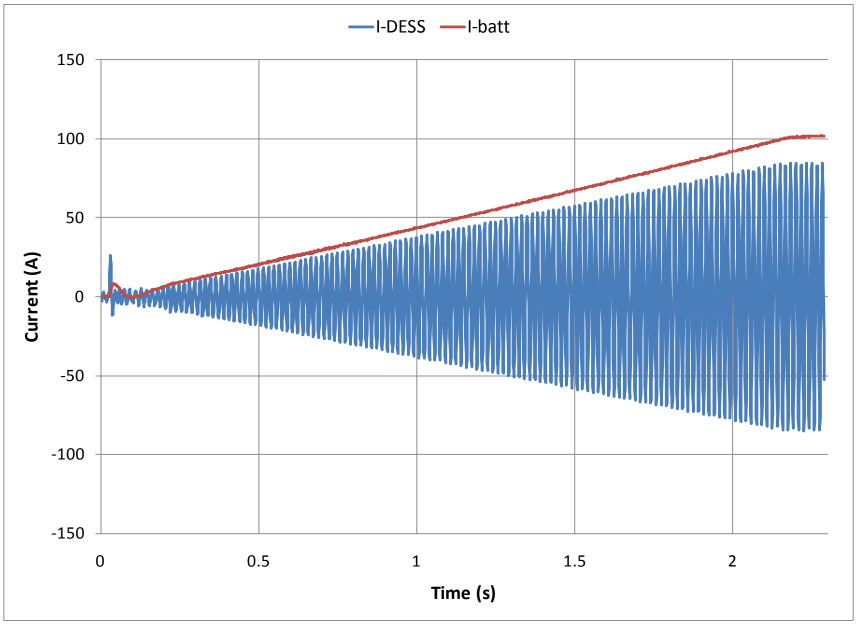

Figure 3-3
Illustration of a DES System Startup Profile

Utility De-Energized Startup

This test is a simple functionality test intended to verify that a DES system will not start and energize its output when no voltage is present. This behavior is important since these systems can cause equipment damage and be hazardous to maintenance personnel if they are capable of energizing a utility bus in an island condition.

Utility Energized Shutdown

This test simply verifies that the DES system shuts down when commanded to do so. EPRI assesses both remote shutdown commands and HMI (in person) shutdown methods when available on any system. In either case, the unit should respond within a few minutes of commanding a shutdown.

Emergency Power off Function

This test verifies that any emergency power off (EPO) switch that may be present on the device operates properly. This procedure consists of pressing the EPO button during discharge at full capacity. Unsatisfactory performance must be corrected before continuing with device testing. Figure 3-4 shows a sample recording of proper EPO button operation for a DES system. Each system should immediately de-energize the utility bus and render the system safe for maintenance as quickly as possible following activation of the EPO switch.

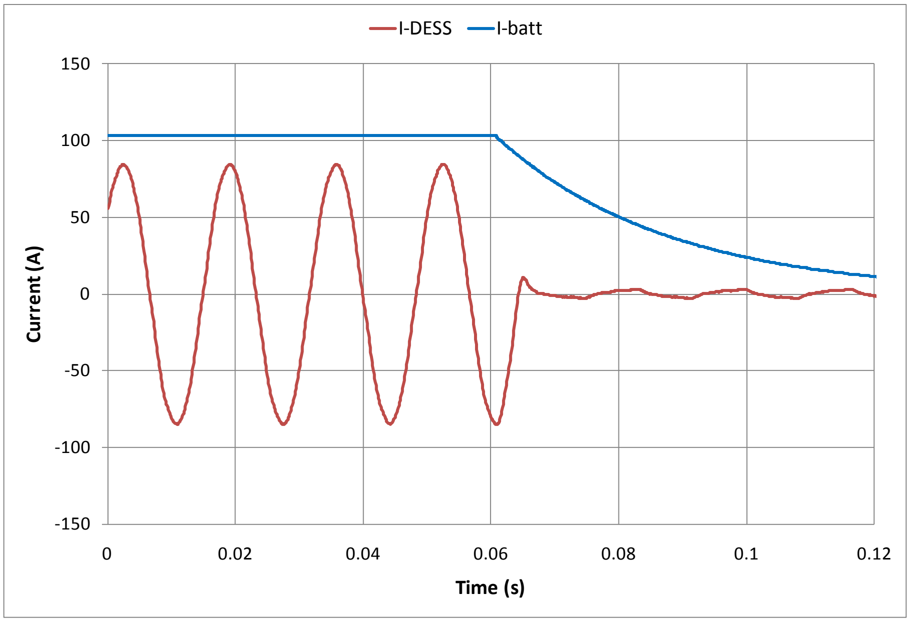

Figure 3-4
Illustration of Emergency Power Off (EPO) Switch Operation.

THE ILLUSTRATIONS IN THIS SECTION REPRESENT GENERAL GRAPHICAL RESULTS FROM THE CORRESPONDING TEST AND DOES NOT PERTAIN TO THE GREENSMITH SYSTEM TESTS IN PARTICULAR. IT PROVIDES A BASIS FOR UNDERSTANDING THE TABULAR PRESENTATION OF DATA BELOW.

Greensmith DESS Test Results

The Greensmith systems (both Power Vault 50 and Power Vault 80) employ the same 50 kW Satcon PCS. For the Power Vault 50 system its maximum power was limited to 25 kW (software limited). It has a RS 232 based local control interface. It can also be commanded and monitored over a network using a proprietary interface. The local control also includes two breakers (AC and DC) mounted on the Satcon Inverter and two toggle switches located on the Greensmith integration box for turning on/off the Battery Management System and Energy Management Systems. All of the Basic Commands testing was performed using the web-based Greensmith remote control portal. Table 3-1 contains the results of the Basic Commands testing. Each test used charge and discharge commands equal to the full rated capacity of the system (25 kW).

The Greensmith integration system is powered off a separate 120 V power source from the 120/208 V feed used to connect the inverter to the grid. As a precaution, a utility failure on the integration box only while the system was in discharge mode was tested. The results of this test are included in Table 3-1 as Procedure Step Number 2a. Note that this is an unlikely situation since a typical installation would power the Greensmith integration system from the same utility source as the inverter.

Table 3-1
Basic Commands Test Results Overview

Procedure Step Number	Tested Action	DUT Behavior	Result (pass/fail)
2	Utility fail in Discharge mode	Ceased discharge operation	Pass
2a	Utility fail on Greensmith integration box only	Battery contactor open; operation interrupted	Pass
3	Utility fail in Charge mode	Ceased charge operation	Pass
4	Utility energized startup	Turned on to operation within a minute	Pass
5	Utility de-energized startup	Did not respond to user remote command	Pass
6	Utility energized shutdown	DUT de-energized when commanded	Pass
7	Emergency Power Off Function	The front panel EPO button successfully shutdown the unit and tripped all the breakers.	Pass

System Basic Performance

The purpose of this test is to record the utility bus voltage and current with the DUT attached, record the DC voltage and current of the battery, and verify the ability of the system to charge and discharge at full rated capacity. This test verifies the system operates properly and the voltage and current waveforms on the AC and DC sides of the PCS are within manufacturer's specifications. The results also serve as a reference of the performance prior to subjecting the unit to any further evaluation testing.

Test Procedure

1. Monitor input/output voltage and current and if possible, record the battery voltage and current. Record the waveforms at a high sample rate (~10 kHz) for later analysis.
2. Verify the batteries are at a full charge. It may be necessary to initiate a few charge cycles followed by a short rest period.
3. Initiate a discharge at full rated capacity for a few seconds and record the resulting waveforms.
4. Discuss any discrepancies between the test results and the manufacturer's ratings with the project manager and/or the manufacturer. Perform this step before proceeding to any additional testing.

Greensmith Power Vault 80 Test Results

The Greensmith Power Vault 80 system is rated for 50 kW for charge and discharge. Initial performance testing showed a 50 kW charge command resulted in a ~52 kW charge rate and a 50kW discharge command resulted in a ~48 kW discharge rate. At full discharge, battery current is ~104 A with no measurable ripple. Figure 3-5 shows the AC and DC waveforms recorded during initial performance testing. EPRI noted nothing unusual with the Greensmith/IB system's operation.

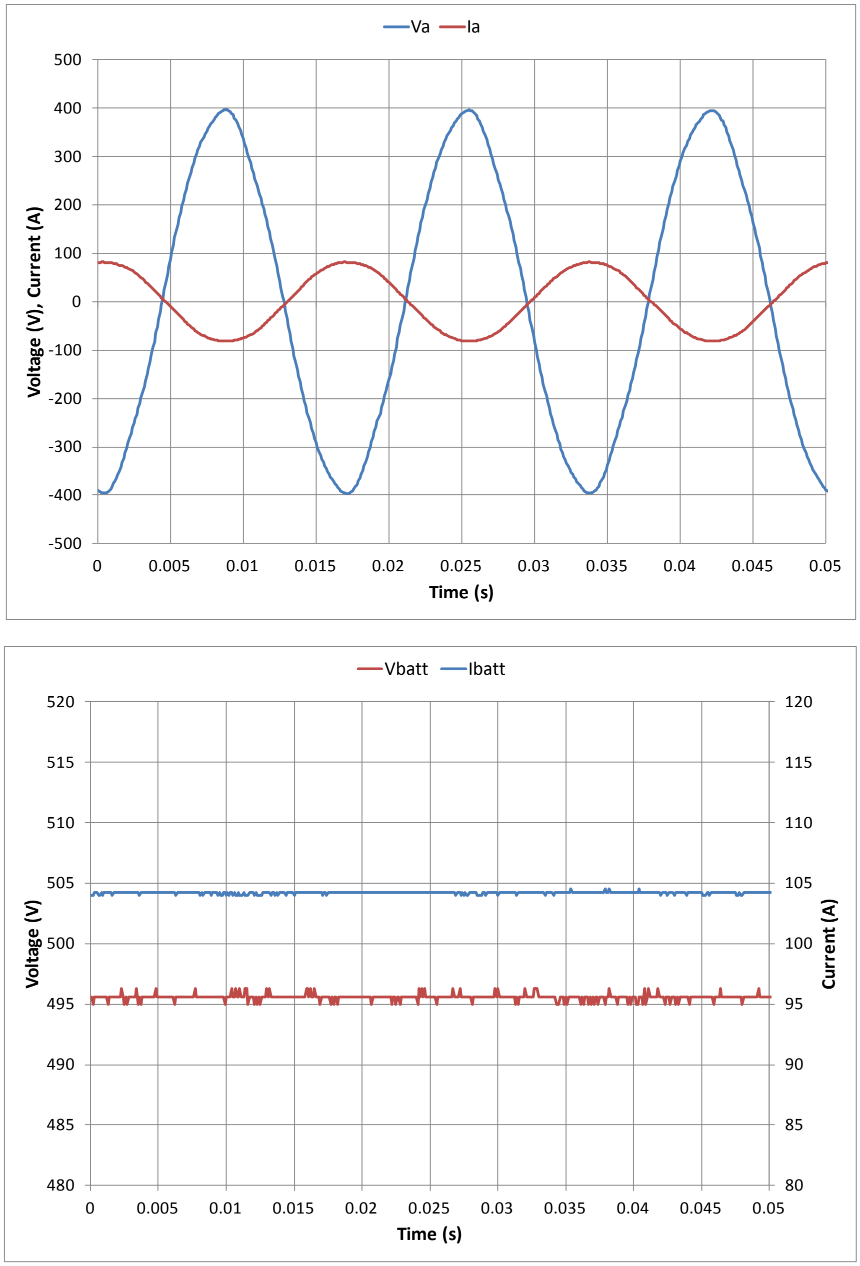

Figure 3-5
Greensmith Power Vault 80 System AC (Top) and DC (Bottom) Steady-State Voltage and Current Waveforms

The Greensmith Power Vault 50 system uses the same Satcon inverter as the Greensmith Power Vault 80 system. The only difference in the two systems is the battery, which should not affect the results of this test.

Unintentional Islanding

This test is adapted from IEEE standard 1547.1. The purpose is to verify that a DES system will disconnect from the grid within two seconds following an islanding condition (loss of upstream grid connectivity). This helps ensure a safe work environment for line maintenance crews by preventing these systems back-feeding from sections of the grid that should be de-energized.

Simply disconnecting grid power from the DES system is not sufficient to ensure a safe work environment. Instead, this test creates a “worst case” condition for recognizing the loss of grid power in which a resistive, inductive, and capacitive (RLC) load resonates, to create the impression that a source is still connected to the system after the true source has been disconnected. DES systems must be able to recognize the sudden rise in source impedance associated with the loss of the real source and react accordingly.

NOTE THAT THIS TEST DOES NOT ADDRESS ANY DOWNSTREAM ISLANDING CAPABILITIES, ONLY LOSS OF GRID POWER.

Test Procedure

During the unintentional islanding test, an RLC load becomes tuned to unity quality factor at the full power level of the DES system. In this condition, current equal to the resistive load current oscillates between the L and C components in the load. Prior to reaching resonance, the DES system supplies the load’s real power, and the source satisfies the load’s reactive power requirement. When properly tuned, the load resonates and requires very little current from the source. The IEEE 1547 standard specifies that the load is sufficiently resonant when the current from the source drops below 2% of the DUT’s full rated current and its quality factor (Q_f) is 1.0 ± 5%. For the purpose of this test, quality factor is defined as:

This means that the reactive power circulating between the L and C load components is equal to the real power going to the load. Satisfaction of the standard source current requirement takes place during the test, as the RLC load is tuned to resonance. The quality factor of the load is calculated based on the R, L, and C values used in the test. The quality factor requires that the resonant current is sufficient to create the impression of an additional source on the system (circulating current equal to the current from the DES system). The challenge for the DES system is to recognize when the true source is disconnected, leaving only the resonant load source.

Figure 3-6 shows the equipment setup for the Unintentional Islanding Disconnect test. It is important to note that while this test is derived from the IEEE 1547 standard, it is not a compliance test. This test is only intended to give a general indication of performance if and when the IEEE 1547.1-2005 Unintentional Islanding Test is conducted for certification.

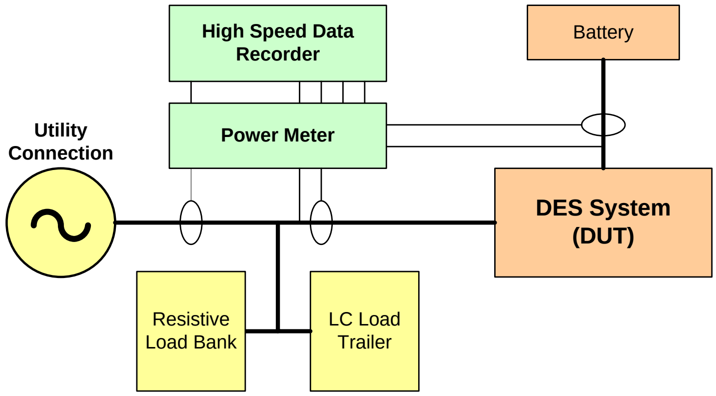

Figure 3-6
Unintentional Islanding Test Setup

> NOTE THAT THIS TEST DOES NOT ADDRESS ANY DOWNSTREAM ISLANDING CAPABILITIES, ONLY LOSS OF GRID POWER.
>
> THE TEST RESULTS PRESENTED HERE SHOULD NOT BE CONSIDERED A CERTIFICATION OF COMPLIANCE WITH THE 1547 STANDARD.

Procedure

1. Connect the DUT, load, and power source as shown in Figure 3-6.
    a. Single Phase: Connect RLC load between phase and neutral.
    b. Three Phase Three-Wire: Connect RLC load between phases.
    c. Three Phase Four-Wire: Connect RLC load between each phase and ground
    d. Ground Connection: DO NOT switch ground connection.
2. Set AC source to nominal voltage (+/- 2%) and to nominal frequency (+/-0.1 Hz).
3. Set DUT for 100% output power.
4. Calculate the RLC load using a quality factor (Q_f) equal to 1.0 (+/-0.05). The reactive RLC load is balanced so that the resonant frequency of the load is as close to nominal frequency as possible. The quality factor requirement ensures that the reactive power circulating between the capacitive and inductive components of the load is within 5% of the real power rating of the system.
    a. Equation for calculating Q_f:

$$Q_f = R\sqrt{\frac{C}{L}}$$

Q_f is the quality factor of the parallel resonant load (RLC)
R is effective load resistance in Ohms
C is effective load capacitance in F
L is effective load inductance in H
(Include the DR measured reactive output components in the C and L amounts.)

    b. Equation for resistance:

$$R = \frac{V^2}{P}$$

P is DR full power per phase

V is nominal voltage

c. Equation for inductance:

$$L = \frac{V^2}{2 \times \pi \times f \times P \times Q_f}$$

f is fundamental frequency

d. Equation for capacitance:

$$C = \frac{P \times Q_f}{2 \times \pi \times f \times V^2}$$

5. Close all switches and wait for the DUT to produce the desired power level.
6. Adjust the RLC circuit so that the fundamental frequency current from the utility is less than 2% of the DR rated current. Balance this current level on each phase and maintain a steady state.
7. Remove utility connection and observe the amount of time it takes the DUT to stop energizing the load. The time should be less than two seconds.

Illustration of Procedure and Results

The critical part of the unintentional islanding test is to tune the RLC load so it resonates sufficiently to meet the requirements of IEEE 1547. EPRI began with component values close to the nominal values. With the generator running and the DES system discharging, the resistive component of the load was tuned to within 100 W of the DES system output. Adjustment of a variable capacitor allowed EPRI engineers to bring the load into resonance and reduce the reactive power required from the generator to <2% of the DES system line current (as required by the standard). Once the generator current was sufficiently low, a quality factor calculation on each phase using the actual load values determined whether the reactive power in the load sufficiently matched its real power.

With the load at proper resonant conditions, EPRI disconnected the generator from the circuit and measured how long each DES system continued to energize the line. Figure 3-7 illustrates the clearing time following disconnection of the source. Note that the IEEE standard requires that the fundamental frequency current drop below 2% of the DUT maximum power (1.2 A in the example case), but not the total current including harmonics. This is a critical distinction since EPRI's generator does not produce a perfectly sinusoidal waveform. Although the total source current in Figure 3-7 is above 6 A at the time of disconnection, the fundamental frequency current is well below the threshold defined in IEEE 1547. The remainder of the current is made up of mainly 3rd, 5th, and 7th harmonics which are impossible to eliminate without a much more sophisticated load or a perfectly sinusoidal source.

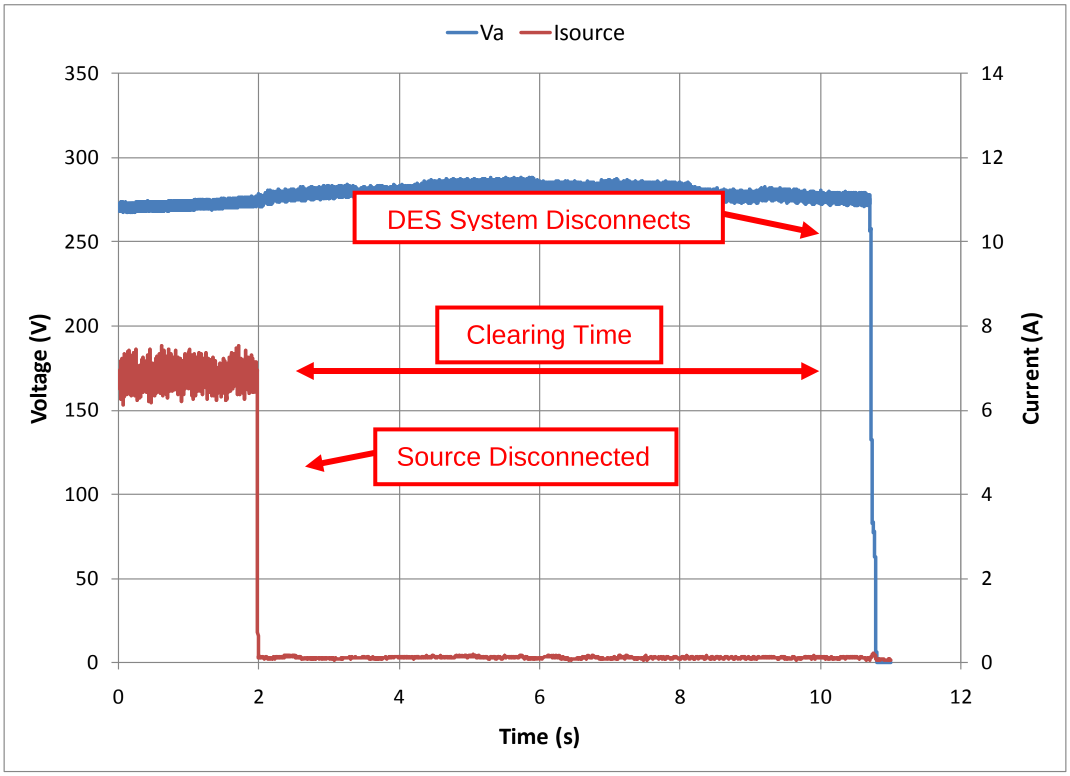

Figure 3-7
Illustration of Clearing Time Interval

Figure 3-7 shows the clearing time interval following loss of the source under highly resonant conditions while a DES system discharges at 50 kW. It is not possible to determine whether the IEEE 1547 test conditions are met from the recording. EPRI uses a power meter that measures fundamental frequency power and current to determine whether the source current requirement is satisfied, and a direct calculation using the L, R, and C values of the load determines whether the quality factor requirement is satisfied.

THE PRECEDING SECTION REPRESENTS GENERAL ILLUSTRATIONS OF GRAPHICAL RESULTS FROM THIS TEST AND DOES NOT PERTAIN TO ANY SYSTEM TESTS IN PARTICULAR. IT PROVIDES A BASIS FOR UNDERSTANDING THE TABULAR PRESENTATION OF DATA BELOW.

Greensmith DES System Test Results

The Greensmith Power Vault 80 operates at 120/208 V, so the rated current is 139 A per phase. The RLC load reached a sufficiently resonant condition once the fundamental frequency source current dropped below 2% of this value (2.77 A rms). EPRI's final load adjustment and the resulting source currents are contained in Table 3-2.The quality factor of 0.96 for this load configuration meets the standard's requirement of 1.0 ± 0.05.

Table 3-2
Greensmith Power Vault 80 DESS Verification of IEEE 1547 Test Requirements

DES System	IEEE 1547 Requirement	Source Current (A)			RLC Load			
I_{DESS} (A)	2% x I_{DESS} (A)	I_a	I_b	I_c	R(Ω)	L(mH)	C(μF)	Q_f
139	2.77	0.97	1.062	1.316	4.6	15	660	0.96

Once the RLC load reached the resonant condition described in Table 3-2, EPRI disconnected the generator from the simulated power system. After the generator was disconnected from the circuit, the Greensmith system remained on-line for 0.97s before de-energizing the load. This is well within the 2.00 s limit set in the IEEE 1547 standard.

EPRI tried two load combinations before arriving at R, L, and C values that satisfy the IEEE 1547 test requirements. Table 3-3 contains the results of the trial that met the IEEE 1547 conditions. The clearing time for this system is within the 2.00 s disconnect threshold.

Table 3-3
Greensmith/IB Unintentional Islanding Disconnect Test Results

$I_{A\text{-}GEN}$ (A)	$I_{B\text{-}GEN}$ (A)	$I_{C\text{-}GEN}$ (A)	IEEE 1547 Limit (A)	DESS System Clearing Time	IEEE 1547 Limit
0.97	1.06	1.32	2.77	97 ms	2.00s

In all tested cases, the Greensmith system shut down well within the 2 s limit required by the IEEE 1547 standard. Prior to disconnecting the source, the voltage on the DUT was slightly leading. When the source was removed, the DUT output voltage increases slightly. This behavior indicates that the Satcon inverter tries to continuously change the grid voltage. When connected to a relatively large source (with a correspondingly low source impedance), the 50kW inverter cannot change the voltage. When the source disappears, the inverter has much greater control over the system voltage, even in the highly resonant conditions of this test. The change in source impedance indicates to the inverter that the source is no longer present and an islanding condition is occurring.

The Greensmith Power Vault 50 system uses the same Satcon inverter as the Greensmith Power Vault 80 and hence this test was not repeated again.

Abnormal Voltage and Frequency

The purpose of this test is to verify that a DES system disconnects from the grid when presented with excessive voltage or frequency deviations. The IEEE 1547 standard sets specific limits for a system's clearing time, or the time between the onset of abnormal grid conditions to the time the DES system disconnects from the grid. Table 3-4 and Table 3-5 contain the clearing time requirements for specific abnormal voltage and frequency levels as specified by the IEEE 1547 standard.

For abnormal voltage conditions, systems of all power levels must adhere to the maximum clearing times set forth in Table 3-4. The standard states that systems must disconnect from the grid more quickly for extreme voltage deviations than for slight deviations. The standard also states that systems above 30 kW must have adjustable clearing times, with the Table 3-4 limits as the maximum possible setting. Systems less than 30 kW can have fixed or adjustable clearing time settings. For the purpose of this test, systems with adjustable clearing time settings are configured for their maximum clearing time to make sure they adhere to the IEEE 1547 limits regardless of user settings.

Table 3-4
IEEE 1547 Clearing Time Requirements for Line Voltage Deviations

Voltage Range (% of base voltage)	Clearing Time (s)
V<50	0.16
50≤V<88	2.00
110<V<120	1.00
V≥120	0.16

For grid frequency deviations, IEEE 1547 sets different limits for systems less than 30 kW than for larger systems. For the larger systems, the low frequency cutoff point and clearing time may be user-adjustable within the limits defined in Table 3-5 (above 57 Hz). Below 57 Hz the systems must all adhere to a well-defined clearing time.

Table 3-5
IEEE 1547 Clearing Time Requirements for Line Frequency Deviations

Size	Frequency Range (Hz)	Clearing Time (s)
≤30kW	>60.5	0.16
	<59.3	0.16
>30kW	>60.5	0.16
	<{59.8-57.0} (adjustable set point)	Adjustable 0.16 to 300
	<57.0	0.16

Test Procedure

Test setup shown in Figure 3-1 was used for the abnormal voltage and frequency tests. EPRI performs this test while the DES system discharges full rated power into the simulated power grid.

1. Connect the DUT as shown in Figure 3-1.
2. Set all parameters to nominal operating conditions for the DUT.
3. Set the AC source to its nominal voltage.
4. Increase the voltage at 0.5 V/s until the DUT trips.

5. Measure the voltage at which the DUT disconnected (trip point).
6. Reset the source to nominal line conditions.
7. Step the source voltage to (trip point x 1.1) (trip point as determined in Step 5).
8. Once the DUT disconnects, measure the time delay between the voltage increase and the disconnection.
9. Record all data and save all the recorded files.
10. Repeat steps 2 through 9 with a voltage decrease at 0.5 V/s and a step to (trip point x 0.9).
11. Repeat steps 2 through 9 with a frequency increase at 0.1 Hz/s and a step to (trip point x 1.1).
12. Repeat steps 2 through 9 with a frequency decrease at 0.1 Hz/s and a step to (trip point x 0.9).

> COMPLIANCE WITH THE IEEE 1547 STANDARD REQUIRES THIS TEST BE RUN FIVE TIMES FOR EACH PHASE CONFIGURATION. FOR THE PURPOSE OF THIS COMPATIBILITY TESTING, EPRI RUNS THE TEST SEQUENCE ONCE ON ALL PHASES SIMULTANEOUSLY.
>
> THE TEST RESULTS PRESENTED HERE SHOULD NOT BE CONSIDERED A CERTIFICATION OF COMPLIANCE WITH THE STANDARD.

Illustration of Procedure and Results

Figure 3-8 through Figure 3-15 illustrate the test sequence for the abnormal voltage and frequency tests. These figures are provided to explain the test procedure, as well as to define the terms ‘trip point’ and ‘clearing time’ for each of the four tests. For all of the abnormal voltage and frequency testing, all input phases’ voltage or frequency vary together, even though the plots contain only one phase for simplicity.

Over-voltage

The first part of the over-voltage test determines the highest continuous voltage at which the DES system will operate before disconnecting from the grid. This voltage is the ‘over-voltage trip point’ of the system. The test begins with the programmable source set to a nominal 277 V_{LN}. Systems requiring different voltages require a transformer to change the 277/480 V system to their nominal voltage, and the voltage is measured on the DES system side of the transformer. EPRI sets the programmable source to increase its output voltage at 0.5 V/s until the DES system disconnects from the line. The point where the DES current drops to zero is the trip point (305 V in this example, see Figure 3-8).

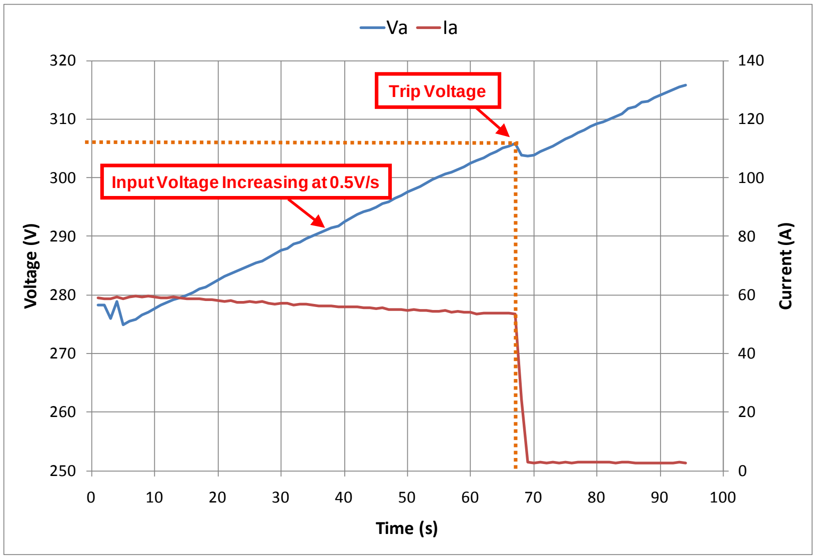

Figure 3-8
Illustration of Over-Voltage Test Ramp and Trip Voltage

Once the trip point is determined, a second test is required to find the clearing time. Starting with the programmable source back at nominal voltage, EPRI executes a voltage step that increases the line voltage to 10% over the overvoltage trip point found in the first part of the test. In the example illustrating the test procedure, the trip point is 305 V, so the voltage step goes from 277 V to 335 V (305 V x 1.1). The interval between the voltage step and the DES system disconnecting from the line is the ‘clearing time’ (see Figure 3-9). While the IEEE 1547 standard does not have a particular trip voltage requirement, it does require that a grid-connected system’s clearing time is less than 1s for voltages 110% to 120% of nominal, and 160 ms for trip voltages above 120% of nominal.

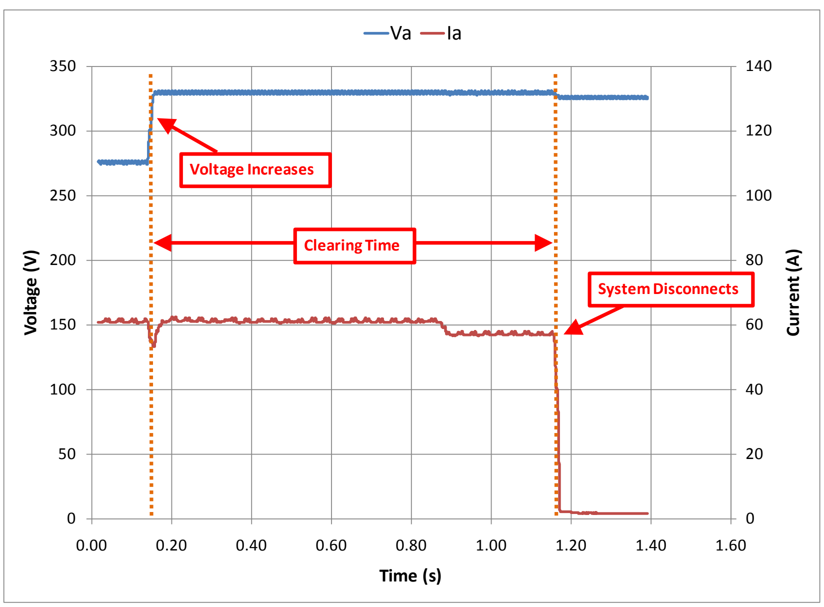

Figure 3-9
Illustration of Over-Voltage Clearing Time

Under-voltage

The under-voltage test is identical to the over-voltage test but involves a voltage decrease. The first part determines the ‘under-voltage trip point’ of the system. EPRI sets a programmable supply to decrease its output voltage from nominal 277 V_{LN} at 0.5 V per second until the DES system disconnects from the line. The point where the DES current drops to zero is the trip point (see Figure 3-10).

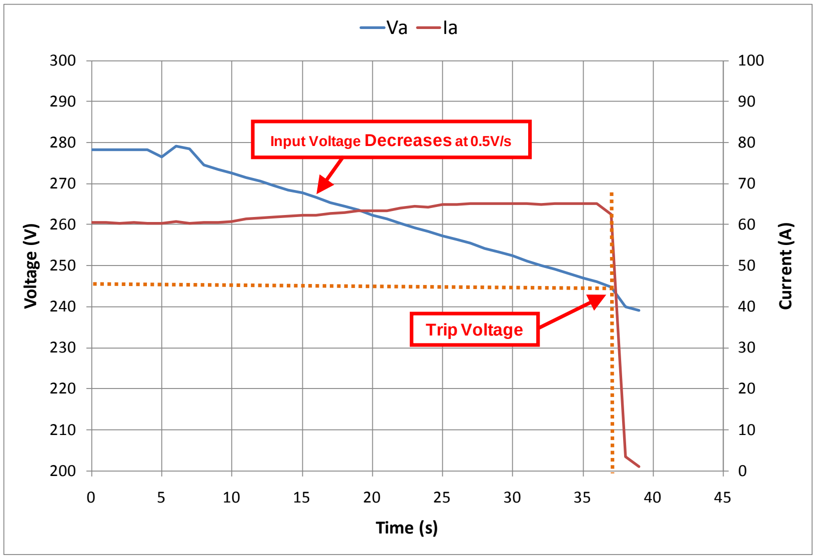

Figure 3-10
Illustration of Under-Voltage Test Ramp and Trip Voltage

To determine the clearing time, EPRI executes a voltage step that decreases the line voltage from nominal to 10% under the under-voltage trip point found in the first part of the test. For the example system, the under-voltage trip point is 249 V, so the voltage step goes from 277 V to 224 V (249 V x 0.9). The interval between the voltage step and the DES system disconnecting from the line is the ‘clearing time’ (see Figure 3-11). IEEE 1547 requires each system’s clearing time is less than 2 s for voltages 50% to 88% of nominal, and 160 ms for trip voltages below 50% of nominal.

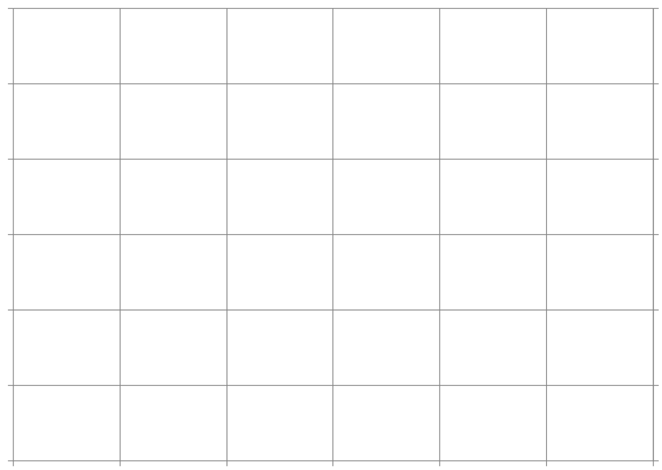

Figure 3-11
Illustration of Under-Voltage Clearing Time

Over-frequency

The over-frequency test is similar to the over-voltage test, except that the simulated power system's frequency is increased until the DES system disconnects. The frequency at which the DES system disconnects from the line is the 'over-frequency trip point' of the system. The test begins with the programmable source set to nominal voltage at 60 Hz. EPRI sets the programmable source to increase its frequency at 0.1 Hz per second until the DES system disconnects from the line. The point where the DES current drops to zero is the trip point (see Figure 3-12).

Figure 3-12
Illustration of Over-Frequency Test Ramp and Trip Frequency

Once the trip point is determined, EPRI returns the programmable source to nominal voltage and frequency and executes a voltage step that increases the line frequency to 1% over the over-frequency trip point found in the first part of the test. In the example the trip point is 60.5 Hz, so the frequency step goes from 60 Hz to 61.1 Hz (60.5 x 1.01). The interval between the frequency step and the DES system disconnecting from the line is the 'clearing time' (see Figure 3-13). Compliance with the IEEE 1547 standard requires a clearing time of less than 0.16 s for frequencies above 60.5 Hz.

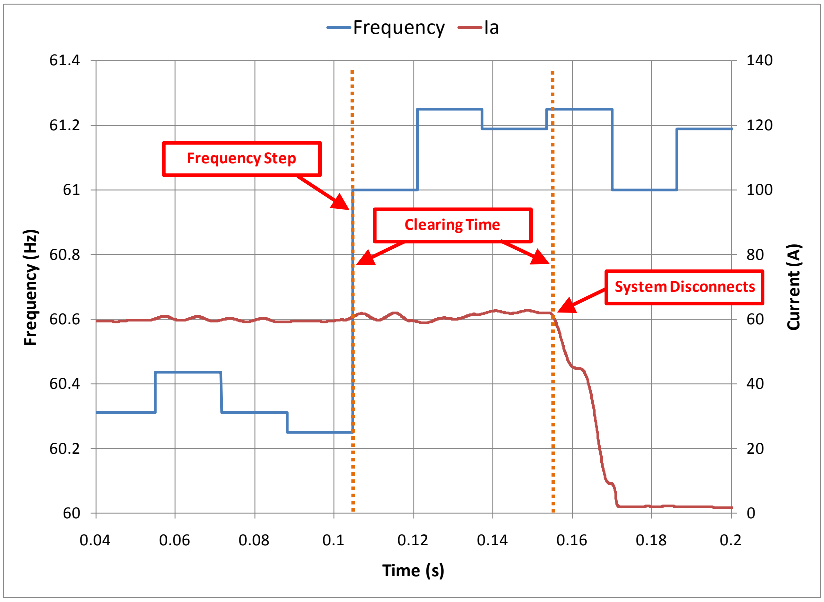

Figure 3-13
Illustration of Over-Frequency Clearing Time

Under-frequency

The under-frequency test is identical to the over-frequency test except that the trip point is the lowest frequency at which the DES system will operate without disconnecting from the line. This voltage is the 'under-frequency trip point' of the system. The test begins with the programmable source set to nominal voltage and frequency. EPRI sets the programmable source to decrease its output frequency at 0.1 Hz per second until the DES system disconnects from the line. The point where the DES current drops to zero is the trip point (see Figure 3-14).

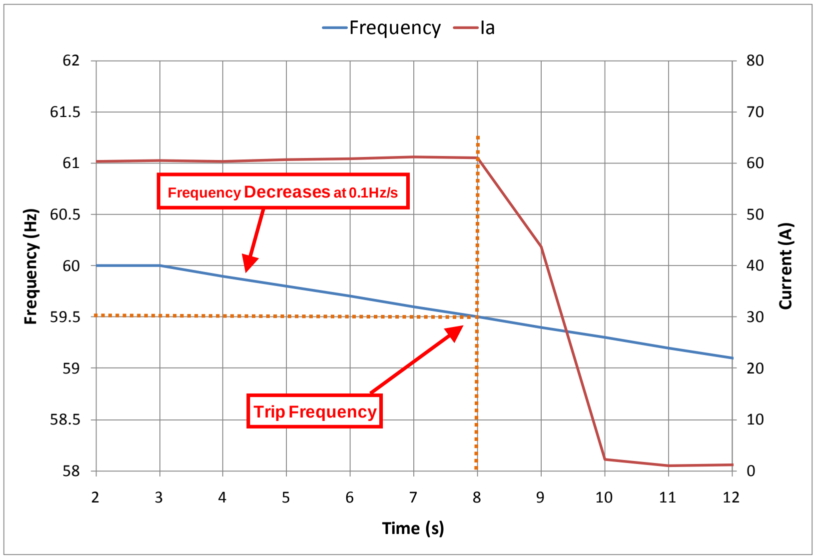

Figure 3-14
Illustration of Under-Frequency Test Ramp and Trip Frequency

The clearing time for the under-frequency test is determined by executing a step change from nominal frequency to 1% under the trip point. In this example, the trip point is 59.5 Hz, so the frequency step goes from 60 Hz to 58.9 Hz (59.5 Hz x 0.99). The interval between the voltage step and the DES system disconnecting from the line is the 'clearing time' (see Figure 3-15). For smaller systems (≤30 kW capacity), the IEEE 1547 standard requires the clearing time be less than 0.16 s for trip frequency below 59.3 Hz. The standard defines two levels of severity for under-frequency events on larger (>30 kW) systems. For events between 57 Hz and 59.8 Hz, the clearing time may be user-adjustable up to 300 s. All events below 57 Hz must be cleared within 0.16 s.

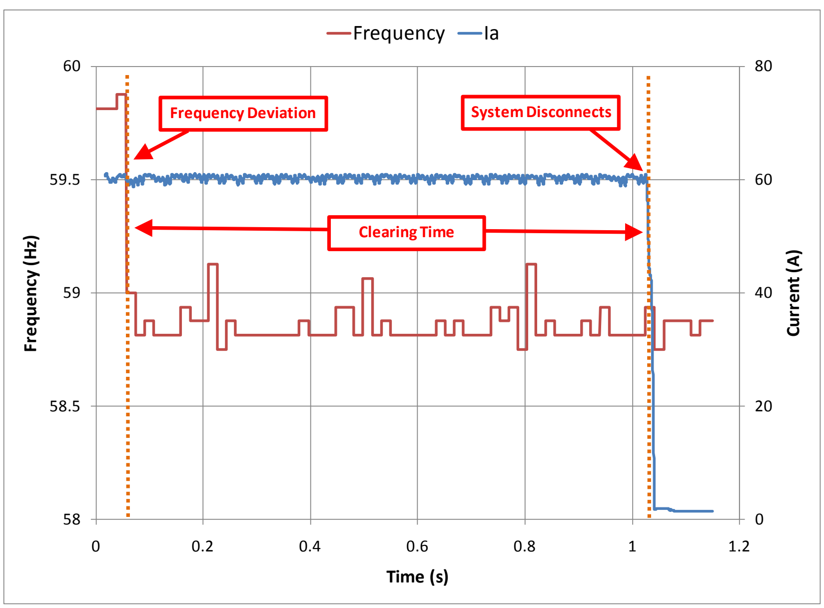

Figure 3-15
Illustration of Under-Frequency Clearing Time

THE PRECEDING SECTION REPRESENTS GENERAL ILLUSTRATIONS OF GRAPHICAL RESULTS FROM THIS TEST AND DOES NOT PERTAIN TO ANY SYSTEM TESTS IN PARTICULAR. IT PROVIDES A BASIS FOR UNDERSTANDING THE TABULAR PRESENTATION OF DATA BELOW.

Greensmith DES System Test Results

The Greensmith Power Vault 80 is above the 30 kW limit that divides small from large DES systems in the IEEE 1547 standard, so the limits for larger systems apply. Table 3-6 shows the specifications of the Satcon inverter that is used in both Greensmith systems. Note that the Satcon inverter is based on a nominal voltage of 120/208, and the trip settings for abnormal voltage are line-to-line values. All of the settings are within the IEEE 1547 limits for trip settings. The clearing time is not specified by Satcon in the product literature.

Table 3-6
Satcon Inverter Specification for Abnormal Voltage and Frequency Conditions

Test Condition	Trip Setting	Percent of Base Voltage/ Frequency	Clearing Time (s)
Over-voltage	229 V	110%	*
Under-voltage	183 V	88%	*
Over-frequency	60.5Hz	101%	*
Under-frequency	59.3 Hz	99%	*

** Value not specified by the manufacturer*

Table 3-7 contains the abnormal voltage and frequency test results for the Satcon inverter used in the Greensmith DES systems. The system meets the IEEE 1547 clearing time requirements for all four of the abnormal voltage and frequency conditions. Note that this system does have adjustable clearing time for under-frequency conditions as required by the standard.

Table 3-7
Greensmith / International Battery Abnormal Voltage and Frequency Test Results

Condition	Threshold		Clearance Time			Conforms to IEEE 1547
	Mfgr. Spec.	Observed	Mfgr. Spec.	Observed	IEEE1547	
Over-voltage	110%	108%	No spec	0.933s	1.00s	Yes
Under-voltage	88%	87%	No spec	0.931s	2.00s	Yes
Over-frequency	60.5 Hz	60.56 Hz	No spec	0.084s	0.16s	Yes
Under-frequency	59.3 Hz	59.25 Hz	No spec	0.067s	<300s	Yes

The voltages at which the system is programmed to disconnect from the grid are identical to those specified in the IEEE standard. The observed trip points match up very closely to the manufacturer’s specifications as well. The frequency limits and clearing times also fell within the limits of the IEEE 1547.

The results of this test cannot determine whether the Greensmith / International Battery system will pass the Abnormal Voltage and Frequency test during IEEE 1547 compliance testing. Actual compliance testing will consider the performance of each individual phase as well as the three phase condition considered here. Overall, the Greensmith / International Battery energy storage system demonstrated the ability to de-energize under abnormal voltage and frequency conditions within the IEEE 1547 thresholds.

The Greensmith Power Vault 50 uses the same Satcon inverter as the Power Vault 80 system and hence these tests were not repeated.

4
DESS ENERGY PERFORMANCE TESTS

This test provides an independent assessment of energy capacity of the DES systems' battery, as well as the end-to-end/ round-trip (AC to AC) efficiency which is of critical importance to utilities interested in deploying this technology. EPRI performed full charge/discharge cycles at several different power levels. During each cycle, engineers compared power into the power conversion system (PCS) with power into the battery to determine charge and discharge efficiency. At the end of the test, total energy provided to the grid divided by total energy provided to the DES system during its charge cycle gave the overall end-to-end efficiency for each load level.

Test Procedure

This test is an independent verification of manufacturer specifications rather than a test modeled from the IEEE 1547 standard. EPRI determined during testing that it is important to execute the test procedure exactly as written to ensure a uniform starting and ending state of charge for each DES system's battery.

1. Connect the system as shown in Figure 3-1.
2. Connect the data recorder to record utility bus voltage and current, and battery voltage and current.
3. Should the DUT have any type of event or data log, clear the logs.
4. Fully discharge the DUT (until it stops itself).
5. Set the charge rate of the DUT to maximum rated capacity.
6. Initiate DUT charge while recording parameters.
7. Allow the DUT to completely charge (until it stops itself) and record the runtime.
8. Set the DUT to discharge at its maximum rated capacity.
9. Once the DUT stops discharging, record its discharge runtime.
10. Repeat steps 4-9 at 50% capacity (and 25% capacity for 50 kW systems)
11. Save the data recorder files.
12. Determine the roundtrip efficiency from the data.

Illustration of Procedure and Results

The runtime test consists of three main tasks: completely discharge system's battery, perform a full charge at a specified output level, and perform a full discharge at the same output level. When the test is run in this sequence, EPRI can make a true comparison of energy into the battery and out of the battery.

Once the test is complete, EPRI calculates runtime and efficiency in two different ways. One is the beginning of a charge/discharge command to the time at which the DUT output drops to 90% of the command. The other calculation considers the entire charge or discharge to the point where the unit stops completely. For some systems these two times may be nearly identical, but others taper output current as their batteries near full charge or depletion. Figure 4-1 illustrates the difference in the two runtimes when a system tapers its output power near the end of its runtime.

The results include two assessments of runtime that represent this 90% point as well as the full discharge point, and the total energy in or out during the test. End-to-end efficiency is calculated as the total energy dispatched during discharge divided by the total energy consumed during charge.

An operation scheme that limits runtime to the 90% limits may be able to raise the overall efficiency for some systems since in most cases the efficiency decreases once the units begin to reduce their power level. For systems with significant power tapering towards the end of charging and discharging, utilities can choose to operate the systems for either maximum efficiency or maximum energy storage.

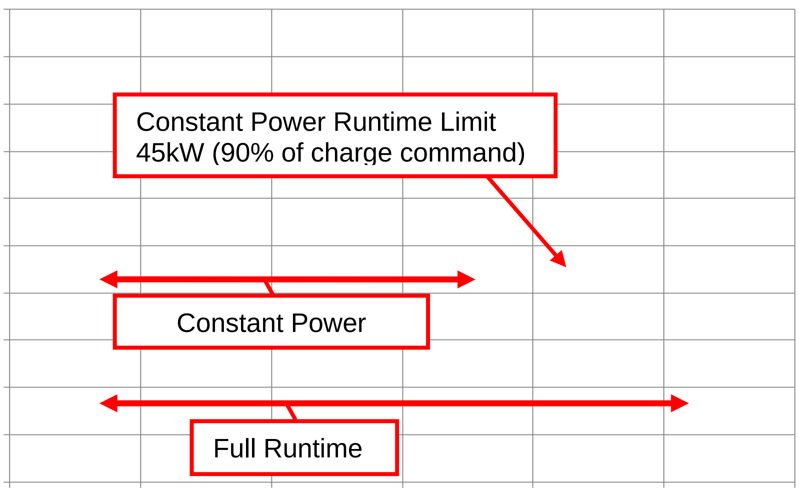

Figure 4-1
Illustration of Constant Power Runtime vs. Fulltime

It is also important to note that the runtime data was recorded with charge and discharge cycles separated by less than one day. Operation schemes that require the unit to be inactive during certain times of the year will clearly affect the end-to-end efficiency of the system. EPRI's testing is not assessing the ability of the batteries to store energy long term. The overall efficiency of the systems will also drop considerably if they are left inactive for long periods of time since the standby losses of the systems can add up to a considerable amount of energy. These losses are not considered in this testing since the total charge and discharge cycle energy integration calculations are limited to the times when the systems are charging or discharging. The power used during the periods of time when the units are inactive between charges and discharges are not included in the calculations.

Greensmith Power Vault 80 DES System Test Results

Table 4-1 provides an overview of the Greensmith Power Vault 80 system's runtime. Since this is a 50 kW system, EPRI tested the unit at 100%, 50%, and 25% of its rated capacity. This Greensmith DES system was configured to operate at 120/208 V. A step-down transformer was necessary to convert the 480/277 V utility bus to the required voltage level, but EPRI recorded AC measurements on the 208 V side of the transformer in order to avoid including the transformer losses in the efficiency results.

Table 4-1
Greensmith Power Vault 80 DES System Efficiency and Runtime Test

Power Settings	% of Rated	Runtime		Energy			Avg. PCS Efficiency (%)	Roundtrip Efficiency (%)
		Const. Power (hr)	Total (hr)	AC (kWh)	DC (kWh)	Battery Spec. (kWh)		
12.5kW Charge	25	7:02	7:23	91.3	84.5	82	92.5	87.0
12.5kW Discharge		6:21	6:23	79.5	82.8		96.0	
25kW Charge	50	3:36	3:55	93.8	86.8		92.6	85.8
25kW Discharge		3:13	3:16	80.5	83.2		96.7	
50kW Charge	100	1:30	2:23	89.8	82.5		91.9	84.6
50kW Discharge		1:31	1:51	76.0	79.4		95.8	

The Greensmith DES system with International Battery integrated with the Satcon inverter was specified for a 3 hour runtime at 25 kW. The system performed as specified during both charge and discharge cycles at 25 kW. The battery system consumes approximately 3 kWh of energy, which becomes heat dissipated by the batteries. For all three tests, the battery system performed very close to its 82 kWh rating. During all tests, the Satcon inverter was about 4% more efficient during discharge than during charge cycles. The DC/AC efficiency of ~96% is very close to the inverter's specification (95.5%), but the AC/DC (charge) efficiency of ~92% falls short of the specification.

Figure 4-2 shows the power levels and efficiency of the Greensmith Power Vault 80 system during its charge/discharge cycle at full rated power. The orange dotted line in the figure at 45 kW represents 90% of the charge and discharge commands, and the cutoff points for the 90% runtime values. The efficiency of the system is very stable up to the 90%, after which the power decreases as the battery nears full charge or depletion. However, even though the efficiency drops after these points, the power level is dramatically reduced; therefore overall efficiency does not decrease significantly.

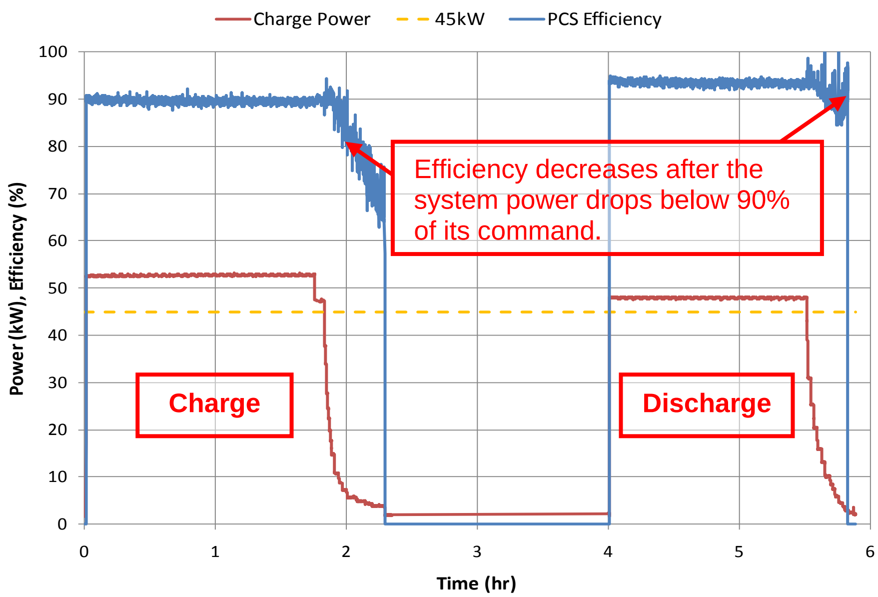

Figure 4-2
Power and Efficiency During Greensmith Power Vault 80 DES System Full Power Battery Cycle

Greensmith Power System Vault 50 System Test Results

Table 4-2 provides an overview of the Greensmith Power Vault 50 DES system's runtime and efficiency. Although this system uses the same Satcon inverter as the Greensmith Power Vault 80 system, its battery is only capable of 25kW charge and discharge. As such, EPRI tested it at full and half power (25 kW and 12.5 kW). Like the other Greensmith system, this DESS was also configured to operate at 120/208 Volts. A step-down transformer was necessary to convert the 480/277 V utility bus to the required voltage level, but EPRI recorded AC measurements on the 208 V side of the transformer in order to avoid including the transformer losses in the efficiency results.

Table 4-2
Greensmith Power Vault 50 DES System Runtime Test Results

Power Settings	% of Rated	Runtime		Energy			Avg. PCS Efficiency (%)	Roundtrip Efficiency (%)
		Const. Power (hr)	Total (hr)	AC (kWh)	DC (kWh)	Battery Spec. (kWh)		
12.5kW Charge	50	3:53	4:32	53.3	49.7	50	93.2	83.9
12.5kW Discharge		3:32	3:36	44.7	46.6		95.9	
25kW Charge	100	1:48	2:35	53.3	49.9		93.6	83.7
25kW Discharge		1:44	2:04	44.6	46.8		95.3	

The Greensmith Power Vault 50 was specified for 50 kWh. The system performed near its specification for charging, although the losses through the system and the battery prevented it from discharging a full 50kWh during either test. The battery system consumes approximately 3 kWh of energy, which becomes heat dissipated by the batteries. During all tests, the Satcon inverter was about 2% more efficient during discharge than during charge cycles. This behavior is similar to the Satcon inverter's result in the International Battery configuration. The PCS and round-trip efficiencies are very close for full- and half-load cases.

Figure 4-3 shows the power levels and efficiency of the Greensmith / Boston Power system during its charge/discharge cycle at full rated power. The system tapered its charge and discharge power during both tests, but the behavior was more pronounced for the full-load case. Even though the efficiency drops near the end of each interval, the power level is dramatically reduced so overall efficiency does not decrease significantly.

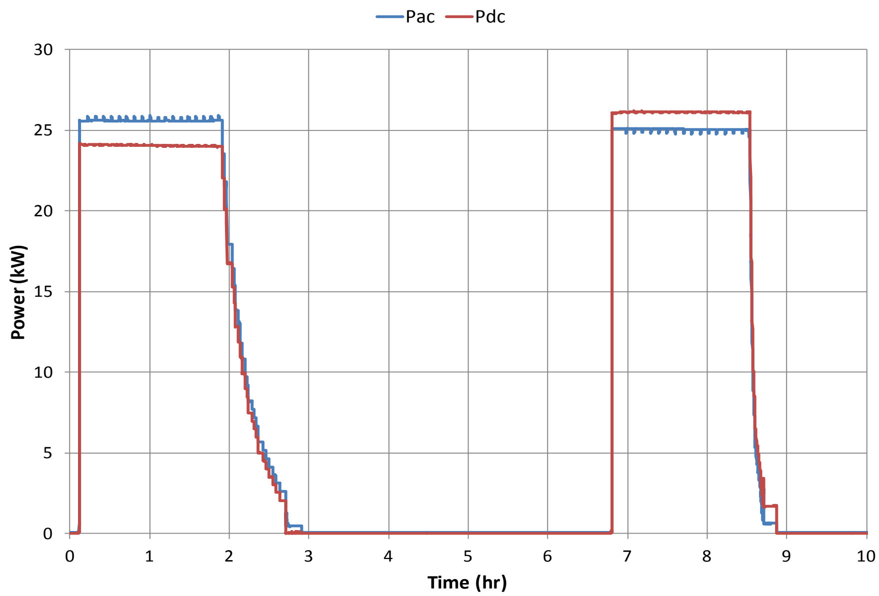

Figure 4-3
Greensmith Power Vault 50 DES System's Charge and Discharge Profile

5

DEMONSTRATION OF ENERGY STORAGE SUPPORT FOR GRID-CONNECTED PV PLANTS

In this chapter grid-connected applications are defined where energy storage is combined with PV power plants to enable energy dispatch and to mitigate output power variability. Five different applications, or operating modes, of energy storage supporting PV are demonstrated using the Greensmith DES systems. A laboratory test set up is devised for integrating programmable AC grid, PV plant and load with the DESS. Each of the five grid-connected applications is demonstrated. The value of scheduling output and the role of predicting PV plant output, planning for daily load demand and forecasting weather are also discussed.

Description of Energy Support Applications for PV

Storage can be beneficial to a PV plant operation by reducing time-of-day and weather-related variability. Previous EPRI work has identified a number of functional requirements that may be applied in use cases where utilities and end users are looking at combining PV and storage.[2],[3],[4] Some key findings from the EPRI work are that requirements vary significantly, the naming and definition of functions (for PV and storage inverters) are not consistent, and that future communication between the electric grid and distributed energy resources will require development of an industry common language. Outside the scope of this project EPRI is supporting the development of functional definitions and the mapping these functions to protocols that are appropriate for different applications.

For this demonstration the different applications are defined around the notion that the primary value for adding storage to PV will come from the grid and will be based on reducing variability and enabling economic dispatch. Benefactors are expected to be the electric system operator or balancing authority responsible for meeting daily system demands. Such value would be recognized via an electricity market or in reduced costs in a utility's overall system operations. Storage benefits for a single location, or in an off-grid stand-alone application, are not considered.

From the electricity market point-of-view both energy and services from generation assets have value. For example scheduled generation and generation to follow the load are energy products while regulation (ramp up and down) and reserves (spinning and non spin) are considered services. The distinction is that a "service" has no net energy component. Combining energy storage with solar can enhance the available generation products or services for a plant, increasing revenues or avoiding a penalty related to not meeting a generation commitment.

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[2] *Common Language for Distributed Storage Integration: Applying the DNP3 Application Profile for Smart Inverters.* EPRI, Palo Alto, CA: 2011. 1023056

[3] *Smart Grid Use Case Depository* - http://smartgrid.epri.com/Repository/Repository.aspx

[4] *Smart Grid Reference Guide to Integration of Distributed Energy Resources*. EPRI, Palo Alto, CA: 2011. 1023412

More discussion about power system planning and operations in energy markets and the functions of generation are provided in Appendix C.

Five applications or modes of operation are defined where energy storage supports a PV plant. Solar variability and time of day are addressed by using the battery for time shifting, energy scheduling, smoothing, load following and ramp rate reduction. Note that other non-PV related storage functions may also have value at a particular location and that more than one function at a time will likely be desirable for a single site. However, for evaluation and demonstration purposes a single objective function is defined for each of these applications.

The applications are ordered from the longer term to short-term energy storage support. Of the five time shifting, energy scheduling, smoothing, load following provide energy products and the ramp rate reduction is assumed to be a service, with no net energy. The storage capacity requirement relative to the PV size depends on the application and, in general, decreases from long term to short term.

Solar Time Shifting

Energy storage time shifts the solar output to better match the system or balancing area peak load. This idea is simply moving solar output to later in the day to meet expected early evening peak. The time period between solar peak and system peak is typically 1-4 hours. This function can also have direct value for an end user if time-of-day electricity rates are in effect. Implementation can be done several ways depending on local energy prices e.g. a battery could be charged in the morning hours or overnight (arbitrage, i.e. buy low, sell high). A forecast of the next day solar output can help to optimize this support. Sizing the energy storage depends mainly on the geographical and seasonal match between solar and system peaks. See graphical illustration in Figure 5-1.

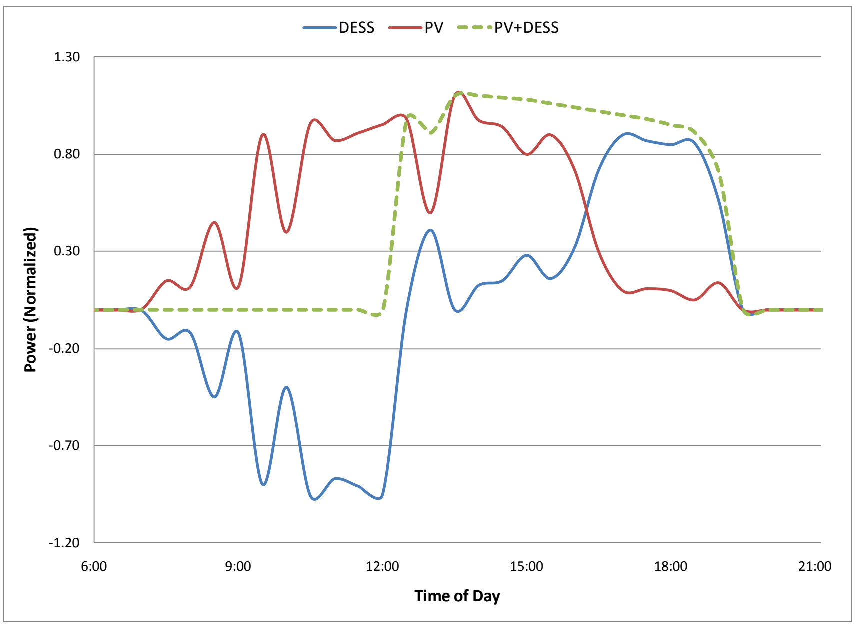

Figure 5-1
Graphical Illustration for Time Shifting of PV Plant Output

Solar Energy Scheduling

Energy storage is used to offset the difference between PV power production and a prescheduled commitment to deliver energy over a specified time period. Charging and discharging during the specified period depends on the difference between the solar output and the scheduled delivery. During other periods charging and discharging should depend on the expected PV output and the cost of energy. The value of the storage is in meeting the schedule commitment. A good forecast of next day solar output can improve the economics and utilization of the energy storage system. Storage requirements depend mainly on the energy market. See graphical illustration in Figure 5-2.

Note: In an energy market generation is scheduled in advance by taking bids and clearing the market based on least cost to meet a forecasted demand. The schedule (creating a demand stack) starts with any generation designated as “must take” and the lowest cost resources and ends with the peaking and highest cost resources. Some generation is committed well in advance and others participate in a day-ahead market. Hour-ahead market clearing is also not unusual, see appendix C.

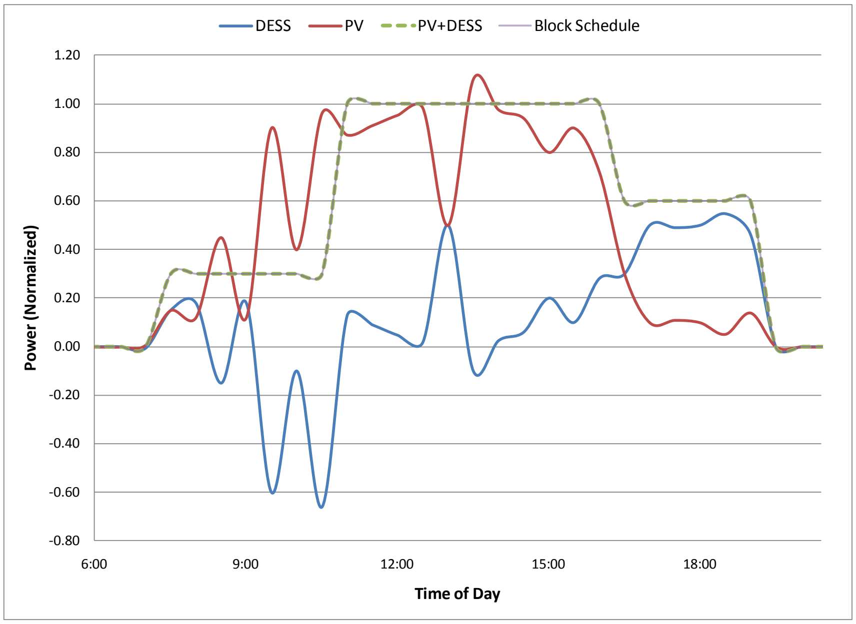

Figure 5-2
Graphical Illustration for Energy Scheduling of PV Plant

Solar Smoothing (a.k.a. Solar Valley Filling or Leveling)

Energy storage is used during the day, charging and discharging, to smooth solar output. The time frame is usually for minutes to hours to reduce solar variability due to clouds. Storage value is not well defined from market view point because the application does not consider daily load demand or scheduling. However, solar smoothing is commonly referred to for PV plants and provides a good test for PV-Battery integration. Storage requirements depend mainly on the weather. See graphical illustration in Figure 5-3.

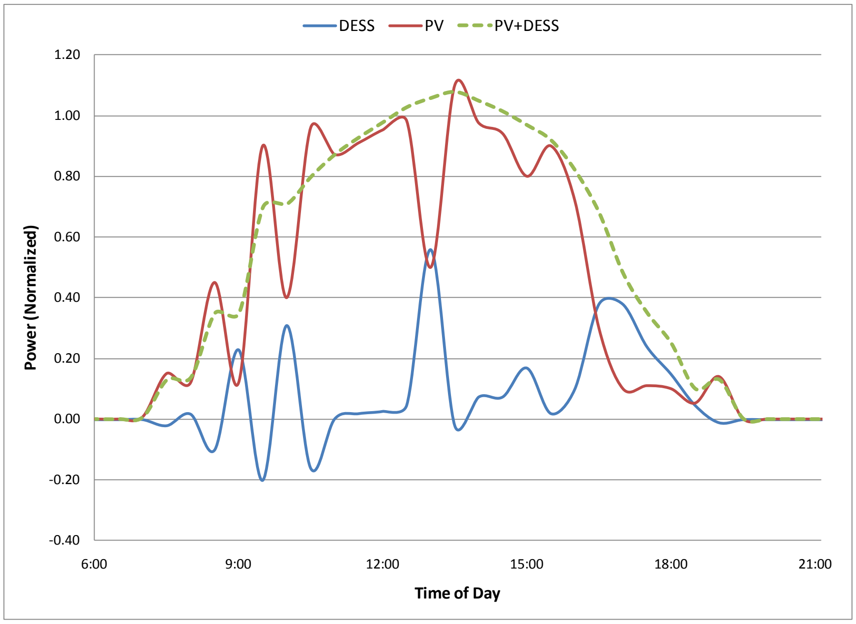

Figure 5-3
Graphical Illustration for Smoothing of PV Plant Output

Load Following with Solar

Storage is used to better match PV plant output with a daily demand curve. Storage charges and discharges during the day to make up the difference between PV output and a demand input. Value is derived from changes in time of day energy rates and in some markets energy storage can participate in the regulation market. The storage requirement is likely to be more demanding in the afternoon when load and PV tend to be going different directions. A day-ahead forecast is useful to plan next day charging and discharging. Storage requirements depend mainly on the energy market. See graphical illustration in Figure 5-4.

Solar Ramp Rate Reduction

Energy storage enables ramp rate control, both up and down. This function is assumed to be valued like a service with no net energy. However, PV plant has a ramping limitation may also be a requirement of interconnection. Note that an inverter can reduce upward moving ramps without storage, although some energy will be loss. The inverter and energy storage response needs to be within seconds and completed in minutes. With a near-term (minutes) PV forecast the storage system may be able to take pro-active measures to reduce the net ramp rate rather than reacting to the PV production changes. This service is similar to conventional frequency regulation or regulating reserves. This can be accomplished with relatively small amount of storage and use is limited to partly cloudy with cloud movement. See graphical illustration in Figure 5-5.

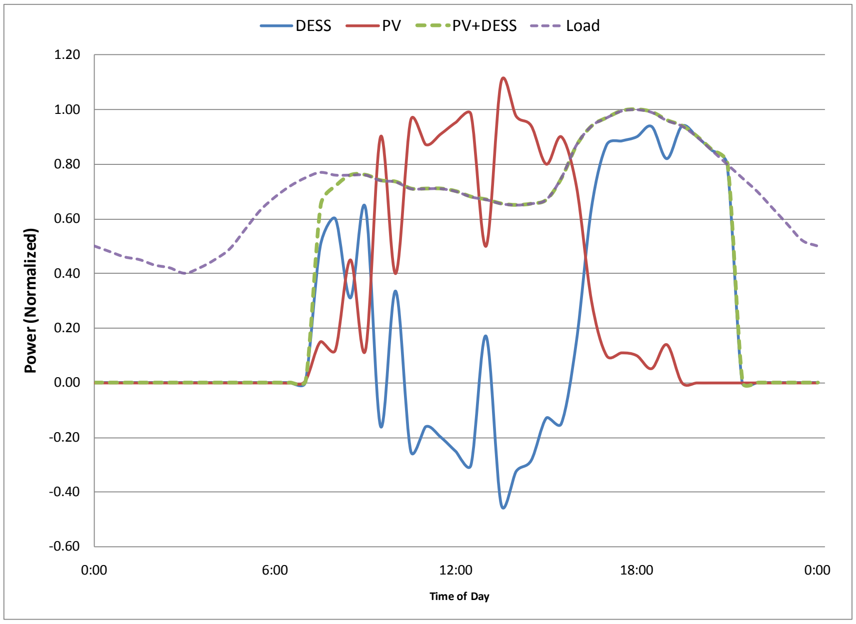

Figure 5-4
Graphical Illustration for PV Plant Output Load Following

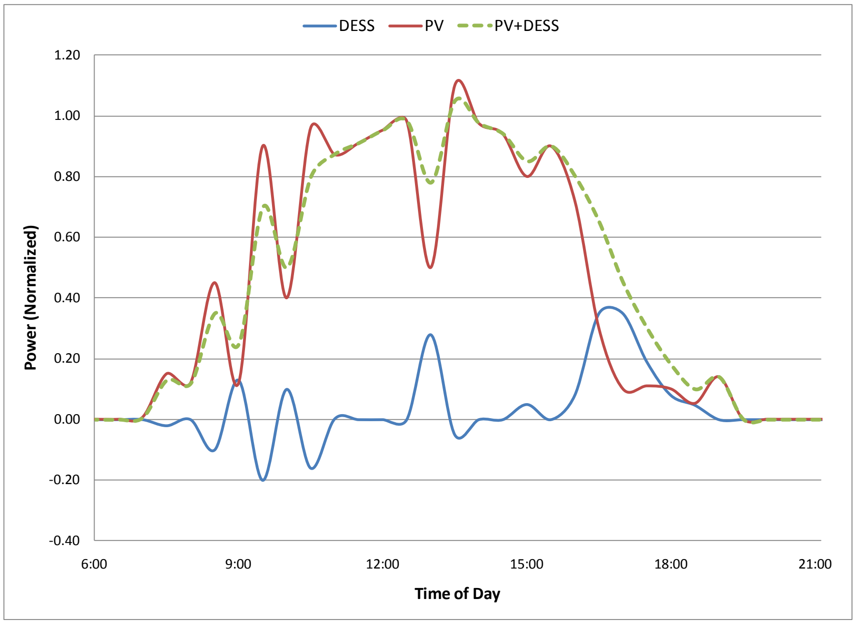

Figure 5-5
Graphical Illustration of PV Plant Ramp Rate Reduction

Another important value that storage may bring for a PV plant is additional "capacity credit," used to determine to what degree a plant can fulfill a reserve requirement. Some markets allow energy storage to participate in the regulating reserve market. This would apply 24 hours per day and would be limited by other demands on the energy storage system. This is also a service that depends on the weather and the relative storage size.

Reactive Power and Voltage control are services that the PV inverter can provide without separate storage. A single installation can provide both products and services if they don't conflict with each other. For purposes of evaluating and demonstrating storage support of PV these functions are intentionally separated.

Test Setup for Laboratory Demonstration of PV with Energy Storage

Greensmith DES systems provided two built-in event algorithms to support photovoltaic integration:

- Renewable ramp rate control
- Renewable and load following

EPRI Integration of Distributed Renewables program engineers configured these two algorithms in different ways to demonstrate the five energy support applications for PV defined earlier. Figure 5-6 shows the test setup used for the demonstration of energy support applications for PV. High resolution (1-sec) solar irradiance data measured by EPRI is used in these tests. A PV simulator is used to mimic actual array output in response to the solar resource data and a three phase grid-tied inverter converts the DC power from simulator into AC power. Two additional Greensmith AC measurement units – a PV meter and a DESS meter are installed for these tests. The PV meter measures the PV power output of the inverter and sends the data to the energy management system (EMS) in every half second. In every two seconds, Greensmith EMS reconfigures its output (charge/ discharge and magnitude) based on ongoing event parameters, battery condition such as state of charge (SOC), cell temperature and voltages, and external inputs including PV and/or load meter data. DESS meter captures the power flow to and from the energy storage system.

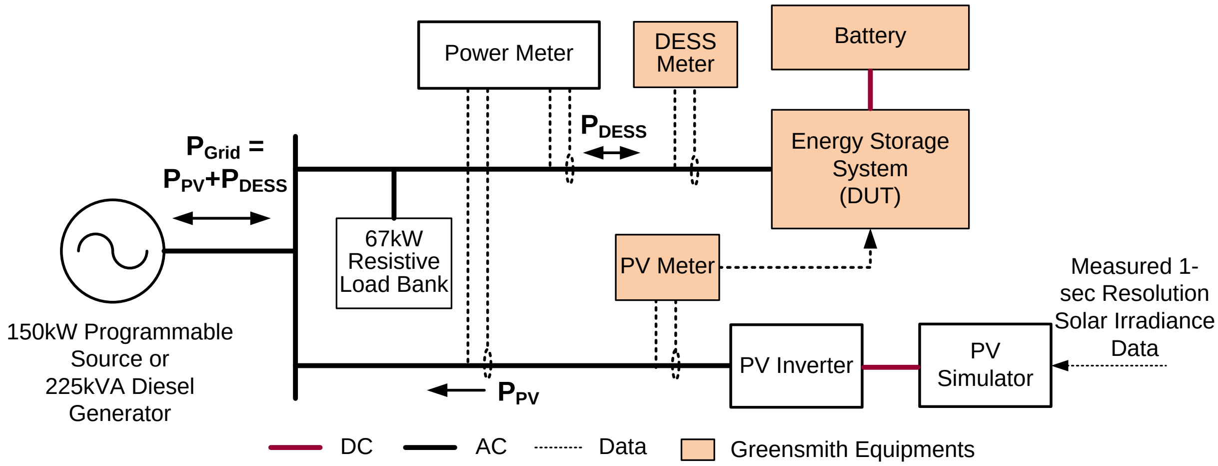

Figure 5-6
Laboratory Setup for PV and Electrical Energy Storage Systems Integration Tests

Using "Renewable Ramp Rate Control" Event Algorithm

Figure 5-8 shows the user input parameters for the Renewable Ramp Rate Control algorithm offered by Greensmith DES systems. Depending on user input this event can be configured for different energy storage support applications defined earlier.

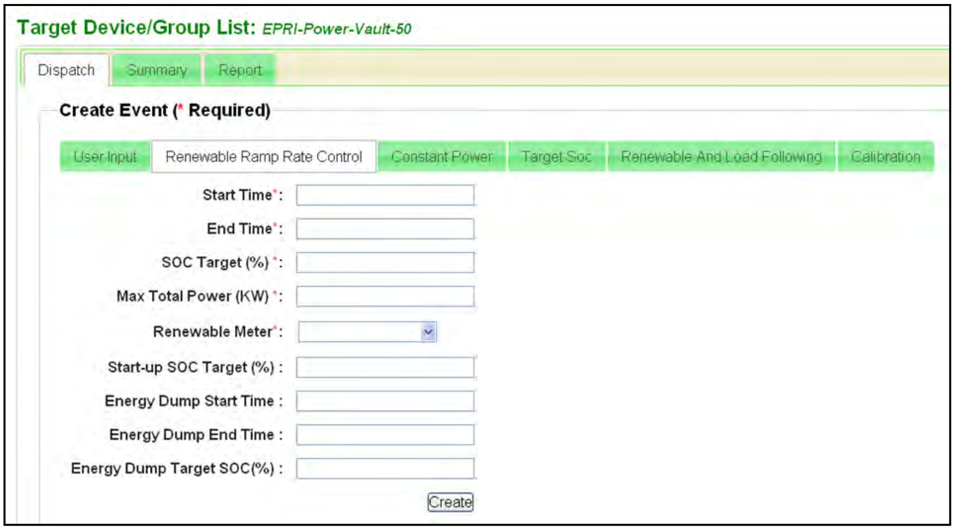

Figure 5-7
User Interface of Greensmith's "Renewable Ramp Rate Control" Algorithm

As per Greensmith's user guide this event executes a ramp rate control algorithm to adjust power input or output levels according to the measured PV output reported by renewable meter with the following control targets:

- DESS plus renewable power ramp rate would not exceed a preset ramp rate limit. For the system tested by EPRI this rate was hardcoded to be 1 kW/min and EPRI did not have the option to edit this parameter
- Overall power level stays below user specified power limit (Max Total Power in kW) to avoid a possible system overload
- Move system energy level close to user specified SOC target (%)

Using "Renewables and Load Following" Event Algorithm

Figure 5-8 shows the user input parameters for the Renewable and Load Following Control algorithm offered by Greensmith DES systems. Depending on user input this event can be configured for the following operations:

- Only renewable power meter- DESS unit charges according to renewable power production level
- Power Level (kW) along with Renewable meter: DESS unit charges or discharges depending on renewable power production to maintain overall power production close to user specified power level
- Only load power meter: DESS unit discharges according to load level
- Both renewable and load power meters: DESS unit charges or discharges to offset the difference between renewable power production level and load power level

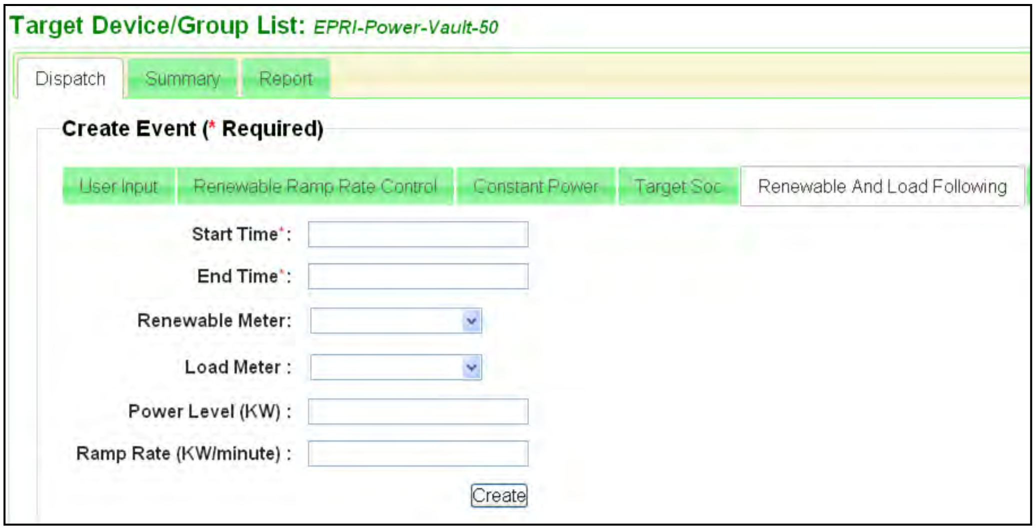

Figure 5-8
User Interface for Greensmith's "Renewable and Load Following" Algorithm

Demonstration of Energy Support Applications for PV

Solar Output Time-Shifting Application

Using Greensmith's "Ramp Rate Control" algorithm event with optional input parameters ("Start-up SOC Target" and "Energy Dump" period) a time shifting application is implemented. This set up can be utilized to charge battery based on PV power output. As shown in Figure 5-9, during the time interval "A", the DESS charged the battery following PV power output until the SOC reached the "Start-up SOC Target". After that, ramp rate control function kicked in to minimize the resultant fluctuation. For this test the "Energy Dump" option was also set to operate for two hours. During the time interval "B" the DESS discharged extra energy into the grid to keep the resultant output high in spite of dropping PV production.

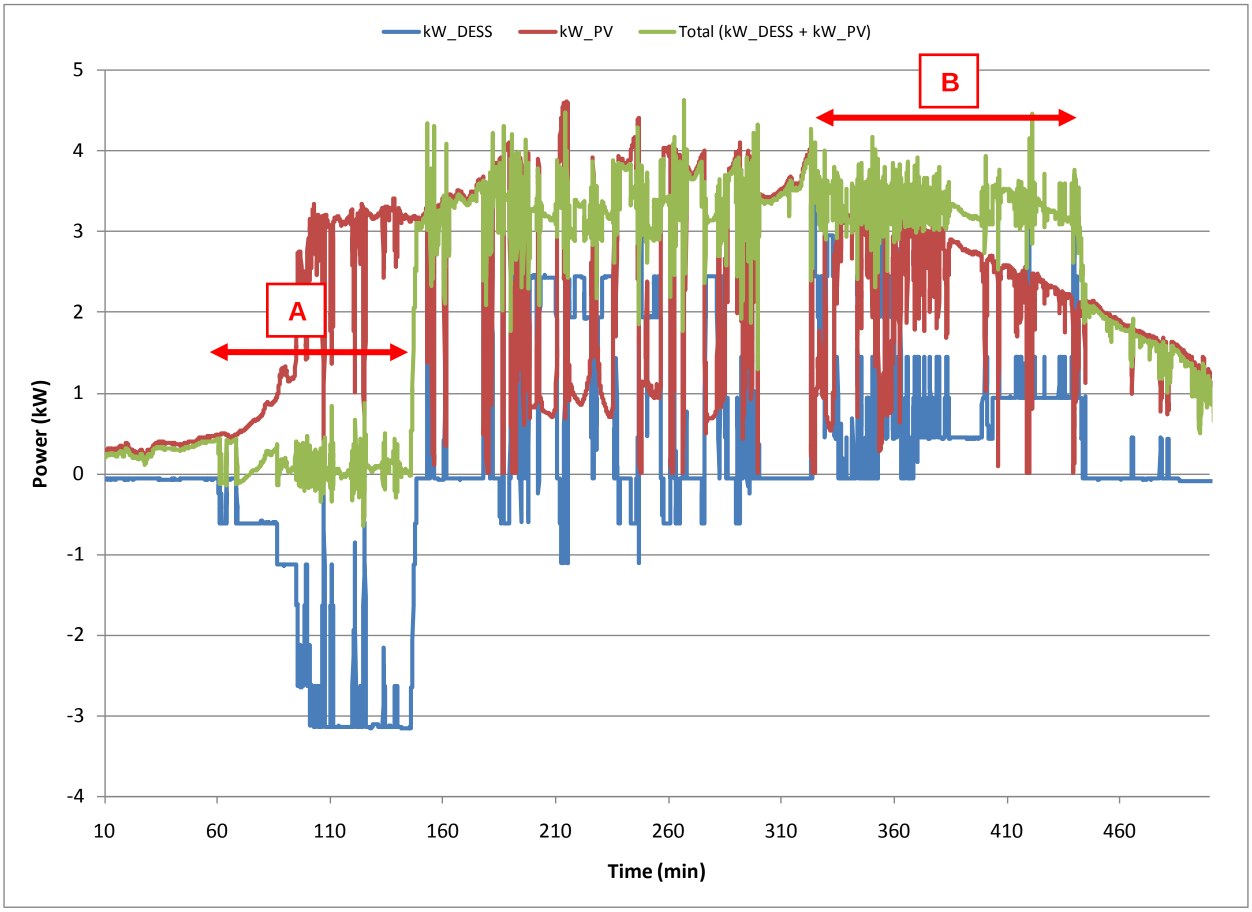

Figure 5-9
PV and Battery Generation are Shifted to later in the Day

Solar Energy Scheduling Application

For this application the DESS is required to input or output power based on the actual PV power production and a predefined generation schedule and target level. The expected available PV energy can be set based on forecasting data or some other means. For example the target level can change at scheduled times during the day.

During this demonstration the "Power level" input parameter within the "Renewable and Load Following" event is used to set a constant PV demand of 4.25 kW. Figure 5-10 shows that excess PV output energy is stored in the battery for the first 30 minutes and during the next 30 minute period the DESS output power to offset low PV power production.

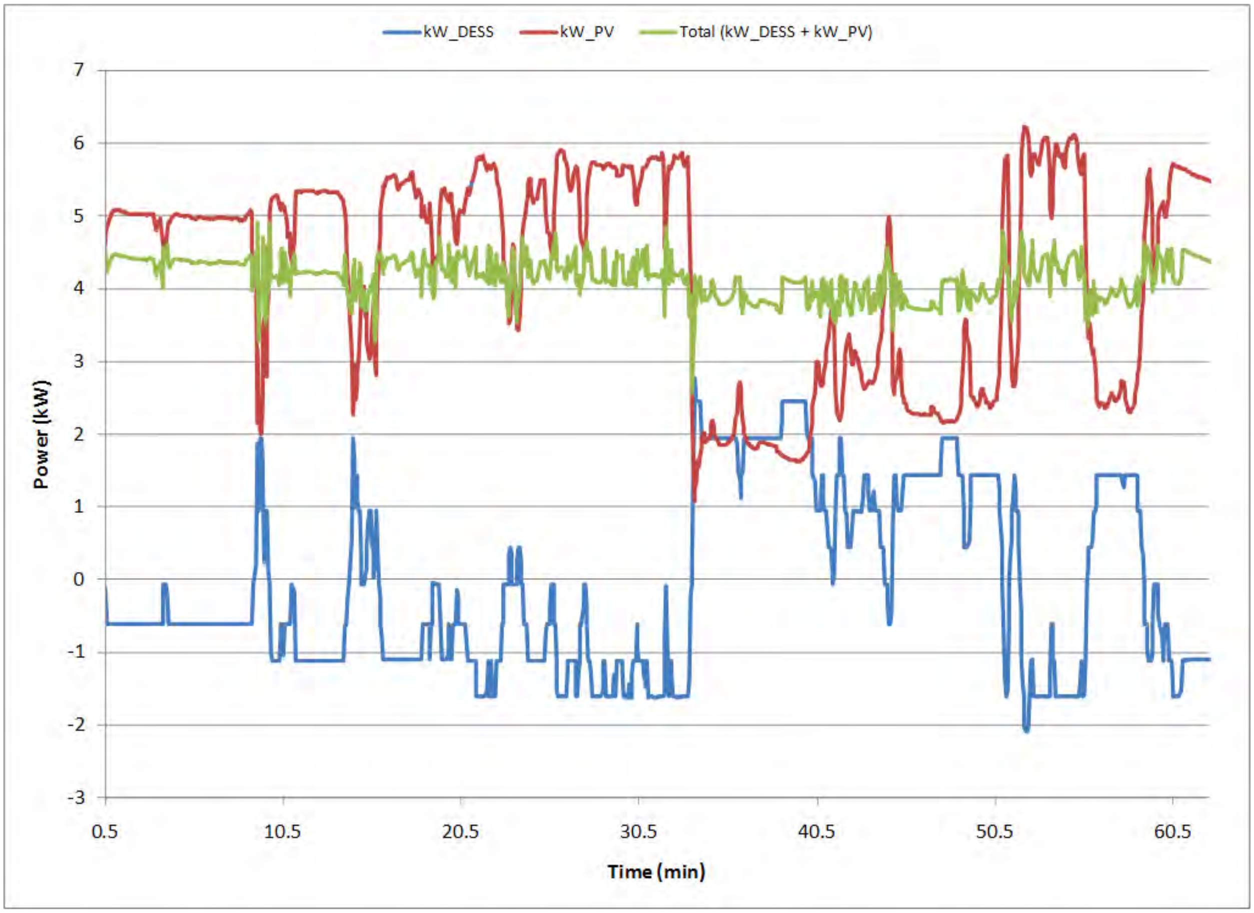

Figure 5-10
PV and Battery Meet a Generation Target Level

Demonstrating a predefined schedule for generation at different levels is shown in Figure 5-11. Two different outputs are demanded over specific intervals. For the time interval "A" the "Power Level" was set to 3 kW whereas for time interval "B" it was set to 4.25 kW. Multiple "Renewable and Load Following" events can be scheduled to meet expected load demands during specified times of the day. In this way the DESS support is customized for the specific economic dispatch and available solar energy.

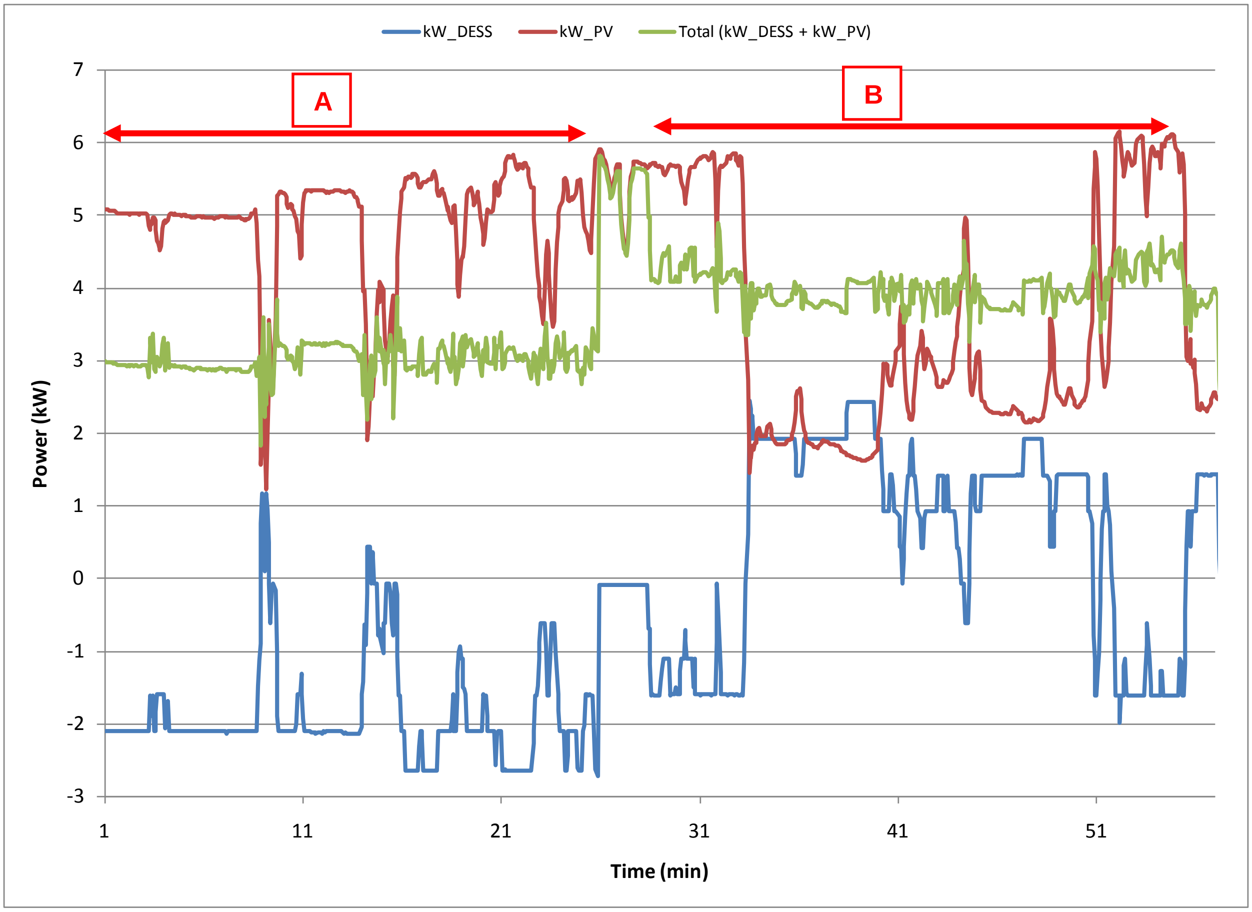

Figure 5-11
PV and Battery Follow a Predefined Generation Schedule

Solar Smoothing Application

In the solar smoothing application the DESS not only limits the ramp rate but also fills valleys in the PV power output. Compared to a ramp rate limiting service, in this operating mode the DESS is required to discharge more energy to offset reduced PV power output. Hence for this demonstration a target SOC was set at 30%, where the starting SOC was 55.6%. In Figure 5-12 the time interval marked as "A" shows the solar smoothing impact on total power.

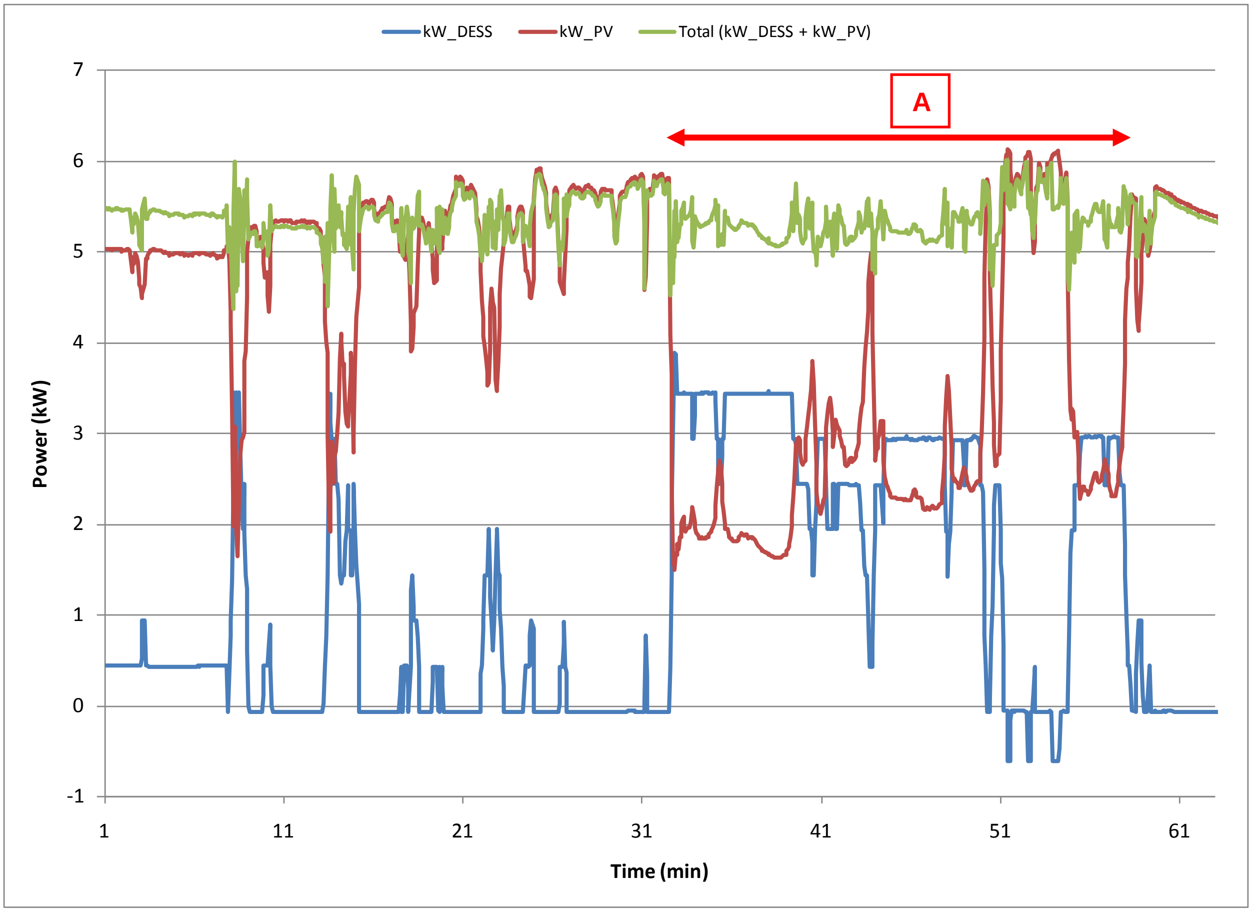

Figure 5-12
Solar Smoothing Operation

Load Following with Solar Application

In this application the DESS controller monitors both PV power production and load power data from electrical meters and charges or discharges to essentially cancel or offset the measured values. This positive and negative smoothing minimizes power output variations and related impacts on the grid. In load following mode of operation storage requirement is likely to be more demanding in the afternoon when load and PV tend to be going different directions.

Demonstration of load following was conducted using Greensmith Power Vault 80 DES system. Instead of using physical meters, two virtual meters were created to store actual field measured PV power production and residential load data for an eight hour period. Figure 5-13 illustrates how DESS unit charged/discharged with varying magnitude in response to fluctuations in PV power production and maintained the resultant power magnitude very close to the load demand.

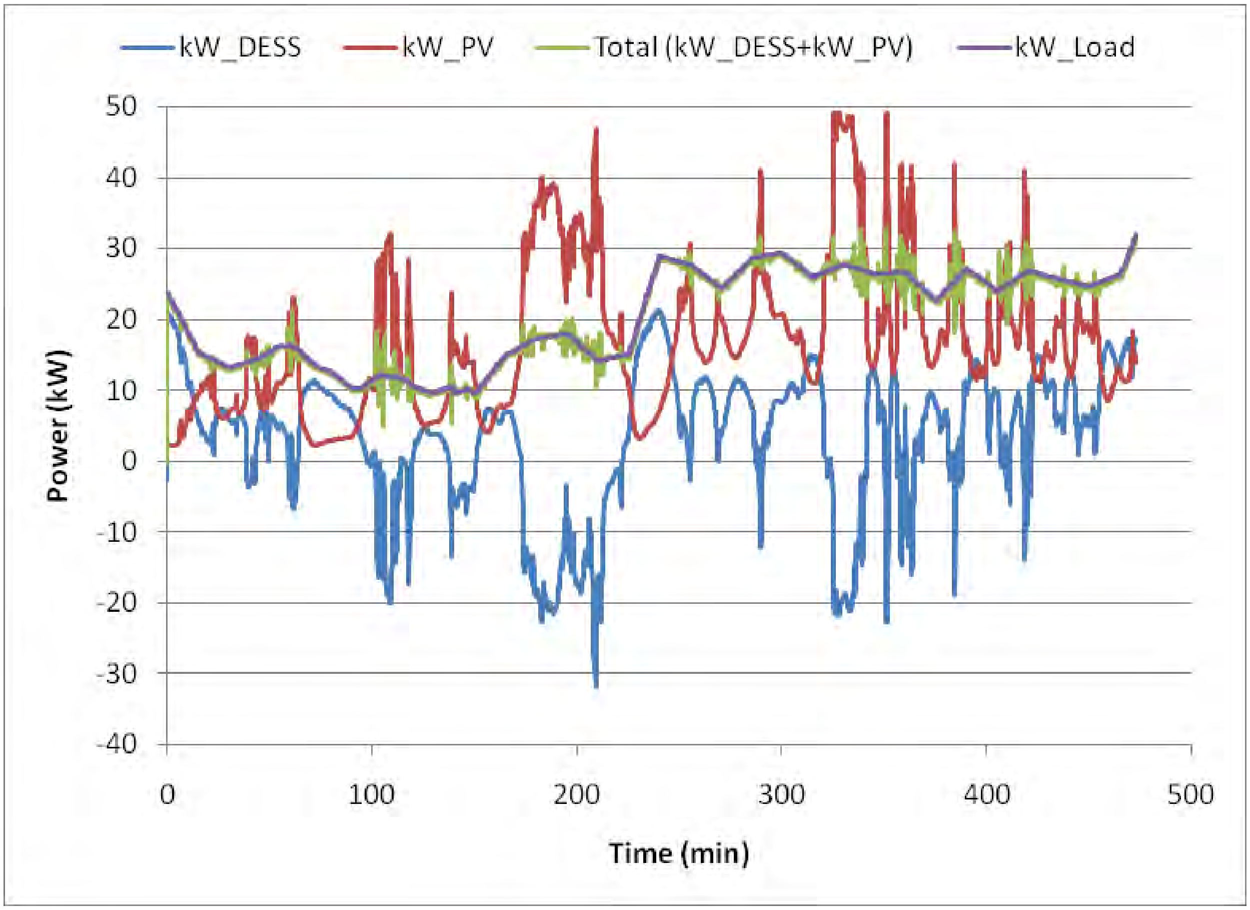

Figure 5-13
PV plus Battery Load Following Operation

Solar Ramp Rate Reduction Application

In solar ramp rate limiting mode DESS requires the battery to be at a partial state of charge so energy can flow in and out of the battery as needed during dynamic PV power output fluctuation conditions. Graphs in Figure 5-14 illustrate that ramp rates of total power output are much lower than that of PV power output. For this test SOC was set equal to the starting SOC and hence DESS tried to conserve the available stored energy.

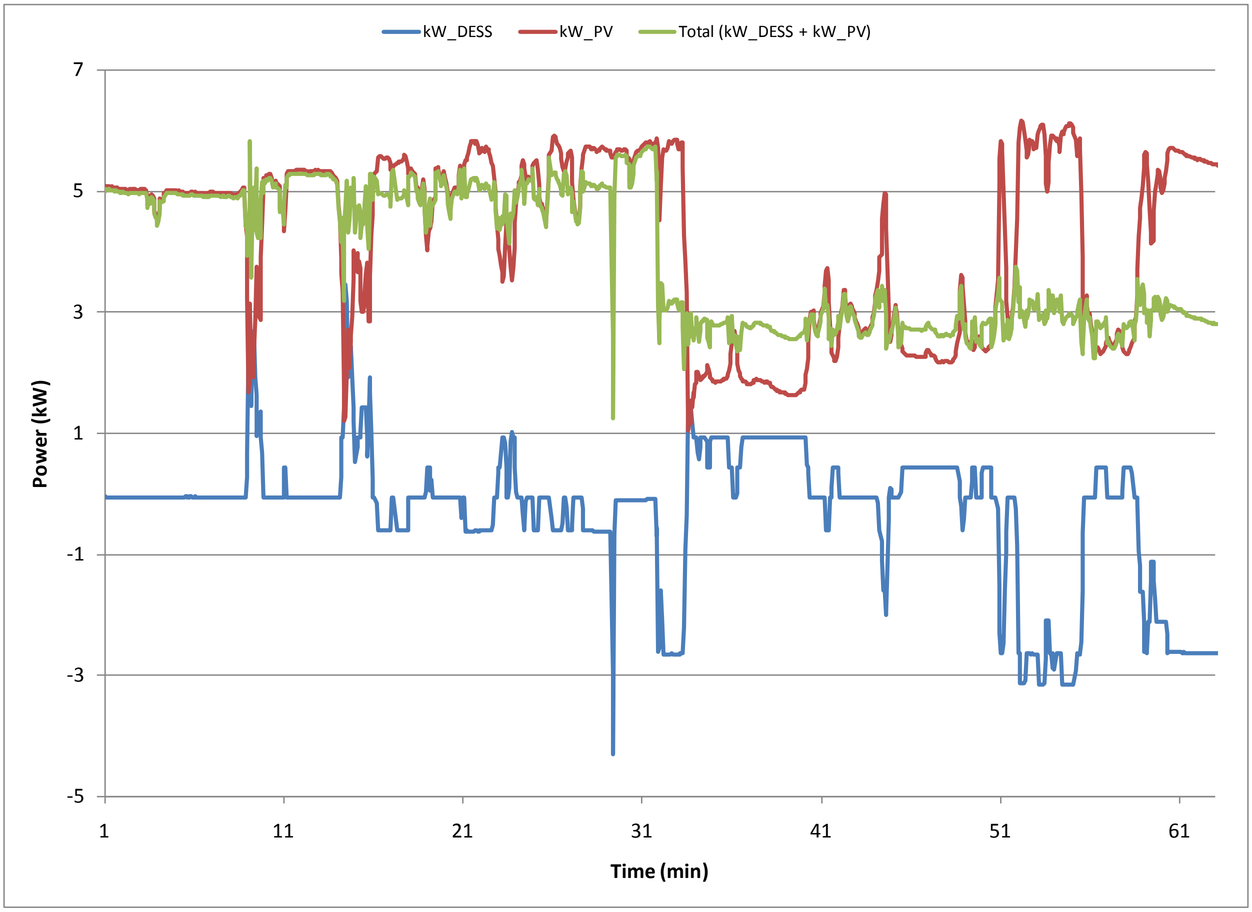

Figure 5-14
Solar Ramp Rate Reduction Operation

6 CONCLUSION

Distributed Energy Storage Systems with grid support capabilities in the 25 to 50 kW/ 25 to 82 kWh range were evaluated to determine grid compatibility, energy performance and configuration for PV system support. It was demonstrated that a DESS, meeting the interconnection requirements of IEEE Standard 1547, was able to provide several different PV support functions while maintaining round-trip energy storage efficiency between 83-87%.

PV support functions were defined and evaluated as to their ability to mitigate the variable nature of PV power output. These were time shifting, energy scheduling, smoothing, load following, and ramp rate reduction. The built-in control algorithms in the DESS were configured in different ways to evaluate all five of these support functions. Results show how energy storage systems can be utilized to counter balance the fluctuating power output from the PV system. The net power flow between the point-of-common-coupling (PCC) and the grid is much smoother than the PV system alone. Besides ramp rate reduction and smoothing, PV peak shifting function was also demonstrated on a limited scale. Use of energy storage is also demonstrated to offset the difference between actual PV output and scheduled customer power demand and load.

Future work

If energy storage with PV is going to provide value added support to the electric grid a more standard communication method will be needed. The next step is to define support functions that can be mapped to common language communication protocols as described in *Common Language for Distributed Storage Integration: Applying the DNP3 Application Profile for Smart Inverters.*[5] With this energy storage manufactures can further develop and build in algorithms that accomplish the functions when selected by a user.

Near-term forecasting data can be integrated with the energy management system to schedule the charge or discharge mode of a battery and rate to synchronize with the PV power production increase or decrease. Effectively this can minimize the delay in DES system response to PV fluctuation and can offer better smoothing response. By integrating both load and PV meters the DES systems can be dynamically charged and discharged to match PV output with load in near real-time. With proper sizing of PV and storage systems net power demand from grid can be minimized. Utilities can use day ahead PV forecasting data to create a customer demand profile for the PV plant and schedule other resources accordingly. In real-time difference between actual PV generation and demand profile can be matched by energy storage systems.

EPRI Integration of Distributed Renewable and Energy Storage research program engineers will continue this research in 2012 and beyond. Future research will aim to incorporate new PV and storage integration functionality, solar forecasting data, and newer system solution providers. EPRI will also work with utility partners to carry out field demonstration of PV power production intermittency mitigation through electric energy storage system.

[5] *Common Language for Distributed Storage Integration: Applying the DNP3 Application Profile for Smart Inverters.* EPRI, Palo Alto, CA: 2011. 1023056

A

GREENSMITH POWER VAULT 50 SPECIFICATIONS

GREENSMITH
energy management systems

Power Vault 50

50 KWh Distributed Energy Storage Unit

Power

AC Voltage Options	208 V_{AC}	183-229 V_{AC}
	240 V_{AC}	211-264 V_{AC}
	480 V_{AC}	422-528 V_{AC}
Maximum Continuous Power Options	25 KW (25 KVA)	Charge or discharge
Maximum Reactive Power Options	25 KVR	Capacitive or inductive
Maximum Power Ramp Time	< 2 Seconds	Ramp Rate Adjustable
Number of Phases	3	
Maximum Current per Phase (25 KVA Model)	70 A	208 V_{AC}
	62 A	240 V_{AC}
	30 A	480 V_{AC}
Nominal Grid Frequency	60 Hz	Adjustable
Grid Frequency Range	59.3-60.5 Hz	Adjustable
Power Factor	> 0.99	At Full Load

GS-BP-50-25: 25 KVA

Greensmith Battery Operating System III

Uniform battery operating environment, communication and control protocols across all Greensmith units

Advanced BMS

Real-time battery module measurement and report: voltage, current, temperature, Cell Capacity, SOC, Efficiency and SOH

Active balancing that keep all cells balanced at all times

Battery module protections against under/over-voltage, temperature and over current

In-field configurations: DOD, voltage protection ranges, power ramp rates and charge rates

Dynamic, real-time power control. Switch between charge and discharge in less than 2 seconds

Ethernet, serial and Web-based communication and control

Peer-to-peer networking across multiple units to form larger, virtual unit

Support drop-in custom modules

Smart Grid ready

Greensmith Distributed Energy Storage Unit — Power Vault 50

Energy		
Energy Storage Capacity	50 KWh	Nominal
Round Trip Efficiency	> 85%	At Rated Power
House Keeping Power	< 100 W	At Idle
Standby Energy Loss Rate	< 35% per year	Grid is Available

Battery Module		
Type	lithium Iron	
Nominal Capacity	102.5 Ah	
Cycle Life	>1,000	100% DOD
	>2,000	90% DOD

Battery Cabinet		
Enclosure Rating	NEMA 3R	Optional
Cabinet Dimensions	91(H)"x72(W)"x36"(D)	
Weight	2,300 lbs	
Transportation	Lifting hooks	

Inverter Cabinet		
Enclosure Rating	NEMA 3R	
Dimensions and Weights	74" (H) x 45"(W) x 26.875"(D) 1,732 lbs	

Thermal Management		
Operating Temperature	0 - +50 °C	
Optimum Storage Temperature	15 - +25 °C	
Cooling	Forced Air	
Cooling Power	< 1 KW	

Communication & Control		
Connection Types	Ethernet, 3G Wireless Broadband, RS232, RS485	
Protocols	TCP, UDP, Modbus, HTTP, Web Services	
Data Formats	Binary Encoded Values, XML	
Network Security	SSL with X509 Certificate	Optional
System Response Time	< 200 ms	

Maintenance and Reliability

Swappable 48Vdc tray for easy replacement and storage maintenance to maximize shelf life

Protection at cell, module, tray and system levels

Redundant communication and control paths

Remote, non-interruptive firmware update

DESS Management Web Portal

Application and Web Portal available from Greensmith that centrally manage large number of storage units over the Internet

System-to-system integration for unit control and utility integration

Web browser-based graphical interface for operation, real-time monitoring and reporting

Central database archive all historical data for analysis

Supported Solutions

Peak Shaving

Renewable Integration

Load Following

Backup Power

Voltage & Frequency Regulation

6710 Democracy Boulevard, Suite 300
Bethesda, Maryland 20817

Phone: 888.882.7430
415.684.7746 (International)

Email: info@greensmith.us.com
Web: greensmith.us.com

Figure A-1
Greensmith Power Volt 50 Specifications (vendor provided)

GREENSMITH
energy management systems

AC Measurement Unit

Measuring Circuits

Accuracy	Voltage	0.5%
	Current	0.5%
	Power	0.5%
	Power Factor	0.5%
Voltage Range		120-480 Vac, L-L, 3 or 4 w
Rated Voltage		280 Vac L-N / 485 V ac L-L
Frequency		45 to 65 Hz
Rated Current		1A to 5A isolated 333 mV for mV CT version
Operating Temperature		-4°F to 131°F
Storage Temperature		-40°F to 185°F
Humidity		5 to 95% R.H. non-condensing
Power Supply	Voltage	90-265 V_{AC}
	Frequency	50/60 Hz
	Burden	5VA

Mechanical

Enclosure	NEMA3
Dimensions	16"(H)x14"(W)x10"(D)
Weight	20 lbs

Communication

Connection	RJ 45, 10/100 Base-T
3G Wireless Router	Optional
Protocols:	Modbus/TCP

CT

Selected based on AC line ratings

6710 Democracy Boulevard, Suite 300
Bethesda, Maryland 20817

Phone: 888.882.7430
415.684.7746 (International)
Email: info@greensmith.us.com
Web: greensmith.us.com

Figure A-2
Greensmith AC Measurement Unit Specifications (vendor provided)

B

SATCON PCS SPECIFICATIONS

	Min	Nominal	Max
Electrical			
DC Voltage	305		600
DC Current	0		172
AC Voltage	183	208	229
AC Frequency	59.3	60	60.5
AC Current	0		139
Overload Capability (Software)			167
AC Breaker Size		250A/0.7s	
Short Circuit Interrupt Rating		65kA	
Short Circuit Capability			300A/4ms
AC Side Power			50kW/50kVA
Efficiency			95.9
No-Load Losses			95W
Power Factor	-0.8	1	0.8
Voltage THD			3%
Environment			
Operating Ambient Temperature	-20C		50C
Shipping Temperature	-30C		70C
Relative Humidity	15 to 95% non-condensing		
Physical			
Location	Indoor/Outdoor		
Enclosure	NEMA 3R, Seismic Rating Zone 4		
Dimensions	74"H x 45"W x 27"D		
Weight	1732lbs (785kg)		
Isolation / Protection	•Input no-load disconnect switch •Input DC contactors •Inverter fuses •AC contactor •AC Interconnection breaker		
Communications and Interface			
Controls / Indicators	•Power generation light •ON/OFF switch		
Metering (HMI)	•Output AC Voltage (all three phases) •Output Current (all three phases) •Real Output Power (kW) •Reactive Output Power (kVAR) •Power Factor •KWh •Neutral Current (if present) •DC Voltage •DC Current •DC Power (kW) •DC Bus Voltage •Stop/Run Status •Fault Status •Local/Remote Status		
Remote Communications	Modbus via RS485 communications link		

Figure B-1
Satcon PCS Specification

C
POWER SYSTEM PLANNING AND OPERATION

System Generation Fundamentals

The main function of generation in an electric power system is to produce electric energy to serve the power system load. This function of generation may include regeneration from stored energy. The Authoritative Dictionary of IEEE Standards Terms, Seventh Edition, ANSI/IEEE Std. 100, defines generation as producing or storing electric energy with the intent of enabling practical use or commercial sale of the available energy. A generating station is also defined as "a plant wherein electric energy is produced from some other form of energy (for example, chemical, mechanical or hydraulic) by means of suitable apparatus."

The operation of electric power systems is fundamentally different from other utilities. Electric systems have two unique physical characteristics:

- Electric energy is not commercially stored[6] like natural gas and water. Production and consumption (generation and load) must be balanced in near real-time. This requires continuous monitoring of loads, generation, and the voltages and flows throughout the power system, as well as adjusting generation output to match consumption.
- The transmission and distribution network is primarily passive, with few "control valves" or "booster pumps" to regulate electrical flows on individual lines. Flow-control actions are limited primarily to adjusting generation output and to opening and closing switches to add, remove, or reroute transmission and distribution lines and equipment from service.

These two operating constraints lead to four reliability consequences with practical implications that dominate power system design and operations:

- Every action can potentially affect all other activities on the power system. Therefore, the operations of all bulk-power participants must be coordinated.
- Cascading problems that quickly escalate in severity are a real threat. Failure of a single element can, if not managed properly, cause the subsequent rapid failure of many additional elements, potentially disrupting the entire power system.
- The need to be ready for the next contingency may limit current operations (for example, likely power flows that occur if another element fails could limit the allowable power transfers).
- Because electricity flows at nearly the speed of light, maintaining system stability and reliability often requires that actions be taken instantaneously (within fractions of a second), requiring automatic computations, communications, and controls.

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[6] Electricity is not "stored" directly. When electricity is "stored," it is converted to another form of energy and re-converted later. Pumped storage hydro converts electricity to mechanical potential energy by lifting water. Batteries convert electric energy to chemical potential energy. The re-conversion to electricity uses conventional generators or inverters.

These concepts have important consequences for what constitutes congestion and how variable renewable energy interacts with the power system.

Expectations Based on Traditional Generators

Reliable and low-cost operation of the interconnected electric utility is not a "natural" state but relies on operational scheduling, planning, and coordination of a multitude of electric utility control systems. Therefore, a traditional electric utility generator is not just a source of energy. There is an array of performance capabilities and specific services that operators have relied on from traditional generators. Some of these services are simply provided by the generators as part of participation in the energy market. Others are obtained from bidding in separate ancillary services markets that have evolved, particularly in light of deregulation. The exact definition of these services varies in different markets, but in general they fall into the categories described in Table C-1.

Response time is one of the critical factors in defining these generation capabilities and services. Time is critical because of the nature of the electric utility as described above. And wind power integration issues as well as the value attributed to wind energy are to a large degree measured by how well the traditional generation functions are fulfilled.

Table C-1
Functions and Services Provided by Generation

Functions and Services	Short Description	Time Frame
Base load units (non-regulating)	**Energy** (firm) scheduled well in advance, based on availability, price, and long-term contracts.	**Long-term** commitments
Committed units (usually with regulation capacity)	**Energy** (firm) scheduled based on availability and price to meet block load, with LOLE† and load forecasts considered.	Day before plan, **hourly** resolution
Load-following or energy-balancing units	**Energy** ramping to follow the load, met by adjusting generation schedules and the imbalance energy market.	Hourly plan with **5- to 10-minute** resolution
Frequency regulation (regulating reserves)	**Service** provides capacity based on a signal from dispatcher, with AGC†† to meet CPS 1 and CPS2††† and no net energy††††.	Every few minutes, **minute-to-minute** resolution
Reactive supply and voltage control	**Service** of injecting or absorbing of reactive power to control local transmission voltages (usually provided with energy).	Continuous with response in **seconds**
Spinning operating reserves	**Service** to provide energy in response to contingencies and frequency deviations.	Begin within **10 sec** full power in **10 min**
Non-spinning operating reserves	**Service** to provide load/generation balance in response to contingencies, not frequency response.	Respond within **10 minutes**
Replacement reserves	**Service** to restore contingency capacity to prepare for the next generation or transmission contingency.	Respond within **60 minutes**, run up to 2 hours
System black start	**Service** to restore all or a major portion of the power system without outside energy after a total collapse.	**As required**

† Loss of load expectation (LOLE) is the probability measure that a load cannot be served with available generation.

†† Automatic generation control (AGC) is a method for adjusting generation to minimize frequency deviations and regulate tie-line flows.
††† Control performance standards (CPS1 and CPS2) are minute-to-minute and 10-minute average criteria for load frequency control in each control area. These criteria require the control areas to maintain their area control errors (ACE) within tight limits. ACE is measured in MW and is defined as the instantaneous difference between the actual and scheduled interchanges plus frequency bias (imbalances that bias the system toward maintaining 60 Hz).
†††† Frequency regulation service is usually provided from generation that is on-line and delivering some level of base energy power on a full-time basis or scheduled. The service is to increase and decrease power output where the average output over the scheduled period does not change—that is, there is no net change in delivered energy attributed to the frequency regulation service. Consequently, energy-storage devices could provide this service.

Typical System-Operating Strategy

A system-operating strategy, with and without renewable generation, will likely include energy balancing (from both committed and reserve units), unit commitment block scheduling, and an economic dispatch procedure. This strategy starts with a forecast of system load with time-varying characteristics and expected minimums and maximums. Inventories of available generation and the estimated cost of energy, as well as other services, are maintained. Desired reserve margins are set. Base-load units and firm energy blocks can be scheduled so that in the short term, the operator is only dealing with the differences between the predicted and actual load and / or available generation.

Thus, the system operator is effectively managing supply and demand over three time scales: (1) days- and hours-ahead scheduling, (2) intra-hour load following and balancing, and (3) fast regulation to maintain system frequency and voltage. The impact that renewable generation may have on this strategy is discussed later. All three time frames are also important to effective integration of any generation resource, including renewable.

Energy Balancing

System operators run load-following and regulation markets to ensure that there is adequate on-line generation capacity for ramping up or down to follow the load and to regulate the faster and more random changes in load.

- For frequency regulation: Load-following units must be on-line and provide fast response to meet the minute-by-minute fluctuation in the system energy balance. North American Electric Reliability Council, NERC, has set the guidelines on control performance in frequency regulation.
- For intra-hour load following: These resources are being dispatched to follow the within-the-hour load change in the frequency consistent with the economic dispatch cycle (5 to 10 minutes per cycle).
- For reliability: This is the primarily contingency reserves (use of spinning and fast-start generators) that can be deployed within 10 minutes in order to replace any MW loss following line or generator outage. Typically, one-half of system operating reserves is spinning, so that a sudden loss of generation will not result in a loss of load, with the balance available to serve the load within 10 minutes. And this includes replacement reserves.

Both regulation and load following are dealt with on a control area basis. Each and every load variation does not have to be compensated for directly, but the aggregate change in the area must be balanced. The fast, random fluctuations associated with regulation are typically uncorrelated.

Consequently, the total regulation requirement is not the sum of all the regulation requirements of the individual loads and uncontrolled generators, but it is the sum of the correlated components.

Load-following requirements tend to be more highly correlated; most area profiles rise in the morning and drop off in the evening. Still, because load-following requirements are not perfectly correlated, the total system load-following requirement is less than the sum of the load-following requirements of individual end users. This aggregation of loads has a powerful effect on system planning and operation because the system must respond to total variations, not the sum of individual variations.

Unit Commitments

Unit commitment (UC) is part of a set of programs for scheduling generation on an hourly to weekly basis. Vertically integrated utilities typically run their unit-commitment optimization computer programs the day before operations. These complicated computer programs accept as inputs detailed information on the characteristics of the individual generating units that are available to produce electricity on the following day. These characteristics include current unit status, minimum and maximum output levels, ramp-rate limits, startup and shutdown costs and times, minimum runtimes, and unit fuel costs at various output levels.

In addition, the inputs include details on the characteristics of the transmission system expected for the operating day. Finally, the operations planner inputs into the model the utility's day-ahead forecast of system loads, hour by hour, as well as any scheduled wholesale sales or purchases for the following day. Forecasts of load for the next hour, day, season, or year drive the utility scheduling process.

Load forecasting is often subdivided into "long-term," where seasonal load peaks and energy requirements are predicted on a long-range basis, and "short-term," where hour-by-hour predictions are made for a particular day. Accurate forecasting of system load is critical for minimizing operating costs. Load forecasts are the primary inputs to the power system scheduling and operations process.

Using these data as inputs, unit commitment programs determine which units are to be put on-line, when they are to be on-line, and when they are to be taken off-line. The optimization model is then run to identify the least-cost way to meet the following day's electricity demands while maintaining reliability. The reliability requirements include the ability to withstand the loss of any single generation or transmission element while maintaining normal service to all loads. The optimization model performs two functions in its search for a least-cost solution. First, it tests different combinations of generating units that are available and therefore could be scheduled to operate the following day (the times each unit will start, operate, and then be turned off). Second, given the units that are on-line and operating during any hour, it selects the least-cost mix to meet that hour's loads.

Economic Dispatch

Once generators are committed (turned on and synchronized to the grid), they are available to deliver power to meet customer loads and reliability requirements. Utilities typically run their least-cost dispatch model every five minutes or so. This model forecasts load for the next 5-minute interval and decides how much additional/lower generation is needed during the next interval for regulation to meet the system load. The model then selects the least-cost combination of units that meet the need for more or less generation during the next intra-hour interval.

Solving this optimization problem is complicated because of all the constraints that generators have. For example, one unit may be cheap to operate (in terms of its variable costs, expressed in $/MWh) but may have high startup and no-load costs (expressed in $/startup and $/hour, respectively), while another unit has just the opposite characteristics. Which unit to commit depends on how many hours it is expected to operate the following day. In addition, the unit-commitment solution must respect system constraints, which include contingency-reserve and regulation requirements and transmission constraints (thermal, voltage, and stability). Finally, the optimization model must consider many different combinations of generating units that could meet the hour-by-hour loads during the day.

Role of Ancillary Services

In addition to committing and dispatching units, system operators may contract for ancillary services to support operation of the grid. FERC has defined ancillary services as those necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system. This statement recognizes the importance of ancillary services for bulk-power reliability and to support commercial transactions. Though the resources necessary to create these services are generators, the services themselves must be deployed and controlled by the same system operator that controls the transmission system.

Ancillary services are conceptually well defined. They have existed throughout the history of the power system. However, the details of obtaining them from markets are still evolving. The following is a description of ancillary services that are normally provided by generation:

***Regulation*:** The power system operator needs rapid, automatic control over some generation resources (AGC) to compensate for normal short-term fluctuations in the aggregated load and generation in order to meet NERC control performance criteria. This is related to maintaining the real power balance and stable frequency in the power system. Time scales are minute to minute.

The power system operator could eliminate the need for regulation by insisting that all end-use consumption conforms precisely (minute-by-minute) to its power purchase schedule. Alternatively, each end-use consumer could be required to contract with a generator to precisely match its individual minute-to-minute load fluctuations. These alternatives are both impractical and wasteful from a viewpoint of minimizing needed resources.

Contingency reserves are also planned in case of sudden loss of generation, off-system purchases, unexpected load fluctuations, and/or unexpected transmission line outages. These contingency reserves may be spinning or non-spinning reserve or simply for replacement. The specific reasons for regulating and reserve generation units may be divided into two categories as follows

***Contingency reserves**:* The power system must always be prepared to survive the unexpected loss of a generator or a transmission line. To accomplish this, the power system operator is required to maintain contingency reserves consisting of spinning reserve and non-spinning reserve sufficient to meet the largest credible contingency.

- ***Spinning operating reserve:*** At least half the contingency reserve is typically spinning reserve. Spinning reserve comes from generation that is on-line, not fully loaded, capable of responding fully within ten minutes, and able to maintain that output for at least two hours. Spinning reserve units are also required to be responsive to frequency deviations.
- ***Non-spinning reserve:*** The definition of non-spinning reserve is similar to that of spinning reserve except that the reserve is not required to be on-line or frequency responsive. In addition, non-spinning reserve does not have to be provided by generation; it can be provided by dispatchable demand, interruptible exports, certified off-line generation, or external imports.
- ***Replacement reserve:*** Contingency reserves must be restored so that the system is prepared for a subsequent unexpected outage. Some regions specifically identify replacement reserves, which are capable of responding within one hour and sustaining that response for an additional two hours. They can be generators, loads, or resources from outside the Independent System Operator's (ISO) control area.

Together, spinning reserve, non-spinning reserve, and replacement reserve provide resources that begin responding immediately to an unexpected event, are fully deployed within ten minutes, are capable of responding to a second event within one hour, and can sustain the total response for three hours. This coordinated set of resources is designed to provide sufficient time for markets to begin functioning again and return the system to normal operations. All of these services, and regulation, are typically procured through day-ahead and hour-ahead markets run by the ISO.

Figure 2-1 provides a summary of deployment times for various ancillary services. Reserves are deployed only during contingency operations, while regulation and voltage control are required during both normal and contingency operations.

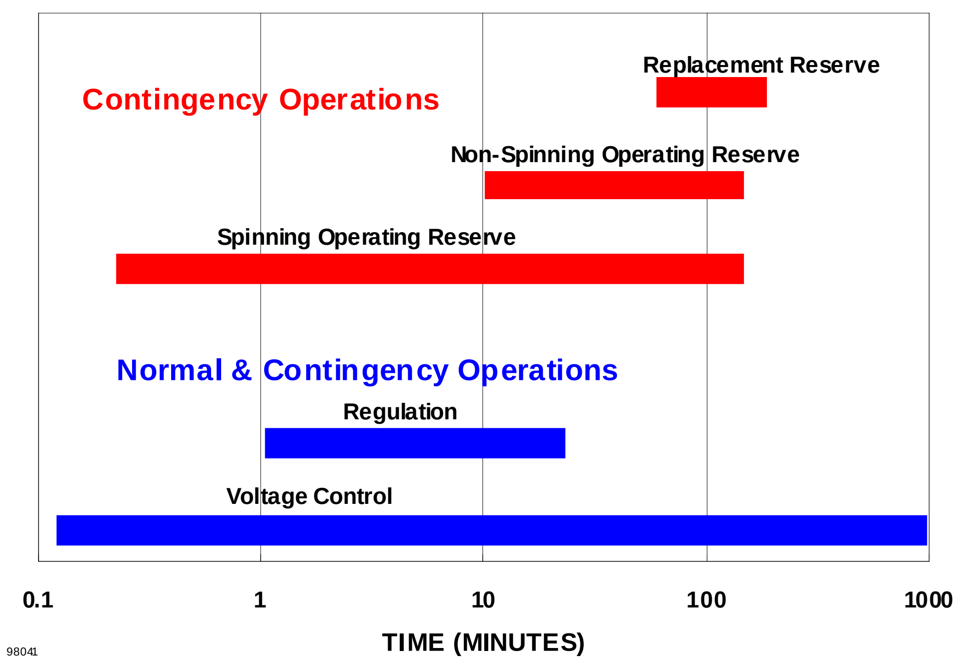

Figure C-1
Ancillary Services Are Distinguished by Their Deployment Times and Durations

Voltage control: Because of relatively strict geographic requirements for voltage control, it is not normally procured through markets. Instead, all generators are required to provide limited reactive support and voltage control without compensation. Reactive support, the generation or absorption of reactive power (MVAR), is the resource that is used to control the voltage in the vicinity of the generator. All generators are required to be capable of following a system-operator-supplied voltage schedule under automatic voltage control within a power factor of typically 0.90 lagging and 0.95 leading. The system operator will typically compensate generators if it requires them to provide additional reactive support and voltage control.

Black start: Because of relatively strict geographic requirements for black-start capability, it is also not normally procured through markets. The system operator determines the system's black-start requirements needed to ensure that the *system* may be restored to service expeditiously if it should ever fail completely. Long-term contracts are established with selected black-start units. Each black-start unit must be capable of starting, without external assistance, within ten minutes. It must be capable of supplying the reactive power requirements and controlling the voltage of the energized transmission system and must be capable of operating for a minimum of 12 hours.

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