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. The modeling adequacy study of such system is performed. 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. The first is solved using frequency domain abstraction to reduce the dimension of the model. The later is handled by exploiting the dynamic property of the reduced-order model (ROM) in an Observer-driven Reduced Copy (ORC) approach.

Proposed Tasks in the Program

- **Task 1 (Modeling) :** Framework to discover interdependencies between NCS and a large power system [**C1**].
- **Task 2 (Computing) :**Reduction in burden of distributed computation: Frequency domain abstraction [**J1, C6, C4**].
- **Task 3 (Control):** Communication dropout-resilient control for grid stabilization [**J3, J2, C5, C3, C2**].

Key Contributions

1. **Task 1: Modeling Adequacy Study**

- Considers a detailed subtransient model of the grid, which includes a modified model of the DFIG-based wind farm (WF).
- Considers a detailed characterization of the communication process with packet loss probability using Gilbert-Elliott model.
- Presents a modeling adequacy study for a Networked Controlled Power System.

2. **Task 2: Frequency Domain Abstraction - Model Reduction**

- Demonstrates the challenges in reducing MIMO models of the modern power grid with renewables using gramian-based (Balanced truncation (BT)) and modal truncation (Subspace Accelerated MIMO Dominant Pole (SAMDP)) approaches.
- Applies relatively new Interpolatory approach of Iterative Rational Krylov Algorithm (IRKA) to reduce such models.
- **Proposes a Heuristic-based IRKA (H-IRKA)** to improve accuracy of the ROMs, while ensuring explicit preservation of the 'critical eigenvalues' of original system.
- Demonstrates an improved accuracy with explicit preservation of the critical modes using three test systems model:

I. Conventional grid with SGs (PS-SG): 2×2 MIMO system, 134 states, see Fig.2.
II. Modern grid with inverter-interfaced Wind Farms (PS-DFIG): 2×2 MIMO system, 167 states, see Fig.2.
III.Larger Brazilian Interconnected Power System (BIPS): 4×4 MIMO system, The sparse descriptor system representation based on the unreduced Jacobian matrix has an order of 7,135 with 606 state variables and 6,256 algebraic variables.

3. **Task 3: Observer-driven Reduced Copy (ORC) Approach**

- **Proposes performance measure I**: based on a bound on the norm of the difference between the power system states and the `reduced copy' states in the inter-sample interval.
- **Proposes performance measure II:** based upon bound on the norm of the difference between the power system states in presence of data dropout and that under ideal communication within an inter-sample interval.
- Useful for power system operators to perform online contingency screening and ranking from damping performance stand point without running expensive time-domain simulations as a part of Dynamic Security Assessment (DSA).

Proposed Architecture and Test System

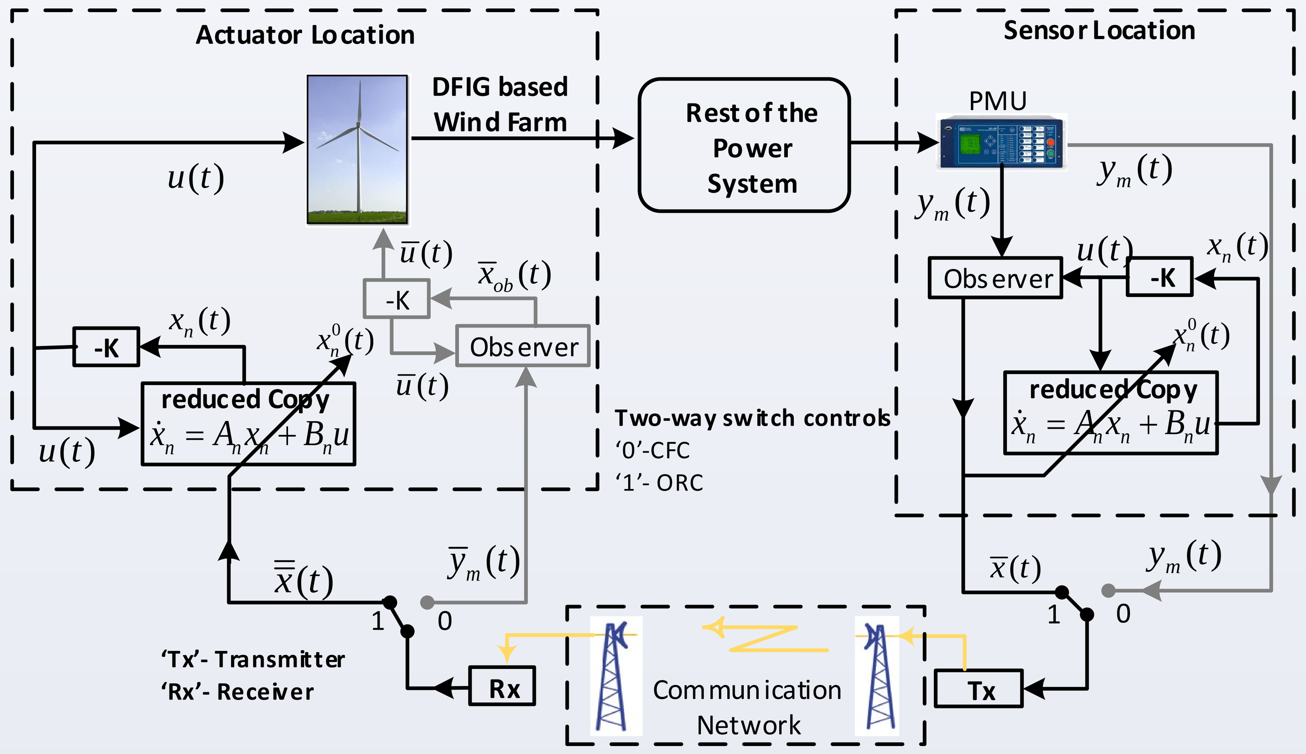

Fig. 1. Overall architecture of the Networked Controlled Power System (NCPS) including conventional feedback control (CFC) in grey and the proposed Observer-driven Reduced Copy (ORC).

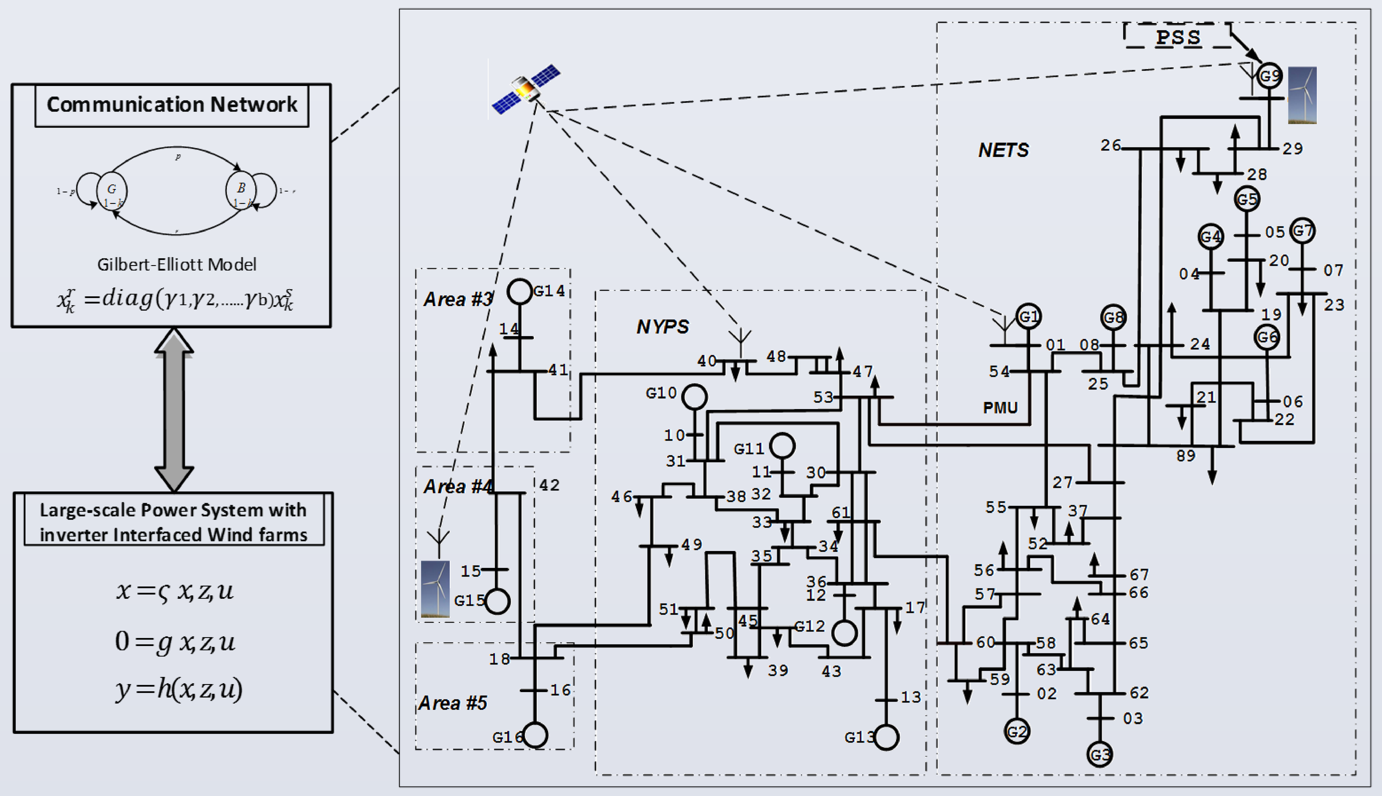

Fig. 2. 16-machine, 5-area equivalent representing New England - New York power system. WFs are connected to bus-9, 15.

Analytical Derivation of ORC and CFC Performance

- **Bound I:** Measures of ORC performance affected by cyber-physical coupling
- The expectation of the maximum norm of the error between the reduced order linearized system state trajectory and that of reduced copy.

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

- **Bound II:** The norm within the inter-sample interval for the difference between the system states under ideal communication and that following data dropout.
- For ORC:

$$\|\xi(t)\| \le \beta\|B_iK\|\left\|\tilde{A}-\tilde{B}K\right\| \quad (2)$$

- For CFC:

$$\|E(t)\| \le p_6\|B_iK\|\|LC_i\| + p_7\|B_iK\|^2\|LC_i\| + p_8\|B_iK\|\|LC_i\|^2 \quad (3)$$

- **Key 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/L: controller/observer gain; 4. B_i/C_i: input/output matrix of the off–nominal system; 5. $K_1, K_2, K_3, \beta, p_6, p_7,$ *and* p_8: proportionality constants.

Simulation Results: Communication Dropout-resilient Control (ORC)

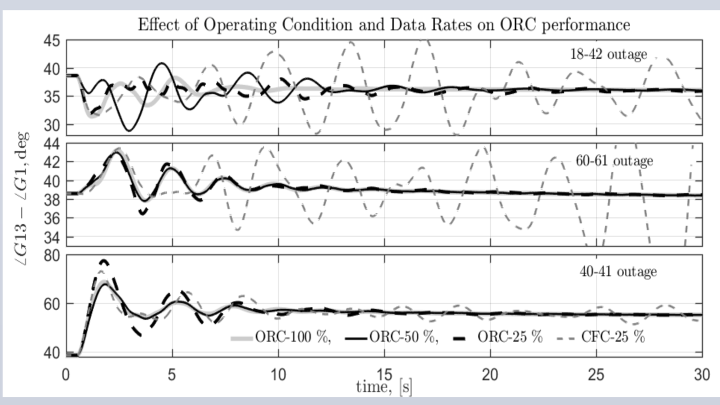

Fig. 3. Comparison between the CFC versus ORC

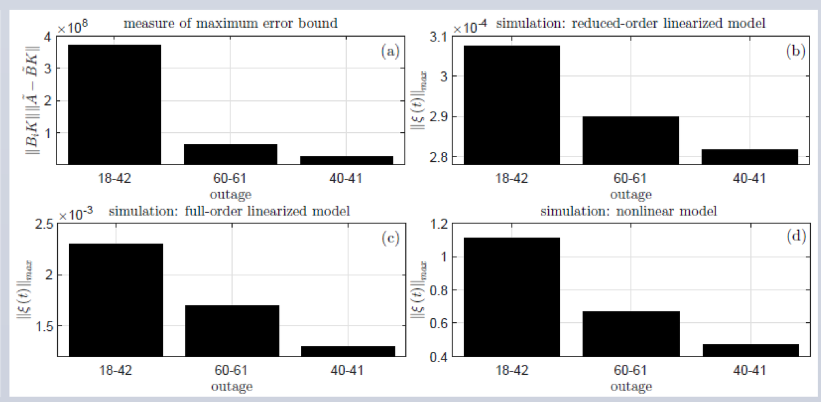

Fig. 4. Bound on norm of deviation in power system state trajectories denoted by $\|\xi(t)\|$.

Results: Reduction of Computational Burden

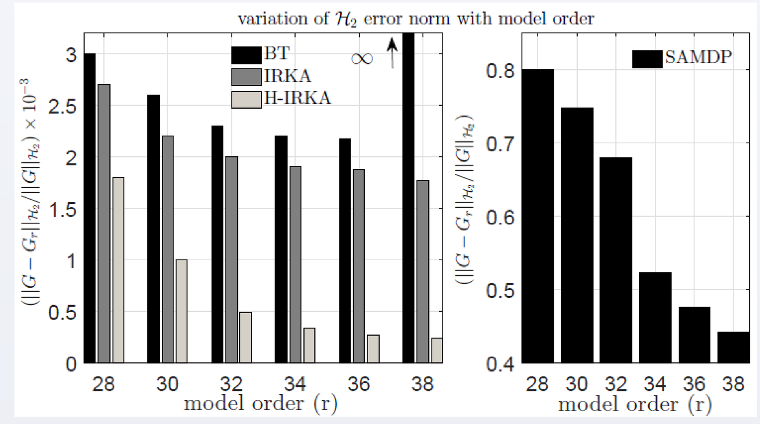

Fig. 5. Relative $\boldsymbol{H_2}$ error norm vs **r** of PS-DFIG model.

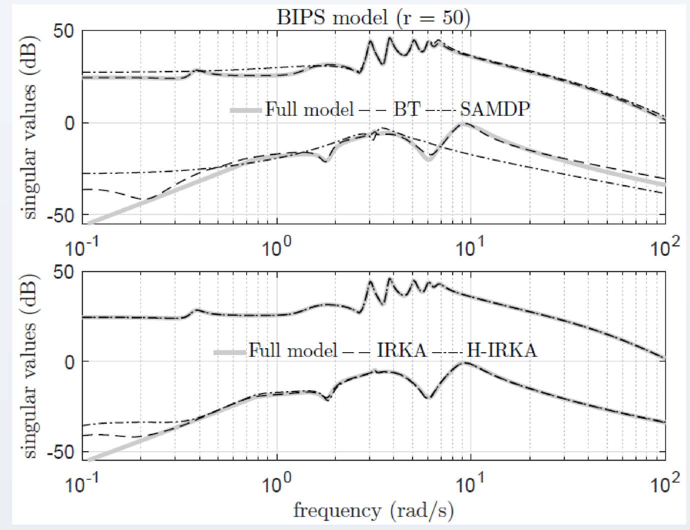

Fig. 6. Maximum and minimum singular value plots.

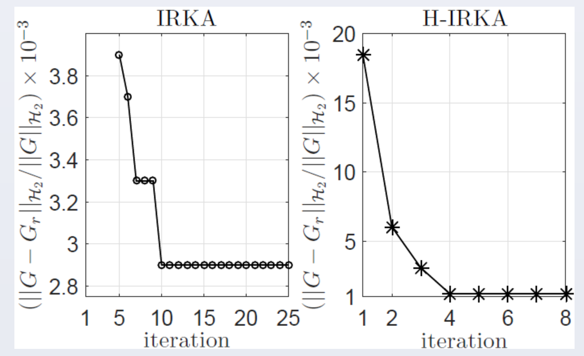

Fig. 7. IRKA vs H-IRKA using BIPS model.

Table 1. Critical eigenvalues of PS-DFIG model for **r** = 38

Full order model		Reduced-order model							
		SAMDP		BT		IRKA		H-IRKA	
ξ, %	f, Hz	ξ, %	f, Hz	ξ, %	f, Hz	ξ, %	f, Hz	ξ, %	f, Hz
1.40	0.403	1.40	0.403	1.40	0.403	1.40	0.403	1.40	0.403
4.30	0.502	–	–	4.20	0.502	4.40	0.503	4.30	0.502
4.50	0.622	4.50	0.621	4.50	0.622	4.50	0.621	4.50	0.622
5.00	**0.791**	–	–	**4.90**	**0.788**	**4.70**	**0.792**	**5.00**	**0.791**

Table 2. Critical eigenvalues of BIPS model for **r** = 50

Full order model		Reduced-order model							
		SAMDP		BT		IRKA		H-IRKA	
ξ, %	f, Hz	ξ, %	f, Hz	ξ, %	f, Hz	ξ, %	f, Hz	ξ, %	f, Hz
2.60	0.481	**2.60**	**0.481**	2.60	0.481	2.60	0.481	2.60	0.481
2.50	0.604	2.50	0.604	2.50	0.604	2.50	0.604	2.50	0.604
2.30	0.776	–	–	2.30	0.776	2.30	0.776	2.30	0.776
3.10	0.806	3.10	0.806	3.10	0.806	3.10	0.806	3.10	0.806
3.70	0.961	3.70	0.961	3.70	0.961	3.30	0.949	3.60	0.961
2.50	**0.981**	–	–	**2.50**	**0.985**	**1.10**	**0.991**	**2.50**	**0.985**

Table 3. Relative $\boldsymbol{H_2}$ error norm vs **r** of BIPS model

Model order r	model reduction technique			
	SAMDP	BT	IRKA	H-IRKA
40	0.6232	0.0098	0.0089	0.0049
50	0.6144	0.0025	0.0029	0.0012

Key Conclusions of Each Contribution

1. The modeling adequacy is dependent on the degree of nonlinearity of the physical layer, coupled with the uncertainty in the cyber layer.

2. ●Traditional model reduction techniques like BT, SAMDP, and IRKA algorithms face challenges in reducing MIMO models of modern power grid with wind farms.

●H-IRKA proposed in this work improves the accuracy of model order reduction of modern grids with explicit preservation of the 'critical eigenvalues' of the system.

3. ●Bound I - The uncertainty in cyber layer due to data packet drop and the off-nominal operation of physical layer affect the ORC performance in a coupled manner, where the coupling is non-trivial.

●Bound II - The ORC-related bound does not depend on observer gain whereas the CFC-related bound is a nonlinear function of the controller/observer gain and the input/output matrix.

●Derived bounds would be useful for system operators to perform online contingency screening and ranking from damping performance standpoint.

Products

J3. A. Yogarathinam, and N. R. Chaudhuri, "Wide-Area Damping Control using Reduced Copy under Intermittent Observation: A Novel Performance Measure," *in IEEE Transactions on Control Systems Technology (TCST)*, 2017.

J2. A. Yogarathinam, and N.R. Chaudhuri, "An Approach for Wide-Area Damping Control with Multiple DFIG-based Wind Farms Under Stochastic Data Packet Dropouts." in *IEEE Transactions on Smart Grid*, 2016.

J1. A. Yogarathinam, J. Kaur, and N. R. Chaudhuri, "A New H-IRKA Approach for Model Reduction with Explicit Modal Preservation: Application on Grids with Renewable Penetration," in *IEEE TCST* (under 2nd round of review).

C6. J. Kaur, and N.R.Chaudhuri, "MIMO Model Reduction of Modern Power Grids with Wind Generation: Some New Findings," in proceedings of *IEEE Power and Energy Society General Meeting (PESGM)*, 2017. ***Selected as one of the Best Conference Papers in IEEE PESGM 2017.***

C5. A. Yogarathinam, and N.R.Chaudhuri, "A Comparative Study on Wide-Area Damping Controllers using Multiple DFIG-based Wind Farms under Intermittent Observations," in proceedings of *IEEE PESGM*, 2017.

C4. 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 .

C3. 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 NAPS*, 2016.

C2. 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.

C1. 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 PESGM*, 2016.

TP1. A. Yogarathinam, "Wide-area power oscillation damping using wind farms in a networked controlled future smart grid," Thesis Proposal submitted and successfully defended during Ph.D. Comprehensive Exam at PSU, 2017.

Outreach Activities: Talks in Three ND Tribal Colleges

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