PXiSE Energy Solutions, LLC

High speed, closed loop frequency control using PMU measurements for power grids

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BEFORE
Ramp Control

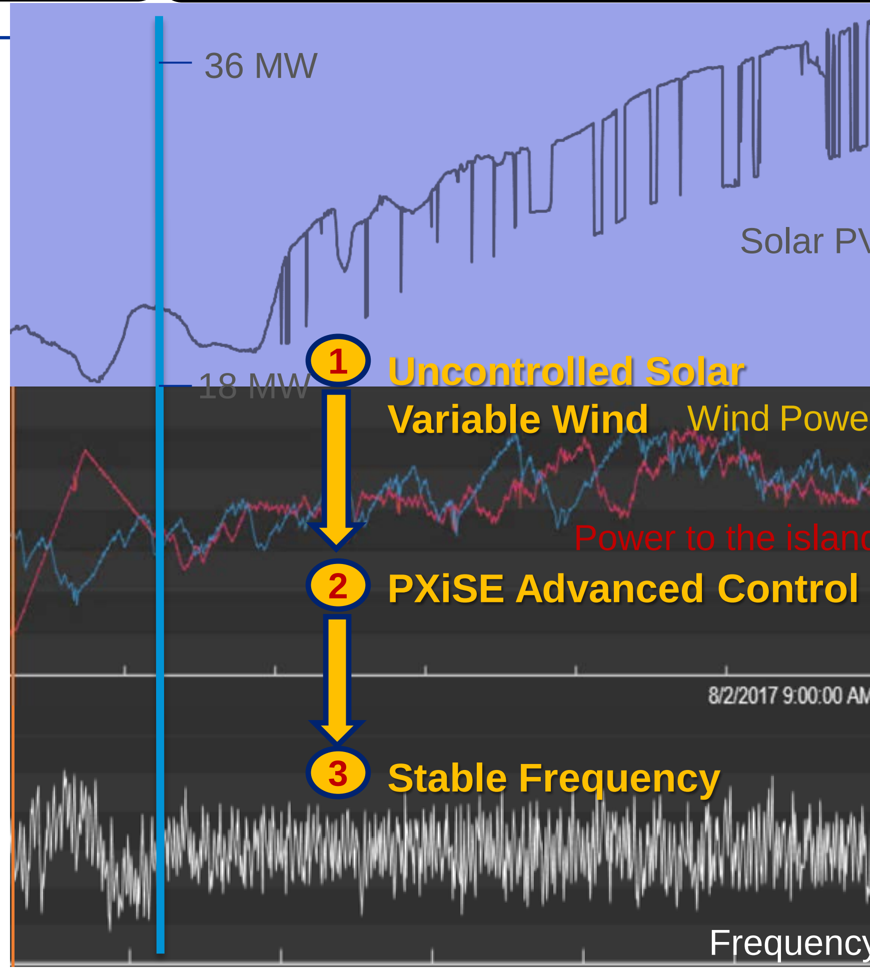
AFTER
Advanced Frequency Control

Before PXiSE

SEVEN REGULATING GENERATORS

THREE BATTERIES

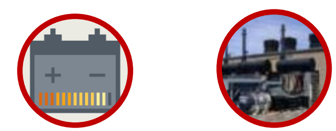
TO ACHIEVE



With PXiSE

ONE BATTERY

ONE COORDINATED GENERATOR



TO ACHIEVE

Value to an Island / Remote Grid:

1. **Reduce generator capital, O&M, and fuel costs**
2. **Enable an increase of renewable mix to lower energy cost**

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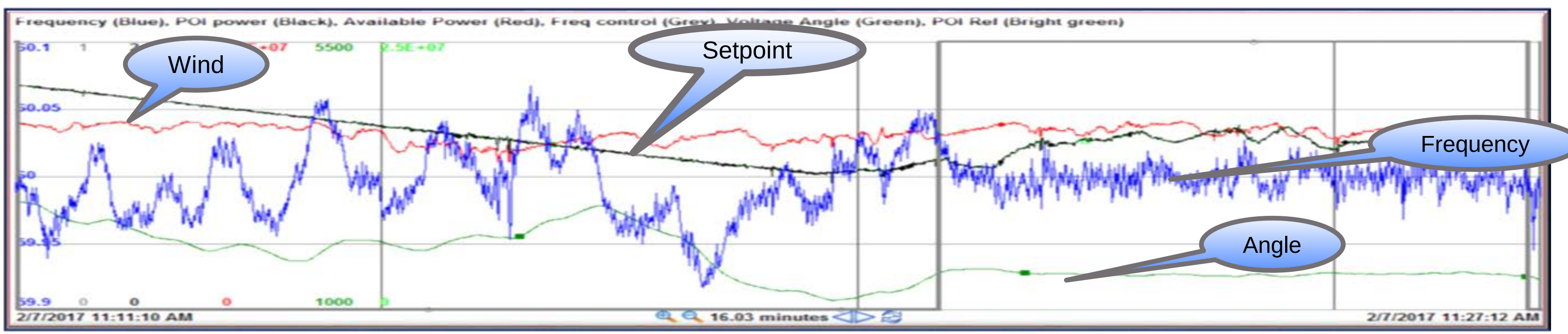
Main Message: Feedback Control with Phasors

Real/Reactive Power and Frequency Control using PMUs:

- Smooth (ramp rate) power output
- Maintain constant power with fixed power factor
- Maintain frequency of local grid
- Control voltage and angle at the POI



Synchrophasor-based Grid Control

O.K. to use Synchrophasor Data for Automatic Control?

- Too fast (60Hz) for control?
  60Hz is no problem for real-time control
- High volume of data?
  Control parameters in PI AF and data PI Archives
- Data dropouts?
  Real-time PMU data quality check and data ride-through
- How to use synchrophasor angle/frequency information?
  Decoupled real/reactive power control and frequency regulation

Other Industries Use Decoupling Feedback Control

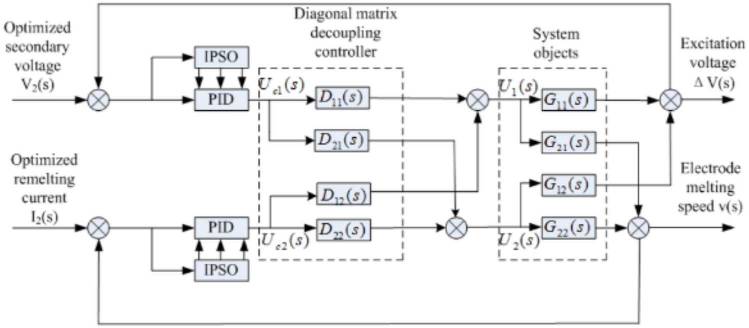
Navy ship and army tank weapon control systems

Aircraft/drone auto pilot (roll, pitch, yaw, altitude)

Hydrocracker for gasoline (OSI patent, 1980)

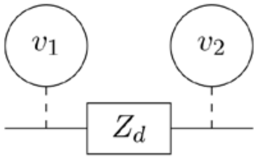
Basis weight and moisture in paper machines

Electroslag Resmelting Process Control



Innovation: PMU-based Decoupling Power Control

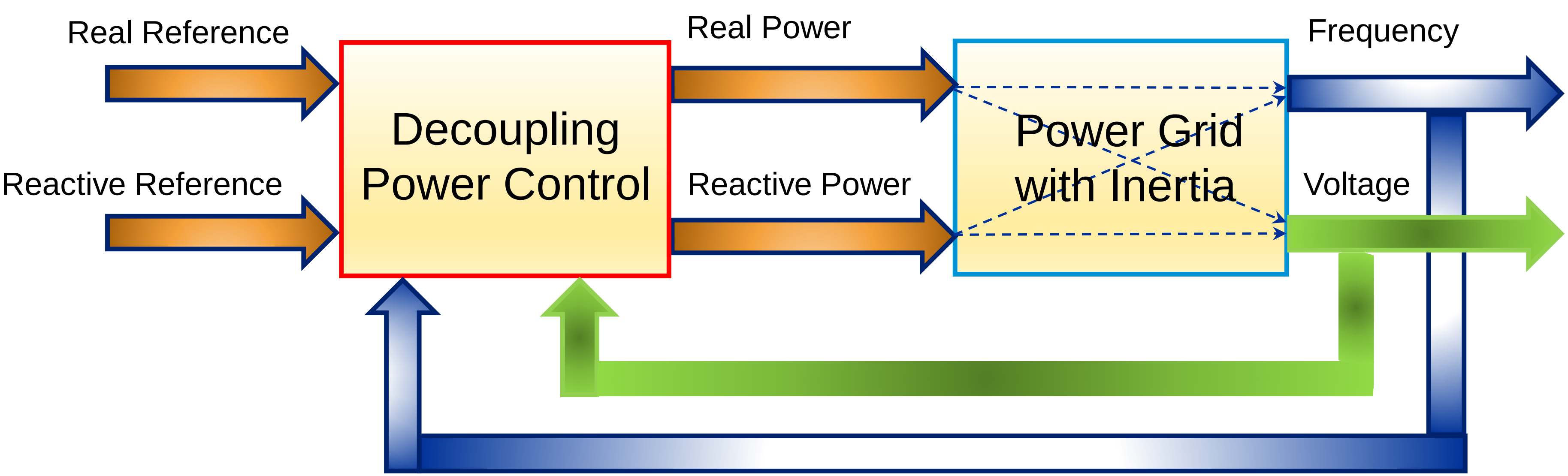
Real/Reactive Power coupled via Impedance:



$$
\begin{aligned}
P &= \frac{1}{2}\frac{V_1^2}{|Z_d(j\omega)|}\cos\angle\{Z_d(j\omega)\} - \frac{1}{2}\frac{V_1V_2}{|Z_d(j\omega)|}\cos(\angle\{Z_d(j\omega)\}-\delta) \\
Q &= \frac{1}{2}\frac{V_1^2}{|Z_d(j\omega)|}\sin\angle\{Z_d(j\omega)\} - \frac{1}{2}\frac{V_1V_2}{|Z_d(j\omega)|}\sin(\angle\{Z_d(j\omega)\}-\delta)
\end{aligned}
$$

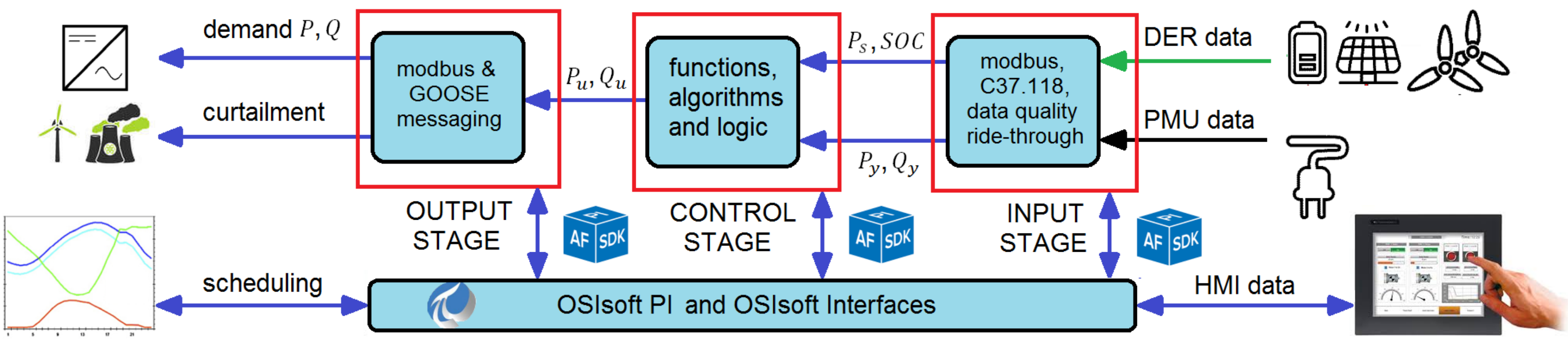
$$
\begin{aligned}
v_1 &= V_1 e^{j\alpha_{v_1}} \\
v_2 &= V_2 e^{j(\alpha_{v_1}+\delta)}
\end{aligned}
\quad \text{where } \delta = \alpha_{v_2} - \alpha_{v_1}
$$

Real Power influences AC frequency dynamically:



Key Elements of PXiSE Control Solution

- PMU based 2x2 decoupled closed-loop control
- Able to control power flow direction in any grid
- Control of “state of the grid” (V,ϴ)
- Executes at 60 Hz on standard hardware
- PI (AF) for configuration, process and control data



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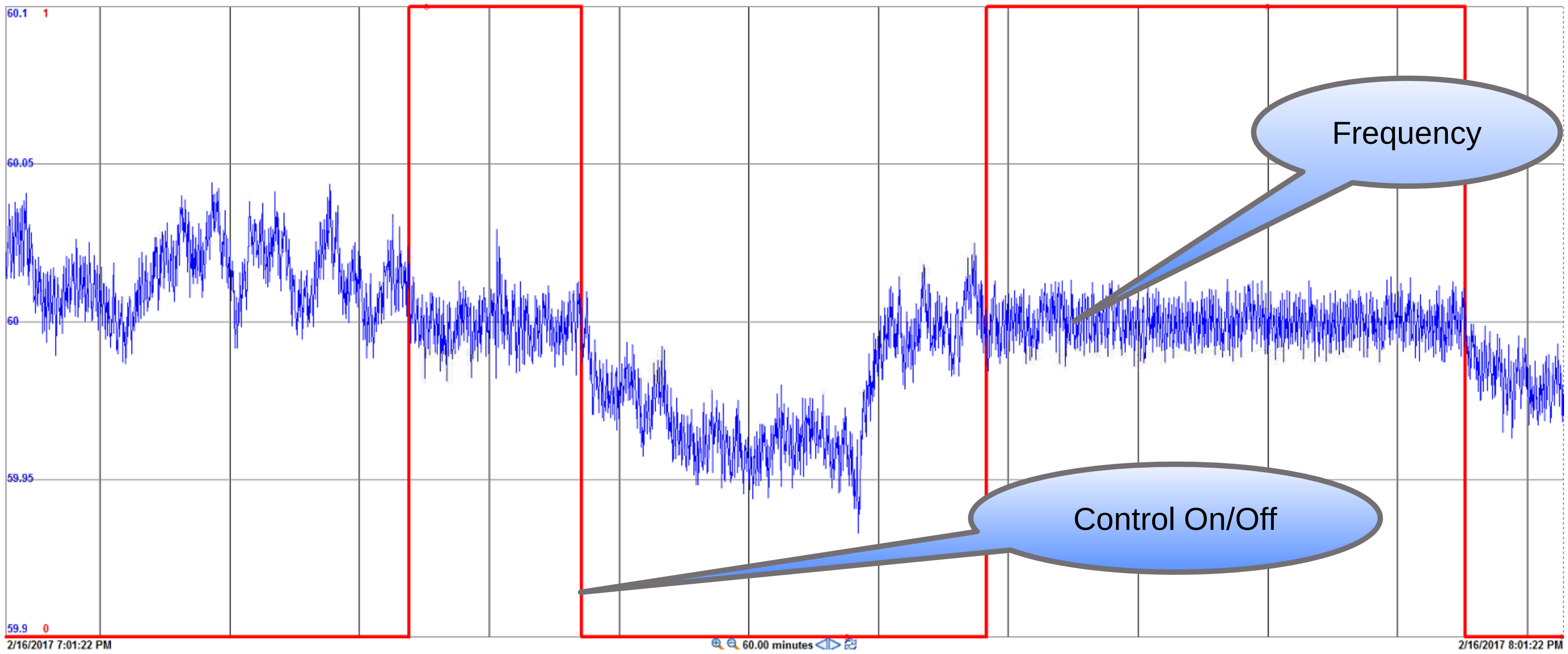
Comparison without and with control

Real-time implementation using a WindFarm/BESS



Multiple times lower frequency variation with real-time synchrophasor control

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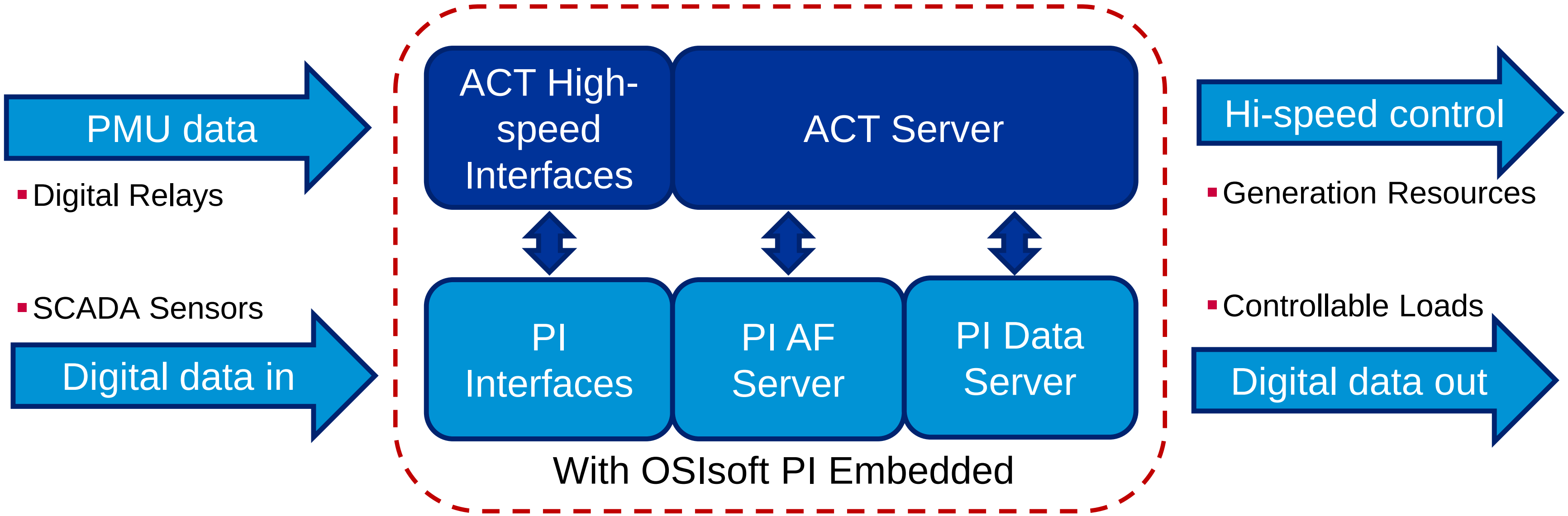
Advanced Ramp and Frequency Control in Action at a Windfarm

PXiSE Energy Solutions, LCC

Advanced Control Technology (ACT) Solution: Integrated Software Built Upon Proven Data Platform



Implemented on Field Proven Hardware

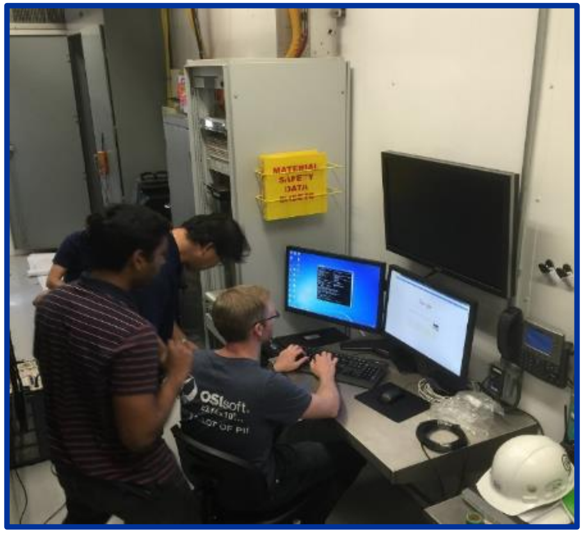
PXiSE ACT Solution

Enabling Fast Field Implementation

PXiSE Energy Solutions, LCC

Fast Substation Commissioning

1. Mount Controller Computer & Connect Network Cable
2. Validate PMU and Data I/O
3. Tune Controller
4. Place PXiSE ACT in Service



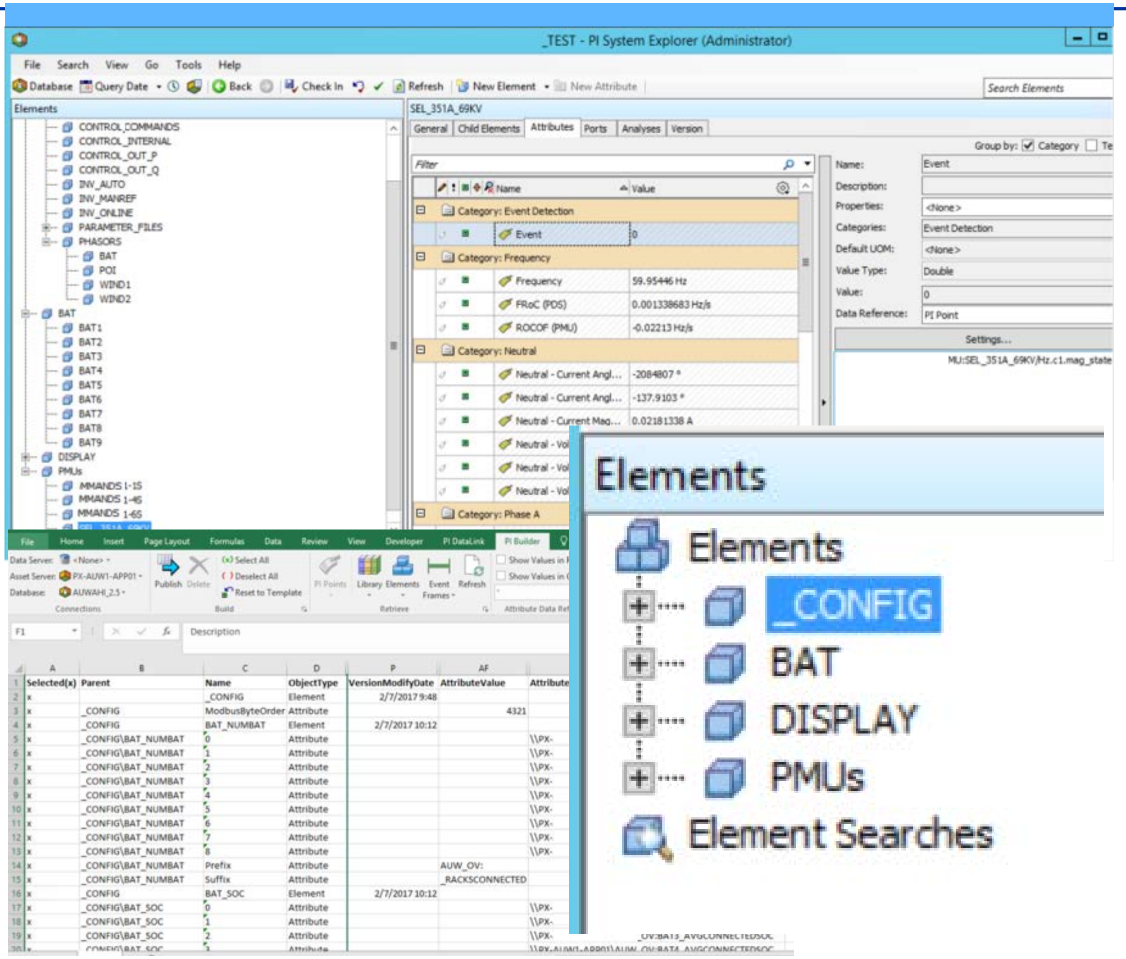
Use existing platforms
Standard equipment
Set-up in 2-3 days

Demonstration: Reduced Config Time

Using PI AF to reduce configuration time

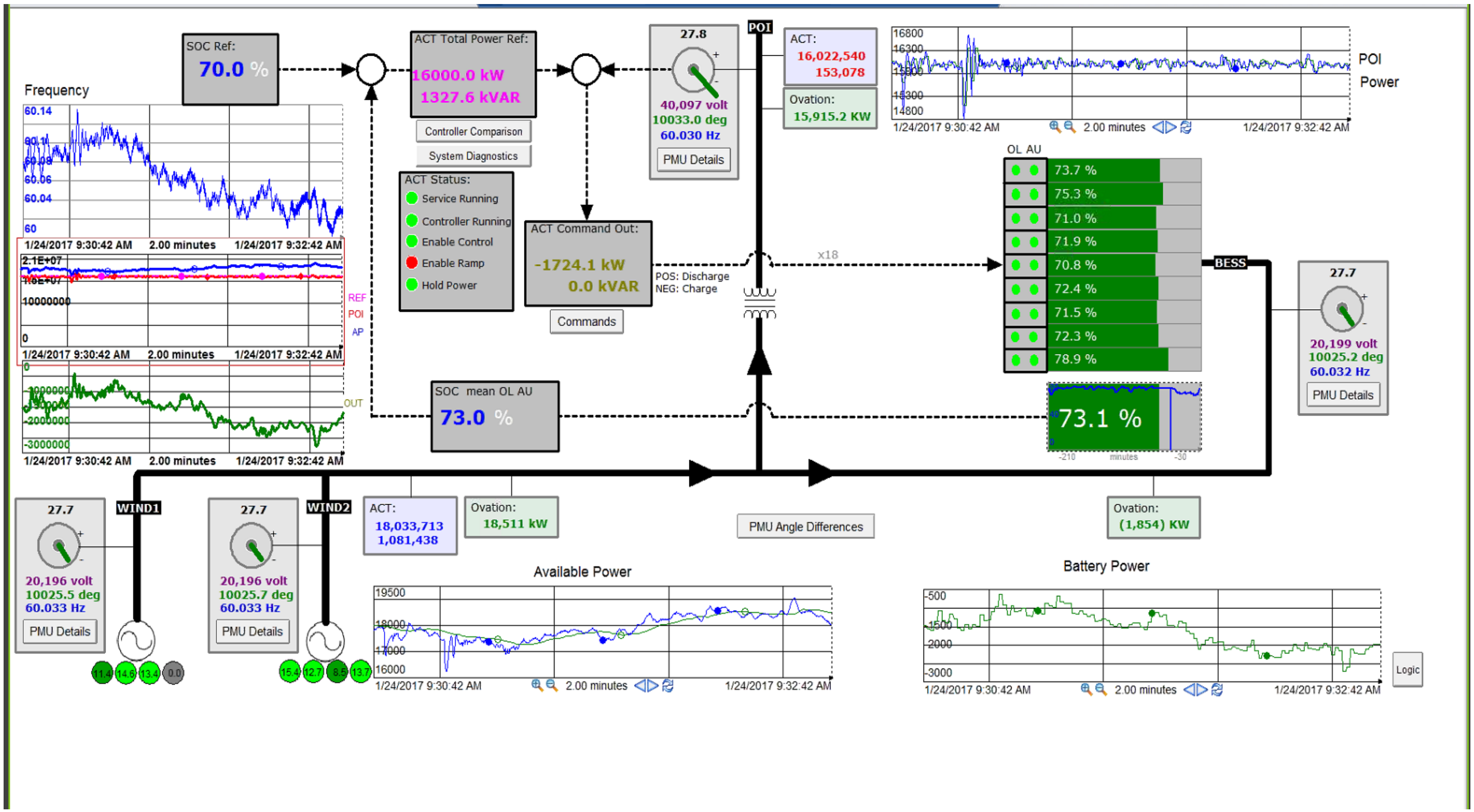
(XML model import via CIM or CSV files)

- General data model
- Import from external files
  - CIM
  - CSV
- Configuration standard PI tools
- Incremental updates
- History of:
  - configuration data
  - tuning data
  - process data
  - diagnostic data



PMU Based High Speed Controller

at a Major Windfarm with Battery Storage



![PESE logo]

Demonstration: Ramp Control on Power

High Speed Precision

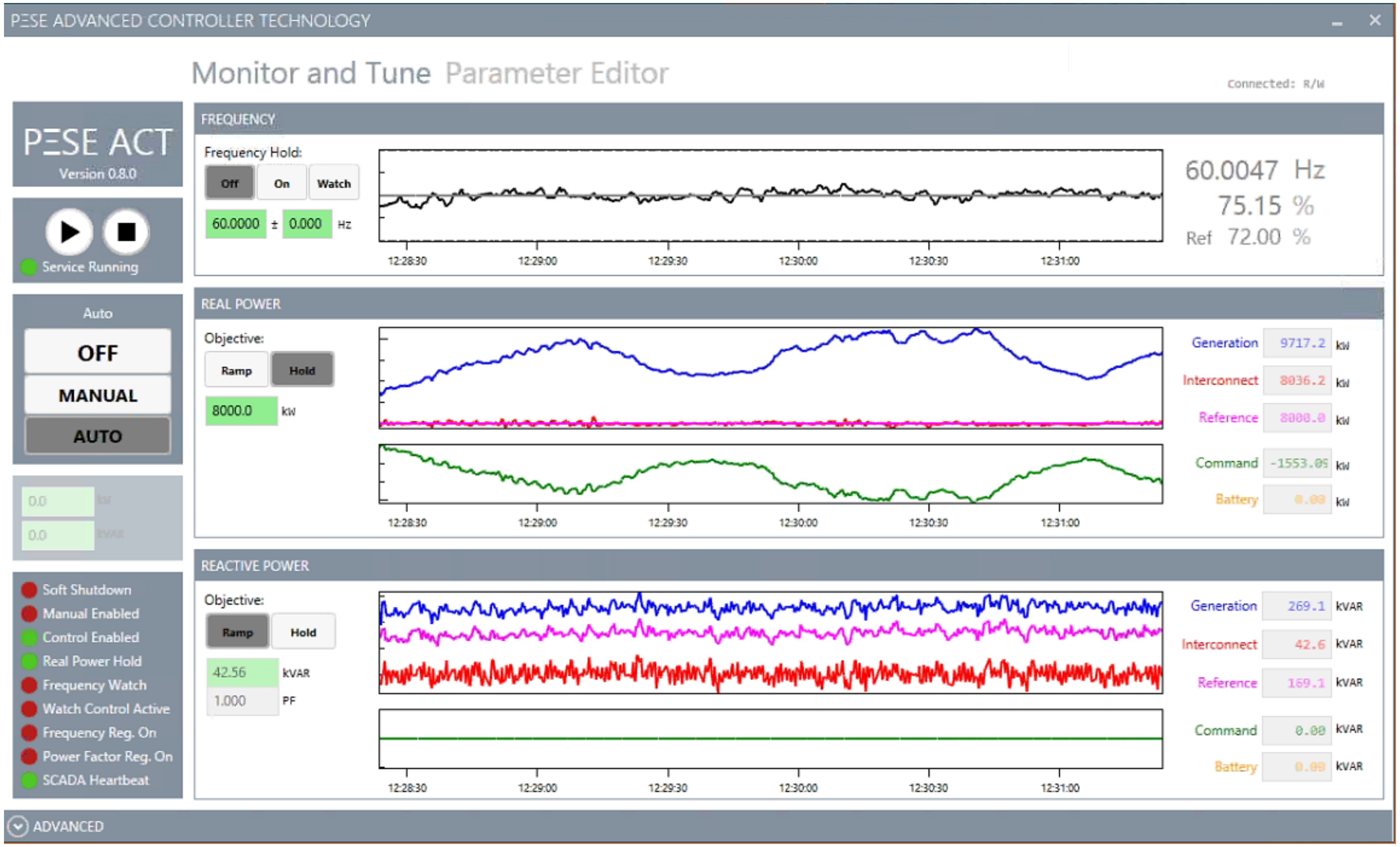
Real Power "Ramp Rate" Control

Mitigates Wind Power Variability!

Demonstration: Hold Power Steady

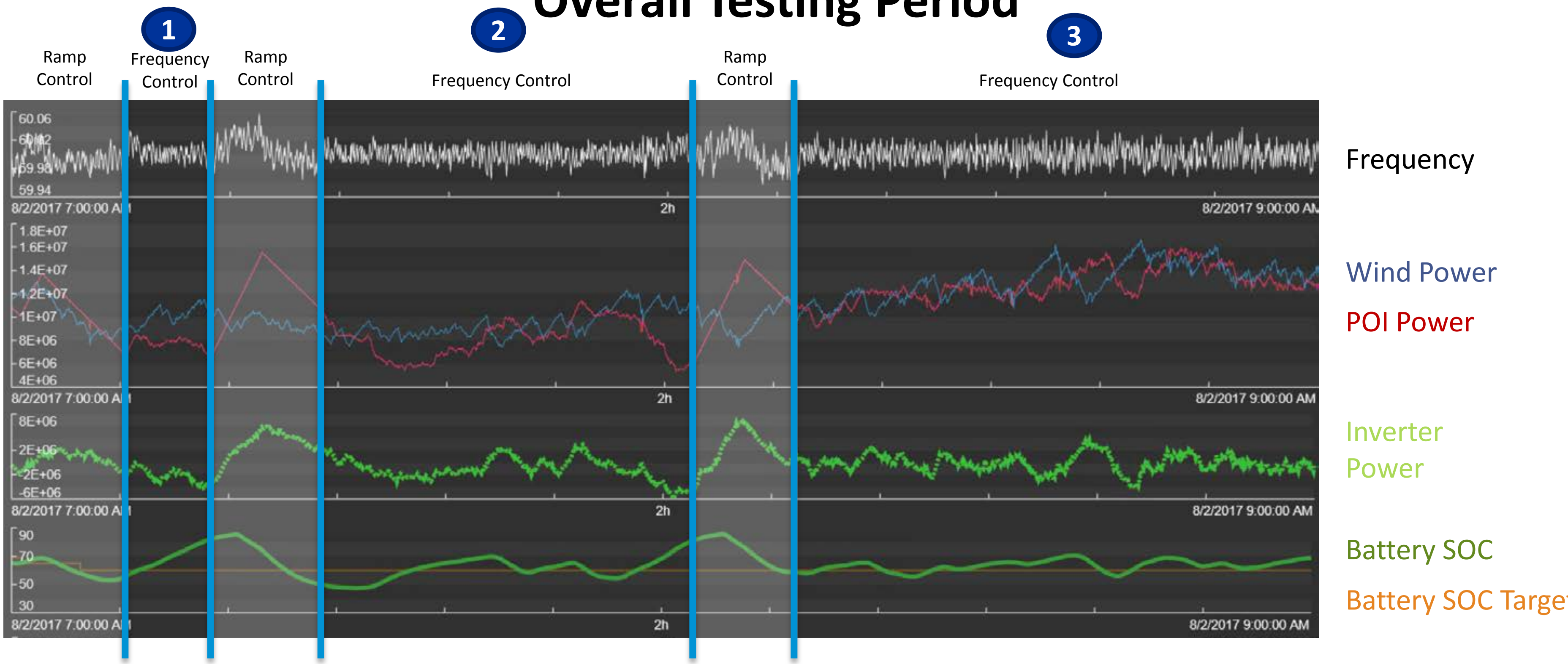
High Speed
Precision
Real Power
“Hold Steady”
Control

Follow any
power demand
(islanding
if demand = 0)!



Additional test – frequency control

Overall Testing Period



Notice the clear difference between Ramp Control and Frequency Control periods.

Takeaway: PXiSE Synchrophasor Control Solution

Power Quality Control

- Fast and precise mitigation of power fluctuations
- Fast and precise power demand tracking
- Islanding via control by zero power flows
- Damping of common grid modes

Financial Benefits

- Supports high penetration of renewable generation
    - Handle systems with low inertia
- Increase revenue by selling ancillary services
- Reduce energy cost by managing demand and time of use
- Faster return on investment of renewable microgrid assets

Potential Applications:

- Grid control for maximum renewable generation
- Direct control of power flow direction
- Distributed regulation of frequency
- Simultaneous control of voltage and voltage angle
- Automatic damping of area and inter-area oscillations
- Real time mitigation of disturbances
- Full compliance with IEEE 2030.7 Microgrid controllers
- Demand charge minimization

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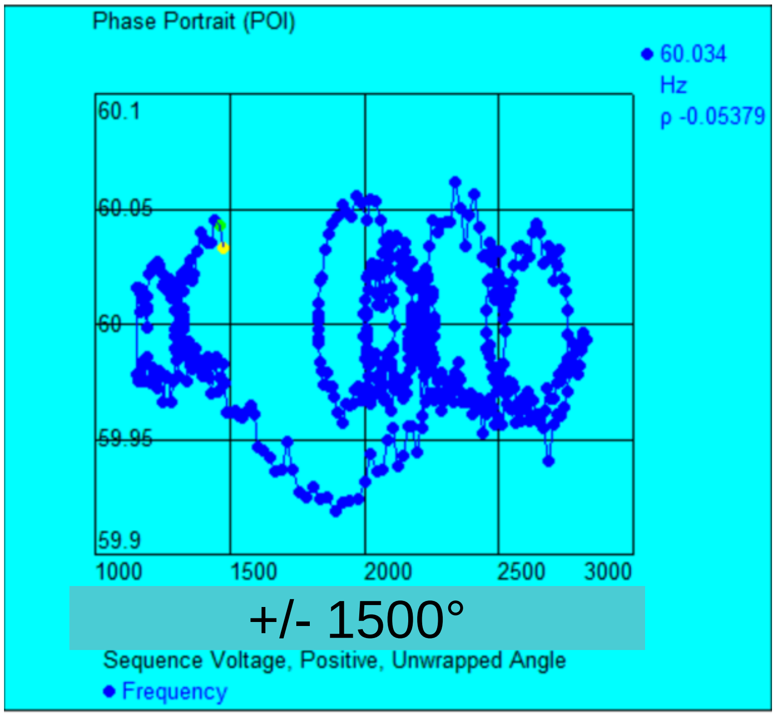
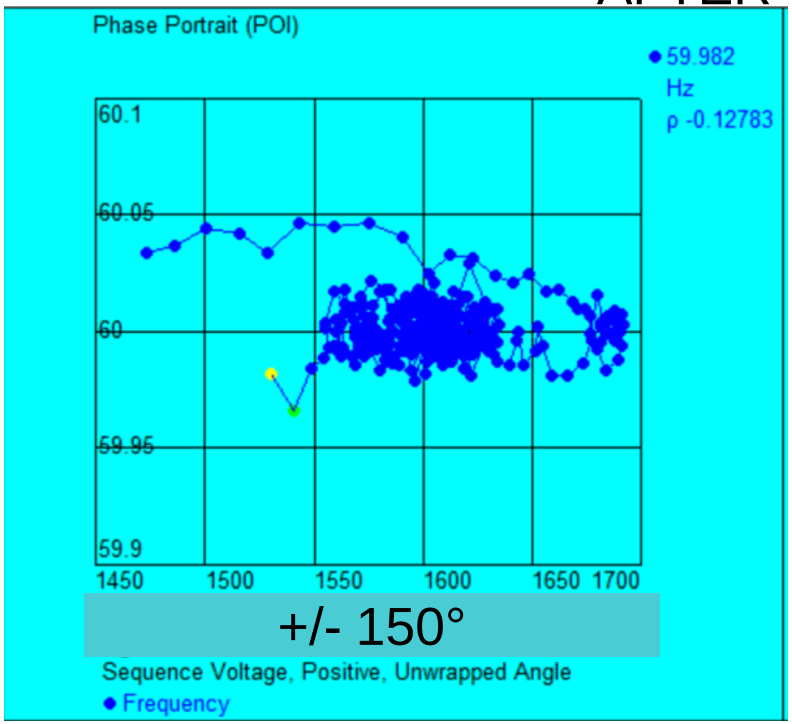
Phase Portraits Before and On Frequency Control

10 minute moving window

BEFORE



AFTER

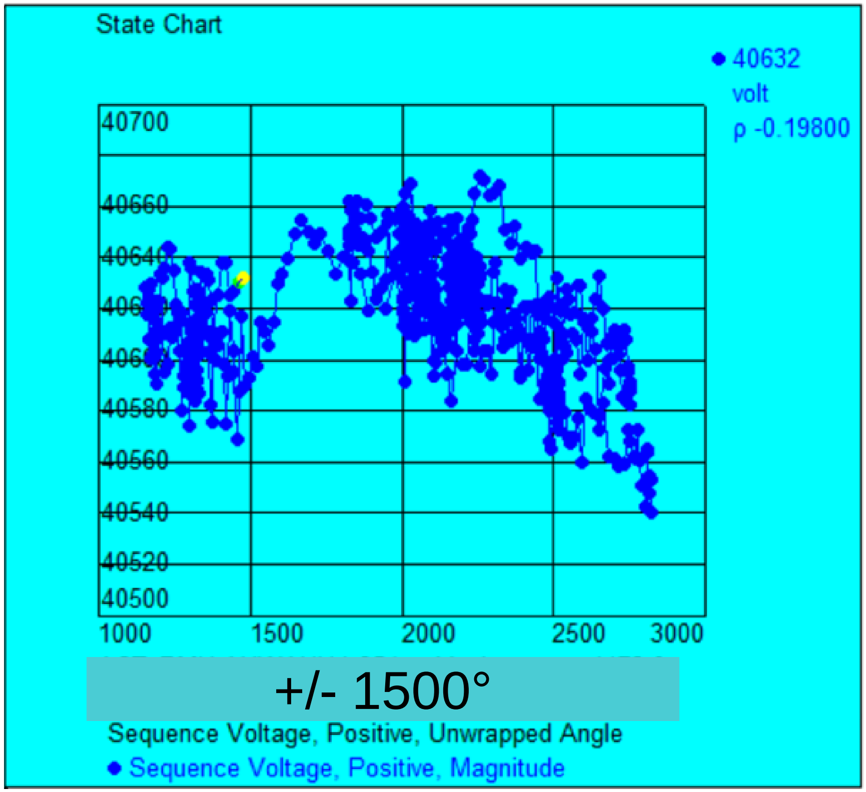


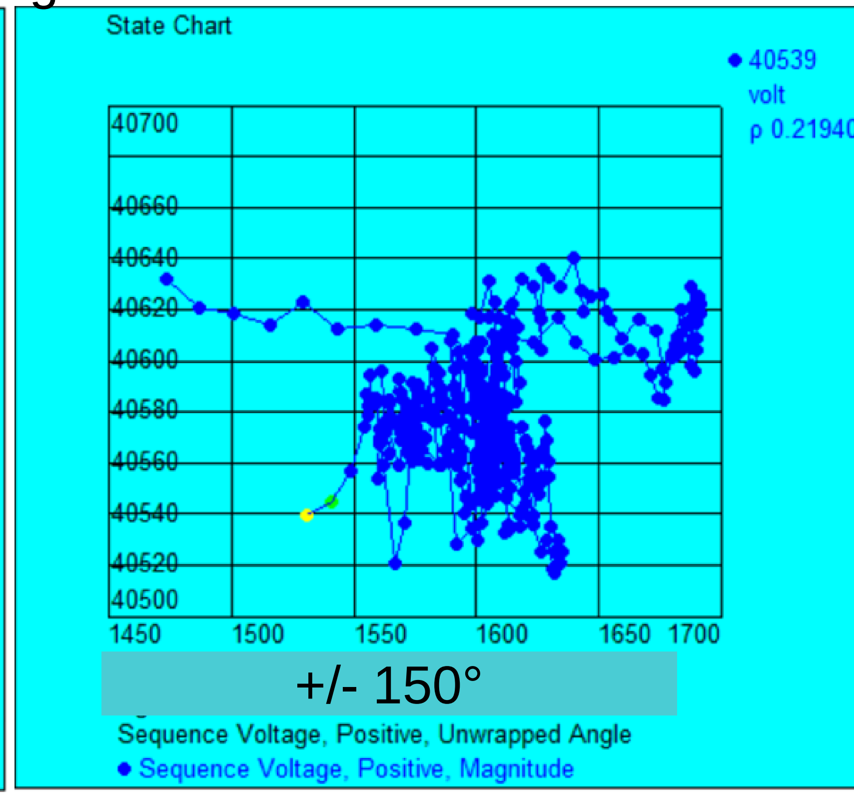
Large oscillations (± 8 mHz)
large angle excursion

Small oscillations (± 4 mHz)
Low angle excursions

State Charts Before and On Frequency Control

BEFORE 10 minute moving window AFTER





Large oscillations
large angle excursion (1500 degrees)

Small oscillations
Low angle excursions (150 degrees)

Software modules in ACT (PMU based controls)

- Wind farm control

  Ramp, hold PQ, curtail PQ, smooth PQ, frequency control
- Solar farm control

  Ramp, curtail PQ, voltage setpoint
- Microgrid control

  Demand cost reduction, hold PQ, seamless connect, disconnect, frequency, ramp PQ
- Grid control

  Voltage and angle control at POI

  Local frequency control
- Alarm system compliant with ISA 18.2 standards

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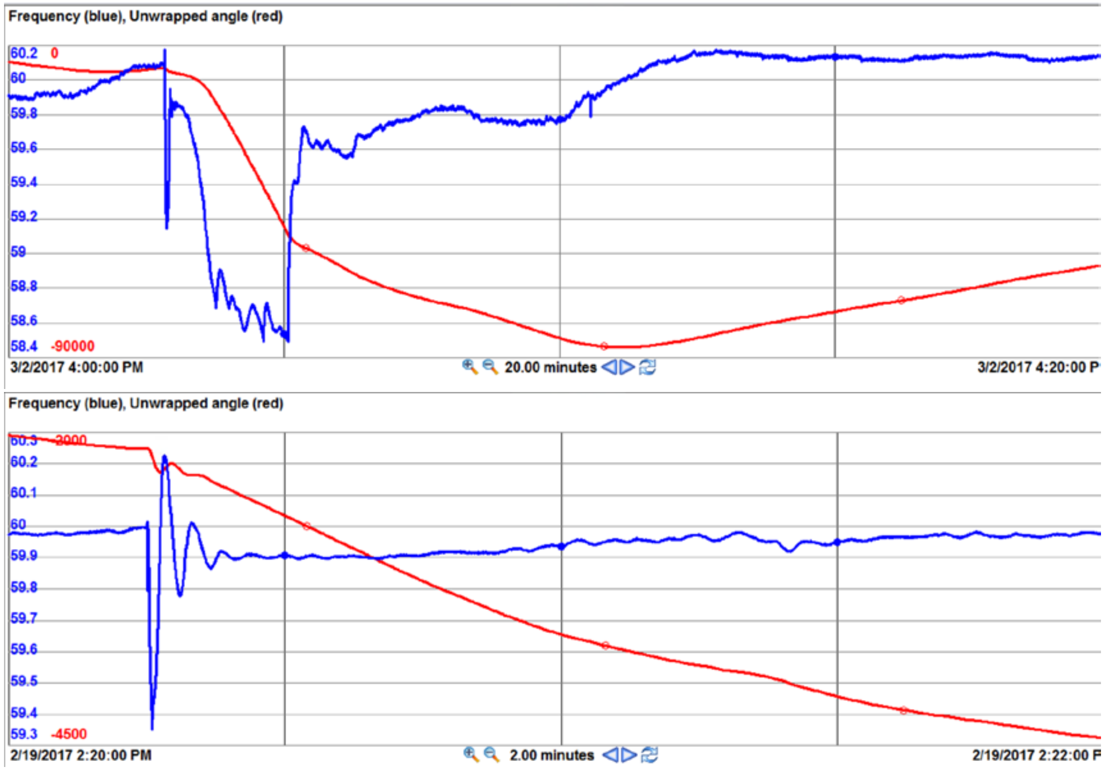
Synchrophasor Data: Angle/Frequency



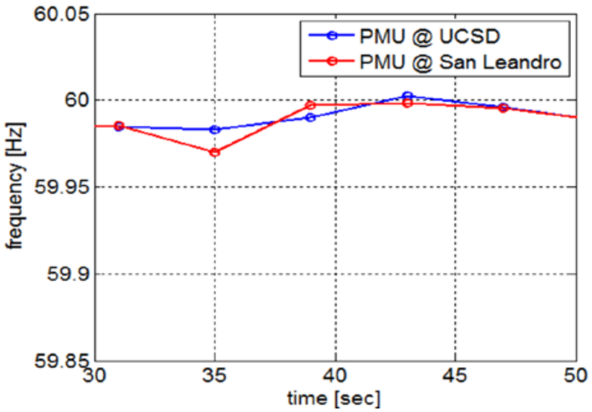
Intermittent Resources Impact the Grid

Possibility of relays trip & blackouts

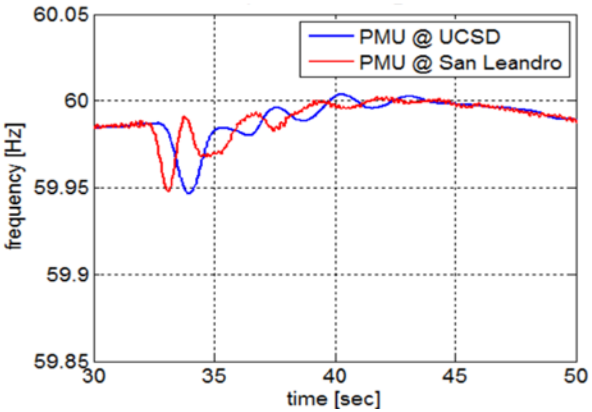
Example: Island/microgrid oscillations (average load = 80 MW)

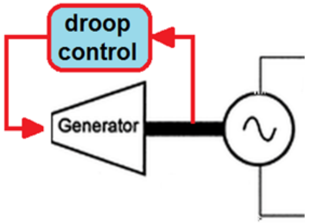
Synchrophasor Data: Power/Frequency

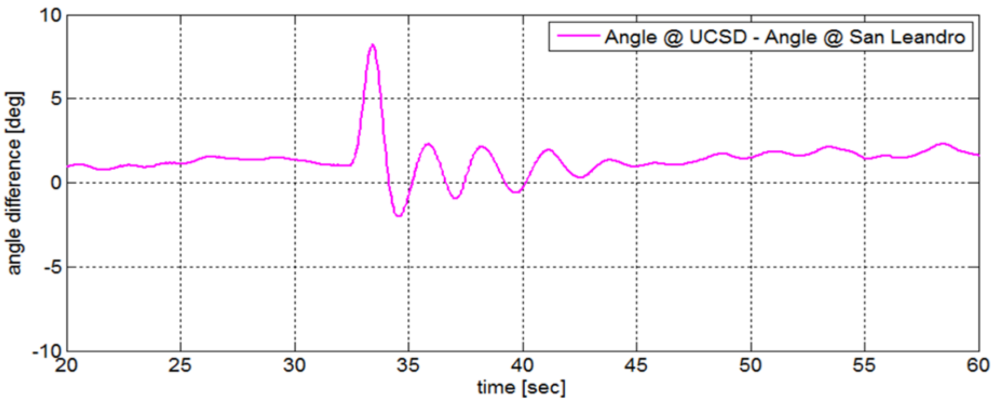
The difference between seeing and believing: Chief Joe Brake

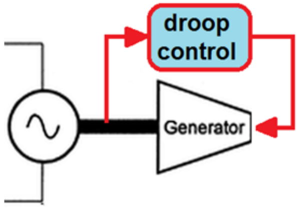


Frequency is not synchronized across the grid; Frequency is local

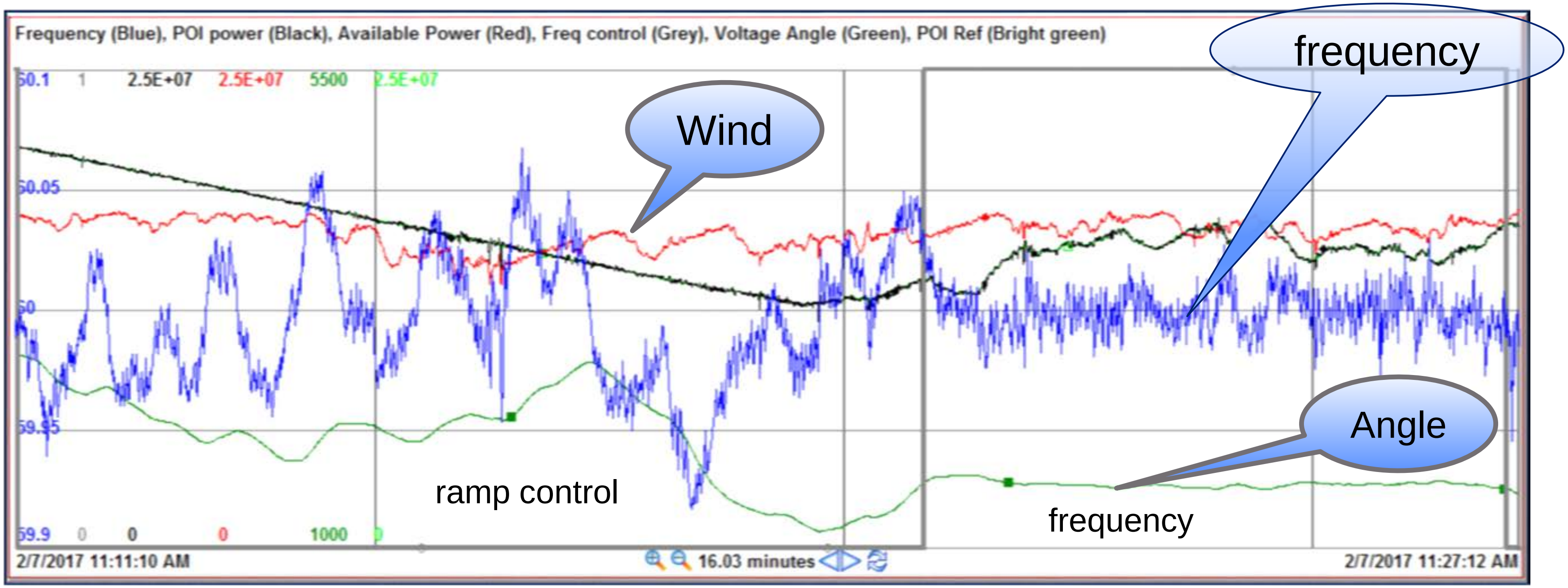








Demonstration: Power Ramp & Frequency Control



Multiple times lower frequency variation with frequency control