CPS: Medium: Data-driven Causality Mapping, System Identification and Dynamics Characterization for Future Power Grid

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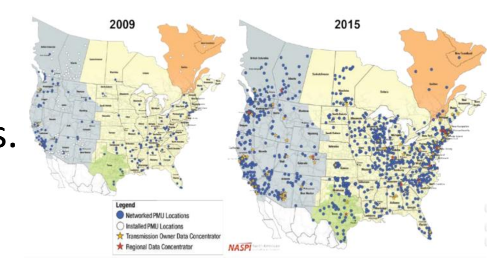
Significance and Objective

PMU deployment in US power grid

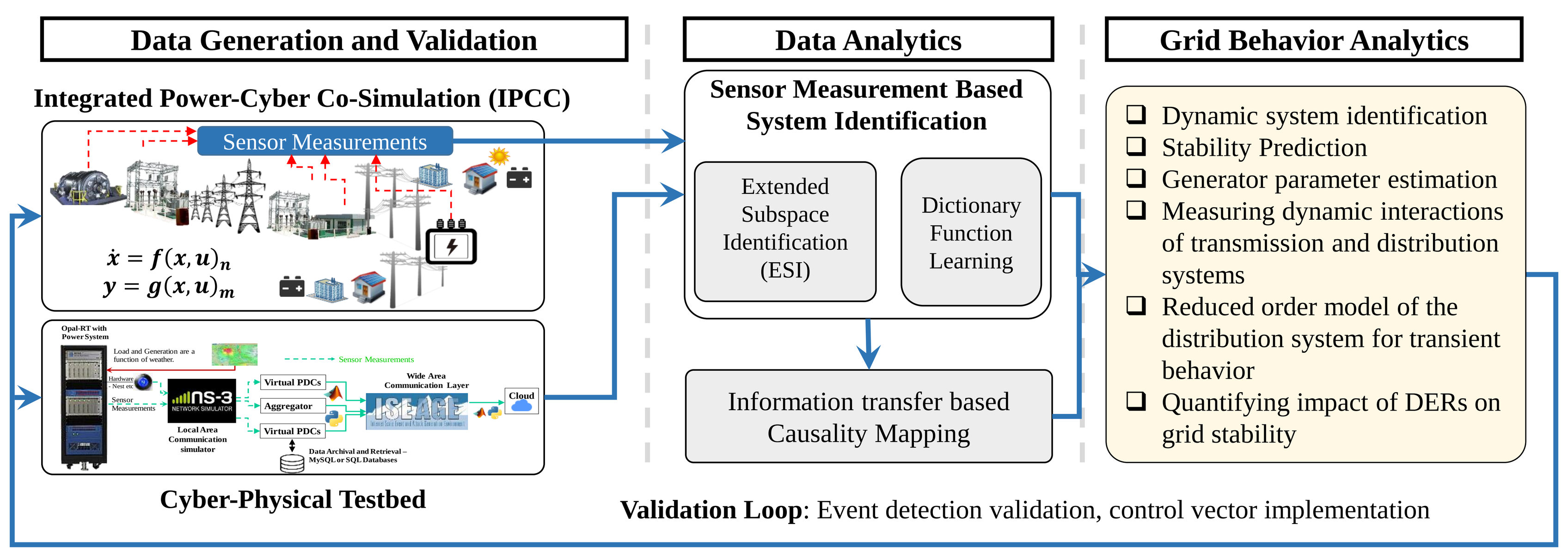


Source: DOE Report on Advancement on SynchroPhasor Technology

- Proliferation of measurement devices in the CPS space.
- Power system is a highly dynamical system with increasing number of sensors.
- Dynamic System Identification using sensor measurements.
- Use of outputs to overcome the challenge of non-measurable system states.
- Causality mapping in dynamical systems reveals system behavior.
- Power-cyber co-simulation to replicate accurate CPS system behavior.
- Hardware-In-the-Loop (HIL) real-time test bed for validation of the control methods validation in a real-time environment.

The objective of the proposal is to develop data-driven tools for dynamic system identification, classification and root-cause analysis of dynamic events, and prediction of system evolution by measure of causality mapping.

Project Overview



Intellectual Merit

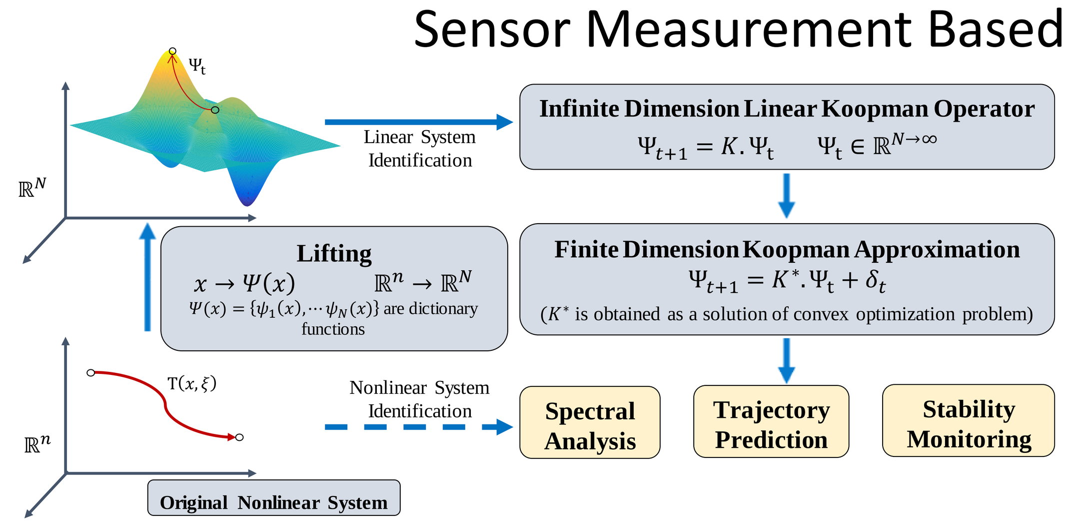
- Addressing the key challenges associated with output based identification of power system dynamics for prediction and control.
- Discover data-driven causality mapping for characterization of highly dynamical power system.
- An integrated power-cyber co-simulator emulating the real cyber-physical power grid by co-simulation of power systems and underlying sensor network [1].

Address the emerging challenges of 'highly dynamical systems' and 'data revolution' in CPS framework.

Applicable for practical CPS systems where sensor measurements capture dynamic behavior of the system.

Technical Approach

Sensor Measurement Based System Identification



- Developed an inertia estimation algorithm for power systems using the Koopman-based data-driven tool for approximating the temporal dynamics [1](results in Fig. 1).
- Developed a data-driven system theoretic approach to identify the source of forced oscillation in power system [2].
- For the responses with forced oscillations shown in Fig. 2, the proposed approach identified the source location of forced oscillations with limited training data-sets as shown in Table bellow (Higher α indicates the source of oscillations)

✓Uses PMU data for system identification, participation factor computation and parameter estimation.

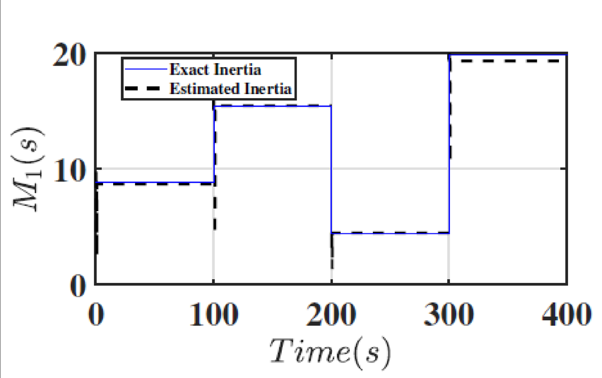


Fig.1 Inertia estimation and comparison.

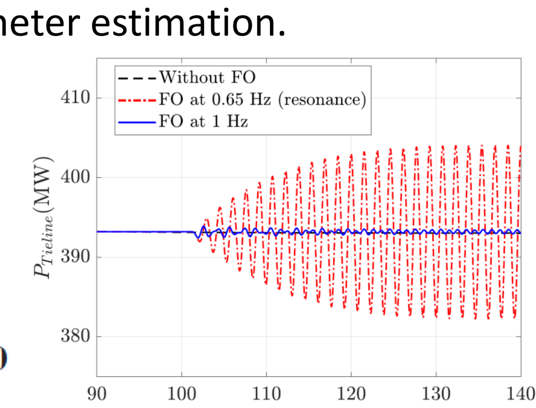


Fig.2 Tie line power flow

Scenario	α_1	α_2	α_3	α_4
γ = 0.005, f= 0.8Hz, base load, source = G1	**1.0000**	0.0000	0.0000	0.0000
γ = 0.016, f= 0.65Hz, base load, source = G2	0.2590	**0.2927**	0.2875	0.1608
γ = 0.016, f= 0.65Hz, base load, source = G3	0.1004	0.1855	**0.5698**	0.1442

1. M. Elnasry, A. R. R. Matavalam, P. Sharma and V. Ajjarapu, "Online Output-based Inertia Estimation of Modern Power Systems," *2023 IEEE Power & Energy Society General Meeting (PESGM)*, Orlando, FL, USA, 2023
2. B. Umathe, M. Elnasry, P. Sharma, U. Vaidya and V. Ajjarapu, "Data-Driven System Theoretic Approach for Identification of Forced Oscillations," *2022 IEEE Power & Energy Society General Meeting (PESGM)*, Denver, CO, USA, 2022

Structured Reduced order model

- Developed a structured reduced order model of distribution system that can replicate partial motor stalling and DER tripping [3].

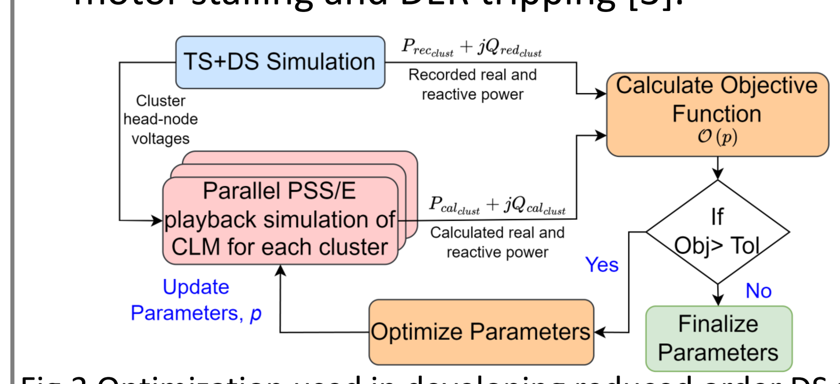


Fig.3 Optimization used in developing reduced order DS model

- Computation time reduced by 10x for systems – overall voltage error is ~ 1.4%

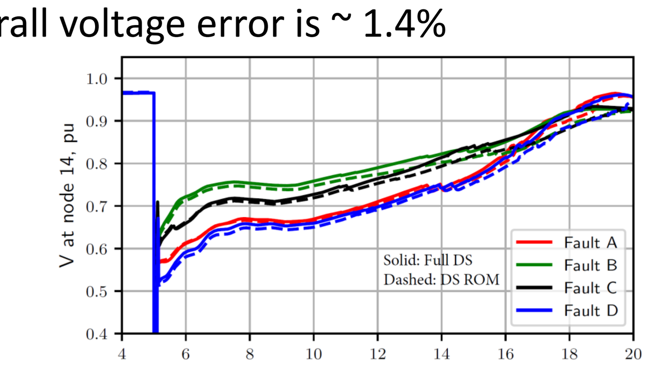
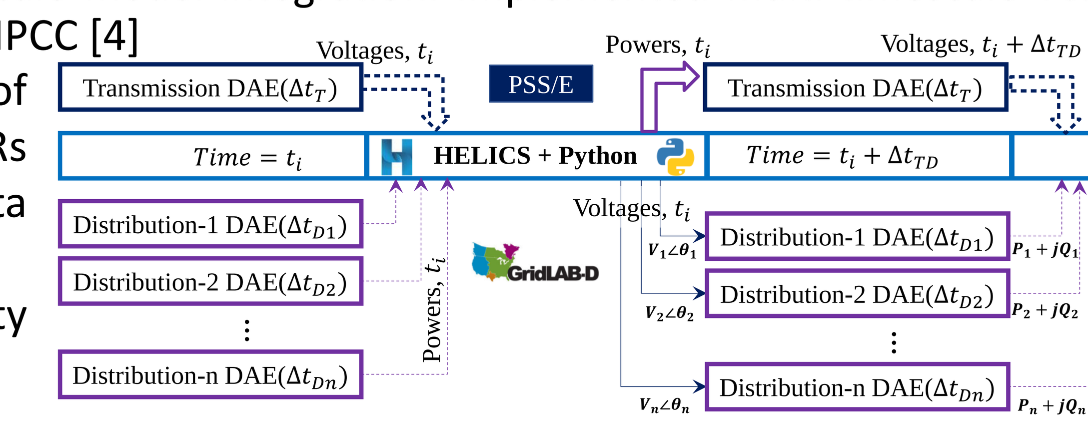


Fig.4 Voltage responses with full and reduced DS model

3. A. R. Ramapuram Matavalam, R. Venkatraman and V. Ajjarapu, "Accurate Representation of Distribution System Dynamics in Bulk System Studies by Clusters of Composite Load Models," *2023 IEEE IAS Annual Meeting*, Nashville, USA, 2023

Integrated Power-Cyber Co-Simulator

- Cyber-physical power system emulation for synthetic data generation and validation using the scalable solvers enabling realistic system multi-timescale model integration. Implemented multi-timescale T&D co-simulation framework as a foundation for IPCC [4]
- Successfully integrated dynamic models of distribution system components including DERs
- Identified scenarios for synthetic data generation and validation
- Studied the impact of DERs on voltage stability margin.



4. A. K. Bharati and V. Ajjarapu, "SMTD Co-Simulation Framework With HELICS for Future-Grid Analysis and Synthetic Measurement-Data Generation," in *IEEE Transactions on Industry Applications*, vol. 58, no. 1, pp. 131-141,. 2022.

Data-driven optimal control

- Developed a framework to quantify and control the information flows among the nodes in a network system following linear discrete stochastic dynamics [5].
- Developed a data-driven optimal control of nonlinear systems through a convex formulation of the optimal control problem with a discounted cost function [6].
- Presented an approach based on the spectral analysis of the Koopman operator for the approximate solution of the Hamilton Jacobi equation in optimal control problem.

5. M. S. Singh, R. Pasumarthy, U. Vaidya, and S. Leonhardt"On quantification and maximization of information transfer in network dynamical systems," Scientific Reports, vol. 13,no. 1, p. 5588, 2023.
6. J. Moyalan, H. Choi, Y. Chen, and U. Vaidya, "Data-driven optimal control via linear transfer operators: A convex approach," Automatica, vol. 150, p. 110841, 2023.

Broader Impacts- Outreach

- The research findings of this project are presented in IEEE panel sessions and working group meetings.
- The Co-PIs and PI offer courses in related aspects of the project. Further, develop integrated courses for the dissemination of the knowledge on data analytics, optimization and power systems operating and control that include using the measurements in the larger power grid.

Broader Impact- Research

- Real-world dynamical systems have limited observables, developed techniques will enable quick transition for field implementation.
- Developed a data-analytical and co-simulation framework that can analyze the impact of distributed energy resources (DERs) on the bulk electric grid.

Broader Impact- Education

- Incorporated the research findings and developments on IPCC in a course for advanced graduate students in electrical engineering at Iowa State University.
- The project team has contributed in writing book chapters related to the research findings in this project.

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