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

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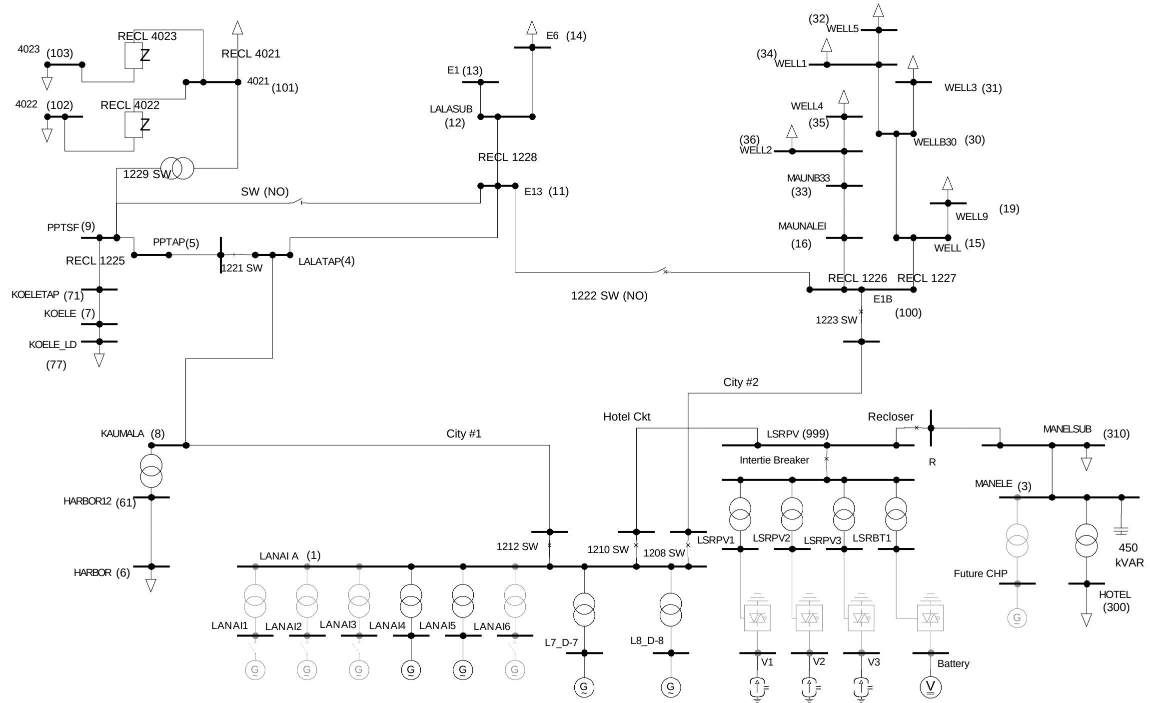
Outline

- 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**



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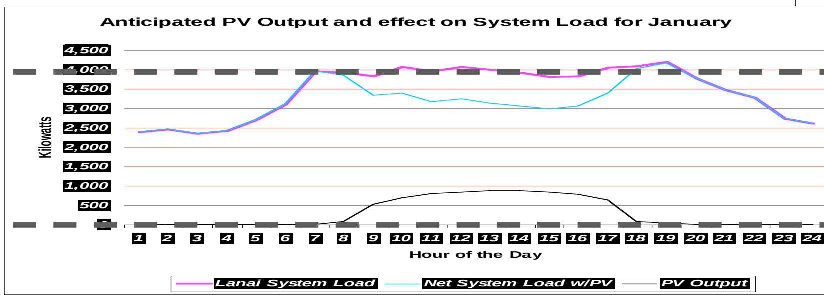
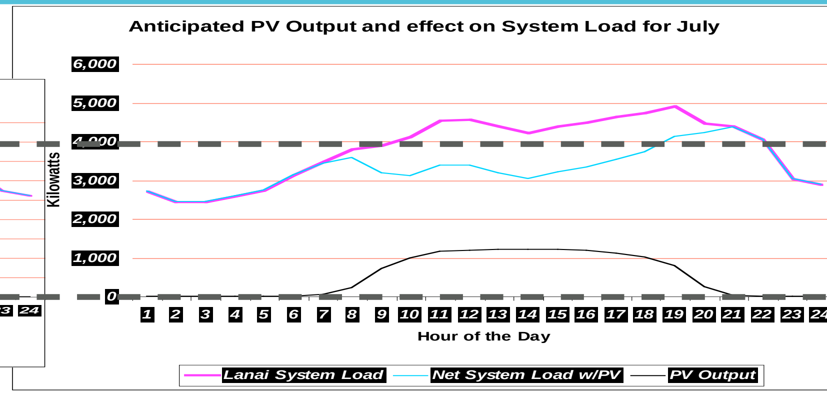
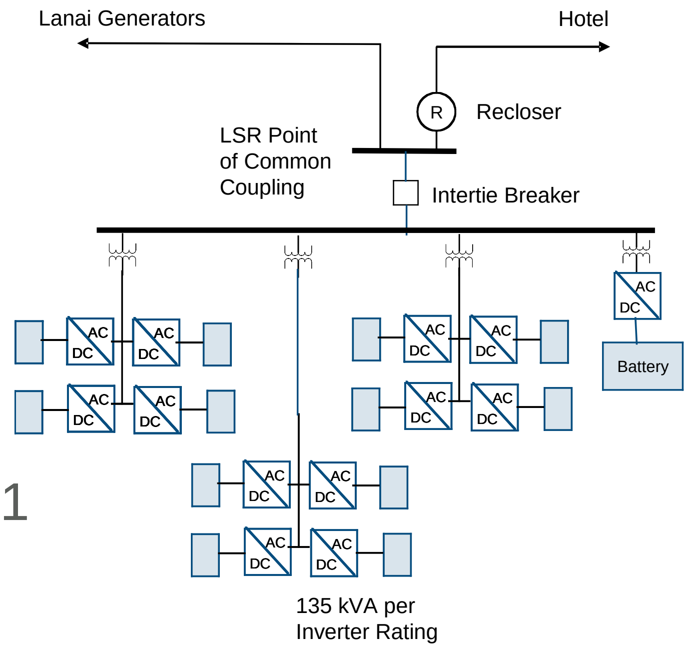
Lana'i PV Plant Impact Overview





- 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



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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**

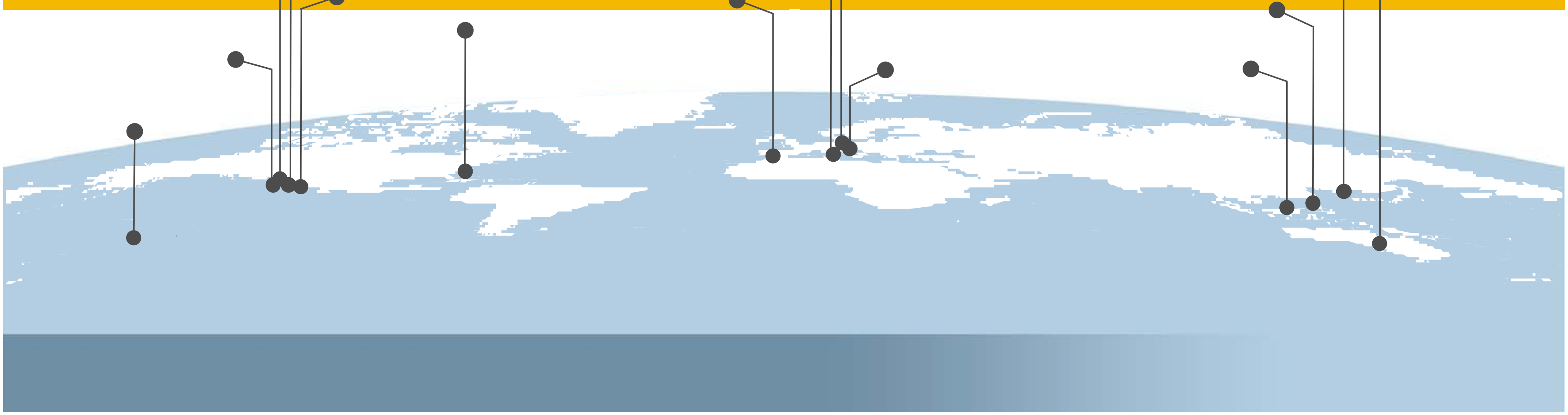
- Lanai PV Interconnect Requirements Study, June 25, 2008, KEMA Inc.
- MECO-LSR Power Purchase Contract, "Power Purchase Contract for As-Available Energy, August 8th, 2008"

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)**

SUNPOWER

- 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





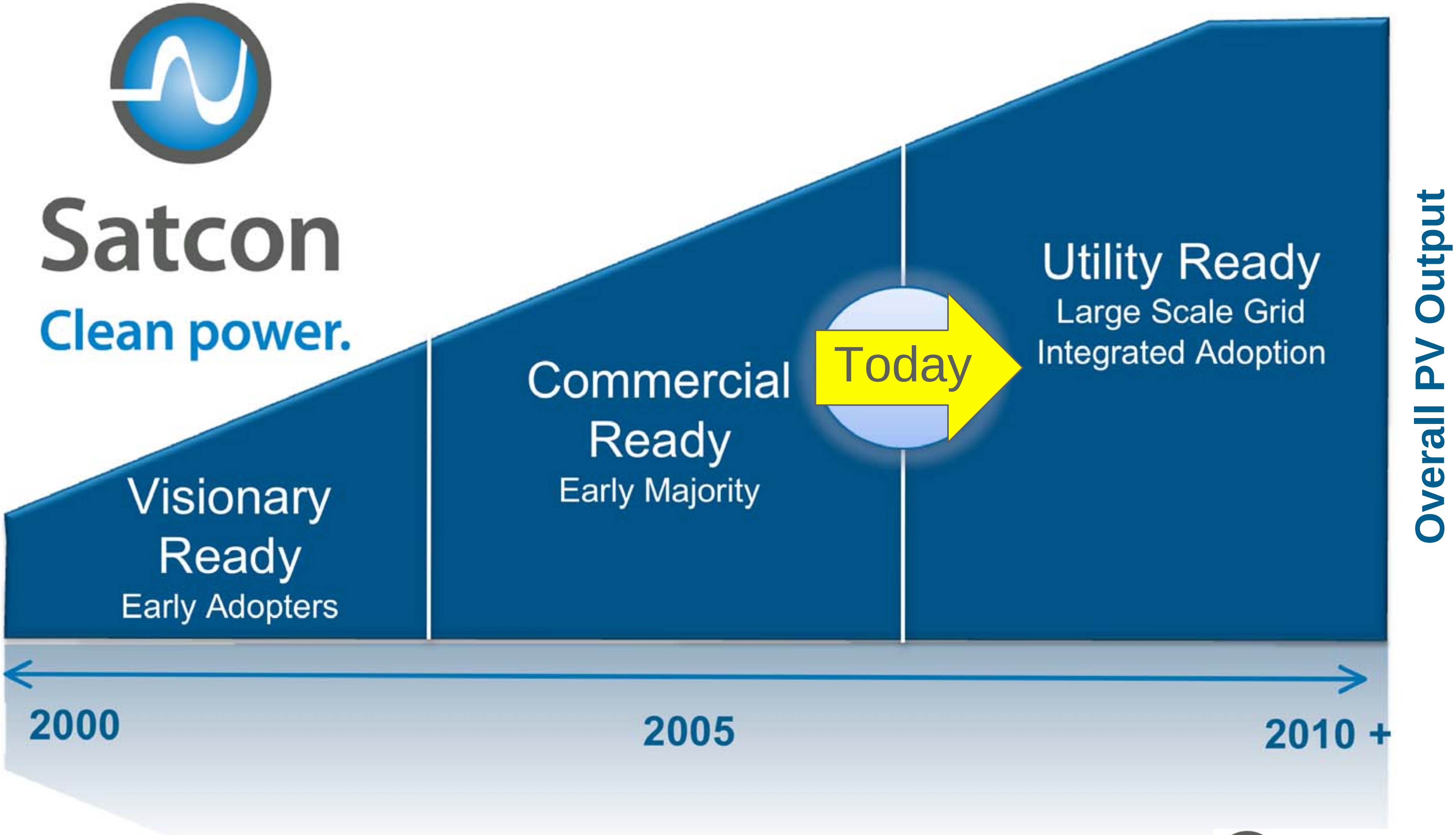


- Founded 1985
- Public 1992 (SATC)
- 275 employees
- 115 patents






The New Value Equation



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Clean power.

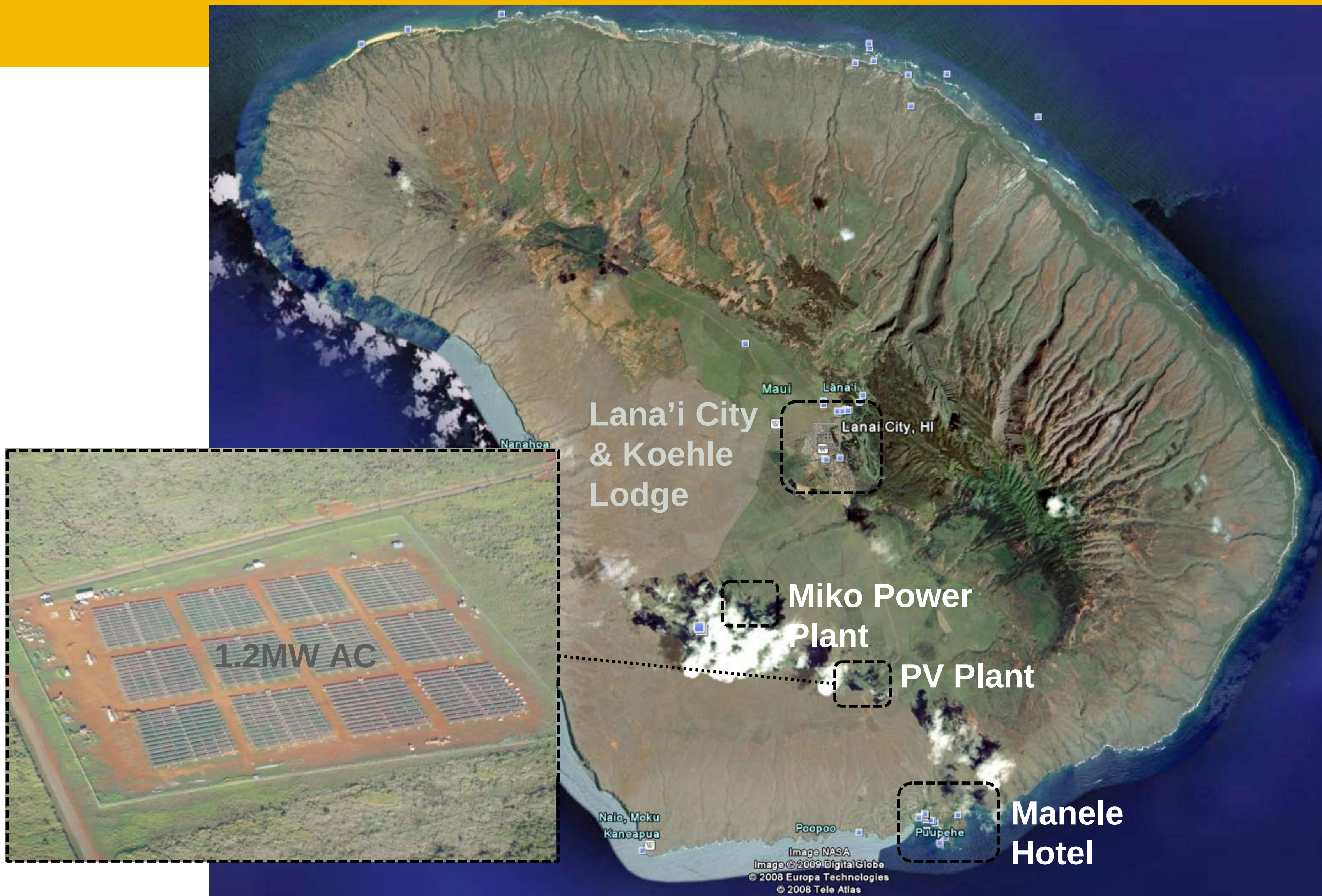
Florida Solar Energy Center

Creating Energy Independence Since 1975

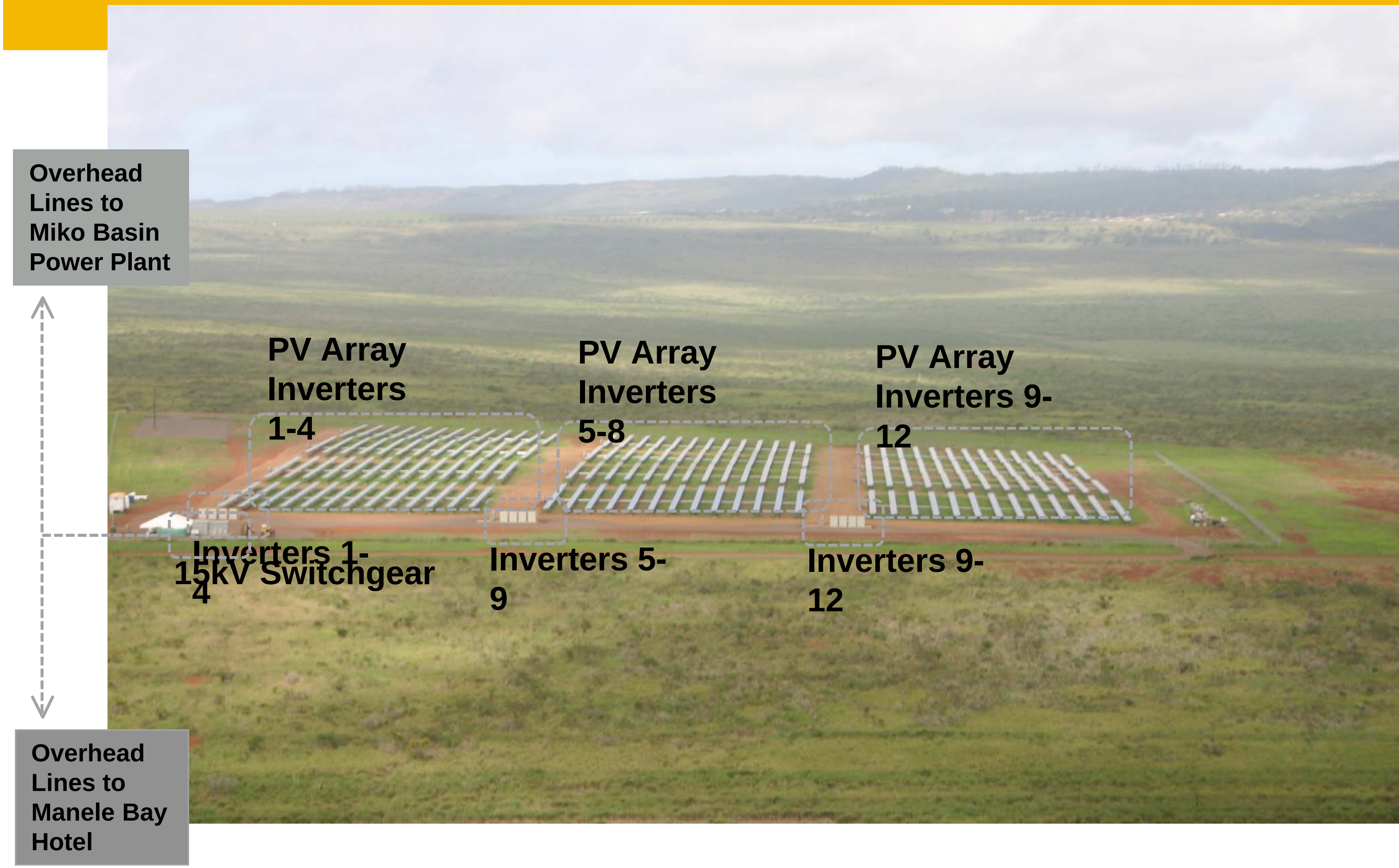
- Research, Applications, Education, Training, Testing
- Solar Energy Division
- Building Efficiency Division
- Advanced Fuels for Energy Division

A Research Institute of the University of Central Florida

Lana’i PV Power Plant – Project Overview



Lana'i PV Power Plant – Project Overview



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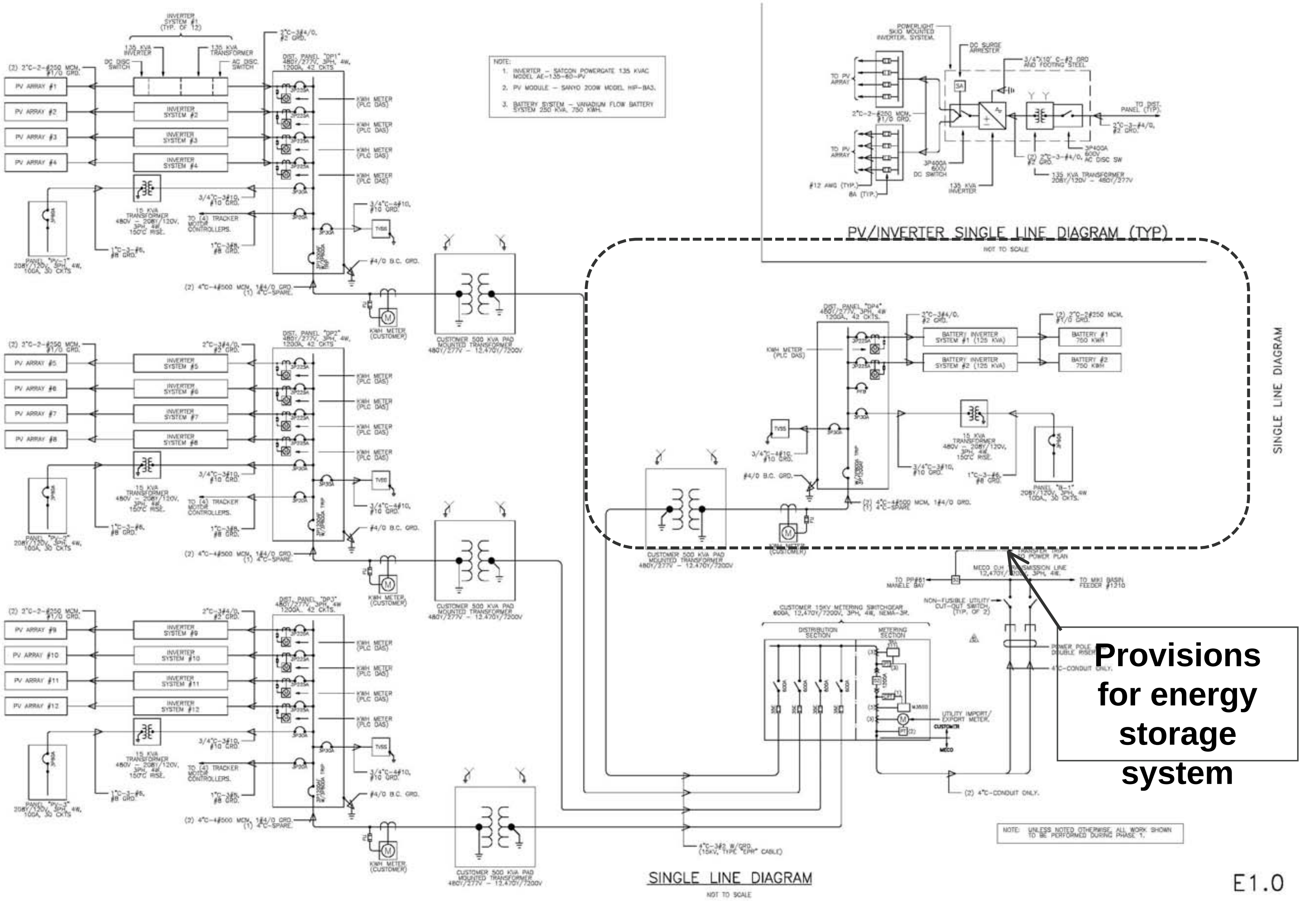
Lana'i PV Power Plant – Single Line



Xref Y:\2007 Projects\07-167 Lanai Castle and Cooke – 1.5 MW PV Phase 1\XREFS\X-SP SHEET.dwg

MECO Control Requirements

- The PPA signed between LSR and MECO stipulates several site control features:
  - **Curtailment Control**
    - Utility provides set point in fairly continuous increments between 0-1200kW
    - 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 6kW/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

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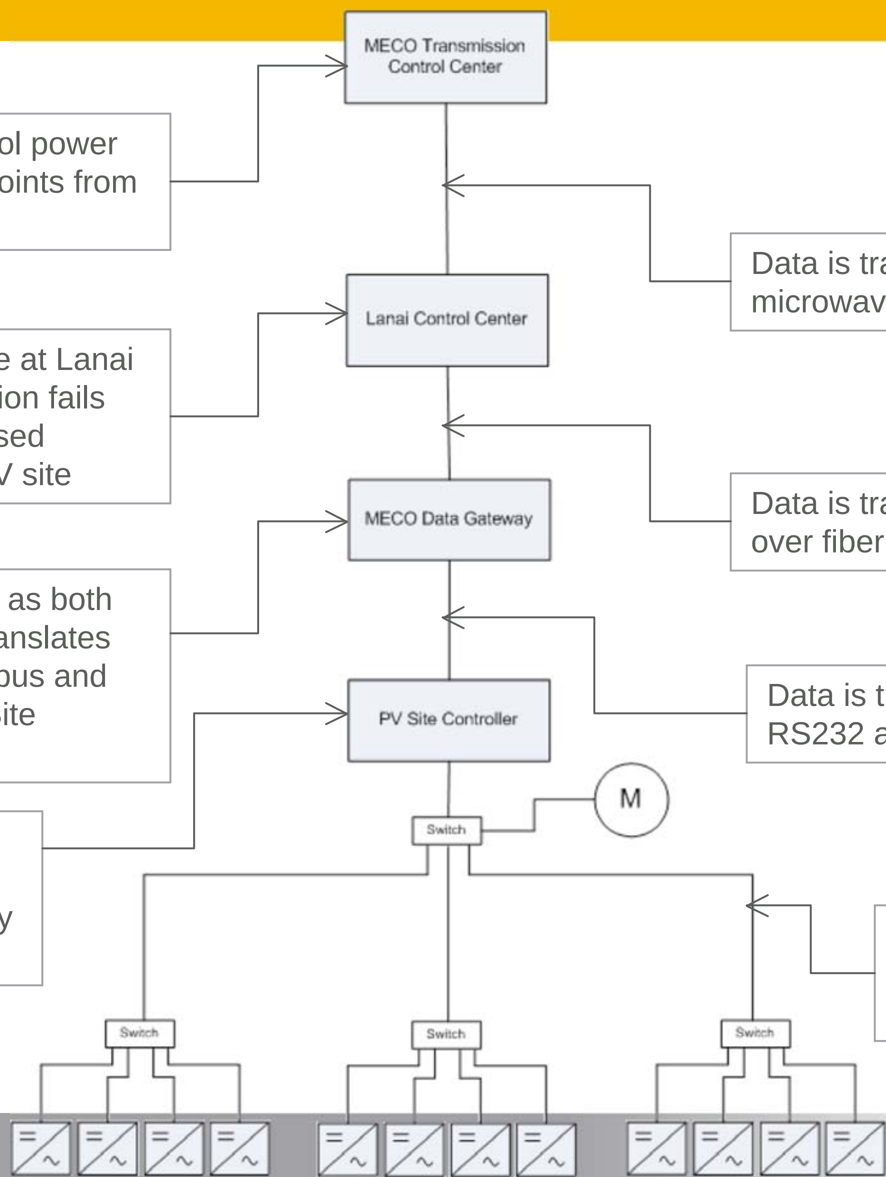
Design – PV Site Controller - Architecture

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 Ethernet over a microwave uplink

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

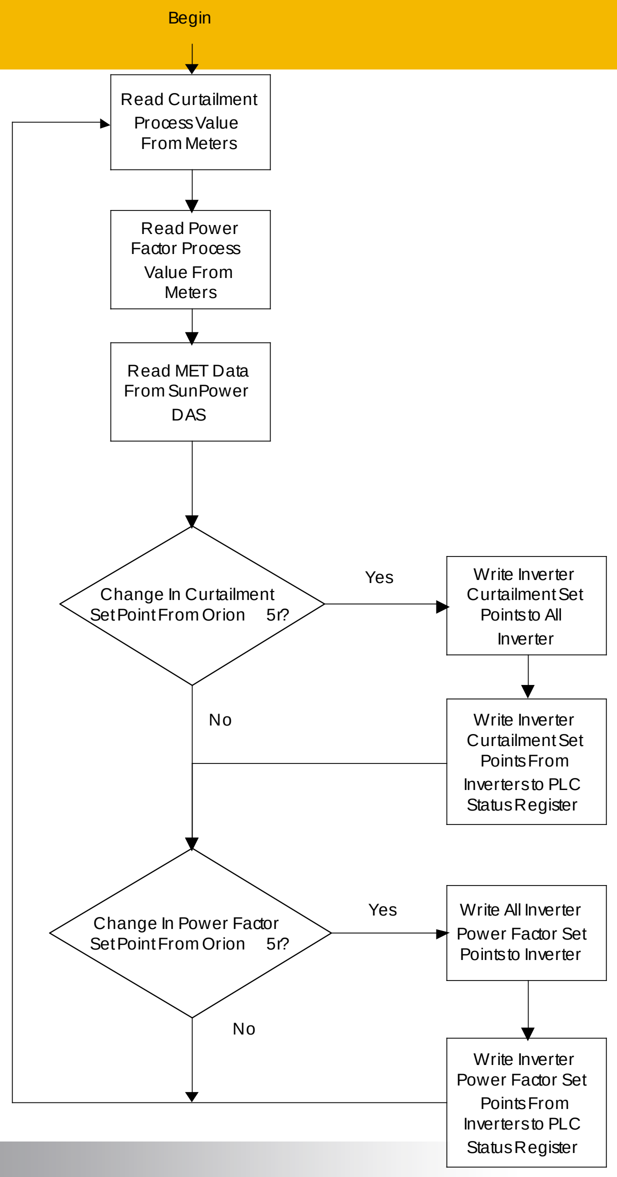
Data is transmitted via modbus over RS232 and RS485 to PV Site Controller

Communication to inverters and other devices is via modbus TCP over fiber and copper

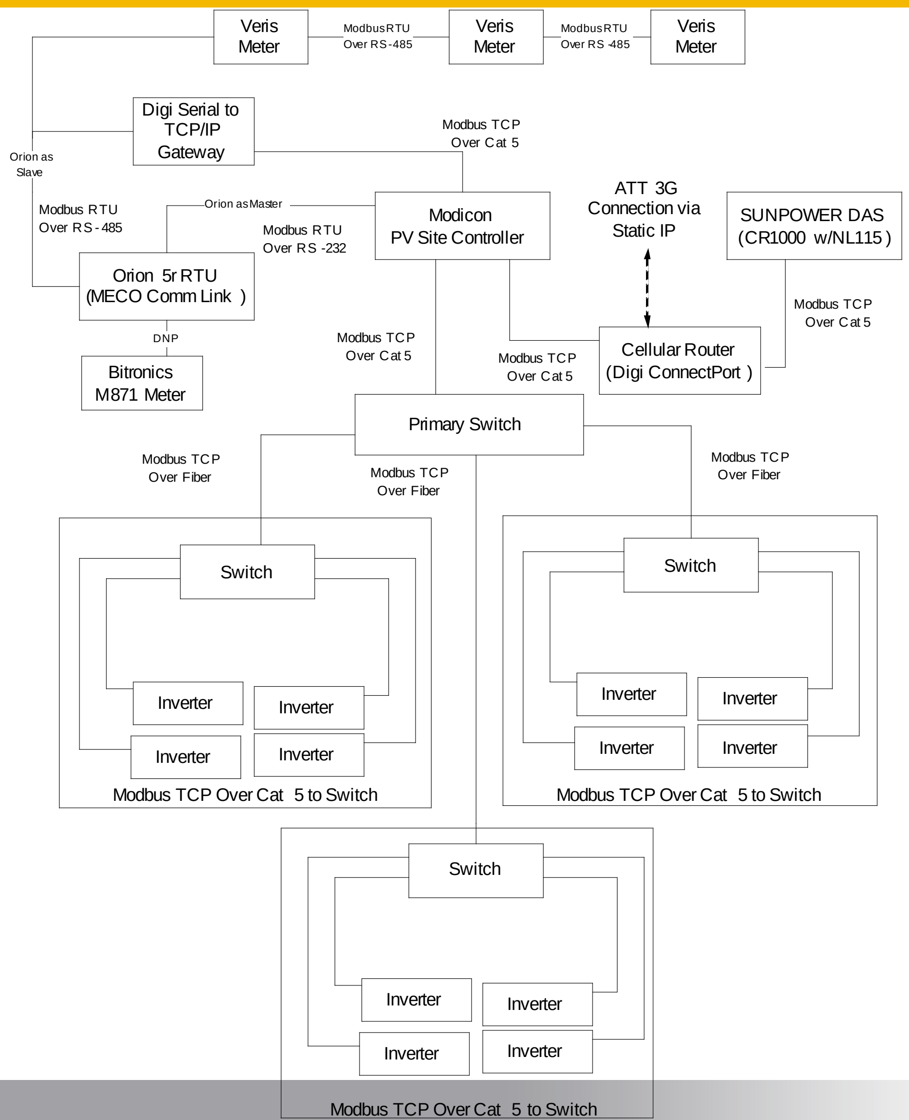
Status Data, Process Values & Control Algorithm

- 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

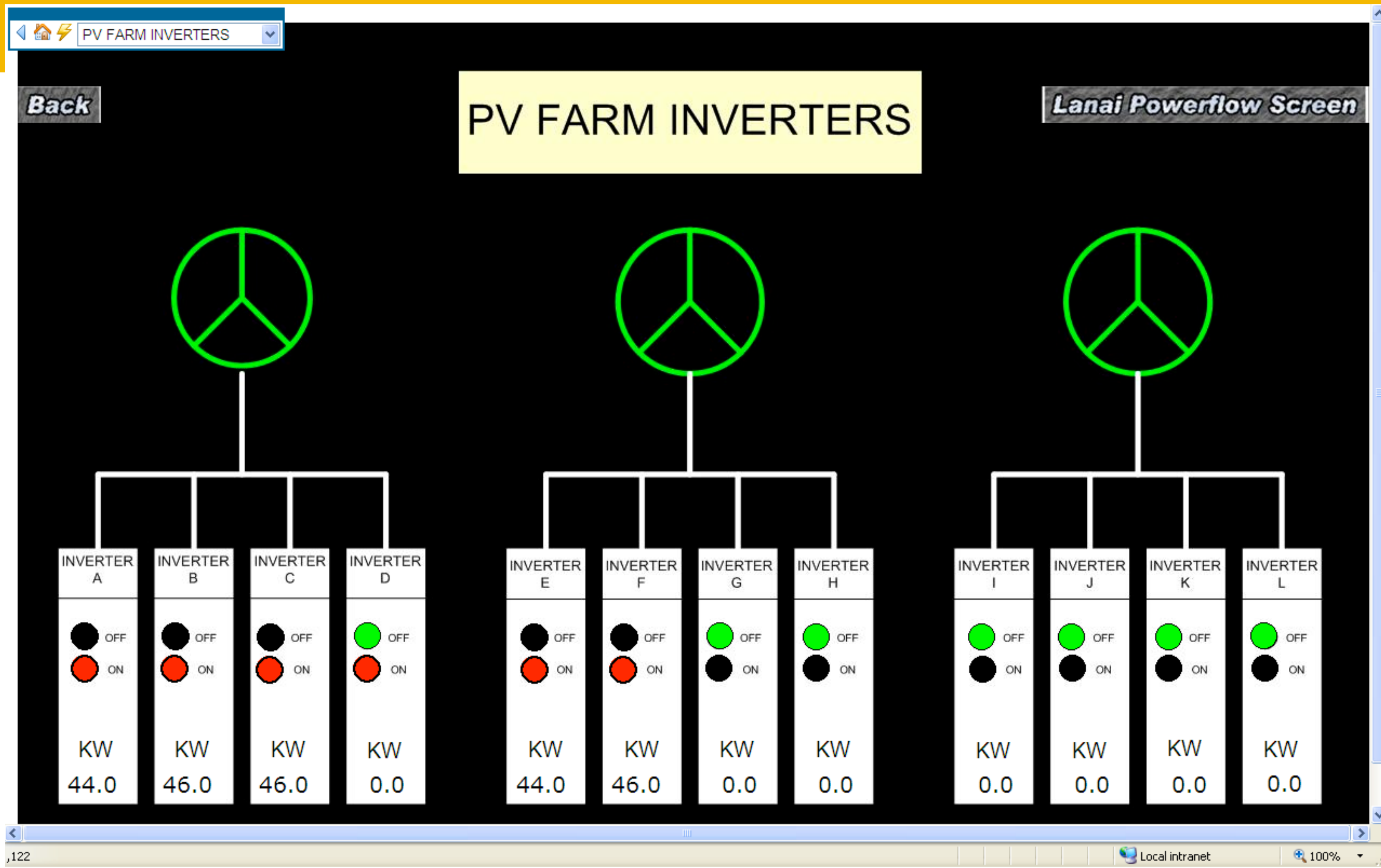
- Status Data
  - Inverter on/off
  - Last commanded global curtailment and power factor set points
  - Last commanded individual inverter curtailment and power factor set points
  - Intertie breaker status open/closed
- Process Variables
  - Real-time power output and power factor at point of interconnection
  - 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



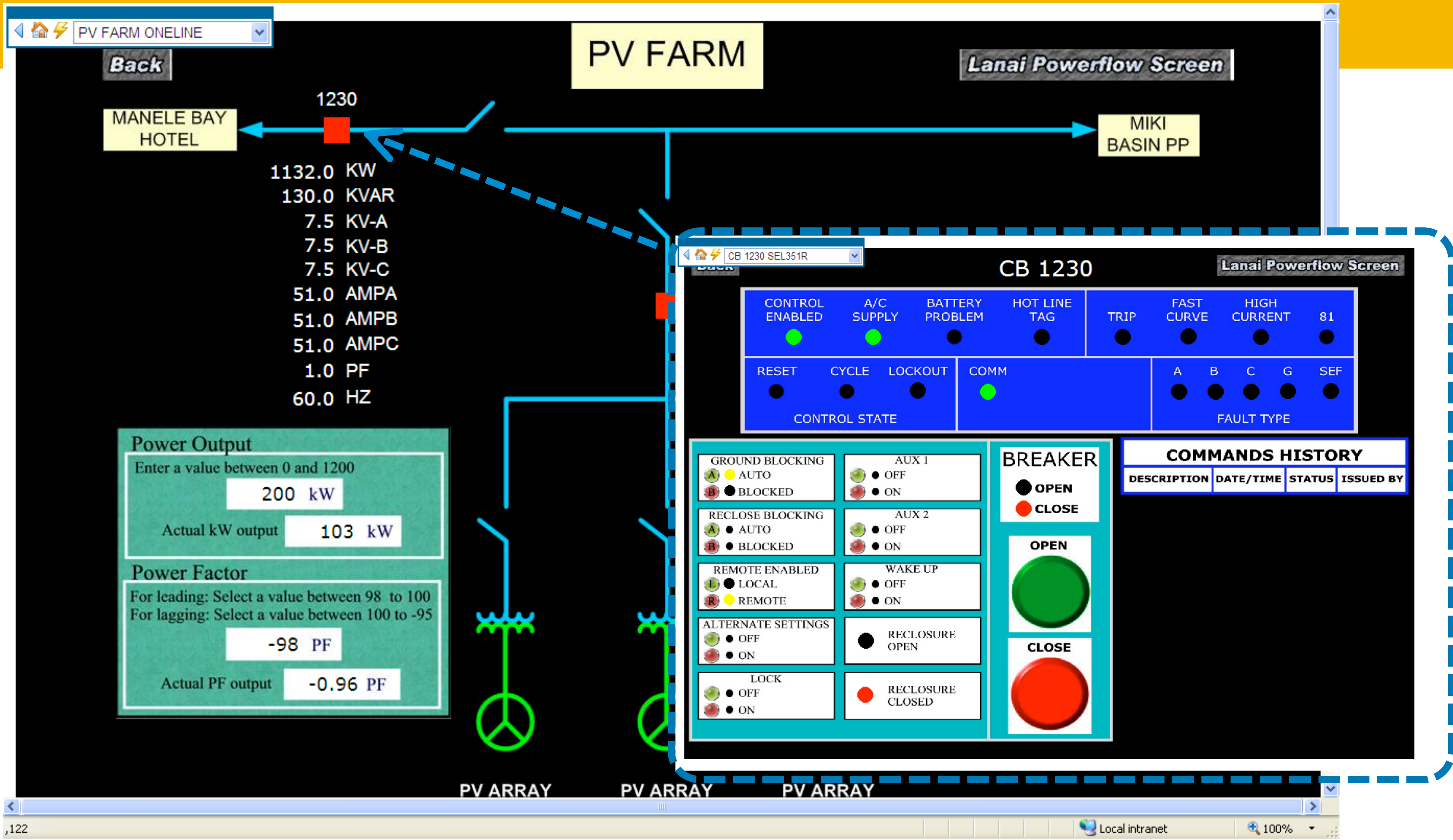
Interfacing with the Utility SCADA



MECO's HMI interface with intertie breaker and recloser

**Screen shots provided by Dwight Weiding of MECO*

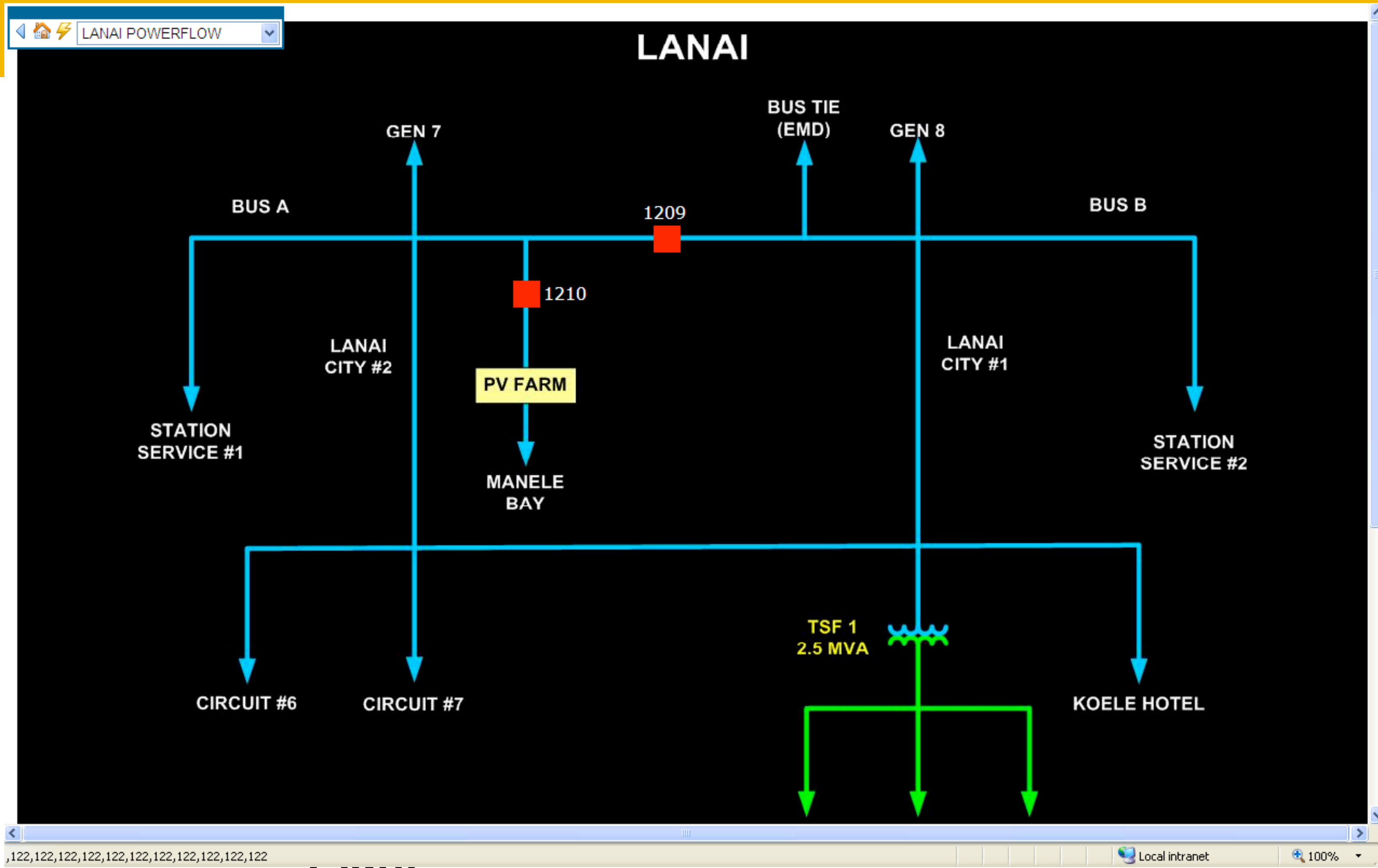
Interfacing with the Utility SCADA



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*

PV Site Controller – Control Details & Challenges

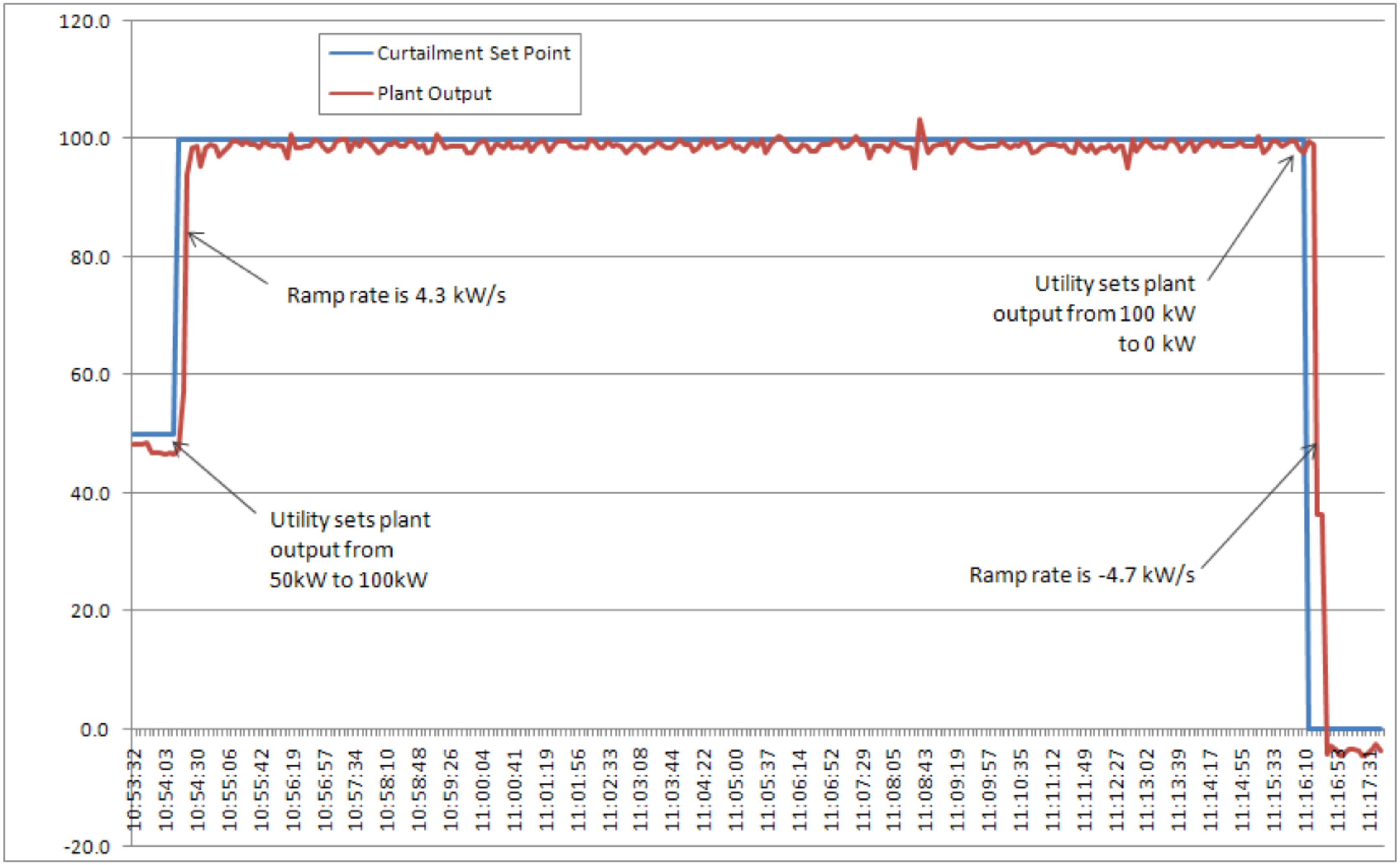
- Curtailment is measured at point of interconnection, but control is achieved at the inverters
  - Must account for variable transformer losses & maintenance scenarios where inverters are offline
  - Suggests a closed loop control approach, but fairly complicated to implement, primarily due to latency 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



Performance Data – Power Factor Control

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**

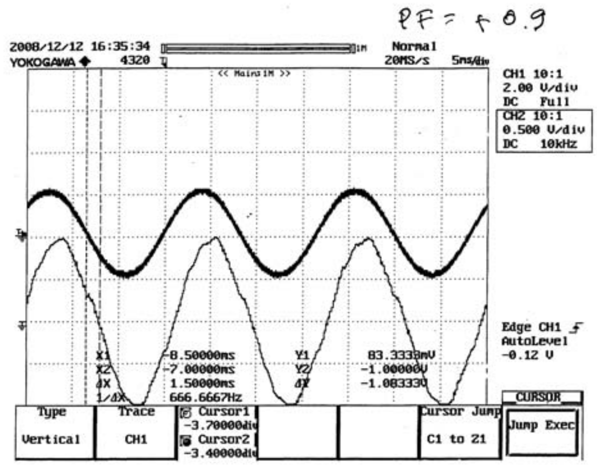
Power Limit (Curtailment) & Power Factor Control

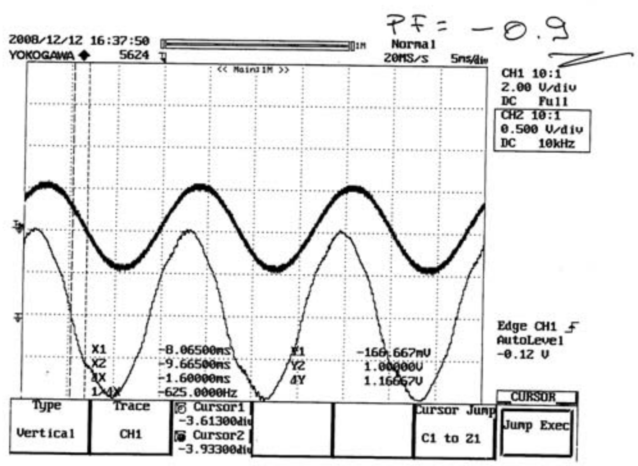
- Power Limit involves disabling MPPT routine (“quasi” slew rate possible within Inverter)
- The full range for the power factor command is from 0.71 leading to 0.71 lagging, plus status flag
- Power factor control is realized by keeping real current and reactive current at a fixed ratio determined by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

Power Limit Control	
Communication of power-limit set point	Modbus TCP
Power-limit range	0-135 kW
Power-limit increment size	32.96 W (135/4096)
Ramp-rate limit	6 kW/s
Response time	<5s

Power Factor Control	
Communication of power factor set point	Modbus TCP
Power factor range	0.98 Leading to 0.95 Lagging
Power factor increment size	0.005
Power Factor response time	<5s

Curtailment Power Factor Control Testing - Results





- **Implemented**
- **Tested in Certification Lab**
- **Verified at PV-Lana'i**

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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

Grid Frequency	Inverter Response
65 Hz < f	Inverters must disconnect after 160 milliseconds
62 Hz ≤ f ≤ 65 Hz	Inverters may disconnect after 2 seconds
61 Hz ≤ f < 62 Hz	Inverters may disconnect after 6 seconds
57 Hz ≤ f < 61 Hz	Inverters will stay online
55 Hz ≤ f < 57 Hz	Inverters will stay online through this extended ride-through range
55 Hz > f	Inverters may initiate disconnection from the grid within 160 milliseconds

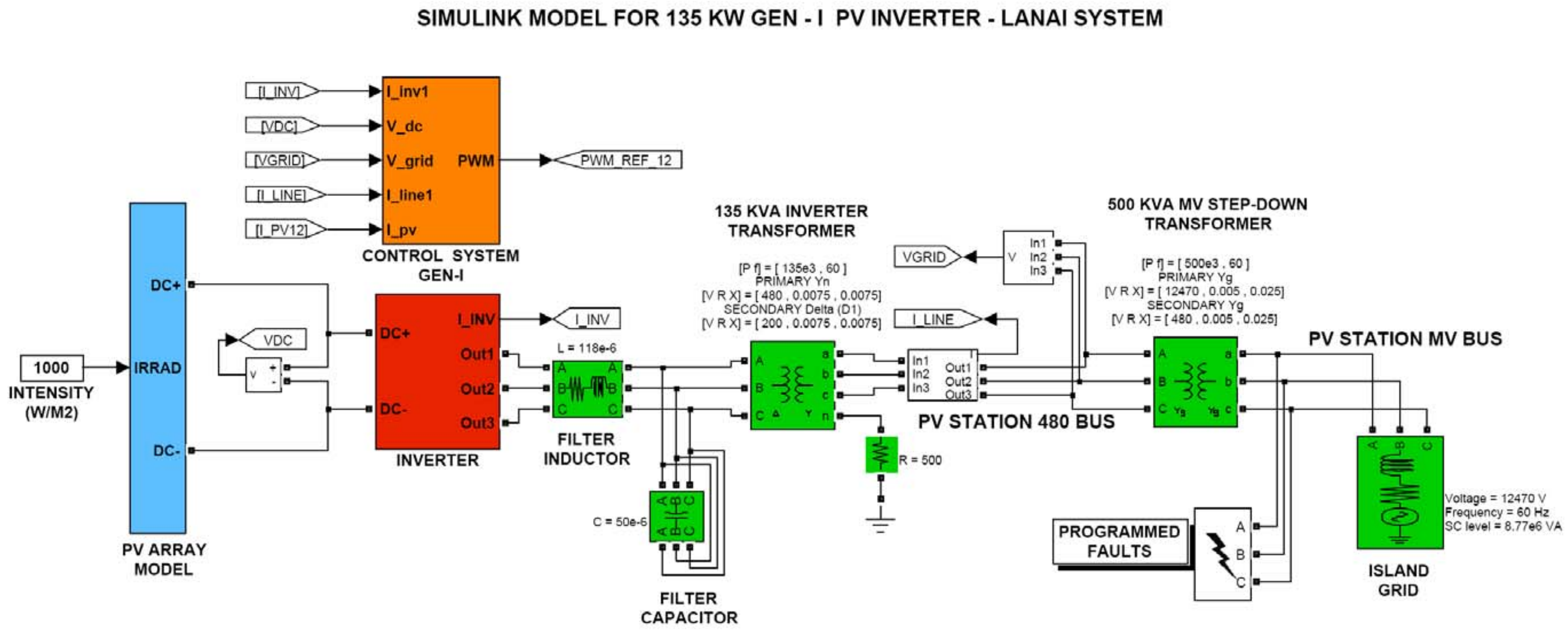
Grid Voltage	Inverter Response
1.20 pu < V	Inverters shall stay online for more than 160 milliseconds
1.10 pu ≤ V ≤ 1.20 pu	Inverters shall stay online for at more than 3 seconds
0.90 pu ≤ V < 1.10 pu	Inverters shall remain online
0.70 pu ≤ V < 0.90 pu	Inverters shall stay online for more than 2 seconds
0.05 pu ≤ V < 0.70 pu	Inverters shall stay online for more than 600 milliseconds
0.05 pu > V	Inverters may initiate disconnection from the grid

- **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



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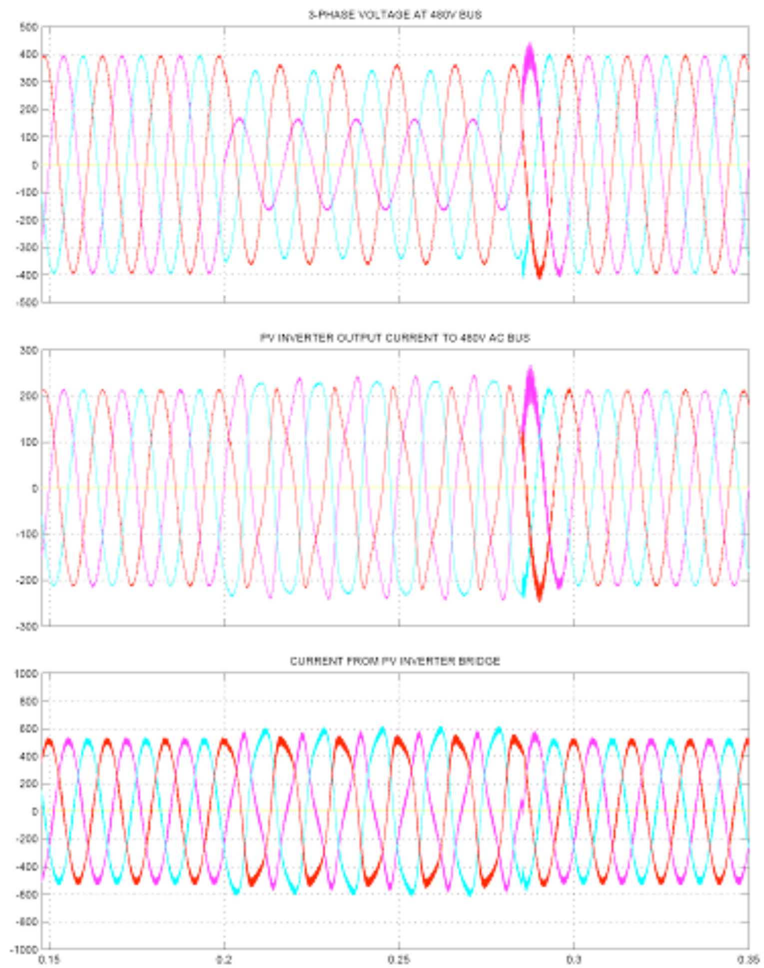
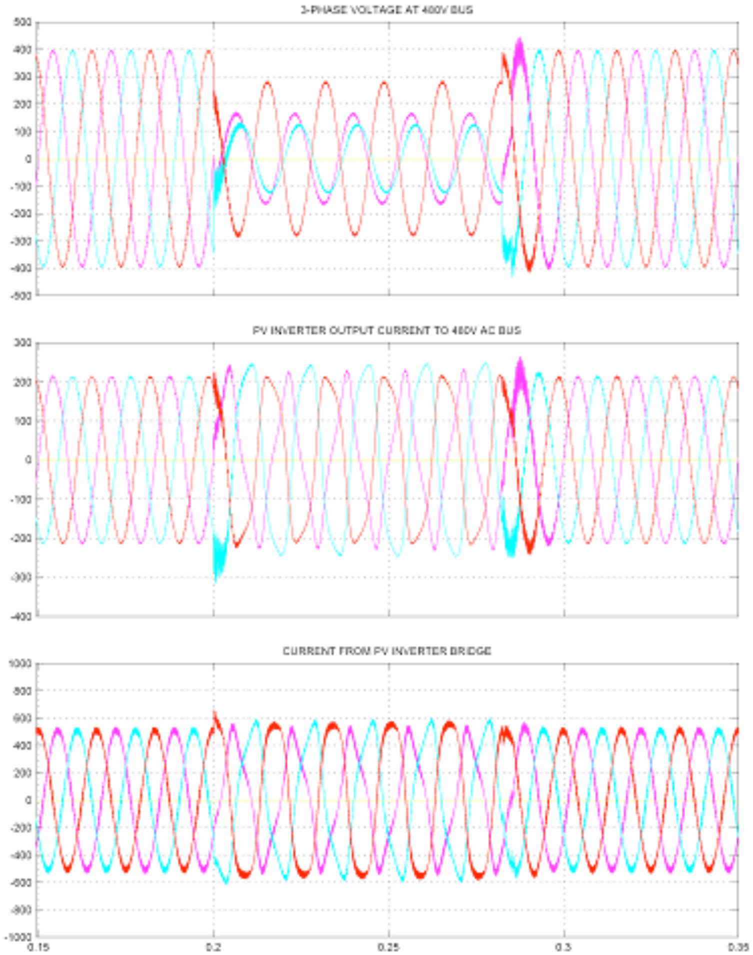
Simulation Results (1)



Simulated A-phase to ground fault at the Lanai PV station MV bus.

Simulation Results (2)



Simulated A-phase to B-phase to ground fault at the Lanai PV station MV bus.

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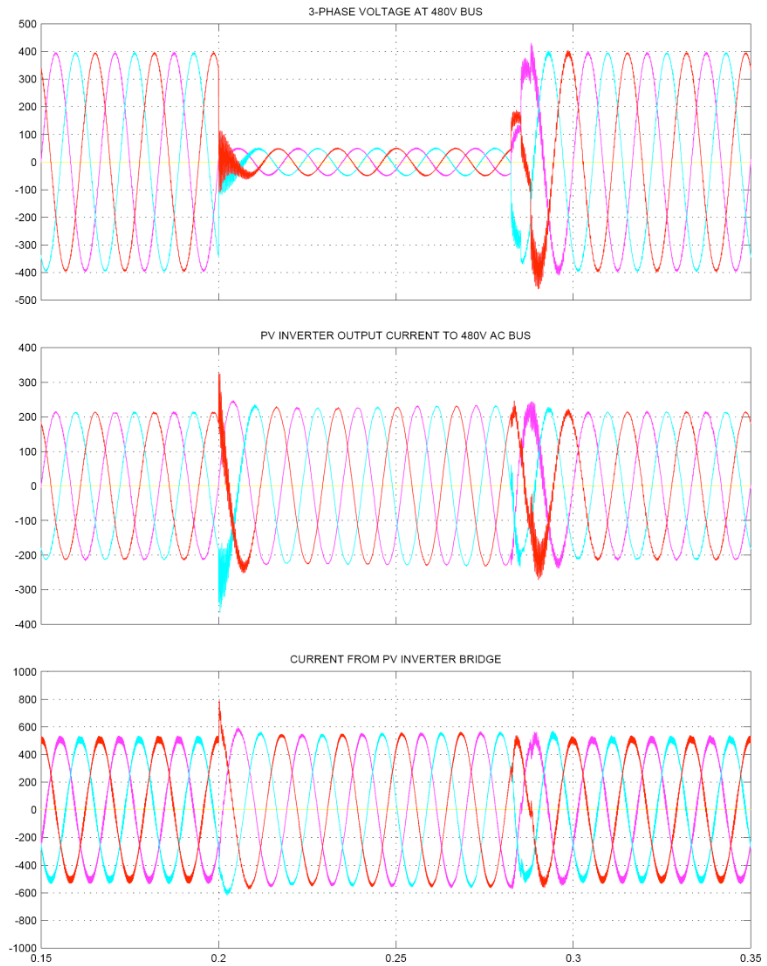
Simulation Results (3)



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

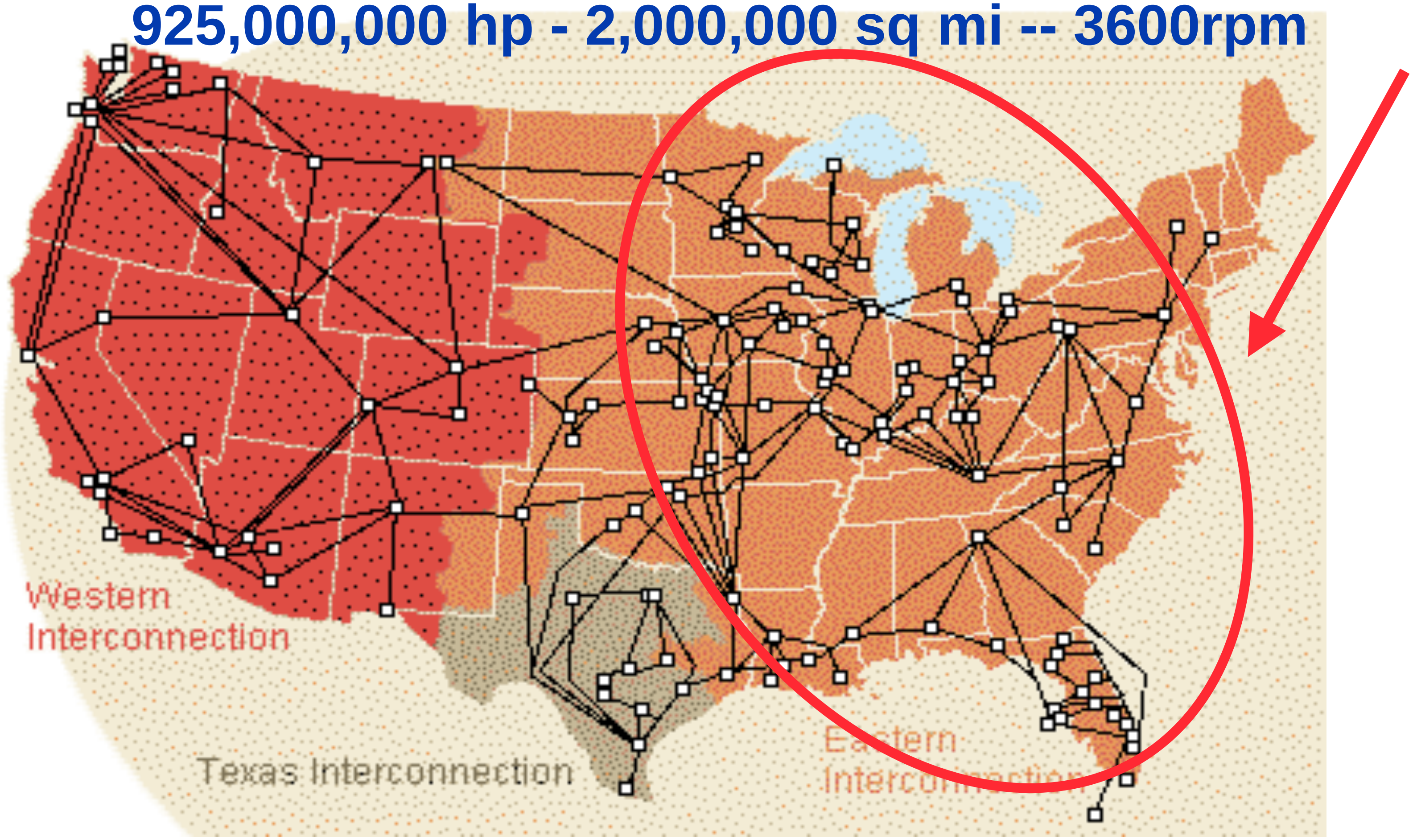
- Enhanced island protection
- Utility control of online/offline status
- PV generation ride-through of grid disturbances
- Fast & Dispatchable VAR Support
- Peak-shifting & anytime-emergency peak generation with energy storage & BEMS

FSEC Team SEGIS: Enhanced Features

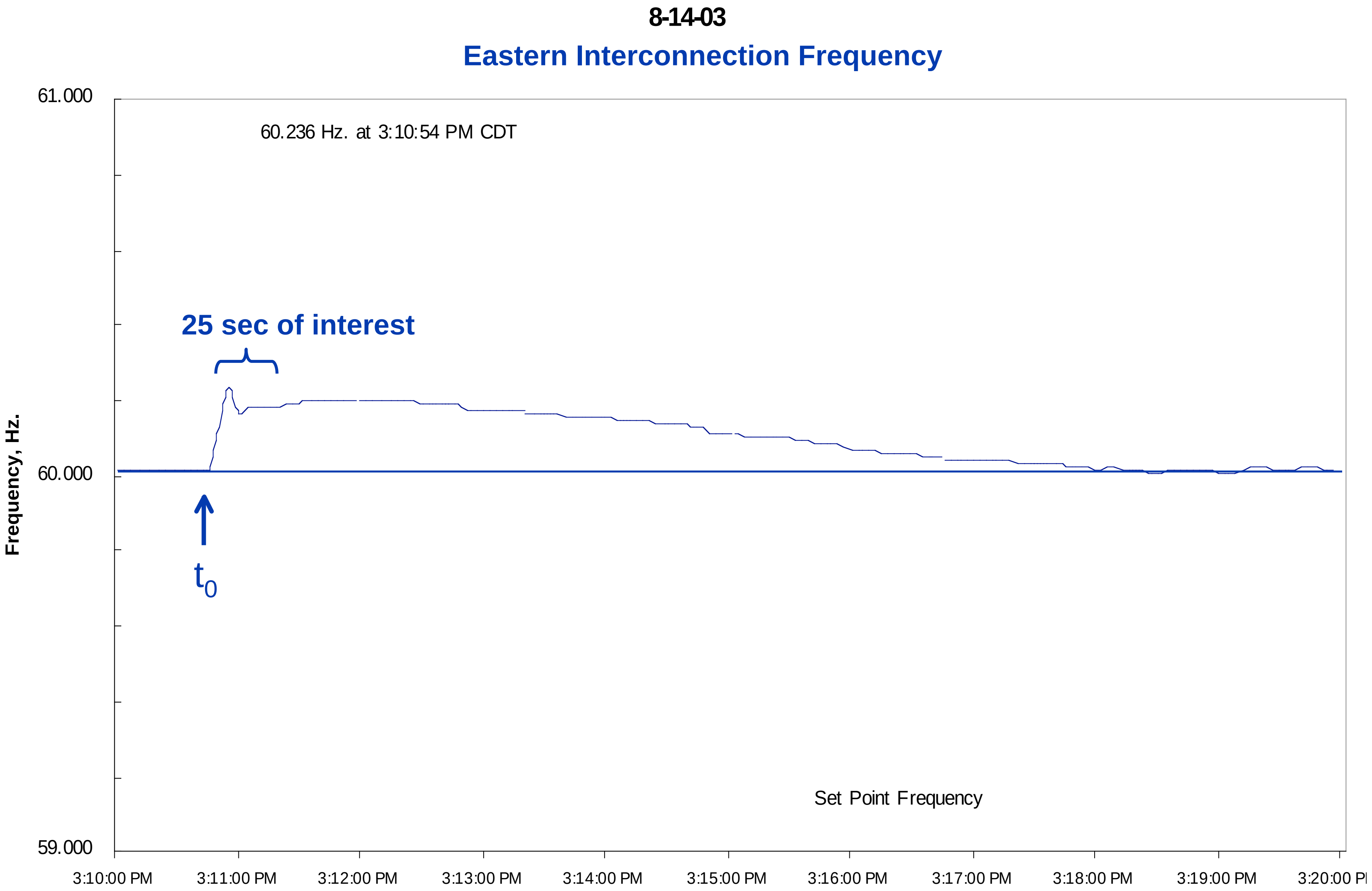
- Stabilization of Mini/Micro Grids (Island
- Harmonic Cancellation
- Deliberate Phase Unbalance
- Prognostics and Diagnostics
- Real-time phase balance of feeder circuits
- Enhanced transient response (H Constant)
- Oscillation Damping
- Spinning & Ready Reserve

The Really BIG ISLAND:

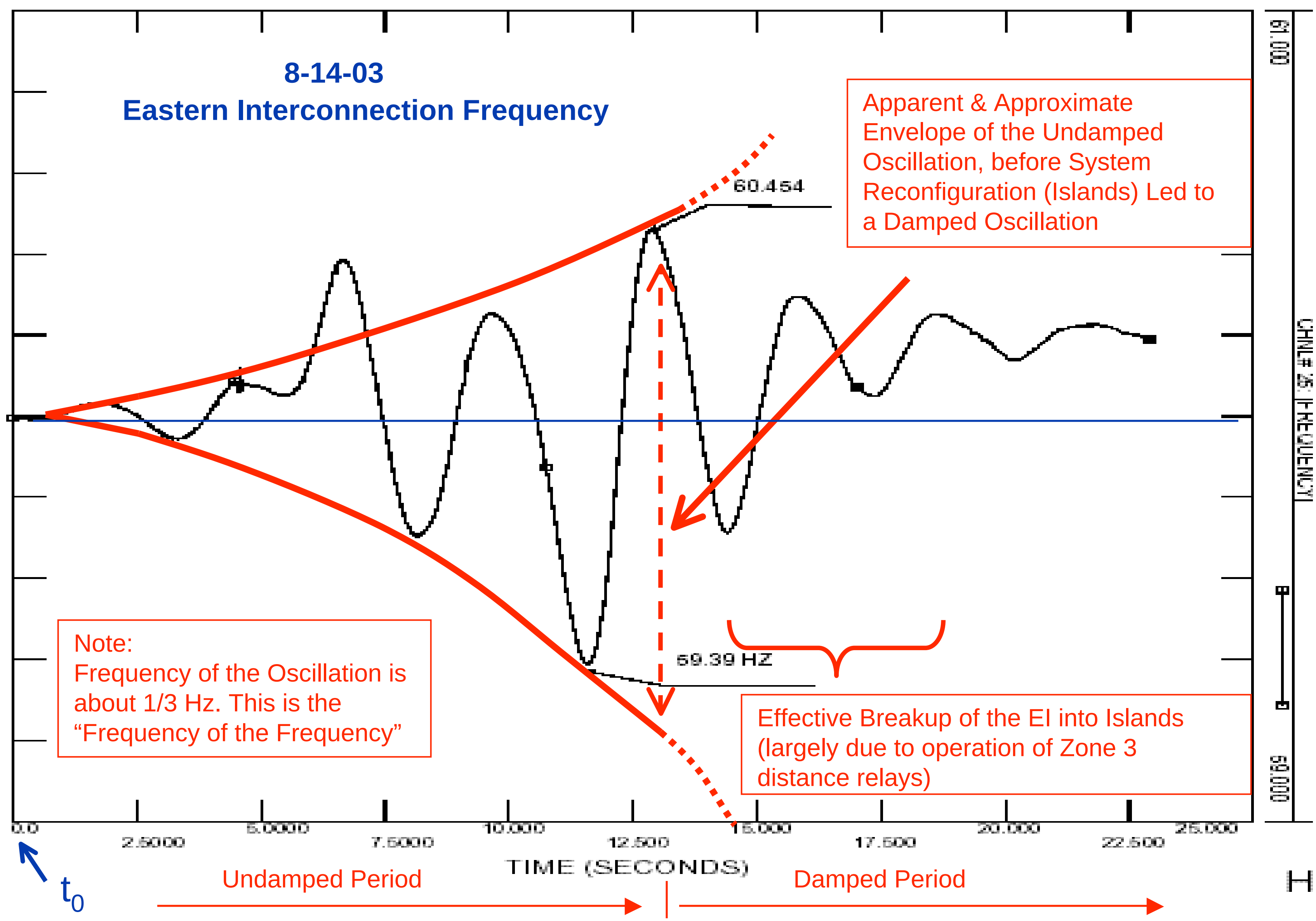
Eastern Interconnect-- "the World's Biggest Machine"
925,000,000 hp - 2,000,000 sq mi -- 3600rpm

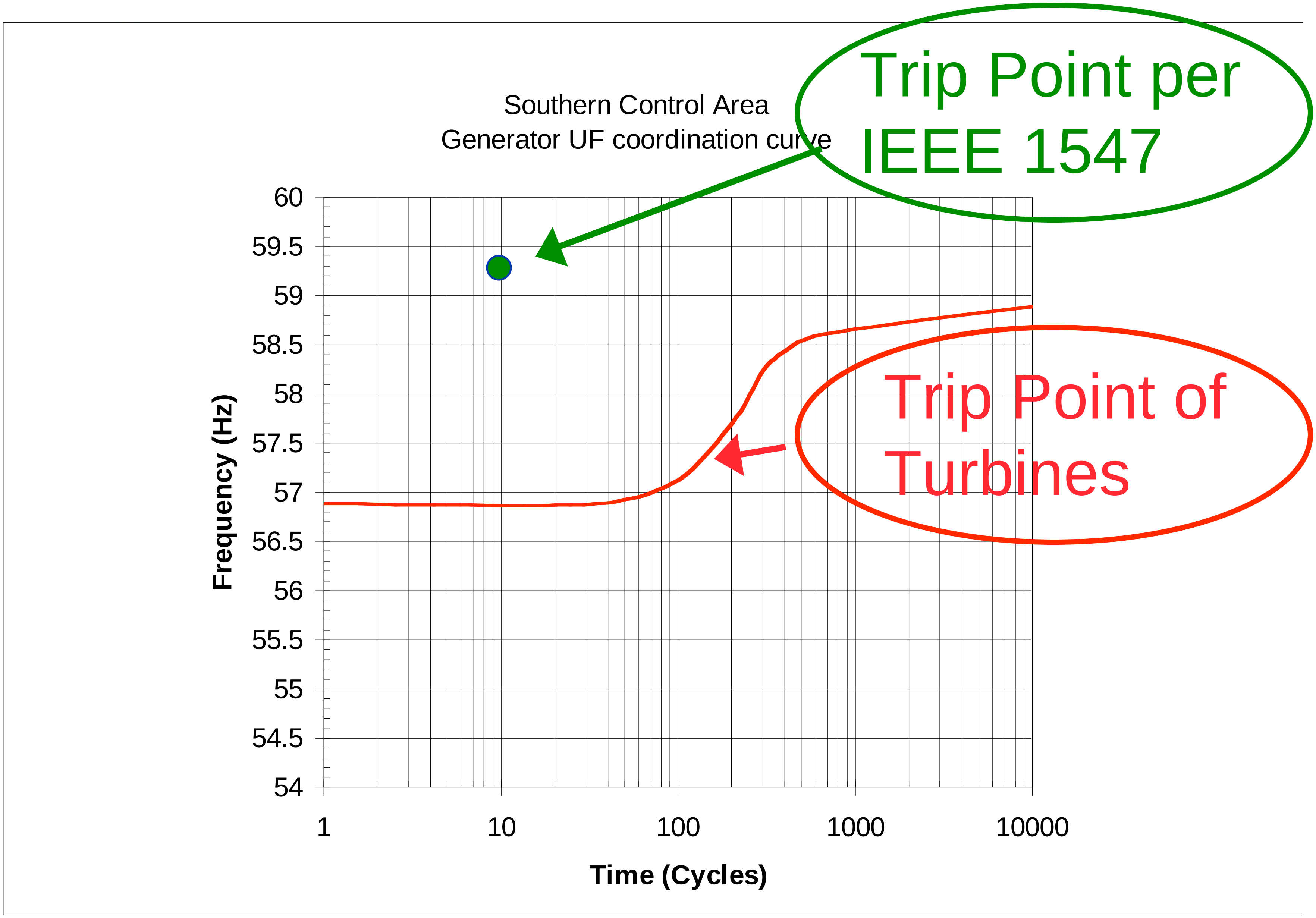


Frequency Excursions



Something Really Scary !




Southern Control Area
Generator UF coordination curve
Trip Point per IEEE 1547
Trip Point of Turbines
60
59.5
59
58.5
58
57.5
57
56.5
56
55.5
55
54.5
54
Frequency (Hz)
1
10
100
1000
10000
Time (Cycles)

"Anti-Anti" Islanding Back to Basics:

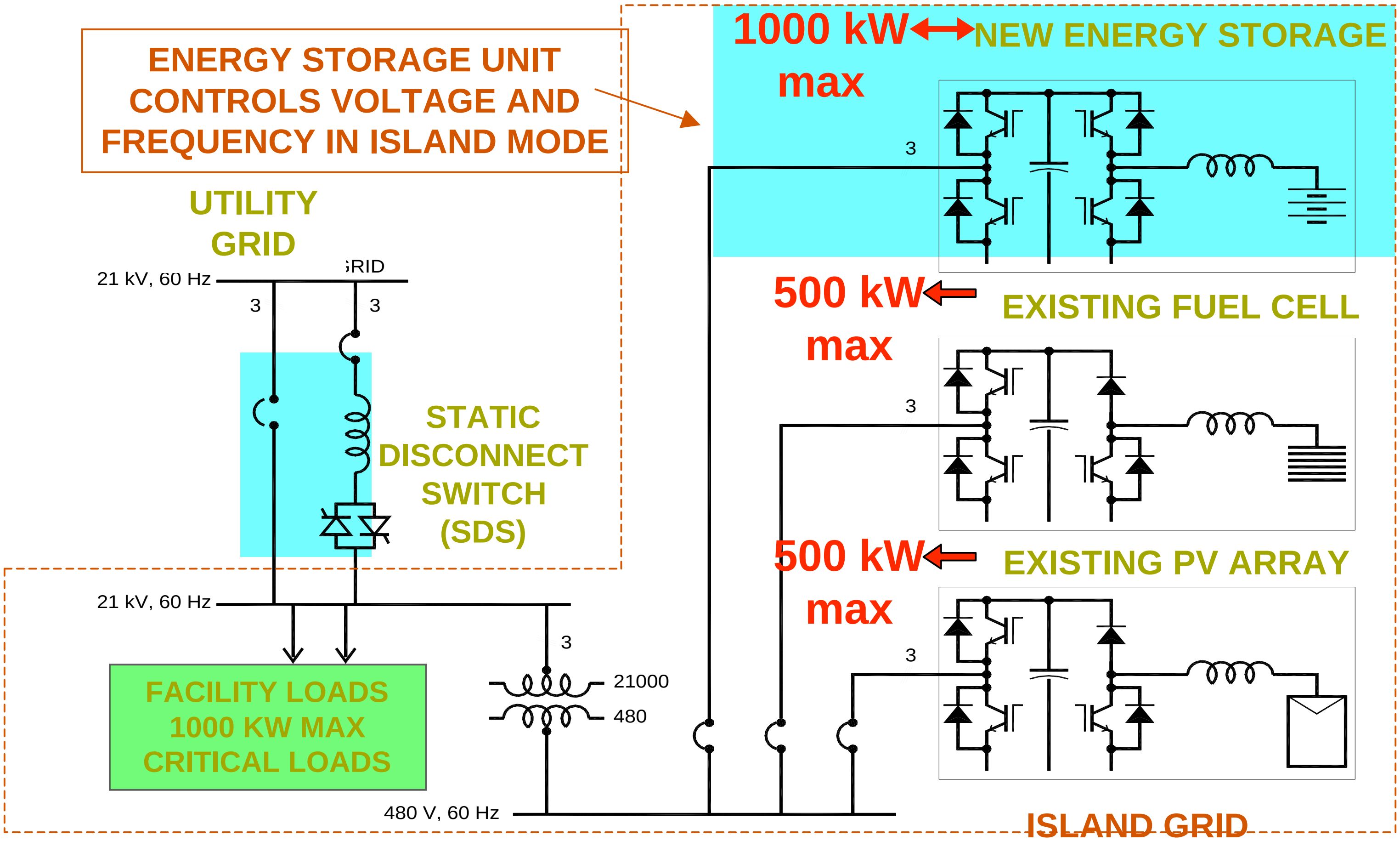
- Control Areas Use Permissive PLCC to Maintain Generation During Disturbances
  - No Freq Push issues with high penetration
  - Certainty with down lines
  - Provides Control Area Shutdown Capability during Over Generation events

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

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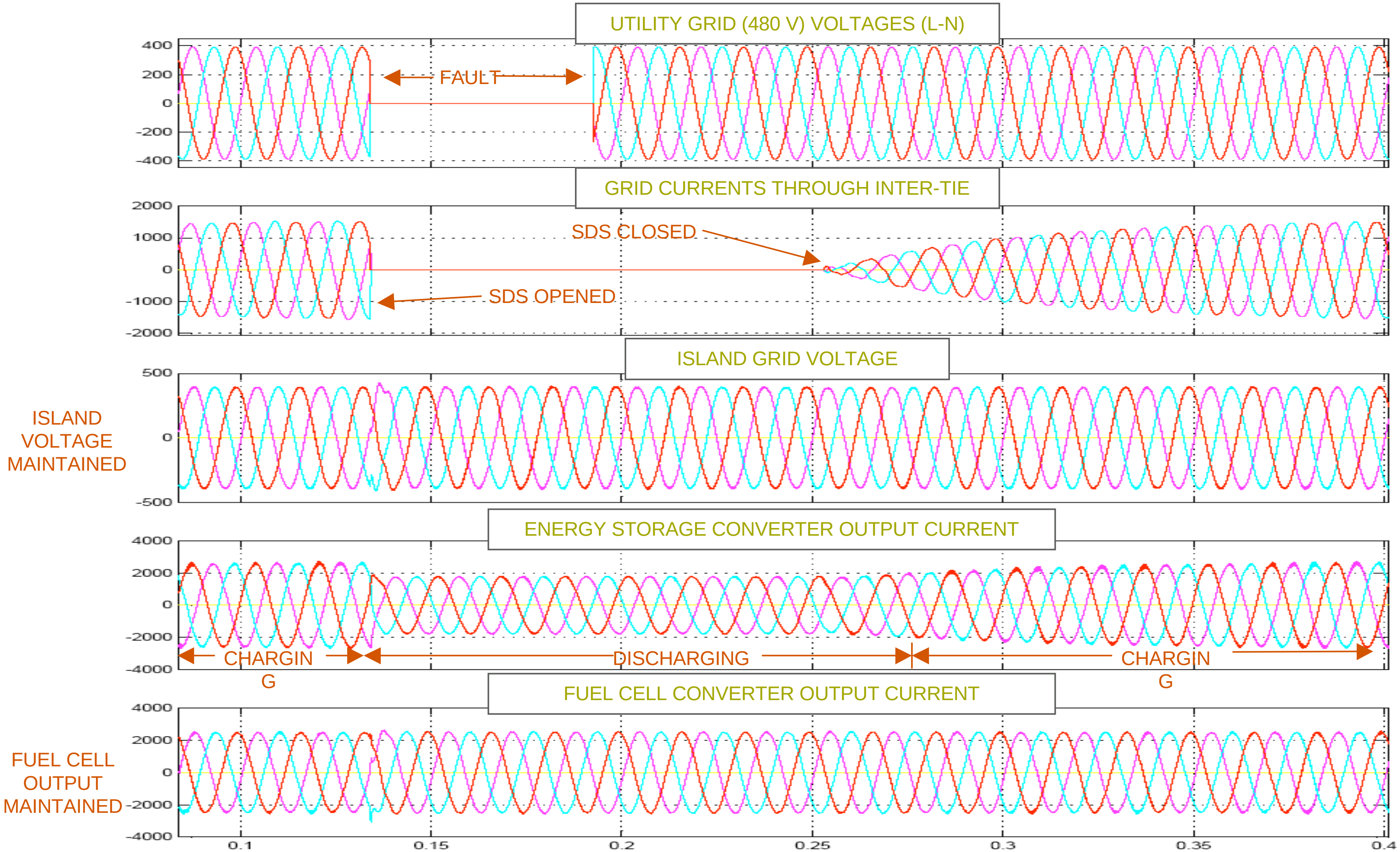
Simulated 3-Phase Fault on Utility Grid
2.2 MVA, 0.8 P.F. Constant Load on MicroGrid



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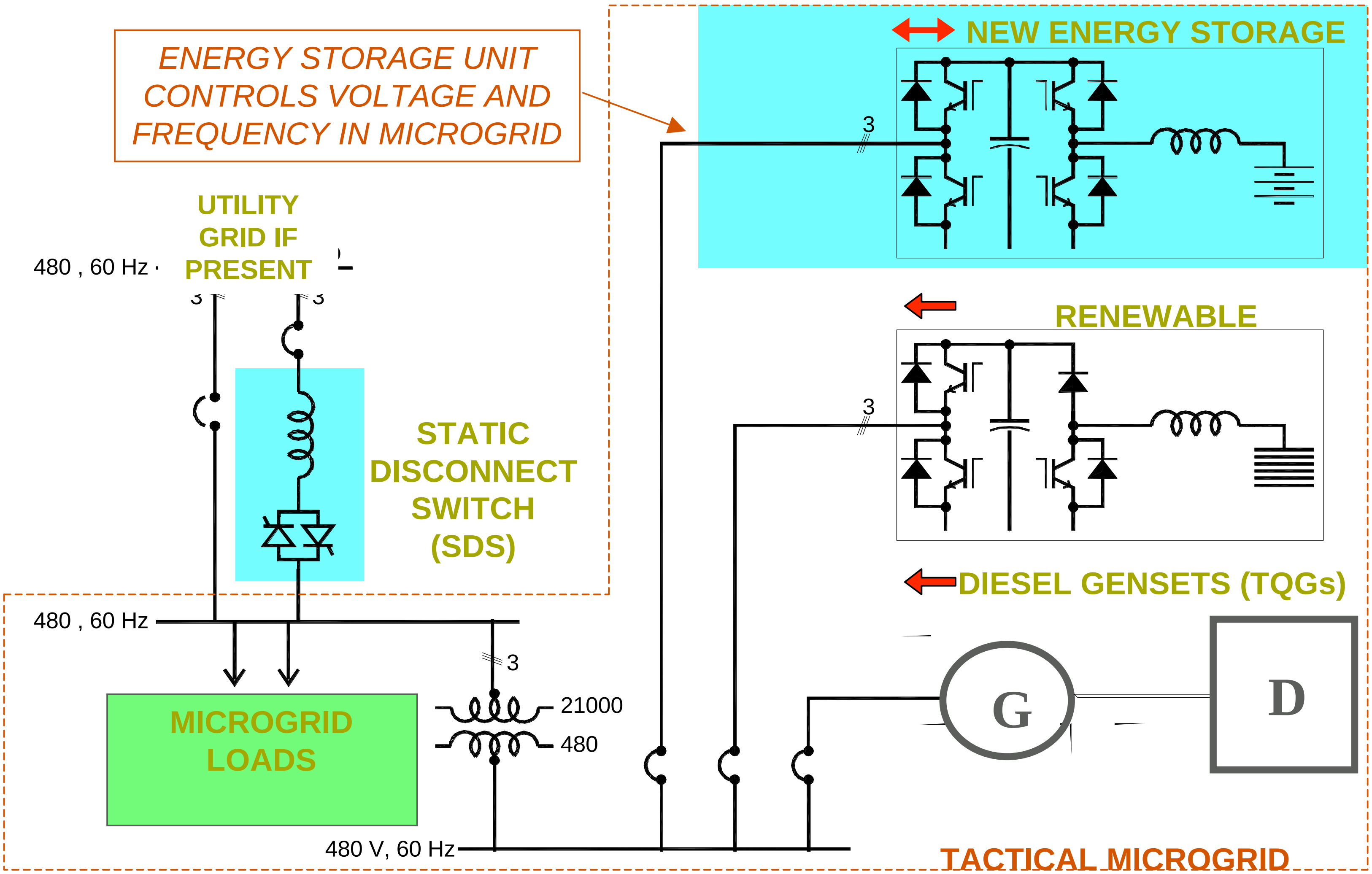
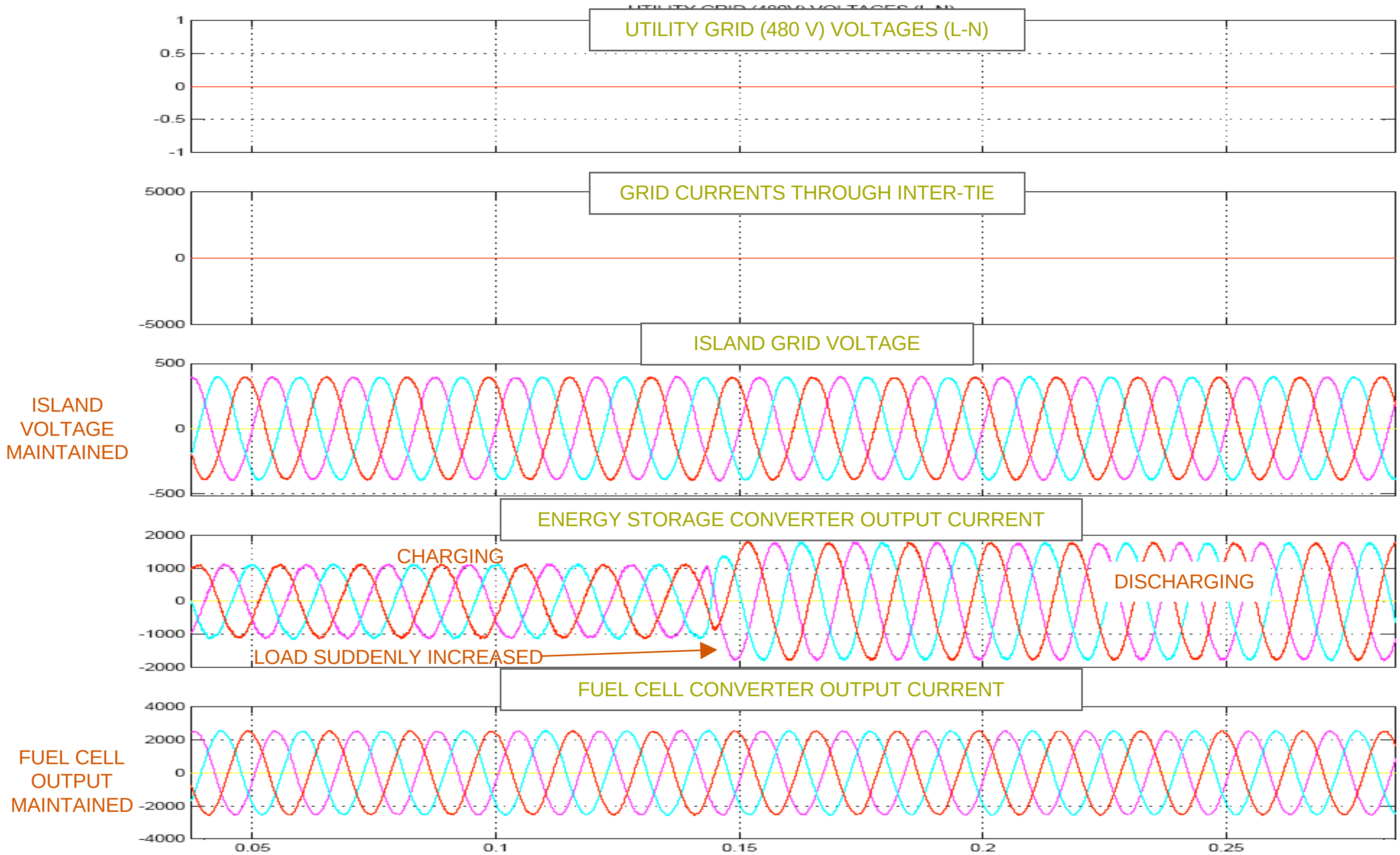
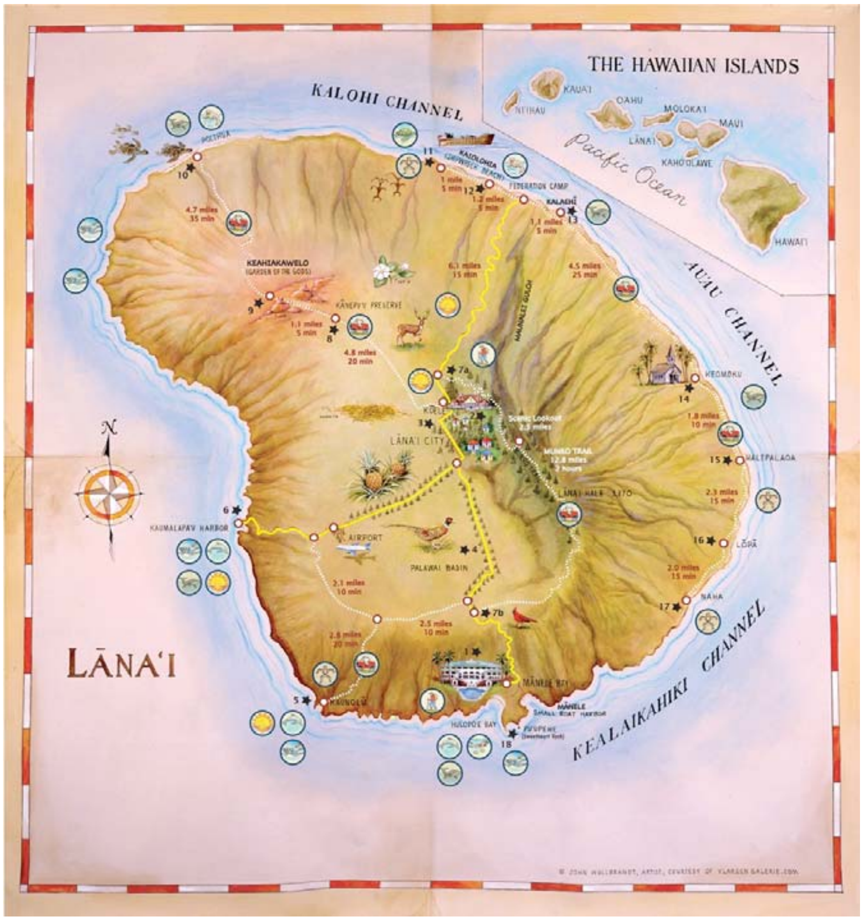
Utility Grid Connection optional – Tactical Micro Grid



Simulated Operation in Island Mode -Load Suddenly Increased (1.1 to 2.2 MVA, 0.8 P.F.)



Lanai



True "Island" Grid

Palawai Basin - 10 Acre Site

Advanced Inverter Features implemented under Utility Contrtol

Thank you.

Contact:

SUNPOWER

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