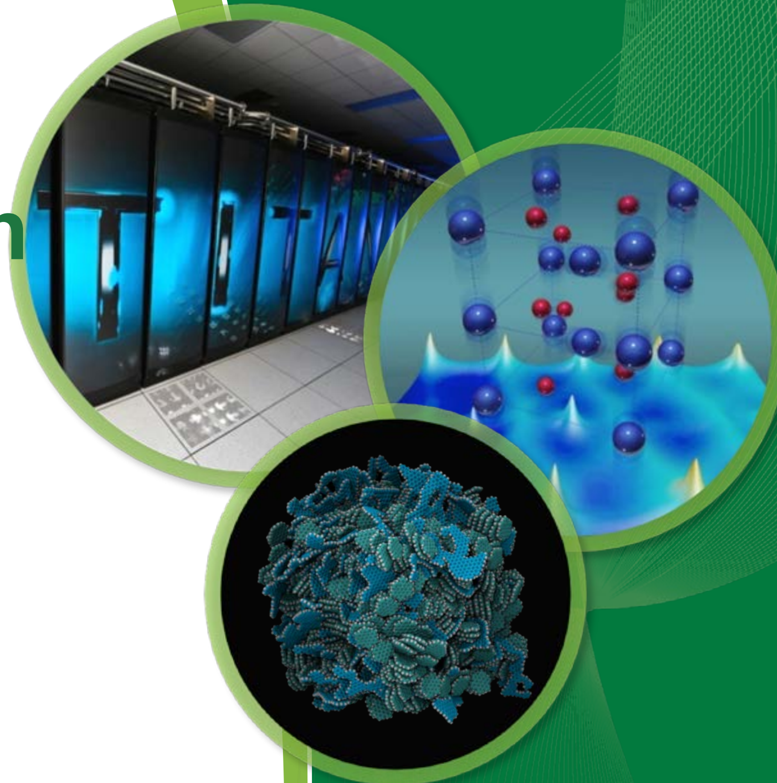
DOE/OE Transmission Reliability Program

Continuous Data-Driven Model Development



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Washington, DC

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ORNL is managed by UT-Battelle
for the US Department of Energy

CERTS CONSORTIUM for ELECTRIC RELIABILITY TECHNOLOGY SOLUTIONS

OAK RIDGE National Laboratory

Key Partners/Collaborators

Time Sensitive Networking (TSN) Testbed

- NI Lead User

HPE Moonshot is an energy-efficient, integrated server system that gives you the right compute for your workloads.

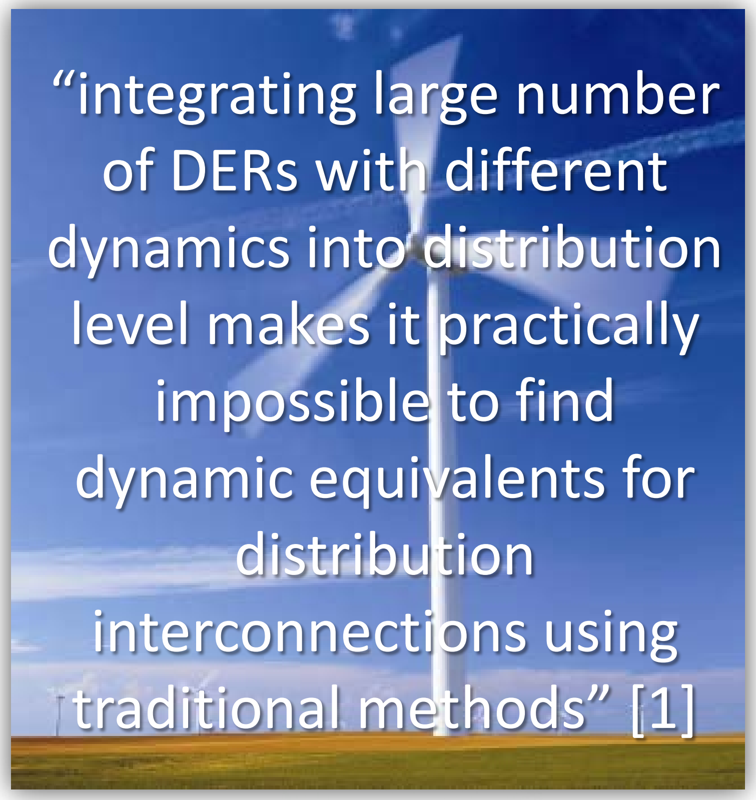
ThingWorx is the most widely adopted IoT technology platform.

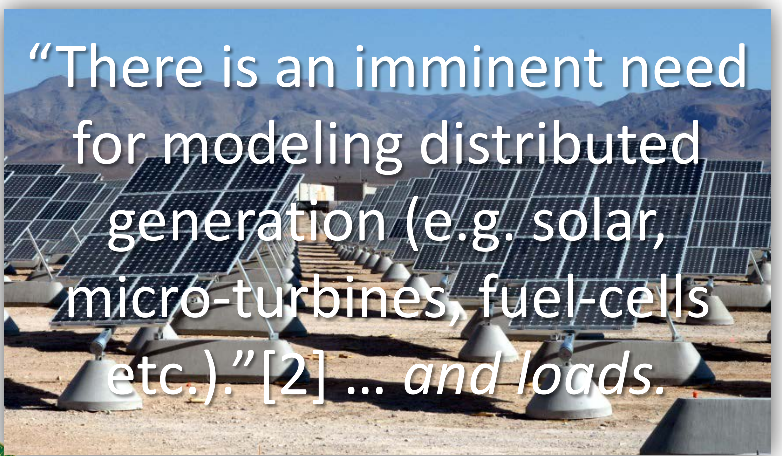
Beyond Limits has emerged as the universal leader in **"Applied Artificial Intelligence" (AAI)** and **Cognitive Cloud Computing** based on more than 20 years of proven success supporting NASA and the Space program…. actively designing and developing products and services for the burgeoning Internet of Things (IOT) market that we call the **Universe of Things (UOT)**.

Top 50 Internet of Things Technology Company. **Most Influential** Industrial IoT Company.

Project Background

- High penetration of renewables
  - Inverter based
  - Controls challenges
- High Fidelity data driven models
  - “Devices”
  - Lines
  - Systems
  - Loads





Need for high fidelity dynamic models of DERs, microgrids, loads, and inter-connected system.

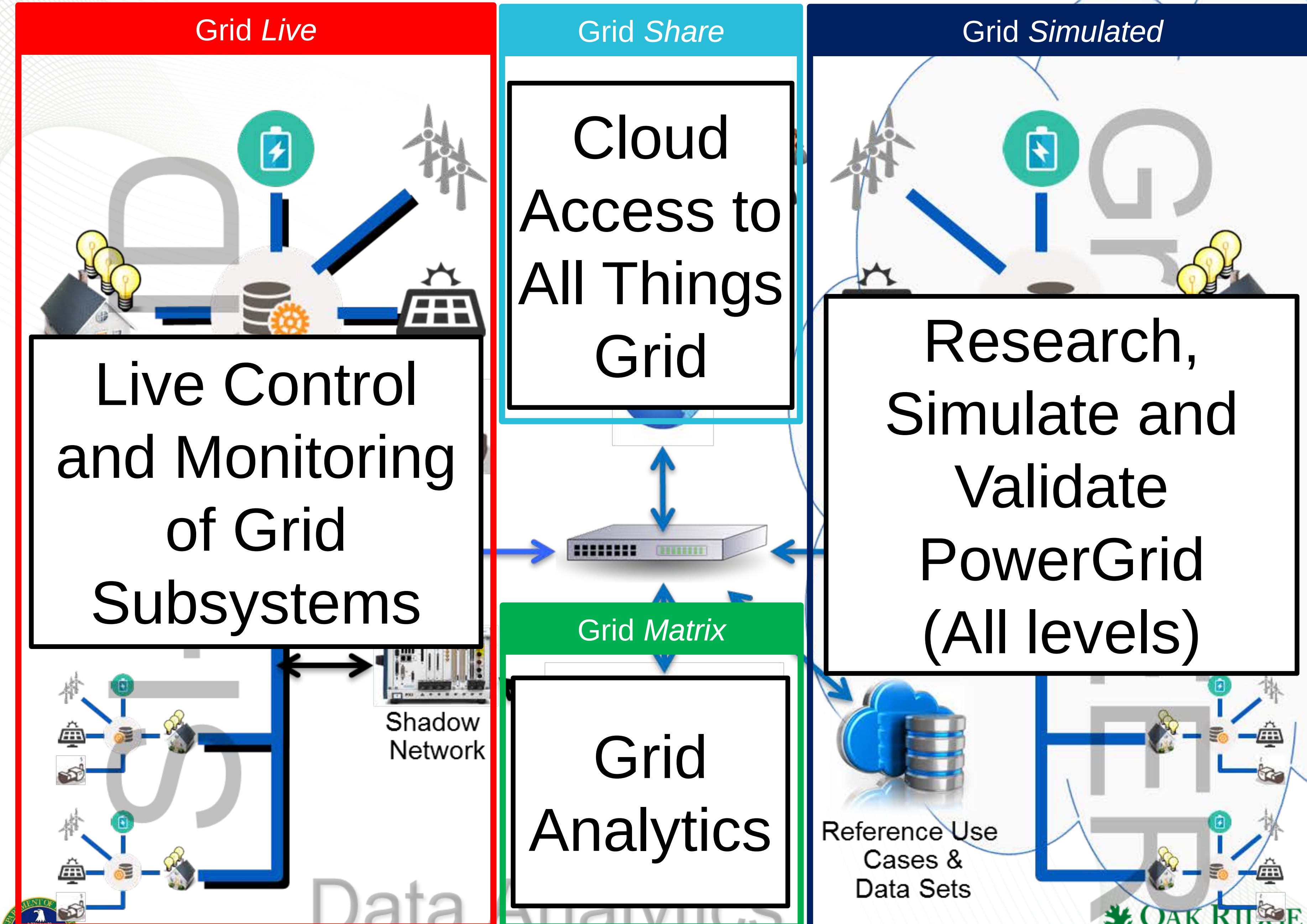
[1] A. Ishchenko, J. Myrzik, and W. Kling, “Dynamic equivalencing of distribution networks with dispersed generation using hankel norm approximation,” *Generation, Transmission & Distribution, IET*, vol. 1, no. 5, pp. 818–825, 2007.
[2] Allen, Eric, D. N. Kosterev, and Pouyan Pourbeik. "Validation of power system models." *Power and Energy Society General Meeting, 2010 IEEE*. IEEE, 2010.

Overall project objective

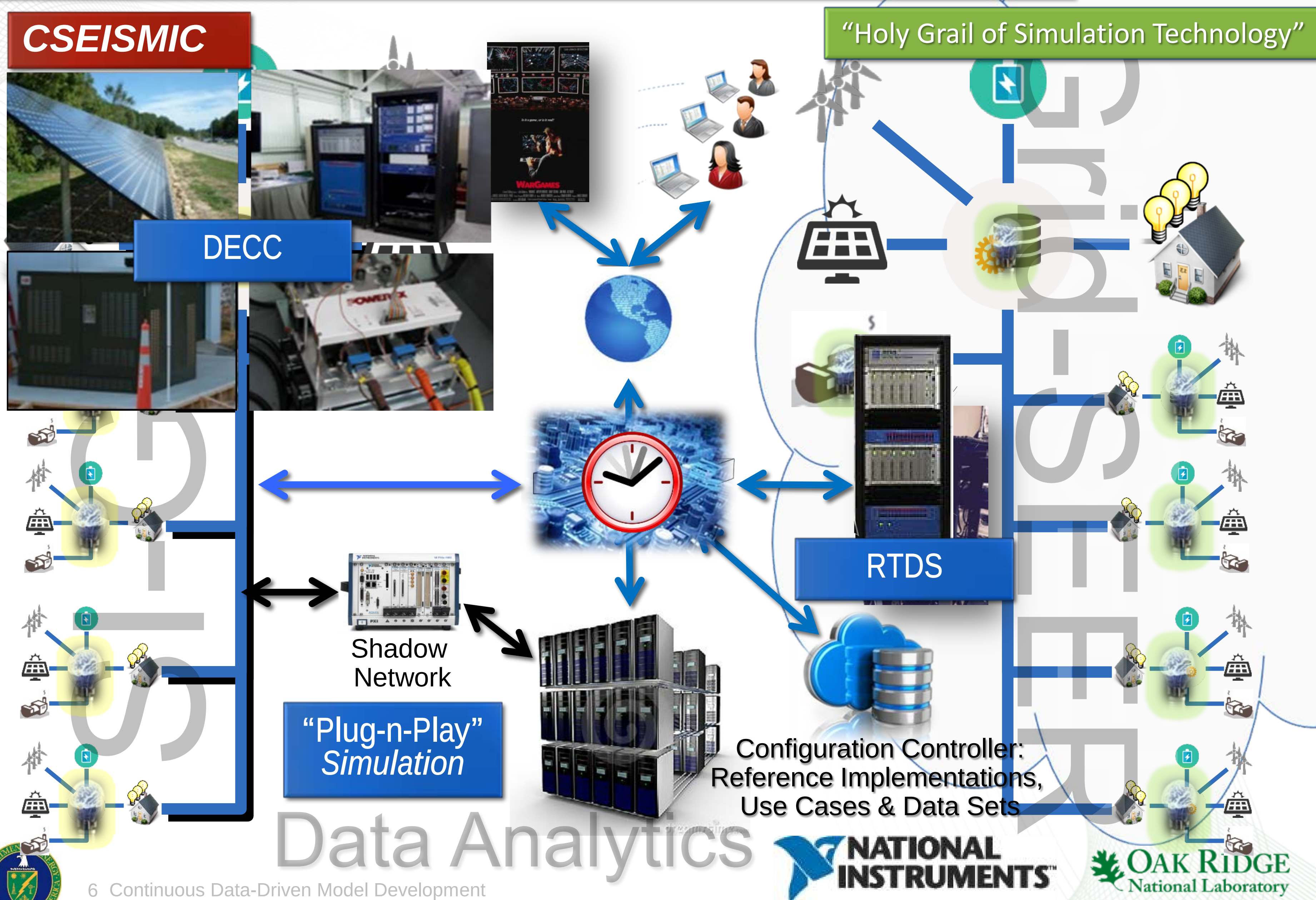
- The objective of this activity is to develop a learning system that adequately characterizes the dynamic performance of generators, loads, and storage devices connected to the electric grid. This includes electronically coupled devices and other low-inertia or no-inertia devices with nontraditional dynamic behaviors. *The ultimate value for electric system operators is to reduce the uncertainty associated with DER, renewable generation sources, and loads.*

A Data Driven Machine Learning Framework that learns device/load models.

An open framework for advanced grid research…



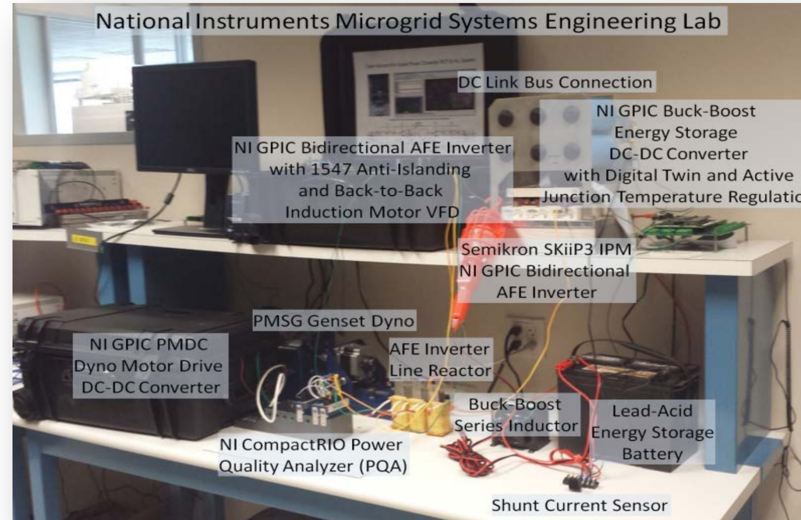
An open framework for advanced grid research…

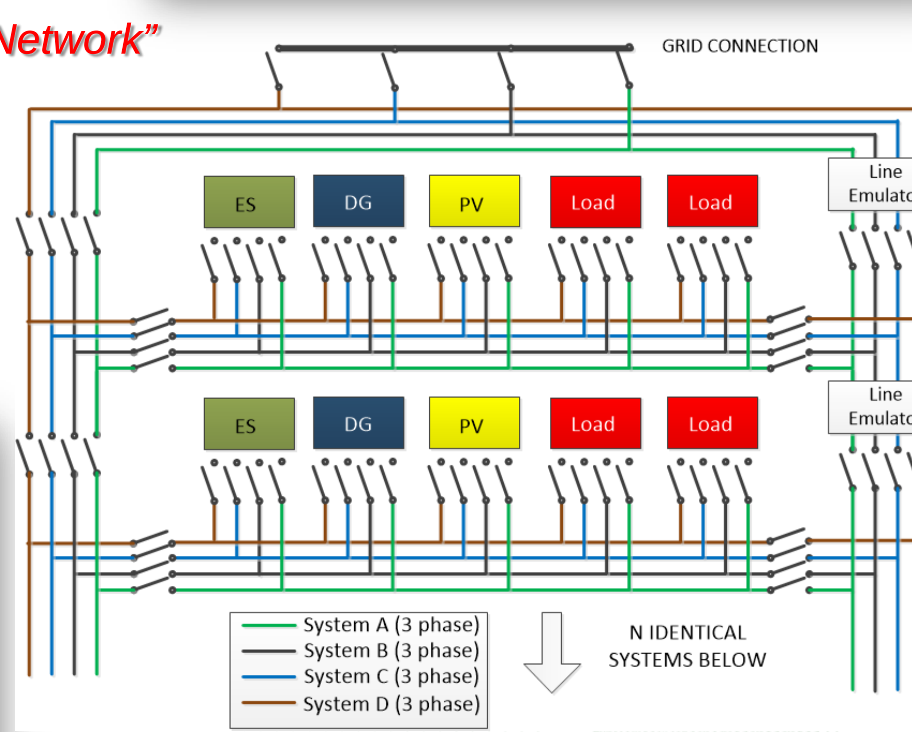


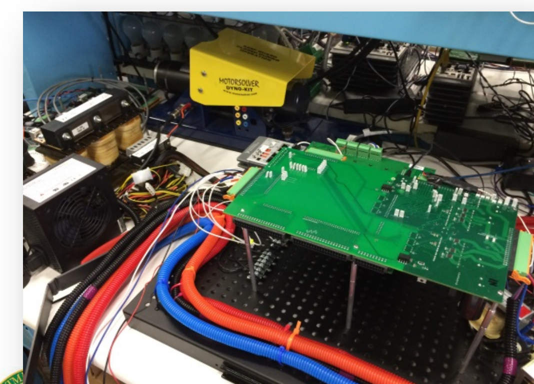
SI-GRID Overview

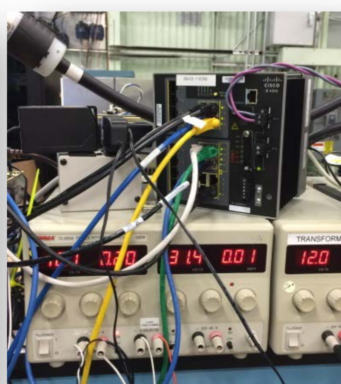
- Multiple local low-voltage (<100V) microgrids
- One remote microgrid
- Minimum definition of microgrid considered
  - One grid connection
  - One controllable source
  - One load
- Maximum reconfigurability
- Rack-mountable
- Diverse resources
  - Currently all inverter-based + DFIG
- Time Sensitive Networking enabled
- Re-configurable/definable comms

"Software-Defined Grid" meets "Software-Defined Network"









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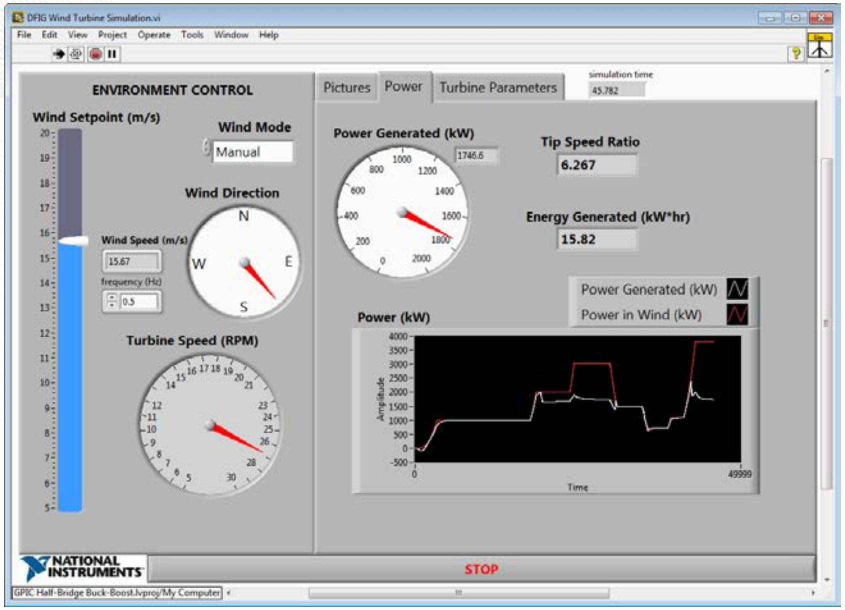
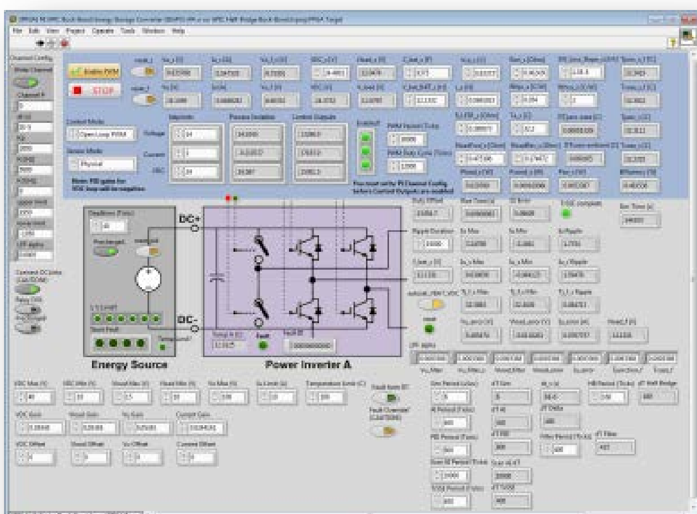
Looking Back

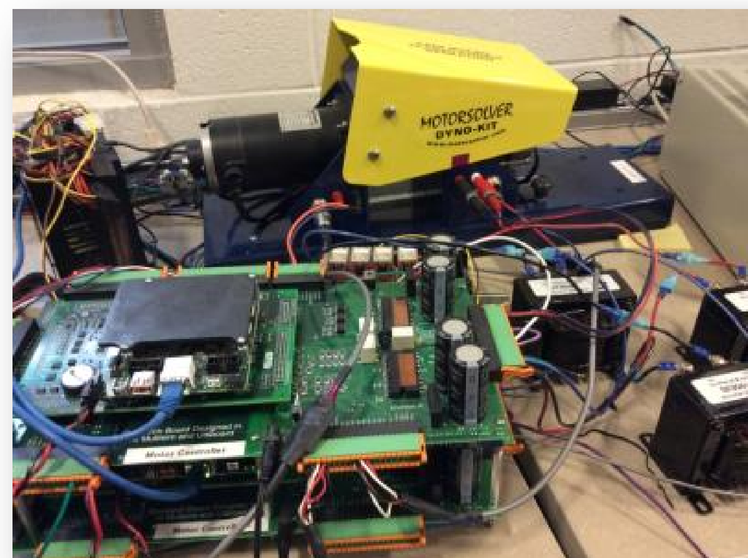
- *Development of SI-GRID machine/device models:*
  - Doubly-Fed Induction Generator (DFIG), Inverter-based motor, PV inverter, and Energy storage BuckBoost inverter.
- *Real-time FPGA-based SI-GRID device models:*
  - DFIG, PV inverter, and energy storage BuckBoost inverter.
- *Characterization of steady state and dynamic parameters (through measurements):*
  - Energy storage BuckBoost inverter, IGBT thermal junction
- *Perform real-time machine simulations:*
  - Non-linear IGBT-diode thermal FPGA models, DFIG
- *Learning framework:*
  - Adaptive Differential Evolution (JADE)
  - Real time/FPGA "digital twin" co-simulations in the cRIO controller
  - Real time implementation of OpalRT's eHS64 in the cRIO
  - JADE + surrogate optimizer is currently "learning" 8+ "multiphysics" parameters
    - PWM waveform parameters, semiconductor device parameters, thermal resistance from case to ambient, and external circuit parameters including the battery.
- *Industry engagement:*
  - *National Instruments, HPE, AgileSwitch, Duke Energy, Dominion, SEL, SEMIKRON, Beyond Limits, ColdLight*

DFIG (Wind Turbine) Setup



FPGA Front Panel During Run-Time - Physical IO and HIL Model Running in GPIC FPGA





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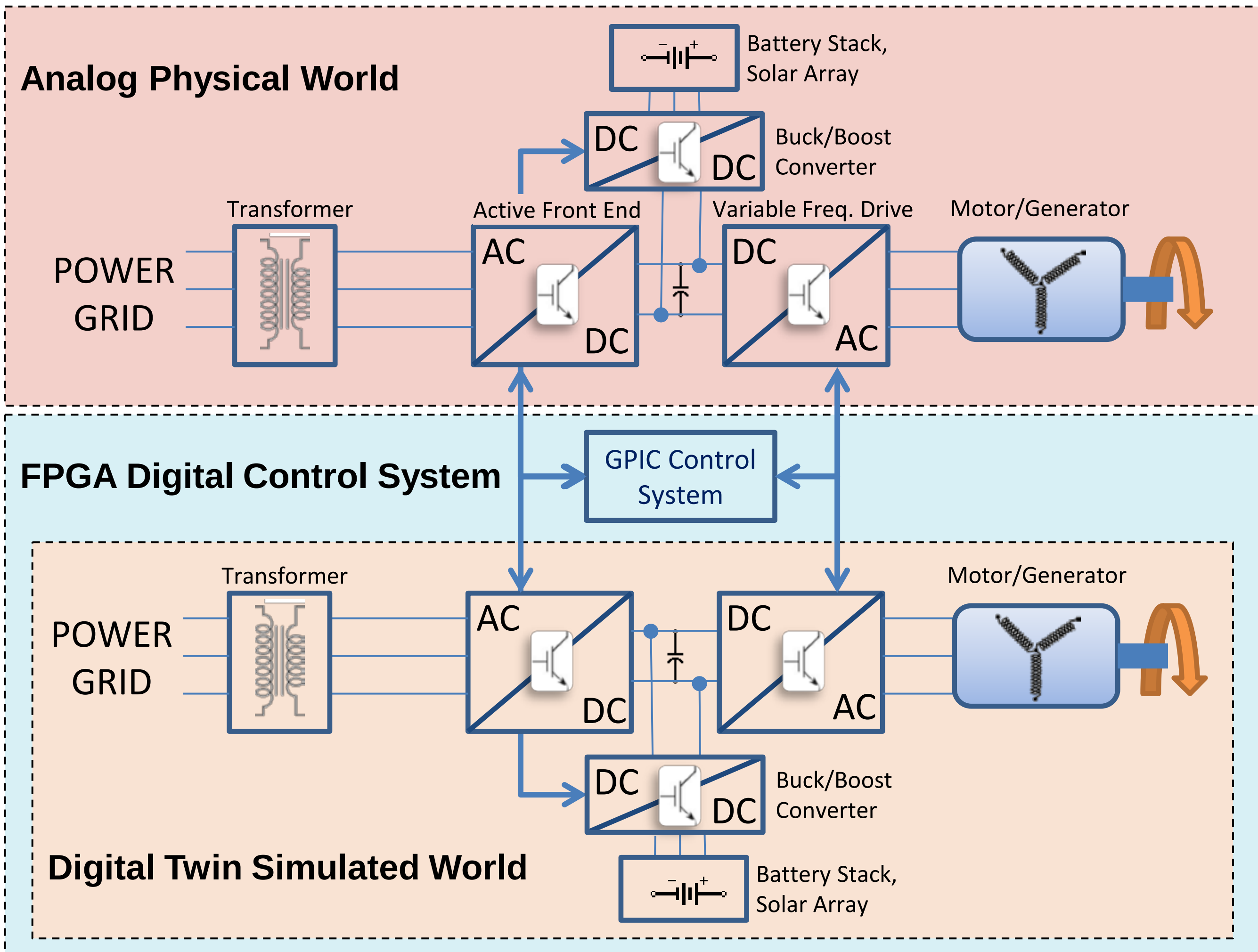
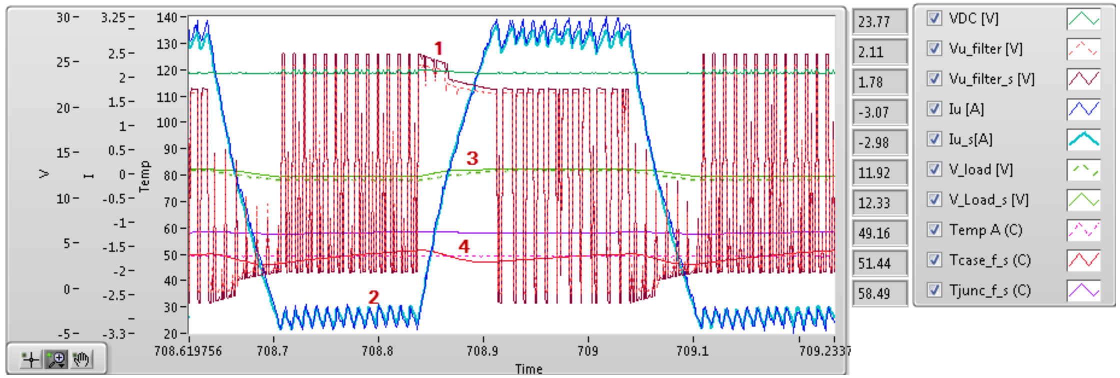
FPGA BASED CONTROL SYSTEM WITH LOCAL DIGITAL TWIN

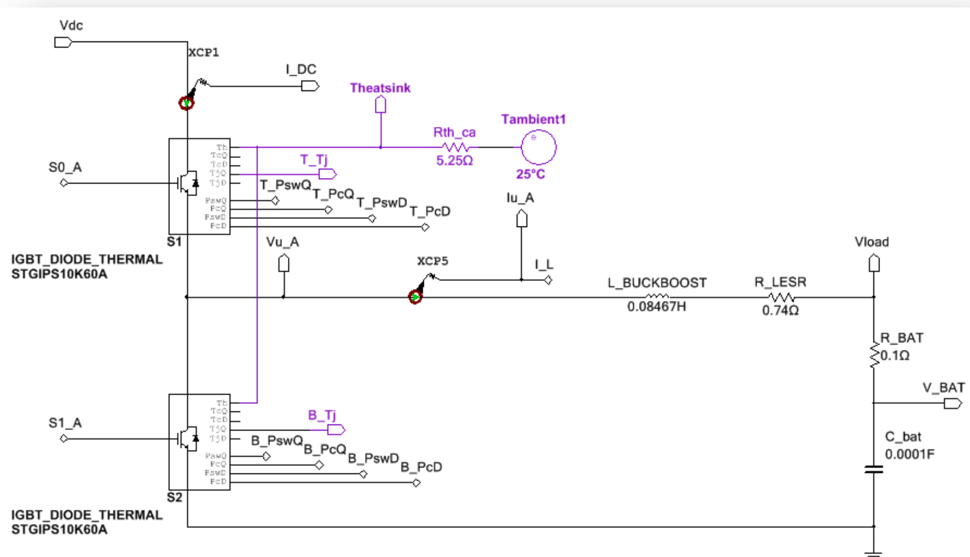


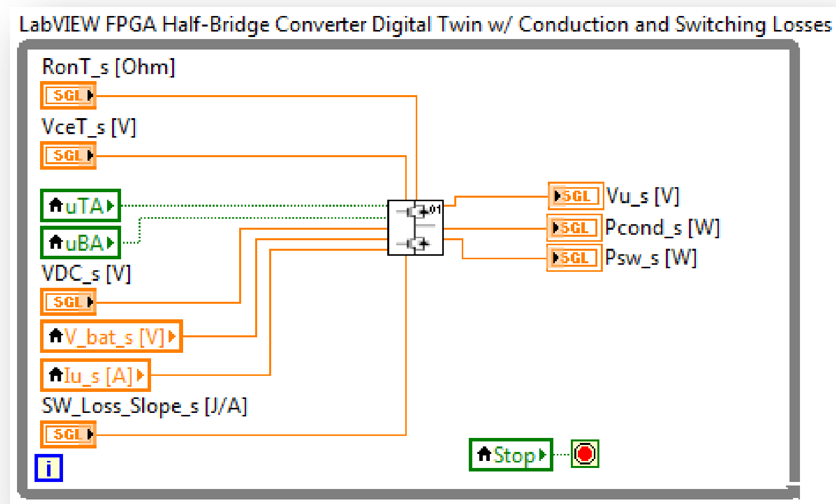
Buck-Boost Energy Storage Converter with Digital Twin for Active Junction Temperature Regulation

1. IGBT half-bridge output voltage (red)
2. Battery Charge/Discharge Current (blue)
3. Battery Terminal Voltage (green)
4. Case Temperature (red)

Single IGBT Half-Bridge Data
(Physical Measurement vs. "Digital Twin")

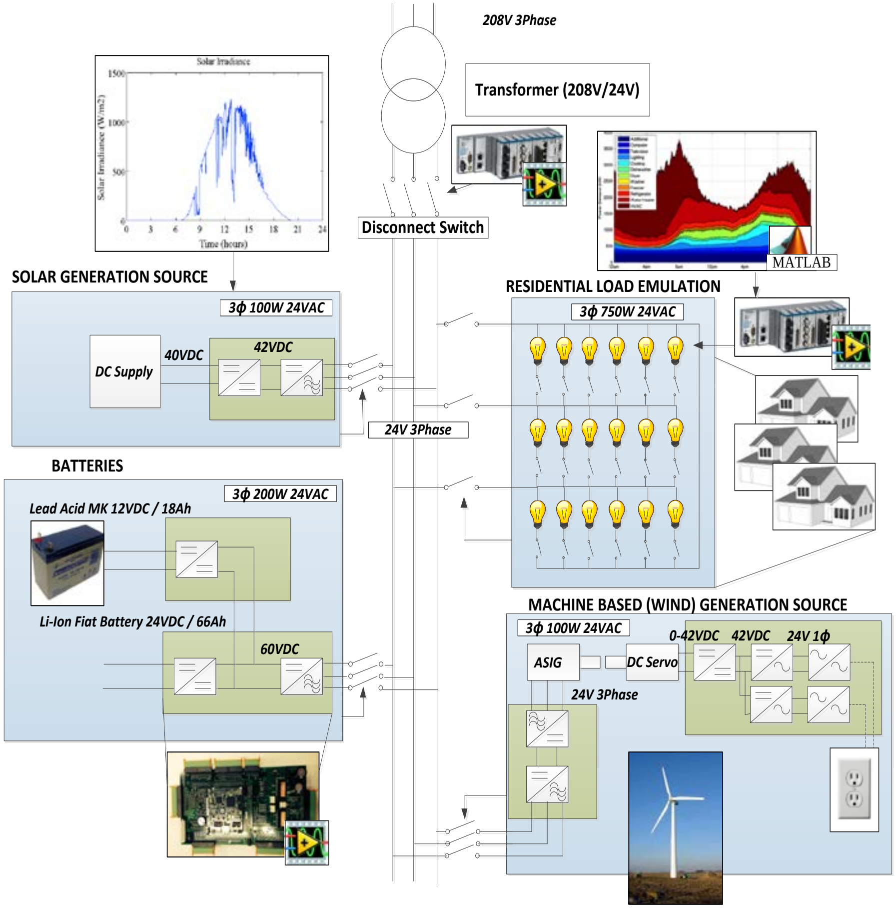






Looking Forward (FY16 – Carryover)

CDDMD + SI-GRID *+ Grid-SEER*



Model Parameters & measurements

Predicted V, I, phase, freq, …

Physical Microgrid(s):

- cRIO FPGA Based Control Systems w/ local "Digital Twins", JADE and TSN
- Learn/validate model parameters
  - DFIG, ES, PV, …
- Pass params to Grid-SEER for system validation

Real-time System Simulation

- SI-GRID devices
- SI-GRID system(s)
- Compare predications to measurements

Presentation/Paper with results.

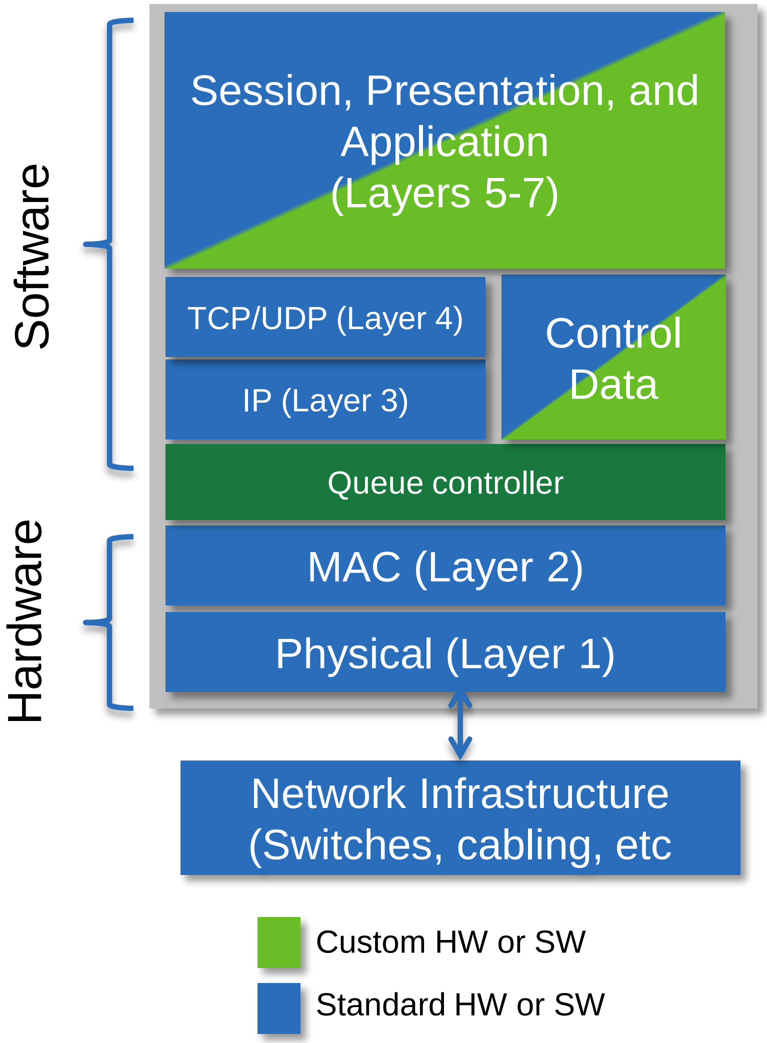
TSN Standards Efforts

- Standards effort through IEEE 802 to improve latency and performance while maintaining interoperability and openness
- Time Sensitive Networking (TSN) will provide:
  – Time synchronization
  – Bandwidth reservation and path redundancy for reliability
  – Guaranteed bounded latency
  – Low latency (cut-though and preemption)
  – Bandwidth (Gb+)
  – Routable to support complex networks and wireless

IEEE Time-Sensitive Networks Overview

Standard	Area	Title
IEEE 802.1ASrev, IEEE 1588	Timing & Synchronization	Enhancements and Performance Improvements
IEEE 802.1Qbu & IEEE 802.3br	Forwarding and Queuing	Frame Preemption
IEEE 802.1Qbv	Forwarding and Queuing	Enhancements for Scheduled Traffic
IEEE 802.1Qca	Path Control and Reservation	Path Control and Reservation
IEEE 802.1Qcc	Central Configuration Method	Enhancements and Performance Improvements
IEEE 802.1Qci	Time Based Ingress Policing	Per-Stream Filtering and Policing
IEEE 802.1CB	Seamless Redundancy	Frame Replication & Elimination for Reliability

TSN Based "Hard Real-Time" Ethernet Devices



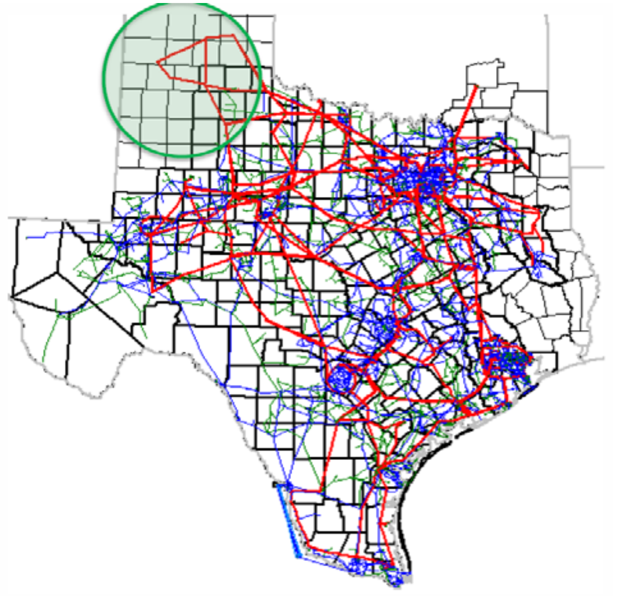
Key technology vendors are driving:

- Intel
- Broadcom
- Marvell
- Cisco

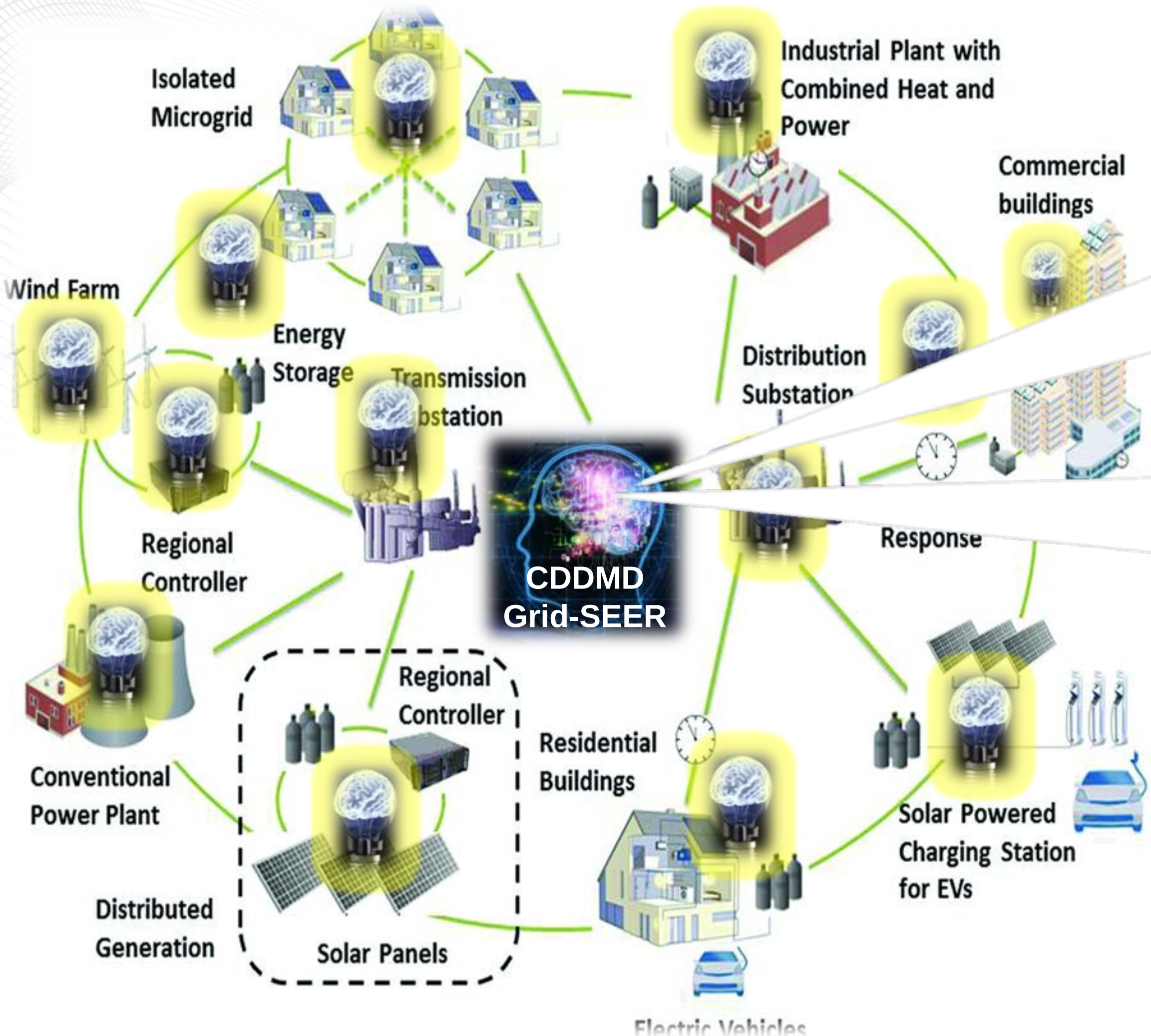
Key industrial, embedded, and automotive vendors are participating to drive requirements

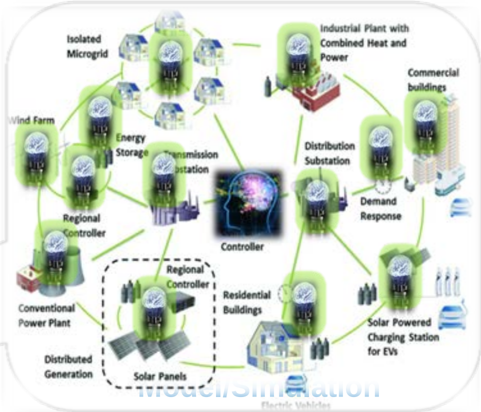
Where is the power industry representation?

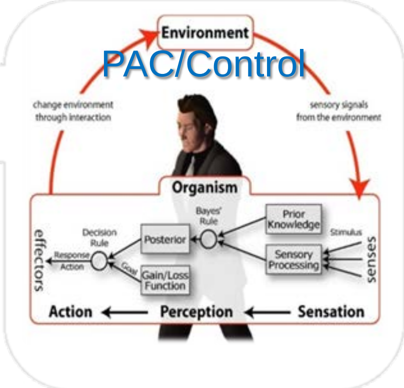
FY17 and Beyond



- Inverter Based DER Integration
  - CDDMD
  - TSN enabled advanced controls
  - Wind Farm in the "ERCOT Panhandle Area" *compare to Synchronous Condensers*
- Anticipatory Intelligent thermal management of Inverter IGBTs *est. 100x life*
- Adaptive Load Orchestration/Coordination
  - Adapt CDDMD to learn loads "Agents"
    - Communities
    - Light Commercial/Industrial
  - Anonymize (load data)
  - Orchestrate Adaptive coordination of opt-in "smart loads" + legacy "learned loads" with multiple goals/objectives
    - Cost
    - Stability
  - Greatly reduces peak load and total load uncertainties

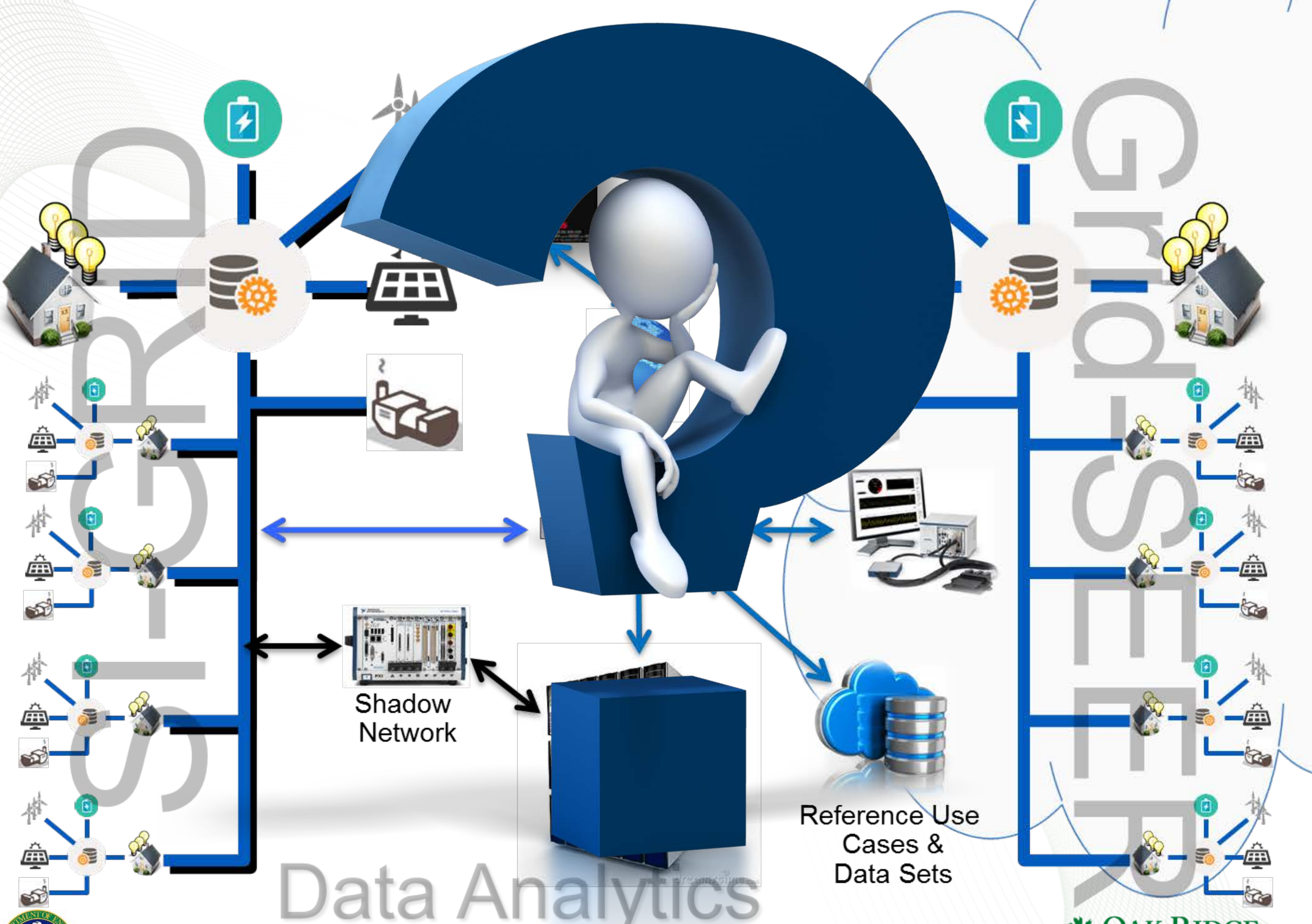






Enable a new generation of real-time, secure, data-driven services reducing load uncertainty and improving Grid Resiliency.

- ***Scalable Architecture***
- ***Data anonymization***
- ***Machine Learning***
- ***Orchestrated load utilization***
- ***Reduced load uncertainty***
- ***Advanced Inverter-Based DER Integration***


SI-GRID
Grid-SEER
Shadow Network
Reference Use Cases & Data Sets
Data Analytics