Design Requirements of Wide-Area Damping Systems
—Using Empirical Data from a Utility IP Network

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Kun Zhu — in brief

2013  Business consultant

2013  PhD, KTH- the Royal Institute of Technology, Sweden

2011  Intern, ABB CRC, USA

2008  Intern, Svenska Kraftnät (Swedish National Grid)
Outline

• Wide-Area Monitoring and Control Systems
• PMU network at Svenska Kraftnät
• Research methods
• Key findings
• Future work
Transmission level challenges

Increased market coupling leads to larger variations in power flow

Inherent variability of supply and power flow increases stress to the system

Large amount of intermittent generations that are far from consumption centers

Source: Tintazul, Maix, JMMesserly

Source: Gunnar Asplund

http://www.windbyte.co.uk/windpower.html
Wide-Area Monitoring and Control (WAMC) systems

In a nutshell:
Synchronized real-time data available through a high performance communication system to provide system-wide early warning and control.

Central applications

Local applications using remote measurement(s)
Wide-Area Monitoring and Control (WAMC) systems

Central applications

State Estimation
Augmented with PMUs
PMU only SE

Wide Area Sit. Awareness
Visualisation
Early warning

Voltage Stability Analysis
Post-fault analysis

Local applications

FACTS/HVDC device control
Oscillation damping
Voltage control

Special Protection Schemes
Anomaly detection
Intelligent Load shedding

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Dependency of WAMC systems on the underlying ICT infrastructure

- WAMC systems (of all types) are dependent on the non-functional characteristics of the underlying Information & Communication Technology (ICT) systems.

- There are two ways to design WAMC system
  - Tailor the ICT system to meet the requirements of the WAMC applications.
  - Design WAMC application based on the capabilities of the underlying ICT infrastructure.

- The purpose of this study is to elicitate design requirements for Wide-Area damping controllers based on empirical data captured from a state-of-the-art utility network.

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PMU network at Svenska Kraftnnät

- PMU frame rate: 50 Hz
- Protocols:
  - Routing protocol: OSPF
  - Transport layer protocol: TCP
- Bandwidth:
  - Substation/Control center LAN: 100 Mbps
  - Core network: 34Mbps
  - Link between Core and Substation: 2Mbps
- Background traffic:
  - RTU
  - VoIP
  - Video
- Quality of Service-WFQ
  - Priority class: RTU=PMU>VoIP>Video
PMU network at Svenska Kraftnät

• Network size:
  – 11 PMU substations
  – 200 RTU substations

The configuration of this utility PMU network is compliant with the common practices documented in “Communication Architecture for IP-based Substation Applications”, Cigre D2.28, Report 507, Aug, 2012.

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Data sets

- Delays are calculated by comparing the time-stamp of the arriving PMU data frame with the instant in time when it is received by OpenPDC.

- Average and maximum delays from eight PMUs are collected in a time window of ten seconds
  - between Nov 2012 and Jan 2013

- PMU data frame loss rates
  - data frame losses due to PDC data aggregation are outside the scope of this work
PMU maximum communication delays

- Delay anomalies
  - do not obey the physical laws
- Delay outliers
  - statistically insignificant

<table>
<thead>
<tr>
<th>PMU</th>
<th>Observation</th>
<th>Min/Max</th>
<th>$\mu/\sigma$</th>
<th>Anomaly</th>
<th>Outlier ($\geq 450$)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>467,768</td>
<td>-2/1266</td>
<td>81.16/93.90</td>
<td>0.0344%</td>
<td>0.0735%</td>
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<td>2</td>
<td>467,761</td>
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<td>72.27/94.81</td>
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<td>0.0708%</td>
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<td>3</td>
<td>467,784</td>
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<td>73.66/95.64</td>
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<td>0.0730%</td>
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<td>0.0942%</td>
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<tr>
<td>5</td>
<td>526,429</td>
<td>-1/5587</td>
<td>72.28/99.21</td>
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<td>0.0933%</td>
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<tr>
<td>6</td>
<td>468,032</td>
<td>-1/2611</td>
<td>77.54/95.56</td>
<td>0.0632%</td>
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<td>7</td>
<td>526,497</td>
<td>-2/2098</td>
<td>72.38/91.96</td>
<td>0.1624%</td>
<td>0.2101%</td>
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<tr>
<td>8</td>
<td>526,493</td>
<td>-1/2773</td>
<td>71.75/91.82</td>
<td>0.0821%</td>
<td>0.1284%</td>
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</tbody>
</table>
PMU data frame loss rates

<table>
<thead>
<tr>
<th>PMU</th>
<th>Observation</th>
<th>Anomaly</th>
<th>Frame loss rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>466,345</td>
<td>0.1568%</td>
<td>0.0012%</td>
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<tr>
<td>2</td>
<td>462,134</td>
<td>0.0033%</td>
<td>0.0007%</td>
</tr>
<tr>
<td>3</td>
<td>465,528</td>
<td>0.0000%</td>
<td>0.0012%</td>
</tr>
<tr>
<td>4</td>
<td>467,087</td>
<td>0.0037%</td>
<td>0.0012%</td>
</tr>
<tr>
<td>5</td>
<td>525,235</td>
<td>0.0065%</td>
<td>0.0009%</td>
</tr>
<tr>
<td>6</td>
<td>465,534</td>
<td>0.0000%</td>
<td>0.0005%</td>
</tr>
<tr>
<td>7</td>
<td>523,142</td>
<td>0.0000%</td>
<td>0.0007%</td>
</tr>
<tr>
<td>8</td>
<td>523,392</td>
<td>0.0013%</td>
<td>0.0009%</td>
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</tbody>
</table>

• Comparable to the results reported in the article below

• Packet loss rate reported over a long period of time will return optimistic results.
  – The maximum packet loss reached 14% (in a time window of 10 seconds) in our study

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Augmented delays

- Data frame loss can be treated as communications delays.
- By applying a liberal assumption that a maximum delay always appears at the first packet available after consecutive packet loss, the augmented delay can be approximated as the sum of maximum delay and delay induced by packet loss.
Goodness of fit study

• A number of potential distributions evaluated using Akaike Information Criterium
  – Normal, Log-normal, Exponential, Poisson, Weibull, Gamma, Generalised Pareto and Tri-modal

\[ AIC = -2 \ln(L) + 2k \]

\( L \) = maximized likelihood function
\( k \) = number of parameters.

<table>
<thead>
<tr>
<th>PMU</th>
<th>EXP</th>
<th>LN</th>
<th>WBL</th>
<th>GAM</th>
<th>PAR</th>
<th>PO</th>
<th>N</th>
<th>Tri-modal</th>
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<td>1</td>
<td>5.044</td>
<td>4.950</td>
<td>5.040</td>
<td>5.044</td>
<td>5.024</td>
<td>5.152</td>
<td>5.373</td>
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<td>4</td>
<td>5.013</td>
<td>4.819</td>
<td>5.207</td>
<td>5.165</td>
<td>4.913</td>
<td>4.996</td>
<td>5.233</td>
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<td>5.298</td>
<td>5.467</td>
<td>5.511</td>
<td>5.501</td>
<td>5.464</td>
<td>5.612</td>
<td>5.197</td>
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<tr>
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<td>5.106</td>
<td>4.867</td>
<td>4.892</td>
<td>5.087</td>
<td>4.955</td>
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<tr>
<td>7</td>
<td>5.483</td>
<td>5.321</td>
<td>5.521</td>
<td>5.433</td>
<td>5.672</td>
<td>5.700</td>
<td>5.723</td>
<td>5.237</td>
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<tr>
<td>8</td>
<td>5.537</td>
<td>5.335</td>
<td>5.430</td>
<td>5.844</td>
<td>5.519</td>
<td>5.411</td>
<td>5.699</td>
<td>5.236</td>
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</table>
Quantile-Quantile plot
Design requirements

• Give the reliability requirement of the damping control function, $R_c$, and the probability of the identified augmented delay distribution, the compensation limit, $T_{arg}$ can be determined.

$$P(x \ll T_{arg}) = R_c$$
Findings

• Tri-modal distribution fits best among all the candidates to model augmented delay of PMU data.

• The performance of three delay robust damping control schemes tuned against $T_{arg}$ are validated against the empirical delays
  – Gain scheduling (GSPOD)
  – Generalized predictive control (GPC)
  – Adaptive compensation (APPOD)

• It is necessary to synchronize the PDC with the PMUs in a precise manner. Network Time Protocol (NTP) may not be sufficient.
Future work

• For Wide-Area damping controllers, time delay corresponds to phase shift input, if known, it can be compensated.

• PMU communication delays over wide-area communication networks are usually stochastic. Therefore, the damping controller is required to adapt to the detected delays.

• However, as the delay compensation strategies are derived by solving nonlinear optimization problem or high-order matrix equations, implementation of such controllers can be complicated.

• If the delays are fixed, then the design and implementation of the damping controller can be simplified. This has not been covered by the PDC standard C37.224.

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• By creating model of the probability distribution of the PMU delays, we can estimate optimal timeout for the PDC, and thereby smooth the delay.

1. Collect PMU communication delays in a memory
2. Estimate PMU communication delay distribution based on the accumulated historical information
3. Determine the PDC wait time by referring the desired packet loss rate to the identified statistical distribution model of the PMU communication delays
4. Buffer PMU data frames until the calculated PDC wait time passes
5. Erase the memory and repeat the step 1.

K, Zhu, S, Rahimi, L. Nordström, Z, Boming "Configuration of Phasor Data Concentrators as Adaptive Delay Buffers in Wide-Area Damping Control System" In review (2nd revision) for IEEE Transactions