Engineering Resilient Cyber-Physical Systems

A PSERC Future Grid Initiative Progress Report

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PSERC Future Grid Initiative

- DOE-funded project entitled "The Future Grid to Enable Sustainable Energy Systems" (see http://www.pserc.org/research/FutureGrid.aspx)
- Overall Project Objective: Enabling higher penetrations of renewable generation and other future technologies into the grid while enhancing grid stability, reliability, and efficiency
- This webinar's focus: accomplishments in the research area "Engineering Resilient Cyber-Physical Systems."

Engineering Resilient System Topics

- Topic is too broad to fully consider.
- Rather, focus has been on three specific topics:
 - Resiliency for High-Impact, Low-Frequency (HILF) Events: Tom Overbye
 - Operational and Planning Considerations for Resiliency: Ian Dobson
 - Improved Power Grid Resiliency through Interactive System Control: Vijay Vittal

Task 6.1 Resiliency for High-Impact, Low-Frequency (HILF) Events

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Resiliency for High-Impact, Low-Frequency (HILF) Events

- Several types of HILFs identified by the North American Electric Reliability Council (NERC) in its June 2010 report*: 1) Coordinated Attack,
 2) Pandemic, 3) Geomagnetic Disturbances (GMDs), 4) Electromagnetic Pulse (EMP)
 - Task has focused on GMD
- GMDs, which are caused by solar storms, have the potential to severely disrupt the power grid.
 Prior to the start of this project, power engineers had few tools to help them assess the impact of GMDs on their systems.

*NERC, High-Impact, Low-Frequency Event Risk to the North American Bulk Power System, June 2010.

Industrial Interaction has been Key

- Task has been heavily involved with industry to help develop these tools. For example, participating in the NERC GMD Task Force, working with EPRI and individual utilities, outside scientists, device manufacturers, software vendors
 - Utility power engineers are crucial to be able to determine appropriate GMD mitigation strategies
- Task worked with PowerWorld to get GMD assessment first put into a commercial power flow; other vendors now have similar functionality
 - So far we've had three conference papers and one journal paper, with a transactions paper under review

Geomagnetic Disturbances (GMDs)

- Solar events can cause changes in the earth's magnetic field (i.e., dB/dt). These changes in turn produce an electric field at the earth's surface
 - Changes in the magnetic flux are usually expressed in nT/minute; from a 60 Hz perspective they produce an almost dc electric field
 - 1989 North America storm produced a change of 500 nT/minute, while a stronger storm, such as the one in 1921, could produce

more than 5000 nT/minute variation



 Storm "footprint" can be continental in scale, for example covering much of the U.S

Electric Fields and Geomagnetically Induced Currents (GICs)

- Electric fields are vectors with a magnitude and direction; values are usually expressed in units of volts/mile (or volts/km); induce a quasi-dc voltage in transmission lines
 - A 2400 nT/minute storm could produce 5 to 10 volts/mile.
- The electric fields cause geomagnetically induced currents (GICs) to flow in electrical conductors such has the high voltage transmission grid
- GICs cause transformer saturation resulting in higher heating and reactive power losses that could result in a large-scale voltage collapse

Integration of GMD into the Power Flow

- By integrating GIC calculations directly within power analysis software (like power flow) power engineers can readily see the impact of GICs on their systems, and consider mitigation options
- GIC calculations use many of the existing model parameters such as line resistance. But some non-standard values are also needed
 - Substation grounding resistance, transformer grounding configuration, transformer coil resistance, whether autotransformer, whether three-winding transformer, generator step-up transformer parameters
 - Can be estimated when actual values are not available

GMD Power Flow Studies

 We've worked with a number of utilities and EPRI to do actual system studies



Recent Efforts

- More detailed GMD storm scenario modeling; determining the appropriate boundary between scientists and power engineers
- Validation using actual transformer neutral current and storm dB/dT values



 Constant electric field models will probably not be appropriate when performing validation

Recent Efforts, Sensitivity Analysis

- Electric grid parameter sensitivity analysis and automated optimizations
 - Recently submitted transactions paper in this area shows the derivation of the sensitivity relationships (i.e., which electric fields provide the transformer GICs), and indicates that the GICs are almost exclusively provided by nearby transmission lines



 Ongoing work is developing algorithms to determine the optimal locations for GIC blocking devices

Recent Efforts, cont.

- We've recently been looking at the dynamic interactions between GICs and power system short-term voltage stability
 - 100 year GMD storm scenarios show rise times on the order of 30 seconds
 - Whether power system models experience short-term voltage collapse can be sensitive to load and transformer tap modeling assumptions

Summary and Future Work

- Research has helped to move GIC analysis into tools for power system engineers
 - First generation software embedded GIC analysis into the power flow with constant field assumptions
 - Second generation is adding sensitivity analysis, more detailed field models and embedding GIC analysis into transient stability
- Potential future research will include looking further into voltage stability aspects, mitigation strategies, optimal blocking device locations and validation algorithms

Task 6.2 Operational and Planning Considerations for Resiliency

Ian Dobson, Iowa State Univ. Graduate Students: Atena Darvishi Lingyun Ding





Objective: Quantify resilience from utility data so that resilience can be engineered

- Quantify effect of cascading in terms of number of line outages from one year of standard utility data (this talk)
- 2. Quantify area stress from synchrophasor measurements around the border of the area

Cascading = initial outages + propagation

- Quantifying and limiting propagation of outages is an important part of resilience.
- Suppose we track number of line outages during cascading.
- We can estimate average propagation of line outages from ~ one year of standard utility TADS data that is reported to NERC by all USA utilities (TADS = Transmission Availability Data System)
- And then, given initial outages, we can predict statistics of the total number of line outages using a branching process model

Example of Processing Observed Transmission Line Outages

- 860 automatic line outages per year
- Simple approach: only look at time of outages
- Group outages into about 500 cascades and then into generations by their timing
- This gives, for example,
 - 625 outages in generation 0,
 - 114 outages in generation 1,
 - 43 outages in generation 2, etc.

The Increasing Propagation λ From Data



 $\lambda_1 = 0.18, \ \lambda_2 = 0.38, \ \lambda_3 = 0.52, \ \lambda_4 = 0.68, \ \lambda_5 + = 0.75$

Distributions of Line Outages (Raw Data)



Blue dots: initial line outages (generation 0) in each cascade Purple squares: total line outages in each cascade

Branching Process Can Compute Extent of Cascading



Distributions of Outages: Testing Branching Model



Purple squares: Empirical from observed data Line: Predicted by branching process with the varying λ

Predicting Cascading Failure Extent Based on Utility TADS Data



Probability distribution of total number of line outages assuming five initial line outages

Predicting Cascading Failure Extent Based on Utility TADS Data



Probability distribution of total number of line outages assuming 26 initial line outages

Conclusion

- We have validated with industry data from BPA and several others.
- The annual tendency to cascade (propagation and distribution of total number of outages) can be monitored and quantified from standard utility data that is already collected
- We are developing prototype software to share so that others can do these calculations
- Questions or TADS data to share?... please contact lan at dobson@iastate.edu
- Papers at http://iandobson.ece.iastate.edu

Task 6.3 Improved Grid Resiliency Through Interactive System Control

Vijay Vittal, Arizona State Univ. Graduate Student: Song Zhang



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 also 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 more 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 synchrophasor units.



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 <u>either in the physical system or in the</u> <u>communication system</u> 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 cyberphysical 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

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 via 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.

Study System

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

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

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



Fig. 2 Setup of SITO feedback system and TISO controller

 G'_1 is the open loop system with the transmission delay integrated based on Padé approximation $G'_1 = G_1 D, \ D = (\frac{1}{12}T_d^2s^2 - \frac{1}{2}T_ds + 1)/(\frac{1}{12}T_d^2s^2 + \frac{1}{2}T_ds + 1)$

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

$$T_{zd}^{(1)} = \frac{G_1}{1 + G_2 K_2} \qquad \qquad T_{u_2 d}^{(1)} = \frac{G_2 K_2}{1 + G_2 K_2}$$

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.

$$\left\|T_{zd}^{(2)}\right\|_{\infty} > \left\|T_{zd}^{(1)}\right\|_{\infty} > \left\|T_{zd}^{(0)}\right\|_{\infty} = \left\|G_{1}\right\|_{\infty}$$

Method I: Resilient TISO Controller



Fig. 3 Sequential H_{∞} synthesis framework

Table	II.	Residue	and	observability	with	regard	to	mode
around	10.2	28 Hz						

Signal	Residue	Observability	
$() \Delta I_{63-66}$	0.0035 + j0.0047	0.3166	
ΔI_{61-63}	0.0029 + j0.0040	0.2688	
ΔI_{1-6}	0.0019 + j0.0024	0.1633	
ΔI_{2-6}	0.0018 + j0.0023	0.1602	
ΔI_{43-46}	0.0009 + j0.0013	0.0834	
ΔI_{33-40}	0.0007 + <i>j</i> 0.0010	0.0650	
($$) ΔI_{44-45} (local)	0.0018 + j0.0023	0.1568	
ΔI_{40-44} (local)	0.0010 + j0.0014	0.0936	
ΔI_{42-44} (local)	0.0009 + <i>j</i> 0.0012	0.0817	

Design procedures



- *Step 1*: reduce the nominal system G_2 to a lower order,
- Step 2: use H_{∞} 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 secondorder 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_{∞} 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.

Numerical Tests

Eigenvalue analysis

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

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

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.

Nonlinear time domain simulations



Fig. 5. P_{G139} with a transmission delay of 0.1 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

• The channel switching requires real-time detection of the channel abnormalities. The comparison of the



Fig. 11. Schematic explanation of the channel fault inspection

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.

Note: multiple comparisons may be implemented in the channel inspection.

Numerical Tests

1. Eigenvalue analysis

G93 & G110	Open loop	Closed loop			
(MW)		z: ∆I ₆₃₋₆₆	<i>z</i> : ⊿ <i>I</i> ₆₁₋₆₃	z : ΔI_{1-6}	
2×1300	9.13%	12.27%	12.11%	11.86%	
	@0.292Hz	@0.306 Hz	@0.306 Hz	@0.306 Hz	
2×1400	8.10%	11.48%	11.20%	10.73%	
	@0.286 Hz	@0.305 Hz	@0.306 Hz	@0.305 Hz	
2×1500	6.47%	10.61%	10.38%	10.01%	
	@0.279 Hz	@0.305 Hz	@0.305 Hz	@0.304 Hz	
2×1600	4.14%	9.96%	9.54%	8.26%	
	@0.273 Hz	@0.303 Hz	@0.302 Hz	@0.301 Hz	
2×1700	1.16%	8.85%	8.62%	5.12%	
	@0.266 Hz	@0.299 Hz	@0.297 Hz	@0.297 Hz	
2×1800	-3.00%	6.69%	6.67%	4.98%	
	@0.261 Hz	@0.296 Hz	@0.294 Hz	@0.294 Hz	

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

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

⁴²

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.
- In the first proposed method, the resiliency is designed in the control which adapts to the loss of the wide area signal.
- In the second method, the resiliency in built in the communication network by utilizing multiple wide area signals to perform control.

Potential Benefits and Uses

- Provides 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.
- Both the proposed approaches, provide adequate damping and are resilient to communication failure.

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