CURENT Overview

Kevin Tomsovic

Center Director

2021 Strategic Planning Meeting

March 31, 2021

Virtual

Agenda

1:00 - 1:15	**Welcome & State of the Center – K. Tomsovic**
1:15 – 1:45	Industry projects overview and roll call of pressing needs – Y. Liu
1:45 – 2:00	Sustainability of the Center - K. Tomsovic
2:00 – 2:15	Industry membership - Discussion on post-graduation structure
2:15 – 2:30	Break

2:30 – 3:45	Input from industry on future research directions
	• Demonstrating center contributions with LTB/HTB demos – F. Wang and F. Li
	• Grid forming converters – L. Tolbert
	• Blurring of transmission and distribution – F. Li
	• Electrification of transportation – K. Bai
	• Resilience – A. Stankovic
	    ○ Microgrids
	    ○ Market incentives
	• Protection and control with inverter based resources – J. Chow
	• Other ideas – storage, hydrogen, small modular reactors, HVDC, off-shore wind, cyber-physical security, etc.

3:45 – 4:00	Wrap-up discussion

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Meeting Objectives

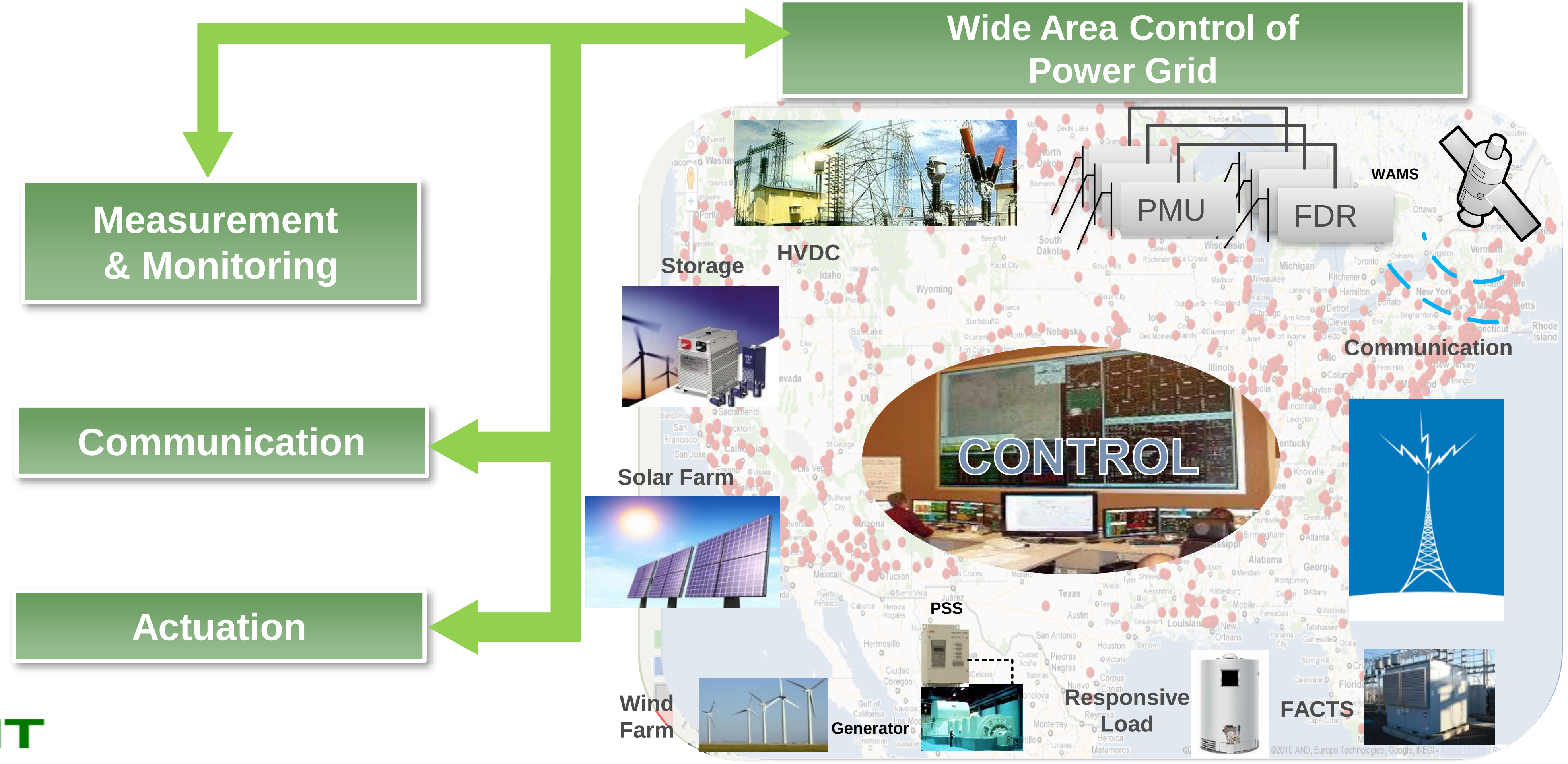
- Update on the status of the Center
- Discuss sustainability of the Center
- Review research contributions with industry
- Strategic planning for the Center for near and long term

CURENT – An NSF/DOE ERC

- Selected by National Science Foundation (NSF) and Department of Energy (DOE) from a few hundred proposals across all engineering disciplines.
- Base budget: ~$4M/year for 10 years, ramping down in Years 9 and 10. Other funding: $5-6M/year
- First and only ERC devoted to power grid (transmission).
- Four universities in the US (UTK, RPI, NE, TU)
- Industry partnership program (35 members as of March 2021)
- Center began Aug. 15th 2011. Funding reviewed every year but we have received full funding.
- CURENT students since inception: ~134 Ph.D, 96 MS, 131 BS

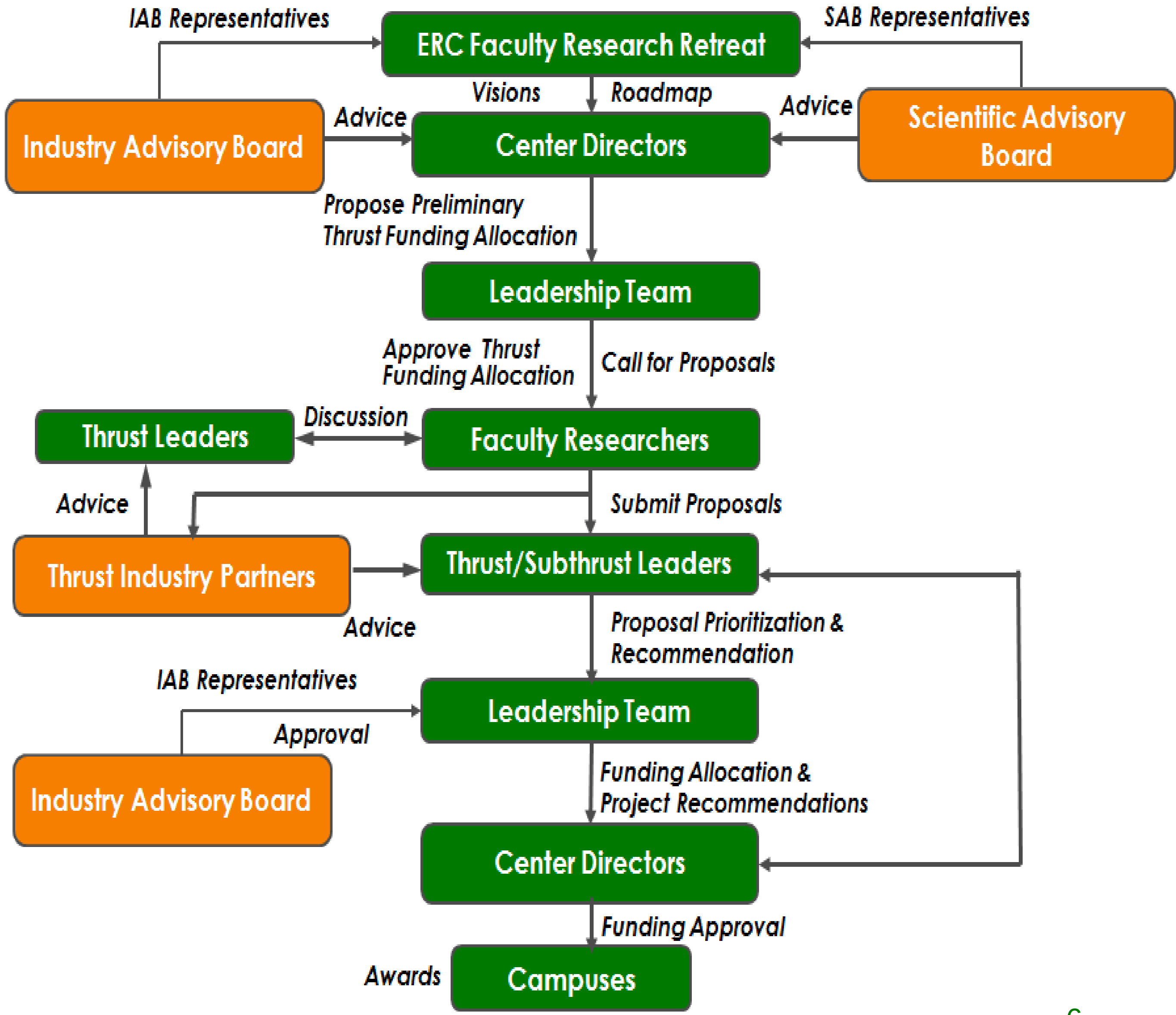
Original CURENT Vision

- A nation-wide transmission grid that is fully monitored and dynamically controlled for high efficiency, high reliability, low cost, better accommodation of renewable sources, full utilization of storage, and responsive load.
- A new generation of electric power and energy systems engineering leaders with a global perspective coming from diverse backgrounds.



Project Planning Process
Needs to be modified going forward

- Annual research retreat held in Spring
- Meeting in July following the IEEE PES General Meeting to finalize projects for next year
- Virtual since March 2020



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Research Roadmap
Needs to be Extended

Year 1~3	Year 4~6	Year 7~10
Generation I	**Generation II**	**Generation III**
Regional grids with >20% renewable (wind, solar), and grid architecture to include HVDC lines	Reduced interconnected EI, WECC and ERCOT system, with >50% renewable (wind, solar) and balance of other clean energy sources (hydro, gas, nuclear)	Fully integrated North American system with >50% energy (>80% instantaneous) inverter based variable sources (wind, solar) and balance of conventional (hydro, gas, nuclear)
System scenarios demonstrating a variety of seasonal and daily operating conditions	Grid architecture to include UHV DC lines connecting with regional multi-terminal DC grids, and increased power flow controllers	Grid architecture to include UHV DC super-grid, interconnecting overlay AC grid and FACTS devices
Sufficient monitoring to provide measurements for full network observability and robustness against contingencies, bad topology or measurement data	System scenarios demonstrating complete seasonal and daily operating conditions and associated contingencies, including weather related events on wind and solar	Controllable loads (converter based, EV, responsive) and storage for grid support
Closed-loop non-local frequency and voltage control using PMU measurements	Full PMU monitoring at transmission level with some monitoring of loads	Fully monitored at transmission level (PMUs, temperature, etc.) and extensive monitoring of distribution system
Renewable energy sources and responsive loads to participate in frequency and voltage control	Fully integrated PMU based closed-loop frequency, voltage and oscillation damping control systems, and adaptive RAS schemes, including renewables, energy storage, and load as resources	Closed loop control using wide area monitoring across all time scales and demonstrating full use of transmission capacity and rights-of-way
		Automated system restoration from outages

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Industry and Innovation Plan Beyond Year 10

Technology Transfer

Establish high-value testing and maintenance services; proof of concept demonstrations, continue annual conference and communications; and complete demonstration/commercialization of prototype software

Research and Development

Continue to build on core competencies in power systems and power electronics, maintain long-term partnerships with organizations of various sizes to expand as needed with technology developments

Innovation

Be a leader in technology trends, publish high visibility white papers, leverage licenses and patents for long term funding

Sustainability of the Center

Kevin Tomsovic

Center Director

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Sustainability Plan
Changing Research Portfolio

- **Research portfolio**
  - Responsive to industry members and other funding sources
  - Maintain identity and build on research strengths
- **Process**
  - Expertise in power systems and power electronics.
  - Center-wide project on developing future research thrusts begun in Year 7
    - Continent-wide system with HVDC overlay
    - Fully inverter based microgrids
    - Distribution system modeling as it impacts transmission system operations
    - Increased emphasis on cybersecurity and other resilience issues

    ➔ Create foundation for projects beginning in Year 9 and 10 that extend beyond year 10
  - Balance new research directions without losing focus
    - Operation of fully inverter based systems, such as, aircraft power
    - Power system interfaces to other infrastructures – e.g., buildings, transportation

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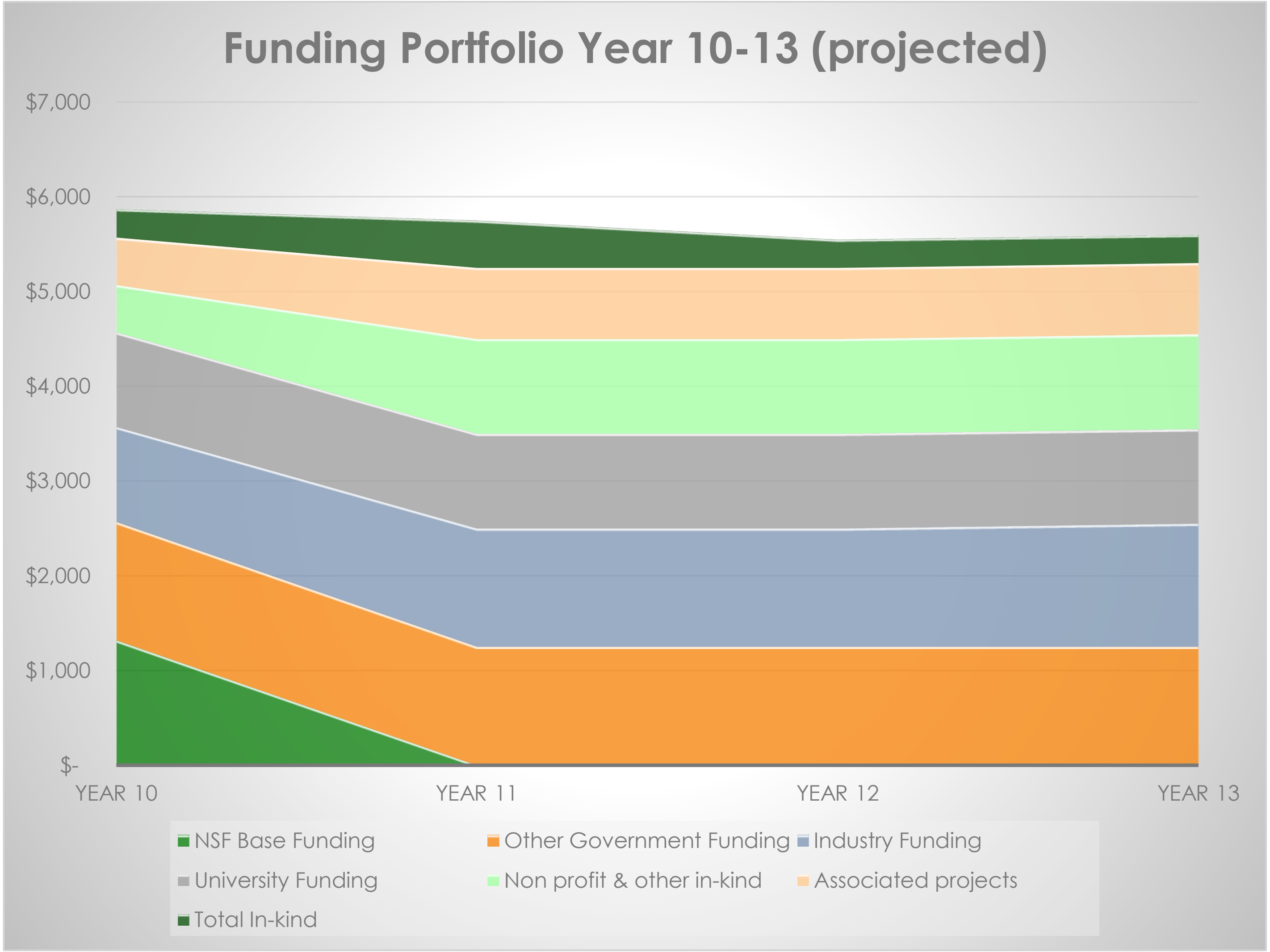
Post-Graduation Business Plan



Funding Portfolio Including Years 10-13 Projection

- Resources
  - $1M State/University
  - $1M Industry (memberships, service fees, licensing)
  - $3.25M Government grants and other associated projects
  - $500K F&A return and other university in-kind support; other foundations

CURENT System Demo Plan

Fred Wang, Fran Li

2021 Strategic Planning Meeting
March 31, 2021
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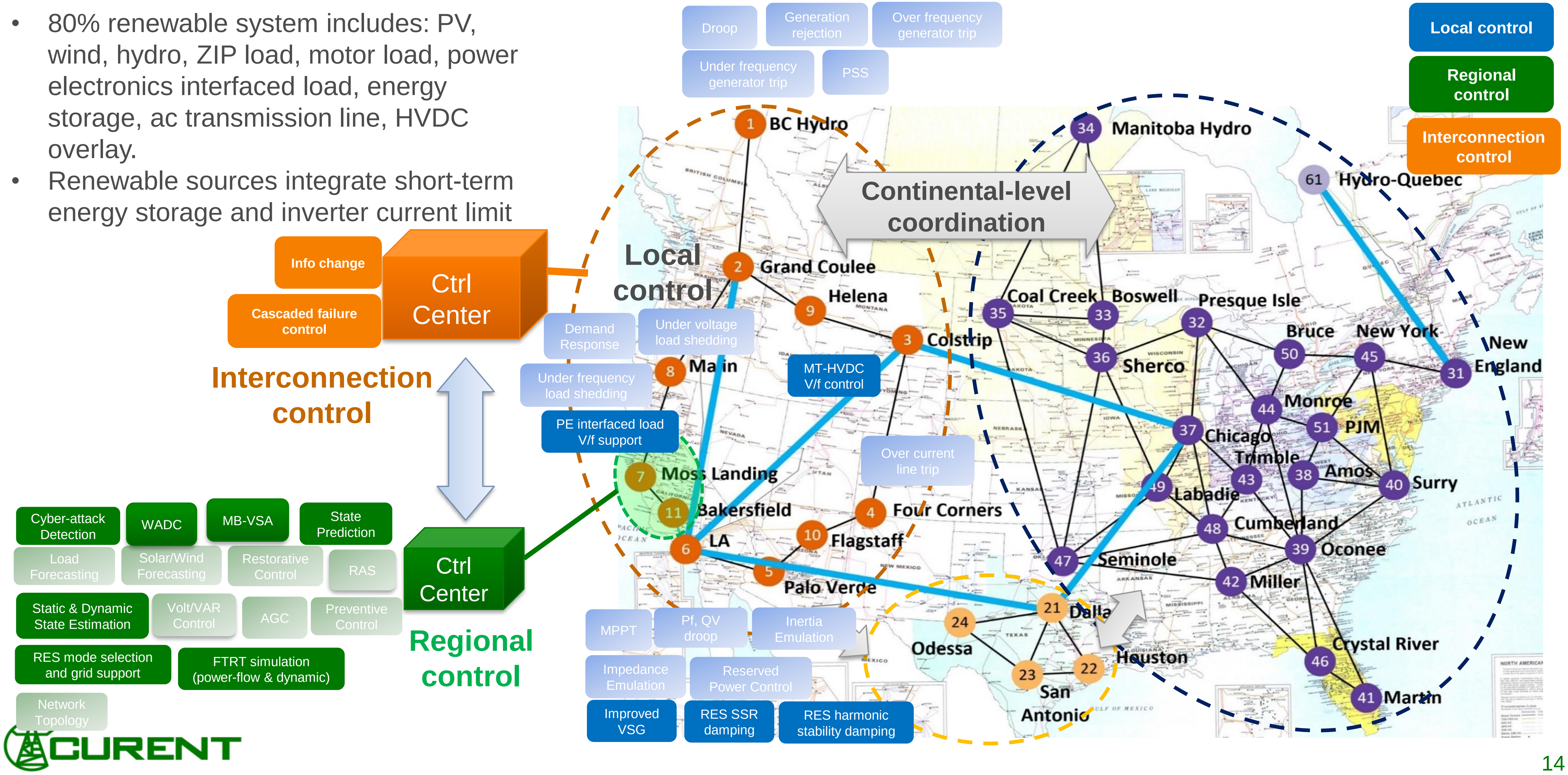
CURENT System Demo

- **Objectives:** Summarize and demonstrate CURENT accomplishments, i.e., wide-area monitoring and control of continental-scale power transmission grid with high-penetration of power electronics interfaced renewable energy sources and loads.
- **Approaches**: Implement key CURENT developed technologies in monitoring, modeling, control, and actuation in LTB and/or HTB in a coordinated and integrated way. Devise appropriate scenarios to demonstrate the effectiveness of the technologies for future grid. The scenarios will include: power flow control, v/f control, stability (small-signal, transient, resonance, harmonics), black start, cyber security. Different contingencies will be considered per NERC and other standards.

Example CURENT Technologies	Implementation	System Functions/Scenarios
Virtual synchronous generator w/ energy storage & current limit	Local	V/f control, stability
Measurement based wide-area damping control & voltage support	Local, regional	Stability, voltage support
Static & dynamic state estimation	Regional	All
Multi-terminal HVDC actuation architecture	Local, regional, interconnection	Power flow control, v/f control, stability

HTB Demo Plan

- 80% renewable system includes: PV, wind, hydro, ZIP load, motor load, power electronics interfaced load, energy storage, ac transmission line, HVDC overlay.
- Renewable sources integrate short-term energy storage and inverter current limit



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LTB Demo Plan: Closed-Loop Cyber-Physical Interaction Demonstration

Demo Plan 1: Upgrade all LTB components for the new ANDES and DiME2

- Upgrade LTBPMU, LTBPDC, and LTB.
- Package the software for distribution (using Docker, for example)
- Write documentation and create test cases for power and communication co-simulation
- Prepare for software release

Demo Plan 2: Wide-Area Damping Controller study considering network latency

- Develop a wide-area damping controller that is robust for network latency
- Prototype the controller with the physical-system simulator
- Convert the controller into a module for LTB demonstration

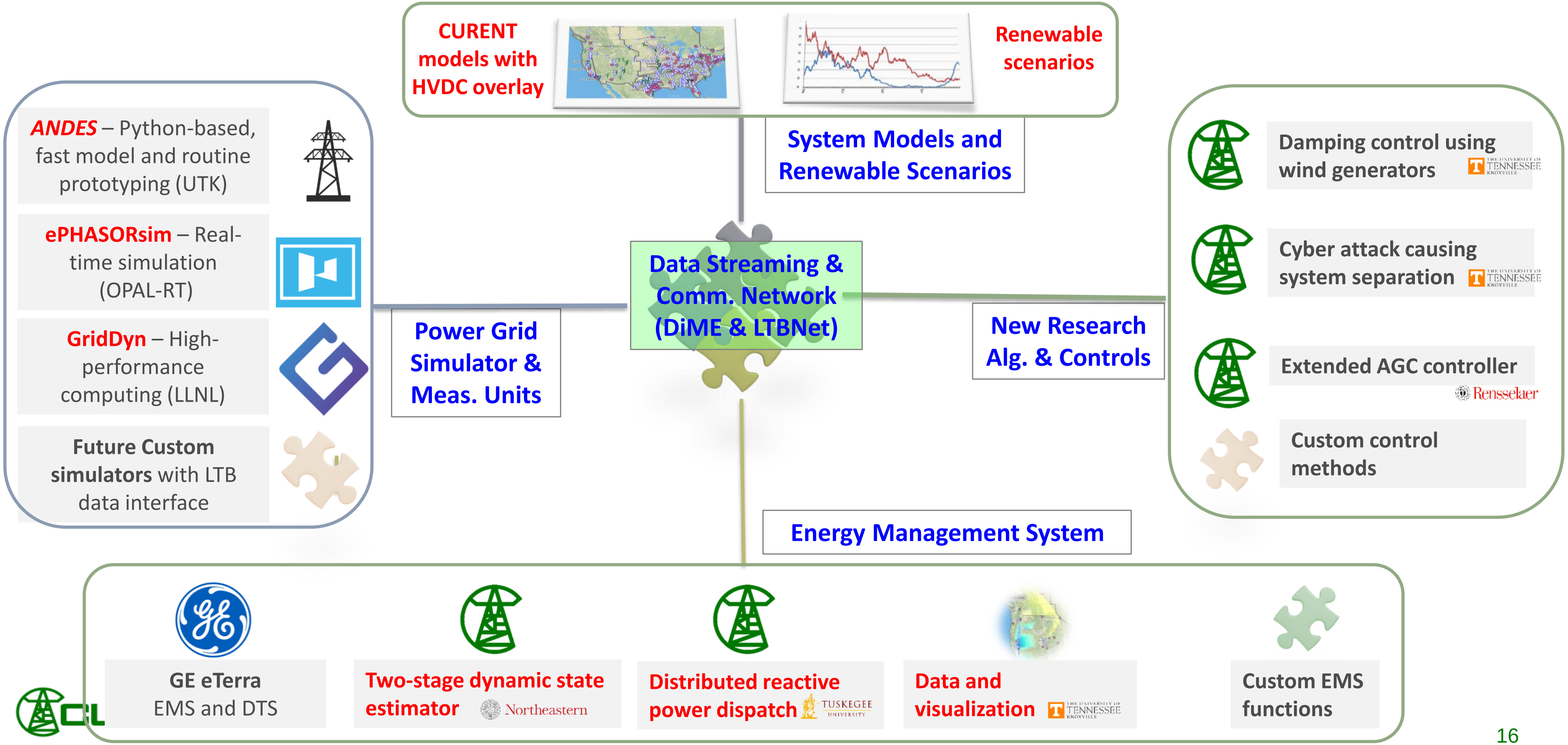
Demo Plan 3: Market Prices Distortion and Manipulation by FDIA

- Establishing the LTB market module
- Establishing the data streaming interface with the LTB visualization
- Performing the FDIA and corresponding defense on the market module and demonstrating it on the visualization module

Demo 4: Synthesize demonstration scenarios

- Benchmark with NERC standard
- Integrate the damping controller into LTB
- Integrate a state estimator for the damping controller
- Improve the visualization based on demonstration needs

LTB Architecture Overview



Grid Forming Converters

Leon Tolbert

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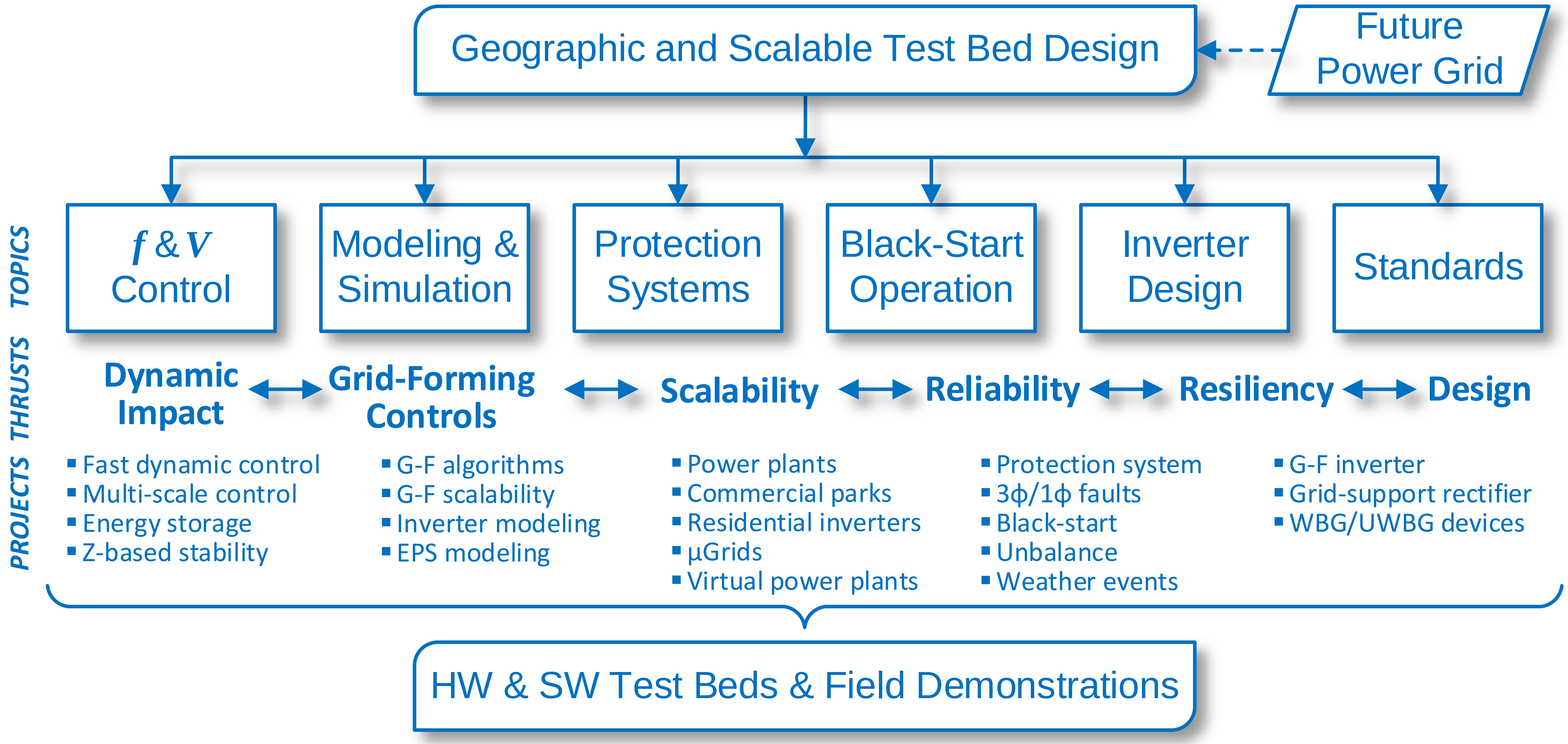
Grid Forming Converters



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Future Research on Grid Forming Converters

Voltage Control

- Coordinate voltage regulation schemes between inverters and with other devices
- Characterize input and output impedance of inverters to capture dynamic behavior
- Reactive power control and its impact on voltage stability
- Transmission vs. distribution-level voltage regulation

Frequency Control

- Reserve requirements for fast frequency control
- Requirement of virtual inertia
- Timescale partition of controls

Modeling/Simulation

- Model validation and fidelity
- Represent large number of connected inverters without additional computation burden
- Electromagnetic transient simulation platforms for inverter-dominated systems
- Consider dynamics of primary energy sources
- Industry data/public network models
- Modeling interactions between inverters and with other grid elements

Protection

- Short-circuit response of inverters and its impact on control schemes
- Ability to produce negative and zero sequence currents
- Analytical/simulati on models to conduct fault studies
- Communication-aided protection
- Inverter ability to detect faults

Standards

- Passive/active regulation bands
- Fault ride-through codes
- Power quality requirements
- Monitoring and information exchange
- Requirements for the interconnection of distributed energy resources (DER) with electric power systems (EPSs)
- Test procedures for verifying conformance
- Inverter limit requirements
- Inverter protection standard

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Blurring of Transmission and Distribution

Fran Li

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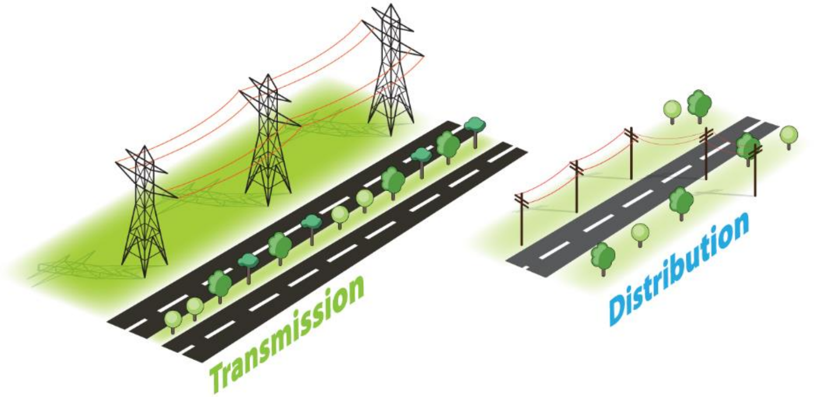
Blurring of Transmission and Distribution

- **Objectives:** Adapt to partially dispatchable generations, accommodate bi-directional energy flow, and motivate dispatchable loads in future transmission and distribution systems through advanced control, and market design
- **Approach**: Aggregate and control distributed generation and load resources



Today's Transmission and Distribution (Image Credit: PJM)

- **Research Agenda:** Potential topics
  - Provide ancillary services (e.g., frequency regulation, congestion management) from behind-the-meter (BTM) distributed energy resources (DER).
  - Provide flexibility and improve grid resilience through the coordination of DERs (both generation and load); aggregate DERs to participate in electricity markets.
  - Community-based energy hubs that are reliable, sustainable and economical against climate changes and natural disasters.
  - Stability enhancement of bulk systems through the coordination of renewable energy systems equipped with controllable battery systems.
  - Co-simulation of transmission and distribution systems; co-simulation of stability programs and market programs.

Electrification of Transportation

Kevin Bai

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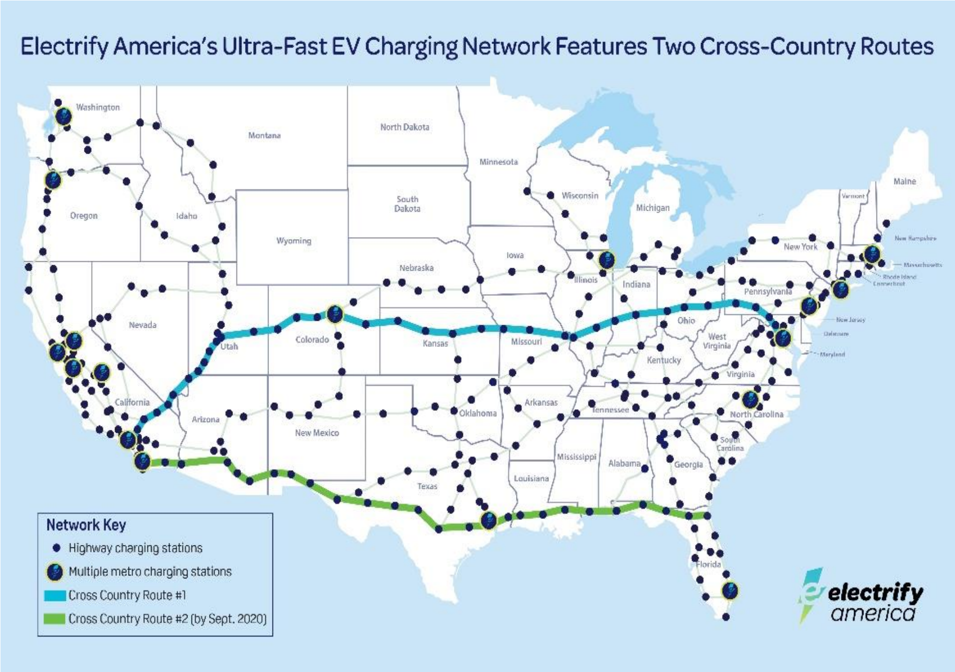
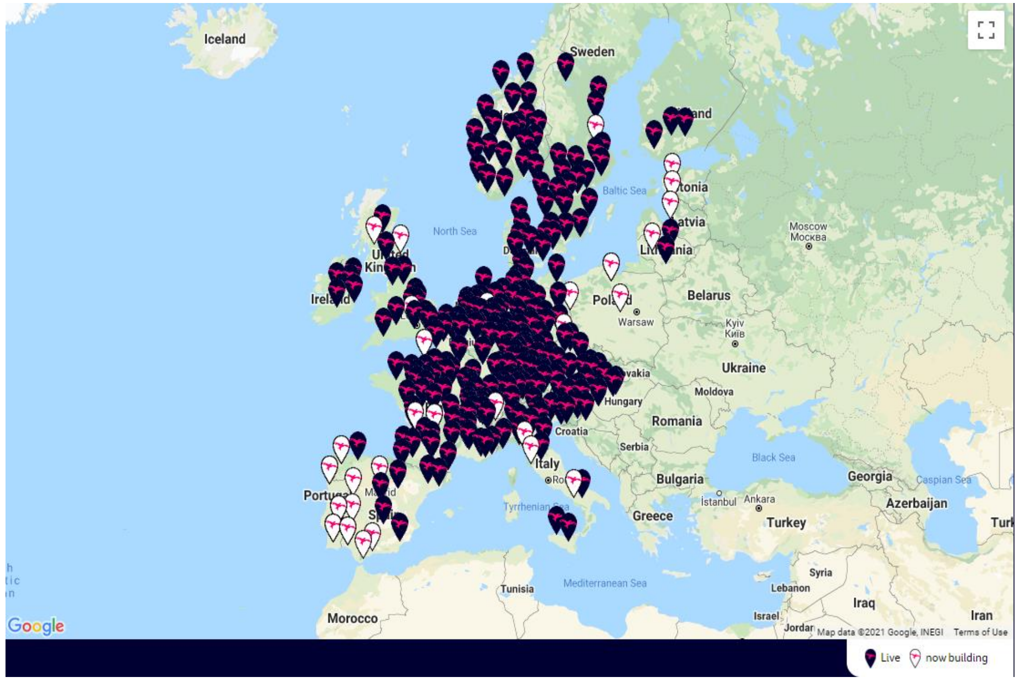
EV Fast Charging Stations





Electrify America: a subsidiary of VW Group of America, established in 2016. It opened California's first 350 kW charge location in 2018, which is available in front of >120 Walmart stores. Electrify America offers stations so widely available that 96 % of Americans live within 120 miles of a charger. It will deploy over 3,500 chargers at 800 charging stations by December 2021.

IONITY: a high-power charging station network for EVs to facilitate long-distance travel across Europe, and a joint venture founded by BMW, Ford, Mercedes Benz, and Volkswagen Group with Audi and Porsche. In 2020 Hyundai entered IONITY as the 5th shareholder. It is privately funded but has been awarded €39.1 million in EU public funds (20% for building out the network).

Specs

350 kW initiative in Europe IONITY

General spec		Current ripple spec		Voltage ripple spec	
Output voltage	200 – 920 V	**Frequency**	**Current ripple limit ***	**Voltage ripple**	±5 % or ±5 V
Output current	Up to 500A	< 10 Hz	1.5 A	**Normal voltage slew rate**	< ±20 V/ms
Current slew rate		< 5 kHz	6 A		
Normal Current ramp up rate	> 20 A/s	< 150 kHz	9 A		
Emergency shutdown current rate	>200 A/s	* Difference between positive peak top and negative peak top at full scale output			According to IEC 61851-23

Electrify America charging stations have 60Hz, 1.5MW, 13.2kV – 480Vac bulky transformer, supplying four 150 - 350kW DC outputs and one 50 kW DC output. Eliminating such bulky 60Hz MW transformers opens doors to HV SiC devices and new topologies.

Summary

- EV Fast Charging Stations provide excellent opportunities for HV SiC devices;
- EV drive inverters need the innovations not only on the semiconductors, but also from passive components (caps, filters, etc), microcontrollers and novel control algorithms;
- Study of the impact of EV fast chargers on the grid (dynamic response, disturbance, cyber securities, etc) is still lagging behind;
- Integration of the inverter, charger or DCDC is a popular trend;
- Other transportation electric power systems (e.g. electrified ships, aircraft, and trains) and associated power electronics, energy storage, control, and protection technologies.

CURENT Contribution to Resilience

Alex Stankovic
Kevin Tomsovic

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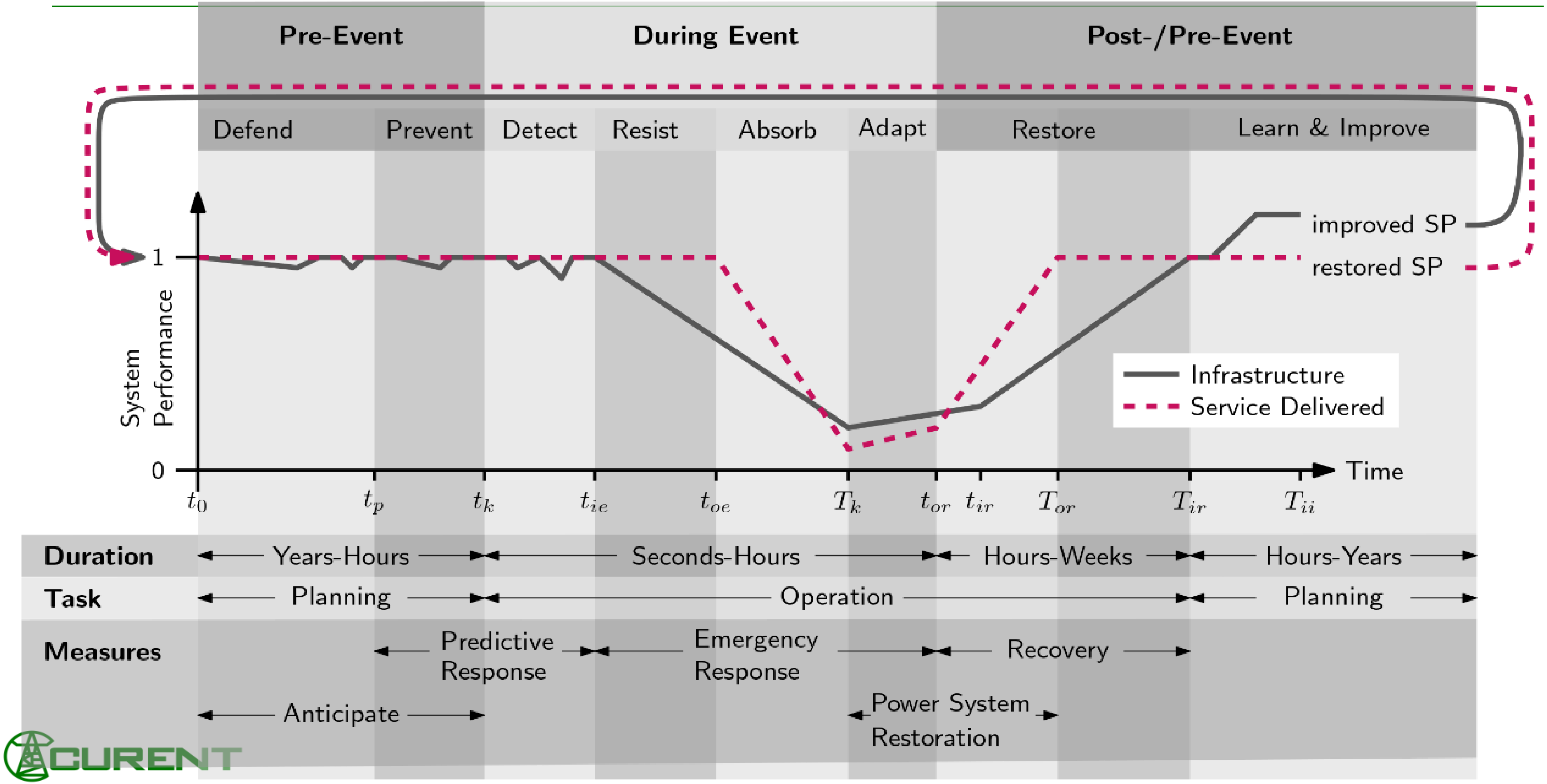
CURENT Work on Resilience

- **Objectives:** Summarize the CURENT accomplishments – power system resilience is a concept of increasing importance for modern power systems. However, there is a disagreement in the literature and in the engineering community about its precise meaning and ways to quantify it.
- **Approaches**: CURENT spearheaded the effort to form a Task Force that would critically review the existing work and attempt to synthesize a definition and quantification methods that are relevant for existing and future systems with increased presence of renewables.
- This effort is sponsored by the Power System Stability Subcommittee of the IEEE PES Power System Dynamic Performance Committee, and Computing and Analytical Methods Subcommittee of the IEEE PES Analytic Methods for Power Systems (AMPS) Committee; Alex Stankovic and Kevin Tomsovic co-chair this Task Force
- TF Report and the companion paper are expected by the end of 2021.
- Working definition: *Power system resilience is the ability to limit the spatial extent, system impact, and duration of system degradation following an extraordinary event. Key enablers for a resilient response include the capacity to anticipate, absorb, rapidly recover from, adapt to, and learn from such an event. Extraordinary events for the power system may be caused by natural threats, accidents, equipment failures, and deliberate physical or cyber-attacks*.

Temporal Aspects of Resilience



Where should CURENT focus on Resilience

- Hardening – contingency tolerance
- Faster restoration after major events
- Graceful degradation
  - Microgrids and networks of microgrids
  - Controlled islanding
- Market incentives vs. regulations
  - Who should pay?
  - What incentives for building in resilience which may be very expensive and perhaps never used?

Protection and Control with Inverter-Based Resources

Joe Chow

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Protection and Control with Inverter-Based Resources

- **Objectives:** Inverter-based resource operation in high-renewable-penetration systems requires fundamental rethinking on the protection (fast time-scale), control (slow time-scale), and dispatch (steady state) of AC power systems with fewer synchronous generators.
- **Approach**: Enabling of converters to provide advanced power system protection, stability, and dispatch functions
- **Research Agenda:** Potential topics
  - Coordinated converter protection schemes to provide backup fault clearing information
  - Stability (transient, damping, frequency) enhancement in power systems at the transmission and distribution levels, and in smart grid
  - With grid-forming converters, converter buses to control power flow with similar functions as a FACTS controller for various power system operation enhancements (ISOs/TOs can dispatch bus angels on certain converter buses, without specifying converter output power)

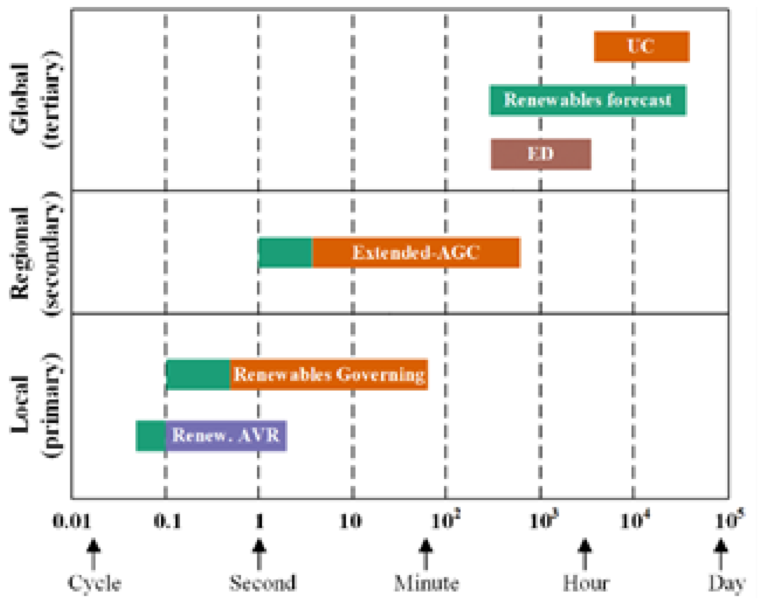

Fig. 1 Time-scale diagram of hierarchical control of a power system extended by renewable energy resources (green band).

Industry Supported Research at CURENT
An Overview

Yilu Liu

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Acknowledgements

ABB
Dominion Energy
Southern Company
conEdison
NewYorkPower Authority
CURENT
NSF
Department of Energy United States of America
Lawrence Livermore National Laboratory
TVA
EPRI ELECTRIC POWER RESEARCH INSTITUTE
KEYSIGHT TECHNOLOGIES
BOEING

This work was supported primarily by the ERC Program of the National Science Foundation and DOE under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

Other US government and industrial sponsors of CURENT research are also gratefully acknowledged.

OAK RIDGE National Laboratory
NERC NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION
pjm
MISO
epb
IPE Integrated Power Engineering, Inc Unite the Technologies
ISO new england
GEIRINA GEIRI NORTH AMERICA
NREL NATIONAL RENEWABLE ENERGY LABORATORY

Optimal PMU Placement (TVA)

Objective:

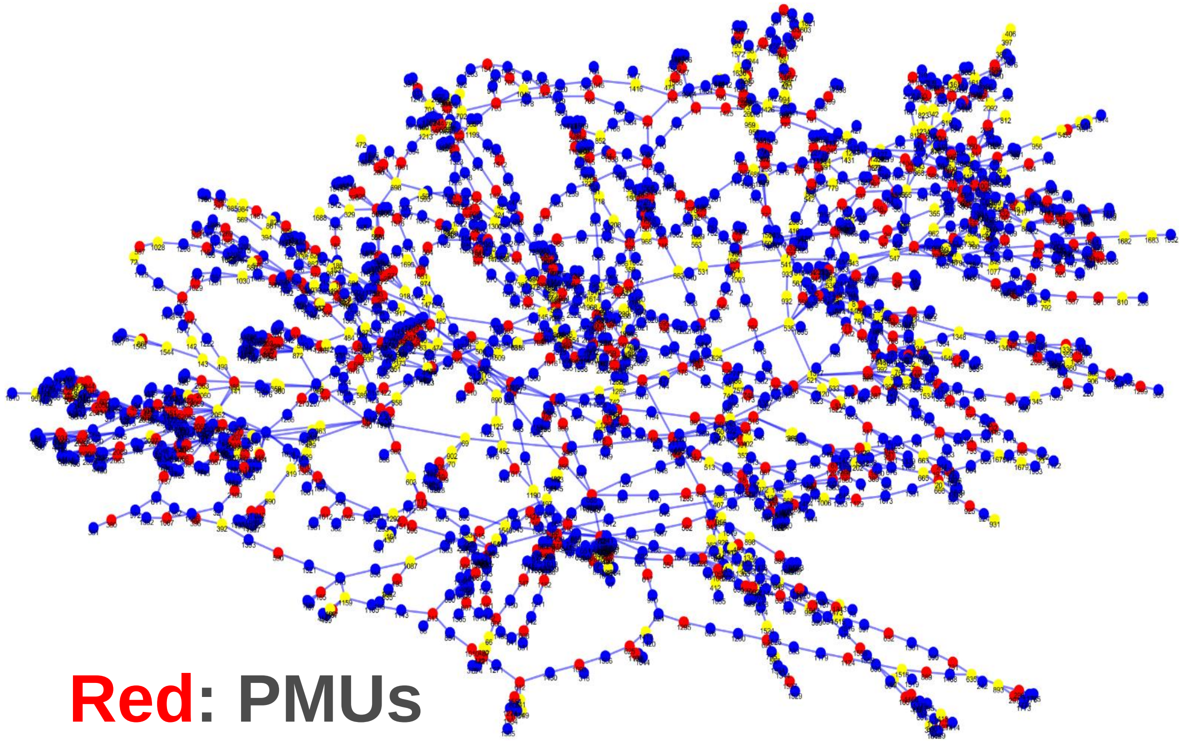
Determine optimal PMU locations to make TVA's Transmission System observable

Technical Approach & Benefits:

Mixed Integer programming; facilitating effective use of linear estimator to observe power grids.

Accomplishments:

Customized PMU placement method; allows placement for geographic area or voltage level.



Red: PMUs
Yellow: Zero Inj. Buses
Blue: Buses without a PMU

Case	Zero injections considered	New PMUs
1	No	632
2	Yes	485

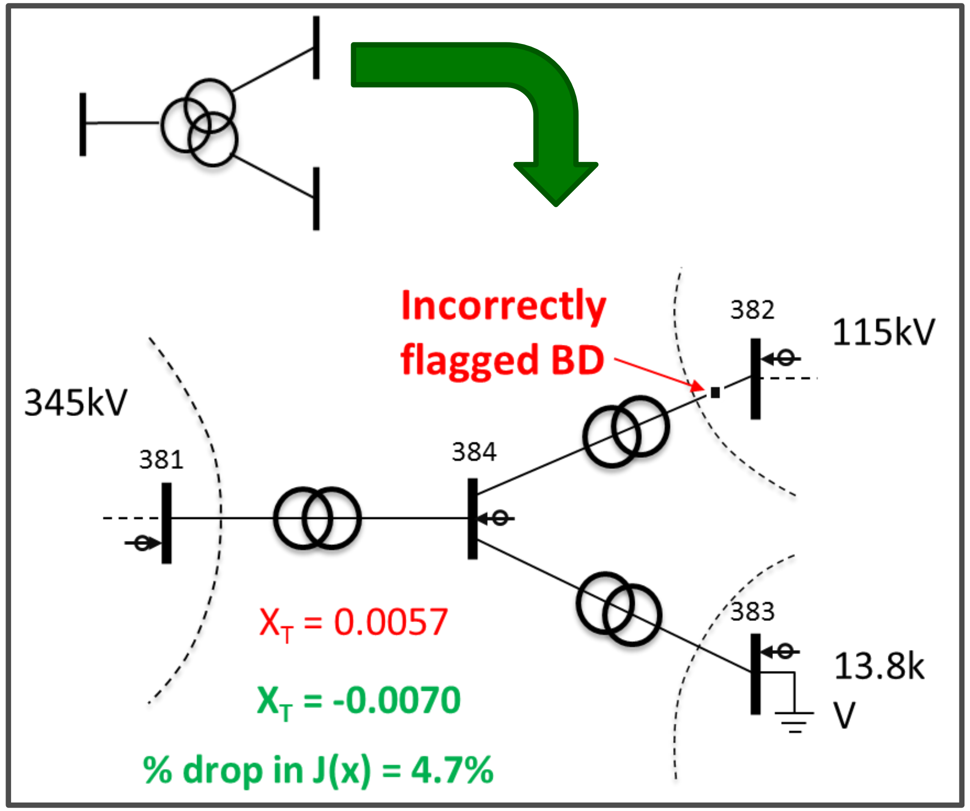
Identification and Correction of Network Parameter Errors (ISO-New England)

Outcome/Accomplishment

- Existence of network parameter errors not only biases the State Estimation solution but may also lead to misidentification and incorrect removal of good measurements as bad data. In this task a practical and effective method is developed and implemented for an actual large scale power grid, making its operation resilient to errors in network model.

Impact and Benefits

- Accurate network parameters will yield accurate results for power market applications which use these parameters hence power markets will be more efficient;
- The nation's interconnected power grid will be operated more reliably and efficiently;
- Developed theory and unified framework will allow researchers to improve various network applications which strongly rely on accurate network models.



Incorrect reactance of a 3-winding transformer detected and corrected by the developed software tool. Existing bad data processor incorrectly flagged a good measurement as the source of this error.

Non-Divergent State Estimator for Large Scale Power Grids (PJM Interconnection)

Task Goals:

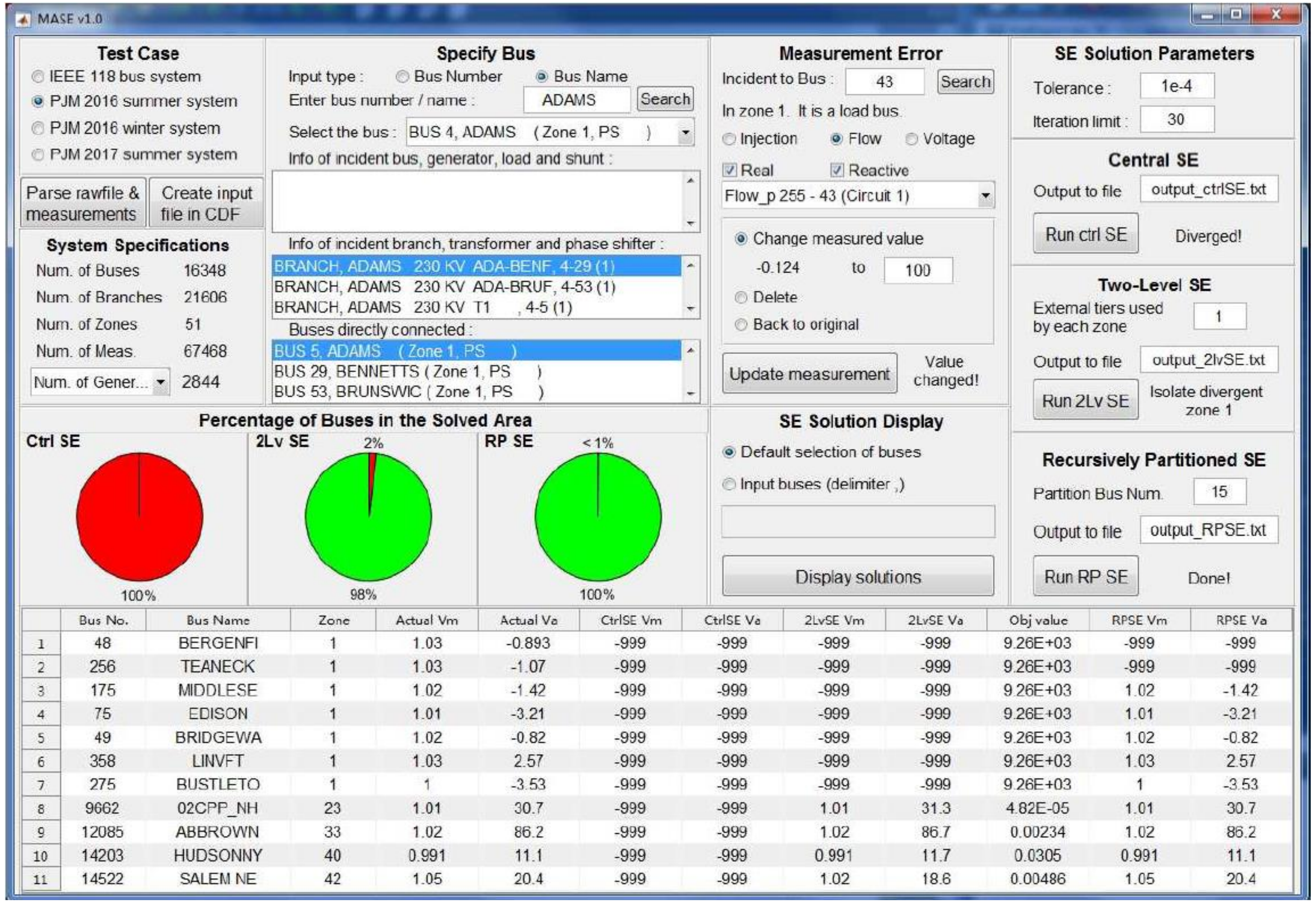
Obtain estimated states for largest possible part of the overall system when the system-wide state estimator diverges.

Barriers:

- High computational burden associated with existing methods to overcome divergence
- Fast response time required during daily operation

Research Achievements:

- Developed a new approach to partition the system
- Developed an algorithm to avoid boundary observability issues
- Implemented the SE solution on a very large scale actual utility power grid
- Validated the method using actual save-cases.



	Bus No.	Bus Name	Zone	Actual Vm	Actual Va	CtrlSE Vm	CtrlSE Va	2LvSE Vm	2LvSE Va	Obj value	RPSE Vm	RPSE Va
1	48	BERGENFI	1	1.03	-0.893	-999	-999	-999	-999	9.26E+03	-999	-999
2	256	TEANECK	1	1.03	-1.07	-999	-999	-999	-999	9.26E+03	-999	-999
3	175	MIDDLESE	1	1.02	-1.42	-999	-999	-999	-999	9.26E+03	1.02	-1.42
4	75	EDISON	1	1.01	-3.21	-999	-999	-999	-999	9.26E+03	1.01	-3.21
5	49	BRIDGEWA	1	1.02	-0.82	-999	-999	-999	-999	9.26E+03	1.02	-0.82
6	358	LINVFT	1	1.03	2.57	-999	-999	-999	-999	9.26E+03	1.03	2.57
7	275	BUSTLETO	1	1	-3.53	-999	-999	-999	-999	9.26E+03	1	-3.53
8	9662	02CPP_NH	23	1.01	30.7	-999	-999	1.01	31.3	4.82E-05	1.01	30.7
9	12085	ABBROWN	33	1.02	86.2	-999	-999	1.02	86.7	0.00234	1.02	86.2
10	14203	HUDSONNY	40	0.991	11.1	-999	-999	0.991	11.7	0.0305	0.991	11.1
11	14522	SALEM NE	42	1.05	20.4	-999	-999	1.02	18.6	0.00486	1.05	20.4

GUI for the non-divergent SE installed at PJM

Multi-Area Robust and Scalable Linear State Estimation

Objective:

Develop a multi-area robust state estimator

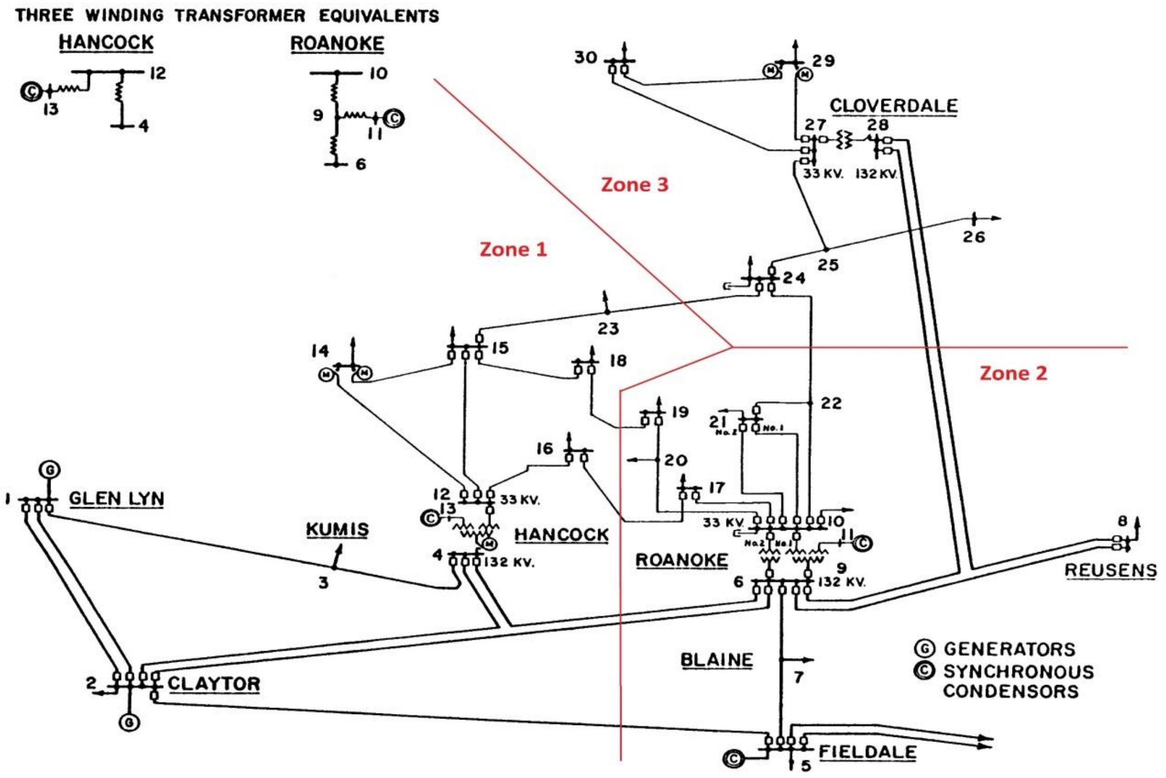
Technical Approach & Benefits:

Robustness properties of LAV estimator are combined with the well-known DW decomposition principle

Accomplishments:

Prototype linear state estimator which can handle large size multi-area systems and is robust against errors.

Accomplishments:

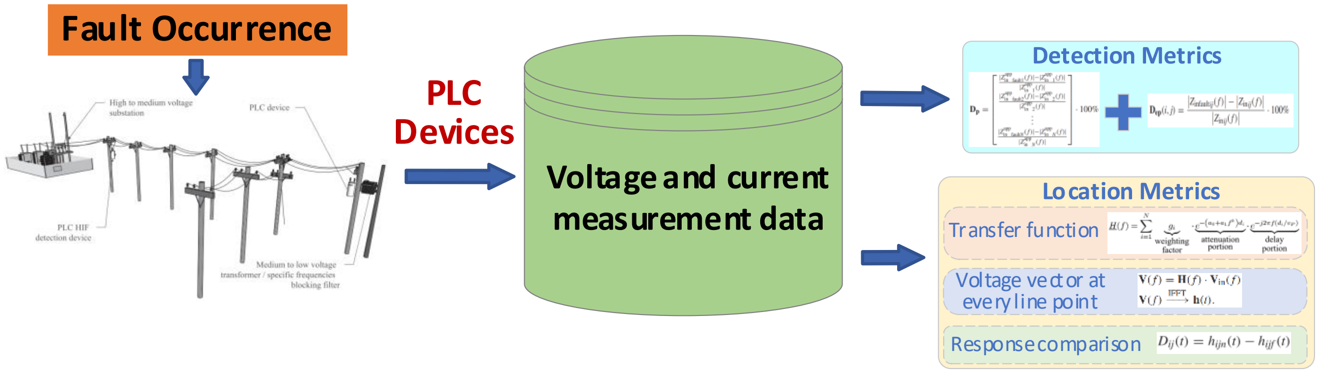


Bus No.	DW	Central
30	0.0910	0.0082
2917	1.3403	2.6575

CPU Time in Seconds

Fault Detection and Location Using Power Line Communication Devices

Project Goals:
- To develop a new approach to accurately and efficiently detect faults using power line communication (PLC) devices with corresponding detection metrics;
- To derive exact fault location by measuring responses to injected impulse along with monitored lines.



Fault detection and location framework with PLC devices and pulse responses

Barriers
- Respective investments with high costs in traditional grid;
- Unclear transfer function with numerous branch and impedance mismatching on power lines.

Methodologies to Overcome Barriers
- Utilizing PLC's narrowband and broadband solutions with techno-economic advantages while further investments are not required;
- Developing an analytical model describing complex transfer functions of typical line networks.

Research Achievements:
- Installed PLC devices along power lines with on-site measurements and data communication;
- Derived analytical transfer function of typical power lines under fault condition through a multipath model;
- Designed fault detection metrics, including deviations to the values of input impedance matrix elements due to fault occurrence;
- Designed fault location metrics, including responses between normal conditions and during fault occurrence.

Mingjian Cui, Fran Li (UTK)
Can Huang (LLNL)

VSC-HVDC Interties for Urban Power Grid Enhancement

Project Goals:

- Develop an urban power grid upgrading scheme using VSC-HVDC intertie for addressing the challenges of urban power grid expansions.
- Realize the conversion from existing AC cable circuit to DC operation.
- improve the flexibility and resilience of the urban power grid with advanced control strategy

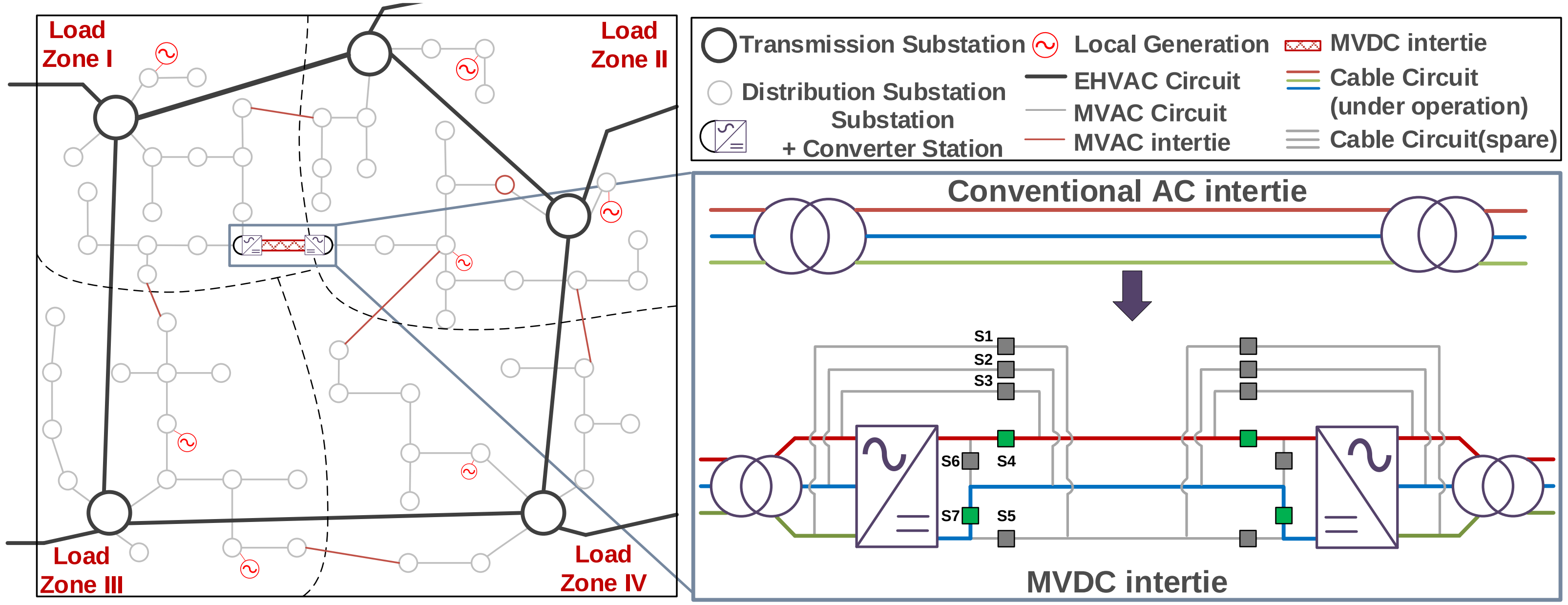
Barriers

- Relatively low cost construction
- Different operation conditions and corresponding control requirements

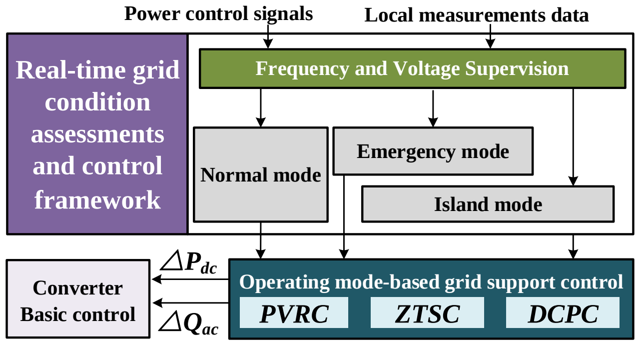
Methodologies to Overcome Barriers

- Novel VSC-HVDC intertie scheme
- Flexible operating modes
- Adaptive emergency control strategy

VSC-HVDC intertie scheme for urban load zones interconnection



Adaptive emergency control strategy



Research Achievements:

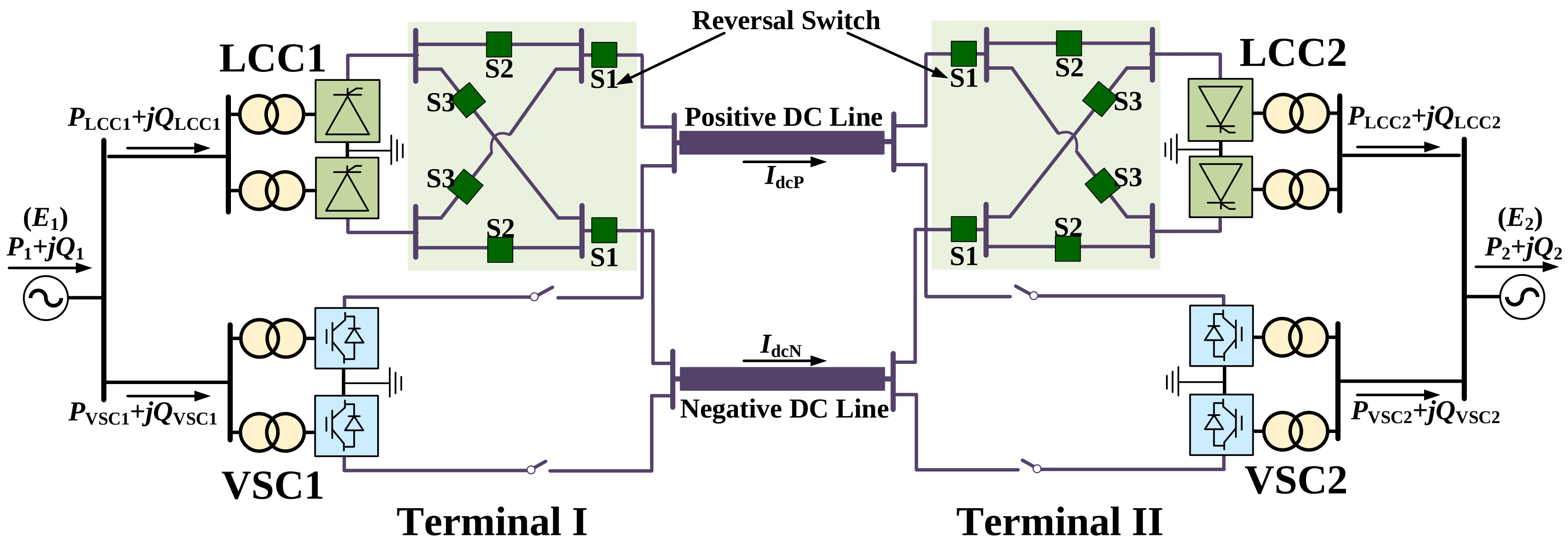
- Develop a Novel VSC-HVDC intertie scheme for urban power grid enhancement and modernization
- Propose operating modes corresponding to various urban power gird operating conditions.
- Develop an adaptive emergency control strategy urban for VSC-HVDC intertie.

Hybrid HVDC system for Cross-seam Interconnections

Project Goals:

- Develop a relatively cost HVDC transmission system scheme for cross-seam interconnections
- Realize the uninterrupted power flow reversal of hybrid HVDC transmission system
- Realize both AC/DC fault ride-through for hybrid HVDC transmission system

Configuration of the Hybrid-station HVDC System



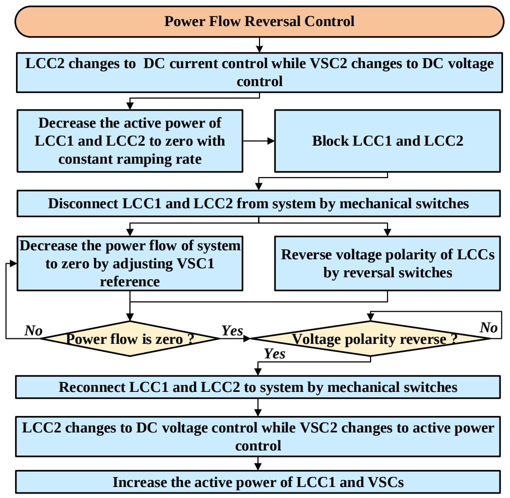
Barriers

- Relatively low cost construction
- Uninterrupted power flow reversal
- AC/DC fault ride-through

Methodologies to Overcome Barriers

- Hybrid HVDC scheme
- Power flow reversal control
- AC/DC fault ride-through control

Power Flow Reverse Control



Research Achievements:

- Develop a hybrid HVDC transmission system scheme for cross-seam interconnections
- Develop a power flow reversal for hybrid HVDC transmission system
- Develop a AC/DC fault ride-through control for hybrid HVDC transmission system

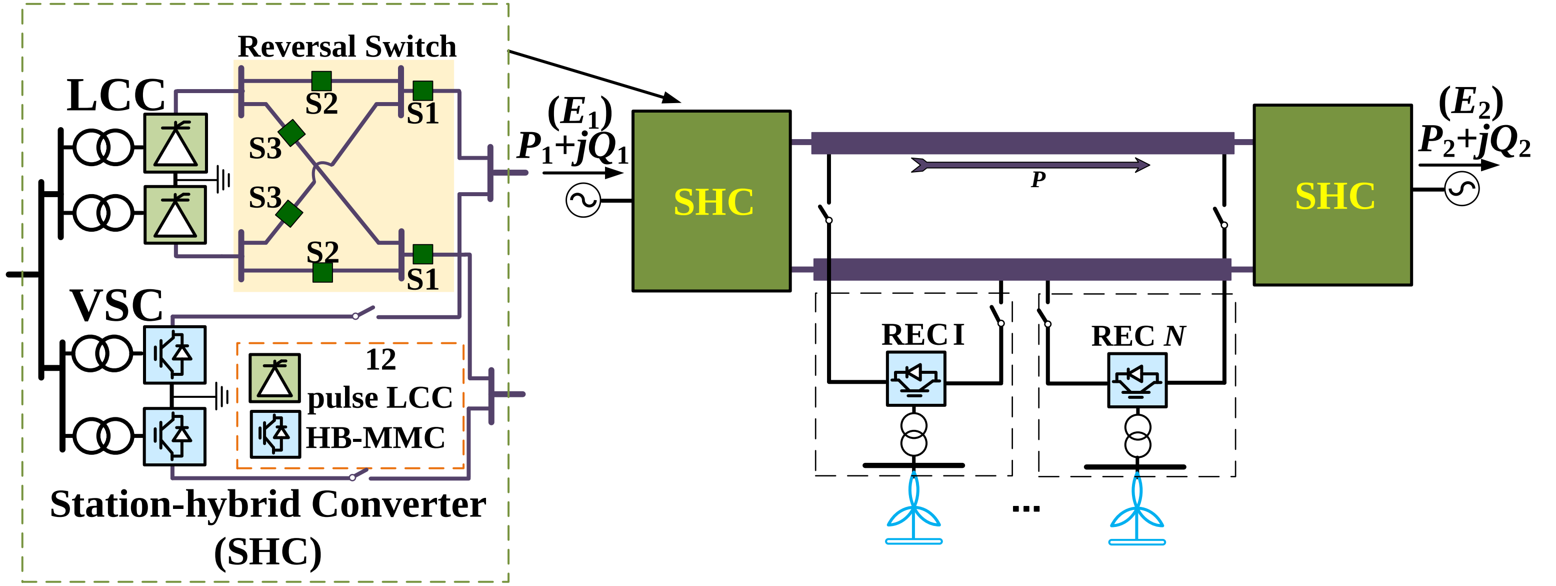
Cross-seam Hybrid MTDC System for Integration and Delivery of Large-scale Renewable Energy

Project Goals:
- Develop a novel topology of the hybrid MTDC system for cross-seam bulk-power transmission and integration of large-scale renewable energies
- Realize the flexible power flow control of hybrid MTDC system
- Realize frequency response control for hybrid MTDC system

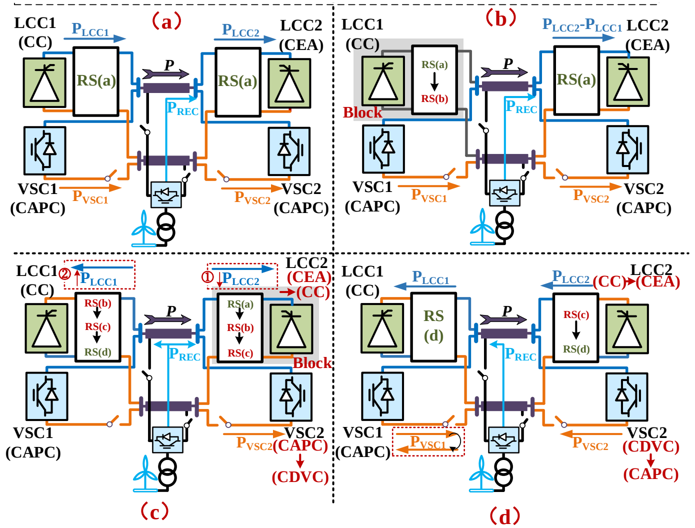
Barriers
- basic operation control of hybrid MTDC system
- Renewable energies connecting
- Power flow control strategy

Methodologies to Overcome Barriers
- Hybrid MTDC scheme
- Different renewable energies connecting method
- Flexible power flow control

The topology of the proposed hybrid MTDC system



Flexible Power Flow Control



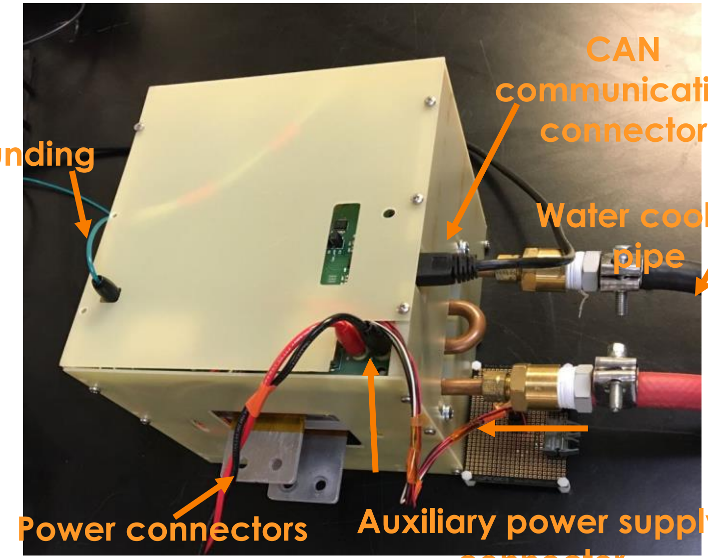
Research Achievements:
- Develop a hybrid MTDC system scheme for cross-seam bulk-power transmission and integration of large-scale renewable energies
- Develop a flexible power flow control for hybrid MTDC system
- Explored the frequency response control strategies of the proposed hybrid MTDC system for improving the frequency stability of the interconnected power systems

Power Electronics Projects

- Solid-state Power Conditioner (SSPC)
  - DC SSPC with 1kV/500A rating
  - 99.48% efficiency and 112.36 kW/kg specific power achieved
  - short circuit protection, i^2t (overload) protection, soft start, grounding fault indication, and remote control

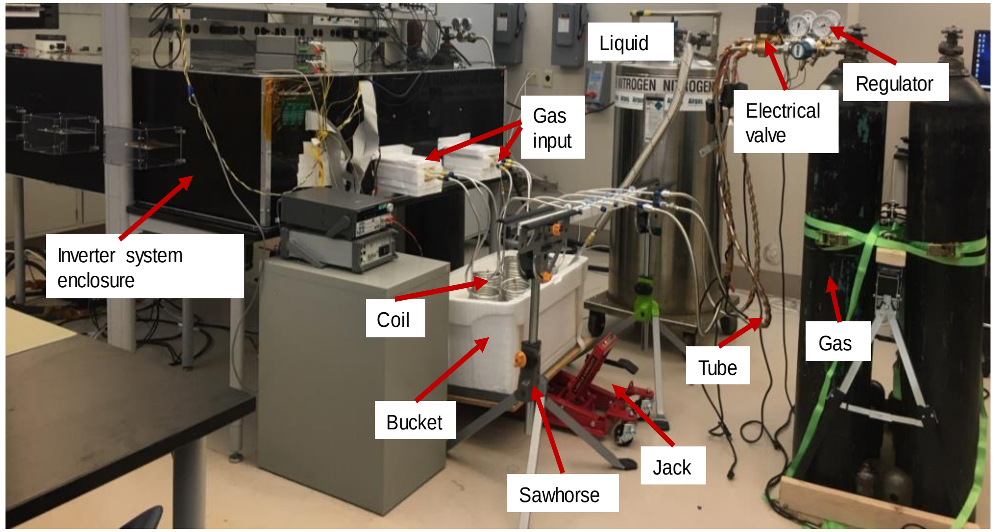
- GaN universal charger
  - 1.5 kW GaN-based universal battery charger (115V & 230V AC input, 28V & 270V DC output)
  - >96% efficiency and >3 kW/lb power density
  - Meet aircraft PQ and EMI requirement

- Boeing/NASA MW cryogenically-cooled inverter project
  - 1 MW inverter with cryogenic cooling for aircraft propulsion
  - 99% efficiency and 18 kVA/kg specific power achieved
  - Meet aircraft PQ and EMI requirement



SSPC w/ enclosure

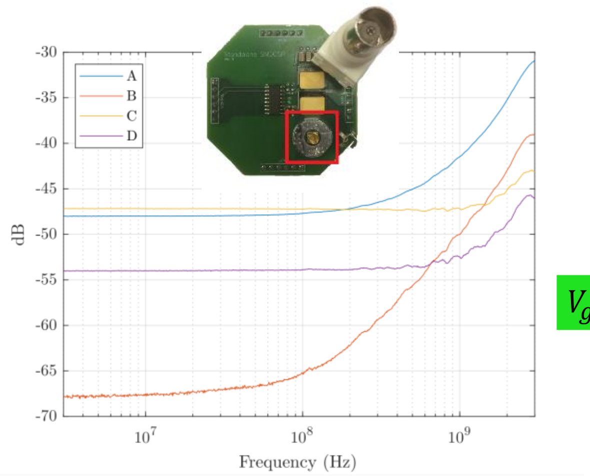
GaN charger w/ enclosure



MW inverter with cryogenic cooling

Keysight Projects

1. High-bandwidth low-inductance shunt for WBG switching device characterization
   - Over 2 GHz bandwidth in 0.11 nH package for *best* fidelity and lowest interference
2. Ultra-fast overcurrent protection scheme for WBG switching devices
   - *Fastest* 7.55 ns detection time ensures safety and easy protection
3. Programmable universal gate driver for easy device driving and speed tuning
   - Drive *almost all* switching devices with easily tunable configuration
4. Combinational Rogowski coil for WBG switching current continuous measurement
   - *Highest* 300 MHz bandwidth to continuously monitor WBG device switching behavior



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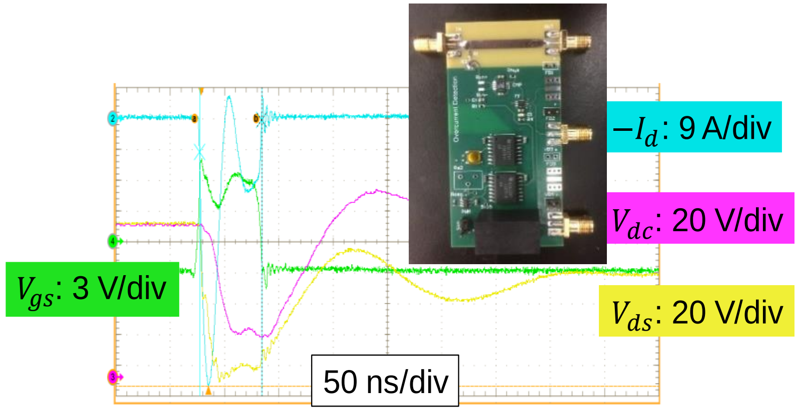

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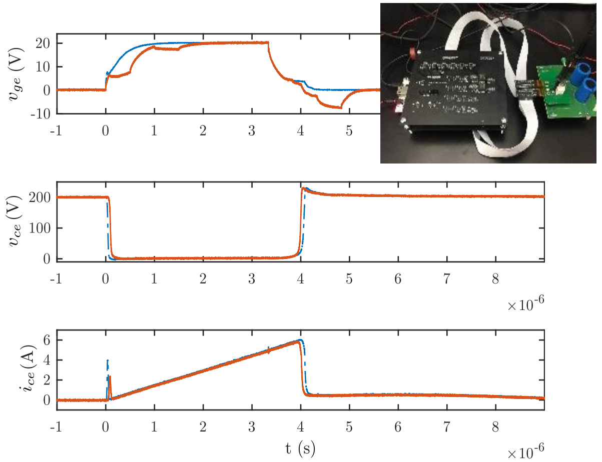

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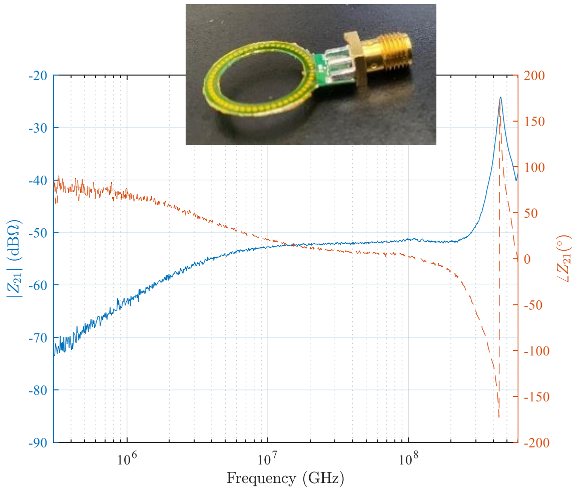

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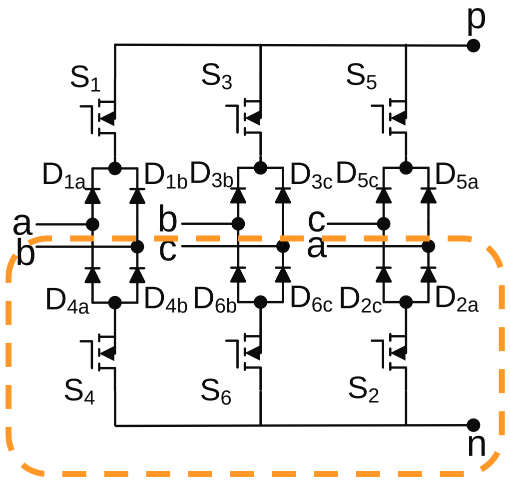
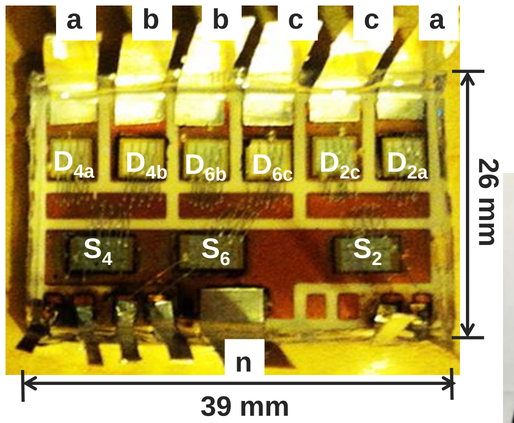
ABB Projects

- Solar PV inverter project
  - 4.5kW all-GaN single-phase solar inverter
  - DC-DC boost converter and DC-AC inverter included
  - CEC efficiency: 96.5% (w/ DC-DC), 97.8 % (w/o DC-DC)
  - Meet < 3% THD and EMI requirement at ac side
  - Lower cost than Si solution

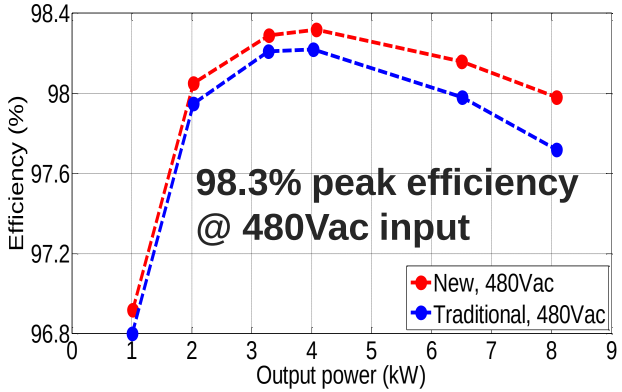
GaN-based PV inverter

- New delta-type current source buck rectifier topology
  - Improved efficiency compared to traditional topology
  - An 8kW all-SiC prototype implemented

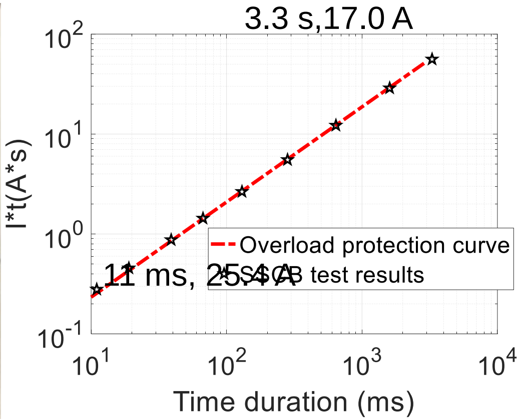




SiC-based delta-type buck rectifier

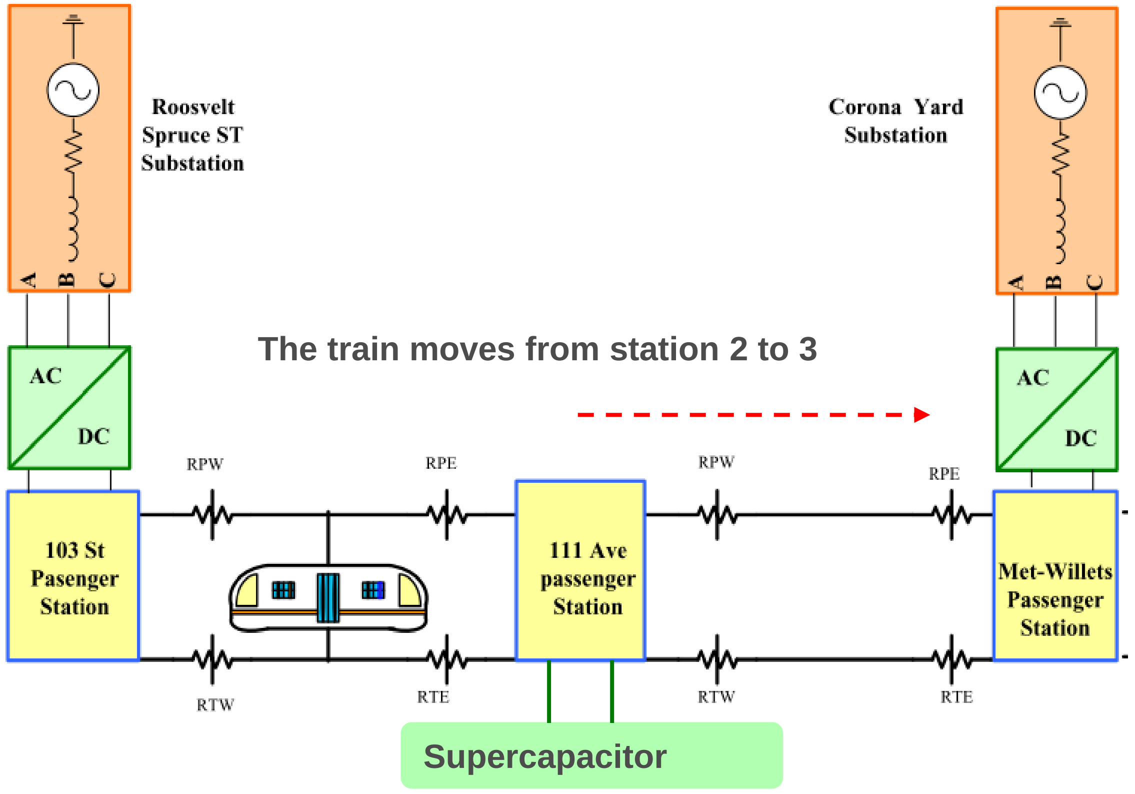


- GaB Based solid-state circuit breaker (SSCB)
  - 400V/8A dc SSCB using GaN Gate-Insulated Transistors
  - 99.6% efficiency, 10.6W/cm^3 power density and 400ns response time achieved
  - Overload protection and short circuit protection included

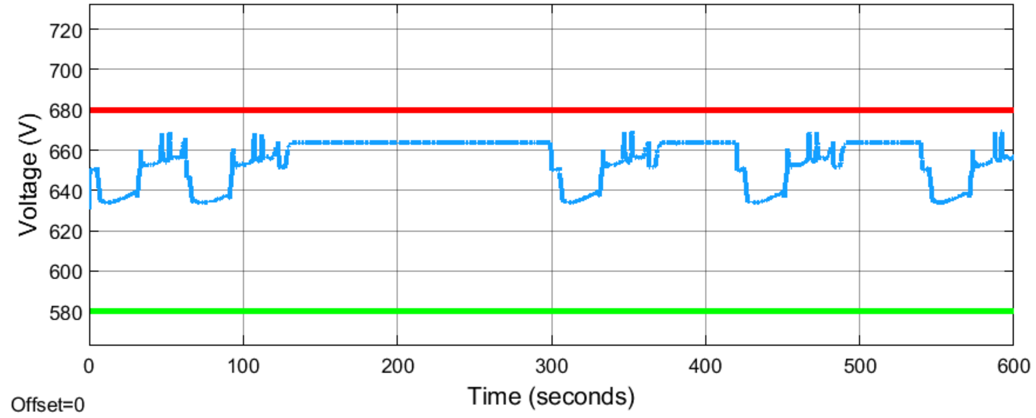


GaN-based DC SSCB with overload protection

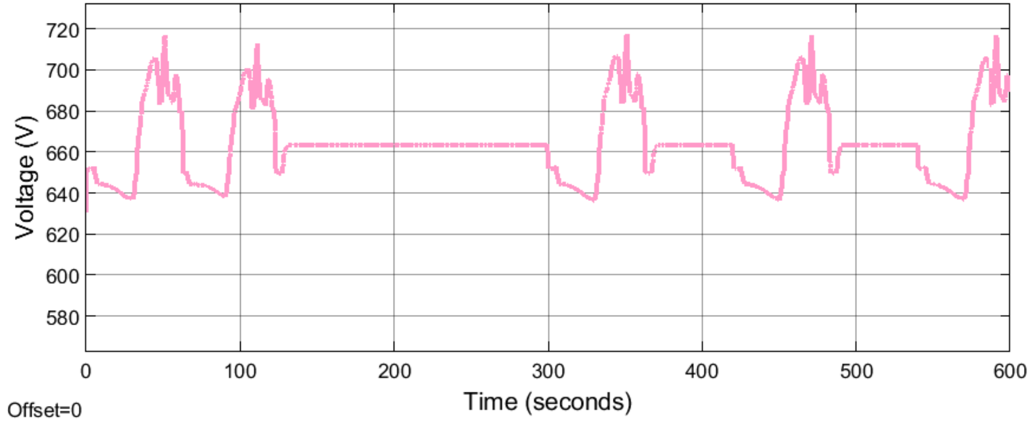
NY Subway System with ESS



Supercapacitor (SC) is at 111 Ave passenger station.



DC-bus voltage with supercapacitor tank



DC-bus voltage without supercapacitor tank

UTK team based on the New York Subway Station schedule designed the supercapacitor (SC) tank. The SC tank absorbs the regenerative energy and provides extra power for train acceleration thereby stabilizing the DC bus. The research offers ConEd the option to eliminate the chopper thereby saving the energy. UTK also surveyed various SC technology.

Battery SOH Calculation

UTK worked with ConEd to:

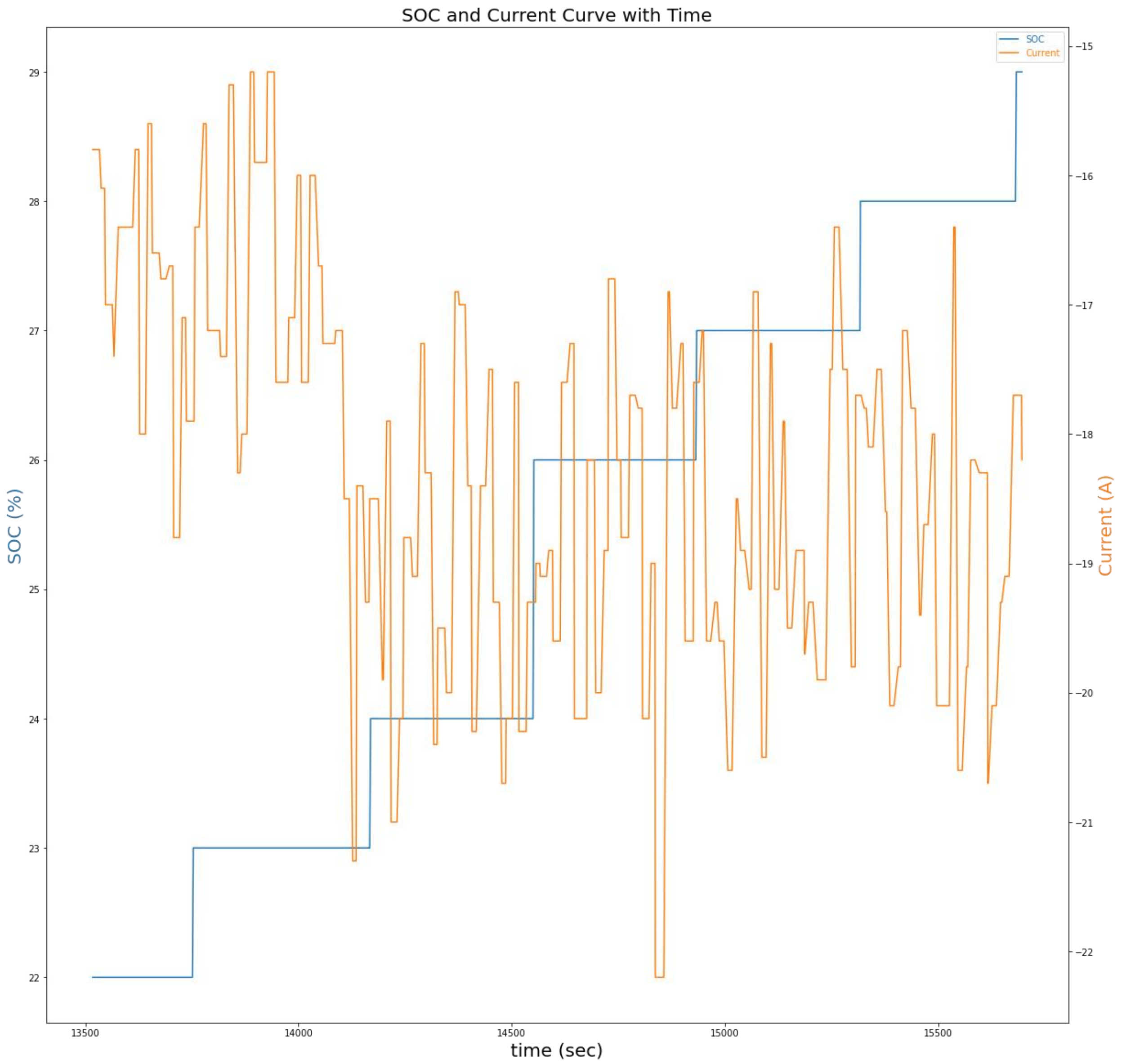
1) Extract the battery voltage and current data;
2) Estimate the SOC based on the Coulomb Counting method;

$$SOC(t) = SOC(t-1) + \frac{\int I(t)dt}{Q} \times 100\%$$

3) Estimate the battery state of health (SOH);

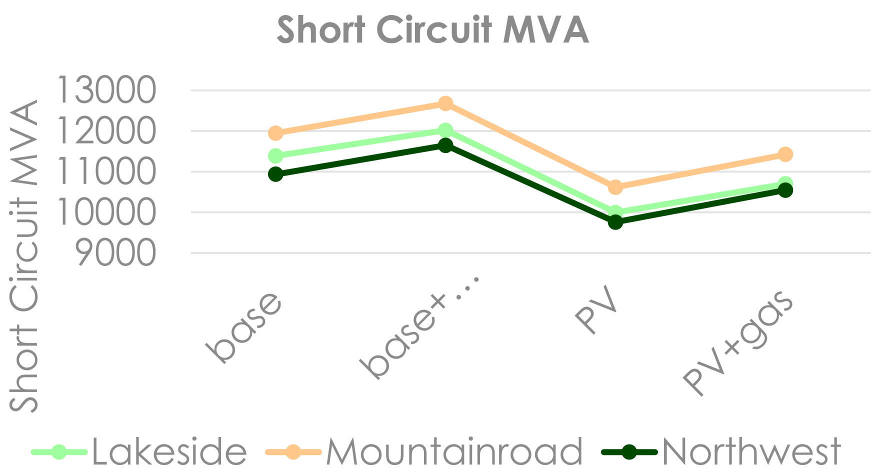
$$SOH = \frac{Q}{Q_{rated}} \times 100\%$$

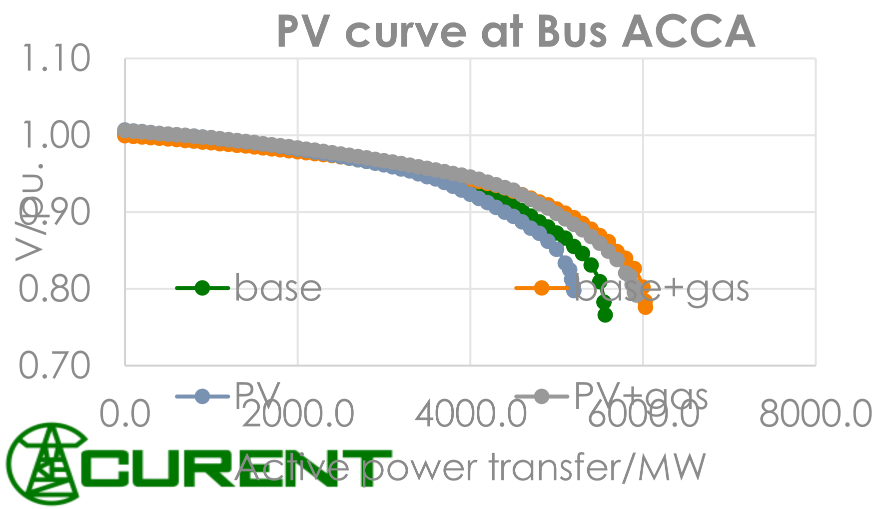
4) Use machine learning to estimate the battery behavior in the long run.

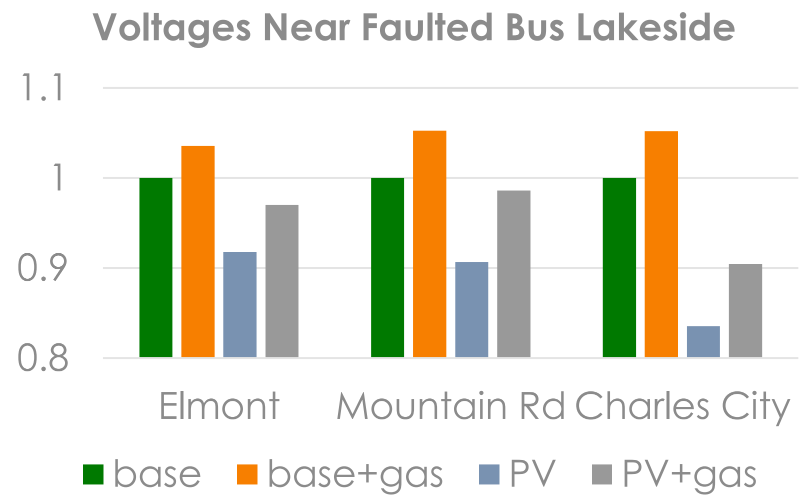


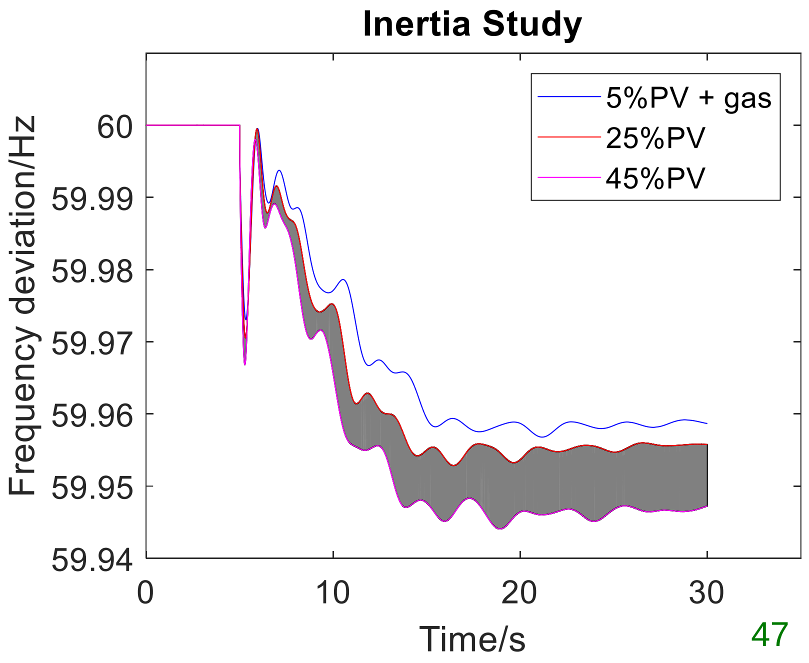
Dominion Energy PV vs Gas Study

- Performed studies on the impact of gas and solar generation on Dominion Energy area
- Study Scenarios (Base case, high PV case, w/ and w/o proposed gas plant)
- **Short Circuit Study**
  - Solar generation provides less short circuit MVA than conventional generation.
- **Voltage Study**
  - Gas generation provides more local voltage support during fault conditions
  - Gas generation increases active power transfer limit
- **Inertia Study**
  - Gas generation contributes more to system inertia than same amount of solar generation



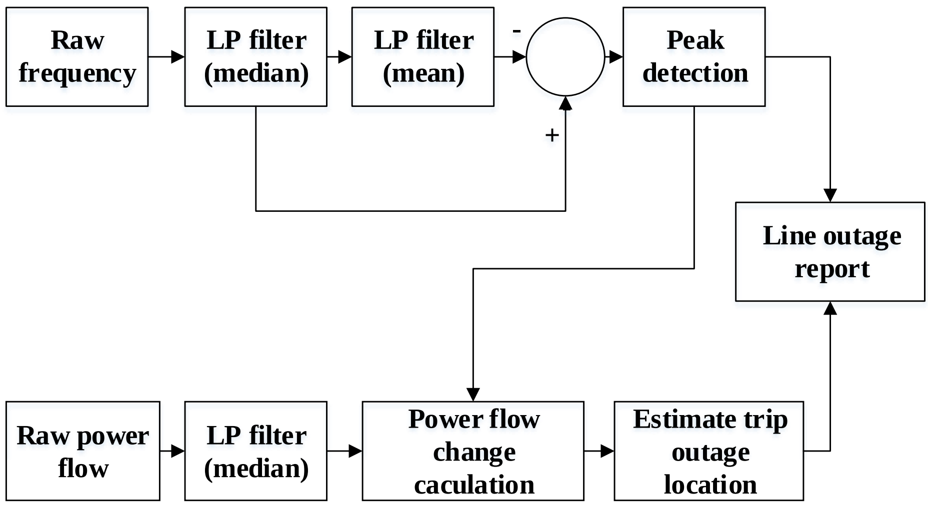


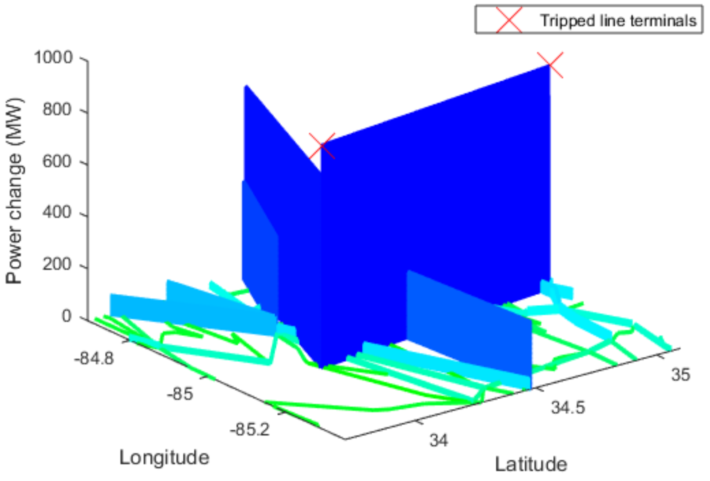


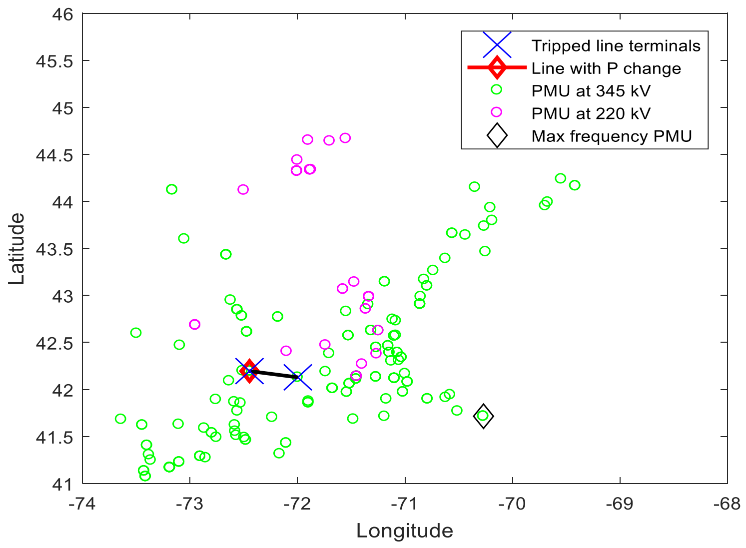


Real-time Line Outage Detection and Localization

- Line outage detection and localization
  - Line outage detection : Implemented and tested with simulation cases
  - Root cause analysis of line trip localization error by using NEISO and TVA systems
  - Line outage localization: A method using power flow to improve accuracy of the previous method
- Demo of the proposed method
  - Tested the proposed method with 95 line outage cases in NEISO system



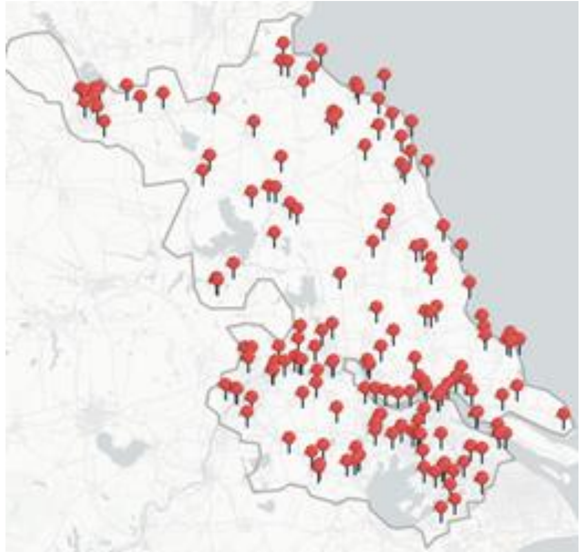


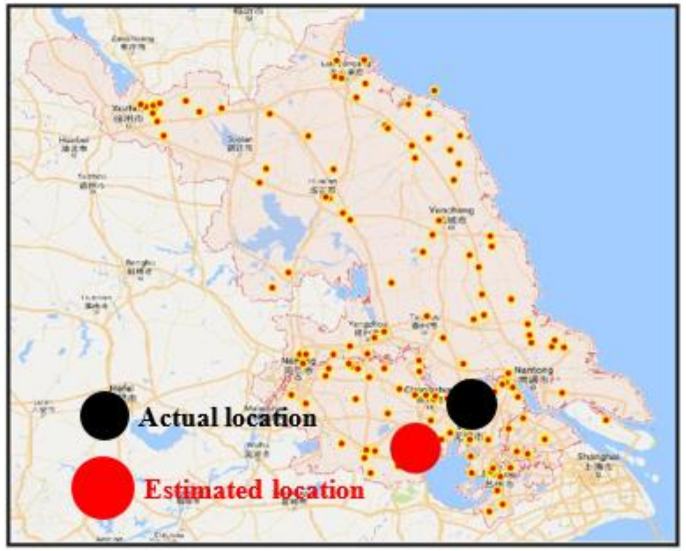


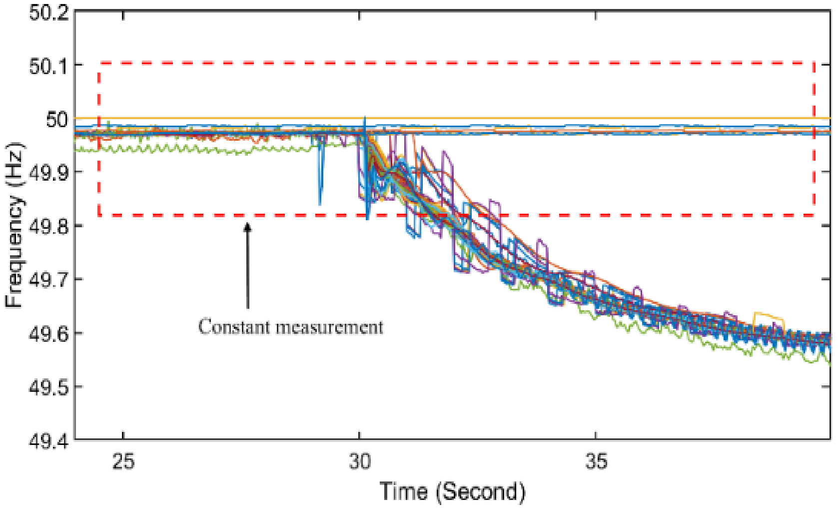
GEIRINA
GEIRI NORTH AMERICA

Real-time Events Detection and Triangulation

- Implemented and operates in a power grid with 400 PMUs
  - Detected event types: Generation trip and load shedding
  - High resolution real-time measurement in huge volume
  - Data quality issues in real time measurements
- Tested accuracy and robust of the application for operational purpose
  - Tested with 10 simulation event cases and 1 real-world event case
  - Tested with 75 ambient cases





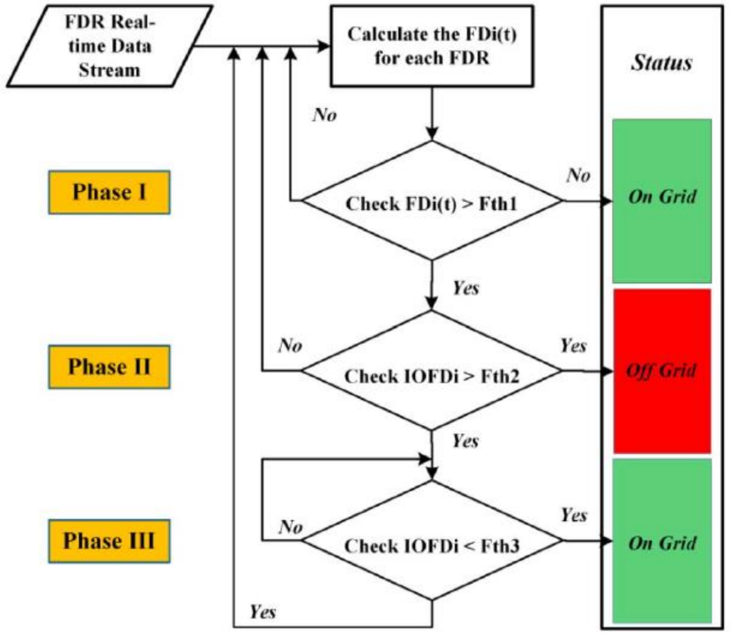


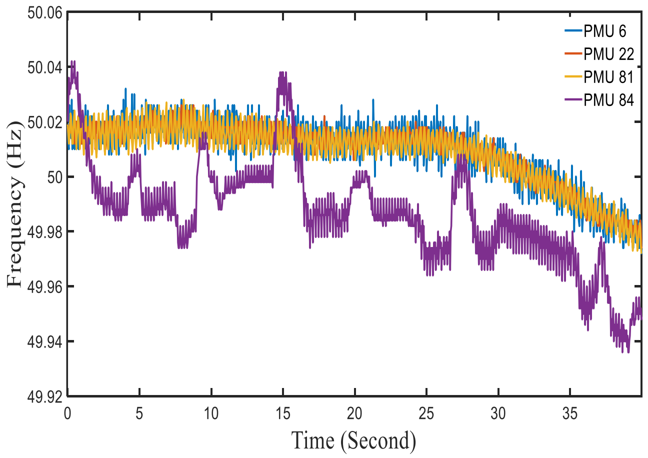
CURENT

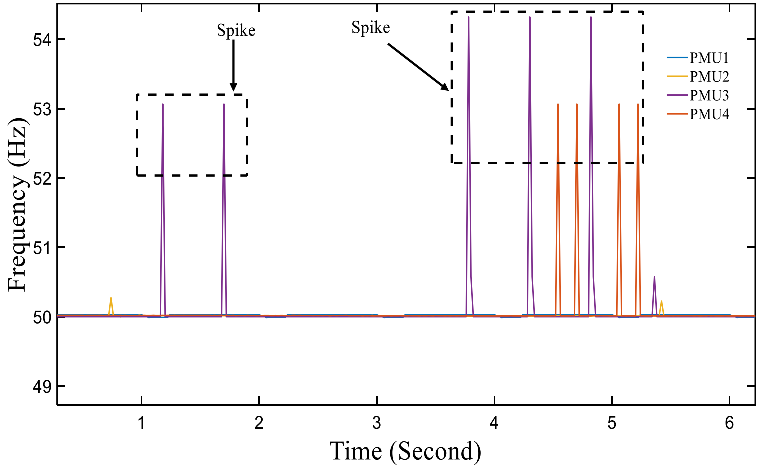
STATE GRID GEIRI NORTH AMERICA · THE UNIVERSITY of TENNESSEE KNOXVILLE · OAK RIDGE National Laboratory · FNET GridEye

Real-time Islanding Detection and Localization

- Islanding detection using measurements with data quality issue
  - Implemented a real time islanding event detection and localization application for GEIRINA
  - Test and validate with high density PMU measurements and simulation events
  - Evaluate impacts of PMU data quality issue to the application
- Progress of the project
  - Testing data provided from GEIRINA was delayed due to COV19 virus
  - GEIRINA was closed and moved to China

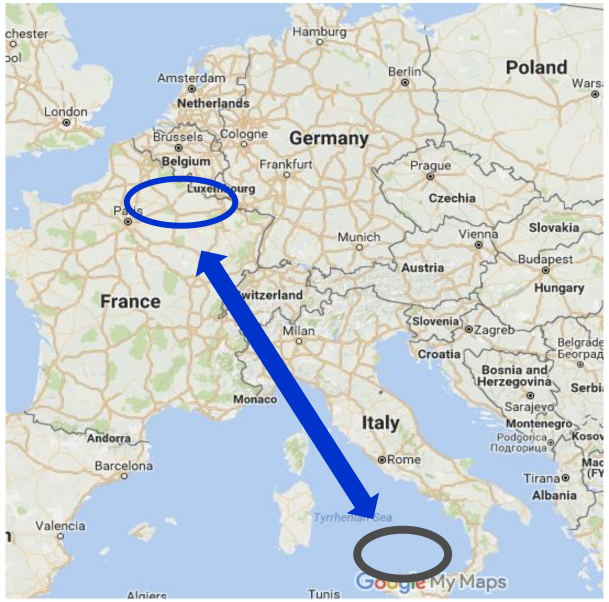


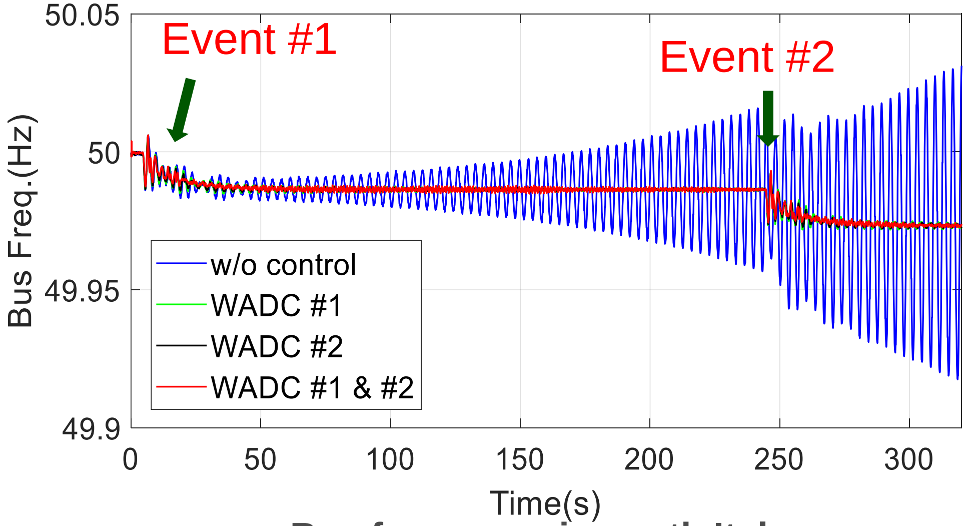




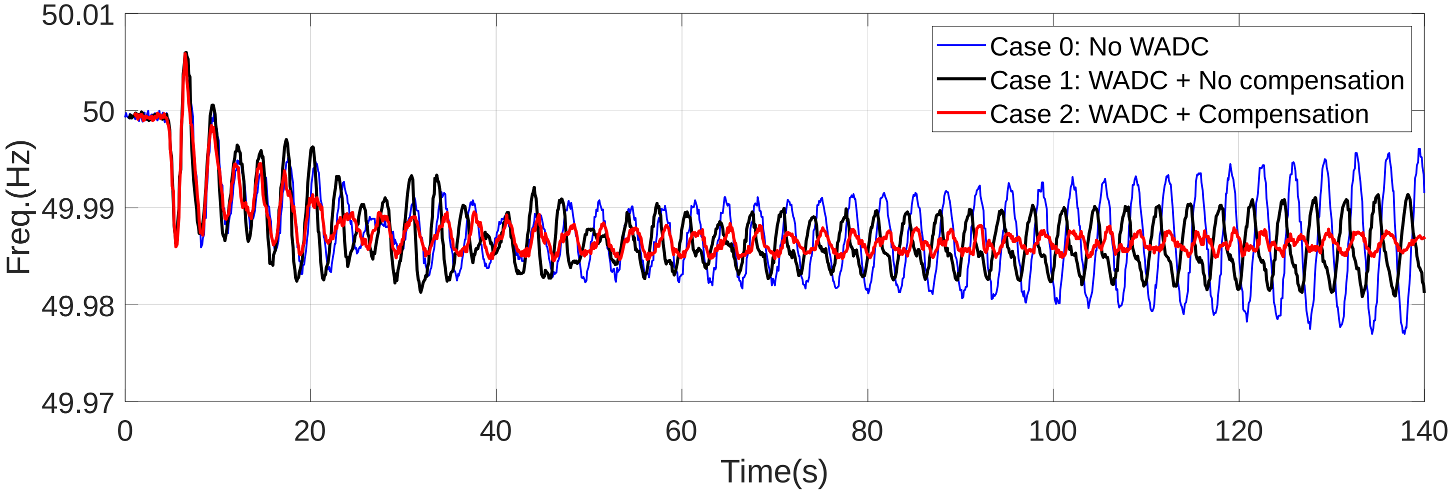
Adaptive Oscillation Damping Control: Terna

- 2k+ bus model with 2017 event replicated in simulation
  - Target mode: South Italy v.s. France/Germany
  - Input signal: South-North frequency difference or local frequency in south
  - Actuators: Two synchronous condensers in South Italy
- 150-950 ms random delay + 60% data loss (25Hz reporting rate)
  - **Case 0:** No WADC
  - **Case 1:** WADC + No compensation & Missing data handling
  - **Case 2: WADC + Compensation & Missing data handling**





Bus frequency in south Italy

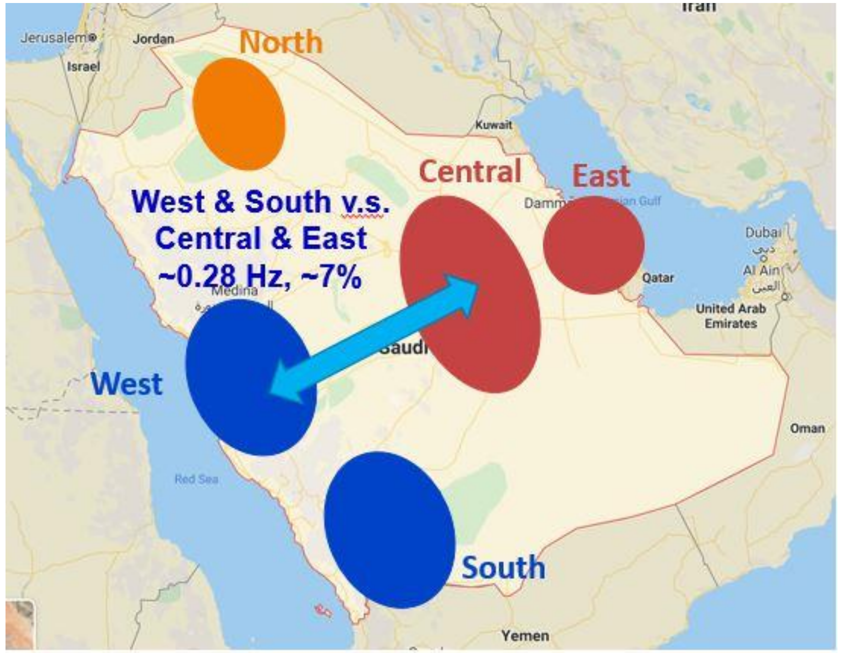


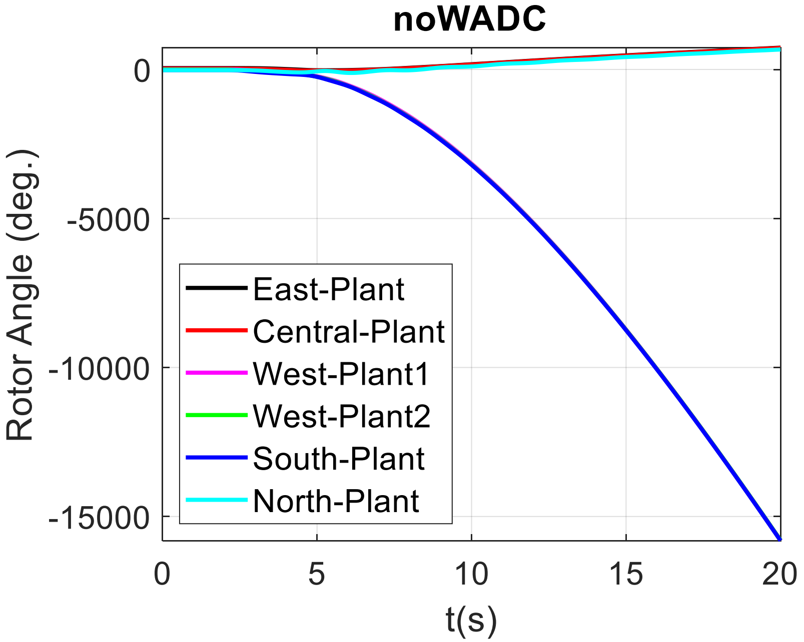
Bus frequency in south Italy (with communication impairment)

CURENT

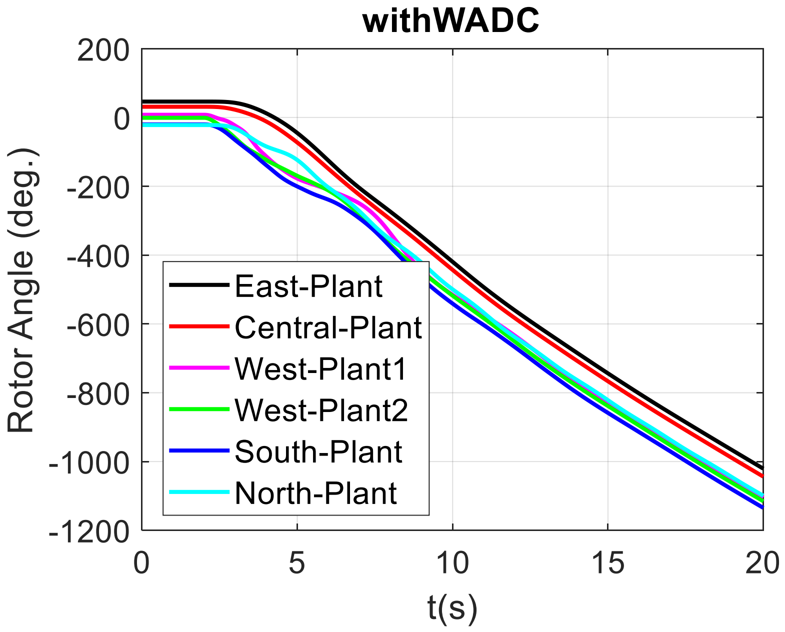
Adaptive Oscillation Damping Control: SEC Case

- 2k+ bus full model with 2017 system separation event replicated
  - Target mode: west/south v.s. central/east
  - Observation signal: Bus frequency between west and central
  - Actuators: Generator governors, exciters, and SVCs
- Improve damping ratio and transient stability simultaneously
  - ❑ Three incidents since 2015 that resulted in tripping tie-line between west and central - system separation





Rotor Angle (no WADC)



Rotor Angle (with WADC)

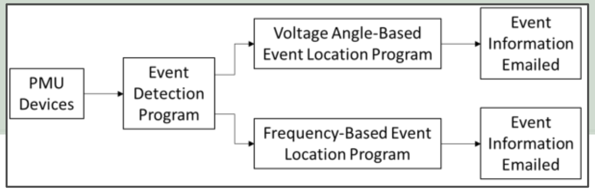
Implementing Event Detection Tools Based on PMUs

Introduction

The frequency monitoring network (FNET) generation and load tripping event detection algorithm was deployed at Southern Company. It was altered to use Southern Company's phasor measurement unit (PMU) data as an input rather than the FNET Frequency Disturbance Recorder (FDR).

Overview of Tool

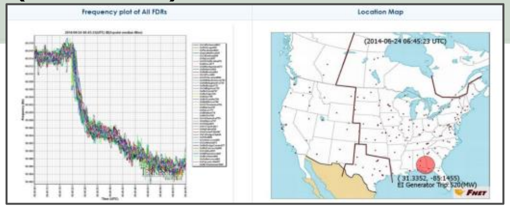
- PMU data used as input
- Event detection program is coded as action adapter in openPDC
- Two different location methods tested



Flowchart for Event Location Tool

Event Example

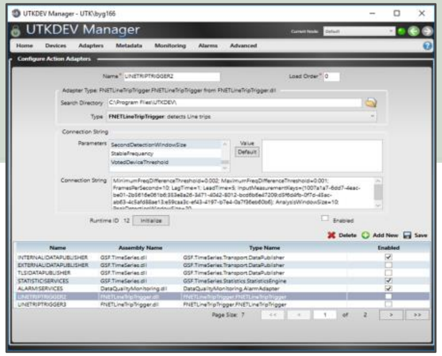
- Tool is used to detect and locate generation trip or load shedding events
- Generation trip decreases frequency
- Load shedding increases frequency
- Calculates the rate of change of frequency (RoCoF) to detect event



Generation Trip Event Detected by FNET

Graphical User Interface (GUI)

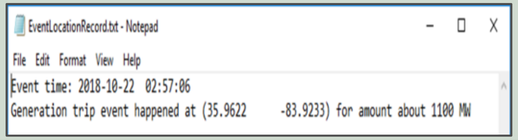
- User starts tool from GUI
- Easy to operate
- Changeable parameters
  - Can alter sensitivity to events
  - Can set who receives results



GUI for Event Location Tool

Output

- Creates event record in text file
- Creates html file of location in Google Maps
- Files packaged in email
- Email sent to those specified in GUI



Event Results Text File

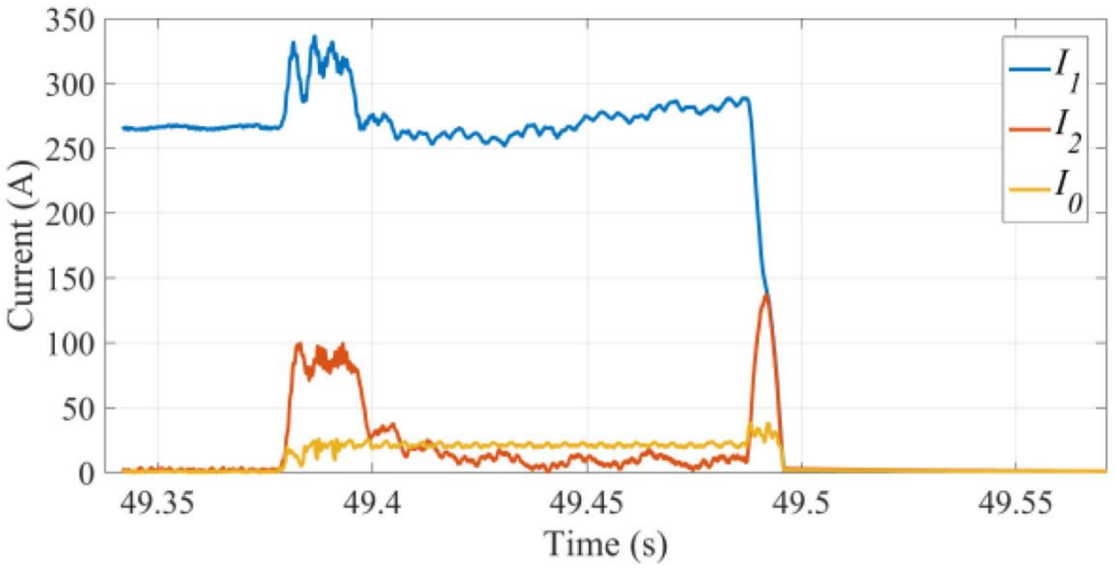
Event Results Map

Distributed solar generation fault current study

- Proposed a method and implemented it in MATLAB and VB script to batch process thousands of in-field recording files. Sorting out all the events that the fault current is fed by distributed solar generation

- Validated the fault characteristic of utility scale distributed solar generation

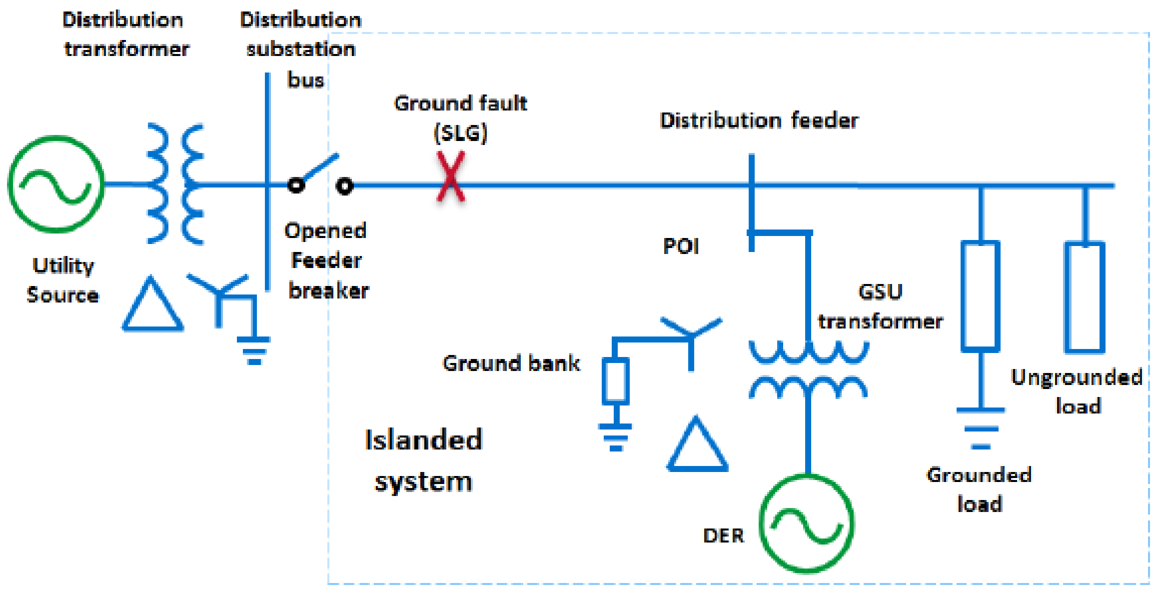
- The findings help the group in modeling distributed generation for fault analysis



Sequence components of an event

DG voltage study during un-intentional islanding

- Analyzed the modeling of DG using sequence components, validated voltage profile of both conventional synchronized DG and inverter-based DG during un-intentional islanding
- Proposed an overvoltage elimination method by changing the sizing of NGR, the proposed method has been verified using Aspen One-liner and RTDS model
- Help the group understand the voltage profile during un-intentional islanding of inverter-based DG

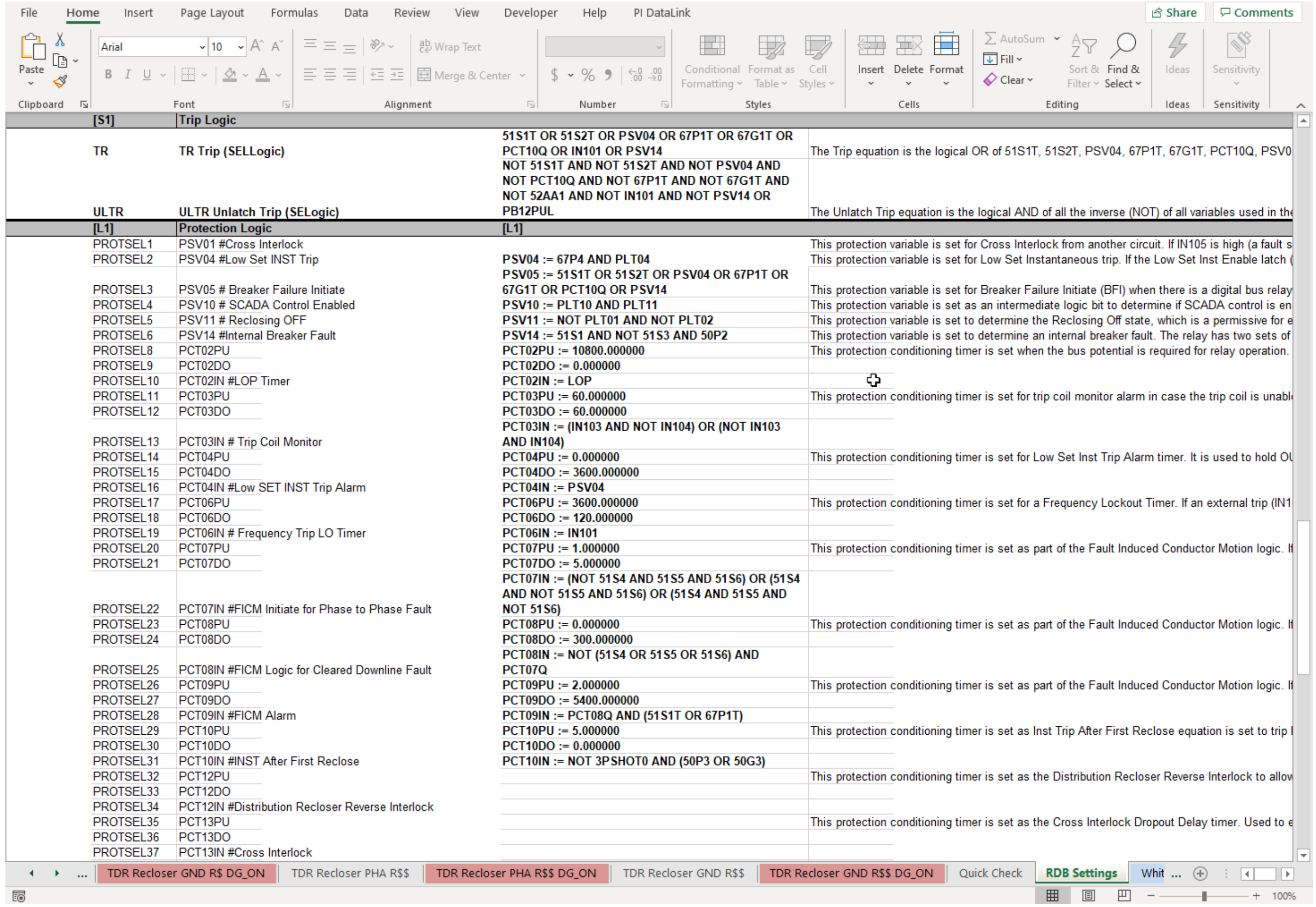


Islanded system of distribution feeder and DER with a ground fault

Automation on relay setting generation

- Designed interface for protection values and schemes input in relay setting documentation spreadsheet, implemented VBA macros to validate setting values and generate setting files
- Instead of manual input by the engineer, the generated files can be imported by relay setting software directly, saving the processing time and reducing the miscalculations and errors in the work process

Relay Type	Task status
SEL 451 feeder relay	Finished
SEL 351 feeder relay	On going
SEL 351 Transformer Overcurrent relay	Finished
SEL 351 Transformer Differential relay	On going

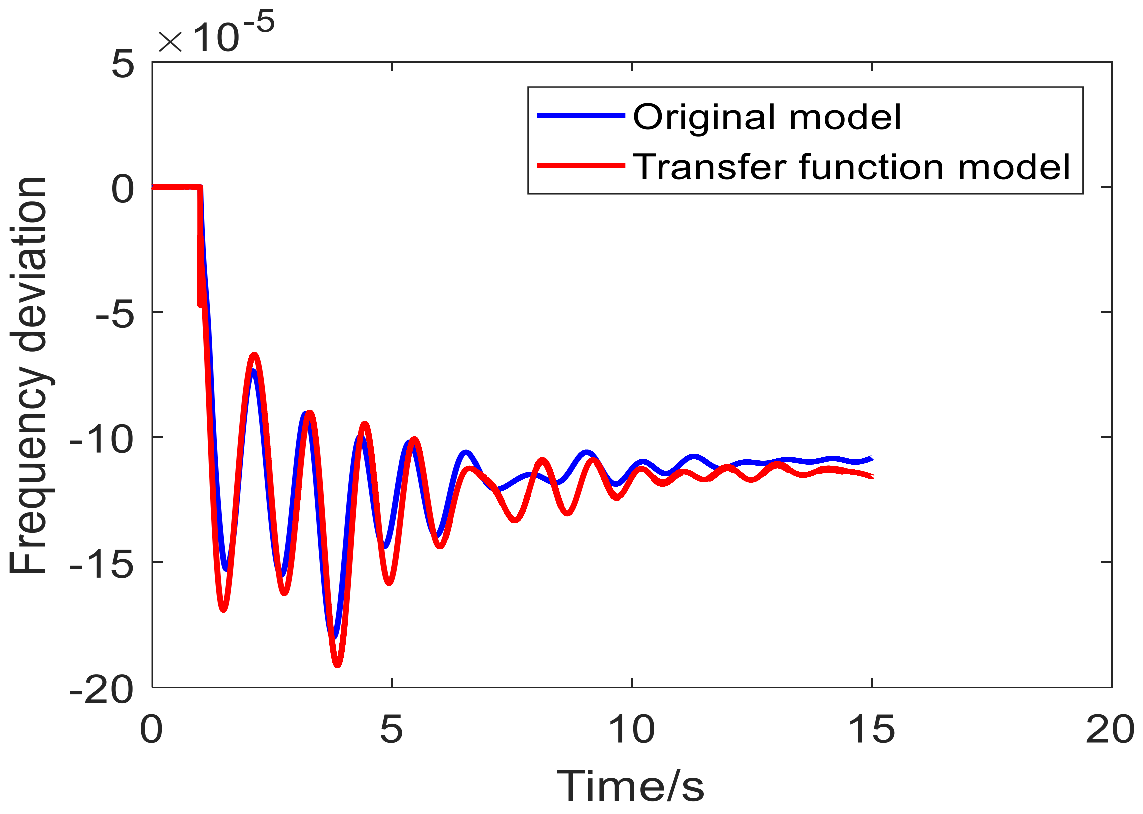


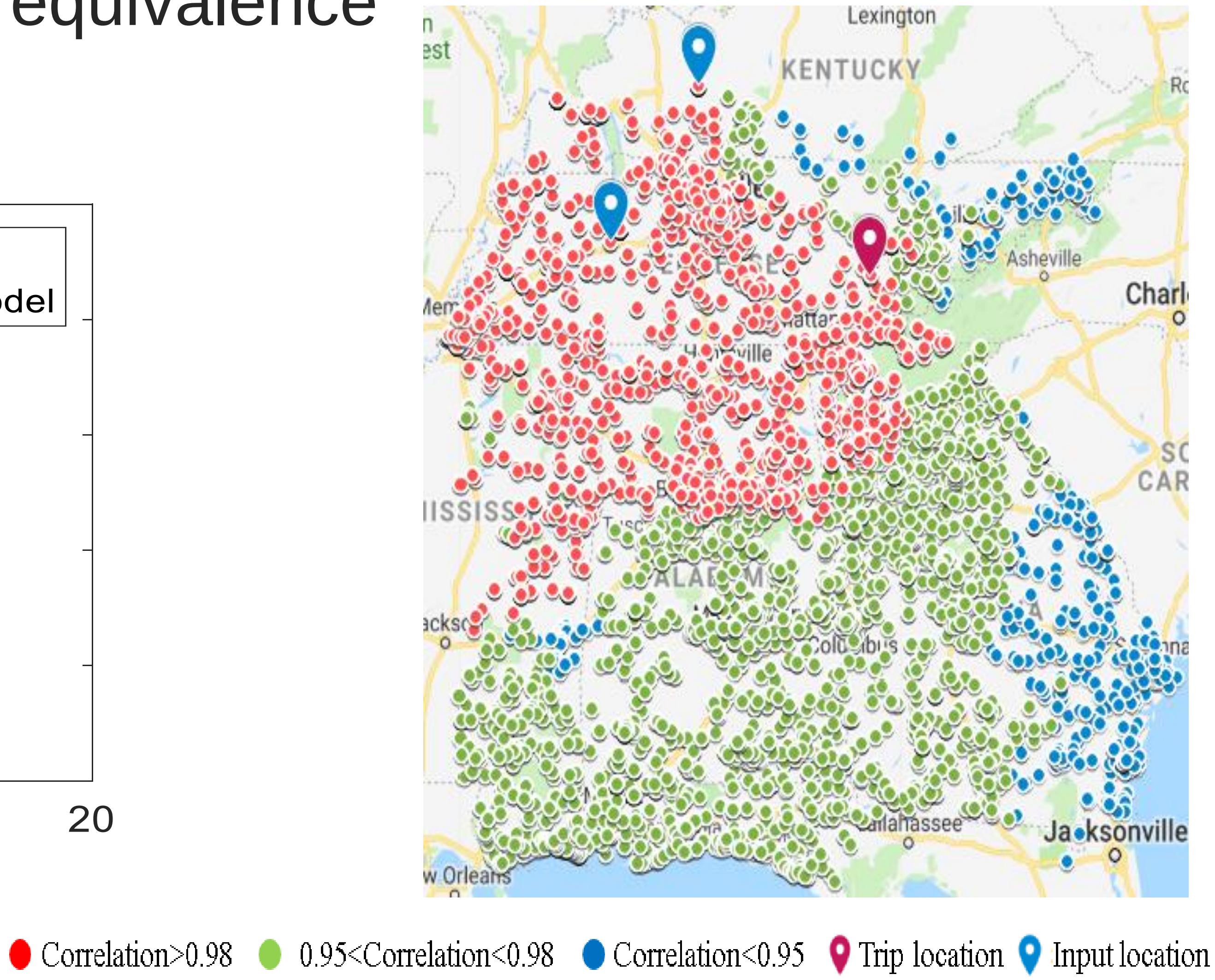
[S1]	Trip Logic		
TR	TR Trip (SELLogic)	51S1T OR 51S2T OR PSV04 OR 67P1T OR 67G1T OR PCT10Q OR IN101 OR PSV14	The Trip equation is the logical OR of 51S1T, 51S2T, PSV04, 67P1T, 67G1T, PCT10Q, PSV0
ULTR	ULTR Unlatch Trip (SELogic)	NOT 51S1T AND NOT 51S2T AND NOT PSV04 AND NOT PCT10Q AND NOT 67P1T AND NOT 67G1T AND NOT 52AA1 AND NOT IN101 AND NOT PSV14 OR PB12PUL	The Unlatch Trip equation is the logical AND of all the inverse (NOT) of all variables used in the
[L1]	Protection Logic	[L1]	
PROTSEL1	PSV01 #Cross Interlock		This protection variable is set for Cross Interlock from another circuit. If IN105 is high (a fault s
PROTSEL2	PSV04 #Low Set INST Trip	PSV04 := 67P4 AND PLT04	This protection variable is set for Low Set Instantaneous trip. If the Low Set Inst Enable latch (
PROTSEL3	PSV05 # Breaker Failure Initiate	PSV05 := 51S1T OR 51S2T OR PSV04 OR 67P1T OR 67G1T OR PCT10Q OR PSV14	This protection variable is set for Breaker Failure Initiate (BFI) when there is a digital bus relay
PROTSEL4	PSV10 # SCADA Control Enabled	PSV10 := PLT10 AND PLT11	This protection variable is set as an intermediate logic bit to determine if SCADA control is en
PROTSEL5	PSV11 # Reclosing OFF	PSV11 := NOT PLT01 AND NOT PLT02	This protection variable is set to determine the Reclosing Off state, which is a permissive for e
PROTSEL6	PSV14 #Internal Breaker Fault	PSV14 := 51S1 AND NOT 51S3 AND 50P2	This protection variable is set to determine an internal breaker fault. The relay has two sets of
PROTSEL8	PCT02PU	PCT02PU := 10800.000000	This protection conditioning timer is set when the bus potential is required for relay operation.
PROTSEL9	PCT02DO	PCT02DO := 0.000000	
PROTSEL10	PCT02IN #LOP Timer	PCT02IN := LOP	
PROTSEL11	PCT03PU	PCT03PU := 60.000000	This protection conditioning timer is set for trip coil monitor alarm in case the trip coil is unabl
PROTSEL12	PCT03DO	PCT03DO := 60.000000	
PROTSEL13	PCT03IN # Trip Coil Monitor	PCT03IN := (IN103 AND NOT IN104) OR (NOT IN103 AND IN104)	
PROTSEL14	PCT04PU	PCT04PU := 0.000000	This protection conditioning timer is set for Low Set Inst Trip Alarm timer. It is used to hold OU
PROTSEL15	PCT04DO	PCT04DO := 3600.000000	
PROTSEL16	PCT04IN #Low SET INST Trip Alarm	PCT04IN := PSV04	
PROTSEL17	PCT06PU	PCT06PU := 3600.000000	This protection conditioning timer is set for a Frequency Lockout Timer. If an external trip (IN1
PROTSEL18	PCT06DO	PCT06DO := 120.000000	
PROTSEL19	PCT06IN # Frequency Trip LO Timer	PCT06IN := IN101	
PROTSEL20	PCT07PU	PCT07PU := 1.000000	This protection conditioning timer is set as part of the Fault Induced Conductor Motion logic. I
PROTSEL21	PCT07DO	PCT07DO := 5.000000	
PROTSEL22	PCT07IN #FICM Initiate for Phase to Phase Fault	PCT07IN := (NOT 51S4 AND 51S5 AND 51S6) OR (51S4 AND NOT 51S5 AND 51S6) OR (51S4 AND 51S5 AND NOT 51S6)	
PROTSEL23	PCT08PU	PCT08PU := 0.000000	This protection conditioning timer is set as part of the Fault Induced Conductor Motion logic. I
PROTSEL24	PCT08DO	PCT08DO := 300.000000	
PROTSEL25	PCT08IN #FICM Logic for Cleared Downline Fault	PCT08IN := NOT (51S4 OR 51S5 OR 51S6) AND PCT07Q	
PROTSEL26	PCT09PU	PCT09PU := 2.000000	This protection conditioning timer is set as part of the Fault Induced Conductor Motion logic. I
PROTSEL27	PCT09DO	PCT09DO := 5400.000000	
PROTSEL28	PCT09IN #FICM Alarm	PCT09IN := PCT08Q AND (51S1T OR 67P1T)	
PROTSEL29	PCT10PU	PCT10PU := 5.000000	This protection conditioning timer is set as Inst Trip After First Reclose equation is set to trip I
PROTSEL30	PCT10DO	PCT10DO := 0.000000	
PROTSEL31	PCT10IN #INST After First Reclose	PCT10IN := NOT 3PSHOT0 AND (50P3 OR 50G3)	
PROTSEL32	PCT12PU		This protection conditioning timer is set as the Distribution Recloser Reverse Interlock to allow
PROTSEL33	PCT12DO		
PROTSEL34	PCT12IN #Distribution Recloser Reverse Interlock		
PROTSEL35	PCT13PU		This protection conditioning timer is set as the Cross Interlock Dropout Delay timer. Used to e
PROTSEL36	PCT13DO		
PROTSEL37	PCT13IN #Cross Interlock		

Part of generated setting logic in spreadsheet template

Measurement-based Model reduction for TVA Grids

- Measurement-based dynamic equivalence and model reduction





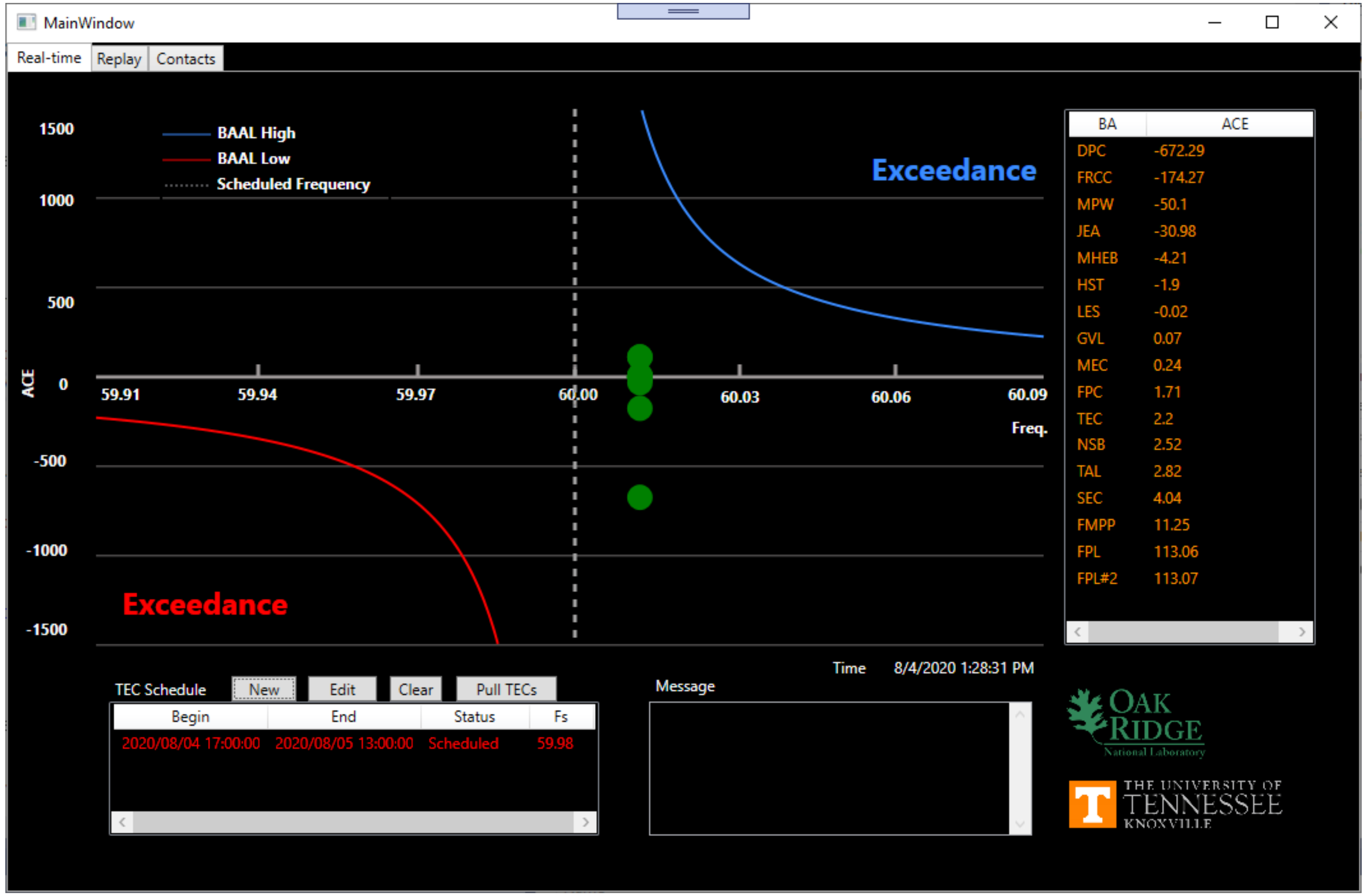
Balancing Authority ACE Limit Visualization

Features

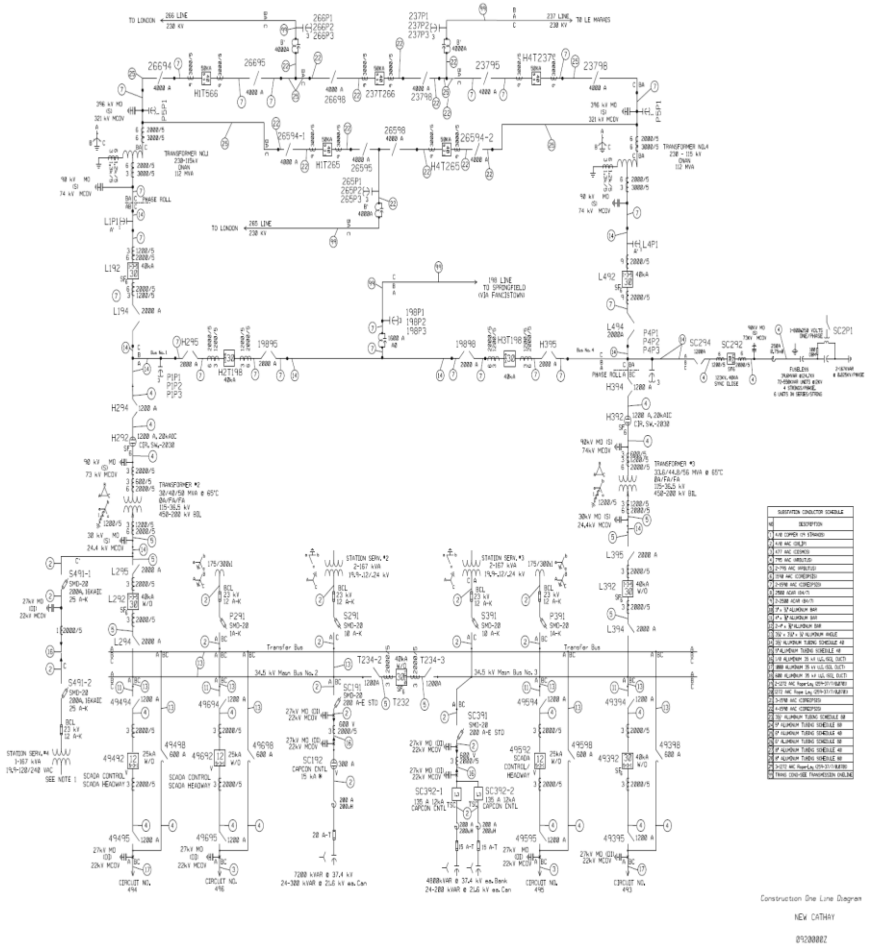
- Monitor the balancing performance of the balancing authorities (BAs) in the North American grids.
- Dynamically display the operating conditions (ACE values).
- Consider the scheduled frequency change during a time error correction (TEC) period.
- Allow operators to edit TEC schedule.

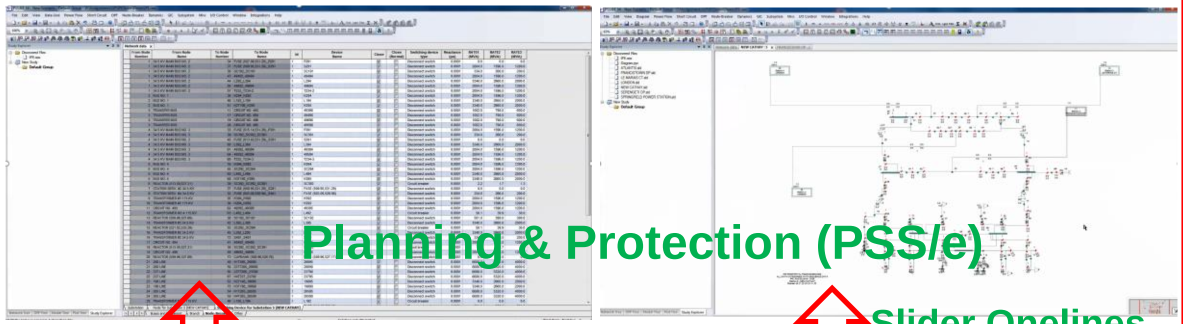
Future Enhancement

- Develop a replay version to help investigate past events.
- Automate the TEC setting procedure.



Substation Drawing Conversion Tool

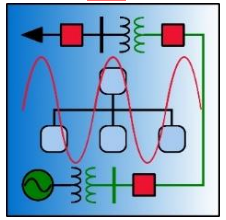




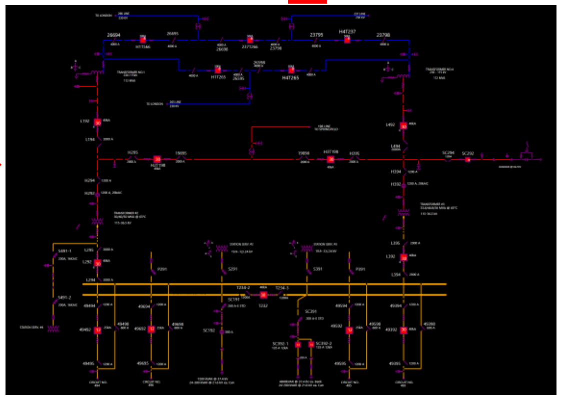
Planning & Protection (PSS/e)

Slider Onelines

PSS/e raw files



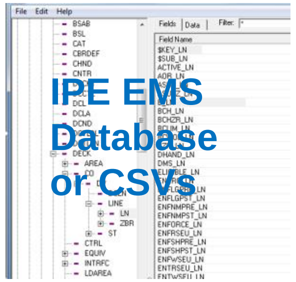
GridPortal.exe



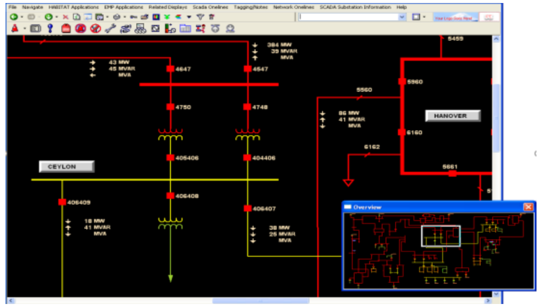
CIM or Vendor Specific CSVs

Operations

EMS Onelines

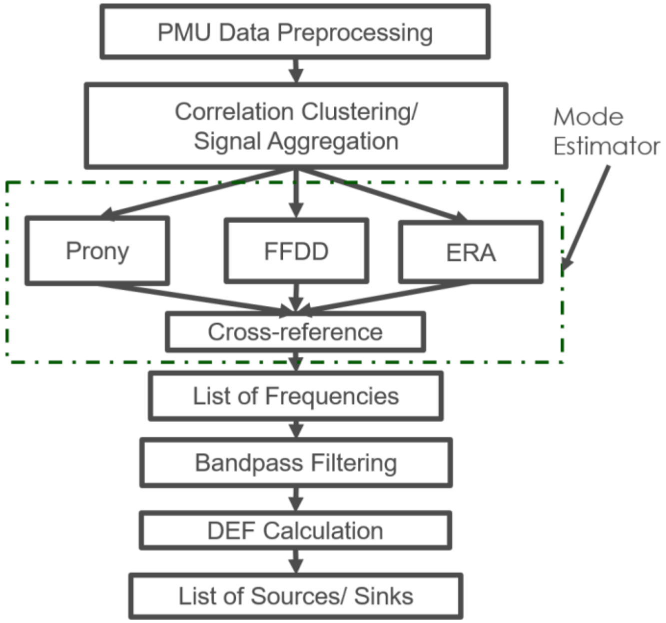


CURENT EMS



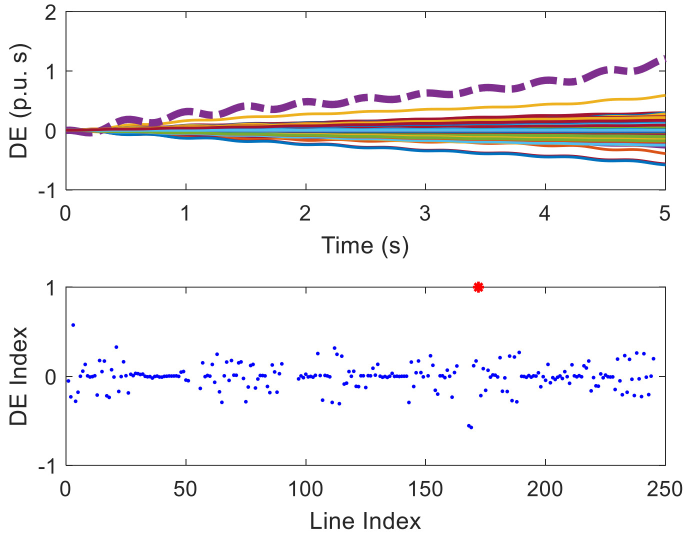
Speeding Up the Dissipating Energy Flow Based Oscillation Source Detection.

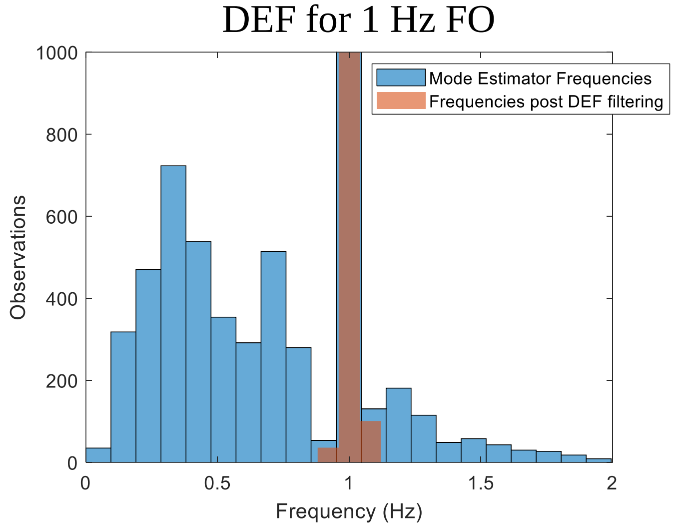
Kenta Kirihara, Jun Yamazaki, Panitarn Chongfuangprinya, Stavros Konstantinopoulos, Christoph Lackner, Joe H. Chow.



Mode Estimator and Source Location Flowchart

- A comprehensive mode estimation and forced oscillation source location tool was proposed.
- Correlation clustering applied to PMU channels.
- Results in decrease of computation effort, and in improved denoising and mode estimation accuracy.
- 3 methods used for cross reference of modal estimates.
- Dissipating energy flow used for source location purposes.
- Dissipating energy calculated for all identified “modes”.
- Modes with small energy are filtered out, reducing false alarm rate.
- Method validated on 3 FO cases from the New England system.



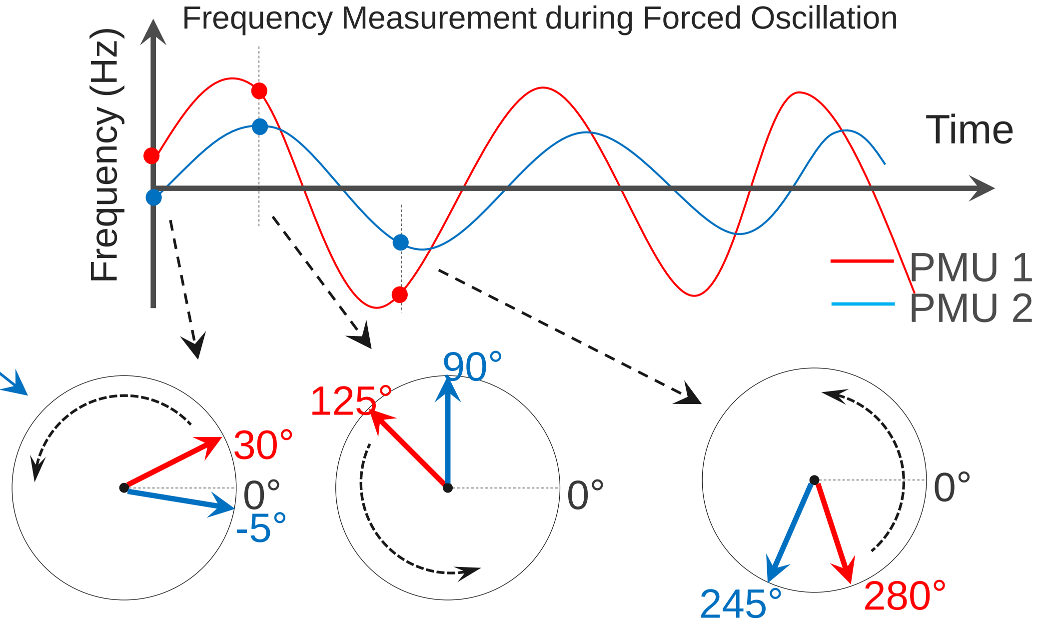


Filtering of noisy modes from the mode estimator via DEF

Locating Source of Forced Oscillation

- **Locate the source of forced oscillation based on mode angle analysis**

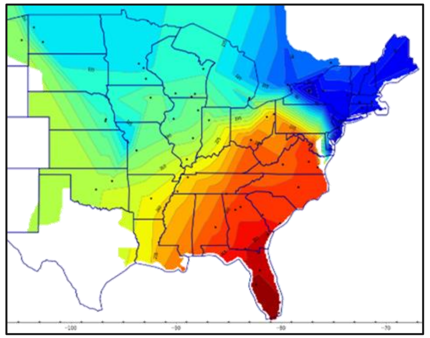
  According to observation, **mode angle** gradually reduces from the source area to other areas.



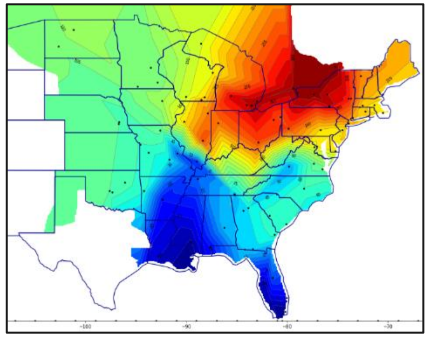
- **Steps:**
  1. FFT analysis to obtain mode angle of the oscillation;
  2. Geographically unwrap the mode angle;
  3. Area with the most leading mode angle is the source.

- **Cases:**

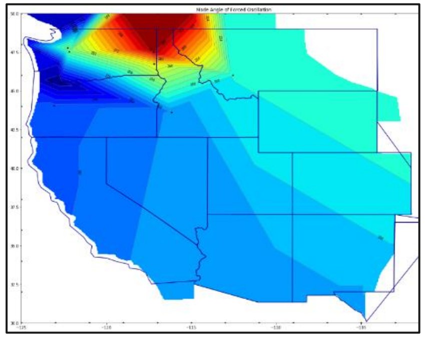
EI case on 01/11/2019 08:44



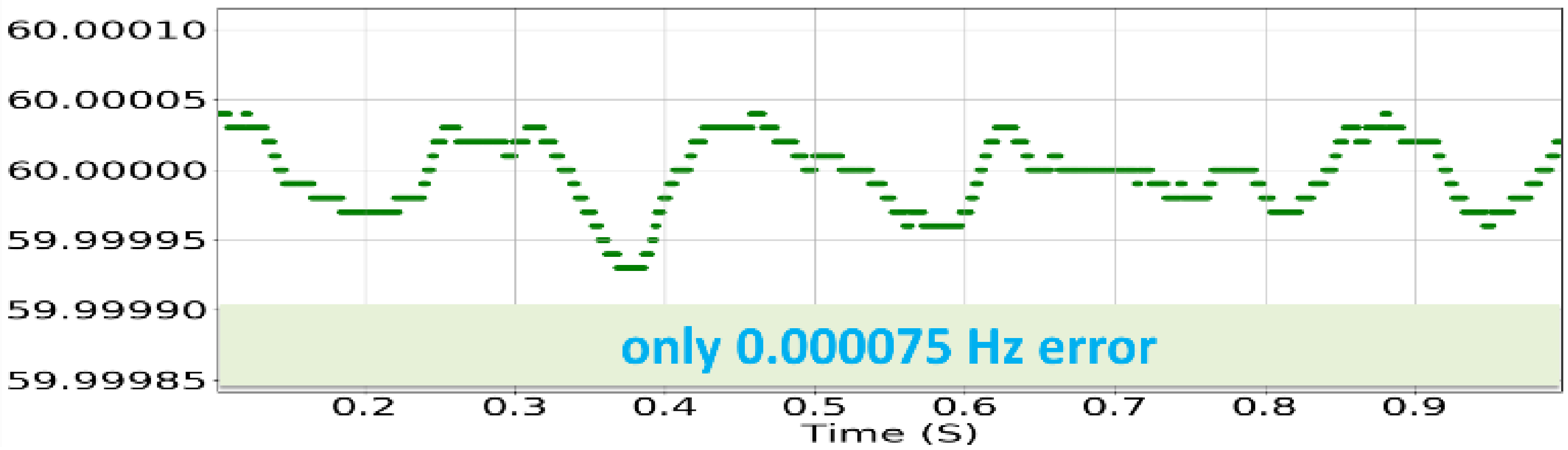
EI case on 04/07/2020 09:36

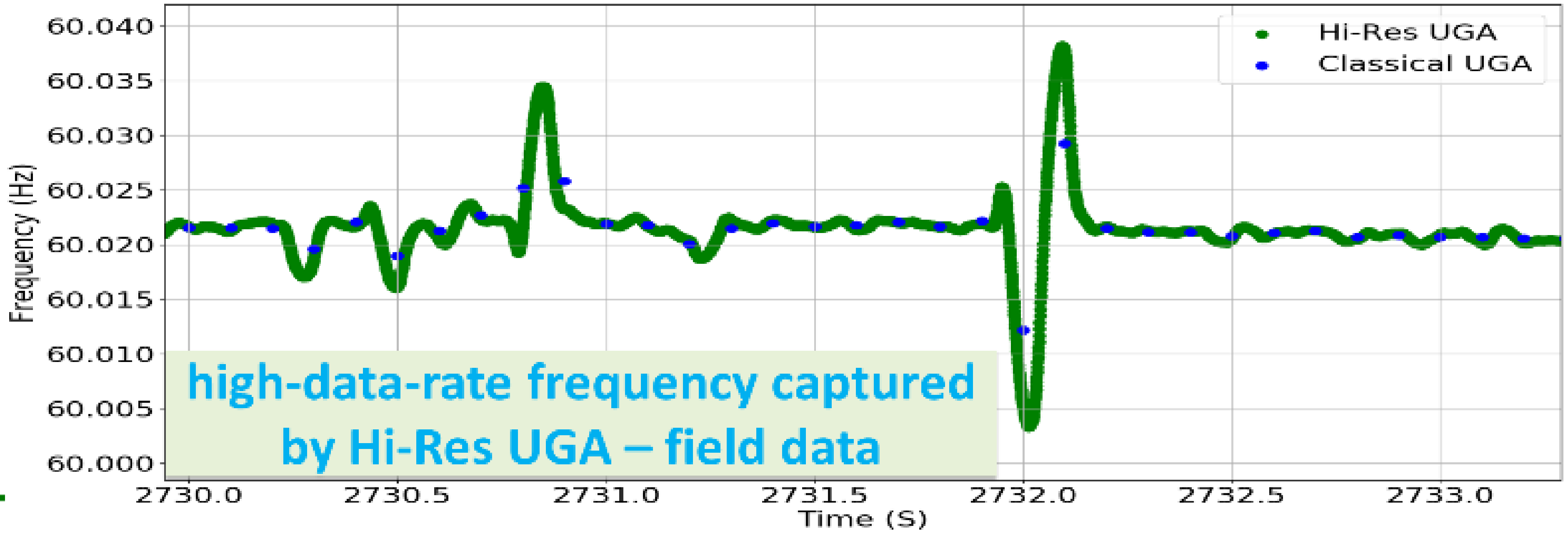


WECC case on 04/28/2020

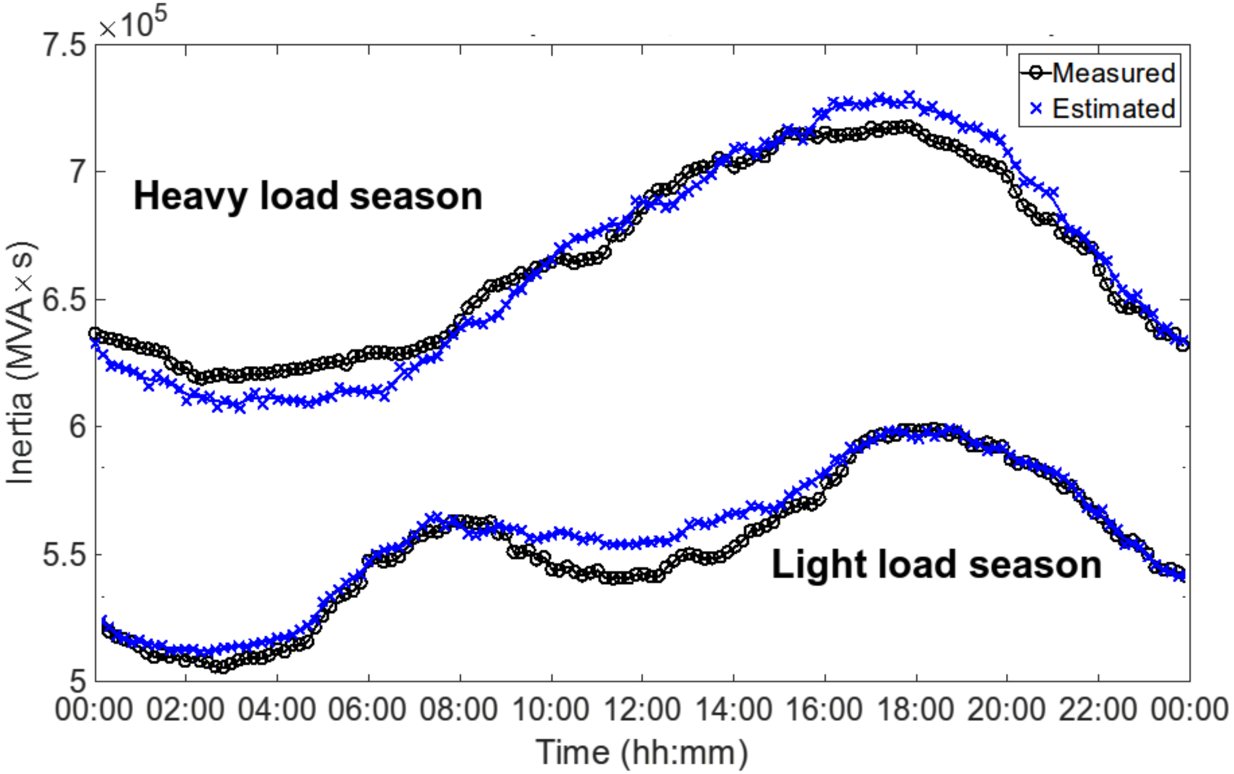


High Speed Frequency Estimation Algorithm Design and Implementation

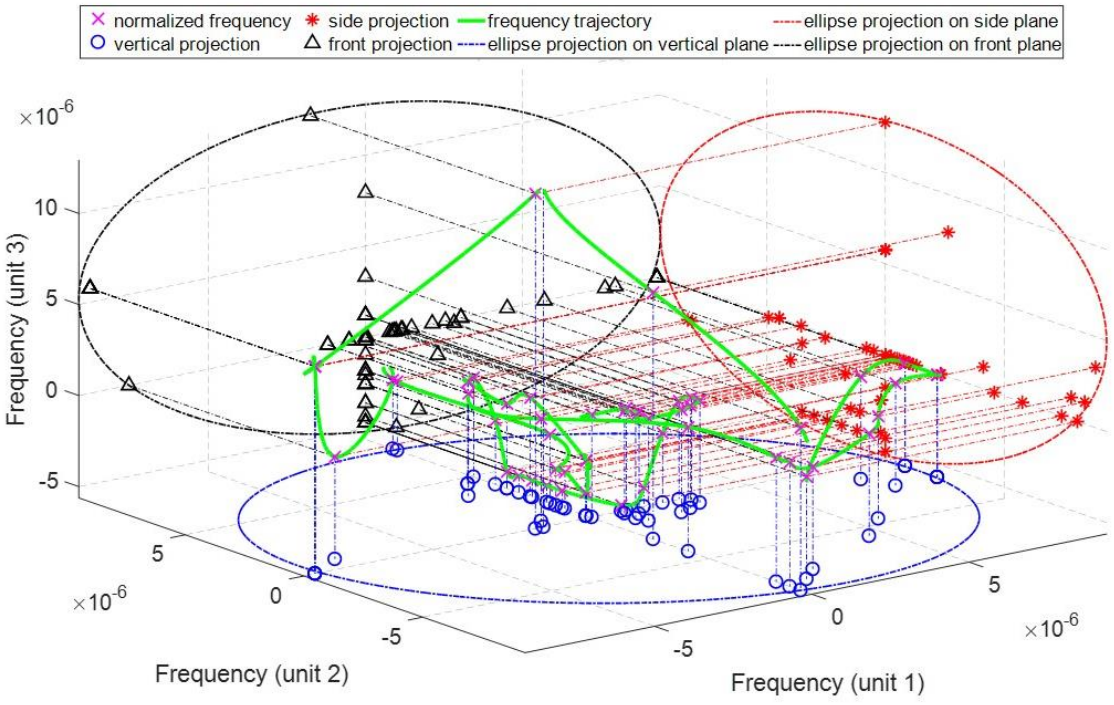




Grid Inertia Estimation by Machine Learning from Ambient Synchrophasor Data



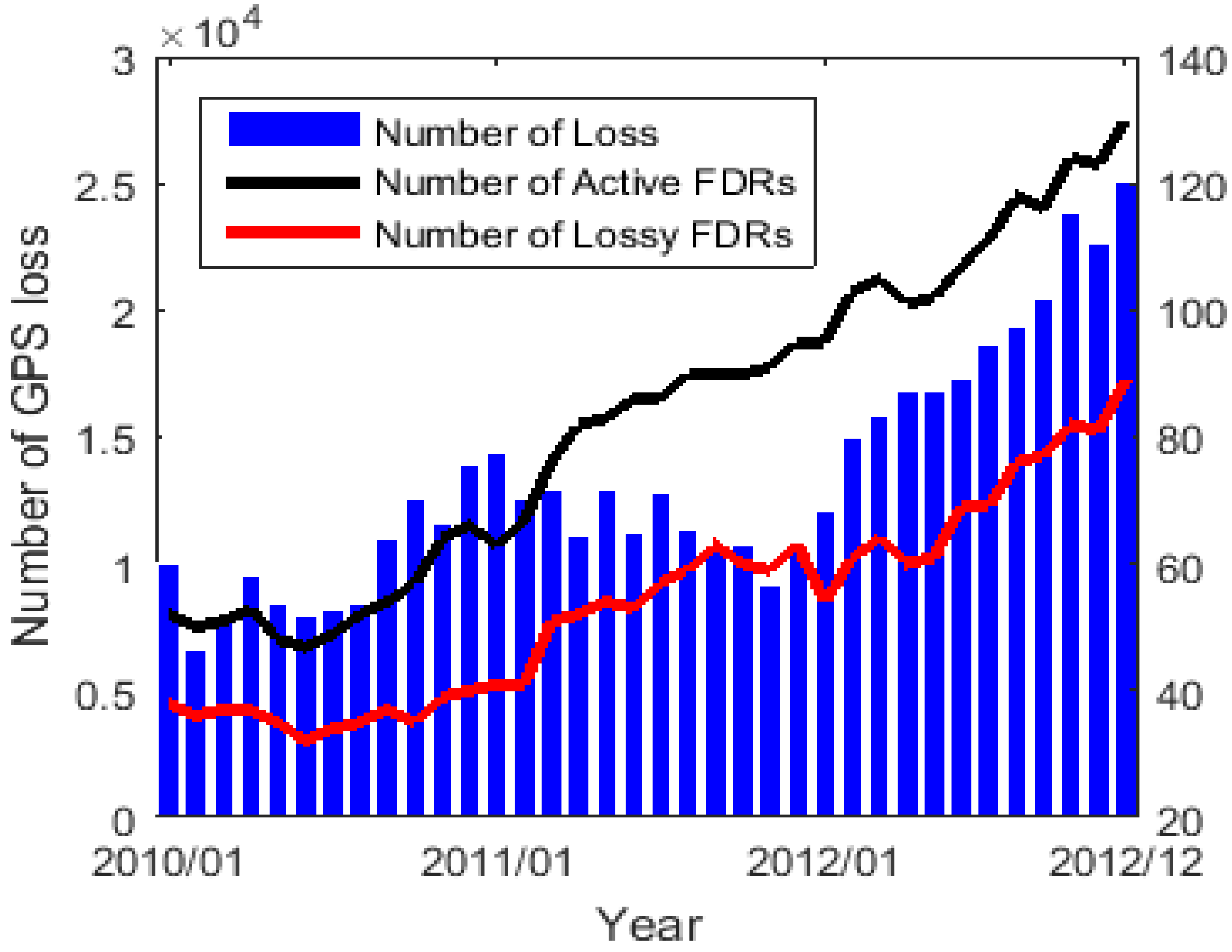
Comparison of measured and estimated daily inertia in WECC during heavy and light load seasons



Ambient frequency trajectory and the projection of characteristic ellipsoid at 100% inertia level

GPS Timing Signal Loss in FDRs and PMUs

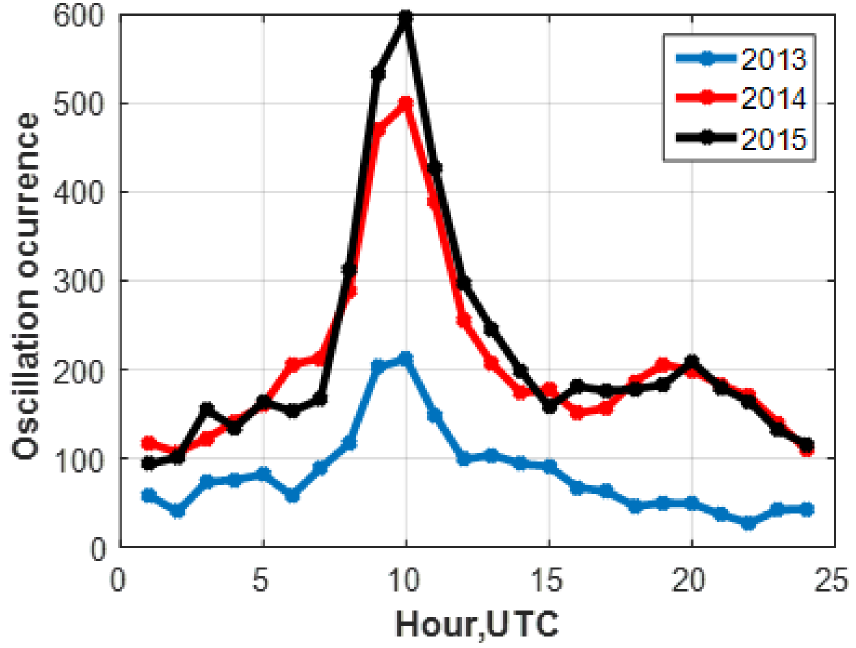
- Historical data from 80 PMUs and 100 FDRs from 2010 to 2012
- Over 50% of FDRs suffer from frequent GPS timing losses.
- Similarly, over 50% of sampled PMUs experienced GPS loss

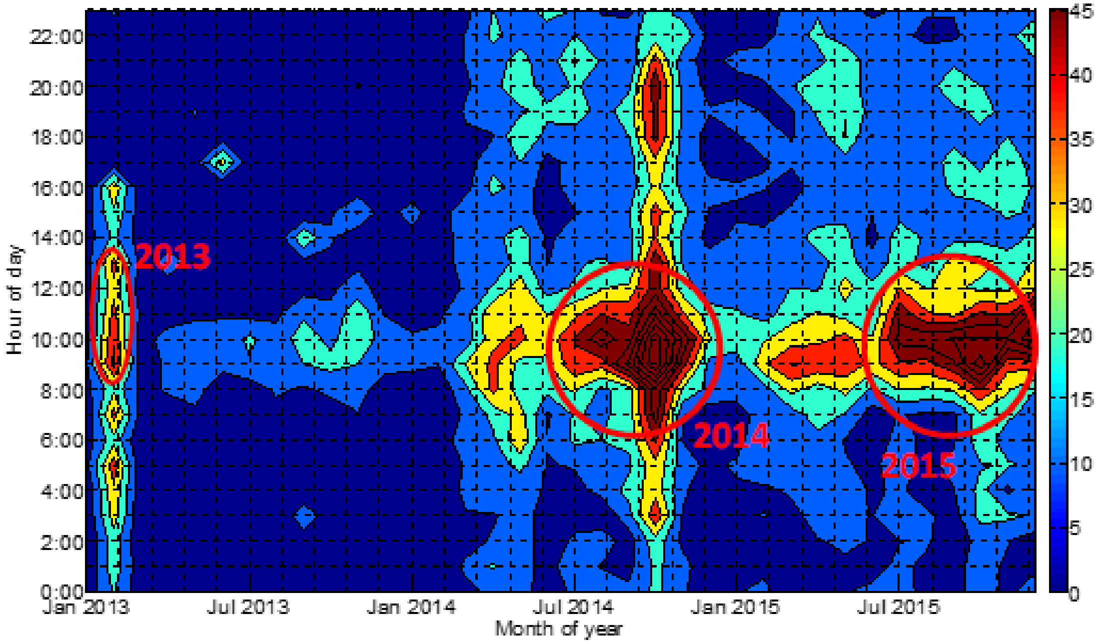


Number of FDR GPS losses from 2010 to 2012

Event Based Oscillations Analysis

- A total of 12,238 inter-area oscillations detected from 2013 to 2015 in EI with dominant frequency mode between 0.1 and 1.2 Hz were investigated.





The hourly oscillation occurrence indicates that more inter-area oscillations were detected around 4 am local time.

Acknowledgements

This work was supported primarily by the ERC Program of the National Science Foundation and DOE under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

Other US government and industrial sponsors of CURENT research are also gratefully acknowledged.