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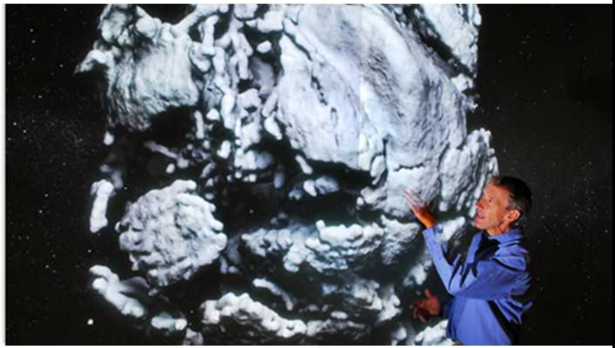

Interoperability and Advanced Inverter Functionality Testing Update

29 April, 2014

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Project Description

		Year 1	Year 2	Year 3
Project Period		01-12-2012 ~ 30-11-2013	01-12-2013 ~ 30-11-2014	01-12-2014 ~ 30-11-2015
Total Budget (Unit: KRW 1000/US$)	KERI	KRW 373,700	KRW 300,000	KRW 300,000
		- determination of DG devices under test : PV and ESS - review of the existing test facilities - basic design of test bed and implementation - writing draft of interoperability test procedure	- construction of test bed - performing interoperability test on various DG devices - comparison of test results	- proposal of international standards -building mutual certification system on interoperability test regarding DG devices
	SNL	200,000 USD-	200,000 USD-	200,000 USD
		- Design and construct testbed - Establish utility to DER communication - Draft standardized test procedure and data acquisition protocol - Develop standardized analysis procedure and test reporting - Comparing Korean and U.S. results - Test PV inverters: 2 to 4 functions	- Amplification of PV inverter tests: 3-10 new inverter functions; residential to commercial scale - Revise interoperability protocol based on prior results - Comparing Korean and U.S. results - Design, construct, exercise testbed for ESS incorporation - Status report on program and results.	- Amplification of PV and ESS tests: complete set of inverter functions - Use experimental results to propose a test protocol standard (IEC) - Final report on program and results.

Inverter Interoperability Test beds at Sandia and KERI

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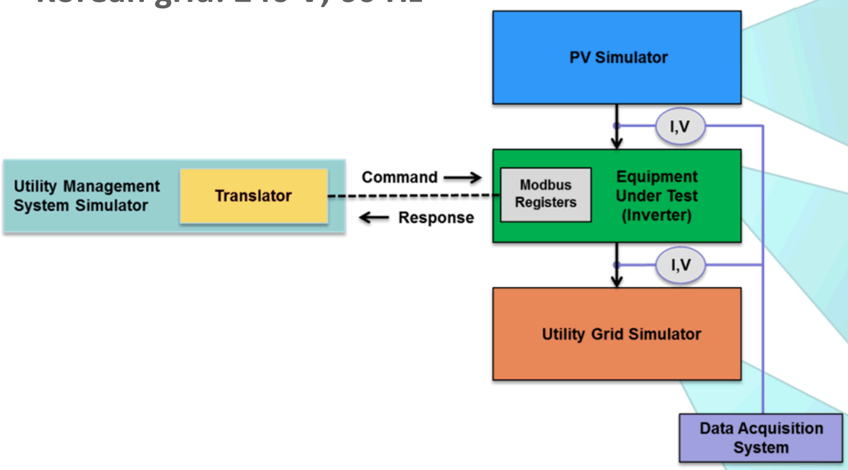
Both Sandia and KERI have designed interoperability testbeds. Differences in hardware and grid voltage and frequency demonstrate the capabilities of the testing protocols.

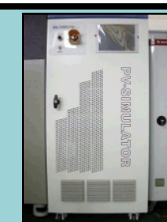
US grid: 120/240 V, 60 Hz

Korean grid: 240 V, 60 Hz



PV Simulator
Power: 200 kW
Voltage: 0-1000 V_{dc}/output
Current: 10 A/output

PV Simulator
Power: 10 kW
Voltage: 0-500 V_{dc}
Current: 50 A



Inverter: European Partner
Power: 3 kW
Communications: Modbus, RS485
- Available worldwide
- Inexpensive
- SunSpec compliant

Inverter: Korean Partner
Power: 3 kW
Communications: SEP 2.0

Grid Simulator
Power: 180 kVA
Voltage: 480 V 3ϕ
Current: 700 A/Phase

Grid Simulator
Power: 10 kVA
Voltage: 380 V_{L-L} 3ϕ, 4-wire

- **AIT is exercising the test protocols on a 5 kW Fronius inverter. They have also worked with a 680 kW Schneider Electric using an IEC 61850-90-7 gateway.**
- **RSE has a 5 kW Fronius inverter.**

SNL Status for IEC 61850-90-7 Function Tests

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Command	Function	Description	Type
INV1	Connect/Disconnect	Physically connect or disconnect from grid	Command
INV2	Adjust Max Generation Level	Set maximum generation level at Electrical Coupling Point	Command
INV3	Adjust Power Factor	Issues a power factor angle value	Command
INV4	Request Active Power	Request charging or discharging of the storage system	Request
INV5	PV/Storage Functions	Change the signal parameters for the storage system	Request
VV11	Volt-Var mode	Provide vars with no effect on watts	Set Parameter
VV12	Volt-Var mode	Provide maximum vars constrained by WMax	Set Parameter
VV13	Volt-Var mode	Establish fixed var settings	Set Parameter
VV14	Volt-Var mode	No var support	Set Parameter
FW21	Set maximum power output	Active power reduction due to high frequency	Set Parameter
FW22	Set maximum power output	Modify frequency-watts-delivered or watts-received curve	Set Parameter
TV31	Dynamic reactive power support	Provide var support at times of abnormally high or low voltage	Set Parameter
L/H VRT	Stay connected/disconnect settings	Set voltage ride-through or disconnect requirements	Set Parameter
WP41	Power factor settings	Set power factor in response to feed-in power	Set Parameter
WP42	Power factor settings	Modify power factor-watts curve	Set Parameter
VW51	Set output to smooth voltage	Voltage-watt curve of generator output	Set Parameter
VW52	Set output to smooth voltage	Voltage-watt curve of storage charge/discharge output	Set Parameter
TMP	Temperature mode behavior	Temperature-based curves	Set Parameter
PS	Signal mode behavior	Mode curves based on utility signal	Set Parameter
DS91	Modify DER Inverter Settings	Set default ramp rate, min./max. storage charge/disch. rate	Command
DS92	Event/History Logging	Request event logs	Command
DS93	Status Reporting	Request inverter status	Command
DS94	Time Synchronization	Set inverter time	Command

Implementation Successful (green box): INV1, INV2, INV3, VV12

Implementation Partly Successful (yellow box): FW21, DS91, DS93

Implementation Unsuccessful (red box): L/H VRT

Near-term Implementation (blue box): WP42, VW51

INV1 – Connect/Disconnect

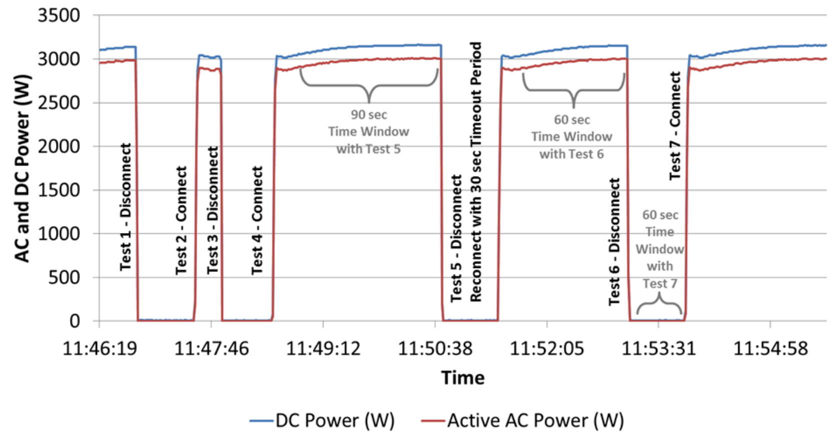
INV1 Test Protocol Sequence.

	Step	Task	Function	Notes
Communication	1	Request Status to EUT.	**DS93** (Status Reporting) & Direct Measurement (**DM**) of inverter output	Log time sent.
	2	UMS receives response to the DS93.command.		Log time received.
	3	Inverter output is measured and logged		Direct Measurement sensors record inverter output
	4	UMS issues a Disconnect /Connect Command to EUT.	**INV1** – Connect/ Disconnect	Log time sent. Command may include the following parameters: time window (optional) timeout period (optional) ramp rate (optional)
	4	EUT responds to the command.	**DS92 –** change in status is noted	Expected response message from EUT: Successful (DS92 status change logged and DM monitored output) Rejected (includes reason)
Electrical Behavior	5	Verify command was successfully executed (DS92 and DM).	**DM –** EUT output is recorded & logged	Monitor electrical output of EUT to determine if EUT connects/ disconnects and at what time. Measure voltage, current, power factor Record time
	6	Repeat test with varying parameters (see Table A1-3). Each test should be repeated at least once as needed.	–	
Analysis	7	Characterize EUT's response.	**DS92; DM**	Determine how command was executed.

INV1 Test Matrix.

Test Number	EUT Initial Operating State	Connect/Disconnect Command	Time Window (seconds)	Timeout Period (seconds)
Test 1	>50% rated power, unity power factor	Disconnect 1	Default (e.g., 0)	Default (e.g., 0)
Test 2	Inverter off	Connect 1	Default (e.g., 0)	Default (e.g., 0)
Test 3	>50% rated power, unity power factor	Disconnect 2	0	Default (e.g., 0)
Test 4	Inverter off	Connect 2	0	Default (e.g., 0)
Test 5	>50% rated power, unity power factor	Disconnect 3	90 seconds	30
Test 6	>50% rated power, unity power factor	Disconnect 4	60 seconds	0 (No Timeout)
Test 7	Inverter off	Connect 4	60 seconds	0 (No Timeout)

Connect/Disconnect (INV1) Test Results at Sandia



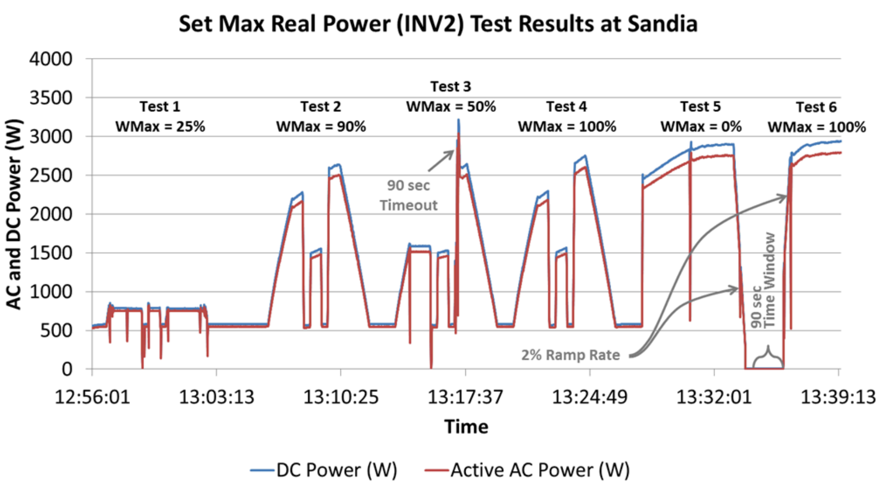
INV3: Set Constant PF – Electrical Characterization Results

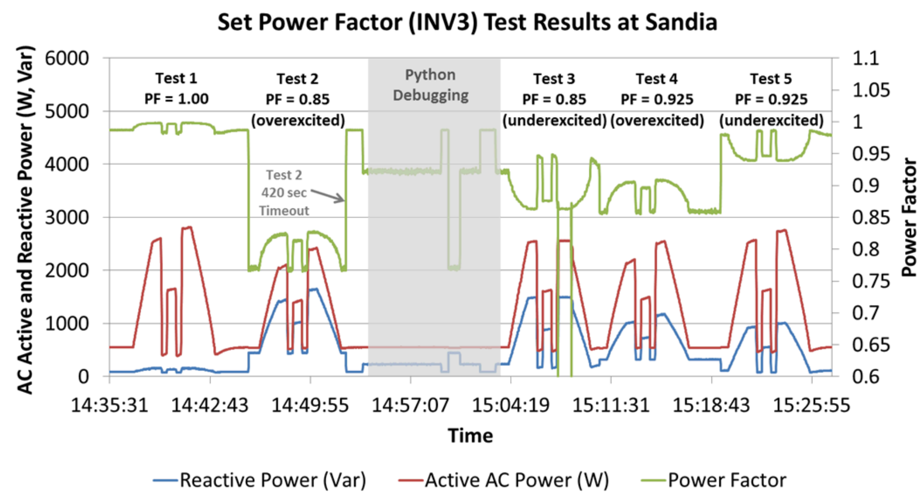
New INV2 Test Matrix.

Test	WMax (% nameplate)	Ramp Rate (% nameplate watts/sec)	Time Window (sec)	Timeout Period (sec)	Input PV Power Curve
Test 1	25	0	0	0	Figure A2- 1
Test 2	90	0	0	0	Figure A2- 1
Test 3	50	20	0	90	Figure A2- 1
Test 4	100	0	0	0	Figure A2- 1
Test 5	0	2	0	0	Constant at 100%
Test 6	100	2	90	0	Constant at 100%

New INV3 Test Matrix.

Power Factor (INV3)	Ramp Rate (%/sec)	Timeout Period (sec)	Time Delay (sec)
1.00 (default)	0	0	0
MaxPFAval (overexcited)	0	60	420
MaxPFAval (underexcited)	0	90	0
0.5+MaxPFAval/2 (overexcited)	10	0	0
0.5+MaxPFAval/2 (underexcited)	0	0	480

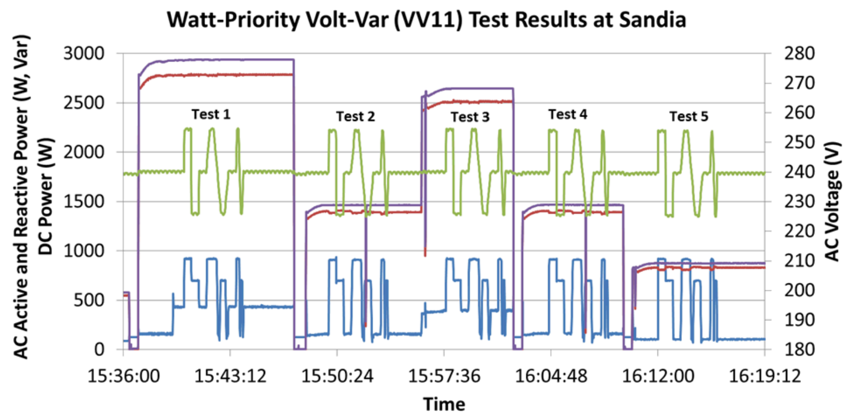


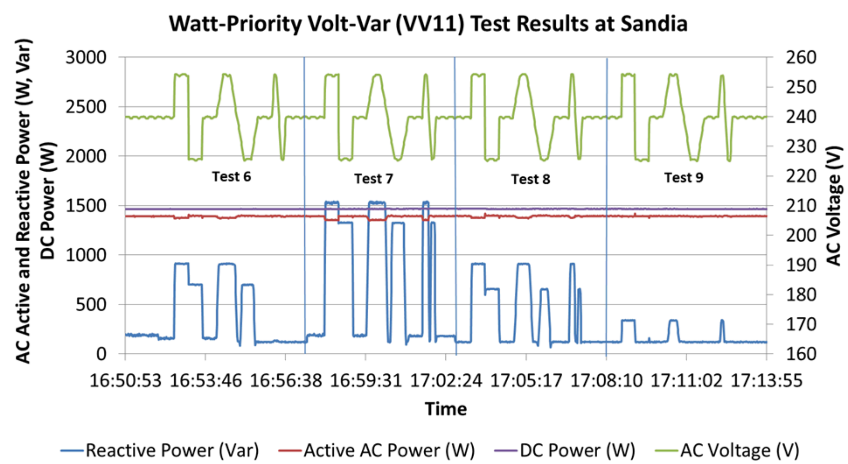


VV11 – Watt-priority volt-var

New VV11 Test Matrix.

Test	EUT Initial Operating State	Volt/Var Initiation	Volt/Var [V,Q] Array				Requested Ramp Time (% VArAval/s)	Time Window (seconds)	Timeout Period (seconds)
1	100% rated power, unity power factor	Binary, 1	V1	97	Q1	50	0	0	0
			V2	99	Q2	0			
			V3	101	Q3	0			
			V4	103	Q4	-50			
2	50% rated power, unity power factor	Binary, 1	V1	97	Q1	50	0	0	0
			V2	99	Q2	0			
			V3	101	Q3	0			
			V4	103	Q4	-50			
3	90% rated power, unity power factor	Binary, 1	V1	97	Q1	50	10	0	0
			V2	99	Q2	0			
			V3	101	Q3	0			
			V4	103	Q4	-50			
4	50% rated power, unity power factor	Binary, 1	V1	97	Q1	50	0	0	0
			V2	99	Q2	0			
			V3	101	Q3	0			
			V4	103	Q4	-50			
5	30% rated power, unity power factor	Binary, 1	V1	97	Q1	50	0	0	300
			V2	99	Q2	0			
			V3	101	Q3	0			
			V4	103	Q4	-50			
6	50% rated power, unity power factor	Binary, 1	V1	97	Q1	50	10	0	180
			V2	99	Q2	0			
			V3	101	Q3	0			
			V4	103	Q4	-50			
7	50% rated power, unity power factor	Binary, 1	V1	97	Q1	100	0	0	0
			V2	99	Q2	0			
			V3	101	Q3	0			
			V4	103	Q4	-100			
8	50% rated power, unity power factor	Binary, 1	V1	95	Q1	50	0	120	0
			V2	98	Q2	0			
			V3	102	Q3	0			
			V4	105	Q4	-50			
9	50% rated power, unity power factor	Binary, 1	V1	80	Q1	100	0	0	0
			V2	95	Q2	0			
			V3	105	Q3	0			
			V4	120	Q4	-100			





SunSpec Alliance Specifications

- SunSpec has released a number of specifications format for Modbus registers on SunSpec-compliant devices:
  - Common Elements v1.4
  - Inverter Models v1.1
  - String Combiner Model v1.1.1
  - Inverter Controls DRAFT 10
  - ….

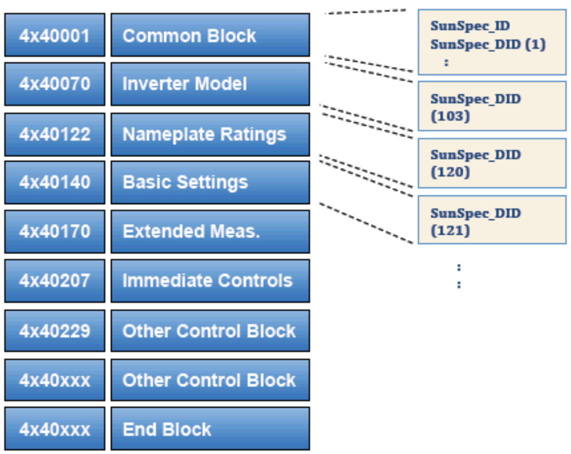


Figure 1: Chained Inverter Control Blocks

Automating Certification Tests

- Using the SunSpec Modbus mapping and python scripting tool, the interoperability test procedure can be quickly executed on any SunSpec-compliant device.

INV1 Main Program

```python
if __name__ == "__main__":

    prompt_resp = raw_input('Do you want to run the script with prompts for connect/disconnect (y/n)?')

    print 'Talking to the inverter... hold on a sec'
    f = client.SunSpecClientDevice(client.RTU, 1, 'COM3')

    print f.models
    print f.controls

    for model in f.models:
        print model, '\n\n'
        print f[model]

    # Test 1
    #parameters: time_window, timeout_period, test_num, prompt_resp
    disconnect(0, 0, 1, prompt_resp)
    time.sleep(5)
    verify_disconnect(50)

    # Test 2
    #parameters: time_window, timeout_period, test_num, prompt_resp
    connect(0, 0, 2, prompt_resp)
    time.sleep(25)
    verify_connect(50)

    # Test 3
    #parameters: time_window, timeout_period, test_num, prompt_resp
    disconnect(0, 0, 3, prompt_resp)
    time.sleep(5)
    verify_disconnect(50)

    # Test 4
    #parameters: time_window, timeout_period, test_num, prompt_resp
    connect(0, 0, 4, prompt_resp)
    time.sleep(25)
    verify_connect(50)

    # Test 5
    #parameters: time_window, timeout_period, test_num, prompt_resp
    disconnect(90, 30, 5, prompt_resp)
    # timeout is 30 seconds
    still_on = True
    count = 0
    print 'Randomization window in use. Wait up to 90 seconds for disconnect'
    while still_on == True:
        time.sleep(1)
        count += 1
        f.controls.read()
        if f.controls.Conn == 0:
            still_on = False
            print 'Inverter disconnected after %d seconds' % (count)
            print 'Please wait 30 seconds for the revert time to reconnect the inverter'
    time.sleep(55)
    verify_connect(50)

    # Test 6
    #parameters: time_window, timeout_period, test_num, prompt_resp
    disconnect(60, 0, 6, prompt_resp)
    still_on = True
    count = 0
    print 'Randomization window in use. Wait up to 60 seconds for disconnect'
    while still_on == True:
        time.sleep(1)
        count += 1
        f.controls.read()
        if f.controls.Conn == 0:
            still_on = False
            print 'Inverter disconnected after %d seconds' % (count)
    time.sleep(5)
    verify_disconnect(50)

    # Test 7
    #parameters: time_window, timeout_period, test_num, prompt_resp
    connect(60, 0, 7, prompt_resp)
    still_off = True
    count = 0
    print 'Randomization window in use. Wait up to 60 seconds for connect'
    while still_off == True:
        time.sleep(1)
        count += 1
        f.controls.read()
        if f.controls.Conn == 1:
            still_off = False
            print 'Inverter is in the process of connecting after %d seconds' % (count)
    time.sleep(25)
    verify_connect(50)
```

Parameters from Sandia Test Protocols INV1 Test Matrix

Main Program Runs through the Test Procedure

```python
# Test 1
#parameters: time_window, timeout_period, test_num, prompt_resp
disconnect(0, 0, 1, prompt_resp)
time.sleep(5)
verify_disconnect(50)

# Test 2
#parameters: time_window, timeout_period, test_num, prompt_resp
connect(0, 0, 2, prompt_resp)
time.sleep(25)
verify_connect(50)
```

Disconnect Function

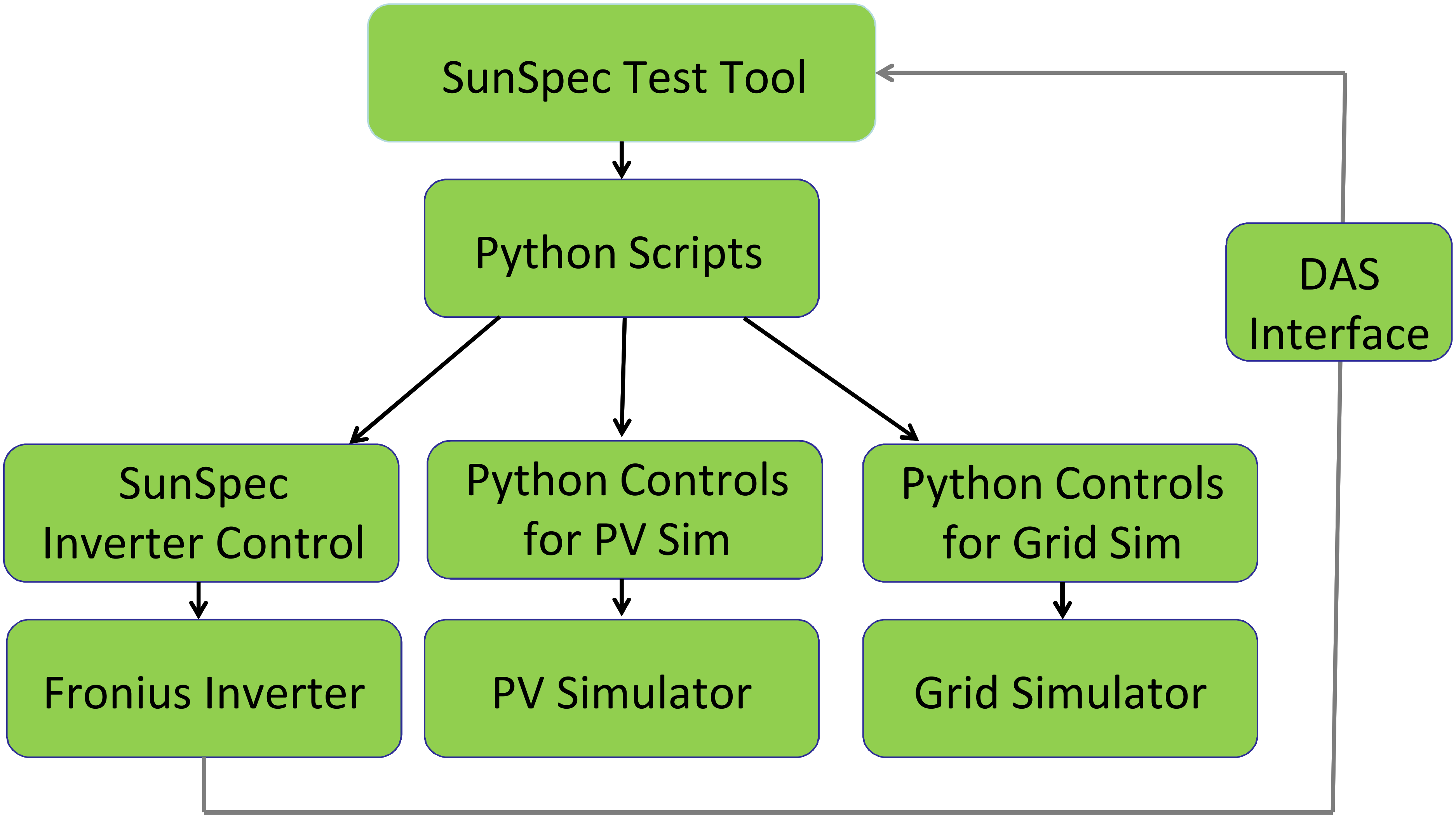
```python
def disconnect(time_window, timeout_period, test_num, prompt_resp):
    #Put EUT in connected state - Initialize test
    f.controls.read()
    if f.controls.Conn == 0:
        f.controls.Conn = 1
        f.controls.write()
        time.sleep(25)

    # Request status from EUT and display connection status
    f.controls.read()
    con_stat = f.controls.Conn
    print 'Current connection status is ', con_stat

    #Inverter output is measured and logged
    f.inverter.read()
    print 'Current power output is ', f.inverter.W

    #UMS issues a disconnect command
    if prompt_resp == 'y':
        prompt("\nExecute disconnect? (Test number is %s)" % str(test_num), prompt_resp)
    else:
        print "\nExecuting disconnect (Test number is %s)" % str(test_num)
    f.controls.Conn_WinTms = time_window
    f.controls.Conn_RvtTms = timeout_period
    f.controls.write()
    f.controls.Conn = 0
    f.controls.write()
```

Sandia Control Architecture



Future work: advanced ESS test protocols

- Sandia and the SIRFN group would like to start shifting toward testing DER functionality on more than just PV inverters.
- Some IEC TR 61850-90-7 functions are specifically designed for energy storage systems. SIRFN will need battery or other controllable ESS in order to evaluate them.
  - INV4 – Request Active Power from Storage
  - INV5 –Signal for Charge/Discharge Action
  - FW22 - limits active power generation and charging in the case of a storage system
  - VW52 - limit energy storage charging rates in response to low grid voltage.
- Sandia is partnering with a SunSpec-compliant power conditioning system designer to start advanced ESS functionality testing with their 3-port design this summer.

Advanced Inverter Collaborations

- Sandia and the Korea Electrotechnology Research Institute (KERI) are comparing test results from PV inverters and ESS.
- Within the SIRFN group
  - SNL, NREL, AIT, RSE are testing residential inverters from the same manufacturer with the Sandia Test Protocols, in order to:
    - exchange technical information on the design and operation of the advanced DER test beds and software for executing interoperability testing
    - provide refinements to the test procedures and test parameters
    - compare results for different DER sizes and designs on grids with different frequencies and voltages
  - SNL, RSE, and AIST will begin testing ESS with the test protocols this year.
  - Sig Gonzalez (Sandia) visited NREL in May 2013 to begin advanced inverter function testing with a domestic company's 500 kW inverter.
- SIRFN Collaborations with other groups
  - SIRFN is updating NIST SGIP (Smart Grid Interoperability Panel) on implementation of test protocols for advanced inverter functions.
  - Collaborating with the California Public Utilities Commission (CPUC) to determine which functions will be required for California's new Rule 21.
  - UL was granted legal permission to use the Sandia Test Protocols to update UL 1741. Similar conversations have started with the IEC Smart Grid Strategic Group.
  - PV manufacturers, CA utilities, SunSpec Alliance, EPRI and Sandia are working on the CSI grant to create translators and create a CA-specific set of test protocols.
  - SNL and SunSpec/Loggerware are creating the inverter control test tool for automating the protocols.

Sandia and AIT collaboration

- Sandia and AIT submitted an abstract regarding advanced inverter testing to EU PVSEC (Amsterdam, 22-26 Sept.)
- The paper:
  - Discusses experience exercising the Sandia Test Protocols and modifications to the test procedures/test matrices (parameters) based on the experiments.
  - Compares the different laboratory test beds (hardware and software).
  - Methods for automating the test protocols
    - Sandia is using python and SunSpec controllers
    - AIT is using Matlab controllers
  - Comparison of results for four (or more) functions
    - Currently INV1, INV2, INV3, VV11

California Solar Initiative (CSI) Proposal

- Sandia partnered with EPRI, SMA, Fronius, SCE, SMUD, and SunSpec on the "Standard Communication Interface and Certification Test Program" to develop communications specifications for the utility-to-DER interchange over Modbus, SEP 2.0, and Zigbee gateways.
- Sandia portion of the grant will:
  - Create test protocols for the certification/conformance of CA Rule 21 inverter control and interoperability requirements.
  - Address cybersecurity concerns by establishing the underlying rules for the utility-to-DER interoperability.