Interoperability

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Context

Too many devices and systems today cannot interoperate or require difficult and time-consuming integration processes. This results in fewer deployed new technologies (including Distributed Energy Resources - DER) and higher costs.

Key Objectives:

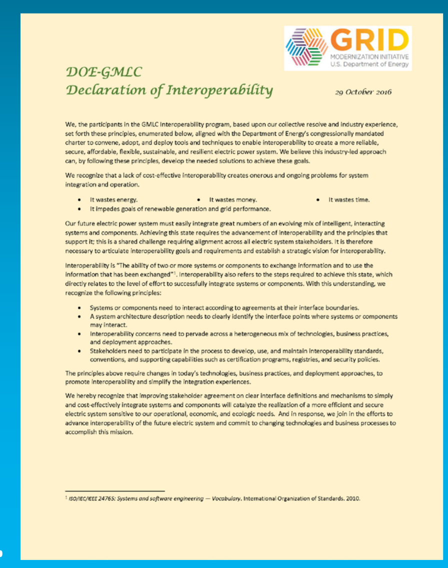
- Advance adoption of interoperable products and services in the energy sector.
- Align stakeholders on a strategic vision.
- Develop measures and tools to support interoperability.

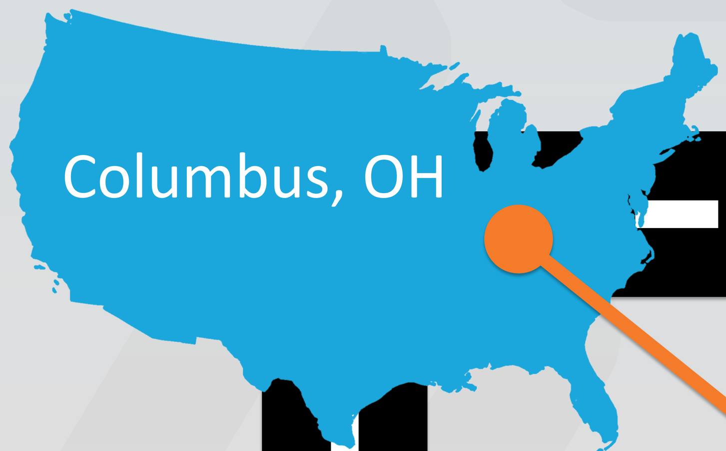
Partner Involvement

Advancing interoperability requires stakeholder alignment; it's a shared challenge. To achieve alignment, the project regularly meets with 16 industry partners and holds 2 public events per year to provide critical review of ideas and plans, and help shape the work to reflect the concerns of industry.

Declaration of Interoperability

About 50 people from a cross section of industry met to create a "declaration of interoperability" that lays out a common definition of interoperability, problems caused by poor interoperability, and a commitment to advance interoperability. This involves changes to integration technologies and business processes within sectors across them.





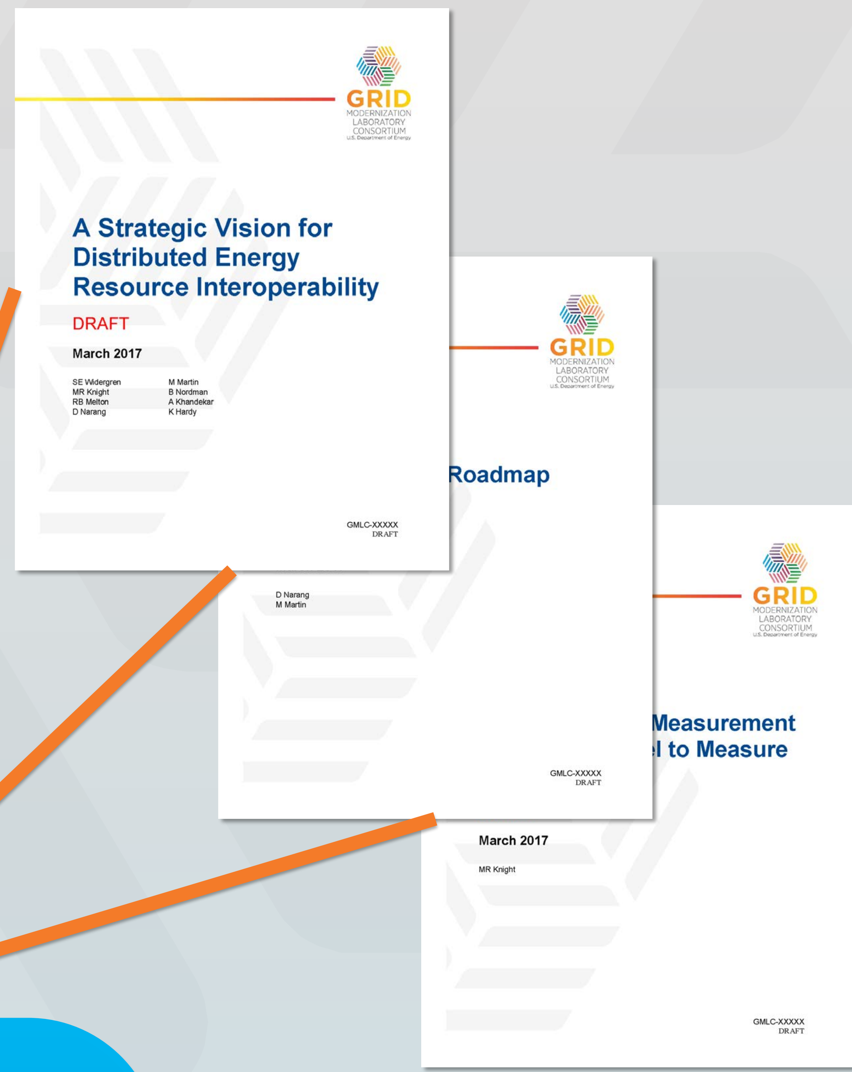
Industry Workshops

At a September 2016 workshop held in Chicago, industry participants advanced criteria for interoperability, enhanced integration vision stories, and affirmed project directions.

The ~50 participants offered diverse perspectives on challenges and goals that tested universal concepts and principles, and explored scope and direction of the project using DER integration as an example. The next event is planned for May 2017 in Columbus.

Project Outreach

The Public Utilities Fortnightly (April 2017) includes an article about this project, discussing the importance of interoperability as more smart devices are deployed. Presentations and discussions have also been held at GWAC, SGIP, and AHR Expo events. Project information has been circulated in the SGIP, NIST, and LonMark newsletters. The project will also be describing its work at the IEEE ISGT, IEEE PES, SEPA Grid Evolution, and Transactive Energy Systems Conferences.



Expected Outcomes

- Establish an interoperability strategic vision.
- Describe the state, challenges, and path forward to advance interoperability.
- Offer tools to facilitate gap analysis, develop roadmaps, and demonstrate vision concepts

Year 1 Deliverables

This project provides leadership visibility to DOE as a champion for grid modernization interoperability with a number of deliverables, including:

- Strategic Vision
- Roadmap Methodology
- Interoperability Maturity Model.

Year 2 Deliverables

- Socialize an interoperability strategic vision document.
- Demonstrate interoperability measurement and path forward.
- Complete draft of interoperability procurement tools.

Year 3 Deliverables

- Introduce incentives for industry participation to advance interoperability.
- Identify commonality across technology domains
- Reduce the uniqueness in the number of DER interface agreements
- Set course for standards convergence

U.S. DEPARTMENT OF ENERGY

April 18, 2017

Devices and Integrated Systems Testing

PNNL-SA-125192

Testing Network and Open Library

PI: Matthew Lave (SNL), +1: Rob Hovsapian (INL)
Project Team: ANL, BNL, INL, LBL, LLNL, NREL, ORNL, SNL, SRNL, PNNL

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Access to testing resources and models at National Labs and beyond is vital to grid modernization.

We are improving access to testing infrastructure for grid devices and systems, and related models and tools:

- **Testing Network (GMLC-TN):** a federated, lab-based resource for testing and performance validation of grid devices and systems
- **Open Library (GMLC-OL):** a public repository for validated models, simulation tools and testing resources

Motivation

- Difficult to find complete and up-to-date information
- Access is confusing, complex, time-consuming
- Lack of coordination between Labs

End of Year Milestones

Stakeholder outreach and coordination

PY1 – Establish Foundations
- draft GMLC-TN framework documents
- resource databases specifications
- catalog of testing capabilities at National Labs

PY2 – Deploy GMLC TN/OL
- GMLC-TN formally established through framework adoption by GMLC-TN full members
- first version of GMLC-OL implementation

PY3 – Ensure Future Sustainability
- GMLC-TN procedures documented
- sustainable mechanism for baseline activities
- GMLC-OL models and test resources available

Project Team

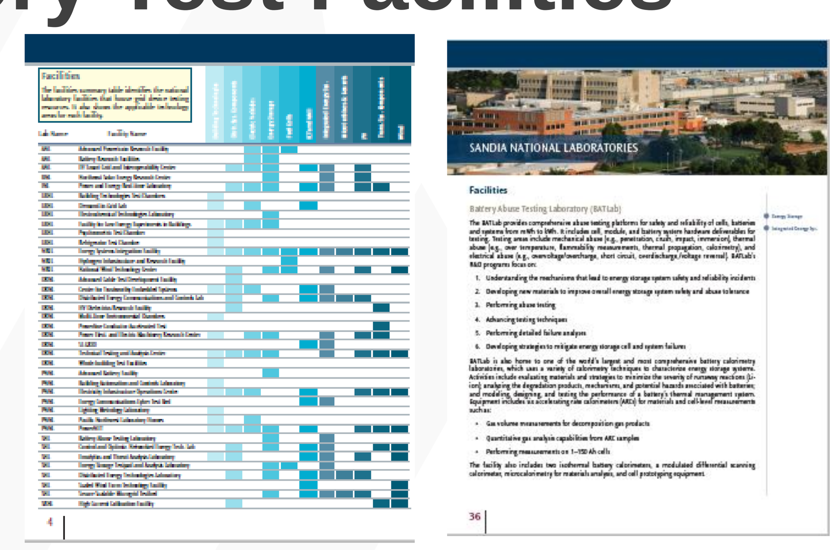
Sandia National Laboratories	Project lead, responsible for TN task
INL Idaho National Laboratory	Responsible for OL task
NREL, SRNL, Oak Ridge, Berkeley Lab, Pacific Northwest, Brookhaven, Argonne	Support TN and OL tasks, including partnerships & outreach; supply models, simulation tools and testing resources
Utilities, National Labs, Academia, Manufacturers	Stakeholders

Progress to Date

Stakeholder Workshop

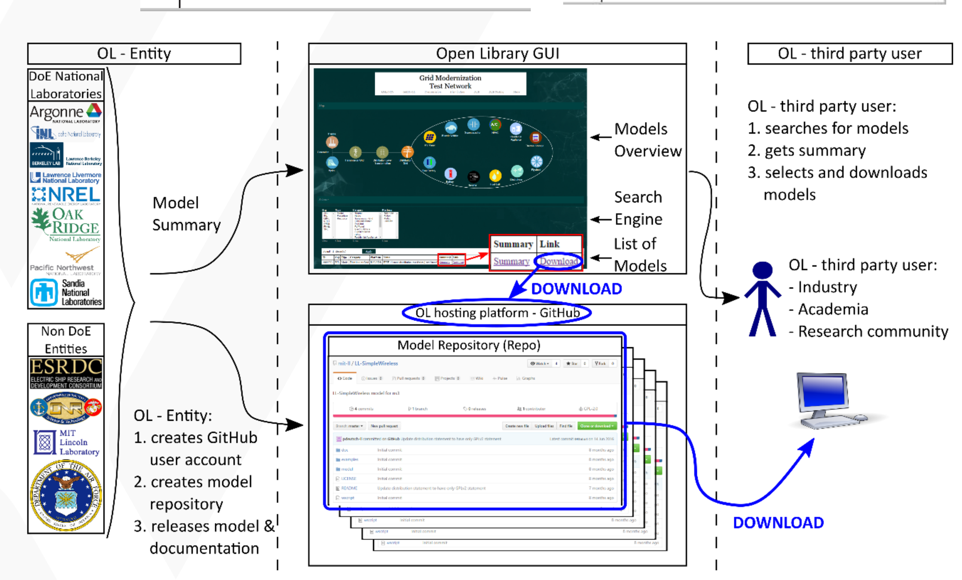
- 35 attendees, ~1/2 from industry and academia
- breakout sessions to solicit feedback from stakeholders

Catalog of National Laboratory Test Facilities & Capabilities



- Self-assessment – 10 National Labs; 39 distinct facilities
- Searchable online version with periodic updates coming soon

Open Library Framework



- Model taxonomy
- Web architecture
- Hosting/collection of models

Expected Outcomes

- Broader awareness of and access to Lab capabilities
- Go-to resource for validated models and test procedures
- Expansion to include other publically accessible facilities
- Improved collaboration and lasting industry impact
- Support adoption and deployment of new grid devices

GMLC 1.3.29
Grid Frequency Support from Distributed Inverter-based Resources in Hawaii

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Hawaii leads the U.S. in the proportion of electricity provided from distributed energy resources (DERs) such as solar PV and energy storage. This leads to challenges maintaining a stable and reliable grid. This project partners with the Hawaiian Electric Companies (HECO) and key stakeholders to investigate, develop, and validate ways that DERs can support grid frequency stability on the fastest time scale (starting within a few line cycles of a frequency event). This is relevant to Hawaii today and will be relevant on the mainland U.S. in the near future as other states incorporate more DERs.

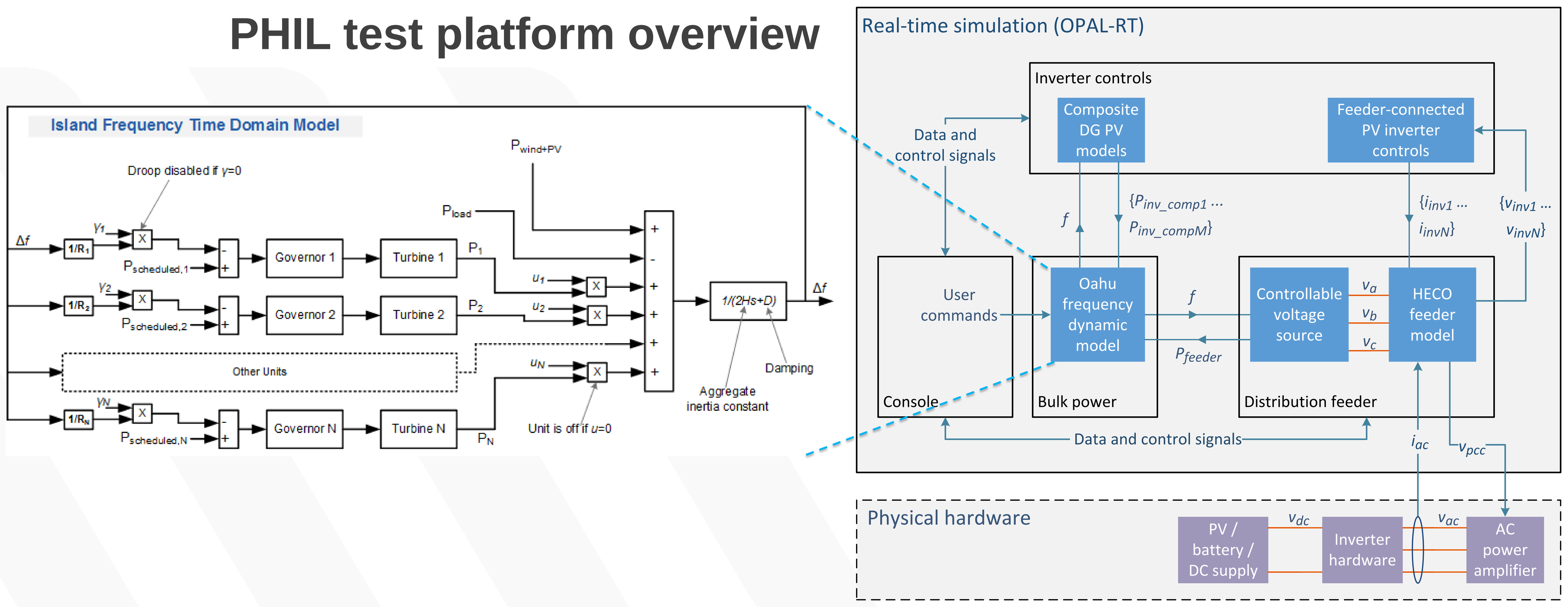
Partners: HECO, NREL (lead), SNL, Enphase, Fronius, FIGII, EEx

Expected Outcomes

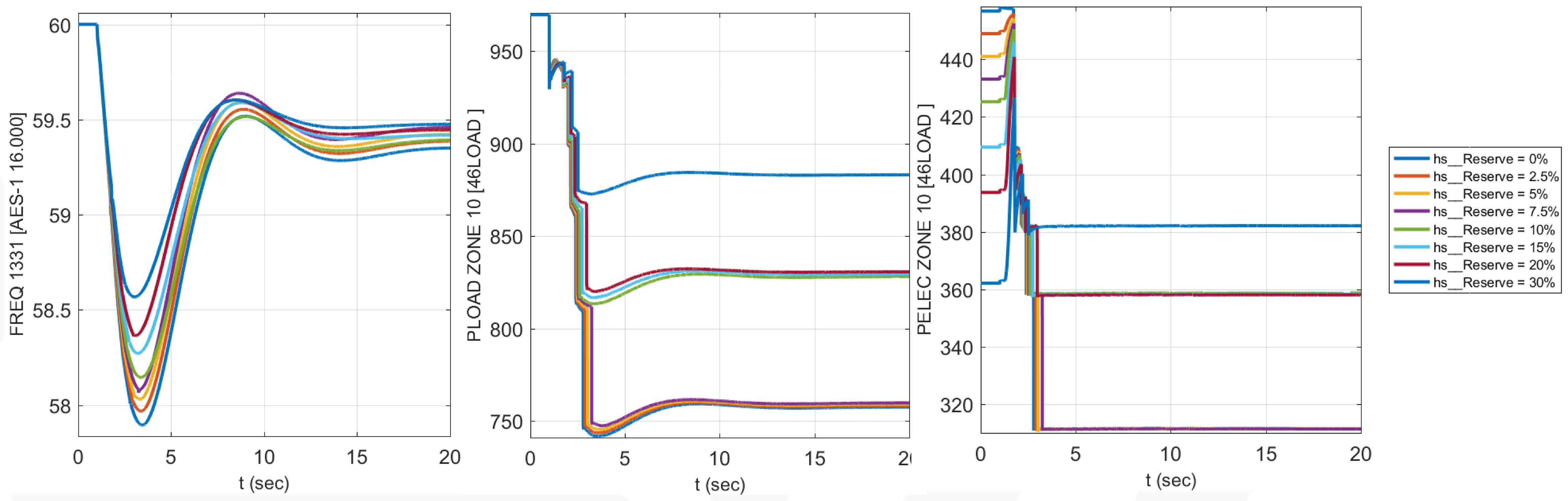
- Enable distributed PV and storage inverters to support grid frequency starting a few AC line cycles after the appearance of a frequency event.
- Characterize frequency support capabilities of existing inverters in the lab and in the field.
- Validate DER frequency support via conventional simulation (PSSE), hybrid T&D simulation, and power hardware-in-the-loop (PHIL) testing.
- Develop new models and modeling methods for DER frequency support functions.
- HECO intends to modify grid operations based on the findings of this work.
- Help ensure a reliable future electric grid.

Significant Milestones	Date
1.2 - Simulations of Oahu frequency events show DER-based frequency support avoids at least one load shedding event	September 30, 2016
2.4 - Prototype inverter controls for improved frequency support developed	March 31, 2017
3.4 - Initial results from PHIL testing of second inverter agree with pure simulation	March 31, 2017
4.5 - Data collection in progress for first field inverter	June 30, 2017
5.6 – Final report complete and Technical Review Committee input incorporated	September 30, 2017

PHIL test platform overview



Underfrequency event with varying levels of PV in reserve



Progress to Date

- Draft IEEE Standard 1547 revision incorporated recommendations on speed of DER droop response from this project
- Developed custom PHIL platform for combined transmission & distribution simulation with high PV penetrations
- Publications:
  - A. Hoke, M. Shirazi, S. Chakraborty, E. Muljadi, D. Maksimovic, "Rapid Active Power Control of Photovoltaic Systems for Grid Frequency Support," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2017

    (Online MPP estimation and PV controls for fast frequency support)
  - M. Elkhatib, J. Neely, J. Johnson, "Evaluation of Fast-Frequency Support Functions in High Penetration Isolated Power Systems," *IEEE Photovoltaics Specialists Conference*, 2017

Standards and Test Procedures for Interconnection and Interoperability

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

- **Accelerate** the development and validation of interconnection and interoperability standards
- Ensure **cross-technology compatibility** & harmonization of requirements for key grid services
- **Eliminate conflicting** requirements across technology domains
- **Streamline** conformance test procedures to the fullest extent possible

Expected Outcomes

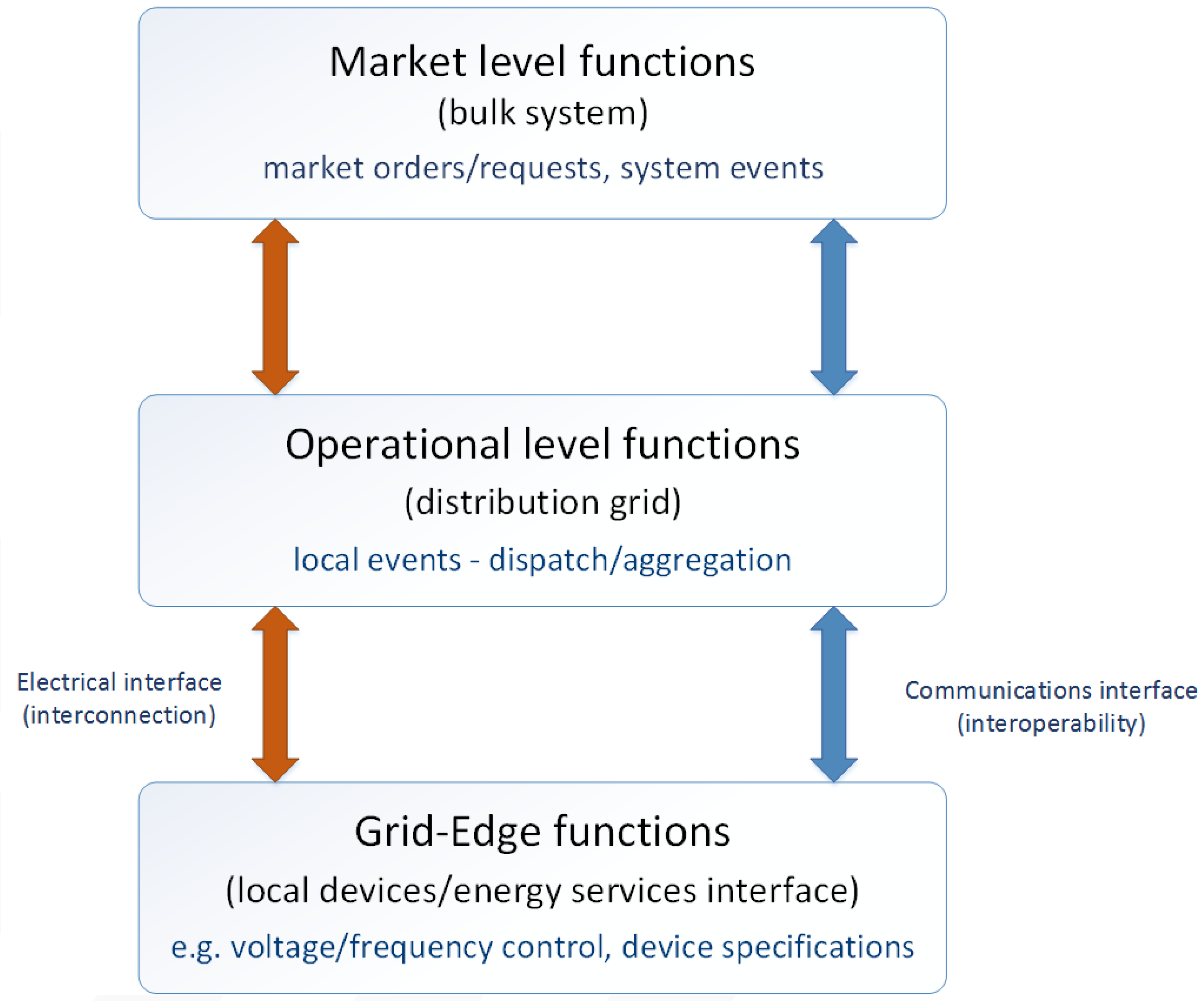
- **Improve coordination** of advanced generation and storage assets
- **Enable expansion** of markets for key devices
- **Eliminate barriers** that may be addressed by improved standards

Significant Milestones	Date
Preliminary gap analysis	9/30/16
Gap prioritization framework	2/28/17
Gap analysis recommendations	3/31/17
Develop test procedures	Q2 2017
Validate test procedures	Q3 2017
Standards coordination	throughout

Progress to Date

- **Stakeholder engagement**
  - GMLC Workshop 9/2016 (Denver, CO)
  - SGIP 2016 Grid Summit 11/2016 (Washington, DC)
  - GMLC workshop, 3/2017 (Atlanta, GA)
- **Gap analysis and prioritization (Mar, 2017)**

Partnering DOE Labs:
NREL, LBNL, PNNL, SNL, ORNL, INL, ANL



High level view of coordinated grid operations

Gap Analysis and Prioritization: Key Findings and Recommendations

- **Maintain focus on key grid services related to:**
  Energy | Regulation | Local voltage management | Artificial inertia
- **Focus on key grid-edge assets**
  Inverter-based (generation/storage) | Electric vehicles | Responsive loads | Microgrids (special case)
- **Inverter-based assets**
  - Affirm updates in revision of IEEE 1547, support updates for DNP3, IEEE 2030.5, IEC 61850, and SunSpec/MESA Modbus protocol maps
- **Responsive loads**
  - Support updates to OpenADR and ASHRAE standards to enable grid services, determine capability and requirements of IEEE 2030.5 (SEP2), explore the requirements for standardizing the energy services interface
- **Electric vehicles**
  - Support updates to SAEJ3072 to include volt/VAR functionality and new IEEE 1457.1 updates
- **Microgrids**
  - Support IEEE 2030, explore capabilities for grid-connected mode

Definitions, Standards and Test Procedures for Grid Services from Devices

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Develop characterization test protocol and model-based performance metrics as a *Recommended Practice* for devices' (DERs') ability to provide a broad range of grid services, i.e., to provide the flexibility required to operate a clean, reliable power grid at reasonable cost.

Devices (DERs)

Responsive, flexible loads
- Water heaters
- Refrigerators
- Air conditioners
- Commercial rooftop units
- Commercial refrigeration
- Commercial lighting
- Electric vehicles (charging only)
- Electrolyzers

Storage
- Battery / inverters
- Thermal energy storage
- Electric vehicles (charging & discharging)

Distributed generation
- PV solar / inverters
- Fuel cells

Grid Services

- Peak load management (capacity)
- Energy market price response (wholesale energy cost)
- Capacity market dispatch (market value)
- Frequency regulation (market value)
- Spinning reserve (market value)
- Ramping (new)
- Artificial inertia (new)
- Distribution voltage management (new)

Objectives/Deliverables

- **Simple, low-cost testing protocols** manufacturers can use to characterize equipment performance
- **General, standard device model reflecting test results** for each device class
- **Proven means of estimating performance metrics** for a **standard set of grid services** from the test results
- **Protocol that can be regionalized** to reflect local markets, new services, weather, loads, etc.
- **Generic DER device flexibility model** based on battery equivalent

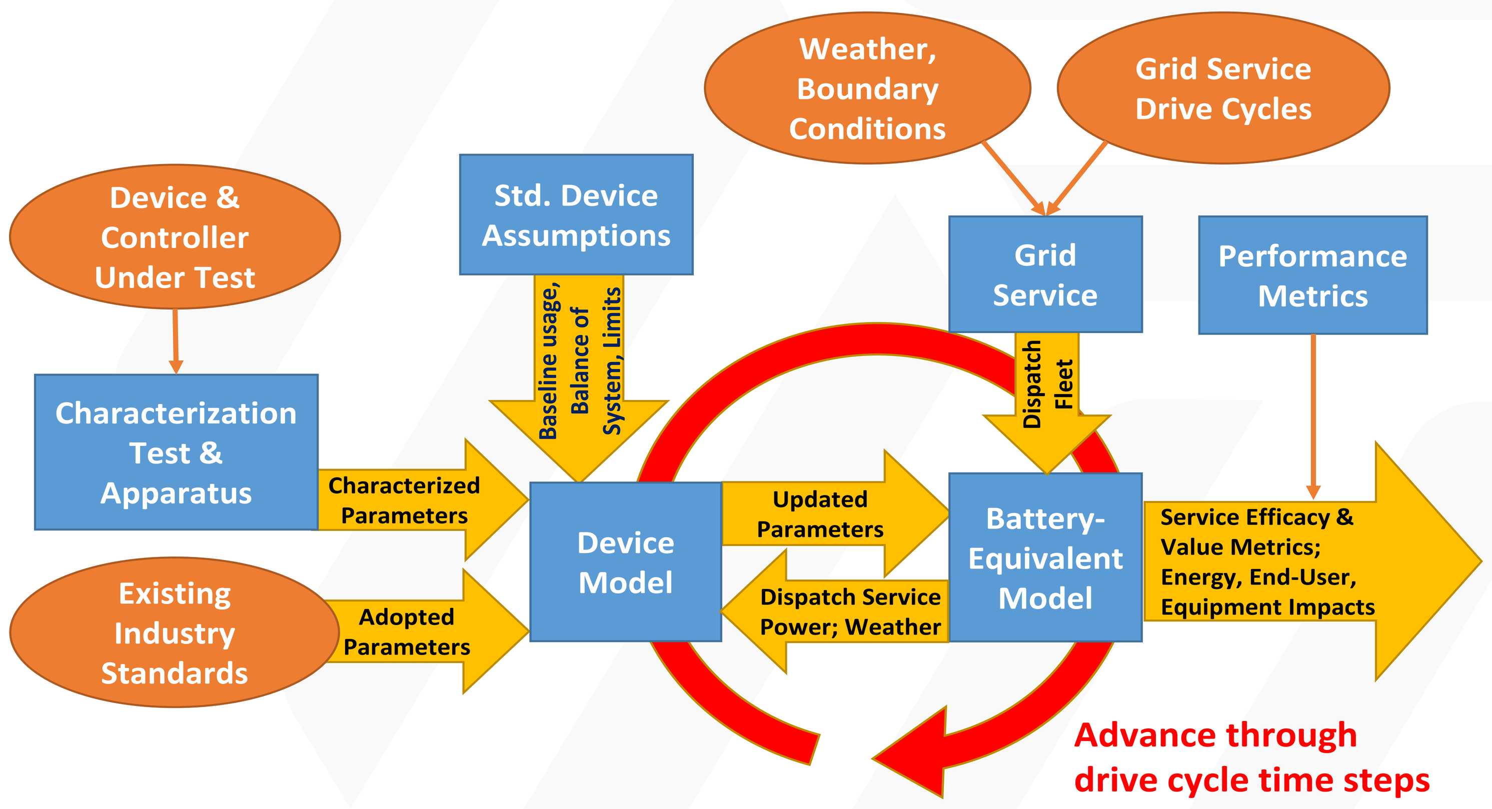


Figure 1. Device Characterization Process

Impacts/Outcomes

- ***Reward innovation,*** help manufacturers understand opportunities, enlarge the market for devices
- ***Validated performance & value for grid operator decisions*** on purchases, programs, subsidies, rebates, markets, planning, operations
- ***Independently validated information for consumers & 3rd parties*** for purchase decisions
- **"Battery Equivalent+" model can provide "plug-and-play"** for device models in planning & operation tools

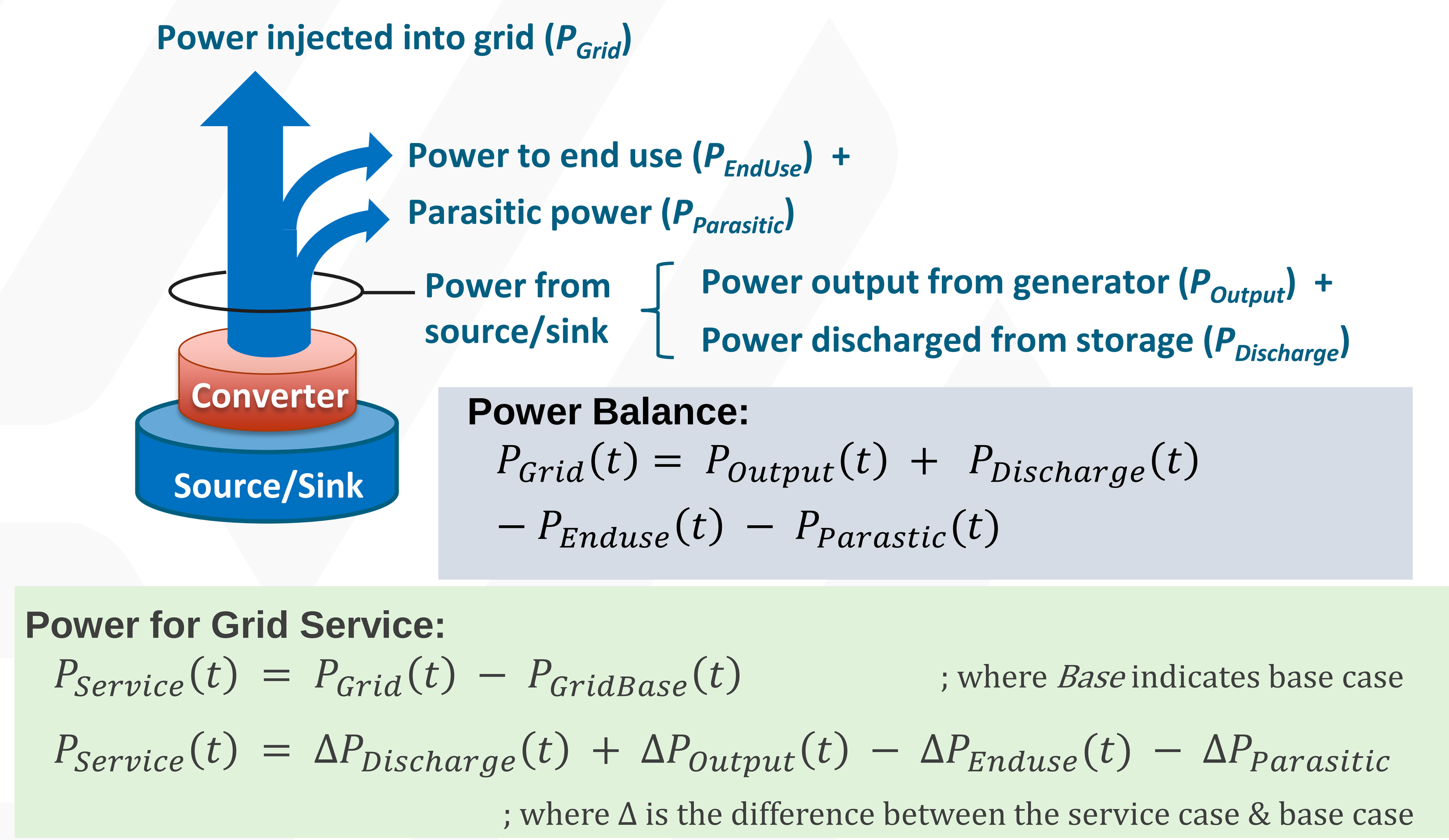


Figure 2. Generic Battery Equivalent+ Device Model

Significant Milestones (FY16-FY18)	Status	Due Date
1. **Standard definitions & drive cycles for grid services** (draft for industry review)	1. Complete	October 1, 2016
2. **General device model** (draft for industry review)	2. Complete	
3. **Extrapolation procedure for performance of grid services**	3. Complete	April 1, 2017
4. **Draft *Recommended Practice*** (vetted with industry)	4. Underway	October 1, 2017
5. **Trials of device characterization protocols** (each device class)		April 1, 2018
6. **Manufacturers review characterization protocol & test results**		
7. **Proof-of-concept testing validates extrapolation procedure**		October 1, 2018
8. **Stakeholder group consensus that *Recommended Practice* is useful & accurate**		April 1, 2019

Progress to Date

- **Developed definitions & drive cycles for broad range of grid services**
- **Developed generic device model (battery equivalent+) & extrapolation framework**
- **Published framework (Recommend Practice Chs. 1 & 2) for industry review (3/17)**
- **Organized series of webinars & briefings leading up to 2nd Industry Workshop:**
  - GridWise Alliance webinar (n = 35*)
  - Thermal energy storage briefings (n = 2*)
  - Electric vehicle meeting briefing (n = 13*)
  - PV/batteries/inverters (n= 321*)
  - Commercial lighting (n = 27*)
  - HVAC & appliances (n=21*)
- **Partnered with the GridWise Alliance to host 2nd Industry workshop with sponsors GE & Intel @ GE's GridIQ Center in Atlanta GA March 21-22, 2017 (n = 36*)**

* Counts exclude DOE and national laboratory participants

Energy Storage Demonstrations-Validation and Operational Optimization

PI: Dan Borneo (Sandia)
Project Team: Ray Byrne (SNL), Ben Schenkman (SNL), Lee Rashkins (SNL), Michael Starke (ORNL), Patrick Balducci (PNNL), Todd Olinsky-Paul (CESA), UET, EPB, PGE, LAC

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

The goal of this project is to use fielded energy storage systems to quantify value and benefits of new technologies in a variety of applications. Project involves collaboration with states, utilities, and energy storage providers to help elucidate storage benefits and integration challenges. The outcome of this two-year effort will be analysis that identifies the value streams for each potential application, as well as methods to operate the device that maximize the value streams.

Expected Outcomes

- Analysis and optimization at 3 existing and 1 newly installed projects in VT, OR, TN, and NM that represent a diversity in location, application, and technology
- Analysis of value streams for each potential application in non-market areas, with results also applicable to market areas
- Develop methods to operate the devices that maximize value streams
- Develop modeling tools that address economics and capacity for designing battery systems
- Share results that address several common impediments to widespread adoption of energy storage to help guide the industry

Significant Milestones	Date
Data collection and analysis for GMP, PGE, and LAC-Develop detailed scope, define roles/responsibilities	May and June 2016.
Initiate data collection at LAC, PGE and GMP – develop list of data required for analysis, ensure that data is being monitored and submitted to team.	May/June 2016
Battery system at VT site was discharged during annual ISO system peak, demonstrating peak shaving for capacity charge reduction	August 2016
New battery delivered and being installed at TN project site	March 2017

Principal Investigator, Dan Borneo, with Sandia National Lab, views a battery system.

Progress to Date

- Operational data collection and analysis underway at 3 energy storage projects
- A fourth energy storage project is under construction
- Modeling tools in development for use in battery design
- Mid-way through testing applications on ENERDEL system

Distribution Transformer Data, Testing, and Control

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

This project will compile extensive data describing distribution transformer performance for both traditional silicon steel and advanced amorphous metal cores. The project will develop and explore alternative control strategies that could enhance transformer efficiency.

Expected Outcomes

- Distribution transformer losses account for 2–3% of U.S. generated electricity, and no-load losses represent approximately 25% of these losses.
  - Adoption of more efficient transformers could reduce no-load losses by 60%
    - Project will assemble data addressing market barriers that impede this adoption
  - Dynamic control and coordination of transformers and building loads could reduce losses by 10%
    - The project will scope control strategies that might deliver this benefit

Significant Milestones	Date
Data report complete	4/30/17
Transformer testing report complete	9/30/17
Control scoping report complete	6/30/17

Virtually all generated electricity eventually flows through a distribution transformer.

Progress to Date

- Defined and reviewed test plan for execution at the Clemson University *e*GRID lab
  - Establishes functional acceptance, efficiency baseline, sweeping tests of efficiency/harmonics, and degradation over time
- Santee Cooper offering eight transformers to the project
  - Significantly reduces project cost
  - Enables project to accelerate testing at the *e*GRID lab
- Santee Cooper sharing 20 years of performance and cost data
- Identified six innovative control strategies to be scoped and analyzed

Collaborative Demo for Secondary Use and Use Case Validation

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

OBJECTIVES

- Developing a low cost energy storage system using repurposed vehicle batteries.
- Deploying energy storage system with PV into a residential building supplied by Habitat for Humanity.
- Evaluating economic feasibility of the technology moving forward and developing appropriate tools.
- Creating a workforce education program for future technicians.

CHALLENGES

- New energy storage technology associated with electric vehicles has exposed a gap in residential energy storage system controls.
- Certification of 2nd life automotive battery storage systems has been difficult as differing regulatory domain exist.
- Secondary-use batteries exist in many grades and must be evaluated and sorted to be packaged into a single system with minimal handling to be cost effective.
- Understanding the value proposition of these deployments with complicated rate structures and use cases that do not have sufficient support.

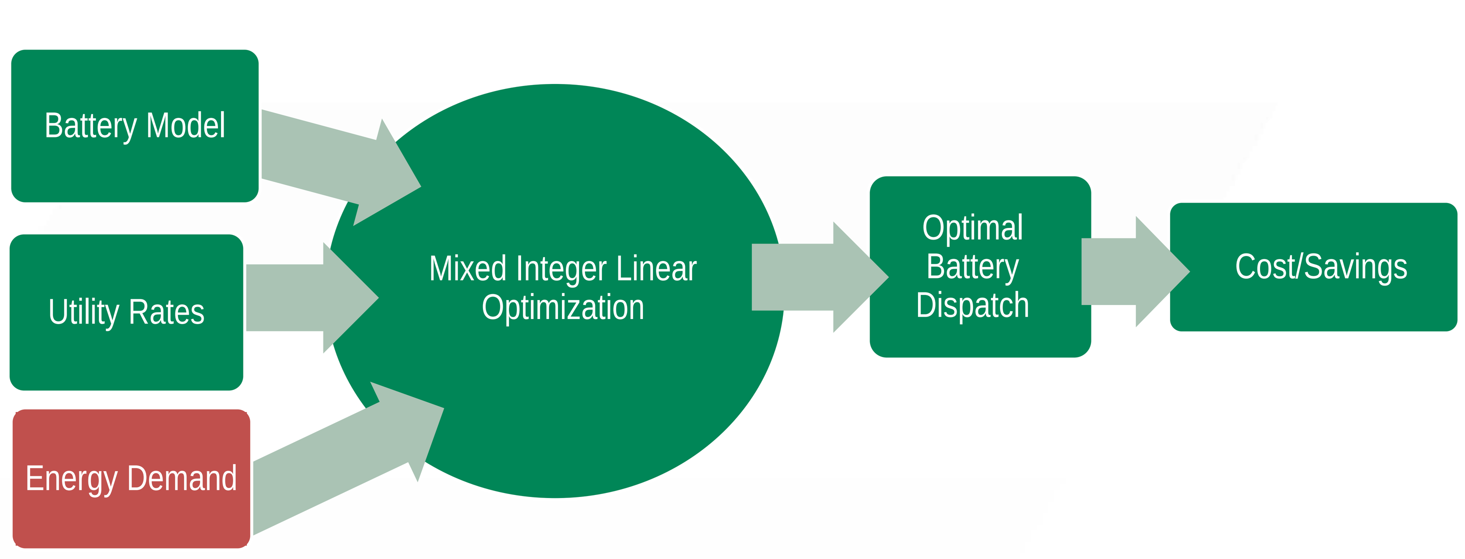
RESEARCH AND DEVELOPMENT

Certification Process

- Module UL certification for batteries already exists with Nissan. Team is working on developing the process to transfer UL certification from first life to second life applications via lab testing and demonstration.

Economic Evaluation

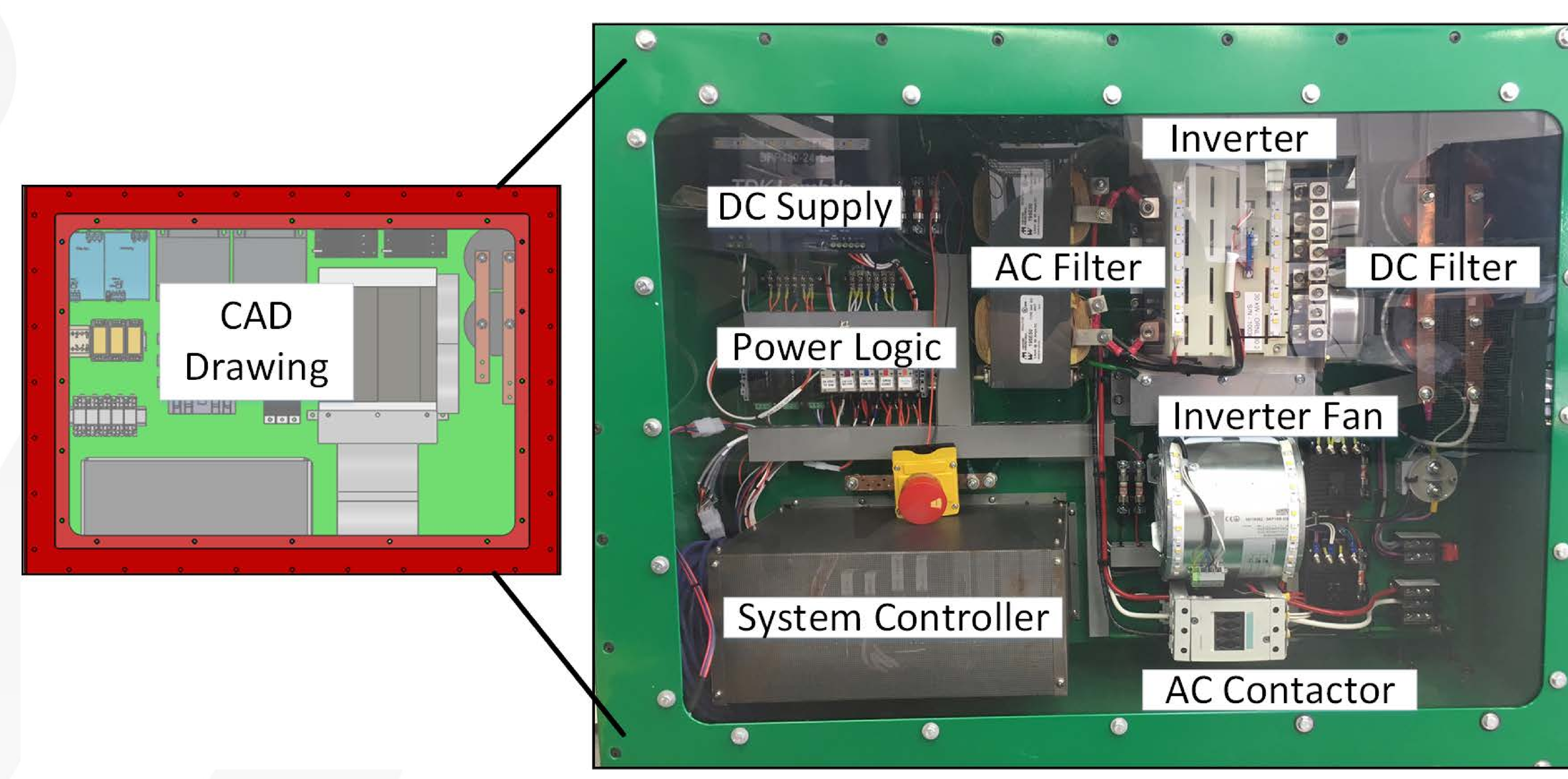
- Developed open-source optimization initial tool for calculation of optimized sizing of battery
- Utilized data from Habitat for Humanity to estimate optimal size of battery system (paper accepted to Power and Energy Society General Meeting)
- Optimization objective is the minimization of energy costs through the dispatch of energy storage.
- Optimization considers battery cost and cycling, utility rate structures, PV generation, and load data.
- Utility rate data is extracted from OpenEI database automatically
- User allowed to specify additional operational constraints and efficiency information.
- Optimization produces a system and maintenance cost as well as a Return on Investment estimate.



Economic Assessment Approach

Prototype Construction

- Battery system has been designed with battery management system and included safety features.
- Initial battery system testing has been performed to validate the electrical connections and confirm battery management system functionality.
- Inverter system designed to support 240V split phase connection, unbalanced voltage control for islanding, and dispatchable real power.
- Inverter system logic and controls have undergone initial testing to confirm all basic functionality is present including pushing power from a DC supply to the grid and supporting a load without grid connection.



Inverter System for Secondary Use Prototype

Battery Pack for Secondary Use Prototype

CONCLUSION AND NEXT STEPS

- Economic analysis simulation tool on an open-source platform has been developed. Public release of tool will be in third year following modifications based on initial results.
- Analysis of energy storage sizing for deployment has been completed and used to specify size of system.
- Energy storage prototype has been constructed and initial testing has begun to demonstrate basic functionality.
- In coming year, testing plan will be drafted and used to test energy storage system.

CONTACT

Michael Starke

Power and Energy Group
Oak Ridge National Laboratory
starkemr@ornl.gov

Universal Hybrid Inverter Driver Interface for VOLTTRON™ Enabled DER Power Electronics Applications

Lead: Oak Ridge National Laboratory
Team: Pacific Northwest National Laboratory

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

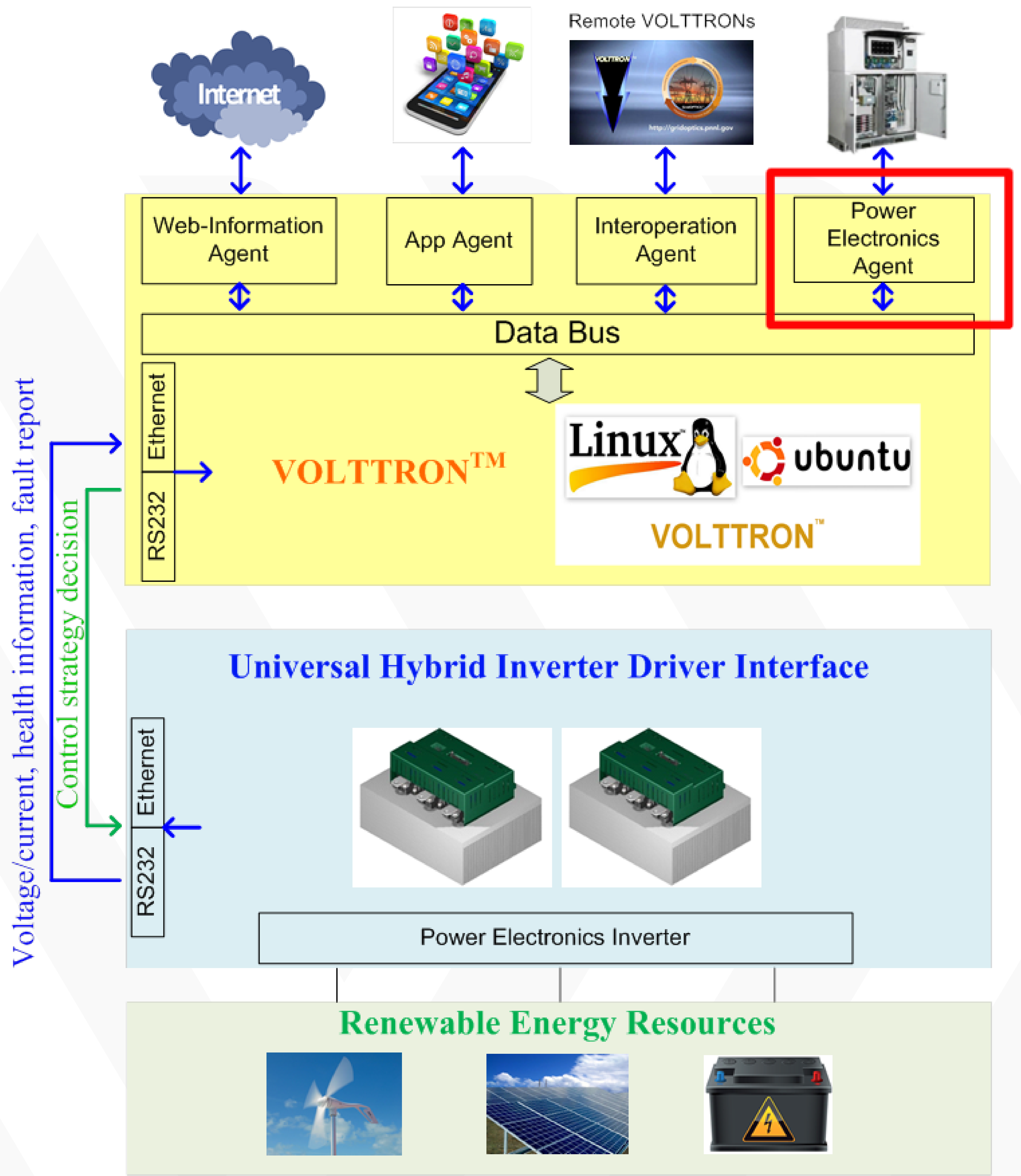
Project Description

- Enable near real-time control and integrate renewable-energy-based power electronics inverters in green buildings by developing a universal driver interface for VOLTTRON™ platform

Expected Outcomes

- Enable interfaces for existing inverters to provide transactive services in a retrofit fashion and test the device functionality
- A VOLTTRON™-based development environment for transactive control grid-tied inverters

Significant Milestones	Date
Emulate functionality of advanced VOLTTRON™ platform to validate the control architecture	12/30/2016
Validate functionality of the hybrid interface using a commercial inverter	12/30/2017
Test the advanced VOLTTRON™ platform using the developed universal hybrid inverter driver interface	12/30/2018



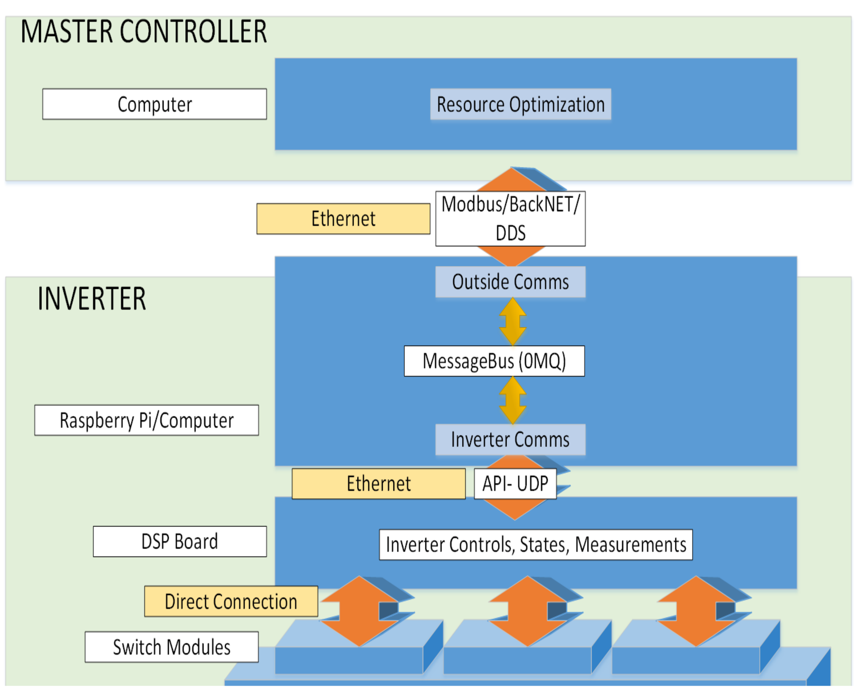
Advanced VOLTTRON™ Control Platform(Software)
- New Power Electronics Agent Interface
- Control strategy decision maker
- Inverter status monitoring
- Communicate with other control platforms

Universal Hybrid Driver Interface (Hardware)
- Control strategy executor
- Online inverter health monitoring
- Communication interface between RES and VOLTTRON™

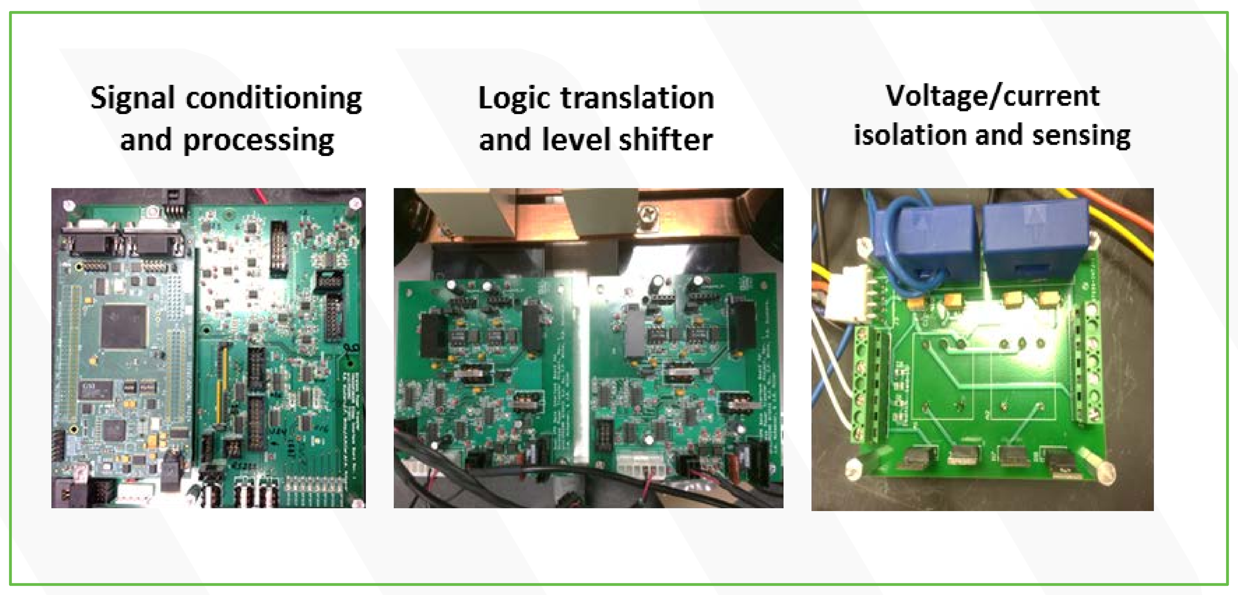
Progress to Date

- **Advanced VOLTTRON™ Control Platform**
  - Completed overall hardware and software requirements for VOLTTRON™ and hybrid driver interface
  - Developed IEEE 1547 and IEEE 2030 functions for grid-tied operation of inverter
  - Emulated functionality of advanced VOLTTRON™ platform to validate communication and overall architecture
- **Universal Hybrid Inverter Driver Interface**
  - Completed testing of hybrid interface with basic functions (version 1.0)
  - Evaluated a commercial inverter and identified technical gaps in SMART inverter operation
  - Simulated hybrid interface functions and their impact on system performance

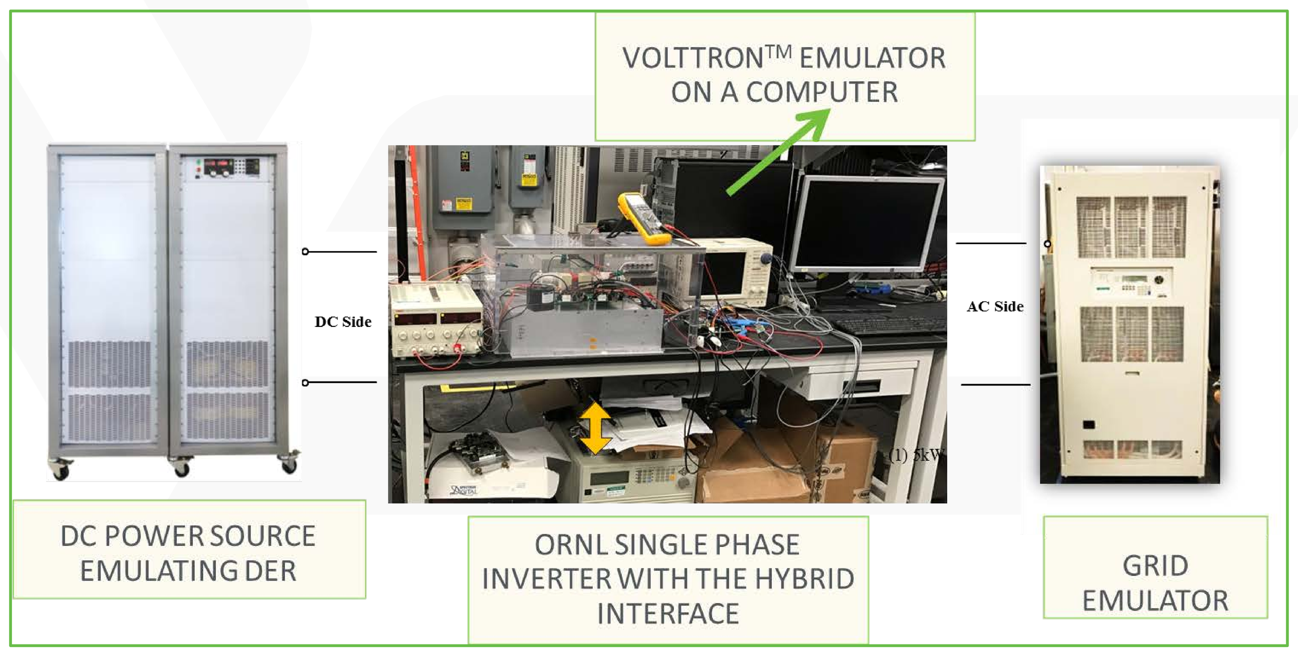
Inverter Communication Protocol



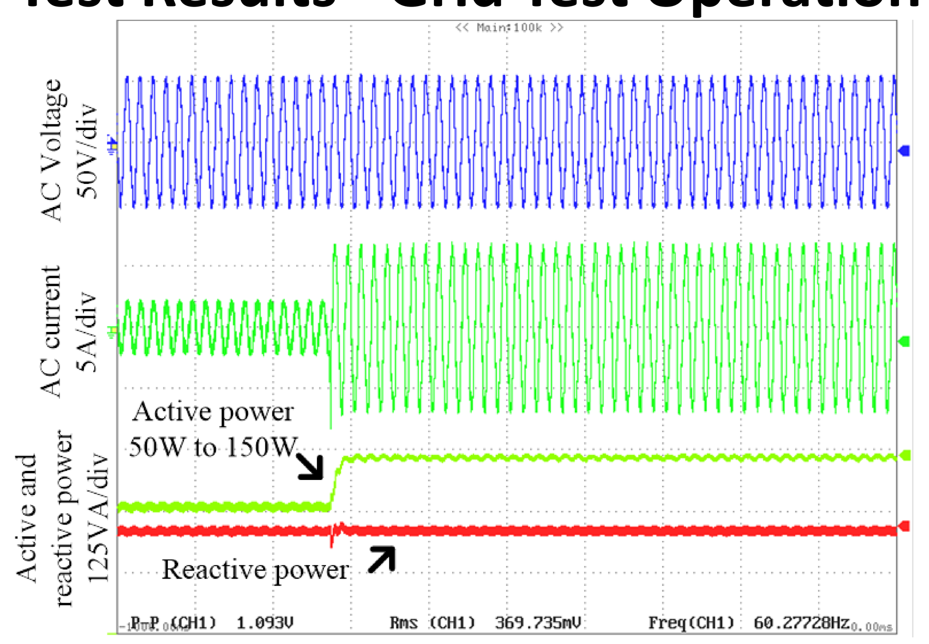
ORNL Universal Interface Board



Interface Grid Test Bed



Test Results - Grid Test Operation



AC voltage: 50V/60Hz (peak); DC voltage: 100V; Power: 150W

HEMP and GMD Impact on Power Transformers

A. G. Tarditi[1], R. C. Duckworth[1], J.Javedani[2], F. R. Li[3], Z. Li[1], Y. Liu[3], B. W. McConnell[1], R. G. Olsen[4], B. R. Poole[2], L. Wang[2], Z. A. Yuan[3]

[1]Oak Ridge National Laboratory, [2]Lawrence Livermore National Laboratory, [3]University of Tennessee Knoxville, [4]Washington State University

DOE Program Manager: K. Cheung

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

General Context: *both HEMP and GMD are considered a potentially large-scale threat for critical, power grid components*

High-altitude EM Pulse (HEMP): refers to a strong burst of EM energy originated by a nuclear explosion in the upper atmosphere, affecting a wide geographical area. HEMP coupling to conductors, from power lines to electronic systems, may cause destructive voltage surges for a variety of electrical equipment.

Geomagnetic Disturbances (GMD): strong fluctuations of the Earth magnetic field caused by ejected solar material reaching the Earth magnetosphere. GMD may induce a quasi-*dc* current on power lines, causing saturation of transformer magnetic cores, possibly leading to large harmonics generation and transformer overheating damage

Motivation: *filling needs for enhanced accuracy and test validation of HEMP and GMD power transformer models*

Scope: electromagnetic vulnerability of transmission-class transformers and related supporting systems against HEMP and GMD

Objective: HEMP and GMD threat characterization, risk assessment, and technical analysis of mitigation solutions

Resources: multi-institution team (ORNL, LLNL, UT Knoxville, Washington State Univ., EPRI), 2.5 year effort (2016-2018)

Approach: correlated theory/modeling and experimental testing

Methodology: physics-based, quantitative assessment of GMD and HEMP coupling to key grid components for estimating damage potential

Expected Outcomes: *resolve technical issues in support of new industry developments and regulatory standards for the protection of the nation's most critical infrastructure against HEMP and GMD*

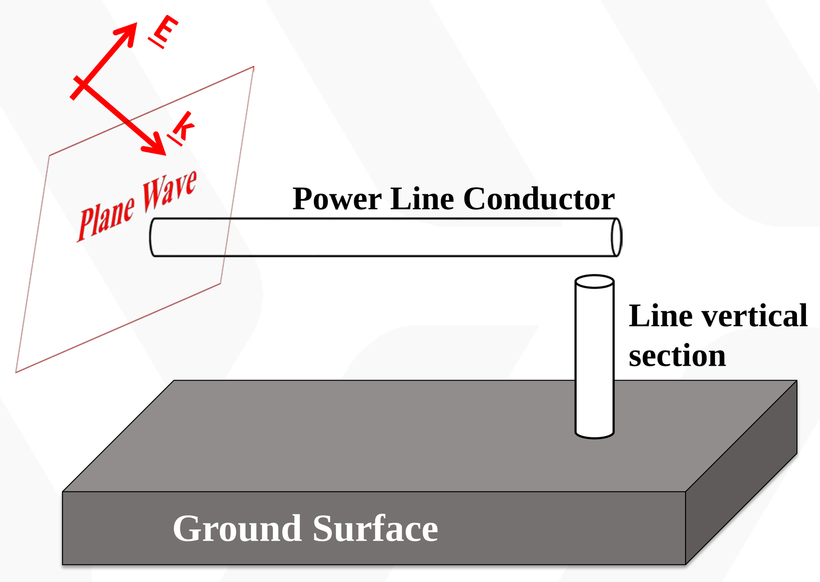
Large Power Transformers EM Vulnerability - Technical Issues:

- HEMP-induced, peak voltages impacting transformers
- HV arresters: aging and response effectiveness to HEMP transients
- Impact on transformer from HEMP coupled on the low-voltage transformer side (via substation cables)
- Primary winding over-insulation requirement vs. HEMP rise-time
- Low frequency (~1 MHz) transformer resonances: impact on possible insulation damage during high-voltage transients
- Characterization of GMD-induced harmonics

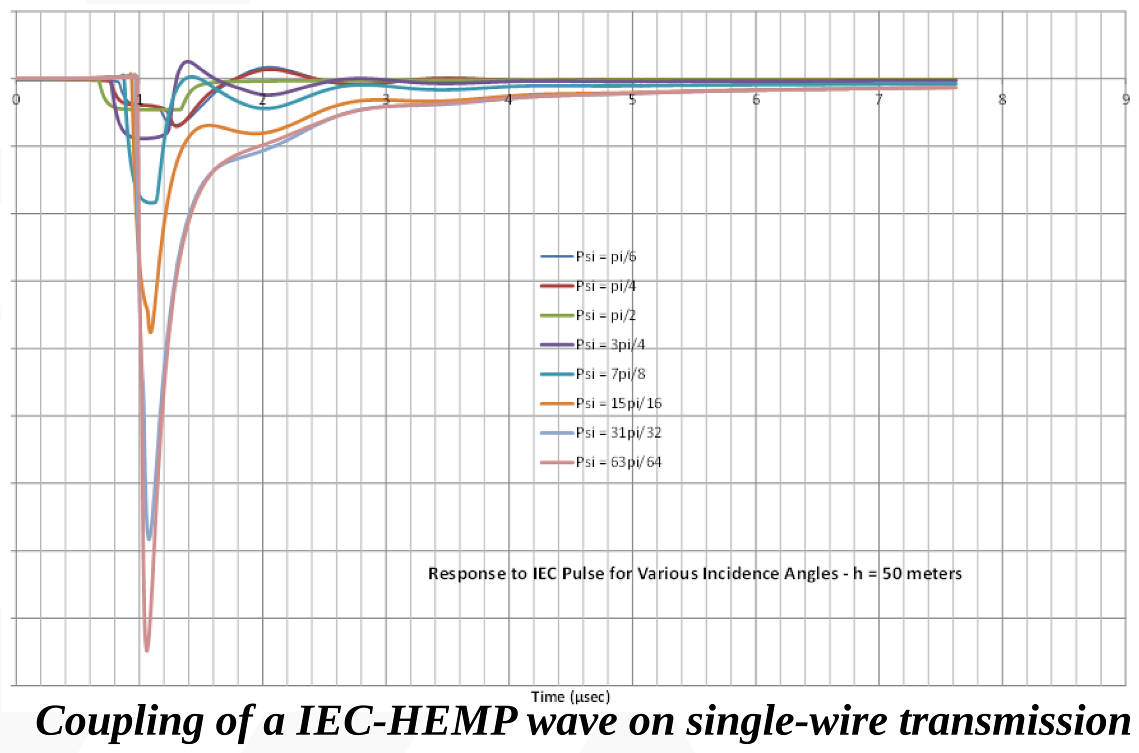
Significant Milestones	Date
Scoping studies for modeling/analysis	Q4-2016
Analytical model of HEMP grid coupling	Q1-2017
Initiation of analysis/validation of HEMP coupling	Q1-2017
Initiation of analysis/validation of GMD coupling	Q2-2017

Progress to Date

Modeling of Fast-Transient Pulse Coupling to a Power Line



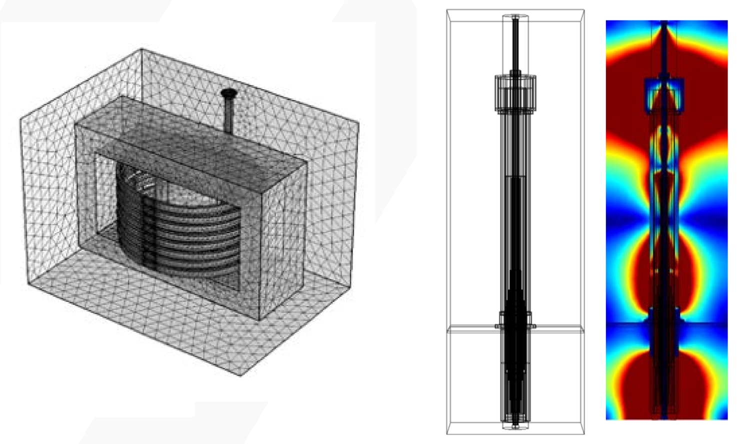
Geometry for the HEMP transmission line coupling model



Coupling of a IEC-HEMP wave on single-wire transmission line: voltage waveform vs. incidence angle

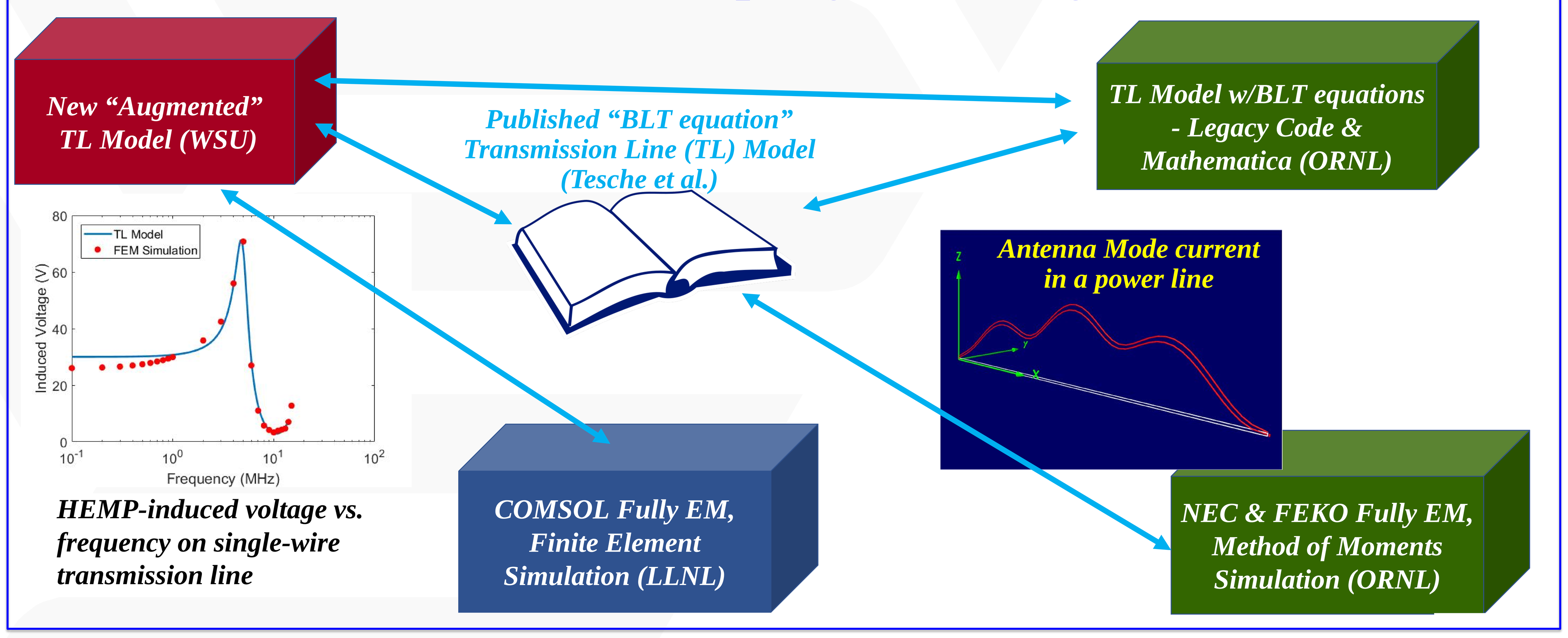
HEMP Waveform Propagation in HV Transformer Bushing

Test of frequency response in HV transformer bushing



3D-FEM Simulation: simplified transformer, and bushing transient wave electric field map

HEMP Power Line Coupling: Modeling Cross-Validation



HEMP-induced voltage vs. frequency on single-wire transmission line

U.S. DEPARTMENT OF ENERGY

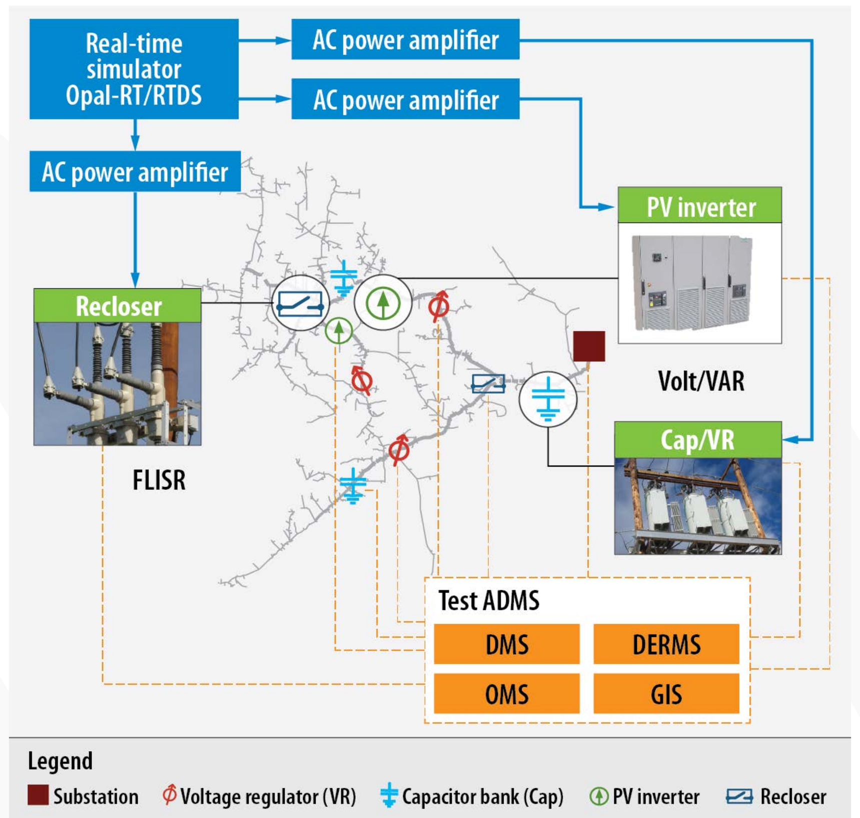
ADMS Program: Advanced Distribution Management System Testbed Development

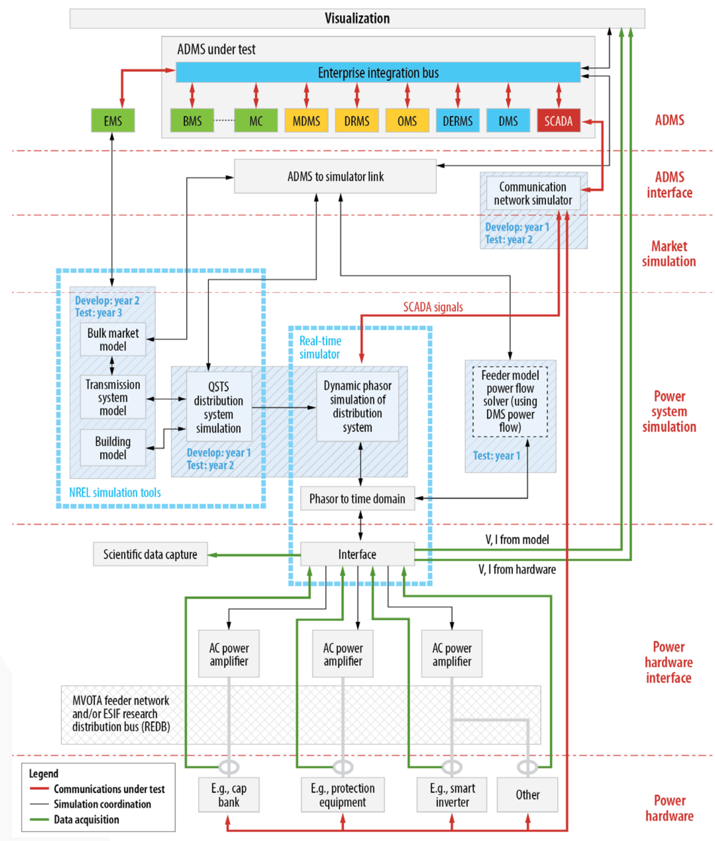
Partnering Organizations: National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory, Argonne National Laboratory, Electric Power Research Institute, Opal-RT Technologies, Schneider Electric, GE Grid Solutions

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

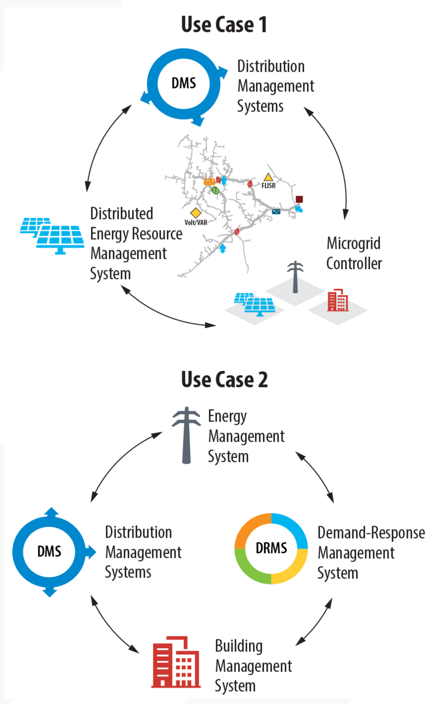
- Model large scale distribution systems for evaluating advanced distribution management system (ADMS) applications.
- Integrate distribution system hardware in NREL's Energy Systems Integration Facility for power-hardware-in-the-loop experimentation.
- Develop an advanced visualization capability to analyze the results for a mock utility distribution system operator's control room.

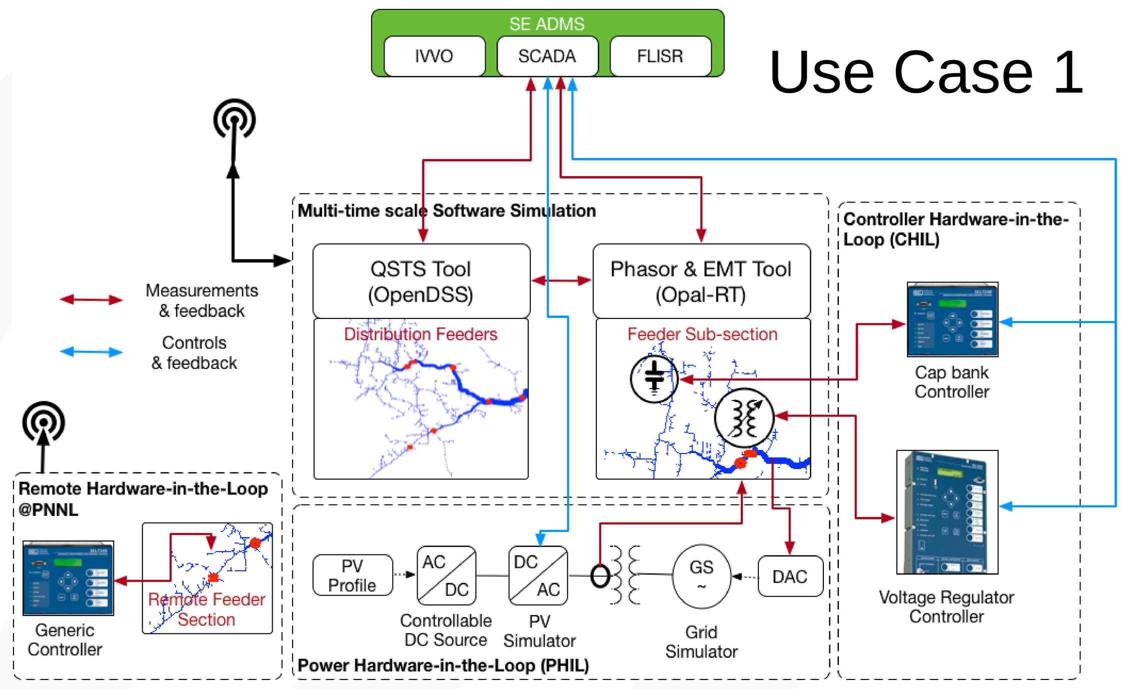




Expected Outcomes

- Test and understand the impact of ADMS functionality.
- Develop a low-cost, pre-pilot testing ground for ADMS functionality.
- Evaluate what-if hypothetical scenarios.
- Identify the right use-case and technical parameters.
- Evaluate interoperability and vulnerability of the ADMS and connected hardware devices.
- Evaluate Integration challenges of ADMS with legacy systems.
- Develop and evaluate new ADMS functions.
- Provide a facility for operator training of utility engineers.





Significant Milestones	Date
Develop a testbed for ADMS using intrinsic DMS power flow.	04/15/2017
Develop a test plan specifying tests to be conducted in Year 3.	04/15/2018
Execute the Year 2 test plan.	04/15/2018
Host a workshop to disseminate the lessons learned in ADMS use case #1.	04/15/2018
Execute the Year 3 test plan.	04/15/2019
Host a workshop to disseminate the lessons learned in ADMS use case #2.	04/15/2019

- Coordinating with other ADMS projects on a monthly basis to develop ADMS testbed capabilities to test the products on other projects.
- Established a combined IAB team for the platform and testbed projects.

Progress to Date

- First Industry Advisory Board meeting held during the DistribuTECH conference.
- ADMS testbed design and construction for use case #1:
  - Communication interface to enable co-simulation of RTDS and Opal-RT underway
  - OpenDSS for QSTS power-flow with power hardware interface established
  - ePHASORSIM-based testbed capabilities development.
- Use case #0 (DMS VVC with intrinsic power flow) executed.
- Published four conference papers over the past year and working on a journal article for use case #0.
- Developed a software process to convert data files from from OpenDSS to a real time ePHASORSIM format.

Stabilizing the Grid in 2035 and Beyond

Evolving from Grid-Following to Grid-Forming Distributed Inverter Controllers

NREL (Lead): B. Johnson (PI), M. Rodriguez, Y. Lin, P. Gotseff

Team Members: F. Bullo (U. of California Santa-Barbara), S. Dhople (U. of Minnesota), P. Chapman (SunPower)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

What Is Inertia in the Context of Power Systems?

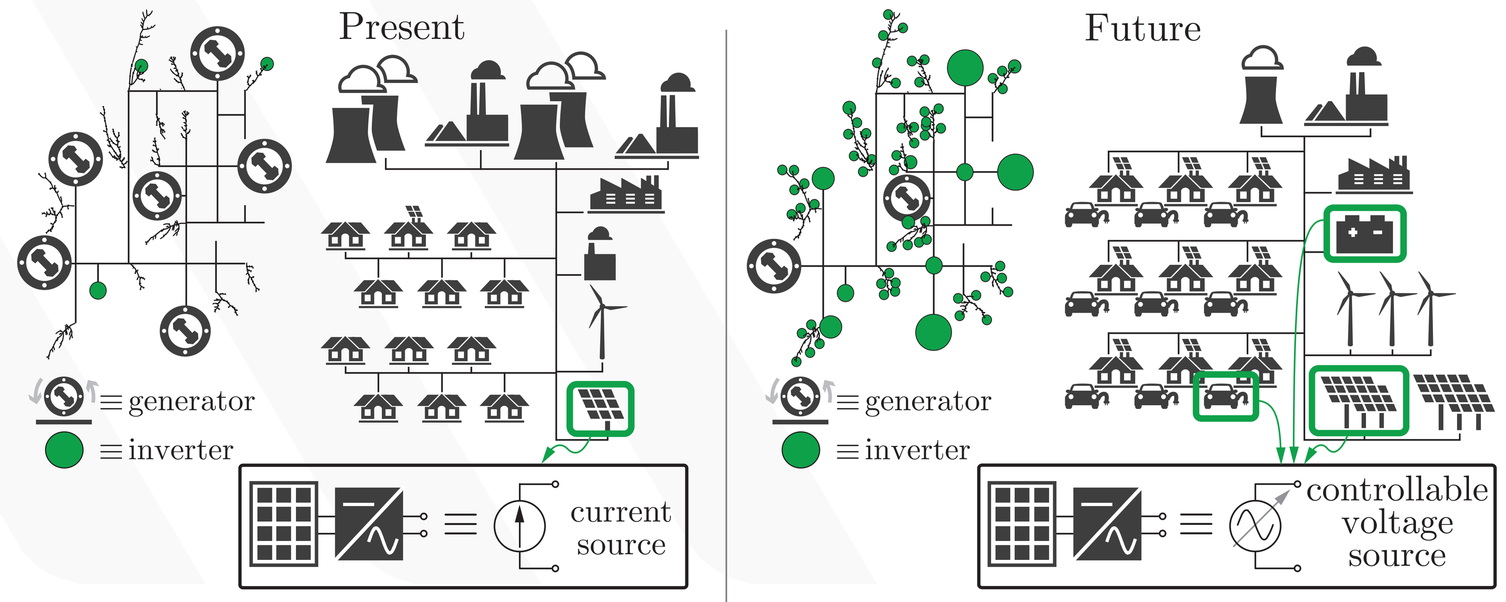
- Historically, power grids have been constructed with interconnected generators with significant rotating mass or inertia.
- The collective inertia of generators enhances system stability and allows for the absorption of unpredictable load variations.
- In contrast, renewables such as PV rely on electronics with no moving parts. Thus, they are inertia-less.

Conventional generator

The future grid interface

Project Objective

Develop distributed inverter controllers that provide a viable path from our existing infrastructure based on electromechanical generators to a highly distributed future grid dominated by electronic PV inverters with hundreds of GWs of PV integration.



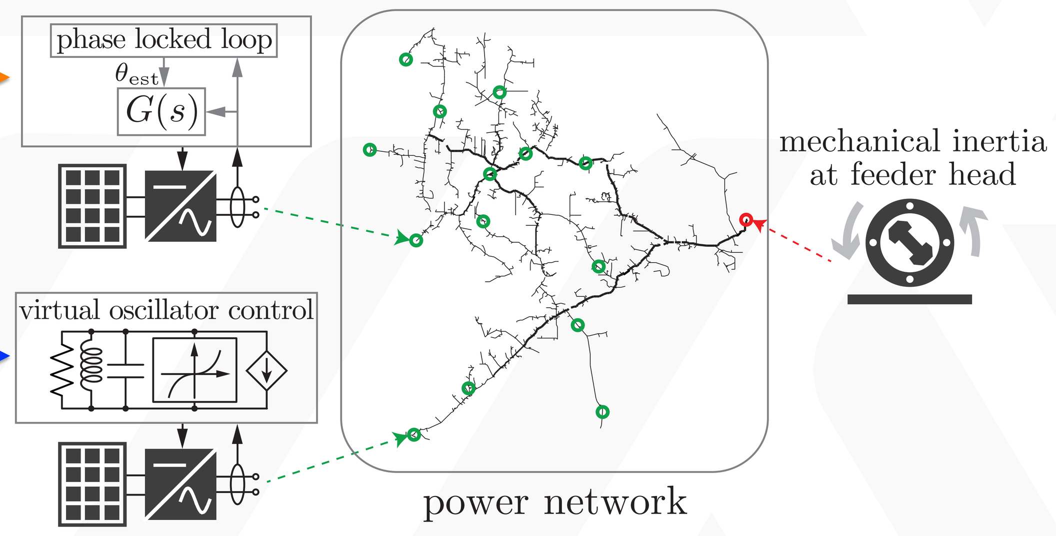
From *grid-following* controls → To next-generation *grid-forming* controls

Challenge and Proposed Approach

- Shortcomings of existing methods: *Grid-following* inverters rely on electric machinery to establish a stable grid and simply inject a controlled current.
- Proposed technology: A new *grid-forming* strategy where inverters are controlled to emulate nonlinear oscillators; we call this **virtual oscillator control.**

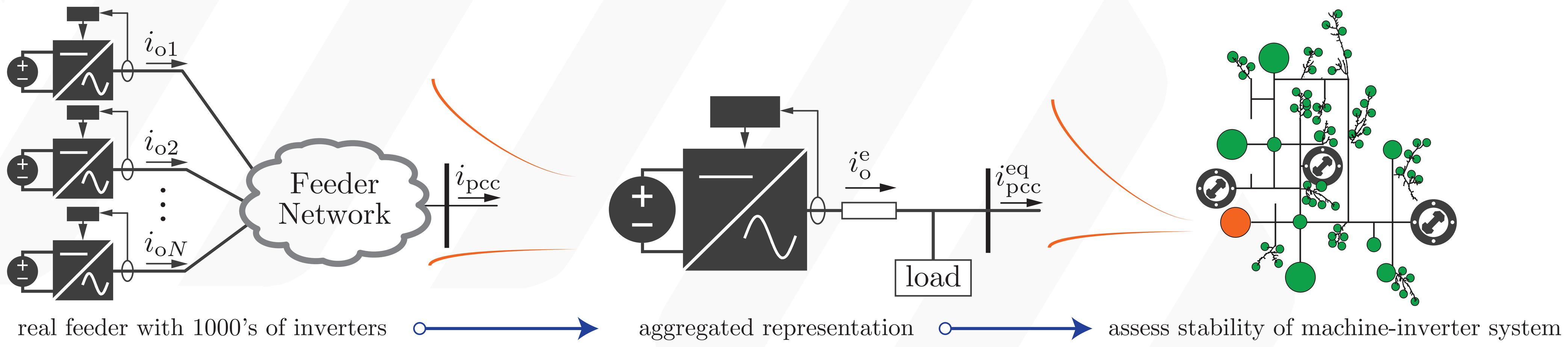
Grid-following units use a "phase-locked loop" to synchronize to an existing grid

Grid-forming virtual oscillators can establish a grid and rapidly synchronize to other inverters without communication



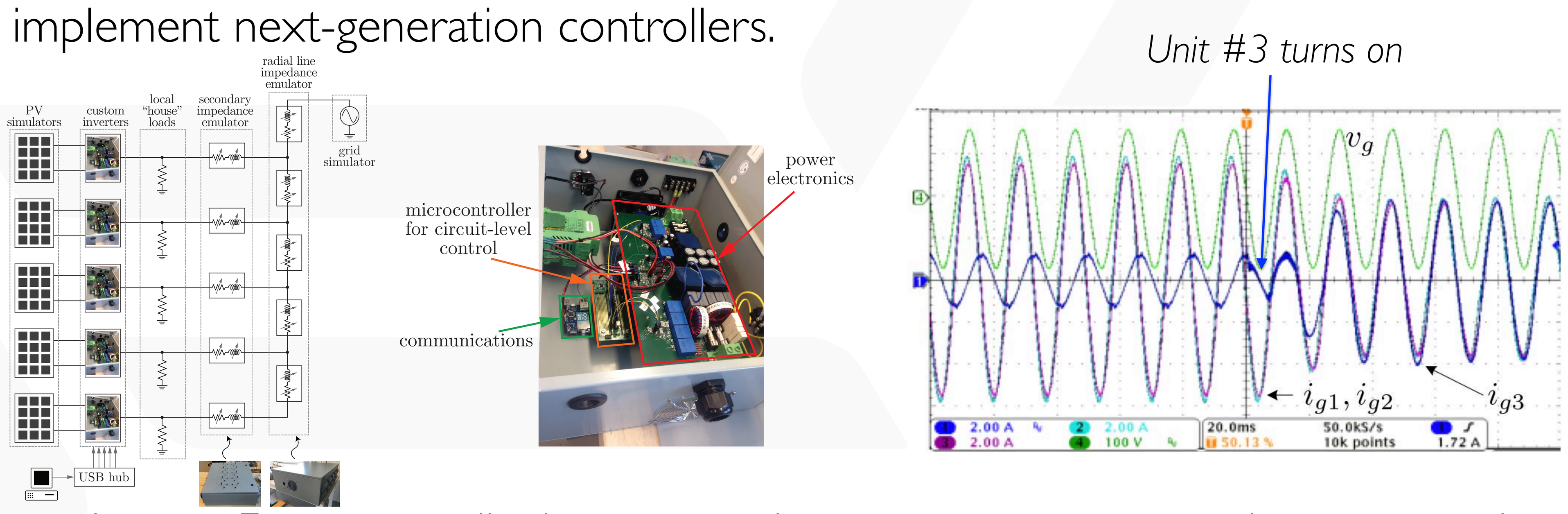
Research Themes: Modeling, Analysis, and Experiments

- (FY17-18) Establish limits of business as usual trajectory: Is there a limit to how many grid-following units a grid can handle? How can such a complex system be modeled?



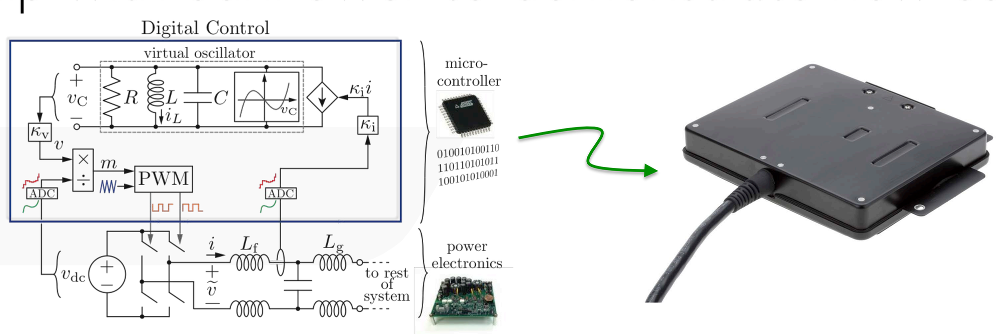
Impact: Showed that stability can be lost for high penetration levels of grid-following units

- (FY16-18) Develop new grid-forming controllers: Here we design, analyze, and implement next-generation controllers.



Impact: Experimentally demonstrated a zero-inertia system with inverters only

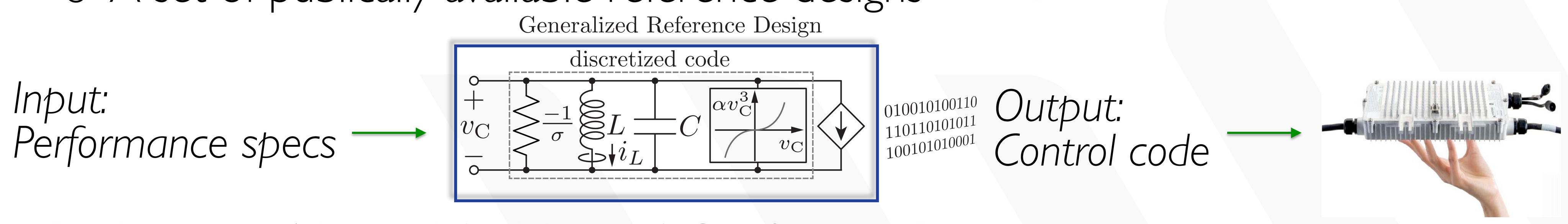
- (FY17-18) Demonstrate compatibility with off-the-shelf commercial hardware: Leverage partnership with SunPower to demonstrate new controllers.



Impact: Applicability on actual commercial devices will be shown

Planned Objectives and Existing Results

- Planned Outcomes of Project:
  - o Zero-inertia demo with a large number of microinverters
  - o A set of publically available reference designs



- Publications: 4 Journal Articles + 6 Conference Papers
- Visibility: Featured on IEEE Spectrum
- Intellectual Property: 3 Records of invention + 1 Patent application

Additively Manufactured Photovoltaic Inverter (AMPVI)

Lead: National Renewable Energy Laboratory
Team: Oak Ridge National Laboratory, Purdue University
Technology Advisory Panel: Yaskawa-Solectria, Semikron, National Instruments, Unified Power

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Develop unique PV string inverter design that combines high-voltage Silicon Carbide (SiC), additive manufacturing, multi-objective magnetic design optimization, advanced control designs, and optimized thermal design to achieve better performance and reliability at lower cost

Expected Outcomes

- World's first additively manufactured SiC-based, air-cooled power block for PV applications
- A new PV string inverter with optimized magnetics and thermal design that supports advanced inverter functions and interoperability
- New tools, concepts, techniques, reference designs and prototypes that will be licensed to the private sector for manufacturing these new power blocks and PV inverters in the U.S. and benefitting the U.S. economy

Innovative Aspects:

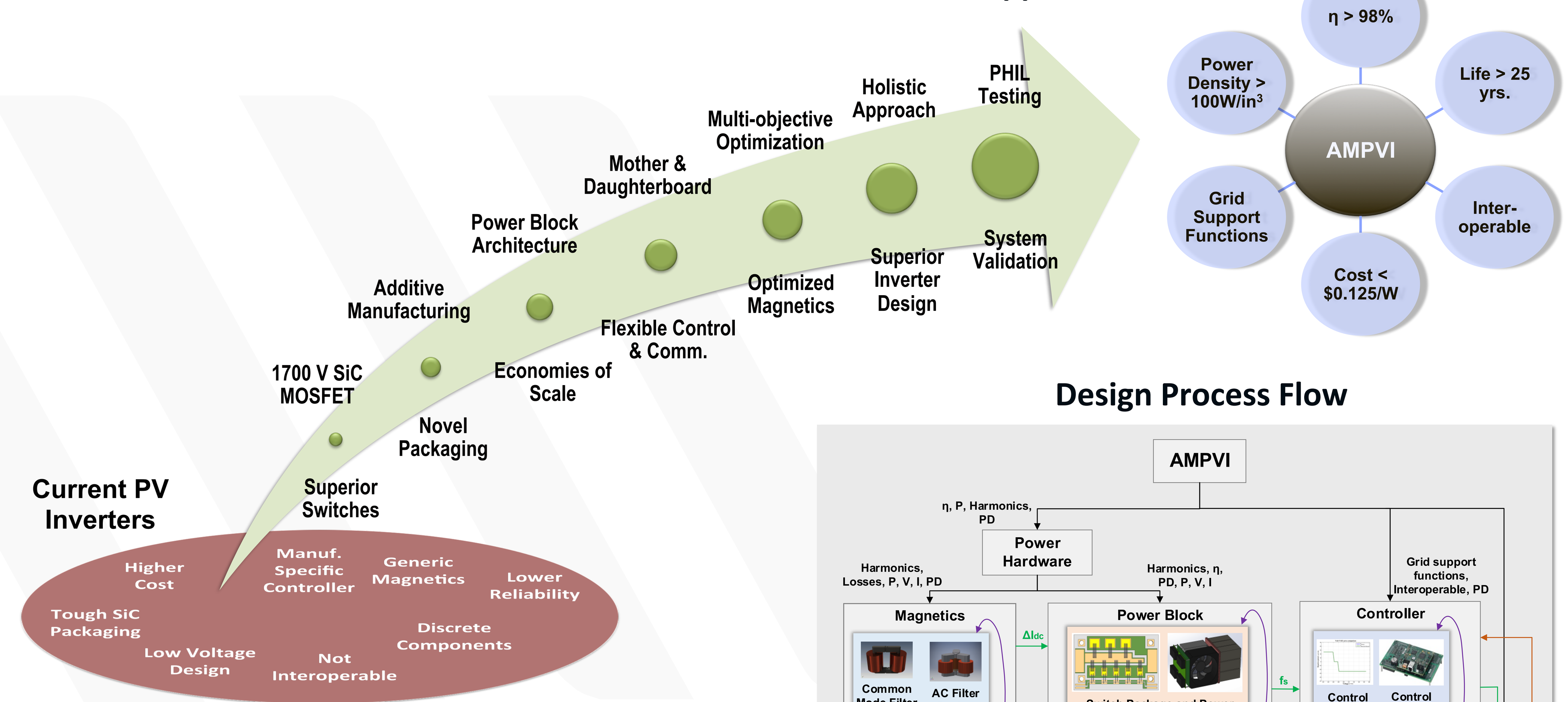
- Higher power density → ~ 6-10 times of state-of-the-art (SOA)
- Higher efficiency → ~ 25-40% loss reduction from SOA
- Better reliability → ~ 25 years MTBF
- Advanced grid support functions

Impacts:

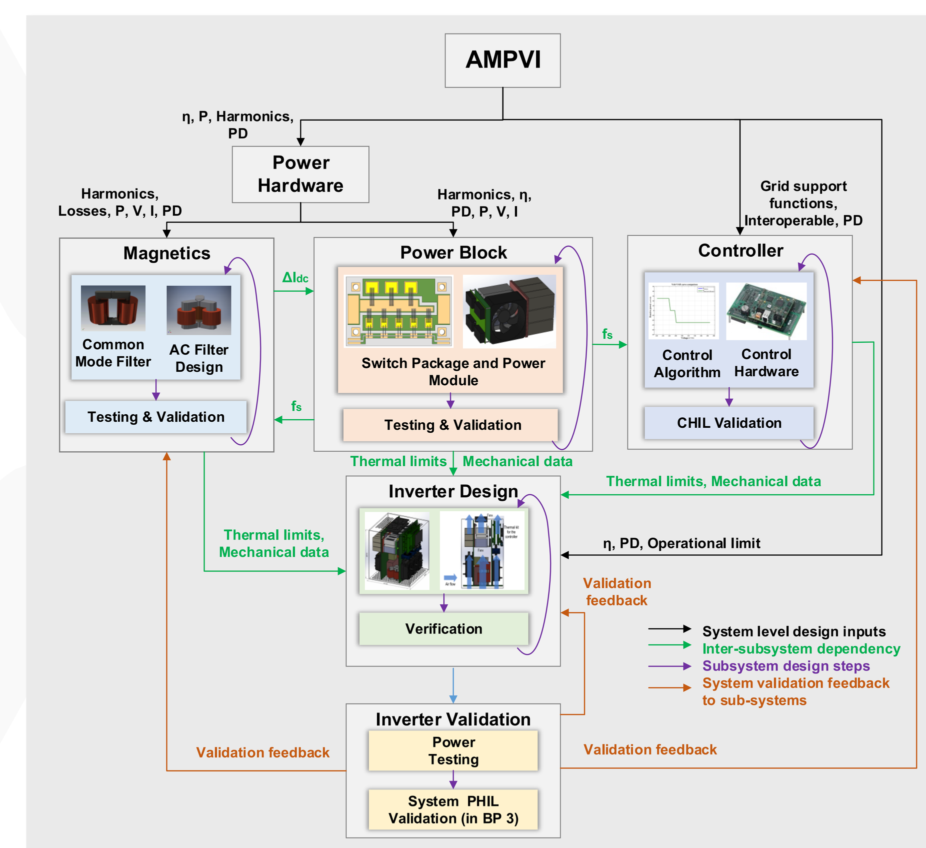
- ❑ Better design of PV inverter for efficient and reliable energy conversion at lower cost to support grid parity of PV by 2020 and integrate GWs of PV by 2030
- ❑ Concepts and building blocks developed here can be utilized in other power electronics applications such as vehicles and industrial motor drives providing path for U.S. leadership in power electronics manufacturing

	Significant Milestones	Date
✓	BP1: Alpha-power block power density six times higher than inverter SOA with η >=99%	9/30/2016
ONGOING	BP2: Alpha inverter η_{peak} >=98% and supports new functions	9/30/2017
	BP3: Optimized inverter with power density 6-10 times of SOA, η >=98% , MTBF 25 years	9/30/2018

AMPVI – Technical Approach

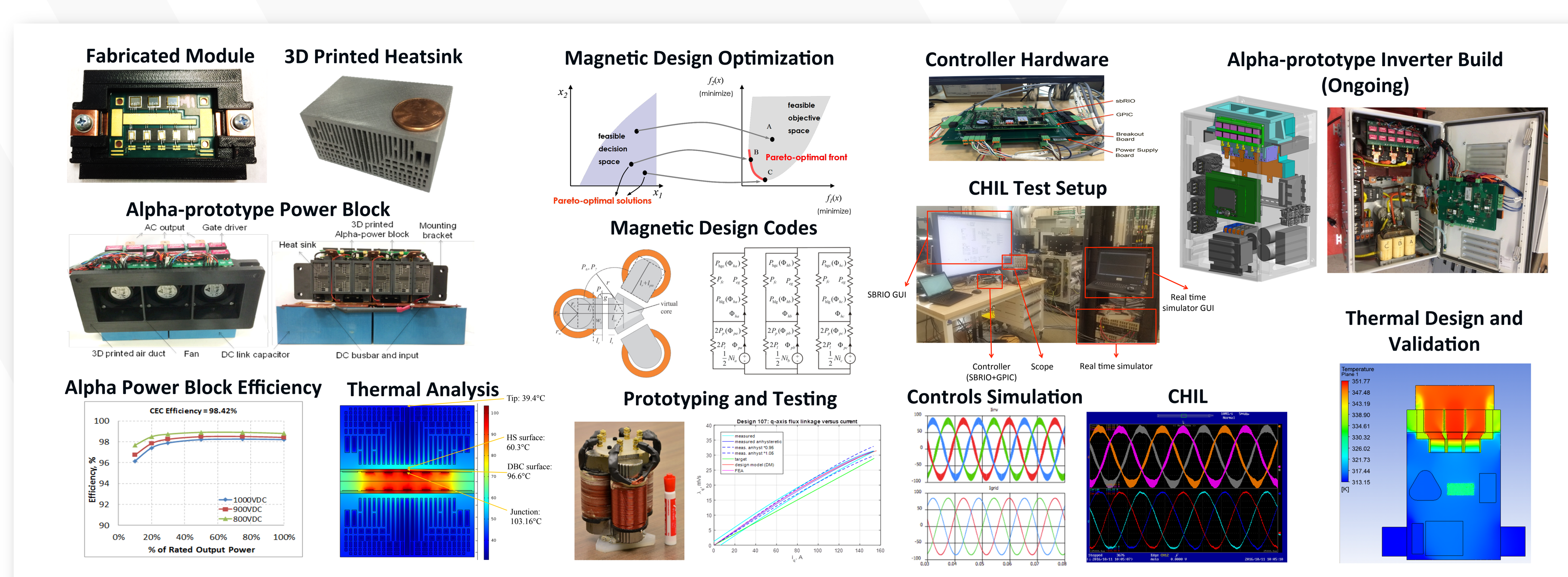


Design Process Flow



Progress to Date

- Additively manufactured three-phase, 50 kW alpha-prototype power block with power density = ~ 221 W/in³, η_{CEC} = ~ 98.42%
- Multi-objective optimization design codes for both AC and DC magnetics and prototyping of magnetics
- Developed controller hardware and advanced control algorithms and validated them by controller hardware-in-the-loop (CHIL)
- Mechanical and thermal design of 50 kW, three-phase, alpha-prototype inverter that is currently being constructed
- Preliminary reliability and cost analysis of the inverter design
- **Dissemination**: One journal paper and one conference paper under review; hosted industry workshop at NREL on Oct. 2016



Accelerating Systems Integration Standards (ACCEL)

(Updates to National Standards IEEE 1547, IEEE 1547.1, and UL1741)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Establish **accelerated development** of new **requirements and conformance procedures** for DER interconnection and interoperability for the full revision of IEEE 1547 (requirements), IEEE 1547.1 (test procedures), and UL 1741 update (safety standard).

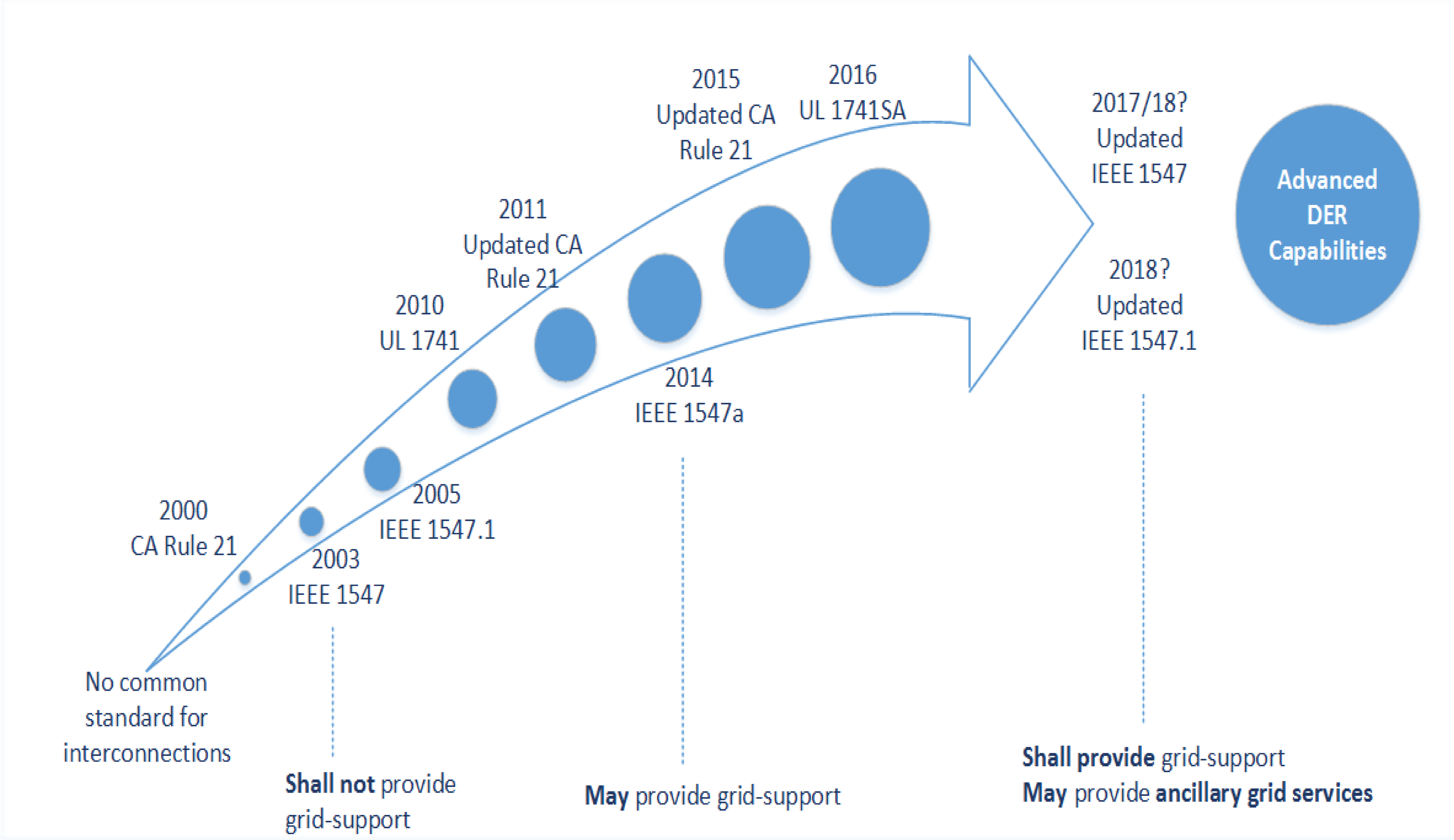
Expected Outcomes

- Improved **harmonization between state and national** standards
- **Increased electric grid resiliency** under abnormal grid conditions through new grid-support capabilities of distributed energy resources
- **Expanded markets** by maximizing feeder hosting capacity through distributed energy resource's increased optimization and interoperability capabilities
- **Accelerate standard development** process by up to one year

Significant Milestones	Date
P1547 - Finalize Officer team, working group & topic subgroups	Oct, 2015
P1547 - Working group meetings to develop requirements	Oct, 2015 – Jan 2017
P1547 - Establish new grid support requirements, reach Working Group consensus	Feb, 2017 – Mar 2017
P1547 – Initial IEEE Ballot (round 1)	May, 2017
P1547.1 - Finalize Officer team, working group & topic subgroups	Oct, 2015
P1547.1 - Working group meetings to develop conformance test procedures	Oct, 2015 – Mar, 2018
P1547.1 - Reach Working Group consensus	Apr, 2018
P1547.1 – Initial IEEE Ballot	May, 2018

Industry Partners:
IEEE P1547 Working Group

Partnering DOE Labs:
NREL, Sandia



Timeline of improvements to interconnection standards

Progress to Date – Major Achievements

- **121 industry experts** on the working group have been meeting via phone weekly for over a year to develop consensus language (WG approved 3/2017). The revisions include many new details on reactive power capabilities and voltage/power control requirements, maximizing hosting capacity while maintaining distribution grid safety (cease to energize, trip on voltage or frequency when necessary) and maintaining bulk power system reliability (rides through voltage and frequency disturbances).
- **The DOE project team is providing leadership** at the officer level and also at the working group level, leading to tighter collaboration between P1547 and P1547.1, and sustained, focused effort towards building consensus among working group members.
- **NREL and Sandia testing facilities** and resources are being leveraged to exercise inverters and validate testing procedures for input to working groups on device and testing requirements and functions. This supports the need to completely revise testing requirements to address new capabilities.

Timely revision and approval of these standards will give local jurisdictions the needed uniform and consistent method for interconnecting grid-supportive distributed energy technologies to enable more coordinated operation under normal conditions, and improved performance under abnormal conditions.

GMLC SuNLaMP #31004:
Combined PV / Battery Grid Integration with High Frequency Magnetics Enabled Power Electronics

Lead: National Energy Technology Laboratory
Partners: Eaton Corporation, North Carolina State University, Carnegie Mellon University, NASA Glenn Research Center

Project Description

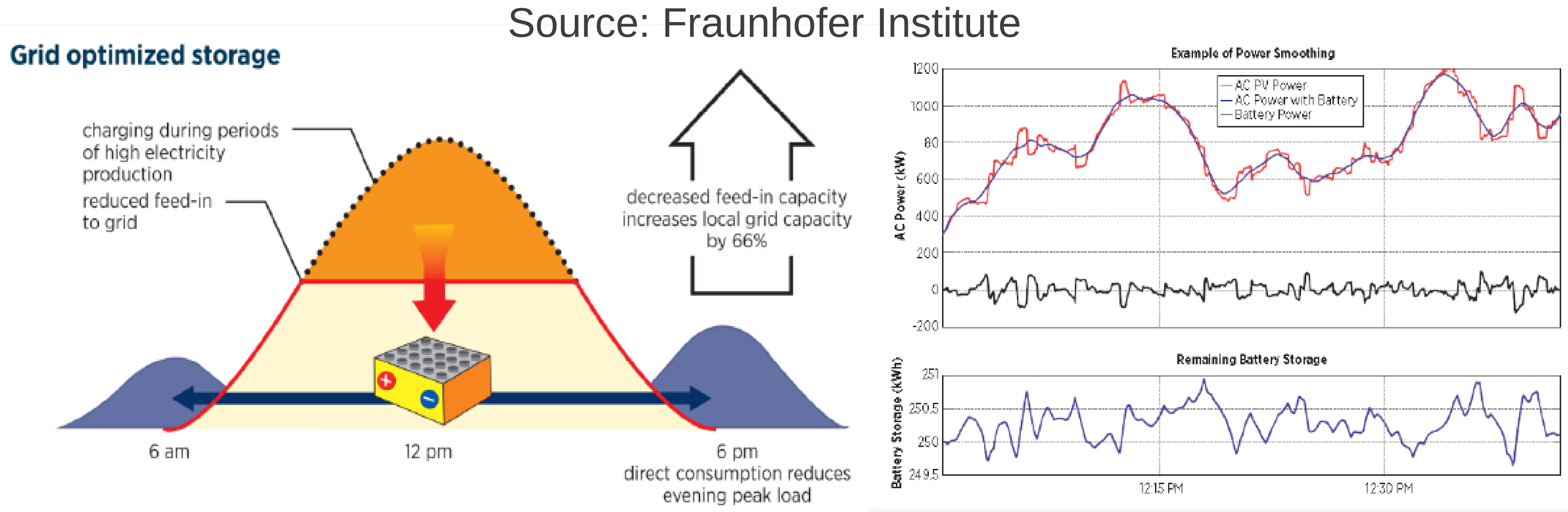
A novel approach to combined integration of solar photovoltaics and energy storage is being developed and demonstrated to mitigate against intermittency inherent to solar PV generation in a cost-effective, high efficiency, and power dense topology. Also core to this technology is the successful development of high frequency transformers for a multi-port DC-DC converter as well as implementation of wide bandgap based SiC switching devices.

Expected Outcomes

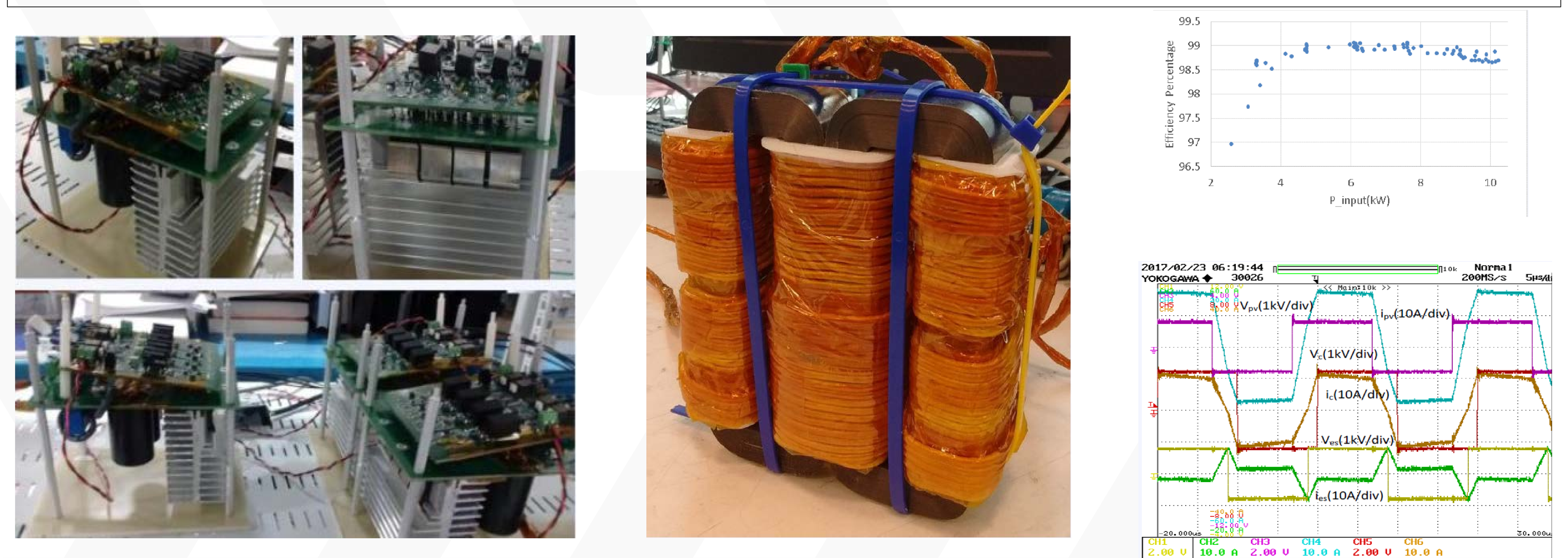
- Successful demonstration of 3-port DC-DC converter technology at 50kW (commercial) scale
- System level studies to show feasibility of implementation at full utility scale (>1MW)
- Development of new enabling magnetics technology for the next generation of high frequency transformers
- Technology transfer of intellectual property and know-how to the private sector to promote near-term commercialization
- Successful completion of these outcomes will enable greater penetration of solar generation through simultaneously:
    - Reducing costs, increasing power density, and increasing reliability of grid interconnection hardware
    - Successfully managing inherent variability of solar

Significant Milestones Completed	Date
Detailed Architecture Studies to Demonstrate the Value Proposition Relative to Existing State of the Art Technology	9/30/2016
Successful Experimental Demonstration of 10kW DC-DC Converter Prototypes	1/30/2017
System Level Simulations Demonstrating Successful Operation of a Full 1MW-Scale Combined Solar / Energy Storage Inverter Architecture	12/30/2016
First Draft Design for a 50kW Prototype Transformer and DC-DC Converter	2/30/2017
Successful Establishment of New Magnetic Core Testing Capabilities for Application Relevant Excitation Waveforms	11/30/2016

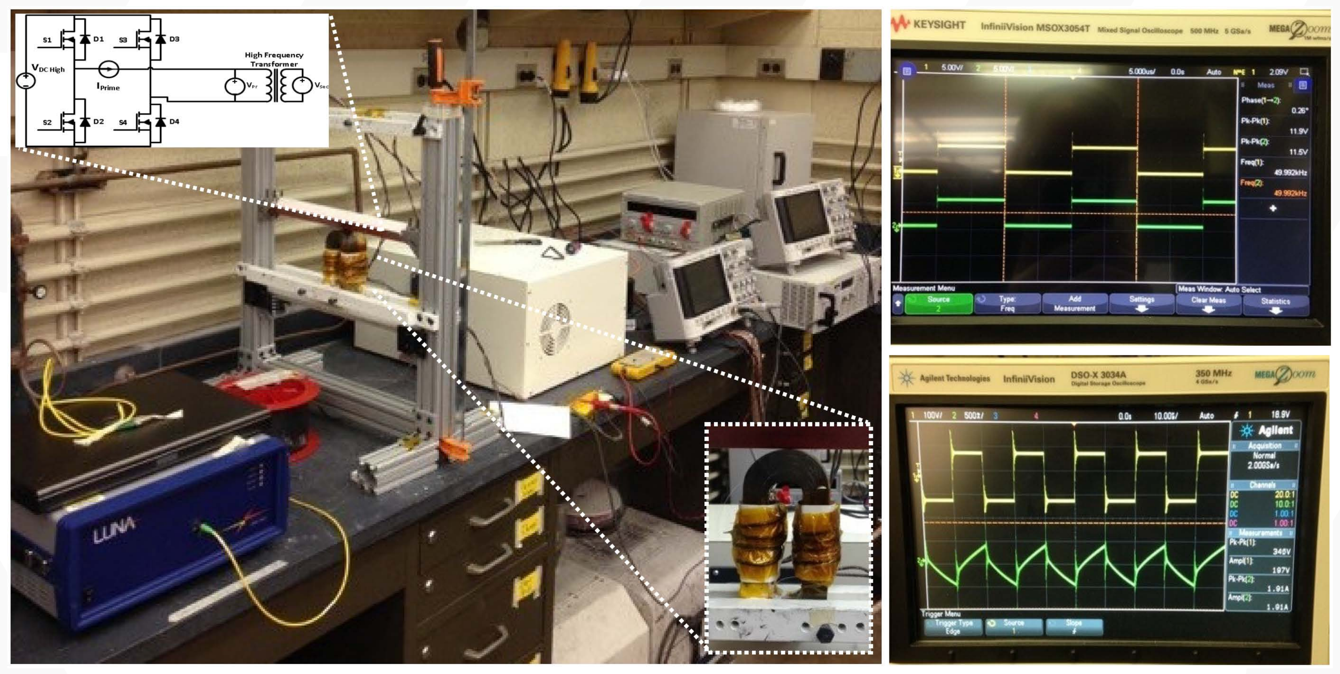
Source: Fraunhofer Institute



Combined Solar PV / Energy Storage Integration Has Inherent Advantages Including "Energy Time Shift" and "Power Smoothing".



Successful 10kW Prototypes of a Full DC-DC Converter (Left) and a High Frequency Transformer (Center) Showing Efficiencies > 98% and Successful Power Flow.



New High Frequency Transformer Fabrication and Testing Laboratory for Full Prototyping at Converter Level.

Progress to Date

- Successful 10kW Demonstrations
- Completion of a First Draft 50kW Design
- New Transformer Fabrication, Testing, and Modeling Capabilities
- Technical Products:
    - Two Peer-Reviewed, Numerous Conference Publications
    - Two Provisional and One Non-Provisional Patent Application
    - Invited Presentation at MRS Spring 2017
    - Numerous Presentations at TMS Annual, APEC, MMM, etc.

Power System Reliable Integration Support to Achieve Large Amounts of Wind Power (PRISALA)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

- ► Work with key power system stakeholders on research in grid operations, resiliency and security, including new power system modeling using advanced algorithms for reliable system operation.
- ► Disseminate the latest scientific power system research to key grid stakeholders.

Expected Outcomes include

- Work closely with the North American Electric Reliability Corporation (NERC) on their Essential Reliability Services Working Group to ensure that key reliability issues are addressed for America's future power grid and also with NERC on their Frequency Response Study to make sure that adequate frequency response is available in all U.S. Interconnections
- This project will help minimize electrical disturbances and increase the resilience and reliability of the U.S. power grid, thereby benefiting consumers, grid stakeholders and the Nation with a more robust and reliable electricity supply

Significant Milestones	Date
• Complete paper "Revenue Sufficiency and Reliability in a $0 Marginal Cost Future"	12/30/2016
• Participate in NERC Essential Reliability Services Working Group	6/30/2017
• Participate in NERC Frequency Response Study	8/30/2017

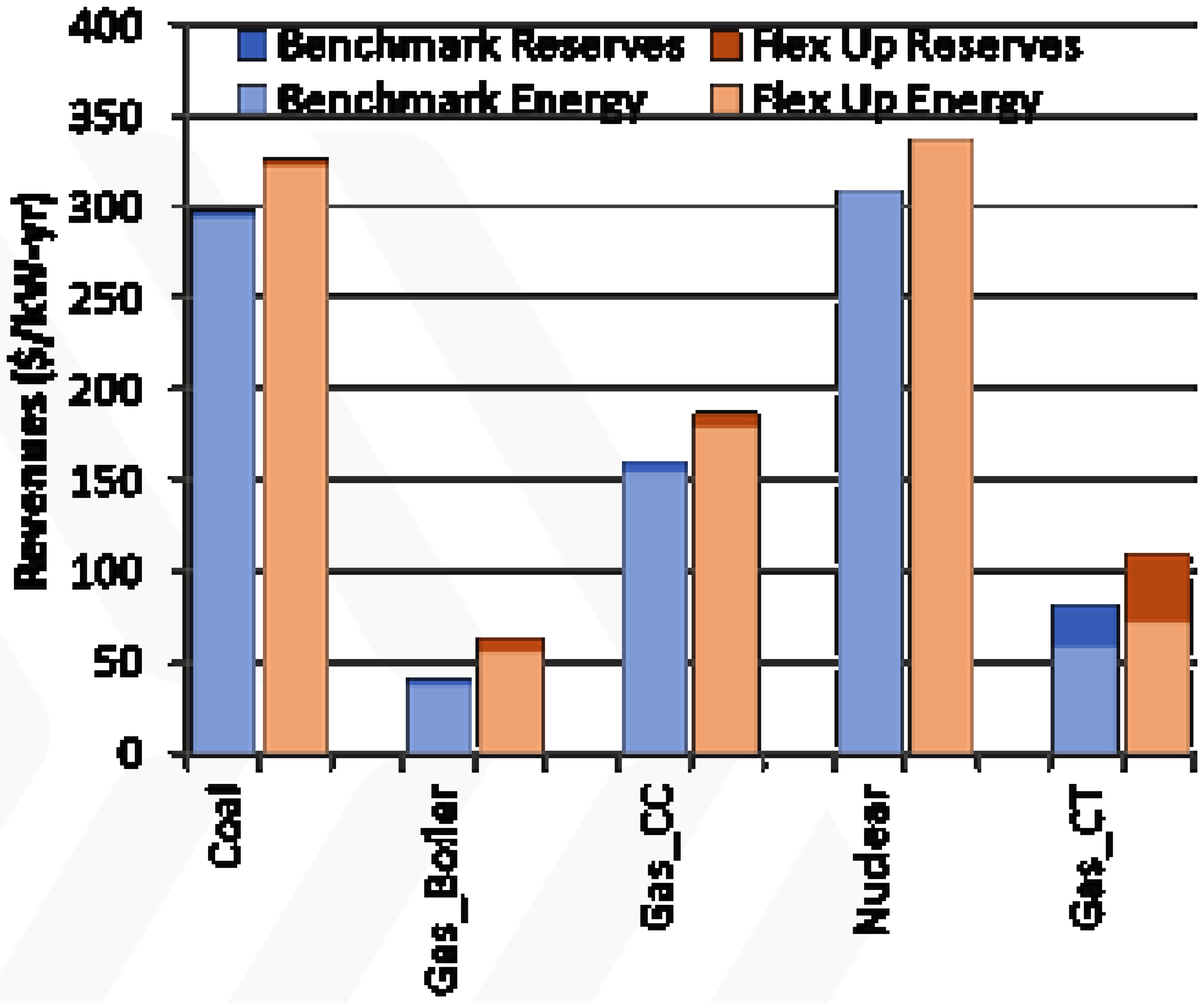


Figure 1. Total revenues for the 2013 Benchmark and Flex Up scenarios - from *Revenue Sufficiency and Reliability in a $0 Marginal Cost Future* paper

Progress to Date

- Utility Variable Generation Integration Group (UVIG) Spring Technical workshop (UVIG, an international leader in power systems grid integration, is sponsored in part by NREL under this project)
- FERC briefing on NREL's Eastern Renewable Generation Integration Study (ERGIS)
- Capacity Value Assessments for Wind Power: An IEA Task 25 Collaboration. Milligan, M., B. Frew, E. Ibanez, J. Kiviluoma, H. Holttinen, L. Söder. Wiley Wires. 2016

GMLC WGRID-49
Understanding the Role of Short-term Energy Storage and Large Motor Loads for Active Power Control by Wind Power

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

The goal of this 3-year effort is to develop and test coordinated controls of active power by wind generation, short term energy storage, and large industrial motor drives for providing various types of ancillary services to the grid and minimizing loading impacts and thereby reducing operation and maintenance costs (O&M) and subsequently the cost of energy (COE) generated by wind power.

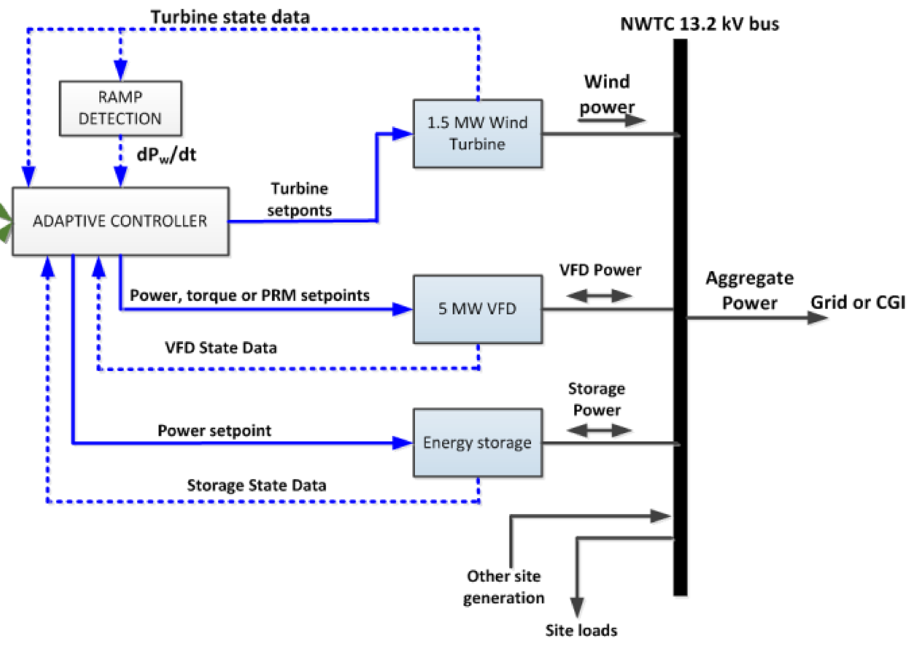
Project team: NREL, INL, Clemson University, GE Energy Consulting

Expected Outcomes

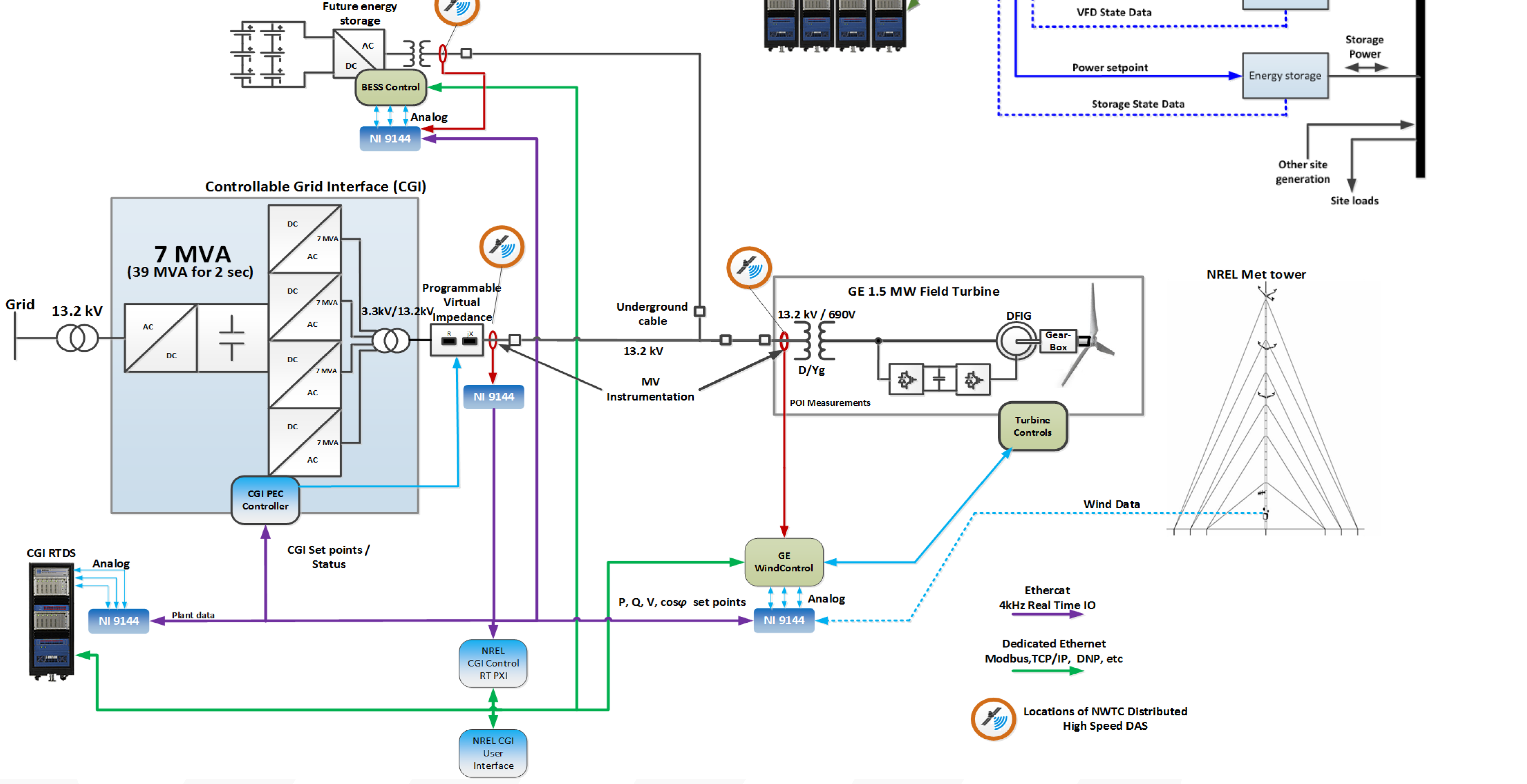
- This project will produce analyzed test data to understand the impacts of a single turbine and wind power plant level short-term energy storage on various types of ancillary service controls by wind power (inertial control, PFC, AGC, variability smoothing, and mechanical loads).
- The results of this project can be used by other parts of DOE Wind Power Program (wind turbine systems reliability, A2E, etc.), to understand the tradeoffs between better gearbox design and predictive control on inflow for mechanical loads minimization and responsive control on the grid side with electrical storage.
- The project will produce data to demonstrate the coordinated control of wind power and industrial motor loads for providing optimized ancillary services to the grid.
- The project will develop and demonstrate the concept of dispatchable power plant utilizing real MW wind power generation, energy storage, loads, elements of resource forecast.
- This project addresses DOE wind program goals in the area of Devices and Integrated Systems for the demonstration of how wind power can be tied to other technologies (energy storage and responsive regenerative loads .

Significant Milestones	Date
Controller Design - develop controller architecture concept	12/31/2016
Develop controller in Matlab Simulink environment for concept testing	3/31/2017
Implement controller in real-time platform	6/30/2017
Conduct testing and demonstration of the controller	9/30/2017

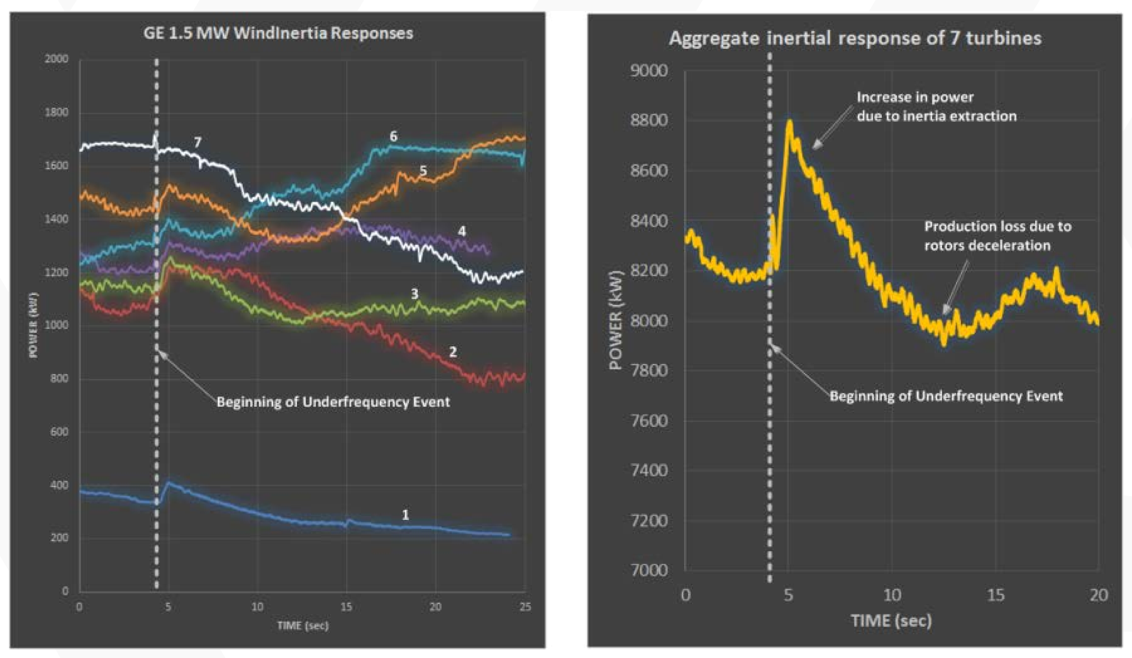
Controller architecture



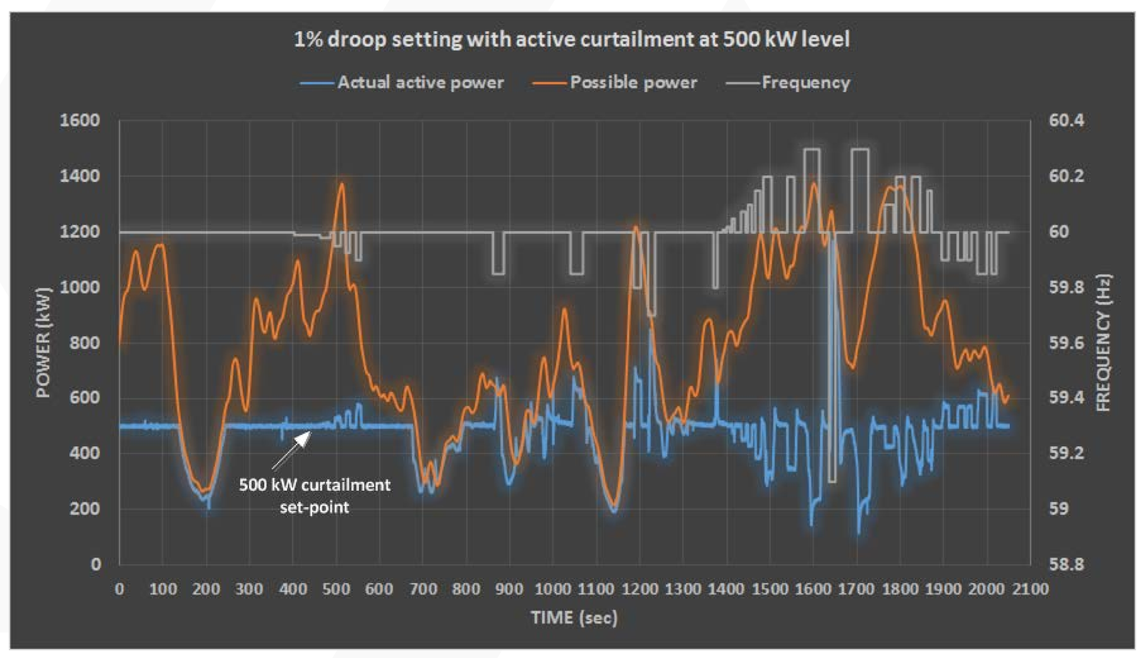
Testbed layout



Example of Inertial Response Tests



Example of Frequency Response Tests



Progress to Date

- Developed a multi-MW PHIL testbed consisting of 1.5 MW wind turbine generator with wind power plant controller, 7 MVA grid simulator, 1 MW / 1MWh battery storage and RTDS-based model of a power system
- Conducted experiments characterizing various forms of active power control by wind power under controlled grid conditions
- Conference presentations and papers::
  - Presented paper at 15th International Workshop on Large-Scale Integration of Wind Power in Power Systems, Vienna, Austria, Nov 15-17, 2016
  - Paper submitted for IEEE COMPEL-2017 conference