CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

Modeling Thrust Overview

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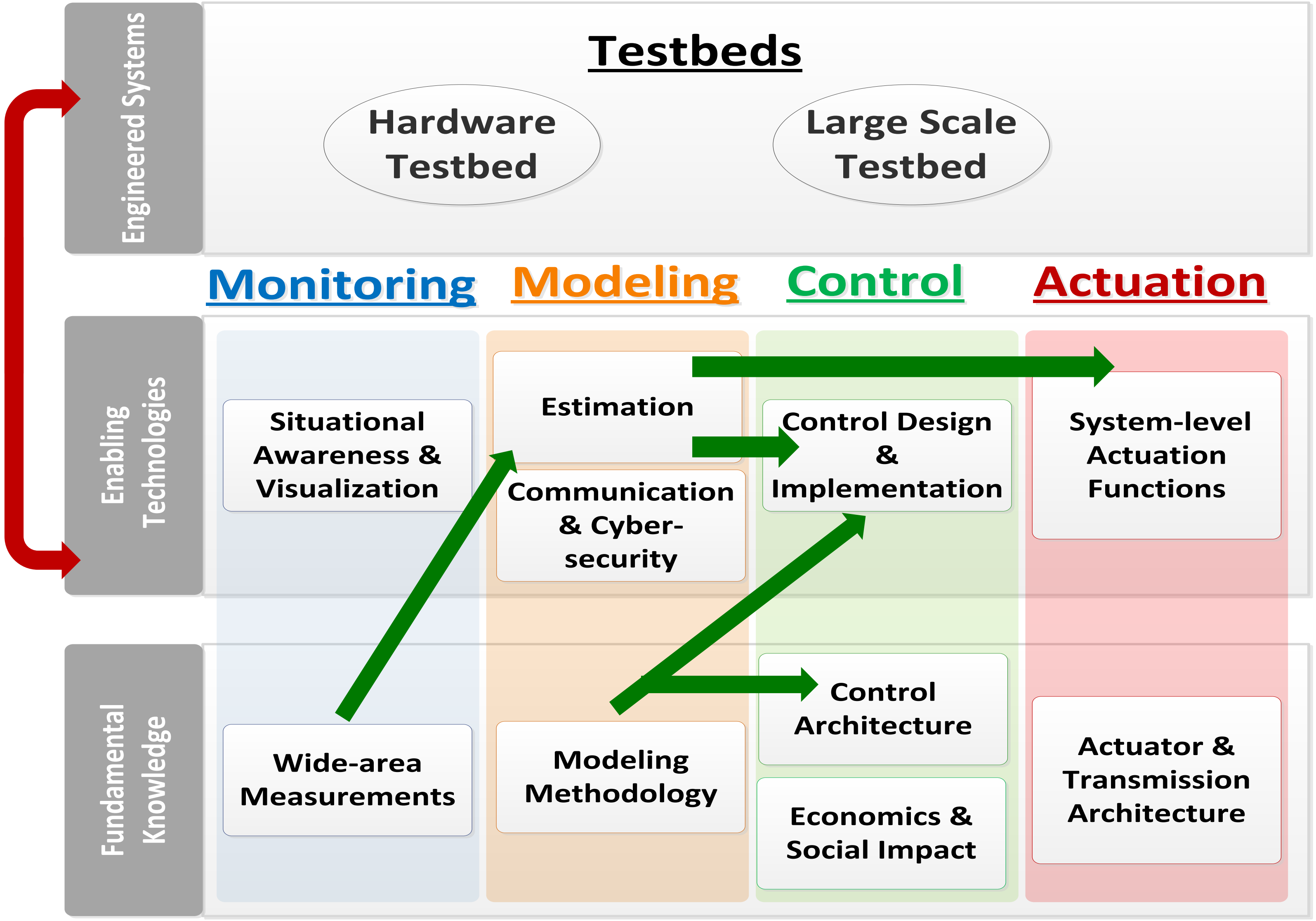
Modeling in CURENT, Linkage, and Research Focus



Objective

Develop modeling and estimation methods to facilitate wide-area monitoring, control and actuation tasks while addressing associated cyber-physical security challenges.

Research Focus

Robustness against errors
Model complexity
CPU requirements
Detection and mitigation of vulnerabilities to cyber and physical attacks

Modeling Thrust Intellectual Merit and Broader Impact

Intellectual Merit:

- Improves situational awareness and enables critical control actions via accurate and robust estimation of key system states
- Facilitates power system studies that require faster-than-real-time simulations

Broader Impact:

- Allows seamless integration and utilization of renewable energy sources by robust tracking of the system state, network model and device parameters under diverse operating conditions.
- Developed methods for power grids can be used in analysis of other networks such as transportation, health care, communication, etc.
- Increased partnerships between academia and industry
- Improved STEM education via REU and other outreach activities

Modeling Thrust Contributors

Faculty

- Stella Sun, Hairong Qi, Kai Sun, Kevin Tomsovic (UTK)
- Joe Chow, Luigi Vanfretti (RPI)
- Mandoye Ndoye (Tuskegee University)
- Alex Stankovic (Tufts)
- Hanoch Lev-Ari, Ali Abur (NEU)

Industry & Other Sponsors/Partners

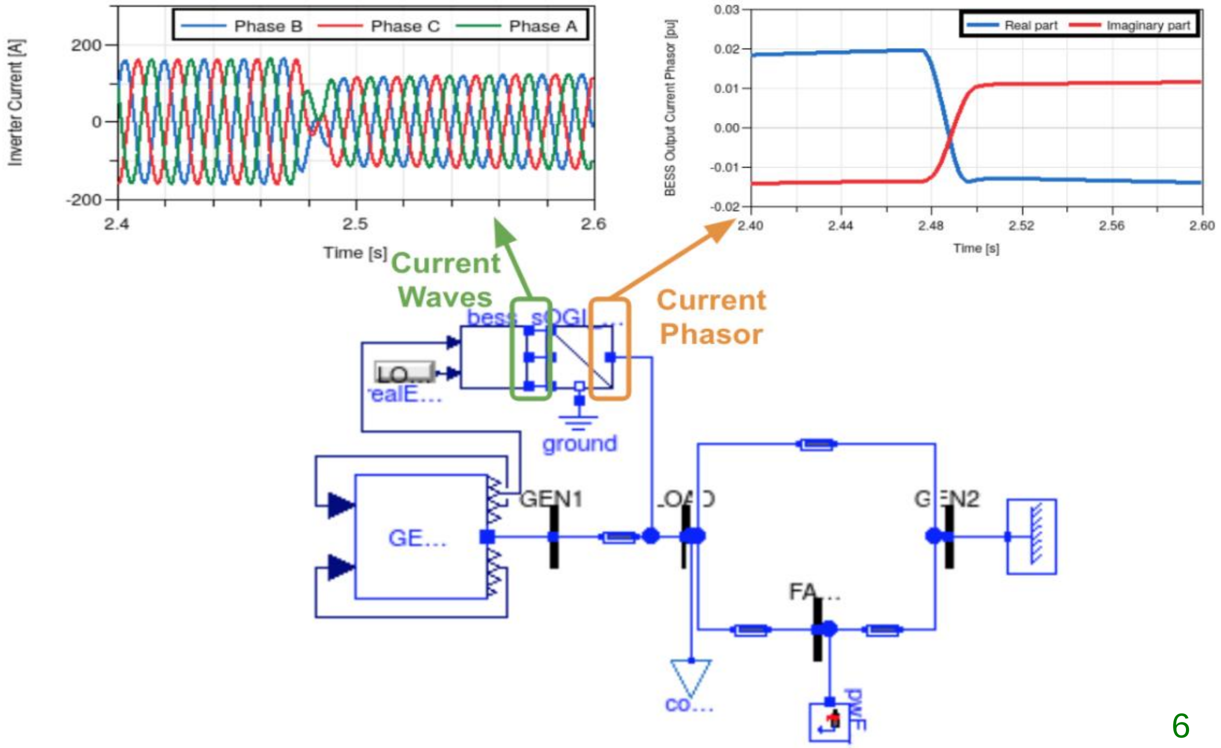
- ISO-New England, PJM Interconnection, ORNL, Dominion, EPRI

Modeling Thrust Roadmap and Key Milestones

	Generation I (Y1-Y3)	Generation II (Y4-Y6)	Generation III (Y7-Y10)
Estimation	• Phasor only state estimator (NPCC system as test-bed) • Phasor data error and contingency management • Resiliency against bad data, sensor failures and data latency • Impact of communication delays	• Multi-area phasor-only estimator • Network model error detection and identification method • Robust and computationally efficient dynamic state estimator: Method development, testing and evaluation	• State and topology estimation using node-breaker model • 3-phase SE for T&D systems with renewable sources. • Incorporating robust estimator into testbeds
Communication & Cyber Security	• Impact of communication delays in estimation • Detection and identification of network disturbances • Defense strategies against cyber-attacks on networks carrying PMU data • Secure outsourcing of intensive computations - method & testing	• Develop architectures for secure communications for wide-area SCADA systems • Determine effective security countermeasures for SCADA/PMU systems • Toward real-time detection and identification of multiple disturbances	• Identification of cyber-attacks on measurements, network parameters, communication links • Characterization and co-simulation of power and communication systems
Modeling Methodology	• Modeling spatial and temporal uncertainties in power and communication networks	• Quantifying vulnerability against uncertainties in network models • Reduced models with analytical and observed data • Fast Time-Domain Simulations	• Detection/removal of 1 and 3-phase network parameter errors • Faster than real-time modeling and simulation of PS dynamics

Year 9 Achievement Summary

- Development in Modelica of a hybrid Electromagnetic-Transient and Transient-Stability interface, allowing the assembling of a heterogeneous power system model in a single environment, that can be analyzed and simulated in multiple tools.
- Validation of the semi-analytical simulation approach on realistic differential-algebraic equation models of the Polish 2383-bus system and a reduced EI system with detailed generator and ZIP load models and integration of the approach with parallel-in-time simulation on HPC.
- Development of a decoupled three-phase state estimator which can be used for systems with non-transposed and/or mixed phase lines.
- Development of a scalable and robust state and topology estimator which uses node-breaker models and eliminates the need for a topology processor.



State Estimation without Topology Processor

Task Goals:

- Develop a generalized state estimator capable of detecting simultaneous topology and metering errors

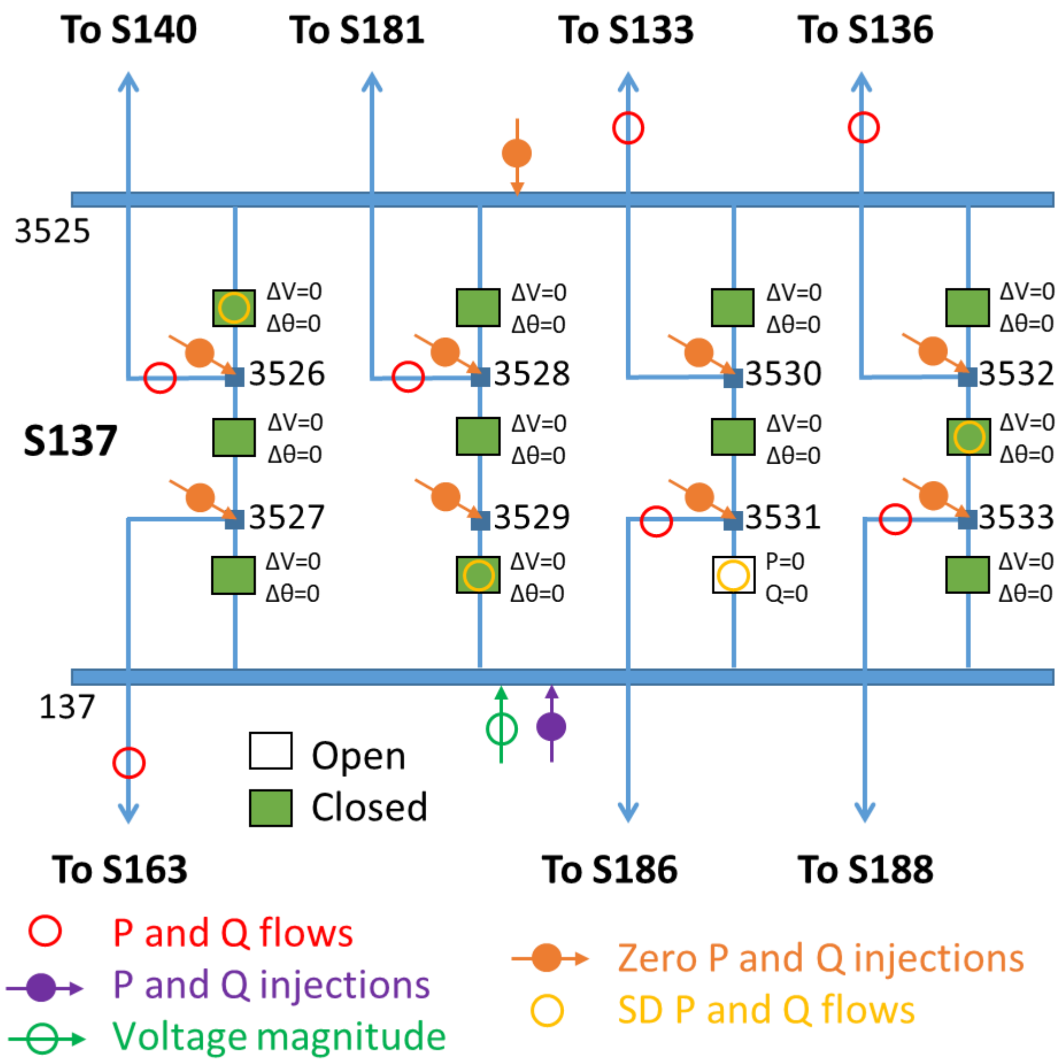
Barriers:

- Numerical issues with the inclusion of switching devices
- Compromised observability and redundancy due to new state variables
- Scalability challenges of node-breaker modeling

Research Achievements:

- Innovations in the estimation techniques to handle equality constraints
- Optimal measurement placement at substation level to minimize the total measurement count
- Judicious use of PMUs to enable zone-partitioning and parallel processing

Node-Breaker Modeling for a breaker-and-a-half substation



A General Decoupled Framework for SE Based on PMU Measurements

Task Goals:

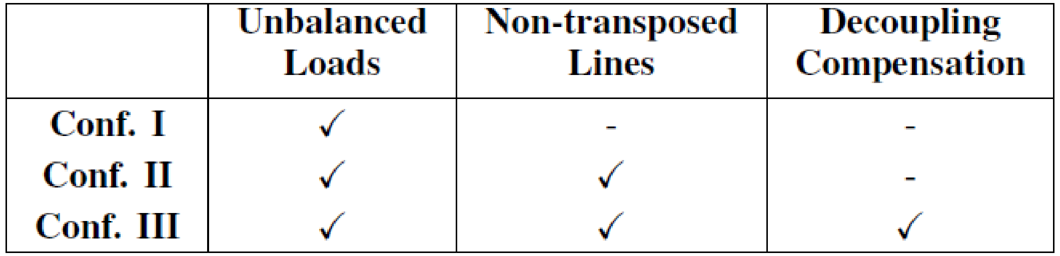
- Develop a decoupled SE method for more general systems with non-transposed and mixed-phase transmission lines
- Introduce a compensation method for decoupled SE

Barriers:

- Three-phase non-transposed lines
- Mixed-phase lines in distribution systems
- Bad data incident to the compensated lines

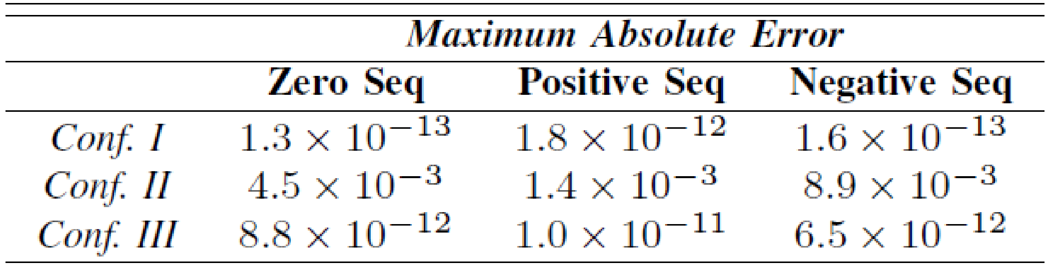
Research Achievements:

- Modeling non-transposed and mixed-phase lines
- Compensation method to use the decoupling to incorporate non-transposed and non-three-phase lines
- Method for decoupled SE using compensation method
- Bad data identification and correction in a decoupled framework



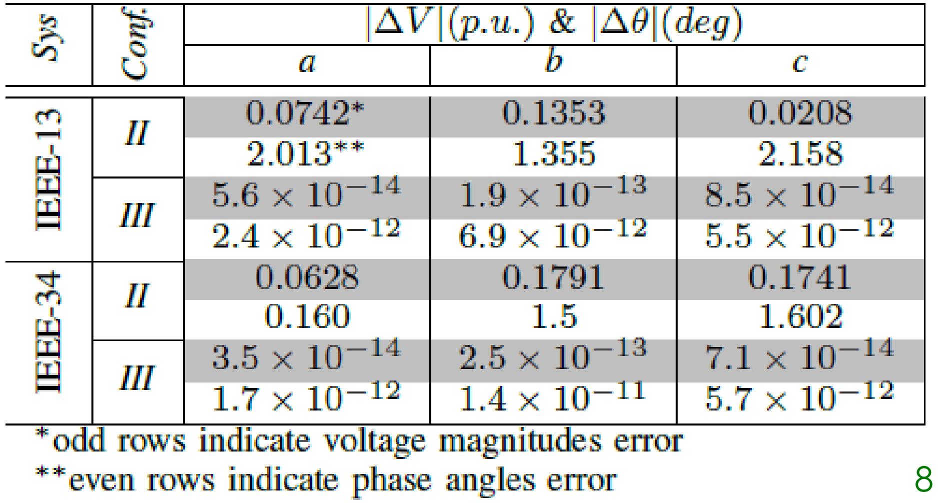
	Unbalanced Loads	**Non-transposed Lines**	**Decoupling Compensation**
Conf. I	✓	-	-
Conf. II	✓	✓	-
Conf. III	✓	✓	✓

Transmission system case: modified 118 bus system



	Maximum Absolute Error		
	Zero Seq	**Positive Seq**	**Negative Seq**
Conf. I	1.3×10^{-13}	1.8×10^{-12}	1.6×10^{-13}
Conf. II	4.5×10^{-3}	1.4×10^{-3}	8.9×10^{-3}
Conf. III	8.8×10^{-12}	1.0×10^{-11}	6.5×10^{-12}

Distribution system cases: IEEE 13 & 34



Sys	*Conf.*	$\lvert\Delta V\rvert(p.u.)$ & $\lvert\Delta\theta\rvert(deg)$		
		a	*b*	*c*
IEEE-13	*II*	0.0742*	0.1353	0.0208
		2.013**	1.355	2.158
	III	5.6×10^{-14}	1.9×10^{-13}	8.5×10^{-14}
		2.4×10^{-12}	6.9×10^{-12}	5.5×10^{-12}
IEEE-34	*II*	0.0628	0.1791	0.1741
		0.160	1.5	1.602
	III	3.5×10^{-14}	2.5×10^{-13}	7.1×10^{-14}
		1.7×10^{-12}	1.4×10^{-11}	5.7×10^{-12}

*odd rows indicate voltage magnitudes error

**even rows indicate phase angles error

Heterogeneous Modeling and Simulation of Coalesced Transmission and Energy Storage Systems for Power System Stability Analysis

Prof. Luigi Vanfretti
Student: Marcelo de Castro

Task goals:

- **Heterogenous modeling:** two different modeling approaches, same environment; i.e. **EMT and Phasor**/+ve Sequence
- **Interoperability:** exploit a **standardized** (many tools adopt it) an equation-based object-oriented **computer modeling language** (focus on modeling not the numerical solution)
- **Model Re-use:** time-domain **simulation, linearization and control** design to be carried on a singular environment

Barriers:

- Today, different isolated tools are used for power-electronics and power system analysis, limits the understanding of interactions
- Phasor (PSS/E-like) simulation with power electronics, imposes simplifications → loss of information → hard to capture interactions
- EMT models addresses these simplifications, but large models lead to unsurmountable computational burden/time and hard to analyze

Research Achievements:

- Development of a heterogeneous EMT-TS power system model that can be modeled in a singular environment
- Tool-agnostic: integrated modeling using standard-based language (Modelica), many tools can understand it
- Simulation and full linearization of heterogeneous models, allowing control design using entire hybrid EMT-TS models

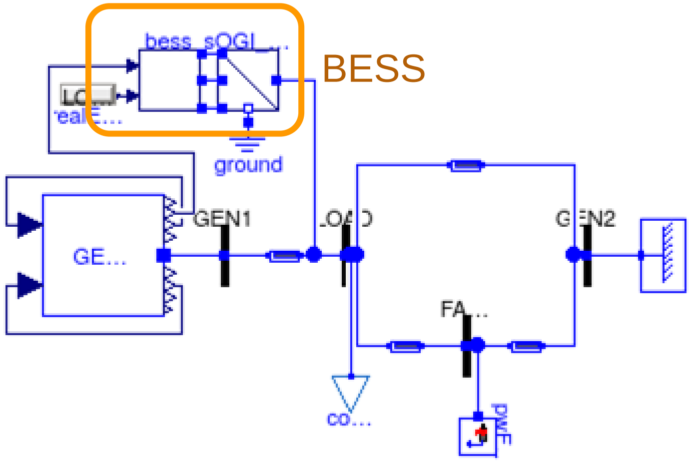


Fig 1. Simple phasor-domain SMIB system with a detailed EMTP-like model of a battery energy storage system.

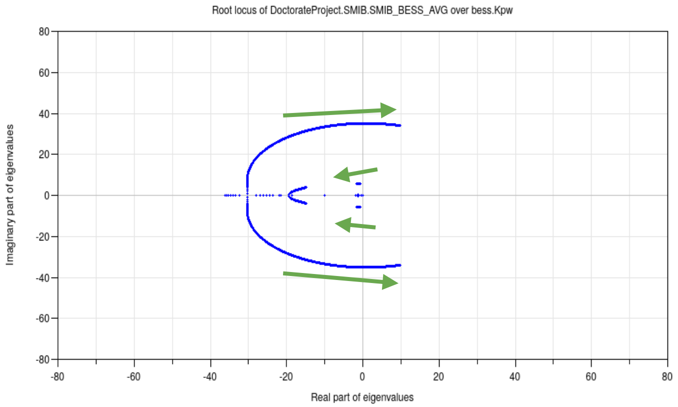


Fig 2. Linearization: Root used for tuning the the PSS controller in the BESS.

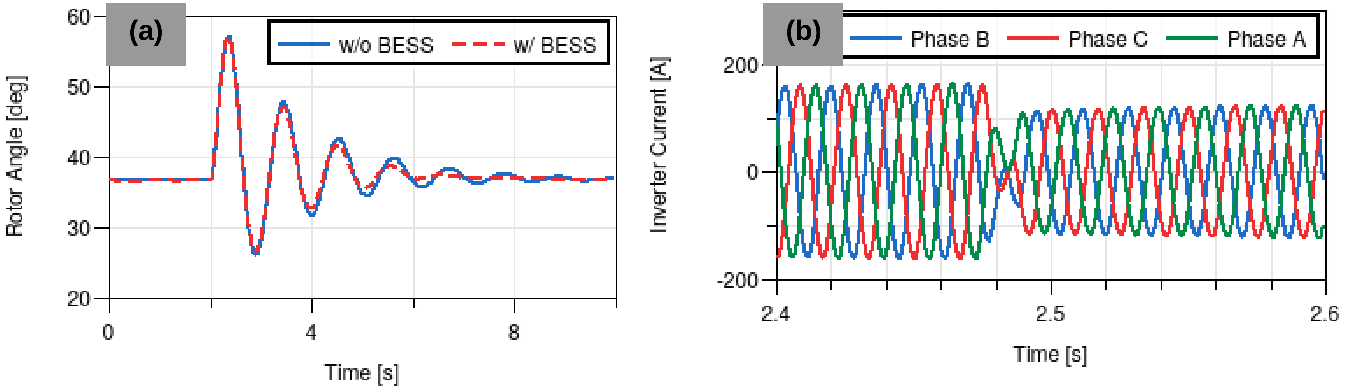


Fig 3. Phasor (a) and wave (b) results obtained from the hybrid model. Fig. 3 (a) shows two simulations, in blue it shows the response without the BESS, and in red the response with the BESS tuned using root locus (Fig. 2)

Semi-Analytical Approach for Simulation and State Prediction

Task Goals:

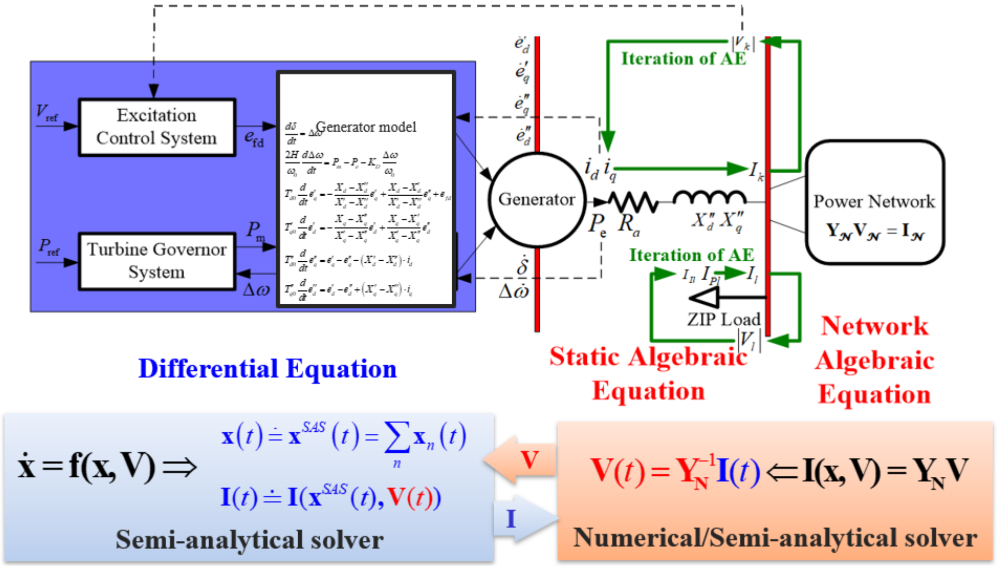
- Enable real-time simulation and prediction of the system state for proactive control considering uncertainties of renewables

Barriers:

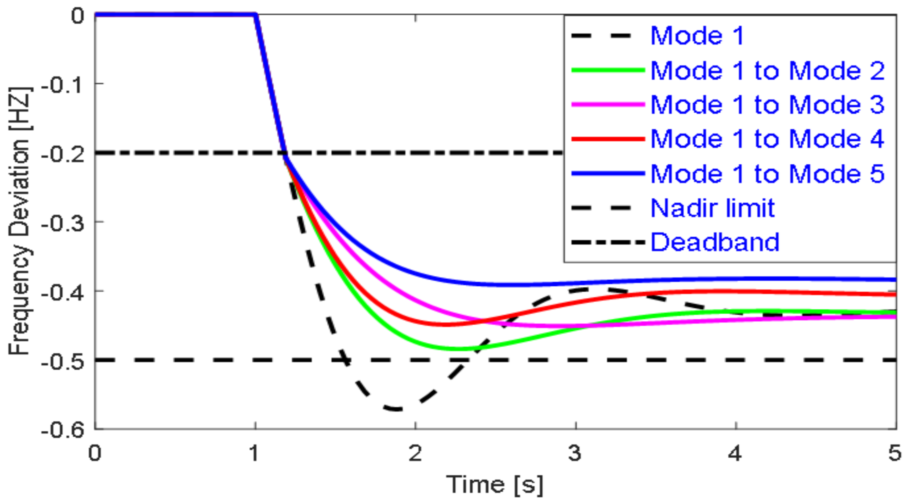
- Low-efficiency of numerical simulation in real time.
- Lack of grid state prediction for control of renewables.

Research Achievements:

- A new semi-analytical approach for real-time grid simulation with renewables.
- A number of new mathematical tools for semi-analytical solutions (SASs) of realistic power grid models.
- Validations on fast simulation of Polish 2383-bus system and reduced EI model and state prediction of wind farms for adaptive frequency response.
- Integration with ORNL’s parallel-in-time simulation on HPCs.
- Interfaced with ANDES to demonstrate simulation speedup.



Semi-analytical solvers for power system DAEs



Improved frequency responses with wind farms by state prediction and mode switching control

PMU Measurement-based Cyber-Physical Security

Task Goals:

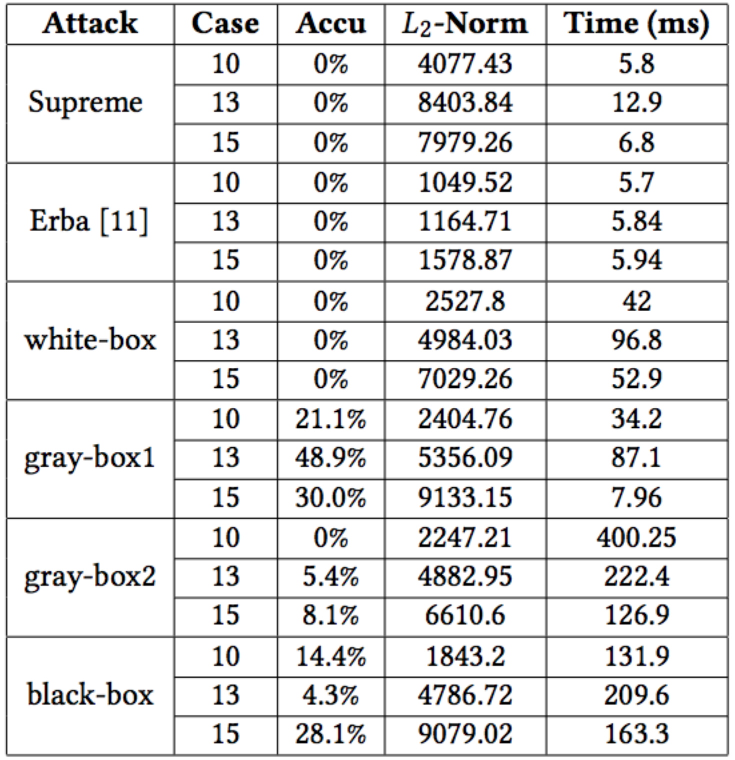
- Vulnerability assessment of machine learning used for detecting false data injection (FDI) attacks

Barriers:

- Lack of study on the security of machine learning used for FDI attack detection and other critical power system applications
- Potential security flaws could cause harm to human and assets

Research Achievements:

- Developed constrained adversarial machine learning, a feasible attack on the machine learning models used for FDI detection
- Developed a general threat model with physical and topological constraints suitable for critical infrastructure cyber-physical systems



Attack	Case	Accu	L_2-Norm	Time (ms)
Supreme	10	0%	4077.43	5.8
	13	0%	8403.84	12.9
	15	0%	7979.26	6.8
Erba [11]	10	0%	1049.52	5.7
	13	0%	1164.71	5.84
	15	0%	1578.87	5.94
white-box	10	0%	2527.8	42
	13	0%	4984.03	96.8
	15	0%	7029.26	52.9
gray-box1	10	21.1%	2404.76	34.2
	13	48.9%	5356.09	87.1
	15	30.0%	9133.15	7.96
gray-box2	10	0%	2247.21	400.25
	13	5.4%	4882.95	222.4
	15	8.1%	6610.6	126.9
black-box	10	14.4%	1843.2	131.9
	13	4.3%	4786.72	209.6
	15	28.1%	9079.02	163.3

Performance of the variants of the adversarial attack. The accuracy (Accu) of machine learning used for FDI detection is significantly reduced.

Modeling Plan for Next Year

	Year 10
Estimation	• Combining distribution and transmission SE and validating on LTB • Development of a decoupled 3-phase SE using SCADA and limited PMU measurements • Extension of parameter error detection to 3-phase network model using SCADA/PMUs
Cyber-Physical Security	• Develop countermeasures for adversarial machine learning attacks • Build security into machine learning used for critical power system applications
Modeling & Simulation	• Real time simulation of heterogeneous phasor/wave systems using the FMI standard • Integration of SAS and numerical methods in the HPC-enabled parallel-in-time framework for simulating future power grids with power electronics • Integration of physics and data driven models of power system dynamics • Implementation of developed methods on testbeds

Modeling Research Directions Beyond Year 10

- Application of Dynamic State Estimation to various power system control, protection and optimization problems.
- Applying the developed software tools for positive sequence network applications to three-phase or mixed phase unbalanced sub-transmission and/or distribution grids.
- Exploiting the development of the hybrid interface and heterogeneous models to assess interaction between controllers in power systems with high penetration of power electronic devices.
- Improving power system resilience during extreme events by exploiting the detection and estimation tools developed in CURENT.
- Demonstration of HPC-enabled faster-than-real-time simulation and analysis tools.

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