Promises and Challenges of Utility Scale PV Grid Integration - lessons from Lana’i

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Robert F. Johnson, SunPower
Bob Reedy, FSEC
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Outline

• Leo Casey, Robert Johnson, Bob Reedy- Introduction to Presenters and Organizations
• Robert Johnson- Lana’i PV Power Plant Project Overview
• Leo Casey- Lana’i Grid Stability Challenges
• Robert Johnson- Communications & Controls Implementation
• Bob Reedy – Integration with SEGIS Plans
The Lana’i Grid and its Stability Challenges for Renewables

- Two 2.2MW diesel Generating Stations
- Six 1MW diesel Locomotive ‘standby’ generators
- Nominal 4MW load
- Expensive power(fuel), great solar resource
- “diesel” grid
Lana’i PV Plant Impact Overview

- 1.5MW Solar Farm
- 12 SatCon, GEN I, 135kW Inverters
- 12 independent tracking solar arrays
- 10% of Lana’i annual power demand
- 30% Supply during peak solar hours (4MW)
- BUT potentially destabilizing AND limits of Lana’i grid are extremely wide so non-UL1741 non IEEE1547 inverter required, and under Utility Control
Players / Rules of Engagement

- MECO – Maui Electric Company
  - Utility Company: Buying power from Solar Farm
- Lanai Sustainability Research, LLC.
  - Owner of Solar Farm: Selling Power
  &
- SunPower, PV System Designer, Integrator
  - Satcon, Grid Connected Inverter manufacturer (Bob Reedy – FSEC, SEGIS partner)
  - Serra, SCADA Interface, SunPower Sub-Contractor

- Lanai PV Interconnect Requirements Study, June 25, 2008, KEMA Inc.

1) Remote control of Real Power, also termed curtailment
2) Remote control of Power Factor, within a fairly narrow range
3) Grid disturbance ride-thru capability
4) Ramp rate limits and control (dP/dt)
Worldwide footprint
4,000 Employees: All we do is solar
Over a quarter century of experience
Over 500 systems on 4 continents
Over 400 MW installed
Largest solar projects in North America

World record solar cell efficiency = MORE POWER
Over 85 patents and over 20 years of R&D
Publicly traded (NASDAQ) and partnerships with top-tier financiers
Energy efficiency expertise

Established and Proven. Technology
SunPower Provides Solar Wherever You Need It

Commercial

Number 1
Largest Commercial Install Base in North America

Residential

Number 1
Largest Residential Install Base in North America

Power Plants

Number 1
Largest Solar PV Power Plants in North America
Satcon - Grid Connected Electronics

Grid Energy + Grid Support + Utility Scale

- Founded 1985
- Public 1992 (SATC)
- 275 employees
- 115 patents
The New Value Equation

Satcon
Clean power.

Visionary Ready
Early Adopters

Commercial Ready
Early Majority

Utility Ready
Large Scale Grid Integrated Adoption

Today

Overall PV Output

2000

2005

2010 +
Florida Solar Energy Center
Creating Energy Independence Since 1975

- Research, Applications, Education, Training, Testing
- Solar Energy Division
- Building Efficiency Division
- Advanced Fuels for Energy Division

A Research Institute of the University of Central Florida
Lana’i PV Power Plant – Project Overview

1.2MW AC
Lana’i PV Power Plant – Project Overview

Overhead Lines to Miko Basin Power Plant

Overhead Lines to Manele Bay Hotel

PV Array Inverters 1-4

PV Array Inverters 5-8

PV Array Inverters 9-12

15kV Switchgear

Inverters 5-9

Inverters 9-12
Provisions for energy storage system
• The PPA signed between LSR and MECO stipulates several site control features:

  – **Curtailment Control**
    • Utility provides set point in fairly continuous increments between 0-1200 kW
    • Plant response should be rapid without violating ramp-rates limits
    • Utility receives status indicating achievement of set point
  
  – **Power Factor Control**
    • Utility provides set point between 0.95 lagging to 0.98 leading
    • Utility receives status indicating achievement of set point
    • The PV Plant produces and consumes reactive power at utility command
  
  – **Ramp-Rate Limiting**
    • Plant output fluctuations need to be limited to 6 kW/s during beginning/end of day and startup and shutdown periods
    • Plant output fluctuations needed to be limited to 40-60 kW/s at other times
Grid Operators on Maui control power output and power factor set points from their Areva HMI.

Redundant control is available at Lanai Control Center if communication fails with Maui. Set points are passed through to data gateway at PV site.

Data Gateway (Orion 5r) acts as both master and slave device. It translates set points from DNP3 to modbus and receives set points from PV Site Controller.

PV Site controller maps set points, status points and process values between Utility SCADA and site devices.

Data is transmitted via DNP3 protocol over fiber to the onsite data gateway.

Data is transmitted via modbus over RS232 and RS485 to PV Site Controller.

Communication to inverters and other devices is via modbus TCP over fiber and copper.
In addition to setting power output and power factor, the grid operator requires data on status and real-time process values to evaluate plant operation.

**Status Data**
- Inverter on/off
- Last commanded global curtailment and power factor set points
- Last commanded individual inverter curtailment and power factor set points
- Intertie breaker status open/closed

**Process Variables**
- Real-time power output and power factor at point of interconnection
- Individual inverter real and reactive power output
- Available generation capacity based on real-time calculation using irradiance, wind speed and temperature data
Control System – Communication Network

- SUNPOWER DAS (CR1000 w/NL115)
- Modicon PV Site Controller (MECO Comm Link)
- Inverter
- Switch
- Modbus TCP Over Cat 5 to Switch
- Cellular Router (Digi ConnectPort)
- AT&T 3G Connection via Static IP
- DNP Orion as Master
- Modbus RTU Over RS-485
- Modbus TCP Over Cat 5
- Digi Serial to TCP/IP Gateway
- Veris Meter
- Celluar Switch
- Modbus TCP Over Cat 5 to Switch
- Inverter
- Digi ConnectPort
- Bitronics M671 Meter
- Primary Switch
- Modbus TCP Over Fiber
- Over Fiber
- Over Cat 5
- Over RS-485
Interfacing with the Utility SCADA

MECO’s HMI interface with intertie breaker and recloser

*Screen shots provided by Dwight Weiding of MECO*
Interfacing with the Utility SCADA

MECO’s HMI interface with Lanai PV Plant*

*Screen shots provided by Dwight Weiding of MECO
Interfacing with the Utility SCADA

MECO’s HMI interface with Lanai Grid

*Screen shots provided by Dwight Weiding of MECO*
Curtailment is measured at point of interconnection, but control is achieved at the inverters
- Must account for variable transformer losses & maintenance scenarios where inverters are offline
- Suggests a closed loop control approach, but fairly complicated to implement, primarily due to latency issues
- Open loop control requires several scale factors dependent on plant configuration

Power Factor also measured at point of interconnection
- Must account for discrepancy in measured PF versus commanded PF
- Difficulty developing HMI for this feature. Actual implementation uses discrete set points, e.g. 0.95, 0.96, 0.97 lagging and 0.98, 0.99 leading, etc.

One big challenge is communication latency
- This latency can occur at the inverter, which requires time to process command and then act
- Another source of latency is created by the communication network itself and the protocol employed

Managing the broad range of device types, protocols, communication mediums and scaling factors makes for a complex system.
Performance Data – Set Points with Ramp Rates

- Utility sets plant output from 50 kW to 100 kW
- Ramp rate is 4.3 kW/s
- Utility sets plant output from 100 kW to 0 kW
- Ramp rate is -4.7 kW/s
Performance Data – Power Factor Control

Graph showing performance data with a blue line for PF Set Point and a red line for Measured PF. The graph indicates an offset from set point measured at point of interconnection, with a utility setting plant PF from 95% lagging to 98% leading.
Future Developments

- These control features are new to PV plants and there is much development work to be done, and many opportunities:
  - Optimization of control techniques
  - Normalization of Utility HMIs
  - Integration with storage
  - Ancillary services like voltage support
  - Open loop versus closed loop control
  - Remote Restart & Reclosing
  - Parallels to Smart Grid
Power Limit (Curtailment) & Power Factor Control

- Power Limit involves disabling MPPT routine ("quasi" slew rate possible within Inverter)
- The full range for the power factor command is from 0.71 leading to 0.71 lagging, plus status flag
- Power factor control is realized by keeping real current and reactive current at a fixed ratio determined by the commanded power factor

<table>
<thead>
<tr>
<th>Power Limit Control</th>
<th>Power Factor Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication of power-limit set point</td>
<td>Modbus TCP</td>
</tr>
<tr>
<td>Power-limit range</td>
<td>0-135 kW</td>
</tr>
<tr>
<td>Power-limit increment size</td>
<td>32.96 W (135/4096)</td>
</tr>
<tr>
<td>Ramp-rate limit</td>
<td>6 kW/s</td>
</tr>
<tr>
<td>Response time</td>
<td>&lt;5s</td>
</tr>
<tr>
<td>Communication of power factor set point</td>
<td>Modbus TCP</td>
</tr>
<tr>
<td>Power factor range</td>
<td>0.98 Leading to 0.95 Lagging</td>
</tr>
<tr>
<td>Power factor increment size</td>
<td>0.005</td>
</tr>
<tr>
<td>Power Factor response time</td>
<td>&lt;5s</td>
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</table>
Curtailment Power Factor Control Testing - Results

- Implemented
- Tested in Certification Lab
- Verified at PV-Lana‘i
Ride-Through

- Traditional Inverters (IEEE1547 & UL1741) operate in narrow range of voltage and frequency and are required by statute to disconnect immediately in the presence of fairly minor deviations.
- The intent here is to operate over a much wider range, and to tolerate fairly rapid dynamics.
- Inverter must operate safely, for extended periods, over the wide voltage and frequency extremes being considered.
- The nominal voltage “V” referenced in the requirements is 12.47 kV at the point of grid interconnect, and 60Hz is the nominal frequency ‘f’ referenced in the table below.
- Implemented, tested (Cert Lab), tested in Microgrid, simulations, observations
### Required Ride-Through Capabilities

<table>
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<tr>
<th>Grid Frequency</th>
<th>Inverter Response</th>
<th>Grid Voltage</th>
<th>Inverter Response</th>
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<tbody>
<tr>
<td>$65 \text{ Hz} &lt; f$</td>
<td>Inverters must disconnect after 160 milliseconds</td>
<td>$1.20 \text{ pu} &lt; V$</td>
<td>Inverters shall stay online for more than 160 milliseconds</td>
</tr>
<tr>
<td>$62 \text{ Hz} \leq f \leq 65 \text{ Hz}$</td>
<td>Inverters may disconnect after 2 seconds</td>
<td>$1.10 \text{ pu} \leq V \leq 1.20 \text{ pu}$</td>
<td>Inverters shall stay online for at most 3 seconds</td>
</tr>
<tr>
<td>$61 \text{ Hz} \leq f &lt; 62 \text{ Hz}$</td>
<td>Inverters may disconnect after 6 seconds</td>
<td>$0.90 \text{ pu} \leq V &lt; 1.10 \text{ pu}$</td>
<td>Inverters shall remain online</td>
</tr>
<tr>
<td>$57 \text{ Hz} \leq f &lt; 61 \text{ Hz}$</td>
<td>Inverters will stay online</td>
<td>$0.70 \text{ pu} \leq V &lt; 0.90 \text{ pu}$</td>
<td>Inverters shall stay online for more than 2 seconds</td>
</tr>
<tr>
<td>$55 \text{ Hz} \leq f &lt; 57 \text{ Hz}$</td>
<td>Inverters will stay online through this extended ride-through</td>
<td>$0.05 \text{ pu} \leq V &lt; 0.70 \text{ pu}$</td>
<td>Inverters shall stay online for more than 600 milliseconds</td>
</tr>
<tr>
<td>$55 \text{ Hz} &gt; f$</td>
<td>Inverters may initiate disconnection from the grid within 160 milliseconds</td>
<td>$0.05 \text{ pu} &gt; V$</td>
<td>Inverters may initiate disconnection from the grid</td>
</tr>
</tbody>
</table>

- **Verified quasi statically**
- **Verified dynamically in MicroGrid**
Transient Ride-Through Performance - Simulation

- The PV inverter equipment was supplied as UL1741 compliant, but the required ride-through capability for this project is a dramatic departure from UL standard practice,

- **Grid Voltage Monitor.** Anti-islanding protection has been disabled, and the ac line voltage monitoring function has been re-designed to accommodate the specified voltage and frequency deviations without initiating an inverter shut-down.

- **Inverter Control and Self-Protection.** The transient response of the inverter controls has been evaluated to make sure that transient grid voltage deviations will not cause inverter over-current to occur.

- A detected over-current would result in an immediate trip for inverter self-protection. This investigation was based on a computer simulation of the power circuit, including a detailed model of the inverter control system. The phase-locked loop (PLL) algorithm was replaced with an alternative algorithm that is considered more suitable for dynamic tracking during voltage disturbances.

- For this project, computer simulation was used to model equipment performance for a number of fault conditions at the PV station MV bus. These cases are illustrated in the following charts.

- The results indicate that the inverter current will not reach the over-current trip threshold for the two unbalanced faults shown in Figs. 2 and 3. In the third case (balanced three-phase to ground fault), shown in Fig. 4, the inverter current peak immediately following the onset of the fault is close to the trip level and indicates that there is a slight possibility of an over-current trip under extreme conditions. We have moved the trip points up accordingly. Automatic restart is another possibility.
Ride-Through Simulation Results - Model
Simulation Results (1)

Simulated A-phase to ground fault at the Lanai PV station MV bus.
Simulated A-phase to B-phase to ground fault at the Lanai PV station MV bus.
Simulated 3-phase to ground fault at the Lanai PV station MV bus
FSEC Team SEGIS
Goal: “Walk Like a Duck”

PV in Aggregate, Behaving Like Conventional Utility Generation--& Then Some
FSEC Team SEGIS: Innovations

- Utility Control of Islanding
  - Maintain DG when needed most
- Utility Control of Inverter VAR Generation
  - Use of DG asset in a new way
- Shared Inverter Designs for Complex Sites
  - Cul-de-Sac Plant, Linear PV Farm, Weird Roofs
FSEC Team SEGIS: Critical Features

- Enhanced island protection
- Utility control of online/offline status
- PV generation ride-through of grid disturbances
- Fast & Dispatchable VAR Support
- Peak-shifting & anytime-emergency peak generation with energy storage & BEMS
FSEC Team SEGIS: Enhanced Features

- Stabilization of Mini/Micro Grids (Island Mode)
- Harmonic Cancellation
- Deliberate Phase Unbalance
- Prognostics and Diagnostics
- Real-time phase balance of feeder circuits
- Enhanced transient response (H Constant)
- Oscillation Damping
- Spinning & Ready Reserve
The Really BIG ISLAND:

Eastern Interconnect-- “the World’s Biggest Machine”
925,000,000 hp - 2,000,000 sq mi -- 3600rpm
Frequency Excursions

8-14-03
Eastern Interconnection Frequency

60.236 Hz. at 3:10:54 PM CDT

Set Point Frequency

25 sec of interest

$t_0$
Something Really Scary!

8-14-03
Eastern Interconnection Frequency

Apparent & Approximate Envelope of the Undamped Oscillation, before System Reconfiguration (Islands) Led to a Damped Oscillation

Note:
Frequency of the Oscillation is about 1/3 Hz. This is the “Frequency of the Frequency”

Effective Breakup of the EI into Islands (largely due to operation of Zone 3 distance relays)

Undamped Period  |  Damped Period
Southern Control Area
Generator UF coordination curve

Trip Point per IEEE 1547

Trip Point of Turbines
“Anti-Anti” Islanding
Back to Basics:

- Control Areas Use Permissive PLCC to Maintain Generation During Disturbances
  - No Freq Push issues with high penetration
  - Certainty with down lines
  - Provides Control Area Shutdown Capability during Over Generation events

William of Ockham
b. 1285  Surrey, England
Old View – Island BAD
New View – Island GOOD
MicroGrids – “ACCESS” & SDS Enable UPS-PQ

- Renewables plus back-up generation plus storage plus SDS
- UPS quality power
Simulated 3-Phase Fault on Utility Grid
2.2 MVA, 0.8 P.F. Constant Load on MicroGrid
Utility Grid Connection optional – Tactical Micro Grid

ENERGY STORAGE UNIT CONTROLS VOLTAGE AND FREQUENCY IN MICROGRID

UTILITY GRID IF PRESENT

STATIC DISCONNECT SWITCH (SDS)

MICROGRID LOADS

480 V, 60 Hz

21000

480

480 , 60 Hz

RENEWABLE

NEW ENERGY STORAGE

DIESEL GENSETS (TQGs)

Utility Grid Connection optional – Tactical Micro Grid
Simulated Operation in Island Mode - Load Suddenly Increased (1.1 to 2.2 MVA, 0.8 P.F.)

- Load Suddenly Increased
- Charging
- Discharging
True “Island” Grid

Palawai Basin - 10 Acre Site

Advanced Inverter Features implemented under Utility Control
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