

Improved Grid Resiliency through Interactive System Control (6.3)

Vijay Vittal

Arizona State University
(vijay.vittal@asu.edu)

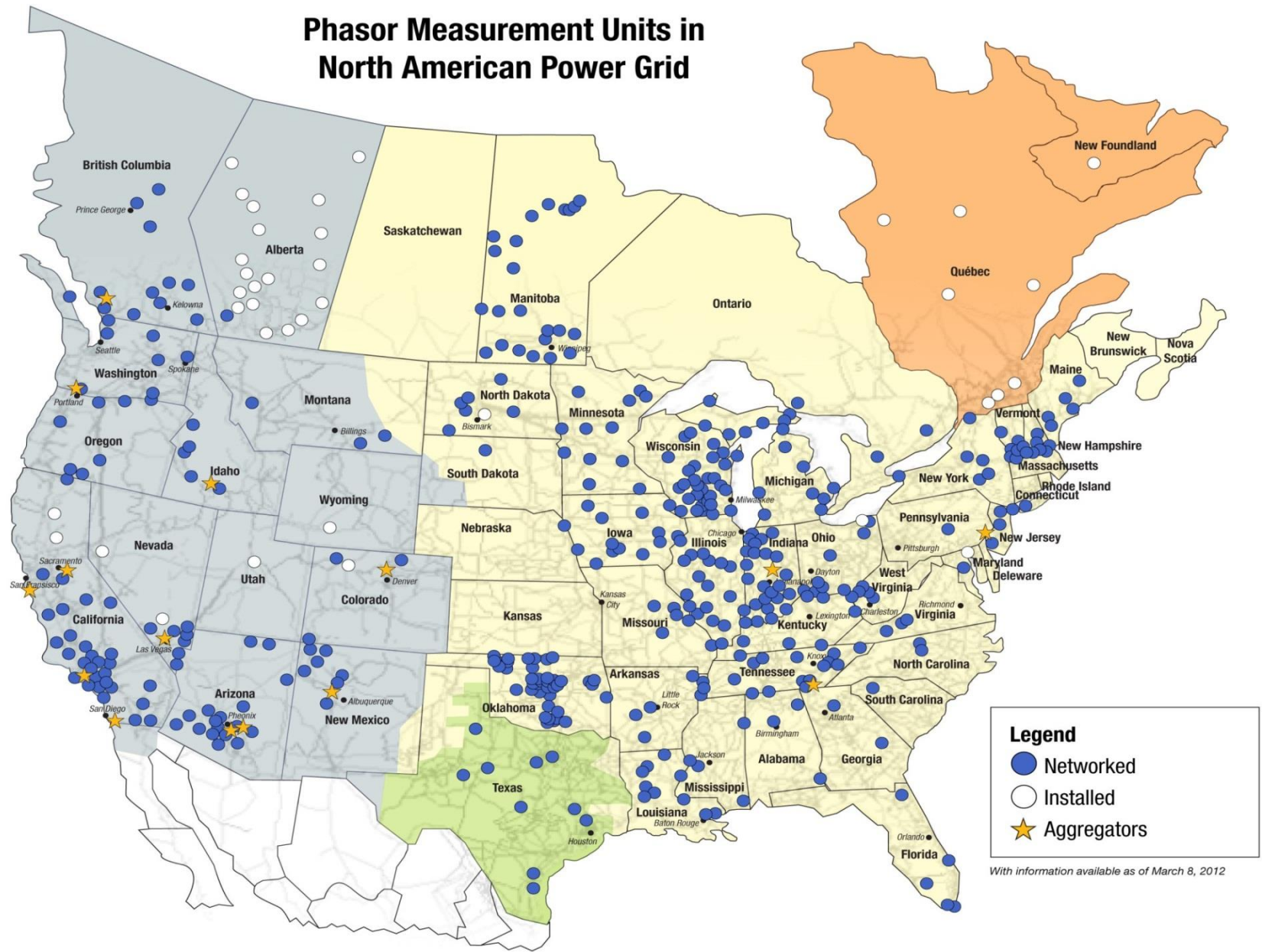


PSERC Future Grid Initiative
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Context

- 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.

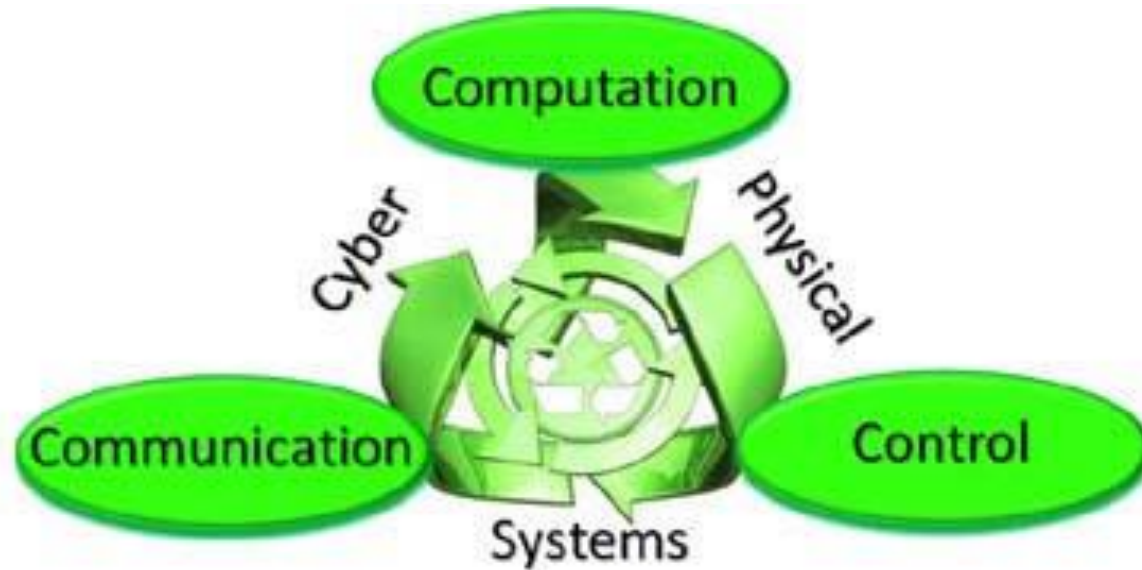
Phasor Measurement Units in North American Power Grid



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



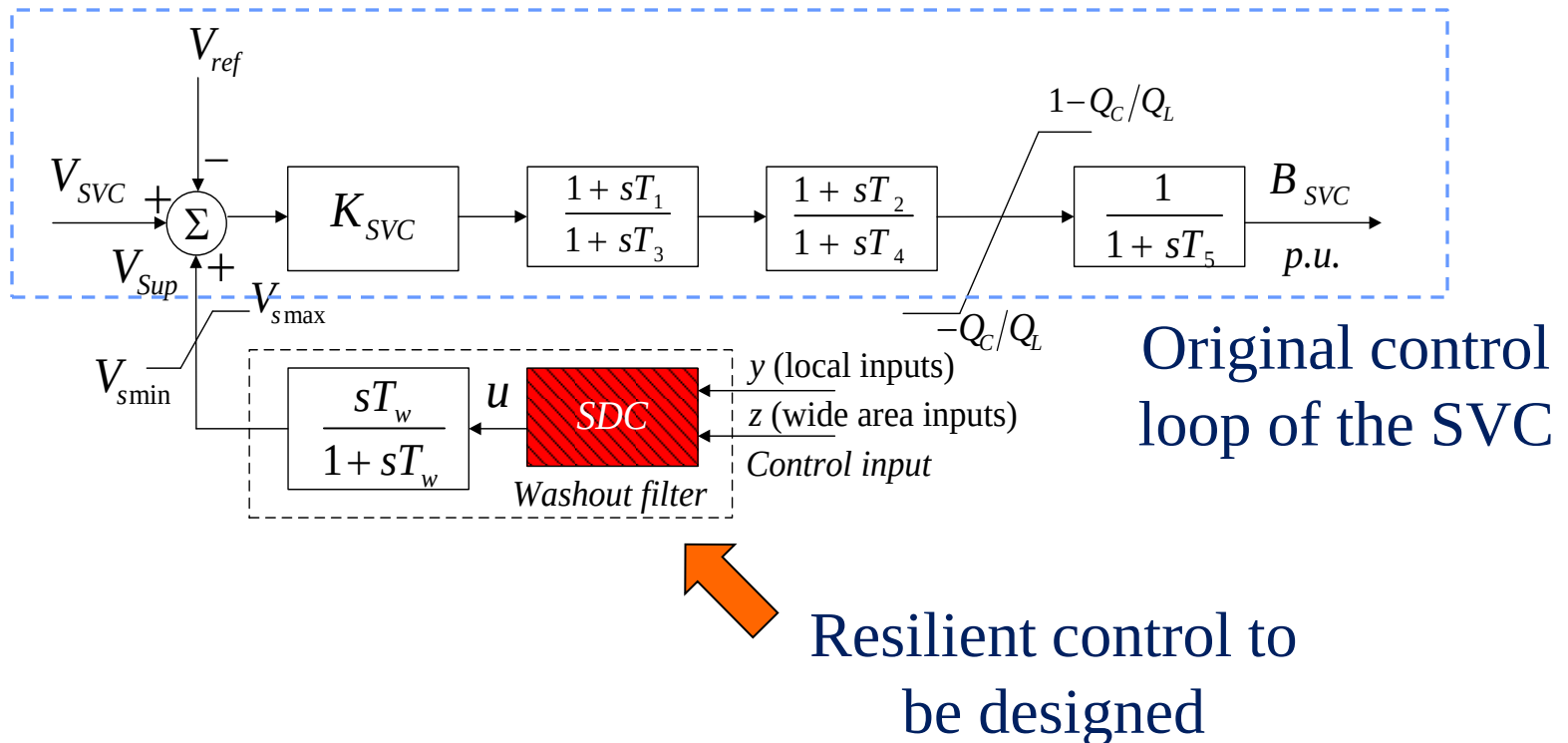
- Addresses a critical issue related to engineering resilient cyber-physical systems
- Provides an effective means to use a hierarchical set of synchronized measurements for corrective control and increase grid resiliency.
- Leverages large investment in installing PMUs across the nation

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

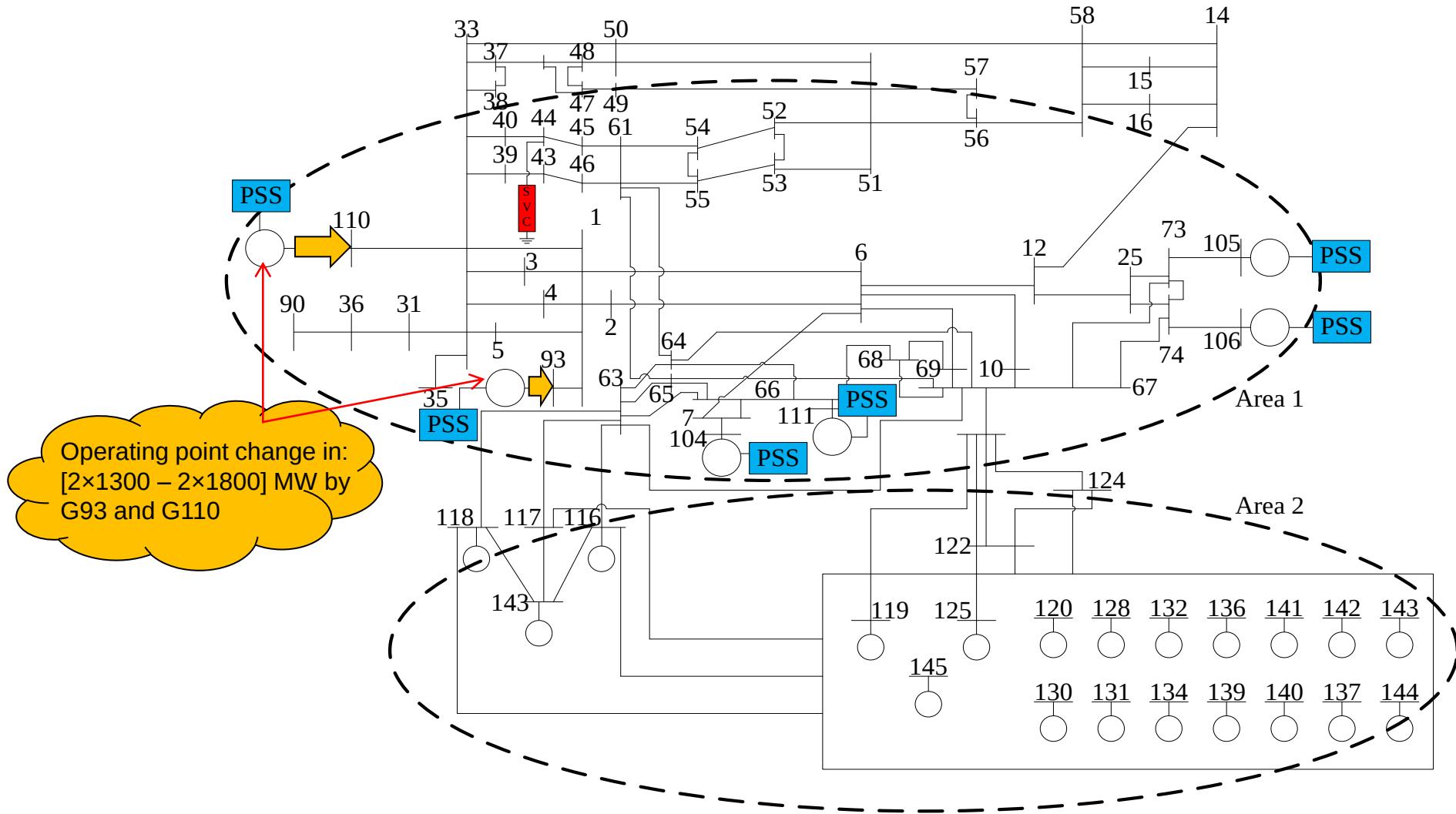


Fig.1 One-line diagram of the IEEE 50-machine system

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

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

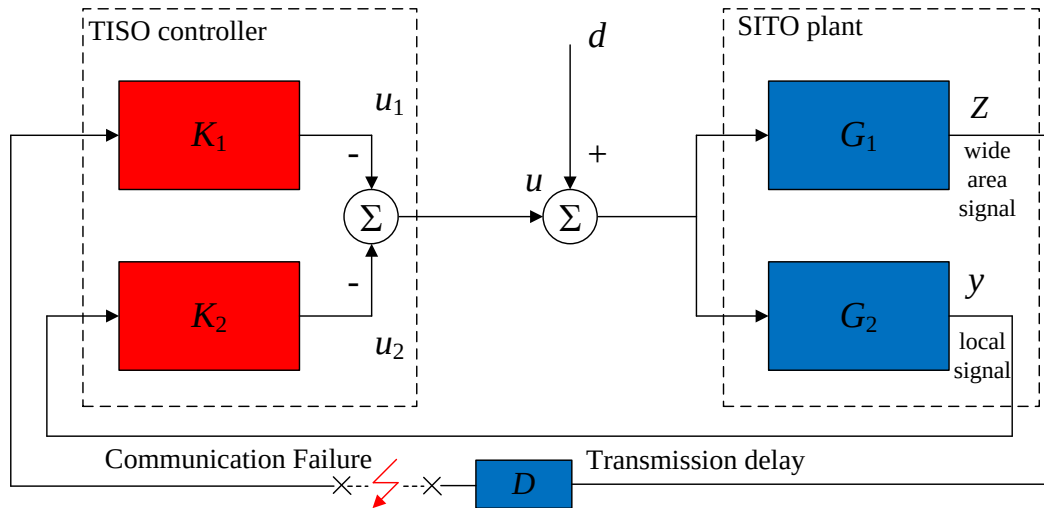
Since Mode 2 has an decreasing damping ratio with the increase of generation, the supplementary damping control is primarily provided to damp this mode to further extend the stability limit in addition to PSS.

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



The associated transfer functions are

$$T_{zd}^{(2)} = \frac{G_1}{1 + G_1'K_1 + G_2K_2} = \frac{G_1}{1 + (G_1D)K_1 + G_2K_2}$$

$$T_{u_2d}^{(2)} = \frac{G_2K_2}{1 + G_1'K_1 + G_2K_2} = \frac{G_2K_2}{1 + (G_1D)K_1 + G_2K_2}$$

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

$$G_1' = G_1D, \quad D = \left(\frac{1}{12}T_d^2s^2 - \frac{1}{2}T_ds + 1 \right) / \left(\frac{1}{12}T_d^2s^2 + \frac{1}{2}T_ds + 1 \right)$$

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

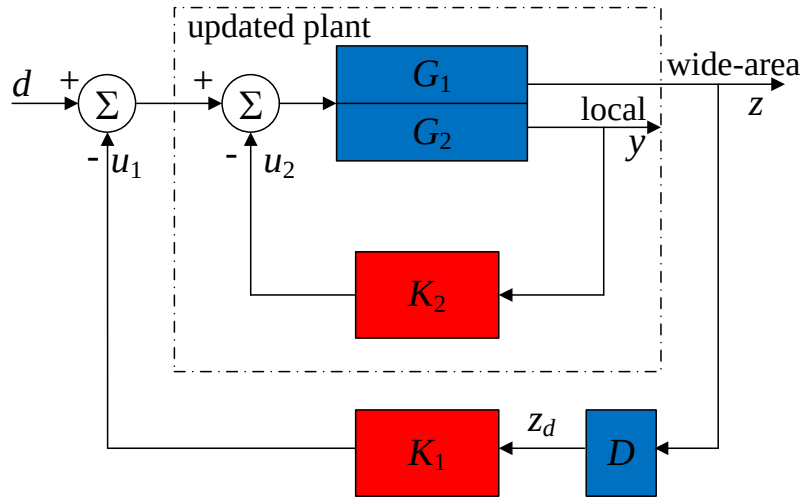


Fig. 3 Sequential H_∞ synthesis framework

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

Signal	Residue	Observability
(✓) ΔI_{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 + j0.0010	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 + j0.0012	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 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_∞ 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

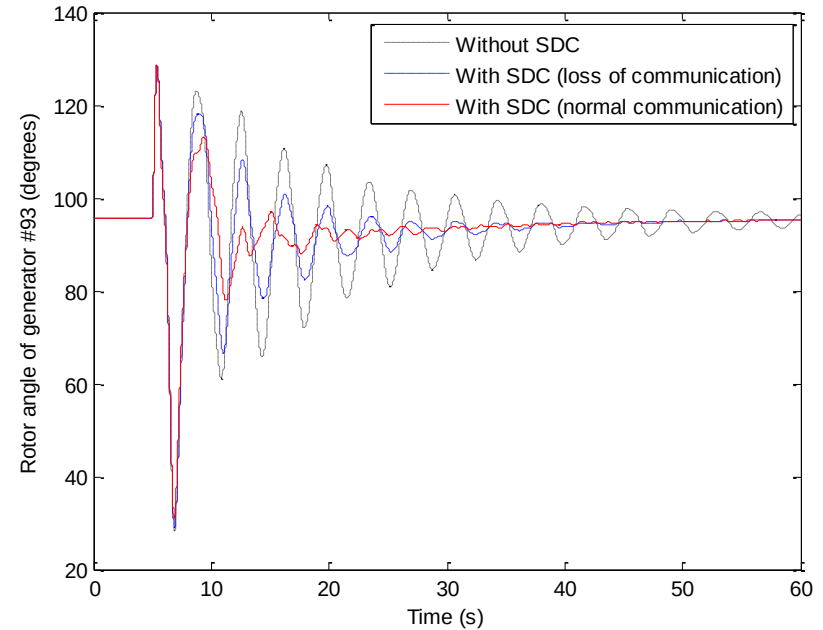


Fig. 4. Rotor angle of G93 with a transmission delay of 0.1 s

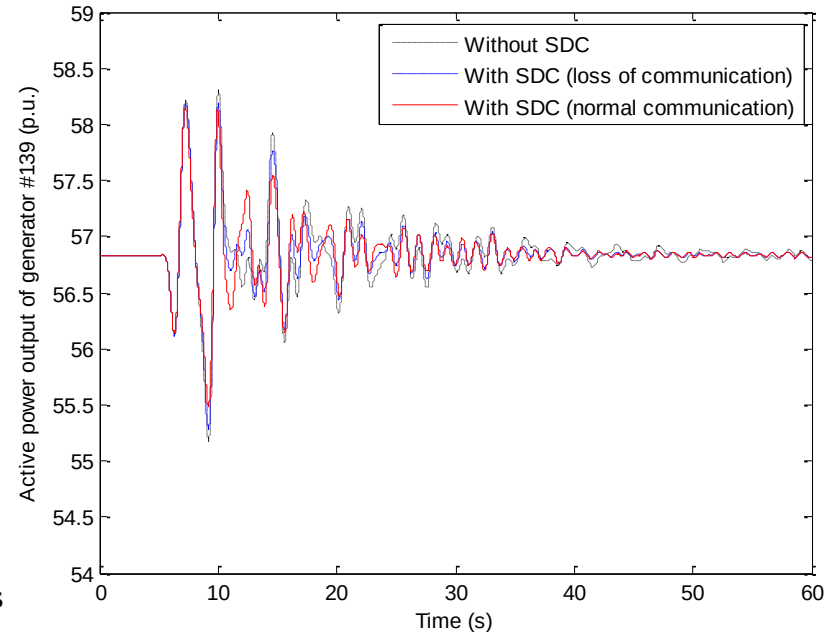


Fig. 5. P_{G139} with a transmission delay of 0.1 s

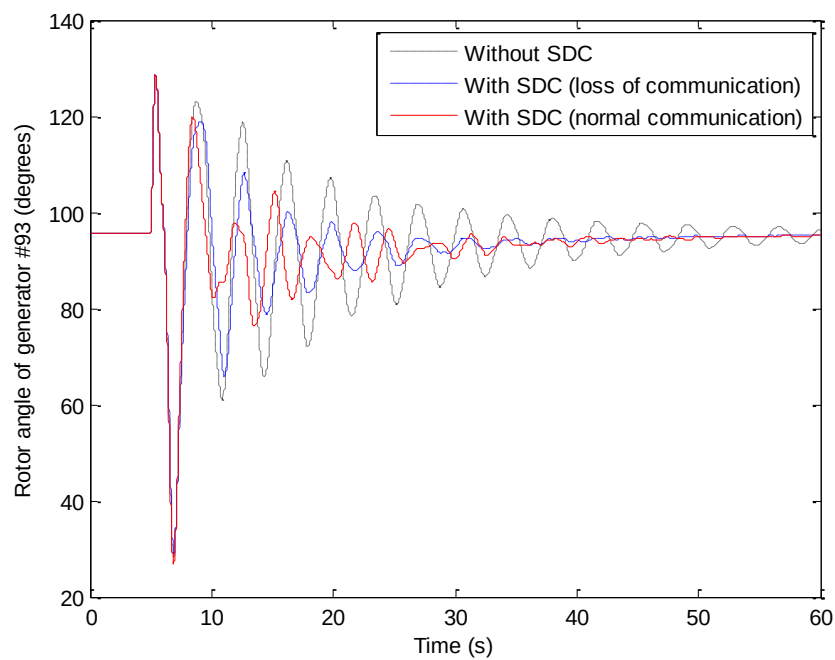


Fig. 6. Rotor angle of G93 with a transmission delay of 0.7 s

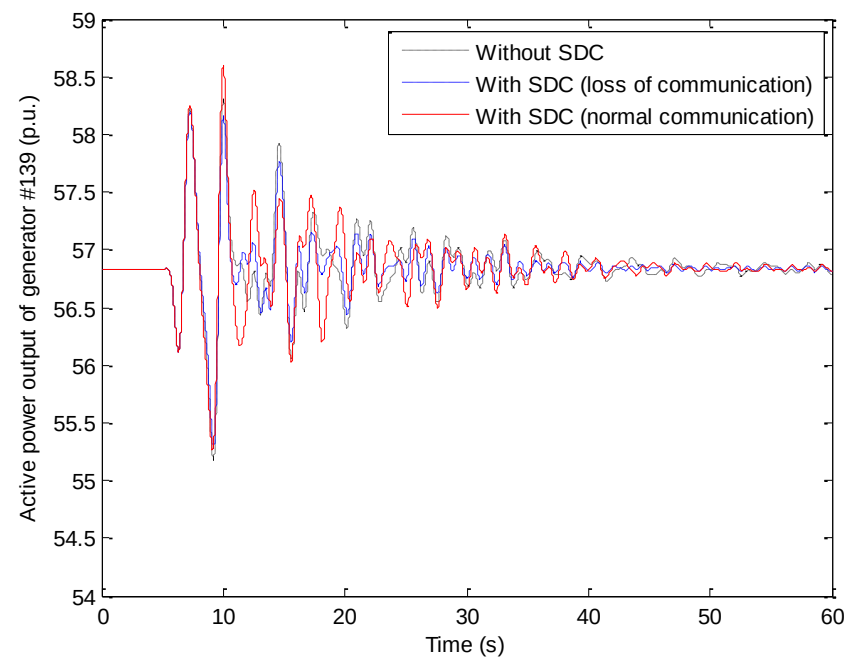


Fig. 7. P_{G139} with a transmission delay of 0.7 s

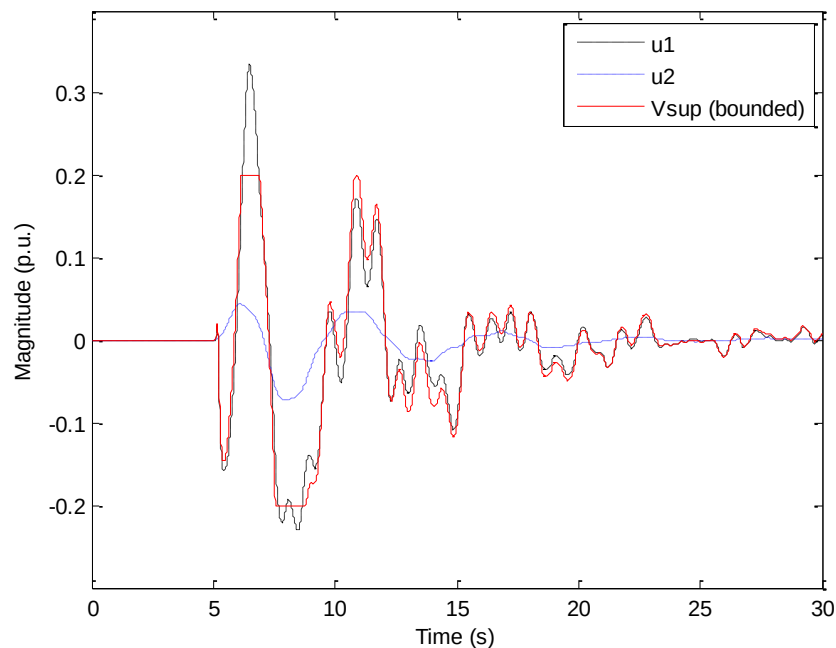


Fig. 8. Controller output with a transmission delay of 0.7 s

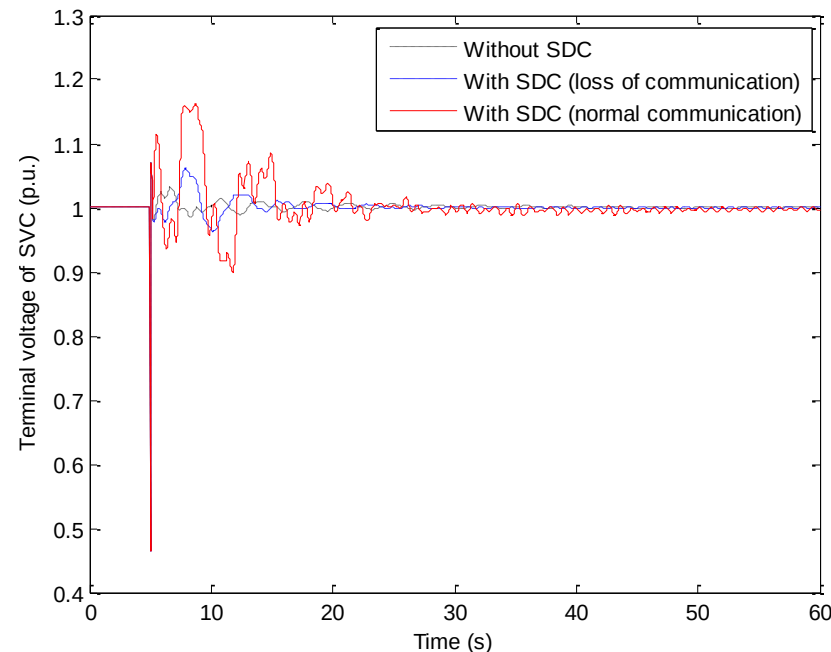


Fig. 9. SVC terminal voltage with a transmission delay of 0.7 s

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.

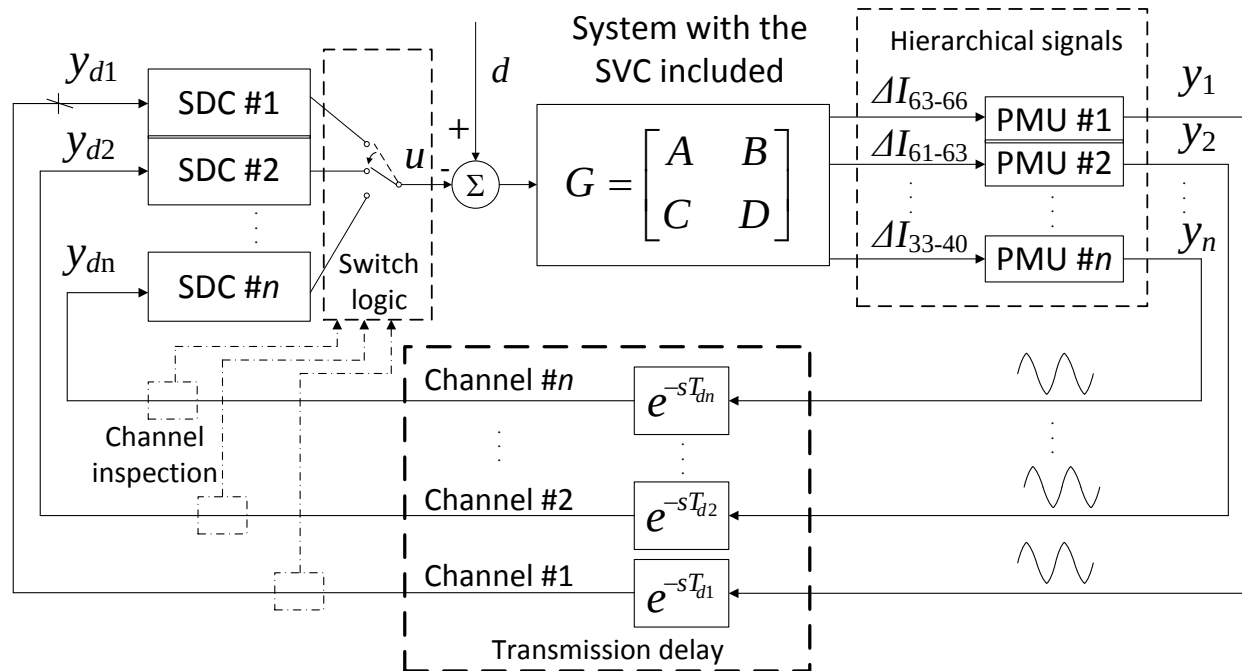
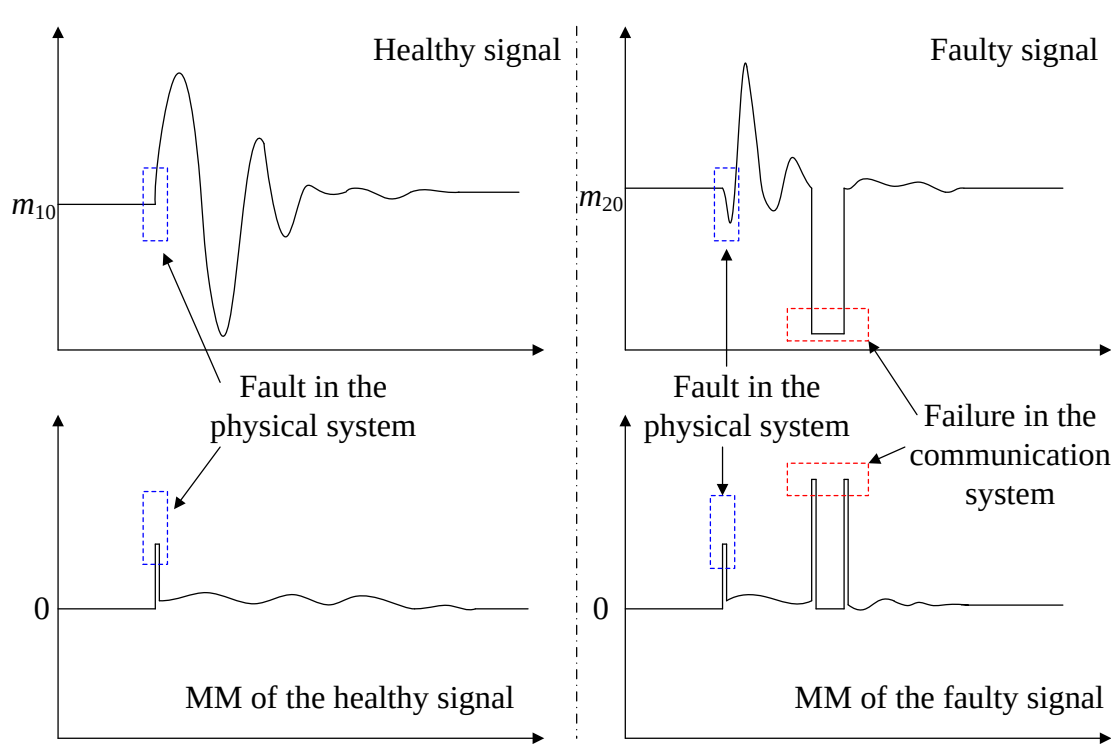


Fig. 10. Resilient control framework with hierarchical signals as the inputs

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

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

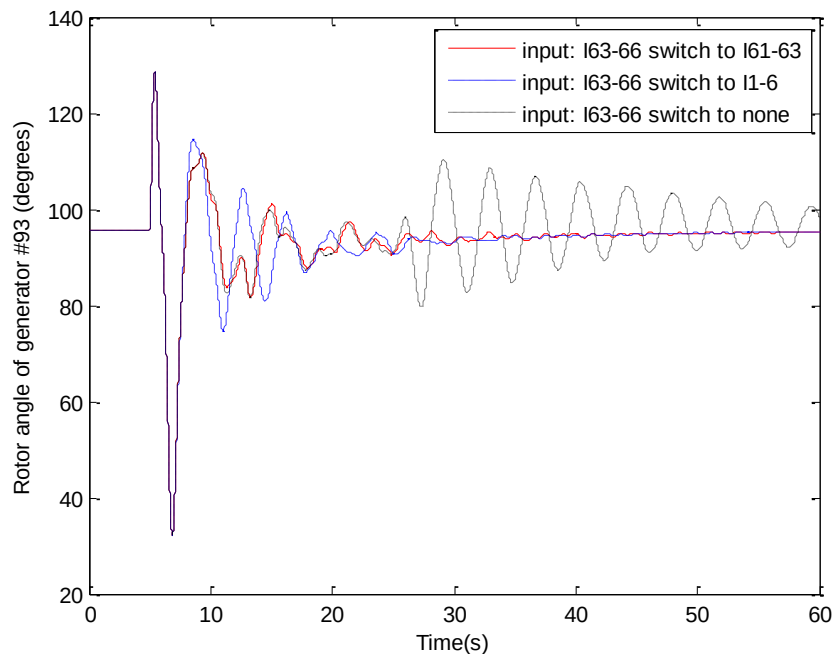


Fig. 12. Rotor angle of G93 with a transmission delay of 0.1 s

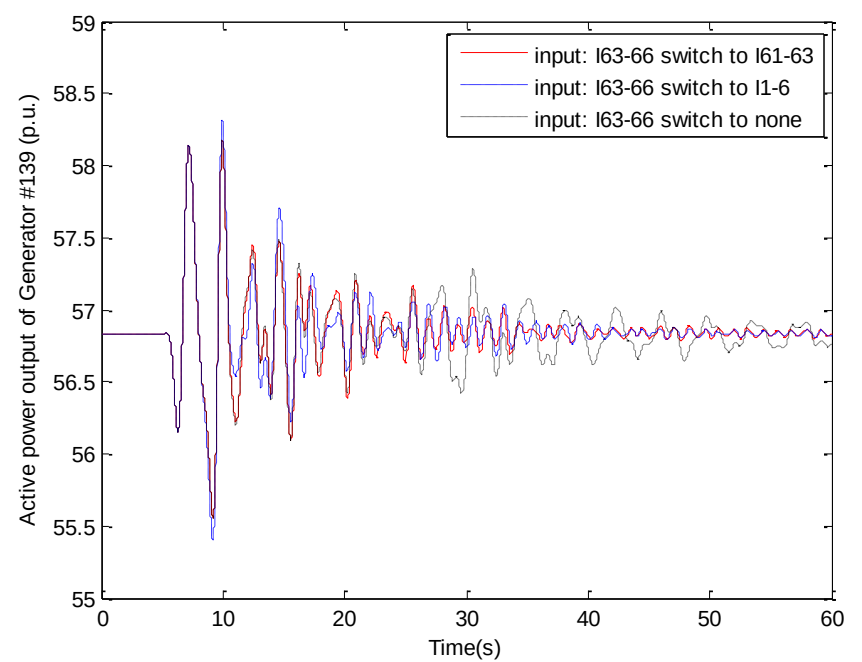


Fig. 13. P_{G139} with a transmission delay of 0.1 s

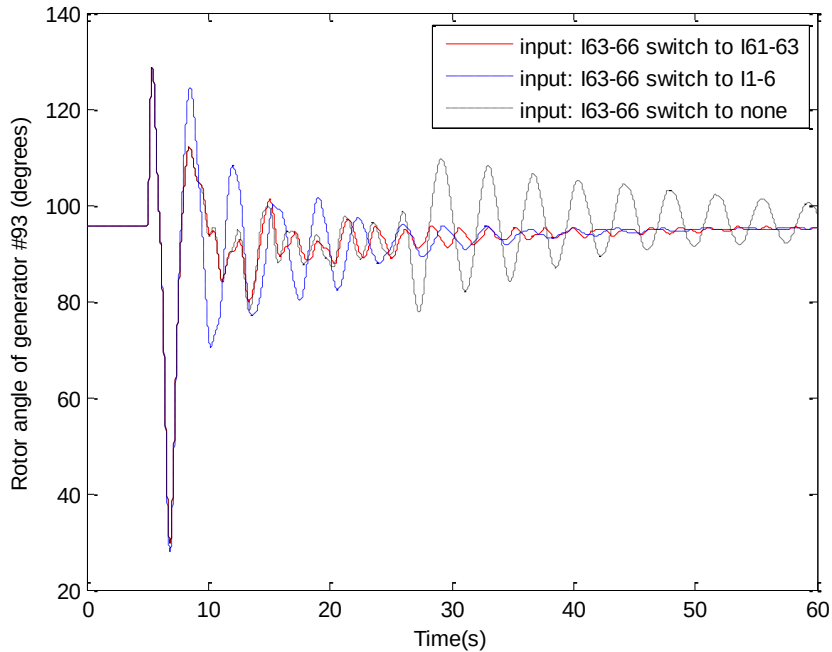


Fig. 14. Rotor angle of G93 with a transmission delay of 0.7 s

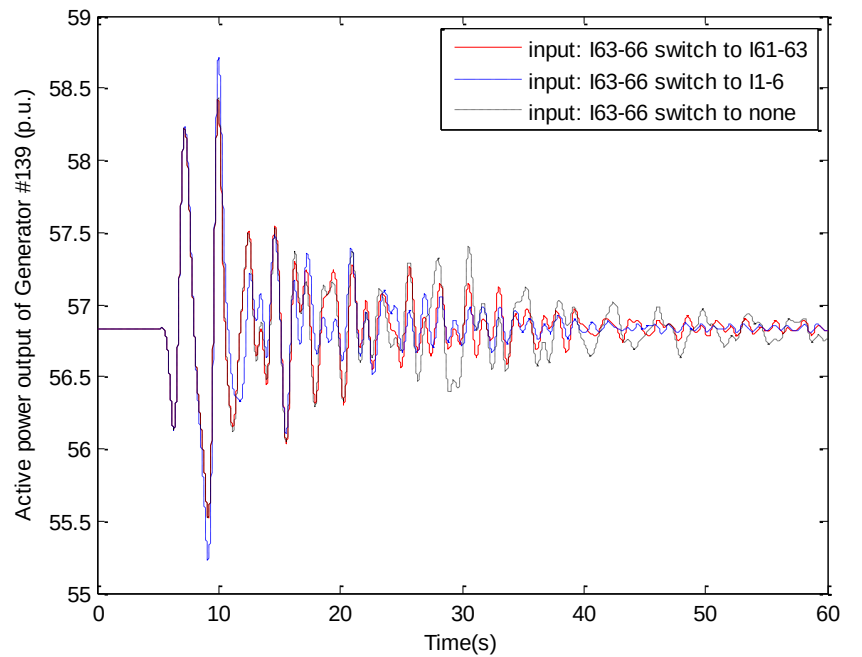


Fig. 15. P_{G139} with a transmission delay of 0.7 s

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

- J. Chow, J. Sanchez-Gasca, H. Ren and S. Wang, "Power system damping controller design using multiple input signals," *IEEE Control Syst. Mag.*, vol. 20, pp. 82-90, Aug, 2000.
- P. Kundur, *Power System Stability and Control*, 2nd ed., New York: McGraw-Hill, 2008.
- V. Vittal, Chair "Transient stability test systems for direct stability methods," *IEEE Trans. Power Syst.*, vol. 7, no. 1, pp. 37-43, Feb. 1992.
- S. Liu, A. R. Messina and V. Vittal, "A normal-form based approach to place power system stabilizers," in *Proc. 2006 IEEE Power Engineering Society General Meeting*, pp. 1-7.
- L. D. Philipp, Ausif Mahmood, B. L. Philipp, "An improved refinable rational approximation to the ideal time delay," *IEEE Trans. Circuits Syst.*, vol. 46, pp. 637-640, May 1999.
- B. Chaudhuri, R. Majumder and B. C. Pal, "Wide-area measurement-based stabilizing control of power system considering signal transmission delay," *IEEE Trans. Power Syst.*, vol. 19, no. 4, pp. 1971-1979, Nov. 2004.