2017 ADMS Program
Steering Committee Meeting

Advanced Distribution Management System Testbed Development

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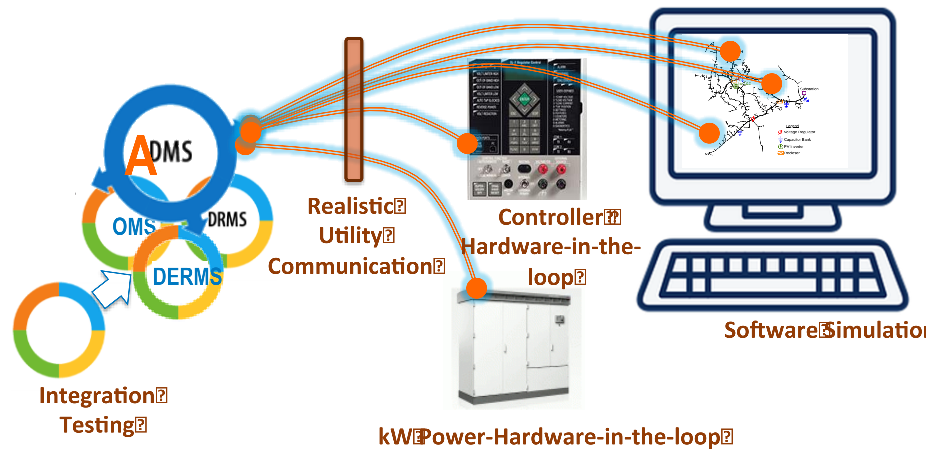
October 11, 2017

ADMS Testbed Development

Objectives & Outcomes

Objective: Establish a national, vendor-neutral Advanced Distribution Management System (ADMS) testbed to accelerate industry development and adoption of ADMS capabilities for the next decade and beyond.

Outcome: The testbed will enable utility partners, vendors, and researchers to evaluate existing and future ADMS use cases in a test setting that provides a realistic combination of multiple utility management systems and field equipment. The project will work closely with an Industry Steering Group to ensure that electric utility needs are met and use cases are realistic and valuable.



Technical Scope

- Model large scale distribution systems for evaluating ADMS applications
- Integrate distribution system hardware in ESIF to simulations for PHIL experimentation
- Develop advanced visualization capability to analyze the results for mock utility distribution system
- Use case 0: Volt-VAR Optimization with PV Inverters, Use case 2: Data remediation/Model Improvement needs, Use case 3: Integrated application demonstration

Life-cycle Funding Summary ($K)

FY16, authorized	FY17, authorized	FY18, requested	Out-year(s)
1.5M	1.2M	1.8M	NA

Presentation outline

- Project context
- Project status
  - Task 1: IAB update
  - Task 2: Use cases
  - Task 3 and 4: Use case 0
  - Task 3 and 5: Test bed and visualization capabilities for use case 1
  - Task 6: Project management and budget update
- FY 2018 plan
  - Use case 1 Execution
  - Use case 2 Design
- Tech transfer activities

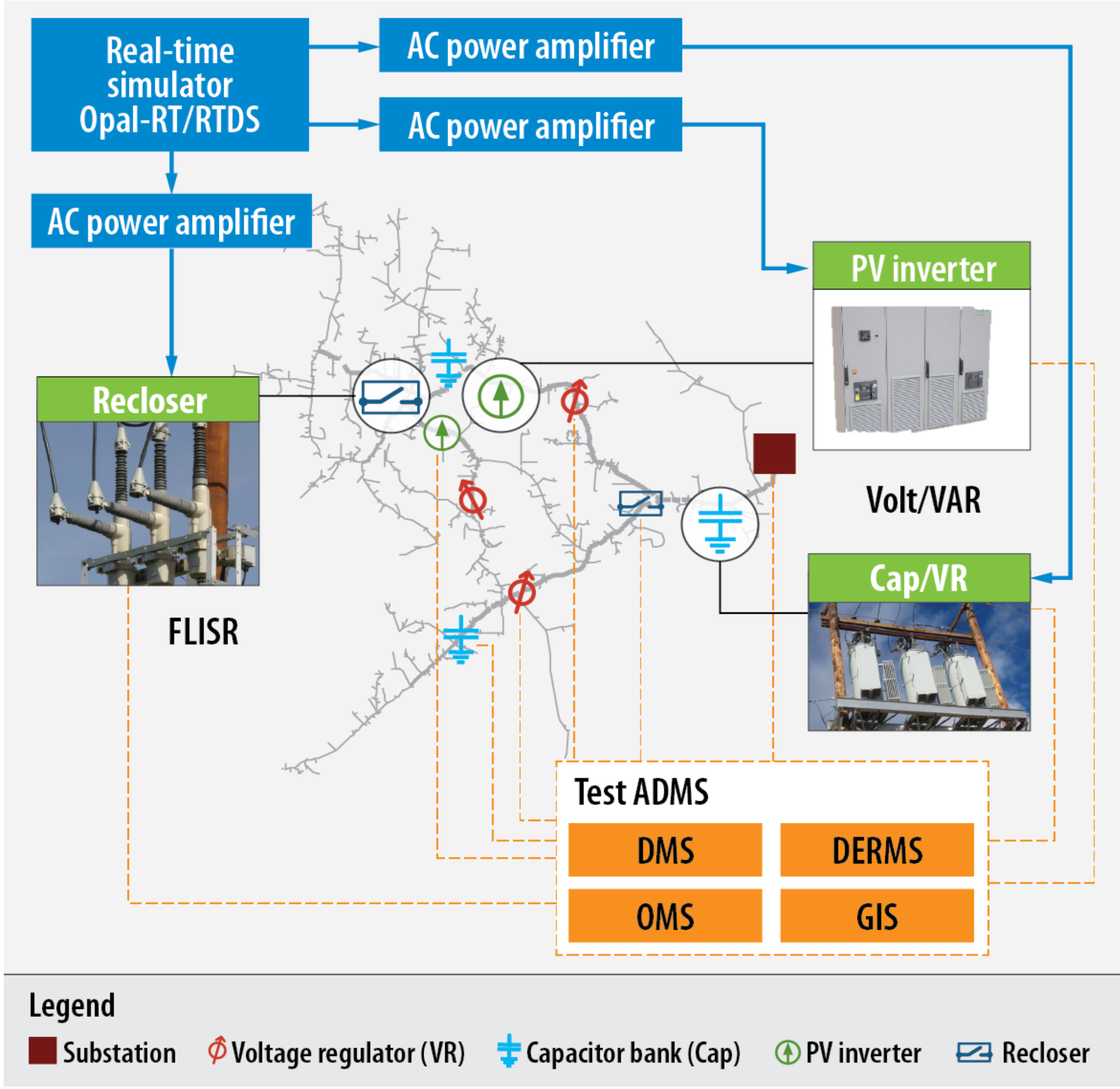
ADMS Testbed Development

Objective: Develop a vendor-agnostic, low-cost, low-risk testing ground at NREL that can evaluate ADMS applications

Project Description

- Model large scale distribution systems for evaluating ADMS applications
- Integrate distribution system hardware in ESIF for PHIL experimentation
- Develop advanced visualization capability for mock utility distribution

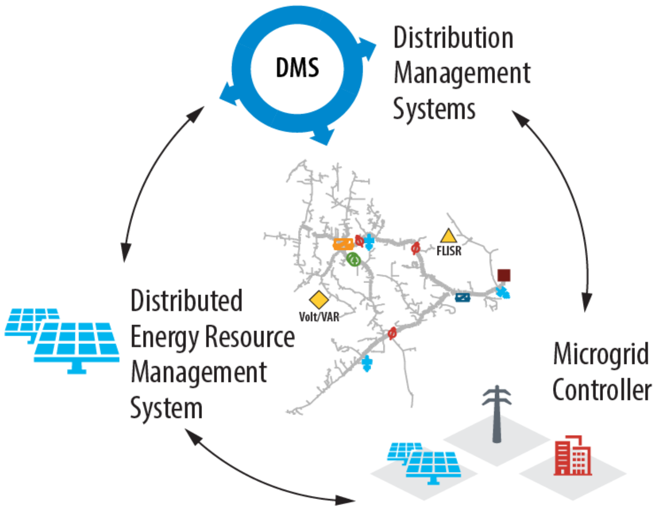
KEY APPLICATION:
Evaluation of advanced DMS functions
NREL is working with utilities and vendors to evaluate advanced DMS applications such as VVO, FLISR, OPF and market participation of distribution assets in a realistic environment developed during this project



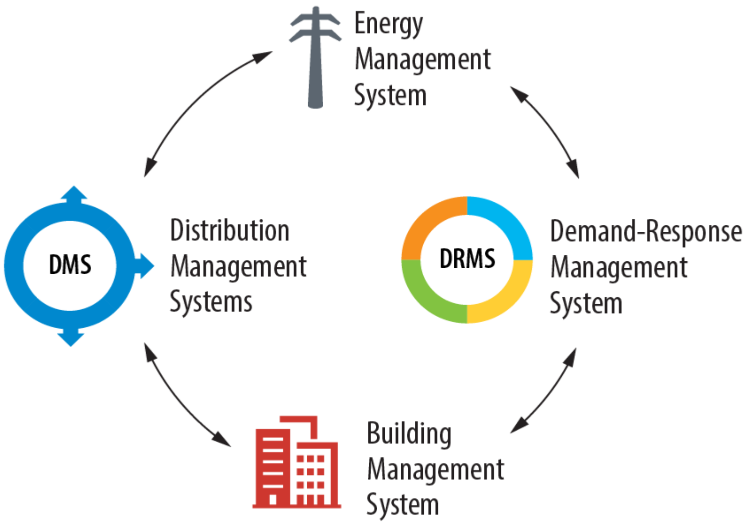
Outcomes and Benefits

- Identifying the **<u>right use-case</u>** and technical parameters for a specific distribution system
- Comprehensive understanding of **interoperability and vulnerability** of the ADMS and connected devices.
- The ADMS testbed will allow utilities and vendors alike to evaluate:
  1. **Interactions with hardware devices**;
  2. **Integration challenges** of ADMS with legacy systems; and
  3. Testing and understanding the **impact of ADMS functionality**
- **Lower-cost pre-pilot testing** ground for full ADMS functionality to reduce utility risk and costs.
- Unique ability to test what-if **hypothetical scenarios**
- Opportunity to work with vendors **to develop and evaluate new functions** and test them in a controlled environment.
- Facility for **operator training** of utility engineers

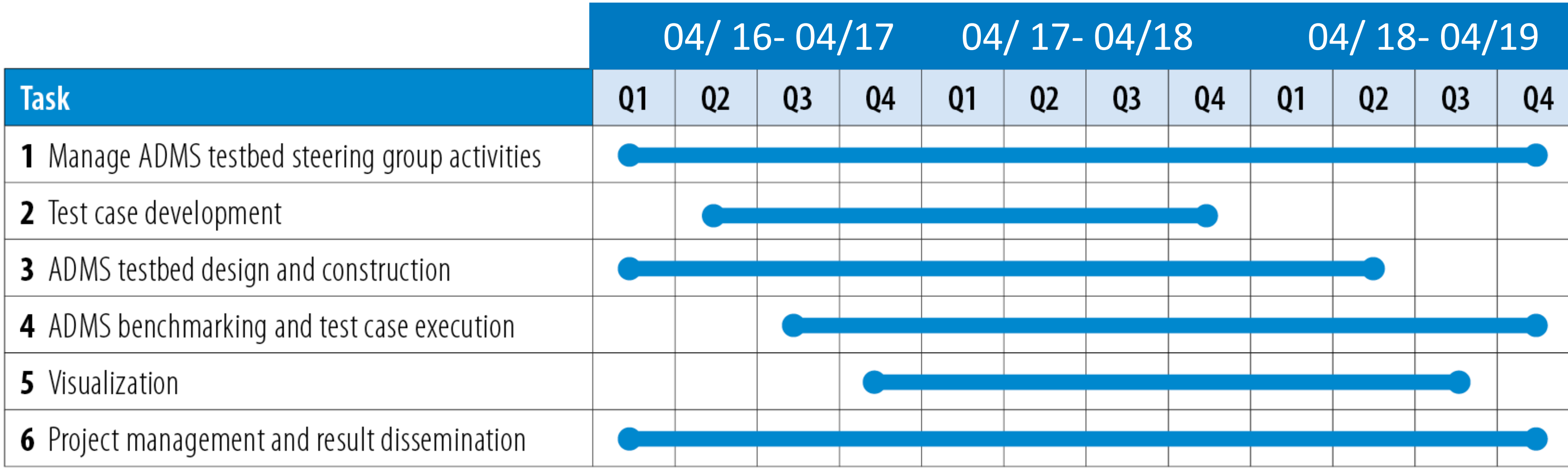
Use Case 1



Use Case 2



Overall Project Timeline and Key Tasks



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 2.	04/15/2017

Task 1: Industry Advisory Board (IAB)

- Approx. 27 organizations
- Joint IAB for 2 projects:
  - NREL's ADMS Testbed
  - PNNL's GridAPP-D

Fall 2016	List of potential IAB members gathered, initial contacts made
January 2017	IAB charter finalized. Has since been used to recruit IAB members
Feb. 2, 2017	First IAB in-person meeting held at DistribuTECH • Discussed description and scope of project, use cases • In attendance: 6 utilities, 5 vendors, NRECA
April 27, 2017	Second IAB meeting held in Washington, DC • Presented results of year 1, plan for year 2 • Discussed IAB members specific interests • In attendance: 3 utilities, 5 vendors, NRECA & EPRI
Sep. 8, 2017	Webinar for IAB • Presented progress report, use case details, graph database
Upcoming	
Nov. 15, 2017	Webinar for IAB
January 2018	In-person meeting in conjunction with DistribuTECH
April 2018	In-person meeting in conjunction with IEEE T&D

Task 2: Use Case development

- 15 ADMS applications considered for review: Volt-VAR Optimization (VVO), Fault Location, Isolation & Service Restoration (FLISR), Switching Order Management (SOM), Short Circuit Analysis (SCA), Demand Response (DR), DERMS, Online Power Flow (OLPF), Distribution System State Estimation (DSSE), Optimal Network Reconfiguration (ONR), SCADA, Load Forecasting, Market functions, Model Management, Predictive Fault Location (PFL)

- Four applications that are being evaluated:
  - Volt-VAr Optimization (VVO) (use case 0, 1 and Future use cases)
  - Online Power Flow (OLPF)/ State Estimation (DSSE) (use case 1)
  - Market Participation (Possible use case 2)
  - Fault Location, Isolation & Service Restoration (FLISR) (future use case)



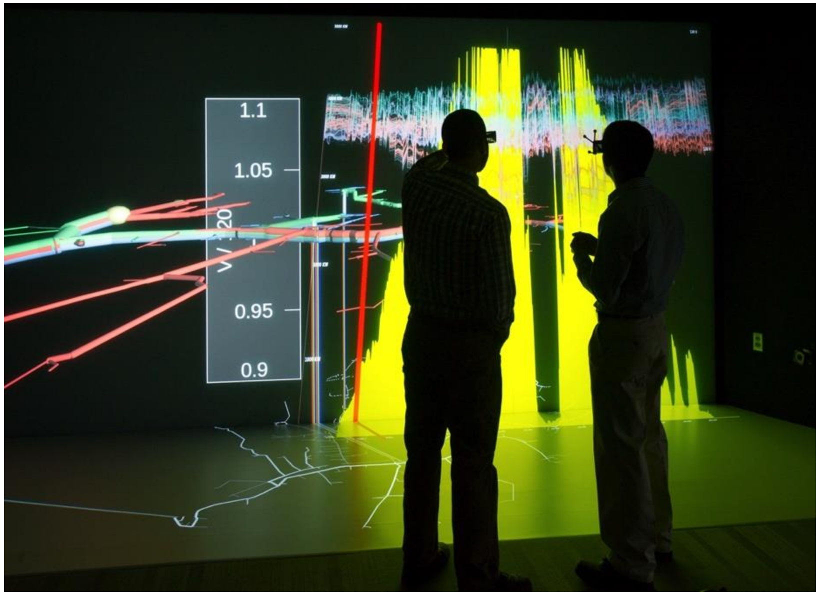


Year 1 results: Task 3 and 4 : Execution of Use Case 0 - Volt-VAR Use Case Evaluation on ADMS Testbed

Murali Baggu

Duke, NREL, & GE: Advanced Inverters and ADMS for Hi-Pen PV

Summary: Detailed system modeling, combined with Power-Hardware-in-the-Loop verification to compare local vs. centralized management of voltage with utility-scale inverters in Duke territory



Simulation (5MW PV 2mi out on 5MW peak rural feeder)

- Simulation using actual DMS system deployed at Duke (via GE's *eTerra* Distribution Operations Training System (DOTS))
- GE has enabled faster than real-time time series analysis and supports advanced inverter modeling through Python (py4etd)
- Simulation of:
  - Baseline: PV active power only
  - Local Control: PV Volt/VAr modes
  - Central control: DMS-based IVVC application

ADMS Testbed: Power Hardware-in-the-Loop (PHIL) in ESIF

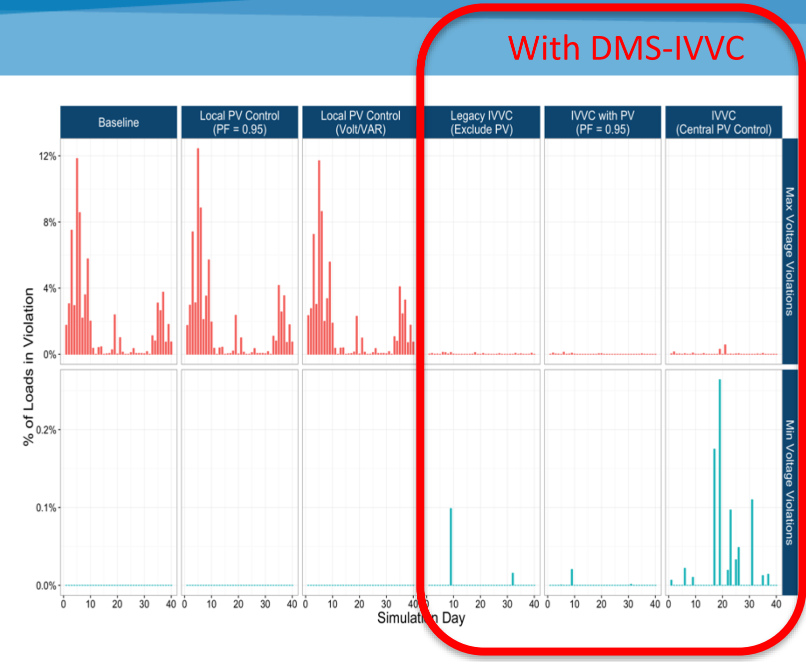
- Co-simulation with DOTS to capture entire feeder
- Validate simulations: actual hardware at power
- 500 kVA advanced inverter

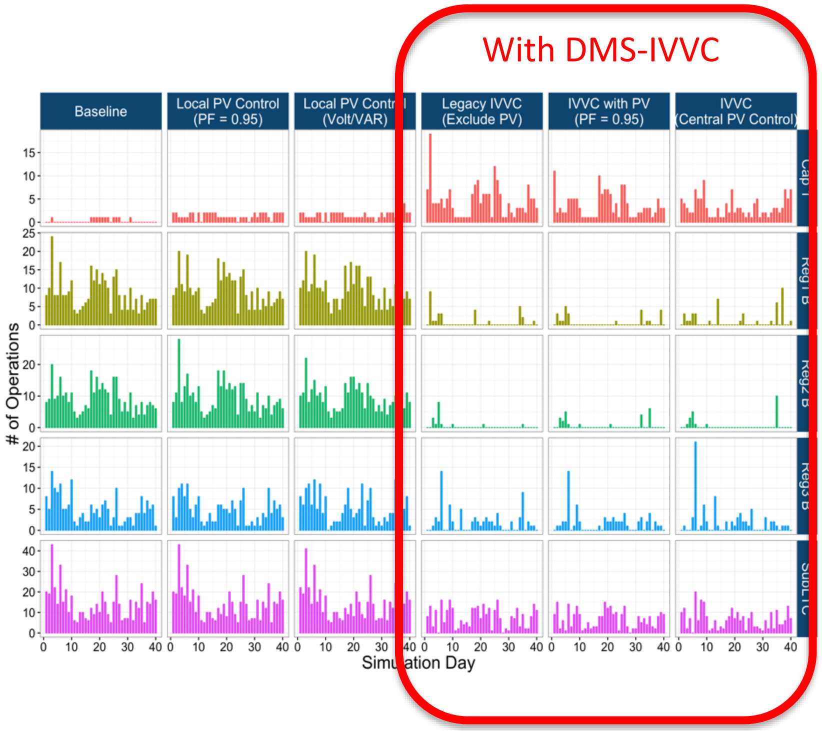
Simulation Results

DMS Coordinated Volt/VAR

Very effective at reducing:

- Voltage Challenges…





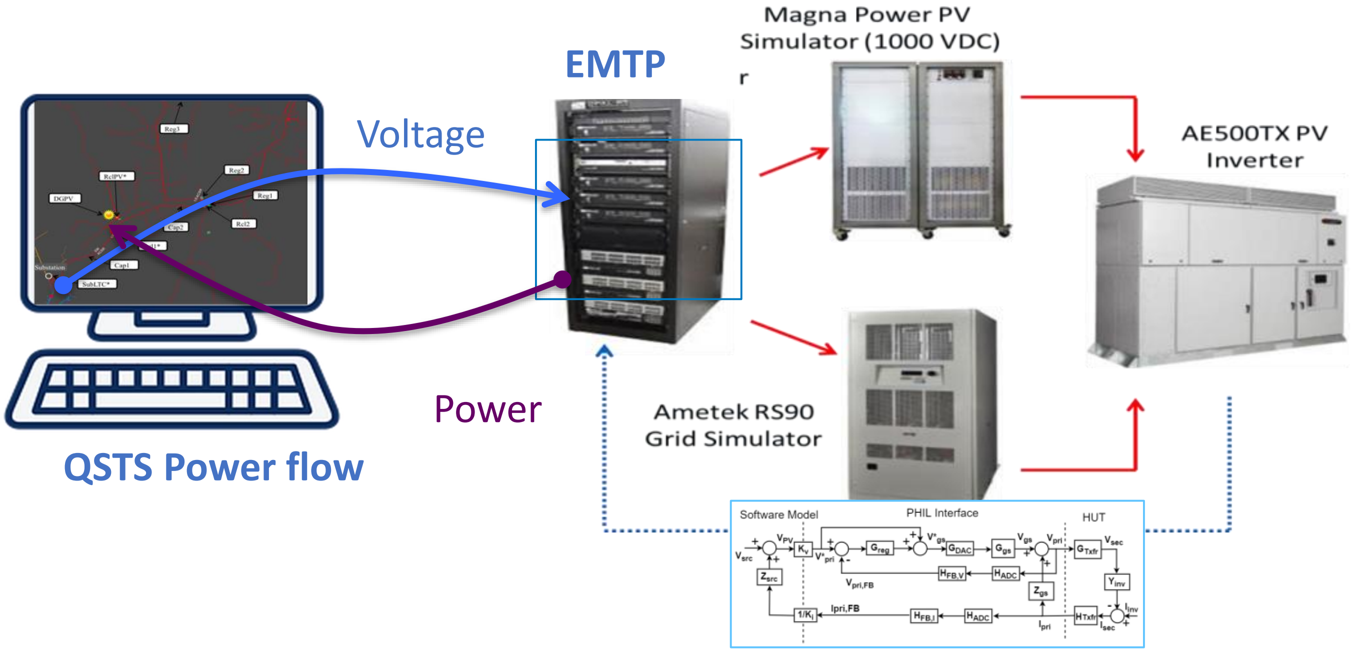
- And Equipment Operations

Which along with precise CVR dramatically reduce costs.

Palmintier, et. al. 2016. ***"Feeder Voltage Regulation with High Penetration PV using Advanced Inverters and a Distribution Management System: A Duke Energy Case Study"*** *NREL/TP-5D00-65551.*

http://www.nrel.gov/docs/fy17osti/65551.pdf

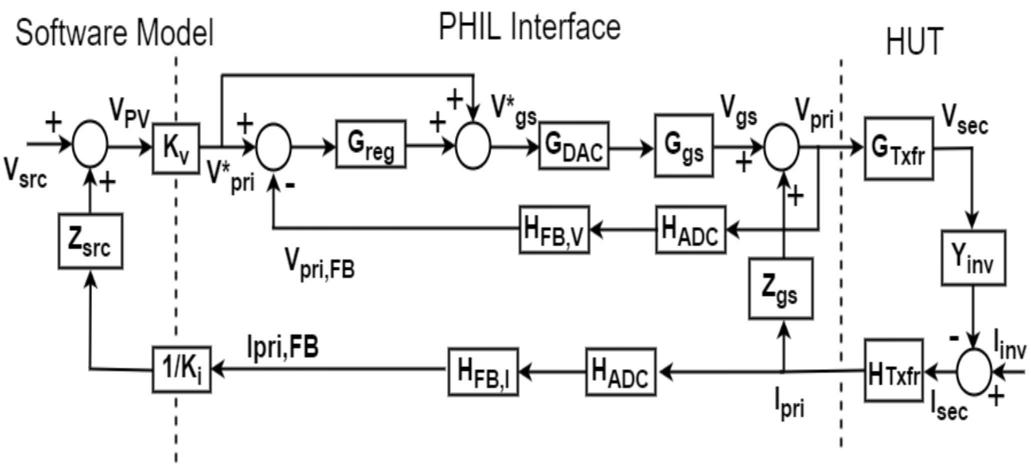
Recent Efforts: Improving Multi-timescale simulation



- Challenge 1: Measurement error amplified by PHIL voltage mismatch
  - Closed-loop PHIL voltage regulator

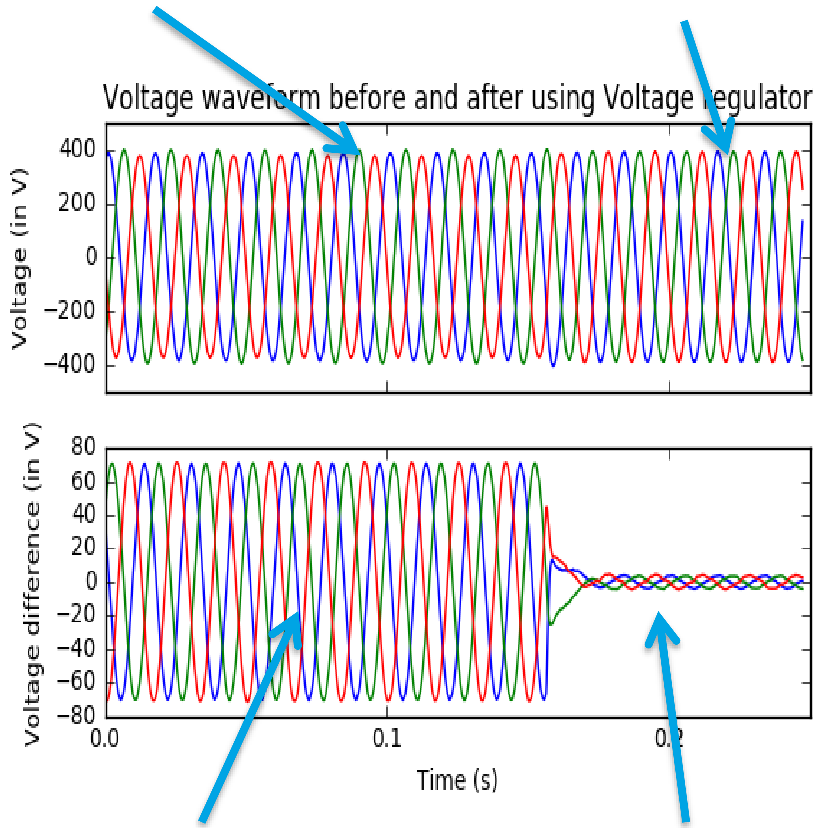
N. Ainsworth, A. Hariri, K. Prabakar, A. Pratt and M. Baggu, "Modeling and compensation design for a power hardware-in-the-loop simulation of an AC distribution system," North American Power Symposium, Sep 2016.

Closed-loop PHIL voltage regulator



Uneven peak

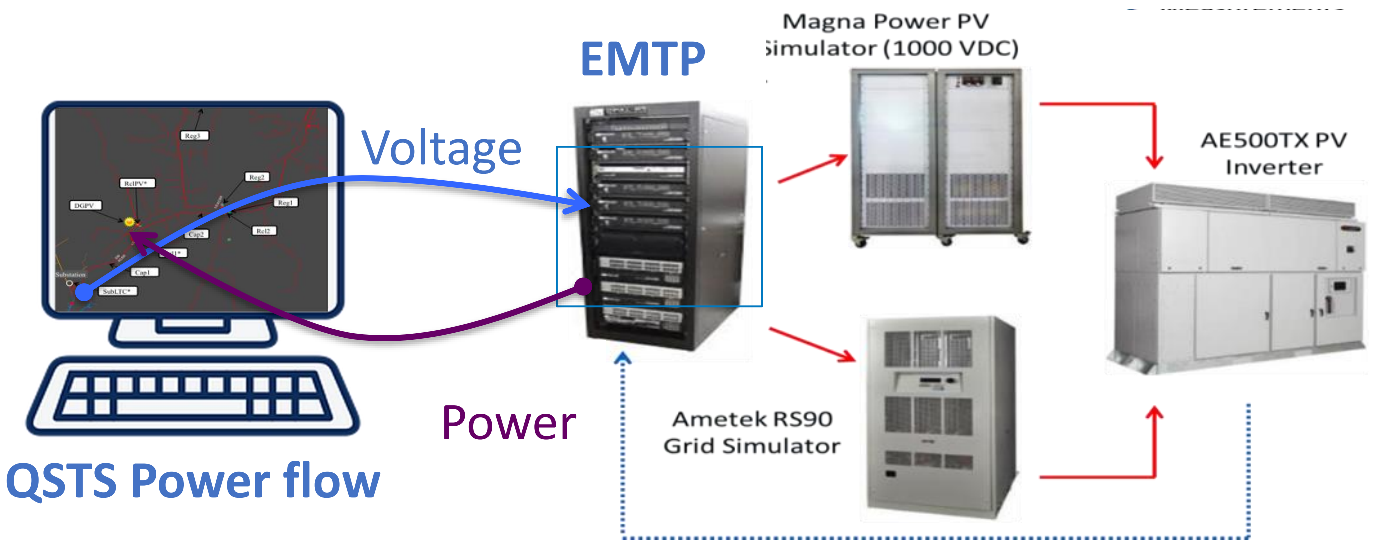
Smoother waveforms



Difference between set point and observed voltage

After turning on voltage regulator

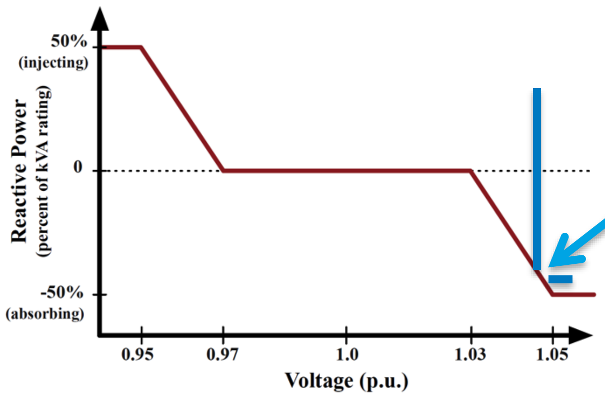
Recent Efforts: Improving Multi-timescale simulation



- Challenge 2: Large-scale QSTS grid simulation may too slow for faster PHIL-QSTS interactions.
  - Reduced-order feeder model

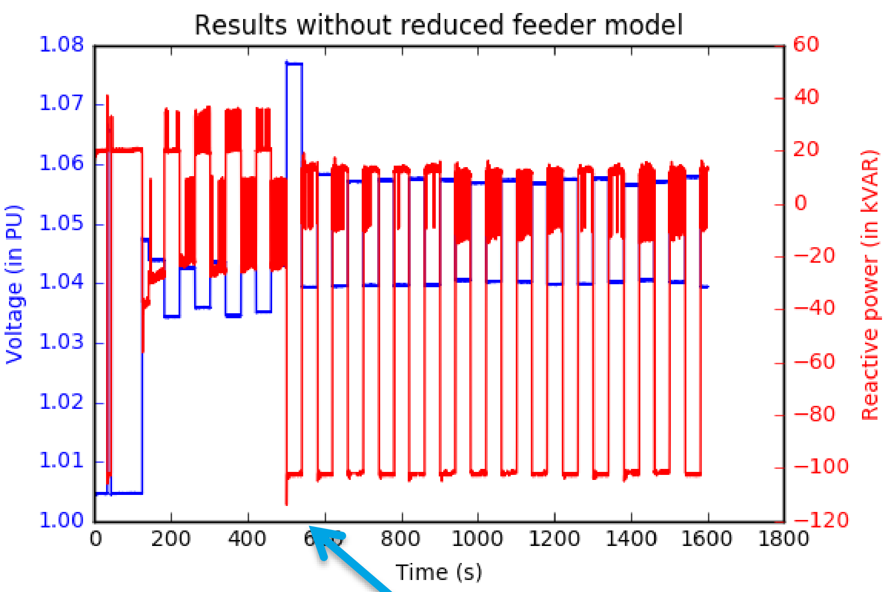
A. Hariri, B. Palmintier, K. Prabakar, I. Mendoza, M. Baggu, and O. Faruque, "Multi-Rate Co-simulation with Power Hardware-in-the-Loop for Dynamic Analysis of Distribution Networks with Photovoltaic Systems," IEEE Transactions on Industrial Electronics, In Preparation.

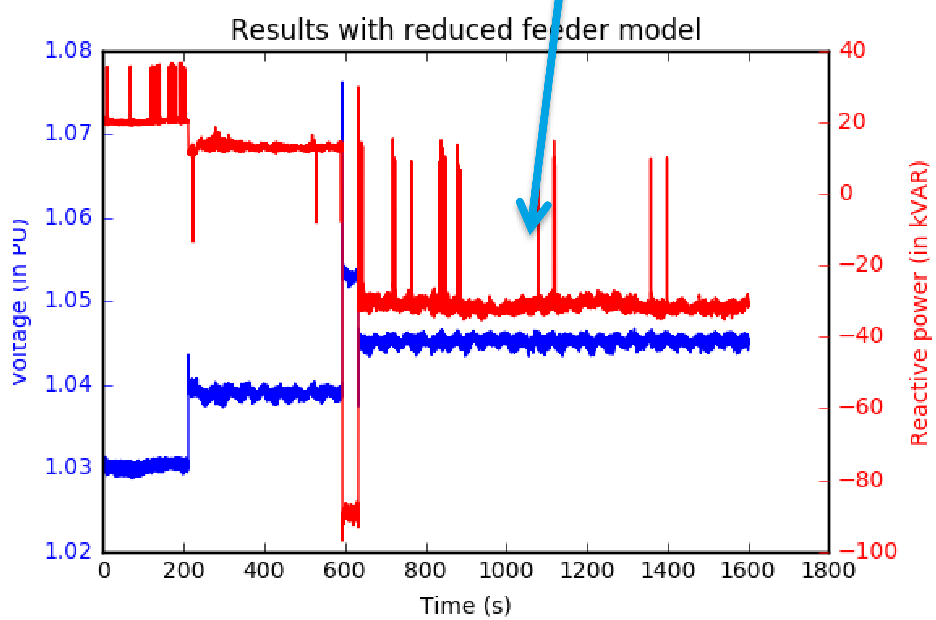
Reduced-order feeder model to stabilize PHIL-QSTS simulations



Voltage set point

Inverter reactive power stabilized





Inverter reactive power not stabilizing

Summary

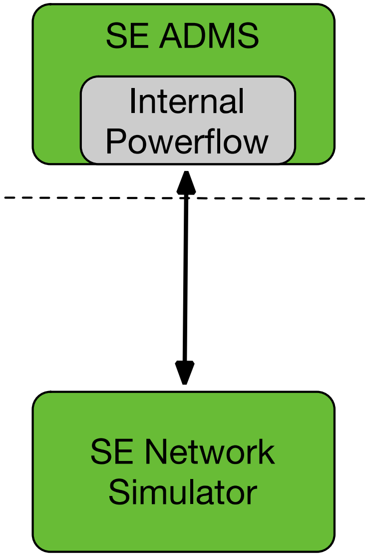
- Steps were taken to stabilize DMS-in-the-loop simulations (DIL)
  - Voltage regulator added
  - Reduced-order feeder model built, added and tested for stable operation of DIL
- The modified DMS-in-the-loop was tested for three different operating modes of AE 500 PV inverter
- Results show stable and appropriate VAR injection by the inverter
- PHIL capability to connect to DMS systems developed

ADMS Testbed: Task 3 and 5: Use Case 1 and Capabilities

Annabelle Pratt and Murali Baggu, NREL

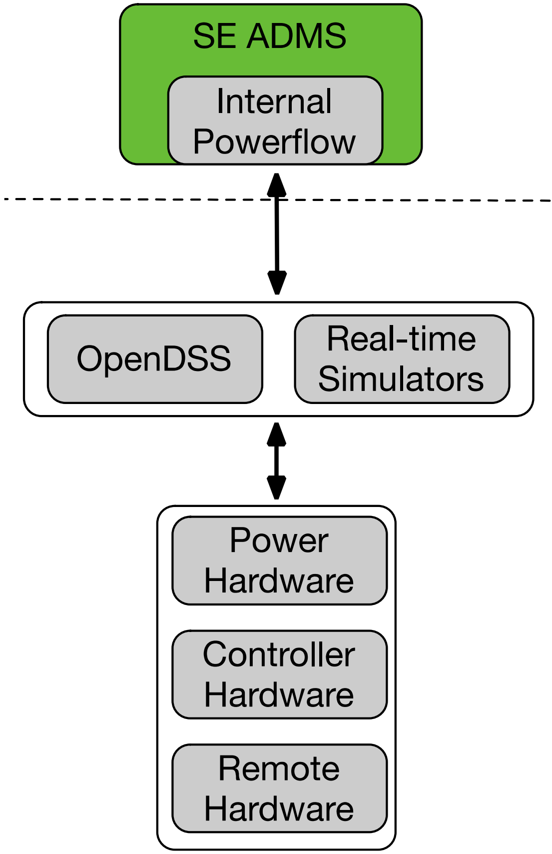
Background: Xcel data remediation project

- Evaluate the performance of the ADMS VVO application for different levels of data remediation *and* different levels of measurement density
- Quantify the trade-off between data remediation and measurement density
- System model = Schneider Electric ADMS power flow
  - 2 instances of SE power flow, inside & outside DMS
- Software simulation only



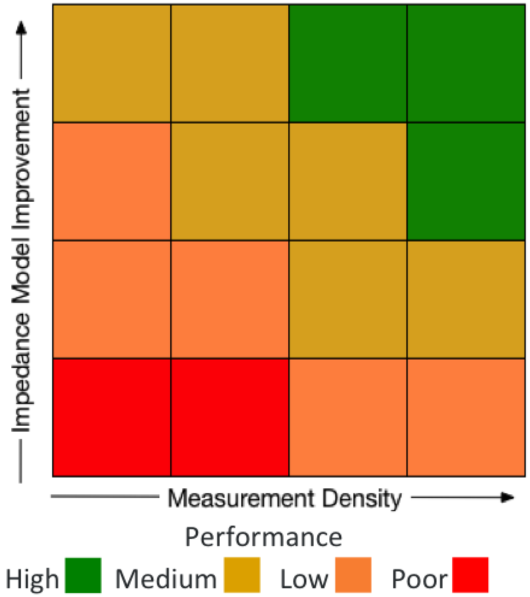
ADMS test bed Use Case 1

- Evaluate the performance of the ADMS VVO application for different levels of data remediation *and* different levels of measurement density
- Quantify the trade-off between data remediation and measurement density
- Uses ADMS testbed to model system
  - External system model
  - OpenDSS and ePhasorSim
- PHIL and CHIL simulation
  - Realistic utility protocols



Test plan

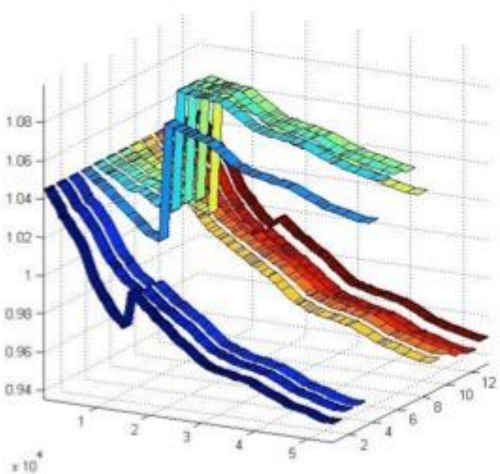
- Developed test plan for use case 1
  - test scenarios
  - test procedures
  - test metrics

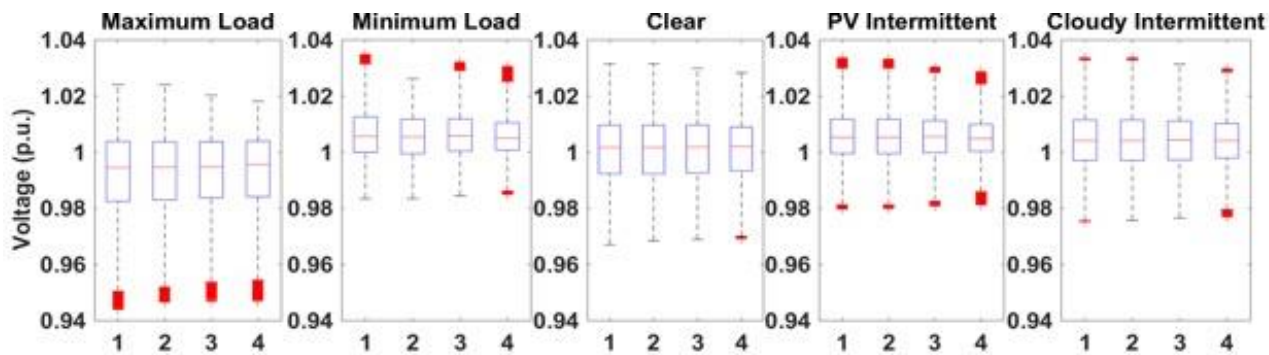


Scenario	ADMS Feeder Data Quality (Data Remediation)	Field Measurement Availability (Measurement Density)
1	Level 4	Level 3
2	Level 4	Level 2
3	Level 4	Level 1
4	Level 3	Level 3
5	Level 3	Level 2
6	Level 3	Level 1
7	Level 2	Level 3
8	Level 2	Level 2
9	Level 2	Level 1
10	Level 1	Level 3
11	Level 1	Level 2
12	Level 1	Level 1

Test metrics

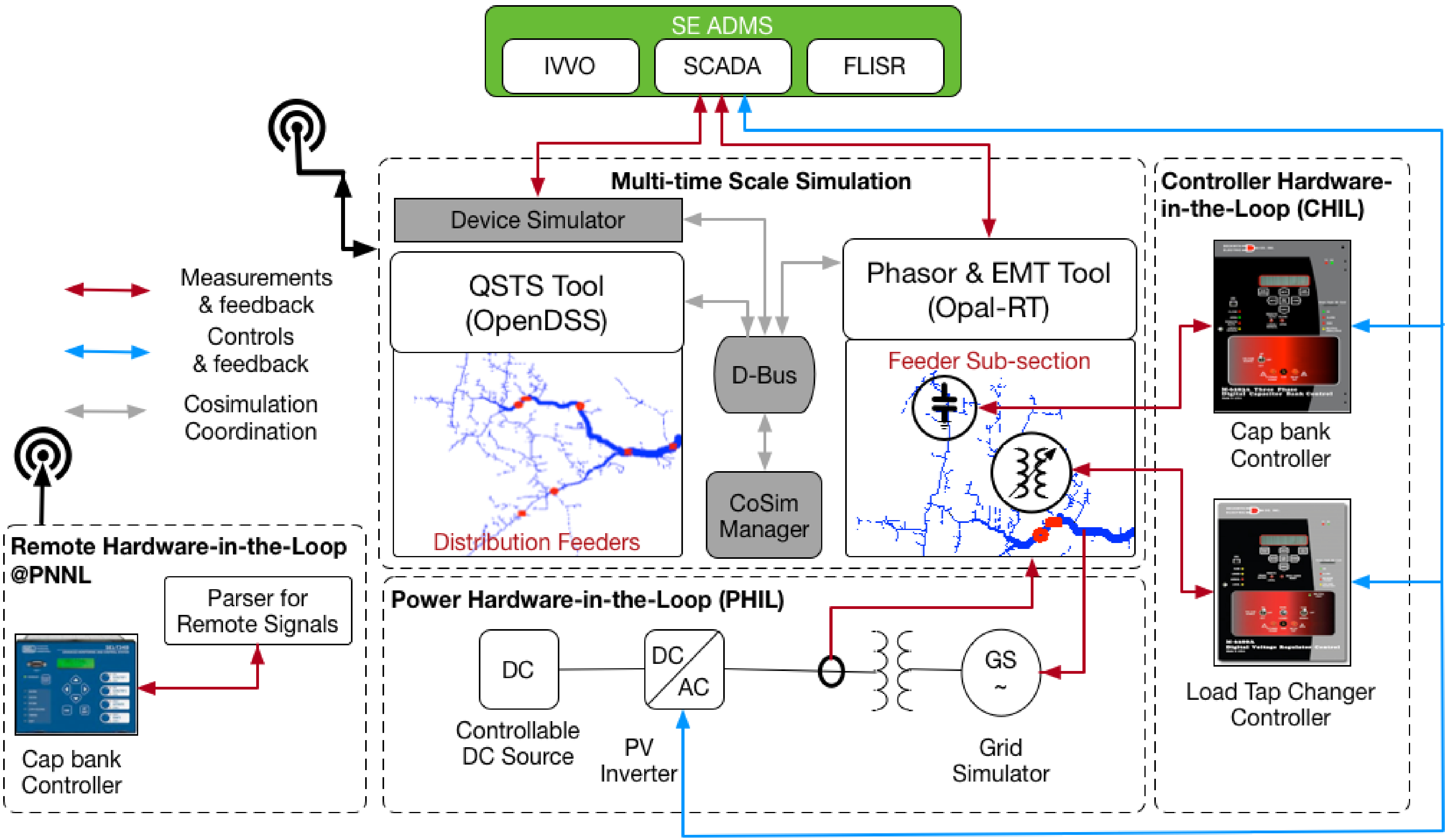
- Aim to measure performance difference when lower quality model data is used
- Proposed primary test metric: deviation of voltages at all the distribution network nodes from the operational objective
  - May update as VVO function is better understood





Voltage range and standard deviation for 1) unity power factor, 2) Volt/VAr curve-1, 3) Volt/VAr curve-2, and 4) Volt/VAr curve-3. Data in red indicate values beyond 1.5 times the interquartile range.

Testbed


SE ADMS
IVVO
SCADA
FLISR
Multi-time Scale Simulation
Device Simulator
QSTS Tool
(OpenDSS)
Distribution Feeders
D-Bus
CoSim
Manager
Phasor & EMT Tool
(Opal-RT)
Feeder Sub-section
Controller Hardware-in-the-Loop (CHIL)
Cap bank
Controller
Load Tap Changer
Controller
Measurements
& feedback
Controls
& feedback
Cosimulation
Coordination
Remote Hardware-in-the-Loop
@PNNL
Parser for
Remote Signals
Cap bank
Controller
Power Hardware-in-the-Loop (PHIL)
DC
Controllable
DC Source
DC
AC
PV
Inverter
GS
~
Grid
Simulator

Testbed Hardware Setup

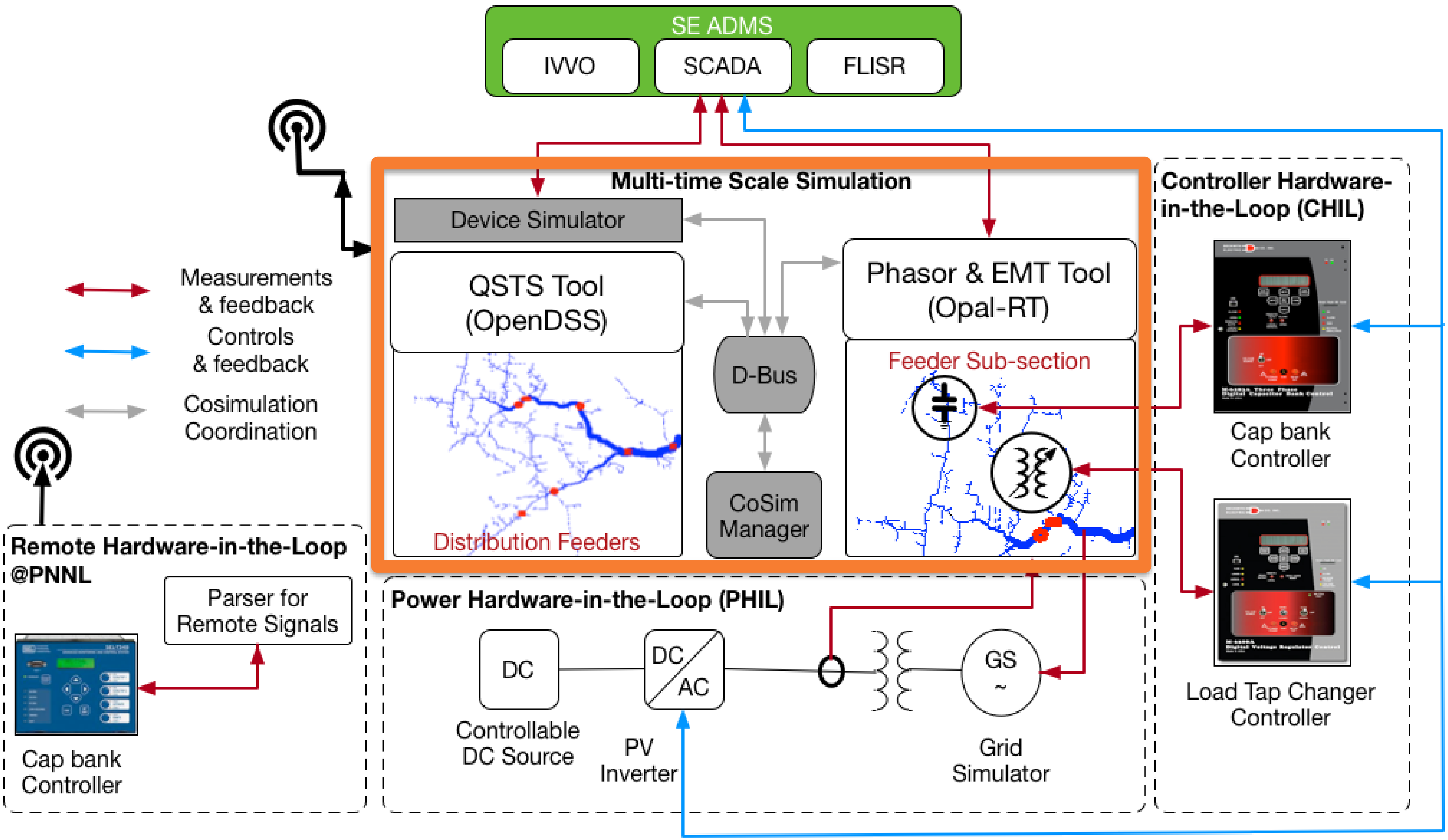
- Cap bank and LTC controllers
- PV Inverter
- Grid and PV array simulators

ADMS test bed capabilities to support use case 1

- Multi-time scale simulations*
- Integration of multi-vendor simulation platforms*
- Enabling tools for communication interfaces*
- Remote HIL
- Controller HIL (CHIL)
- Power HIL (PHIL)
- Enabling tools for model conversion
- Integrated data collection and management system*

* Indicates new capabilities

Testbed capabilities: Multi-time scale/vendor co-simulation



Testbed capabilities: Multi-time scale/vendor co-simulation

Co-Simulation Manager

- Coordinate simulation across multiple platforms

Data Bus Architecture (D-bus)

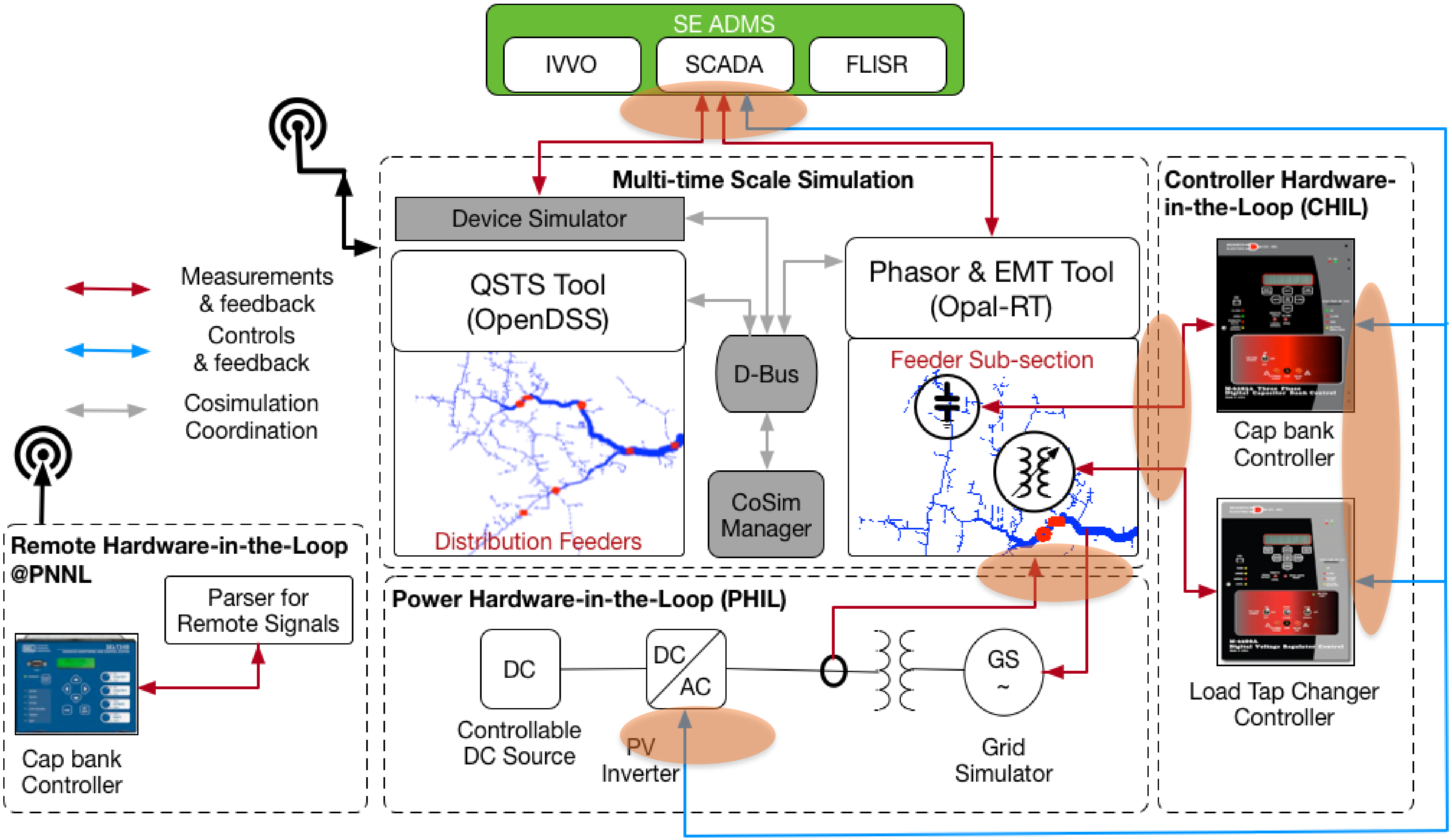
- Exchange data/control setpoints between platforms
- EPRI cost-share contribution
- Specification developed by EPRI and accepted by team

Device Simulators

- Enable OpenDSS to interface with SCADA through DNP3
- Under development by EPRI
- Meters, cap bank controller, PV inverter

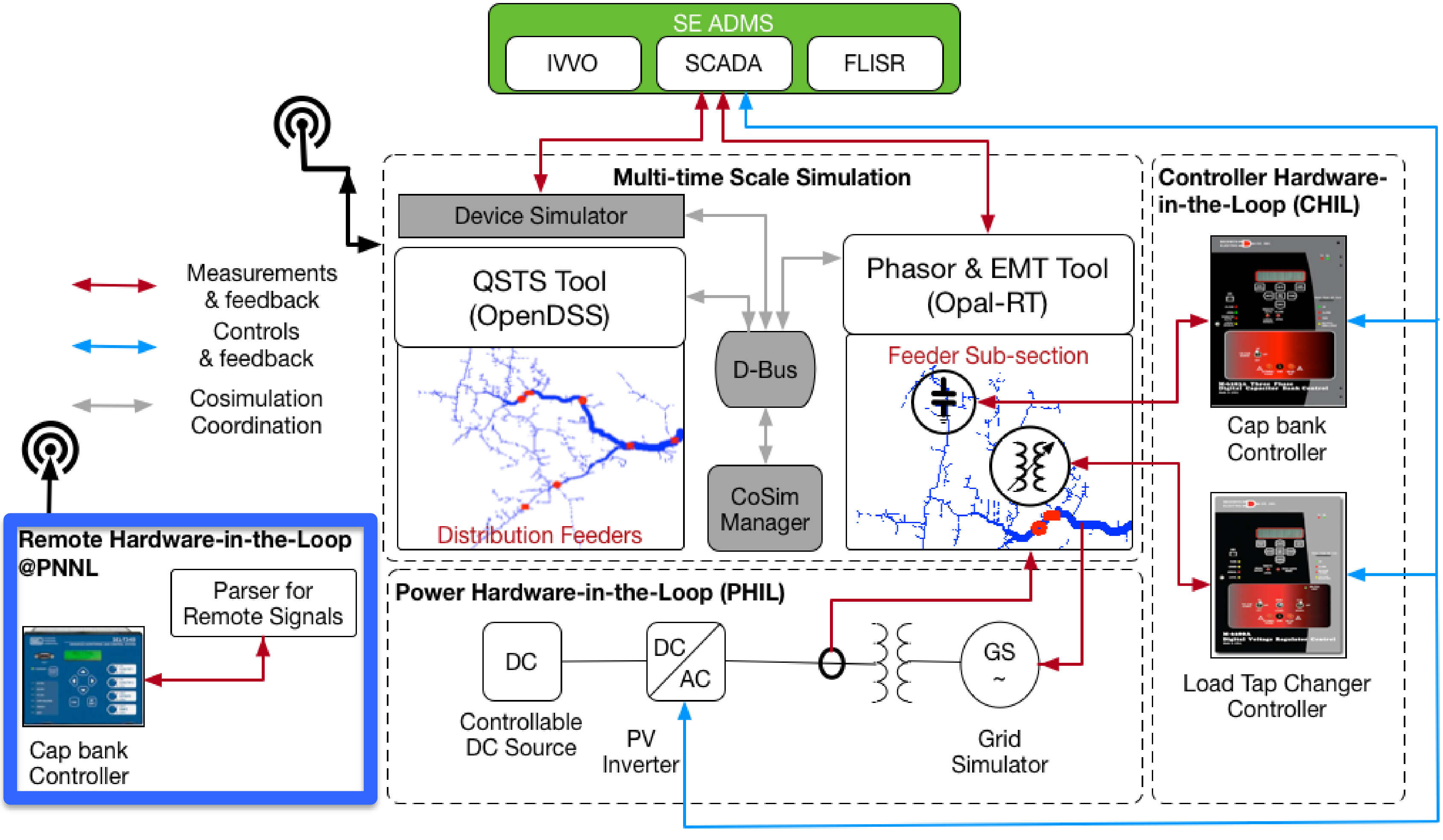
Testbed capabilities: communication interfaces

- May need data translator for protocol conversion

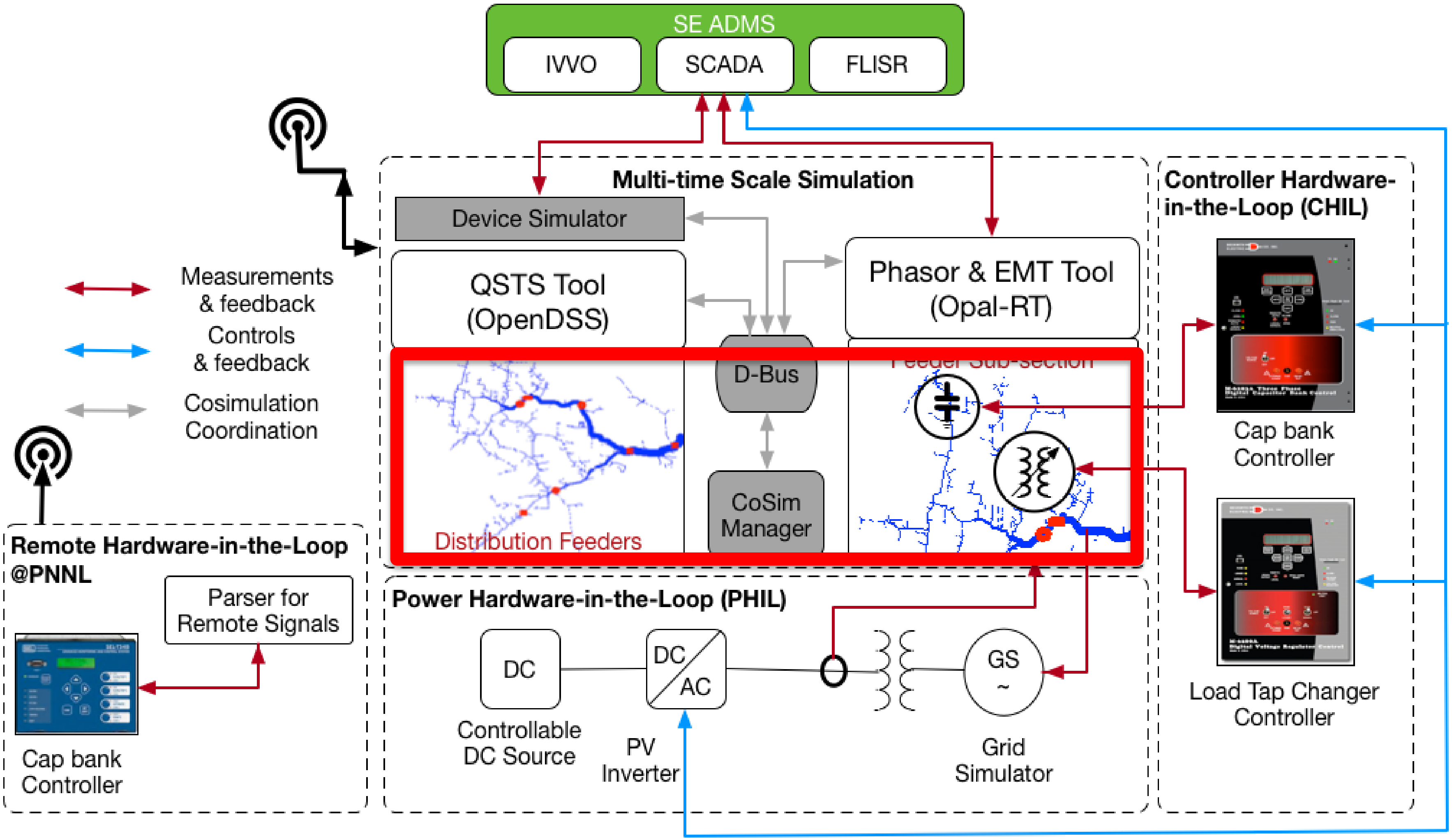


Testbed capabilities: remote HIL (PNNL)

- MOU signed; test scheduled for Oct 17

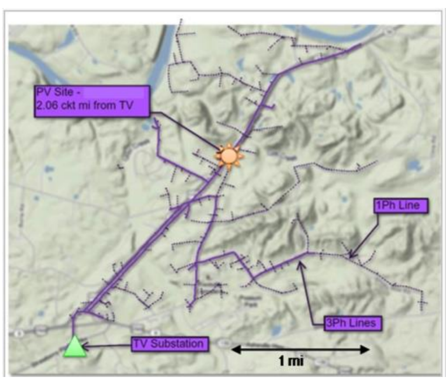


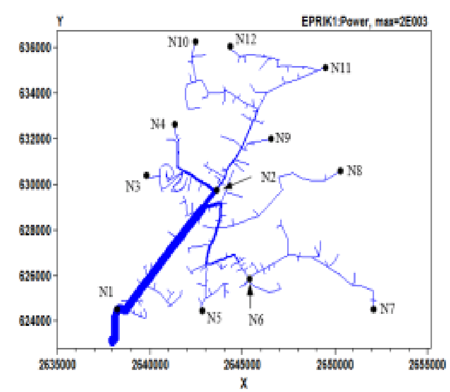
Testbed capabilities: model conversion

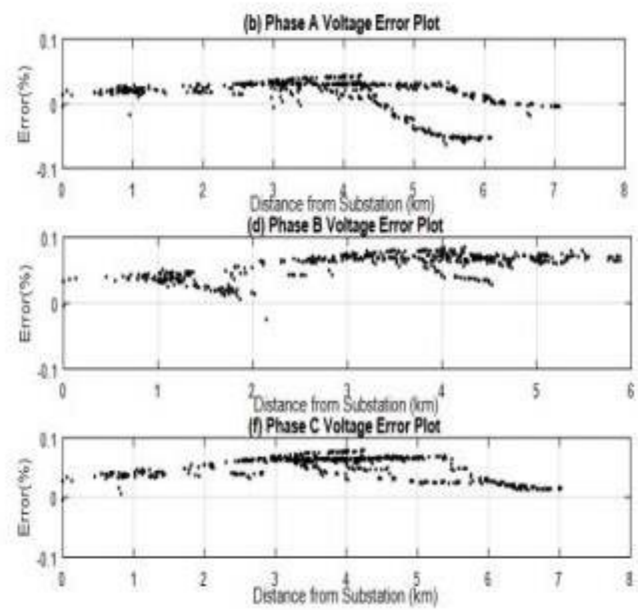


Testbed capabilities: model conversion

- Utility models to OpenDSS
  - Existing suite of conversion tools at NREL
  - GridLAB-D/SynerGee to OpenDSS
  - SynerGEE/CYME to GridLAB-D
  - CIM to OpenDSS
    - Received example SE CIM file and evaluating tool
- OpenDSS to ePhasorSim
  - Developed as part of project
  - Tested on EPRI K1 & J1 feeders

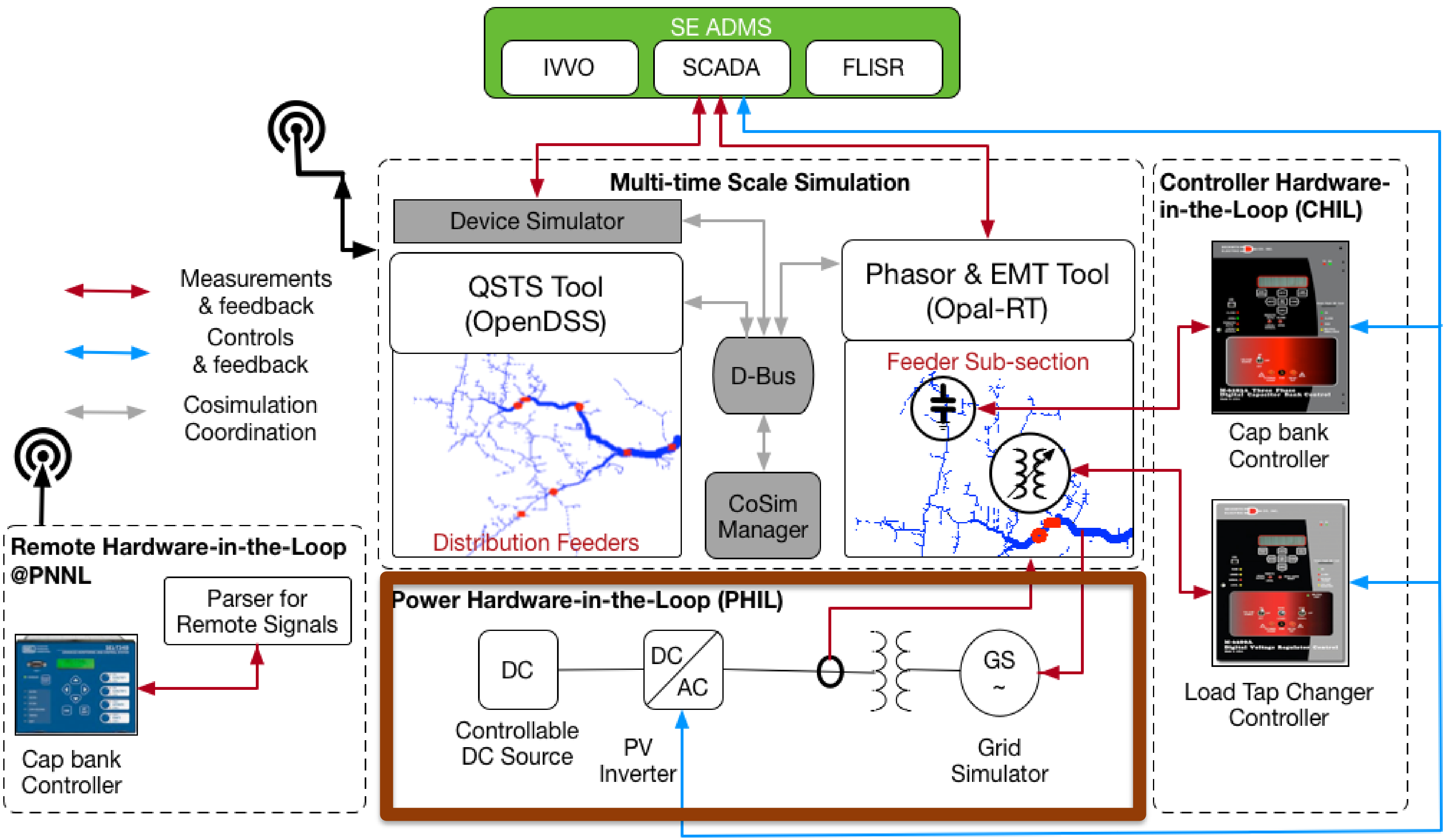




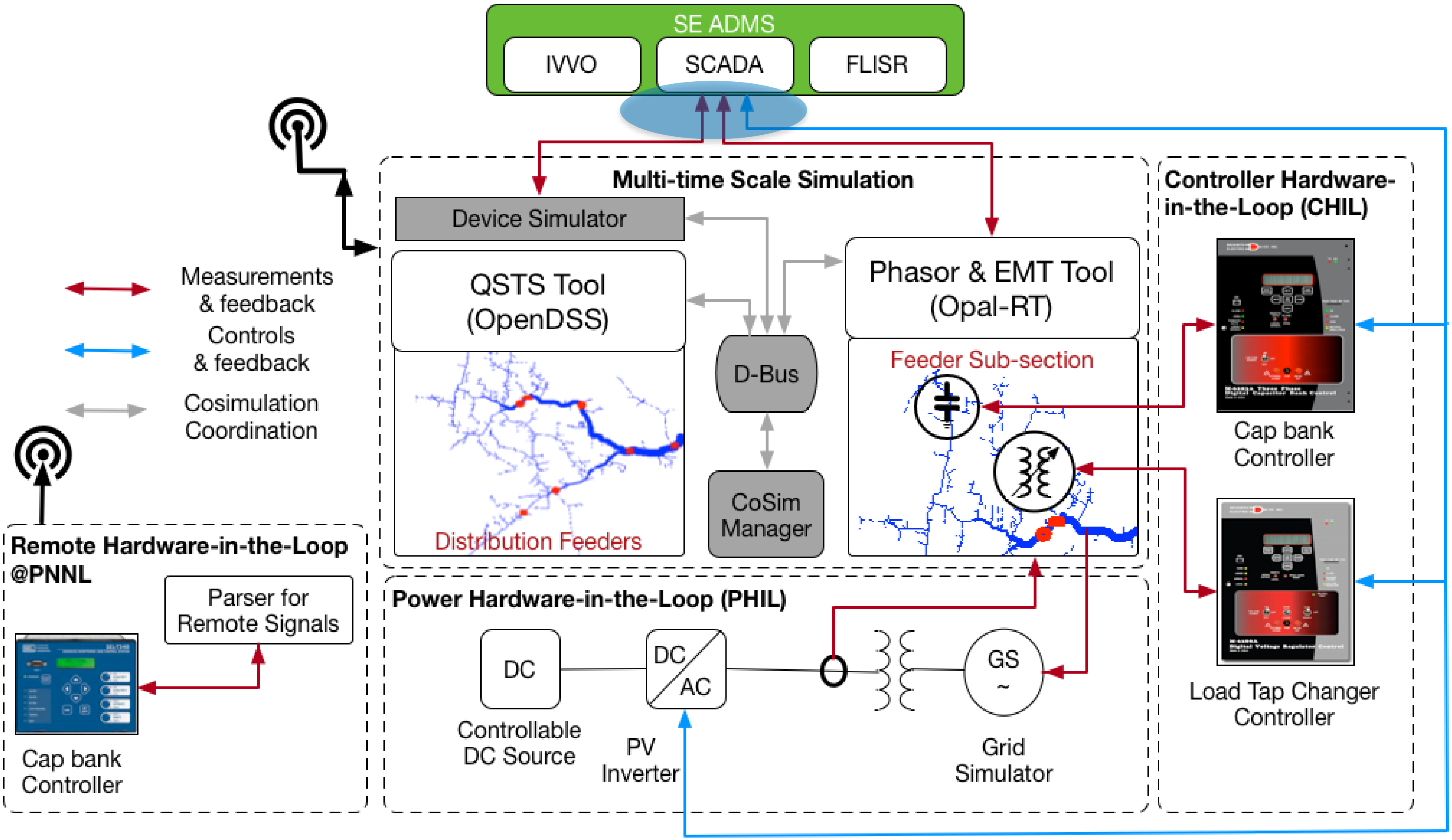


Testbed capabilities: PHIL

- 12 kVA, three phase SMA PV inverter

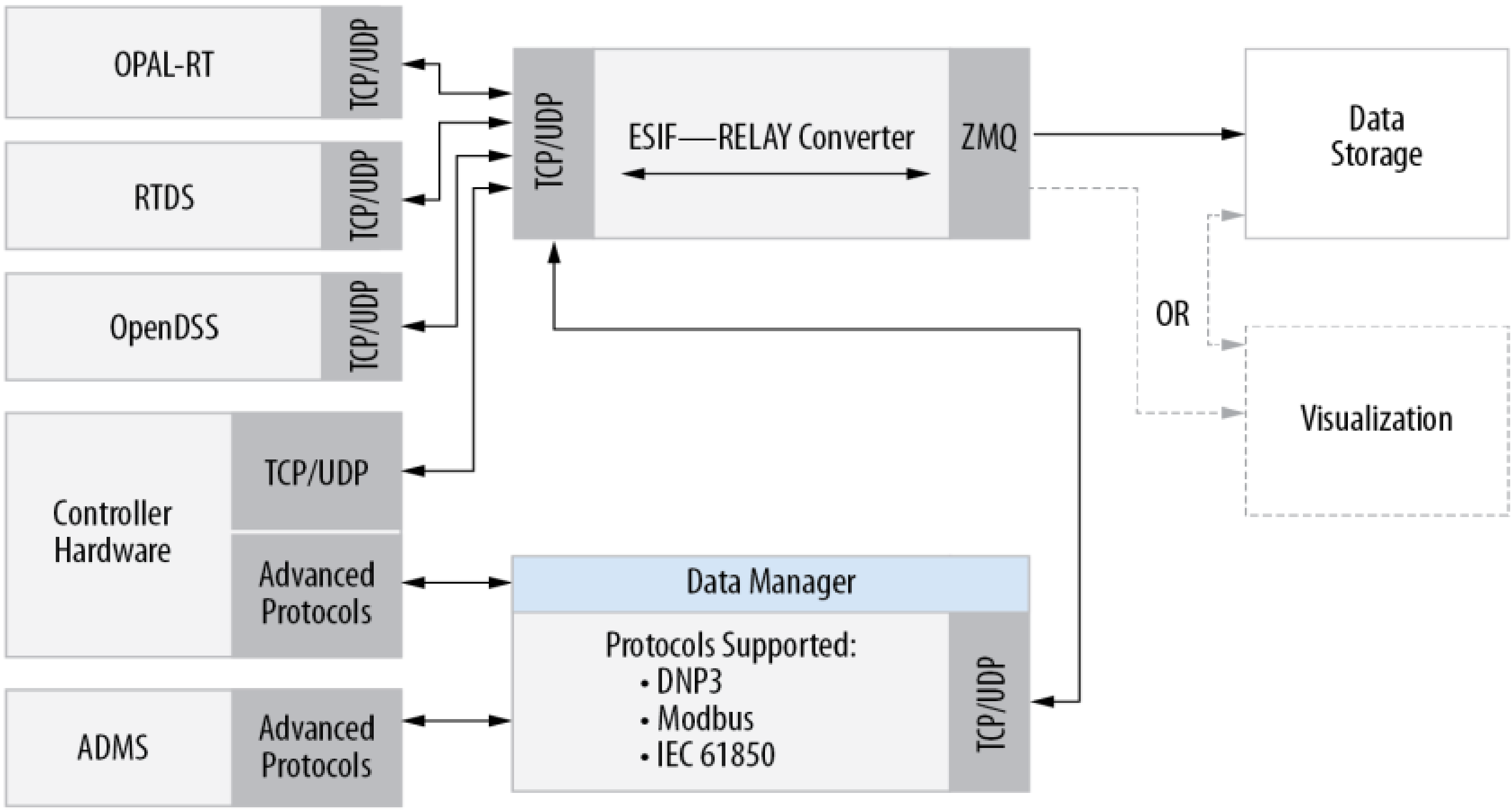


Testbed capabilities: telemetry models (ANL)

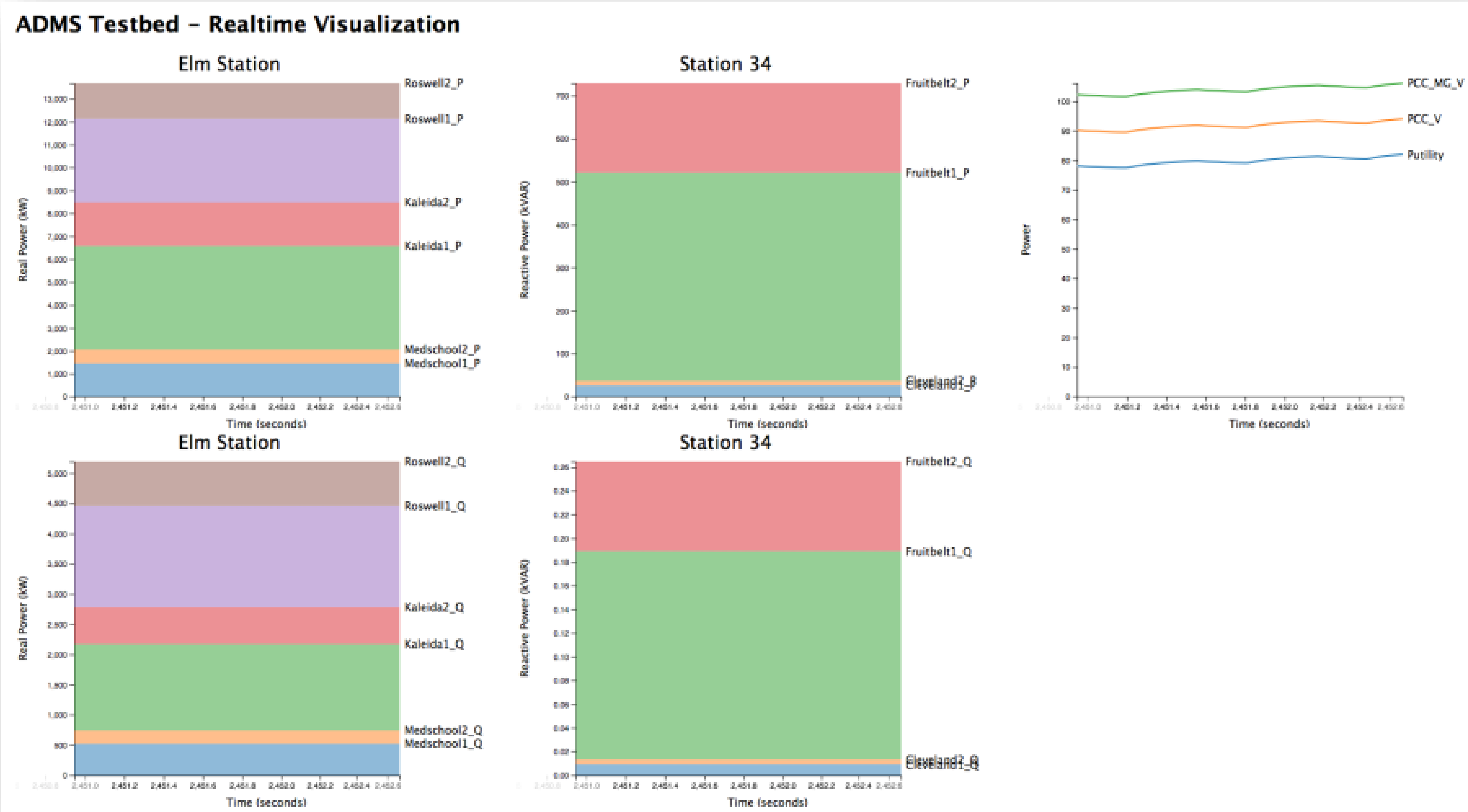


Scientific Data Capture & Storage

Task 5 – *Visualization*
Subtask 2.5.1 – Data-flow plan
Subtask 2.5.2 – Human-machine interface design for the testbed



Visualization



Summary

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- ADMS test bed has been architected
- Progress is being made on capabilities by all partners
- Use case 1 has been defined and test plan developed

Task 6: Project Management: Unanticipated challenges, lessons learned

- Subcontract process took far longer than anticipated causing significant delays in execution of use case 1
  - This includes technical scope and legal reviews
  - Was able to get one of the subcontractors on board in FY16 but could only get the other two by FY17
- Software licensing wasn't trivial; we need more dedicated support to enable the needed functionality

Overall Project Budget FY16 and FY17

Institution	Allocated Funds	Planned Spending	Actual Spending	FY18 Carryover
NREL	$2,110,228	$1,637,500	$1,438,163*	$672,065
PNNL	$462,500	$362,500	$254,908	$207,592
ANL	$141,269	$108,135	$74,965	$66,304
Total	**$2,713,997**	**$2,108,135**	**$1,768,036**	**$945,961**

*Includes subcontract commitment of $279,424

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

FY18+ Plans

Murali Baggu

FY18 Q1 and Q2 plans

Task 1 – *Manage ADMS testbed industry steering group activities*

Subtask 2.1.1 – ADMS testbed ISG meetings

Task 2 – *Test case development*

Subtask 2.2.1 – Case selection {for use case 2}

Task 3 – *ADMS testbed design and construction*

Subtask 2.3.1 – Design of software infrastructure for integration of multiple utility management systems

Subtask 2.3.2 – Implementation of software infrastructure for integrating multiple utility management systems

Task 4 – *ADMS benchmarking and test case execution*

Subtask 2.4.1 – Use-case 1 benchmarking vs. historical data

Subtask 2.4.2 – Testing of use-case 1 using the multi-timescale PHIL testbed

Task 6 – *Result dissemination*

Subtask 2.6.1 – Project management

Subtask 2.6.2 – Results dissemination

Key milestones, Go/No-Go and FY18 Q1 and Q2

Milestone Name/Description	End Date	Type
Task 2 – Develop test plan specifying tests to be conducted in Year 3 Criteria: Acceptance of the Year 3 test plan by DOE	04/15/2018	Annual Milestone
Task 4 – Execute the Year 2 test plan. Criteria: Successful completion of the Year 2 test plan as agreed by ISG and DOE	~~04/15/2018~~ **07/15/2018**	Annual Milestone
Task 6 – One-day workshop disseminating the lessons learned in ADMS use-case 1. Criteria: Successful participation from broader utility audience	~~04/15/2018~~ **07/15/2018**	Annual Milestone

Go/No-Go Description	Criteria	Date
Approved test plan for Year 3	Approval from DOE	04/15/2018

Description	Severity	Response
Identifying and developing use-case 2	Med	Work with ISG, DOE, and stakeholders on a regular basis to define and refine use cases
Implementing and executing use-case 1	High	Work with vendors and standards developers to mitigate integration issues

FY18 Q3, Q4 and FY19 plans

- **Task 1 – *Manage ADMS testbed steering group activities***: *Subtask 3.1.1 – ADMS testbed ISG meetings*
- **Task 4 – *ADMS benchmarking and test-case execution***
- *Subtask 3.4.1 – Use-case 2 benchmarking vs. historical data*
- *Subtask 3.4.2 – Testing of use-case 2 using the multi-timescale PHIL testbed*
- **Task 5 – *Visualization***: *Subtask 3.5.1 – Human-machine interface development for the testbed*
- **Task 6 – *Result dissemination***: *Subtask 3.6.1 – Project management*

Milestone Name/Description	End Date	Type
Task 4 – Execute the Year 3 test plan. Criteria: Successful completion of the Year 3 test plan as agreed by ISG and DOE	04/15/2019	Annual Milestone
Task 6 – One-day workshop disseminating the lessons learned in ADMS use case 2. Criteria: Successful participation from broader utility audience	04/15/2019	Annual Milestone

Description	Severity	Response
Implementing and executing use-case 2; Integrating multiple utility management systems	High	Work with vendors and standards developers to mitigate integration issues

Tech Transfer Activities: Industry Collaborations

- NREL is collaborating with **Xcel Energy** and **Schneider Electric** to evaluate the need for model improvement for its ADMS deployment
  - Xcel Energy is pursuing grid modernization across its operational territory, starting with feeders in Colorado
  - The insights gained from the NREL project is expected to inform and reduce costs for Xcel Energy's approach to ADMS deployment in Colorado and beyond

- The ADMS Testbed team is actively pursuing a collaboration **with Austin Energy** and other **DERMS vendors** to identify a use case for Year 3.
  - Use case 2 is targeted at improving the testbed capabilities to evaluate ADMS applications that integrate other utility management systems (DERMS)
  - Working with Austin Energy to identify specific performance metrics for use case 2
  - Other utilities will be consulted for potential use cases
  - DERMS vendor to be identified after finalizing utility participation

Tech Transfer Activities: Outreach

- A software process was developed to convert quasi-static time series (QSTS) based distribution models (from OpenDSS) to a real time dynamic phasor simulator format (ePHASORSIM).
- A. Nagarajan, B. Palmintier and M. Baggu, "Advanced inverter functions and communication protocols for distribution management," *2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Dallas, TX, 2016, pp. 1-5.
- N. Ainsworth, A. Hariri, K. Prabakar, A. Pratt and M. Baggu, "Modeling and compensation design for a power hardware-in-the-loop simulation of an AC distribution system," *2016 North American Power Symposium (NAPS)*, Denver, CO, 2016, pp. 1-6.
- A. Nagarajan, B. Palmintier, F. Ding, B. Mather and M. Baggu, "Improving advanced inverter control convergence in distribution power flow," *2016 North American Power Symposium (NAPS)*, Denver, CO, 2016, pp. 1-5.
- S. Veda, H. Wu, M. Martin, M. Baggu "Developing Use Cases for Evaluation of ADMS Applications to Accelerate Technology Adoption" 9th Annual Green Technologies Conference, Denver, CO, March 2017
- M. Chamana, K. Prabakar, B. Palmintier, M. Baggu, "Conversion and Validation of Distribution System Model from a QSTS-Based Tool to a Real-Time Dynamic Phasor Simulator" 9th Annual Green Technologies Conference, Denver, CO, March 2017.
- A. Hariri, B. Palmintier, K. Prabakar, I. Mendoza, M. Baggu, and O. Faruque, "Multi-Rate Co-simulation with Power Hardware-in-the-Loop for Dynamic Analysis of Distribution Networks with Photovoltaic Systems," IEEE Transactions on Industrial Electronics, **In Preparation**.
- Presented on "**NREL ADMS Research Activities**" at the Schneider Electric Smart Grid IT User Conference.
- Invited to speak on a industry panel on "**Distributed Energy Resources Management use cases**" at the GE Grid Software Solutions 2017 Americas User Conference, Thursday June 22, 2017 Bellevue, WA, USA.
- Invited to speak on a panel "**Advanced Distribution Management Systems Research and Development at the U.S. DOE**" on Volt-VAR use case evaluation on ADMS testbed at the 2017 IEEE Innovative Smart Grid Technologies Conference, April 25, 2017, Washington D.C., USA.
- Organized and moderated a panel on "**Testbed Efforts for Evaluating Advanced Distribution Management Systems (ADMS)**" at the DistribuTECH 2017 Conference and Exhibition February 2, 2017, San Diego, CA, USA.
- Invited to speak on "**Distributed Energy Resource Management Systems (DERMS): Designing for Architectural Flexibility**" at the Internet of Things and Big Data for Utilities, December 6, 2017, Foster City, CA, USA.
- Invited to speak on a panel "**Development and Applications of Advanced Distribution Management Systems (ADMS)**" on ADMS testbed Development at the 2016 IEEE Innovative Smart Grid Technologies Conference, September 5, 2016, Minneapolis MN, USA.
- Invited to speak on "**Testbed for Evaluation of ADMS Applications, Early Results from Duke Energy, GE Grid Software Solutions and NREL Collaboration**" at the 2016 GE Grid Software Solutions North America Users Group Conference, June 3, 2016, Bellevue, WA, USA.

Questions?

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This work was supported by U.S. Department of Energy Office of Electricity Delivery and Energy Reliability ADMS Program through the ADMS Testbed development Funding at NREL

Back-up Slides

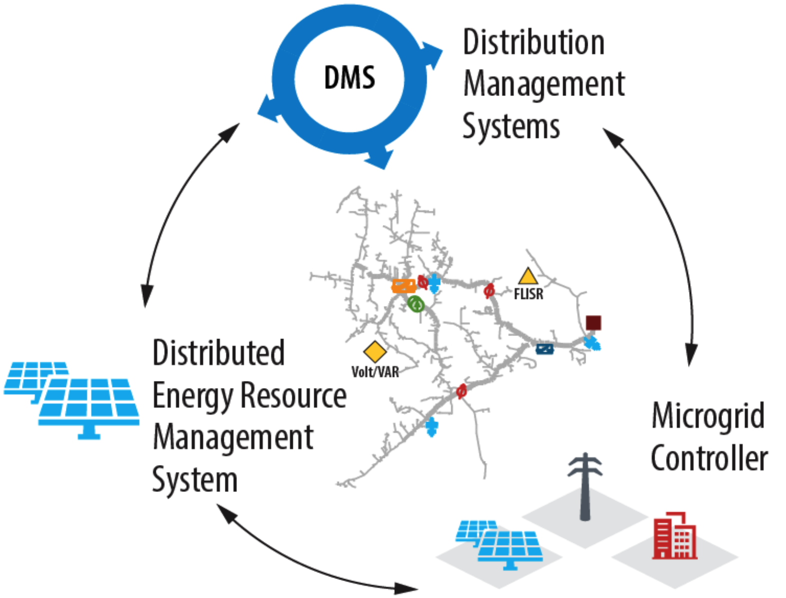
Volt-VAr Optimization (VVO) and OLPF/DSSE Use Cases

- Voltage Regulation **(Use Case 0)**
  - legacy voltage control assets, smart inverters, energy storage, autonomous controllers
- Peak Load Management Regulation **(Use Case 0)**
  - CVR for peak load management and interaction with "aggregators" like DERMS and DRAS
- Performance evaluation Regulation **(Use Case 0)**
  - Multi-objective VVO, different control architectures
- Interaction with Active Grid Edge Devices **(Futuristic Use Case)**
  - Centralized VVO with grid-edge controllers

- Model Improvement **(Use Case 1)**
  - data needs for feeder models; specs and locations for adding new telemetry points; evaluate impact on ADMS applications
- Calibrate OLPF/DSSE functions
  - Compare the states testbed measurements, tune algorithms
- Evaluate performance of hierarchical distributed sensing **(Futuristic Use Case)**
  - Integrating sensing technologies like AMI, OpenFMB, OpenADR, grid-edge smart controls, distribution PMUs
- Modeling loss of PV
  - Behavior of behind-the-meter components (PV), net load allocation, integrate forecasting, customer facility data, load models, etc.

Market Participation and FLISR Use Cases

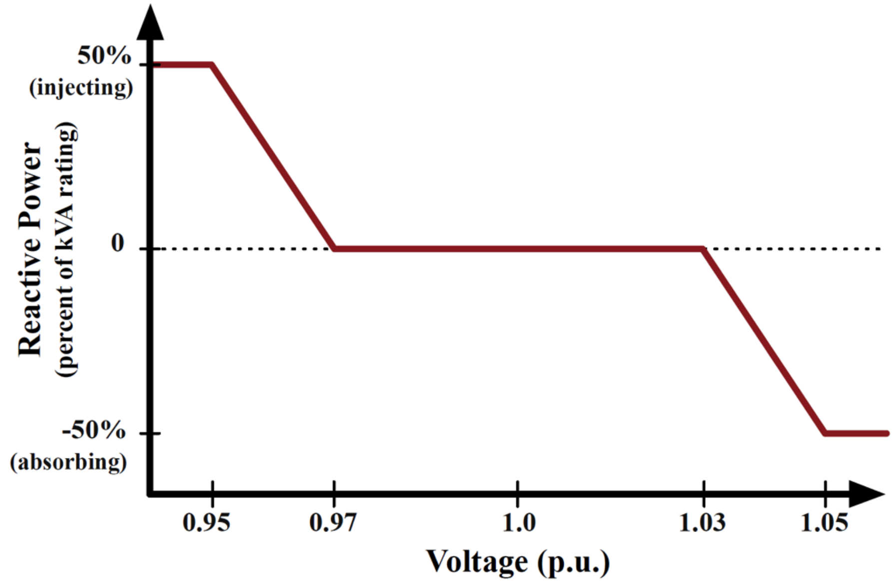
- Maintaining power quality while providing bulk grid services
- Distribution System Operations (DSOs) providing market functions
- Estimating available capacity for bidding in energy markets
- Integrated DERMS and DMS operations for grid services



- High Penetration of DERs: Upstream & downstream DERs; line loading before and after fault; intermittency & visibility challenges
- Interaction with Microgrids: Impact of temporary fault, black start, need for direct comm
- Very High Loading Conditions: Unnecessary backup feeder trip, Use of load forecasting
- Multiple Simultaneous Faults: Thunderstorms leading to multiple faults, feeder re-tripping & lockouts
- Widespread Outages: Uncertain distribution configurations, comm status and feeder outages

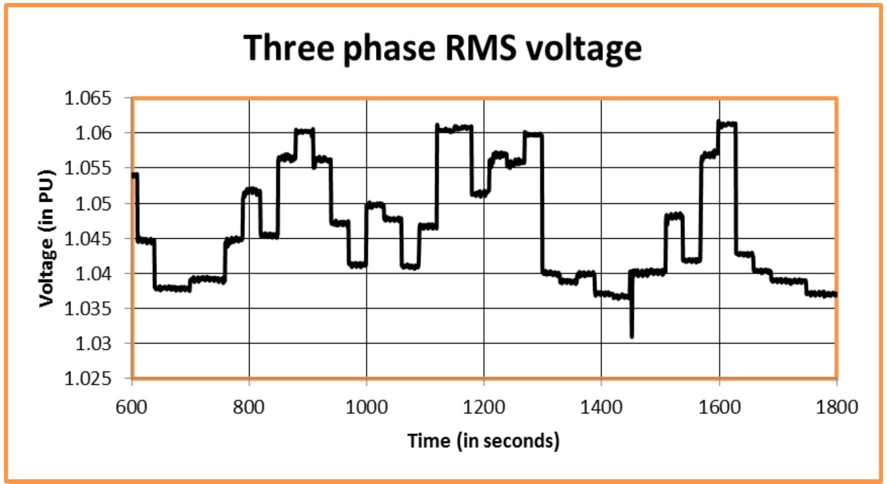
Test cases

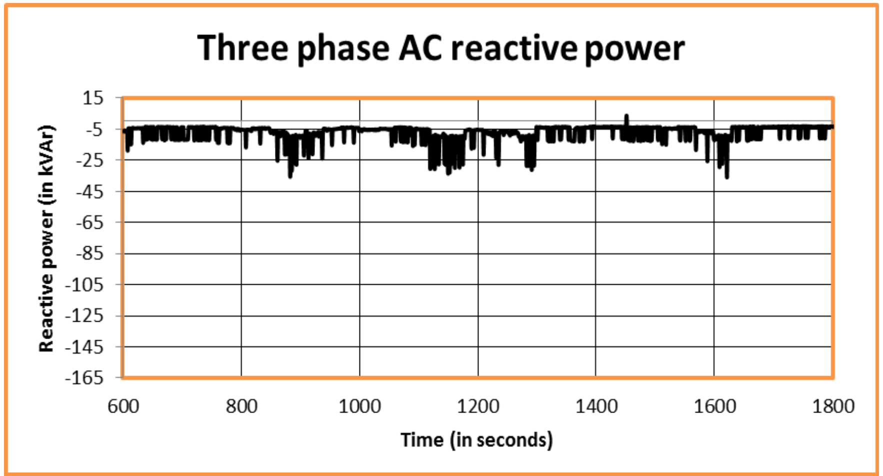
- Inverter operating at
  - Unity power factor
  - 0.95 power factor
  - Volt-VAR mode

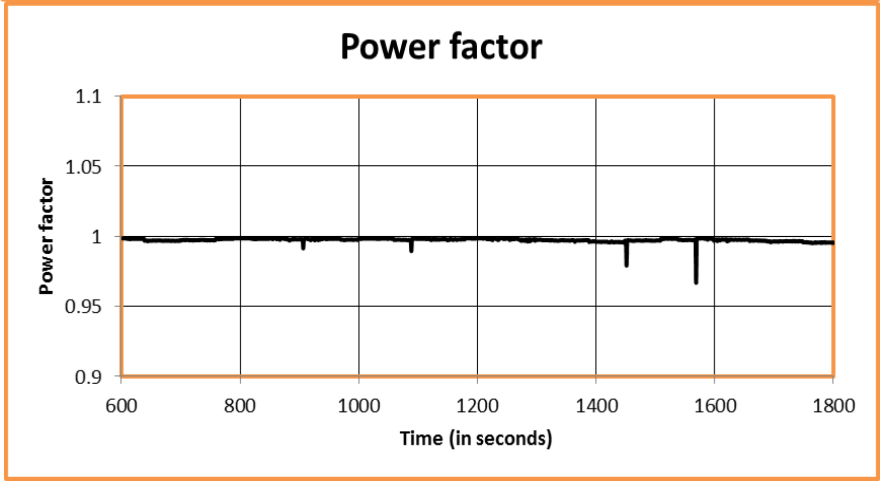


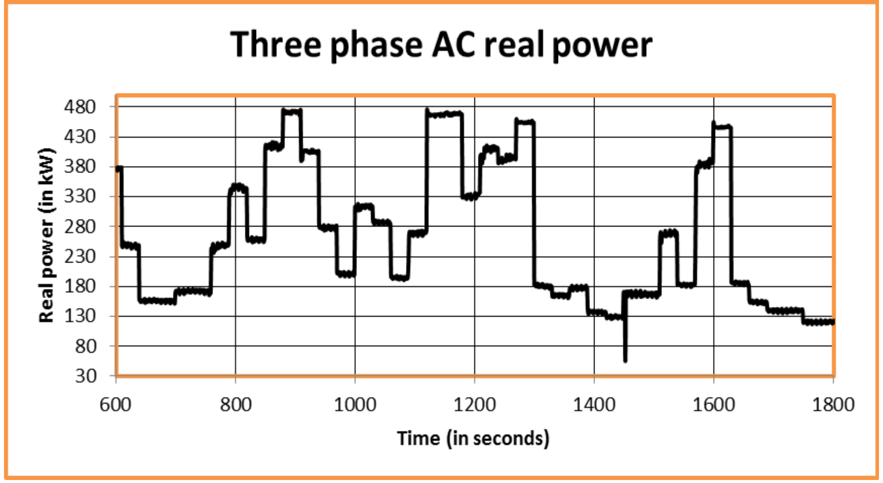
- Maximum reactive power 500 kVAR
- A Volt-VAR curve is programmed and activated in AE500 during VVAR mode test.
- The three different modes operated in a stable fashion.

Unity power factor

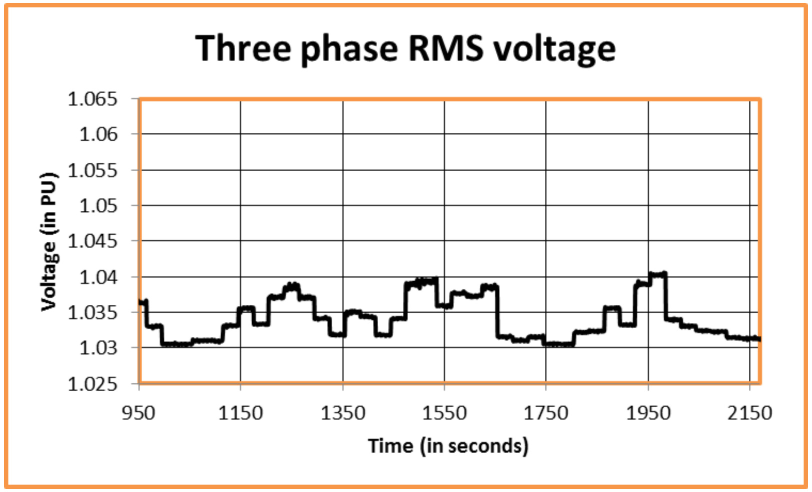


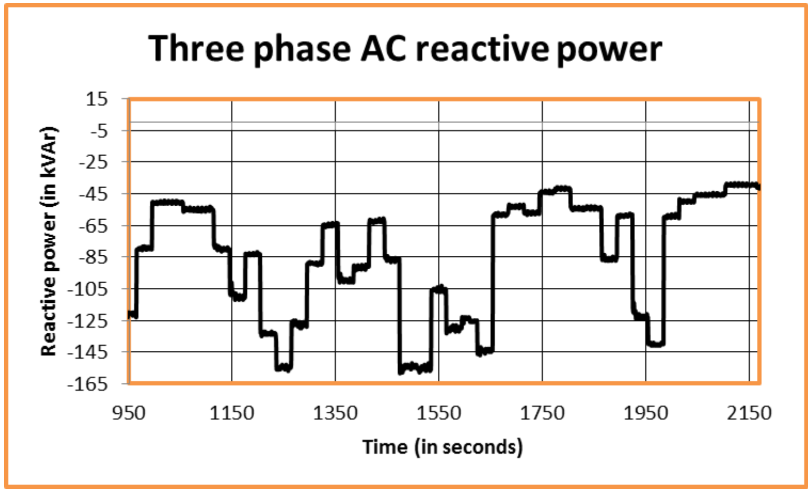


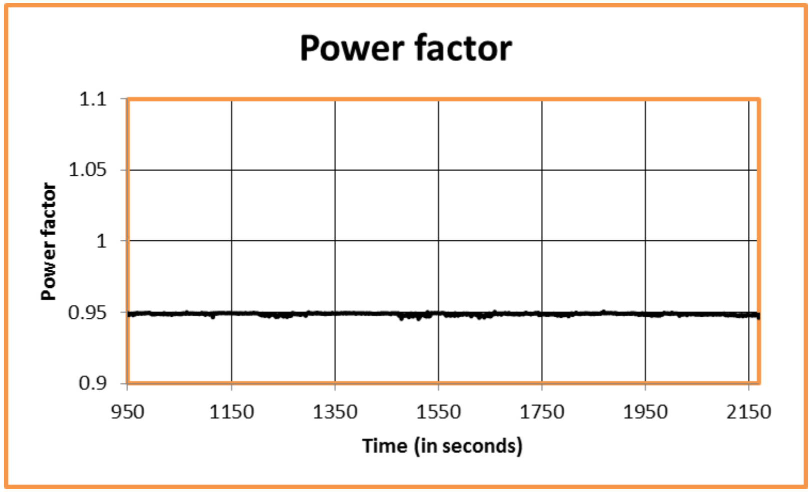


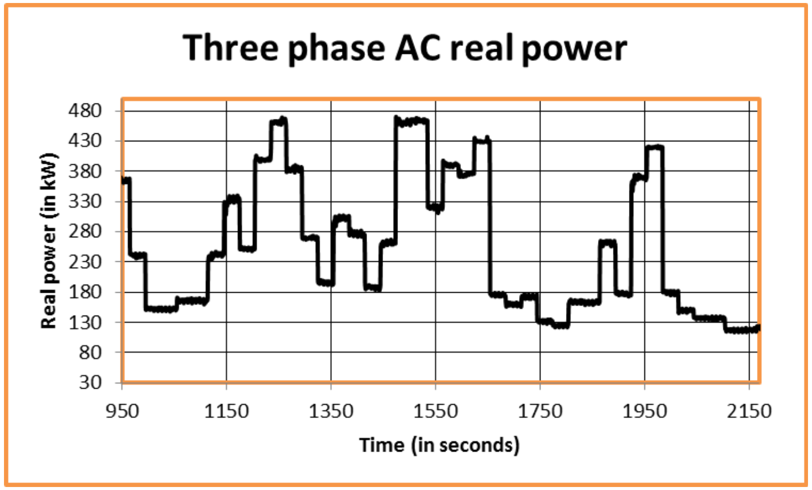


0.95 power factor



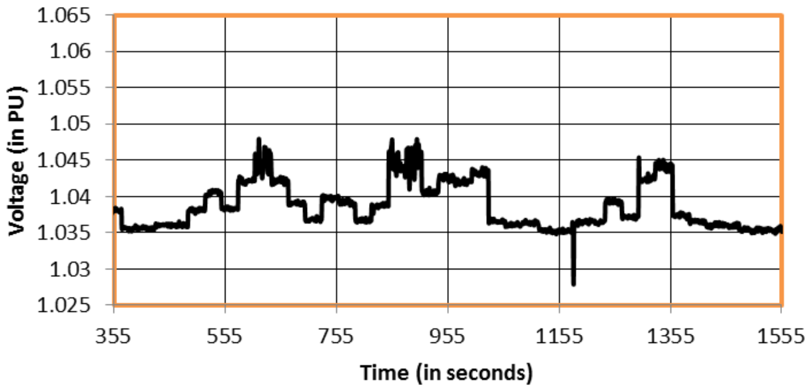




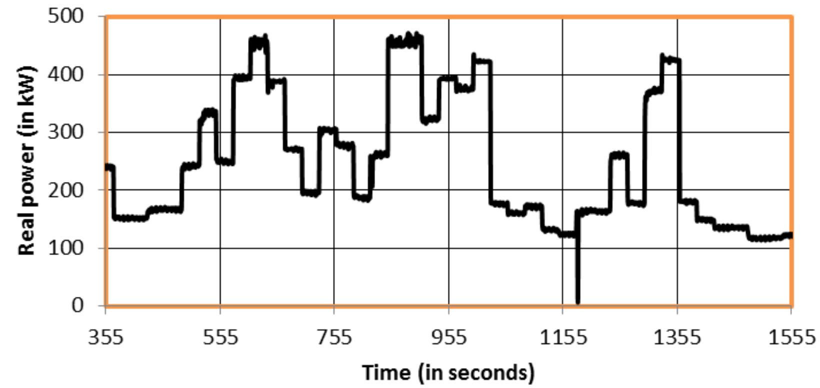


Volt-VAR mode

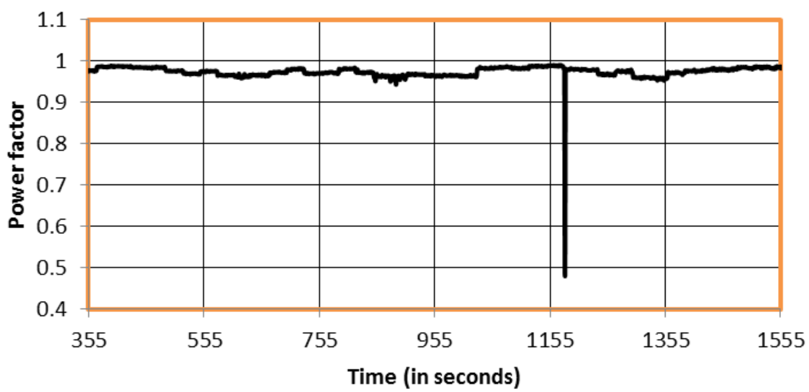
Three phase RMS voltage



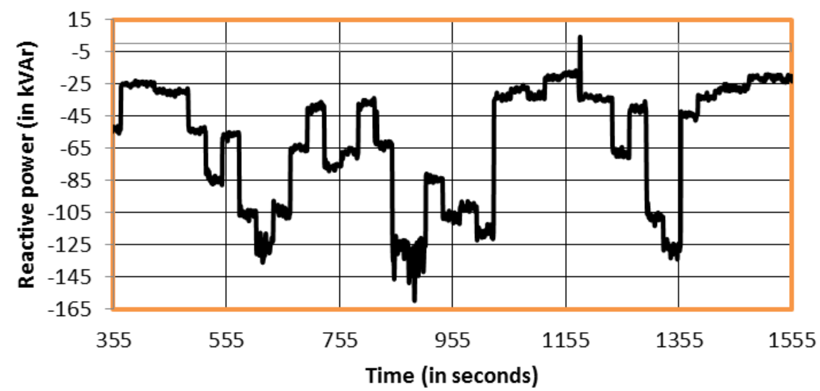
Three phase AC real power



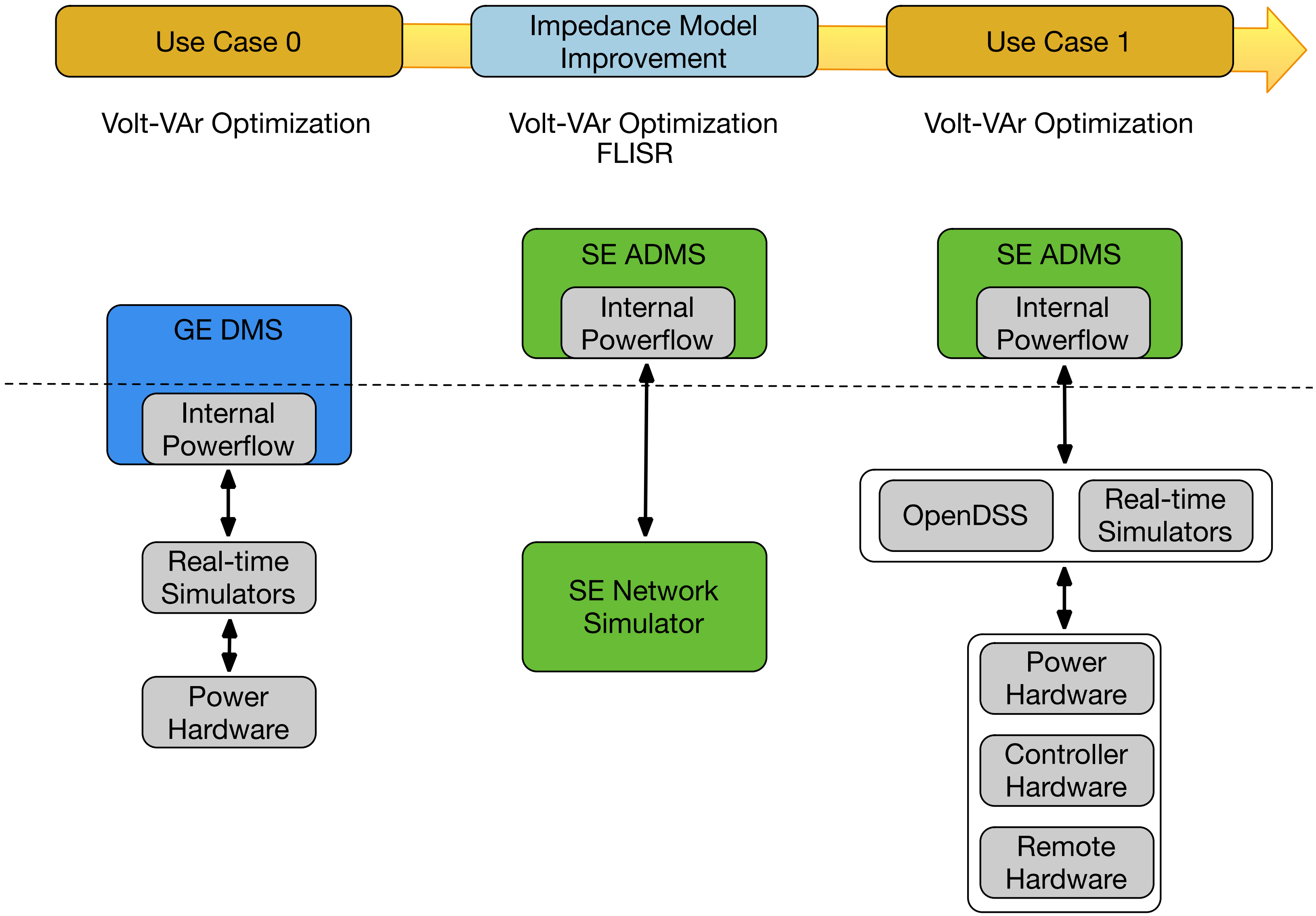
Power factor



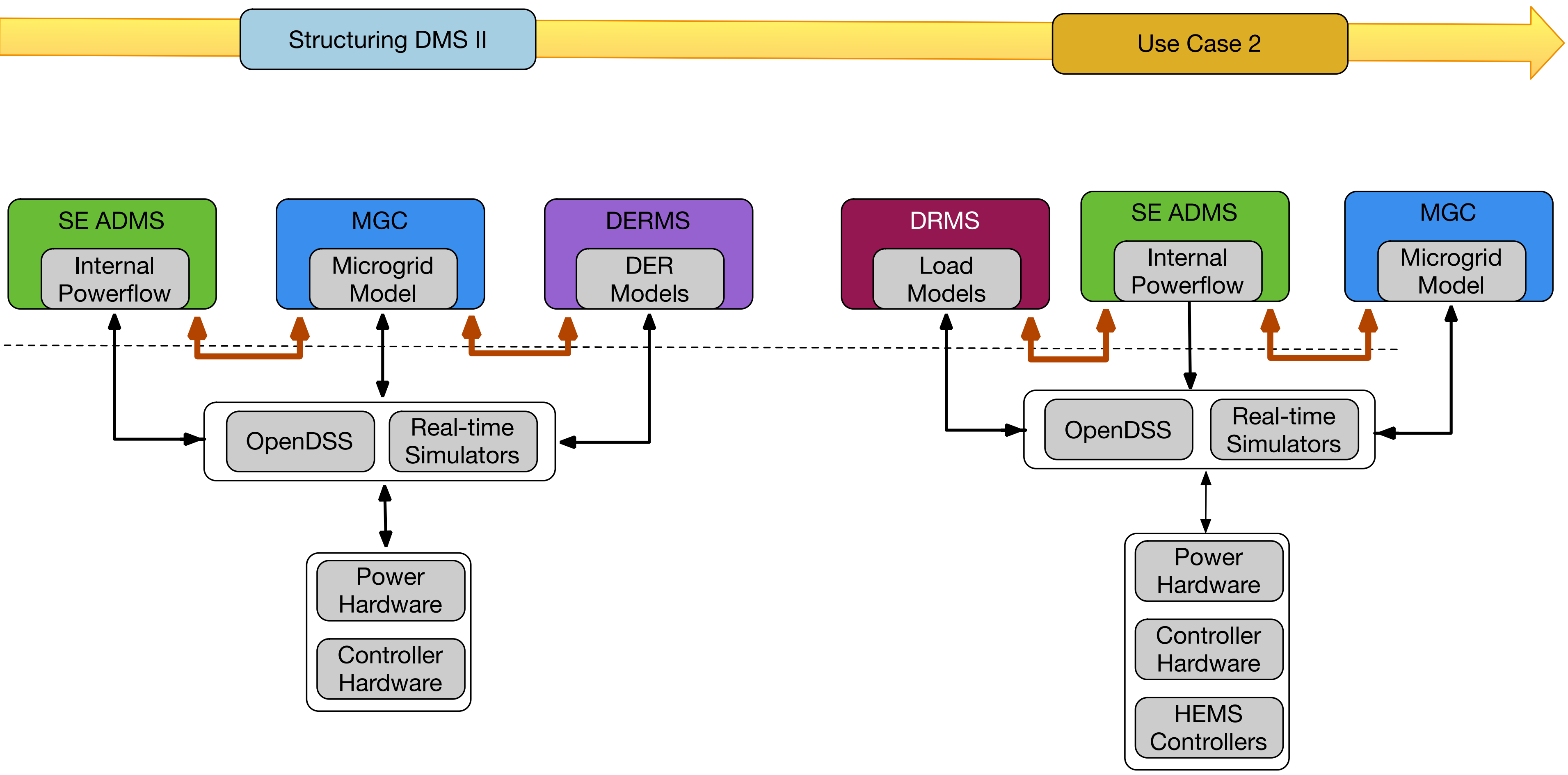
Three phase AC reactive power



ADMS Testbed Capability Development



ADMS Testbed Capability Development



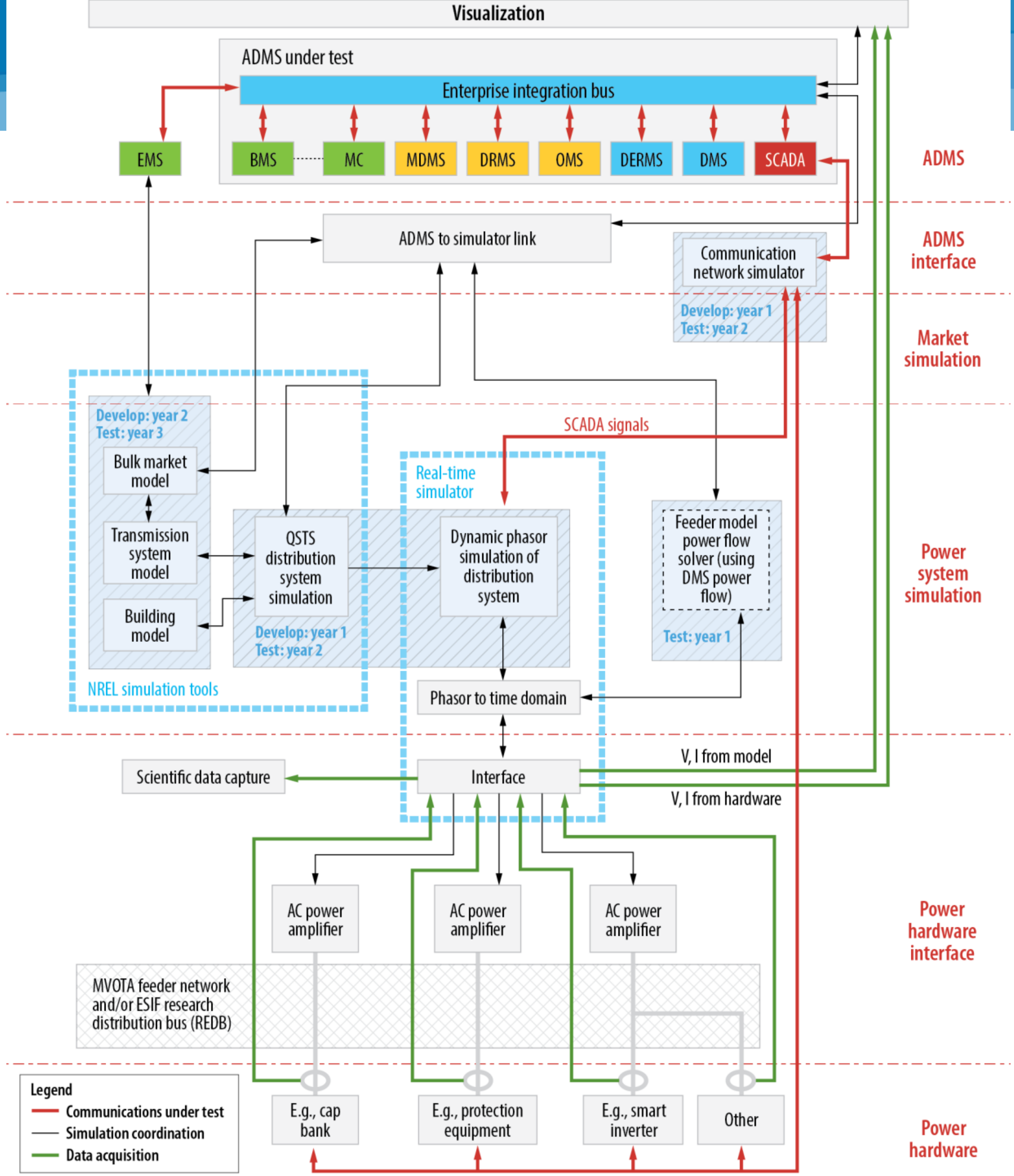
Functional Specifications

- ADMS
- A supervisory control and data acquisition (SCADA) interface, and
- Other utility management systems

Year 1: Internal Power Flow Solver implementation

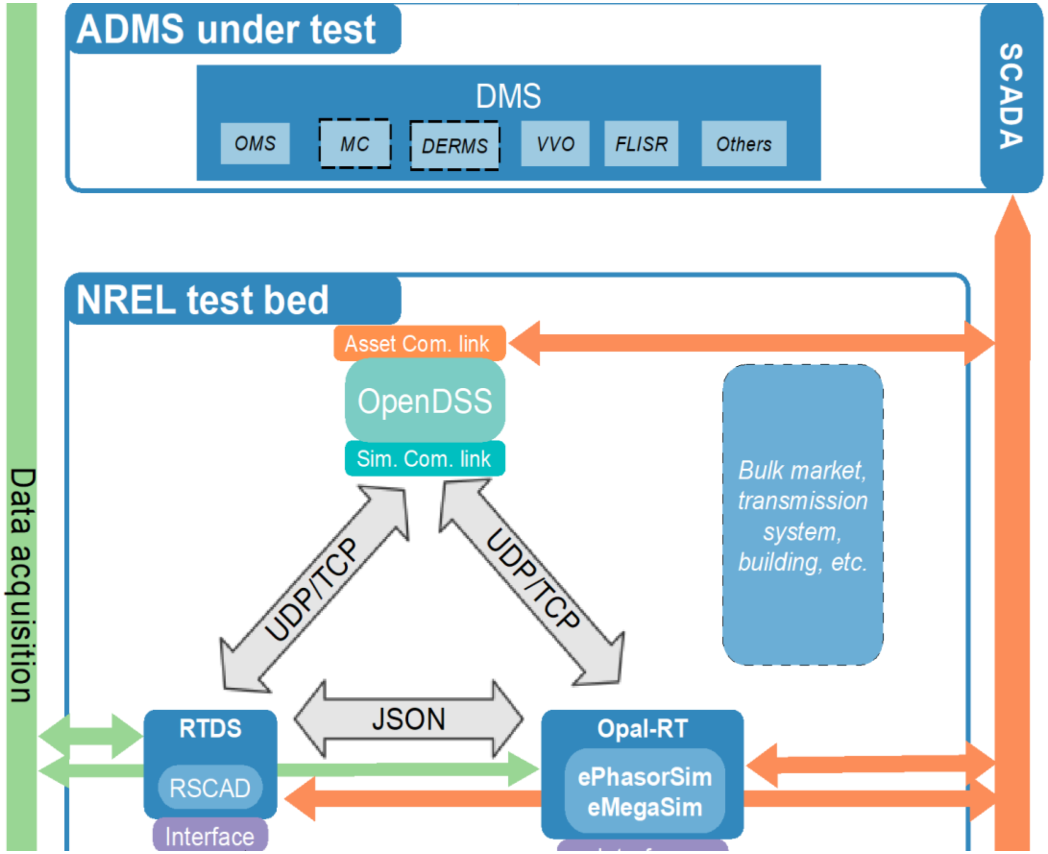
Year 2: multi-timescale software model evaluation

Year 3: Integrated application demonstration



Software Simulation

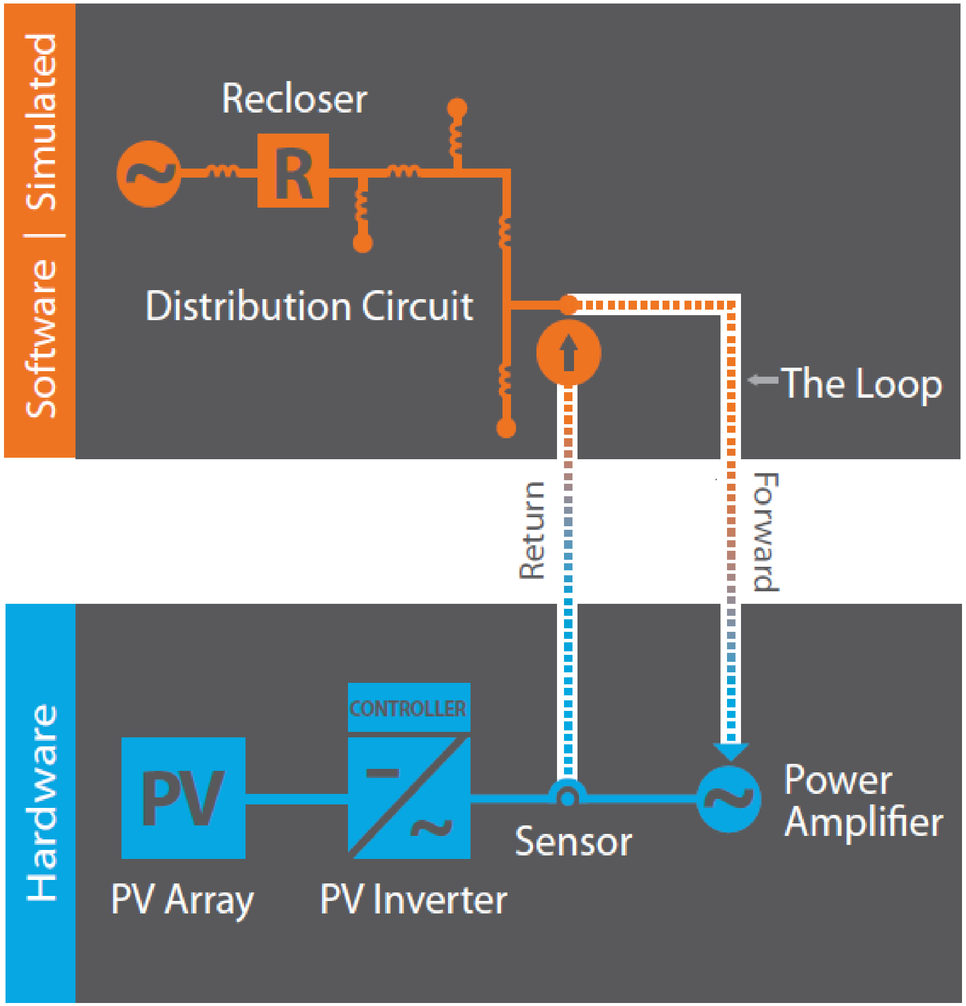
- Full-scale distribution system
  - Multiple feeders
  - Substation details
  - Connections to Bulk system
- Segmented into multiple tools
  - OpenDSS (QSTS)
  - ePhasorSim (ms)
  - RTDS/eMegaSim (EMTP)
- Utility/SCADA comms
  - Mimic actual ADMS connections
- Flexible timing:
  - Real-time (with HIL)
  - Faster than real-time (QSTS)



Hardware-in-the-Loop (HIL)

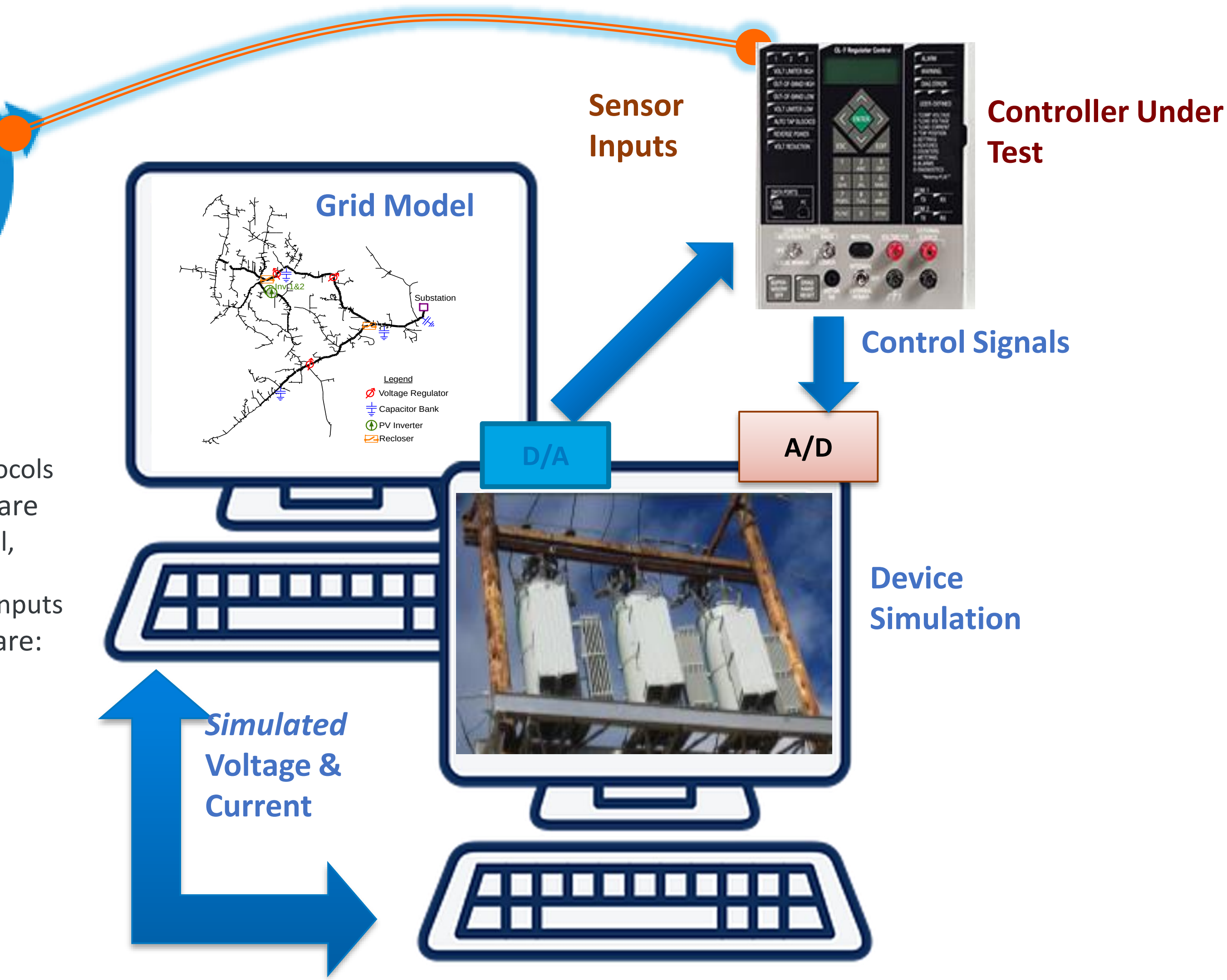
Real-time software simulation
+ Actual Hardware
Hardware-in-the-loop

- Hardware doesn't know difference
- Full control of "grid" environment
  - Off-nominal conditions
  - Extreme event testing
  - Control the weather
  - Repeatable Testing
  - Different locations with same test



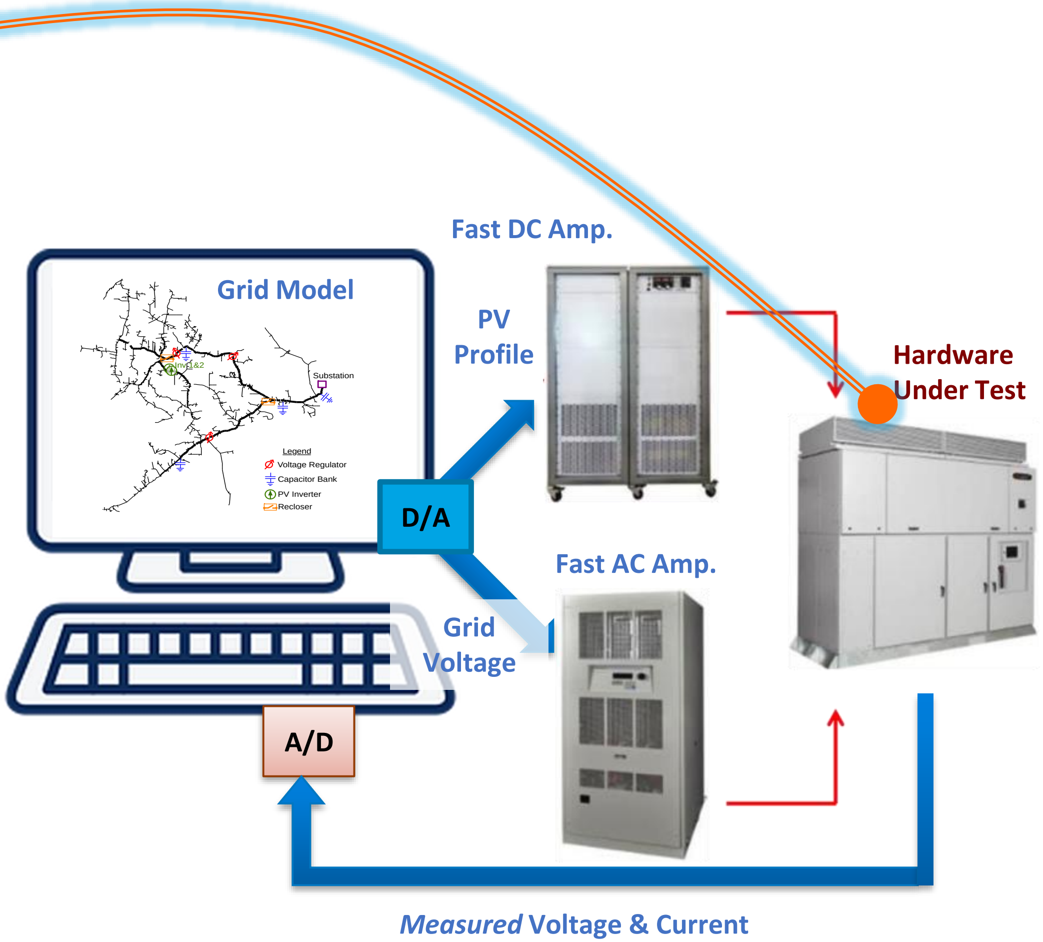
Controller Hardware-in-the-Loop (CHIL)

- ADMS Under Test
  - Modules of interest
  - Utility comms. protocols
- Actual Controller Hardware
  - E.g.: Cap/tap control, Relay
  - Low power Sensor inputs
- Everything else in software:
  - Feeder behavior
  - Device behavior
-



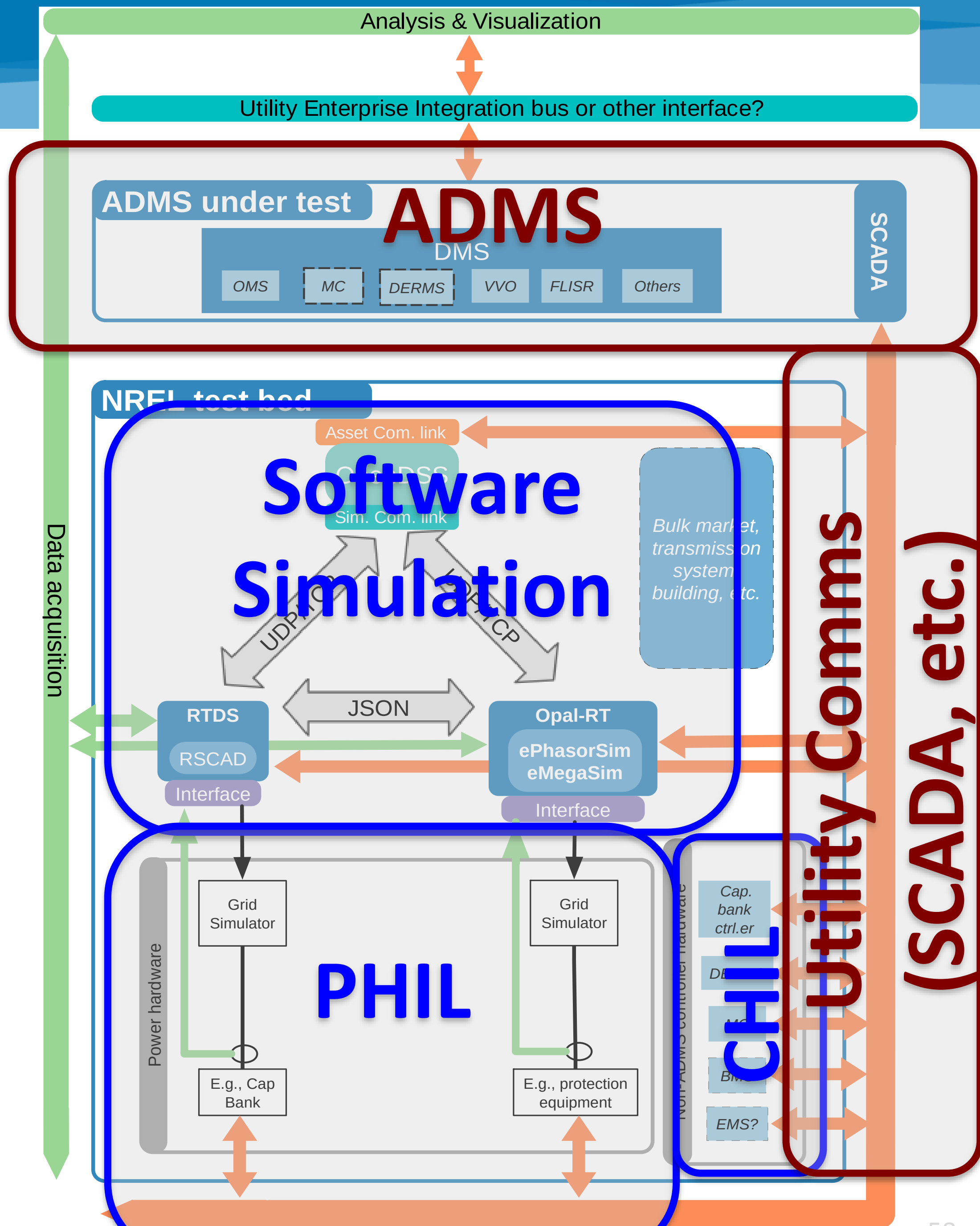
Power Hardware-in-the-Loop (PHIL)

- ADMS Under Test
  - Modules of interest
  - Utility comms. protocols
- Actual Controller + Device Hardware
  - E.g.: PV inverter, Battery, Cap bank
- AC and DC Power Amplifiers
  - Full power (watts to MWs)
  - Full control of voltage/weather
- Only feeder simulated in software



Managing multiple data streams

- ADMS Communications Under Test
  - Utility protocols
  - Delays/losses to simulate real networks
- Simulation Coordination
  - Virtual representation of physical connections
  - As fast as possible
- Data Acquisition
  - Separate from ADMS: validation and consistency
  - Research-grade sensors

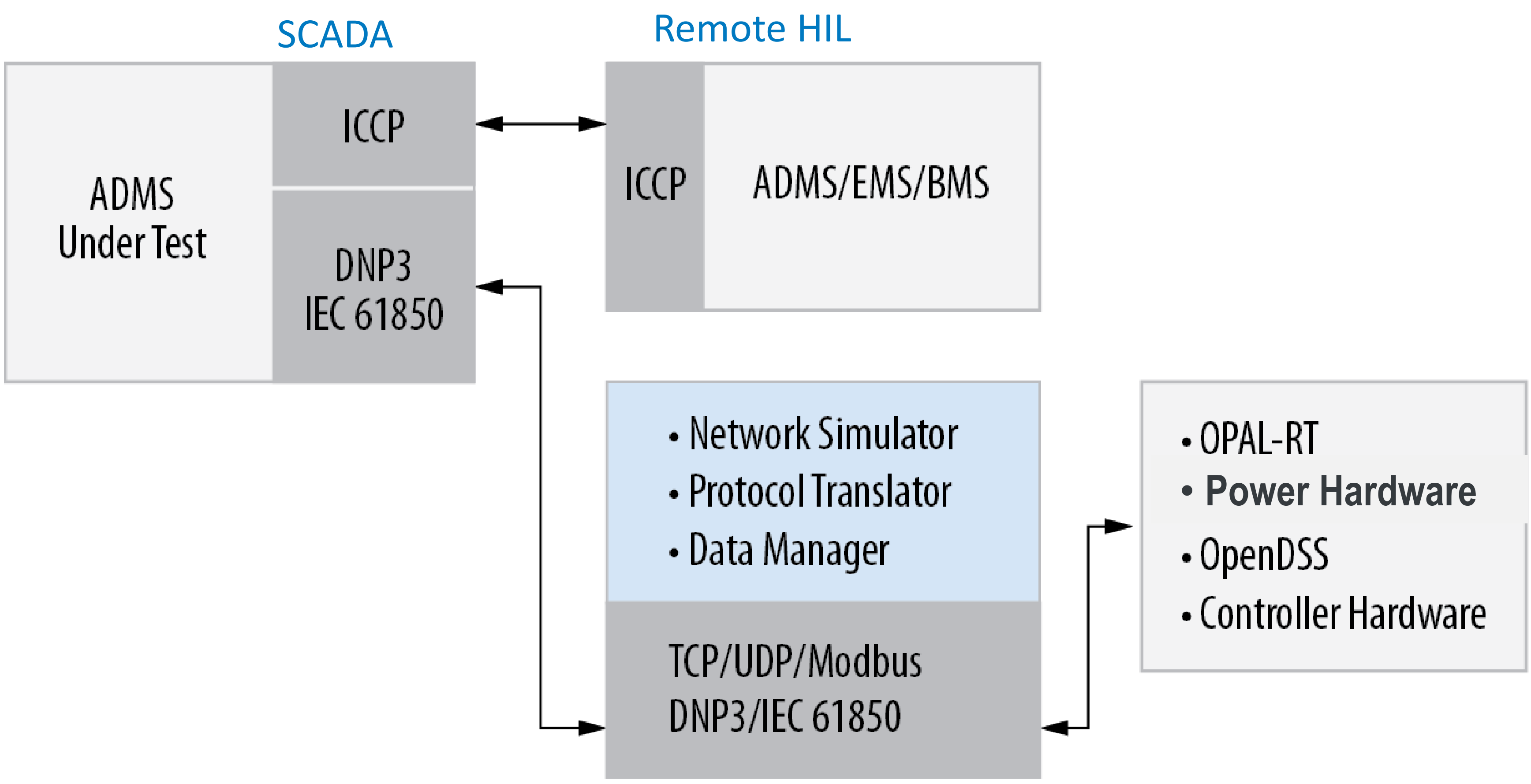


Use Case Summary

ADMS Testbed Use Case 1	
Use Case	Evaluate the performance of the ADMS VVO application for different levels of data remediation and different levels of measurement density. Quantify the trade-off between data remediation and measurement density.
Capabilities Demonstrated	Multi-time scale simulations*, integration of multi-vendor simulation platforms*, remote HIL, CHIL, PHIL, enabling tools for model conversion and communication interfaces*, integrated data collection and management system*
ADMS Deployment	Xcel Energy feeders, Schneider Electric ADMS with VVO and SCADA applications
Test Set-up	
Software Simulation	External power flow* co-simulated using OpenDSS Opal-RT's ePhasorSim* and Opal-RT's eMegaSim
CHIL	Capacitor bank and voltage regulator controllers*
PHIL	12 kVA three phase PV Inverter
Remote HIL	Open-loop substation automation controls*

Testbed capabilities: interfaces

Communications



Test Procedure

- Not all steps will be applicable to all tests
- Step 1: Configure the ADMS:
  - Load ADMS with selected data representing a certain level of data remediation and measurement density
  - Configure the ADMS's SCADA application based on the level of measurement density
  - Configure VVO application with the selected objective
  - Bring VVO and SCADA applications online, through remote desktop connection to the ADMS server virtual machine
- Step 2: Configure Software Simulation:
  - Load OpenDSS and Opal-RT platforms with electrical models of selected feeders
  - Select and enable the telemetry points based on the level of measurement density
  - Load the load profiles and insolation profile over the selected duration (e.g., 4 hours)
- Step 3: Configure remote HIL components:
  - Test the communication link between NREL and PNNL
  - Initialize the network model at PNNL
  - Start up the remote controller and verify its operation
  - Verify that the ADMS can receive measurements from and send set points to PNNL

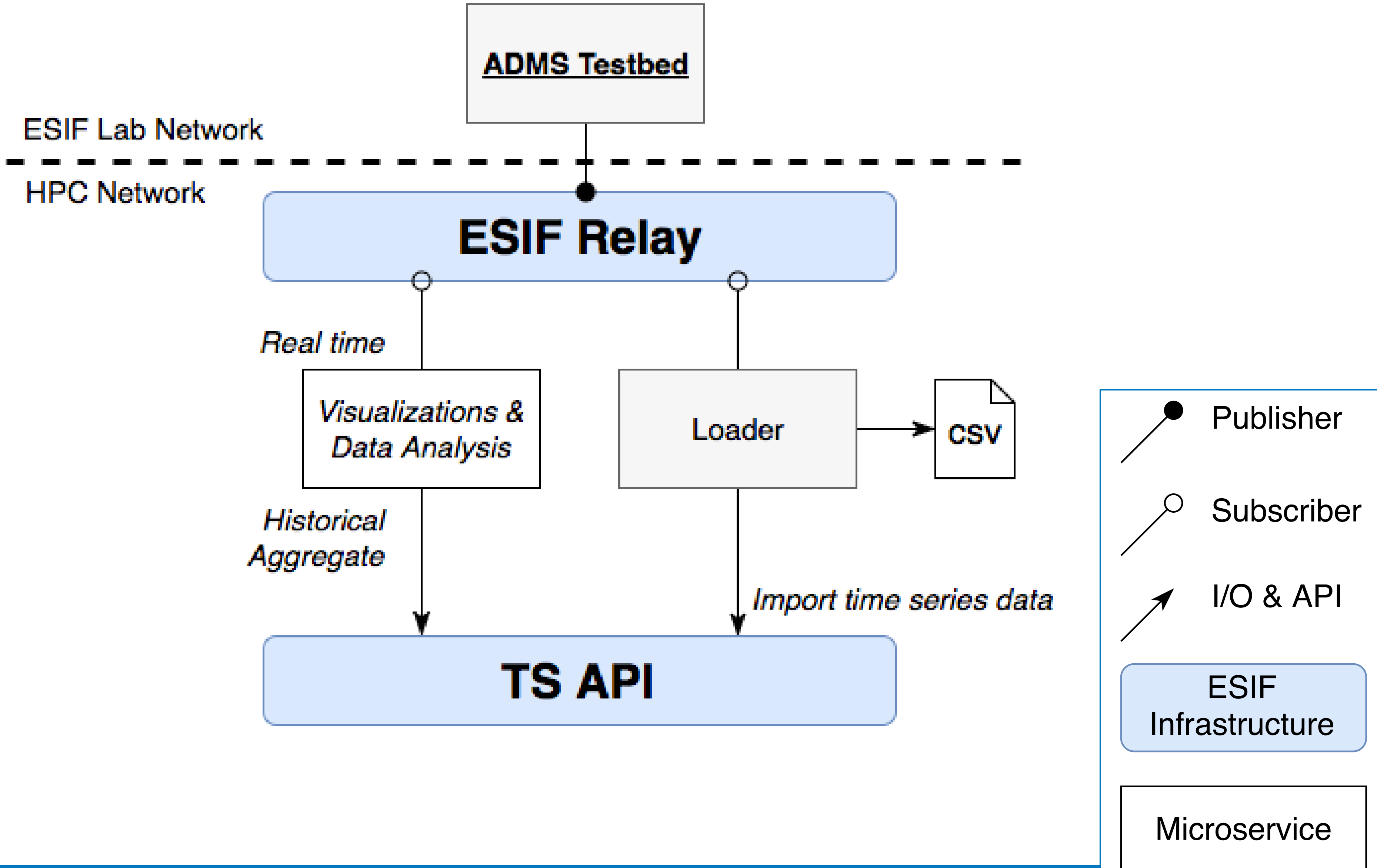
Test Procedure

- <u>Step 4: Configure local CHIL components</u>:
  - Verify the configuration of the capacitor bank and voltage regulator controllers
  - Start up the capacitor bank and voltage regulator controllers
- <u>Step 5: Configure local PHIL components</u>:
  - Verify the configuration and operating limit set points on the controllable AC and DC sources that act as grid and PV simulators respectively
  - Energize the grid and PV simulators using nominal manual set points
  - Verify the operation of the PV inverter in the desired mode
- <u>Step 6: Enable data collection and management systems</u>:
  - Enable the data collection system
- <u>Step 7: Perform simulation</u>:
  - Initialize the co-simulation from the co-simulation coordinator

Test Metrics

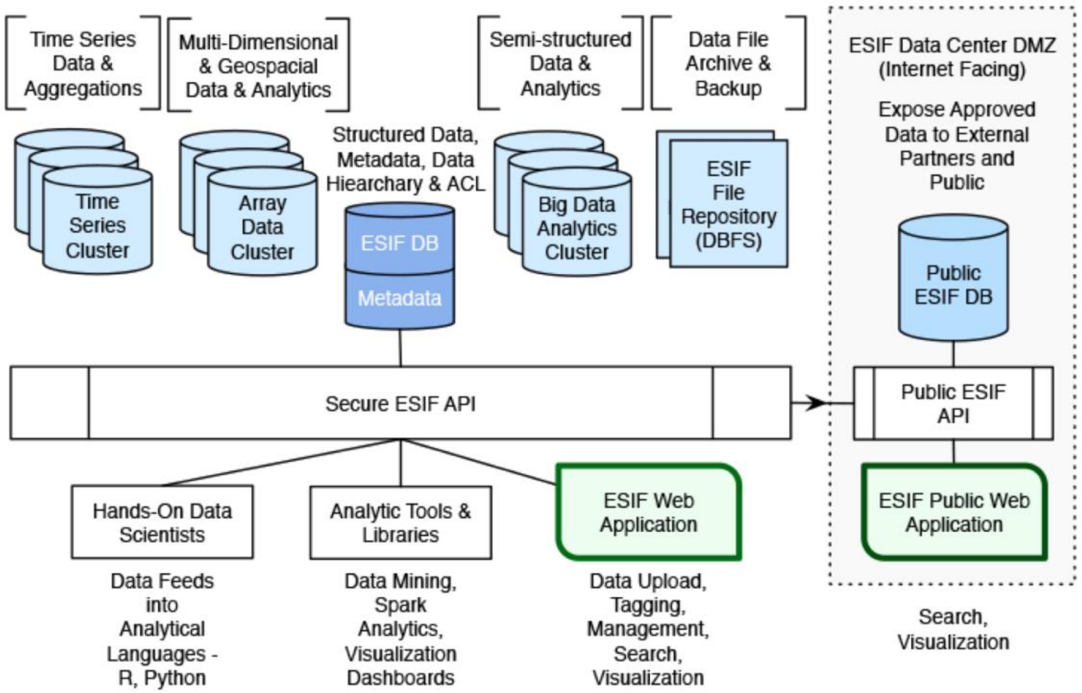
Test Metric	Description	Measurement
CVR Energy Reduction*	Feeder energy consumption before and after application of CVR	Feeder head voltage and current measurements
Average Absolute Deviation*	Sum of absolute voltage deviation at each node divided by number of nodes.	RMS voltage at every node collected from software-based simulation platforms
Voltage Excursions	Number of voltage violations (beyond the acceptable range of 0.95-1.05pu)	RMS voltage at every node collected from software-based simulation platforms
Capacitor bank operations	Number of times the cap banks were turned on or off	Cap operations as recorded from the cap bank controller
Voltage Regulator operations	Number of times the voltage regulators were operated	Regulator operations as recorded from regulator controller
Cost of operation	Cost of voltage regulation; incurred from operation of cap banks, regulators, etc.	ADMS output
Power factor	Power factor will be computed at selected nodes	Voltage and current or power measurements collected from software-based simulation platforms

ADMS Test bed



Testbed capabilities: data collection & visualization

- Collect and record data from the ADMS, the various CHIL/PHIL components and the software-based simulation platforms



ESIF Research Data System: The ADMS testbed will utlize the time-series and metadata databases of the ESIF Research Data System, leveraging the analytic libraries to support real-time and post hoc visual analysis