Smart Inverters for Grid Interconnections

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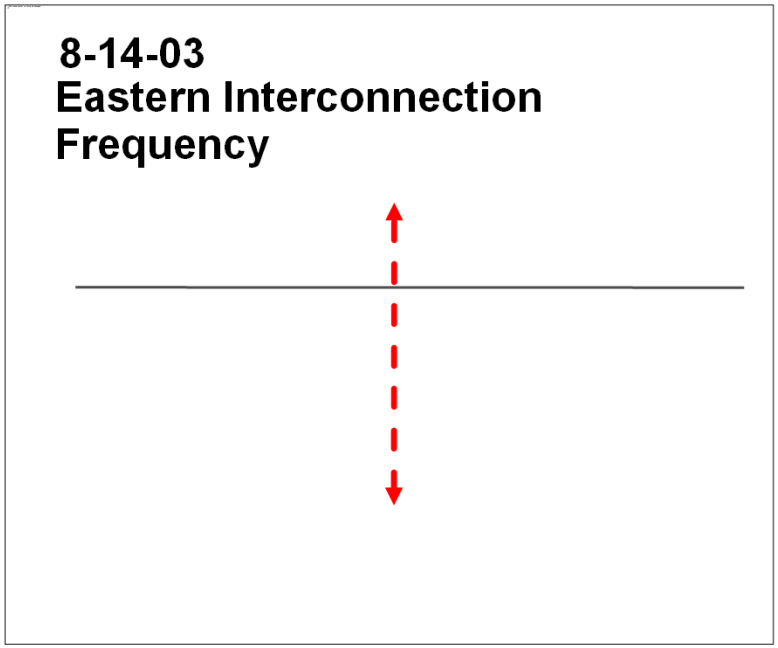
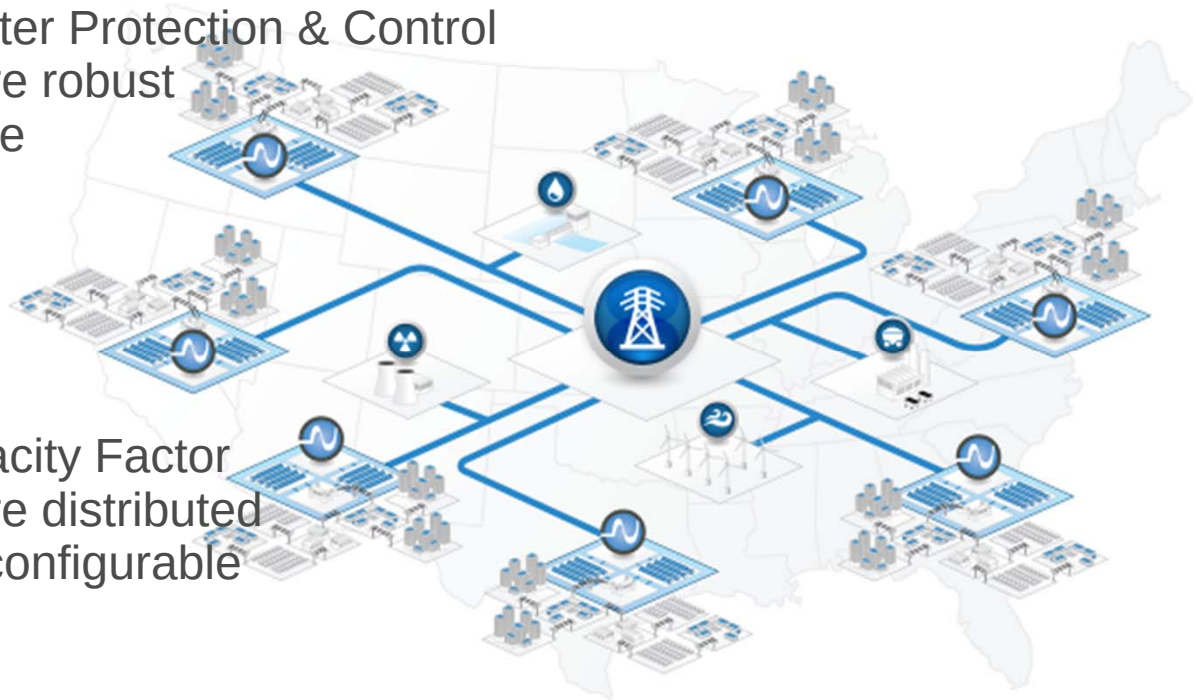
Modern Grid Issues

- An age of Increasing Electrification (1.1TW in EI),
  - BUT
    - Energy sources problematic (climate, security!)
    - Grid Power Quality is inadequate to electronic age
    - Slow and Archaic Electromechanical Hardware & Controls
  - SOME ANSWERS
    - Efficiencies
    - Renewables
    - Hi-Speed Controls
    - Hi-Speed Devices
    - Reconfiguration
  - TO SOME PROBLEMS
- Grid stabilization



Future Grid Vision

- More Electronics
  - Higher PQ
  - More μGrids
    - Improved Capacity Factor
      - More distributed
      - Reconfigurable
  - More efficient
  - More DC systems
    - More renewable
      - More robust
        - Faster Protection & Control

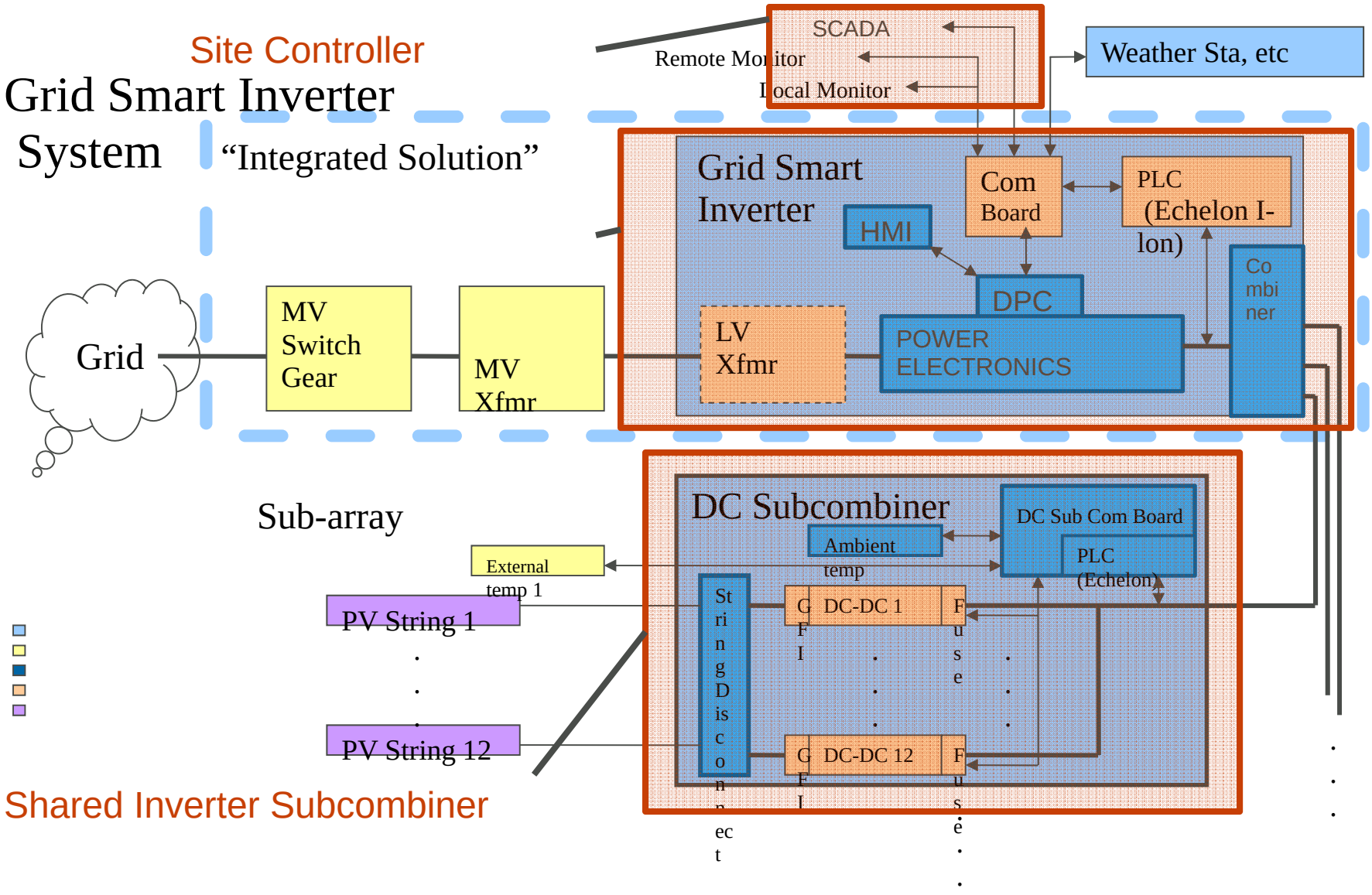


Electronics add Value beyond kWHr, The Grid is a Power System

- Mitigate Intermittencies
- Dispatchable Renewables (Hybrid plants)
- Control of Real and Reactive Power (dynamic)
- Voltage and frequency Ride-Through
- Distribution backfeed Capability
- DG instrumentation and control via SCADA
- Voltage mode for Grid Recovery

GRID ELECTRONICS In & On

Grid Smart Inverter Block Diagram



Intermittency Issues and Effects

- Weather, differing variation and time scales
- Forecasting very valuable for prediction of average power production over a region (geographic averaging)
- Solar PV with high penetration at distribution feeder level, this could have a sudden and significant effect on power supply and quality within the feeder.
- Addressing the disturbances in Solar Energy input to ensure that the Grid is not unduly disturbed and power quality maintained is a key element of the technical challenge to the large scale Grid Integration of solar PV.

Mitigation: Ramp-Rates, Storage

- Geographic averaging (transmission level solution)
- Bulk energy storage (technical and economic challenge)
- Ramp rates that do not excite grid transients or cause flicker (IEC voltage flicker)
  - Ramp-up simple
  - Ramp-down
    - Disturbance measurement (upwind)
    - Dynamic overhead
    - Appropriate energy storage
  - Dynamic VARs?

Lessons from Lana'i

- Nominal 4MW load
- "diesel" grid
- 1.5MWdc Solar Farm
- 12 SatCon, 135kW Inverters, 12 SunPower tracking arrays
- 10% of Lana'i annual energy
- 30% Supply during peak solar hours (4MW)
- CONCERNS: potentially destabilizing AND limits of Lana'i grid are extremely wide so non-UL1741 non IEEE1547 inverter required, and under Utility Control
    1. Remote control of Real Power, also termed curtailment
    2. Remote control of Power Factor
    3. Grid disturbance ride-thru capability
    4. Ramp rate limits and control (dP/dt)

Voltage and Frequency Ride-Through

IEEE 1547

Lana'I "La Ola"

Table 1—Interconnection system response to abnormal voltages

Voltage range (% of base voltage[a])	Clearing time(s)[b]
V< 50	0.16
50 ≤ V< 88	2.00
110 < V < 120	1.00
V ≥ 120	0.16

[a]Base voltages are the nominal system voltages stated in ANSI C84.1-1995, Table 1.
[b]DR ≤ 30 kW, maximum clearing times; DR > 30kW, default clearing times.

Voltage (at POCC) Condition	Action
0.9 p.u. < V < 1.10 p.u.	Normal Operating Range
0.70 p.u. < V < 0.90 p.u.	no trip until after 2.0 seconds
0.05 p.u. < V < 0.70 p.u.	no trip until after 0.6 seconds
V < 0.05 p.u.	no trip until after 0.15 seconds
1.1 p.u. < V < 1.2 p.u.	no trip until after 3.0 seconds
V > 1.2 p.u.	trip within 0.16 seconds

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Table 2—Interconnection system response to abnormal frequencies

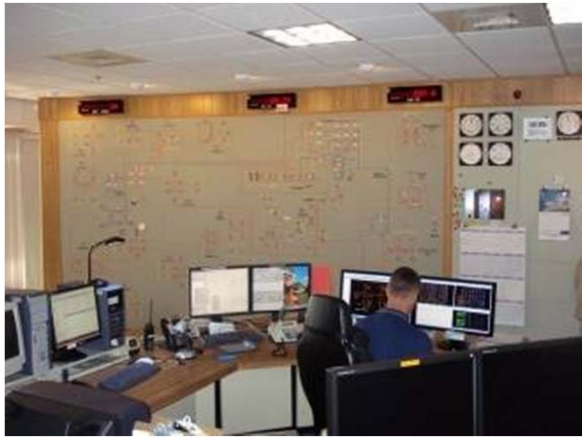
DR size	Frequency range (Hz)	Clearing time(s)[a]
≤ 30 kW	> 60.5	0.16
	< 59.3	0.16
> 30 kW	> 60.5	0.16
	< {59.8 – 57.0} (adjustable set point)	Adjustable 0.16 to 300
	< 57.0	0.16

[a]DR ≤ 30 kW, maximum clearing times; DR > 30 kW, default clearing times.

System Frequency Condition	Action
57 Hz < F < 61 Hz	Normal Operating Range
F > 65 Hz	trip within 0.16 seconds
62 Hz < F < 65 Hz	no trip until after 2 seconds
61 Hz < F < 62 Hz	no trip until after 6 seconds
55 Hz < F < 57 Hz	No trip, extended ride-through range
F < 55 Hz	trip within 0.16 seconds

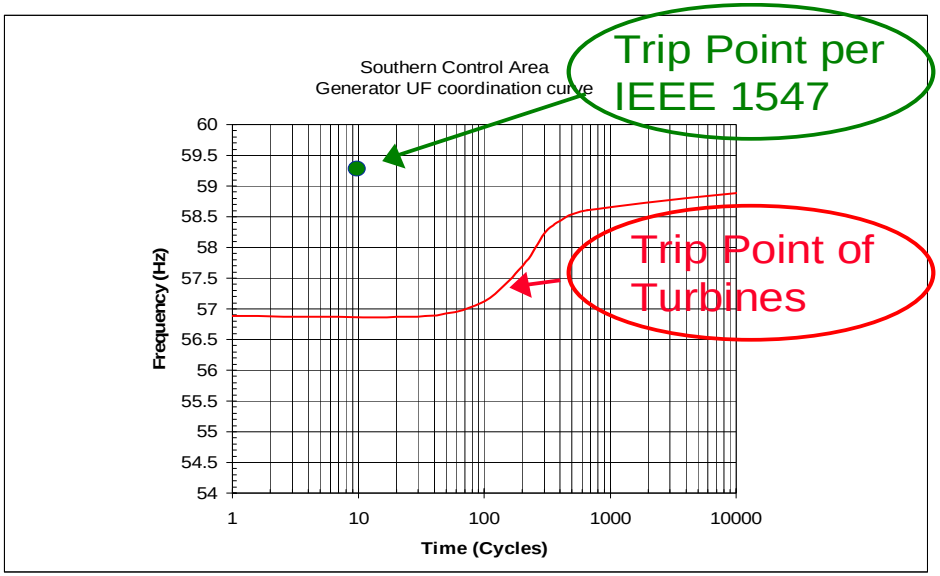
Utility Control

- Fully Bidirectional, SCADA Interfaced
- Remote ability to control (on/off), curtail P and Q, control power factor, reconfigure, …
- Monitoring visible to Utility Control Center
- Remote diagnostics, prognostics, help desk



IMPROVED ACCEPTANCE

- Utility/Government
  - IEEE 1547 Interconnection Standards Committee
  - NEC
  - NIST High MegaWatt Workshop (DOE Clean Energy Systems)
  - SMARTGRID STANDARDS
- IEEE
  - Power Engineering Society (PES)
  - Power Electronics Society (PELS)
  - Industry Applications Society (IAS)
- Trade Associations/Conferences
  - SEPA
  - InterSolar
  - PowerGen
- Demonstrations
  - Lanai
  - Santa Rita
  - SEGIS Stage 3

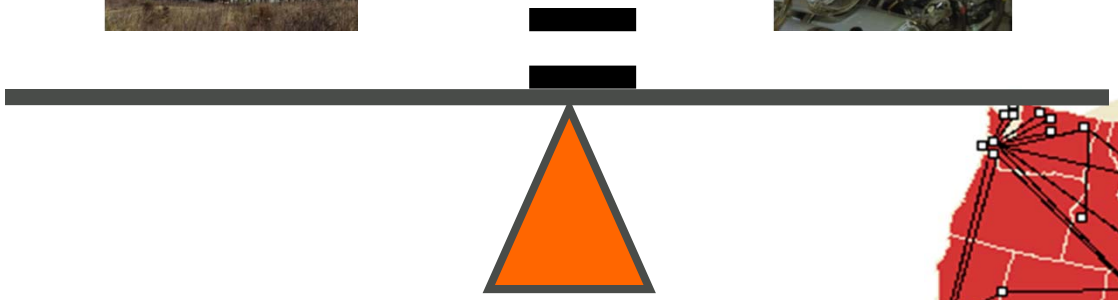


Backup

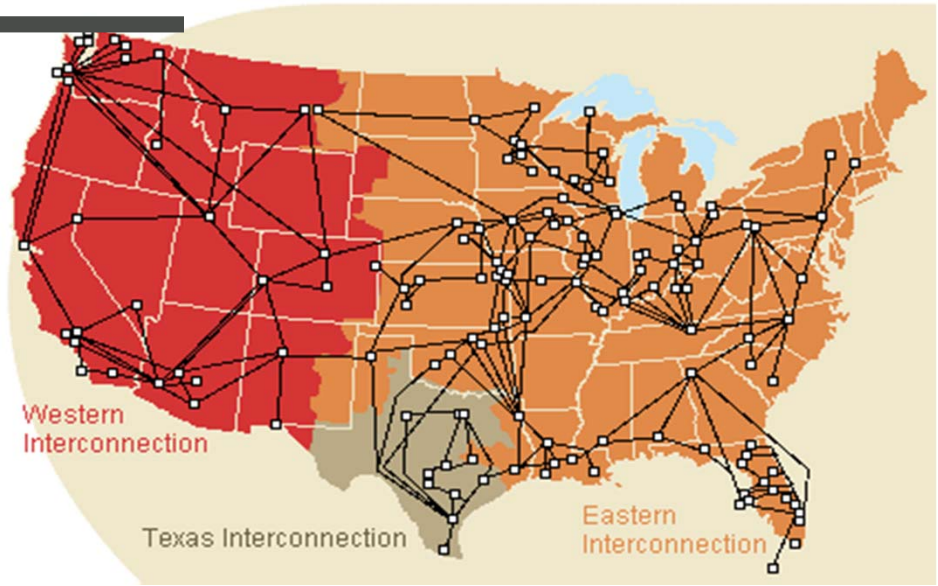
System Stability - dynamic

Supply **must equal** Load at all points in time

OR



Eastern Interconnect-- “the World’s Biggest Machine”
975,000,000 hp - 2,000,000 sq mi



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

- Implemented
- Tested in Certification Lab
- Verified at PV-Lana’i

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