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
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:

\[
P = \frac{1}{2} \frac{V_1^2}{|Z_d(j\omega)|} \cos \{Z_d(j\omega)\} - \frac{1}{2} \frac{V_1 V_2}{|Z_d(j\omega)|} \cos(\{Z_d(j\omega)\} - \delta)
\]

\[
Q = \frac{1}{2} \frac{V_1^2}{|Z_d(j\omega)|} \sin \{Z_d(j\omega)\} - \frac{1}{2} \frac{V_1 V_2}{|Z_d(j\omega)|} \sin(\{Z_d(j\omega)\} - \delta)
\]

Real Power influences AC frequency dynamically:

\[
v_1 = V_1 e^{j\alpha_{v1}} \quad \text{where} \quad \delta = \alpha_{v2} - \alpha_{v1}
\]

\[
v_2 = V_2 e^{j(\alpha_{v1} + \delta)}
\]
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
Comparison without and with control

Real-time implementation using a WindFarm/BESS

Multiple times lower frequency variation with real-time synchrophasor control
Advanced Ramp and Frequency Control in Action at a Windfarm
Advanced Control Technology (ACT) Solution: Integrated Software Built Upon Proven Data Platform

- PMU data
  - Digital Relays
  - SCADA Sensors
- Digital data in
- Hi-speed control
  - Generation Resources
  - Controllable Loads
- Digital data out
- Implementing on Field Proven Hardware

Enabling Fast Field Implementation

- PXiSE ACT Solution
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
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

Demonstration: Reduced Config Time
PMU Based High Speed Controller
at a Major Windfarm with Battery Storage
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

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

Large oscillations (± 8 mHz)
large angle excursion

AFTER

Small oscillations (± 4 mHz)
Low angle excursions
State Charts Before and On Frequency Control

BEFORE  10 minute moving window  AFTER

Large oscillations  Small oscillations
large angle excursion (1500 degrees)  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**
Synchrophasor Data: Angle/Frequency

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

Intermittent Resources Impact the Grid

Possibility of relays trip & blackouts
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