Wide-area monitoring and Control

Platform and Applications

Mats Larsson
Principal Scientist
Corporate Research
ABB Switzerland
Agenda

- PSGuard – The ABB Wide Area Monitoring solution
- Wide-area Monitoring Applications
- Example Installations
- Future Perspectives: Wide-area Control and Protection
- Summary
Positioning WAMS towards SCADA & local protection

PSGuard bridges the gap between control and protection systems

SCADA / EMS
Actions initiated by long-term phenomena based on a rather static view

PSGuard
Coordinated measures based on dynamic view for monitoring, protection and control of power systems

Object Protection
Direct local actions by online status information

Dynamic
Reaction time
Static
ABB – Phasor Measurement Unit RES 521 – provides High Accuracy

- Submits time tagged phasors of AC voltages / currents up to 50/60 Hz with highest accuracy
- GPS -synchronized sampling in different substations
- TCP/IP protocol
- Synchrophasor data formats
- Analog Inputs, Binary Inputs, Binary Outputs
- Typical: 4 x 3 currents, 2 x 3 voltages
Example: 400 kV S/S
double line / double busbar

CT’s: high accuracy in small current values requires connection to measurement cores
PMU Based Wide-area Monitoring
PSGuard: Scaleable system structure

- PSG870
- PSG850
- PSG830

- Advanced network calculation
- Connectivity and topology
- Advanced control
- Control action recommendation
- State calculator
- Interface manager
- Frequency stability monitoring
- Power oscillation monitoring
- Voltage stability
- Line thermal monitoring
- Phase angle monitoring
- Event driven data archiving

- Protection & Control
- Monitoring
- Measurement
- Advanced monitoring
- Data storage and export
- Basic monitoring
- Connectivity
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Applications

- Advanced Visualization of Raw Measurements
  - Voltage and Phase Angle Profiles
  - Frequency and Islanding Display
  - Real-time power Swing Display
  - Contour mapping of Line Loading

- Monitoring & Prediction of Transmission Capacity (Wide Area Monitoring)
  - Corridor Voltage Stability Monitoring
  - Oscillation Detection
  - Thermal Line Monitoring

- Coordination of Actions in Emer Situations (Wide Area Control and Protection)
  - Coordinated Control of FACTS devices
Demo Advanced Visualization

- Line Monitoring
- Voltage/Phase Angle Display – contours
- Line loading overview display
- Real-time power oscillation monitoring
Objectives

- Assess distance to Point of Maximum Load ability, PML (in MWs)
- Stay on top section of PV Curve!
- Trigger emergency actions when Power Margin too small
Classical Solution – Undervoltage Load Shedding

- Critical voltage uncertain
- Does not give information about distance to PML
- Does not require PMU’s
Parameters of equivalent model calculated from PMU measurements

Twopole equivalents of load and generation side and fourpole equivalent of corridor

Rapid response < 10 Hz
Shape of PV curve can be determined on-line
Power margin analytically determined
Demo – Voltage Stability Monitoring
Key benefits: Voltage Stability Monitoring

- Provides power margin to the point of maximum loadability of transmission corridors w.r.t. voltage stability

- High accuracy by using PMU data (dynamic data)

- Fast reaction (Usage of real-time data)

- Can be used to trigger emergency actions

- For complex (meshed) network topologies other methods should be used
Line Thermal Monitoring

Grid A  ———  Grid B

Measurement of:
• Current
• Voltage
as Phasors (magnitude & phase) synchronized with the Global Positioning System (GPS)

PSGuard:
On-line display of average temperature of conductor
The changes in the average line temperature are estimated using only the electrical quantities measured by PMU.

- Increase of power transfer 950 MW to 1150 MW -> temperature increase from 46 degrees to 49 degrees in 30 min.
Key benefits: Line thermal monitoring

■ No sensors along the corridor necessary: Measurement sensors at begin and end of the line, where already existing communication infrastructure

■ Short measurement intervals for fast identification of critical temperature level (in the frame of some seconds)

■ Direct integration in SCADA EMS / Network control systems

■ Cost effective solution for investment and operation by using measurement equipment in substations

■ Can serve as indicator for preventive control, e.g., power flow control
Power oscillation monitoring

- Detection of power swings in a high voltage power system.
- Algorithm is fed with the selected voltage and current phasors.
- Detection of the various swing (power oscillation) modes.
- Quickly identifies the amplitude, frequency and the damping of swing modes.
Power oscillation monitoring

1. Modal Analysis
2. System Identification
3. Eigenvalue Spectrum
Scenario file – Oscmon.mat
Key benefits: Power oscillation monitoring

- Detection of oscillation
- Increased power transfer at defined security
- Early warning to avoid power system collapse
- Assessment of power system damping
- Oscillation monitoring as base for system planning/studies
WAM as a complement to SCADA / EMS

Increased operator awareness.

Wide Area Alarms and Events in Network Manager.
PSGuard integrated with network management
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PSGuard World Map
PSGuard was the first commercial Wide-area Measurement system on the market
Still the only one with advanced monitoring applications

- HEP Croatia, 2 PMUs, extension foreseen
- ETRANS Switzerland, 4 PMUs, extension foreseen
- Tennessee Valley Authority (TVA), USA, 16 PMUs
- HTSO Greece, 1 PMU
- CFE/CENACE Mexico, 2 x 2 PMUs
- Statnett, Norway, 3 PMUs

Discussions ongoing with a number of other customers.
October 10th 2004 9:34
Zagreb / Croatia
System Load: 223 GW
System Load: 21 GW

UCTE Power System Reunification
PSGuard References: UCTE grids reconnection

Voltage Phase Angle Difference (Mettlen - Ag. Stefanos)

- Sandorfalva - Subotica
- Ernestinovo - Mladost
- Rosiori - Mukacevo
- Trebinje - Podgorica
- Arad - Sandorfalva

October 10th 2004
PSGuard project at EGAT, Thailand: Power oscillation monitoring
PSGuard project at EGAT, Thailand: Power oscillation monitoring
PSGuard project at EGAT, Thailand: Power oscillation monitoring

230 kV

System Monitoring Center (Master)

Interface Manager (SCADA / EMS)

System Monitoring Center (Client)

230 kV line or cable

230 kV bay with measurement of current phasor (3~)

230 kV bay with measurement of voltage phasor (3~)

Legend

--- **Communication-link**

**POM**

Application (bold)

**PMU**

Basic Monitoring (BM) for all PMU measurements

Legend

--- **Power Oscillation Monitoring (POM)**

--- **System Monitoring Center (Master)**

--- **System Monitoring Center (Client)**

--- **Interface Manager (SCADA / EMS)**
PSGuard project at EGAT, Thailand: Power Oscillation Monitoring
Power oscillation monitoring: Application output example EGAT

- Identification and values of the most dominant frequencies
- **Amplitude and Damping** of dominant oscillation modes
- Basis for feedback control using existing FACTS / SVC installations
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Wide Area Protection and Control

Defence Actions Against Collapse

- Islanding
- Load Adaptation
- Generation Adaptation
- Tap Changer Blocking
- FACTS

Power Flow Control

Stability Information

EMS

Wide Area Monitoring Applications

System Monitoring Center

Voltage / Frequency monitoring

PMU

Load

Adaptation

Automatic Generation Control

Tap Changer Control

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Complete Network Observability

- Linear state- and topology estimation

- State-estimation can be done several times per second

- Delivers
  - Voltage and currents
  - Power Extraction/Injections at each bus
  - Topology and islanding data
  - Bus admittance matrix

- Can serve as a platform for on-line optimization and advanced control schemes
PMU Network Coverage Requirements

- No redundancy and no detection of topology => ~20% of buses
- No redundancy and detection of topology => ~50%
- Redundancy = 1 and no detection of topology => ~50%
- Redundancy = 1 and detection of topology => 80% - 90%
- Redundancy=2 usually not possible without duplication of PMUs in same substation
Some examples and literature references

- **Co-ordinated Emergency Voltage Control**

- **Emergency Frequency Control**

- **Optimal FACTS Coordination and Transfer Capability Enhancement**
Voltage Instability

- Transfer of power over long distances
- Disturbances triggers move into unstable region
- Usually a blackout occurs if no emergency actions are taken

- Fresh examples
  - Swedish blackout 2003 (and 1983 ...)
  - Northeastern US blackout 2003
Emergency Voltage Control

Typical Scenario:
- A disturbance triggers instability

**AIM:**
- Apply corrective control in time (~30 s)
- Minimize load shedding!
Model Predictive Control Approach

- Optimize a performance index based on *predicted* trajectories over a prediction interval
Selecting the Optimal Control

- Combinatorial optimization problem
  
  \[
  \text{minimize} \quad J(t, x^*, u^+)
  \]
  
  \[
  \text{subject to} \quad u^+ \in S(u^-)
  \]
  
  \[
  J(x^*, u^+) = \int_{t^*}^{t_{p+1}} \tilde{y}^T Q\tilde{y} + \tilde{u}^T R\tilde{u} + P \, dt
  \]
  
  \[
  \tilde{y}(t, x^*, u^+) = y(t, x^*, u^+) - y_{ref}
  \]
  
  \[
  \tilde{u} = u^+ - u^-
  \]
  
  \[
  P = P(t, x^*, u^+)
  \]

- Output constraints made ‘soft’ and included in penalty term

- Dissimilar controls are given different weights
  
  - e.g., load shedding controls are very expensive
  
  - Proper selection of weights aims to insure
    
    - that use of load shedding is minimized
    
    - that constraints are enforced
Solving the Optimization Problem

- Combinatorial problem

- Use of approximate predictors
  - Various non-linear and linearized predictors (Larsson et. al)
  - Trajectory sensitivities (Hiskens, Zima)
  - Mixed-logical Dynamic Systems (Geyer, Beccutti et.al)

- Efficient solution techniques
  - Search tree reduction (Larsson et.al.)
  - Lagrangian decomposition (Beccutti)
  - Transformation to Linear Program (Zima)

- These techniques can give near-optimal solutions in predictable time
Example Scenario – Nordic 32 CIGRE Test System

- 52 Discrete control inputs
  - 19 Generator voltage setpoints (8 steps each)
  - 11 Tap changers (16 steps each)
  - 22 Load shedding (4 steps each)
    (~ $10^{43}$ combinations)

- Control Objectives
  - Stabilize load voltages at 0.9 p.u. or higher
  - Use load shedding controls minimally
  - Do not overload generators
  - Reaction time ~ 30 seconds

- 10 Controlled outputs
  - Load voltages

- 67 Constrained outputs
  - All voltages, generator currents
Generator Trip Example

- **At 10 s – Gen 4062 Trips**
  - Lost generation compensated by hydro units in the north
  - Increased losses in transmission corridor, lower voltage in southern region
  - Generators in the south increase reactive power production

- **At 30 s – Gen 1043 and 4042 at limit**
  - Voltage support lost in middle and southern parts

- **At 50+ s – Tap changers restore load**
  - Further voltage decrease
  - Collapse at 180 s
Generator Trip – Model Predictive Control

Time Control

<table>
<thead>
<tr>
<th>Time</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>tap T4041-41 +1 step</td>
</tr>
<tr>
<td>30</td>
<td>tap T4042-42 +1 step</td>
</tr>
<tr>
<td>30</td>
<td>tap T4061-61 +1 step</td>
</tr>
<tr>
<td>30</td>
<td>tap T4062-62 +1 step</td>
</tr>
<tr>
<td>30</td>
<td>Gen 1043 s.p. -3 steps</td>
</tr>
<tr>
<td>30</td>
<td>Gen 2032 s.p. +1 step</td>
</tr>
<tr>
<td>30</td>
<td>Gen 4021 s.p. +1 step</td>
</tr>
<tr>
<td>30</td>
<td>Gen 4041 s.p. +1 step</td>
</tr>
<tr>
<td>30</td>
<td>Gen 4042 s.p. -2 steps</td>
</tr>
<tr>
<td>30</td>
<td>Gen 4047 s.p. +2 steps</td>
</tr>
<tr>
<td>60</td>
<td>tap T4041-41 +1 step</td>
</tr>
<tr>
<td>60</td>
<td>tap T4042-42 +1 step</td>
</tr>
<tr>
<td>60</td>
<td>tap T4047-47 -1 step</td>
</tr>
<tr>
<td>60</td>
<td>tap T4061-61 +1 step</td>
</tr>
<tr>
<td>60</td>
<td>Gen 2032 s.p. +1 step</td>
</tr>
<tr>
<td>60</td>
<td>Gen 4021 s.p. +1 step</td>
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<tr>
<td>60</td>
<td>Gen 4041 s.p. +1 step</td>
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<td>60</td>
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<td>90</td>
<td>Gen 4021 s.p. +1 step</td>
</tr>
<tr>
<td>120</td>
<td>Gen 4041 s.p. +1 step</td>
</tr>
<tr>
<td>150</td>
<td>Gen 2032 s.p. +1 step</td>
</tr>
<tr>
<td>300</td>
<td>tap T4047-47 -1 step</td>
</tr>
<tr>
<td>330</td>
<td>tap T4046-46 -1 step</td>
</tr>
</tbody>
</table>
Benefits of Coordinated Emergency Voltage Control

- Optimal Coordination of
  - Load Shedding
  - Voltage and Power Flow Controller Setpoints
  - Tap locking

Benefits
- Tighter voltage control during disturbances
- 50% Less load shedding for scheme which includes voltage controllers
Summary

- Successful application to Emergency Voltage Control

- Good but **not** guaranteed optimal control

- Typically automatic local protection is still in place

- Predictive and search methods can be combined to systematically control "complex systems"
  - Simplified predictors (application dependent)
  - Search enhancements (application independent)
Summary

Early warning system against instabilities leading to blackouts

Benefits:

- Detects potential instabilities due to abnormal voltage-, frequency-, thermal line-conditions or power swings
- Predicts critical events and focus operator attention
- Enables to start effective countermeasures in time
- Stop cascading domino effects
- Avoid spreading of disturbances
Conclusions

WAM-System benefits

- Increased operator awareness
- Transient stability monitoring
- Increased security of power supply
- Enhanced utilization of assets
PSGuard is ready to protect your transmission system capacity

Contact us for further details:

wide.area@ch.abb.com