Faculty Research Overview

CURENT Annual Industry Conference

April 29 and May 1, 2024

Knoxville, TN

Fangxing “Fran” Li

- **UTK John W. Fisher Professor, CURENT Director, LTB Lead**
- **Research Interests: resilience, demand response, power system economics, machine learning for power.**
- **fli6@utk.edu; http://web.eecs.utk.edu/~fli6/**

2023-24 Research Projects/Highlights

1. CURENT Large-scale testbed (LTB)
2. Development of Load Flexibility Valuation Methodology & Framework to Input into Planning Tools (**Southern Company**)
3. Networked Microgrids and Solid-State Power Substations Hierarchical Systems Frameworks (**ORNL**)
4. Production Cost Modeling to Assess the Benefit of Geothermal Deployment (**ORNL**)
5. Model-Free Adaptive Control (MFAC) for Autonomous and Resilient Microgrids (**DOD ESTCP**)
6. Adaptive dynamic coordination of damping controllers through deep reinforcement and transfer learning (**NSF**, PI: H. Pulgar)
7. An Equitable, Affordable & Resilient Nationwide Energy System Transition (EARNEST) (**DOE/Stanford**)
8. POSE: Phase I: Toward an Open-Source Ecosystem for Power Systems Research, Education, and Industry Applications (**NSF/Oklahoma State University**)

CURENT Large-scale Testbed (LTB)

Project Objectives

- To develop a closed-loop platform that includes both dynamic and dispatch/market simulation
- To enable dispatch-dynamic interfaced co-simulation

Recent Achievements

- Created Homepage for CURENT LTB
- Created Linkedin Account for CURENT LTB
- AMS development, benchmark, and release
- AGVis backend improvement with web application

Best Graduate Paper Award, NAPS 2024

Hybrid symbolic-numeric power system modeling and simulation

ANDES
Dynamic Modeling and Simulation

AGVis
Energy System Visualization

Geographical visualization for energy system

Dynamic information interfaced scheduling modeling and simulation

AMS
Scheduling Modeling & Sim.

DiME
Multi-terminal Data Streaming

Data messaging between multiple power system components

LTB Structure

Model-Free Adaptive Control (MFAC) for Autonomous and Resilient Microgrids (1)

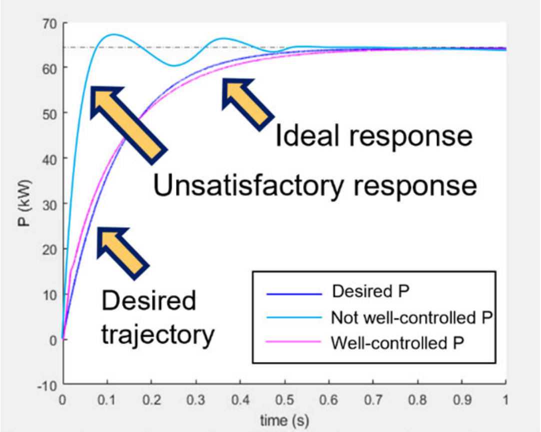
Project Objectives

- Employ domain knowledge and **AI** to achieve autonomous grid-following and grid-forming controls for microgrids
- Achieve higher grid resilience
- Microgrid control under insufficient capacity
- Virtual Inertia Scheduling

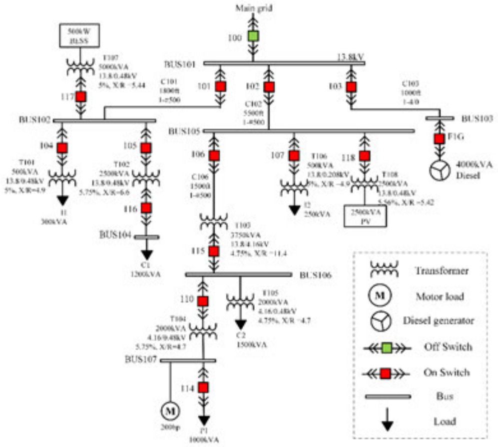
Recent Achievements — Part I:

PQ Control with trajectory tracking capability [1]

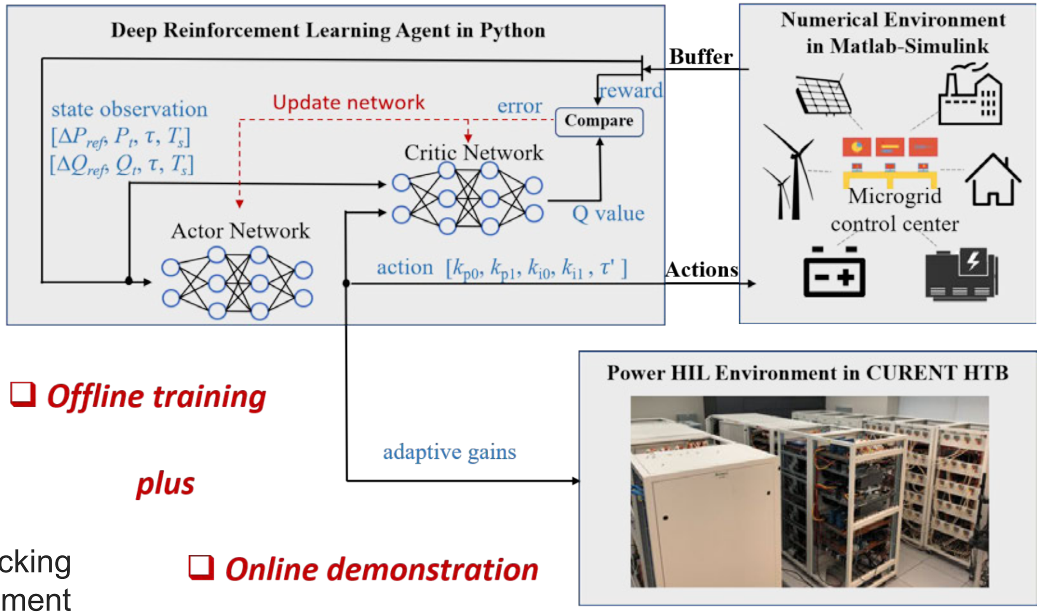
- Developed inverter PQ control for trajectory tracking using physics-informed deep reinforcement learning
- Configurate modified Banshee microgrids in CURENT HTB and validate the controller through power HIL experiment



Power curve tracking the predefined trajectory



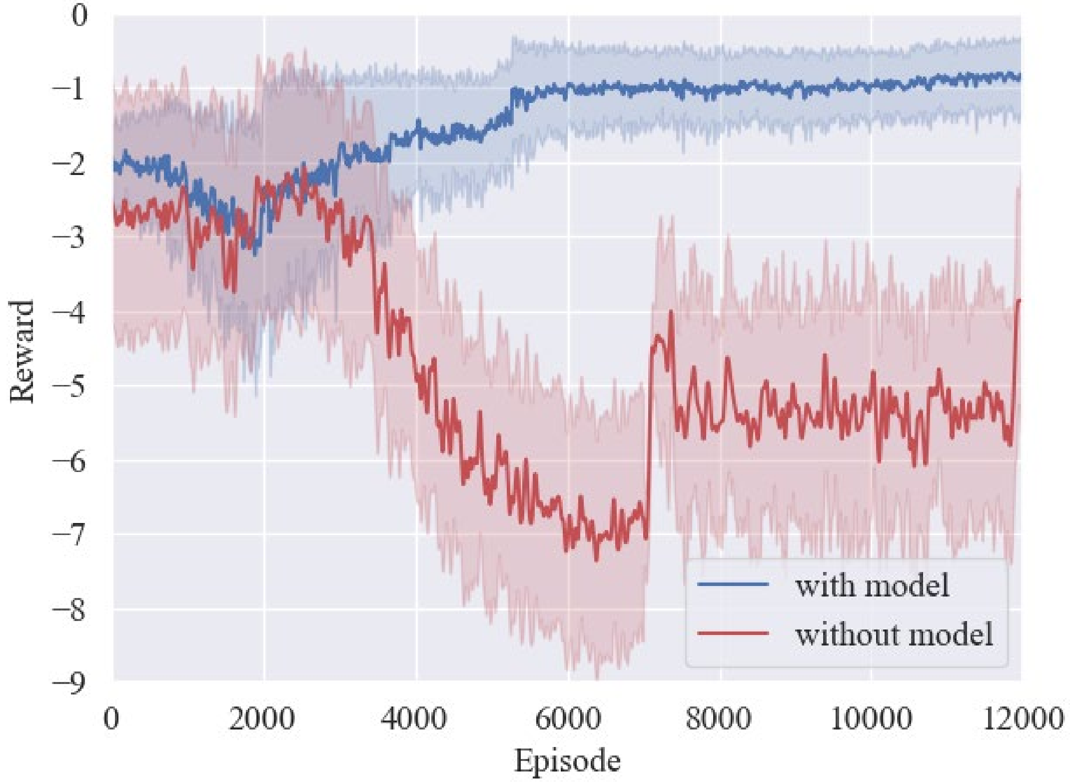
Modified Banshee microgrid in HTB



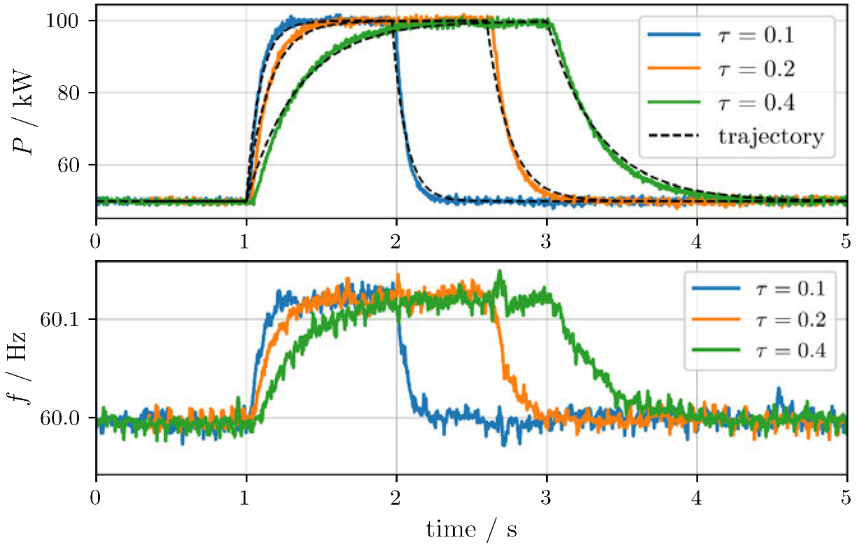
Model-free adaptive PQ control based on physics-informed reinforcement learning and power HIL experiment

[1] B. She, F. Li*, et.al. "Inverter PQ Control with Trajectory Tracking Capability for Microgrids Based on Physics-informed Reinforcement Learning ", *IEEE Transactions on Smart Grid*, 2024.

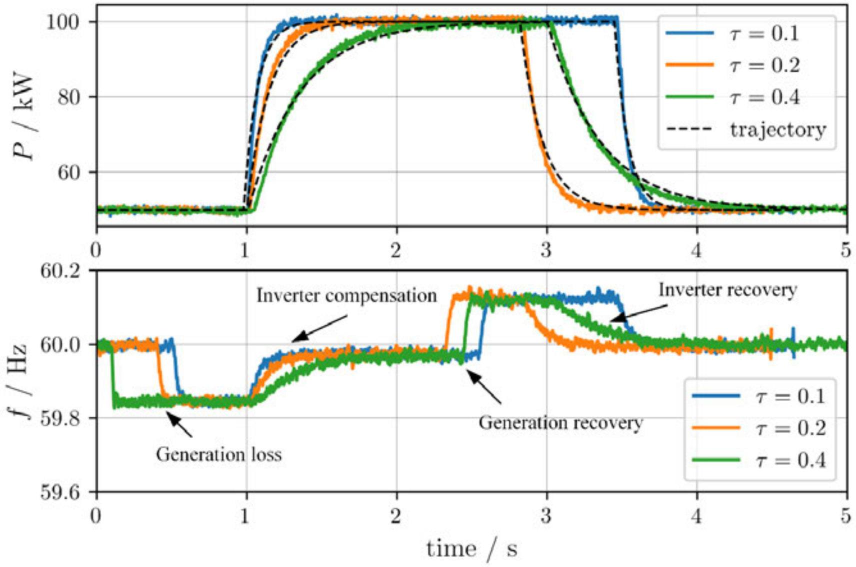
Results of PQ control with trajectory tracking



Reward curve with and without model-based analysis



Scheduling reference change



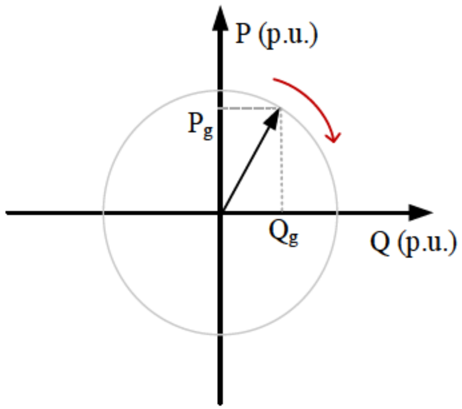
Generation reduction & recovery

Model-Free Adaptive Control (MFAC) for Autonomous and Resilient Microgrids (2)

Recent Achievements – Part II:

V-f Control considering DER inadequacy [2]

- Developed decentralized and coordinated V-f control under insufficient resource capacity for islanded microgrids
- Mathematically proved the existence of equilibriums and small signal stability



Grid-forming inverter output following the limited DER capacity

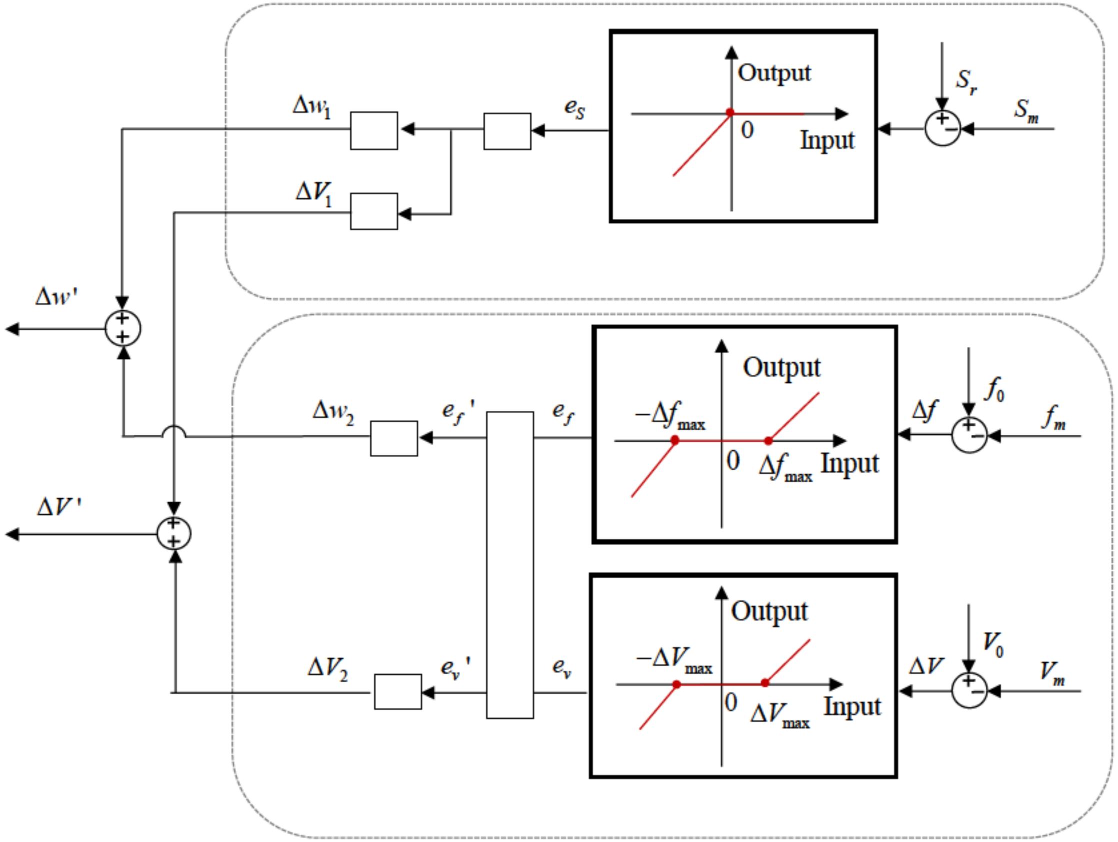
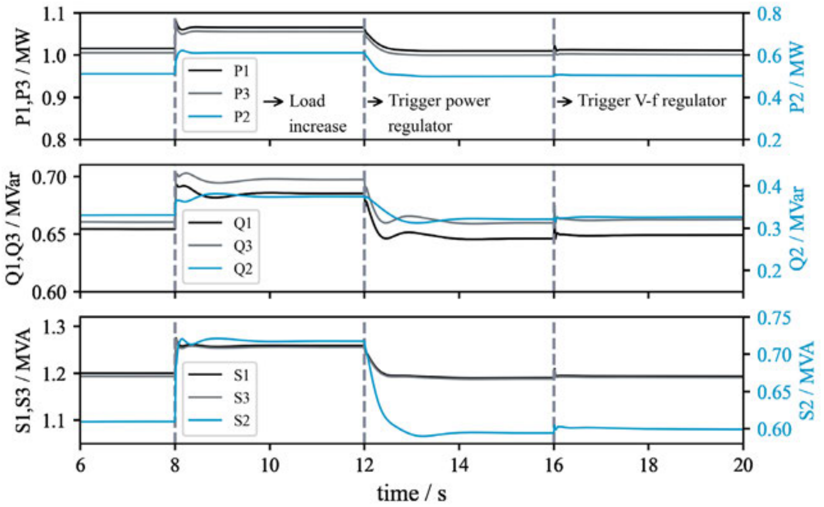


Diagram of the proposed decentralized and coordinated control framework

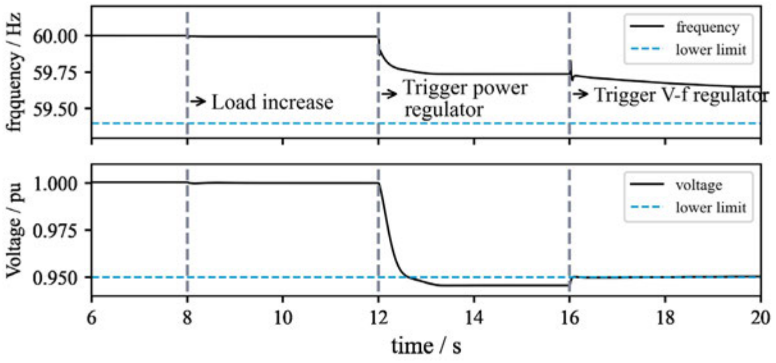
[2] B. She, F. Li*, et.al. "Decentralized and Coordinated V-f Control for Islanded Microgrids Considering DER Adequacy and Demand Control ", *IEEE Transactions on Energy Conversion*, 2023.

Results of V-f control with DER inadequacy

Simulation results: Scenario 1

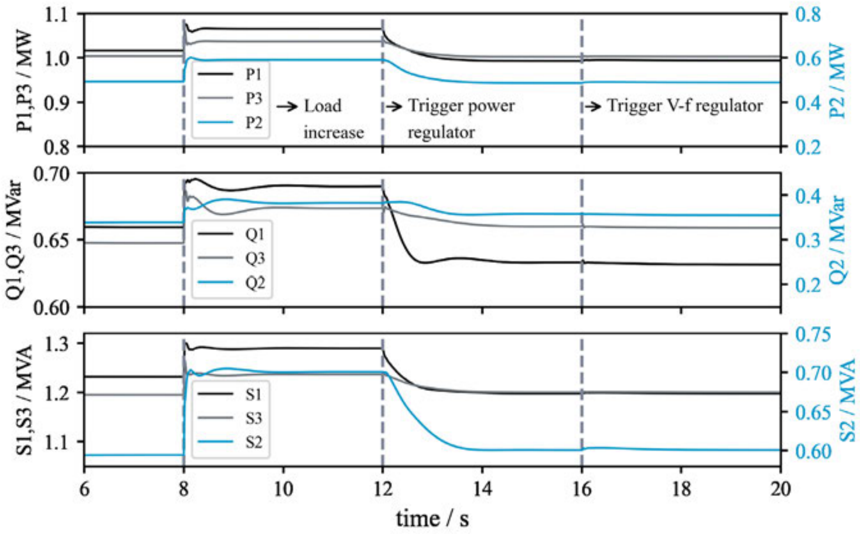


Dynamic inverter output

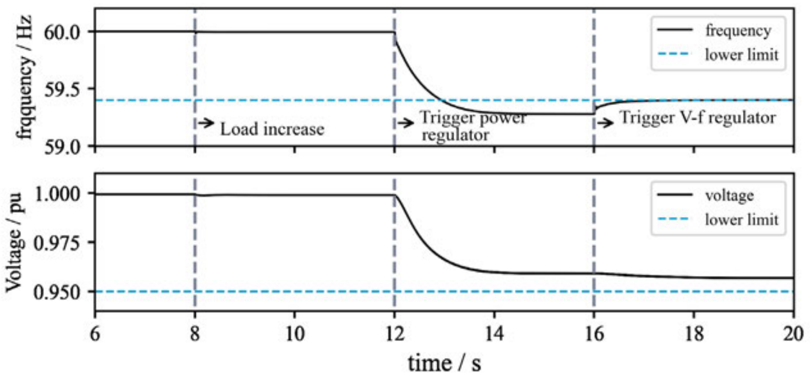


V-f response: increase Q, decrease P

Simulation results: Scenario 2



Dynamic inverter output



V-f response: increase P, decrease Q

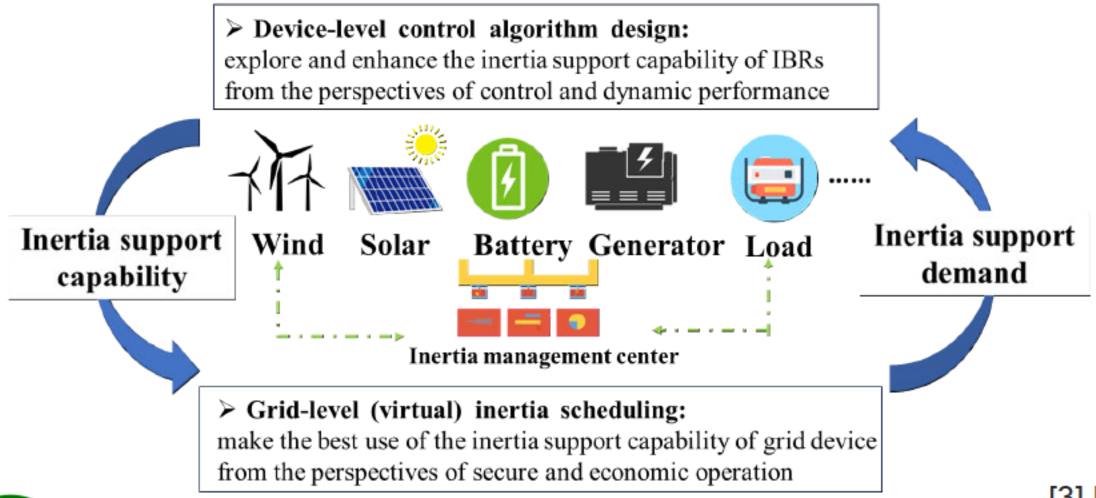
Model-Free Adaptive Control (MFAC) for Autonomous and Resilient Microgrids (3)

ESTCP

Recent Achievements – Part III:

Virtual Inertia Scheduling (VIS) for low inertia grids [3]

- Proposed the concept of VIS, a security-constrained and economy-oriented inertia scheduling and generation dispatch framework for power grids with a large scale of IBRs.
- VIS schedules the power setting points, as well as the control modes and control parameters of IBRs to provide secure and cost-effective inertia support.



➢ **Formulation of VIS**

Inertia support cost

$$\min_{P,M,D} C_{gen}(P) + C_{aux}(P,M,D)$$

Generation cost

s.t. 1) Standard dispatch constraints

2) $$\begin{cases} M_i^{\min,ibr} \le M_i^{ibr} \le M_i^{\max,ibr}, \forall i \in \{1,\cdots,N_{ibr}\} \\ D_i^{\min,ibr} \le D_i^{ibr} \le D_i^{\max,ibr}, \forall i \in \{1,\cdots,N_{ibr}\} \end{cases}$$

3) $$\begin{cases} -RoCof_{\lim} \le f_0 \dfrac{\Delta P_{e,t}}{M_t} \le RoCof_{\lim}, \ \forall t \in \{1,\cdots,T\} \\ f_{\min} \le f_0 + \Delta f_{nadir,t} \le f_{\max}, \ \forall t \in \{1,\cdots,T\} \end{cases}$$

[3] B. She, F. Li*, et.al. "Virtual Inertia Scheduling for Power Systems with High Penetration of Inverter-based Resources". *IEEE Transaction on Sustainable Energy*, 2024.

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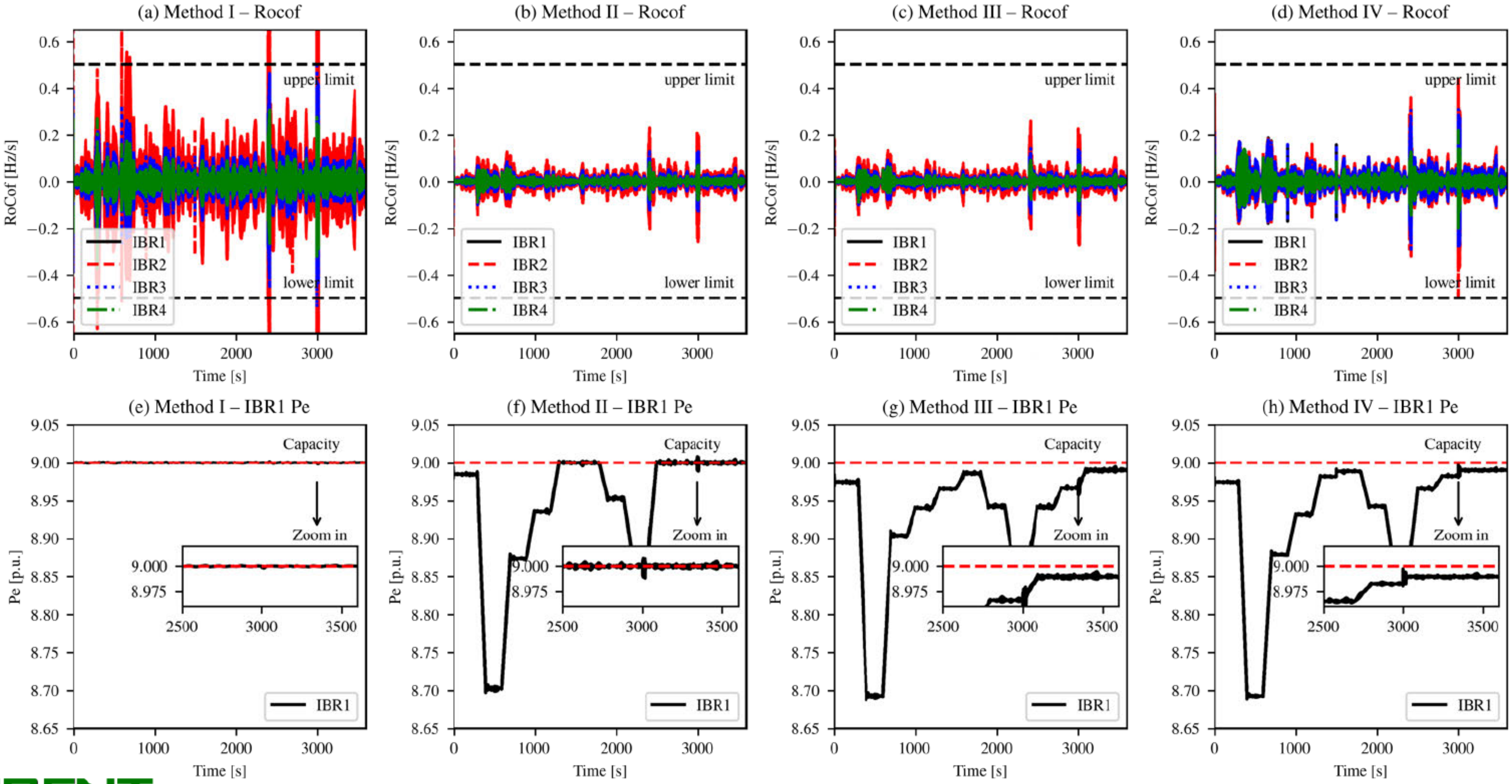
Results of Virtual Inertia Scheduling (VIS)

➢ **Comparison study of one-hour dispatch + time-domain simulation**



(I) Constant power; (II) Fixed M & D, no reserve; (III) Fixed M & D, with reserve; (IV) VIS algorithm

Yilu Liu

- UT/ORNL Governor's Chair, CURENT Deputy Director
- Research Interests: grid monitoring and applications, oscillation damping control, Inertia and grid strength, EMP impact, Micro Grid,
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2023-2024 Research Projects

1. Forced oscillation source location tool (EPRI)
2. Forced oscillation source type classification (TVA)
3. EI system inertia trending study (Dominion)
4. Data center models (Dominion)
5. Digital twin for microgrid (Southern Company)
6. Adaptive oscillation damping control and field test (EPRI, NYPA, TERNA, DOE)
7. EMP susceptibility characterization of generation stations (ORNL, TVA, Domimion)
8. Secure timing system using pulsar signal (NSF)
9. BESS probing for inertia estimation in real time (NREL, KIUC, AES, GPTech)
11. Pump storage operation signature-based inertia estimation (WPTO, Dominion, TVA, PG&E)
12. Develop low cost syn-wave monitors for PV systems (ORNL, DiGiCollect).
13. OEDI Distribution state estimation, VW control, and transient data generation (ORNL, DOE SETO)
14. Virtual Operator Assistance – AI based fast real time transient stability prediction tool (ORNL, DOE AGM)
15. FNET/GridEye data transmission, visualization, and real time applications (NERC, AGM)
16. Oscillation and inertia trending (ORNL)
17. Landfill site microgrid development feasibility study (EPB, KUB)
18. Real time grid frequency prediction (Apple)

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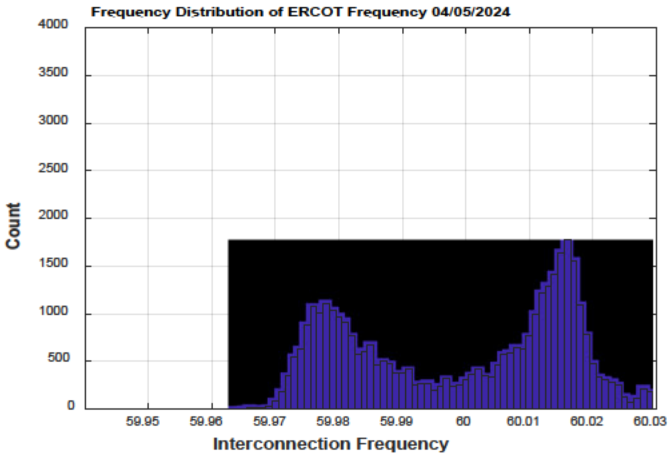
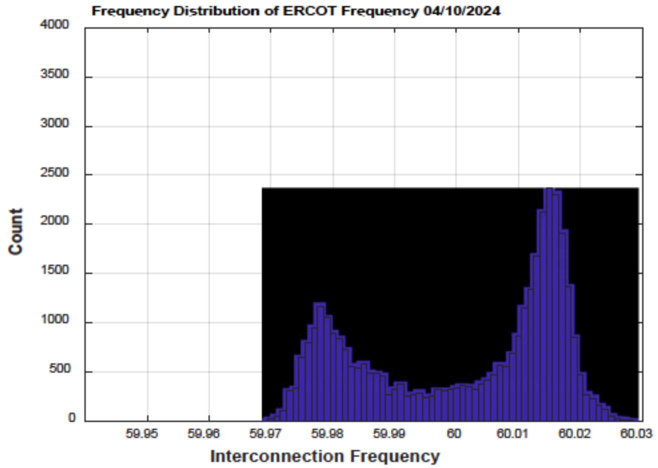
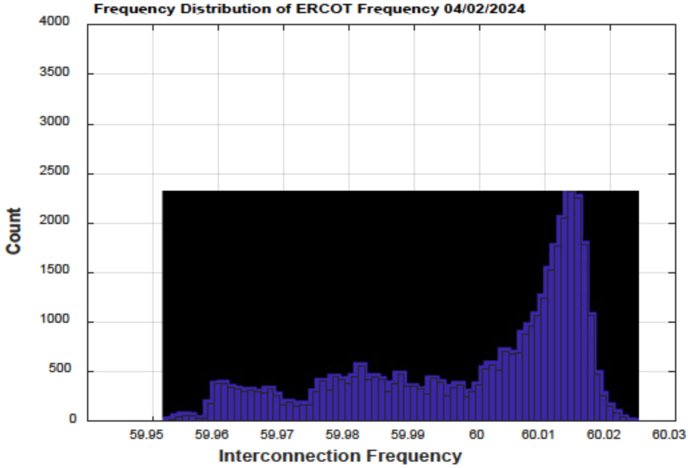
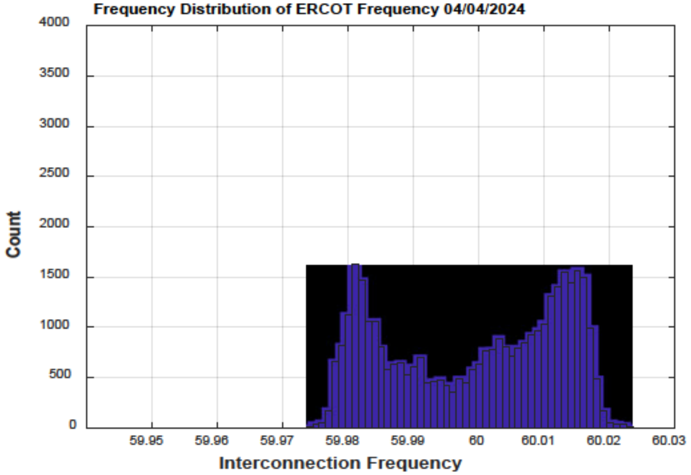
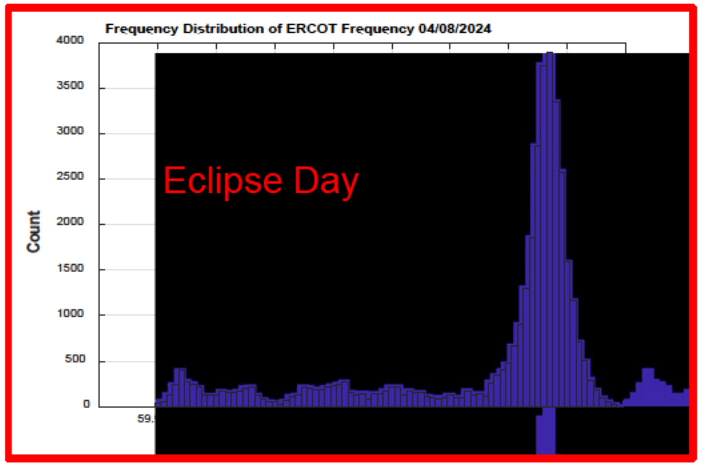
ERCOT Frequency - Eclipse Time 18:00 -19:00 UTC











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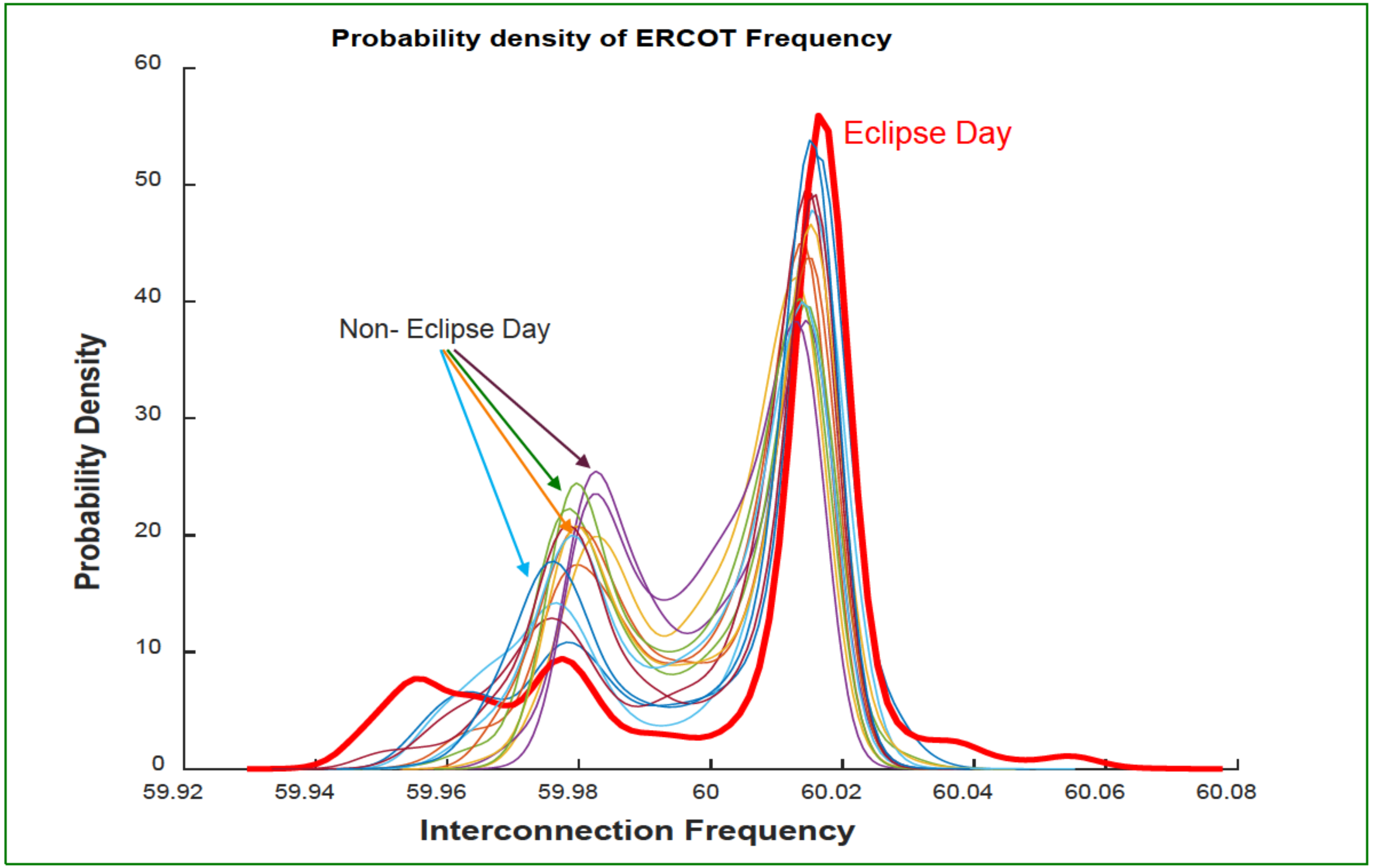
Map Source: https://science.nasa.gov/eclipses/future-eclipses/eclipse-2024/where-when/
Photo Source: Dr. Anil Pahwa

Probability Density of ERCOT (Eclipse hours)



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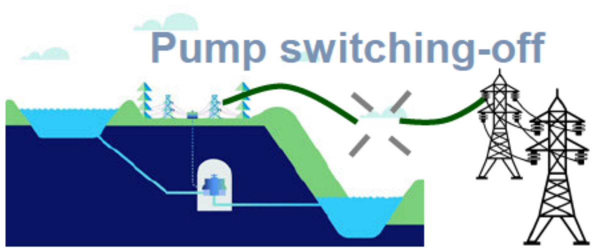
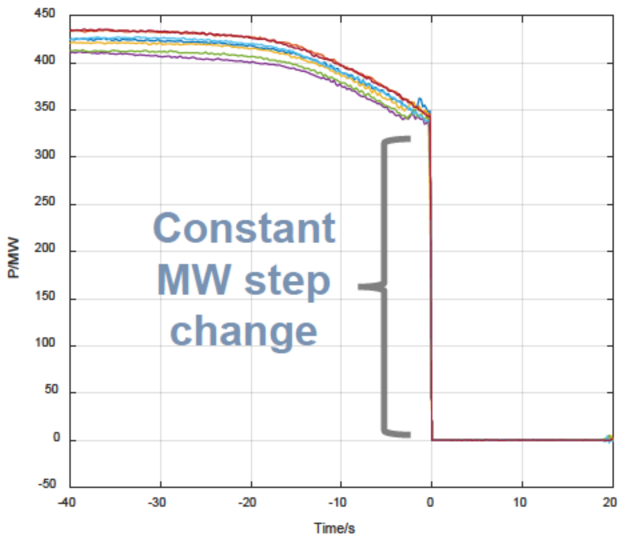
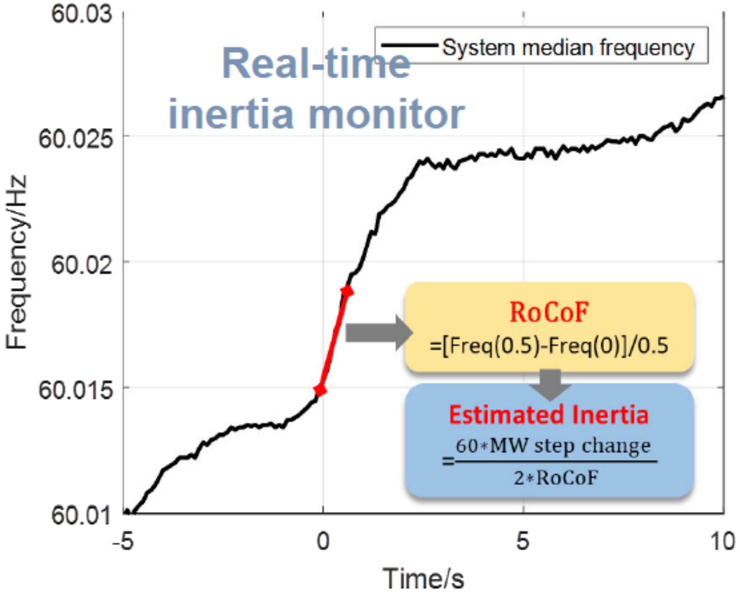
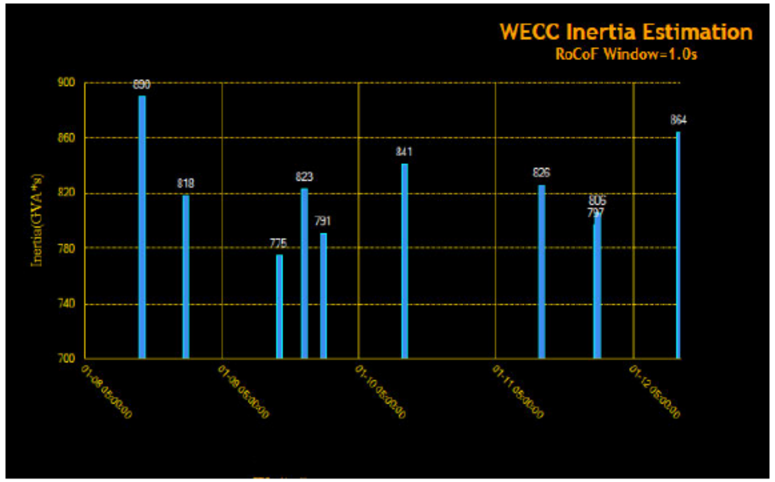
Inertia Monitoring – EI, WECC, KIUC

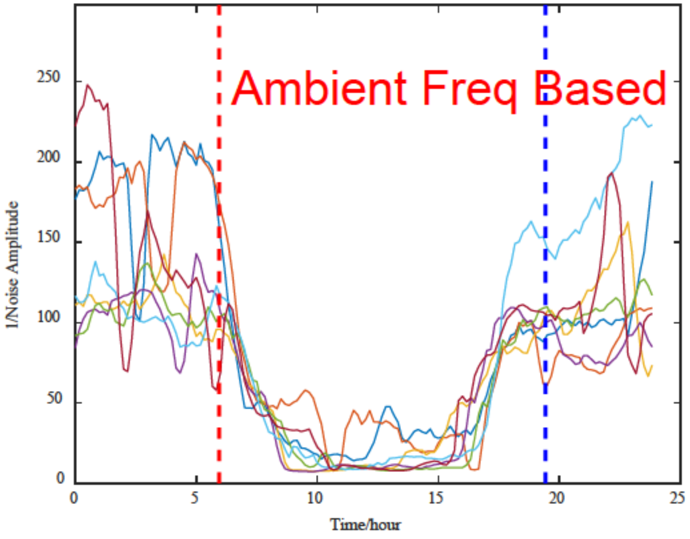


Helms (PG&E)
Bath County (DOM)
Racoon Mt (TVA)

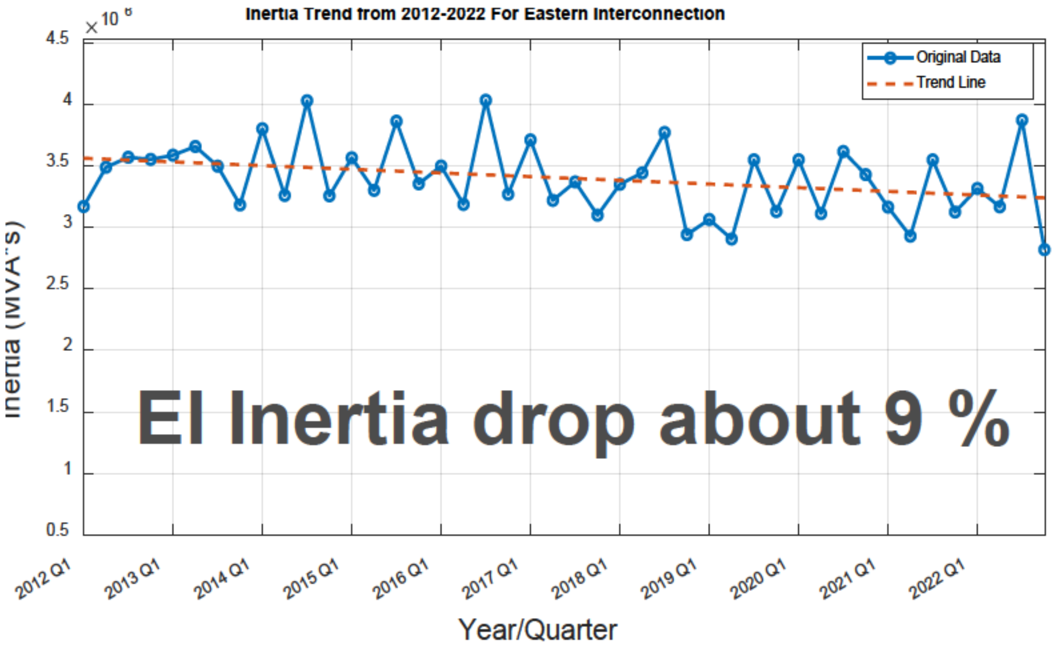


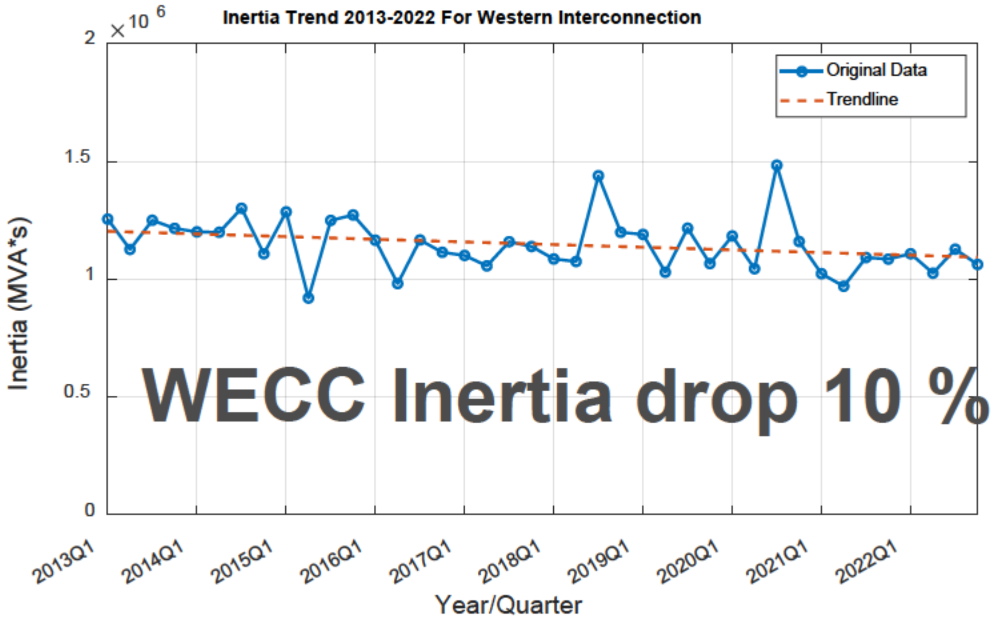


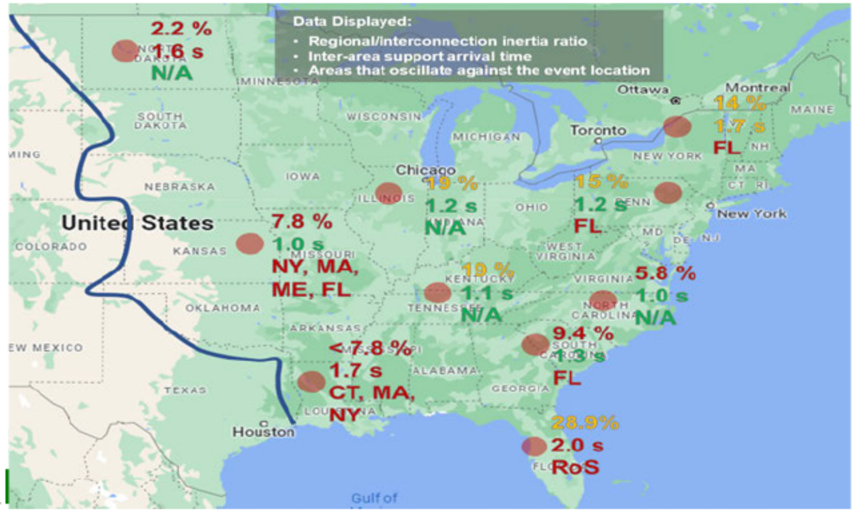


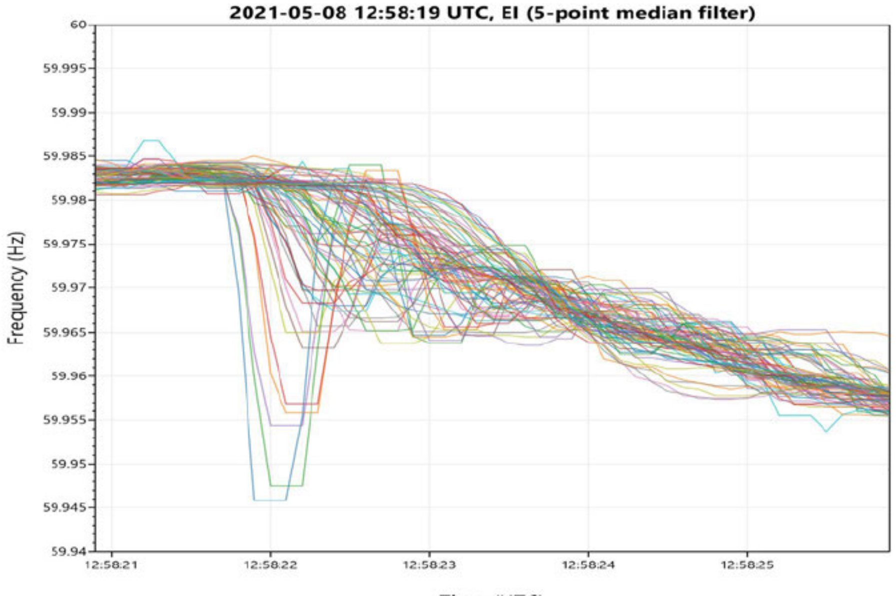


EI, WECC Inertia Trend 2012-2022 (DOM, ORNL)

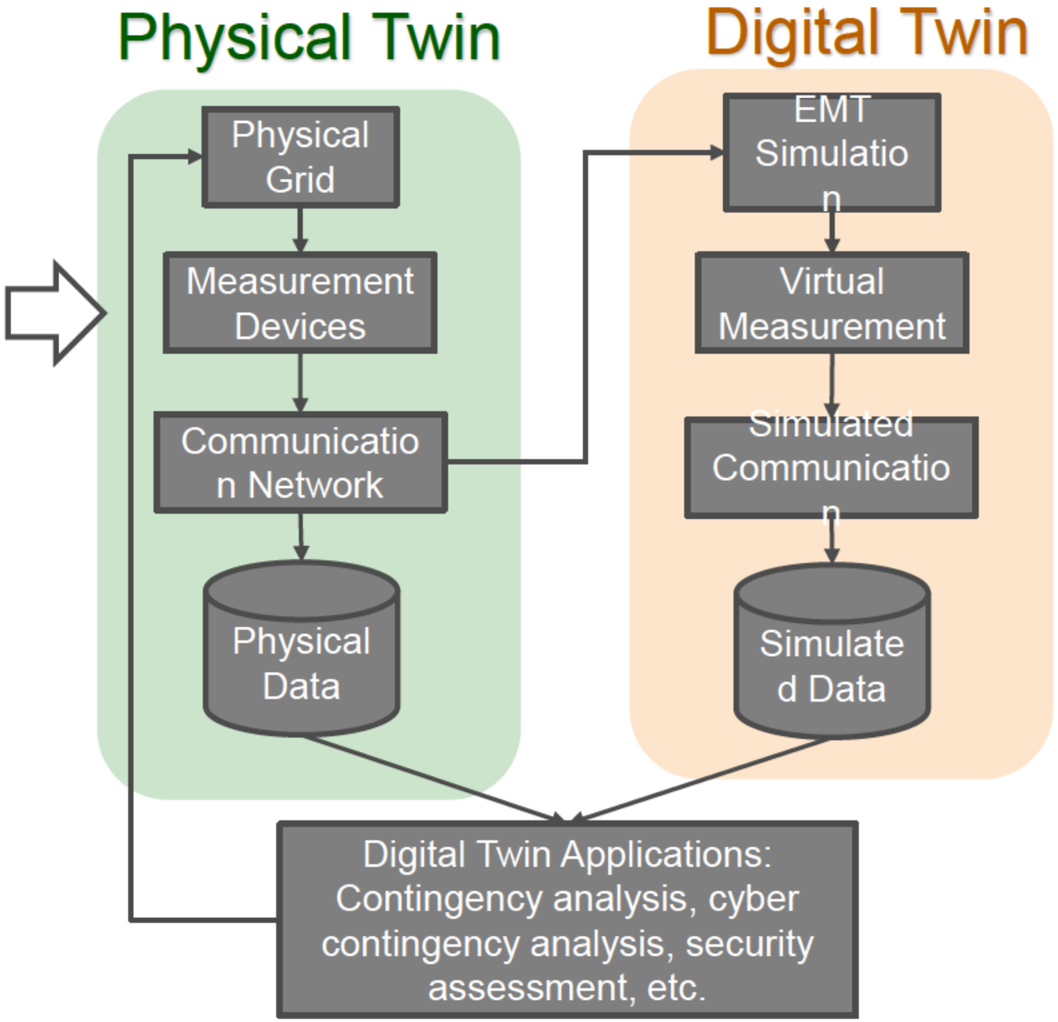








Micro Grid Digital Twin (Southern Company)



Microgrid Components

- Photovoltaic generation
- Battery energy storage
- Diesel Generation
- Residential load

Digital Twin Functionality

- RMS voltage and current measurements
- 14 second measurement period
- Opal-RT real-time simulator

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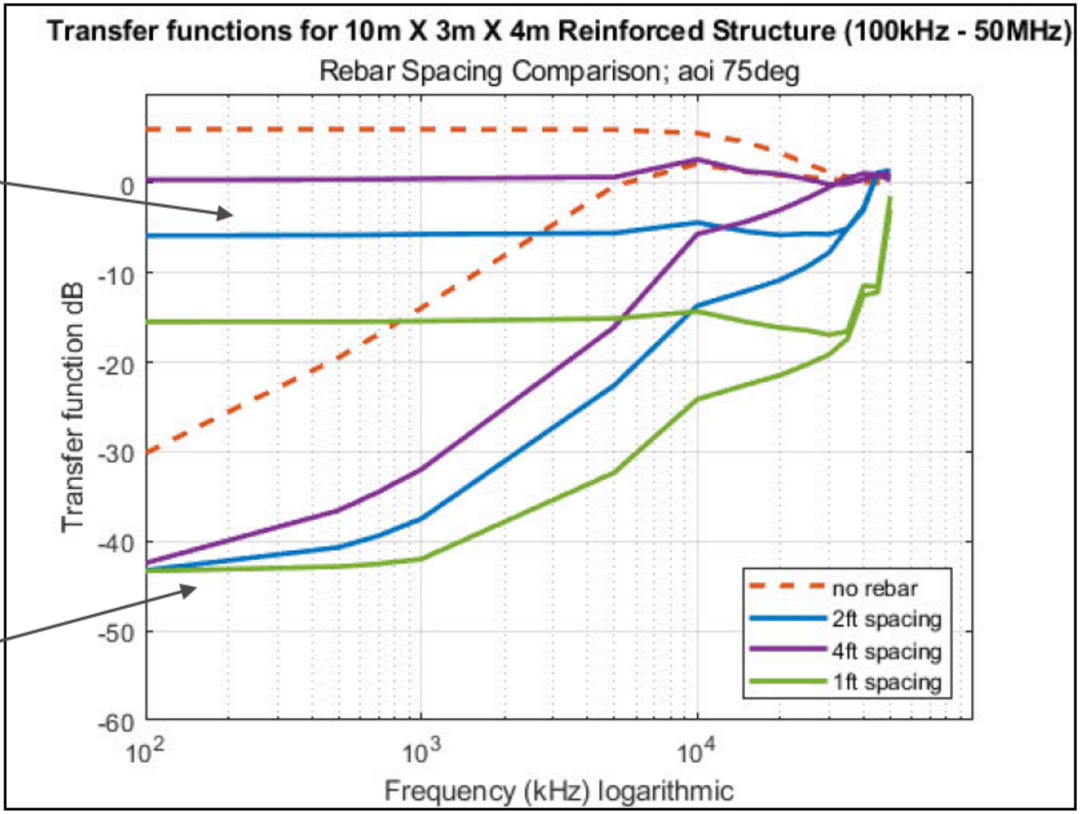
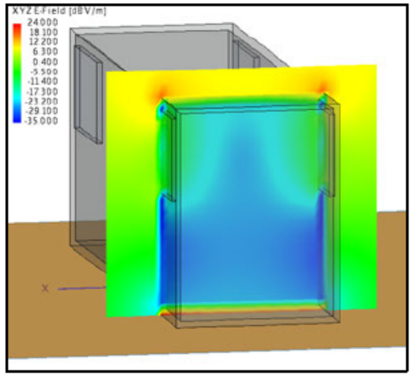
Building EMP Shield Effect (ORNL)

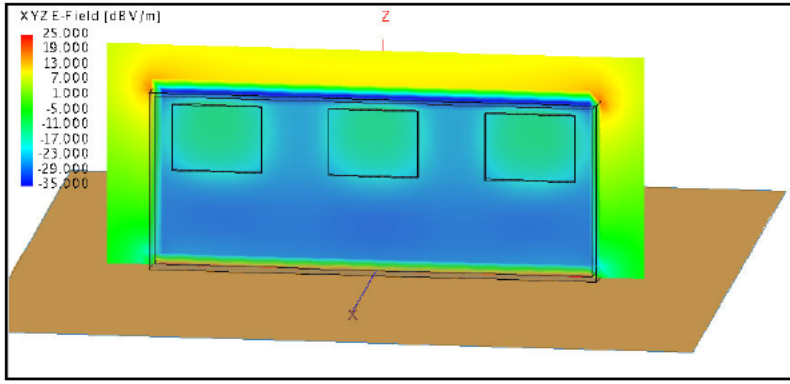
Reinforced Concrete

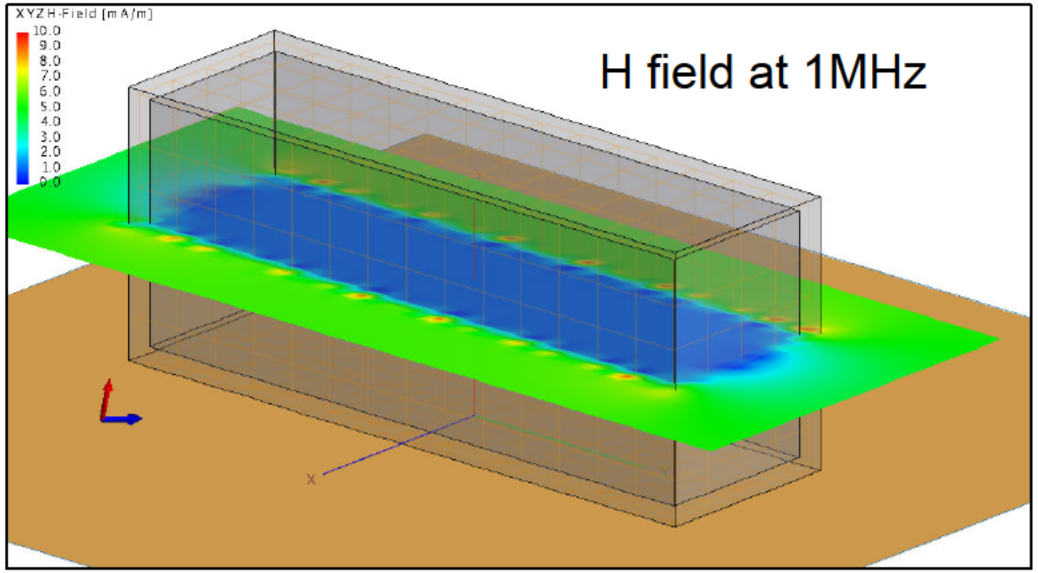
H field



E field







Rebar provides significant H field shielding throughout the frequency range

Tool Development

- Distribution three phase state estimator
- SPOT- distribution grid sensor placement tool
- Distribution Volt-Watt optimization tool
- Automatic DC to AC power flow conversion tool.
- Forced oscillation source location tool
- PSS/e to PSCAD model conversion tool
- Renewable integration tool – in development
- Regional inertia estimation tool – in development

Hector Pulgar

- **UTK Associate Professor**
- **Research Interests: Power system stability and dynamics, energy storage systems and renewable generation.**
- **hpulgar@utk.edu**

2023-2024 Research Projects

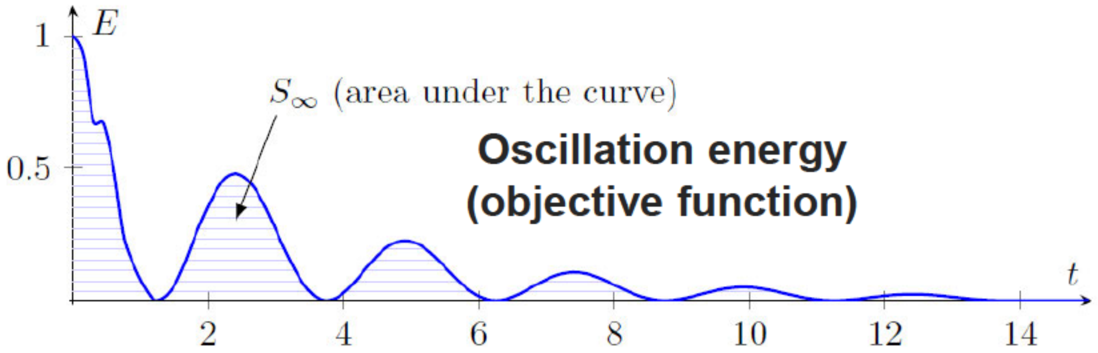
1. Adaptive dynamic coordination of damping controllers: Enhancing oscillation damping through a data-driven approach (funded by NSF)
2. Towards enhanced grid robustness: Augmenting grid regulating capabilities through discrete controls on emerging power technologies (funded by NSF)

Adaptive dynamic coordination of damping controllers: Enhancing oscillation damping through a data-driven approach

Project Objectives

- Adaptability to faults and operating conditions.
- Modal-based and data-driven approaches.
- IBRs are used for damping control only when the system requires them (control commitment determined promptly using activation/deactivation signals based on our data-driven scheme)

IBRs (wind, solar, storage)



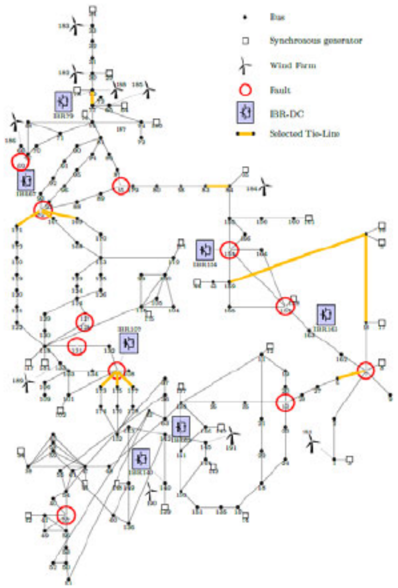


Fig. 4: 179-bus, 30-machine, 7-DC test system.

Results

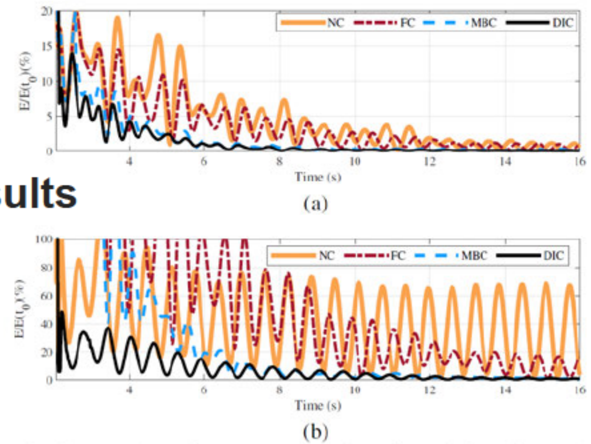
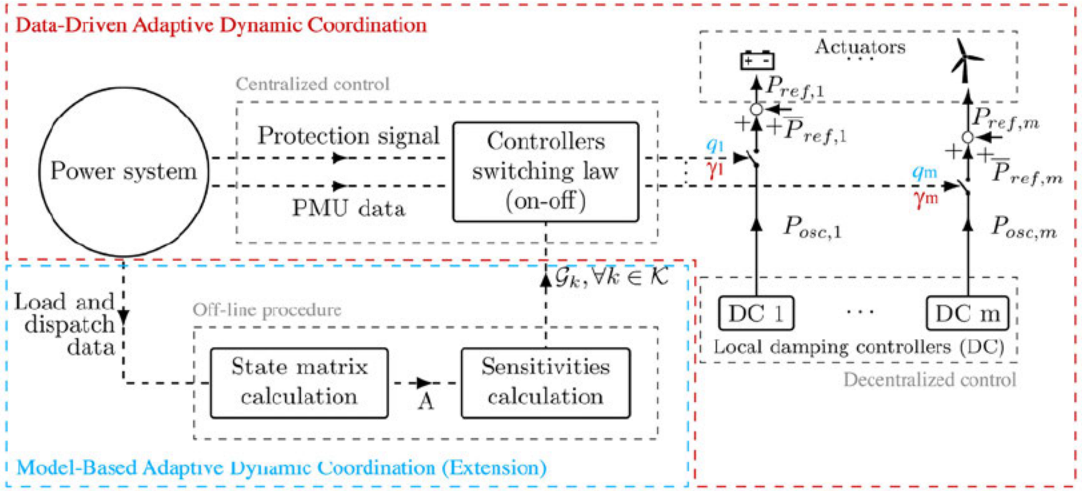


Fig. 10: Comparison between MBC and DIC for short-circuit at bus: (a) 157, and (b) 69.



Control coordination framework

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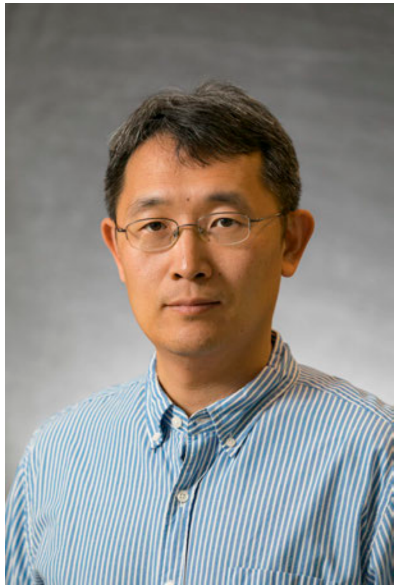

Kai Sun

- **UTK Professor in Power Systems**
- **Research Interests:** Power System Dynamics, Stability and Control; Cascading Outages; Renewable Integration.
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2023-2024 Research Projects

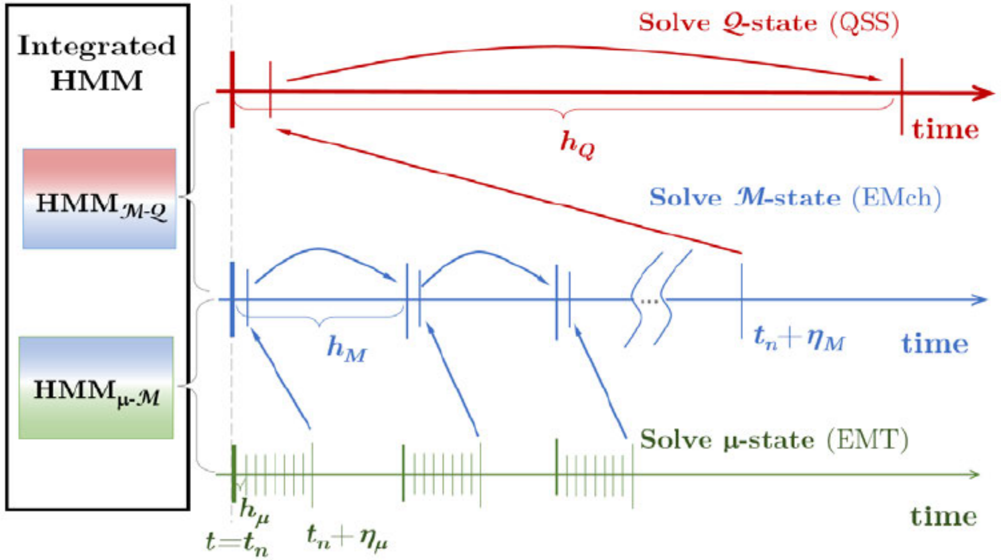
1. A Semi-Analytical, Heterogeneous Multiscale Method for Simulation of Inverter-Dense Power Grids (NSF, ANL)
2. Intelligent Phasor-EMT Partitioning for Hybrid Simulations to Accelerate Large-scale IBR Integration Studies (SETO/NREL, ISO New England, EPRI)
3. Mobility-Energy-Coordinated Platform for Infrastructure Planning to Support AAM Aircraft Operations (NASA/New Mexico State University)

A Semi-Analytical, Heterogeneous Multiscale Method for Simulation of Inverter-Dense Power Grids

Project Objectives:

- Developing a Heterogenous Multiscale Method (HMM) framework for automatic, case-specific model reduction on the fly of each EMT/phasor simulation.
- Developing variable-order variable-step semi-analytical solution (SAS) methods to accelerate EMT/phasor simulations.
- Targeting a 10-100x speedup of EMT simulations on large-scale grid models with 50-100% IBR penetration.

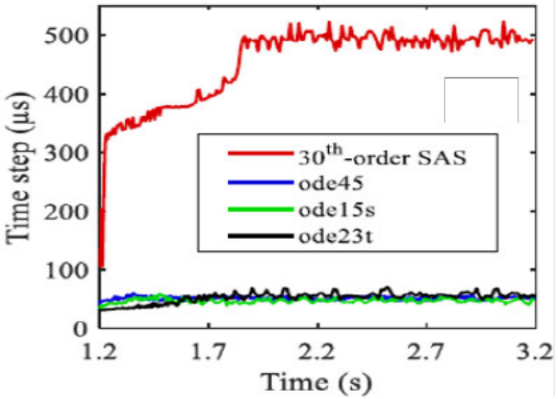
HMM framework for simulating multi-timescale (EMT, electromechanical and quasi-steady-state) grid dynamics

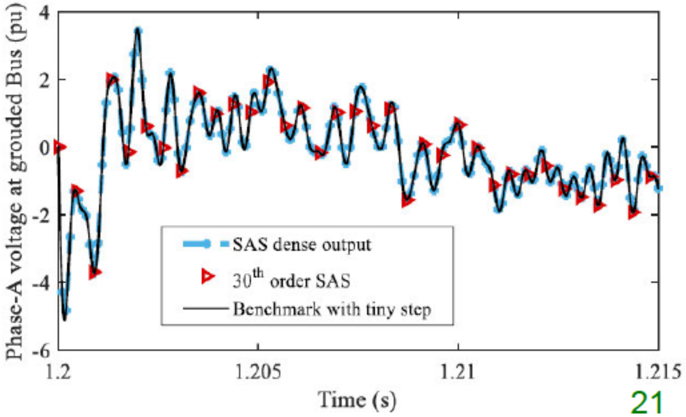


High-order SAS method achieves a 5-20x speedup of accurate EMT simulation by using a 10-100x stepsize.

COMPARISON OF PERFORMANCE ON A 390-BUS SYSTEM

Approach	PSCAD				SAS
Time step (μs)	5	50	75	100	534
Time cost (s)	425	42.5	28.3	21.5	98
Maximum error (pu)	0.22	2.58	3.36	3.85	7×10^{-4}
Average error ($\times10^{-3}$ pu)	0.41	2.61	2.91	3.3	0.0012





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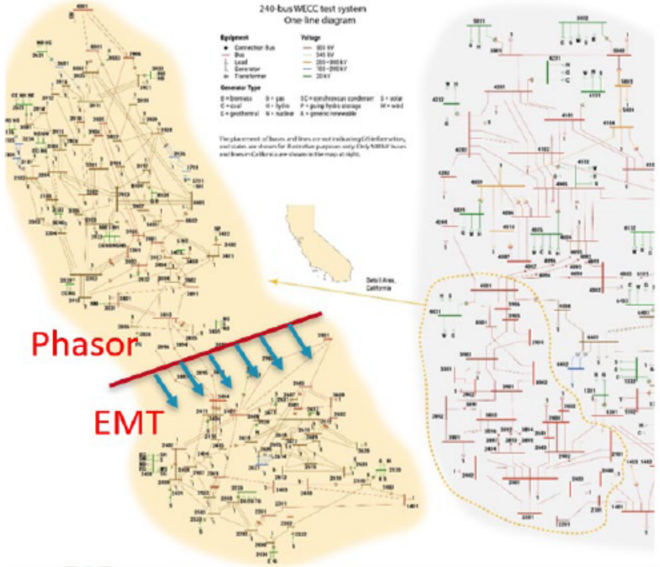
THE UNIVERSITY OF TENNESSEE KNOXVILLE
Argonne NATIONAL LABORATORY

Intelligent Phasor-EMT Partitioning (I-PEP) for Hybrid Simulations to Accelerate Large-scale IBR Integration Studies

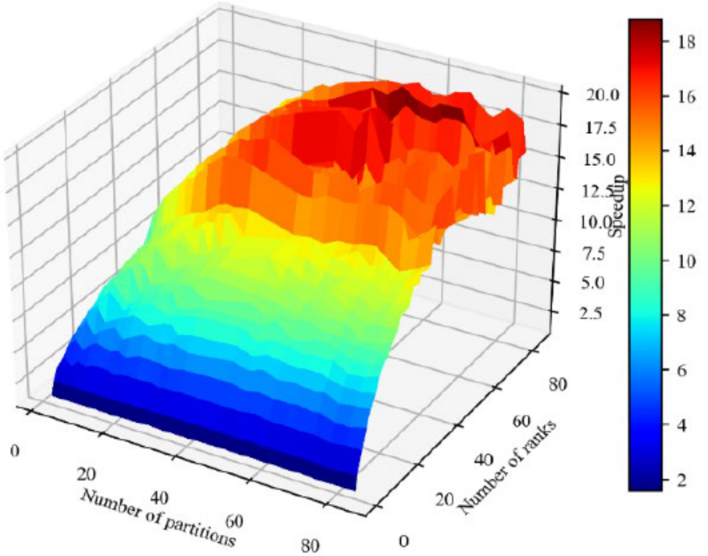
Project Objectives and Achievements:

- Intelligent determination of which portions of the grid to be simulated in EMT models while the rest in phasor models.
- Accelerated NREL's opensource simulator ParaEMT by integrating the SAS method.
- Validation of the method on realistic grid and IBR models.

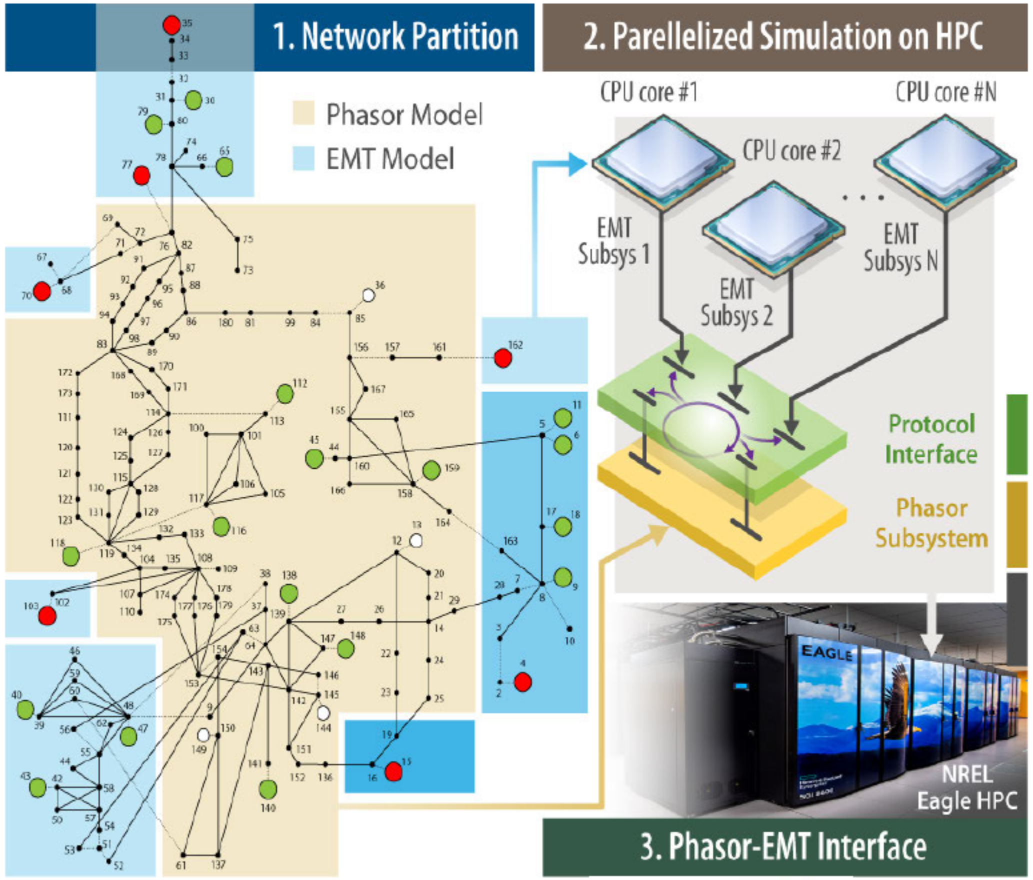
Participation Factor-based Boundary Determination



Speedup by SAS & HPC using 50 μs time step on a 10K-bus EMT model



I-PEP project overview

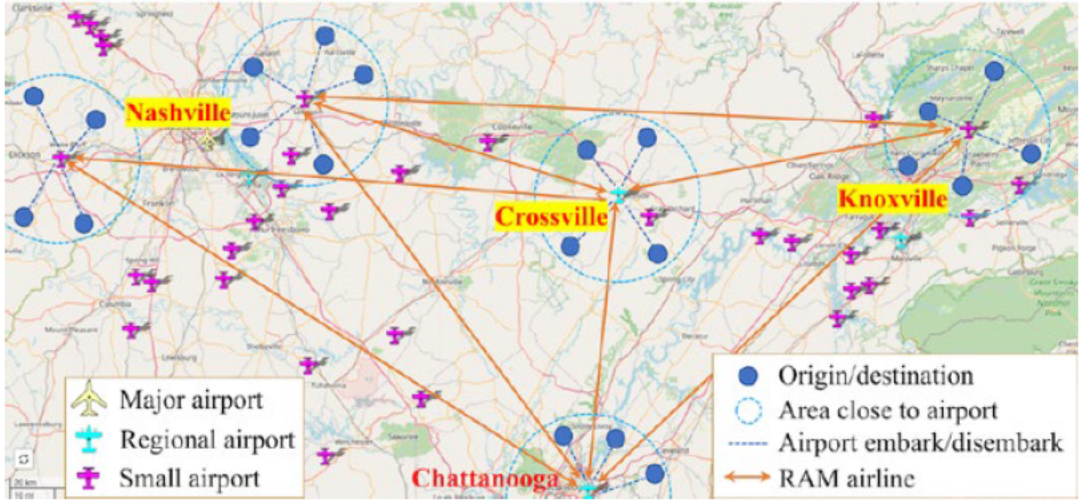


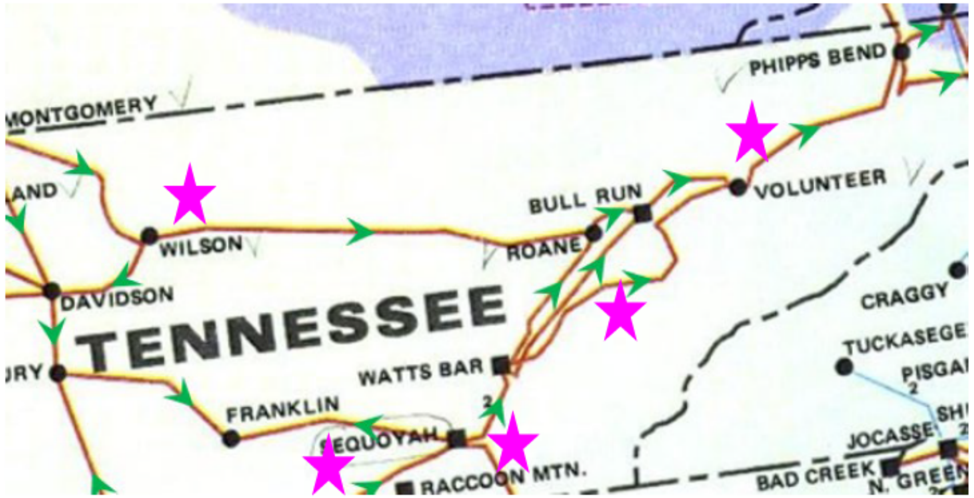
Mobility-Energy-Coordinated Platform for Infrastructure Planning to Support AAM Aircraft Operations

Project Objectives:

- Building power system testbeds to support Advanced Air Mobility (AAM) planning and operation studies.
- Evaluating the impacts of AAM operations on grid reliability and resilience based on power system reliability criteria.
- Accessing electric infrastructure readiness to support AAM aircraft charging.
- Supporting the optimal siting studies on UAM (Urban Air Mobility) and RAM (Regional Air Mobility) portals.

Concept of AAM in Tennessee and candidate locations for RAM portals





CURENT

THE UNIVERSITY OF TENNESSEE KNOXVILLE

NM STATE

Kevin Tomsovic

- **UTK Chancellor's Professor and CTI Professor**
- **Research Interests: control, optimization, renewable energy integration, demand response, resilience, cybersecurity.**
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2023-24 Research Projects/Highlights

Recently Completed

1. WISP: Watching grid Infrastructure Stealthily through Proxies (**DOE, Raytheon**) (PI: F. Li PI; co-PI: J. Sun)
2. National Transmission Resilience and Reliability (**DOE**) – (PI: F. Li)

Recently awarded and on-going

1. CPS: Medium: Secure Constrained Machine Learning for Critical Infrastructure CPS (**NSF**) (PI: J. Sun, co-PI: H. Qi, H. Lee)
2. A Novel Approach to Mitigating Communication Failures (**NSF**) (co-PIs: S. Djouadi, F. Taousser)

A New Approach to Control under Network Communication Delays

Project goals and previous accomplishments

- A new mathematical method to estimate the maximum allowed communication delay that does not violate the stability and performance of the power system.
- Manage continuous and discrete dynamics as switching between a continuous-time subsystem (when the communication occurs without any interruption) and a discrete-time subsystem (when the communication fails) by introducing time scales theory.

Recent activities

- A stability criteria has been derived to estimate bounds of the communication loss duration, which guarantees the stability of the system.

Future works

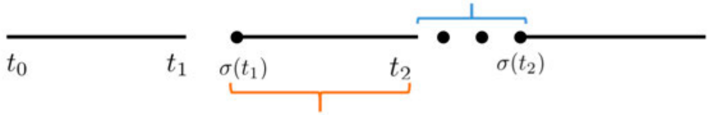
- Test stability criteria in larger system with considering communication failure.

PIs – Djouadi, Taousser and Tomsovic (PI)

Students: Yichao Wang

Time scales

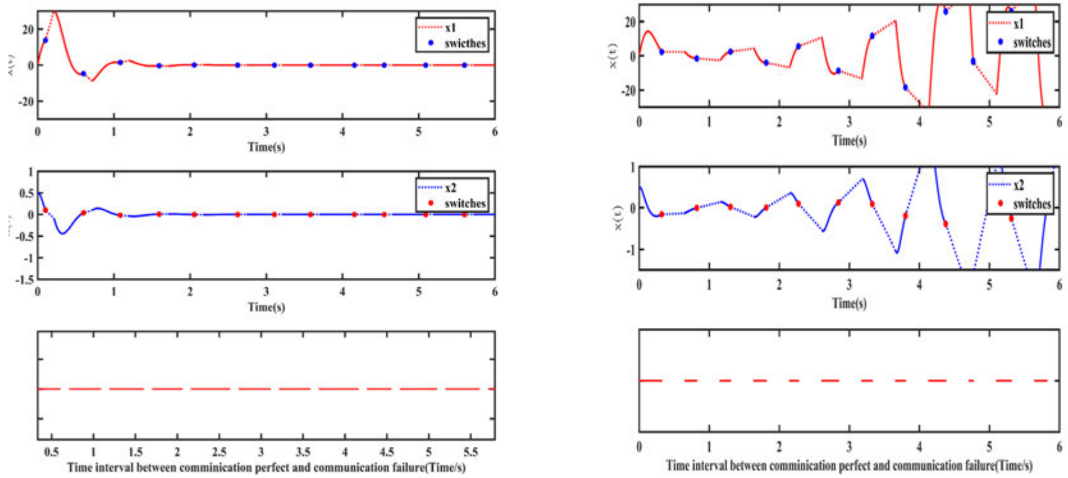
$$\mu(t_2) = \sigma(t_2) - t_2$$



$$\tau(t_1) = t_2 - \sigma(t_1)$$

Switched system

$$x^{\Delta}(t) = \begin{cases} (A+BK)x(t), & t \in \cup_{i=0}^{\infty}[\sigma(t_i), t_{i+1}) \\ \left(\frac{e^{A\mu(t)}-I}{\mu(t)}\right)\left(I + A^{-1}BK\right)x(t), & t \in \cup_{i=0}^{\infty}\{t_{i+1}\} \end{cases}$$



Exploring Physical-Based Constraints in Forecasting: A Defense Mechanism Against Cyberattack

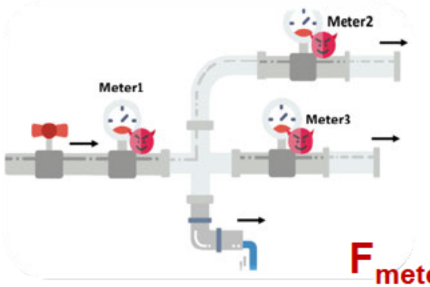
Project goals and previous accomplishments
- Concern with Cyber attacks in machine learning systems
- Physical-based constraints can provide obstacles that makes attacks more difficult.
- Attacker needs to meet the constraints imposed by the physical/topology of system and evade any built-in detection mechanisms in the system.

Recent activities
- Proposed a framework to spatially investigate STLF for a defense mechanism (also for traffic systems)
- Applied similarity measures to explore physical-based constraint.
- Outperformed of SAX method, showing more sensitivity to false data injection.

Future works
- Test stability criteria in larger system with considering communication failure.

Pis – Han, Qi, Sun (PI) and Tomsovic

Students: Mojtaba Dezvarei, Farhin Farhad Riya, Ony Hoque, Diyi Liu, Lanmin Liu, Quan Zhou



linear equality/ inequality constraints

$F_{meter1} > F_{meter2} + F_{meter3}$

Water flow measurement

Spatial correlations

- Correlation-based distance: $d_{COR}(X,Y) = \sqrt{2(1-COR(X,Y))}$
- Periodogram-based distance: $d_p(X,Y) = \sqrt{\sum_{j=1}^{[\frac{N}{2}]}[\rho_x(\omega_j) - \rho_y(\omega_j)]^2}$
- Autocorrelation-based distance: $d_{ACF}(X,Y) = \sqrt{(\hat{\rho}_{X_T} - \hat{\rho}_{Y_T})^T \, \Omega \, (\hat{\rho}_{X_T} - \hat{\rho}_{Y_T})}$
- Symbolic representation SAX: Time series transforming into a string.
- Euclidean-based distance: $d_{EUC}(X,Y) = \sqrt{\sum_{j=0}^{N-1}(x_i - y_i)^2}$