PMU-based Power Plant Operation Monitoring and Innovative PMU Implementation

NASPI Work Group meeting
March 22-23, 2017
Gaithersburg, MD

Pavel Kovalenko
Alexey Danilin
Viktor Litvinov
Design, Develop and Deploy digital transformation solutions for InterConnected World.

- Power system and industrial automation
- Business Analytics, Data Warehousing and Big Data
- Information Security and Compliance
GRT Sample Clients
PowerLink - APDC

- Highly customizable scalable platform for building WAMS using multi stream technology
- Distributed historian with very fast search and data export capabilities
- High performance (sampling rate of 50-200 measurements per second for one channel)
- Advanced visualization features
- Implemented in a very large geographically distributed system spanning more than 2000 miles with very low latency
- Advanced PDC
Phasor measurements data applications

Power system applications

Wide-area applications
- Electromechanical oscillations monitoring and analysis
- Synchronous machines participation in the oscillations damping assessment
- System controllers operation monitoring system
- Novel PMU/PDC development
- Centralized automatic emergency control system

Local applications (power plant, substation etc.)
- Power plant operation monitoring system
- Equipment monitoring and diagnostics system
- Basic emergency control alarm signals

© 2017 GRT Corporation
Power plant operation monitoring system

GRT APDC-based integrated solution
Low-frequency oscillations real-life cases

- 390 MW
- 8 minutes
- 0.6 Hz
Low-frequency oscillations real-life cases
Low-frequency oscillations real-life cases
Low-frequency oscillations real-life cases
Key risks for power systems and power plants:
- Reduced power plants and generators output
- Possible equipment damage
- Asynchronous operation conditions risk

Possible ways of mitigation:
- Timely LFO detection
- Quick localization
- Early warning for the operators
- Automatic control actions
Online wide-area LFO monitoring visualization
Detailed retrospective analysis

<table>
<thead>
<tr>
<th>Object</th>
<th>Type</th>
<th>Start time</th>
<th>Duration (s)</th>
<th>Frequency</th>
<th>Magnitude</th>
<th>DR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen1</td>
<td>Active Power</td>
<td>13.03.2015 14:30:11.180</td>
<td>6.28</td>
<td>0.96</td>
<td>9.239 MW</td>
<td>9.1%</td>
</tr>
<tr>
<td>Gen2</td>
<td>Active Power</td>
<td>13.03.2015 14:30:11.640</td>
<td>2.96</td>
<td>0.99</td>
<td>28.4 MW</td>
<td>15.0%</td>
</tr>
<tr>
<td>Gen3</td>
<td>Active Power</td>
<td>13.03.2015 14:30:11.300</td>
<td>4.04</td>
<td>1.14</td>
<td>14.8 MW</td>
<td>27.8%</td>
</tr>
<tr>
<td>Gen4</td>
<td>Active Power</td>
<td>13.03.2015 14:30:11.320</td>
<td>3.2</td>
<td>1.16</td>
<td>22.1 MW</td>
<td>12.4%</td>
</tr>
</tbody>
</table>

Local oscillations, frequency 0.98

| Gen4   | Active Power    | 13.03.2015 14:30:00.020 | 48           | 0.59      | 36.9 MW   | -2.1%|
| Gen3   | Active Power    | 13.03.2015 14:30:01.020 | 47           | 0.60      | 44.3 MW   | -1.9%|
| Gen1   | Active Power    | 13.03.2015 14:30:02.020 | 46           | 0.59      | 28.8 MW   | -2.0%|
| Gen2   | Active Power    | 13.03.2015 14:30:17.540 | 30.48        | 0.52      | 26.8 MW   | -2.4%|

Interarea oscillations, frequency 0.59

| Gen3   | Active Power    | 13.03.2015 14:30:01.100 | 19.92        | 1.04      | 4.329 MW  | 0.9% |
| Gen4   | Active Power    | 13.03.2015 14:30:01.300 | 18.72        | 0.96      | 4.732 MW  | 1.0% |

Local oscillations, frequency 1.00

| Gen1   | Active Power    | 13.03.2015 14:30:01.160 | 20.86        | 0.07      | 5.666 MW  | 2.0% |
| Gen2   | Active Power    | 13.03.2015 14:30:01.180 | 20.84        | 0.05      | 7.123 MW  | 1.1% |
Electromechanical oscillations monitoring software: geographical visualization

Geographical representation of the in-phase and antiphase objects oscillations
Power plant operation monitoring system: low-frequency oscillations

<table>
<thead>
<tr>
<th>Generators</th>
<th>A, MW</th>
<th>D, %</th>
<th>F, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gen 1</td>
<td>2.5</td>
<td>8.0</td>
<td>0.27</td>
</tr>
<tr>
<td>Gen 2</td>
<td>7.4</td>
<td>4.5</td>
<td>0.27</td>
</tr>
<tr>
<td>Gen 3</td>
<td>4.3</td>
<td>6.9</td>
<td>0.26</td>
</tr>
<tr>
<td>Gen 4</td>
<td>3.4</td>
<td>7.2</td>
<td>0.28</td>
</tr>
<tr>
<td>Gen 5</td>
<td>4.3</td>
<td>8.0</td>
<td>0.26</td>
</tr>
<tr>
<td>Gen 6</td>
<td>9.6</td>
<td>3.5</td>
<td>0.27</td>
</tr>
<tr>
<td>Gen 7</td>
<td>5.5</td>
<td>5.5</td>
<td>0.28</td>
</tr>
<tr>
<td>Gen 8</td>
<td>5.2</td>
<td>8.2</td>
<td>0.27</td>
</tr>
<tr>
<td>Line 1</td>
<td>47</td>
<td>4.7</td>
<td>0.27</td>
</tr>
<tr>
<td>Line 2</td>
<td>37</td>
<td>4.8</td>
<td>0.27</td>
</tr>
<tr>
<td>Line 3</td>
<td>32.0</td>
<td>7.3</td>
<td>0.27</td>
</tr>
<tr>
<td>Line 4</td>
<td>27.0</td>
<td>7.8</td>
<td>0.27</td>
</tr>
<tr>
<td>Line 5</td>
<td>29.0</td>
<td>7.2</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Power plant low-frequency oscillations monitoring subsystem
Unbalanced operation case
Unbalanced operation case
Unbalanced operation real-life case

70 minutes
Key risks for power systems and power plants:

- Increased power losses
- Rotor overheating
- Mechanical vibrations
- Generator damage
  - Isolation abrasion and deterioration
  - Windings deformation and/or displacement

Possible ways of mitigation:

- Timely unbalanced operation detection
- Quick localization
- Early warning for operators
- Automatic control actions
Power plant operation monitoring system: unbalanced conditions

Generator 1

\[ I_1 = 8990 \, A \]
\[ I_2 = 10 \, A \]
\[ \frac{I_2}{I_1} = 0.1 \% \]

\[ U_{AB} = 15.71 \, kV \]
\[ U_{CA} = 15.73 \, kV \]
\[ U_{BC} = 15.72 \, kV \]
\[ I_0 = 9.8 \, A \]

<table>
<thead>
<tr>
<th>G1</th>
<th>G2</th>
<th>G3</th>
<th>G4</th>
<th>G5</th>
<th>G6</th>
<th>G7</th>
</tr>
</thead>
<tbody>
<tr>
<td>U_1</td>
<td>15.73</td>
<td>15.73</td>
<td>15.73</td>
<td>15.73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U_2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U_0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I_1</td>
<td>8990</td>
<td>8990</td>
<td>8990</td>
<td>8990</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I_2</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I_0</td>
<td>9.8</td>
<td>9.8</td>
<td>9.8</td>
<td>9.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I_2/I_1, %</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>G8</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
<th>L5</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.73</td>
<td>331.3</td>
<td>331.3</td>
<td>331.3</td>
<td>331.3</td>
<td>331.3</td>
</tr>
<tr>
<td>0.3</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
<td>3.3</td>
</tr>
<tr>
<td>0.1</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
<td>3.1</td>
</tr>
<tr>
<td>8990</td>
<td>450</td>
<td>450</td>
<td>450</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>10</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>9.8</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>0.1</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
</tbody>
</table>

© 2017 GRT Corporation
Power plant operation monitoring system: unbalanced conditions

Power plant 1

P = 1155 MW
Q = 550 MVar
F = 49.97 Hz
Δ = 9.9°

Unbalanced conditions alarm!

Predicted threshold violation:
Gen-1, Gen-2, Gen-3

Cause:
Line-1 Open phase
Supplementary equipment monitoring/diagnostics system for

- **Circuit breakers**
  - Phases unsynchronized switching – basic equipment damage
    - Mechanical drive wear
    - Contacts failure etc.

- **Instrument transformers**
  - Significant measurement errors – protection and automation misoperation, metering errors
    - Connection failure
    - Windings failure
    - Secondary circuit isolation deterioration
    - Capacitor aging etc.
### APDC-based WAMS in Eastern Europe Power System

![Map of Eastern Europe showing PMU objects](image)

- **Planned PMU object**
- **Offline PMU object**
- **Offline/online PMU object**
- **Online PMU object**

<table>
<thead>
<tr>
<th>PMUs</th>
<th>Objects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PMUs</strong></td>
<td><strong>Total</strong></td>
</tr>
<tr>
<td>Total</td>
<td>544</td>
</tr>
</tbody>
</table>
24 object APDC installations, 10 control center installations
3-month raw data storage
Experimental base

All applications under development are validated involving Real-time digital simulator (RTDS) system and the large Physical electrodynamic simulator:

- quality assessment
- performance tests
- IEEE C37.118 and IEC 61850 compliance tests
- optimization
Physical electrodynamic simulator

- 8 simulators for DC transmission lines, converter substations
- 700 Pi-cells for transmission lines simulation and 150 power transformer simulators
- 80 synchronous machines with various power ratings
- 160 electric load nodes formed by the combination of asynchronous-motor, shunt and converter loads
- FACTS devices, controlled shunt reactors, static VAR compensators, series capacitor banks
Direct measurements of the synchronous generator load angle

Secondary data-stamp time source capability

Excitation parameters and rotor angular position measurement subsystem
Instantaneous state parameters measurements for the determination of dynamic properties.

Current source signal and amplitude

The novel PMU
Generalized damping component calculation

\[ J \cdot \omega_0 \frac{d\omega}{dt} = P_T - P_e. \]

\[ \tau_j = \frac{J \cdot \omega_0^2}{S_H} \]

Electrical measurements → Defining the damping component → Adjusting the system regulators and emergency automatics
Real Synchronous Generator

Rated value: 6.1 s

Derived value (average): 5.8
Provides

- Studies of the power systems dynamic properties
- Verification of the computational dynamic models
- Quick emergencies detection
- Power system conditions control against the angle
- Monitoring the synchronous generator load angle and its trend to assess the static and dynamic stability margins
- Determining the synchronous generators natural oscillations parameters in order to detect the resonance phenomena and prevent the machine self-swing
- Assessing the effectiveness of automatic control systems with automatic adjustment and faults self-recovery
- Developing a new generation control systems based on the real-time computational models variations based on the rules of FACTS control and dynamic properties of power systems
- Additional possibilities for generators monitoring (the air gap unevenness detection under the magnetic poles and the magnetic conductor asymmetry; the stator winding electric asymmetry detection, the rotor damper winding or field winding defects)
Power system equipment adaptive models

Synchronous generator

Transmission line

Power system model

SG model parameters evaluation

Line model

© 2017 GRT Corporation
Conclusion

- PMU-based power plant monitoring system proposed allows:
  - Preventing equipment physical damage
  - Improving operation efficiency
  - Increasing economic benefits

- Innovative PMU designed provides:
  - Deeper insight into power system dynamic properties
  - Fast emergency detection
  - Possible development of equipment and power system adaptive models
Q&A

www.grtcorp.com

Thank You
GRT Corporation

© 2017 GRT Corporation
Phasor measurements data applications

**Target:** Improving the reliability and stability of a power system through developing and advancing the methods of dispatch and automatic control.
Electromechanical oscillations monitoring software
Based on the automatic WAMS data acquisition system

- Data pre-processing
- Express-analysis
- Low-frequency oscillation identification
- Modal analysis
  - Dominant modes territorial incidence
  - Permanent modes identification
  - Grading and grouping
  - Assessment of the SG participation
  - LFO severity assessment
  - ALARM

Database, information visualization

© 2017 GRT Corporation
Low-frequency oscillations monitoring implementation examples

- The dominant modes of the Eastern Europe Power System were determined based on analysis of 2013-2014 years daily data.
- Local and interarea dominant modes were identified and the normal conditions low-frequency oscillations parameters were defined.
- Power system facilities with undamped modes within 0.2÷2.1 Hz frequencies range were identified.
- Low-frequency oscillations were identified for bulk power transit lines of up to tens MW magnitude.
- Statistical analysis was accomplished determining the stability level for the power system.
- The analysis was fulfilled for the forced low-frequency oscillations reaching the power system stability margin.
No details sneak under the radar with full multi-display configurations support
APDC visualization means

Any platform, any device
The primary objective is enhancing the stability of the generating equipment synchronous operation in the power system:

- adjustment of the automatic excitation control settings
- troubleshooting the synchronous generator excitation systems

The typical faults/misoperation currently detected:

- Relay excitation forcing under emergencies in the power system
- Synchronous generator rotor oscillation damping at normal, repair and post-fault power system conditions
- Support for a stable synchronous generator operation at under-excitation (minimal excitation limiter) and over-excitation (maximal rotor current limiter) conditions

Factory acceptance test phase now
Unbalanced operation may lead to:

- Increased power losses
- Rotor overheating
- Mechanical vibrations
- Voltage asymmetry

![Generator damage]

- **Generator damage**
  - Isolation abrasion and deterioration
  - Windings deformation and/or displacement

- Poor power quality