CRII: CPS: Architecture and Distributed Computation in the Networked Control Paradigm: An Autonomous Grid Example

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Abstract

This project is focused on the fundamental research in establishing a foundational framework towards the development of an autonomous Cyber-Physical System (CPS) through distributed computation in a Networked Control Systems (NCS) paradigm. Specific attention is focused on an application where the computational, and communication challenges are unique due to the sheer dimensionality of the physical system. An example of such CPS is the smart power grid, which includes large-scale deployment of distributed and networked Phasor Measurement Units (PMUs) and wind energy resources. A systematic approach is proposed for wide-area oscillation damping control, which can handle data packet dropout in the communication channels in such smart power grids. The major challenges identified in the controller design are: a) computational burden, b) communication network delays and data drops. To handle the challenges of computational burden, frequency domain abstraction is explored to reduce the dimension of the model. To that end it is demonstrated that a widely-used technique Balanced Truncation (BT) fails to produce stable reduced order model (ROM) when modern grid with wind generation is considered while a relatively new approach - Iterative Rational Krylov Algorithm (IRKA) is able to give an ROM retaining the essential properties of the system. To handle the delays and data drops the dynamic property of the ROM is exploited in an Observer-driven Reduced Copy (ORC) approach. The key contribution comes from the analytical derivation of the impact of coupling between the cyber and the physical layer on ORC performance. Nonlinear time-domain simulations following large disturbances (e.g., faults, line outages, etc.) demonstrate that the ORC gives significantly better performance compared to conventional feedback under higher data drop situations.

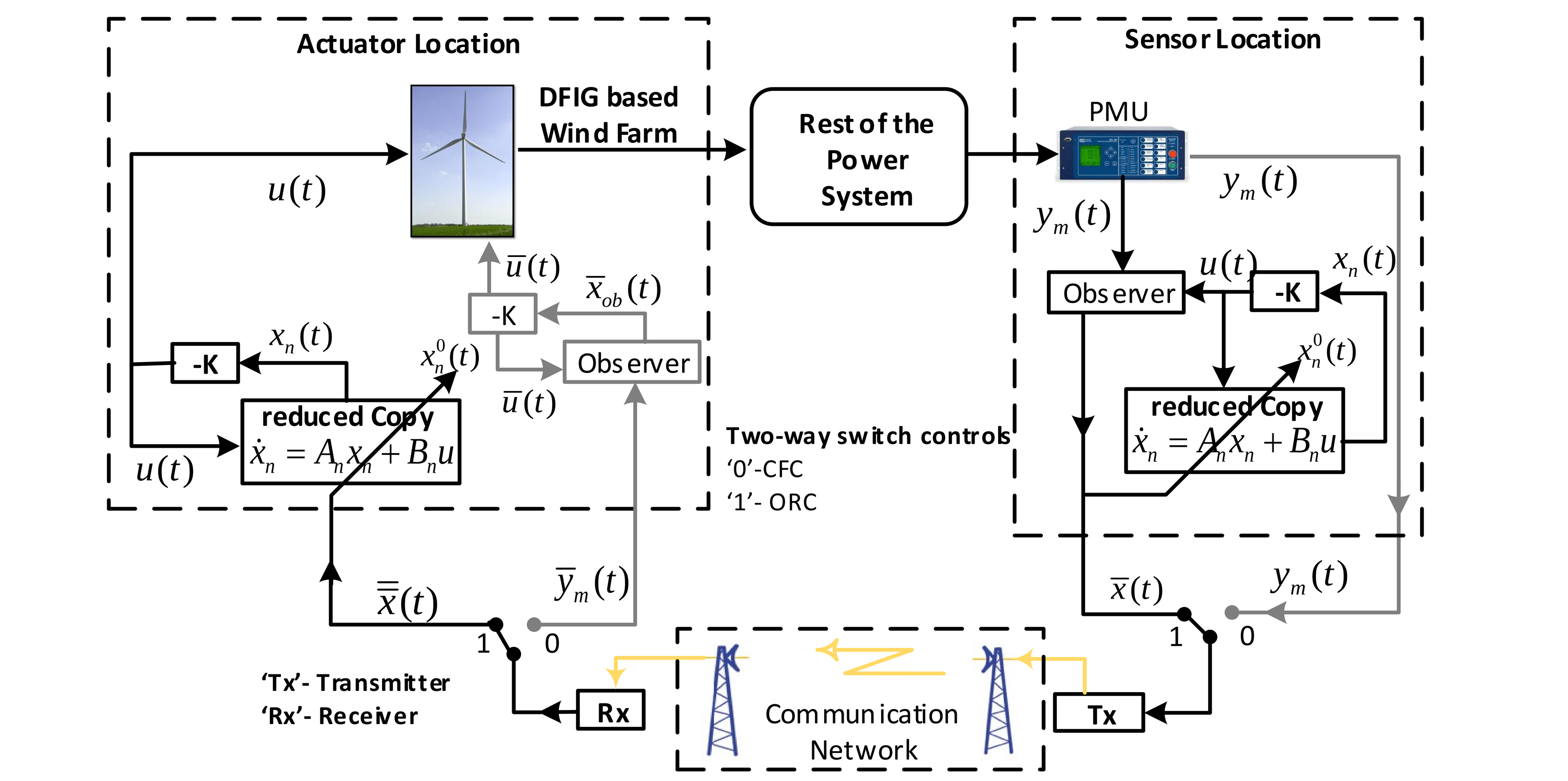

Fig. 1. Overall architecture of the Networked Controlled Power System (NCPS) including conventional feedback control (CFC) in gray and the proposed Observer-driven Reduced Copy (ORC).

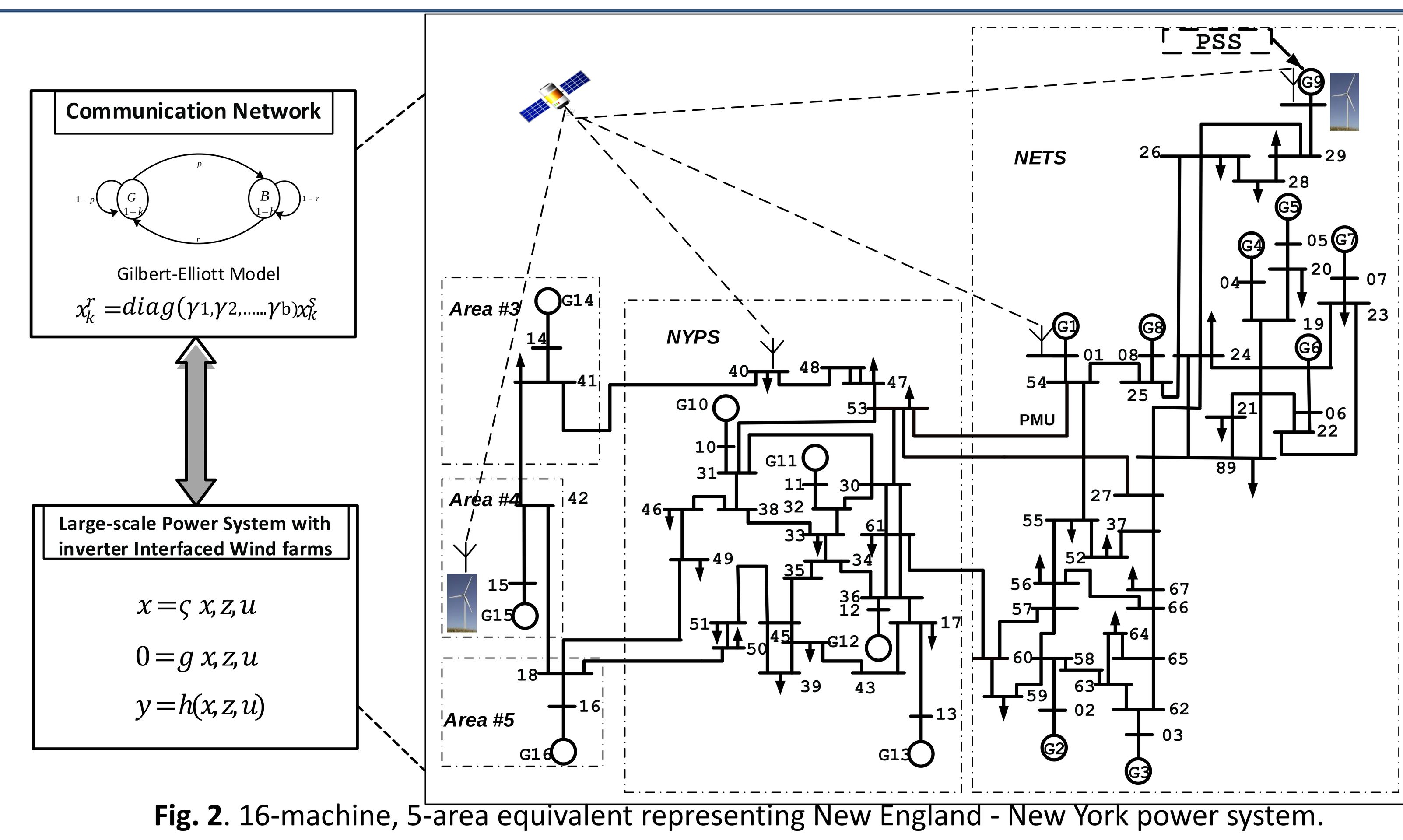

Fig. 2. 16-machine, 5-area equivalent representing New England - New York power system.

Wind Farms are connected to bus-9 and 15.

Proposed Tasks in the Program

- Framework to discover interdependencies between NCS and a large power system: Modeling Adequacy Study (presented in CPS PI meeting 2015). [1]
- **Reduction in burden of distributed computation: Frequency domain abstraction. [2]**
- **Communication dropout-resilient control for grid stabilization.[3,4,5]**

Reduction of Computational Burden: Frequency Domain Abstraction

Using Frequency domain abstraction a stable SISO 'n' order system is reduced to 'r' order system (r<<n), which has the following objectives: accuracy, stability, scalability, and applicability.

Model reduction techniques:

- **Balanced truncation (BT):** Based on Singular value decomposition and uses controllability and observability gramians for ordering Hankel singular values and form ROM.
- **Iterative Rational Krylov Algorithm (IRKA):** Based on Moment matching approach which uses sigma points to iteratively correct the ROM.
- These techniques were tested in two scenarios: Conventional power grid with SGs only (PS-SG) and modern power grid with inverter-interfaced WFs (PS-DFIG).

Communication Dropout-resilient Control: Principle of Proposed ORC

- An observer at each sensor location uses the reduced-order linearized model of the power system to estimate the states.
- For each feedback signal the corresponding control input $(u(t))$ at the actuator and sensor locations are calculated using two reduced order models of the power system, see Fig. 1.
- When data packet drops out the states of each copy are allowed to evolve naturally otherwise switched to reset its states.

Analytical Derivation of ORC Performance Affected by Cyber-physical Coupling

- **The error between the reduced order linearized system state trajectory and that of reduced copy can be expressed as:**

$$\xi(t) = e^{A_i(t-t_k)}(x_{ik}^0 - \bar{x}_k) + e^{A_i(t-t_k)}(I - \mathbf{\Psi_k})(\bar{x}_k - x_{nk}) + \int_{t_k}^{t} e^{A_i(t-\tau)}(\tilde{A} - \tilde{B}K)e^{(A_n - B_n K)\tau}(\mathbf{\Psi_k}(\bar{x}_k - x_{nk}) + x_{nk})d\tau \quad (1)$$

- **Assumptions:**

1. The open-loop system and the closed-loop nominal system are stable.
2. The observer tracks the actual states perfectly: $(x_{ik}^0 - \bar{x}_k) = 0$.

- **The expectation of the maximum norm of error can be derived as:**

$$\mathbf{E}[\|\xi(t)\|_{max}] \propto K_1(1-\rho) + K_2\left\|\tilde{A} - \tilde{B}K\right\| + K_3\left\|\tilde{A} - \tilde{B}K\right\|\rho \quad (2)$$

- **Important Notations:**

1. $\tilde{A}$ *and* $\tilde{B}$: Deviation in A *and* B matrix from nominal operating condition; **2**. ρ: Data receiving rate in the communication channel; **3.** K: Controller gain; **4**. $K_1, K_2,$ *and* K_3: Proportionality constants.

- **Observations from Equation (2):**

1st –Term: Impact of cyber-only term indicates the error norm increases with increase in data dropout.

2nd –Term: Impact of physical-only term indicates increase in error norm under off-nominal condition.

3rd –Term: The cyber-physical coupling term indicates a **non-trivial** impact on the error norm.

Conclusion [2-5]

- Both BT and IRKA can produce acceptable ROM for conventional power grids but for modern power grid BT results in an unstable ROM whereas IRKA produces stable ROM capturing poorly-damped modes.
- The uncertainty in the cyber layer due to data packet drop and the off-nominal operation of the physical layer affect the ORC performance in a coupled manner, where the coupling is non-trivial.

Simulation Results

Reduction of computational burden: Frequency domain abstraction

Table: Comparison of relative H_2 error norm in power system with two model reduction approaches (r = 32)

Type of PS	Model reduction approach	
	BT	IRKA
PS-SG	1.7737×10^{-4}	4.1345×10^{-5}
PS-DFIG	∞	5.9×10^{-3}

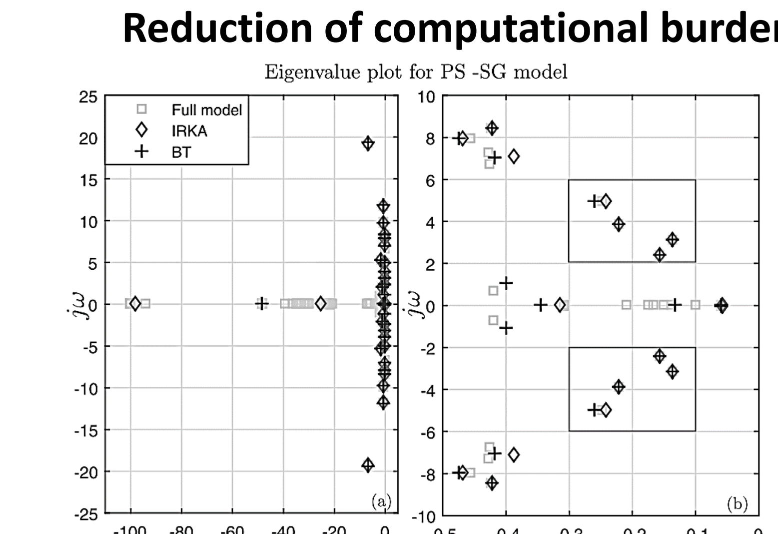

Fig.3. a): Eigenvalue plot for full system (n = 133) and reduced-order systems (r = 32) in conventional power grid with SGs. b): Zoomed inter-area modes.

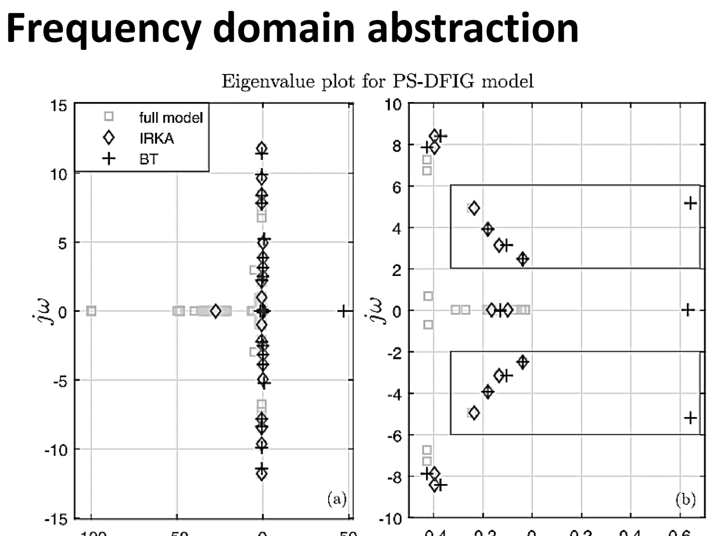

Fig. 4. a): Eigenvalue plot for full system (n= 148) and reduced-order system (r=32) in modern power grid with inverter-interfaced WF. b): Zoomed inter-area modes.

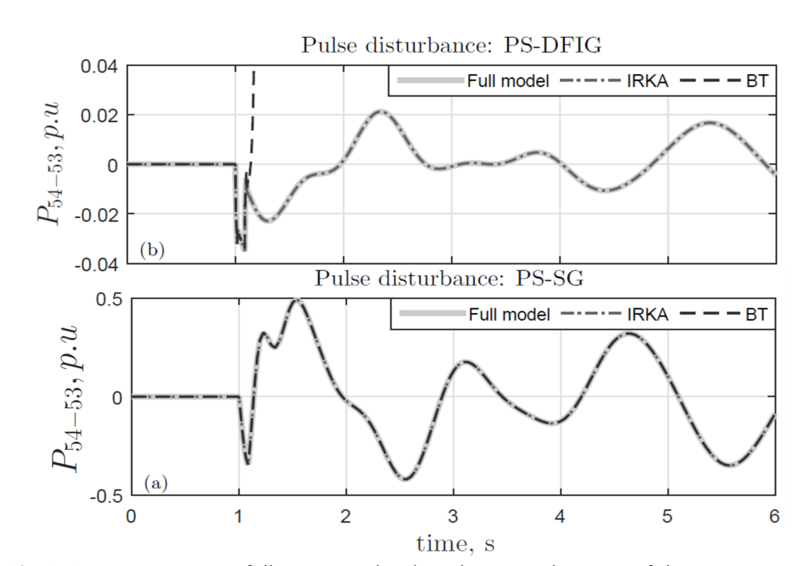

Fig. 5. Dynamic response following a pulse disturbance at the input of the conventional and modern power grid when represented with their ROMs (r= 32) with different model reduction techniques.

Communication dropout-resilient control: ORC Approach

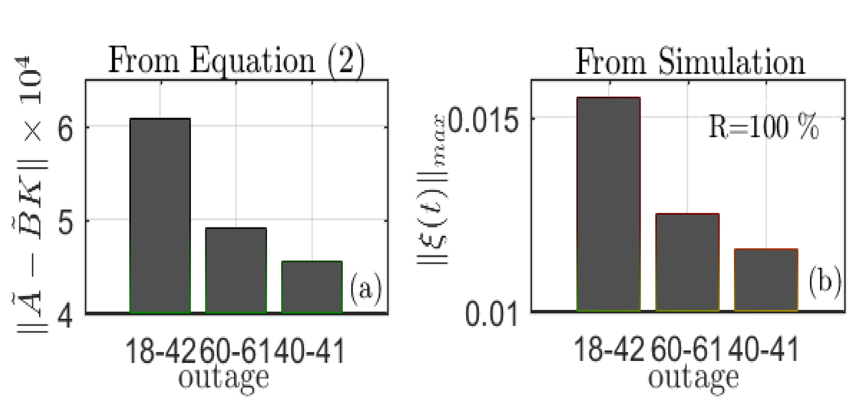

Fig.6. Dynamic performance after a three-phase fault near bus 18/60/40 following by the outage of one of the tie-lines between buses 18-42/60-61/40-41, respectively, see Fig. 2.

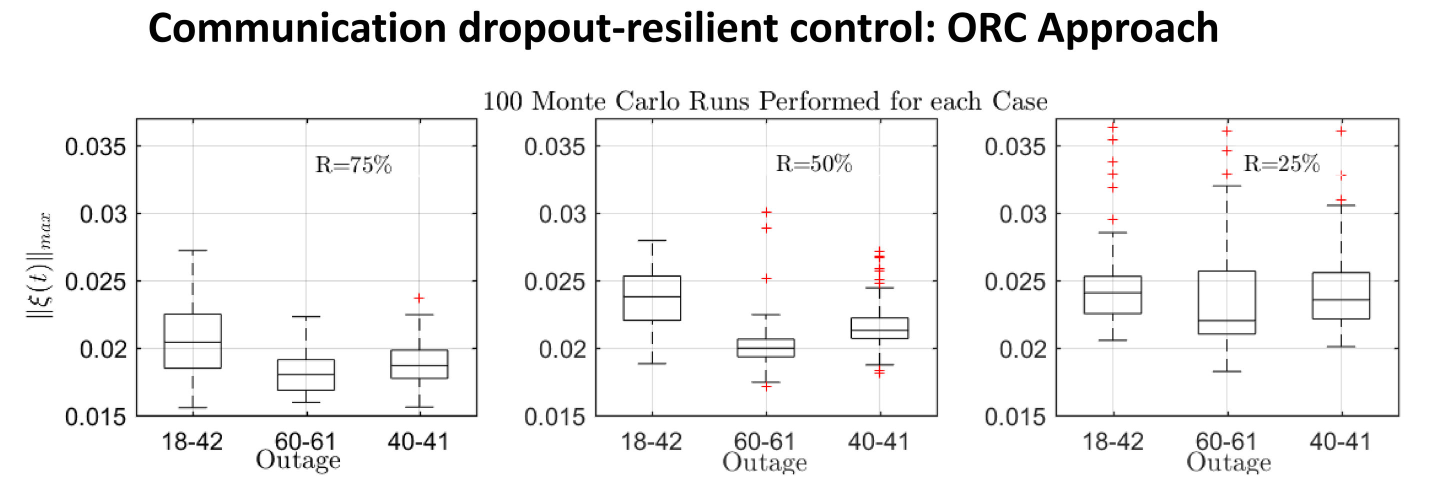

Fig. 7. Boxplots of maximum error bound of state trajectories in the inter-sample interval with non-ideal communication channel calculated from linear time-domain simulation. 100 Monte Carlo runs were conducted for each outage and data rates, totals 900 runs.

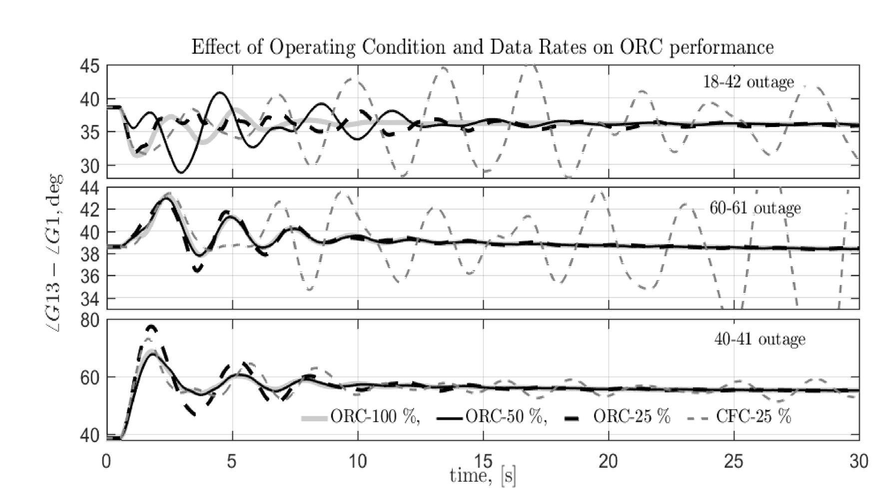

Fig.8. Bound on error norm of state trajectories in the inter-sample interval with ideal communication channel: (a) measure of bound on error norm from equation (2), (b) calculated bound on error from linear simulation

Publications

1. A. Yogarathinam, J. Kaur, and N.R. Chaudhuri, "Modeling Adequacy for Studying Power Oscillation Damping in Grids with Wind Farms and Networked Control Systems (NCS)", in proceedings of IEEE Power and Energy Society General Meeting (PESGM), 2016.
2. J. Kaur, and N.R. Chaudhuri, "Challenges of Model Reduction in Modern Power Grid with Wind Generation", in proceedings of IEEE of 48th North American Power Symposium (NAPS), 2016 .
3. A. Yogarathinam, and N.R. Chaudhuri, "Data Packet-drop Resilient Wide-Area Damping Control Using DFIG-based Wind Farms", in proceedings of IEEE of 48th North American Power Symposium (NAPS), 2016.
4. A. Yogarathinam, and N.R. Chaudhuri, "An Approach for Wide-Area Damping Control using Multiple DFIG-based Wind Farms to Deal with Communication Dropouts", in proceedings of IEEE of 7th Innovative Smart Grid Technologies (ISGT) Conference, 2016.
5. A. Yogarathinam, and N.R. Chaudhuri, "An Approach for Wide-Area Damping Control using Multiple DFIG-based Wind Farms Under Stochastic Data Packet Dropouts." Under review in IEEE Transactions on Smart Grid.

Financial support from NSF under grant award #1657024 is gratefully acknowledged