Improved Grid Resiliency through Interactive System Control (6.3)

Vijay Vittal
Arizona State University
(vijay.vittal@asu.edu)
Context

• With growing complexity of power grid interconnections, power systems may become increasingly vulnerable to low frequency oscillations, especially inter-area oscillations.

• Increased penetration of renewable resources could result in reduced damping of inter-area modes of oscillations and thus impact power system performance.

• In such situations, the use of wide-area signals could be beneficial in damping inter-area oscillations. The ability and potential to use wide-area signals for control purposes has increased due to a significant investment made in U.S. in deploying PMUs.
Research Objective

- In order to transmit wide-area signals for use in controls, fast and reliable communication systems are required. However, communication systems are vulnerable to disruptions as a result of which the reliability of the power system could be jeopardized.

- Given this background the motivation for this work is to build resiliency either in the physical system or in the communication system to respond to failures in the cyber communication network when wide-area signals are used as the control input.
Importance for the future grid

• Addresses a critical issue related to engineering resilient cyber-physical systems
• Provides an effective means to use a hierarchical set of synchronized measurements for corrective control and increase grid resiliency.
• Leverages large investment in installing PMUs across the nation
Problem formulation

- The approach formulated is depicted by implementing in simulation the proposed solution for a specific control application in a realistic test system.
- This test system is an IEEE benchmark system.
- The analytical work to develop the control methodology is done.
- The control approach is implemented in a commercial transient stability analysis package for testing the developed approach.
Study system

• In order to formulate the problem of establishing resilient control, the IEEE 50-generator system is considered to be the study system. The resiliency is achieved by robustly designing a supplementary damping control (SDC) associated with a SVC installed in the system.
Study system

Fig. 1 One-line diagram of the IEEE 50-machine system

SVC is selected to locate at Bus #44, The rating of the SVC is $Q_C = Q_L = 400$ MVar.

Operating point change in: 
$[2 \times 1300 – 2 \times 1800]$ MW by G93 and G110
Study system

Table I. Two inter-area modes of the open-loop 50-machine system

<table>
<thead>
<tr>
<th>Operation Level: G93, G110 (MW)</th>
<th>Mode 1</th>
<th>Mode 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2×1300</td>
<td>3.53% @ 0.482 Hz</td>
<td>9.13% @ 0.292 Hz</td>
</tr>
<tr>
<td>2×1350</td>
<td>3.57% @ 0.481 Hz</td>
<td>8.68% @ 0.289 Hz</td>
</tr>
<tr>
<td>2×1400</td>
<td>3.55% @ 0.481 Hz</td>
<td>8.10% @ 0.286 Hz</td>
</tr>
<tr>
<td>2×1450</td>
<td>3.53% @ 0.482 Hz</td>
<td>7.38% @ 0.283 Hz</td>
</tr>
<tr>
<td>2×1500</td>
<td>3.59% @ 0.480 Hz</td>
<td>6.47% @ 0.279 Hz</td>
</tr>
<tr>
<td>2×1600</td>
<td>3.65% @ 0.479 Hz</td>
<td>4.14% @ 0.273 Hz</td>
</tr>
<tr>
<td>2×1700</td>
<td>3.70% @ 0.479 Hz</td>
<td>1.16% @ 0.266 Hz</td>
</tr>
<tr>
<td>2×1800</td>
<td>3.77% @ 0.478 Hz</td>
<td>-3.00% @ 0.261 Hz</td>
</tr>
</tbody>
</table>

Since Mode 2 has an decreasing damping ratio with the increase of generation, the supplementary damping control is primarily provided to damp this mode to further extend the stability limit in addition to PSS.
Design of controls resilient to communication failure

Method I: Build resiliency in the physical grid controls directly

Method II: Build resiliency in the cyber system
Method I: resilient TISO controller

The associated transfer functions are

\[ T_{zd}^{(2)} = \frac{G_1}{1 + G_1'K_1 + G_2'K_2} = \frac{G_1}{1 + (G_1D)K_1 + G_2K_2} \]

\[ T_{u_2d}^{(2)} = \frac{G_2K_2}{1 + G_1'K_1 + G_2'K_2} = \frac{G_2K_2}{1 + (G_1D)K_1 + G_2K_2} \]

**Fig. 2** Setup of SITO feedback system and TISO controller

\( G' \) is the open loop system with the transmission delay integrated based on Padé approximation

\[ G' = G_1D, \quad D = \left( \frac{1}{12} T_d^2 s^2 - \frac{1}{2} T_d s + 1 \right) \left( \frac{1}{12} T_d^2 s^2 + \frac{1}{2} T_d s + 1 \right) \]

When wide area signal \( z \) is lost due to a communication failure, TISO controller then becomes a SISO controller since \( u_1 = 0 \).

\[ T_{zd}^{(1)} = \frac{G_1}{1 + G_2K_2}, \quad T_{u_2d}^{(1)} = \frac{G_2K_2}{1 + G_2K_2} \]

In order to improve system damping with both wide area and local signal while maintain the ability to stabilize the system with only the local signal, requirements as below should be satisfied.

\[ \|T_{zd}^{(2)}\|_\infty > \|T_{zd}^{(1)}\|_\infty > \|T_{zd}^{(0)}\|_\infty = \|G_1\|_\infty \]
**Method I: resilient TISO controller**

**Step 1:** reduce the nominal system $G_2$ to a lower order,

**Step 2:** use $H_{\infty}$ optimization method to design the controller $K_2$ in which the local measurement $y$ is used as the only feedback,

**Step 3:** obtain the closed loop plant using $K_2$, treat this plant as the new plant to be stabilized,

**Step 4:** model the transmission delay using the second-order Padé approximation,

**Step 5:** integrate the delay model into the updated plant,

**Step 7:** reduce the integrated model to a lower order,

**Step 8:** solve the $H_{\infty}$ optimization problem a second time to obtain the controller $K_1$,

**Step 9:** reduce both controller $K_1$ and $K_2$ to a lower order at which they can be easily realized.

$z = \Delta I_{63-66}$ and $y = \Delta I_{44-45}$ respectively, because both of them have the largest residue and observability factor in their respective categories.

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**Table II. Residue and observability with regard to mode around 0.28 Hz**

<table>
<thead>
<tr>
<th>Signal</th>
<th>Residue</th>
<th>Observability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta I_{63-66}$</td>
<td>0.0035 + j0.0047</td>
<td>0.3166</td>
</tr>
<tr>
<td>$\Delta I_{61-63}$</td>
<td>0.0029 + j0.0040</td>
<td>0.2688</td>
</tr>
<tr>
<td>$\Delta I_{1-6}$</td>
<td>0.0019 + j0.0024</td>
<td>0.1633</td>
</tr>
<tr>
<td>$\Delta I_{2-6}$</td>
<td>0.0018 + j0.0023</td>
<td>0.1602</td>
</tr>
<tr>
<td>$\Delta I_{43-46}$</td>
<td>0.0009 + j0.0013</td>
<td>0.0834</td>
</tr>
<tr>
<td>$\Delta I_{33-40}$</td>
<td>0.0007 + j0.0010</td>
<td>0.0650</td>
</tr>
<tr>
<td>$\Delta I_{44-45}$ (local)</td>
<td>0.0018 + j0.0023</td>
<td>0.1568</td>
</tr>
<tr>
<td>$\Delta I_{40-44}$ (local)</td>
<td>0.0010 + j0.0014</td>
<td>0.0936</td>
</tr>
<tr>
<td>$\Delta I_{42-44}$ (local)</td>
<td>0.0009 + j0.0012</td>
<td>0.0817</td>
</tr>
</tbody>
</table>
Numerical tests

Eigenvalue analysis

Table III
Comparison of damping ratio of the critical mode around 0.28 Hz

<table>
<thead>
<tr>
<th>G93 &amp; G110 (MW)</th>
<th>Without SDC</th>
<th>SDC (loss of communication)</th>
<th>SDC (normal communication)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2×1300</td>
<td>9.13%@0.292 Hz</td>
<td>11.00%@0.296 Hz</td>
<td>13.23%@0.313Hz</td>
</tr>
<tr>
<td>2×1400</td>
<td>8.10%@0.286 Hz</td>
<td>10.65%@0.289 Hz</td>
<td>12.15%@0.309Hz</td>
</tr>
<tr>
<td>2×1500</td>
<td>6.47%@0.279 Hz</td>
<td>9.78%@0.280 Hz</td>
<td>11.34%@0.302Hz</td>
</tr>
<tr>
<td>2×1600</td>
<td>4.14%@0.273 Hz</td>
<td>7.99%@0.271 Hz</td>
<td>10.48%@0.294Hz</td>
</tr>
<tr>
<td>2×1700</td>
<td>1.16%@0.266 Hz</td>
<td>4.95%@0.262 Hz</td>
<td>9.57%@0.282Hz</td>
</tr>
<tr>
<td>2×1800</td>
<td>-3.00%@0.261 Hz</td>
<td>0.12%@0.254 Hz</td>
<td>8.24%@0.253Hz</td>
</tr>
</tbody>
</table>

The transmission delay $T_d = 100$ ms since the delay of a signal feedback in a wide area power system is usually of this order, yet the controller $K_1$ designed robustly adapts to the change of time delay in a certain range. To evaluate the impact of the transmission delay, different values $T_d = 0.1$ s, 0.3 s, 0.5 s and 0.7 s are considered in the simulations.

Contingency: a three-phase fault is applied to bus #1 for six cycles at 5.0 s.
Fig. 6. Rotor angle of G93 with a transmission delay of 0.7 s

Fig. 7. $P_{G139}$ with a transmission delay of 0.7 s

Fig. 8. Controller output with a transmission delay of 0.7 s

Fig. 9. SVC terminal voltage with a transmission delay of 0.7 s
Method II: incorporate a hierarchical set of measurements

- To survive communication errors, this approach proposes setting up a hierarchical set of candidate signals which are transmitted via different channels independent from each other. If one of these channels suffers a communication failure, the control will switch to using another wide-area signal in the hierarchy through a healthy communication route instead of the faulty one.

Fig. 10. Resilient control framework with hierarchical signals as the inputs
Channel inspection and switch

• Apparently, channel switch requires real-time detection of the channel abnormalities.

The comparison of the mathematical morphology (MM) of two independent signals is utilized to distinguish the failures in the communication system from those in the physical system:

(1) a threshold is set to screen out all the significant values which indicate a physical system fault or communication fault occurs,

(2) the communication fault is identified if the signal’s MM value in the corresponding channel is uniquely significant compared to signals in other channels at a time.

Fig. 11. Schematic explanation of the channel fault inspection

Note: multiple comparisons may be implemented in the channel inspection
Numerical tests

1. Eigenvalue analysis

Table IV
Comparison of damping ratio of the critical mode around 0.28 Hz

<table>
<thead>
<tr>
<th>G93 &amp; G110 (MW)</th>
<th>Open loop</th>
<th>Closed loop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$z: \Delta I_{63-66}$</td>
<td>$z: \Delta I_{61-63}$</td>
</tr>
<tr>
<td>2x1300</td>
<td>9.13% @0.292 Hz</td>
<td>12.27% @0.306 Hz</td>
</tr>
<tr>
<td>2x1400</td>
<td>8.10% @0.286 Hz</td>
<td>11.48% @0.305 Hz</td>
</tr>
<tr>
<td>2x1500</td>
<td>6.47% @0.279 Hz</td>
<td>10.61% @0.305 Hz</td>
</tr>
<tr>
<td>2x1600</td>
<td>4.14% @0.273 Hz</td>
<td>9.96% @0.303 Hz</td>
</tr>
<tr>
<td>2x1700</td>
<td>1.16% @0.266 Hz</td>
<td>8.85% @0.299 Hz</td>
</tr>
<tr>
<td>2x1800</td>
<td>-3.00% @0.261 Hz</td>
<td>6.69% @0.296 Hz</td>
</tr>
</tbody>
</table>

2. Time domain simulations

Contingency: a three-phase fault is applied to bus #1 for six cycles (0.1 s) at 5.0 s, then the wide-area control input is lost at 25.0 s in the simulation.
Fig. 12. Rotor angle of G93 with a transmission delay of 0.1 s

Fig. 13. $P_{G139}$ with a transmission delay of 0.1 s

Fig. 14. Rotor angle of G93 with a transmission delay of 0.7 s

Fig. 15. $P_{G139}$ with a transmission delay of 0.7 s
Summary

- This work proposes two approaches to build resilient control in response to communication failures. The simulation results have demonstrated that controls presented in both approaches provide supplementary damping to the system irrespective of whether the system suffers a communication failure or not and thus improve the stability performance and control resiliency of the system.

- For the first proposed method, the control is designed to automatically adapt to the number of inputs without channel inspection. Hence this kind of control is free of stochastic errors and time delay associated with the control switch.

- For the second method, channel inspection enables that incorrect control output due to the use of an incorrect input can be avoided. As a result, the risk of deteriorated control response because of unexpected transmission errors could be accordingly reduced. In addition, a large set of wide area measurements are used as the backup to the faulty signal.
Potential benefits and uses

• Provide an approach to utilize a wide range of measurements in control and also add robustness to the control.

• The approaches from this work could be used to establish controls resilient to communication failures in power systems based on the present facilities without increasing investment in building communication networks.

• With any of these two proposed resilient control adopted, the damping control is going to be much more reliable, and thus few oscillations and less self-recovery time of the system will be felt from the perspective of the industry and public
Reference


