CURENT

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

2023-2024 PROJECT REPORT

Lead Institution:

The University of Tennessee

Core Partner Institutions:

Northeastern University

Rensselaer Polytechnic Institute

Tuskegee University

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Northeastern University

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TUSKEGEE UNIVERSITY

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1. Resilient operation of networked community microgrids with high solar penetration

Project Lead: Fred Wang (UTK), Yilu Liu (UTK), Leon M. Tolbert (UTK) **Graduate Students and Research faculty/associates:** Yu Su (UTK), Dingrui Li (UTK)	
Project Duration: 1/2022 – 3/2024	
Funding Source: ORNL/DOE	

Summary

This project aims at developing new operation and control strategies for networked microgrids, where inverter-interfaced sources act as the main grid-forming sources for the microgrids. In the reporting period, UTK completed two tasks: dynamic boundary algorithm development considering three phase unbalance, and grid-forming inverter modeling for power flow analysis.

For the first task, the focus is to address the inherent unbalance characteristic of the three-phase distribution system, where the networked microgrid is based on. The algorithm can be summarized below.

> ***Objective***. Minimize system load shedding (different penalties for critical and non-critical loads).
>
> ***Subject to***.
> 1) Power balance constraints.
> 2) BESS power constraints.
> 3) BESS SoC constraints.
> 4) Three-phase power unbalance constraints.
> 5) Bus voltage constraints.
> 6) Line thermal constraints

The algorithm can be formulated into an optimization problem, where relaxation techniques are applied to the power flow equations. The result is a mixed-integer linear program (MILP) or a mixed-integer semidefinite program (MISDP).

For the second subtask, the existing models for grid-forming inverters under unbalanced load conditions are not accurate, because they do not consider the control implemented in the grid-forming inverters. A typical grid-forming inverter with dual-loop voltage control is shown in Figure 14.1.

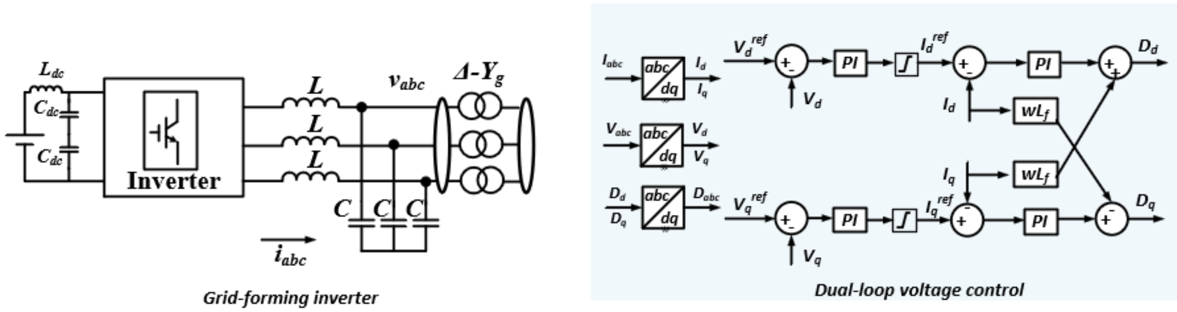


Figure 14.1: Grid-forming inverter with dual-loop voltage control.

The inverter is three-wire, which may only provide positive and negative sequences currents. The voltage unbalance results from the negative sequence current. Based on the control loop, the negative sequence current will result in a negative voltage at the inverter output terminal. After the *dq* transformation, both the negative sequence voltage and current will be transformed to be 120 Hz components. Since the PI controller only has an infinite gain at dc components, the PI controller is not able to regulate the 120 Hz components to be zero. Therefore, the control loop impacts on the output voltage unbalance needs to be derived. After the derivation, for the negative sequence, the control loop can be viewed as an impedance. The value is dependent on the control parameters of the grid-forming inverter. Case studies on IEEE standard systems show that the proposed model significantly improves the negative sequence voltage calculation results.

2. SiC-Based Modular Transformer-Less MW-Scale Power Conditioning System and Controller for Flexible Manufacturing Plants

Project Lead: Fred Wang (UTK), Yilu Liu (UTK), Leon M. Tolbert (UTK), Kevin Bai (UTK) **Graduate Students and Research faculty/associates:** Ruirui Chen (UTK), Dingrui Li (UTK), Zihan Gao (UTK), Min Lin (UTK), Yu Yan (UTK), Jiahao Niu (UTK), Jingxin Wang (UTK)
Project Duration: 10/2020 – 6/2024
Funding Source: DOE

<u>Summary</u>

The objective of this project is to develop a 10 kV SiC MOSFET-based 1 MW bi-directional power conditioning system (PCS) for manufacturing plants, consisting of back to back 13.8 kV AC/DC converetrs and a 200-kW isolated DC/DC converter connected to the PCS MV DC bus. The proposed PCS converter will meet performance targets including >99.4% power efficiency, <0.3 m^3/MW volumetric density, >10% dispatchability, <$30/kW cost (excluding SiC die cost), > 10 years lifetimes, 300 Hz voltage control bandwidth and >1 kHz current control bandwidth, and grid requirements including 1) complying with IEEE 1547 and IEEE 2030.7; 2) grid support functions including var support, low voltage ride through, protection, stability and harmonic filtering; 3) multiple operation modes including grid connected, islanded and stand-by; 4) unbalanced load (max 30%) and fault; 5) cyber security requirement. The PCS converter can also be scaled to form at needed power (> 10 MW) and support multi-port operation.

Figure 17.1 shows the PCS architecture. It serves as the interface between a 13.8 kV AC distribution grid and a manufacturing plant power system to enable various FMP architectures. With the PCS, an FMP power system can be operated as one or more AC asynchronous microgrid. With DC/DC converters ports interfacing directly with DC-fed loads and source, the FMP can also be operated as one or more hybrid AC asynchronous and DC microgrids. BP1 of this project has been completed last year, which focus on the design of this PCS and controller. In BP2, the focus is to build and test one phase of the designed 1 MW back to back AC/DC/AC converter and one module of the designed 200 kW DC/DC converter.

During 2022-2023, the design of the 1 MW DC/AC converter and the 200 kW DC/DC converter are finalized. The hardware for one phase of the 1 MW DC/AC converter is built and the testing is ongoing. One 10 kV module-based submodule is tested. The hardware for one module of the 200 kW DC/DC converter is built and tested. EMP controller algorithm considering cyber security is developed and HIL testing is completed. A downscaled PCS for control validation is prepared and HTB testing is ongoing.

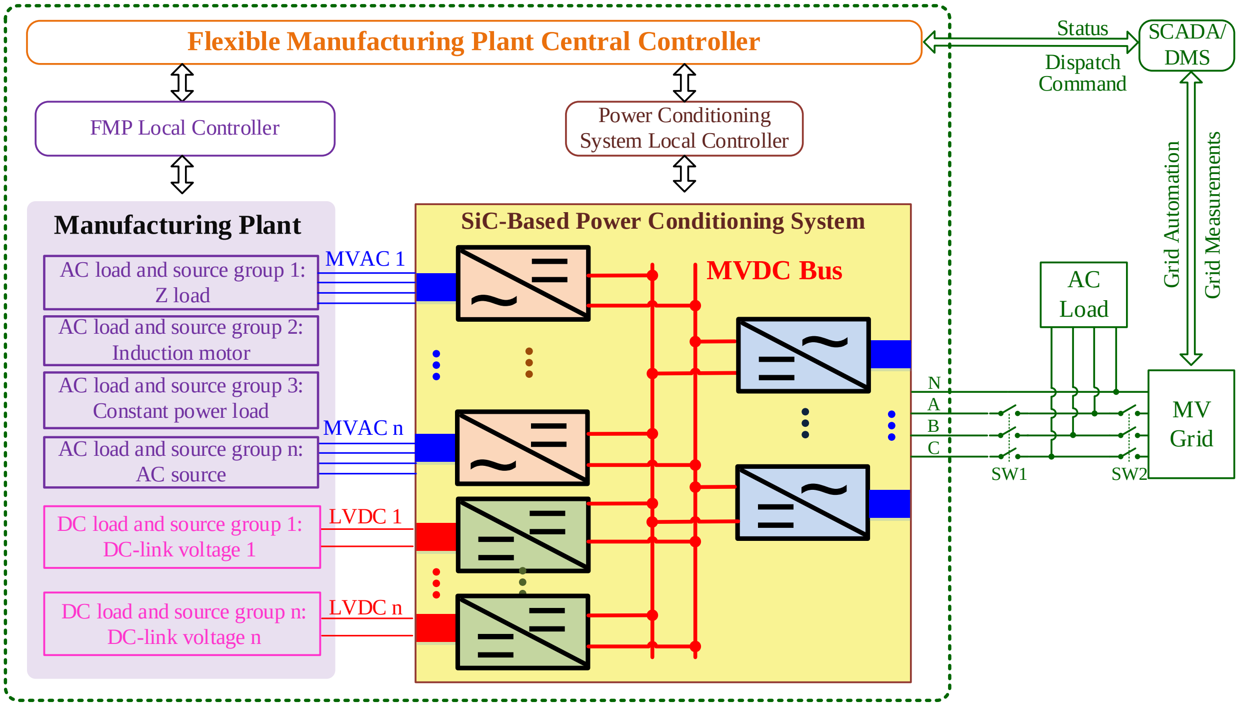


Figure 17.1: PCS architecture for FMP system.

3. Development of high-density and high efficiency AC/DC converter using wide band gap device

Project Lead: Fred Wang (UTK), Kevin Bai (UTK) **Graduate Students and Research faculty/associates:** Shimul Dam (UTK), Yanda Lyu (UTK)	
Project Duration: 4/2022 – 12/2024	
Funding Source: Boeing	

Summary

The objective of the project is to develop a high-density and high efficiency 45 kW AC/AC frequency converter to convert a variable frequency 230V to fixed frequency 115V, 400Hz for driving induction motor load in an aircraft system, while meeting EMI requirements for both input and output ac sides of the converter. The project targets to develop a converter with efficiency above 98% and power density above 4 kW/lb. In order to meet the power density and efficiency goals and also considering the reliability, solutions in several areas are being evaluated: converter topology and control, design of filters including both common-mode (CM) and differential-mode (DM) filters on both input and output sides, semiconductor devices and related gate-drive and protection circuit, as well as passive components including magnetics, capacitors and heatsink.

In Phase I, the team has selected several popular ac-ac converter topologies for this application including voltage source topologies, current source topologies, and direct ac-ac converter topology. An automated design tool is developed to perform optimized design of each of the selected topologies and to compare their efficiencies and power densities. Simulation model and EMI filter design are completed for all the selected topologies. Each optimized converter design is performed using physical design of different elements of the converter and considering commercially available components such as devices, heat sinks, core etc. to obtain a design that is feasible to implement without using any special or custom-made component. Based on this optimized design comparison, most promising topologies have been identified.

In phase II, the limitations of the available topologies in this application are identified and a new topology is proposed. The detailed design for a 45 kW converter is carried out and the prototype development is now at the final stage.

This project is expected to be finished by in December of 2024. As future works in Phase II of the project, the team will develop and test a 45 kW AC-AC converter prototype. Converter operation, thermal performance, and EMI filter performances will be verified.

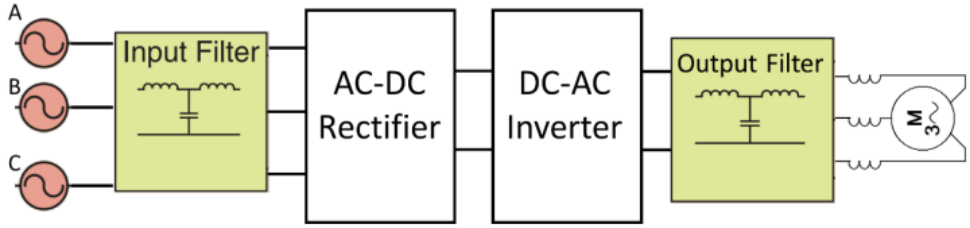


Figure 1: Two stage ac-ac converter architecture with input and output EMI filters.

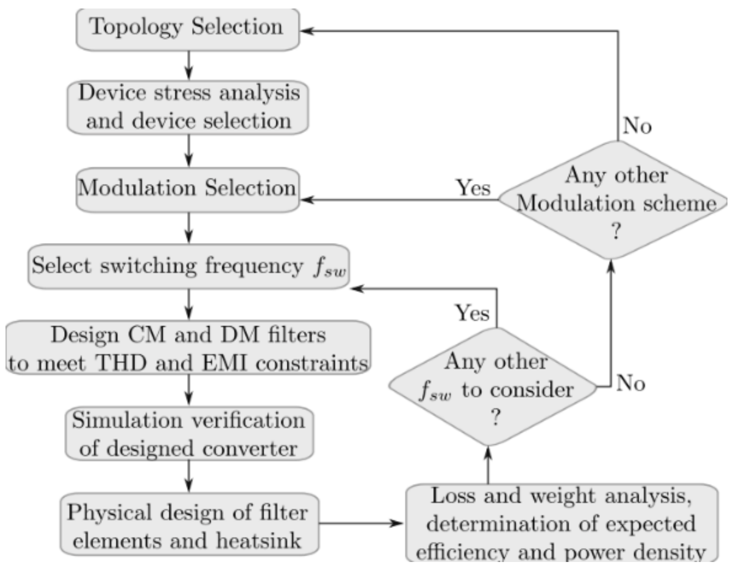


Figure 2: Automated converter design for weight optimization.

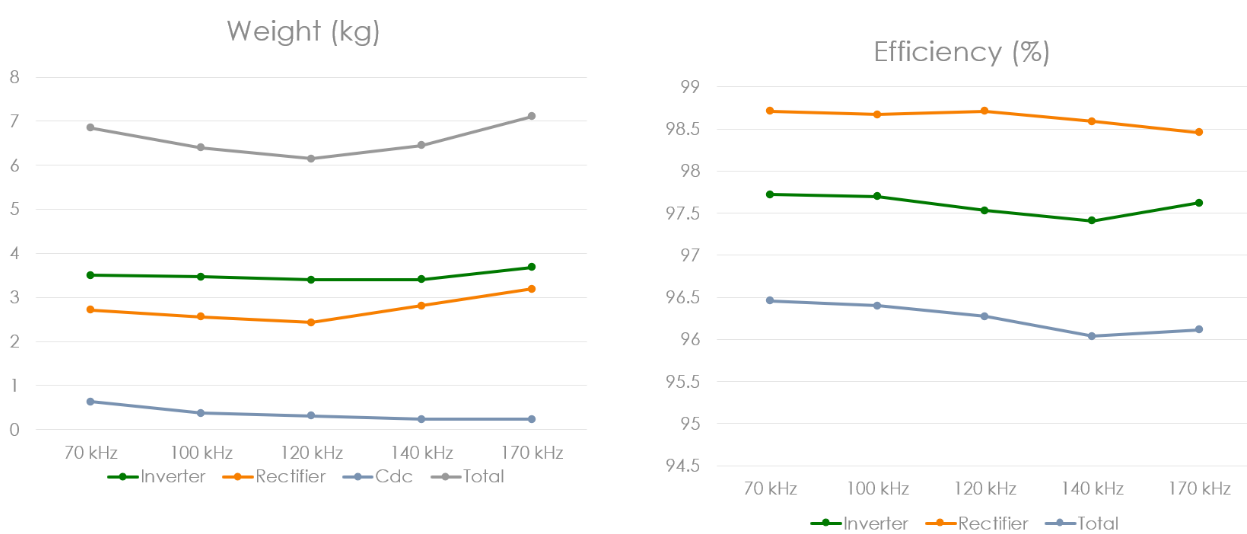


Figure 3: Weight and efficiency of optimized design of 5-L hybrid ANPC inverter and rectifier topology.

4. An Ultra-Light Tightly-Integrated Modular Aviation Transportation Enabling Solid-State Circuit Breaker (ULTIMATE-SSCB)

Project Lead: Fred Wang (UTK), Kevin Bai (UTK), Zheyu Zhang (RPI), Kaushik Rajashekara (UH) **Graduate Students and Research faculty/associates:** Shimul Dam (UTK), Jimmy Yang (UTK), Ruirui Chen (UTK), Anil Kumar Reddy Siddavatam (UH)
Project Duration: 7/2021 – 12/2024
Funding Source: ARPA-e

Summary

The project aims at developing and testing in simulated flying environment an ultra-light tightly-integrated modular aviation-transportation enabling solid-state circuit breaker (ULTIMATE-SSCB). The proposed ULTIMATE-SSCB will meet several objectives important for future electrified aircraft propulsion (EAP) systems: extremely light, efficient, fast, reliable, suitable for future medium voltage EAP system at >10 kV DC, taking advantages of cryogenic cooling enabled by liquified natural gas (LNG) or liquid hydrogen fuel of future EAP system. The developed SSCB will be highly flexible with modular structure, intelligent and easy for protection coordination and system integration, with built-in directional function, and current limit function.

In phase I of the project, the team identified the specification and requirements of the 10 kV, 100A SSCB and completed conceptual design of the SSCB using cryogenically cooled GaN devices and key components testing. The SSCB is designed to interrupt up to 10x current during fault. Design of modularized SSCB, sensors, intelligent gate driver, control and communication strategy have been developed. A notional electrified aircraft propulsion architecture is identified and investigated with simulation to determine capability requirement of SSCB and to validate the protection and co-ordination strategy.

In phase II of the project, the team has developed a 750V, 100A SSCB module that can be used in 5 kV unipolar or a 10 kV bipolar MVDC system. A series combination of 14 such modules will meet the requirements of 10 kV, 100A SSCB for future EAP system. A liquid Nitrogen based cooling system is developed and the module is successfully tested to interrupt a fault current of 1 kA. A cryogenic packaging for the module is developed and successfully tested to achieve good thermal and electrical performance at cryogenic temperature and medium voltage environment. The module is also designed for high-altitude operation and successfully tested in a emulated high-altitude test setup.

The team is currently working towards developing 14 modules to construct the 10 kV, 100A SSCB. This project is expected to be finished by the December, 2024. Future works include development of 10 kV, 100A SSCB prototype and cryogenic as well as high altitude testing of the developed SSCB prototype.

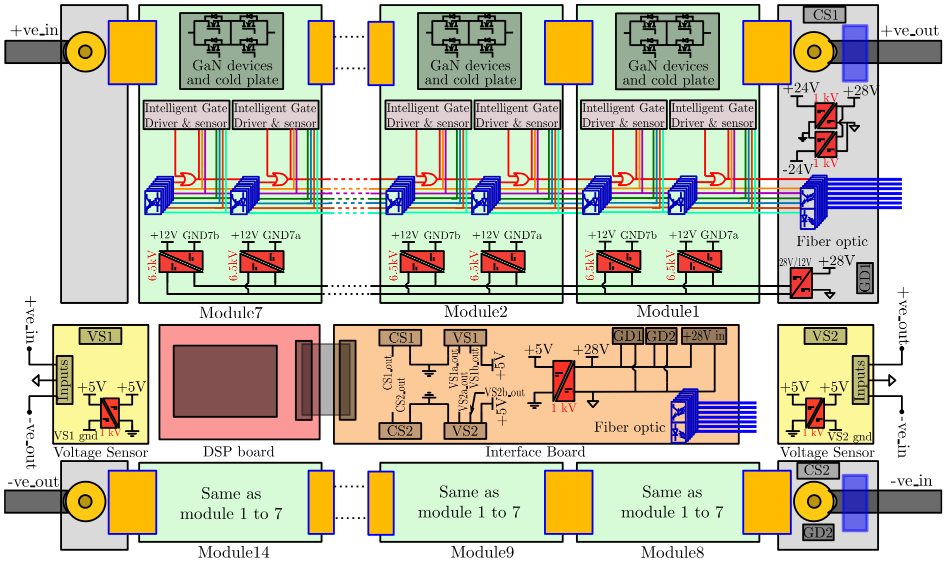


Figure 1: Architecture of 10 kV modular SSCB.

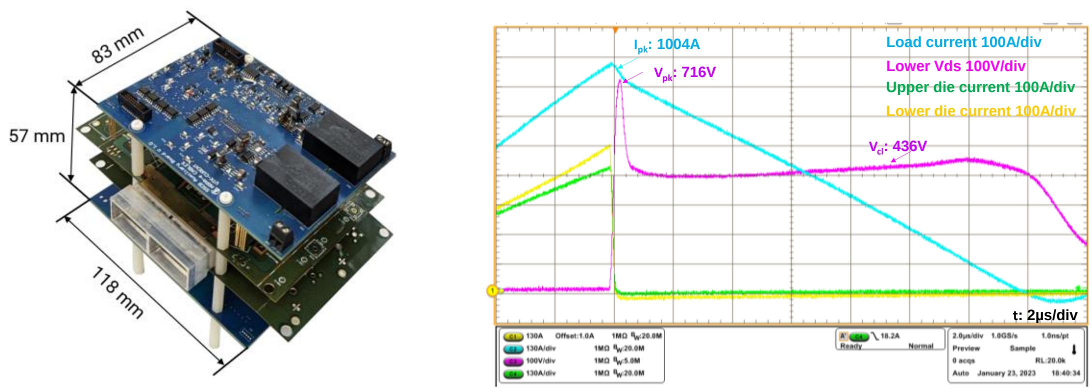


Figure 2: Developed SSCB module with cold plate assembly and test results of 1 kA fault current interruption test.

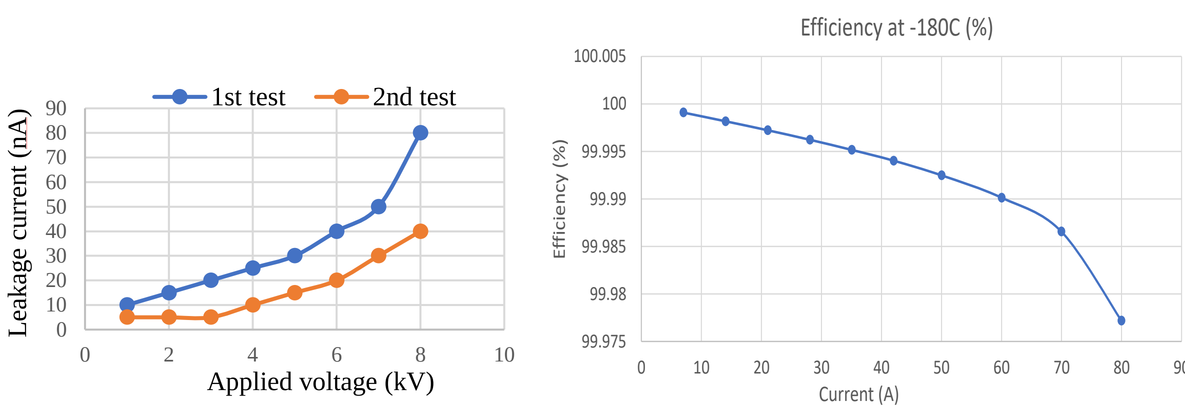


Figure 3: (a) Insulation test results and (b) efficiency measurement of the SSCB module.

5. Expanding Transmission Capacity: A Low-cost Hybrid AC/DC Scheme for Increased Transmission Capacity

Project Lead: Fred Wang (UTK), Sonny Xue (ORNL) **Graduate Students and Research faculty/associates:** Anubrata Das (UTK)
Project Duration: 10/2022 – 09/2025
Funding Source: DOE

Summary

With ever-increasing electricity consumption, conventional thermal power plants have been retired and new generations from renewable energy resources have been built to address environmental concerns. This has added operational stresses to the existing transmission corridors, making some of the transmission lines operating at or near to their rated transmission capacity and in certain occasions, the renewable power (e.g., wind) being curtailed due to a lack of transmission capacity. In the meantime, building new transmission corridor (HVAC or HVDC) or converting existing HVAC into HVDC systems is either restricted by high implementation cost or delayed due to the land licensing process, low public acceptance, and environmental issues. Thus, the challenge of expanding transmission capacity is to provide an affordable or economically viable solutions to reduce transmission losses and boost conductor utilization.

To achieve this, a hybrid ac/dc power transmission approach is identified as the potential solution. In 2023-24 the operating constraints for this type of power transmission are identified. Subsequently, the methodology of selecting the operating voltage is developed which includes insulation coordination for hybrid ac/dc line considering contamination. Furthermore, the methodology of selecting the current level is also developed considering solar heating, stability limit, sag limit, altitude etc. In Fig. 1 the schematic of hybrid ac/dc power transmission approach is given.

Additionally, a zero-sequence voltage injection technique is proposed to uprate the power transmission capacity. This solution proves to be easier to implement and cheaper than all the other power uprating techniques particularly for the short transmission line. The implementation challenges are identified and the proposed technique is initially validated through simulation for a practical short transmission system. Later a scaled down experimental prototype is developed to validate the proposed technique. In Fig. 2 (a) and (b) the schematic of the zero sequence voltage injection and experimental prototype are shown respectively.

As future tasks the abnormal operating conditions like system voltage unbalance, faults etc. would be considered and proposed technique would be modified accordingly.

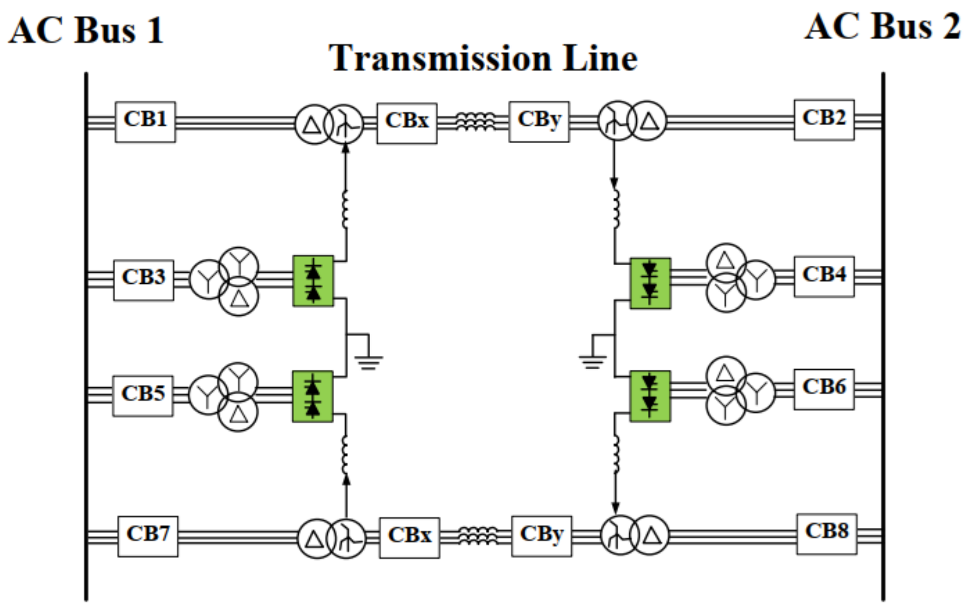


Figure 1: Enhancement of Transmission Capacity using Hybrid AC-DC

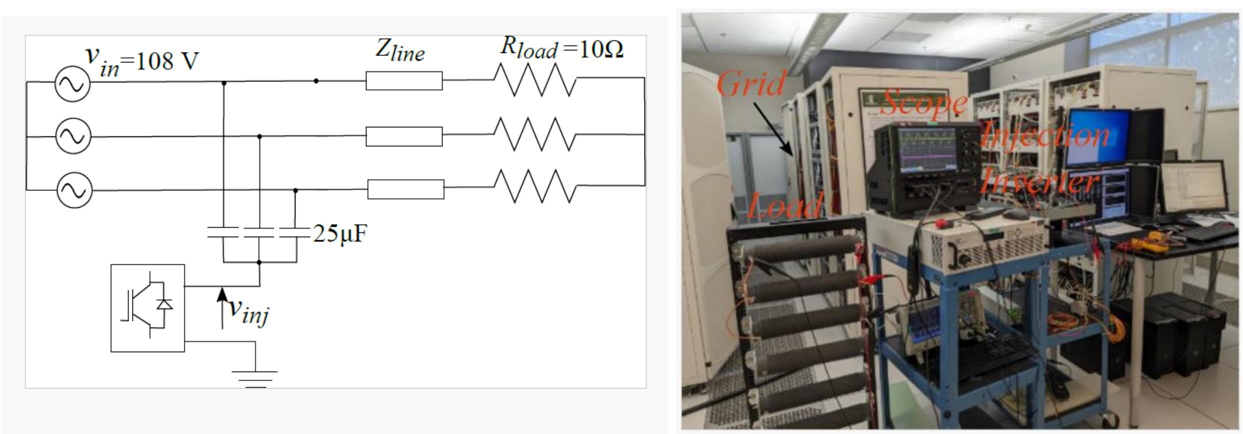


Figure 2: (a) Schematic of Zero-Sequence Voltage Injection (b) Experimental Prototype

6. Operation and Control Strategies of Large-Scale Power Electronics-Based Power Grids

Project Lead: Fred Wang (UTK) **Graduate Students and Research faculty/associates:** Nupur (UTK), Liang Qiao (UTK)
Project Duration: 1/2020 – 12/2025
Funding Source: ORNL

Summary

Converter-driven stability (CDS) is a new stability class introduced by the integration of emerging power electronics technologies into power systems. This project aims to explore the modeling and analysis of CDS phenomena, as well as the detection and identification of oscillatory instability at the utility scale. The primary objective is to develop an innovative impedance-based small-signal stability criterion suitable for analyzing large-scale power grids. Subsequently, this criterion will be utilized to create a small-signal converter-driven stability detection tool for large-scale power electronics-based power system.

A partition-based approach is proposed for analyzing the small-signal stability of large-scale power electronics-based-power systems. This approach involves partitioning the system into several sub-areas and analyzing the small-signal stability at both the sub-area and interconnection levels. A graph theory method called the spectral partitioning algorithm is implemented for partitioning. This algorithm entails constructing a graph representation of data points, computing its Laplacian matrix, and extracting eigenvalues and eigenvectors. These spectral components facilitate data transformation into a new space, enabling the application of traditional clustering methods like k-means. The proposed method reduces the computation burden by using lower-order matrices with system partition while maintaining the accuracy of the original matrix-based analysis, thus making the small-signal stability analysis of large-scale systems solvable. Simulations were conducted on a modified 140-bus U.S. Northeast Power Coordinating Council (NPCC) system with 100% power electronics penetration in PSCAD and the results confirmed the effectiveness of the proposed method.

7. Design of Next Generation eVTOL Systems

Project Lead: Daniel Costinett (UTK) **Graduate Students and Research Faculty/Associates:** Kody Froehle (UTK), Arka Basu (UTK), Anwesha Mukhopadhyay (UTK)
Project Duration: 8/2021 – 07/2026
Funding Source: ARL

Summary

This collaboration between the U.S. Army Research Laboratory (ARL) and the University of Tennessee Knoxville (UTK) will develop technologies to improve the performance of unmanned aerial vehicles (UAVs) charged by wireless power transfer (WPT). The project will focus on two parallel development pathways to improve performance of power electronics systems:

1. Designing high-efficiency, lightweight onboard wireless power conversion circuitry

UAV performance across a variety of applications is limited by feasible time on mission, which is determined by the amount of onboard energy storage, and the efficiency of use of onboard energy use. In the latter case, efficiency can be increased by both reducing electrical energy loss in power conversion stages, and reducing the weight of power conversion systems such that a lower amount of energy is needed to propel the UAV through the same mission profile.

This task will leverage existing modeling and optimization frameworks developed in prior research to design an optimized circuit for onboard power conversion systems, including WPT receiver coil and rectifier, dc/dc converter, and battery charger. The project will include prototyping hardware and experimentally validating the design performance.

2. Prototyping through-metal ultrasonic wireless power transfer using piezoelectric transducers

Using ultrasonic power transfer, the team will model and prototype wireless power transfer that can operate through metal, allowing wireless charging of UAVs without the need for ports or discontinuities in the case of the charging system. Recent studies of energy storage technologies indicate that piezoelectric transducers have the potential for higher power density that mechanical or electrical energy storage elements, alone. However, leveraging this high energy density requires precise modeling and converter design to track high-Q resonances in the piezoelectric element.

In this task, the team will model through-metal piezoelectric power transfer, and design power conversion stages to maximize efficiency and power transfer within thermal limits. Following successful demonstration of sufficient power transfer, the team will apply the same high-gravimetric power density optimization framework to lightweight the ultrasonic onboard conversion stages.

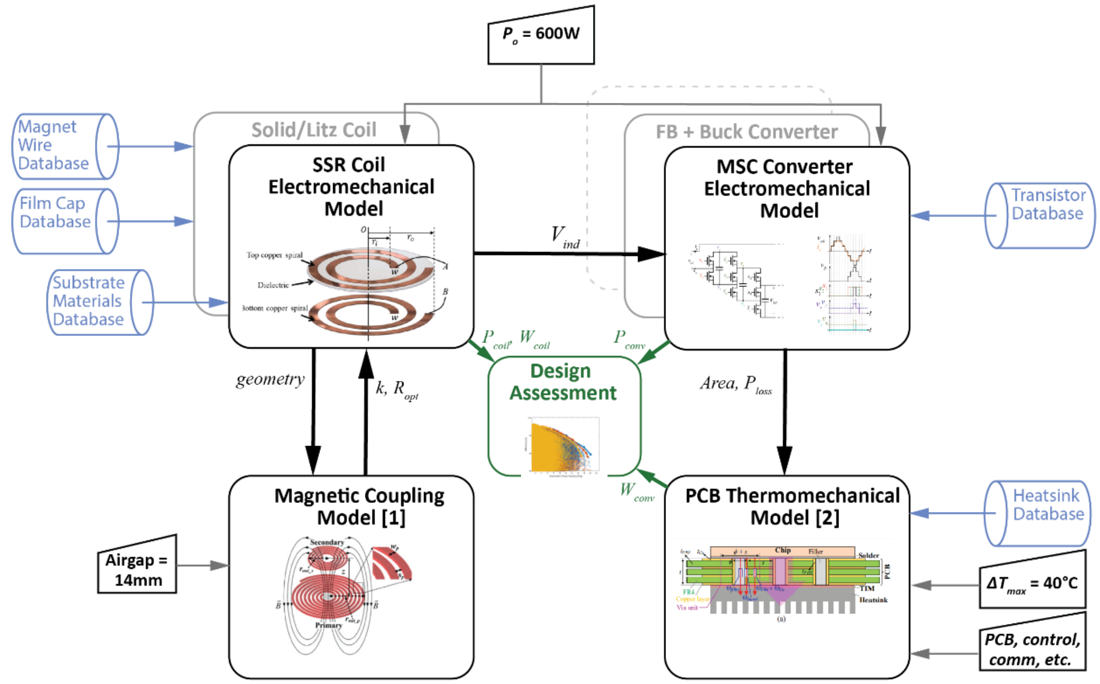


Figure 1.1: Modeling and optimization framework used for ultralightweight wireless power converter design

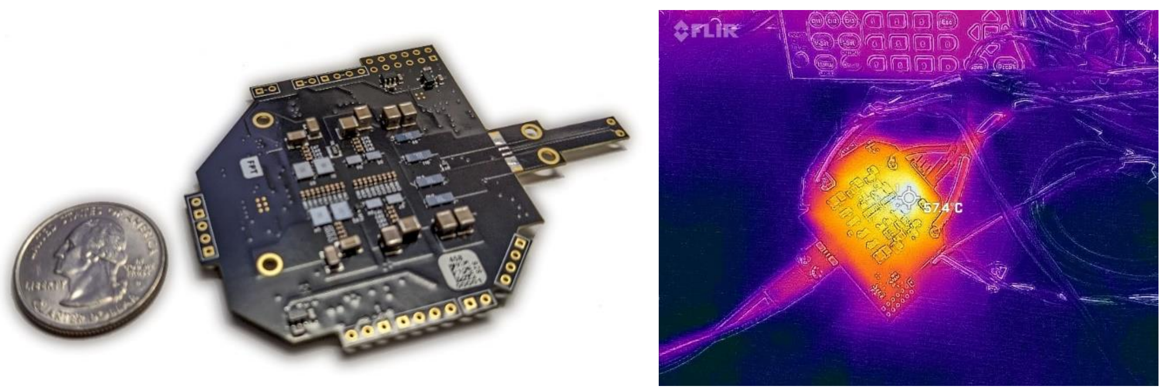


Figure 1.2: Prototype wireless power receiver and thermal image during operation

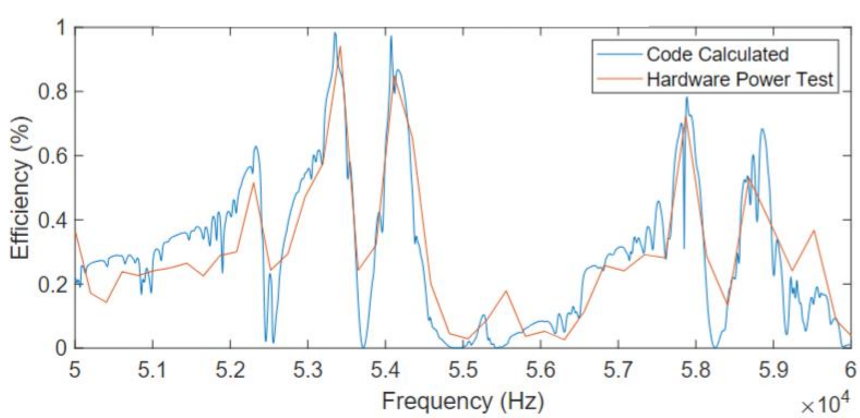


Figure 1.3: Accurate model validation of ultrasonic wireless power transfer across a range of operating frequencies

8. High-Efficiency Regulated Charge-Pump

Project Lead: Daniel Costinett (UTK) Graduate Students and Research Faculty/Associates: Mohammad Farhan (UTK)
Project Duration: 8/2021 – 07/2024
Funding Source: Texas Instruments

Summary

This project is deigning a monolithic, inductorless, high current, regulated battery charger for mobile electronics. The approach leverages prior work in switched-capacitor-based wireless power transfer into a wired application. The design uses the parasitic cable inductance of generic USB cables to provide sufficient impedance to allow regulation in otherwise unregulated switched capacitor topologies.

The project goal is to develop new approaches to high-current, fast charging of mobile devices with minimal footprint. Developing inductorless topologies eliminates the largest, and often most lossy, component from the system. As mobile devices (including cell phones, tablets, etc.) continue to trend towards greater functionality in small volumes, increased power density of battery charging circuits that maintain high current output for fast charging speed are critical.

This project is designing and fabricating a fully-integrated power stage in a high voltage silicon CMOS process. Full-integration allows high density, greater design optimization, and greater possibility of advanced control and sensing compared to discrete designs. The project is targeting 20W wired charging with thermal limitations constraining efficiency.

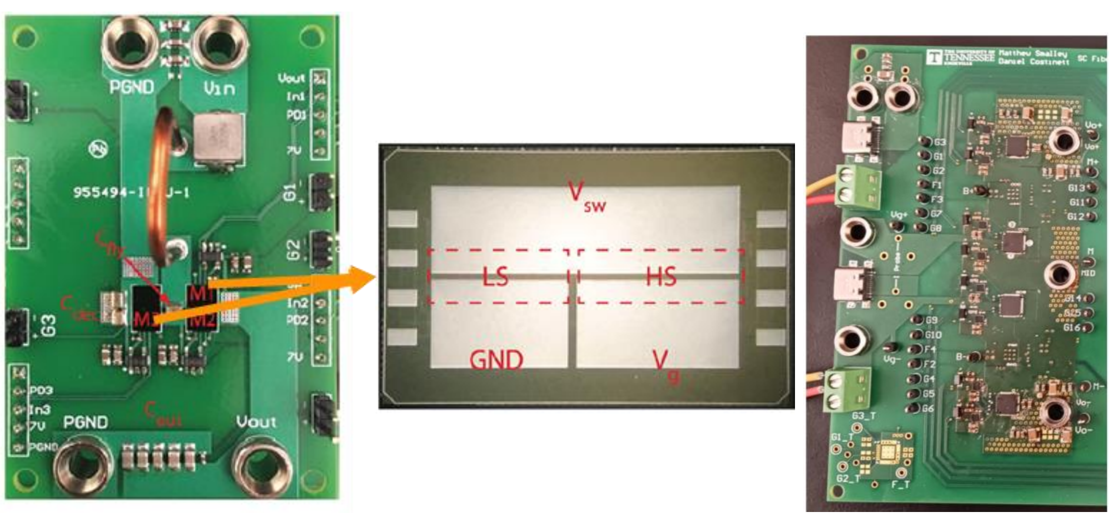


Figure 2.1: Prior prototypes using monolithic-integrated power stages.

9. CAREER: Unified Design Framework for Advanced Power Electronics

Project Lead: Daniel Costinett (UTK) Graduate Students and Research Faculty/Associates: Jared Baxter (UTK) Kamal Sabi (UTK)
Project Duration: 01/2018 – 12/2023
Funding Source: NSF

Summary

The research objective of this proposal is to develop the analytical tools and design resources necessary to create an analysis framework for advanced circuit modeling and design of switching power converters. Specifically, the framework is constructed to be

- Accurate: integrates nonlinear behaviors to result in non-idealized predictions of real-world performance

- Unified: can be applied to designs across topological, implementation, and operational barriers

- Rapid: can be completed without the need for extensive computational resources or long simulation times

- Adaptable: robust to varying levels of design data and applicable to varying physical implementations

The resulting paradigm integrates the generality and design insight of circuit simulators, the accuracy of high-order nonlinear models and empirical prototyping results and allows for setup and revision times beyond current established approaches. By advancing beyond the speed-accuracy front of modern analysis and simulation techniques, the framework facilitates a broad expansion in the scope of tractable multivariate design optimization in power electronics.

The framework developed in this work will simplify the task of selecting a power conversion circuit and schematic-level implementation for a given application. The approach uses a discrete-time framework, including extensions which allow the framework to inherently model nonlinearities present in the operation of advanced power electronics. These results are then coupled with a continuously-growing database of experimental and analytical results that ensures the highest degree of accuracy possible given an inherently uncertain design space. Leveraging these two, the research will develop techniques for holistic optimization of power conversion circuits. The result will be a new analytical framework that allows designers to rapidly select topology, operating mode, semiconductor and passive devices, and switching functions which will achieve maximal performance in a given application. The framework is developed to retain designer engagement, allowing for shorter prototyping cycles in the design process.

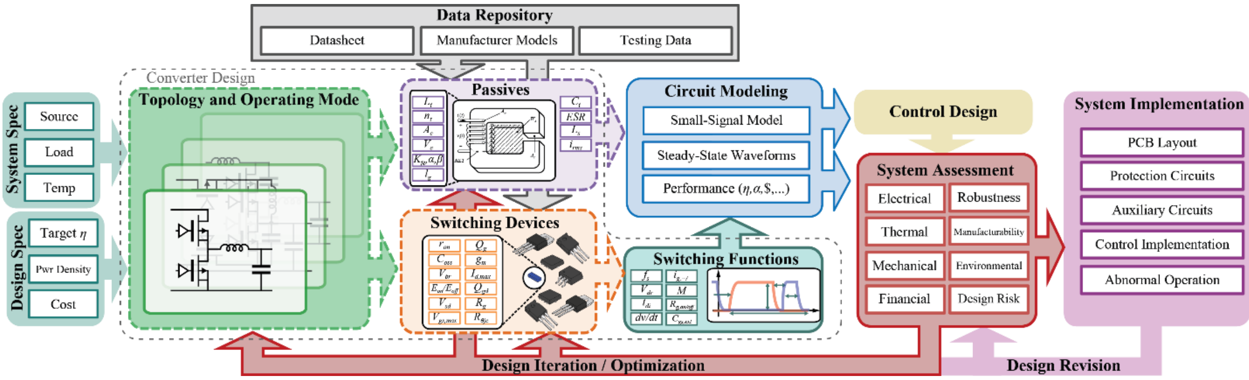


Figure 3.1: Example design flow and optimization

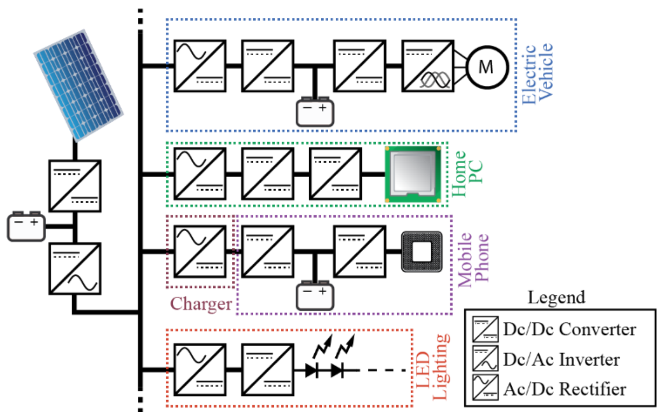
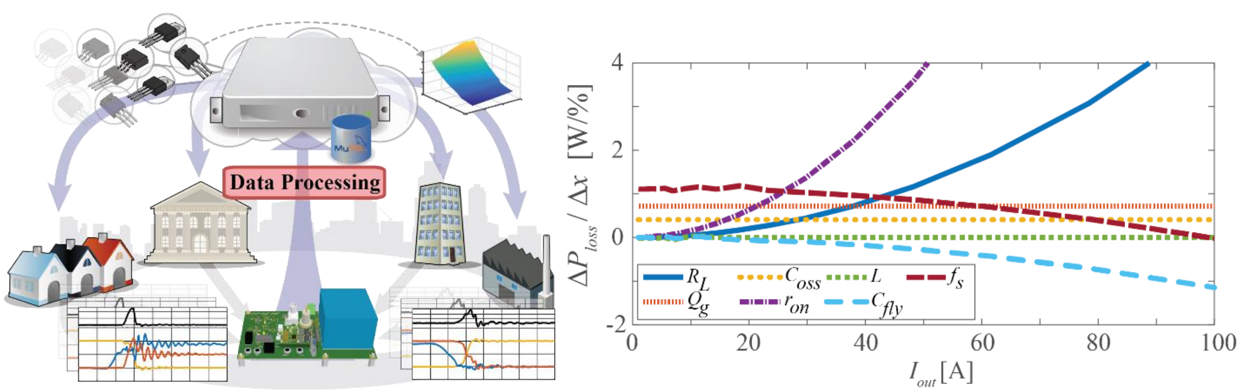


Figure 3.2: Example application showing the number of distinct power conversion stages that need to be individually designed



(a) **(b)**

Figure 3.3: Data processing and storage for design framework (a) and example outputs from modeling showing the impacts of each design parameter on converter performance

10. Wireless power transfer loss simulation and demonstrator for fast charging

Project Lead: Daniel Costinett (UTK) Graduate Students and Research Faculty/Associates: Andrew Foote (UTK)
Project Duration: 10/2019 – 09/2023
Funding Source: Volkswagen

Summary

Wireless power transfer (WPT) for Electric Vehicles (EVs) has several benefits over conductive charging including improvements in convenience, safety, automation, and vandalism resilience. WPT system power levels continue to rise and power levels up to 400kW may be needed to enable short charging times. With higher power levels, the amp-turns passing through the coils increase and stronger electromagnetic fields are created. However, for EV applications, these fields must be contained to certain extents without exceeding magnetic field limits. It is possible to do this. At Oak Ridge National Laboratory, 120kW wireless charging has recently been demonstrated at 97% DC-DC efficiency without exceeding stray-field limits .

This project is sponsored through the recent partnership between Volkswagen Group and the University of Tennessee, Knoxville and seeks to apply WPT technology to Volkswagen Group electric vehicles. Some of these electric vehicles will be produced by Volkswagen at the Chattanooga, TN plant.

This research project is focused on developing a new analytical method to rapidly design WPT systems with complex coil shapes for various objectives and constraints. The method directly designs WPT coil magnetic fields and currents to meet performance objectives and constraints through the optimization of Fourier basis function weights of varying spatial frequencies. Similar approaches have been applied in the design of MRI gradient coils, and electric machines. In the field of WPT, this method has many benefits and does not assume a specific coil geometry, number of turns, or rely on iterative finite-element analysis (FEA) simulations. After the continuous coil shape is optimized, the method can determine coil conductor paths and accurately predict self and mutual inductance for a desired number of turns and calculate the DC-DC losses for various gauges of wire and switching devices. This allows for convenient multi-objective optimization of a broad variety of coil shapes, operating frequencies, and DC-link voltages. The design framework is validated on a 120kW prototype system that has been tested to full power at ORNL.

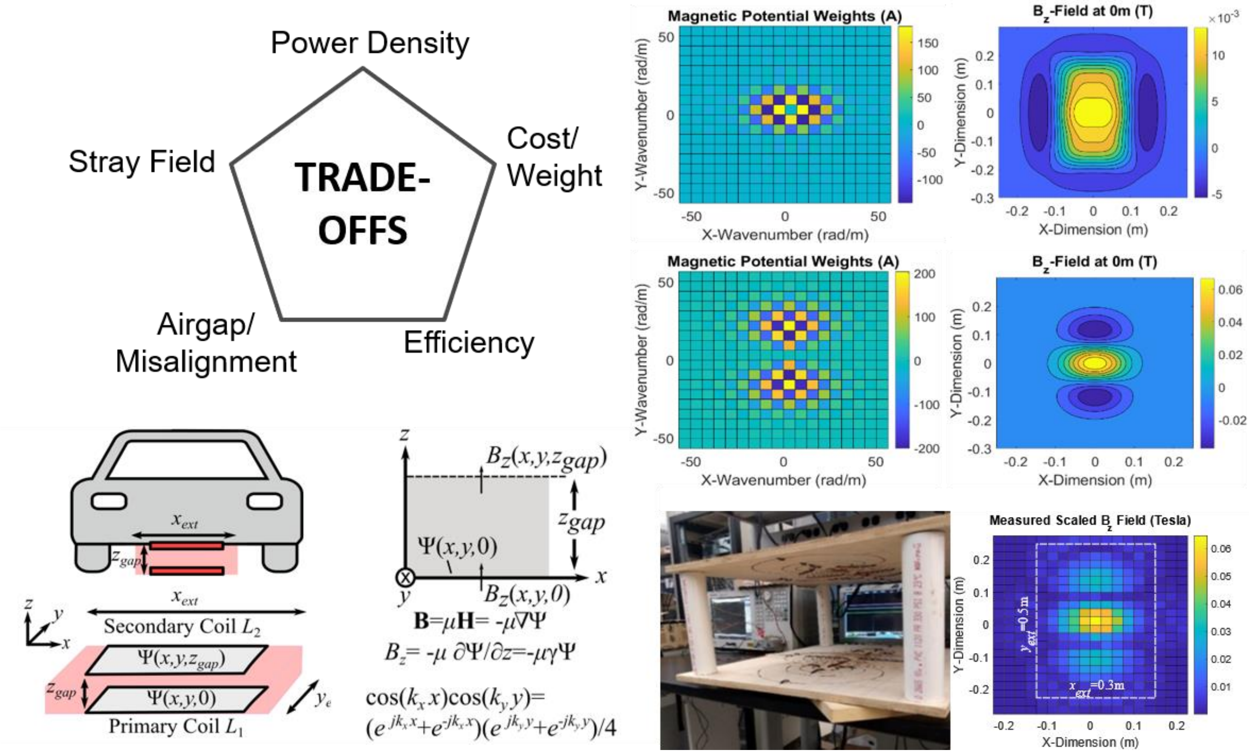
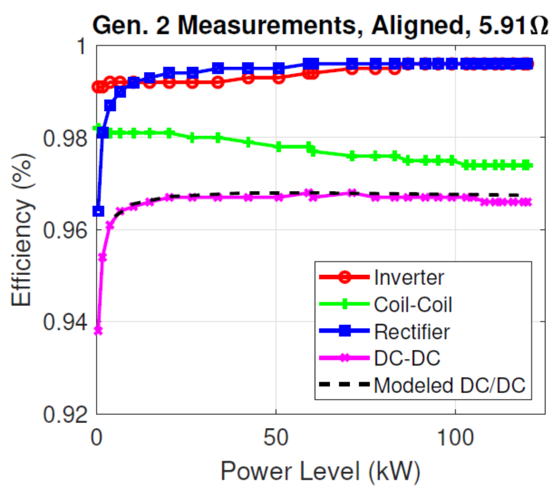
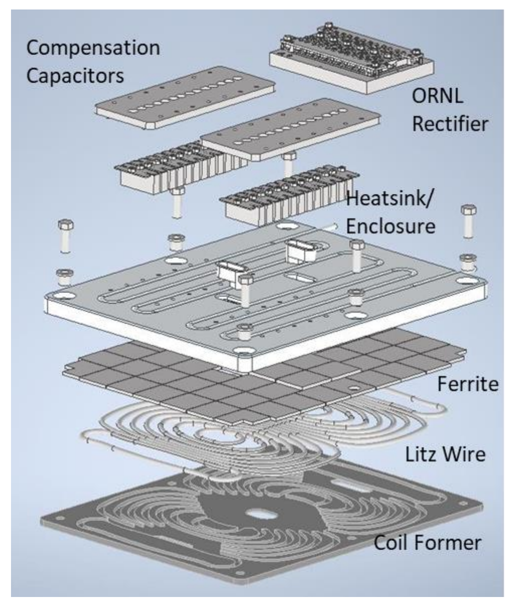


Figure 4.1: Example design flow and optimization





(a) **(b)**

Figure 4.2: Measured performance of 120kW prototype coils (a) and exploded view of coil, thermal system, matching network, and power stage

11. Design and Test A 800V/>50kW Three-level Active Neutral Point Clamping Motor Drive Inverter using 650V/60A GaN HEMTs for Electric Vehicles

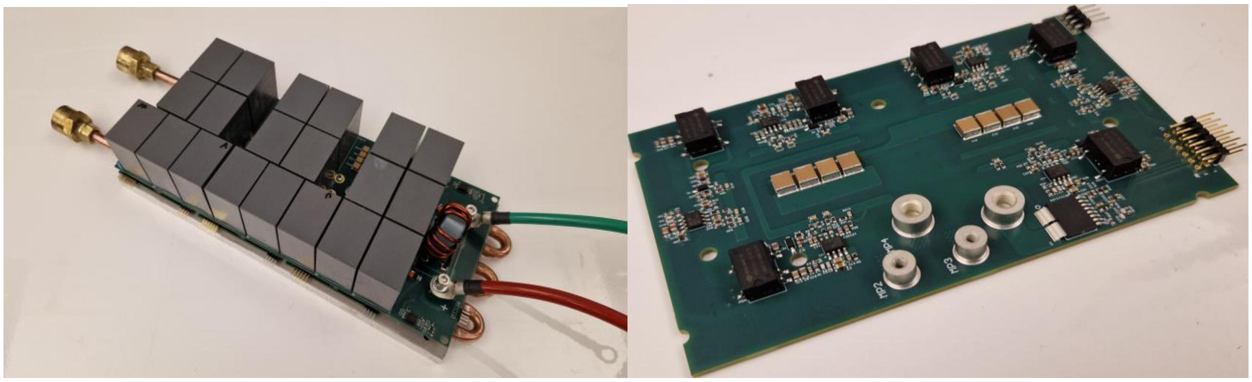
Project Lead: Kevin Bai (UTK) **Graduate Students and Research faculty/associates:** Xin Xia (UTK), Rajib Bijukchhe (UTK)
Project Duration: 11/2022 – 8/2023
Funding Source: PowerAmerica

Summary

The project aimed to use off-the-shelf automotive qualified 650V/60A GaN HEMTs from GaN Systems to build an 800V/>50kW DC/AC inverter. A three-level active neutral point clamping topology is the primary candidate, yielding enough voltage margin for switches. The proposing team used 9 months for the prototype packaging and proceeded comprehensive lab test and eventually the motor test on the dynamometer of Mercedes Benz facility. Upon the completion of the project, a high-efficiency, high-compactness and affordable lateral GaN based inverter for 800V battery systems is expected in future electric vehicles.

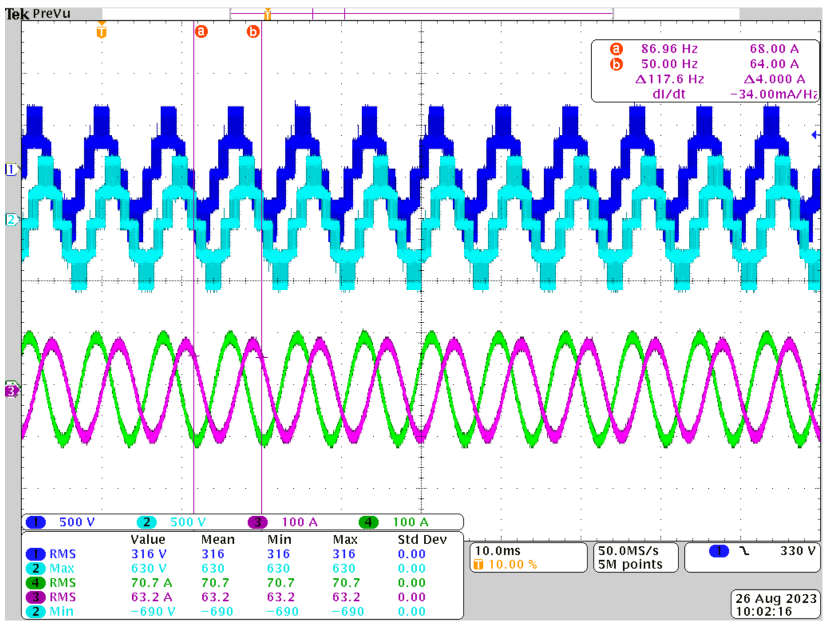
The key technology includes: 1) Control algorithms to secure the differential and common-mode performance, as well as balance the neutral point voltage; 2) multi-layer PCB design and assembly, which is essentially employing the decoupling cap for flux cancellation to offset the potential parasitic inductance. In addition, the gate-drive circuit of all switches including the needed power supply is soldered on this PCB. This can also ensure the similar distance and parameters of gate drive circuits to all paralleled switches, securing the static and dynamic current balancing.

Upon the completion of the project, the planned accomplishments include 1) a 800V/>50kW three-level ANPC inverter using 650V GaN HEMTs, as shown in Fig.1, with the efficiency and waveform shown in Fig.2; 2) an enhanced graduate-level course offered in UTK (ECE-585, Electric Vehicles).

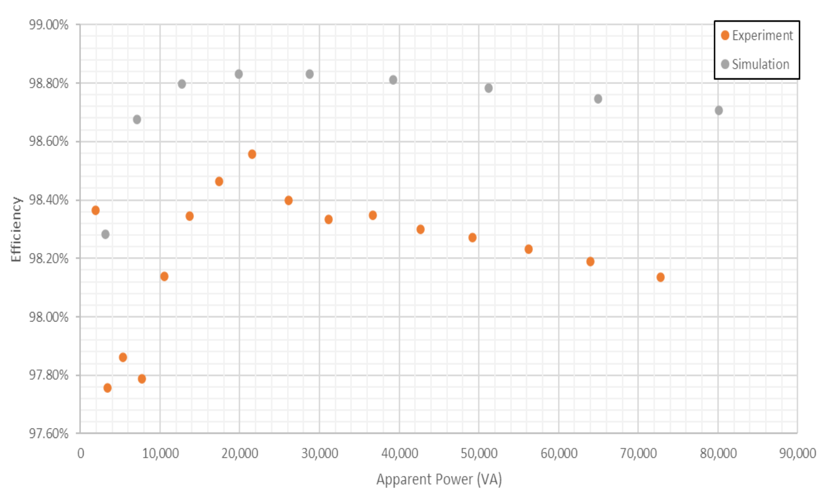


(a) 800V/75kVA prototype (b) the packaged phase power module

Figure 1 the built GaN inverter prototype



(a) Test line-line voltage (upper two) and phase current (lower two)



(b) simulated and test efficiency

Figure 2: Efficiency test across the whole load range.

12. Phase-2 Development for A Smart and Highly Compact Power Electronics Box to Provide OBC and DCDC

Project Lead: Kevin Bai (UTK) **Graduate Students and Research faculty/associates:** Ziwei Liang (UTK), Rajib Bijukchhe (UTK)
Project Duration: 2/2023 – 4/2024
Funding Source: Magna Powertrain

Summary

The project is the Phase-2 development of a highly integrated power electronics box embracing multiple functions for electric vehicles (EVs), e.g., three-phase 11kW on-board charging (OBC), single-phase 6.6kW OBC, and 3.7kW DCDC conversion from 400~800V HV battery to 12V. Based on the Phase-1 development, key improvement at this stage includes 1) paper design of the system without wireless charger; 2) revising the Phase-1 charger to undertake 800V battery; 3) enhancing the wire harness and thermal performance; and 4) optimizing control algorithms and communication to switch among V2G, G2V and V2L (vehicle-to-load) seamlessly. The primary switch choice is still 650V/60A GaN HEMTs from GaN Systems.

One graduate student works to develop the complete OBC system, focusing on the schematics, PCB design, prototyping, debugging and testing. The second graduate student carries out the paper design, communication and software optimization. Magna team provides the enclosure and heatsink manufacturing, etc. By the end of this project, UTK team will send the prototype to Magna for on-vehicle test.

13. A Converter-based Supercapacitor System Emulator for PV Applications

Project Lead: Leon M. Tolbert (UTK) **Graduate Students and Research Faculty/Associates:** Paychuda Kritprajun (UTK), Jingxin Wang (UTK), Nattapat Praisuwanna (UTK), Elizabeth Sutton (UTK), Jingjing Sun (UTK), Yunting Liu (PSU), Maximiliano Ferrari (ORNL)
Project Duration: 8/2022 – 07/2024
Funding Source: UT-ORII

Summary

The objective of this project is to develop a converter-based supercapacitor (SC) system emulator for photovoltaic (PV) applications in the CURENT hardware testbed (HTB). The developed emulator is used to demonstrate the SC capabilities to support a PV system by providing grid ancillary services. It is also used as a test platform for controller development and verification. This emulator can be potentially used for various power system scenarios in addition to the PV applications by integrating with other emulators developed on the HTB.

After confirming the effectiveness of the emulator in the previous phase of the project, the emulator has been utilized to investigate fast frequency support services provided a grid-connected PV with SC system (PVSS). The fast frequency support service has been conducted on HTB to study the PVSS dynamics under different setpoints of inertia coefficients. The PVSS can effectively reduce the rate of change of the frequency by injecting active power according to the inertia coefficient. However, experiments show that power oscillations occur with high inertia coefficients, thereby limiting the PVSS's efficiency in providing support during the event. To address this issue, this work proposes adjusting the inertia coefficients during the support to reduce power oscillations. Therefore, the SC utilization during the fast frequency support event can be improved while maximizing inertia emulation services. This study also implements bang-bang control to improve frequency recovery performance. The control prevents the PVSS from absorbing active power under the frequency drop events, which would prolong the frequency recovery period, thereby enabling faster return of the frequency to nominal conditions.

This project also continued the study on state of charge (SOC) management of SC to ensure its availability during low voltage ride through (LVRT) operations from the previous phase. This work considers the grid conditions and the SC limitation in terms of voltage, current, and temperature to enable the SOC management. The control concept was tested and compared with other techniques in existing literature. The experimental results on the HTB show that the proposed SOC reservation concept can ensure SC availability to provide LVRT services complying with grid code requirements while maintaining PVSS's stability during LVRT operations.

This project is expected to be completed by the end of July 2024. Future works include improving and testing the proposed fast frequency support control under different scenarios and evaluating its service provision performance with the existing literature. Additionally, the project will investigate control mode transition during LVRT events when the SC is unavailable to ensure seamless transition and continued LVRT service provision by PVSS during severe LVRT events.

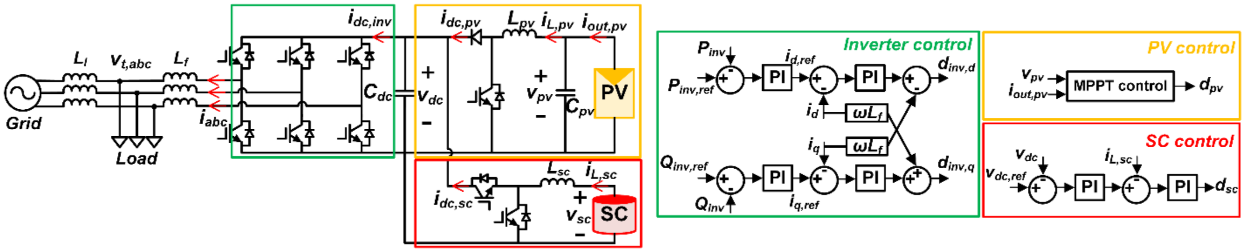
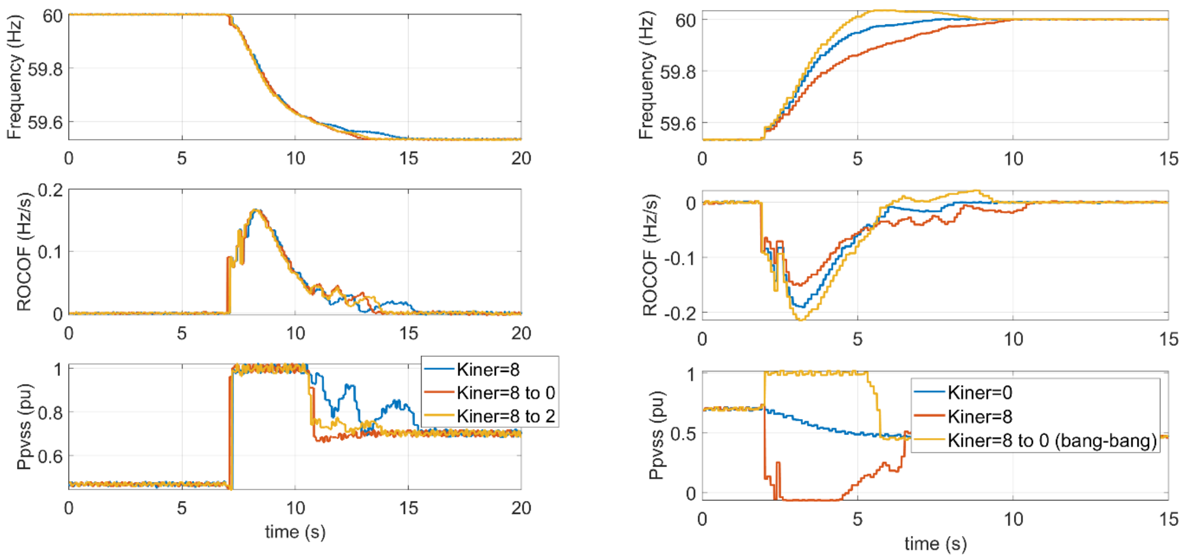
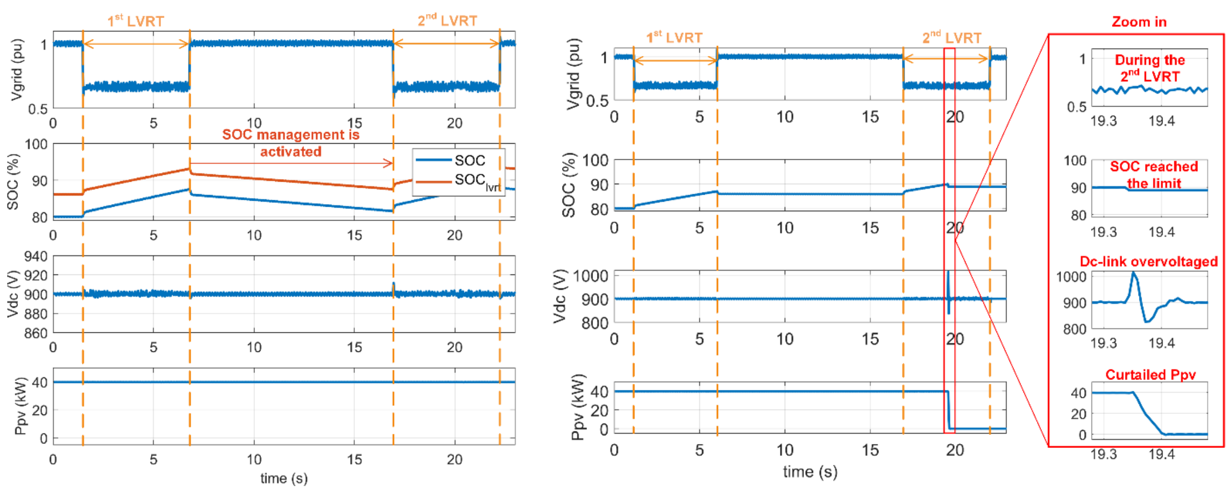


Figure 1.1: Circuit diagram and control of the grid-connected PV with SC system (PVSS).



(a) (b)

Figure 1.2: PVSS dynamics during fast frequency support when (a) changing of inertia coefficients to reduce power oscillations (b) implementing of bang-bang control to improve frequency dynamic during the recovery period.



(a) (b)

Figure 1.3: Comparison of LVRT performances between (a) the proposed SOC reservation concept and (b) the existing literature.

14. A Physics Based Circuit Model to Predict Magnetic Material Characteristics

Project Lead: Leon M. Tolbert (UTK)

Graduate Students and Research Faculty/Associates: Sadia Binte Sohid (UTK), Sakib Islam (UTK), Harmon M. Christian (UTK), Anwesha Mukhopadhay (UTK), Leon M. Tolbert (UTK), Daniel Costinett (UTK), Gong Gu (UTK)

Project Duration: 8/2022 – 07/2026

Funding Source: Office of Naval Research (ONR)

Summary

The modeling of magnetic materials holds significant importance in the development of high-frequency power transformers and inductors. However, the nonlinear and dynamic nature of magnetic behavior challenges conventional modeling techniques, often resulting in discrepancies between design and prototype. Addressing this issue requires an extensive physics-oriented model capable of capturing these nonlinearities, serving as a bridge between power electronics and material science, which is the subject matter of this project.

Magnetic materials at a specific temperature exhibit varying behaviors in response to external magnetic fields, depending on their moment configuration, impurities, crystallographic directions, and so on. The magnetization dynamics in a magnetic material is governed by a phenomenological equation, known as Landau-Lifshitz-Gilbert (LLG) equation, $\frac{d\vec{M}}{dt} = -\mu_0 \gamma \vec{M} \times \vec{H} + \frac{\alpha}{M_s} \vec{M} \times \frac{d\vec{M}}{dt}$.

Here, for an applied field H, the rate of change of magnetization ($\frac{d\vec{M}}{dt}$), is dependent on a precessional motion expressed by the first term on right-hand-side and the other term consisting of damping factor, α, describes a damped motion. The resultant motion describes the equivalence of magnetization dynamics that takes place within a magnetic material. In an attempt to overcome this challenge of modeling magnetization dynamics, the rate of change in magnetization along dimensional projections is modeled through an equivalent circuit as shown in **Figure 1. 1.** By doing so, the field and magnetization components are expressed in terms of nonlinear electrical components, for a specific gyromagnetic ratio $\boldsymbol{\gamma}$, and damping factor, $\boldsymbol{\alpha}$. making it easier to grasp the behavior of magnetization in relation to applied fields. This equivalent circuit model is designed to take the field effects only in the z-direction.

The energy balance within a magnetic material, is largely dictated by, anisotropy, exchange, magnetostatic, magnetoelastic energy etc. To simplify the scenario, a single-domain particle aligned by anisotropy energy is considered. To disregard shape dependent magnetization and allow continuous induction, simulations is performed for a toroidal structure. **Figure 1.2** shows **(a)** magnetization components along different projections, **(b)** alignment of net magnetic moment with the applied field, and **(c)** the hysteresis loop. Simulated data matches material datasheets closely, confirming agreement.

To accurately incorporate all field effects, a more generalized equivalent circuit model has been developed. This generalized model has been implemented in both LTSpice and MATLAB Simulink. The 3D visualization of magnetization projections (*Mx*, *My*, and *Mz*) in Figure 1.3 demonstrates that all three ports exhibit symmetrical behavior.

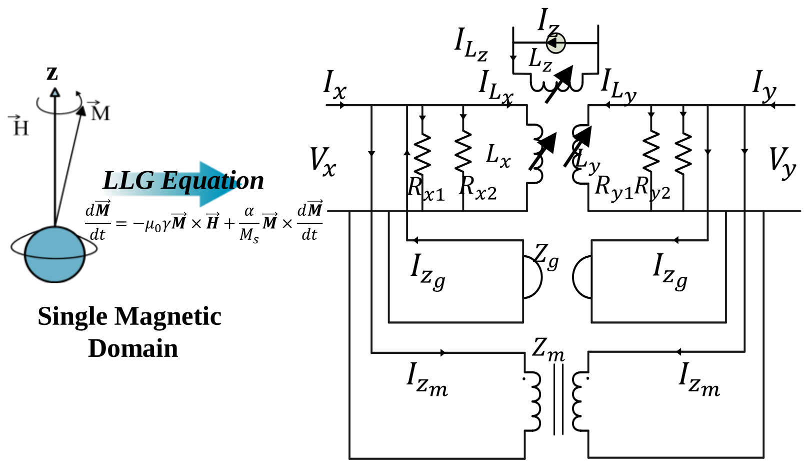


Figure 1. 2: Equivalent circuit diagram for a single domain derived from the complete implementation of LLG equation where external excitation is applied across z- port.

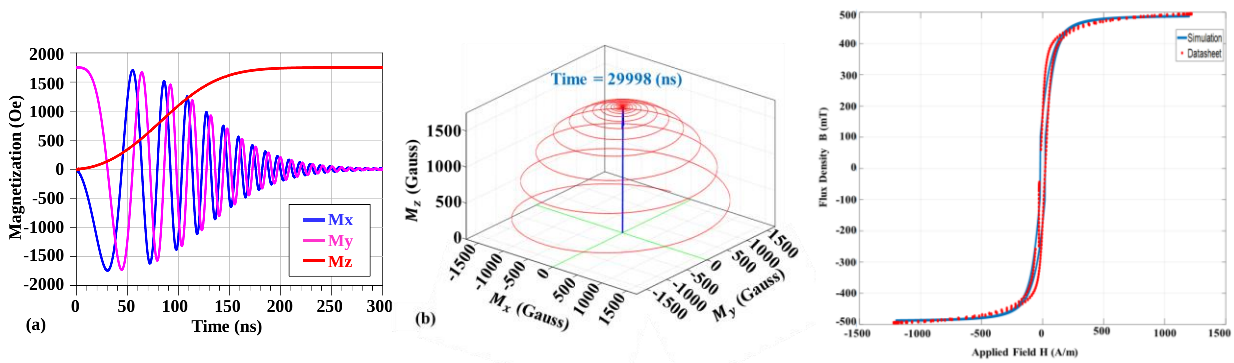


Figure 1.2: Trajectory of the domain's initial magnetization process (a) using ADS (b) in 3D plot using MATLAB. (c) B-H loop for the excitation field of 10 kHz at 25°C for the material N87.

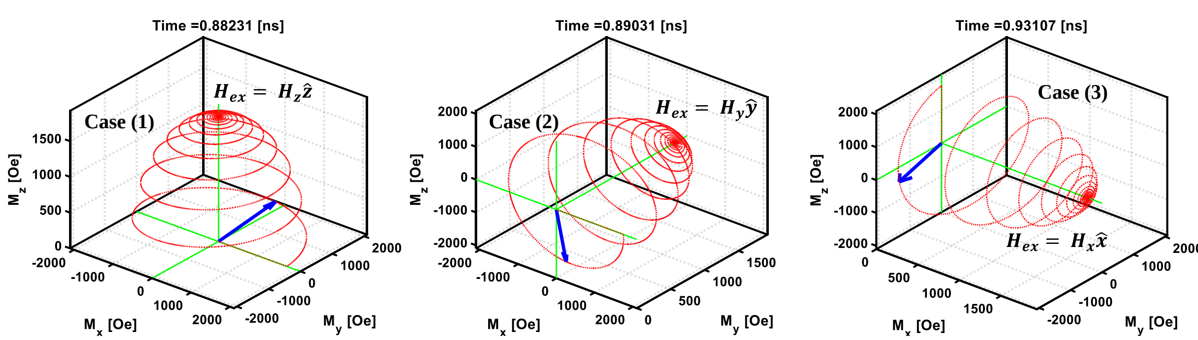


Figure 1.3: 3-D projection of Mx, My and Mz for Case (1), Case (2), and Case (3). All three ports exhibit symmetrical behaviour in the improved version of the circuit model. The H_{ex} is the the applied external field.

15. Using Second Life Batteries from Electric Vehicles to Provide Grid Services

Project Lead: Hua Bai (UTK), Leon Tolbert (UTK), Fred Wang (UTK) **Graduate Students and Research faculty/associates:** Yousef Alamri (UTK), Elizabeth Sutton (UTK), Nattapat Praisuwanna (UTK)
Project Duration: 08/2023 – 08/2024
Funding Source: Volkswagen

Summary

This project is the second phase of using second life batteries from electric vehicles to provide grid services. This phase aims to develop a 40 kW battery energy storage system (BESS) that uses retired batteries from Volkswagen electric vehicles, and it will be installed at Volkswagen Chattanooga. The BESS schematic is illustrated in Fig. 1. The BESS includes second life batteries, a battery management system (BMS), a power conditioning system (PCS), controllers, measurements, switches, and an uninterrupted power supply (UPS). The BESS can operate in both grid connected mode and grid forming mode.

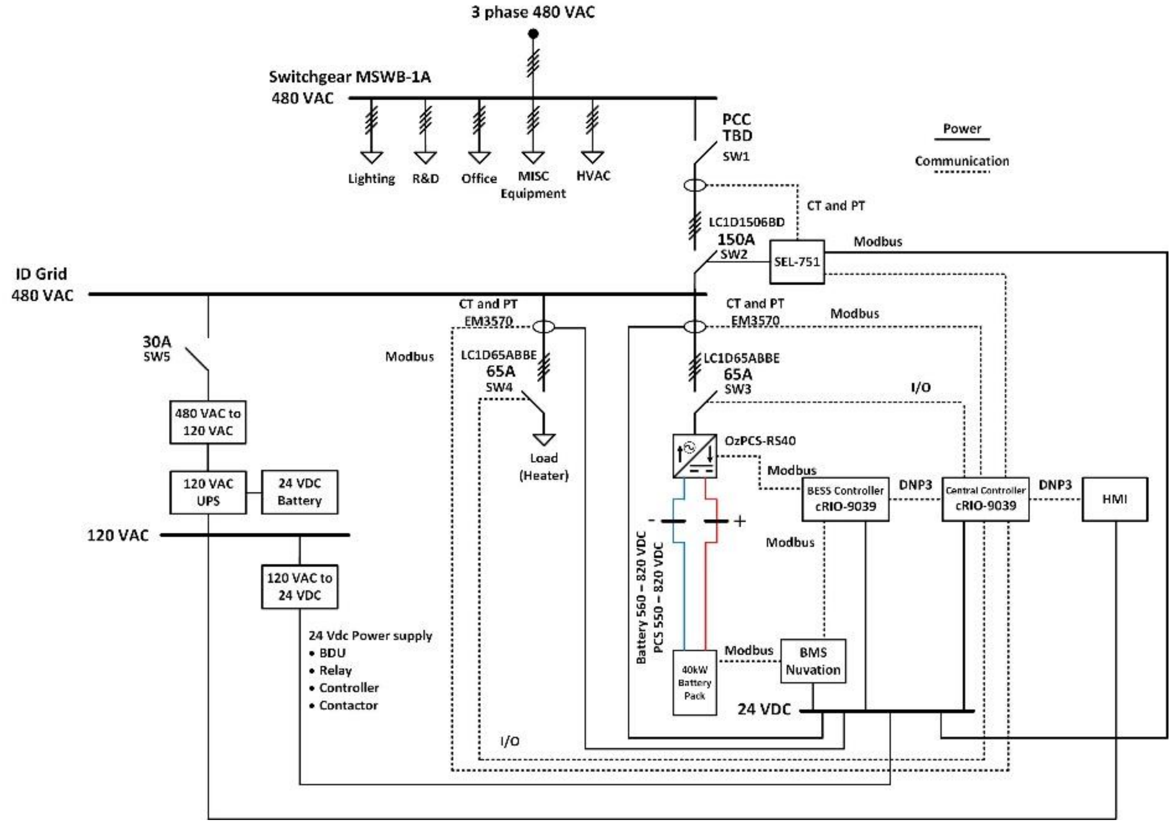
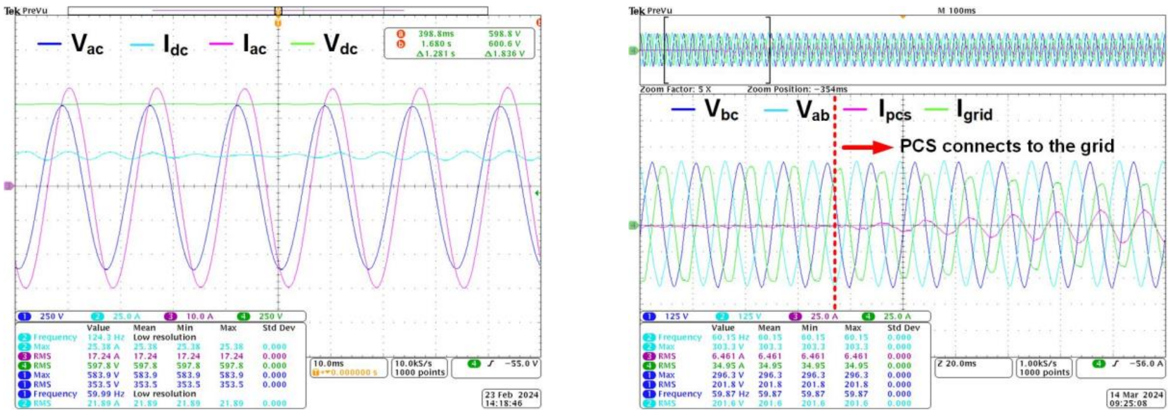


Fig. 1. BESS Schematic.

In this phase of the project, some of the main selected components, including the PCS and BMS, have been tested in a lab to verify operation conditions and gain experience setting up the system. This will allow for an easier set up when installing on site. The PCS testing shows the grid forming and grid connected operation modes of the BESS. Fig. 2 shows experimental results of the PCS testing. Grid forming operation is shown in Fig. 2a while Fig. 2b illustrates grid connected operation.



a. Grid forming operation. b. Grid connected operation.

Fig. 2. Experimental results.

Testing the BMS in the lab verifies that all protections and measurements of the BMS are operating properly. Additionally, the testing helps to familiarize with the configuration methods for state of charge, voltage, current, and thermal limits, contactor setup, etc.

In addition to preparing for installation, ideal operating conditions are also studied with the intent to minimize energy cost from the utilities and decrease battery aging. The cost of energy from the utilities is mostly dependent on time of use and the maximum power used in a month. Decreasing the peak power or shifting the peak to a time when demand is lower can significantly decrease the cost. Different methods to lower the peak have been examined, showing that between 6 and 8 hours of peak shaving is optimal for cost saving, but it is not necessarily the best for battery health.

Prolonging the lifespan of a battery significantly hinges on understanding the battery degradation and the various factors influencing its longevity under both storage and operational conditions. It is vital to harness this knowledge to find strategies that optimize how batteries are stored and used over time. The combined model developed during the first phase serves as a basis in identifying and implementing the most favorable conditions for battery storage and usage. This model provides insights into the best practices for extending battery life by adjusting storage conditions and usage patterns.

II. Power System Group

16. Adaptive Wide-Area Damping Control Using Measurement-Driven Transfer Function Model for New York State Power Grid

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Xinlan Jia (UTK), Yi Zhao (UTK), Chengwen Zhang (UTK), Wenpeng Yu (UTK)
Industry advisors: Evangelos Farantatos (EPRI), Lin Zhu (EPRI)
Project Duration: 03/18/21 – 12/31/23
Funding Source: DOE

Summary

This project is to develop advanced adaptive wide-area damping controllers (WADCs) based on a measurement-driven approach to mitigate low-frequency oscillations. The adaptive WADC is designed and implemented on an industry-grade hardware platform and tested in a controller hardware-in-the-loop (HIL) setup using the New York State grid model. The New York Power Authority (NYPA) is the industry partner of this project. In the next phase of this project, realistic issues for field implementation of WADC will be addressed. The related field testes and demonstrations will be scheduled.

In addition, mitigation of forced oscillation using WADC through inverter-based utility-scale Battery Energy Storage Systems (BESS) is also investigated in this study, including the critical location identification of forced oscillation, the optimal actuator selection on mitigating forced oscillations using damping control technology, and the controller design method on damping forced oscillations.

Major activities conducted by the project team in this year are summarized as follows:

1. A two-dimensional scanning forced oscillation grid vulnerability analysis method has been proposed to identify the forced oscillation frequency and areas/zones critical to forced oscillation in large-scale power grid. The critical area that could excite the most serious forced oscillation event can be selected as optimal locations of actuator for damping controller.

2. The damping control strategy is simply based on droop control to modulate active power of utility-scale BESSs to cancel forced oscillation energy. The control effect of this strategy has been validated in the 70,000-bus EI model which includes NYPA power grid under the January 11 2019 oscillation event by simulations.

3. An improved measurement-driven identification module with considering the environment ambient noise impact was designed and tested under hardware-in-the-loop platform. Advanced data preprocessing methodology has been developed and integrated into system identification to improve the identification accuracy and guarantee the WADC performance under different operating conditions.

In the next year, time synchronization enhancement of openPDC to NTP server will be further improved. Time synchronization error detection and updated compensation module will be developed for WADC field implementation. Soft-start function and initialization module will be developed for WADC control commands.

17. A Real-time Short-term Power System Frequency Prediction Model

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Chujie Zeng (UTK), Chang Chen (UTK), Hongyu Li (UTK), He Yin (UTK)
Project Duration: 9/2022 – 9/2023
Funding Source: Top IT company not to be named

Summary

This project aims at developing an accurate real-time prediction model of short-term power system frequency by using FNET/GridEye synchrophasors.

The first and second phases of this project have been completed. In phase I, the team investigated the frequency distributions in 32 worldwide power systems based on the measurements collected by FNET/GridEye. Non-stationarity and non-Gaussianity are widely observed in worldwide frequency distributions. Besides, in power systems, the frequency indicates the active power imbalance between load and generation, thus load power change, generator power change, generator control and protection, load control and protection, stability issue, and measurement issue are the major factors impacting power system frequency. Phase II targets at developing a preliminary prediction model and selecting evaluation metrics. Mean absolute error (MAE), also known as L1 error, is selected as the primary evaluation metric. The 99-th percentile of absolute error is also used. Given the non-stationary and non-Gaussian nature of frequency and the prevalence of Deep Learning (DL) model in the time-series forecasting field, a DL model is tested. A simple linear regression prediction model is also tested. Both have been evaluated on 12-Month field data collected from Eastern Interconnection in 2021. The MAEs of both models are lower than 0.01 Hz when the prediction horizon is within 20 seconds.

This project is expected to be finished by Sept. 2023. Future works include further improvement and comprehensive evaluation.

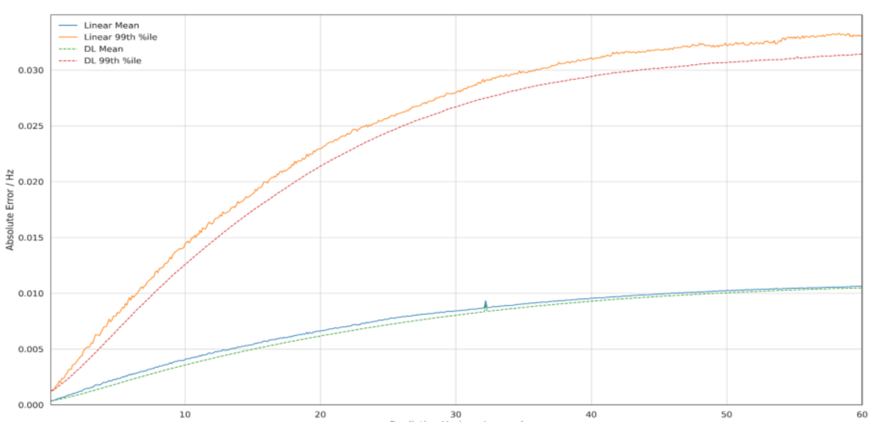


Figure 28.1: Evaluation result of preliminary prediction models

18. Damping High Frequency Forced Oscillations in Power Grids

Project Lead: Yilu Liu (UTK), Yi Zhao (UTK) **Graduate Students and Research faculty/associates:** Fariha Hakim Sneha (UTK)
Project Duration: 8/2022-Present
Funding Source: EPRI/DOE

Summary

The objective of this project is to improve the damping performance of high frequency forced oscillations in power grids by proposing an innovative controller structure that can effectively suppress these oscillations.

This project focuses on identifying the limitations of the existing controller structure in suppressing high frequency forced oscillations and proposing a new controller structure that can effectively damp high frequency oscillations while minimizing the impact on other frequency bands. The performance of the proposed controller has been validated through simulations on a 13-bus power grid model in PSCAD.

The traditional droop controller can suppress low frequency oscillations to a great extent. However, in case of high frequency oscillations, the controller has limitations and can only damp them by no more than 65%. While performing simulation using high frequency forced oscillation, the actuator (PV models) did not respond sufficiently to those oscillations compared to low frequency ones which is a key factor limiting the damping performance of the conventional controller. This limitation of the existing controller leads to the development of the proposed controller, which is illustrated in Figure 32.1. The proposed controller consists of a control gain, second order high pass filter, and phase shift blocks.

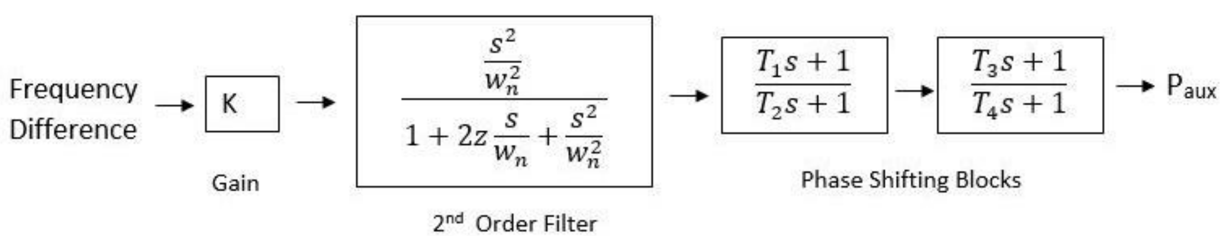


Figure 32.1: Proposed Controller Scheme

To test the effectiveness of the proposed controller, simulations were performed using a 13-bus model developed in PSCAD. The results show that the proposed controller achieves 81%-84% damping at all buses, representing a significant improvement over the conventional controller.

Overall, this project addresses the challenges of mitigating high frequency forced oscillations in power grids and provides a better solution to improve the stability and reliability of power systems. By proposing an innovative controller structure, the project offers a more effective and reliable approach to suppress high frequency forced oscillations, which is a critical aspect of ensuring the secure operation of power systems.

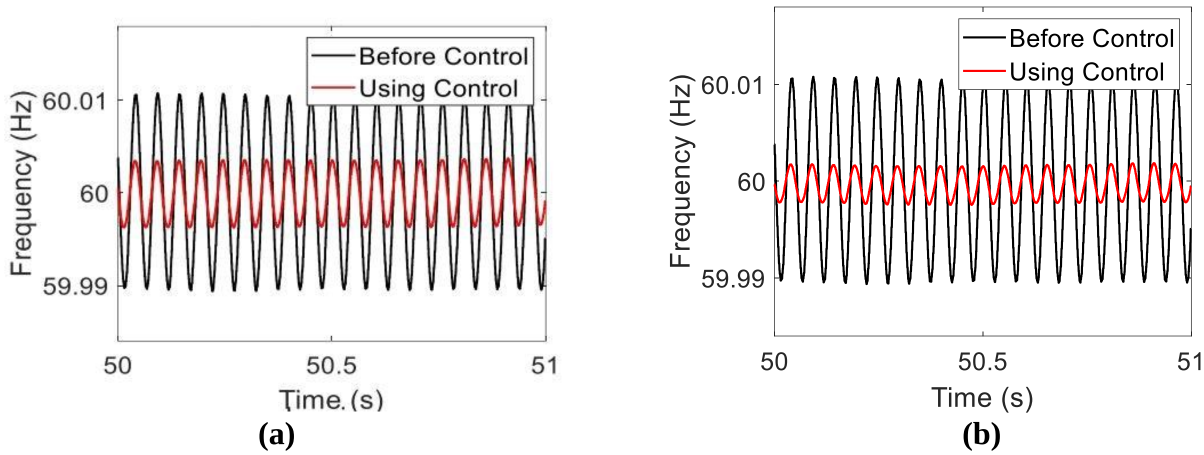


Figure 32.2: Comparison of damping performance between (a) existing controller and (b) proposed controller in case of 19.5 Hz forced oscillation

19. Electromagnetic Penetration of Structures with Applications in Vulnerability Assessment

Project Lead: Yilu Liu (UTK; ORNL), Larry C. Markel (ORNL) **Graduate Students and Research faculty/associates:** DaHan Liao (ORNL), David P. Mignardot (UTK)	
Project Duration: August 2022 – September 2023	
Funding Source: DoE	

Summary

High altitude electromagnetic pulse (HEMP), and other weaponized EMP, pose a threat to the security and reliability of the electrical power system. This study focuses on the vulnerability of power generation facilities specifically. Electromagnetic simulations are conducted to determine the shielding effectiveness of structures and which parameters are most critical. Results indicate a structure's susceptibility to penetrating electromagnetic radiation.

The first phase of the project consists of running electromagnetic simulations and identifying critical parameters. The team studied parameters such as angle of incidence, polarization, frequency dependence of dielectric materials, and dielectric ground planes. With understanding of how these parameters influence a structure's shielding effectiveness, we can apply approximations and worst-case scenarios to more complicated models. The general observations collected in phase I can be applied to future work. In phase II, more complicated models will be studied including structures with apertures, structures constructed with reinforced concrete, and structures with penetrating above and underground cables. Finally, obtained transfer function data can be convoluted with the early time component (E1) pulse of HEMP. The convoluted representation will describe the overall shielding effectiveness of the structure, and field intensities can be estimated.

So far, a multitude of rudimentary electromagnetic simulations were conducted testing the mentioned parameters. Transfer function results of the simulations were analyzed and documented. Additional simulations were carried out to observe the effect of apertures including glass windows and metallic doors.

Future work will include modeling and simulating a structure composed of reinforced concrete. Also modeling a plant with infiltrating cables to study how much electromagnetic radiation enters through coupling.

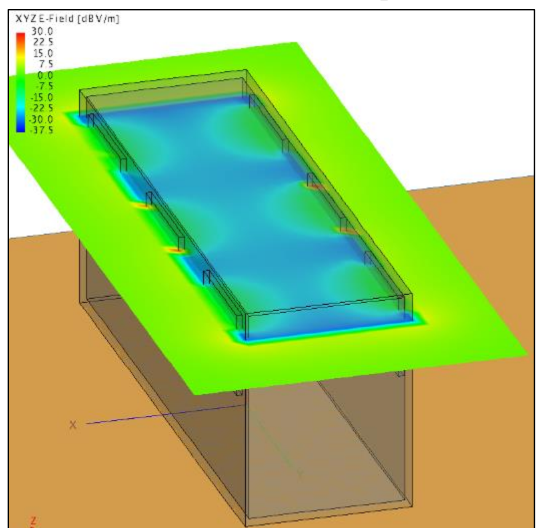


Figure 33.1: Electric Field results for 10m by 3m by 4m structure with six 2m square windows.

20. Field Implementation and Hardware-In-the-Loop Testing of Wide-Area Damping Controller as OpenPDC Adapter

Project Lead: Yilu Liu (UTK), Lin Zhu (EPRI), Evangelos Farantatos (EPRI), Cosimo Pisani (Terna), Roberto Zaottini (Terna) **Graduate Students and Research faculty/associates:** Xinlan Jia (UTK), Yi Zhao (UTK), Wenepng Yu (UTK), Chengwen Zhang (UTK),	
Project Duration: 1/2022 – 6/2023	
Funding Source: EPRI	

Summary

This project developed a wide-area damping controller (WADC) software prototype and tested it on an enhanced hardware-in-the-loop (HIL) test setup. In our previous research, a measurement-driven WADC design method for suppressing inter-area oscillations has been proposed and a hardware prototype was developed and validated through Opal-RT real-time simulator. This continuation work introduced the implementation of WADC software prototype, which is developed and operated as an openPDC adapter. The WADC's structure is shown in Figure 35.1. A graphical user interface (GUI), shown in Figure 35.2, is also developed to monitor the input frequency signals, communication delays from the primary and backup PMUs, the status of WADC, and the output WADC command. The WADC can generate control commands and send them to the synchronous condenser at the substation. An enhanced PMU device was used as the interface device to receive the control commands, convert them into analog signals, and inject them to the voltage setpoint of the synchronous condenser.

The developed WADC was fully tested in an enhanced HIL test setup. Different from the HIL test in the previous phase of this project, an enhanced PMU device was included in the loop to mimic the actual operation environment of the WADC. The performance of the WADC system using the centralized control structure was validated under various communication uncertainties, including constant time delay, random time delay, random data loss, and consecutive data loss.

The HIL testing results show that the WADC software can have effective damping performance under large constant and random delays for both communication protocols with the proper buffer size selection. In addition, UDP/IP would be recommended for the future field deployment of WADC with consideration of regular random data drop and chunk of data loss situations. The HIL experiments have provided valuable support for future field deployment of wide-area damping controller in the Italy power grid.

Future work may focus on the continuation of the field tests, e.g., demonstration of damping ratio improvement by WADC under large disturbances, control performance of WADC with two actuators. Other works on the upgradation of WADC software functions, such as adding the system identification module for online adjustment of controller parameter, will also be conducted.

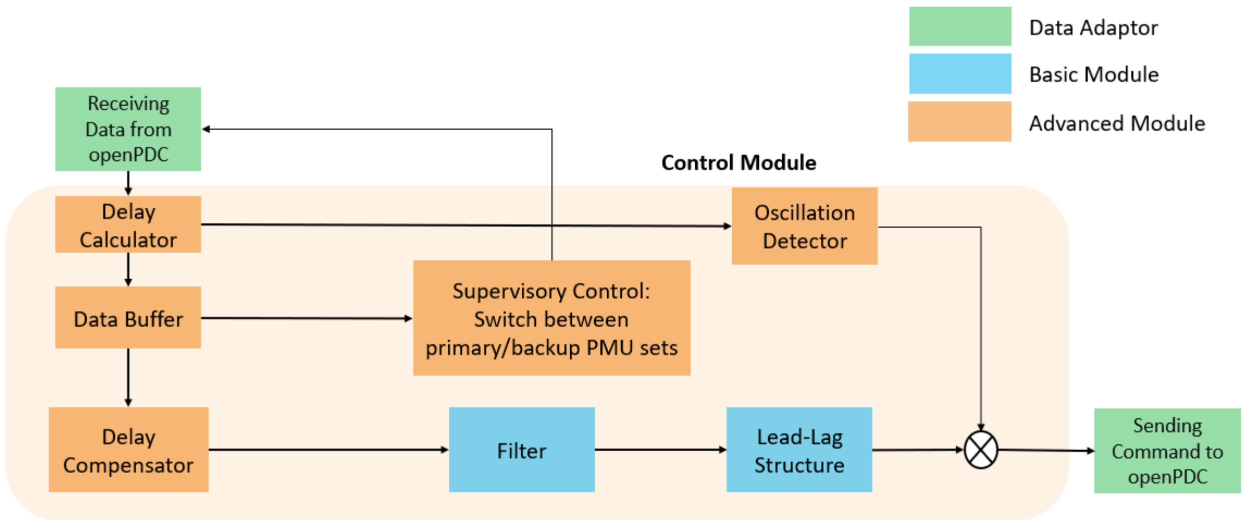


Figure 35.1: Overall structure of WADC

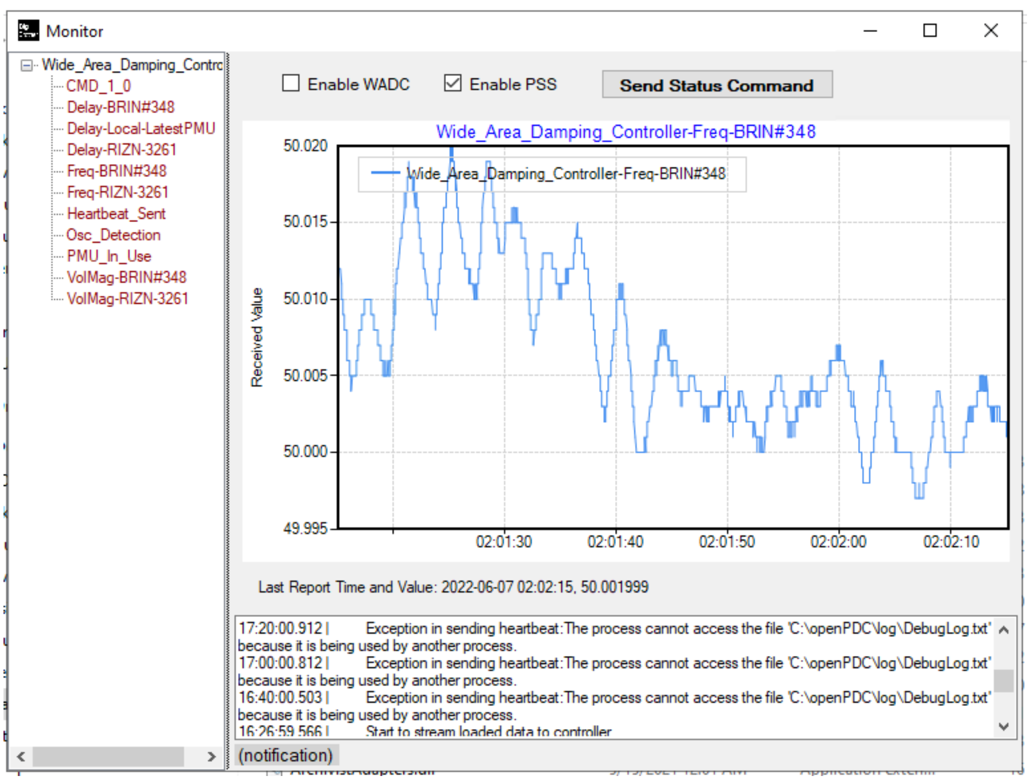


Figure 35.2: WADC monitoring GUI interface

21. Forced Oscillation Source Localization Tool Development

Project Lead: Yilu Liu (UTK)

Graduate Students and Research faculty/associates: Wenpeng Yu (UTK), Yi Zhao (UTK)

Industry Advisors: Antos Varghese (EPRI), Evangelos Farantatos (EPRI), Lin Zhu (EPRI)

Project Duration: 1/2021 – Present

Funding Source: ORNL/DOE

Summary

Low-frequency natural oscillations have been a significant threat to secure and economic operation of large-scale power systems. These oscillations have been observed across all interconnections in North America and worldwide over the years. They can lead to system instability, system separation, and widespread outages if not adequately mitigated. Equally importantly, multiple severe forced oscillation events have been observed across the North American interconnections. Unlike natural oscillations, forced oscillations are usually excited by a periodic driving source, and they can persist indefinitely until the source is located and removed. These forced oscillations can cause sustained power swings, limit power transfer capability, and damage equipment.

This project aims to develop mitigation measures for these oscillations. For forced oscillations, a source location algorithm and tool will be developed. For natural oscillations, this work will investigate the design of local POD controls at utility-scale wind/solar plants to damp the oscillations.

This continuation work will focus on the development of the Forced Oscillation Localization Tool (FOLT) offline version 2.0, in which the current measurement will be utilized to improve the observability of the power grid and then improve the estimation accuracy of the forced oscillation source.

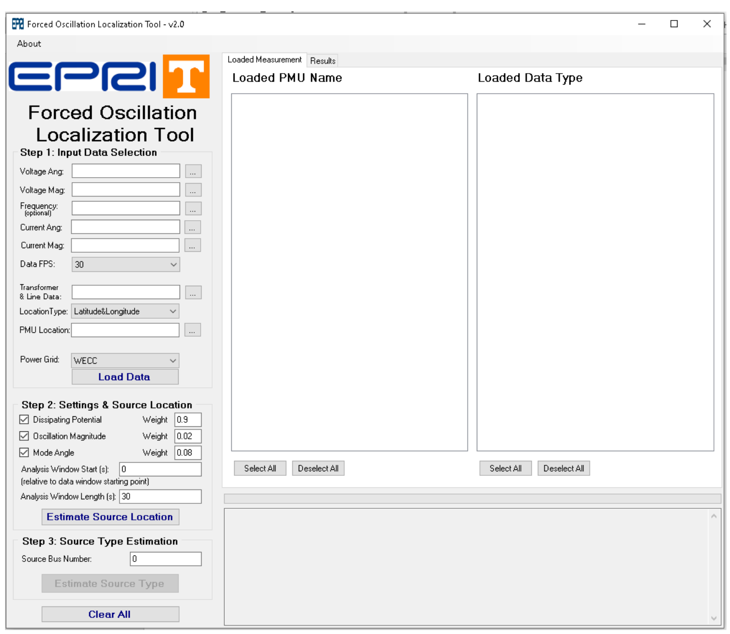


Figure 38.1: GUI of Forced Oscillation Localization Tool

22. Geomagnetic Disturbance Vulnerability Assessment and Situational Awareness Improvement for a Real U.S. Power System

Project Lead: Katelynn Vance (DE), Xiawen Li (DE), Andrea Pinceti (DE), Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Adedasola A. Ademola (UTK)
Project Duration: 8/2021 – 7/2023
Funding Source: Dominion Energy (DE)

Summary

The main aim of this project is to identify the system-specific vulnerabilities of the Dominion Energy Virginia power system and better prepare it for realistic geomagnetic disturbance (GMD) events. This project combines fundamental frequency, harmonic, and thermal analysis to discover overlaps between different GMD effects in the power system to provide a holistic security evaluation of the grid during extreme GMD events. The objectives of this project are classified under three main thrusts. The first thrust involves a comprehensive equipment- and system-level GMD vulnerability assessment for the Dominion grid and the evaluation of strategies to limit the effects of geomagnetically induced current (GIC) flow. This research thrust is nearing conclusion because the following tasks have been completed: 1) GMD modelling and GIC calculation in the Dominion grid, 2) identification of highly vulnerable transformers followed by their thermal impact assessments, 3) impact study of GIC on voltage stability in the system, and 4) evaluation of GIC mitigation strategies in the Dominion grid. The only pending task under this thrust is harmonic flow analysis involving the use of an EPRI software (GICharm) which is undergoing some debugging.

The second project thrust is the development of an easy-to-implement and cost-effective scheme to monitor GIC in the grid. This portion of the project has been completed and it involved the electromagnetic transient (EMT) modeling and simulation of GIC injections into high-voltage transformers of a 2-bus model representing a Dominion substation. The EMT simulations were followed by feature extraction from the simulation data to train the convolutional neural network (CNN) shown in Figure 39.1. The performance of the trained CNN was subsequently tested based on its capability to accurately estimate GIC magnitudes in response to certain harmonics inputs (see Figure 39.2). The test data were created using actual GIC measurements data from a GIC monitor in the Dominion grid along with some GIC waveforms from literature.

The third project thrust involves the following tasks: 1) system impact study of a planned GIC field test in the Dominion system by EMT modeling and simulation, 2) comparison of the EMT simulation results with field measurements to validate the EMT model, and 3) use of the validated EMT model to study the interactions of GIC effects with voltage source converters in the grid. The first task under this thrust was completed last year while the second task is ongoing. The last task will begin in the coming weeks.

The whole project is expected to be finished by June 2023.

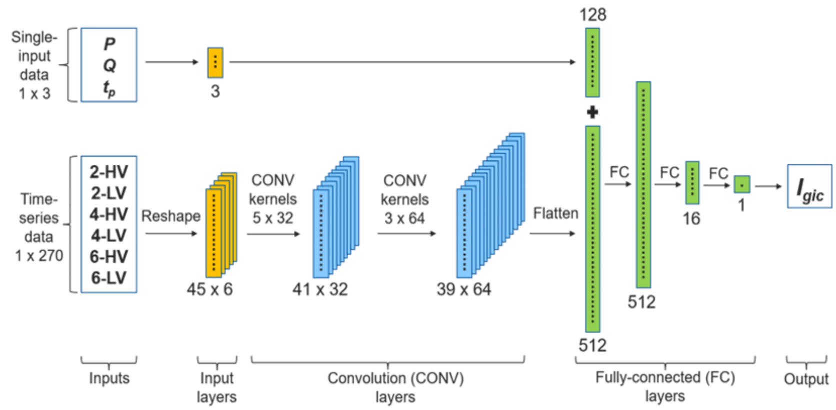


Figure 39.1: Convolutional Neural Network for GIC monitoring

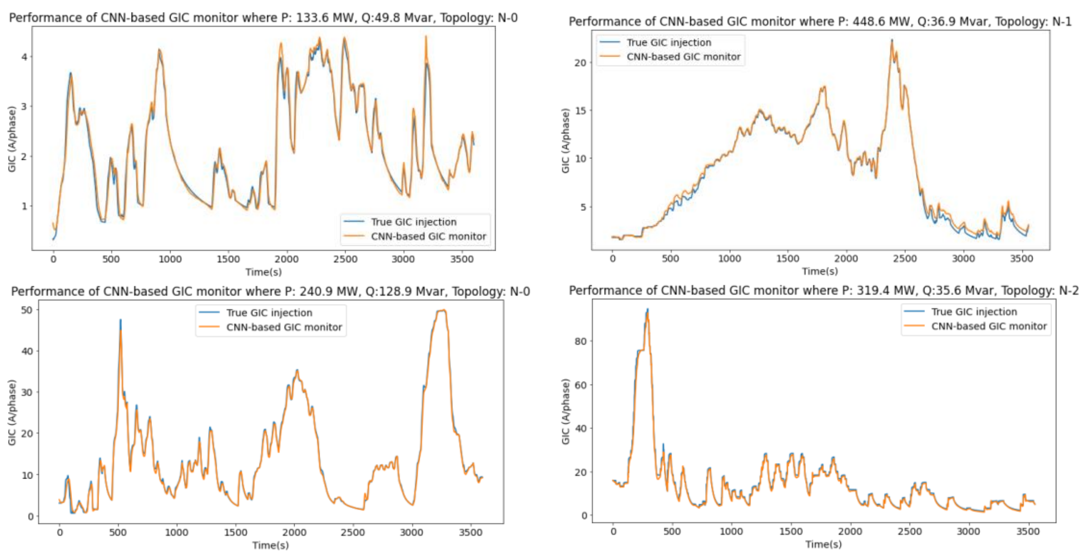


Figure 39.2: Performance of the CNN-based GIC monitor

23. Grid Strength Assessment of High Renewable Power Grids

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Zhihao Jiang (UTK), Abigail Till (UTK)
Industry advisors: Katelynn Vance (Dominion Energy), Xiawen Li (Dominion Energy), Andrea Pinceti (Dominion Energy)
Project Duration: 4/2021 – Present
Funding Source: DOE

Summary

This project aims at conducting interconnection-wide grid strength assessment of future high renewable power grids in the U.S., identifying potential weak grid conditions and proposing mitigation strategies in advance. The first year of the project is sponsored by DOE under the Near-Term Reliability and Resilience (NTRR) project. The team first developed a projected 2025 model of Eastern Interconnection (EI) based on MMWG planning models by integrating new generation projects and confirmed retirements collected from public data sources, such as Energy Information Administrative (EIA), Independent System Operators (ISOs) and interconnection queues. The team then carried out a grid strength assessment of the Dominion Energy service territory by projecting future grid strength trends and identifying weak locations. In addition, the team also investigates the impacts of grid strength changes on a wide range of grid voltage characteristics, including short circuit current level, steady state voltage stability and voltage dynamics during serious events. Furthermore, using developed grid strength metrics, the team identified plants that are critical for maintaining grid strength, which could serve as a reference for policymakers to develop market structures.

The team is working on expanding the study scope of the grid strength assessment to the entire EI and WECC interconnection. Ongoing work includes 1) study of short circuit level changes when all existing fossil-fueled generation are replaced 2) estimation of hosting capability of inverter-based resources at different locations using short-circuit-ratio-based metrics.

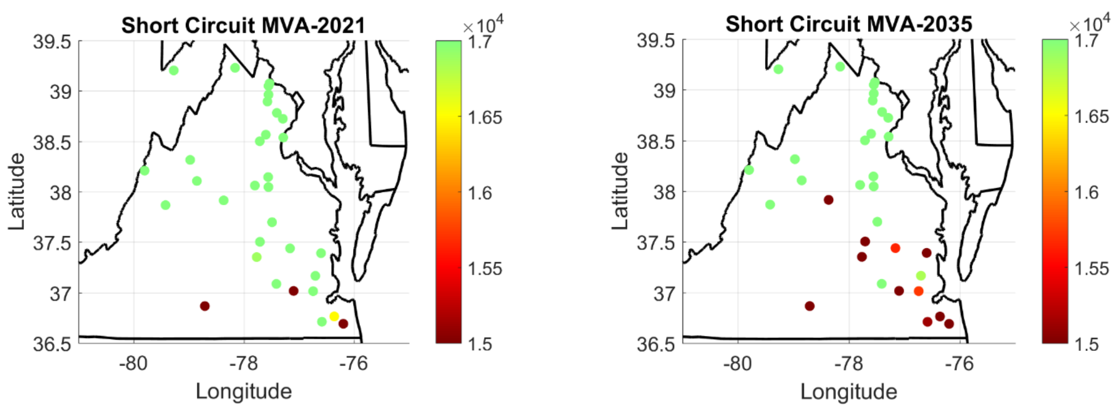


Figure 41.1: Comparison of SCMVA level at 500kV buses in Dominion Energy service territory for 2021 and 2035

24. Increasing the stability of large-scale electric power systems through an adaptive measurement-driven controller prototype

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Adedasola Aanu, Ademola (UTK), Yi Zhao (UTK)
Industry advisors: Evangelos Farantatos (EPRI), Lin Zhu (EPRI)
Project Duration: 05/01/2020 - 04/30/2024
Funding Source: NSF

Summary

The proposed project will develop an innovative adaptive wide-area damping controller (WADC) prototype to suppress low-frequency oscillations in large-scale power systems. The developed prototype will be demonstrated on a real-time simulation platform that mimics a realistic power system operating environment using realistic grid models. This project also includes the education and training of graduate students to prepare them for leadership roles in the future innovative work team.

Major activities conducted by the project team in this year are summarized as follows:

1. Based on last year's wide-area damping controller prototype, the prototype was deployed in the control center of Italy for field test to damp the oscillations. All the advanced control modules have been tested and validated through the field test.

2. During the field tests, several newly emerged practical issues for field implementation of WADC has been discovered and addressed, including time synchronization error detection, soft-start and shutdown function of WADC command, and initialization module development for WADC control commands.

3. All the updated and newly developed function module has been tested through hardware-in-the-loop test and will be further validated though field tests.

4. The research results was disseminated through CURENT industry conference, NSF/DoE annual site visit, and international conferences.

5. The NSF I-Corps training class has been finished and around 105 interviews have been completed to discover new potential customers.

In the next year, we plan to continue validating the controller performance through long-term field test in Italy. In addition, we will provide technical support for the industry-grade WADC development with GPA and finished all the HIL tests of the functions of the industry-grade WADC.

25. Lossless and Lossy Compression for Point-on-Wave data in Grid Edge Sensor

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** He Yin (UTK), Yuru Wu (UTK), Qiu Wei (UTK)
Industry advisors: Ben La Riviere (ORNL), Bruce Warmack (ORNL), Hari Achuthan (DigiCollect)
Project Duration: 1/2021 – 12/2024
Funding Source: ORNL/DOE

Summary

This project aims at developing a compression strategy to effectively compress the point-on-wave (POW) data to less than 20% of the original data size and successfully implement the algorithm in a Grid Edge sensor. The first phase of the project has been completed last year. Multiple lossless compression methods are investigated and implemented in both the simulations and experiments, such as Simple-8b, cyclical high-order delta modulation (CHDM), Lempel–Ziv–Markov chain algorithm (LZMA), and Huffman encoding. The compression ratio (CR) strongly depends on the noise level and duration of the original signal. For the signal with a 60dB noise level, the best CR of lossless compression can reach 4.0 in the simulation and 3.83 in the experiment.

Therefore, lossy compression methods are introduced to improve the CR of non-event data. In Phase II, the team studied multiple lossy compression methods, including singular value decomposition (SVD), digital cosine transform (DCT), digital Fourier transform (DFT), and digital wavelet transform (DWT). The compression of POW data could be either 1 dimension like a signal or 2 dimensions like an image. Since information loss in lossy compression is inevitable, three metrics are used to evaluate the performance of different methods: waveform distortion, frequency distortion, and harmonic distortion. Overall, the highest CR reaches 16 which is achieved by the DWT compression, but the waveform and harmonic are distorted. To preserve the harmonics, DCT and DFT compression are good candidates when CR is equal to 8.

This project is expected to be finished by the end of 2024. This year, the team is making good progress with the hardware development of the Grid Edge Sensor as Phase III.

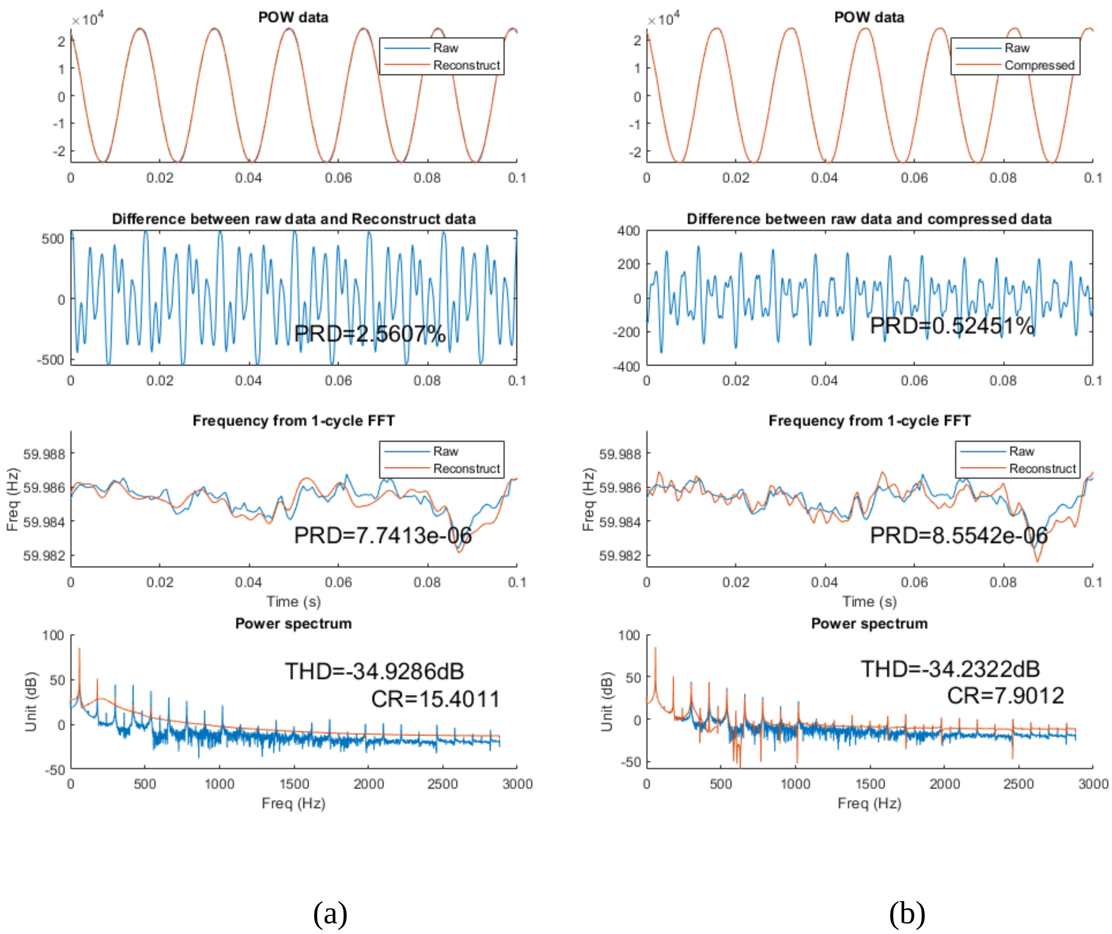


Figure 46.1: Lossy compression of POW data via (a) DWT and (b) DCT methods.

26. NERC GridEye Frequency Data Transmission and Visualization

Advisor and Industry: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Wenpeng Yu (UTK), Chang Chen (UTK), Hongyu Li
Industry Advisors: Warren Wu, David Till
Project Duration: 1/2021 – 12/2023
Funding Source: NERC, DOE

Summary

This project is to develop a series of applications that can efficiently make use of both streaming synchrophasor data and raw burst event data from the GridEye's and develop analytic and visualization tools. The overall objective is to help NERC fulfill its mission to ensure the frequency reliability and security of North American interconnections. The tools developed could be used by the DOE to obtain information through SAFNR-3 and later Eagle-I to help the department gain situational awareness of the North America grids.

1. Time Error Calculation based on Synchrophasor Measurement

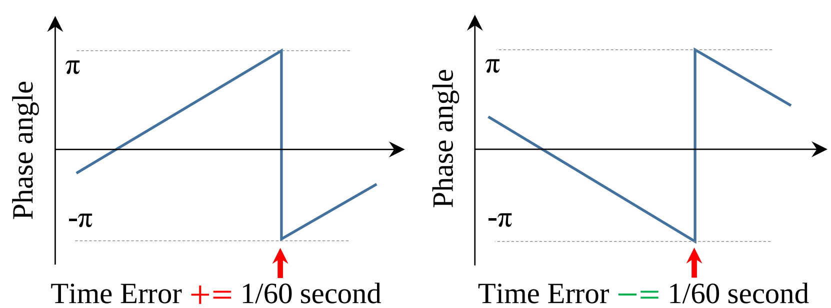
To meet NERC Time Correction Standard, FNET developed online applications to calculate, track and visualize the time error continuously based on the synchrophasor measurement.

Three time-error calculation methods are developed, which calculate the time error based on system median frequency, phase angle of individual FDRs or system average phase angle respectively.

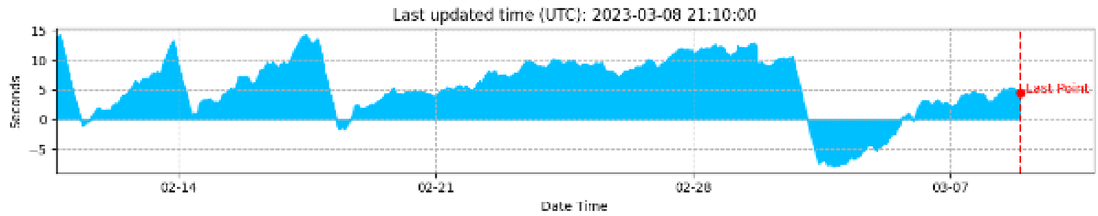
In the median-frequency-based method, the system median frequency is calculated for each time frame, then the following equation is applied to calculate the time error.

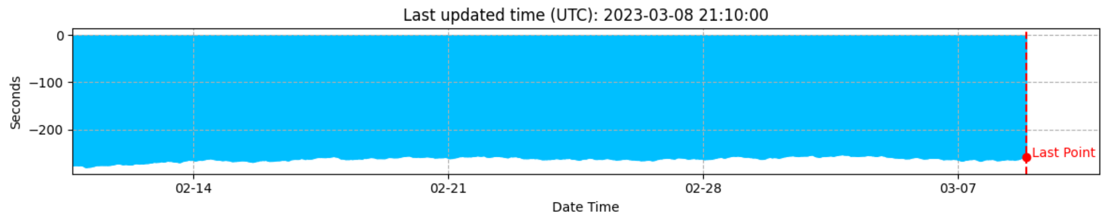
$$T_{err} = \sum \frac{(f_{sys} - 60) \times 0.1}{60}$$

In the phase-angle-based method, the angle wrapping will be captured and the time error T_{err} will be added by 1/60 second when the phase angle is wrapped downward, and subtracted by 1/60 second when the angle is wrapped upward, as shown below.



A database is created to keep the records of the time error, and a webpage is developed to visualize the time error record in the last 30 days. The time error of EI and WECC are show below.



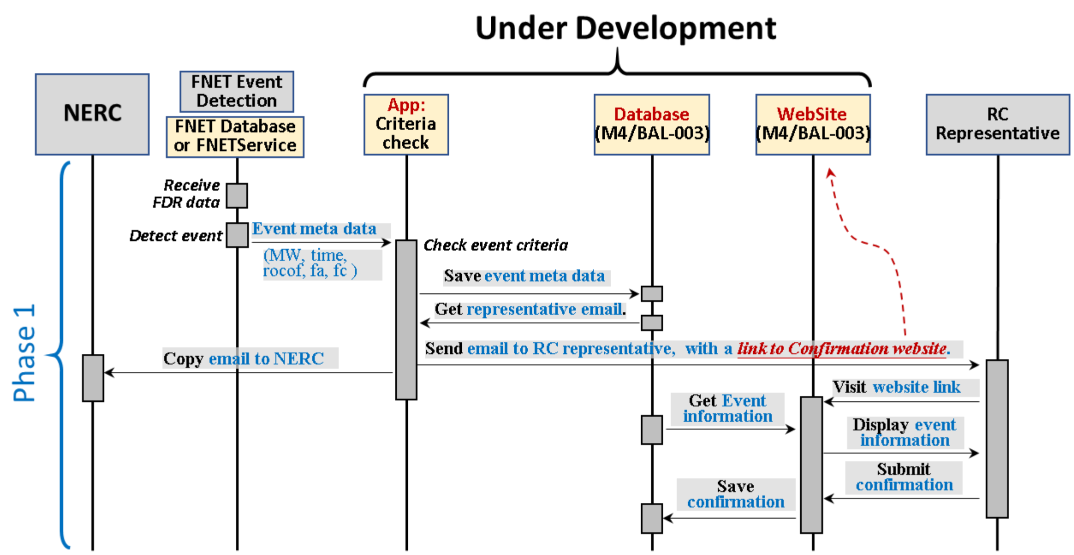


NERC forward the RCIS message about the time correction procedure to FNET, from which the time error information is extracted and utilized as a reference to synchronize the time error result calculated by FNET.

To test the accuracy of the time error calculation, the synchronization with RCIS message was paused by 9 months, and the accumulated calculation error is -0.14 second, which demonstrates the excellent performance of the algorithm.

2. Automation of NERC Candidate Event Detection and Confirmation

When large event happened, NERC will estimate the active power changing and send message to Reliability Coordinators to request the event confirmation information, including the tripped generator and amount of active power. To save the great human effort in this procedure, FNET is developing an online application to automate this procedure.



Large frequency event will be detected and located based on FNET synchophasor measurement and corresponding information is saved into a database. Then an email alert will be sent to the RC representatives, and a link to the event confirmation website will be included in the email. The RC representative can obtain the event information and plots from the website and submit the confirmation if the event happened in the corresponding area.

27. OEDI – Solar Grid Integration Data and Analytics Library

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Jiaojiao Dong (UTK), He Yin (UTK), Yuqing Dong (UTK), Teja Kuruganti (ORNL), Jin Dong (ORNL), Ajay, Yadav (ORNL), Srikanth Yoginath (ORNL), Boming Liu (ORNL)
Project Duration: 09/2021 – 09/2024
Funding Source: ORNL/DOE

Summary

The objective of this Open Energy Dataset Initiative (OEDI) project is to develop and demonstrate novel distribution state estimation, control optimization, and transient analysis along with providing access to data, data integration & mapping information to enable the R&D community, the vendors, and the utilities to download the data, the scripts, the translators, and the source code. More specifically, this effort is to develop and demonstrate the distribution system state estimation (DSSE) algorithm and tool that utilizes various types of available measurements in distribution systems, including supervisory control and data acquisition (SCADA) measurements, Phasor Measurement Unit (PMU) measurements, Point-on-Wave (POW) measurements, virtual measurements, and pseudo measurements.

The project team formulates the DSSE as a nonlinear weighted least square (WLS) problem to develop a comprehensive DSSE tool that fully utilizes available measurements in distribution networks. The formulated nonlinear WLS problem was converted to a nonlinear algebraic equation using the first-order optimality condition, and then solved by the Newton-Raphson method.

This year, the major functionalities of the DSSE tool have been developed. Key features are summarized in Figure 53.1. First, the developed DSSE tool integrates various types of measurements that are available in distribution systems. Especially, we have incorporated the PMUs measurements and POW measurements into the DSSE tool, in addition to the conventional SCADA measurements, virtual measurements representing zero-injection nodes and pseudo measurements representing historical load profiles. These measurements with different levels of accuracy are incorporated into the DSSE tool. For example, Figure 53.2 shows the DSSE error before and after integrating PMU measurements. Second, the tool could perform time series analysis in addition to the state estimation of a single snapshot. Third, the tool fully models the three-phase unbalanced distribution network with three-phase unbalanced loads. Finally, the tool fully models the nonlinearity of the distribution network by formulating the DSSE as a nonlinear weighted least square problem and solving it using the Newton Raphson method with detailed Jacobian matrices information. All these functionalities are implemented in MATLAB and are also re-written in Python for further integration test under the HELIC-based GADAL framework. In addition to the above key functionaries, we have also developed various interfaces to read and export various types of data (distribution system circuit data, realistic load profile, realistic PV data, etc.) in various formats during the collaboration with other labs. These interfaces are in their preliminary versions and could be made more mature in the future as needed.

In the following year, we will continue fine-tune our DSSE algorithms and interface to support the large system test and the integration test with other algorithms developed by the team members.

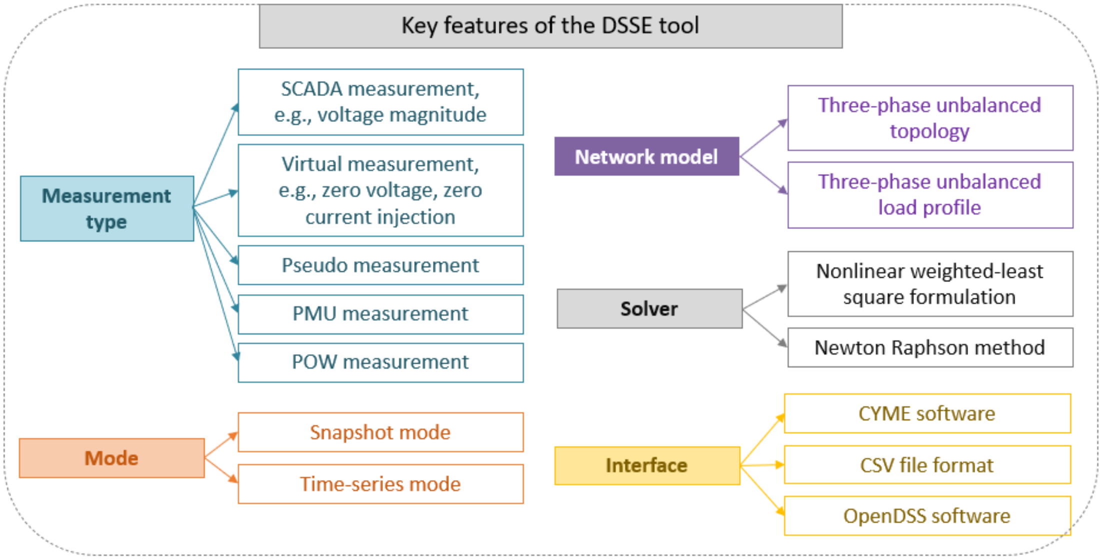
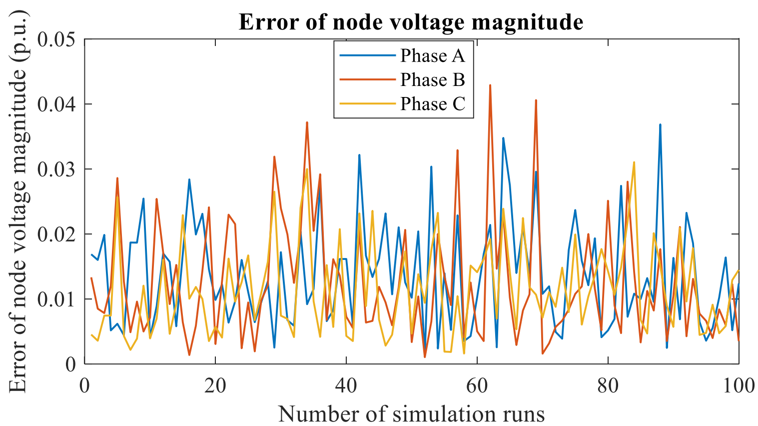
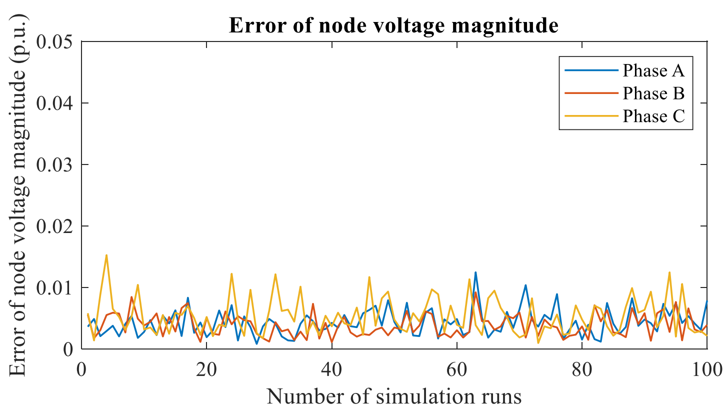


Figure 53.1: Key features of the developed DSSE tool



(a)



(b)

Figure 53.2: Maximum error of node voltage magnitude on IEEE 123-node system: a) case 1 without PMUs, b) case 2 with PMUs

28. Point-On-Wave-based Anomaly Detection and Categorization in Low Inertia Power Systems

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** He Yin (UTK), Yuru Wu (UTK), Wenpeng Yu (UTK)
Project Duration: 1/2021 – Now
Funding Source: NREL/DOE

Summary

Inverter-based resources (IBRs), such as Photovoltaic (PV) and battery storage systems, are widely deployed to achieve carbonfree power systems. However, the anomalies, such as waveform distortions, and wide-band oscillations, caused by the IBRs have brought challenges to situational awareness, especially in the low inertia power systems. The anomalies such as generation trips and load shedding also have higher frequency deviation and voltage magnitude drops caused by the changing of inertia. To achieve effective anomaly identification, this paper proposed a point-on-wave (POW) based algorithm utilizing the real-time POW measurements from synchronized measurement units (SMUs). Four SMUs are specially designed and deployed on Hawaii islands to receive instantaneous POW measurements. Then, different physical characteristics, as well as statistical features are extracted from POW measurements to filter the anomalies. The anomaly identification approach based on the random forest is developed and deployed into the FNET/GridEye system considering the trade-offs among accuracy, computational burden, and deployment cost. To verify the performance of the proposed algorithm, different experiments are carried out with collected field test data. The result demonstrates that the performance of the proposed POW-based anomaly categorization algorithm can reach 94.54% which has comparable performance among benchmarking algorithms.

This year, we have compared the outage list from the KIUC and our event detection results. About 50% accuracy has been achieved. Considering the sensor deployment location and real-world noise, this number makes sense. We are also trying to analyze the oscillation and its causing factors and we believe they are related to the diesel generators and their droop control parameters.

This project is expected to be finished by the end of 2024. Future works include probing based inertia estimation and its deployment in the field.

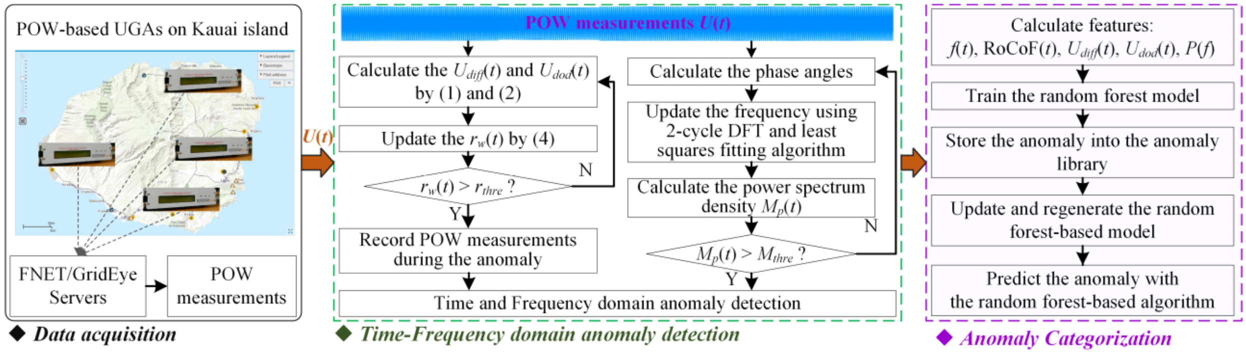


Figure 55.1: Overall flowchart

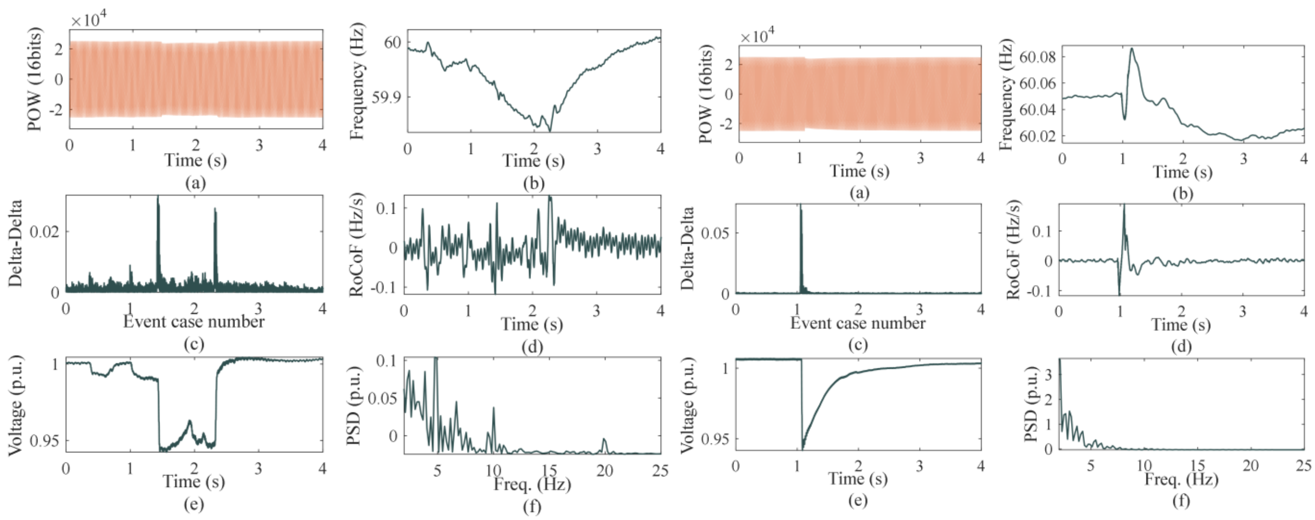


Figure 55.2: Example generation trip and fault events

29. Power System Digital Twin

Project Lead: Clifton Black (Southern Company), Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Jeremy Till (UTK)	
Project Duration: 8/2022 – 5/2024	
Funding Source: Southern Company	

Summary

The goal of this project is to apply 'digital twin' technology to power systems. As power systems advance, the importance of leveraging grid modeling and monitoring only increases. Digital twin technology proposes the use of an extremely accurate model of the power system, capable of running on specialized hardware to simulate the model at or faster than real-time. However, one of the most important aspects of a digital twin is the ability to feed the model data from the physical power system (or physical twin), and produce a simulated result identical to the physical system. Digital twins are a relatively new phenomenon, primarily being utilized outside of power systems.

This project is broken into three-phases. The goal is to create a model, data interface, and controls necessary to implement a digital twin for three phases. The first phase is a microgrid owned by Southern Company. The second phase will be a subsection of the Southern Company transmission system. The third phase will include the second phase with additional buses. The digital twin is being modeled in Hypersim and run on hardware from Opal-RT to enable real-time capability. Southern Company has many data-streams that will be utilized in the digital twins.

The project is in the first phase currently. The microgrid has been modeled and validated for steady state performance. Event data is currently being used to validate the transient performance of the model.

One of the primary goals in this project is the inclusion of cyber-physical modeling in the digital twin. As the digital twin will be able to utilize data from the physical system and generate simulated measurements mirroring the physical system, an accurate model will be created for the cyber or networking components as well as the electromechanical components. This will create potential for contingency analysis considering cyber events. Another goal is to feed the digital twin real-time data and use the digital twin to actively diagnose the physical system, as divergence of the two would indicate improper behavior.

The project is expected to be finished by May, 2024. Future work would include expansion of the phase three digital twin, as well as application development for the twin to be used by departments within a power utility.

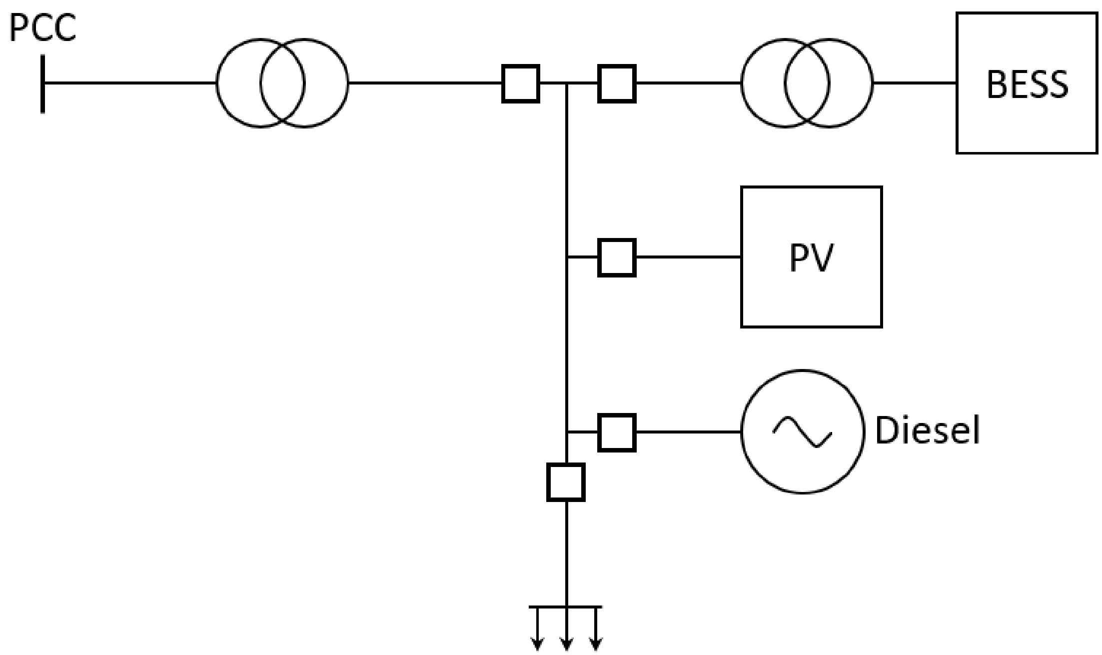


Figure 56.1: Phase 1 Microgrid Single Line Diagram

30. PR100: Puerto Rico Power Grid Simulation-based Model Validation

Project Lead: Marcelo Elizondo (PNNL) **Graduate Students and Research faculty/associates:** Melanie Bennett (UTK), Matin Rahmatian (Quanta), Alexandre Nassif (LUMA), Yilu Liu (UTK)
Project Duration: 01/2022 – 01/2025
Funding Source: NREL/DOE

<u>Summary</u>

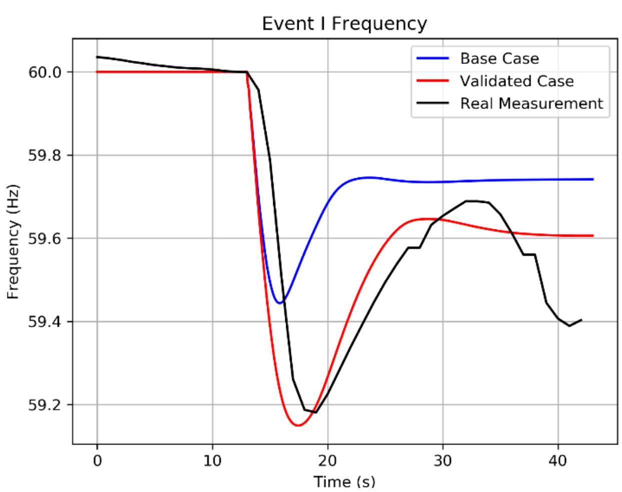
The Puerto Rico (PR) power grid model must accurately represent real-world conditions, otherwise the true vulnerability of the grid may be drastically over- or under-estimated. The goal is to validate the generators frequency dynamic response of the existing PR power grid model. In lieu of field validated governors, this is accomplished by simulating real historical generation trip events that caused large disturbances. Two generator trip events are used in the process to increase the confidence in the model validation results. Simulations of the events showed that a group of generator governors in the model were providing support for grid frequency, when in reality they did not. Additionally, the generator governors that did provide support during the actual events showed a more aggressive support in the simulation. Therefore, the grid model was tuned by (a) turning off some governors in the model and (b) adjusting the deadband and droop parameters of governors that did respond during the actual event. The final validated results are able to match the measurements well for both events. Future work includes assessing the current grid model's voltage strength in preparation to host higher penetration levels of renewable energy.

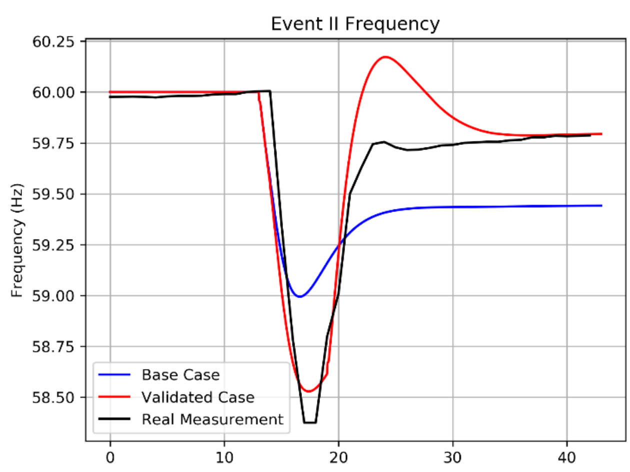
Event I: Loss of a Single Generator Unit

A generator tripped offline while providing approximately 10% of the total generation. The event did not trigger under-frequency load shedding.

Event II: Loss of a Power Plant (Multiple Units)

A power plant disconnected from the grid resulting in the loss of 20% of the total generation. Frequency decreased significantly to a level where automatic load shedding actions took place.





31. Probing-Based Inertia Estimation Using Hybrid Power Plants

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Zhihao Jiang (UTK), He Yin (UTK), Hongyu Li (UTK)
Industry Advisors: Jin Tan (NREL), Andy Hoke (NREL), Brad Rockwell (KIUC), Cameron Kruse (KIUC)
Project Duration: 4/2022 – Present
Funding Source: DOE

Summary

With the displacement of synchronous generation by inverter-based resources (IBRs), power systems could face the challenge of reduced inertia since IBRs do not inherently contribute to system inertia. Therefore, there is rising interest in monitoring system inertia in real-time applications for situational awareness. In addition, there is a growing number of IBRs that provide fast frequency responses (FFR) in the form of synthetic inertia and P-f droop. It is desirable to quantify the contribution of these FFR controls as equivalent inertia. This project proposes a probing-based inertia estimation method using a PV-battery hybrid power plant in the Kauai island power system. Active power pulses are injected by battery energy storage systems (BESSs) and system inertia is estimated using system frequency responses. The flowchart of the proposed approach is shown in Figure 58.1.

In the first year of the project, the team has worked on the design of the suitable probing signal for the Kauai island system by considering a series of factors, including ambient load noise, frequency disturbances of the probing and accuracy estimation. For future work, the team is working on validating the approach through Power-Hardware-In-Loop (HILP) and implementing field demonstration in Kauai Island Utility Cooperation (KIUC).

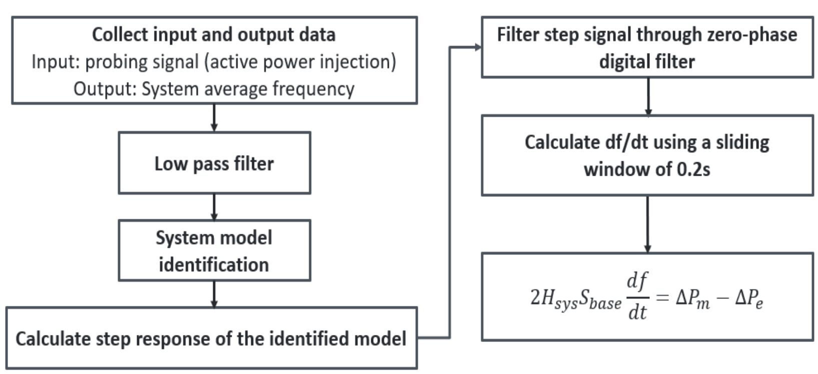


Figure 58.1: Flow chart of the approach

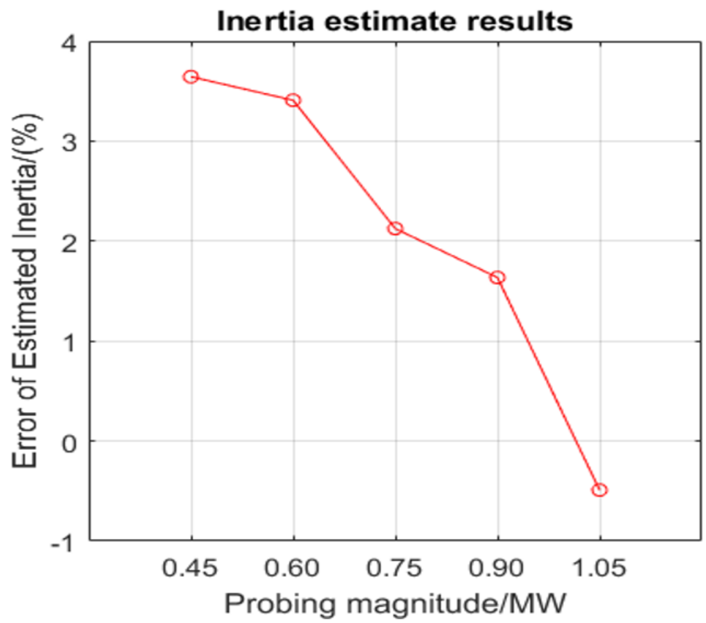


Figure 58.2: Simulation validation of the probing-based inertia estimation

32. Real Time Inertia Monitor Based on Pumped Hydro Operation Signatures

Project Lead: Yilu Liu (ORNL) **Graduate Students and Research faculty/associates:** Hongyu Li (UTK), Chang Chen (UTK), Wenpeng Yu (UTK), Shutang You (UTK), Lingwei Zhan (ORNL)
Industry advisors: Mark Baldwin (Dominion Energy), Larry Markel (ORNL)
Project Duration: 1/2022 – Present
Funding Source: ORNL/DOE

Summary

Real-time knowledge of the system inertia is critical for stable system operation, especially in high renewable grids. It is a challenging task due to the substantial number of resources contributing to the power grid's effective inertia. The most used inertia estimation approach only considers mechanical inertia by summing up the dispatched generators' individual values, missing contributions from load and synthetic inertia. As most pumped storage hydropower (PSH) plants have consistent switching patterns with a fixed amount of instant power change when tripping pumps, they are ideal resources for effective inertia monitoring in high-renewable power grids. PSH can be used as a yardstick to calibrate inertia monitoring technologies. This project will develop, demonstrate, and deploy the real-time, low-cost, and accurate monitoring system to quantify system effective inertia based on PSH plant operation signature from PMU measurements. By partnering with NERC, TVA, and Dominion Energy, this work will address one of the key challenges for operating the high-renewable low inertia grid and pave the way for the development of a U.S. carbon-free power sector by 2035. Figure 60.1 shows the concept of inertia estimation using pumped hydro operation signatures. Several key works are also shown as follows:

1. Analysis of pump events based on PMU measurements;
2. How to select pump storage for interconnection inertia estimation;
3. Deployment of grid frequency monitors to capture pump event signatures;
4. Design of pump event detection trigger;
5. Estimation and validation of WECC inertia using pump signatures.

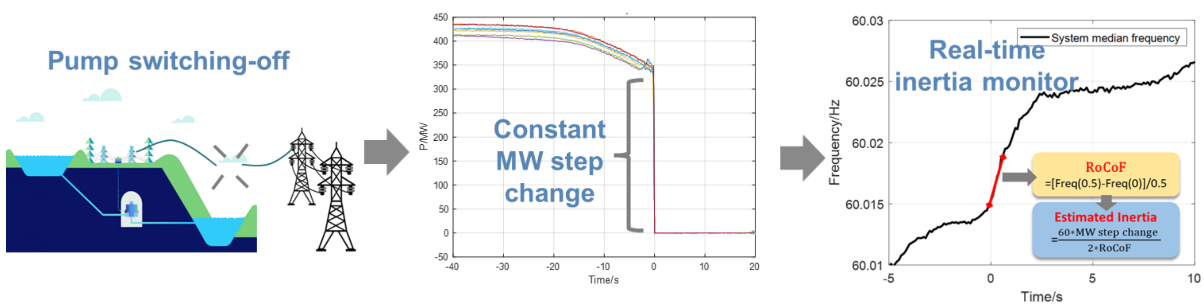


Figure 60.1: Concept of Inertia Estimation Using Pumped Hydro Operation Signatures

33. Study of Impact of High Penetration of Inverter Based Resources on Grid Strength

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Abigail Till (UTK), Zhihao Jiang (UTK)
Project Duration: 1/2022 – 7/2023
Funding Source:

Summary

This project investigates the impact of high penetration of inverter based resources (IBRs) on grid strength. It uses the short circuit apparent power (SCMVA) as an indicator of grid strength. In the first part of this project, the SCMVA was measured in the Eastern Interconnection at varying IBR levels using PSS/E. Conventional generation was replaced with IBR and the SCMVA was measured for the base case as well as the cases with IBR added. The SCMVA was then compared for base and edited cases to determine the impact of IBR.

For the second part of this project, the capacity for IBR before the grid strength becomes weak was explored. Using the calculated SCMVA from the first part of the project, and the short circuit ratio (SCR) at which the grid becomes considered to be weak strength, the maximum amount of IBR that could be added at each bus was determined.

While this project was initially started observing the Eastern Interconnection, it is currently being expanded to determine the impact of IBR on the Western Interconnection as well. The same process of converting conventional generation to IBR and measuring and comparing SCMVA in PSS/E is being used, as well as determining the amount of IBR that can be added before the grid becomes weak.

The project is expected to be finished in July of 2023. Future work includes more analysis with differing levels of IBR.

34. Virtual Operator Assistant (VOA) – Powering the Next-generation Control Room by Artificial Intelligence and Digital Twins Technology

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Jiaojiao Dong (UTK), Xinlan Jia(UTK), Mirka Mandich(UTK), Yinfeng Zhao(UTK), Yang Liu(UTK), Shutang You(UTK), Hongming Zhang(Stronghold Resource Partners)
Project Duration: 9/2020 – 12/2023
Funding Source: DOE AGM

Summary

This project aims at developing an AI agent for power system stability prediction, including power grid transient stability assessment and real-time frequency stability monitoring. We propose an artificial intelligence (AI) -based method that predicts the system's stability margin information (e.g., the frequency nadir in frequency stability assessment and the critical clearing time, or CCT value in the transient stability assessment) directly from the system operating conditions without performing the conventional time-consuming time-domain simulations over detailed dynamic models. Since the AI method shifts the majority of the computational burden to offline training, the online evaluation is extremely fast. The primary objective of this project is to test the effectiveness of the AI approach on practical large power systems. Specifically, we aim at verifying the AI-based stability assessment method using multiple dispatch cases that are converted and tuned from actual dispatch cases of the Western Electricity Coordinating Council (WECC) system model with more than 20,000 buses.

Figure 66.1 shows the overall implementation of the proposed AI based stability assessment tool. It includes: 1) Dispatch data module, which is used to develop a set of robust dis-patch cases and the associated dynamic models for the tests of the AI algorithm. 2) Massive simulation module, which used to perform batch simulations and calculate the frequency nadir and CCT values for the dispatch cases. 3) Feature extraction module, which is used to extract selected features from the dispatch cases; 4) AI agent module, which is used to build the dataset from the above label and feature data, splitting them into training, validation, and testing datasets, and performing AI training and tests using AI algorithms. The outputs of this module are the predicted nadir values and the predicted CCT values.

This year, we have completed the scheduled tasks for both transient stability assessment and frequency stability assessment based on the above implementation. Especially, the dynamic models for full WECC system were created based on the power flow from actual WECC EMS data records under different dispatches. These models were manually tuned and selected to serve our purpose. Eventually, we obtained 138 cases for frequency stability assessment and 69 cases for transient stability assessment from the original 228 WECC dispatch cases on March 19th, 2019. Simulation data from these actual WECC system dynamic models were used in developing and implementing the AI agents, as well as verifying their effectiveness.

Figure 66.2 shows the results we obtained from the tests on the full 20,000-bus WECC system, including the predicted frequency nadir and CCT value using both the random forest algorithm and the neural network algorithm. It shows the AI agent provides an accurate prediction of this

stability margin information. Regarding the time performance, the AI approach only takes less than 1 hour for offline training and the online evaluation only takes less than 0.2 milliseconds to complete the stability prediction of all dispatch cases. This is significantly faster than the conventional time domain simulation approaches, which take more than 1 hour to calculate this stability margin information. These results demonstrate the great potential of AI techniques in achieving faster-than-real-time stability assessment.

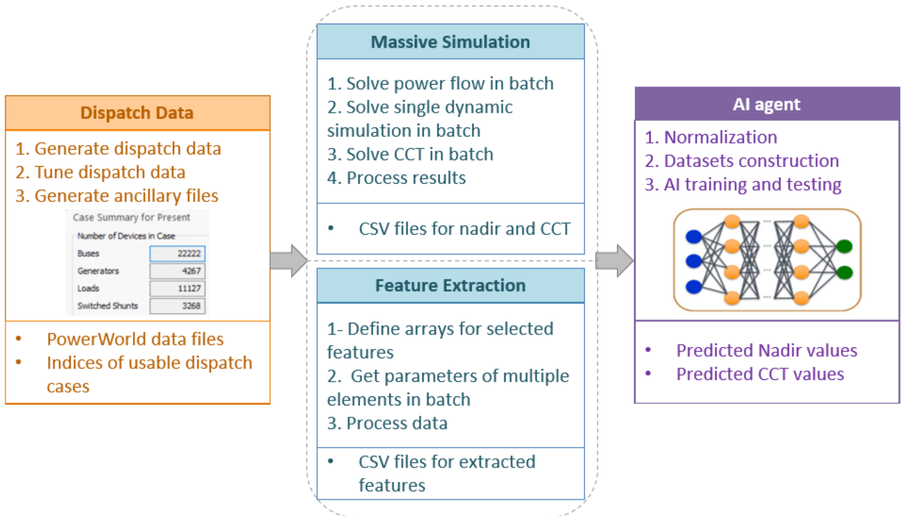


Figure 66.1: The overall structure of the technical approach.

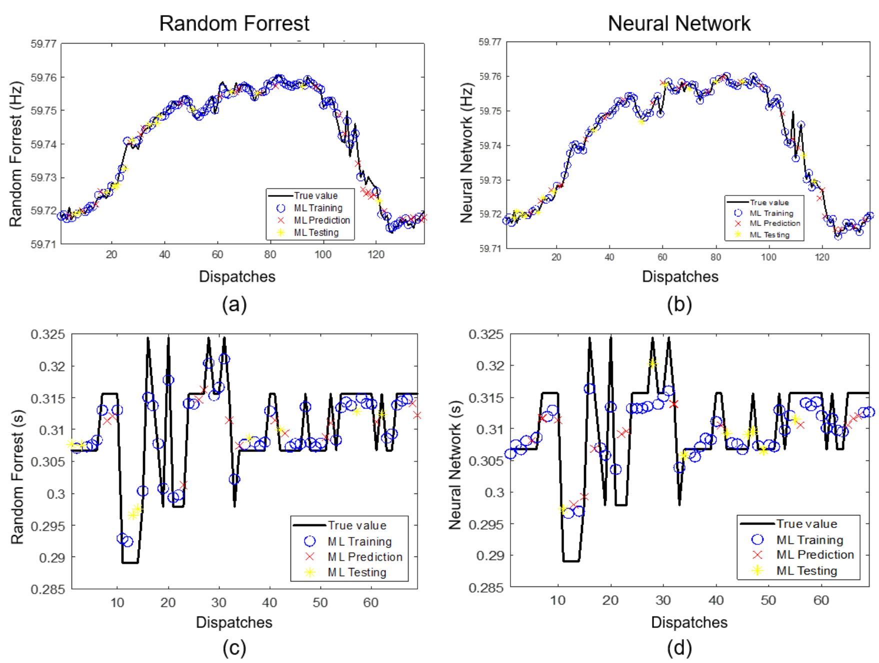


Figure 66.2: Performance of the developed AI-based stability assessment tool on the full 20,000-bus WECC system: a) predicted frequency nadir using the random forest algorithm, b) predicted frequency nadir using the neural network algorithm, c) predicted CCT value using the random forest algorithm, d) predicted CCT value using the neural network algorithm

35. Adaptive Oscillations Damping Control Using Measurement Derived Transfer Function Model-TERNA Case Study Field Implementation

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Xinlan Jia (UTK), Wenpeng Yu (UTK), Yi Zhao (UTK)
Industry Advisors: Lin Zhu (EPRI), Evangelos Farantatos (EPRI)
Project Duration: 9/2023 – 9/2024
Funding Source: EPRI

Summary

This project aims at developing a wide-area damping controller (WADC) using a measurement-driven transfer function model to adaptively damp natural low-frequency oscillations in the power grid. In Phase I of this project, the proposed WADC was designed and validated through simulations for Terna's system through software simulation. The simulation results have validated the effectiveness of the WADC for an actual oscillations event that took place at the Terna system in 2017. In Phase II of this project, the WADC was implemented on a generic-purpose hardware platform (CompactRIO) and tested in a hardware-in-the-loop setup, where the Terna model was emulated on a real-time digital simulator (OPAL-RT). Realistic operating conditions were emulated to evaluate the performance of the WADC, including random time delays, PMU data package loss, PMU measurement noise, and multiple PMUs as backup.

In this year, the WADC is developed on the openPDC platform as a user-defined action and is deployed at the Terna control center. The WADC collects PMU measurements and generates the control command to damp the North-South oscillation mode. Frequency measurements from two PMUs are selected as the primary and backup input signals respectively, and one synchronous condenser is selected as the actuator. More actuators including synchronous condensers, HVDC links, FACTS devices, and inverter-based resources can be added in future phases of the project. IEEE C37.118 is used as the communication protocol for both frequency measurements and control commands. An enhanced PMU device is deployed at the substation to parse the control commands and interface to the synchronous condenser.

Two rounds of field tests was conducted in Terna power grid, which include the following five categories: 1) Communication test to ensure reliable communication of the entire loop, 2) Synchronous condenser exciter response test and logics to verify the actuator’s response to control command, 3) Commissioning test to understand the measurement delay, control command delay, and entire loop delay, 4) Control loop test to tune and verify controller parameters in open-loop and verify controller performance in closed-loop under the ambient environment, and 5) Oscillation damping test to verify controller performance under large disturbances (e.g., load rejection). Figure 1 shows the field deployment of WADC system at Terna. Table 1 shows the closed-loop testing results of the WADC under a large load rejection event, which demonstrate the developed WADC can improve the damping ratios of two low-frequency oscillation modes in Terna system.

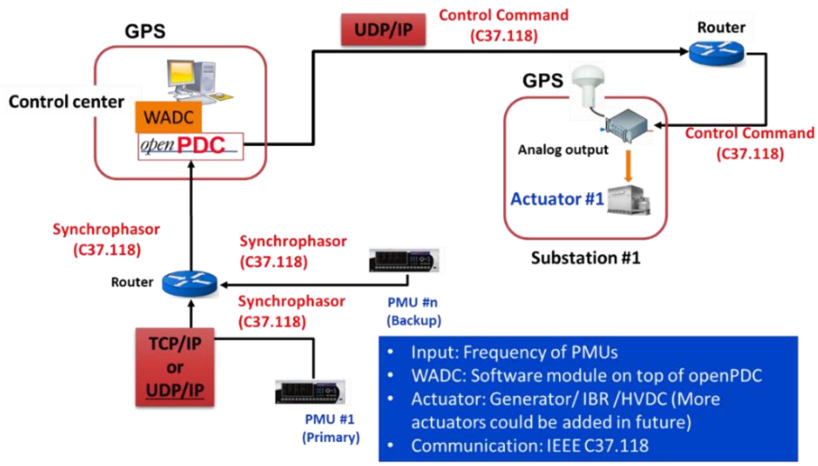


Figure 1. Field Deployment of WADC system at Terna.

Table 1. Comparison of oscillation frequency and damping ratio (With and without WADC)

Data Type	WADC	PSS	Mode #1		Mode #2	
			Freq. (Hz)	Damping (%)	Freq. (Hz)	Damping (%)
Ambient	ON	ON	0.212	19.42	0.261	17.02
Event	ON	ON	N/A	N/A	0.262	20.46
Ambient	OFF	ON	0.200	12.23	0.286	11.67

36. Grid Strength Assessment for High Levels of Inverter-based Resources in the Puerto Rico Power System

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Melanie Bennett (UTK)
Project Duration: 1/2022 – 12/2023
Funding Source: ORNL

Summary

The strength of a grid refers to the voltage stiffness following a fault disturbance. During these disturbances, synchronous generators can provide 5 to 10 times their rated current capacity while inverter-based resources (IBR) may only provide 1 to 1.3 times rated current. With the dwindling fault current availability in IBR-dominant grids, voltage instability issues may become more prevalent leading to more impacts from disturbances than previously seen. Weak grid issues can take the form of voltage instability, harmonic resonance, and fault induced delayed voltage recovery (FIDVR). Grid strength assessments can provide an indicator for which locations may be more susceptible to weak grid issues and where could be candidate locations to place compensation devices.

This project assessed the change in short circuit capacity (SCMVA) from a 40% renewable grid to a 100% renewable grid. The results in Figure 1 show that high voltage transmission substations may experience a decrease of about 70% in SCMVA while other locations along the 38 kV system show relatively little change. This indicates that high voltage pathways with relatively low impedance will see a significant drop in available short circuit current during faults and could potentially lead to larger regions of voltage issues than before. Next, the short circuit ratio (SCR) is compared to the equivalent circuit-based SCR (ESCR) and the results show that SCR may be overestimating grid strength due to not accounting for interactions between neighboring IBR while ESCR does consider neighboring IBRs and is a much more conservative approach. The last SCR metric considered is the weighted SCR (WSCR) which is a regional metric based on the impedance characteristics of the whole system. Considering the small island power system, the entire grid can be considered one region and thus, the WSCR is calculated as a single value. The results for all three methods are shown in Table 1. This last metric does not provide enough granularity to observe localized impacts and thus, the ESCR is preferred. However, none of the metrics can indicate what types of voltage stability issues may be more likely at the weak grid locations.

The last task of the project considered synchronous condensers for improving the grid strength in the 100% renewable case to the same levels in the 40% renewable case. Synchronous condensers are spread throughout the island at 8 locations but two cases are considered: either they are all placed at 115 kV buses or at power plant facilities on the lower voltage system. The comparisons of the locations of synchronous condenser and the capacity required to improve the grid strength is shown in Figure 2. Overall, placing synchronous condenser at the high voltage buses can more than double the benefit as placing the condensers at lower voltages due to the significantly lower impedance on the high voltage system and thus the ability for the capacity to travel longer distances.

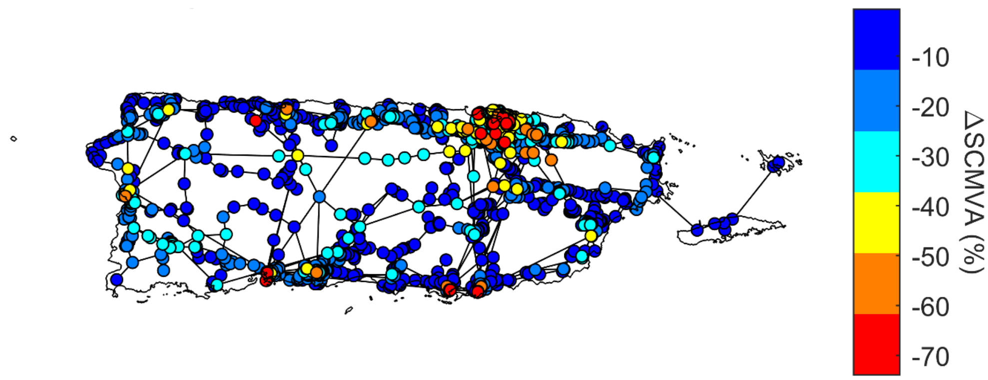


Figure 1 Change in SCMVA from 40% to 100% renewables

Table 1 Comparison of Short Circuit Ratio metrics

Location	SCR	ESCR
Santa Isabel	8.19	2.43
Breñas	12.30	1.74
Aguirre	12.71	8.10
Juncos	15.61	3.08
Jobos	16.66	3.96
Barceloneta	16.90	3.71
Cambalache	20.41	4.55
Jobos	23.33	3.74
Yabucoa	26.19	5.41
San German	29.75	2.58
Bairoa	34.23	4.31
Juana Diaz	39.18	5.13
Costa Sur	39.79	9.63
Vega Baja	40.62	5.79
Daguao	46.77	1.49
Yabucoa	63.94	3.22
Regional Metric	**WSCR**	
All Locations	1.947	

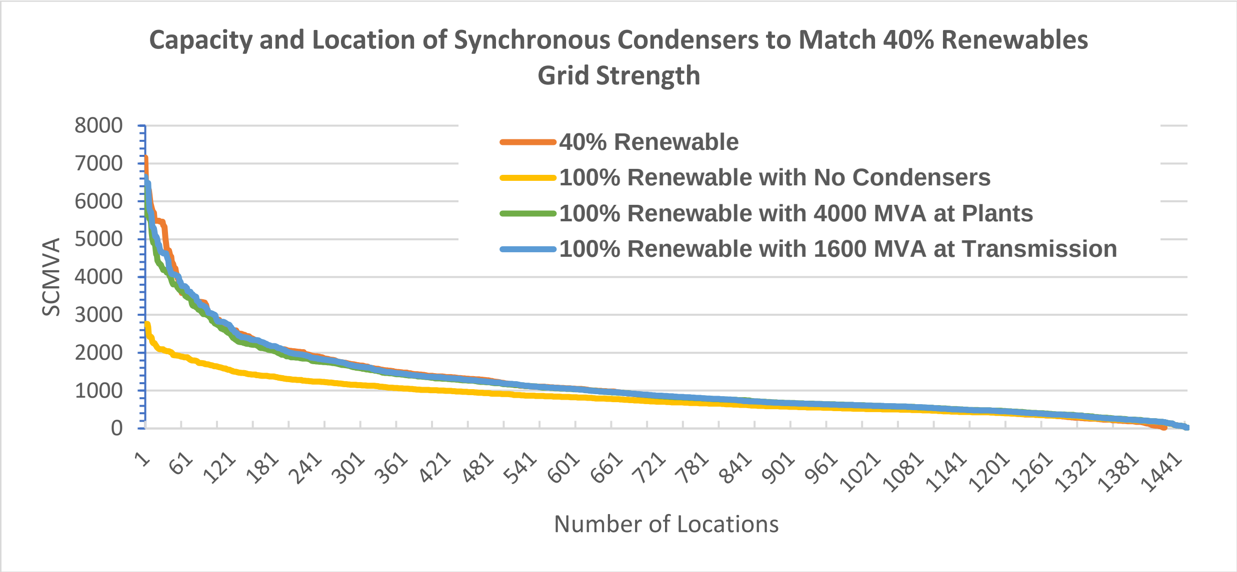


Figure 2 Synchronous condenser sensitivity study

37. AI-Assisted Algorithms for Automatic AC Power Flow Model Creation based on DC Dispatch

Project Lead: Yilu Liu (UTK/ORNL) **Graduate Students and Research faculty/associates:** Samuel Okhuegbe (UTK), Adedasola Ademola (UTK)
Project Duration: 6/1/2023 – 5/31/2026
Funding Source: NSF

Summary

A converged AC power flow case is fundamental to many power system studies such as contingency analysis, transient and voltage stability studies. Generally, these AC power flow cases are created from production cost models using DC power flow. Based on the assumptions made in DC power flow, it is sometimes difficult to successfully convert these DC dispatches into a solved AC power flow case. This difficulty in converging AC power flow is further compounded by the increase in intermittent renewable energy sources.

This project aims to develop a set of novel algorithms and user-friendly tools to create converged and high-quality chronological AC power flow cases from DC power flow dispatch. These algorithms would create realistic snapshots of real U.S. electric grids for many futuristic operating scenarios with variable proportions of conventional and renewable energy generators. The developed automated AC power flow convergence tools would combine physics-based principles with artificial intelligence to help in significantly reducing model development time and increase the operating conditions that can be considered by power system planners.

In the first phase of the project, a machine learning initializer was developed to assist in converging an ERCOT 6102-bus AC power flow. The initializer was designed based on the assumption that the Newton-Raphson AC power flow is very sensitive to the initial voltage magnitude and angle guess. Based on this assumption the machine learning initializer is designed to accurately predict the initial guesses. These voltage magnitude and angle predictions are then used to initialize previously non-converging AC power flow cases. The machine learning initializer uses the random forest algorithm and successfully converged 2106 cases out of 3,899 non-converging dispatches by providing better Newton-Raphson initialization. This represents a 54.01% success rate. The machine learning initializer framework is shown in Figure 1. and the model training setup is shown in Figure 2.

The next phase of the project includes improving the success rate of the initializer by investigating the use of various deep learning models, incorporating an iterative framework to handle situations with insufficient training data and combining the concept of incremental hot-start homotopy continuation with the machine/deep learning initializer.

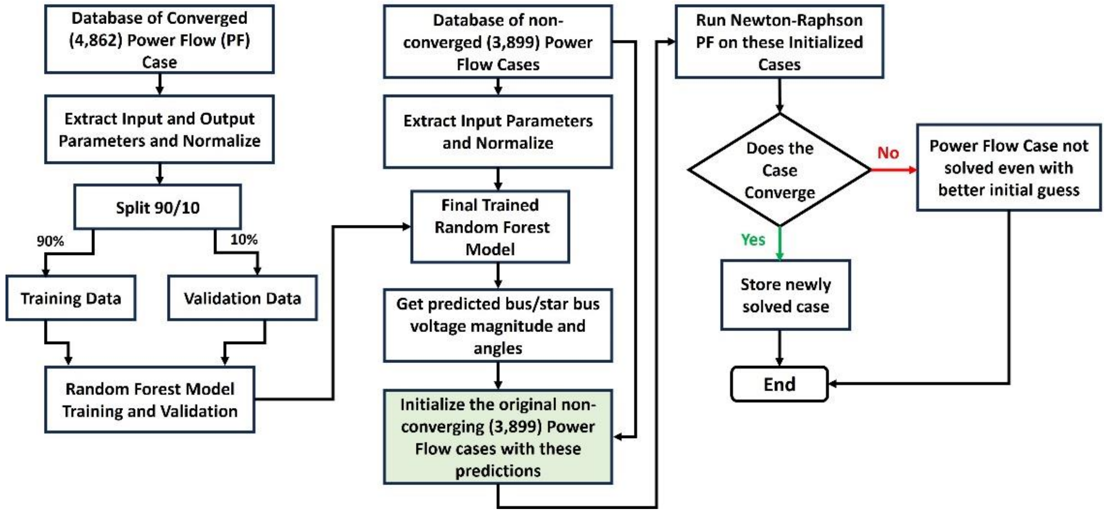


Figure 1: Proposed Machine Learning Initializer Framework.

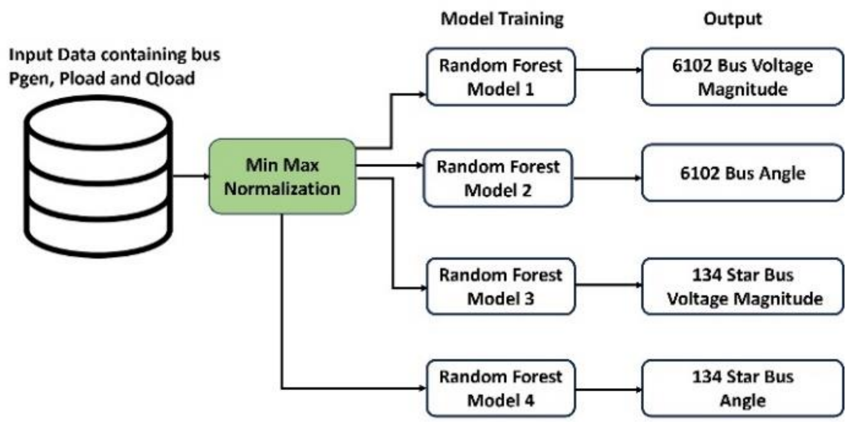


Figure 2: Model Training Setup.

38. Power Grids Frequency Analysis and Prediction

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Chujie Zeng (UTK) Chang Chen (UTK)
Project Duration: 9/2022 – 12/2023
Funding Source: anonymous company

Summary

This project aims to analyze the power system frequency of worldwide grids and develop a power system frequency prediction model for 60 Hz power grids. The project mainly contains two subtasks. The first subtask is to investigate the frequency and its distribution in all available power grids, and the second subtask is to develop a short-term prediction model for 60 Hz power grids. In this project, frequency data is provided by Frequency Monitoring Network (FNET/GridEye).

In the first subtask, frequency distributions of 32 power grids were investigated. The significant differences between grids and the common absence of Gaussianity and stationarity were revealed. This project proposed a R^2-based method to measure the frequency correlation between different locations within the same power grid, which is able to detect and visualize local and subregional noise.

For the second subtask, various factors contribute to the dynamic of power systems, making frequency prediction difficult. The rich diversity in the distributions of frequency further prevents a unified prediction model. Rare but unpredictable power system events introduce more difficulties. Some events, like islanding or separation, can render certain areas unpredictable as the local grids will be running independently. While other events, including generation trip and pumped storage, can introduce sudden and significant frequency changes. Due to their rarity, events were not taken into full consideration in the project. The project experimented Sample Convolution and Interaction Network (SCINet), the current state-of-the-art deep learning (DL) time-series forecasting model, simple linear model and polynomial model. The DL model achieves the highest accuracy however the advantage over the other two models is marginal, which can not justify the cost of interpretability and robustness. In terms of model complexity, the SCINet in fact has much fewer learnable parameters compared to the simple model thanks to its well-designed weight-sharing structure which makes it memory efficient. However, the convoluted computation logic does not only sacrifice interpretability but also denies the desirable computation boost from data parallelization. On the contrary, the execution of the polynomial model can be easily accelerated as its equation only contains simple matrix manipulation. With a simple polynomial model, high prediction accuracy can be achieved for Eastern Interconnection (EI) and Western Electricity Coordinating Council (WECC).

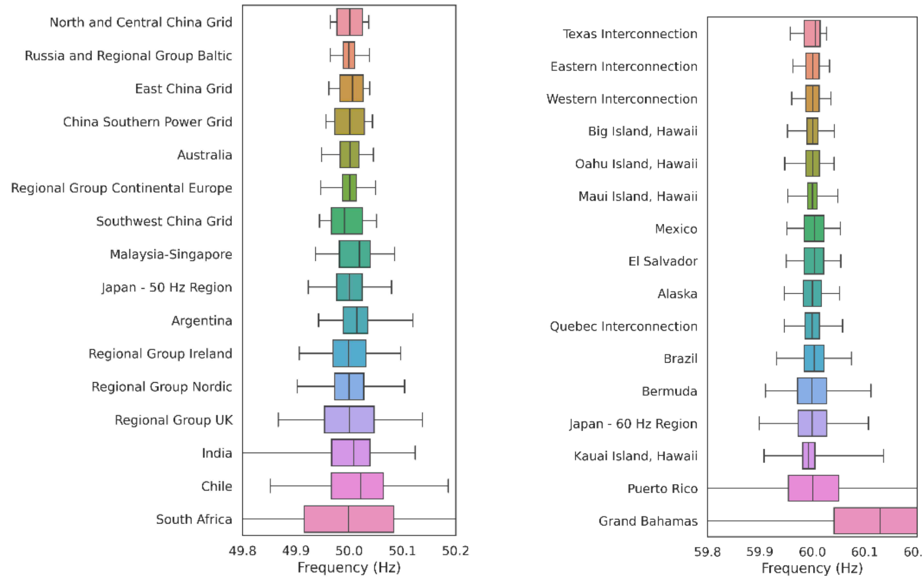


Figure 1: Frequency Boxplot of Worldwide Grids

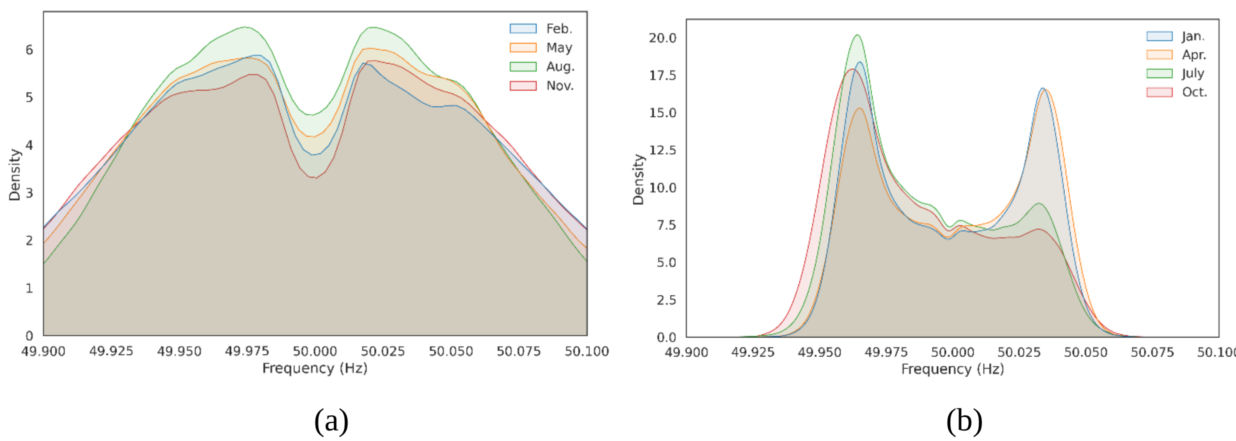


Figure 2: Non-Gaussian and non-stationary distribution in (a) United Kingdom (b) Southwest China

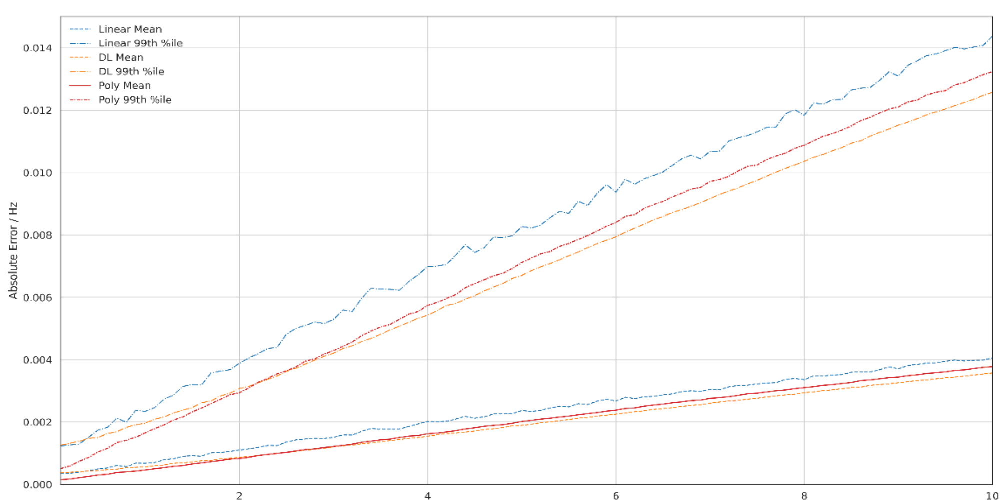


Figure 3: Prediction Error in Eastern Interconnection

39. Development of inter-area oscillation detection algorithms and conducting inertial analysis under variable penetration of inverter-based resources (IBRs)

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Saurav Dulal (UTK), Hao Fu (UTK),
Industry Advisors: Mohammed M. Olama (ORNL), Narayan Bhusal (ORNL), Ajay Yadav (ORNL)
Project Duration: 10/2023 – 9/2024
Funding Source: DOE

Summary

This project aims to conduct power grid wide-area performance analysis, such as developing inter-area oscillation detection algorithms and conducting inertial analysis for the past decade of different US interconnections leveraging the historical data.

The first part of the project performs power grid wide-area performance assessments by developing spectral analysis methods to identify and categorize inter-area oscillation modes. Specifically, it focuses on observing and analyzing frequency response trends during significant generation trip events, especially under varying levels of integration of IBRs. The work conducts a comprehensive statistical analysis of inter-area oscillations in the U.S. Eastern interconnection, using data from the FNET/GridEye system collected between 2017 and 2023. This analysis includes detecting oscillation occurrences, identifying dominant modes, and categorizing excitation types of over 38,000 events to uncover patterns in oscillation frequency, damping ratios, and seasonal variations. The combined efforts thoroughly understand the grid's behavior, offering crucial insights for enhancing system stability and developing effective damping control strategies to increase IBR penetration.

The second part of the project focuses on the inertia trend study of different interconnections utilizing the historical database of FNET. Generator trips are common occurrences in power systems, and analyzing the associated frequency drop waveforms provides insights into the extent of power loss and the collective capability of the entire interconnection to recover frequency. Over time, however, this restorative capacity has been diminishing due to the growing presence of IBRs such as photovoltaic (PV) and wind, which lack traditional inertia. Understanding the velocity and magnitude of this shift is crucial for assessing its impact on grid stability. Insufficient grid inertia resulting from IBRs can lead to excessively low-frequency drops, prompting under-frequency protection mechanisms to shed significant portions of load to avert blackouts. Therefore, it is imperative to refine methodologies that can accurately gauge these dynamics and anticipate their consequences for grid resilience.

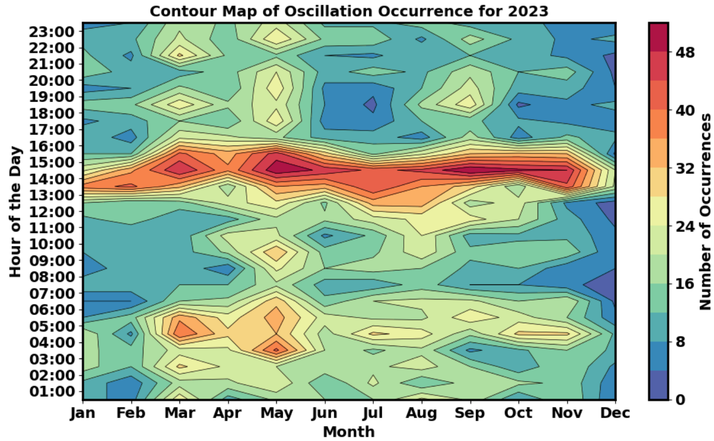


Figure 1: Hourly and Monthly Contour Map of Oscillation Occurrence in 2023 for Eastern Interconnection

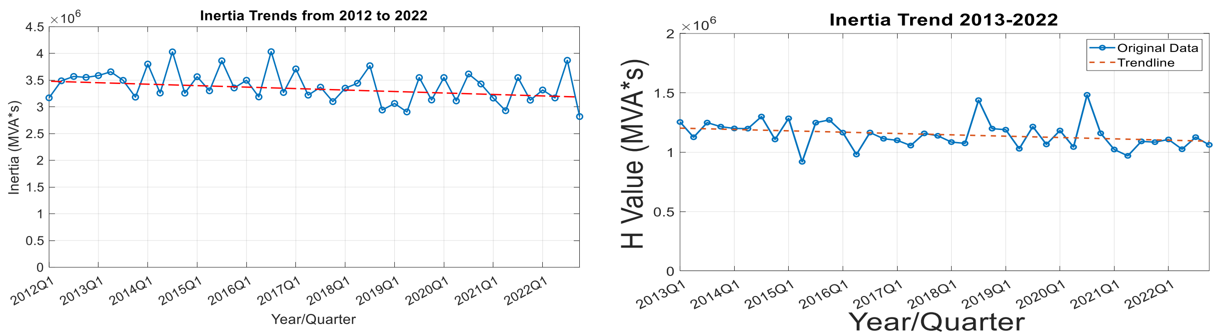


Figure 2: Inertia Trend Result for the Past Decade (a) Eastern Interconnection (b) Western Interconnection

40. Dynamic Load Modeling for High Penetration of Large-scale Data Centers

Project Lead: Katelynn Vance (DE), Amirreza Sahami (DE), Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** David P. Mignardot (UTK), Xinlan Jia (UTK)
Project Duration: 10/2023 – 5/2024
Funding Source: Dominion

Summary

The main aim of this project is to develop a dynamic power system load model, which more accurately represents the performance of large-scale data centers. An immense amount of data center load has been added to Dominion's service territory in recent years and this trend is predicted to continue. Several GW of data center load currently exists in the Dominion Energy Virginia (DEV) service territory, and much of this load is concentrated in Northern Virginia.

This study employs a hybrid strategy utilizing both measurement-based and bottom upload modeling methodologies. The work's scope of analysis can be separated into three components: firstly, gathering information on data center load composition and protection, then parameterizing a dynamic load model, and finally simulating the model and comparing performance with grid measurement data.

Data centers are a unique class of load unable to fit within traditional characterizations such as residential, commercial, or industrial. The load composition at a data center includes a large fraction of power electronic load demanded by the IT equipment. Another fraction of load is consumed by the cooling system, which can be induction motor or variable frequency drive (VFD) driven. Also, data centers must operate with extremely high reliability and thus employ backup generation, uninterruptible power supply (UPS) equipment, and operate with special protection schemes. The qualities of data centers introduce the requirement of a unique load model.

Previously created load models, both static and dynamic, will be parameterized according to data center load composition and operational characteristics. Various tools and strategies utilized to parameterize the models will be evaluated and compared.

Power system dynamic simulations are to be conducted testing the numerical performance and operational accuracy of the load models. Such simulations are conducted with PSSE on the MMWG model, which is a large-scale representation of the United States Eastern Interconnect. Actual recorded disturbance events such as faults are programmatically searched and selected from DEV's phasor measurement unit (PMU) and digital fault recorder (DFR) data. Comparison between simulated and actual results can be made by observing bus voltages and line currents. Additional analysis can be conducted by analyzing the simulated load active and reactive power consumption.

Ideally the simplest model, exhibiting the best accuracy with measurement data shall be employed for data center load throughout the system. Therefore, more reliable system studies can be conducted.

41. Development of Pulsar-based Power Grid Timing Instrumentation and Technology

Project Lead: Yilu Liu (UTK) **Graduate Students and Research faculty/associates:** Yu Liu (UTK), Yuru Wu (UTK)
Project Duration: 2021 – 2025
Funding Source: NSF

Summary

This project aims to develop a pulsar-based timing instrument that can provide accurate and stable timing signals that are immune to physical attacks. Based on potentially revolutionary timing technology, this instrument will include four major parts, including: (1) a pulsar signal adapter for pulsar signal reception from existing radio telescopes; (2) a pulsar signal transmission and processing system to filter out noises and extract millisecond timing pulses from pulsar signals; (3) a timing signal generation system to output high-precision timing pulse; and (4) a timing distribution system to distribute the time signal generated by pulsar receiver system to power system devices.

For the first and second part, the team communicated and worked with GBO to observe continuous millisecond pulsar data. Analyzed the observed continuous millisecond pulsar data and upgraded the pulsar period estimation algorithm. Improved the pulsar period estimation algorithm with dynamic period considering Doppler Effect and time influence.

For the third part, the team improved the local clock calibrate algorithm considering the oscillator frequency on the micro controller unit. Improved the radio telescope antenna emulation system to better emulate real world pulsar signals in the lab. Designed a radio telescope front-end system in the lab. Tested the radio telescope antenna emulation system and front-end system in the lab. Finished the development of the radio telescope back-end with fully functional ADC and 10 Gbe. Developed the PPS generation and calibration system on the back-end. Designed a GPS calibration algorithm to calibrate the pulsar signals with GPS and provide PPS when GPS is off-line.

For the fourth part, remote locations, such as transmission substations, may not be the proper environment for pulsar receiver installation, a timing distribution system is used to distribute the time signal generated by the pulsar receiver to remote power system devices that needs synchronized timing signals. The timing distribution system will transmit accurate and synchronized timing signals from the timing signal generation subsystem to remote locations without an installation of a pulsar receiver at each location.

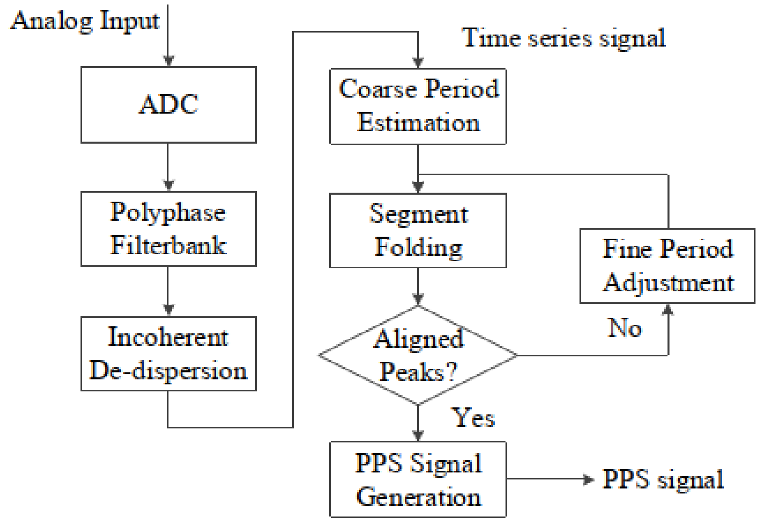


Figure 1: Flowchart of the proposed pulsar period estimation algorithm

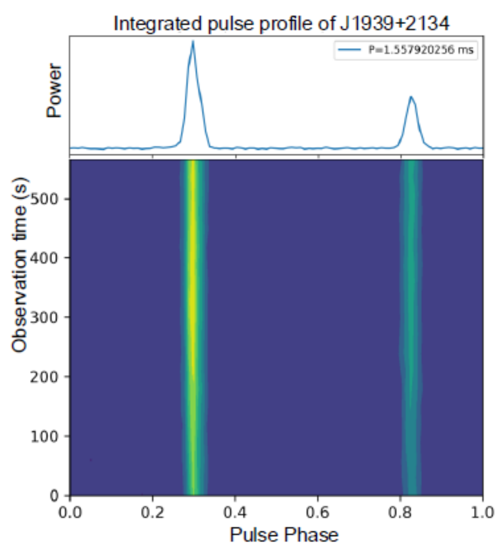


Figure 2: Segment folding with the correct period

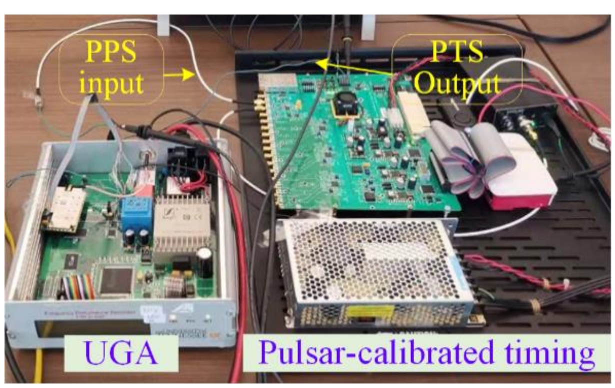


Figure 3: Setup of Pulsar-calibrated timing source with UGA

42. Intelligent Phasor-EMT Partitioning (I-PEP) for Accelerated Large-scale IBR Integration Studies

Project Lead: Kai Sun (UTK) **Graduate Students and Research Faculty/Associates:** Mahsa Sajjadi (UTK), Mohammed Khamees (UTK), Tianwei Xia (UTK), Min Xiong (UTK)
Project Duration: 02/2022 – 02/2024
Funding Source: DOE SETO through NREL

Summary

In an IBR-rich power grid, where numerous inverters are connected through the power grid, the partitioning of the grid model into EMT and phasor zones is of great importance for co-simulations. The EMT-phasor partitioning minimizes the EMT models for only the components that have a substantial impact on the system's dynamics so as to significantly reduce the computational complexity. The objective of this project is to partition the EMT and phasor domain models using participation factors (PFs) such that the best compromise between model accuracy and simulation speed is achieved. The PF is a measure of the contribution and reaction of each component such as a generator or an IBR to a specific dynamic response in the system.

The main steps to conduct the PF-based partitioning approach can be summarized as follows:

1) Identify a group of modes of interests based on historical dynamic events or simulation results on critical contingencies. These modes are chosen from electromechanical modes or sub-synchronous oscillation (SSO) modes that can be captured by a phasor model such as the modes with a frequency lower than 7 Hz. These modes should provide a good representation on how IBRs or key generators are involved in a major oscillation or stability concern following a large disturbance.
2) For each contingency to be simulated, conduct simulation for a short time using the phasor model or the EMT model of the grid. Here, the simulation period only needs to cover 2 to 3 oscillation cycles of the slowest mode of interest so as to estimate the PFs from the system response. For each mode, estimate linear or nonlinear PFs of each IBR and generator using both model and response-based methods. Response-based PF estimation directly from the

simulation result can complement the model-based PF estimation when the state-space EMT/phasor model of the grid is not available.

3) According to the estimated PFs, decide whether the EMT model of each IBR needs to be retained or can be reduced to a phasor model in the final grid model for fast simulation, or in other words, determine the boundaries between EMT models and phasor models for the entire grid. Only those IBRs, generators and buses having PFs exceeding a threshold are necessarily represented in the EMT domain; otherwise, a nonlinear phasor model or a reduced phasor model will be used.

This approach enables adaptive, intelligent partitioning and results in a speed-optimized hybrid EMT-phasor simulation that captures the relevant dynamics. When two adjacent regions are modeled in different domains, their interface model uses some techniques to preserve the dynamics of interest. The resulting partitioned EMT-phasor model will compute more rapidly because its internal dynamic models will include only the level of detail necessary to capture the dynamics of interest. We have designed and tested both model-based and response-based PF estimation methods to aid in boundary determination. The partitioning approach has undergone thorough validated on a small two-area system and has also been demonstrated on the WECC 240-bus model, considering SSO scenarios involving IBRs in California area. The locations of important IBRs highly participating in the mode are shown by red color on the WECC map in Figure 1.1. The IBRs that participate the most in the 4.6 Hz oscillation are located in the south California region. The partitioning of the system into EMT and phasor zones is refined by using oscillation magnitudes of bus frequencies obtained from Prony analysis for only one second of simulation time. The bus frequencies obtained by perturbing a state variable of an IBR are shown in Figure 1.2., which indicates the SSO at 4.6 Hz. Considering a bus frequency oscillation magnitude that is higher than a threshold 0.4, i.e., 40% of the largest oscillation magnitude, a partitioning can be suggested as the red line in Figure 1.3.

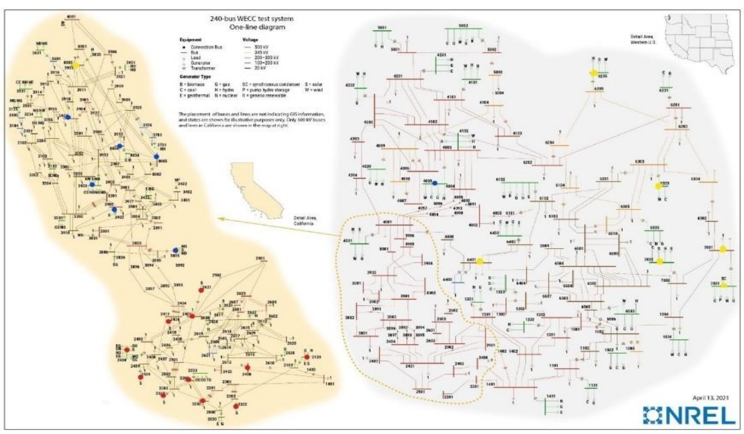


Figure 1.1: Identification of highly participating IBRs (Red)

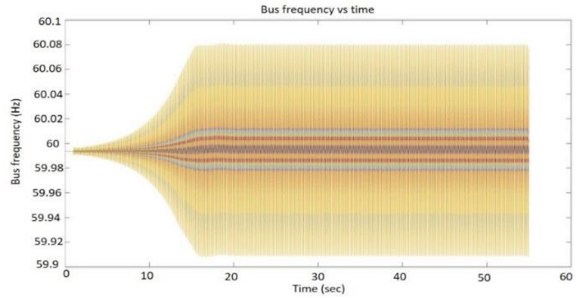


Figure 1.2: IBR bus frequencies after a disturbance

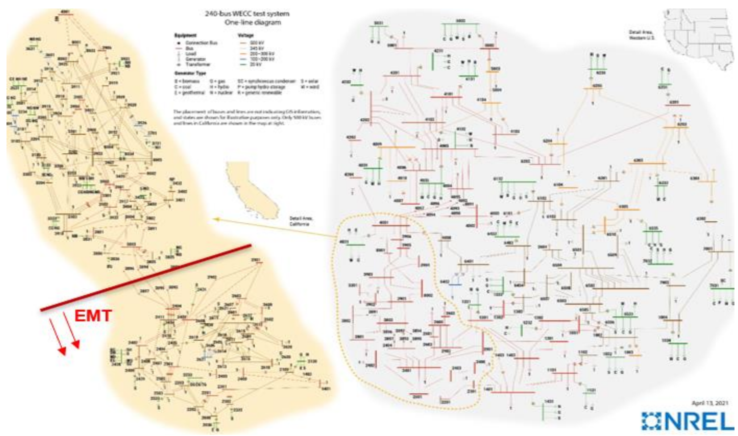


Figure 1.3: EMT-phasor partitioning for a 4.6-Hz SSO

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

Project Lead: Kai SUN (UTK) **Graduate Students and Research Faculty/Associates:** Kaiyang Huang (UTK)
Project Duration: 4/2024 – 07/2027
Funding Source: NSF

Summary

The proposed project aims to revolutionize power system simulation by introducing a unified HMM framework for accurately capturing the dynamics of multiple timescales, from microseconds to hours, in an inverter-dense power grid. The HMM approach takes large time steps to evolve the macroscopic behavior of the grid for most of the simulation period when microscopic dynamics are either monotonic and predictable or reaching the end of a dissipative transient following a switch. To ensure numerical stability throughout the simulation, the proposed framework links low-level micro-state simulations over disconnected intervals via macro-state solutions. These micro-state simulations are distributed either regularly or adaptively throughout the simulation period to capture the most important details of the simulation. The overall HMM framework enables automatic "zoom-in" and "zoom-out" functions between the most macroscopic behaviors and most microscopic dynamics on the fly during the simulation. This method efficiently

compresses computational burdens for a simulation, and the overall time cost is comparable to a purely macroscopic simulation, while the error compared to a purely microscopic simulation is bounded. Specifically, this project will establish a Heterogeneous Multiscale Method (HMM) framework for power systems, which can adaptively adjust the simulation resolution between microscopic and macroscopic levels. This framework will also incorporate advanced semi-analytical solution (SAS) techniques to enable variable-step and variable-order mechanisms of both microscopic and macroscopic simulations for optimal performance. To achieve this goal, the following three objectives will be pursued:

- Objective-1: Developing HMM algorithms for automatic, case-specific reduction of microscopic component models into a macroscopic model on the fly during simulation, which can efficiently capture all relevant dynamics of interests for inverter-dense power grids.
- Objective-2: Finding variable-order semi-analytical solutions with variable step-sizes to ensure optimal performance for both microscopic models and macroscopic models.
- Objective-3: Validating the developed HMM framework by realistic scenarios on power grid testbeds having high IBR penetration of 50% to 100%.

This project is expected to be finished by the end of July 2027. Future works include testing the proposed method in a more practical large-scale power system, and implementing toolbox of the proposed scheme in MATLAB. The following Figure 1.1 illustrates a three-level HMM framework to simulate a power system involving EMT, electromechanical and quasi-steady-state multi-timescale dynamics. Figure 1.2 provides a schematic illustration of the SAS method, which will be embedded into the HMM framework. Figure 1.3 demonstrates the implementation of the HMM algorithm on a two-area system for a contingency simulation having fast EMT dynamics at the beginning and quasi-steady-state behaviors dominated at the end.

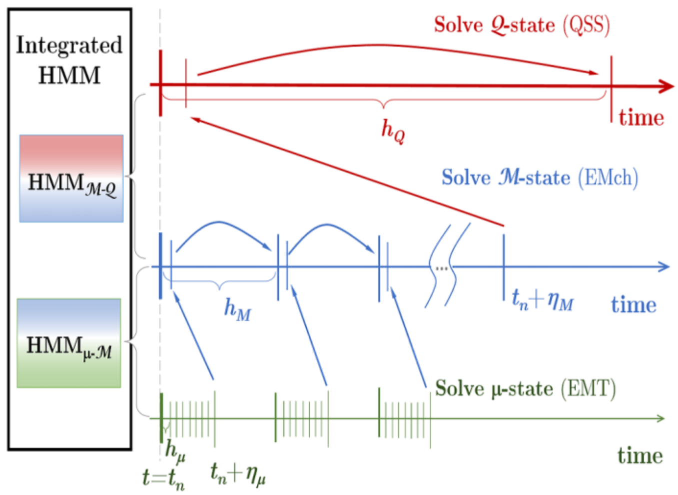


Figure 1.1: Illustration of a 3-timescale HMM.

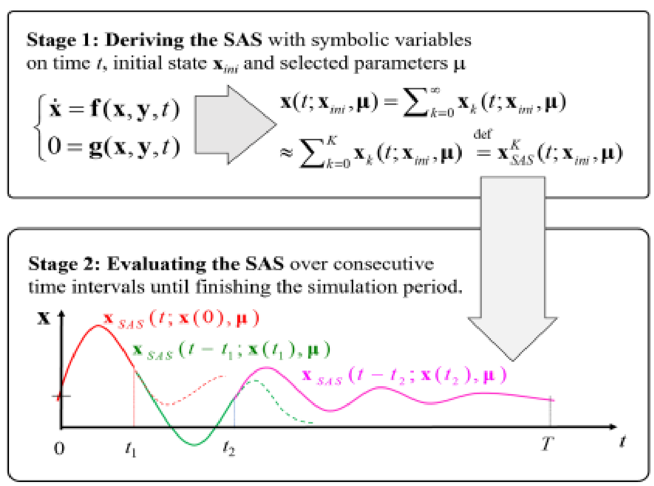


Figure 1.2: SAS-based simulation in two stages.

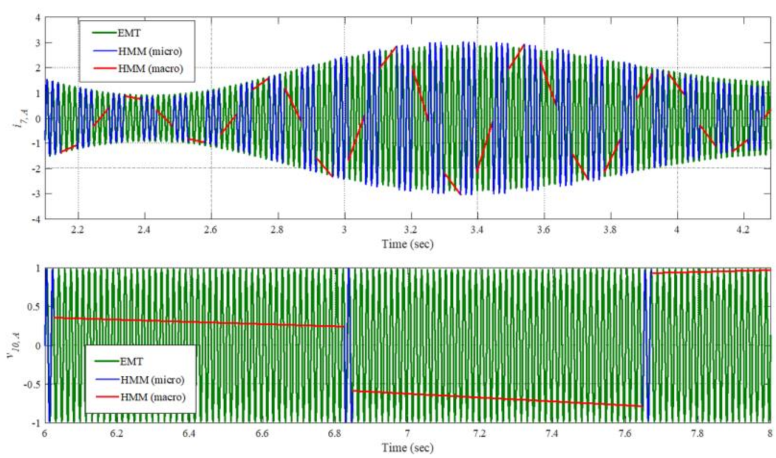


Figure 1.3: HMM results on the EMT model of a 2-area system after a disturbance (top) and at the end (bottom).

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

Project Lead: Kai Sun (UTK) **Graduate Students and Research Faculty/Associates:** Zhenping Guo (UTK)
Project Duration: 9/2023 – 08/2026
Funding Source: NASA through New Mexico State University

Summary

The objective of this project is to evaluate reliability and resilience impacts of AAM (Advanced Air Mobility) operations on power grids to support the integration of multiple UAM (Urban Air Mobility) /RAM (Regional Air Mobility) portals for aircraft operations. AAM implementation will bring both beneficial and adverse impacts on the electric grid. Therefore, the placement of AAM portals needs to address reliability and resilience criteria, mitigate adverse impacts, and facilitate beneficial impacts.

Initially, a power system software testbed is established for the RAM portal. This testbed includes a regional transmission network connecting Knoxville, Nashville, Chattanooga and Crossville. To mimic the topology, major power plants, and power flow directions of the actual TVA (Tennessee Valley Authority) region, a selected region of the well-developed NPCC (Northeastern Power Coordinating Council) test system is modified accordingly. The flow directions within the TVA region are approximated based on the power flow solution of an EI (Eastern Interconnection) model. Adjustments to parameters, such as generators' outputs, are made to align the flow directions with those of the TVA region. Additionally, the flow limits of transmission lines are further determined based on the "N-1" contingencies analysis.

In the future, each RAM portal in the grid will be modeled based on the load level of each portal and the typical daily load curve (charging) for each airport. To account for differences in geographic locations and charging demands towards electric infrastructures, a testbed for UAM vertiports will also be constructed. This testbed will include an urban power distribution system with charging vertiports, which may be connected to the RAM testbed or a reduced grid model.

After the development of UAM and RAM testbeds, we will design representative scenarios concerning critical contingencies under typical peak/off-peak load conditions for each testbed with representative configurations. Additionally, several test scenarios focusing on critical contingencies of initial portal siting will be conducted according to NERC reliability standards and guidelines addressing IBRs (inverter-based resources). We will evaluate the significance of impacts on grid reliability, develop a method for quantifying the risk and consequence for each adverse impact, and define reliability metrics used as constraints of portal siting optimization. For beneficial impacts, we will propose AAM-based grid services with estimated costs and benefits, which will be considered during portal siting optimization. The portal placement will undergo several iterations based on the impact evaluations to achieve the optimal portal placement.

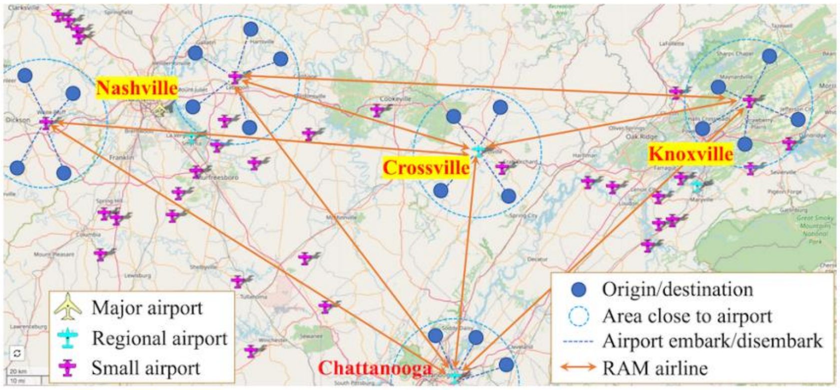


Figure 1.1: Illustration of a Sample RAM network in Tennessee

Figure 1.2: Tennessee Transmission Network

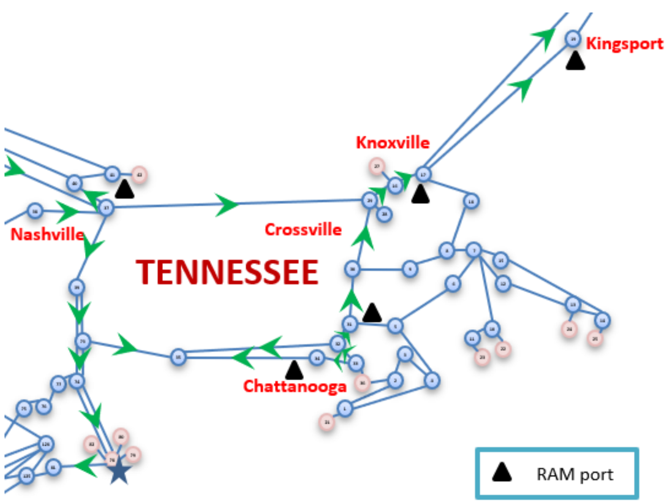


Figure 1.3: RAM Testbed

45. Grid Model Partitioning for Hybrid Phasor-EMT Simulation Addressing Increasing IBRs

Project Lead: Kai Sun (UTK) **Graduate Students and Research Faculty/Associates:** Mohammed Khamees (UTK), Mahsa Sajjadi (UTK).
Project Duration: 09/2023 – 08/2024
Funding Source: ISO New England Inc

Summary

The primary objective of this study is to precisely define the boundary between the (EMT) model and the phasor model for hybrid phasor-EMT simulation. Establishing such an adaptive, limited, small EMT zone for an IBR or a group of IBRs is crucial as it enables to identify and conclude comparable qualitative stability behaviors to those observed by a full EMT model with significant reduction in simulation time.

First, the project has created a number of different IBR-induced SSO events in the 39-bus system. This involved placing the IBR at various locations within the network, exerting the system to its limit, by applying severe faults, in order to provoke specific boundary cases that challenge the hybrid phasor-EMT simulation to comprehensively address stability issues. The events include the cases of SSOs being limited only to a local area of the IBR and SSOs propagating over a wide area. Some sample events are illustrated in Figures 1.1 and 1.2.

Next, the project will define a threshold to determine how far the propagation of the IBRs dynamics and SSOs throughout the network's elements. The participation factors will exploit how the buses' voltages and transmission lines' currents participate into an SSO mode on one hand and the actual visibility of the SSO mode from buses and lines on the other hand. For each event generated, the participations will be ranked for both currents and voltages separately, serving as quantitative theoretical indicator on the SSO propagation. Also, visibilities of the SSO from different locations are also evaluated and ranked as empirical indicators. Utilizing these rankings, a composite index with its threshold will be defined resulting in a preferably small EMT zone that can accurately address the stability issue. Initially, the EMT boundary will start at the highest ranked bus and extend to all connected lines, tier one lines, along with buses linked to the opposite ends of these lines, thereby identifying the boundary bus. The harmonics distortion will be utilized as another indicator to provide insights into the similarity between signals generated by the phasor program and the full spectrum signals from the EMT model. Hence, additional lines exhibiting harmonic distortion exceeding 60% of the highest line's distortion will be incorporated. These lines, designated as tier two lines, along with their associated buses, will be included in the boundary analysis. If generated boundaries fail to capture the qualitative stability behavior, adjustments will be made by adding more lines with highest PFs that were not initially included in the boundary.

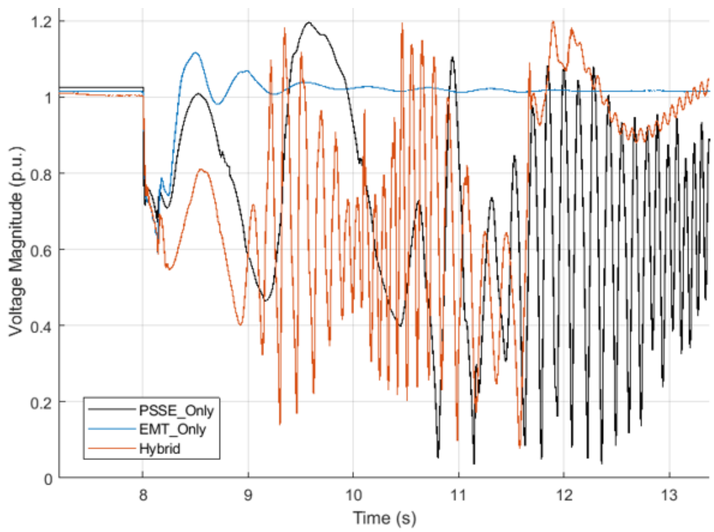


Figure 1.1: 3-phase fault at a remote 115kV bus, cleared after 8 cycles, highlighting interactions between IBR EMT dynamics and Phasor grid dynamics.

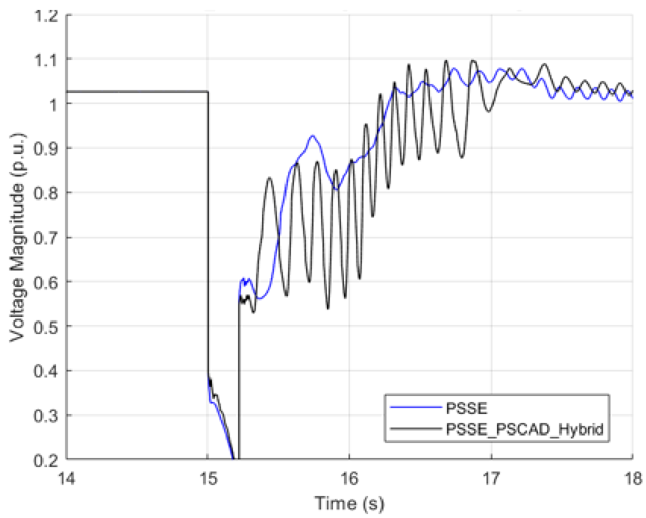


Figure 1.2: 3-phase fault at a remote 345kV bus, cleared after 13 cycles with a line tripping, highlighting IBR EMT dynamics that are not present in the phasor model.

46. Energy Equity Consideration in Siting and Sizing Distributed Generations

Project Lead: Fran Li (UTK) **Graduate Students and Research faculty/associates:** Chenchen Li (UTK), Sufan Jiang (UTK), Xiaofei Wang (UTK), Jinning Wang (UTK)
Project Duration: 1/2023 – 1/2024
Funding Source: UTK Enrichment Fund

Summary

This project aims to develop generalized models and guidelines for distributed generators (DGs) planning problems while considering energy equity. However, quantifying the energy equity of power systems is a big challenge. Furthermore, embedding energy equity in the DG planning problem is another difficulty that needs to be solved.

This year, we successfully developed a model for economic-oriented DG planning problems considering energy equity and concluded generalized guidelines. Firstly, energy equity was quantified by energy burden which is the percentage of households' income spent on energy costs, representing the ability to obtain reliable energy. Then, the DG planning problem was formulated as a stochastic bi-level model, where energy equity was considered as a constraint. The upper level determined the optimal sites and sizes of DGs under investment and energy burden constraints, while the lower level optimized the distribution operation. Next, a solution method combining Karush-Kuhn-Tucker optimality conditions and Progressive Hedging Algorithm was applied to solve the proposed model. In this project, the effectiveness of the model and solution methods was verified on the IEEE 123-bus system, as shown in Figure 1.

Results in Figure 2 show that the energy burden of low-income communities is reduced by installing DGs. There is a free ride for other communities, which is possible when planners intend to improve energy equity at a specific location to meet the energy burden criterion. More importantly, following generalized guidelines can be concluded.

(1) DG units are not always installed near low-income communities, even considering the energy equity constraint. The decision of whether DG units are installed near low-income communities depends on the communities' location in the system as well as technical constraints.
(2) When multiple low-income communities are spread throughout a system, it is generally more effective to install DGs near the low-income communities in the downstream of feeders.
(3) To achieve a lower level of energy burden for low-income communities, a quantitative economic evaluation is needed for accurate siting and sizing such as the proposed method, which is related to the system topology and the location of low-income communities, as well as the technical and energy burden constraints.

This project was finished in January 2024, and future work will investigate resilience-oriented DG planning problems considering energy equity.

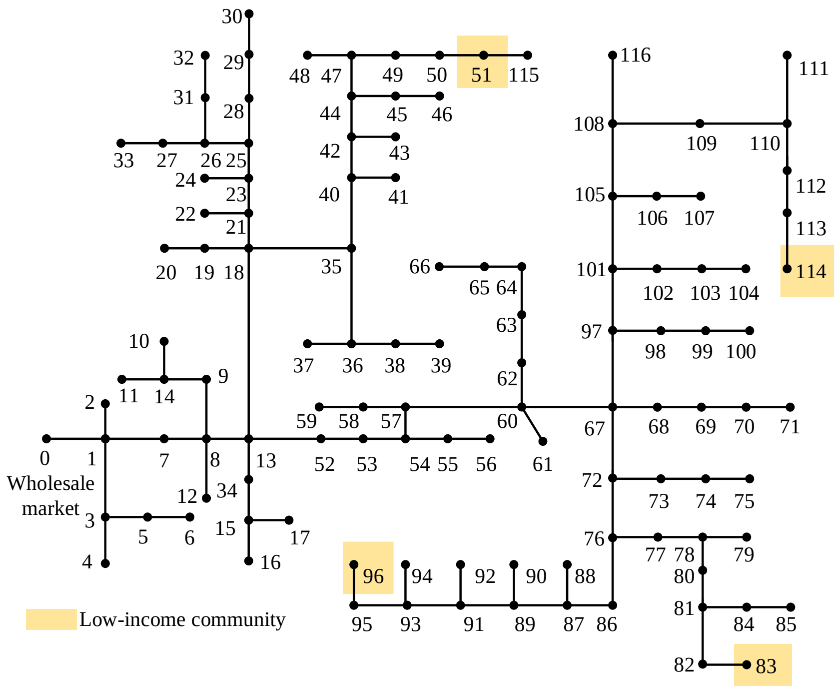


Figure 1: Modified IEEE 123-bus system

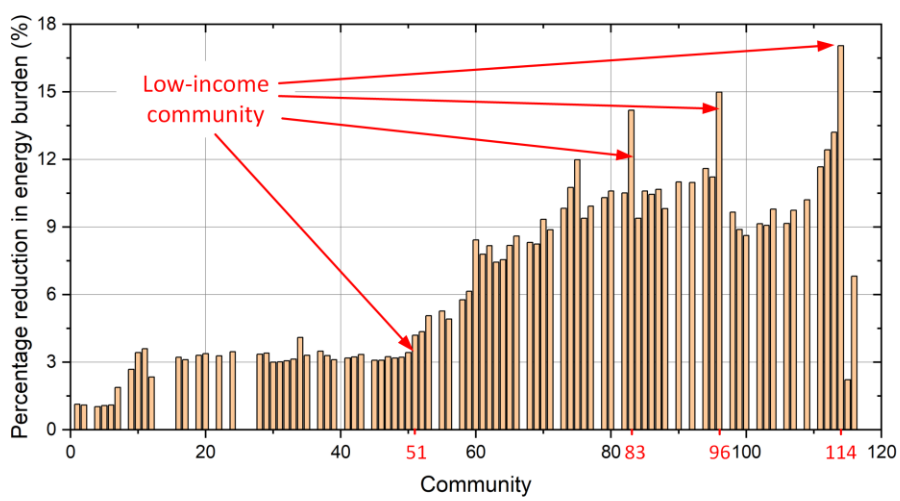


Figure 2: Percentage reduction in energy burden of each community

47. Model Free Adaptive Control (MFAC) for autonomous and resilient microgrids

Project Lead: Fran Li (UTK), Hantao Cui (Oklahoma State), Rui Bo (Missouri Univ of Sci. and Tech.), Jonathan Kimball (Missouri Univ of Sci. and Tech.) **Graduate Students and Research faculty/associates:** Buxin She (UTK), Junjie Yin, Oboreh-Snapps Oroghene (Missouri Univ of Sci. and Tech.)
Project Duration: 7/2020 – 4/2024
Funding Source: DOD ESTCP

Summary

The objective of this project is to develop a model-free adaptive control (MAFC) strategy for autonomous and resilient microgrids. Three main tasks were developed, including MAFC control algorithm design, control algorithm integration, and system-level validation, each with a few subtasks. Specifically, the control algorithm design covers microgrid P-Q control and V-f control, which will be integrated into the seamless mode transition of microgrids. A power hardware-in-the-loop (HIL) experiment will also be performed to validate the proposed MAFC approach, using the CURENT hardware testbed (HTB).

An adaptive PQ control method with trajectory tracking capability was proposed for grid-following microgrids, combining model-based analysis, physics-informed reinforcement learning (RL), and power hardware-in-the-loop (HIL) experiments. Fig. 1 shows the diagram of the proposed method, and Fig. 2 shows the tested microgrid configured in Simulink and HTB. Also, a virtual synchronous generator (VSG) control using deep RL was developed for islanded microgrids. The microgrid shows improved performance by actively changing the virtual inertia and damping of VSG. In addition, a decentralized and coordinated voltage and frequency (V-f) control framework is proposed for islanded microgrids, with full consideration of the limited capacity of distributed energy resources and V-f dependent load.

Furthermore, the performance of the proposed MFAC algorithm for microgrids. Active and reactive control (P-Q control), as well as frequency and voltage (f-V) control, are two of the

challenging tasks in microgrid operation. This project developed MFAC for both P-Q and V-f control in microgrids, which has been verified in MATLAB-Simulink. Also, the HIL test results of the proposed MFAC algorithm for microgrids, rather than the simulation results. The performance of the algorithm was verified in MATLAB-Simulink, which has been included in the control algorithm performance report. In this report, the algorithm is further validated through a hardware-in-the-loop experiment in CURENT HTB. Through the results from the simulation and hardware test, the efficiency of the proposed MFAC algorithm is verified.

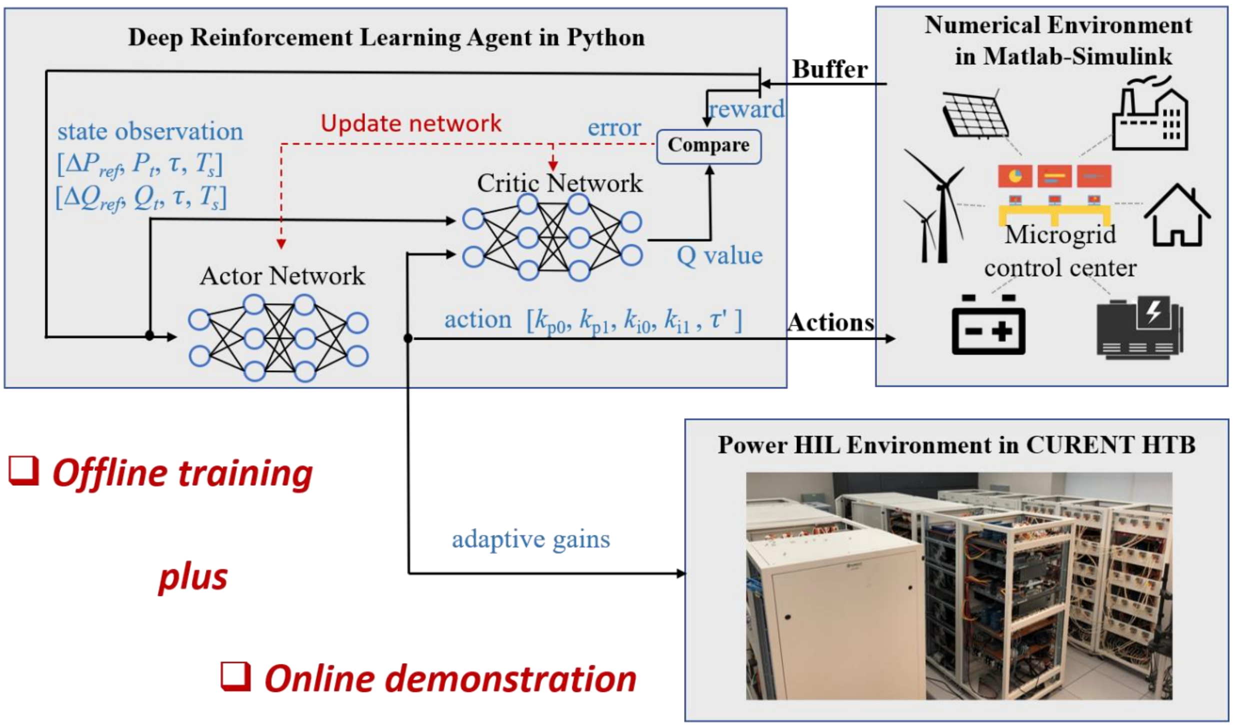


Figure 1: Diagram of the model-free adaptive PQ control based on physics-informed reinforcement learning and power HIL experiment.

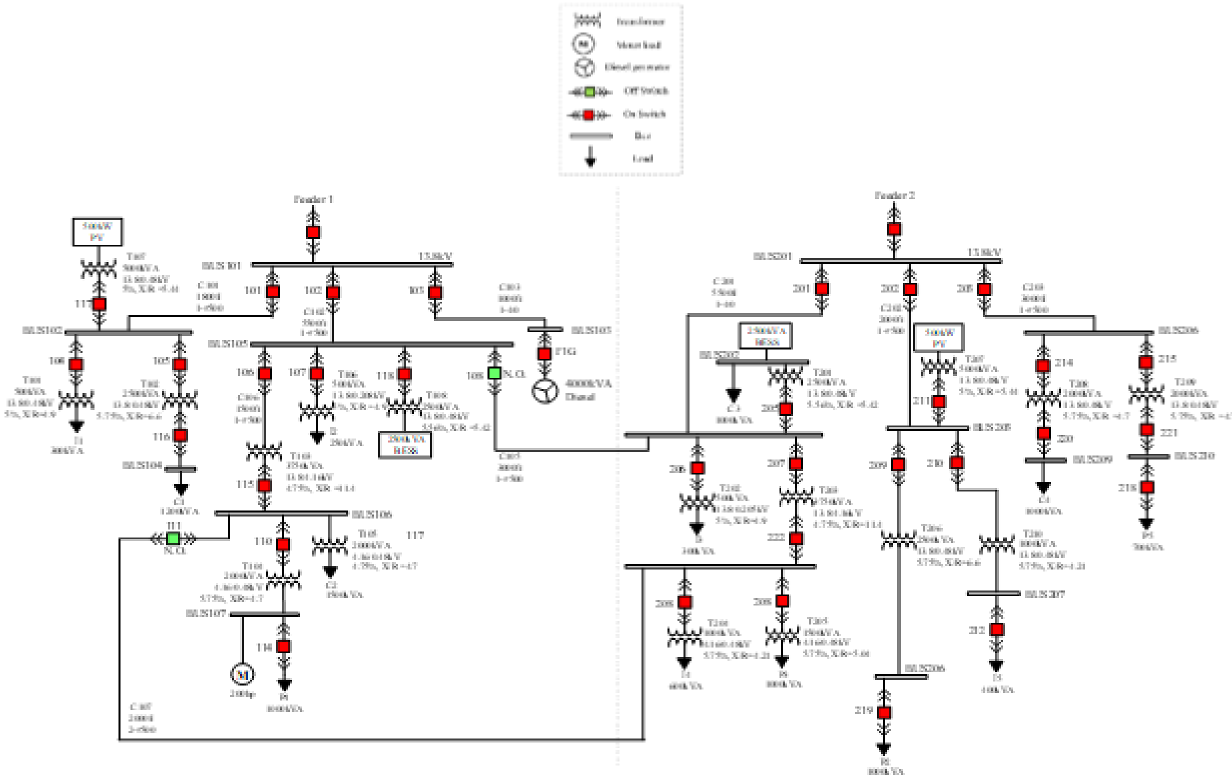


Figure 2: One-line diagram of the two-feeder microgrid model modified from the Banshee model.

48. CURENT Large-scale Testbed (LTB)

Project Lead: Fran Li (UTK), Kevin Tomsovic (UTK), Hantao Cui (Oklahoma State Univ.), Xin Fang (Mississippi State Univ.) **Graduate Students and Research faculty/associates:** Jinning Wang (UTK)
Project Duration: 5/2023 – 2/2024
Funding Source: NREL, ESTCP

<u>Summary</u>

Towards a decarbonized power gird, emerging challenges confronted to power grid operators include not only dynamic stability and economic optimality, but also reliable and deliverable energy and ancillary services from inverter-based resources (IBR).

This year, the developed AMS completed CURENT LTB with the dispatch functionality. The LTB platform architecture is shown in Figure 1. The compatible data structure and dynamic interfaces allows smooth interoperation with dynamic simulators. Consequently, LTB opens new research opportunities. First, the platform enables the development of dispatch algorithms that can leverage the flexibility of renewable energy sources effectively and reliably. Second, it facilitates the creation of a virtual energy market by developing a market layer, which is essential to devise and test new energy market mechanisms. Third, a full-timescale digital twin for the power grid is achievable using the dispatch-centric virtual power grid with dynamic integration.

Results demonstrate the consistent and concise modeling scheme with LTB, as shown in the Figure 2. More importantly, the delivered open-source tools have high quality. The continuous integration and deployment are applied to secure the software quality and accessibility. The online community provides an activate connection between the users and developers.

In the next phase, we aim to demonstrate a grid-scale digital twin by coordinating multi-timescale dispatch and interfacing dispatch and dynamics.

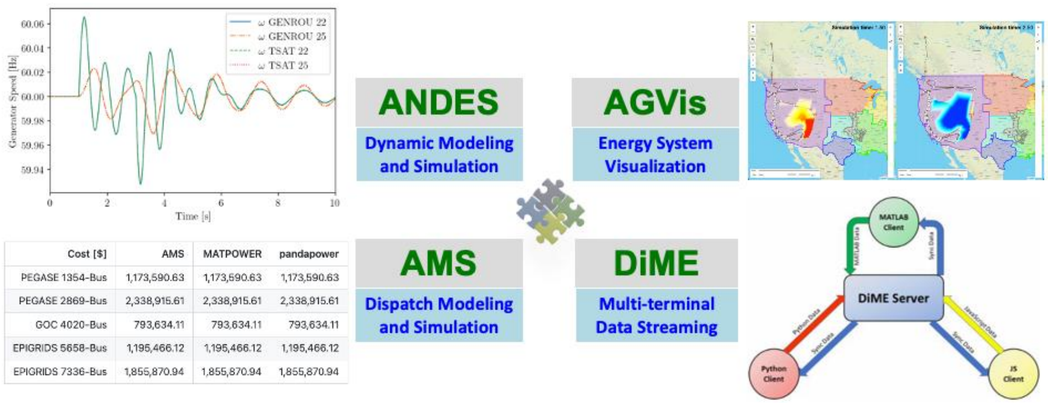


Figure 1: Products under LTB platform

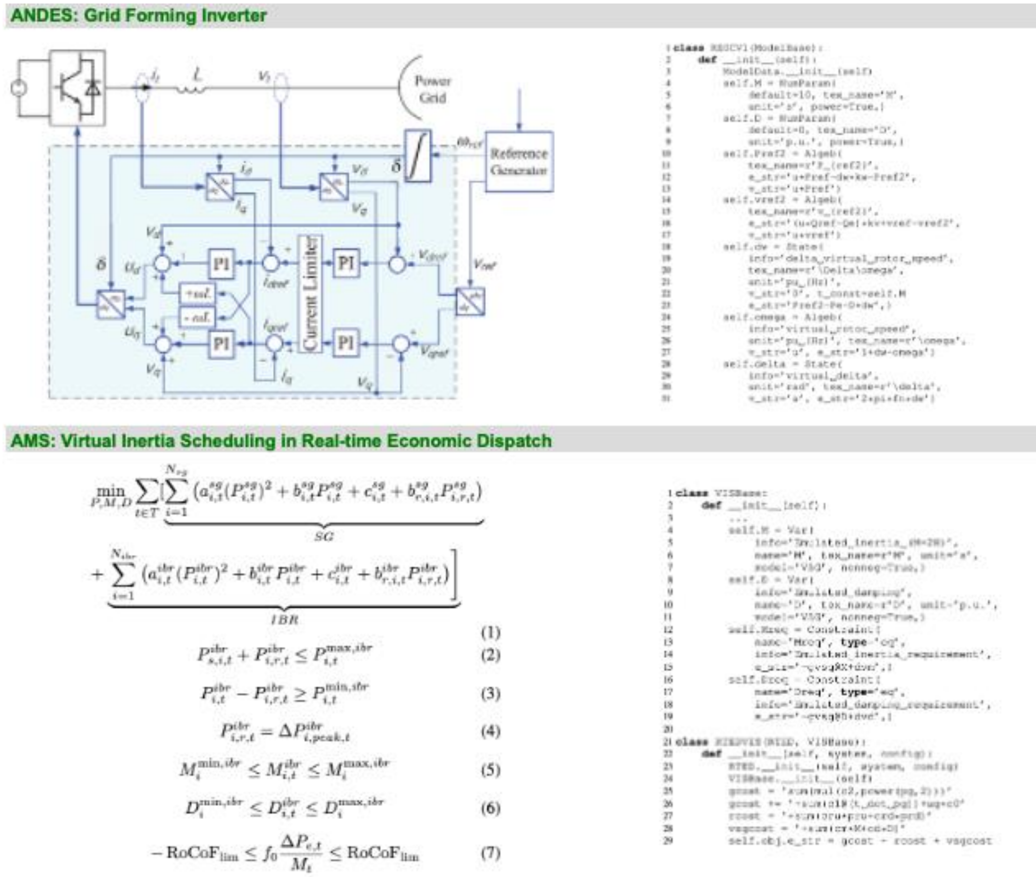


Figure 2: Modeling examples of IBR in both dynamics and dispatch

49. CURENT Large-scale Testbed (LTB) Development

Project Lead: Fran Li (UTK), Hantao Cui (Oklahoma State Univ.), Kevin Tomsovic (UTK) **Graduate Students and Research faculty/associates:** Nicholas Parsly (UTK), Jinning Wang (UTK), Nick West (UTK)
Project Duration: 1/2021 – 4/2024
Funding Source: ESTCP, NREL

Summary

The CURENT Large-scale Testbed (LTB) consists of a series of independent open-source packages with federated use. LTB features large-scale simulation, communication, and geographical visualization. The primary purpose of LTB is to facilitate and speed up the process of power system prototyping. Another Grid Visualizer (AGVis) has seen a substantial rework to the backend among other improvements to provide more quality and better fit in with LTB.

AGVis is a Web-based JavaScript visualization application that runs in users' web browsers that is designed to be an open-sourced general purpose grid visualizer. This year's development efforts include major software quality improvements, UI elements, testing, and other various bug fixes and quality of life improvements for the AGVis application. Most Importantly, recent developments have resulted in a complete overhaul of the backend for the LTB AGVis platform. This involved removing the old simple HTTP server built into python, and invoking a chain of open source, industry standard tools to provide a secure, reliable, and robust system of handling serving the AGVis application to the end user.

Whether hosting it locally or accessing it through the demo environment through a server, the security needs of application users can be better met with this approach. It also provides better scalability for user load, flexibility with how it is integrated, optimized for faster clients, and efficient request handling, and has allowed for the creation of a demo environment, designed users to better market the tool for new users.

Future works involve visualizing the new LTB AMS dispatch functionality.

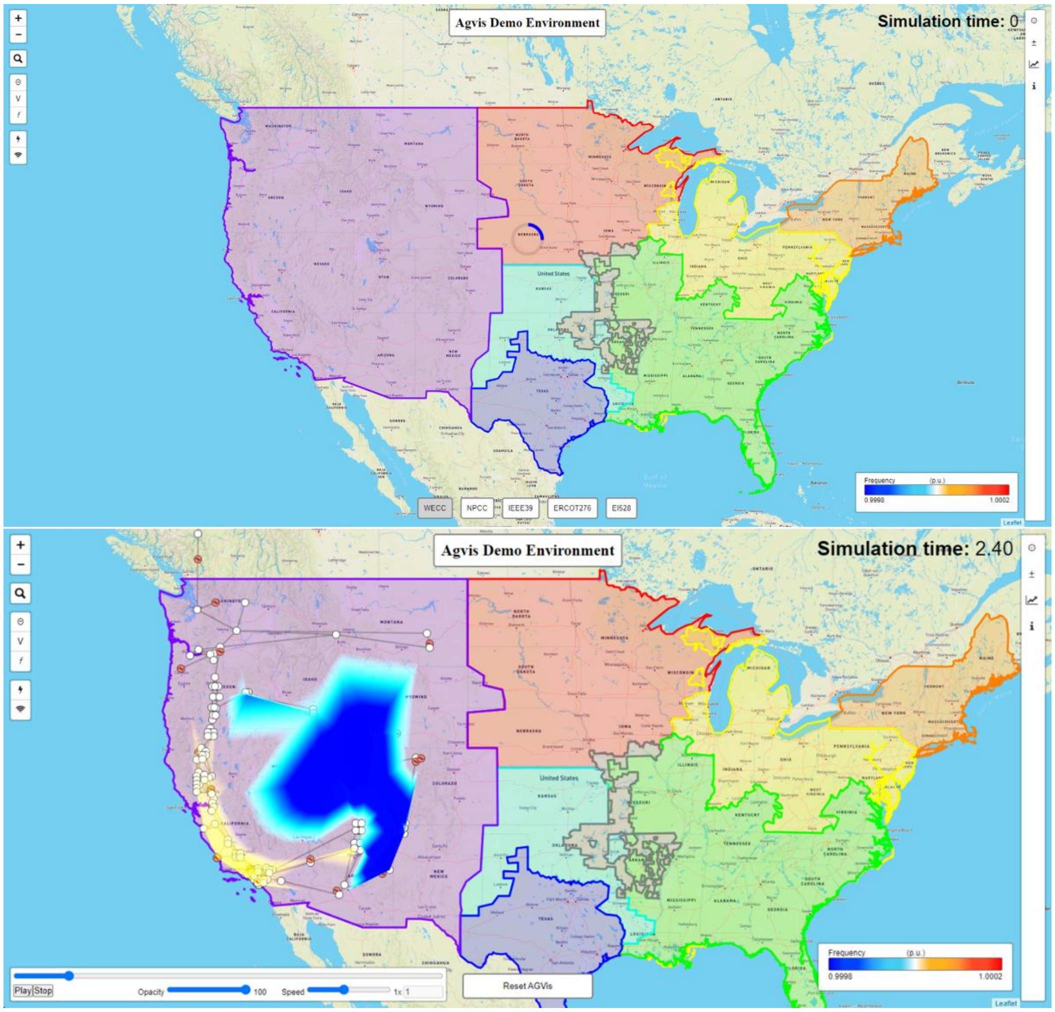


Figure 1: AGVis Demo WECC Simulation Example with Newly Added UI Elements

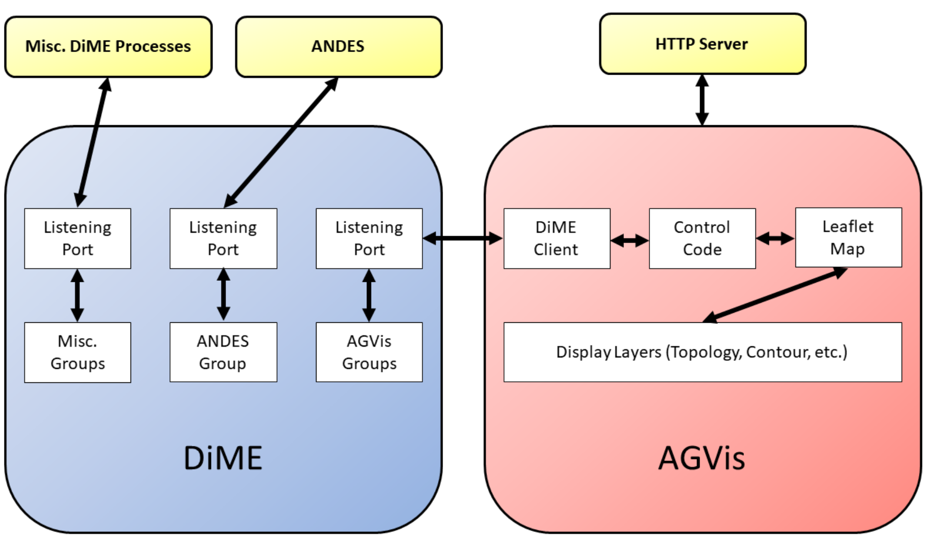


Figure 2: How DiME, ANDES, and AGVis interact with federated use

50. Development of an Adaptable Dispatch Modeling Framework

Project Lead: Fran Li (UTK) **Graduate Students and Research faculty/associates:** Jinning Wang (UTK)
Project Duration: 1/2023 – 4/2024
Funding Source: NREL, ESTCP

Summary

This project aims to develop the market simulator Another Market Simulator (AMS), and thus complete the dispatch functionality for CURENT Large-scale Testbed (LTB).

This year, we developed the dynamics-incorporated hybrid symbolic-numeric modeling for stability constrained production cost simulation framework.

The modularized dispatch modeling framework, as shown in Figure 1, is designed to enable a dynamics-incorporated power system production cost modeling. This unique framework incorporates an adapted hybrid symbolic-numeric approach for production cost dispatch modeling, effectively bridging the gap between device-level models and system-level dispatch models and streamlining the dispatch modeling. The adaptability of the proposed framework stems from four key aspects: extensible dispatch formulations through modeling blocks, scalable performance via effective vectorization and sparsity-aware techniques, compatible data structure aligned with dynamic simulators by common power flow data, and interoperable dynamic interface for bi-direction data exchange between steady-state generation scheduling and time-domain dynamic simulation.

Through extensive benchmarks with various usage scenarios, the framework's accuracy and scalability are validated. As shown in Figure 2, the developed AMS has advantages over other exiting tools. The results also demonstrate the efficient interoperation of generation dispatch and dynamics, significantly reducing the modeling conversion work in stability-constrained grid operation.

In the next phase, we aim to coordinate the multi-timescale dispatch. Along with the interoperability with dynamic simulators, we expect to demonstrate the full timescale digital twin for power grid.

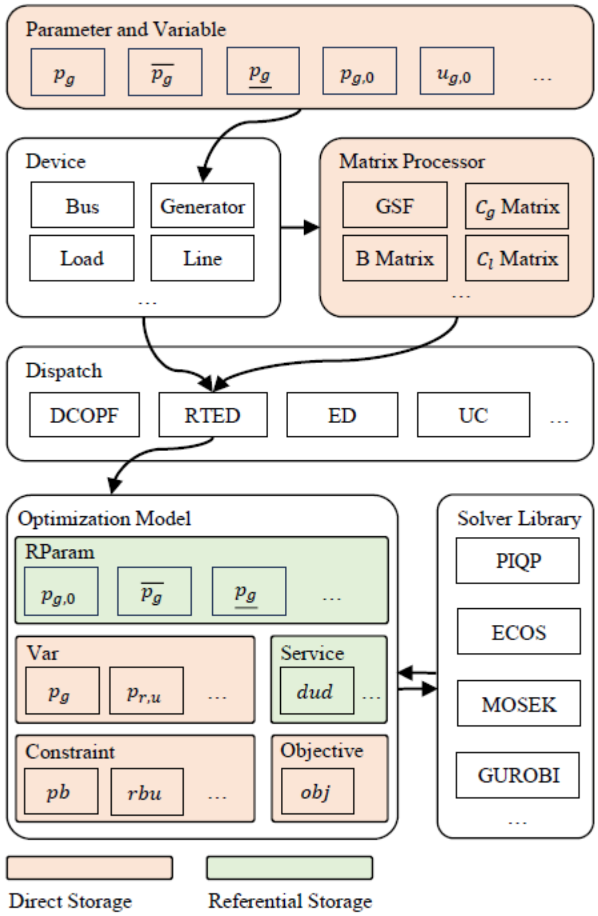


Figure 1: Dispatch modeling scheme

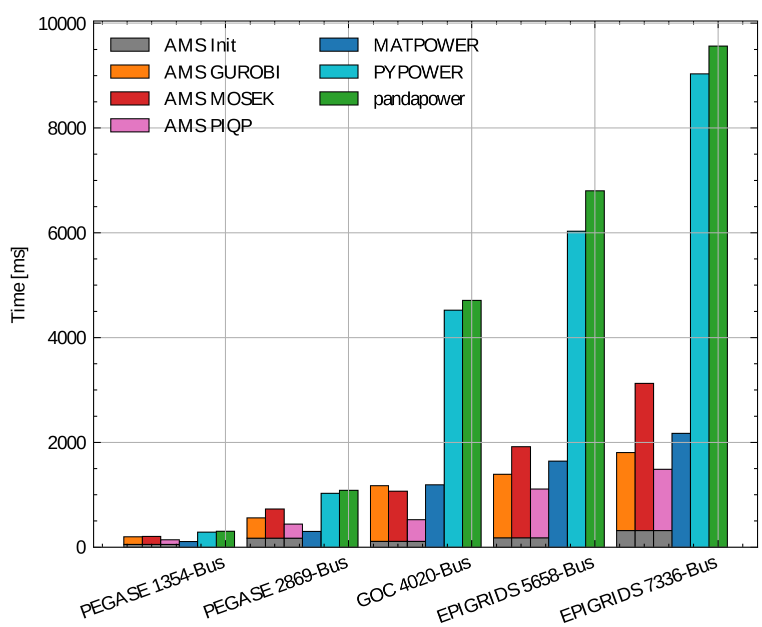


Figure 2: Computation time of OPF on large scale cases.

51. Investigation of variations in data ownership models effect on multi-microgrid control

Project Lead: Fran Li (UTK), Michael Starke (Oak Ridge National Lab) **Graduate Students and Research faculty/associates:** Vince Wilson
Project Duration: 2/2024 – 10/2024
Funding Source: ORNL

Summary

The objective of this project is two-fold. The first is to further develop an existing virtual inertia scheduling (VIS) algorithm to enable multiple microgrid coordination. The second objective is to use the multi-microgrid VIS formulation to examine how different data sharing regimes between microgrids affects both internal control and the ability of multiple MG. System level experimentation and simulation of microgrids will be carried out using CURENT's ANDES platform. Device level stability will be examined and verified using hardware in loop-based resource emulations provided by ORNL's Control and Optimization using Distributed Agent-based System for Real Time Operations (CODAS) platform.

The project will consist of three main tasks. The first will be to expand the existing VIS formulation for microgrids to account for interchange of power between microgrids; this will be done by altering the real-time economic dispatch optimization program component. Next, variations in data privacy between microgrids will be determined by constraining the availability or preciseness of certain types of information exchanged between microgrids. Real time dynamic simulations will then be carried out using the ANDES platform to determine the effect of privacy variations on a system scale. Effects on the device level will be examined using small scale simulations performed using CODAS.

Work on this project is in its early stages. The students prior work on CODAS's optimization backend has provided them with familiarity for the platform in addition to an overall expansion of its capabilities. Current work consists of literature review to examine previous efforts in multi-microgrid control and formulation and implementation of the new VIS algorithm.

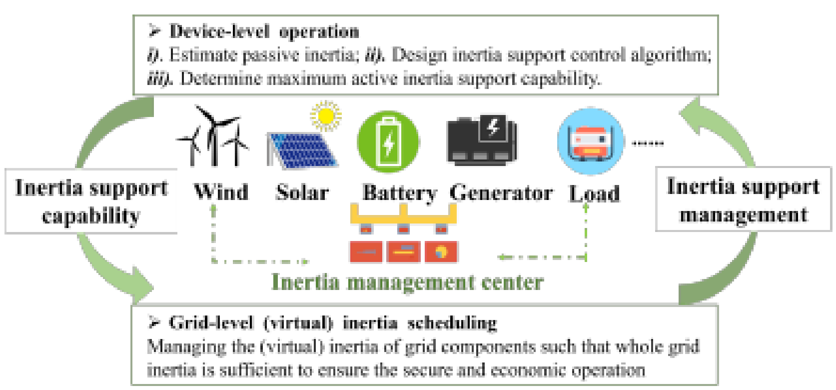


Figure 1: Diagram of Virtual Inertia Scheduling (VIS)

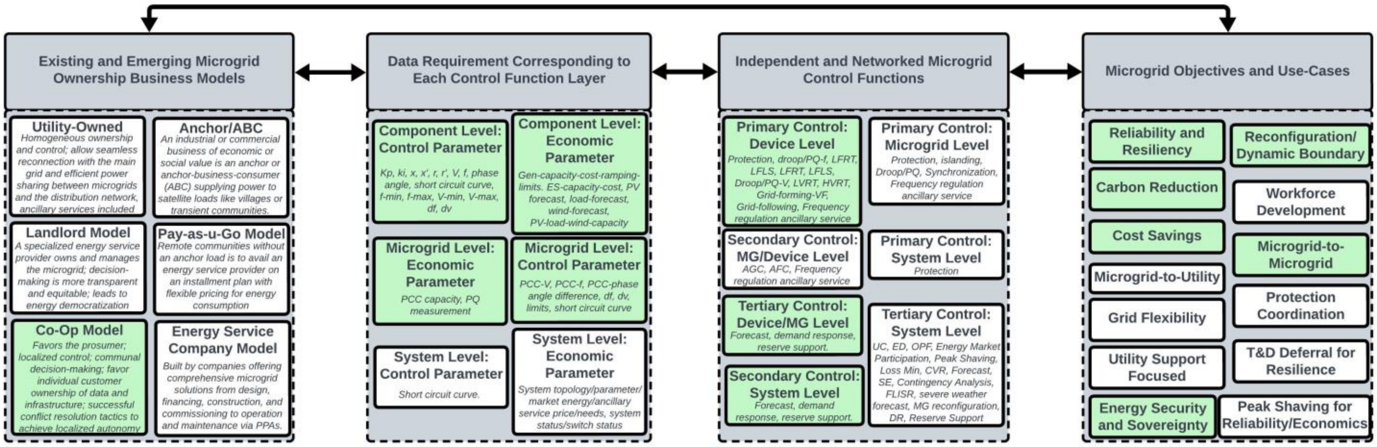


Figure 2: Schema for determining relationships between Microgrid business models, data, and control objectives

52. Modeling and Validating System Dynamics in Saudi Synthetic Electric Grids

Project Lead: Fran Li (UTK) **Graduate Students and Research faculty/associates:** Mishal Alonize (UTK), Jinning Wang (UTK), Zackery Malkmus (UTK)
Project Duration: 8/2021 – 12/2024
Funding Source: TVTC

Overview:

This project introduces a modeling approach for creating a synthetic Saudi power network, designed to mimic the transient dynamics of a real power grid. This synthetic network model, created from open-source data, is available for open sharing and can be utilized for educational, training, and research purposes. The cases are built to match a detailed model of Saudi power system elements, Saudi code requirements, and statistical characteristics found in actual power grids. First, we describe how we built, tested, tuned, and validated this synthetic Saudi grid model by using statistics from currently available data. The CURENT Large-scale Testbed (LTB) and its ANDES package enabled power flow calculations, simulations of transient stability, and analysis of small-signal stability in transmission systems. Second, we describe our use of the ANDES package for dynamic simulation and testing, and our use of the LTB's AGVis package for grid visualization. The Saudi synthetic grid model project has 224 buses that have been tested, tuned and validated to ensure that they are realistic and are practical for various studies. This project has the following technical contributions:

- This project represents an initial step towards constructing synthetic networks for the Saudi electric grid that are geographically and statistically plausible.
- The synthetic network model is built and subjected to various disturbances at various parts of the system to verify the stability of this synthetic model.
- The results of simulations presented in this project provide empirical evidence validating the assertion that the system under investigation exhibits dynamic stability based on code requirements.
- Employing the CURENT LTB packages significantly simplifies power system prototyping and simulation on a large scale, guaranteeing that the synthetic networks accurately implement according to the geographic constraints of real systems.

- The 224-bus synthetic Saudi electric grid model represents geographic coordinates, load and generation profiles, and the results accurately replicate the geographic constraints as similar real systems.
- In future projects, there is potential to extend this model to create test cases for various domains within power systems research and for educational purposes.

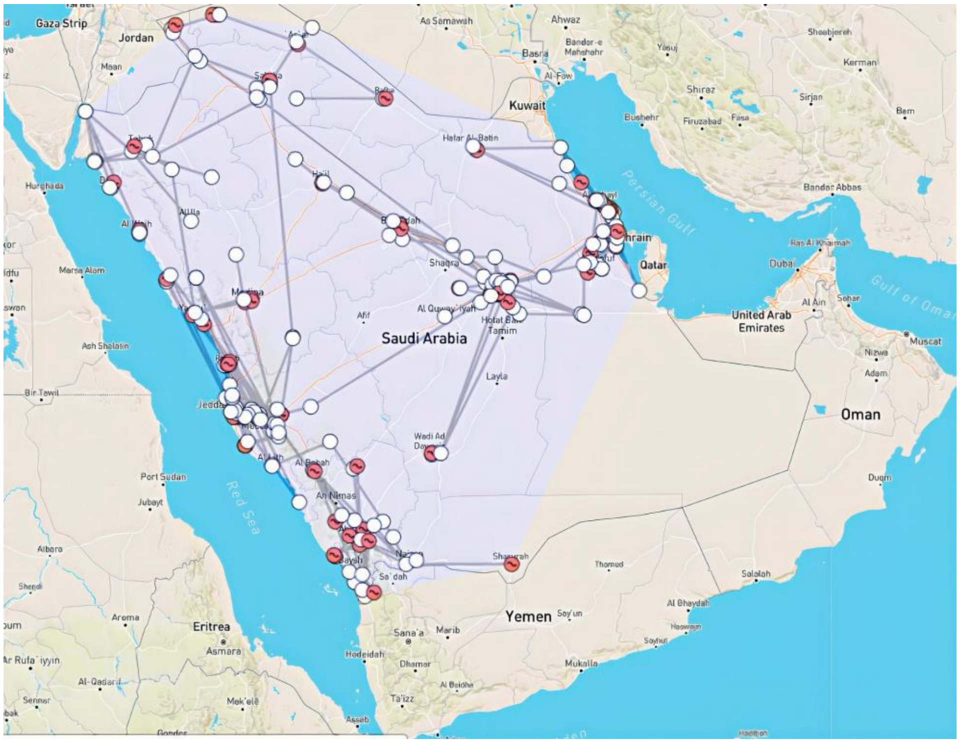


Figure 1. Visualization of the synthetic Saudi power system grid by CURENT LTB

Parameter	**Value**
Voltage limits (pu)	0.953 to 1.045
Total active power generation (MW)	64,637.7
Total reactive power generation (Mvar)	19,087.8
Total active power load (MW)	64,033.3
Total reactive power load (Mvar)	14,569.1

Table 1. The comprehensive power flow result

Area	CENTRAL300	EASTERN 200	WESTERN 100	NORTHERN 500	SOUTHERN 400

Generation (MW)	17,761.6	22,027.2	17,805.0	3,430.4	3,613.5
Generation (Mvar)	5,936.7	6,343.7	4,812.2	947.7	1,047.6
Load (MW)	18,471.8	20,673.8	17,531.7	3,323.7	4,032.3
Load (Mvar)	4,399.6	4,769.8	3,822.4	767.4	809.9

Table 2. comprehensive overview of the operating regions power flow

53. Development of Load Flexibility Valuation Methodology & Framework to Input into System Planning Tools

Project Lead: Fran Li (UTK) **Graduate Students and Research faculty/associates:** Jingzi Liu (UTK), Chenchen Li (UTK)
Project Duration: 10/2023 – 9/2024
Funding Source: Southern Company

Summary

This project aims to develop a methodology and framework for assessing load flexibility by converting energy load shapes and data related to energy usage into a format suitable for input into reserve margin and production cost modeling tools (or grid planning tools such as SERVM, Plexos/Aurora, or similar tools). The objective is to accurately predict how flexible loads can be utilized in the future. Additionally, the final deliverable should include a detailed example of integrating specific household appliances (such as HVAC, water heating, refrigeration, etc.) into the tool, along with a generalized framework applicable to various device types.

In this context, a project framework comprising three specific steps to figure out how users' load consumption behaviors will change under varying financial incentives. Briefly, these steps involve data processing, load flexibility analysis, and visualization. Our focus is the aggregation of total household load consumption data within the SOCO service region and the implementation of financial incentive strategies to observe changes in load consumption reduction among households. As such, it allows us not only to forecast future changes in load flexibility but also to provide guidance for the utility to adjust supply curves. Specifically, our initial step is to generate the load profile of household energy usage data. Subsequently, we analyze the functional relationship between financial incentives and the potential for load reduction among users. This culminates in establishing a functional relationship between household load consumption and financial incentives with a three-dimensional visualization of a curve incorporating load, time, and financial incentives.

The initial phase of the project concluded by the end of March 2024. We generated a Python conversion script to extract discrete load data for each load component from data files, calculated net load based on a household's net load formula, and ultimately construct the load profile of the total load for households in the region. In addition, due to the presence of outlier data in the data files, we devised a data-cleaning script to clean the outliers collected by the monitors. The project is expected to be completed within 12 months. Subsequent tasks within the project framework is to determine the appropriate functional relationship between financial incentives and the reducible load among users for reference, and to visualize the relationship between household load consumption and financial incentives.

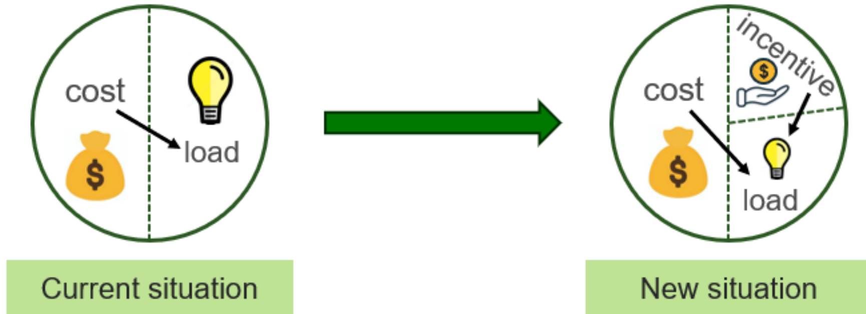


Figure 1: Background of the proposed project framework

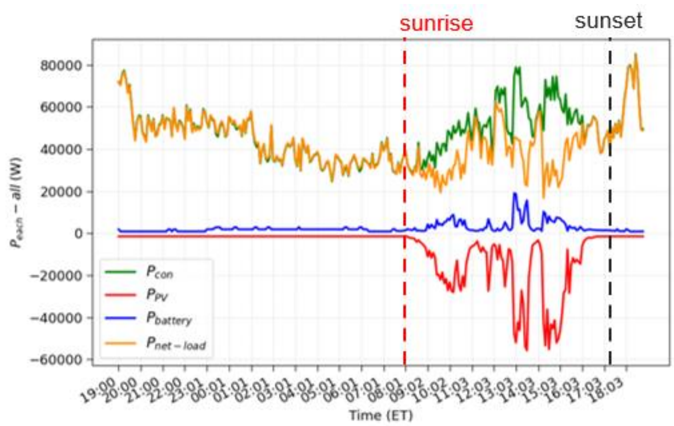


Figure 2: Load profile of all load types for the households in the region in 01/01/2022

54. Resilient State Estimation Formulation

Project Lead: Ali Abur (NEU) **Graduate Students and Research Faculty/Associates:** Tuna Yildiz (NEU)
Project Duration: 8/2022 – 08/2023
Funding Source: EPRI

Summary

This project's focus is on state estimation function in order to make it resilient against cases that prevent state estimation to converge to a solution. Such cases are difficult to investigate since measurement residuals will not be available to apply detection and identification tests to find the source of the problem. This research avoids such situations by carrying out the state estimation solution separately for multiple zones of the large scale system and then gradually creating smaller size zones until one or more divergent zones are found. This way, the operator will have visibility for the largest possible part of the overall system and also will be informed about the location of the problem causing divergence.

KEY FINDINGS

- It is demonstrated that the developed Resilient State Estimator, ensures unbiased system states by isolating the affected area in scenarios involving measurement losses around zone boundaries or communication link outages.
- Conventional State Estimators often yield a biased solution in case of lost communication links and/or partial loss of measurements, thereby influencing the decisions made by system operators, whereas the developed Resilient State Estimator manages to avoid biased estimates by isolating and removing the areas impacted by the lost measurements.
- The developed Recursive State Estimator detects divergent zones and minimizes the size of the affected subsystem by using recursive partitioning to provide unbiased estimates of the largest possible subset of states for the entire system, thus facilitating maximum visibility of the system for the system operators.
- A Graphical User Interface (GUI) is also developed for each proposed method, allowing the users to construct their own cases and test different scenarios. It provides an opportunity to comparatively observe the performance of both proposed methods versus the Conventional State Estimator.
- The software does not require any user intervention or tuning. It reads the measurement and network data and produces the results including the location of the affected buses, and the unbiased state estimate for the remaining part of the system.
- Utilities that rely on measurements received over communication links from neighboring systems in executing their state estimators will benefit from these two software tools when they lose communication links for extended periods.

- Avoiding divergence of the state estimator for the wide-area system will add significantly to the system reliability since a large part of the system will be guaranteed to be observable even for cases when conventional state estimators declare the system unobservable without any state estimates for any of the system buses.

55. A Comprehensive Approach to Monitoring Active Distribution Systems

Project Lead: Ali Abur (NEU) **Graduate Students and Research Faculty/Associates:** Etki Acilan (NEU)
Project Duration: 8/2022 – 08/2025
Funding Source: NSF

Summary

This project is concerned about the challenges in monitoring active distribution systems. Historically, analysis of distribution systems has been treated in isolation since they were mainly passive networks serving customer loads. The situation has drastically changed in the recent years with the penetration of renewable energy sources into the distribution networks, implementation of active/smart management of flexible loads, introduction of electric vehicle charging stations and energy storage facilities and bi-directional power flows between distribution and transmission systems. Moreover, there is potential benefits in incorporating distributed energy sources in the bulk power generation dispatch in order to improve optimal operation of overall power grids. This can only be possible if the state, topology and model parameters of distribution systems and associated generation can be reliably and efficiently monitored.

While there is a rich and sophisticated set of tools and methods developed for transmission systems, regretfully, extension of these methods to the full coupled three-phase network models presents several challenges and may require novel problem formulations and solutions. Specifically, the project aims to address the following issues: (a) Three or mixed phase distribution system state estimation formulation where the network may not necessarily remain strictly radial. Investigation of added complexity of computations and coding, use of a hybrid set of SCADA and PMU measurements and robustness against errors; (b) Detection and identification of three phase line model parameter errors by exploiting modal decomposition and extending the Lagrangian formulation developed for positive sequence networks. Dynamically tracking changes in line model and decoding them to detect and locate different types of faults and disturbances; (c) Remote (soft) calibration of three phase synchronized phasor measurements by integrating the calibration models in three phase state estimation formulation; (d) Localizing and isolating topology errors in three-phase networks by recursive multi-area estimation.

56. Graph-Learning-Assisted State and Event Tracking for Solar-Penetrated Power Grids with Heterogeneous Data Sources A Converter-based Supercapacitor System Emulator for PV Applications

Project Lead: Ali Abur (Northeastern University) **Graduate Students and Research Faculty/Associates:** Tuna Yildiz (NEU), Ugur Can Yilmaz (NEU), Prof. Lin (NYU), Prof. Liu (Brandeis University)
Project Duration: 6/2021 – 12/2024
Funding Source: Department of Energy, SETO Program

Summary

The main objective of this project is to make the distribution systems fully observable, such that the hosting capacity for solar generation can be accurately estimated, and unnecessary solar curtailments can be avoided. The expected outcome of the project is a prototype software with two main parts: 1) a grid-model-informed machine learning (ML) tool which integrates heterogeneous data streams and creates synchronous measurement snapshots for the state estimator (SE); and a hybrid robust SE which provides not only accurate state estimates but also real-time feedback for ML model refinement. The project will also develop an event/topology tracker that detects and locates switching events and faults, providing up-to-date grid models to the ML and SE algorithms.

57. Towards Enhanced Grid Robustness: Augmenting Grid-Regulating Capabilities Through Discrete Controls on Emerging Power Technologies

Project Lead: Hector Pulgar **Graduate Students and Research Faculty/Associates:**
Project Duration: 3/ 2021 – 2/ 2026
Funding Source: NSF

Summary

This NSF CAREER project aims to improve power system performance and its ability to uptake increased penetration of renewable energy. This project will bring transformative change by enhancing grid robustness through activating a large number of control actuators that would otherwise offer very limited control capabilities. This will be achieved by designing innovative discrete control mechanisms in emerging technologies such as energy storage systems, solar power generation, and wind turbines. The intellectual merits of the project include advancing knowledge in the field of system dynamics, and a holistic approach that can handle the constraints and characteristics of very large-scale systems such as the electric power grid. As broader impacts, this project will provide insights into related problems from other fields where discrete control is applicable. In addition, this project will benefit society with a more reliable power grid with fewer blackouts, and facilitate environmentally friendly power production leading to fewer public health problems caused by local pollution from fossil fuel power plants.

The project will develop a framework that extends knowledge of continuous and discrete power grid controls. Actuation design on emerging power technologies to achieve a fast response, and tests on both hardware and simulation-based testbeds are considered. Discrete logics have been explored before for power grid control, but using several simplifying assumptions such as single inter-area oscillation mode, system aggregation on both of the oscillation ends, and a unique controllable component located right on the oscillation path. This project will reexamine this problem from a new perspective and will develop a new theory that connects power system oscillatory behavior with momentary shifting of equilibrium points when discrete power changes are enforced at controllable components. Topics of study will include large-scale dynamic systems, multiple oscillation modes, multiple controllable components, and adaptation to disturbances, all geared towards enhancing power system stability for increased penetration of renewable energy. An integrated educational plan will leverage the research through specific projects for undergraduate and pre-college students and through mentoring programs for Hispanic Americans to support their pursuit for professional or academic careers.

This award reflects NSF's statutory mission and has been deemed worthy of support through evaluation using the Foundation's intellectual merit and broader impacts review criteria.

58. Adaptive dynamic coordination of damping controllers through deep reinforcement and transfer learning

Project Lead: Hector Pulgar, Fangxing Li **Graduate Students and Research Faculty/Associates:**
Project Duration: 9/ 2020 – 8/ 2023
Funding Source: NSF

Summary

In the last decades, global environmental pollution, concerns with fossil fuel reserves, and advances in technology have led to actions that are transforming the power grid. Over the years, several states have adopted renewable portfolio standards and goals to increase electricity production from renewable sources such as solar and wind power. This has resulted in new grid behaviors in response to disturbances in the system. This phenomenon has created concerns about an increased risk of sustained oscillations that can cause poor electric service quality and can even lead to blackouts. A search for new effective control systems has created a new breed of controllers. Specifically, the design of new controllers has been studied for wind turbines, energy storage systems, and other emergent components. However, with this massive presence of non-standard controllers and the existing controllers in conventional power plants, there is an urgent need for coordination that would enhance the combined effect of all the controllers to avoid conflicting interactions among them. Presently, there is no coordination of this magnitude in either actual systems or theoretical studies. The problem is challenging and it requires adaptability as the grid is permanently changing during its operation. This project will add intelligence to the grid, and through a real-time adaptable coordination, it will diminish possibilities of blackouts by mitigating the unwanted oscillations in the system. The proposed adaptive controller coordination has tremendous potential to enable the current and forthcoming power grid with superior dynamic performance and stability. This research will help increase awareness of the importance of the power grid for our nation including the benefits and challenges of renewable energy. Pre-college students and teachers will be exposed to engineering principles and practical applications through participation in outreach programs.

This project will transform the conventional notion of controller coordination to make it suitable for real-time control as well as adaptive to disturbances and operating conditions. This project will seek controller coordinating signals that will minimize the system oscillation energy. The physical concept of oscillation energy not only allows avoiding the use of arbitrary objective functions, but also serves as a mechanism to weight the importance of the different oscillation modes without having to target in advance the most critical ones. As preliminary work, the PIs have derived an analytical procedure for on/off controller coordination using the time integral of the oscillation energy and its sensitivity with respect to the controller gains. As this procedure is based on the linearization of the state-space model, matrices, eigenvalues, and sensitivities must be either calculated promptly after a disturbance or collected previously off-line for the most representative operating points and disturbances. To overcome this drawback, and to make the coordination feasible and practical, a deep reinforcement learning (DRL) framework is proposed that would make the coordination not only adaptive but also more effective. In this regard, this DRL framework will allow exploring both discrete and continuous coordinating signals. While a discrete signal can be seen as a controller's on/off mechanism, a continuous signal can be understood as a quantity that can scale up/down the controller gains within a specified range. Furthermore, as the system can be subjected to extreme disturbances, this project

proposes the use of transfer learning so the DRL training can be transferred even if there are topological changes or severe operational changes such as generator outages or load rejections.

This award reflects NSF's statutory mission and has been deemed worthy of support through evaluation using the Foundation's intellectual merit and broader impacts review criteria.