PNNL-SA-137565

System Operations, Power Flow, and Control

Jeff Dagle, PE

Pacific Northwest National Laboratory

Grid Modernization Initiative Peer Review

System Operations, Power Flow, and Control

Advanced control technologies to enhance reliability and resilience, increase asset utilization, and enable greater flexibility of transmission and distribution systems

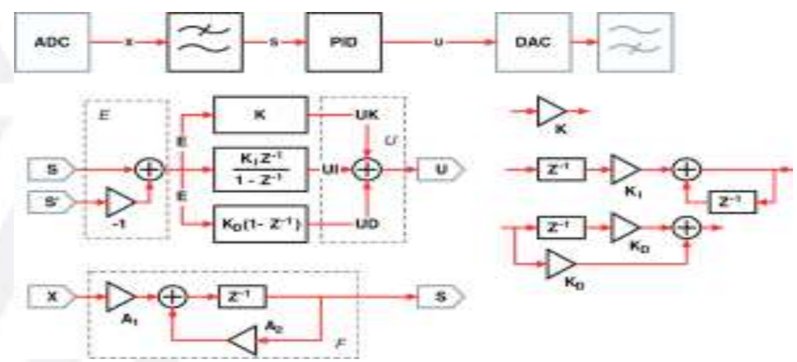
Expected Outcomes

- By 2020 deliver an architecture, framework, and algorithms for controlling a clean, resilient and secure power grid
  - Leveraging advanced concepts, high performance computing, and more real-time data than existing control paradigms
  - Involving distributed energy resources as additional control elements
- Develop software platforms for decision support, predictive operations & real-time adaptive control
- Deploy, through demonstration projects, new classes of power flow control device hardware and concepts
- Advance fundamental knowledge for new control paradigms (e.g., robustness uncompromised by uncertainty)

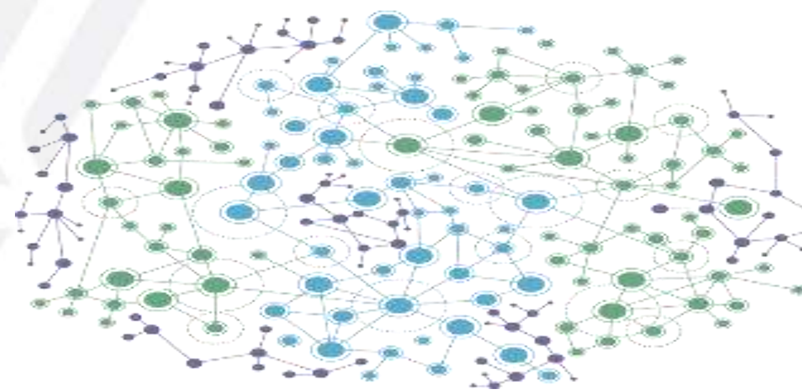
Federal Role

- Convening authority to shape vision of advanced grid architecture, including new control paradigms for emerging grid to support industry transformation
- Deliver system engineering and other supporting capabilities from the National Laboratory System to research & develop integrated faster-than-real-time software platforms and power electronics controls

Conventional Controls



Distributed Controls

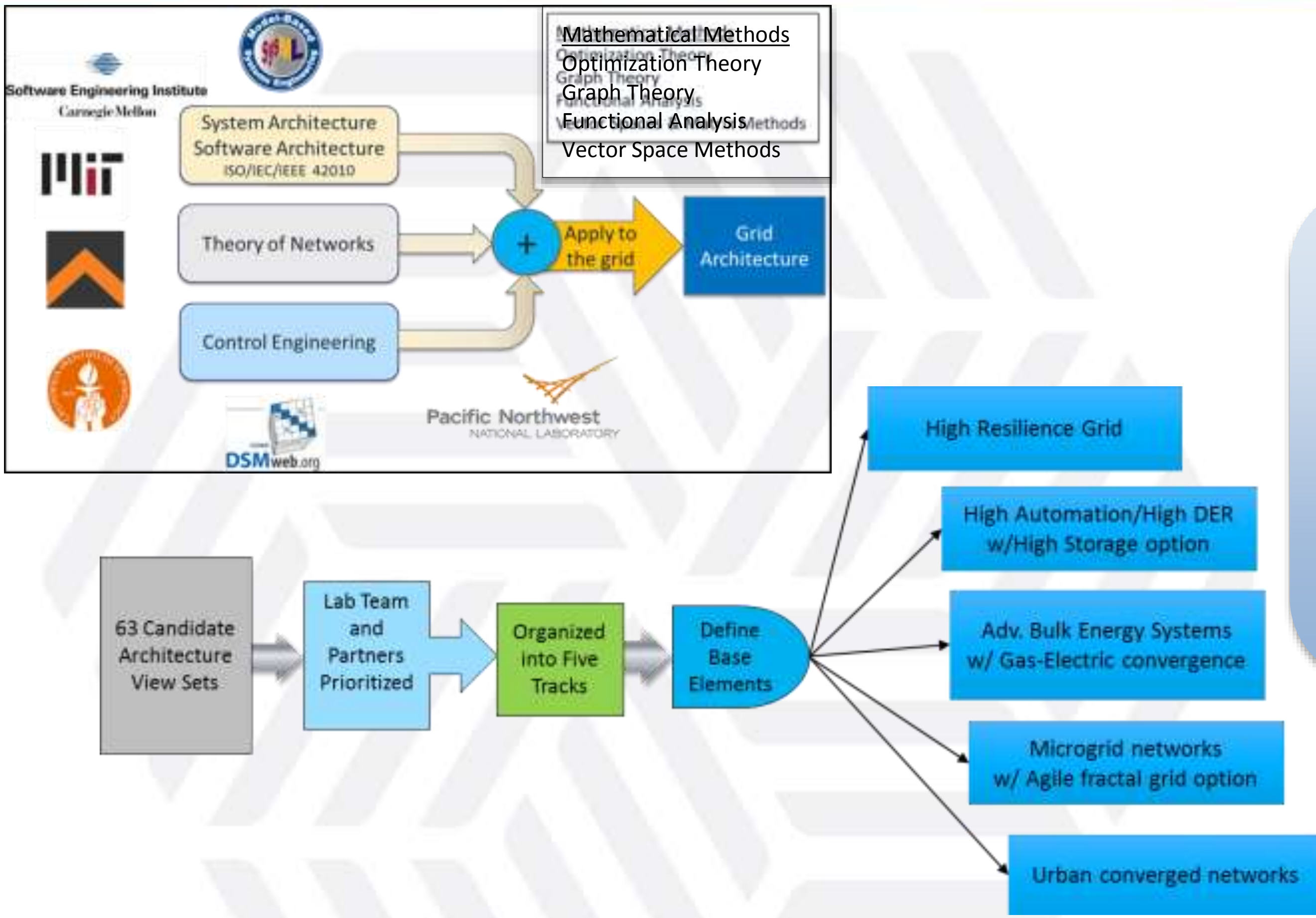


Multi-Year Program Plan (MYPP) Activities

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

Activity	Technical Achievements by 2020
1. Develop Architecture and Control Theory	• Comprehensive architectural model, associated control theory, and control algorithms to support a variety of applications to improve grid flexibility, future adaptability, and resilience while not compromising operational reliability or security. • Wide-area control strategies to improve reliability, resilience, and asset utilization.
2. Develop Coordinated System Controls	• New control grid operating system designs reflecting emerging system control methodologies. • Framework(s) for integrating the next generation energy management system (EMS), distribution management system (DMS), and building management system (BMS) platforms.
3. Improve Analytics and Computation for Grid Operations and Control	• Future and real-time operating conditions with short decision time frames and a high degree of uncertainty in system inputs can be evaluated. • Automation with predictive capabilities, advanced computational solvers, and parallel computing. This includes non-linear optimization of highly stochastic processes. • Decision support to operators in control rooms through pinpoint visualization and cognitive technologies.
4. Develop Enhanced Power Flow Control Device Hardware	• Low-cost, efficient and reliable power flow control devices that enable improved controllability and flexibility of the grid.

1.2.1: Grid Architecture



PoP: FY16/17/18

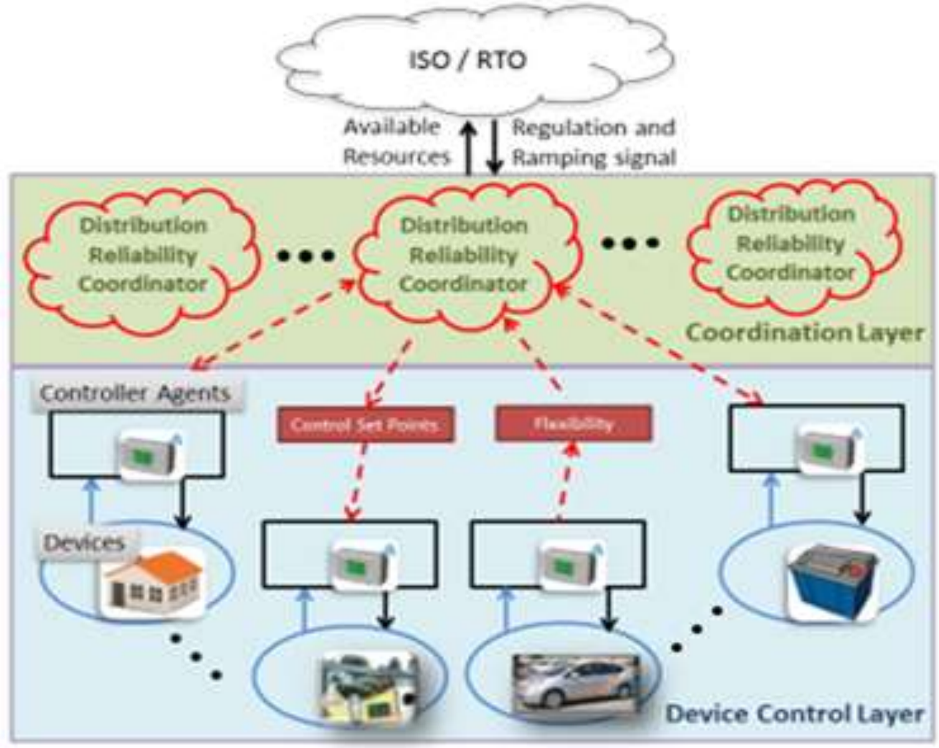
Budget: $3M

Labs: PNNL, ANL, NREL, ORNL, LANL, LBNL, LLNL, SNL

Partners: EPRI, SEPA, GWU, UTC, Omnetric Group, CA ISO, MISO, SMUD, AMEREN, BPA, ERCOT

Build a new set of five reference architectures for grid modernization, provide to the industry along with the tools they need to adapt them to their needs, and use them to inform the playbook for the GMLC program managers. The result will be superior stakeholder decision-making about grid modernization activities of all kinds.

1.4.10: Control Theory



Candidate hierarchical distributed control architecture based on future distribution reliability coordinator model

PoP: FY16/17/18

Budget: $6.5M

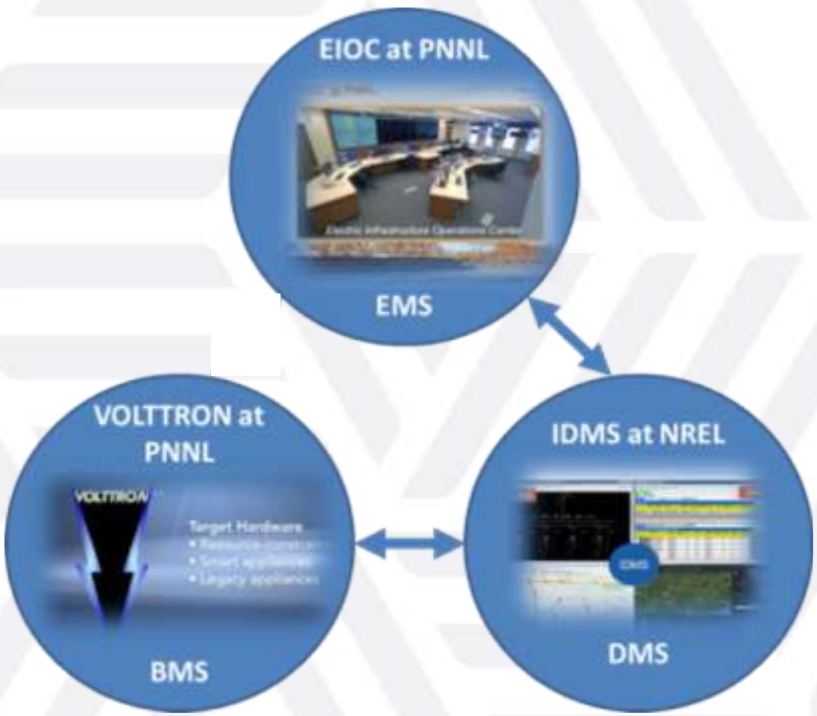
Labs: LANL, PNNL, ANL, INL, NREL, SNL, LLNL, ORNL

Partners: Oncor Electric Delivery, PJM Interconnection LLC, United Technologies Research Center

Develop new control solutions including topologies, algorithms and deployment strategies for transitioning the power grid to a state where a huge number of distributed energy resources are participating in grid control to enable the grid to operate with lean reserve margins. The theoretical aspect of this project will recognize the need to engage legacy control concepts and systems as we transition to more distributed control.

1.4.11: Multi-Scale Integration of Control Systems

Energy Management System (EMS)



Building Management System (BMS) **Distribution Management System (DMS)**

PoP: FY16/17/18

Budget: $3.5M

Labs: ANL, LANL, LLNL, NREL, PNNL, SNL

Partners: GE, Duke Energy, PJM Interconnection LLC

Create an integrated grid management framework for the end-to-end power delivery system – from central and distributed energy resources at bulk power systems and distribution systems, to local control systems for energy networks, including building management systems.

Connections and Collaborations
Foundational Projects

MYPP Area	Foundational Projects
1. Develop Architecture and Control Theory	1.2.1 – Grid Architecture 1.4.10 – Control Theory 1.5.2 – Resilient Alaskan Distribution System Improvements Using Automation, Network Analysis, Control, and Energy Storage (RADIANCE)
2. Develop Coordinated System Controls	1.4.11 – Multi-Scale Integration of Control Systems (EMS/DMS/BMS) 1.3.1 – Southeast Regional Consortium 1.3.9 – Smart Reconfiguration of Idaho Falls Power Distribution Network for Enhance Quality of Service 1.3.99 – Transactive Campus Demonstration 1.5.5 – CleanStart DERMS
3. Improve Analytics and Computation for Grid Operations and Control	1.3.10 – Vermont Regional Partnership Enabling the use of DER

Connections and Collaborations
Program-Specific Projects

MYPP Area	Program Specific Projects
1. Develop Architecture and Control Theory	• Development of an Open-Source Platform for Advanced Distribution Management Systems (GM0063) • Modeling and Control Software Tools to Support V2G Integration (GM0086) • Optimal Stationary Fuel Cell Integration and Control (DG-BEAT) (GM0252) • Dynamic Building Load Control to Facilitate High Penetration of Solar PV Generation (SI-1673) • Providing Ramping Service with Wind to Enhance Power System Operational Flexibility (WGRID-04)
2. Develop Coordinated System Controls	• Virtual battery-based characterization and control of flexible building loads using VOLTTRON (GM0061) • Vehicle to Building Integration Pathway (GM0062) • Systems Research Supporting Standards and Interoperability (GM0085) • Unified Control of Connected Loads to Provide Grid Services, Novel Energy Management, and Improved Energy Efficiency (GM0091) • VOLTTRON Controller for Integrated Energy Systems to Enable Economic Dispatch, Improve Energy Efficiency and Grid Reliability (GM0140) • VOLTTRON Message Bus Protocol Adapter (GM0172) • Community Control of Distributed Resources for Wide Area Reserve Provision (GM0187)
3. Improve Analytics and Computation for Grid Operations and Control	• Emergency monitoring and controls through new technologies and analytics (GM0076) • Operational and Strategic Implementation of Dynamic Line Rating for Optimized Wind Energy Generation Integration (GM0253) • Enabling High Penetration of Distributed Photovoltaics through the Optimization of Sub-Transmission Voltage Regulation (SI-1714) • A ToolSuite for Increasing Performance and Reliability of Combined Transmission-Distribution under High Solar Penetration (SI-1748)

Accomplishments and Emerging Opportunities

Accomplishment

- Architecture (1.2.1)
  - Over a dozen documented new concepts for grid resilience, communications, DER coordination, industry structure, and architecture tools and methods
  - Creation of industry structure, market structure, and regulatory structure models, and grid services master list
  - Extensive progress on uptake of Grid Architecture discipline in the industry nationally and internationally
  - Strong stakeholder engagement
- Control Theory (1.4.10)
  - Developed mathematical foundation for integrated optimization and control strategies
  - Ensure more robust distribution system operations while integrating large numbers of DERs participating in grid control
- Control Integration (1.4.11)
  - Multi-site connections

Path Forward

- Architecture (1.2.1)
  - Complete reference architectures
  - Train more Grid Architects
  - Develop/provide new grid architecture tools to the industry
  - Validate/field prove new architectures
- Control Theory (1.4.10)
  - Finalize test case for distribution feeder deployment
  - Complete control integration into testbed
  - Numerical demonstration at scale
- Control Integration (1.4.11)
  - Conduct the full-scale integration and demonstration.
  - Complete the deployment of stochastic unit commitment and economic dispatch into EIOC computational environment.

GRID MODERNIZATION INITIATIVE PEER REVIEW
1.2.1 Grid Architecture

JEFFREY D TAFT, PHD, PNNL (PI)

September 4–7, 2018

Sheraton Pentagon City Hotel – Arlington, VA

Grid Architecture

High-Level Project Summary

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

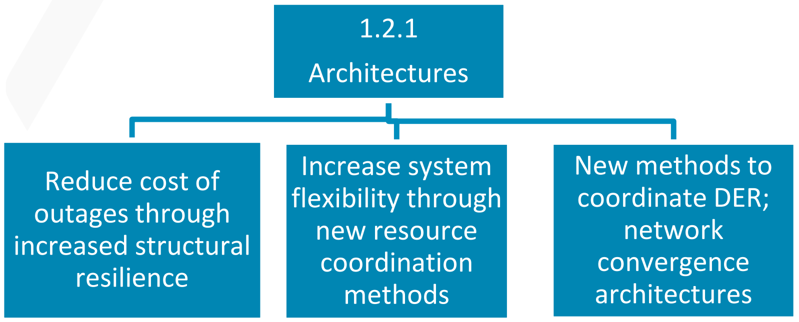
Grid architecture is the application of system architecture, network theory, and related disciplines to the whole electric grid. The purpose of this project is to re-shape the grid, remove essential barriers to modernization, redefine key grid structures, and identify securable interfaces and platforms.

Value Proposition

- ✓ Relieve essential constraints that impede grid modernization; define platforms and structures that provide resilience, functionality, security, and interoperability; manage complexity
- ✓ Proper structure (architecture) future-proofs grid modernization investments; poor structure results in high costs and low performance

Project Objectives

- ✓ Build stakeholder consensus around a DOE-convened vision of grid modernization, expressed as a new set of grid reference architectures
- ✓ Establish and win industry acceptance for the use of Grid Architecture work products and methodologies
- ✓ Supply a common basis for roadmaps, investments, technology and platform developments, and new services and products for the modernized grid



Grid Architecture
Project Team

Lab members have various roles on the Grid Architecture team, including SMEs, validators, architects, and researchers.

External partners are SMEs and validators.

External Partners	
SEPA	EPRI
SMUD	GridWise Alliance
CA ISO	UTC
MISO	BPA
Ameren	ERCOT
Avista	Great River Energy

PROJECT FUNDING			
Lab	FY16 $	FY17$	FY18 $
PNNL	500,000	500,000	500,000
ORNL	100,000	125,000	100,000
LANL	100,000	50,000	50,000
ANL	50,000	75,000	50,000
LBNL	100,000	100,000	100,000
LLNL	50,000	50,000	50,000
NREL	50,000	50,000	50,000
SNL	50,000	50,000	100,000

Grid Architecture
Approach

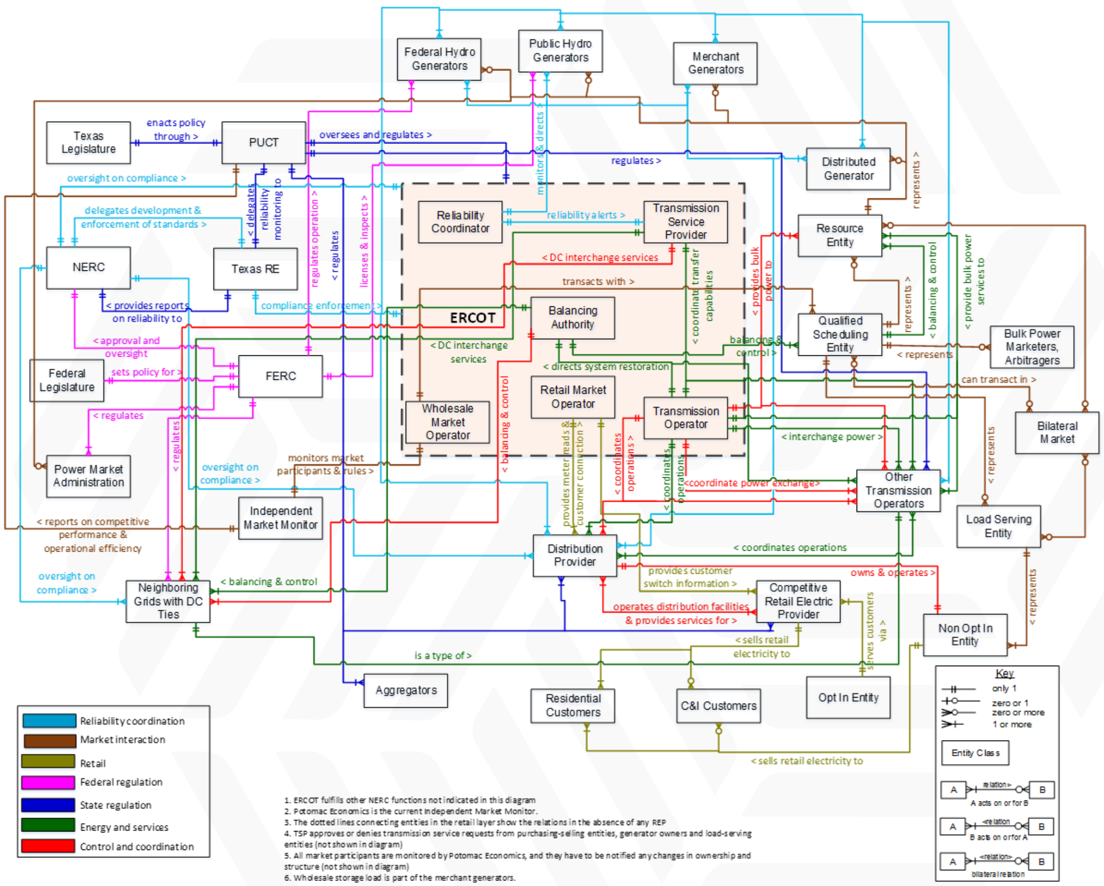
- Approach:
  - ❑ Architecture development
    - Develop five reference architectures covering a range of scenarios and industry segments, using the discipline of Grid Architecture (see below)
  - ❑ Stakeholder engagement
    - Three stage process; continual engagement
  - ❑ GMLC Inter-project collaboration
    - Interaction with other GMLC projects via work products and consultations
  - ❑ Grid Architecture tools development
    - Browser-based diagram tools
    - Comparative analysis and mathematical representation
    - Evaluation and optimization
- Key Issues:
  - ❑ We have inherited legacy structure form the 20th Century grid that does not match the needs of the 21st Century grid. Structural changes are necessary to relive legacy constraints, enhance characteristics such as resilience, and enable new capabilities such as integration of high penetrations of DER (including storage) and smart grid edge devices.
- Distinctive Characteristics:
  - ❑ Grid Architecture is the application of system architecture, network theory, and control theory to the electric power grid. A grid architecture is the highest level description of the complete grid, and is the key tool to understand and define the many complex interactions that exist in present and future grids.

Grid Architecture

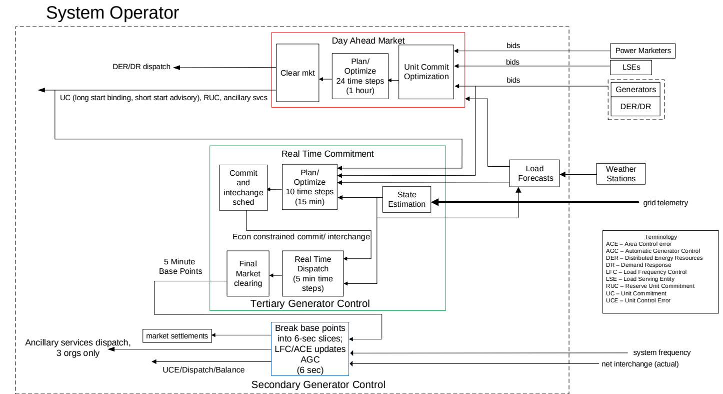
Accomplishments to Date: Structure Models

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

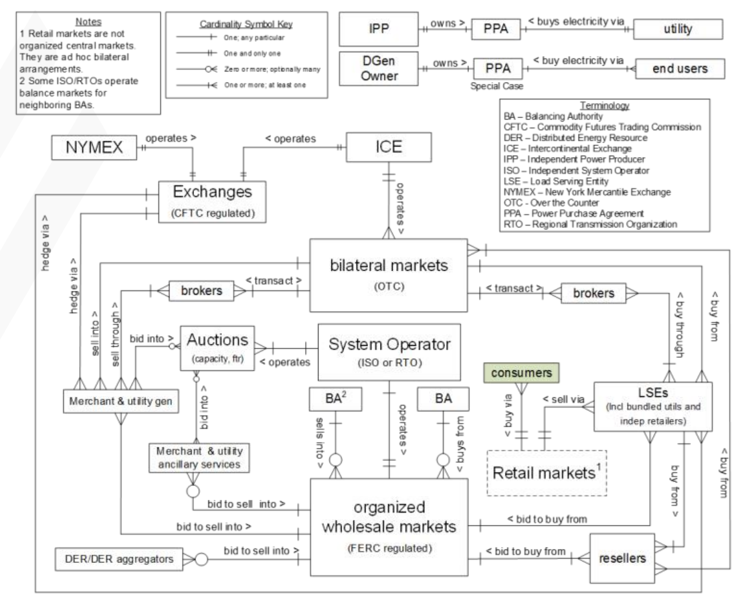
A few examples…



ERCOT Industry Structure



Market-Control Process – NY ISO



Electricity Market Structure

U.S. DEPARTMENT OF ENERGY

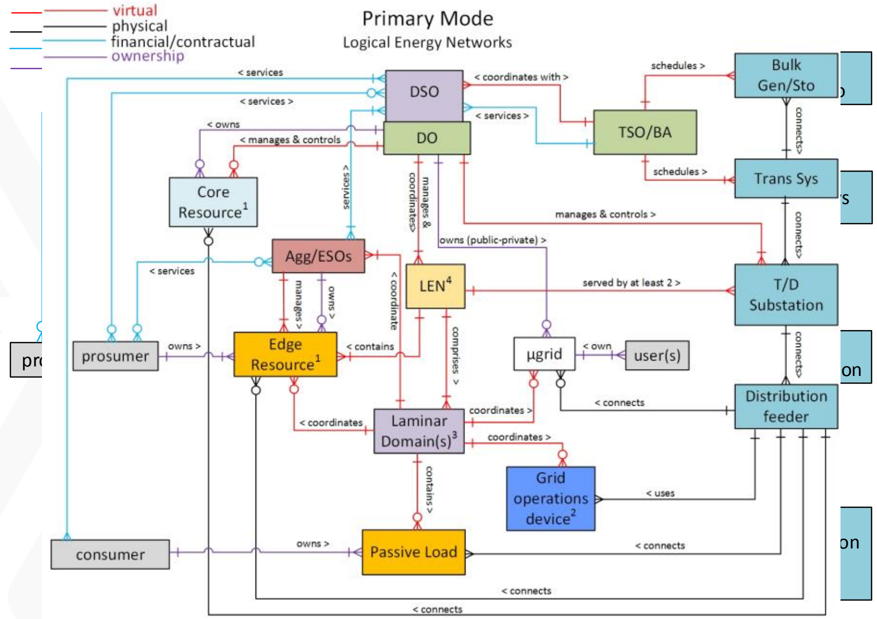
Grid Architecture

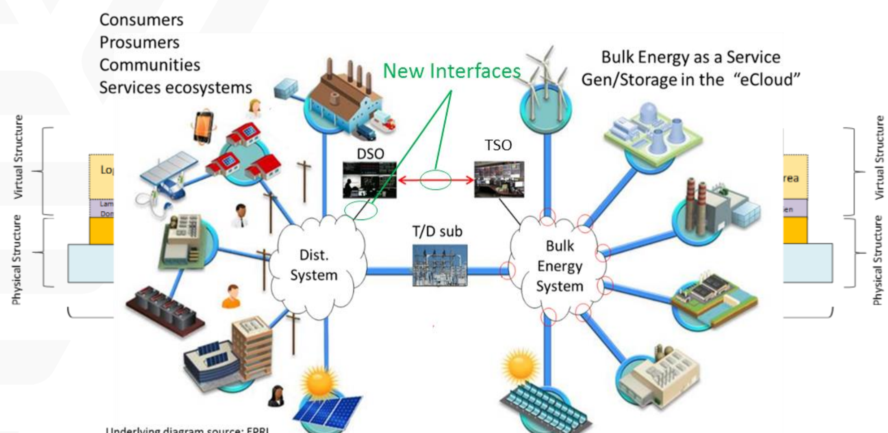
Accomplishments to Date: Example Innovations

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

<u>New Grid Architecture Concepts</u>

- Laminar Coordination Frameworks & Grid Codes
- Sensor/Communication Layer Platforms
- Logical Energy Networks and Distribution Virtualization
- Distribution Storage Networks
- Analytical Architecture Methods and the Architecture Equation
- New resilience definition for electric grids & theory of grid resilience
- DER Telemetry Structure for Dual DER Markets and DSOs
- Market-Control Models and Relationships
- Network Convergence and Value Creation
- Gas-Electric Resilience Inner Loops



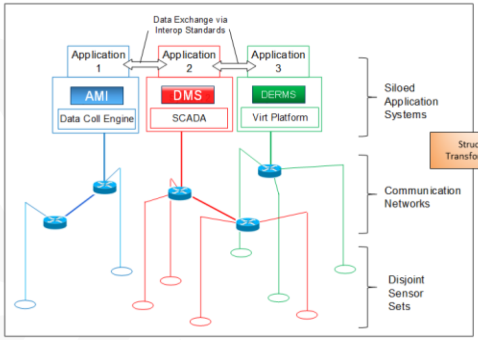


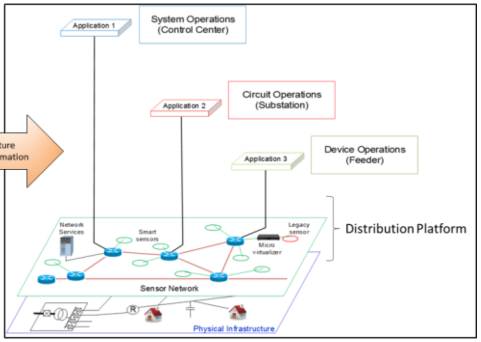
Grid Architecture

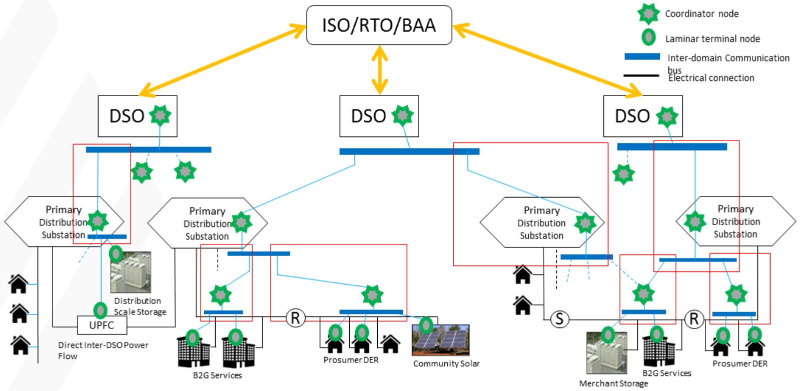
Accomplishments to Date: Partial List of Documents

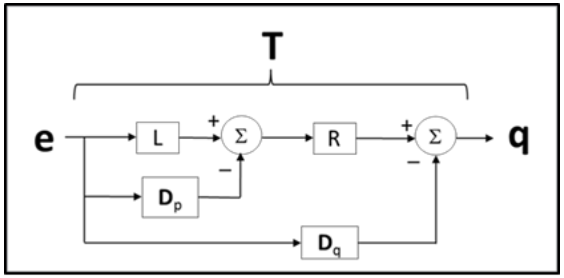
Example Intermediate Work Product Documents

- Grid Services Master List
- Pacific Northwest Industry Structure Model
- ERCOT Industry Structure Model
- Electricity Market Structure & Components Models
- Grid Architecture at the Gas-Electric Interface
- Electric Grid Resilience and Reliability for Grid Architecture
- Toward a Practical Theory of Grid Resilience
- Electric Grid Market-Control Structure
- DER Telemetry Communication Architecture for ESOs, DSOs, and System Operators
- Distribution Storage Networks
- Comparative Architecture Analysis: Using Laminar Structure to Unify Multiple Grid Architectures
- Advanced Networking Paradigms for High-DER Distribution Grids
- Architectural Basis for Highly Distributed Transactive Power Grids: Frameworks, Networks, and Grid Codes
- A Mathematical Representation of System Architectures







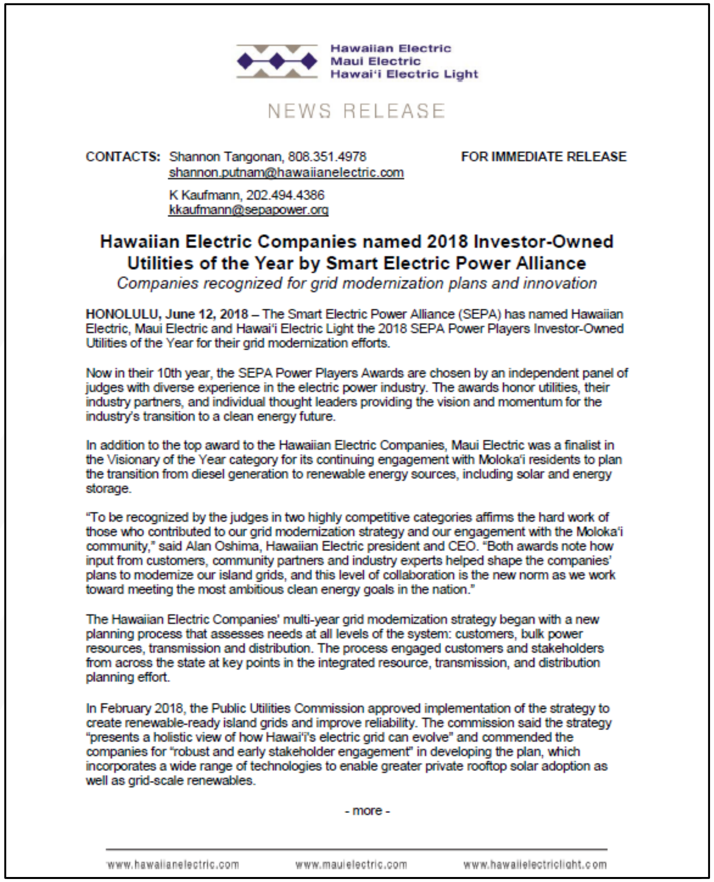


Architecture Equation

Grid Architecture

Accomplishments to Date: Industry Uptake Examples

- Sensor network infrastructure and general Grid Architecture methods at HECO
- Basis for much of the DSPx Technical Assistance Project
  - Uptake in at least 26 states
- Electric Power Research Institute adopted DSPx as basis for utility modernization roadmaps
- National Institute of Standards and Technology adopted our reference architecture track models for their Economics of Interoperability study
- Laminar Coordination Framework
  - Duke Energy resilience project
  - Avista/Duke OpenDSP project
  - Commonwealth Scientific and Industrial Research Organization (CSIRO) applied laminar framework and other work to inform re-organization of the Australian utility industry
  - Alliander – comparative architecture analysis
- PUCO PowerForward support
- Australian Energy Market Operator (AEMO) Global Grid Architecture analyses
- Southern California Edison 2018 Rate Case
  - Grid Architecture methodology



Hawaiian Electric
Maui Electric
Hawai'i Electric Light

NEWS RELEASE

CONTACTS: Shannon Tangonan, 808.351.4978
shannon.putnam@hawaiianelectric.com
K Kaufmann, 202.494.4386
kkaufmann@sepapower.org

FOR IMMEDIATE RELEASE

Hawaiian Electric Companies named 2018 Investor-Owned Utilities of the Year by Smart Electric Power Alliance

Companies recognized for grid modernization plans and innovation

HONOLULU, June 12, 2018 – The Smart Electric Power Alliance (SEPA) has named Hawaiian Electric, Maui Electric and Hawai'i Electric Light the 2018 SEPA Power Players Investor-Owned Utilities of the Year for their grid modernization efforts.

Now in their 10th year, the SEPA Power Players Awards are chosen by an independent panel of judges with diverse experience in the electric power industry. The awards honor utilities, their industry partners, and individual thought leaders providing the vision and momentum for the industry's transition to a clean energy future.

In addition to the top award to the Hawaiian Electric Companies, Maui Electric was a finalist in the Visionary of the Year category for its continuing engagement with Moloka'i residents to plan the transition from diesel generation to renewable energy sources, including solar and energy storage.

"To be recognized by the judges in two highly competitive categories affirms the hard work of those who contributed to our grid modernization strategy and our engagement with the Moloka'i community," said Alan Oshima, Hawaiian Electric president and CEO. "Both awards note how input from customers, community partners and industry experts helped shape the companies' plans to modernize our island grids, and this level of collaboration is the new norm as we work toward meeting the most ambitious clean energy goals in the nation."

The Hawaiian Electric Companies' multi-year grid modernization strategy began with a new planning process that assesses needs at all levels of the system: customers, bulk power resources, transmission and distribution. The process engaged customers and stakeholders from across the state at key points in the integrated resource, transmission, and distribution planning effort.

In February 2018, the Public Utilities Commission approved implementation of the strategy to create renewable-ready island grids and improve reliability. The commission said the strategy "presents a holistic view of how Hawai'i's electric grid can evolve" and commended the companies for "robust and early stakeholder engagement" in developing the plan, which incorporates a wide range of technologies to enable greater private rooftop solar adoption as well as grid-scale renewables.

- more -

www.hawaiianelectric.com www.mauielectric.com www.hawaiielectriclight.com

Grid Architecture

Accomplishments to Date: Recent Stakeholder Engagements

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

- One Hour Keynote on Grid Resilience at Resilience Week, Aug 2018
- Four-hour tutorial on Grid Architecture at IEEE PES General Meeting, August 2018 (largest attendee signup)
- Five hour ARID review of the High Resilience architecture track, SEPA Utility Summit, July 2018
- MACRUC Conference Panel – *Using Grid Architecture for Futureproofing Grid Modernization Investments*, June 2018
- 14 Week Grid Architects' Boot Camp, concluded April 2018
- SEPA Utility Conference Panel, April 2018
- Day-long ComEd Senior Staff Strategy Meeting, January 2018

https://gridarchitecture.pnnl.gov/

Grid Architecture

Next Steps and Future Plans

Key Goals:

- ► Adoption of grid architecture methodology for large scale grid structure problems
- ► Uptake and adaptation the GMLC reference grid architectures for field use

Next Steps:

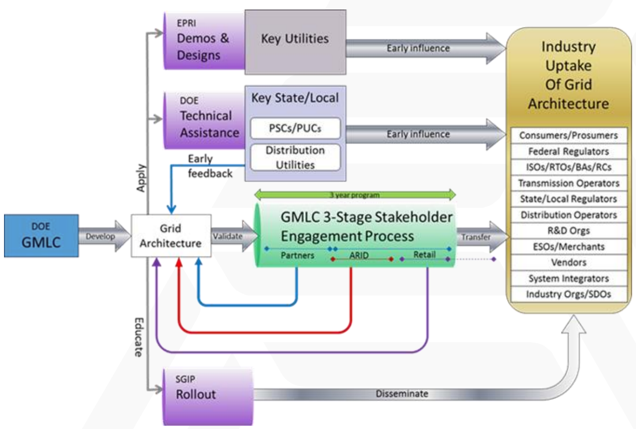
- ► Complete writing of the reference architectures and implement the new architecture tools (4/19)
- ► Complete the documentation and make it available to the industry (4/19)

Beyond the present program:

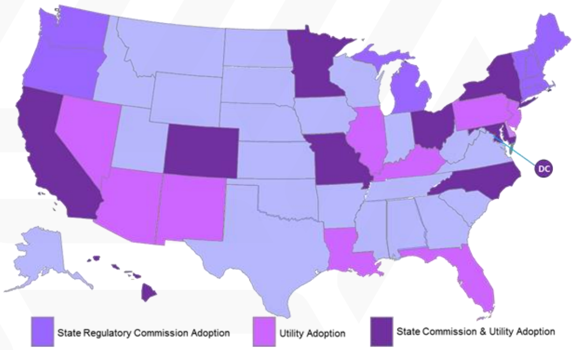
- ► Align various GMLC/DOE and related efforts under one or more of the reference architectures from this project and *field validate* *(6/19 – 4/22)*
  - Multi-microgrid controllers & ADMS/GridApps-D
  - Sensor/communications layering & Distribution Storage Networks
  - Logical Energy Networks, Laminar Coordination & Total DSO
  - Extended Grid State and Sensor Placement Optimization Tool (SPOT)
- ► Individually, these will elements have some positive impact;
  organized via an architecture they will reinforce each other and change the industry
- ► Build a complete ecosystem around Grid Architecture (present – 4/20)

Grid Architecture

Accomplishments to Date: Regulatory Impact via DSPx



- Phase 1: 3 volume set
  - Uptake in 26 states so far
- Phase 2 underway now
  - NECPUC Practicum
  - First Energy grid mod roadmap (with EPRI)
  - Grid Modernization Technology Management Guide



State Regulatory Commissions and Utilities Leveraging Modern Distribution Grid Report

Based on State Commission Requests & Documents, Utility Feedback & Filings

FERC Notice of Technical Conference on Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators (Docket RM18-9-000) and Distributed Energy Resources-Technical Considerations for the Bulk Power System (Docket AD18-10-000) to be held on April 10 and 11:

"Knowing that a variety of grid architectures are being explored in various regions, does it make sense for the Commission to consider specific architectural requirements for RTOs/ISOs for the effective integration and coordination of DER aggregations?"

In the footnote to this statement, it says "As an aid to thinking about the electric power grid, **Pacific Northwest National Laboratory and others have coined the term "grid architecture," which they define as the application of network theory and control theory to a conceptual model of the electric power grid that defines its structure, behavior, and essential limits.** See, e.g., https://gridarchitecture.pnnl.gov/."

GRID MODERNIZATION INITIATIVE PEER REVIEW

GMLC 1.4.10—Control Theory

SIDHANT MISRA

September 4–7, 2018

Sheraton Pentagon City Hotel – Arlington, VA

Control Theory
High-Level Summary

Project Description

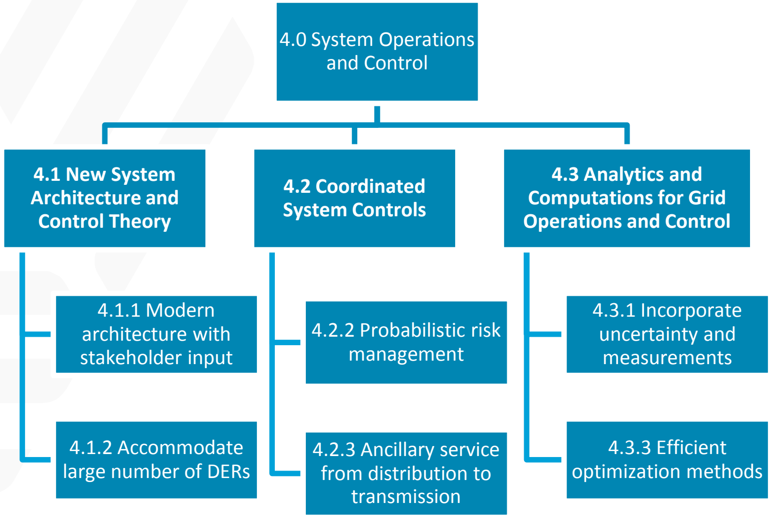
Develop new integrated optimization and control solutions, including architectures, algorithms, and deployment strategies to transition to a large number of distributed energy resources (DERs) participating in grid control.

Project Objectives

- Ensure **architectural compatibility** of control theory and solutions.
- **Coordinate time scales** to enable tractable control of >10,000 DERs.
- **“Homogenize” diverse DERs.**
- **Incorporate power flow physics** and **uncertainty management.**

Value Proposition

- Large and diverse number of DERs that are not directly dispatched by the system operator.
- Traditionally used redundancy and reserve margins are insufficient for risk management due to growing uncertainty and complexity.



Control Theory
Project Team

Project Participants and Roles

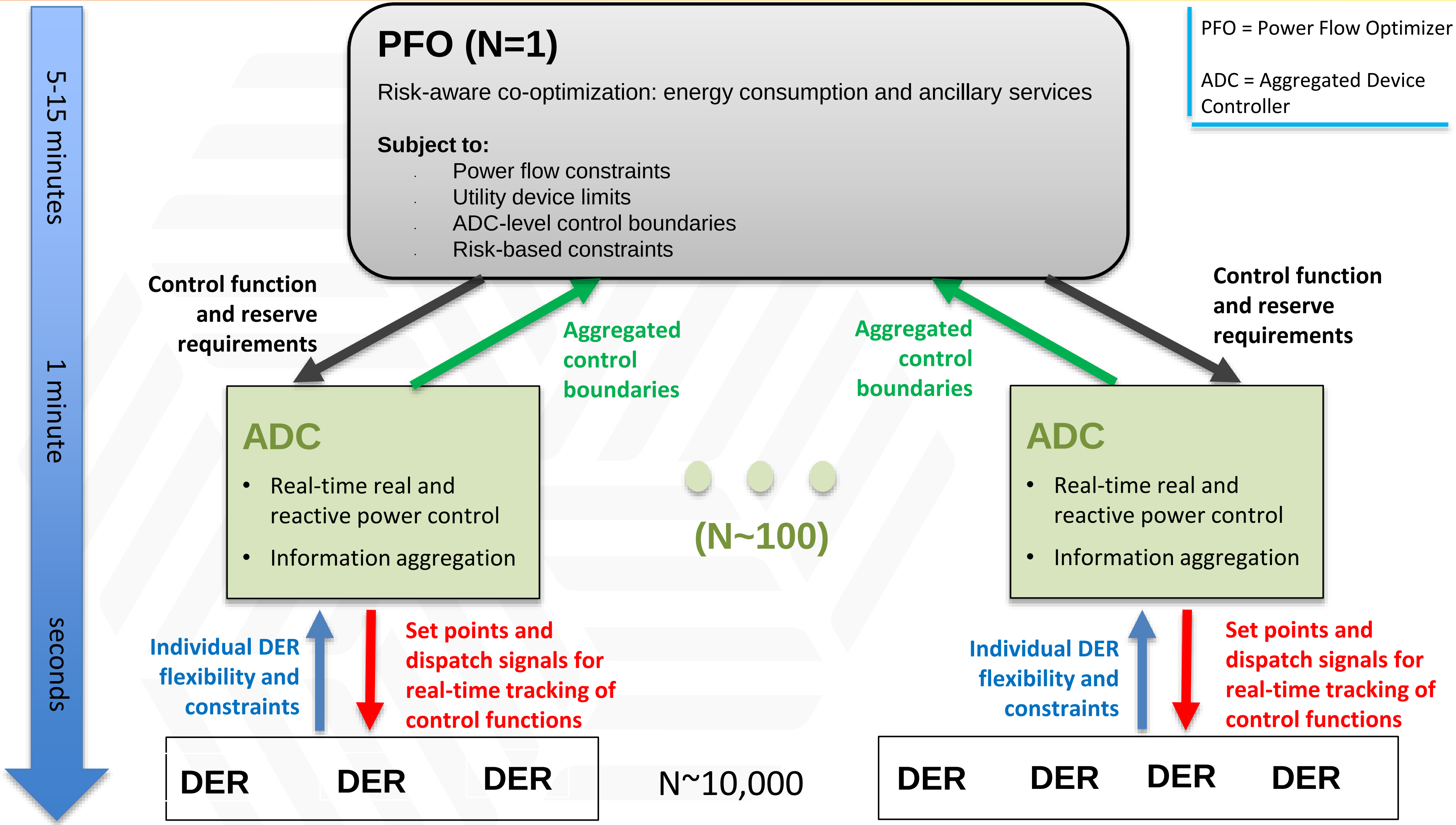
R&D Team:
- LANL (lead)—risk-aware optimization, aggregate device modeling
- PNNL (co-lead)—real-time control, aggregate device modeling, simulation-based testing
- NREL—real-time control, aggregate device modeling
- ANL—power flow
- INL, ORNL, LLNL, SNL—metrics, testing and control design

Industry Advisors:
- Oncor Electric Delivery
- PJM Interconnection LLC
- United Technologies Research Center

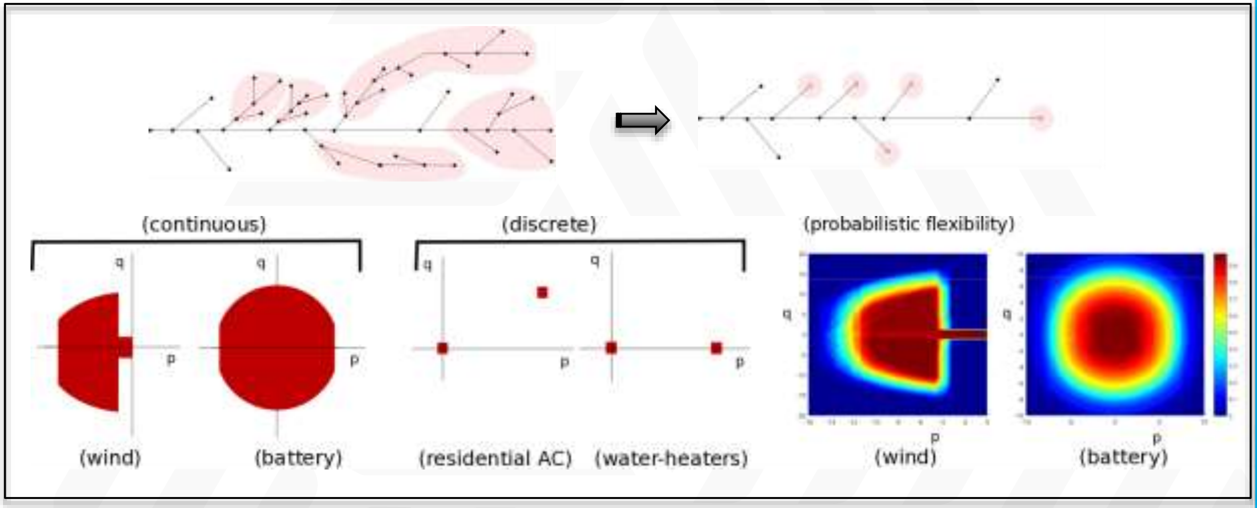
(IAB meeting 04/27/18 – positive feedback on technical soundness and approach)

PROJECT FUNDING			
Lab	**FY16 $**	**FY17 $**	**FY18 $**
LANL	905,000	670,000	405,000
PNNL	785,000	525,000	720,000
INL	185,000	225,000	0
ANL	290,000	220,000	145,000
ORNL	50,000	50,000	0
LLNL	50,000	100,000	60,000
SNL	100,000	100,000	0
NREL	215,000	245,000	425,000

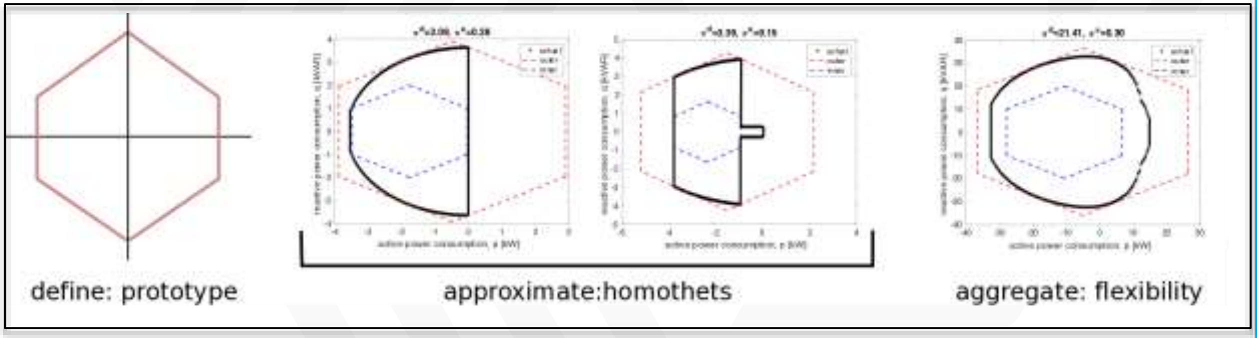
Control Theory
Approach



Aggregating flexibility of heterogenous DERs



Producing convex aggregation domains



DER aggregation and flexibility models (8/1/18)

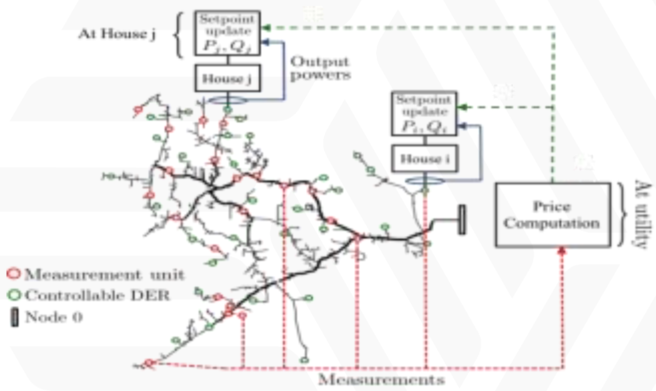
Geometric method of aggregating flexibility in heterogeneous loads
- Published in conference

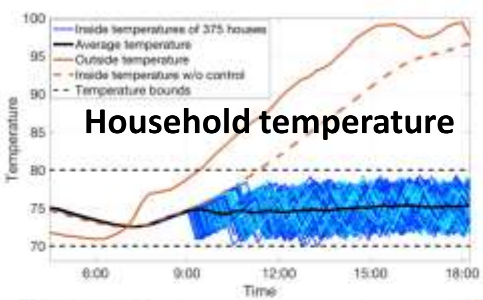
Scalable computing of methods for aggregating heterogenous flexibility
- Submitted to conference

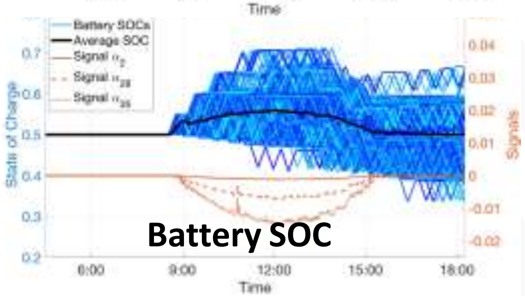
Aggregating DER flexibility domains under parametric uncertainties
- Submitted to conference

Control Theory
Accomplishments to Date

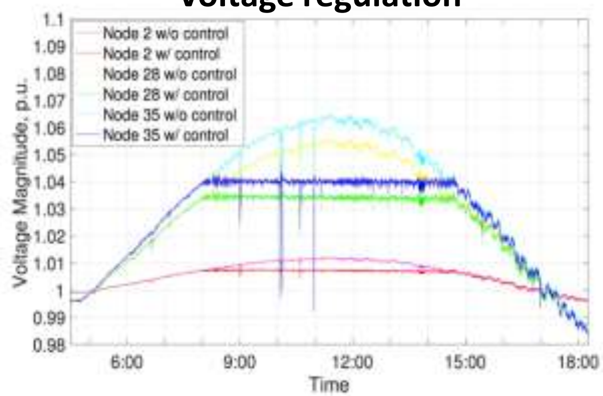
Incentive-based control of DERs within an ADC control area







Voltage regulation



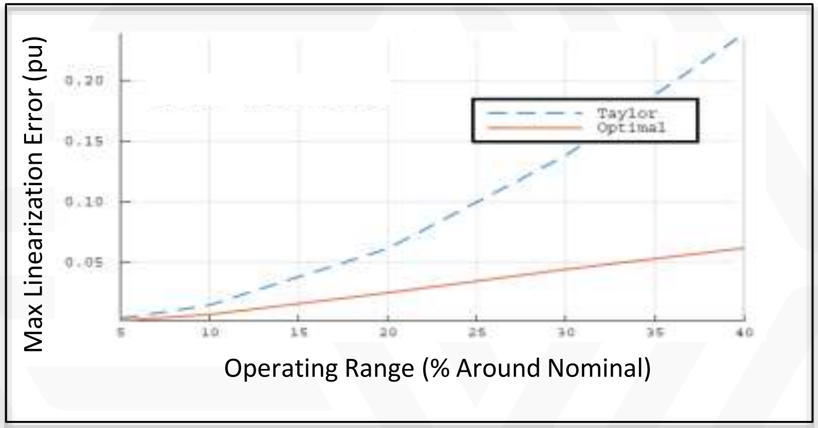
Real-time control strategies for DERs (8/1/18)

DER control algorithm to track ADC setpoints

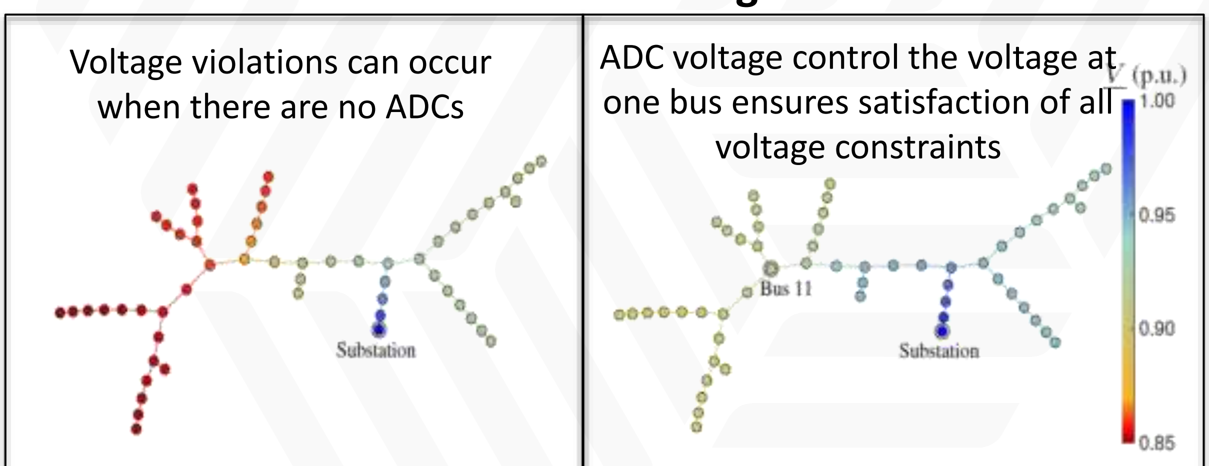
- Incentive-based
- Online
- Distributed
- Privacy preserving

4 journal/conference publications

Optimal Adaptive Linear Power Flow Approximations



ADC Placement Algorithm



Power Flow relaxations & approximations

Extensive **survey and analysis** of the power flow relaxation and approximation literature. (4/1/18)
- Submitted for journal publication

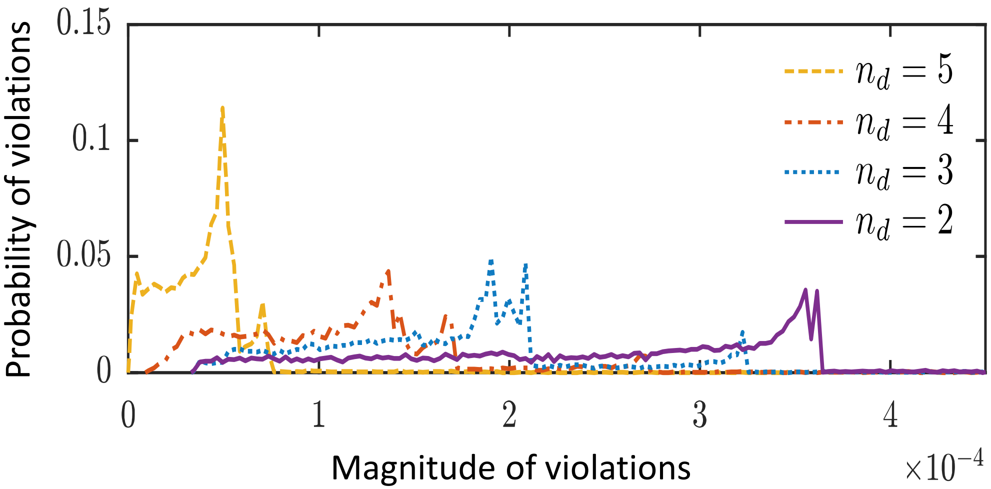
Algorithms for computing **optimal adaptive linear approximations** (12/1/17)
- Published in conference

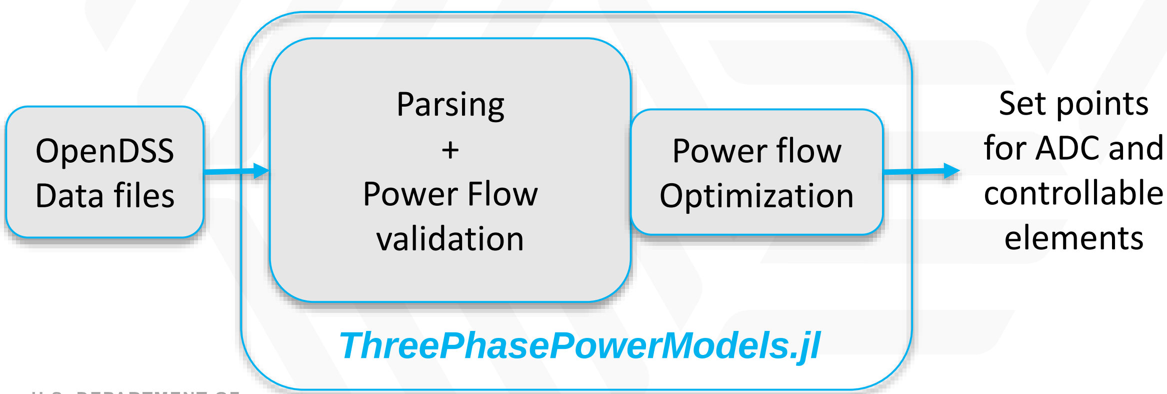
ADC placement algorithm that determines when power flow constraints can be neglected. (8/1/18)
- Submitted to conference

Control Theory

Accomplishments to Date

Risk-Aware non-linear Power Flow Optimization





Risk-aware PF optimization with integrated DER control

Optimization methods for PFO that account for **non-linearity** and **uncertainty** (4/1/18)

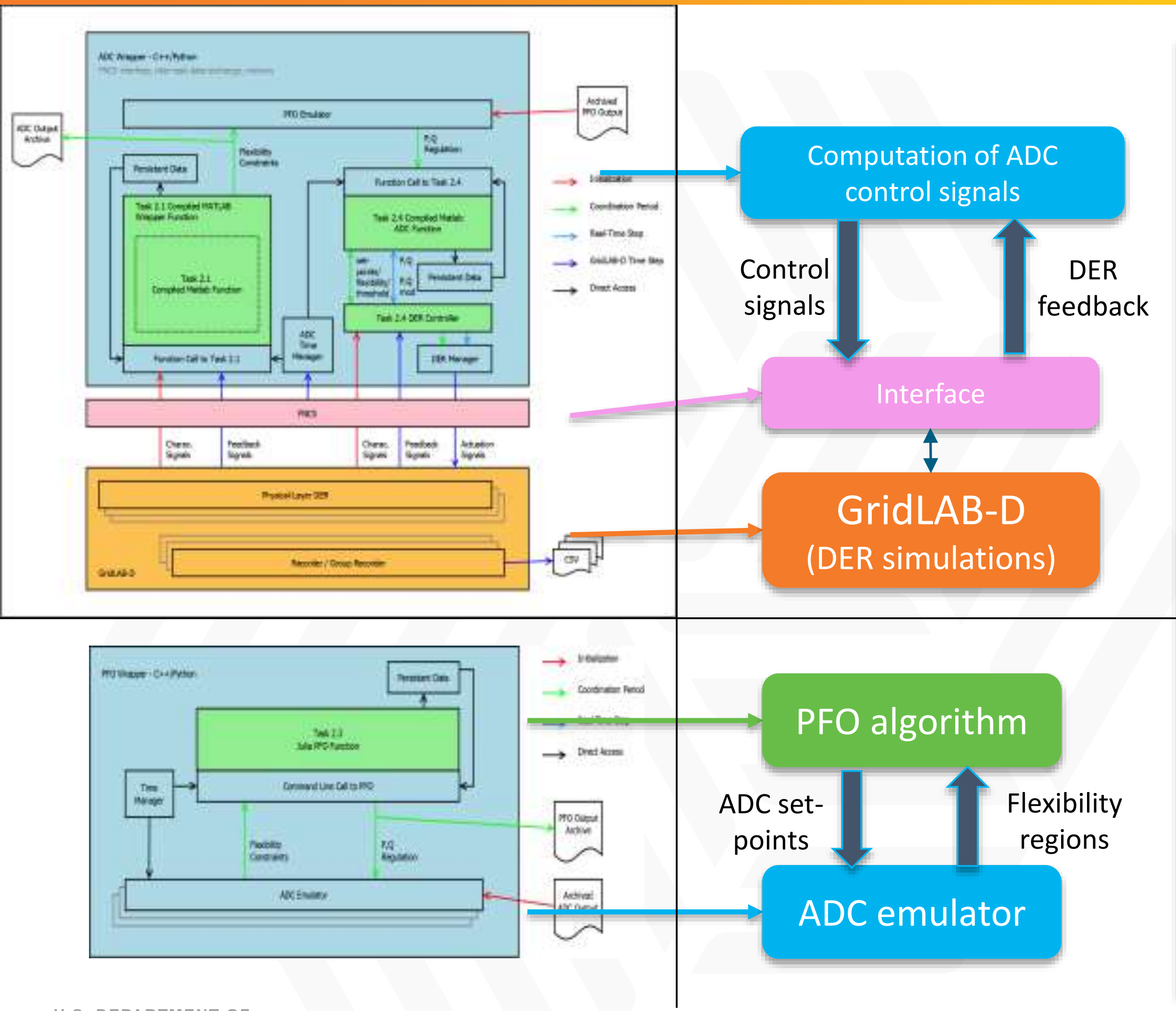
- *Submitted for journal publication*
- *2 papers in preparation*

Parsing data from OpenDSS format into Julia and power flow validation (8/1/18)

- Software package completed (ThreePhasePowerModels.jl)

Control Theory

Accomplishments to Date



Numerical testing

PFO-ADC-DER Test Bed: *supervisory module (8/1/18)*

1. Pass I/O between DER in GridLAB-D and ADCs
2. Manage PFO-DER I/O and execution

Control Theory
Next Steps and Future Plans

Project Next Steps

- Finalize test case for single distribution feeder with ADC placements (12/31/18)
- Complete PFO and DER control integration into test-bed (4/1/19)
  - Down-select PF representations, PFO and DER control algorithms
- Numerical demonstration on ~10 distribution feeders ~10000 DERs (10/1/19)

Future Plans

- Distributed algorithms for distribution grid optimization and control (FY20)
  - ADC-based Power-Flow-aware architecture naturally supports distributed computations
- In-depth exploration of ancillary service provision capabilities of distribution grids to the bulk transmission system (FY20)

GRID MODERNIZATION INITIATIVE PEER REVIEW

1.4.11 Multi-Scale Integration of Control Systems (EMS/DMS/BMS Integration)

LIANG MIN/LLNL, MARK RICE/PNNL

September 4–7, 2018

Sheraton Pentagon City Hotel – Arlington, VA

DOE Project Managers: Eric Lightner and Charlton Clark
Lab team: Liang Min and Philip Top/LLNL, Mark Rice and Emily Barrett/PNNL, YC Zhang and Rui Yang/NREL, Bryan Arguello/SNL, Sidhant Misra/LANL, and Zhi Zhou/ANL

Multi-Scale Integration of Control Systems

High-Level Project Summary

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

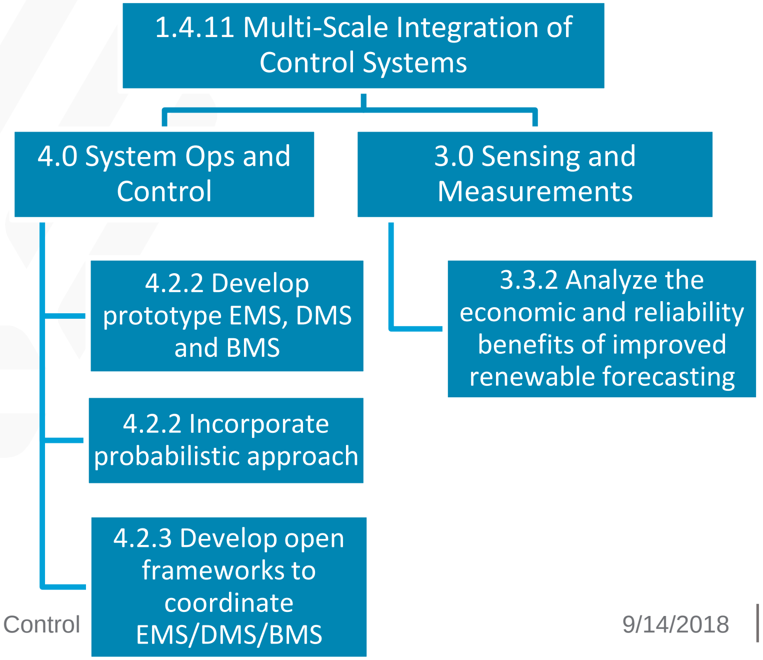
Create an integrated grid management framework for the end-to-end power delivery system – from central and distributed energy resources at bulk power systems and distribution systems, to local control systems for energy networks, including building management systems.

Value Proposition

- ✓ The current grid operating systems were developed over the last three to four decades using a piecemeal approach, within narrow functional silos.
- ✓ The rapid growth of DERs and the increased need to integrate customers with the power system are rendering the current generation of grid operating systems obsolete.

Project Objectives

- ✓ Develop an open framework to coordinate EMS, DMS and BMS operations.
- ✓ Demonstrate the new framework on a use case at GMLC national lab facilities.
- ✓ Deploy and demonstrate new operations applications on that framework.



Project Participants and Roles

Lab team:

- LLNL – PI, use case and scenarios
- PNNL – Plus 1; Energy management system and Building management system
- NREL – Distribution Management System
- SNL – Stochastic unit commitment
- LANL – Stochastic economic dispatch
- ANL – Renewable Forecasting

DOE project manager:

- Eric Lightner/OE
- Charlton Clark/EERE

Industry partners:

- GE– e-terra EMS and DMS providers
- Duke Energy – Distribution feeder data
- PJM Interconnection LLC – Transmission Data

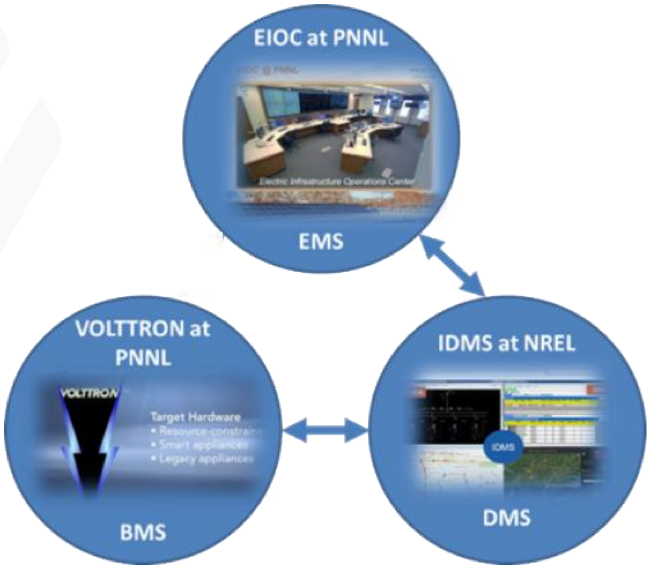
PROJECT FUNDING

Lab	FY16 $	FY17$	FY18 $
LLNL	300	266	290
SNL	100	187	170
LANL	70	82	75
PNNL	380	276	270
ANL	150	142	150
NREL	200	197	195
Total	1200	1150	1150

Multi-Scale Integration of Control Systems
Approach

- **Technical tasks**
  - Task 1: Use case development
  - Task 2: Open framework development for EMS/DMS/BEMS integration
  - Task 3: Integration of new stochastic applications into EMS operations models
  - Task 4: Demonstration of EMS/DMS/BMS Integration

- **Key innovations and project uniqueness**
  - An platform linking EMS, DMS, and BMS operations, and being the ***FIRST*** in the national lab complex to demonstrate EMS/DMS/BMS interactions on industry test systems.
  - New transformative operations applications (stochastic operations and forecasting data integration and decision support) that transform or extend existing EMS applications.



Multi-Scale Integration of Control Systems

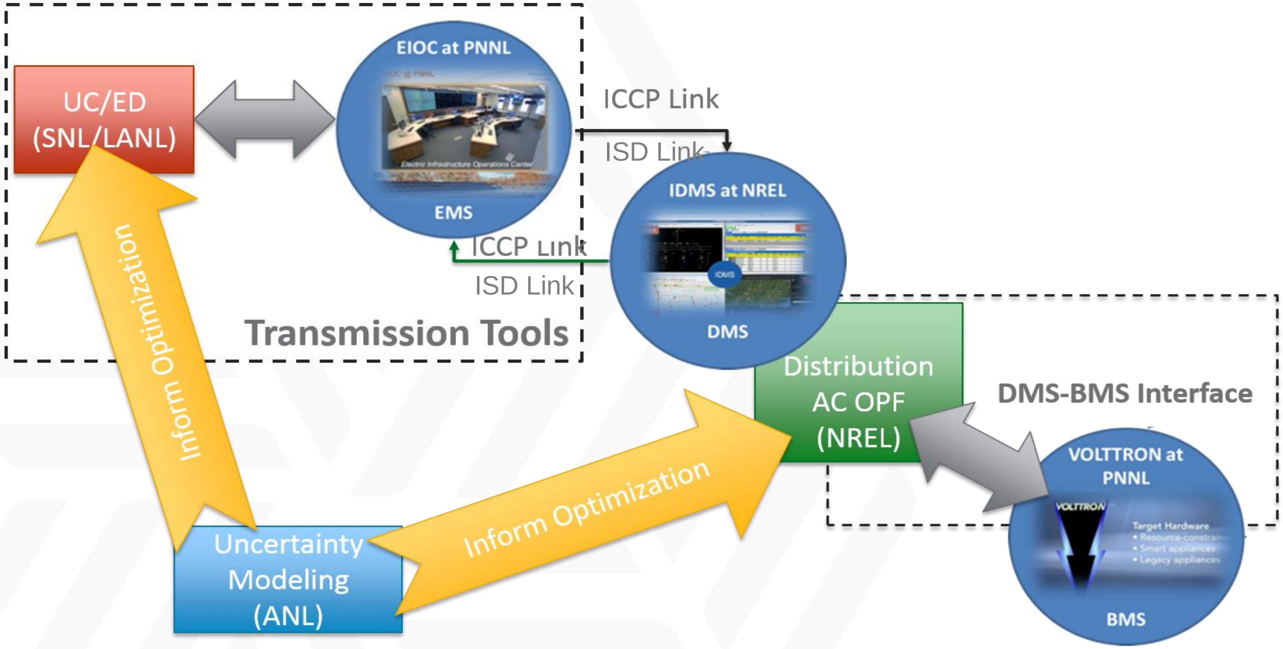
Accomplishments to Date

GRID MODERNIZATION INITIATIVE U.S. Department of Energy

- **Accomplishments to date**
  - Year 1 - Completed the use case report and data exchange requirements/protocols report (*12/2/2016*); completed the integration of stochastic UC/ED/forecasting (*3/30/2017*).
  - Year 2 - Demonstrated the integration of DMS and BMS information on the use case (*3/30/2018*); Established the link between EMS and DMS (*6/30/2018*).
- **Workshops or other stakeholder engagement**
  - Participated and presented at the advanced Distribution Management System (ADMS) Industry Steering workshops 2016 and 2017.
  - Participated and presented at IEEE Innovative Smart Grid Technologies ADMS panels, 2016, 2017 and 2018.
  - Proposed to be on the panel for the IEEE General Meeting TSO-DSO panel 2019.
- **Market Impact**
  - Reduce generation, transmission, and distribution capital costs by reducing annual peak demand.
  - Dynamically balance electricity supply and demand to integrate variable renewable energy and maintain system reliability.

We have completed the data exchange requirements.

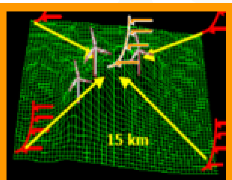
Interface Definition



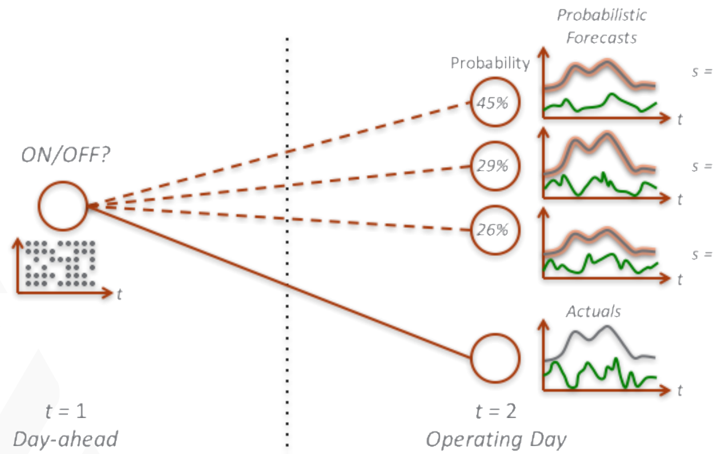
- The connection between EIOC at PNNL and IDMS at NREL through the ICCP or InterSiteData (ISD) link (engaged the vendor, coordinating with another two GMLC projects.)
- The connection between VOLTTRON™ at PNNL and DMS at NREL through VOLTTRON™ Internet Protocol (VIP) - Standardization is important.

We have successfully integrated stochastic UC/ED/wind forecasting.

NWP Output Data
Weather Data
Off-site Met Data
Site Power Gen & Met Data



Physical Models



Wind forecast scenarios

CSV, json

Power system data

E.g., MATLAB parser for Matpower cases

EMS-UC (python): Reads data and creates stochastic UC model using pyomo

pyomo (python): algebraic modeling language for describing MILP

CPLEX/Gurobi: Solves optimization

EMS

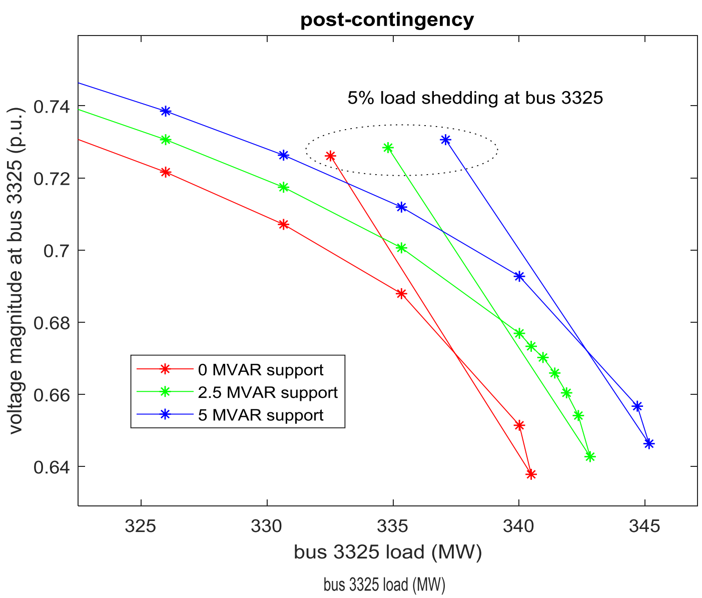
ED

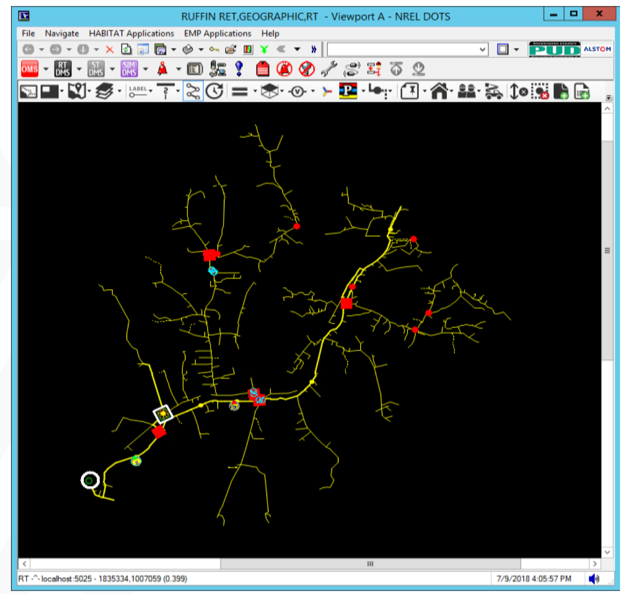
Unit on/off status per hour

We have established the link between e-terra EMS (PNNL) and DMS (NREL).

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

EMS - InterSiteData (ISD) Link - DMS





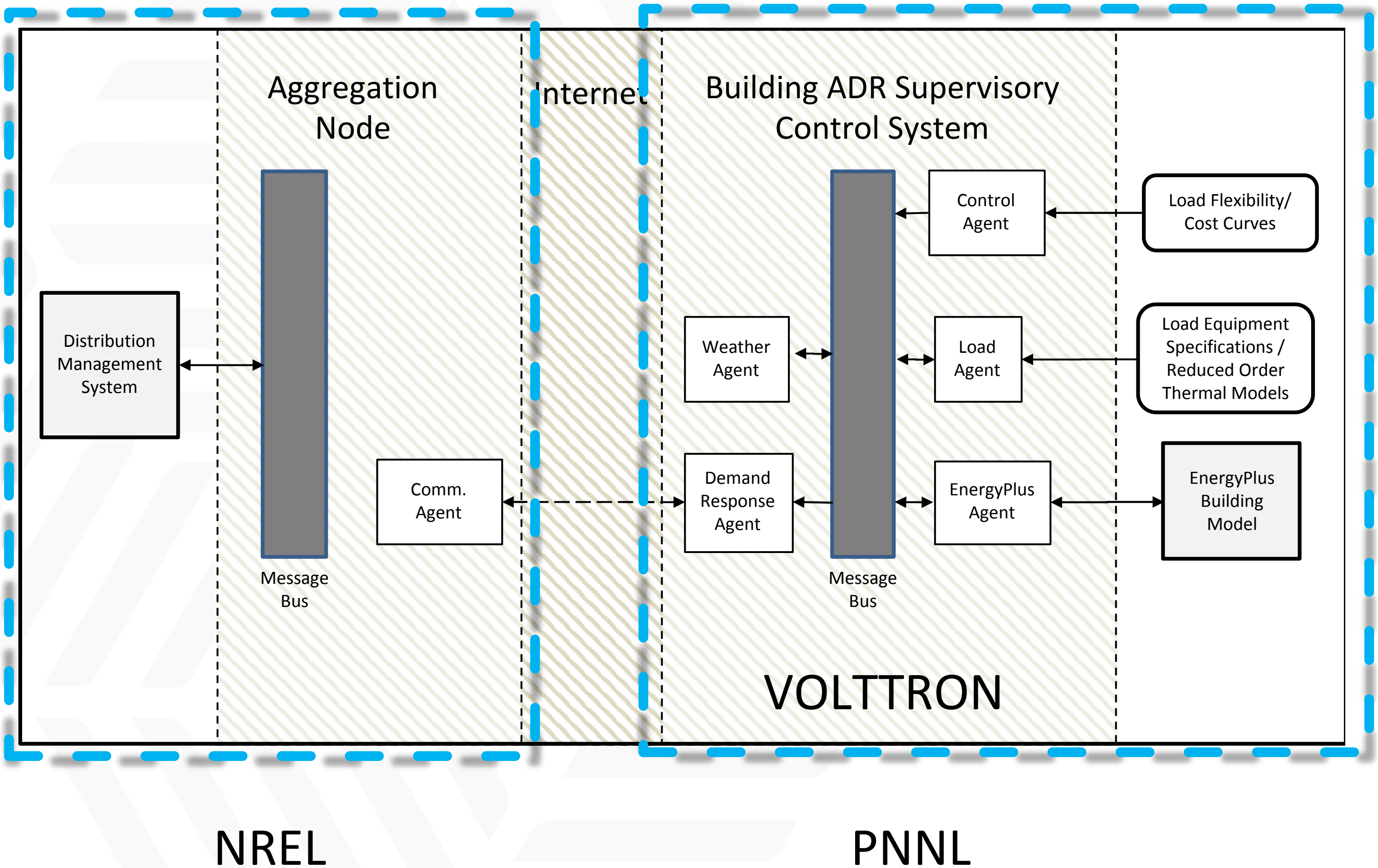
- PJM generic system model with 15572 buses.
- PV studies were performed to analyze the effectiveness of P and Q controls.

- Duke's Test Feeder
  - In Duke's North Carolina service territory
  - Nominal voltage is 12.47 kV
  - Native winter peak load of 5.26 MW
  - One 5-MW PV plant
  - Voltage control devices

We have established the link between DMS (NREL) and Volttron agent at PNNL.

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

DMS - VOLTTRON Internet Protocol- BMS



We have demonstrated the integration of DMS/BMS on the use case.

- Increase air-conditioning set points by 3°F
- Perform lighting control – dimming demand
- Maintain new set points for an hour after the event to prevent issues associated with the rebound effect

4:00 PM

Event Notification

4:30 PM

Event Begins

- BMS takes curtailment actions

5:00 PM

5:30 PM

Event Ends

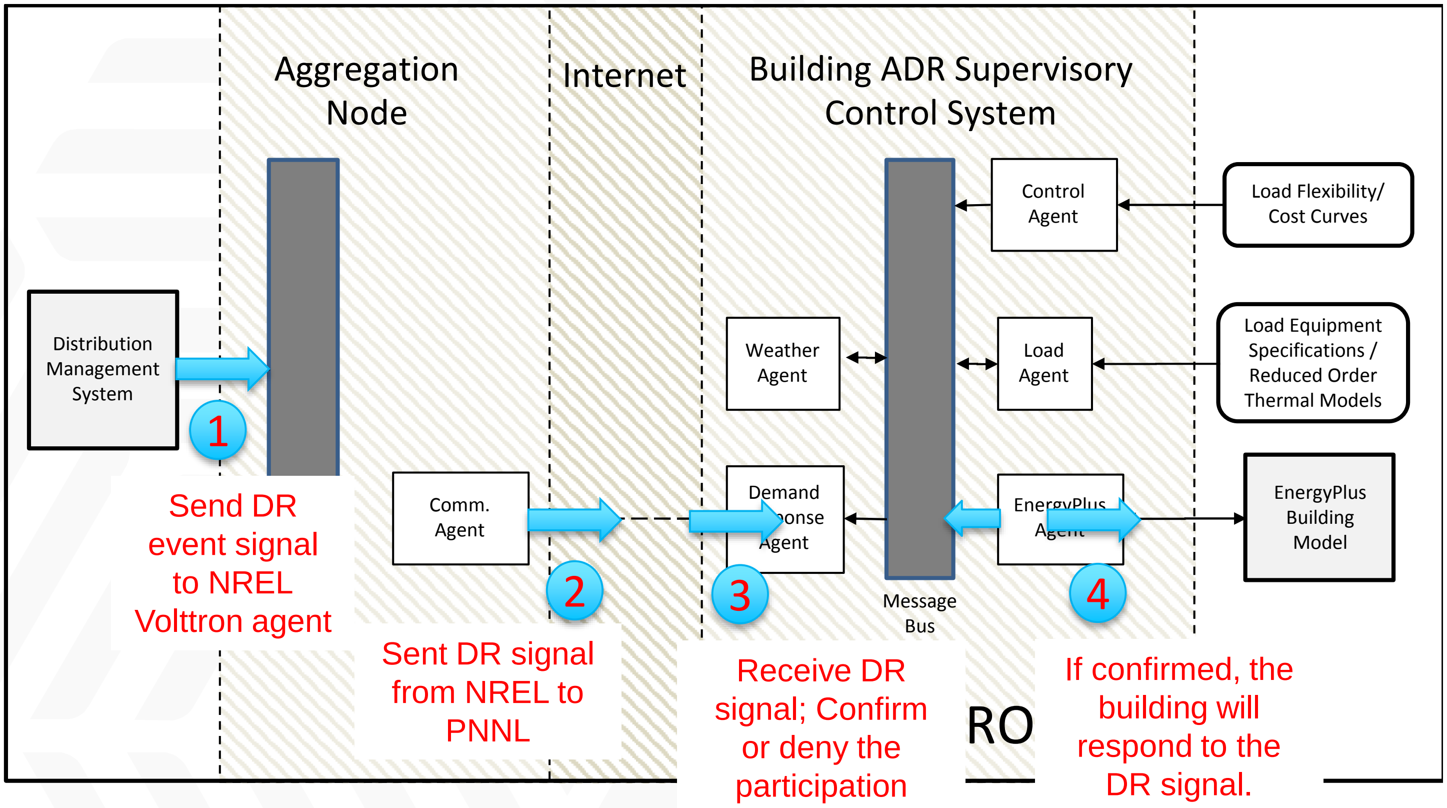
6:00 PM

6:30 PM

- BMS returns to normal operating schedules

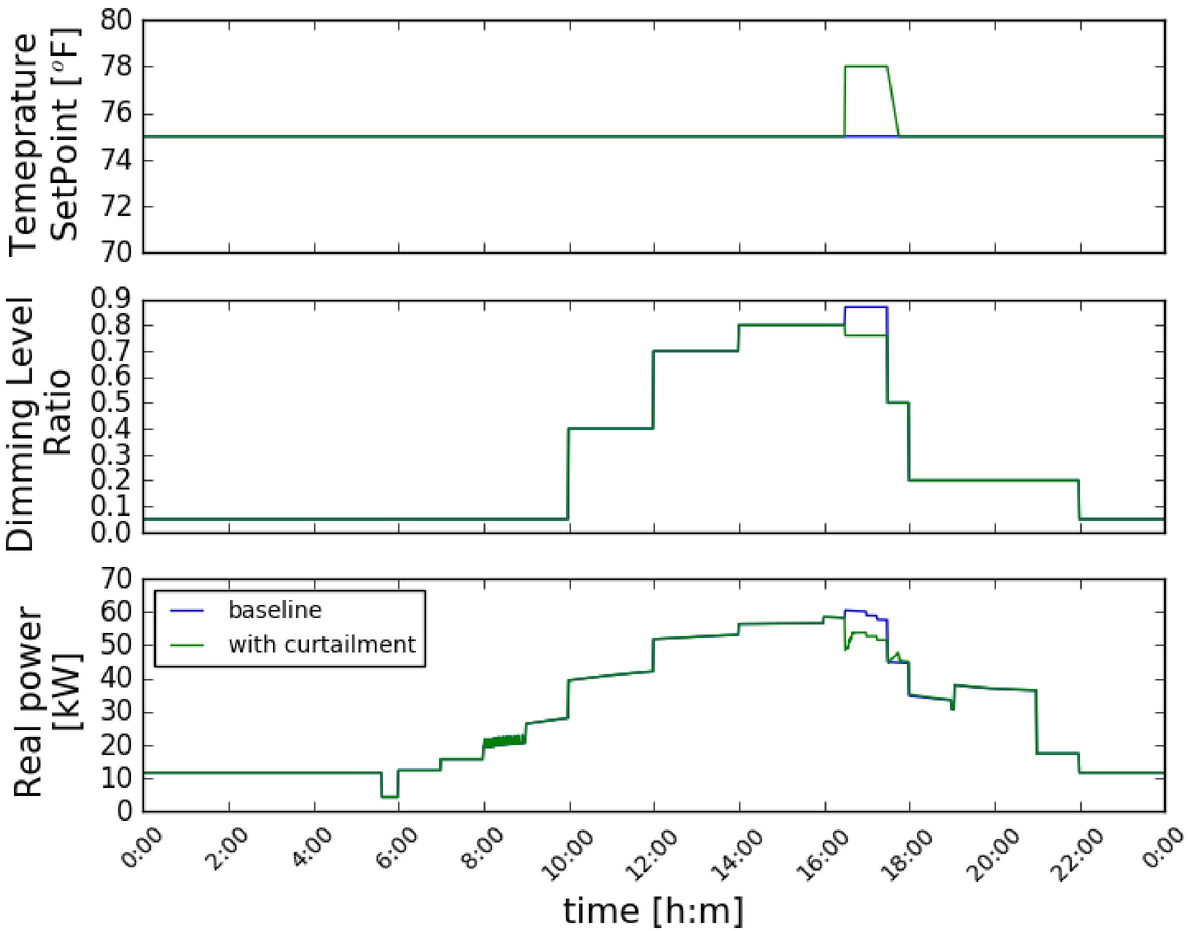
DMS at NREL successfully communicates with BMS at PNNL.

DMS - VOLTTRON Interface- BMS



Simulated building successfully responds to the DR signals.

- If confirmed, below is the response from the simulated buildings (EnergyPlus model)



- Increase air-conditioning set points by 3°F
- Perform lighting control – dimming demand
- Maintain new set points for an hour after the event to prevent issues associated with the rebound effect

Multi-Scale Integration of Control Systems
Next Steps and Future Plans

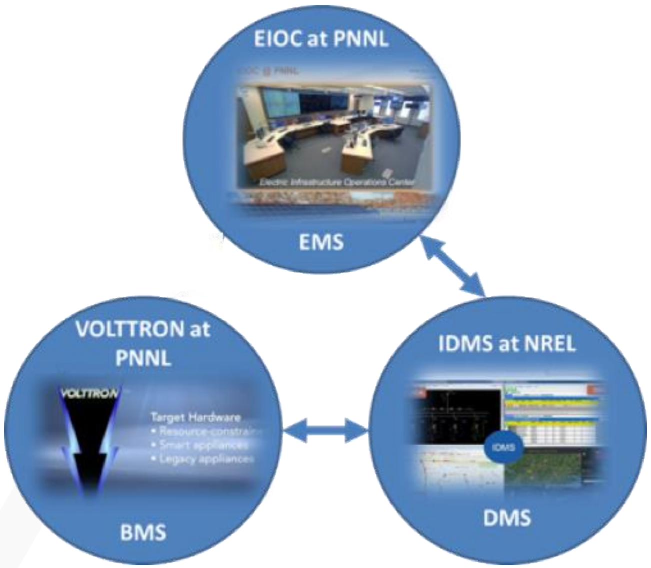
GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

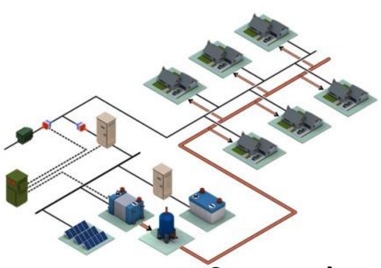
Next step activities planned for PY3 include:

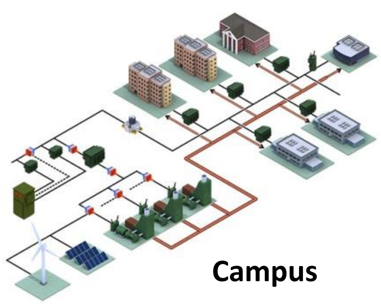
- Complete the deployment of stochastic UC and ED into EIOC computational environment (12/30/2018).
- Conduct the full-scale integration and demonstration (3/30/2019).

Future plans:

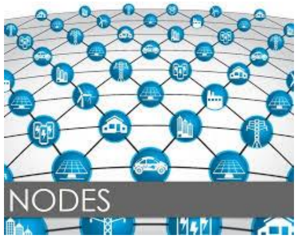
- This project consolidates national labs' capabilities and provides a platform for future R&D and validation on "Beyond Batteries".
  - Current capability: grid-interactive Efficient Buildings
  - Future efforts: controllable loads and hybrid systems (DERMS, NODES)




Community


Campus


Building



Questions?