Edge Intelligent Devices and Cloud-based Analytical Platform for Behind-the-meter Solar Situational Awareness

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PSERC

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- **Hitachi America Ltd:** Dr. Bo Yang, Dr. Joseph Chongfuangprinya
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- **DOE Solar Energy Technologies Office:** Shay Banton, Robert Reedy, Dr. Hariharan Krishnaswami

Outline

- Overview of proposed solutions to address high PV penetration challenges
  - High penetration feeder models
  - Integrated, dynamic transmission-distribution analysis
  - Deep learning based dynamic hosting capacity (DHC)
  - Advanced DER (distributed energy resource) control
  - Attack-resilient DER cyber-physical system
- Edge intelligent devices (EIDs)
- Hardware-in-loop testbed
- Cloud-based end-end solar energy optimization platform (eSEOP) - Bo Yang
- Demo of eSEOP features and use cases – Joseph Chongfuangprinya

Challenges of high DER penetration and project goals

- Overvoltage and thermal violations, shortcomings of conventional mitigation methods
- Large reverse power flows and potential miscoordination of protection devices
- Potential for adverse control interaction among inverters, and with legacy control
- Power quality, safety issues with unintentional islanding
- **Lack of situational awareness especially behind-the-meter DERs, and T&D interactions**

- Goal of the project is to enable extreme levels of DER in distribution systems, while enhancing its reliability, resiliency, cyber security and power quality
- By a data-driven approach for planning, operation and control of distribution systems with **total situational awareness** afforded by a network of sensors, edge intelligent devices (EIDs), cloud-based analytical platform, and secure communications.

Solar situational awareness and control

eSEOP cloud platform

- Integration point of DER providing holistic view to grid operators
- Provides near real time visibility into DER generation, inverter grid-support, storage, loads and utility equipment
- Commands large numbers of DERs for feeder voltage, fault management

Edge intelligent device (EID)

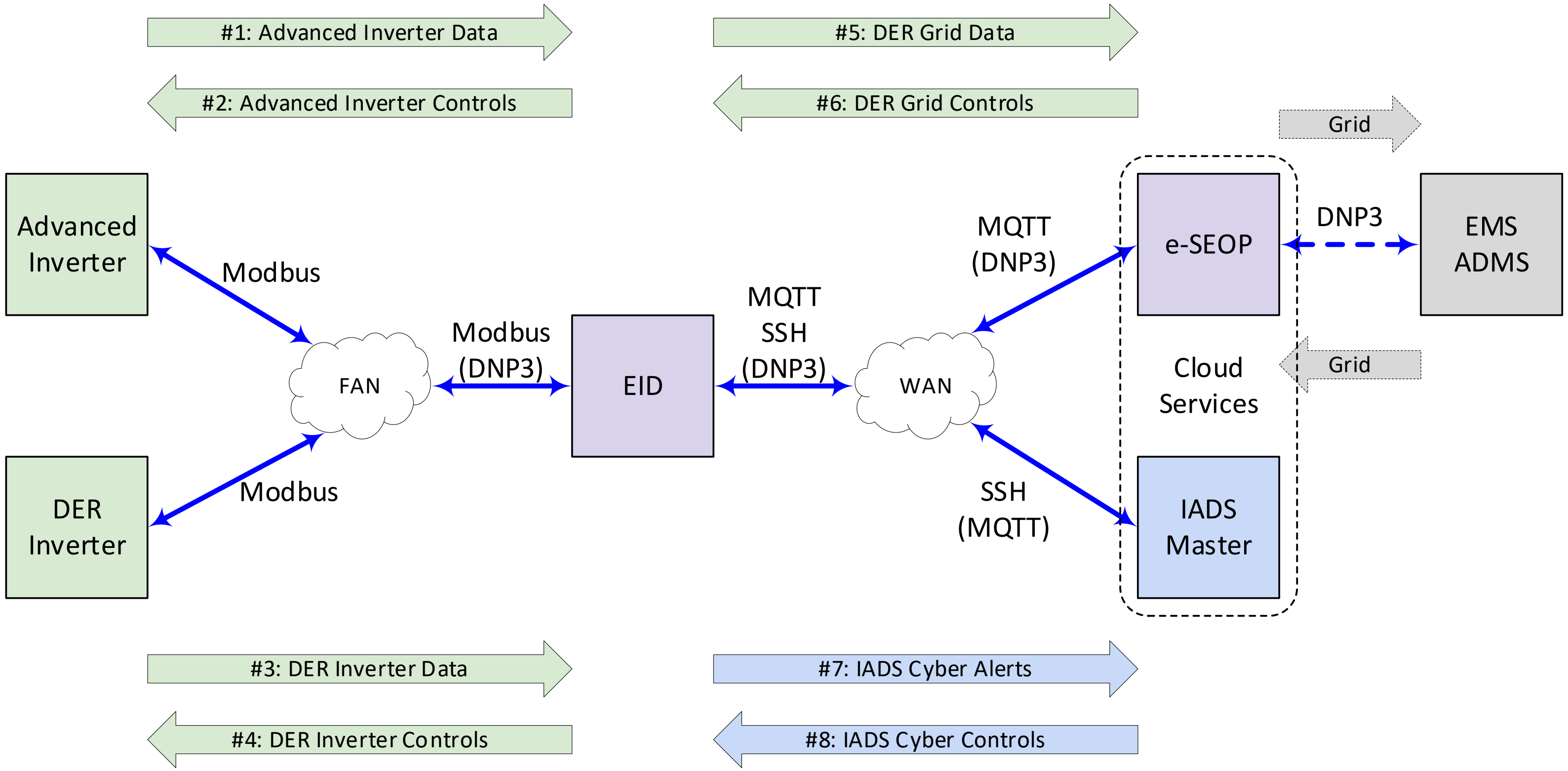
- Two-way interface between DERs & cloud
- Move data and processing closer to DER
- Optimize latency and autonomy

Advanced DER inverter

- Programmable control parameters, modes and settings; integrated sensors
- Robust control exploiting real-time information from EIDs

Cybersecurity

- Continuous monitoring for compliance with advanced protocols
- Real-time anomaly detection and monitoring critical cyber logs/events for resiliency



Some analytical modules in eSEOP cloud

Integrated T&D analysis	Dynamic hosting capacity	Integrated feeder voltage management	Integrated fault management

eSEOP: end-to-end solar energy optimization platform

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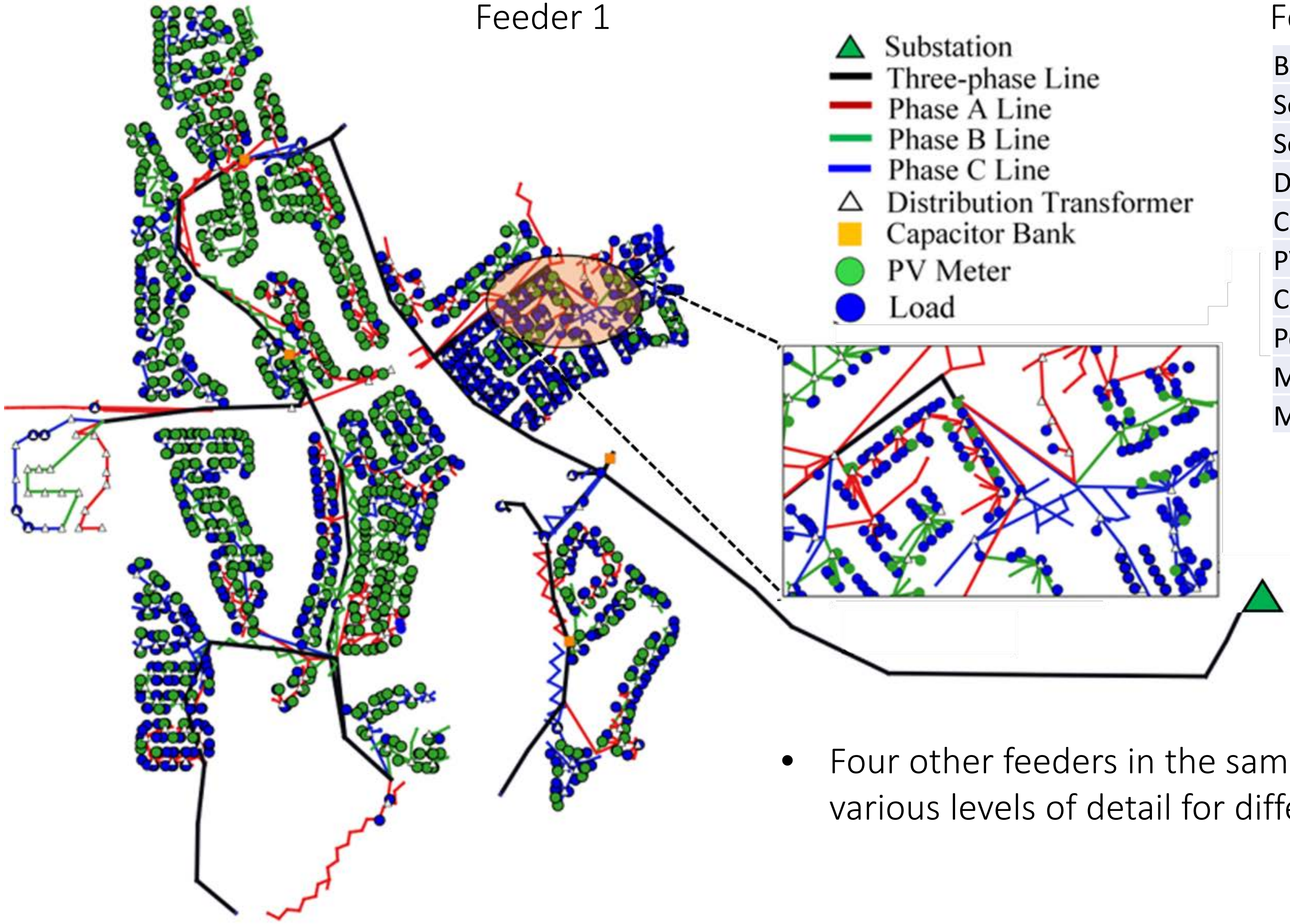
Modeled distribution feeder



Feeder 1

Buses	7862
Sections (primary)	1790
Sections (secondary)	5700
Distribution transformers	371
Customers	2474
PV systems	767
Capacitor banks	4 x 1.2 MVAr
Peak load	7.35 MW
Max. PV generation	3.8 MW
Max. instantaneous PV penetration	**236.84%**

- Four other feeders in the same substation also modeled in various levels of detail for different study objectives

Feeder modeling with GIS, AMI and SCADA data

- Available data:
    - CYME model including the secondary lines and loads
    - GIS data for all the sections and meters
    - Feederhead measurements at 5s resolution
        - P, Q, phase currents, and phase A voltage
    - AMI data (P and voltage) at most loads - hourly or 15-min
    - All PV production data at 15 min resolution
- OpenDSS model based on CYME data from utility and AMI/GIS data [1],[2]
- Time series model:
    - Active load/PV profiles – based on meter readings
    - Reactive power profiles: Optimization based on ACOPF and feederhead measurements to estimate individual Q_{load} to match AMI voltage measurements [3]

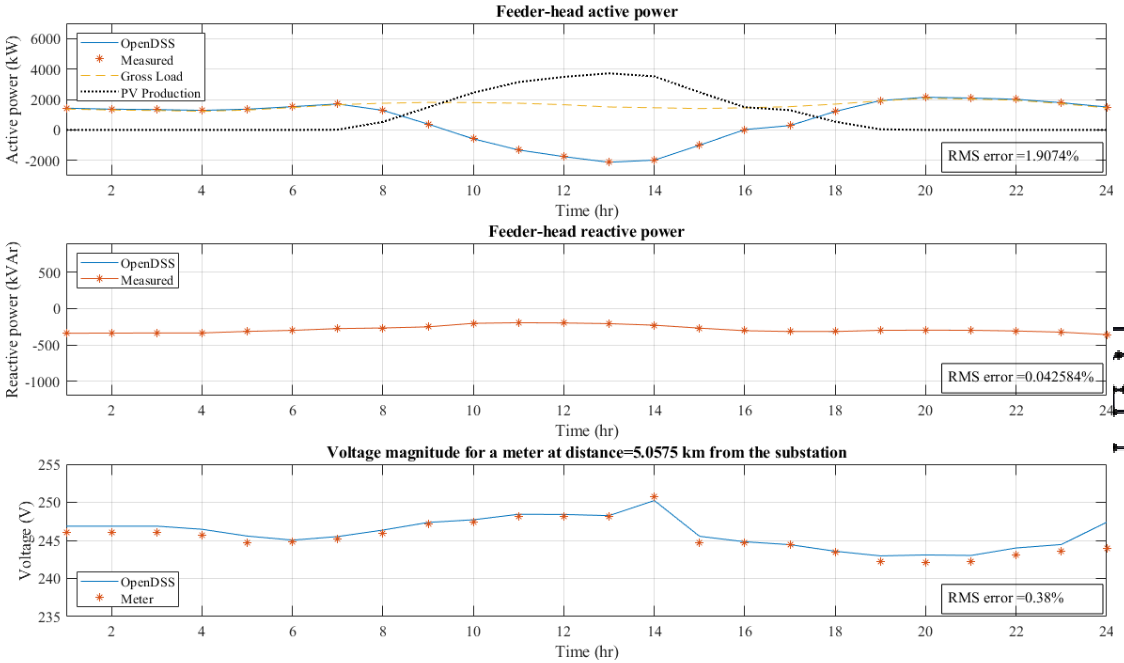
[1] K. Montano and S. Thakar, “DISMOTT: Distribution System Model Transformation Tool,” 2020. https://github.com/thakars/DISMOTT.

[2] K. Montano-Martinez, S. Thakar, V. Vittal, R. Ayyanar and C. Rojas, "Detailed Primary and Secondary Distribution System Feeder Modeling Based on AMI Data," *2020 52nd North American Power Symposium (NAPS)*, 2021, pp. 1-6, doi: 10.1109/NAPS50074.2021.9449779.

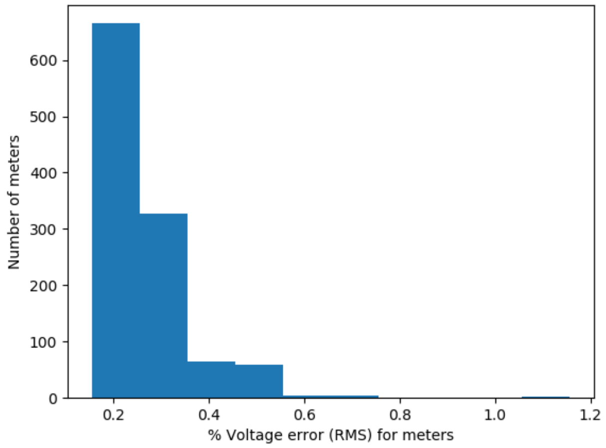
[3] Ongoing ARPA E project at ASU “Sensor Enabled Modeling of Future Distribution Systems with Distributed Energy Resources”

Model validation and some interesting cases

Graphs for March 15, 2019

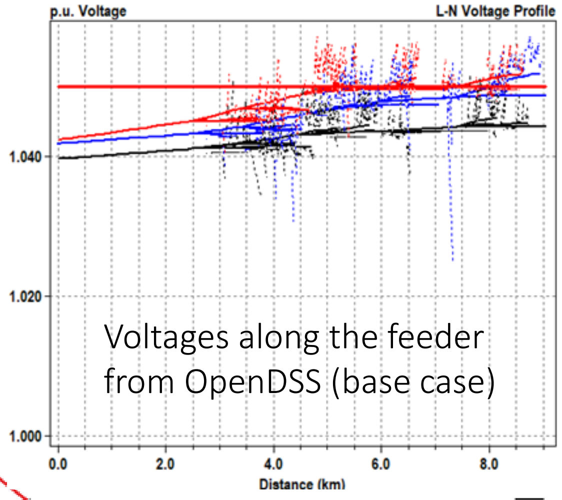


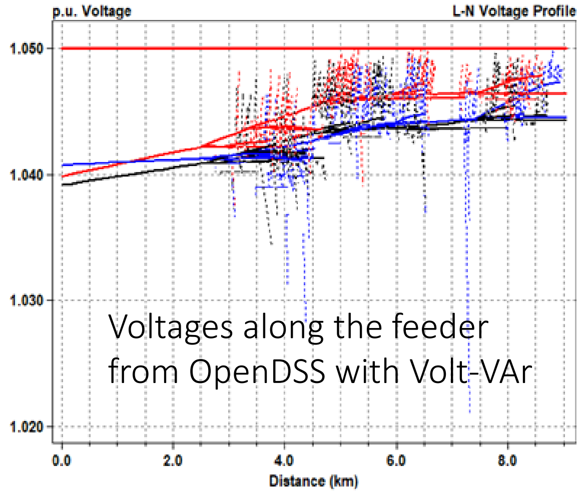
RMS errors for different meters computed for the day of 15 March 2019



13:00 March 15

- Red lines indicate reverse power flow
- Red dots indicate overvoltages





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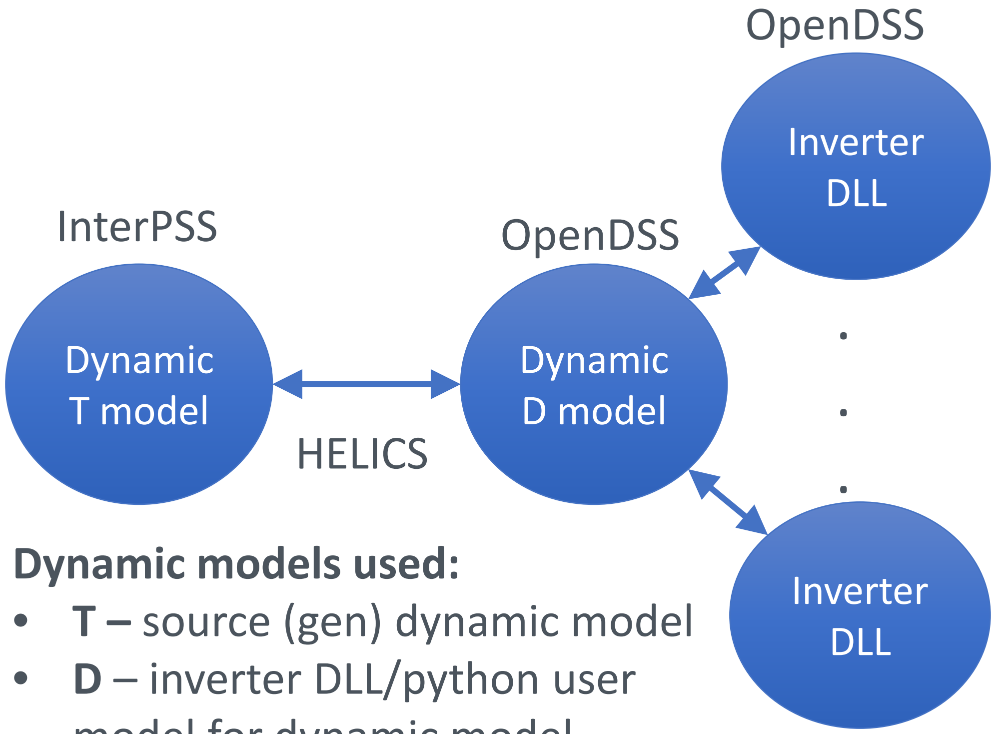
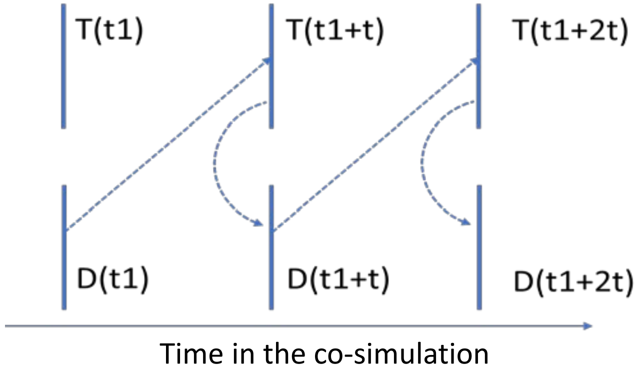
Integrated T&D dynamic co-simulation

- Critical to understand the mutual impact, protection, and hosting capacity
- Transmission system:
  - Three-sequence model of network in InterPSS
  - Dynamics of generators and any controls
- Distribution system
  - Unbalanced, three-phase model in OpenDSS
  - DER inverters, advanced control modeled in DLL
- HELICS for data coordination, conversion between 3-sequence and 3-phase, synchronization
- In each time step, the current injections from dynamic elements $I_x(X,V)$ obtained after integration to solve I=YV network solution

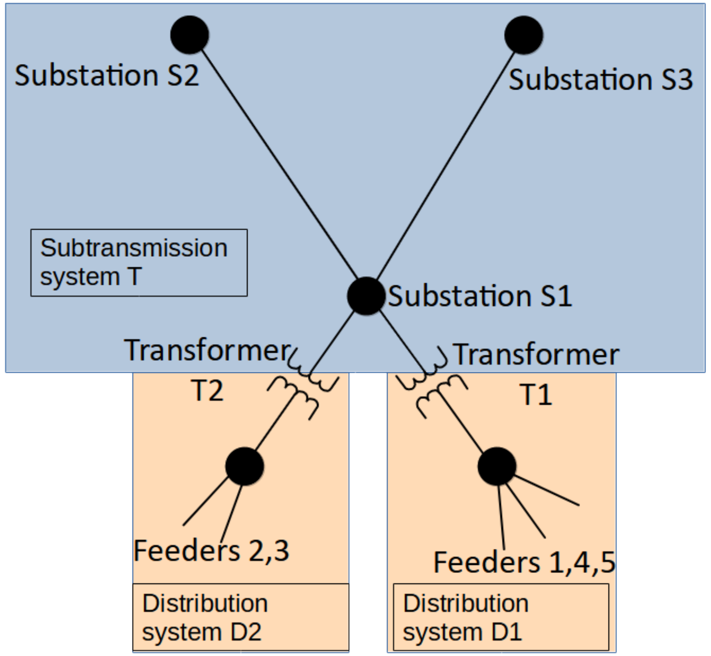


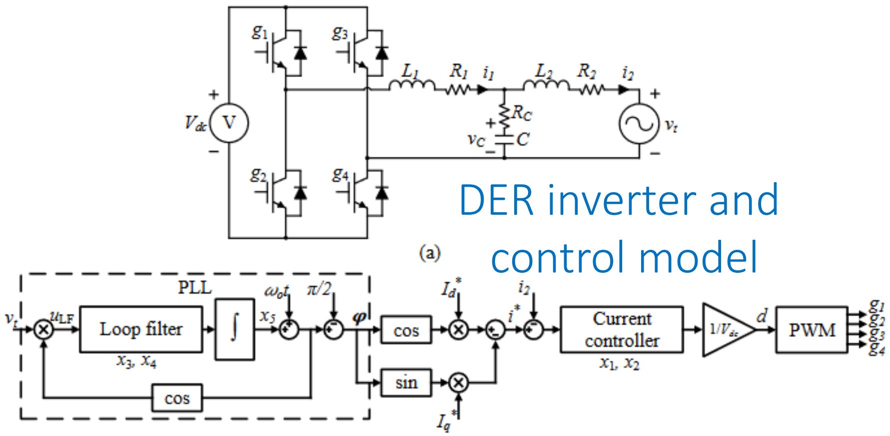
Dynamic models used:
- **T –** source (gen) dynamic model
- **D** – inverter DLL/python user model for dynamic model



T&D co-simulation: system model

- Feeder 1: detailed model with secondaries
- Feeders 2-5: detailed model, no secondaries
- Inverters (all 767) using custom user models
  - Dynamic phasors
  - Different P, Q control (IEEE 1547) modes, and detailed abnormal voltage response
  - OpenDSS DLL – using Delphi, python user model for use with dss-python
- Overcurrent protection at Substation S1
- Network time series results verified with measurements, and DLL verified with PLECS
- Balanced/unbalanced faults on distribution/su transmission system studied



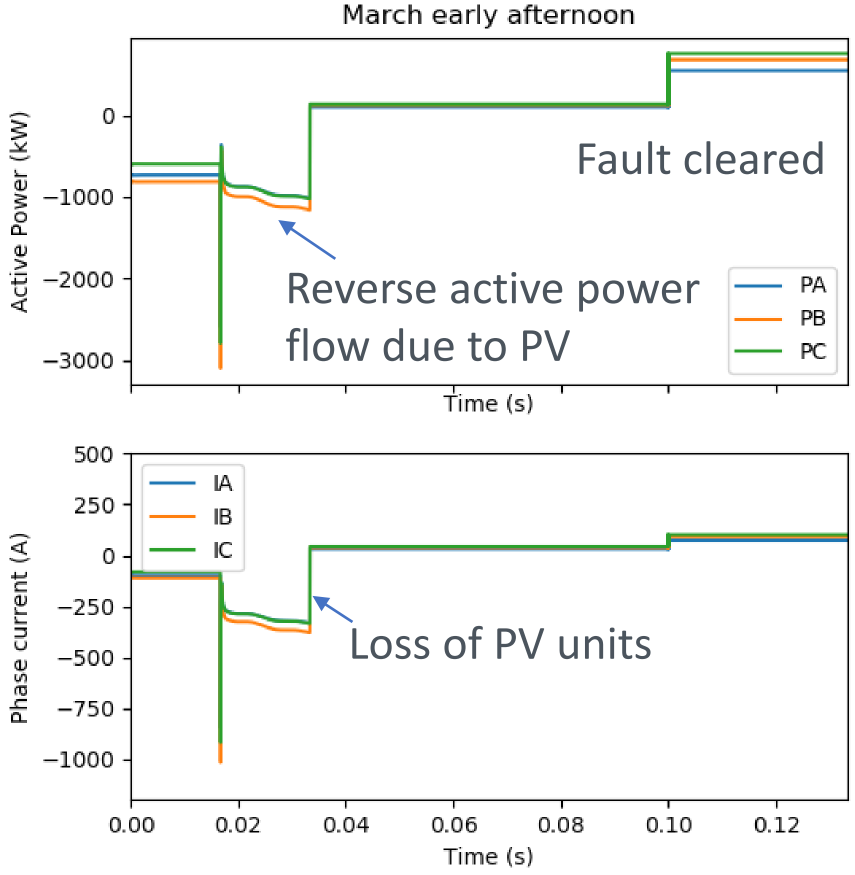


DER inverter and control model

Dynamic T&D co-simulation: initial results

LLLG fault on sub-transmission system [4]:

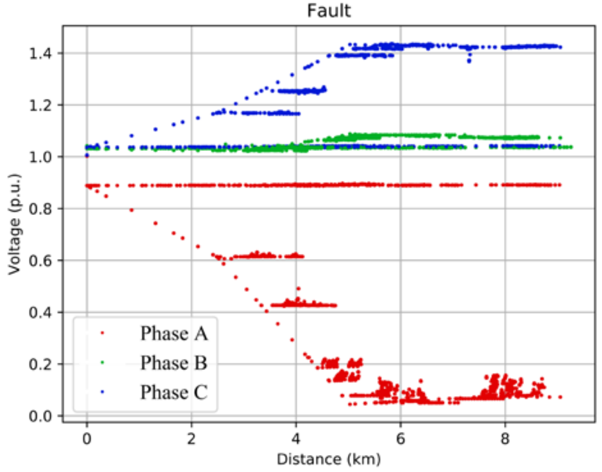
All solar PV units trip due to low voltage



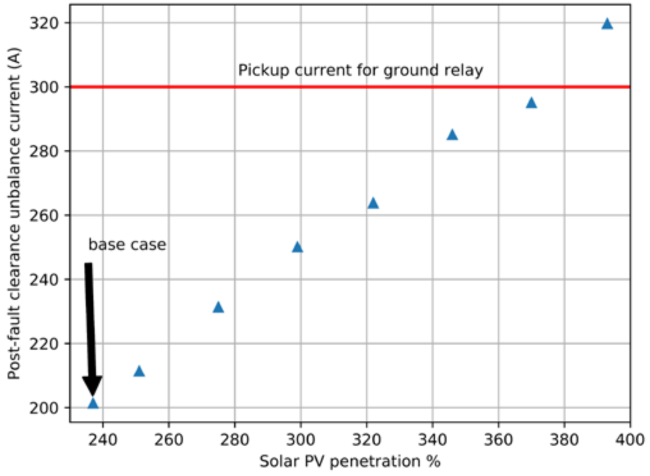
SLG fault in Feeder 1:

- Low voltage on faulted phase A, high voltage on phase C
- Solar PV units on phases A and C trip
- Unbalance after clearing the fault increases
- At higher penetration, unbalance enough to cause ground relay to trip

Voltage profile during fault



Post fault-clearance unbalanced current vs. PV penetration level



[4] S. Thakar, V. Vittal and R. Ayyanar, “An Integrated Transmission-Distribution Co-Simulation for a Distribution System with High Renewable Penetration,” IEEE 48th Photovoltaic Specialists (PVSC) conference, June 2021, Miami-Fort Lauderdale, FL.

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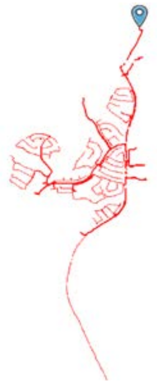
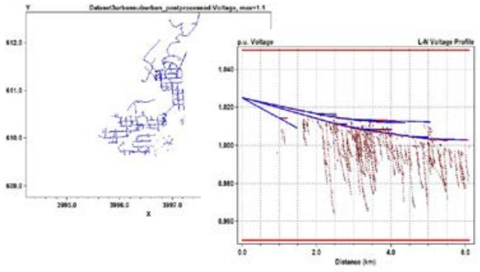
Deep learning-based hosting capacity analysis: objectives



Feeder data file

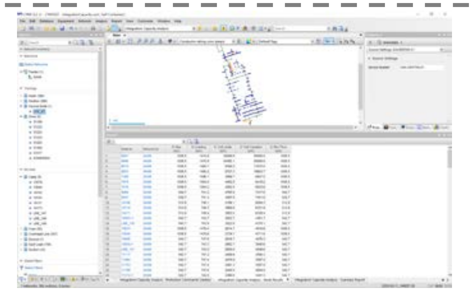
→

Topology
Power Flow Analysis
Short-Circuit Analysis



Deep Learning
Algorithm in Python

Hosting Capacity Analysis
in CYME



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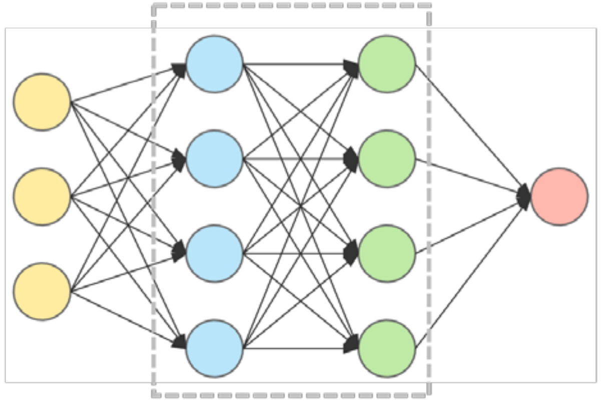
Neural Network Model Edited in Python

Features: Network Settings

Input 1: Thévenin Impedance
Input 2: X/R ratio
Input 3: Load Factor
Input 4: Thermal limit
Input 5: Power Factor
Input 6: Voltage Threshold
Input 7: Asymmetric fault
…

→



Label: Generate from CYME

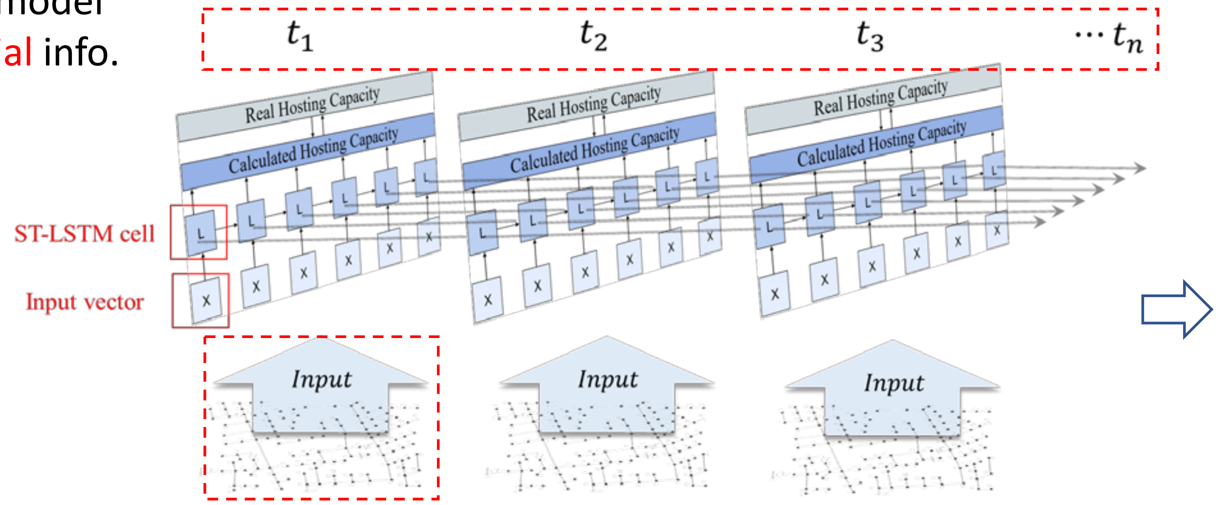
→ Output:
Hosting Capacity

Deep learning-based hosting capacity: approach

- Which DL model to use for HC analysis?

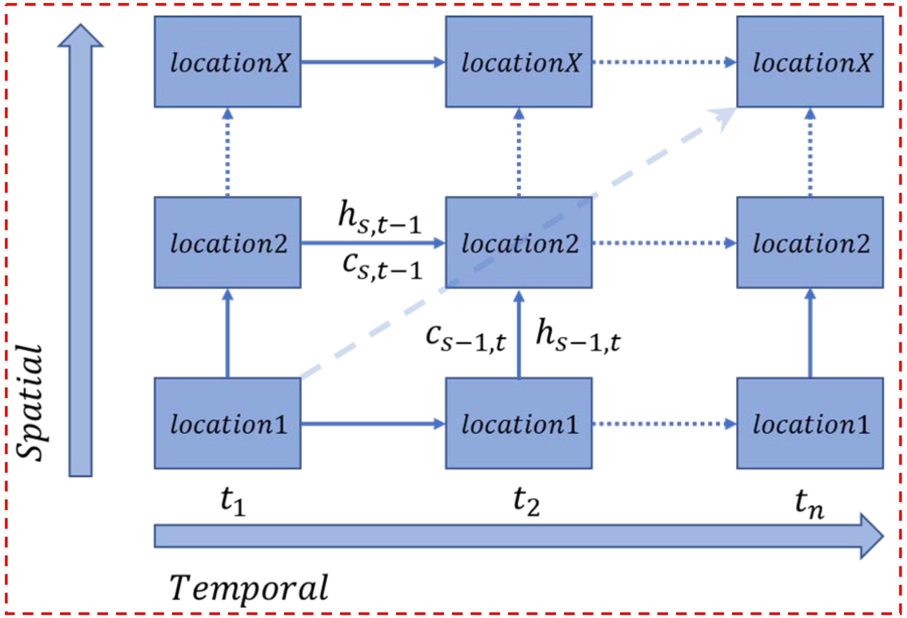
Power system data (Input) → **Deep learning model** → Hosting capacity (Output)

Well-formed model with sequential info.



- Time-series data (Temporal correlation).
- Connections of buses (Spatial correlation).

Proposed deep learning model: **ST-LSTM.**



(Spatio-Temporal Long Short-Term Memory)

Deep learning-based hosting capacity: some results

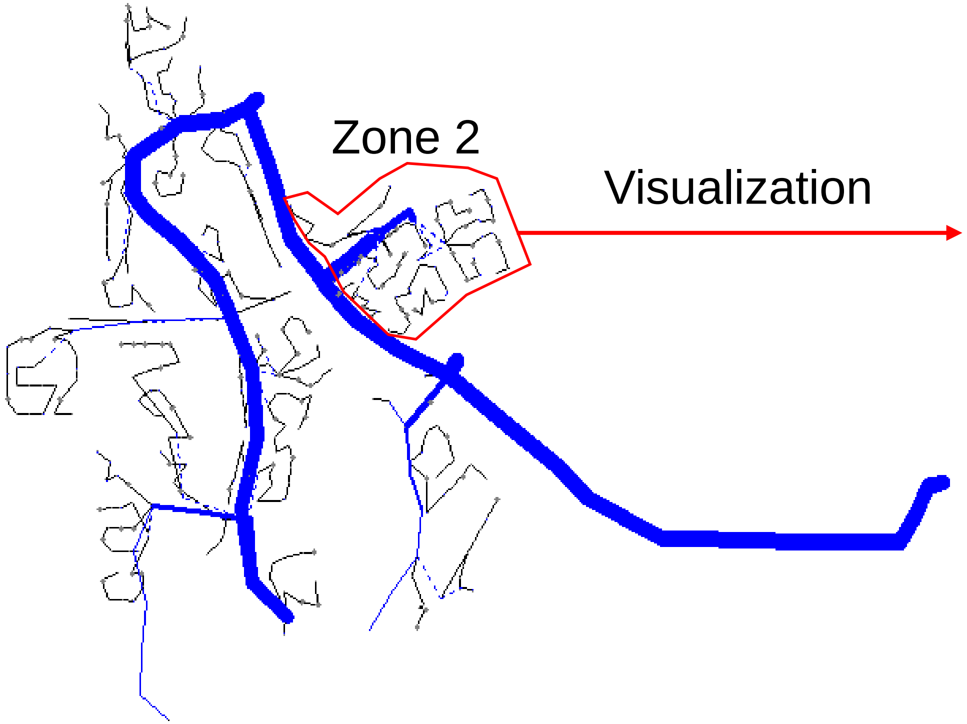


Table: Average percentage error in different zones using the ST-LSTM model.

Zone Index	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Avg. Percentage Err.	**2.6%**	**4.4%**	**6.6%**	**5.9%**	**6.0%**

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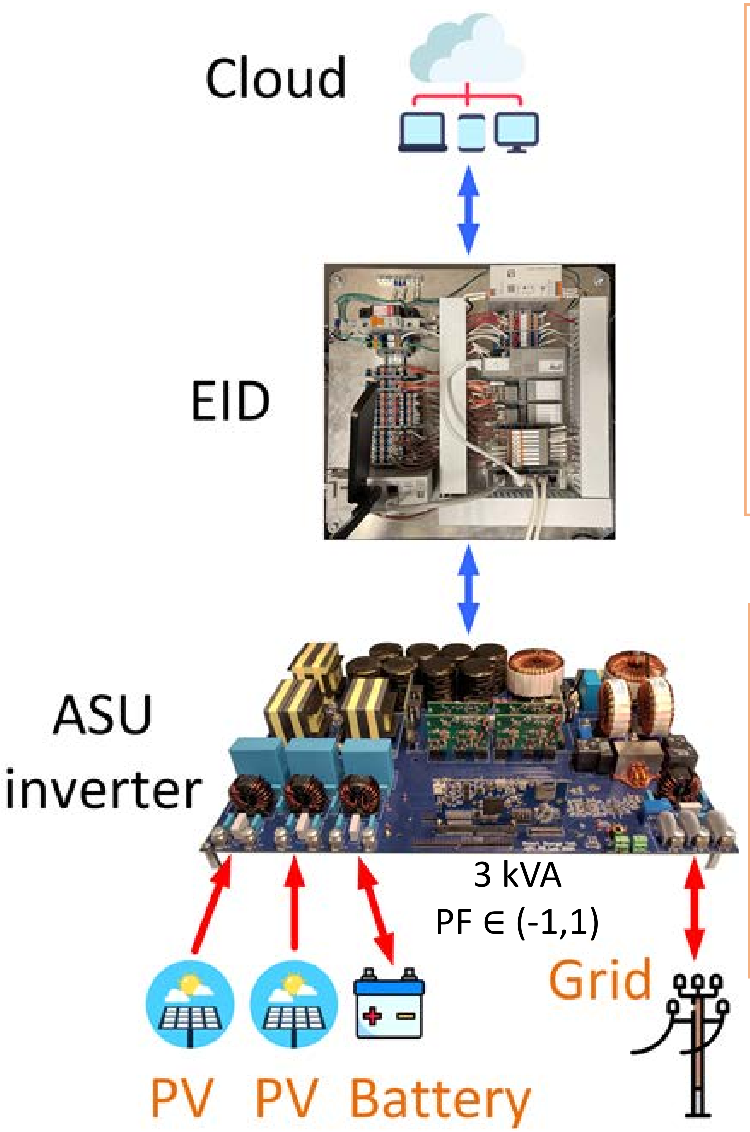
Advanced DER inverter development

1547 modes with controllable settings

Real-time controlled
- Power Factor
- Reactive power
- Volt-VAr settings
- Volt-Watt settings
- Q-P settings

High pen. support

- H-inf control for range of PCC characteristics
- Integrated sensors
- EID programmable control parameters
- Fault support with V and f ride-through
- Energy storage



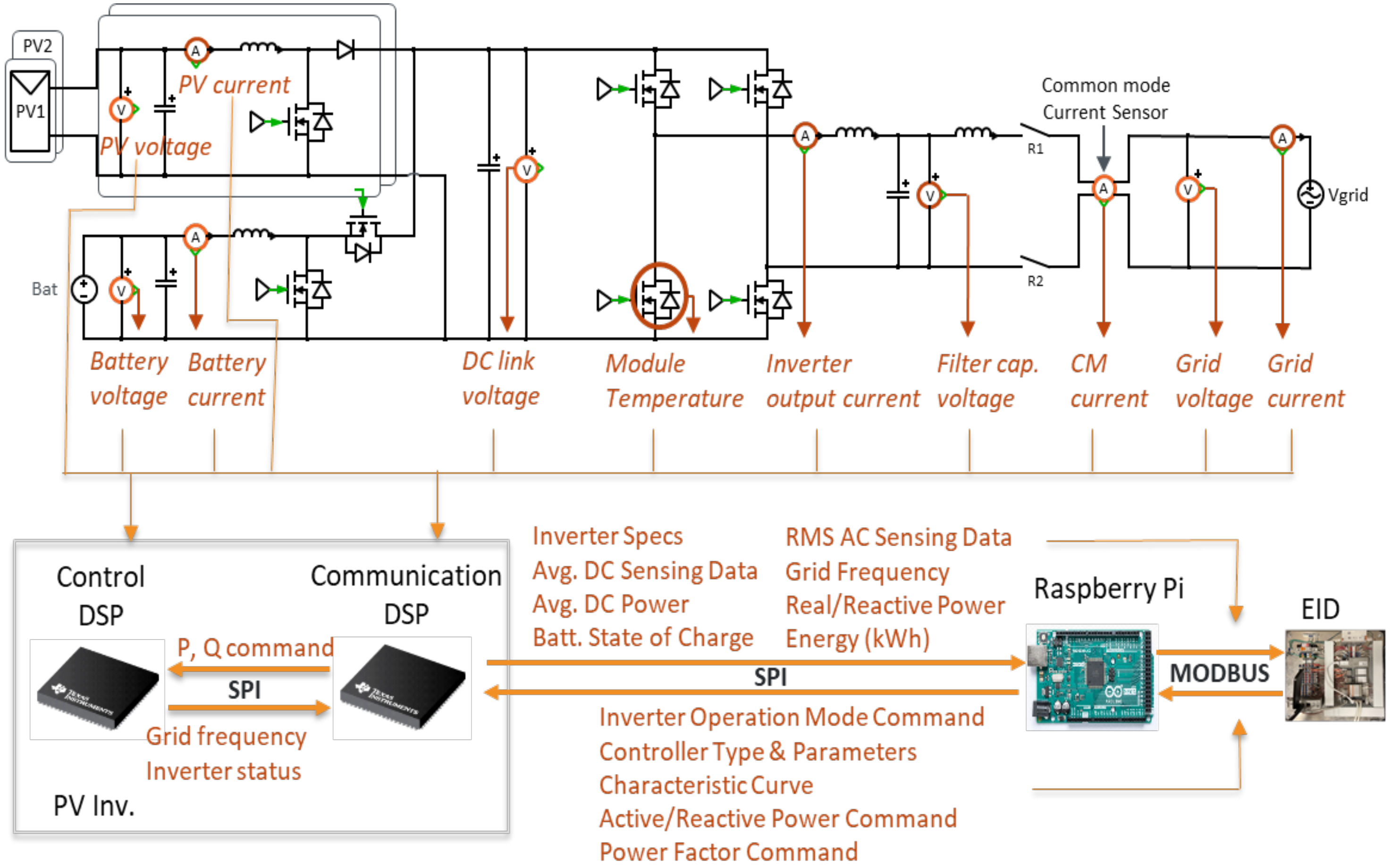
Communication & Interoperability

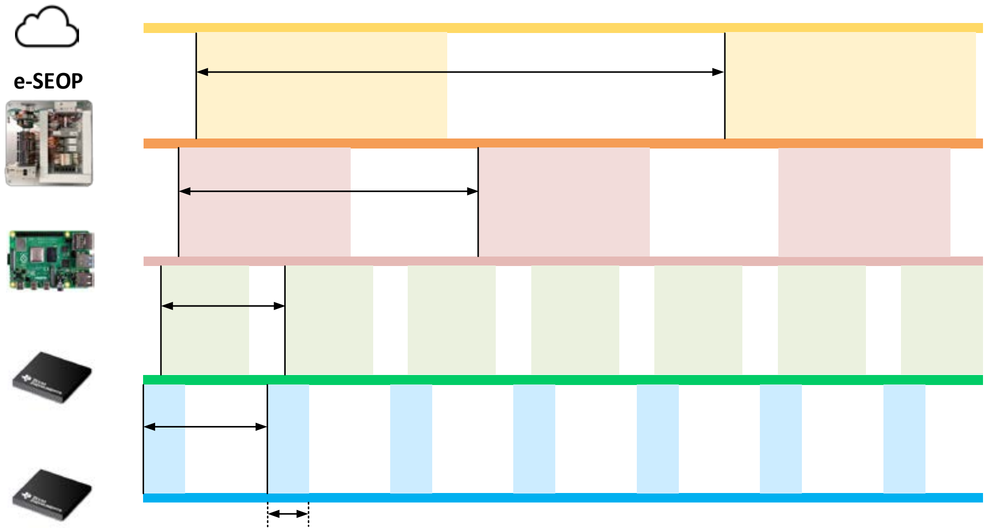
- Bidirectional Data Exchange with EID and Cloud
- High resolution data and high update rates
- Fast response to cloud/EID commands

Inverter cluster coordination

- Active/reactive power sharing
- Advanced droop algorithm
- Grid forming capability
- Grid characteristic estimation

DER inverter and communication design



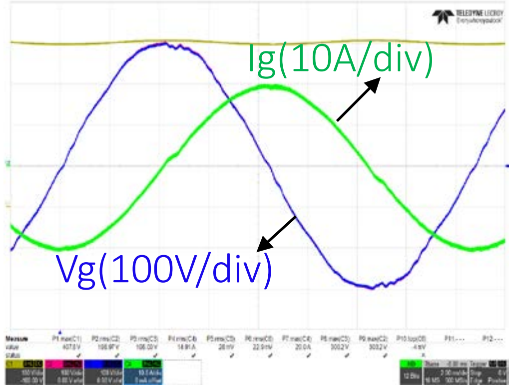


- One data exchange (command & status) within a switching cycle (55.5 us) in DSPs
- Data resolution of 1 set of data per fundamental cycle
- Data update rate of 1 cycle for low layers and 6 cycles (100 ms) for EID

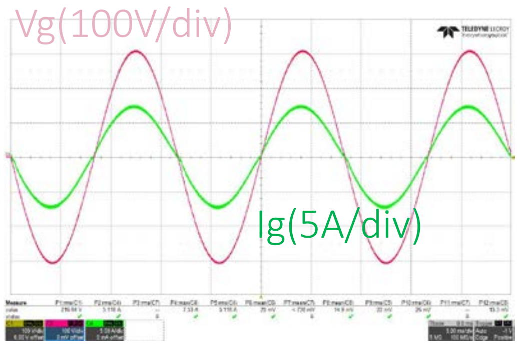
- Two DSPs for control & communication
  - Boost data transmission capacity
  - Minimize interference on control

Y. Si, N. Korada, R. Ayyanar and Q. Lei, "A High Performance Communication Architecture for a Smart Micro-Grid Testbed Using Customized Edge Intelligent Devices with SPI and Modbus TCP/IP Communication Protocols," in *IEEE Open Journal of Power Electronics*, vol. 2, pp. 2-17, 2021

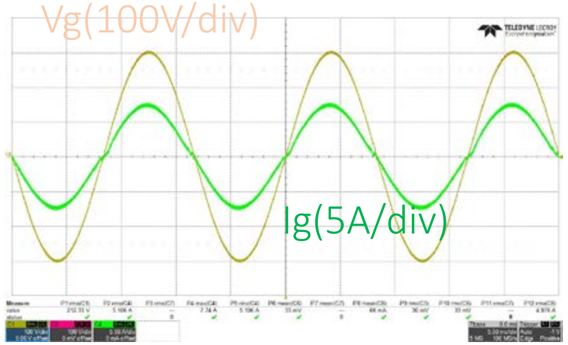
Some experimental results from ASU inverter



Night-time VAr support with 3 kVAr reactive power and 0 real power

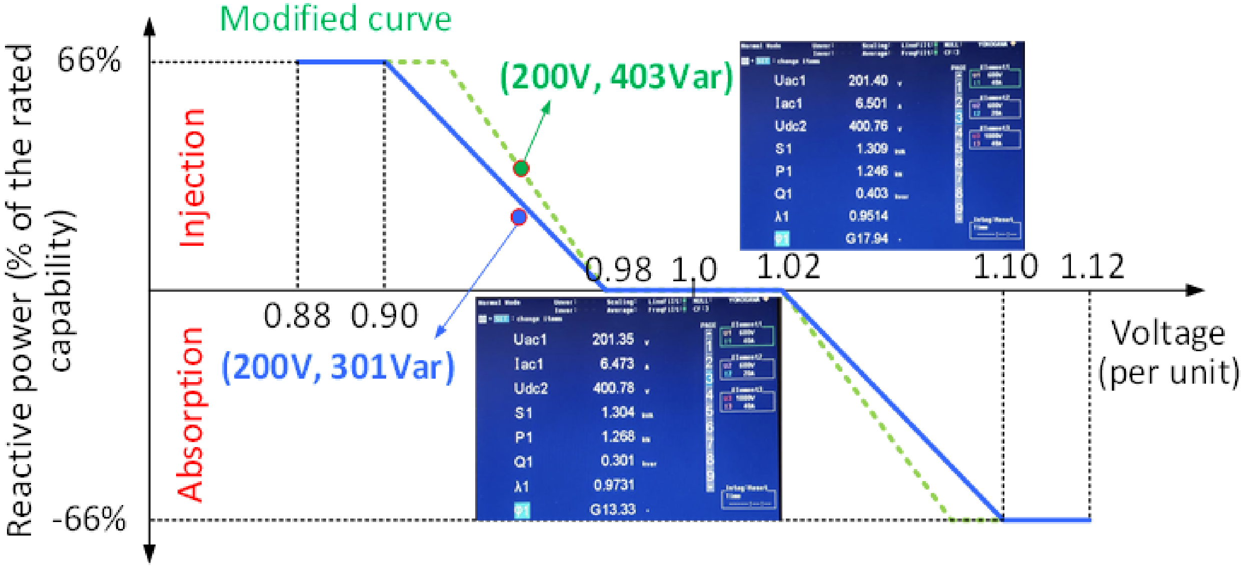


Low grid impedance case



High grid impedance case

Stable UPF operation with H-infinity current controller under different grid impedances



- Volt-Var operation under different Q-V curves
- Online change of the Q-V curve by EID through Modbus

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Cybersecurity for DER – Iowa State University

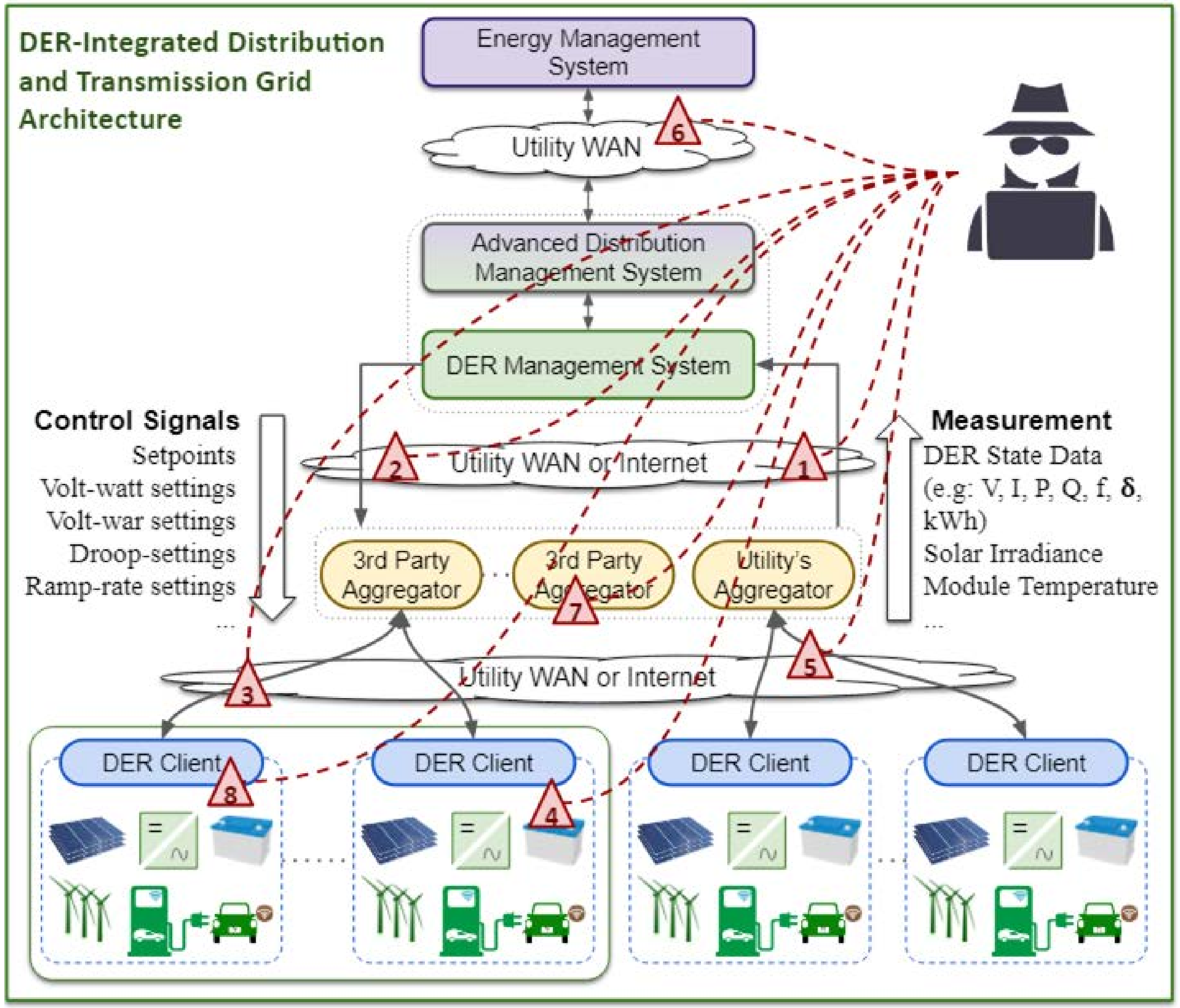
- Intrusion Detection System for DER
- Anomaly Detection System for DER
- Two-tier implementation architecture – IDS/ADS Sensors and Master
- Testbed-based end-to-end system integration and security evaluation

Team members: M. Abdelkhalek, G. Ravikumar, and M. Govindarasu

Overview of attack surface & cybersecurity

Cyberattacks

1. Data-integrity attacks on measurement signals
2. Data-integrity attacks on control signals
3. Malicious DER commands send through WAN
4. Ransomware-like attacks on DERs and/or Aggregators
5. DOS/DDOS attacks on DER clients and/or aggregators
6. Data-integrity attacks on WAMPAC
7. Attacks from cloud with Aggregator connectivity
8. Attacks from 3rd parties with DER interconnectivity



Cybersecurity

- Device-level cybersecurity
- Network-level cybersecurity
- Protocol-specific/Application-specific cybersecurity
- Intrusion/anomaly detection/prevention systems
- Standards like NERC CIP, C2M2, NIST
- Security Information and Event Management
- Defense-in-Depth layered cybersecurity
- Physics-based and Cyber-logs based cybersecurity and resiliency

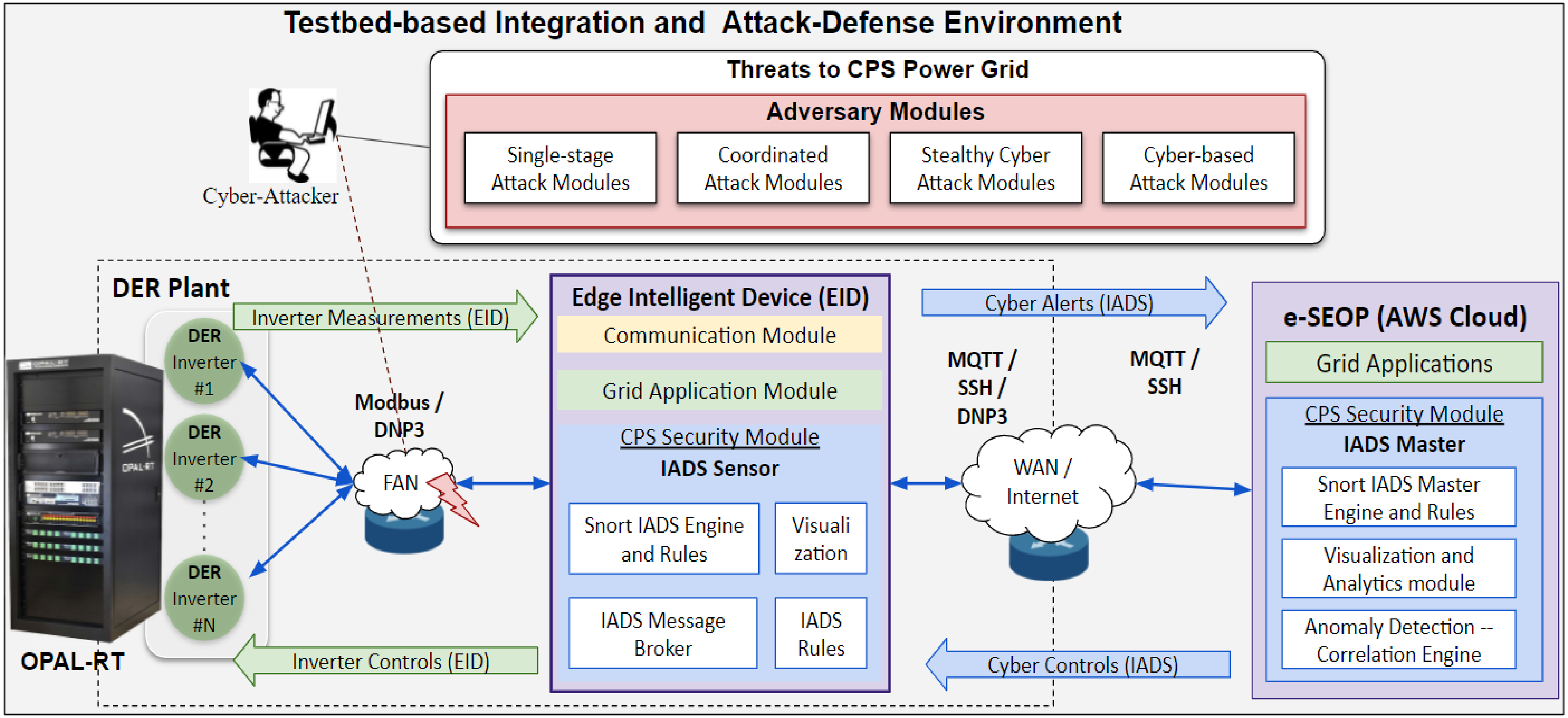
DER Intrusion and Anomaly Detection System (IADS)

- Design of rule-based IDS for Modbus and DNP3 protocols
- Testbed-based, end-to-end implementation with Opal-RT, PV inverters, EID platform and cloud
- Performance evaluation of IDS quantifying IDS's detection accuracy and latency characteristics (for efficacy and feasibility)

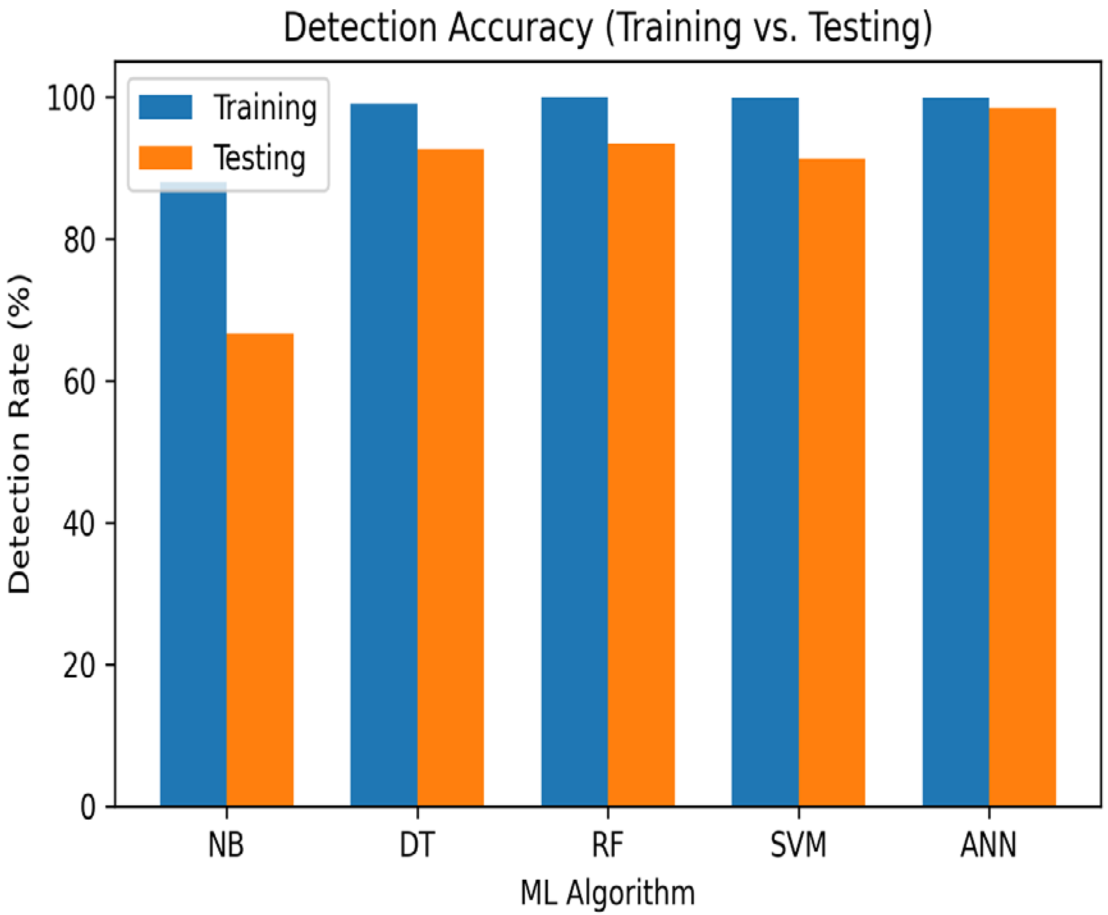
G. Ravikumar, A. Singh, J. R. Babu, A. Moataz, and M. Govindarasu," D-IDS for Cyber-Physical DER Modbus System - Architecture, Modeling, Testbed-based Evaluation" in Proc. of Resilience Week Symposium (RWS), 2020. https://ieeexplore.ieee.org/document/9241259

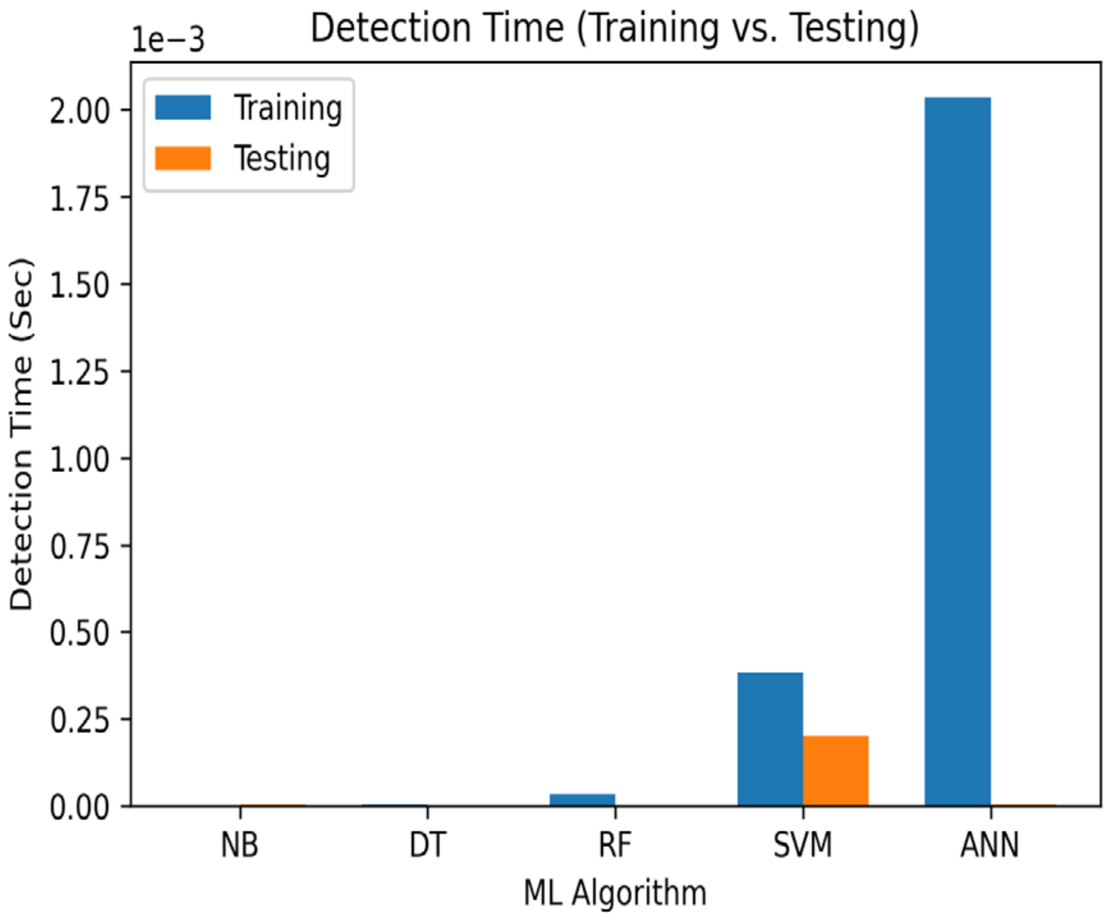
- Design of ML-based ADS for Modbus and DNP3 protocols
- Creating realistic datasets, by augmenting existing IT datasets, for DER security evaluation
- Training and studying the performance of multiple ML models and algorithms
- Performance evaluation of ADS quantifying detection accuracy and latency characteristics (for efficacy and feasibility)

End-to-end IADS implementation architecture

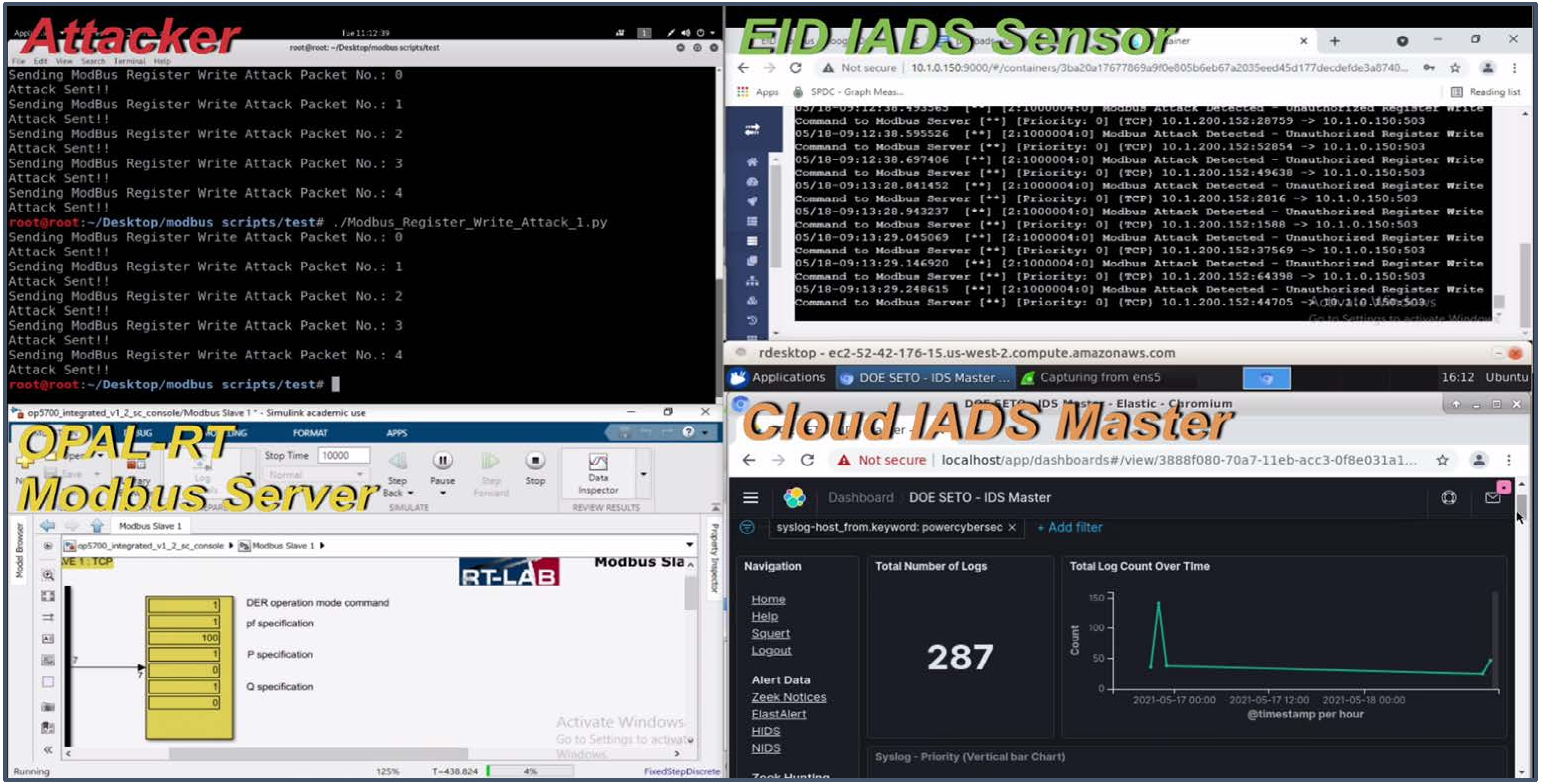


ML-based Anomaly Detection Evaluation





End-to-end IADS attack detection evaluation



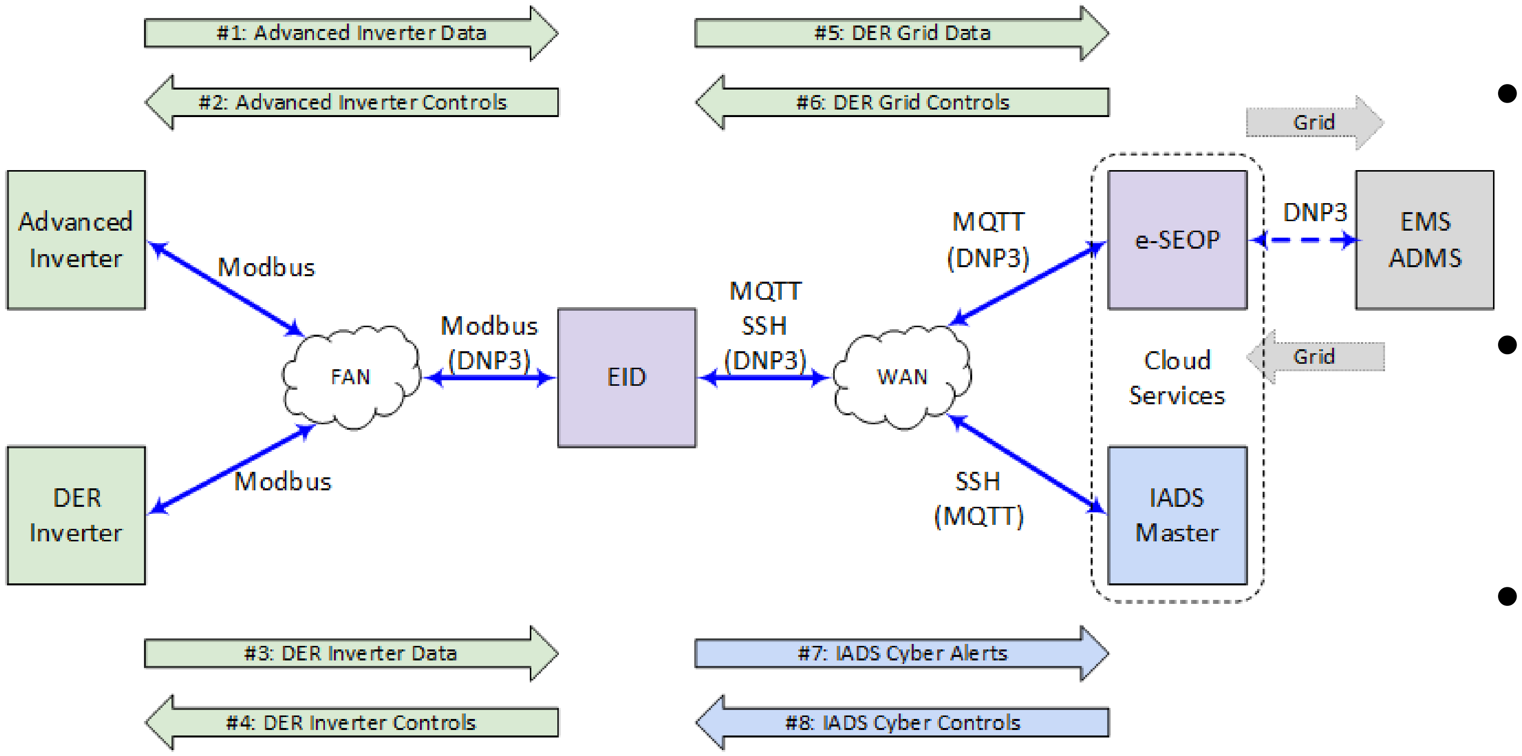
Edge Intelligent Devices (EID) – Poundra LLC

Team members: Dr. Devarajan Srinivasan and Kunal Shah

Why edge computing

- Edge computing topology
  - Use intelligence (computing power) in DER local interaction (data and control)
  - Optimize latency, autonomy, and security
- Edge relationship to cloud in DOE-SETO project
  - Communication can be initiated by cloud or edge
  - Edge & cloud are both required to achieve situational awareness
  - Cloud-edge in our architecture is many-many relationship

ASSIST communication architecture



Connectivity Options – FAN & WAN

- Hardwired – **Copper** or Fiber
- WiFi
- Bluetooth
- **Cellular**
- RF (including MIMO)
- Satellite

- Extend reach of secure utility systems to non-utility DER (including BTM)
- Provide secure, aggregated, high-quality data to utilities and other stakeholders
- Implement OT cyber-physical security
  - Go beyond IT firewall rules
  - Rule based intrusion detection
  - Machine learning based anomaly detection

Edge intelligent device (EID)

- EID designed as a *platform*
  - Set of tools and capabilities that are vendor agnostic
  - Built on COTS (Commercial-Off-The-Shelf)
- 10 DERs supported with 500 tags total
- 1s scan rate of connected DERs – all 500 tags
- Local storage – at least 6 weeks of historical data and events

EID feature comparison

Feature	Utility Data Concentrator	EID
Ruggedized industrial hardware	✓	✓
Multi end device (DER) hardware interfaces	✓	✓
Cloud communication channels	✓	✓
Digital and Analog IO	✓	✓
IEC61131 – Real time and industrial automation	✓	✓
Local storage historian	✓	✓
Standard utility/industrial protocols	✓	✓
Protocol conversion	✓	✓
Time synchronization – GPS, NTP, PTP	✓	✓
Machine-to-machine (peer) communication	✓	✓

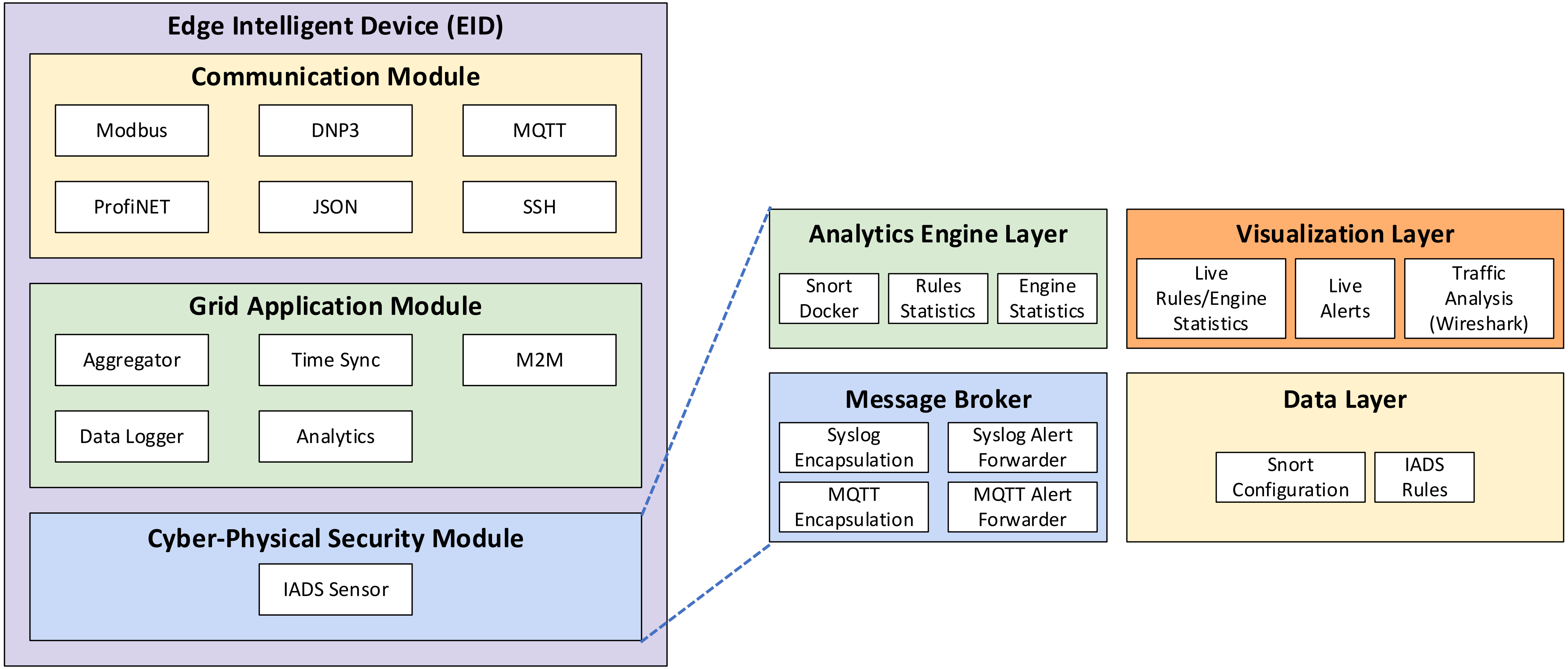
EID feature comparison

Feature	Utility Data Concentrator	EID
IT firewalls and user authentication	✓	✓
NERC CIP and CAISO RIG certified	✓	✗
Open platform – Linux OS access	✗	✓
High level language support – Python, C++, Matlab	✗	✓
Use open-source libraries, containers, and software	✗	✓
Protocol development e.g., IEEE 2030.5, non-standard, or future	✗	✓
Intrusion and anomaly detection	✗	✓
IOT protocols for cloud (AWS, Google, Azure) integration	✗	✓
Vendor agnostic COTS platform	✗	✓

EID and e-SEOP advantages

- Advantages over DER vendor-provided cloud services:
  - IOT protocol support – use flexible, secure, scalable, commercial cloud services
  - Aggregate data – multiple vendors, device types (i.e., revenue meters, meteorological systems) – highly adaptable to new devices
  - Ensure high data quality at edge and cloud
  - High temporal resolution – 1 second or faster data from DER
  - Multi-stakeholder (e.g., utility, ISO, system owner, energy management companies), siloed and secure data access
  - Enable advanced toolsets – dynamic hosting capacity, integrated T&D, machine learning, quasi-real-time load flow, OT cyber-physical security

EID software architecture



EID platforms chosen for implementation

- COTS (commercial off-the-shelf)
  - Proven long life in multiple installation environments
  - Repairable system
  - Easy maintenance
  - Adaptable and scalable
  - UL listing

PLCNxt® from Phoenix Contact

cRIO®/ LabView® from NI

EID Platforms – vendor agnostic

Wago

Kunbus

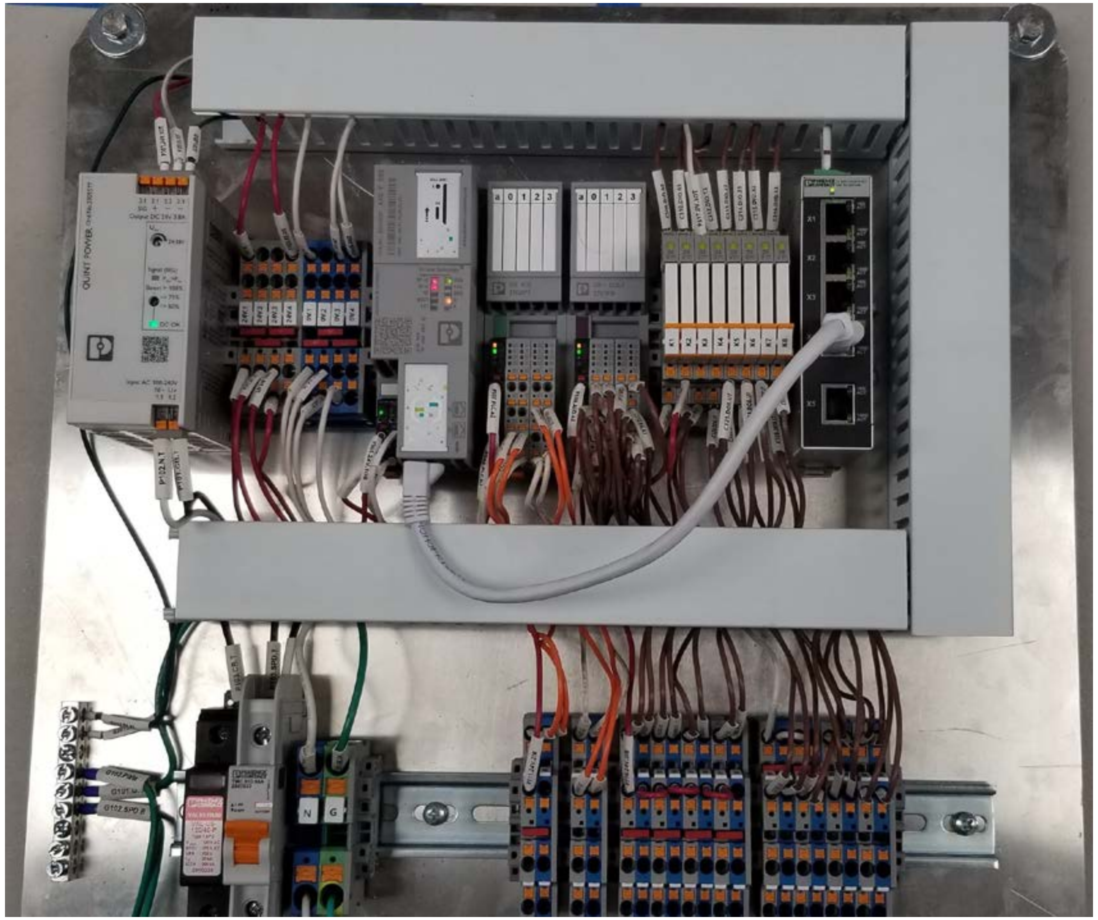
Weidmuller

Campbell Scientific

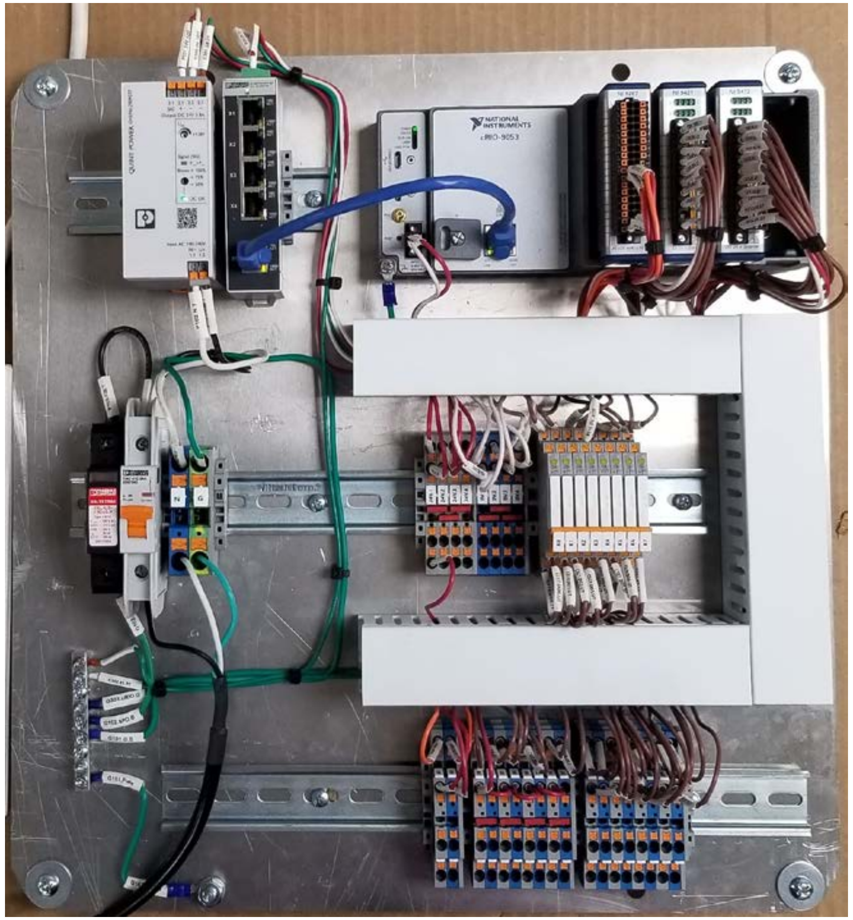
Opto22

EID Prototypes

PLCNxt® based Platform 1



cRIO®/ LabView® based Platform 2



UL508A listed EID

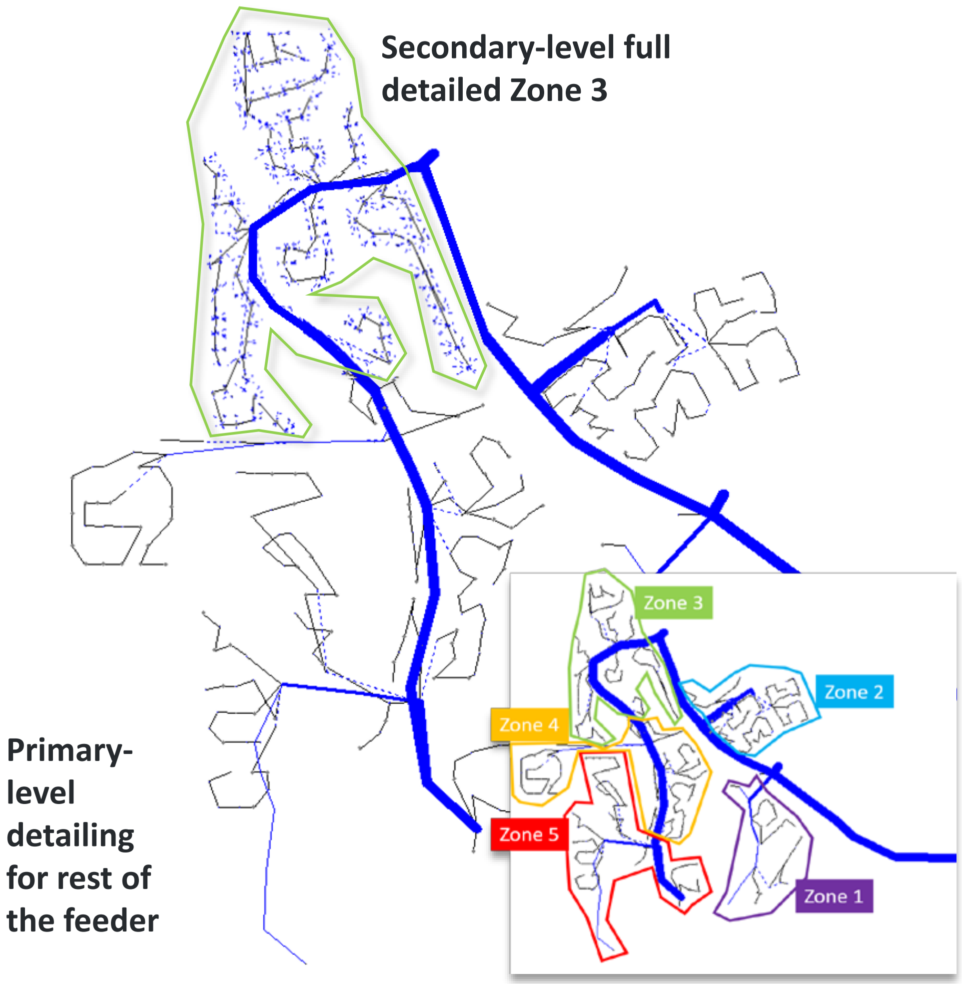
- UL508A
  - Accepted by AHJ and utilities
  - Field installation ready – residential, commercial, industrial, and utility sites

LISTED
NO. XX 000000
Enclosed Industrial Control Panel

Outline

- Overview of proposed solutions to address high PV penetration challenges
  - High penetration feeder models
  - Integrated, dynamic transmission-distribution analysis
  - Deep learning based dynamic hosting capacity
  - Advanced DER (distributed energy resource) control
  - Attack-resilient DER cyber-physical system
- Edge intelligent devices (EIDs)
- **Hardware-in-loop testbed**
- Cloud-based end-end solar energy optimization platform (eSEOP) - Bo Yang
- Demo of eSEOP features and use cases – Joseph Chongfuangprinya

Utility feeder model in ePHASORsim real-time simulation



Zone division of the utility network

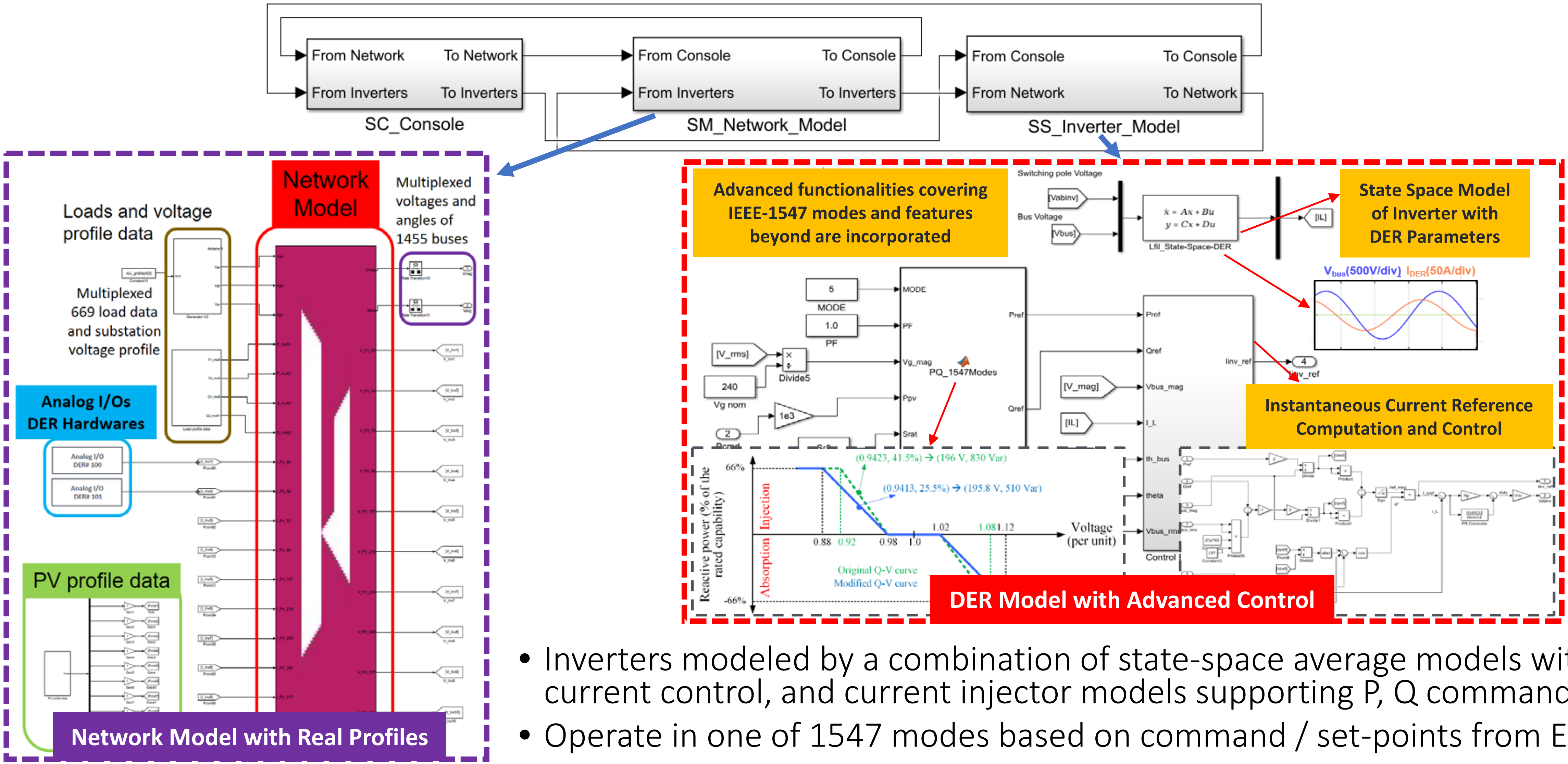
- A detailed, distribution network model of the feeder developed in ePHASORSIM (OPAL-RT) starting from the OpenDSS model [5]
- Feeder is divided into 5 zones. Zone 3 is implemented with secondary-level detail and other zones are primary-only
- Zone 3 consists of 329 PV inverters with highest number of over-voltage violations for March 15th dataset
- Percentage error in voltage magnitudes compared to OpenDSS below **0.1%** for more than **99%** of the buses with a maximum error of 0.25%; maximum phase angle difference is **0.1131^{0}**

Models	Network Details
Original model	8036 buses, 5208 lines, 371 transformers, 1737 loads and 766 DERs
Zone-3 with secondary level & rest primary-only*	1455 buses, 1017 lines, 371 transformers, 669 loads and 494 DERs

*optimized to remove redundant buses

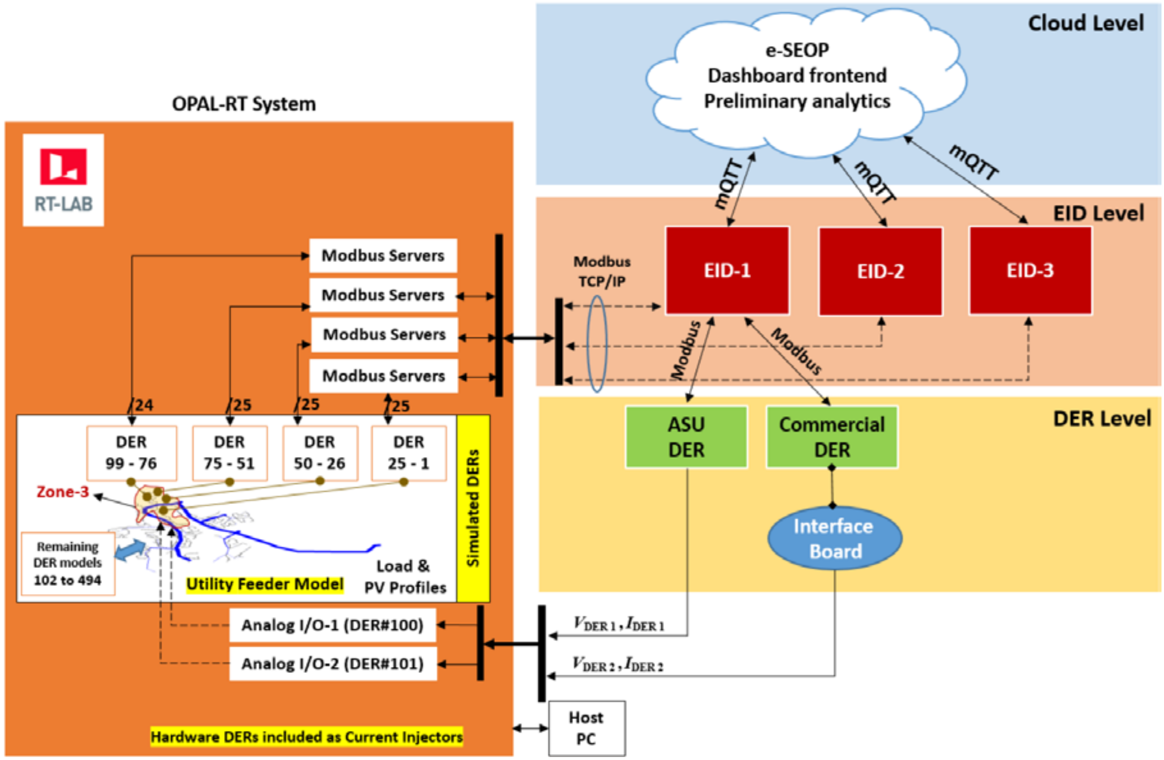
[5] M. Sondharangalla, N. Korada and R. Ayyanar, "Challenges and Solutions for Real-Time Phasor Modeling of Large-scale Distribution Network with High PV Penetration," 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), 2021, pp. 0630-0636, doi: 10.1109/PVSC43889.2021.9518525.

Opal-RT ePHASORSIM network and DER model with HIL

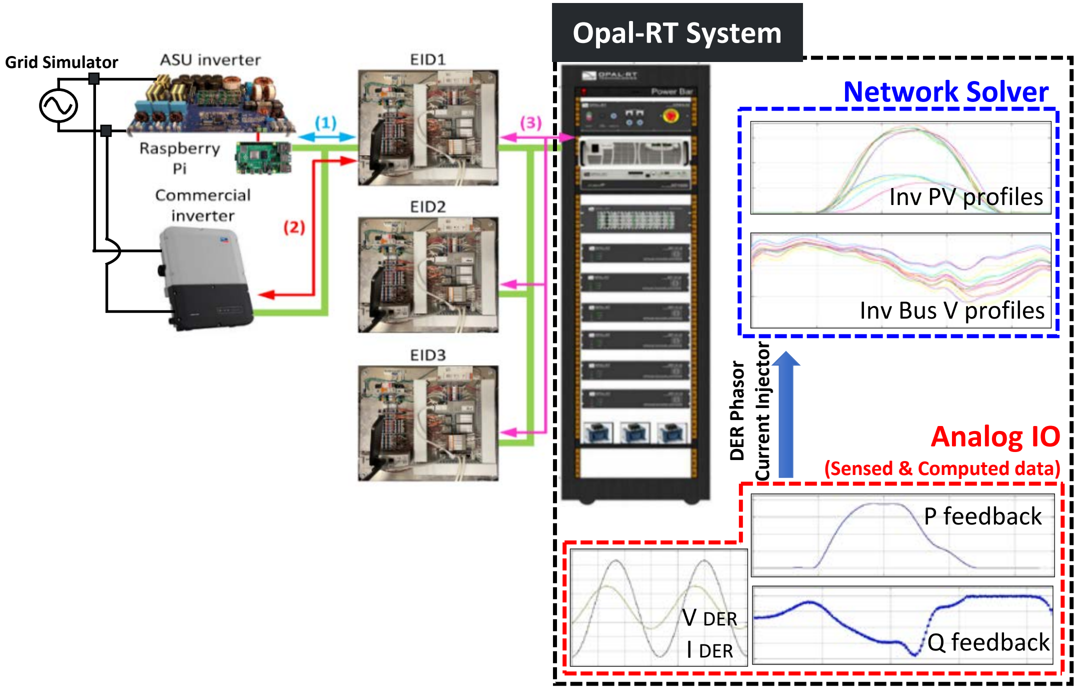


- Inverters modeled by a combination of state-space average models with current control, and current injector models supporting P, Q commands
- Operate in one of 1547 modes based on command / set-points from EID
- Dedicated analog IO blocks in ePHASORSIM for hardware-in-loop testing

Configuration of HIL testbed with end-to-end communication



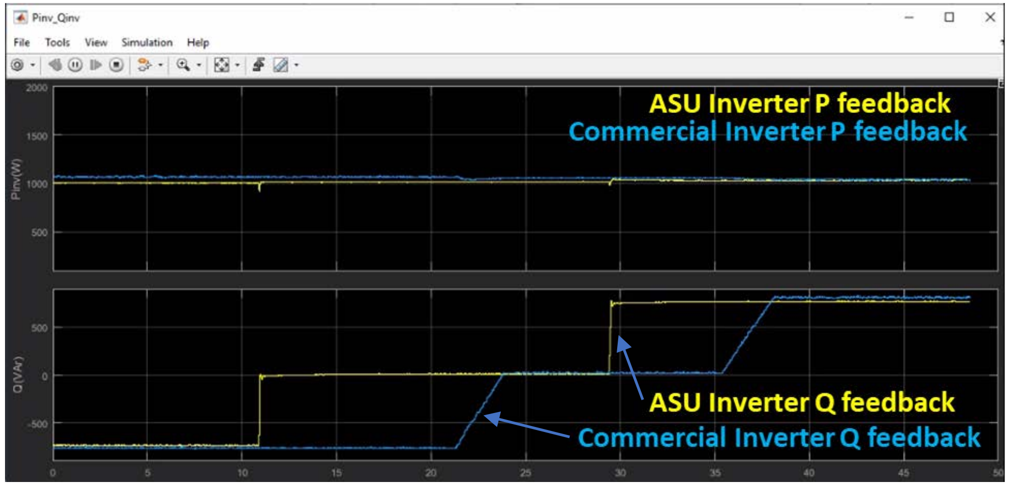
Modbus communication and HIL testing

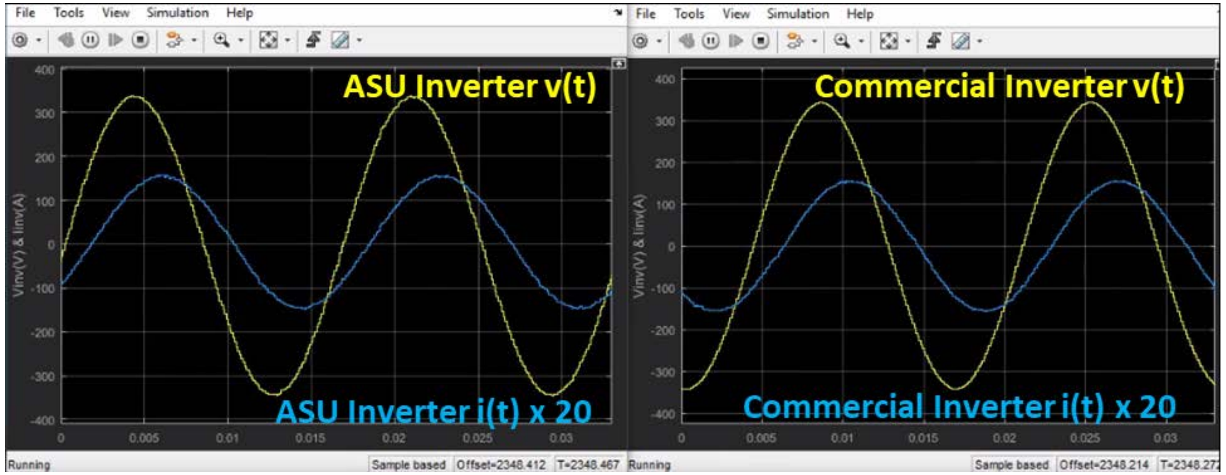


- Utility feeder model with detailed Zone-3 runs in ePHASORSIM
- 3 hardware EIDs each communicating to 25 simulated DERs
- EID-1 also interacts with 2 hardware DERs (ASU & commercial)
- Bidirectional Modbus communication is implemented with different DER hardwares and simulated models.
- MQTT for EID-cloud communication

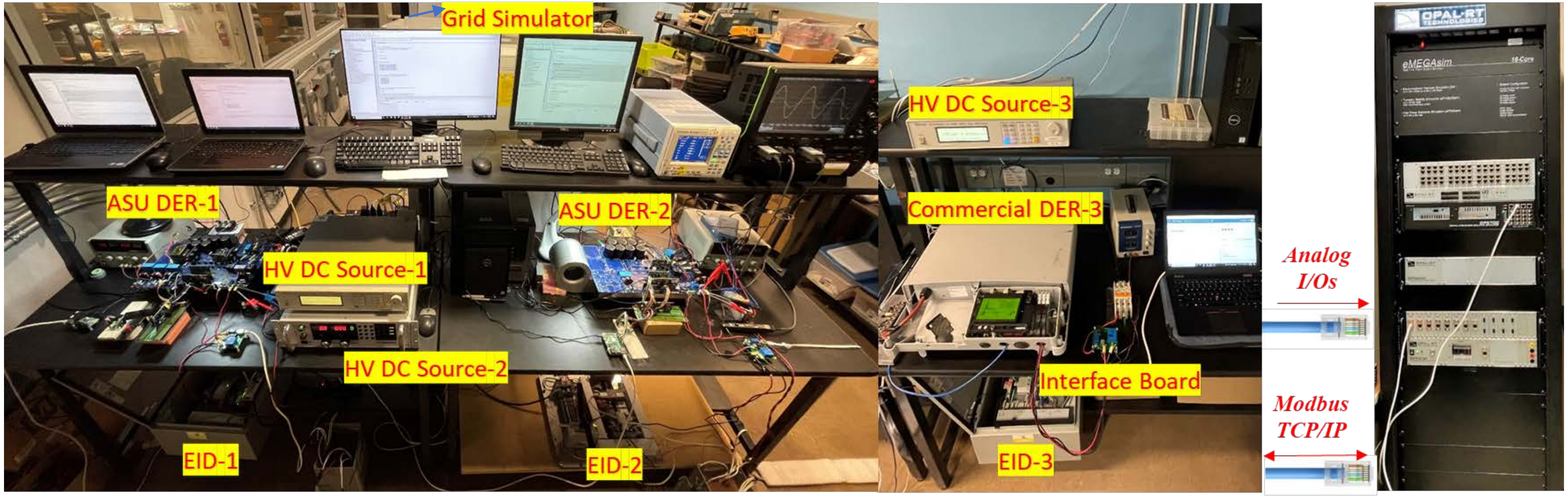
- Selected DER PCC voltage profiles from network power flow analysis used for HIL testing through EID
- Hardware DERs emulate actual PV injection based on P profile and Q commands from EID based on V_{PCC} profile
- Impact of dynamic response of hardware DERs included as phasor current inputs into the network model
- Ability of a subset of inverters running in volt-VAr mode to eliminate overvoltage violations demonstrated

Real-time HIL simulation testbed and some results





HIL results for ASU and commercial hardware inverters controlled through EID



e-SEOP cloud platform

Bo Yang, Ph.D.

Energy Solutions Lab, R&D, Hitachi America, Ltd

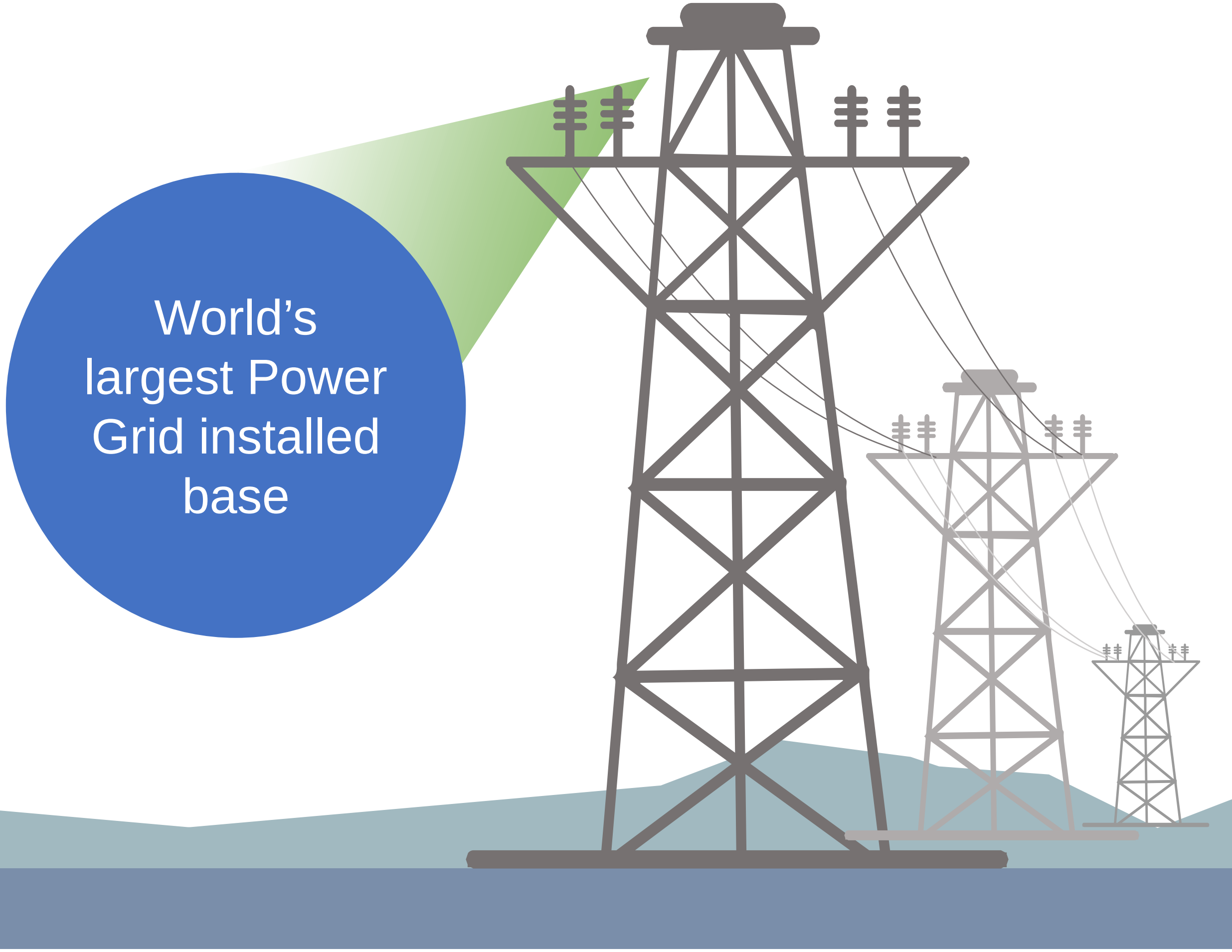
HITACHI
Inspire the Next

Hitachi LTD

Century old, $90bn global company, $4bn annual R&D investment

Hitachi Energy (prior Hitachi ABB Power Grids)

#1	World's largest Power Grid installed base
++130GW	Leader in HVDC systems (>130GW installed)
+1.8B	Providing stable supply of energy to 1.8B people
+36,000	Hitachi ABB Power Grid employees in 90 countries
+25%	of the world's high-voltage substations managed



ASSIST project – Voice of utilities

1. Inverter coordination during normal conditions

- More inverters are installed by customer and operate on their own, lacking proper coordination.
- Nearby inverters may compete with each other unnecessarily to control voltages.
- New stability challenges during normal operation conditions

2. Inverter coordination during grid disturbances

- When disturbances on med/low voltage grids, inverters are typically cut off and not actively contributing to disturbances mitigations.
- Field inverters cannot “see” the fault and lack of coordination on proper responds.
- Waste of resources and more pressure on utility infrastructures

ASSIST project – Voice of utilities

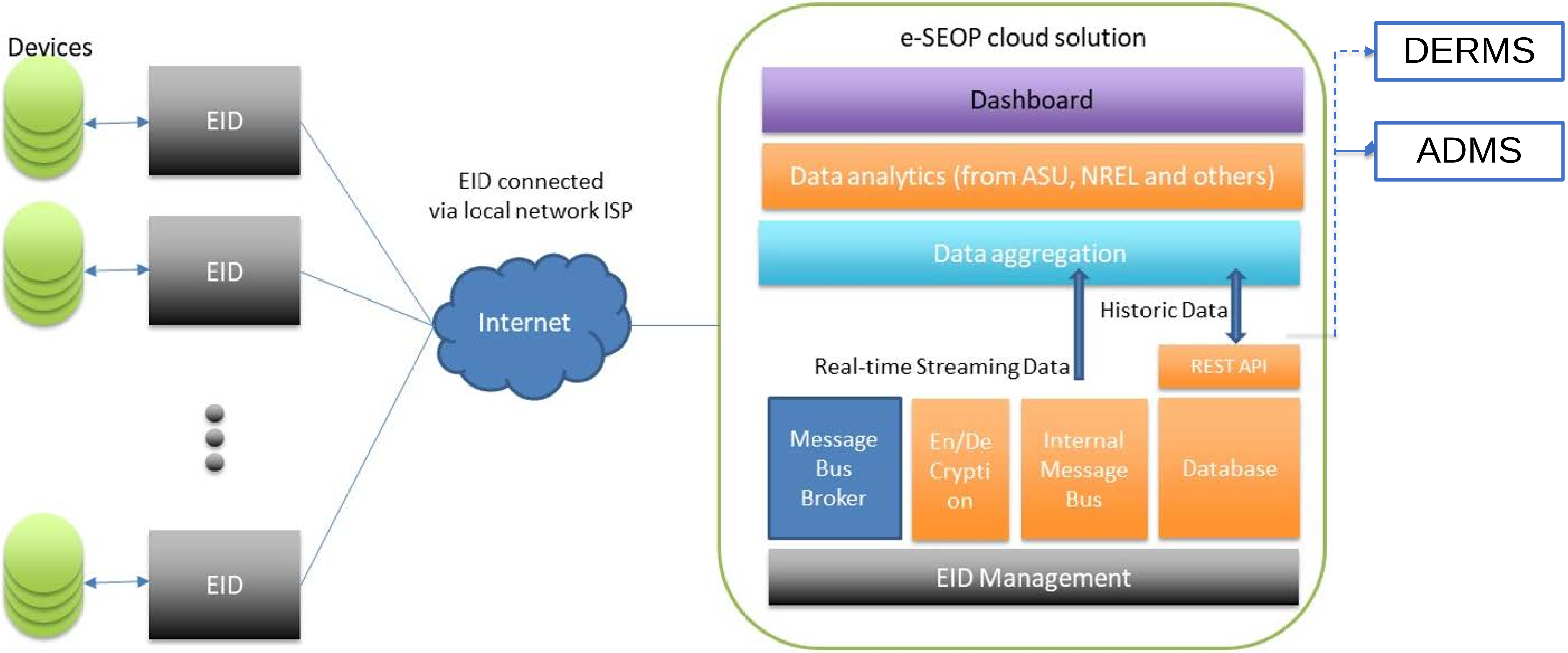
3. Better situational awareness and mitigation on 69KV networks

- Large penetration of solar energy at distribution grids during light load condition will introduce reverse power flow at lower voltage level.
- If the condition is severe, it may in turn cause adverse impacts on adjacent sub-transmission networks, i.e. 69KV.

Key design objectives

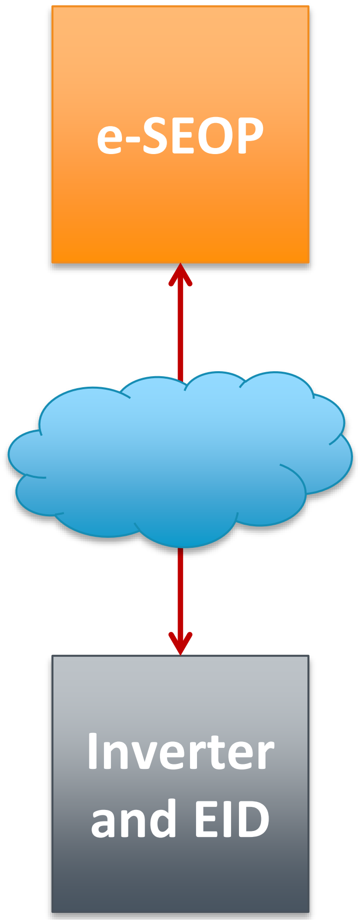
- A real time operation system for DERs
- Data supported operational insight visualization
- Human in the loop automatic control

End-to-end Solar Energy Optimization Platform (e-SEOP) – Architecture



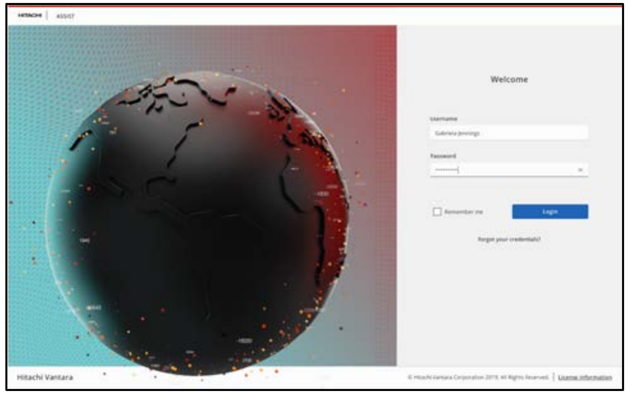
e-SEOP – key benefits

- Flexible and open architecture:
  - On the cloud or on utility premise, depending on aggregators
  - Design to integrate with 3rd party analysis
- Situational awareness to rapid growing DERs
  - Location, nameplate, history
  - Voltage, power, efficiency
- Aggregation and control assist to grid operators
  - Combine millions of device measurements into operational insights
  - Distribute utility centralized control signals to individual DER
- In compliment to DERMS and ADMS
  - Provide additional layers of monitoring and integration points for DERs
  - Free up communication bandwidth for critical feeder control
  - Extend reach to behind the meter resources



Implementation status

- Cloud platform
  - Human centered dashboard design
  - Backend data lake with micro-services
  - Message broker for real time data ingestion
  - Layers of security, i.e. user credential, data encryption through TLS/SSL



- Open and transparent software development
  - PostgreSQL, MQTT, JSON, REST API, Python

- Release schedule
  - Sep 2021, Live on AWS with real time data feeds from 75-100 inverter
  - Aug 2022, Live with 1000+ inverter

E-SEOP can be used for:

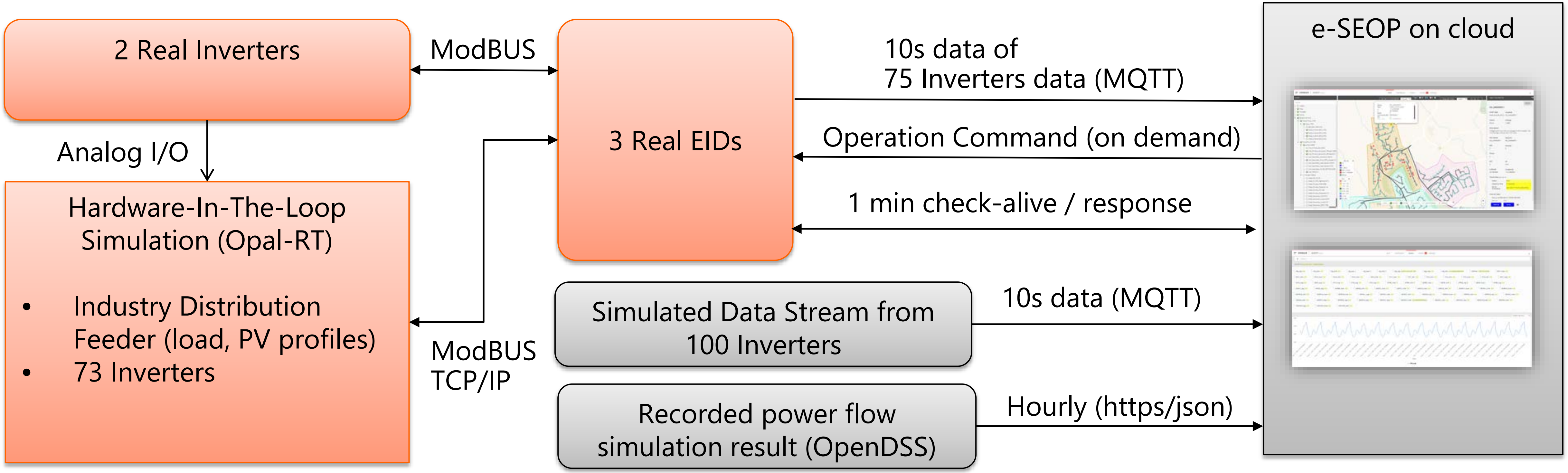
Visualization

Control testbed

Live data streaming

Initial Benchmark

- Hybrid testbed
  - Industry feeder (HIL) with 8000+ buses, 75 solar inverters
  - Real inverter and real EID with simulated peers
  - Real communication and data streaming to the cloud
  - Real data ingestion and analysis on the cloud



Related IoT and AI Solution Prototypes

HERO – IoT based industry app store

- Real time updates of DER status
- Performance summary
- Two-way communication and control
- Forecast/BESS optimization

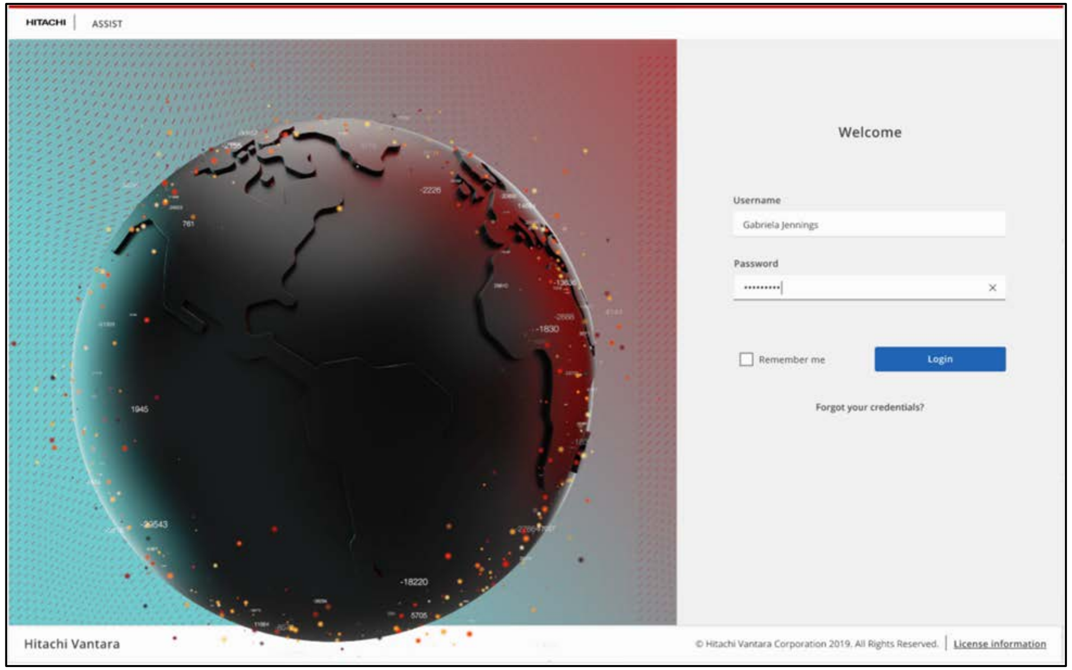
GLOW – open-source simulation platform

- DER & grid modeling
- Power flow simulation
- Hosting capacity
- Grid resilience
- Electrification
- Tariff
- <u>Open test in Sep 2021</u>

Demo

Panitarn (Joseph) Chongfuangprinya, Ph.D.

Energy Solutions Lab, R&D, Hitachi America, Ltd



Demo

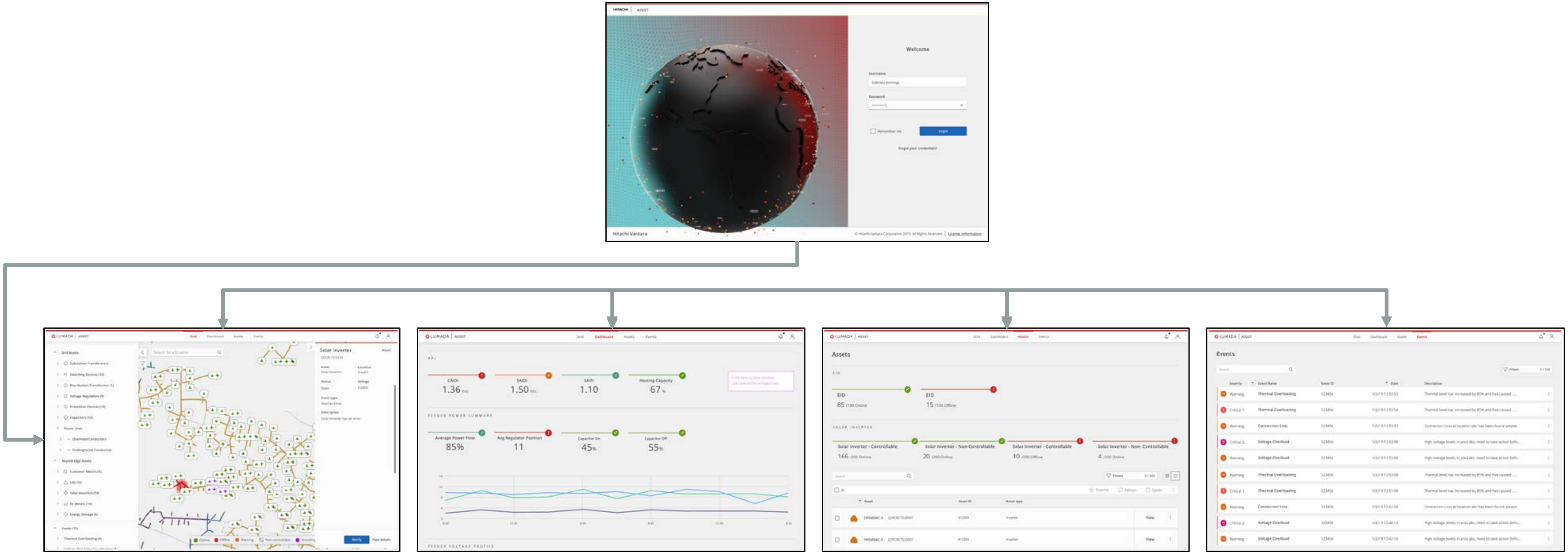
- Demo 1: Overview
  - Recorded feeder hourly data
  - Scenarios
    - Normal Operation
      - Grid View
      - Dashboard
      - Asset View
    - Overvoltage
    - Inverter Error
    - Outage

- Demo 2: Real-time operation
  - HIL data
  - Real data streaming of 75 inverters through 3 EIDs from the edge to the cloud
  - 10 seconds resolution data
  - End-to-end communication
    - Check alive command and response
    - Inverter operation mode command (Unity power factor to Volt/VAR control)

e-SEOP – Cloud Application

- Wire frame of cloud application

1.0 Home



2.1 Grid 2.2 Dashboard 2.3 Assets 2.4 Events

Questions?

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