CENTER FOR ULTRA-WIDE-AREA RESILIENT ELECTRIC ENERGY TRANSMISSION NETWORKS

Monitoring of Active Distribution Networks using PMU Apps

Benefiting Joint T&D Operations

NASPI North American SynchroPhasor Initiative

NASPI Work Group Meeting
Albuquerque, NM
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Dr. Luigi Vanfretti

RPI
ECSE, Troy, NY, USA
Web: ALSETLab.com
Email: vanfrl@rpi.edu
luigi.vanfretti@gmail.com

Rensselaer ALSET Lab

About Me - http://ALSETLab.com - Dr. Luigi!

YOB. 1981 Guatemala

2000 – 2005. 5 year Electrical Power Engineering program @ Universidad de San Carlos de Guatemala.

2006 – 2009 MSc and PhD @ RPI

2010 Post-Doc @ RPI

2010 – 2017, KTH Royal Inst. Of Tech., Stockholm, Sweden
2010: Associate Professor
2012: Docent (Habilitation)
2013: Associate Professor (‘tenured’)

2011 – 2017, SmarTS Lab. Research Group

Rensselaer

Fall 2004 Intern at INDE (National Electrification Institute), Substations Engineering

Visiting Researcher @ The University of Glasgow, Scotland

2011 -External Scientific Advisor (Consultant)

2011 – 2016 Special Advisor R&D Division

2016 - 2017 Consultant.

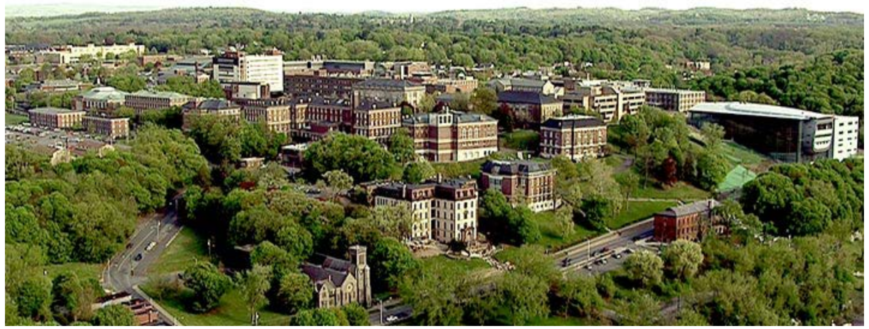
All @ Statnett SF, Oslo, Norway (Power System Operator)

Research Areas:

- Modeling and Simulation of cyber-physical systems in general, specializing in power systems; real-time simulation, multi-domain simulation, co-simulation.
- Synchronized phasor measurement technologies and PMU Apps for monitoring and control
- Application of System Identification Methods to cyber-physical power system modeling, monitoring and control.
- Stability, Control and Security of cyber-physical systems, specializing in power systems.
- Application of computer languages and software technologies for cyber-physical system modeling and simulation - e.g. UML, SysML, Modelica and FMI.

Outline

- **Motivation and Goal**
  - Needs
  - PMU technology for real-time ADN monitoring
- **Tooling for Real-Time Monitoring App Prototyping:**
  - The STRONgrid Library: A IEEE C37.118.2 client for synchrophasor data mediation
  - The S3DK (Smart grid Synchrophasor Software Development Toolkit)
- **Modeling for Real-Time Monitoring Apps**
  - Development of **“active”** grid model
- **Monitoring Applications**
- **App. 1:**
  - Steady State Model Synthesis
- **App. 2:**
  - Distribution Feeder Dynamic Line Rating
- **App. 3:**
  - Decoupled voltage stability analysis
- **App. 4:**
  - Distributed mode estimation
- **Conclusions and Further Work**



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Motivation

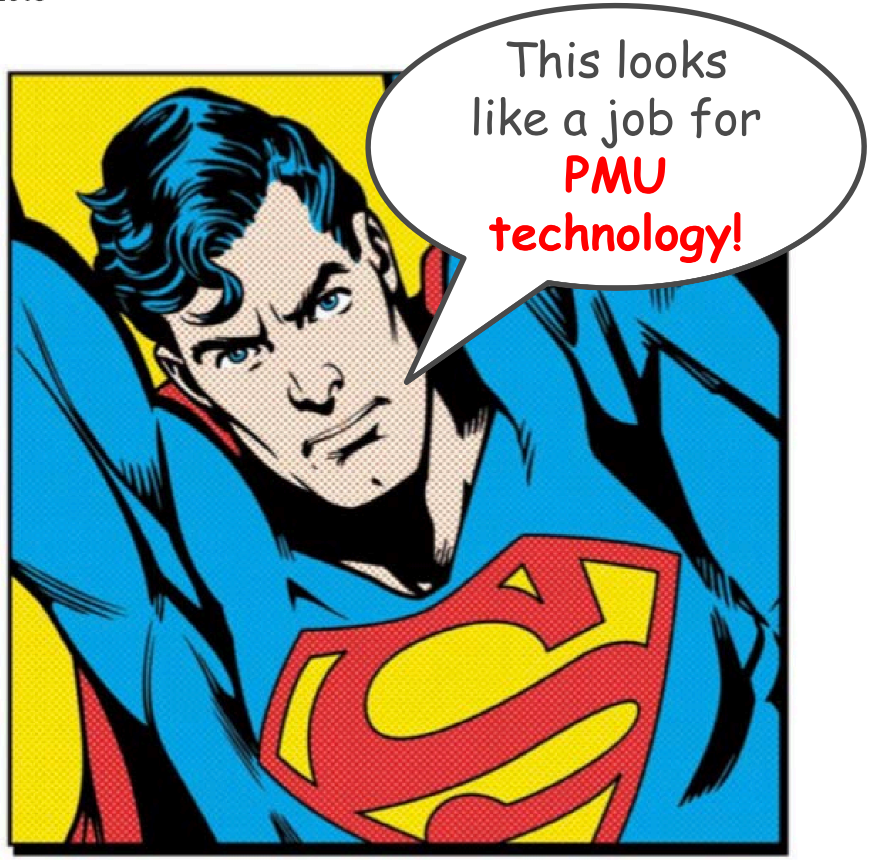
- Utilities and grid operators stressed the need for real-time information on distributed energy resources to a Federal Energy Regulatory Commission panel in Washington, D.C. on Wednesday (04/11/2018)
  - "The worst thing that could happen for distribution companies is to not have visibility on…that distributed energy resource,"
  - "We need to know where it is, the size of it, and how it's being operated on a real-time basis."
  - "Communication today with DER is really low-tech. It's phone and it's emails,"

REGULATION & POLICY

Utilities, Grid Operators Tell FERC They Need Real-Time Data to Better Manage DERs

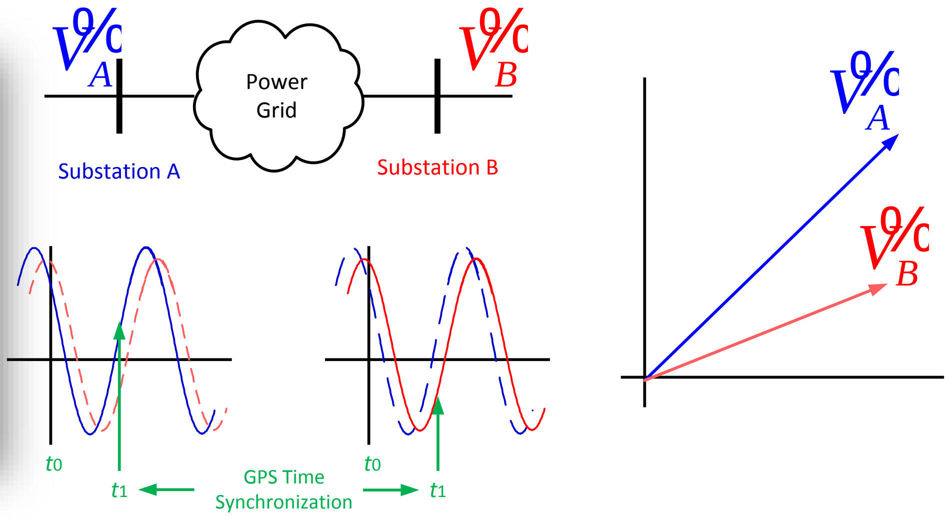
It's unclear how federal regulators will tackle the problem.

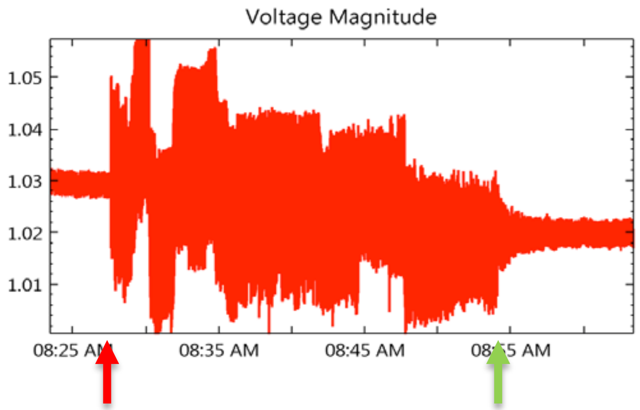
LACEY JOHNSON | APRIL 12, 2018

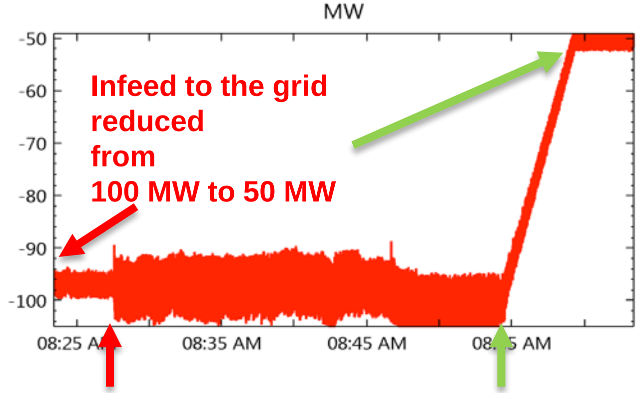


Motivation

- Synchrophasor measurement units (or PMUs), provide time-synchronized measurements that can be networked into a synchrophasor system:
  - This would allow for real-time measurement data exchange between different asset owners and grid operators, using a broadly adopted standard for data transfer.
  - Higher resolution than traditional measurement systems used at SCADA/DMS/EMS: 30,50,60,120 Hz.
- With increased penetration of renewable energy sources, it will be necessary to increase observability between T&D grids:
  - Grid *dynamics becoming are becoming more active* in the system.
  - Example: WT curtailed due to emerging sub-synchronous control interaction **dynamics that compromise grid operation.**







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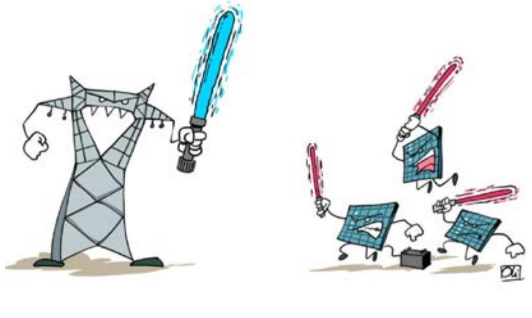
L. Vanfretti, M. Baudette, J.L. Dominguez-Garcia, M.S. Almas, A. White, and J.O. Gjerde, "A PMU-Based Real-Time Oscillation Detection Application for Monitoring Wind-Farm Dynamics," Electric Power Components and Systems, Taylor & Francis, Vol. 44, Iss. 2, 2016. http://dx.doi.org/10.1080/15325008.2015.1101727

Need for "Interaction" between
Active Distribution Networks (ADN) and Transmission Network Operators (TNOs)

Need for Interaction

View from the ADN



View from TNOs

As distribution networks become more **"active"**:

- Operational security of the overall grid **requires ADNs and TNs to interact** tightly.

Interaction begins with "Information Exchange"

Information **can only be derived** from measurements or *models!*

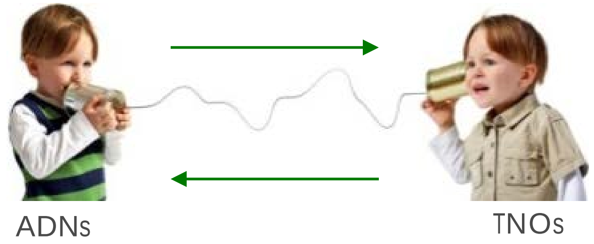
Today, DN and TN share very little information in operations.

- Litter (or non) measurement data exchanged, and without required technical features (time-synch, sampling rate, etc.)
- Outdated/limited/unavailable models or equivalents

How to Derive Information?

PMU Applications

Extract operational information to serve as as "enablers" for interaction between:



- **Start with adding one or few PMUs in the ADN**
- First step towards "information exchange" between ADNs and TNOs
- **Extract information from PMU data across operational boundaries.**

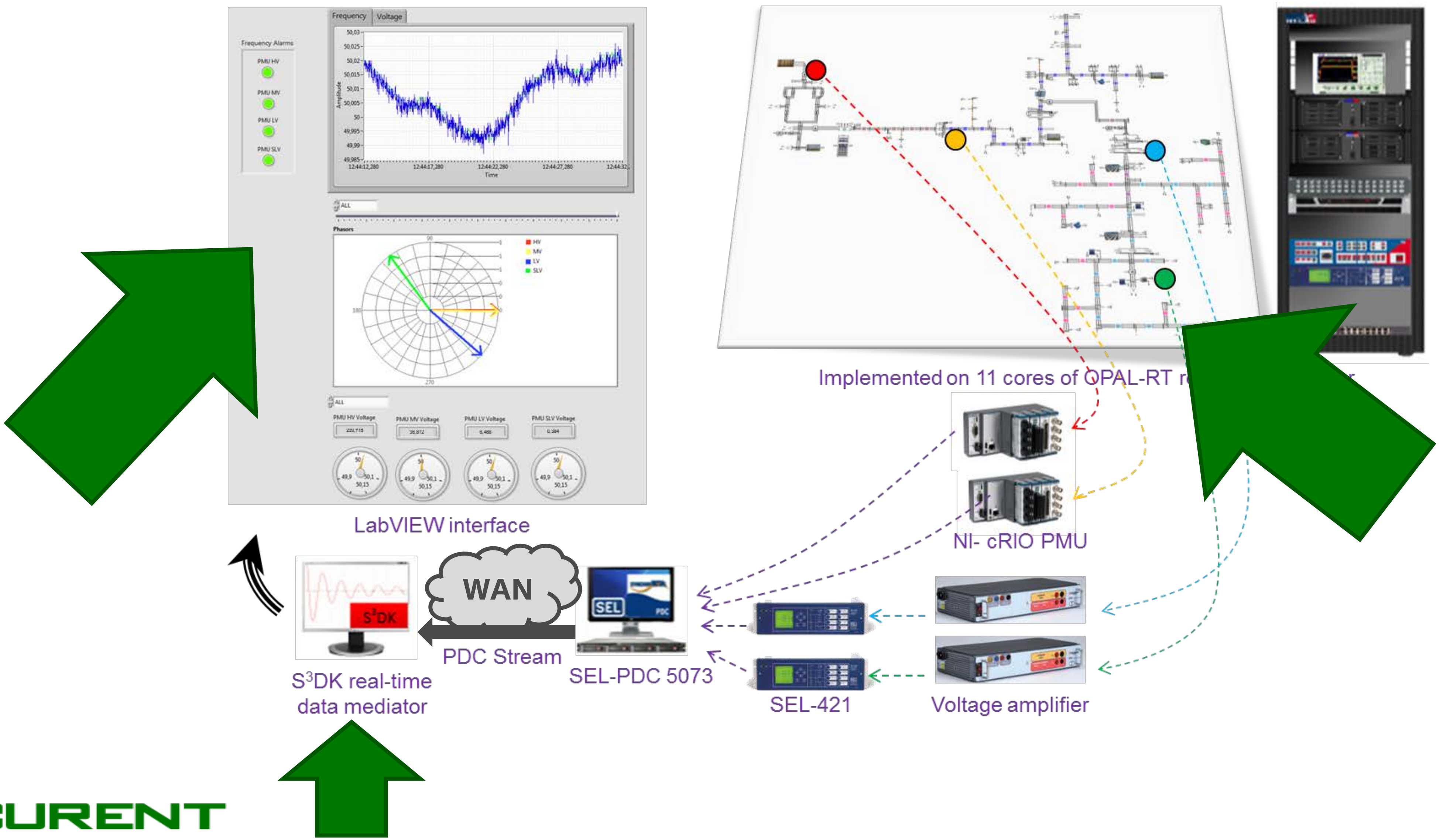
Potential common view

Goal

- It is possible to develop PMU-based applications to ***synthesize* real-time information** from PMU data to provide:
  - **Real-time monitoring, control** and protection across multiple-voltage levels, and operational boundaries of different actors → exchanging real-time measurements and information between transmission, distribution, DER owners, prosumers.
  - **Real-time operation** → track, analyze, make a diagnosis and to help taking preventive / corrective actions.
  - **Planning** → **learn** from *measurement data and synthesized information, so* to develop grid enhancements that increase hosting capacity.

- The architecture of HW/SW required for this type of applications needs to be understood.
  - Two examples: one partially distributed, and one partially centralized application.

PMU App Development Approach and Areas Covered in this Presentation

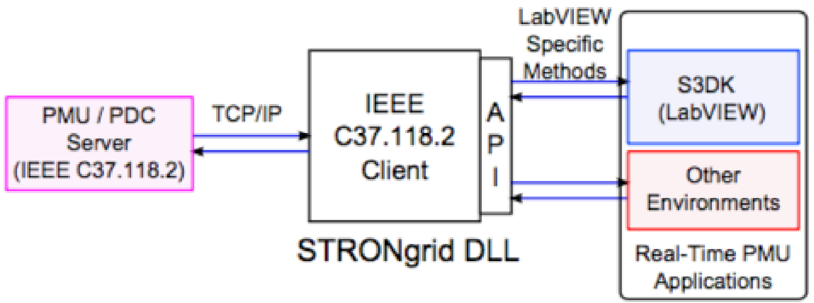


STRONgrid Library

A PMU Real-Time Data Mediator a.k.a. “DLL”

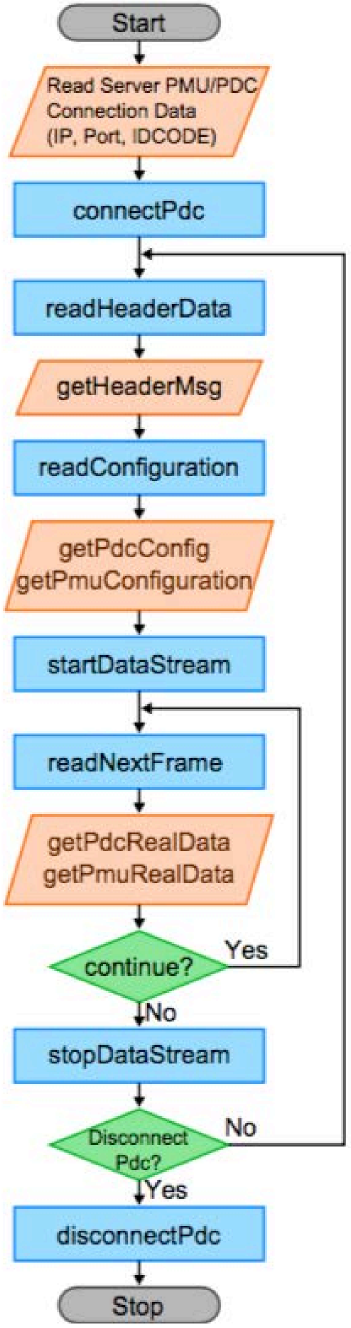
- A library in C++ was implemented with an architecture design that provides modularity and re-use.

- It provides C++ methods that can be accessed from any environment and a dedicated API for LabView:



Listing 1: Source code snippets showing some of the Strongrid DLL API methods

```
int connectPdc( char *ipAddress, int port, int32_t pdcId, int32_t*
    pseudoPdcId);
int disconnectPdc( int32_t pseudoPdcId);
int readHeaderData( int32_t timeoutMs, int32_t pseudoPdcId);
int readConfiguration( int32_t timeoutMs, int32_t pseudoPdcId);
int startDataStream( int32_t pseudoPdcId);
int stopDataStream( int32_t pseudoPdcId);
int readNextFrame( int32_t timeoutMs, int32_t pseudoPdcId);
int getPdcConfig( pdcConfiguration* pdcCfg, int32_t pseudoPdcId);
int getPmuConfiguration( pmuConfig* pmuconf, int32_t pseudoPdcId, int32_t
    pmuIndex);
int getPdcRealData( pdcDataFrame* rd, int32_t pseudoPdcId);
int getPmuRealData( pmuDataFrame* rd, PmuStatus* status, int32_t pseudoPdcId,
     int32_t pmuIndex);
int getHeaderMsg( char* msg, int maxMsgLength, int32_t pseudoPdcId);
```



- Includes multi-threading, and provisions to expand for other protocols.
- https://github.com/ALSETLab/S3DK-STRONGgrid

Get it on Github!

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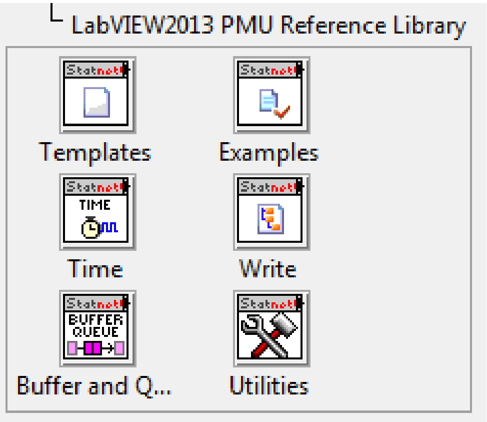
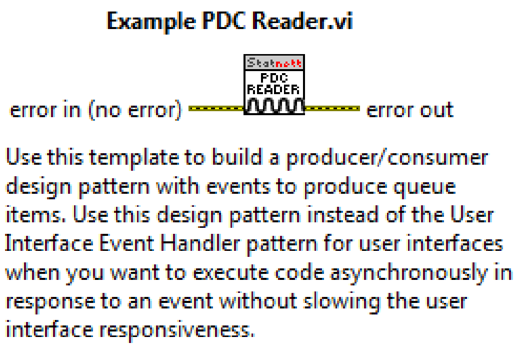
Tooling for Implementation of Real-Time PMU Apps

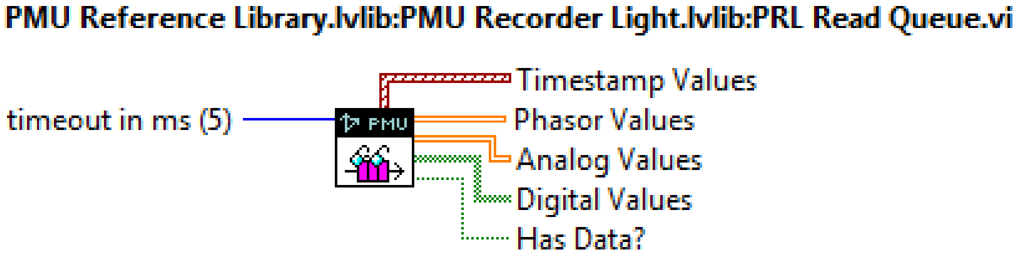
Get it on Github!

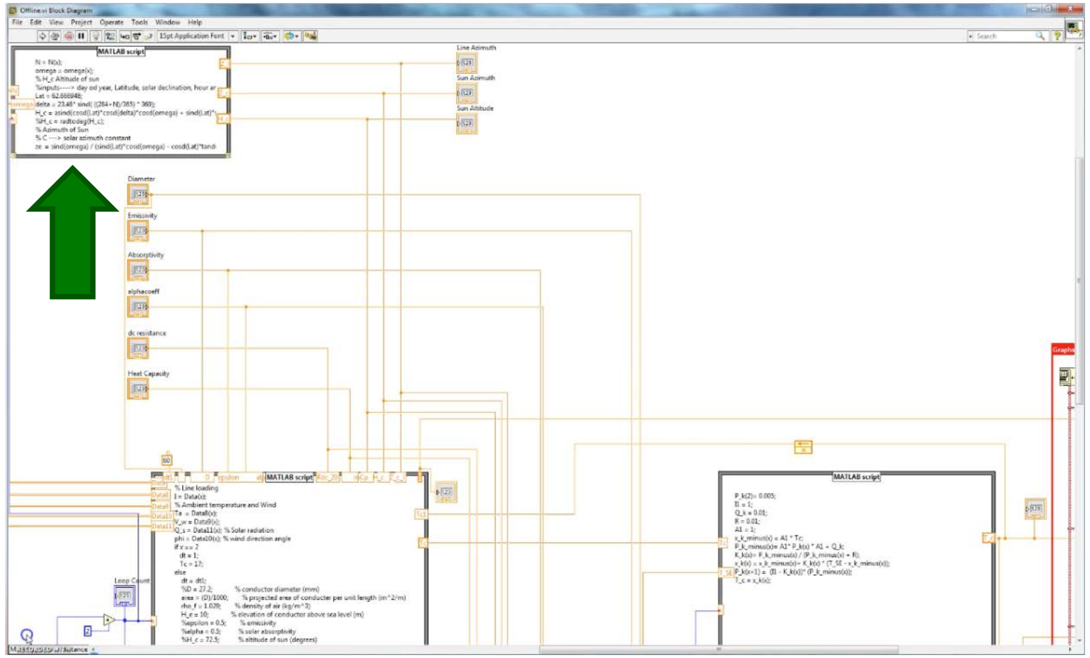
- Real-Time PMU Data
- S3DK: https://github.com/ALSETLab/S3DK
  - Open source "toolbox" for PMU application implementation in LabView.

Following RT data acquisition, all methods go through scripts implemented within LabVIEW









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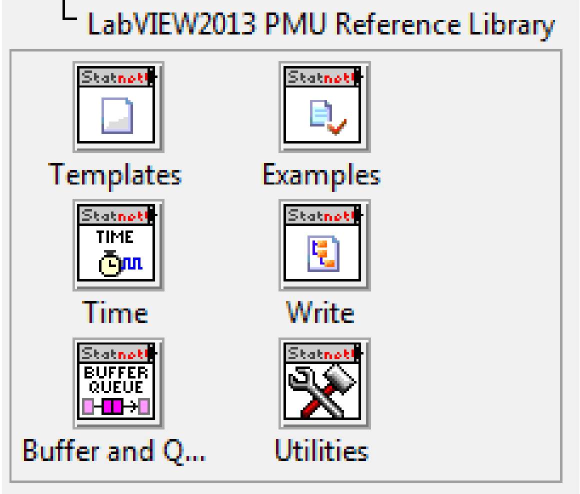
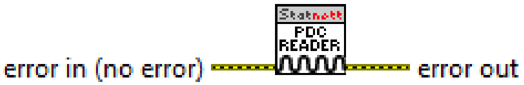
S3DK's LabVIEW

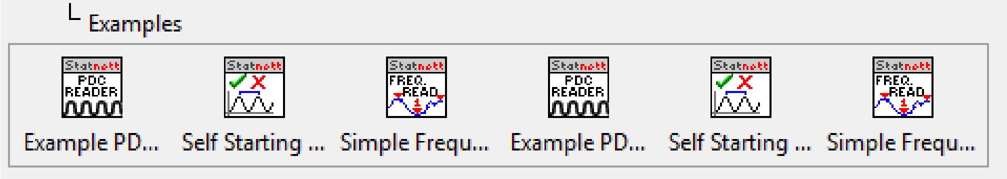
Function Library/Toolbox/Pallete (aka PRL)



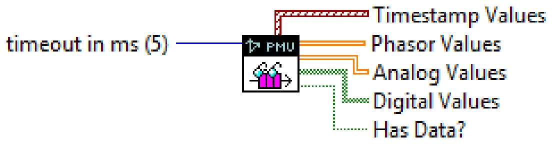
Example PDC Reader.vi



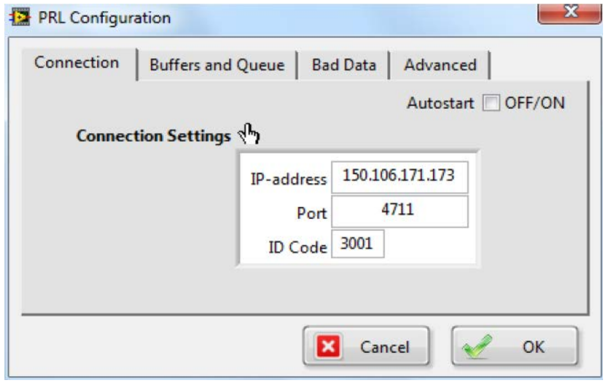
Use this template to build a producer/consumer design pattern with events to produce queue items. Use this design pattern instead of the User Interface Event Handler pattern for user interfaces when you want to execute code asynchronously in response to an event without slowing the user interface responsiveness.

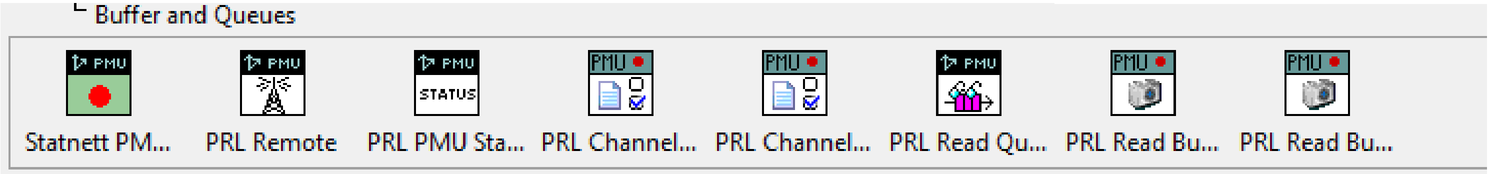


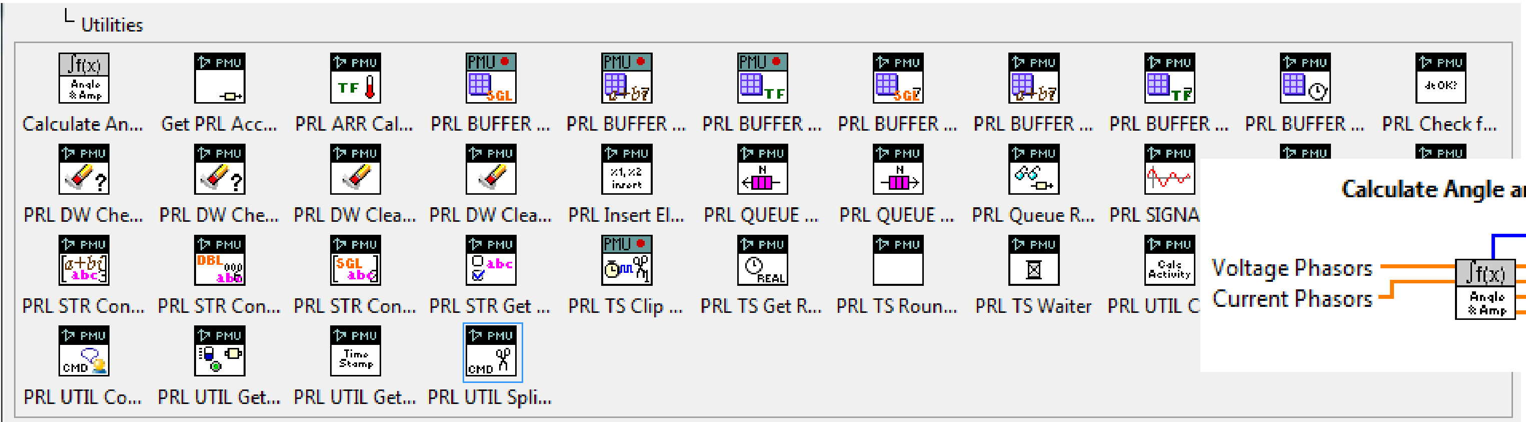
PMU Reference Library.lvlib:PMU Recorder Light.lvlib:PRL Read Queue.vi



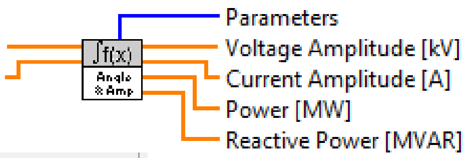
Communication Configuration

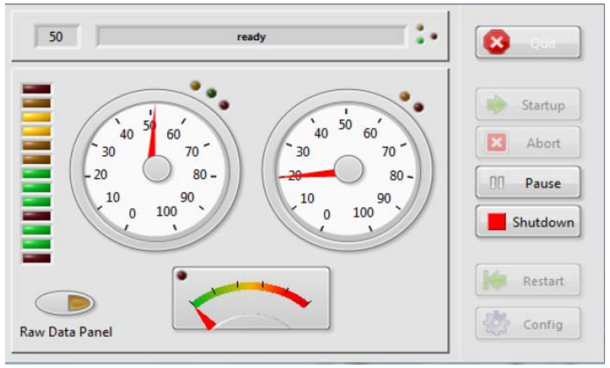






Calculate Angle and Amplitudes.vi





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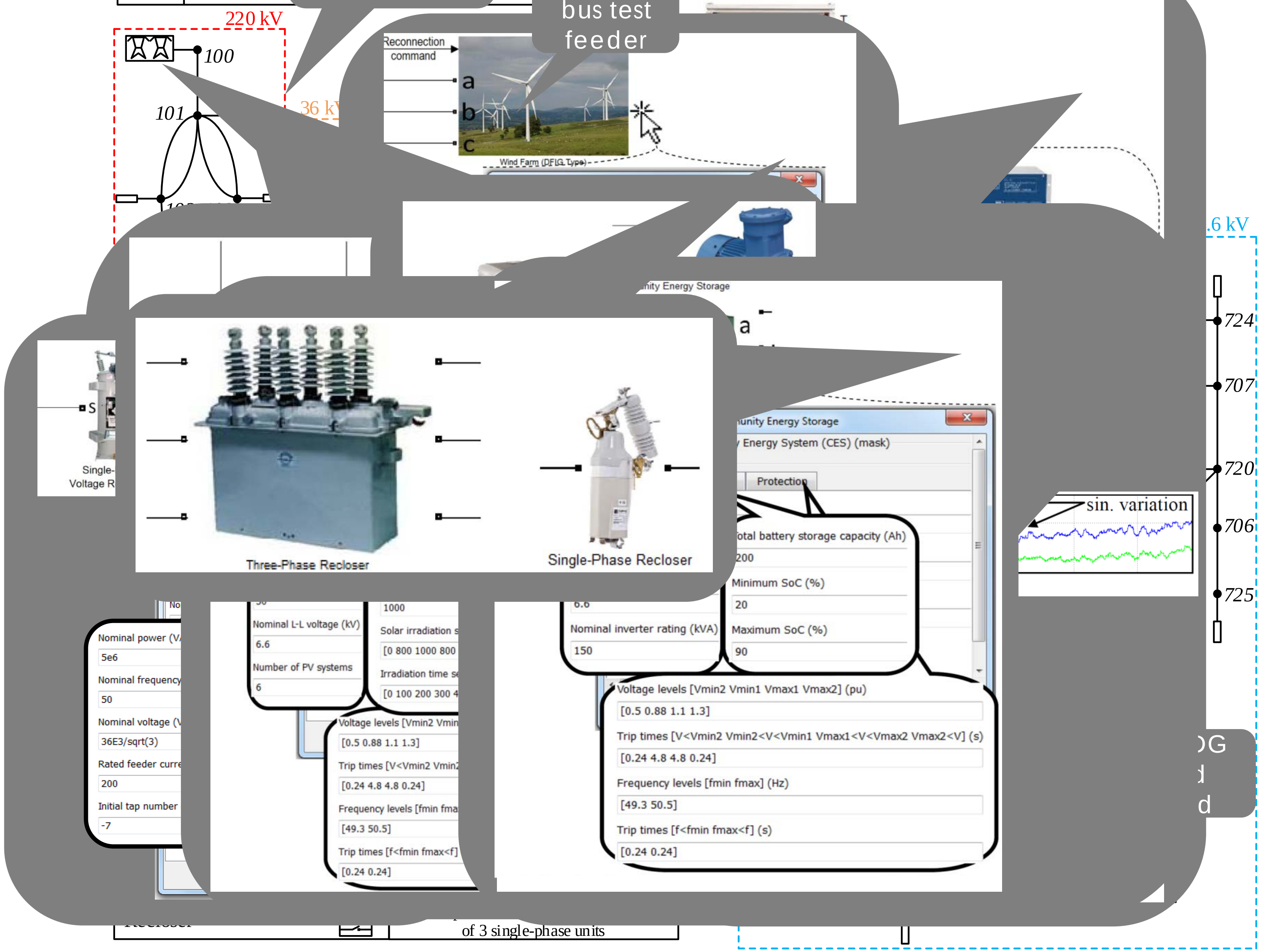
Modeling for Real-Time Apps.:

	Rated Voltage	No. of buses	Number of branches
HV	220 kV	6	7 three-phase
MV	36 kV	[illegible]	ree-phase, 8 single-phase
LV	6.6 kV	[illegible]	39 three-phase
RLV	0.4 kV	[illegible]	1 t



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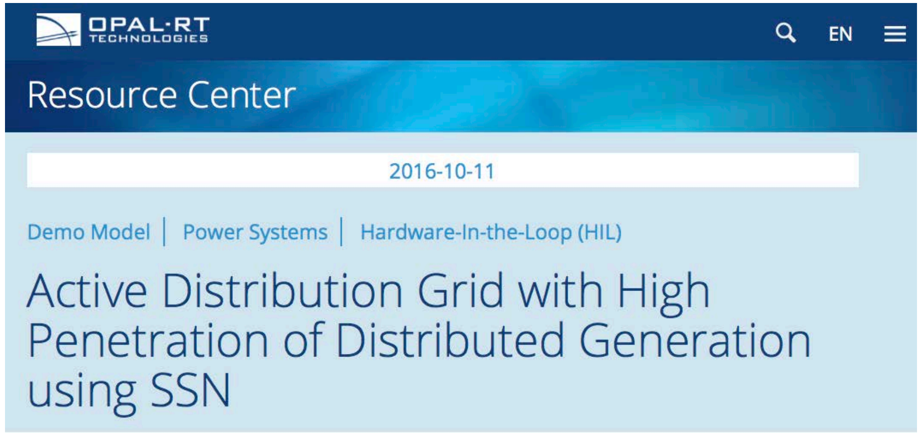
Model Setup for Real-Time Simulation:

Get it on Github! https://github.com/ALSETLab/ADN-RT-EMTP-Model

- The model is included as an ARTEMiS demo in Opal-RT's RT-Lab:
- https://www.opal-rt.com/resource-center/demo/?resource=L00143_0095


OPAL-RT TECHNOLOGIES
EN
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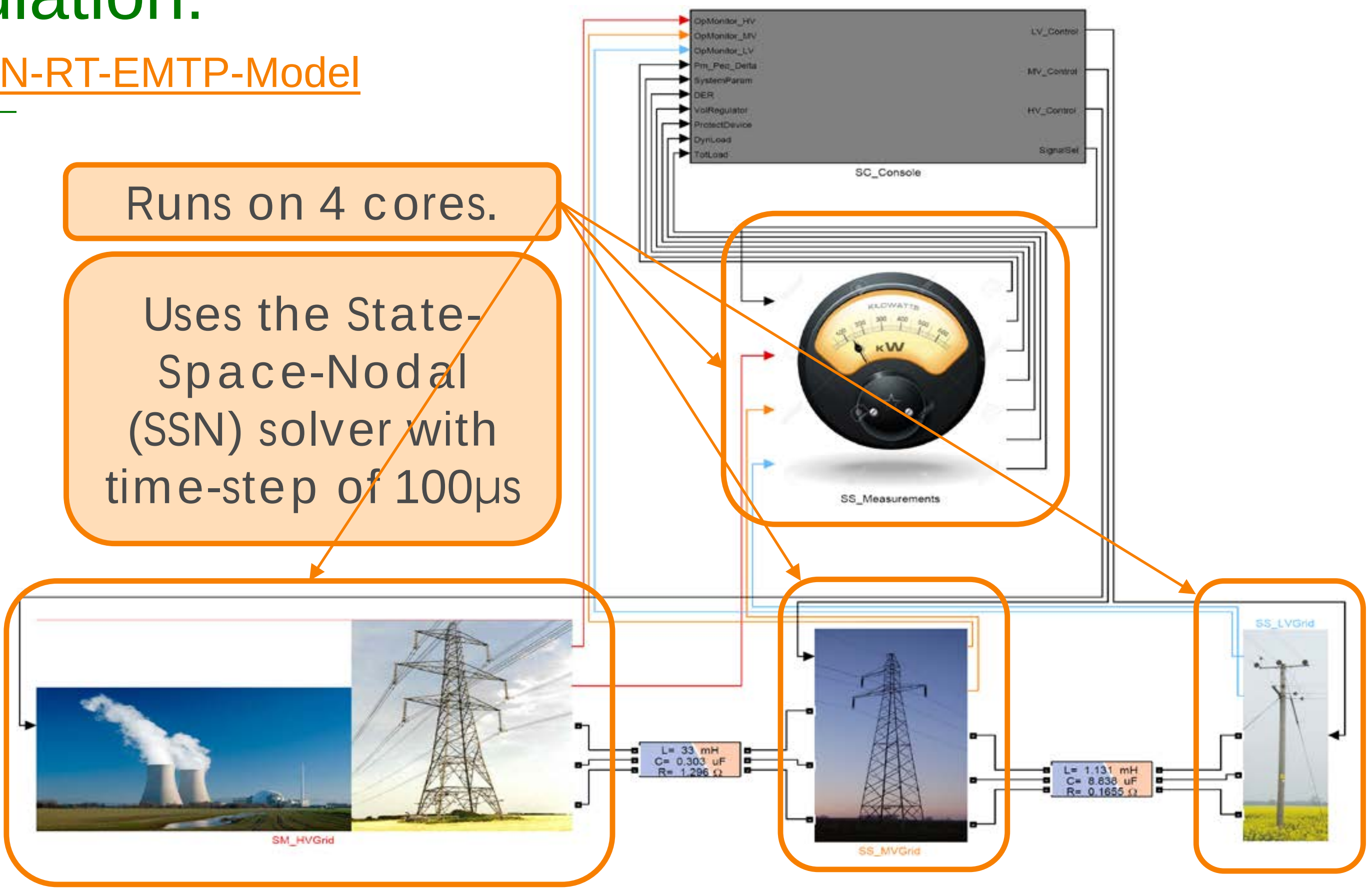
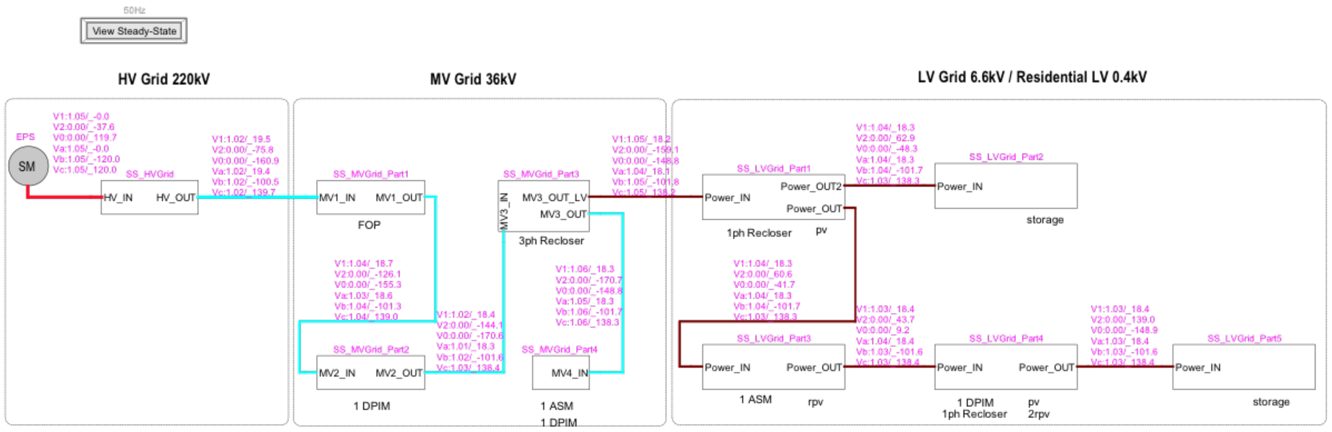
2016-10-11
Demo Model | Power Systems | Hardware-In-the-Loop (HIL)
Active Distribution Grid with High Penetration of Distributed Generation using SSN



- Model also available for off-line analysis using the EMTP-RV software!

EMTP-RV
The reference for power systems transients

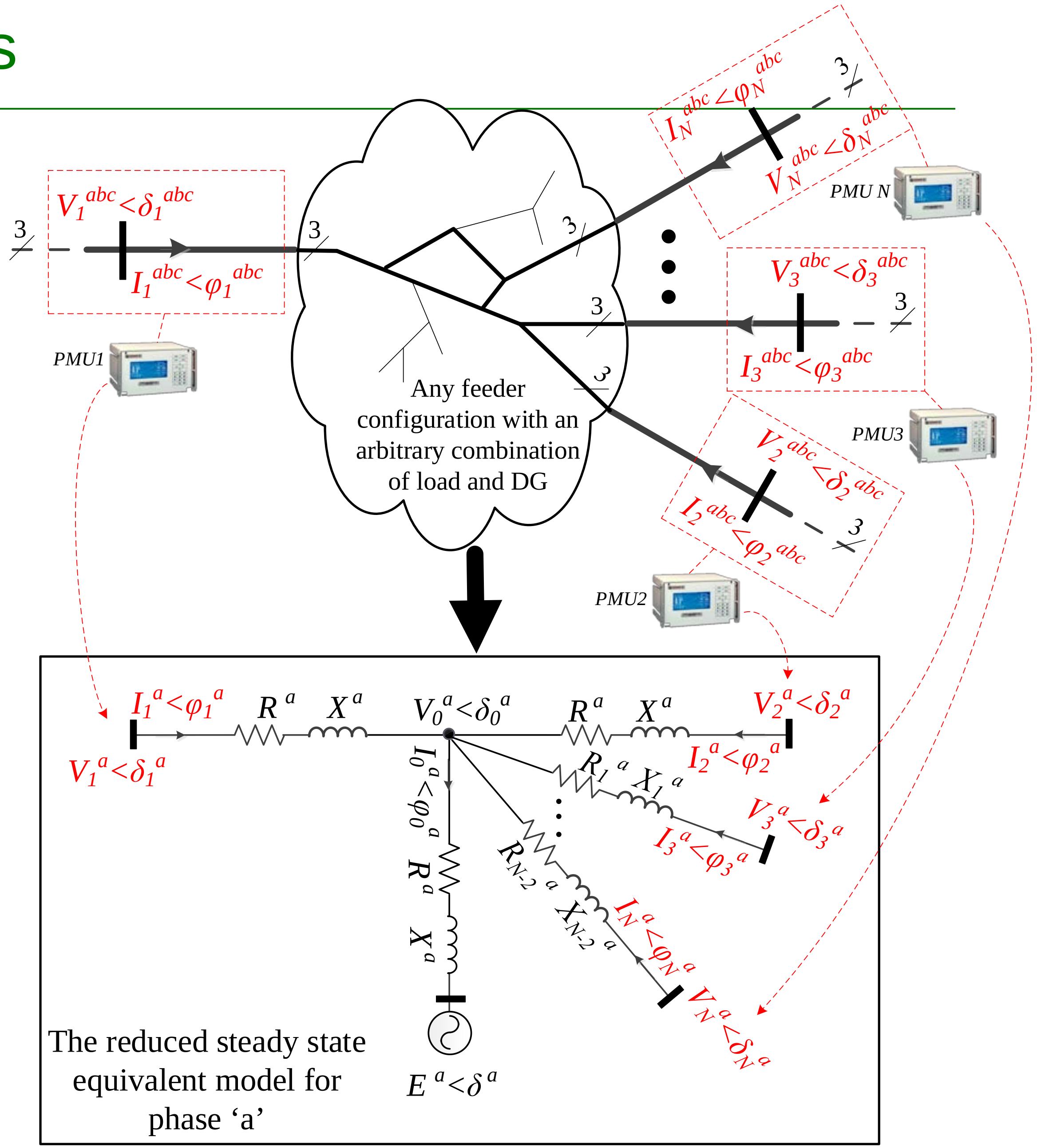


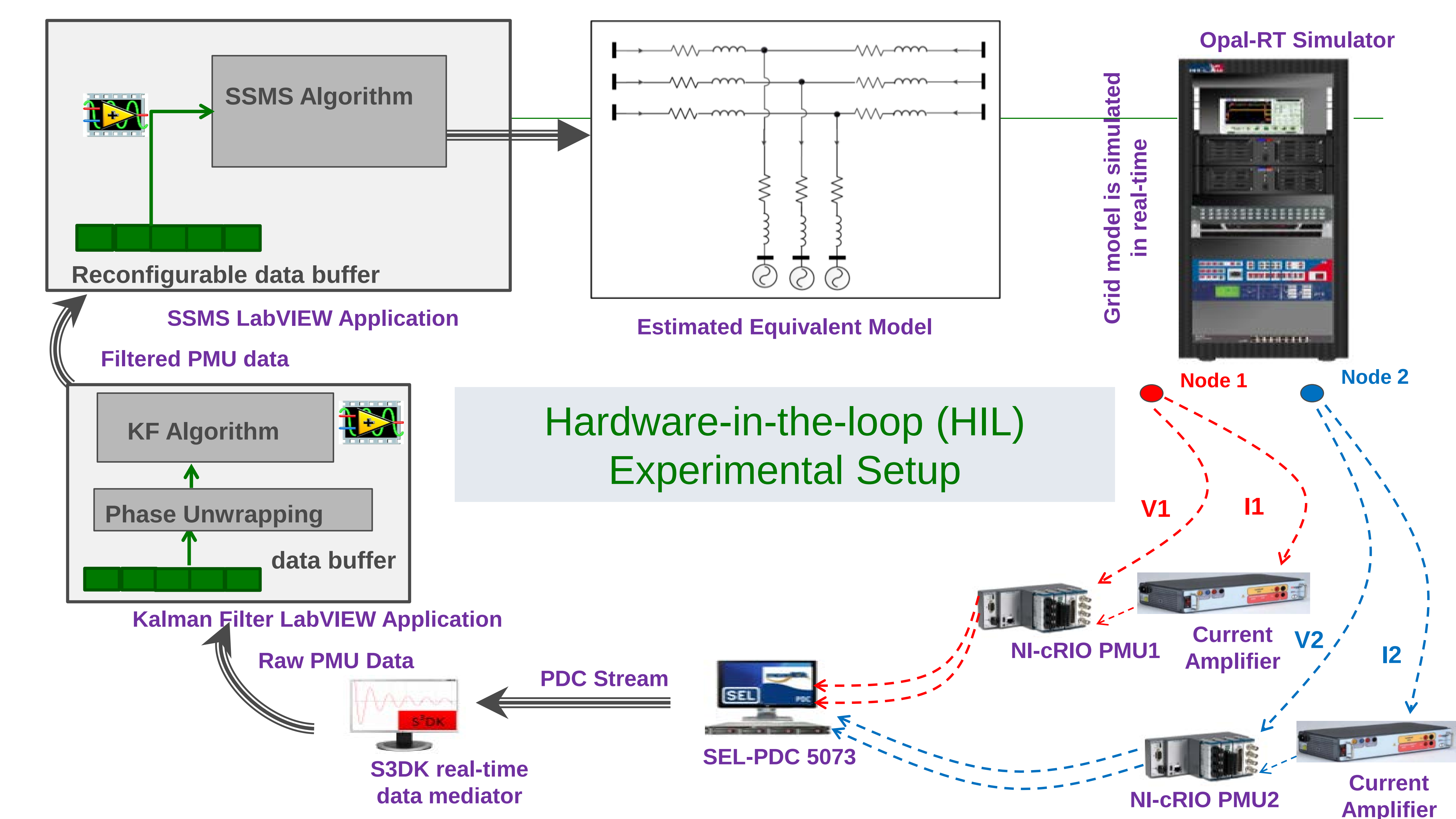
App. 1: Steady-State Model Synthesis

- Assumptions:
  - PMU measurements are available between two (or more) buses in a distribution network
  - They measure all *three-phase voltage and current phasors.*

- A three phase steady state equivalent model can be synthesized for the portion of the distribution network that is located between the installed PMUs.

- The model's parameters are obtained by writing KVL equations across the model branches and equate V_i's and I_i's to PMU measurements.

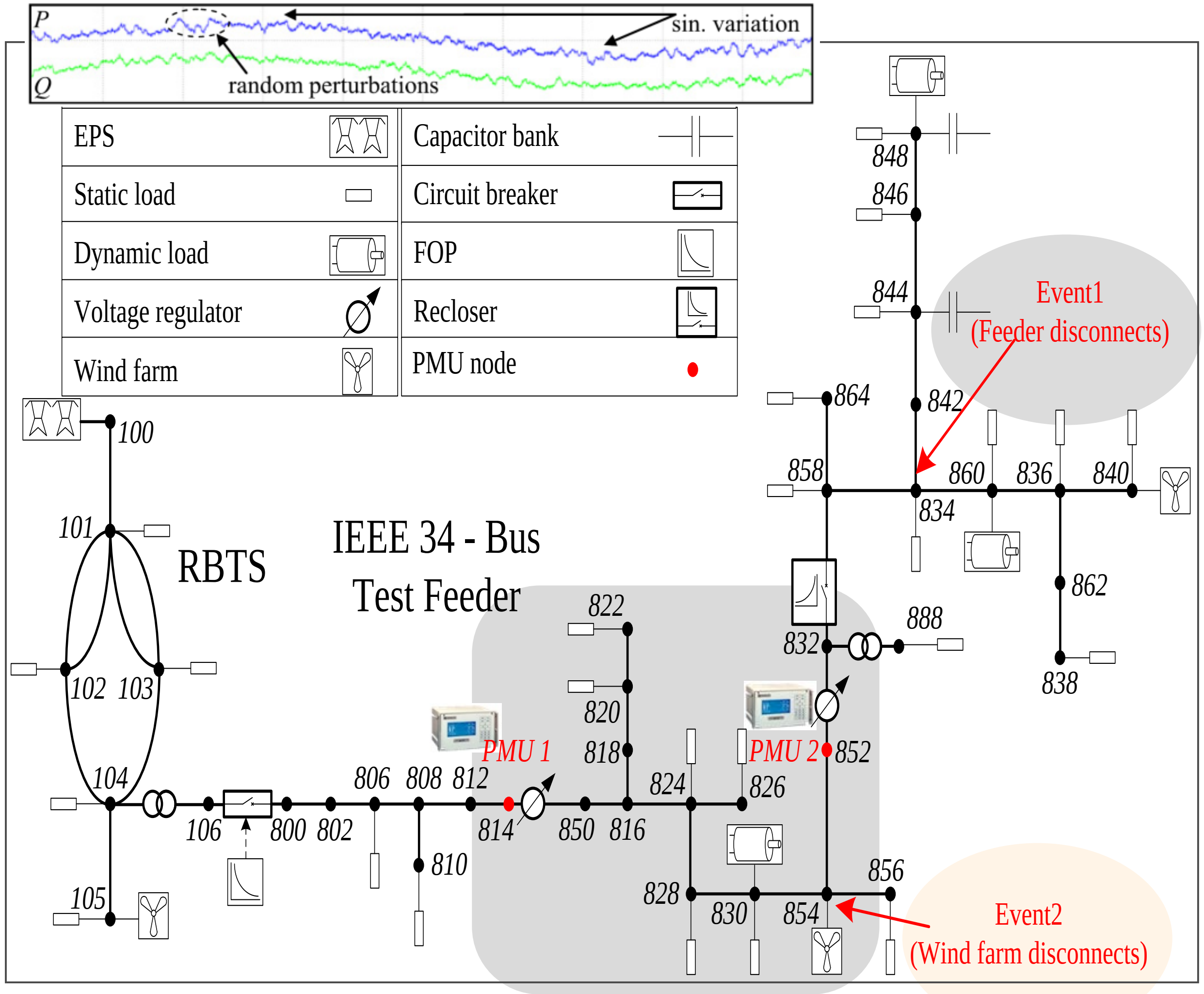




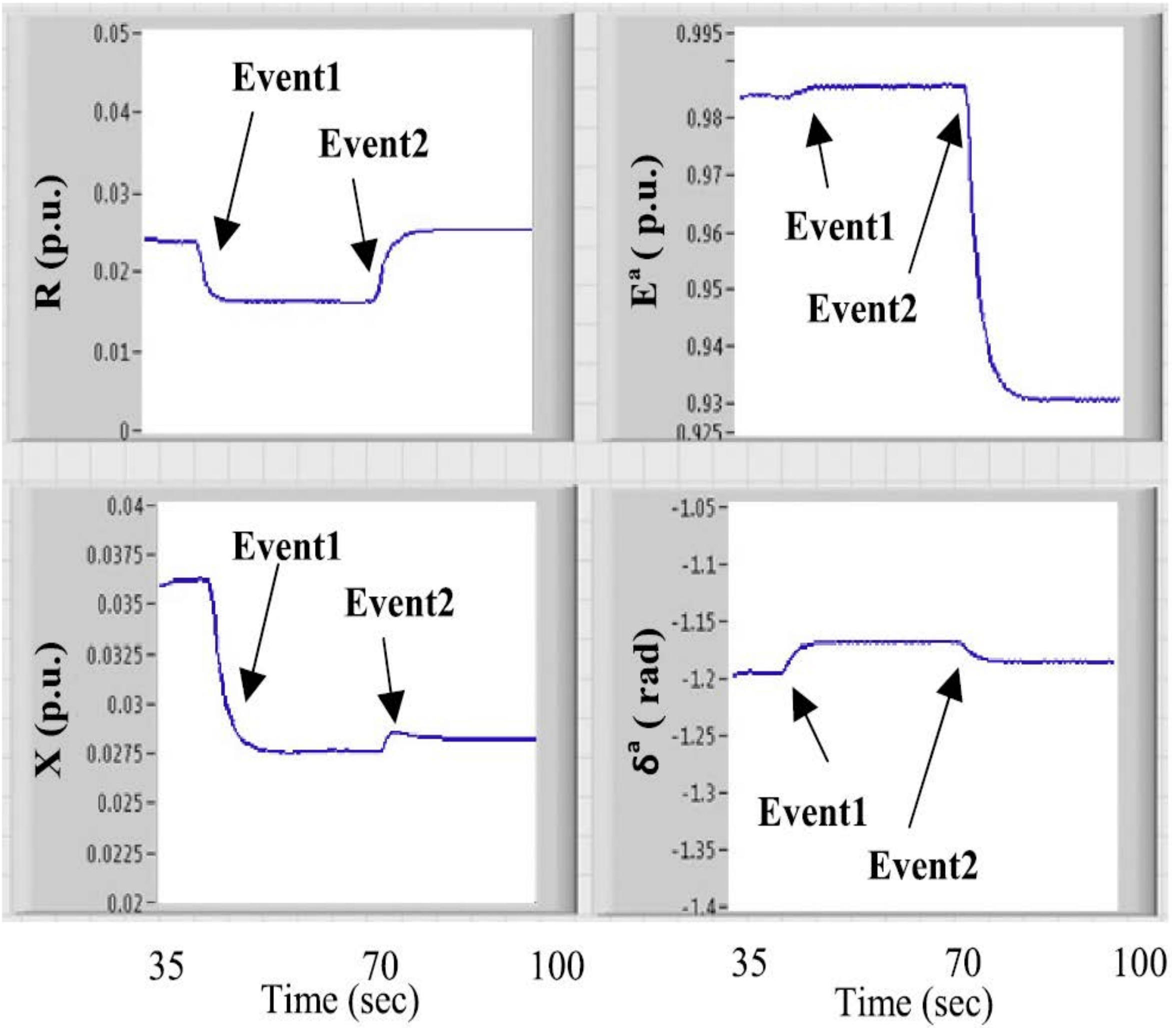
SSMS Algorithm
Reconfigurable data buffer
SSMS LabVIEW Application
Estimated Equivalent Model
Grid model is simulated in real-time
Opal-RT Simulator
Filtered PMU data
KF Algorithm
Phase Unwrapping
data buffer
Kalman Filter LabVIEW Application
Hardware-in-the-loop (HIL) Experimental Setup
Node 1
Node 2
V1
I1
V2
I2
NI-cRIO PMU1
Current Amplifier
NI-cRIO PMU2
Current Amplifier
Raw PMU Data
PDC Stream
SEL-PDC 5073
S3DK real-time data mediator

RT Testing using ADN Model

Event 1: *A lateral MV feeder disconnects at Node 834 at t = 40 s*



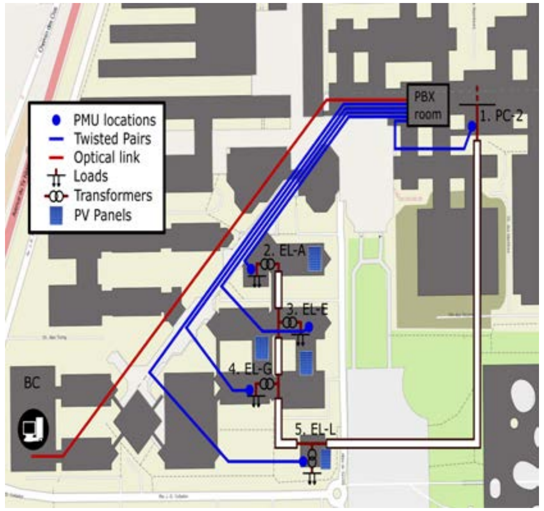
Event 2: *A wind farm generation of 1 MW (0.2 p.u.) disconnects at Node 854 at t = 70 s.*

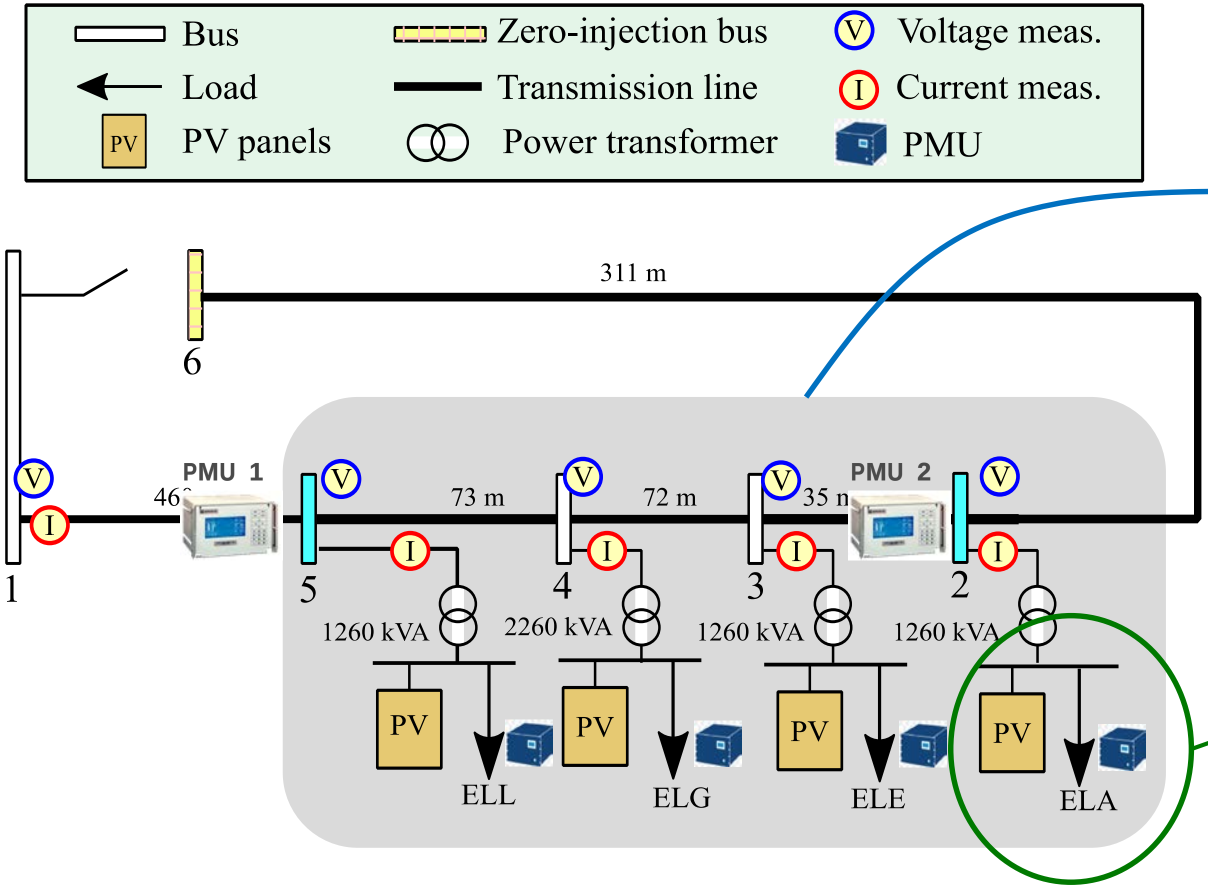


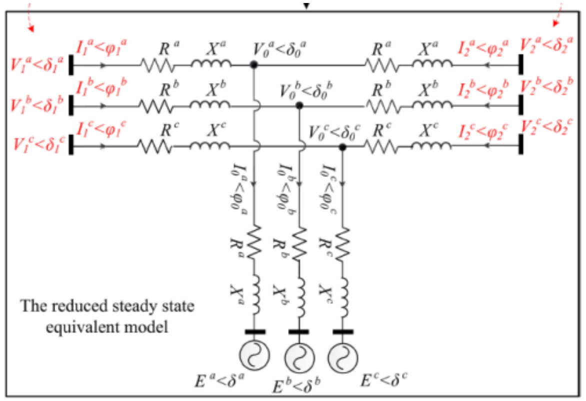
Field Testing @ EPFL Campus, Switzerland w. Prof. Mario Paolone's Group

- Test Site and Conditions:
  - Actual consumed power from each building is measured by a PMU.
  - HV side of transformer feeding the building also measured by a PMU – includes rooftop PV impact.

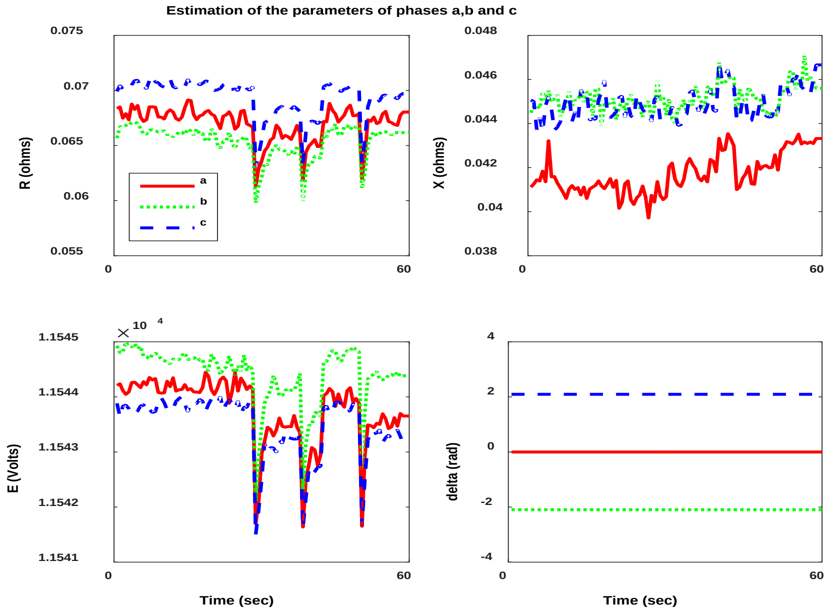
Test Site



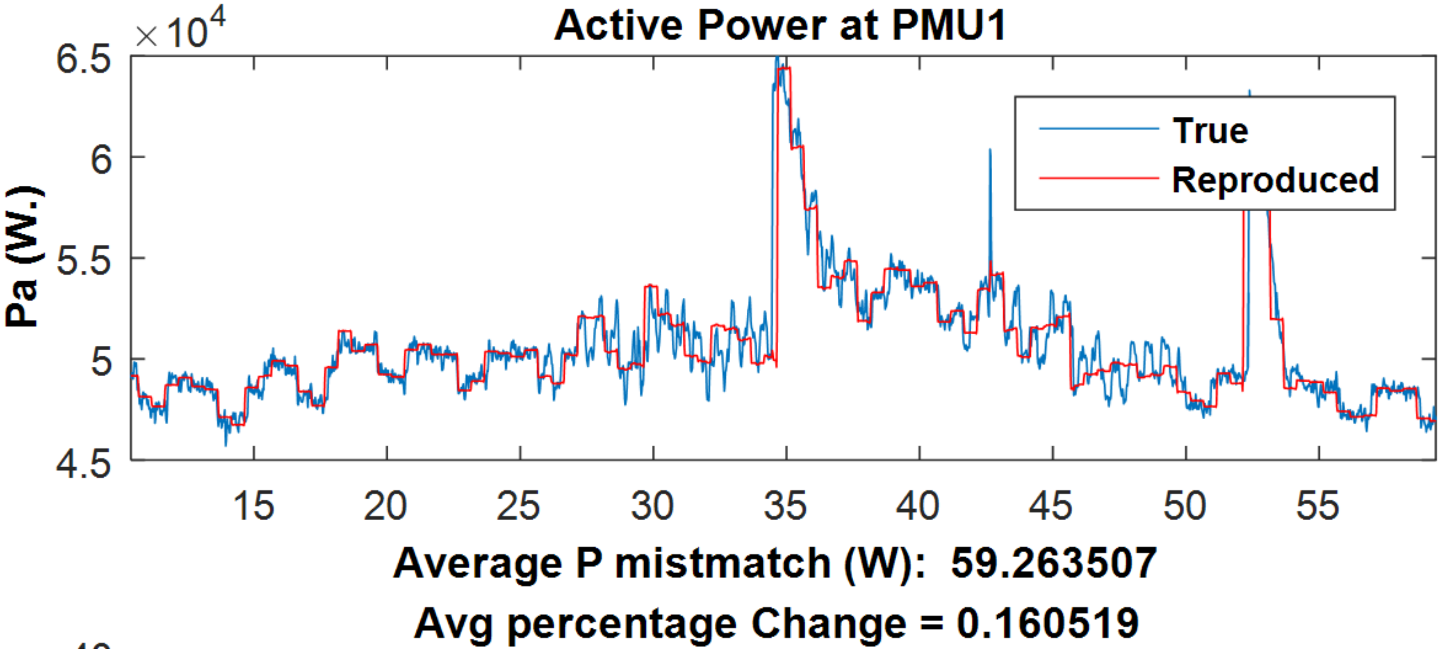


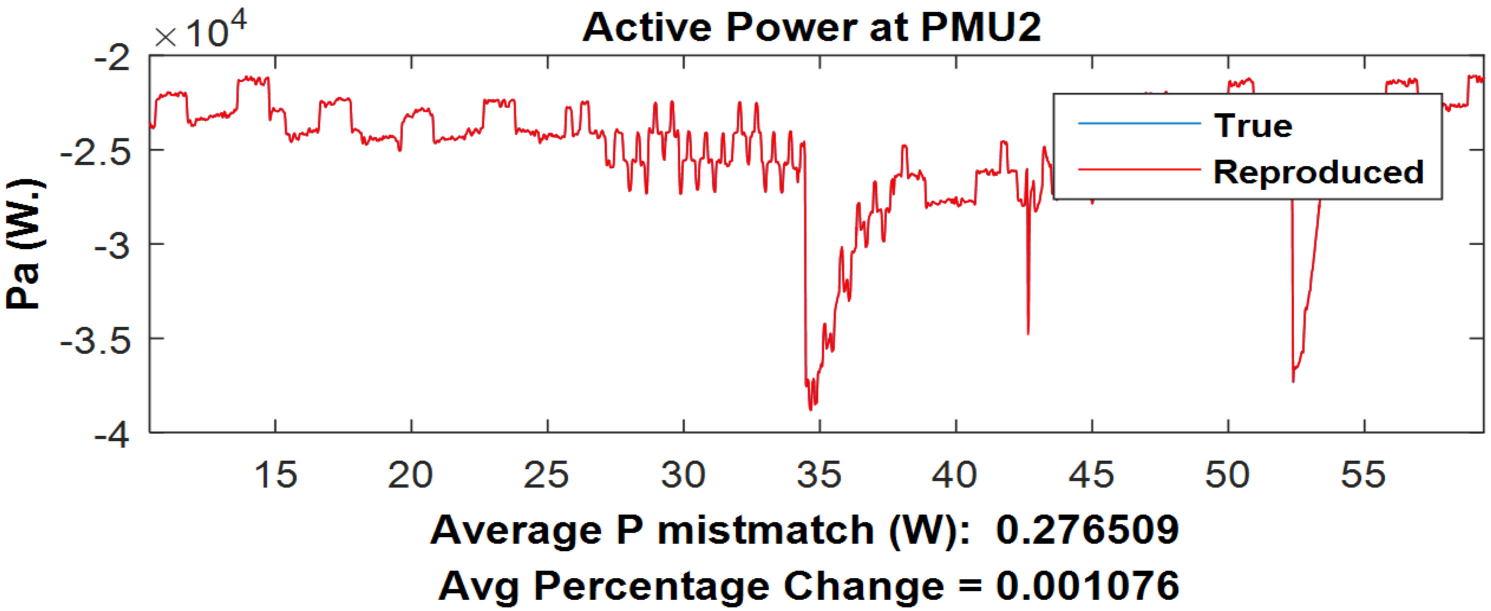


Field Test Results



The SSMS method reproduces the active power accurately, which shows the validity of the SSMS method on a real active distribution network model using real PMU data.





Dynamic Line Rating (DLR) Systems
for Aerial Distribution Feeders

Temperature dependent system

Sag dependent system

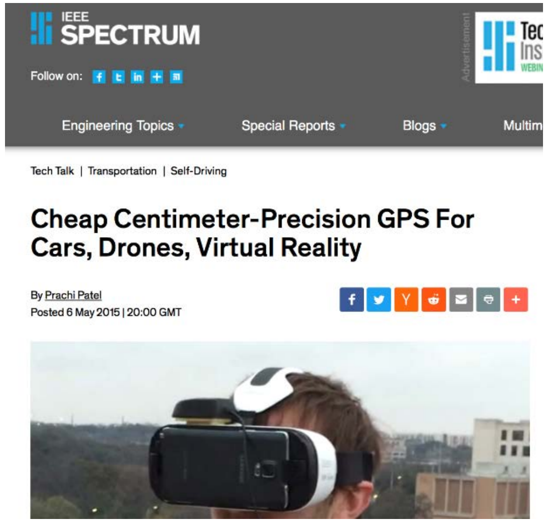
- Based on real time measurements from different types of techniques, and broadly used in transmission.
- Techniques and Physical Principle:
  - o Temperature dependent systems
  - o Tension monitoring systems
  - o Sag dependent systems

Thermal Principle-Based DLR Computations

Mechanical Principle-Based DLR Computations

Tension dependent system

- During favorable conditions line can be loaded more without exceeding maximum allowed conductor temperature
- DLR System for aerial distribution systems:
  - o Why? Manage loading in bi-directional flow feeders.
  - o Low-cost GPS-based positioning is becoming available, and also sag sensors based on this technology.
  - o Weather data => provided by a close-by weather station.
  - o Line loading => provided by PMU!
  - o Real-time sag => provided by a GPS-based measurement device.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By Prachi Patel
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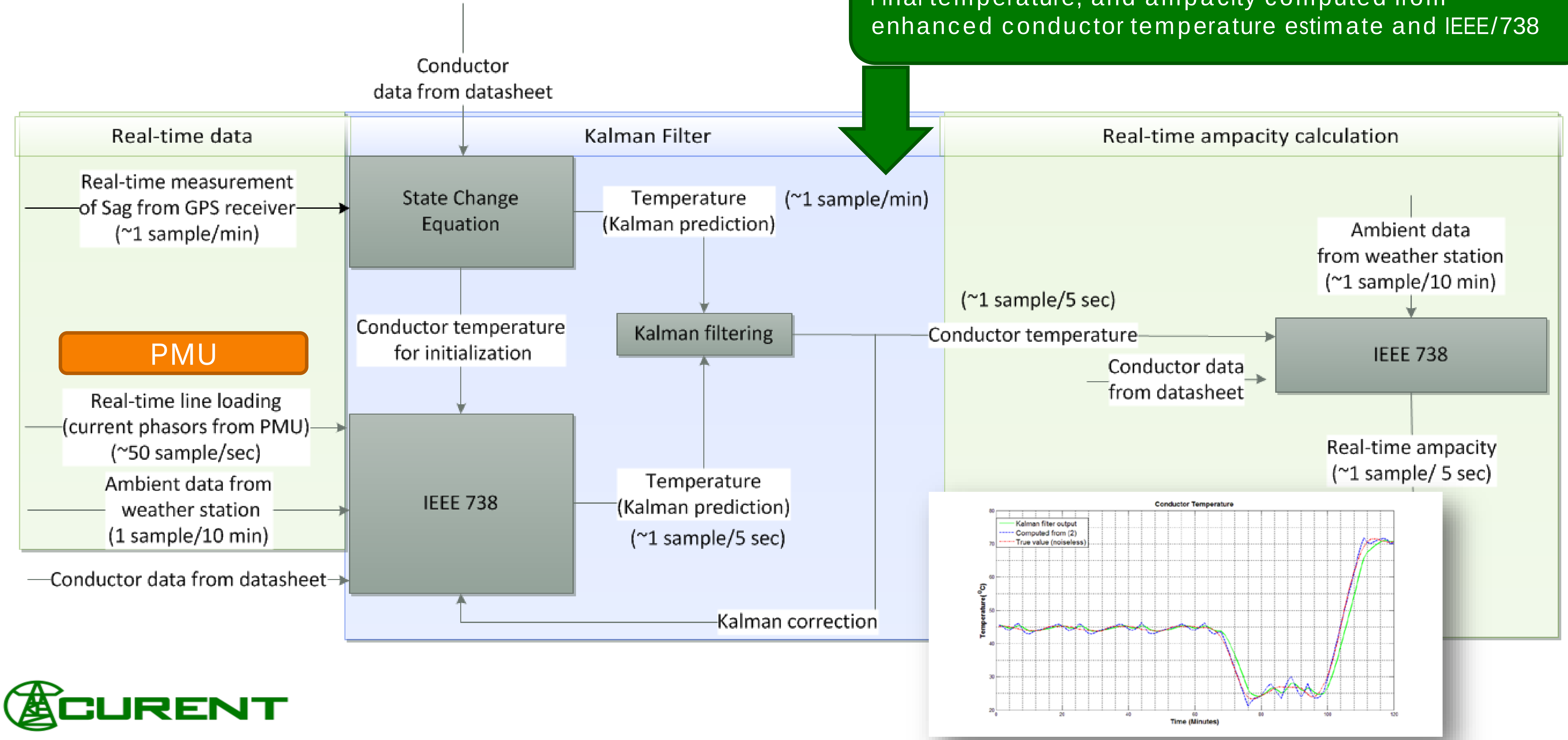
Enhancing conductor temperature estimates:
Use both principles → Apply Kalman Filtering

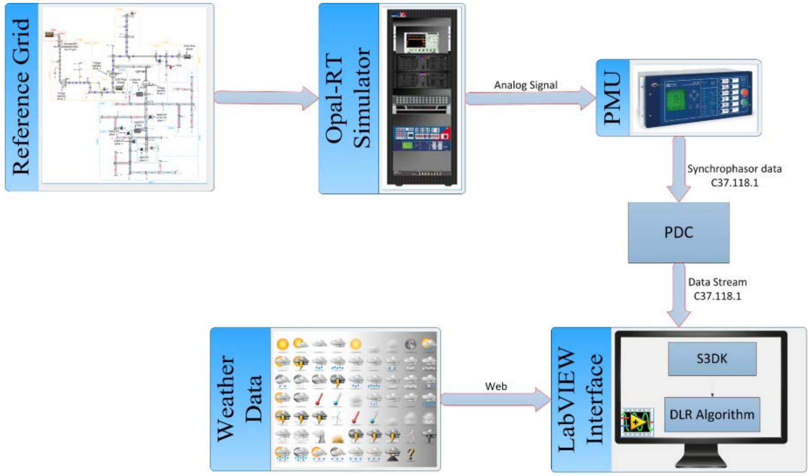
Kalman filter is used to merge the conductor temperature estimates from both methods (thermal and mechanical principles combined)

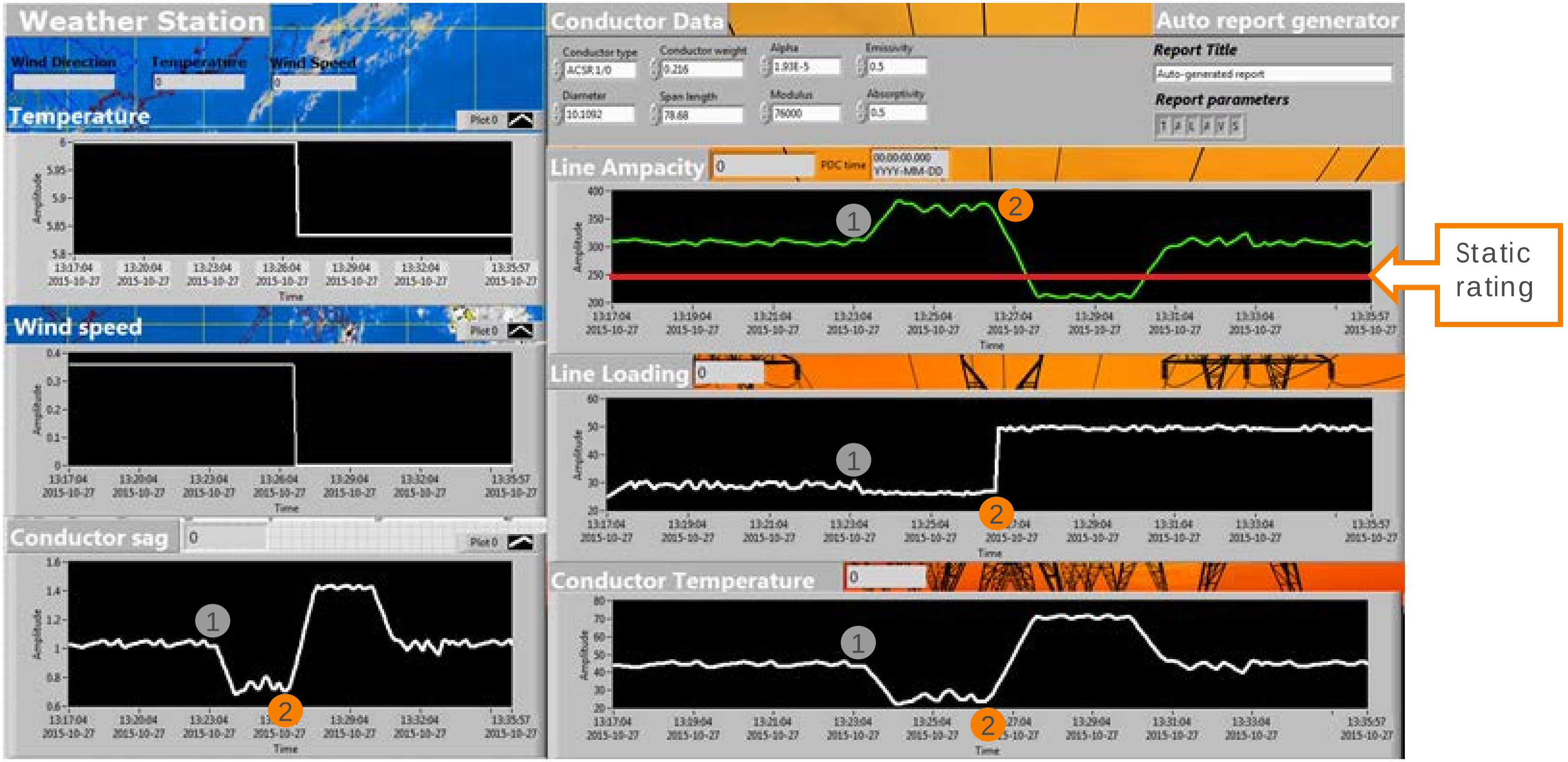
Final temperature, and ampacity computed from enhanced conductor temperature estimate and IEEE/738



Rea-Time HIL Simulation Testing

PMU Data, Weather data from weather station, sag data (pre-calculated)





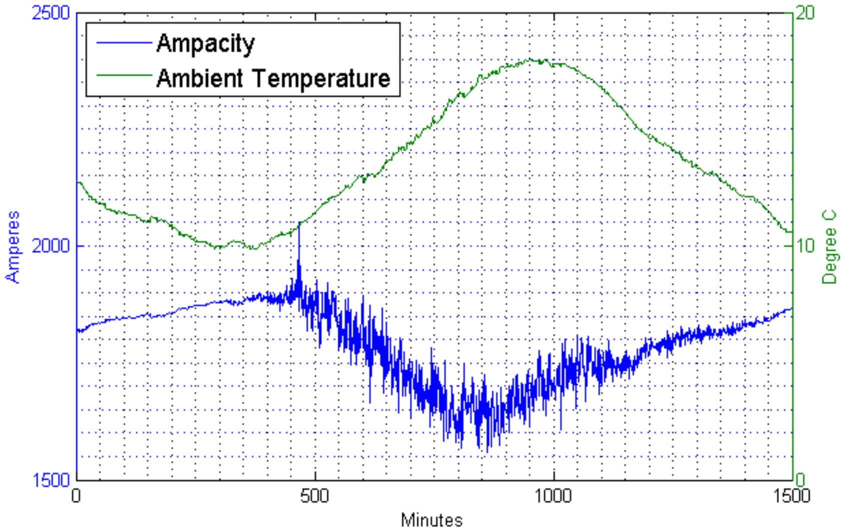
Event 1 (1)   Event 2 (2)

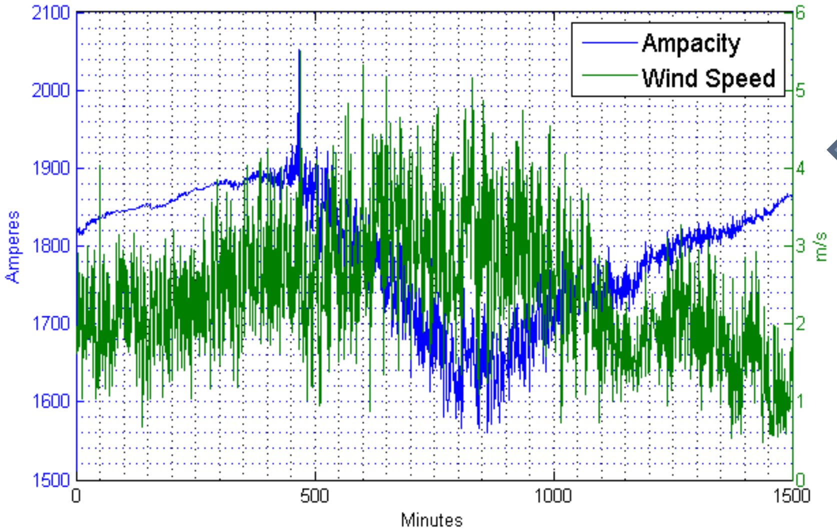
Event 1: Outage of a line.

Event 2: Outage of a wind generation (more power to be drawn from the grid).

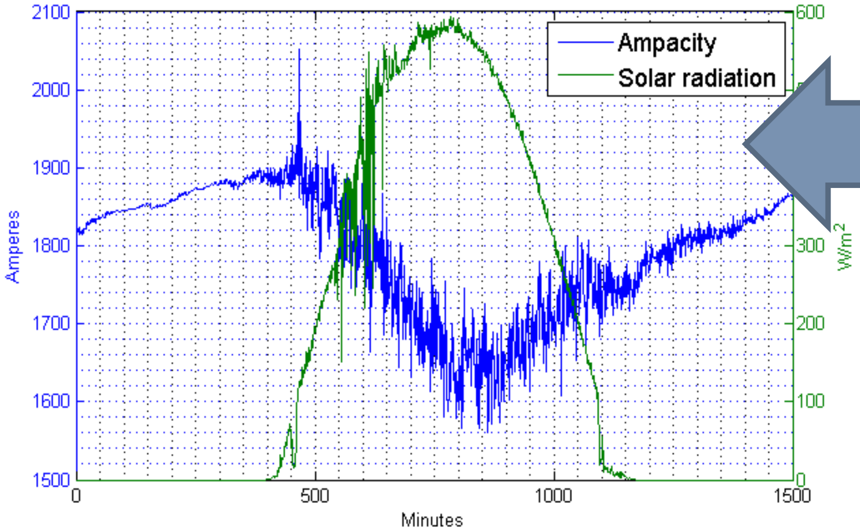
Field Data Analysis using the Proposed Method

Impact of different variables from **real** recorded sensor data, and correlation analysis





Ambient temperature correlates with Ampacity, not wind.



Solar radiation correlates with Ampacity.

	Ampacity	Conductor.Temperature	Solar.Radiation	Ambient.temperature	Wind.Speed	Line.loading
Ampacity	1	-0.8	-0.65	-0.88	-0.09	-0.41
Conductor.Temperature	-0.8	1	0.64	0.87	0.24	0.79
Solar.Radiation	-0.65	0.64	1	0.47	0.54	0.44
Ambient.temperature	-0.88	0.87	0.47	1	0.17	0.48
Wind.Speed	-0.09	0.24	0.54	0.17	1	0.21
Line.loading	-0.41	0.79	0.44	0.48	0.21	1

1 0.8 0.6 0.4 0.2 0 -0.2 -0.4 -0.6 -0.8 -1

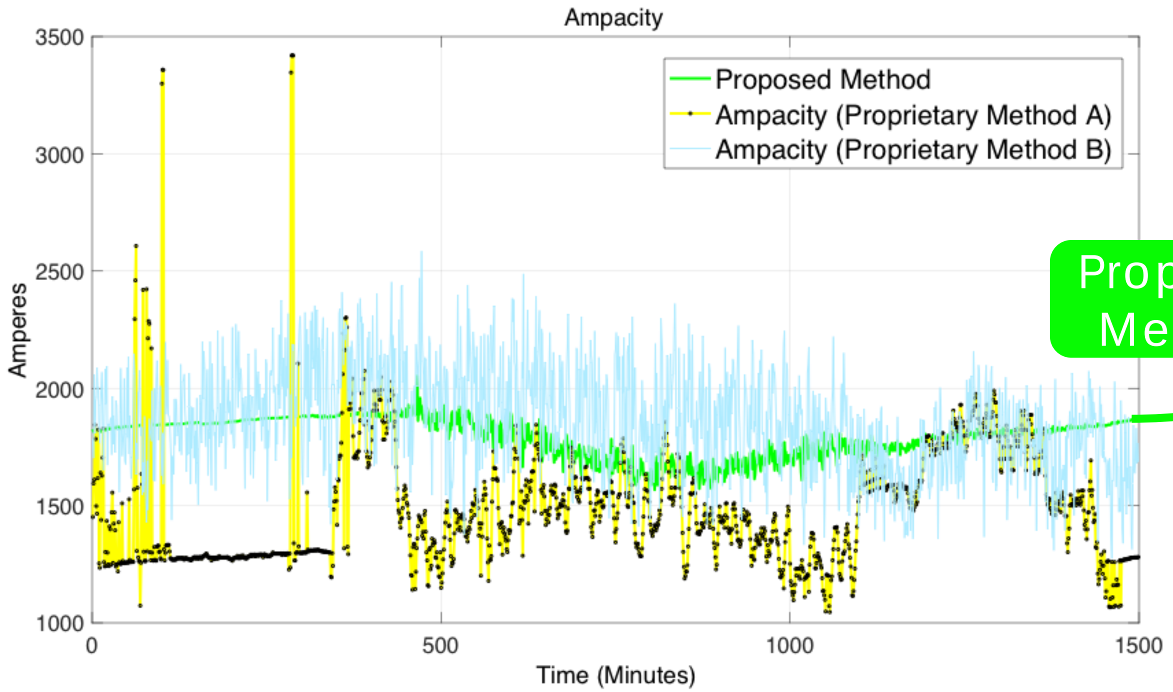
Comparison with Proprietary Solutions

Kalman Filtering vs respect of two commercial solutions

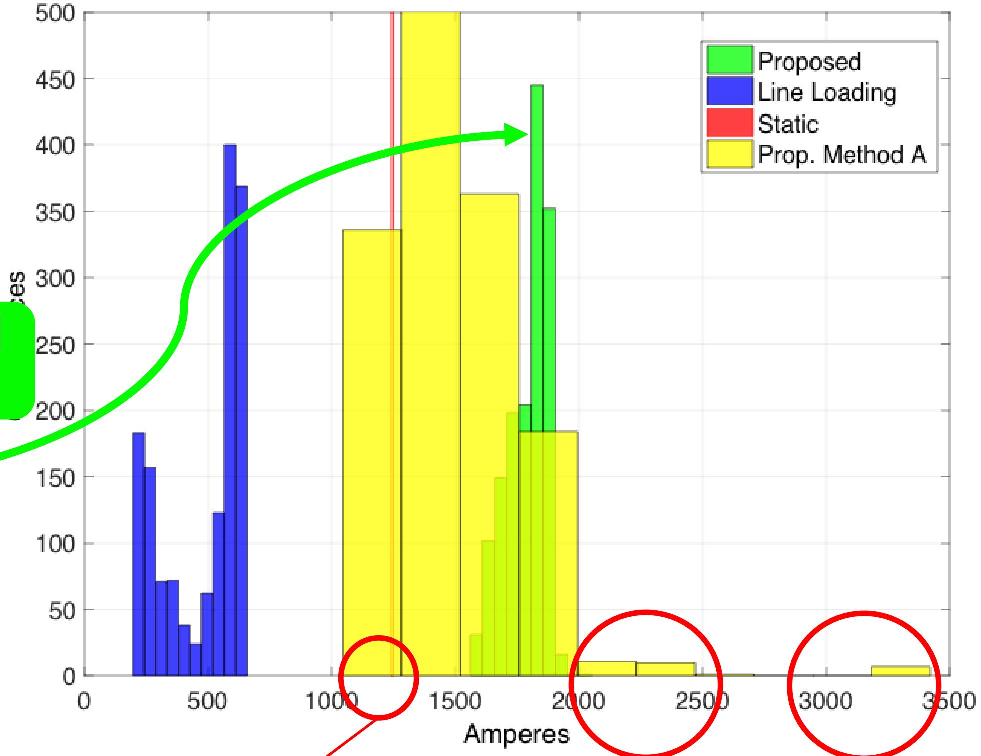
http://www.sciencedirect.com/science/article/pii/S2352467717300528

Important to determine correctly the Ampacity and setting of operation limits.

Kalman filter helps in reducing variance of output!

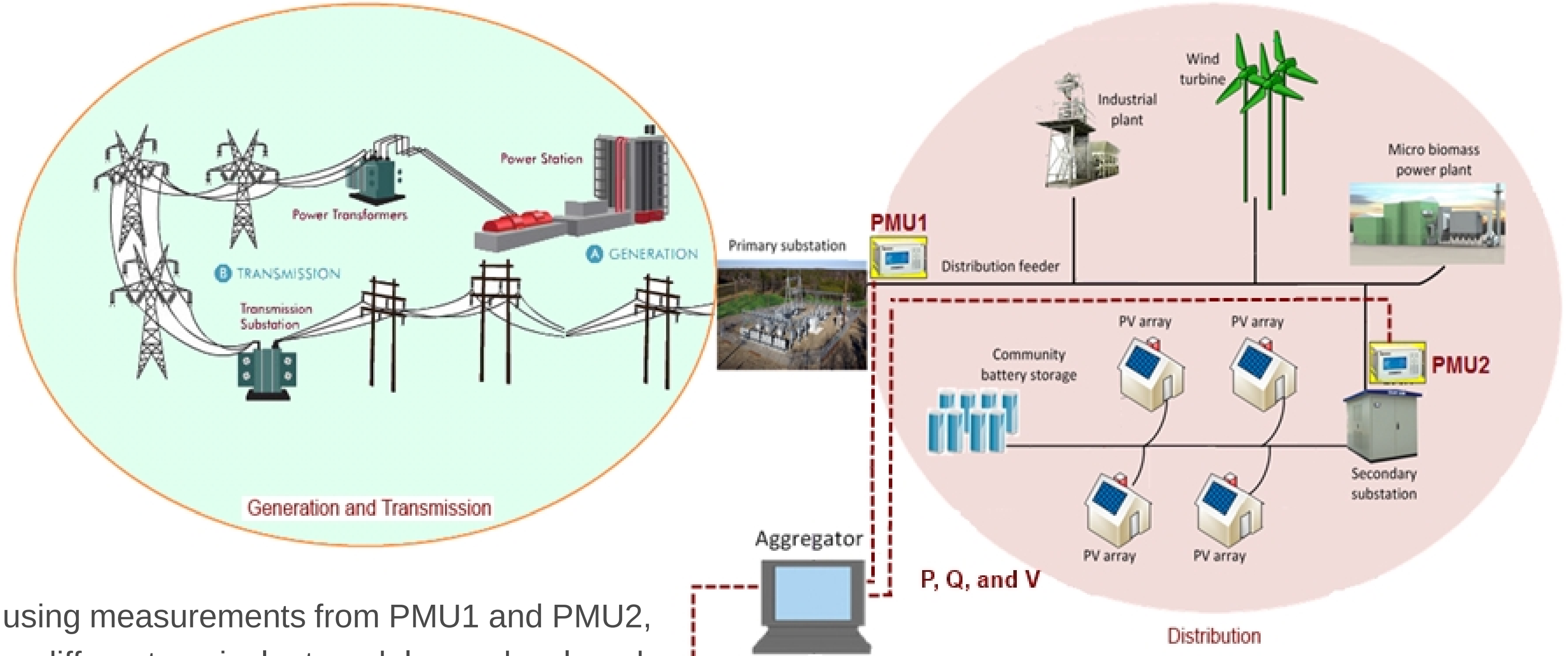


Proposed Method

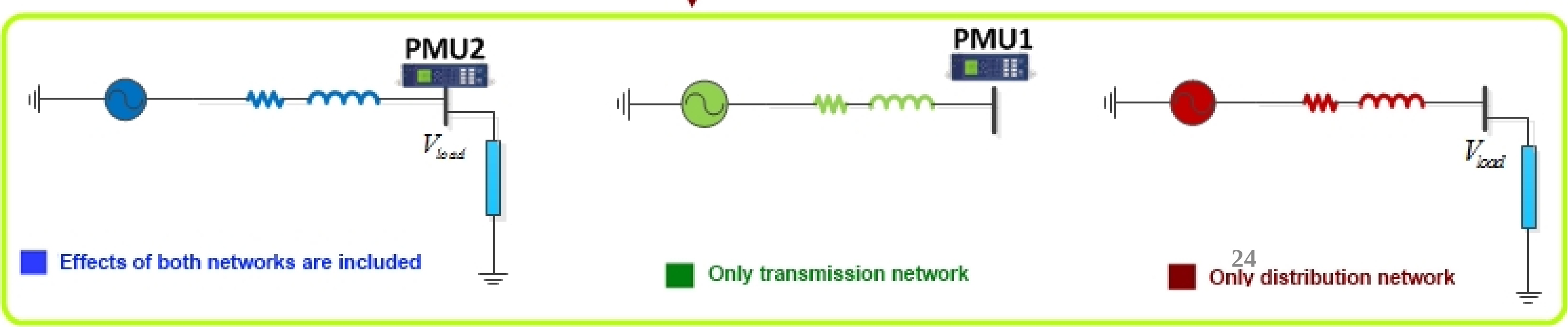


Over/Under Estimation of Proprietary Method

App. 3: Decoupled Voltage Stability Analysis of TNs and ADNs

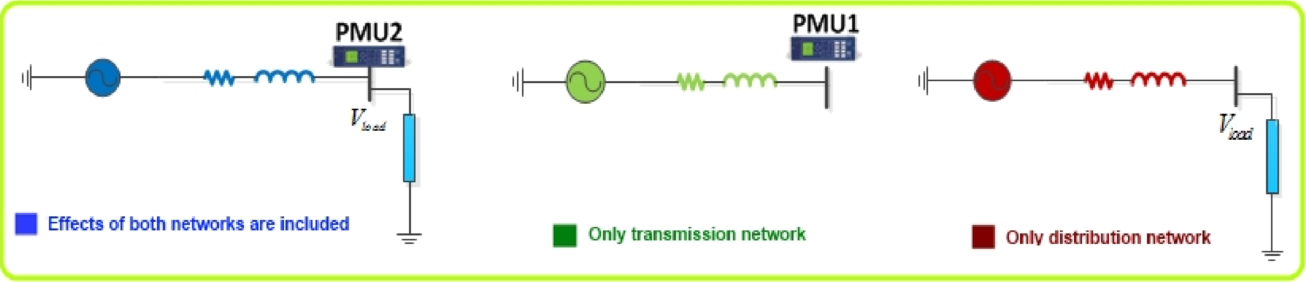


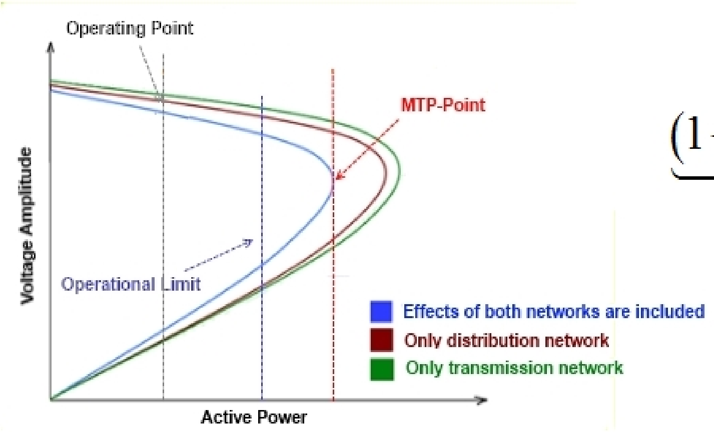
By using measurements from PMU1 and PMU2, three different equivalent models are developed



App. 3: Methodology

- Three different Power vs. Voltage (or PV) curves are calculated from the three models.
- The voltage stability and instability indices are calculated from these models:
  - **Can help to pin-point the contributions of two networks on the overall system voltage stability!**

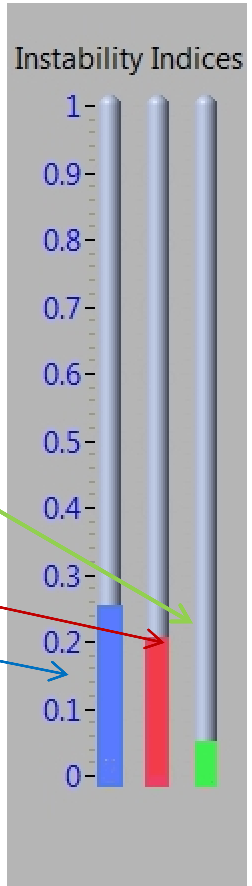




$$\underbrace{(1-VSI_{total})}_{VISI_{total}} = \underbrace{(1-VSI_{dist.})}_{VISI_{dist.}} + \underbrace{(1-VSI_{trans.})}_{VISI_{trans.}}$$

$VSI =$ Voltage Stability Index

$VISI =$ Voltage Instability Index



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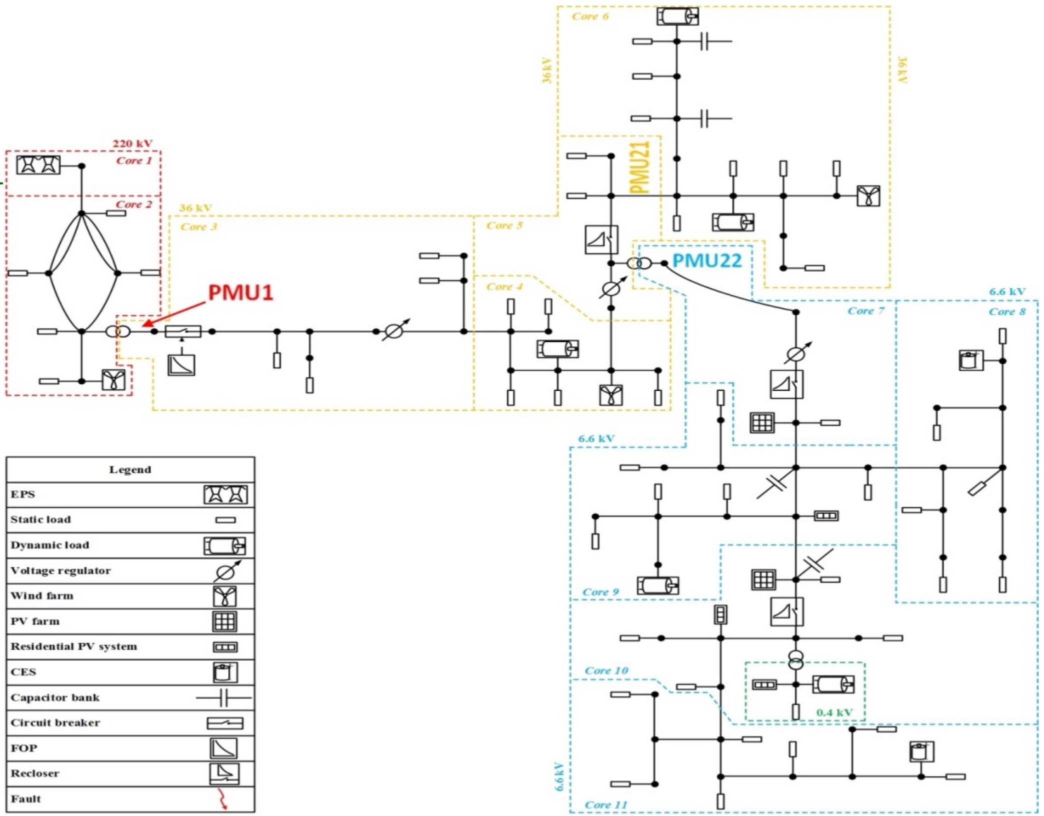
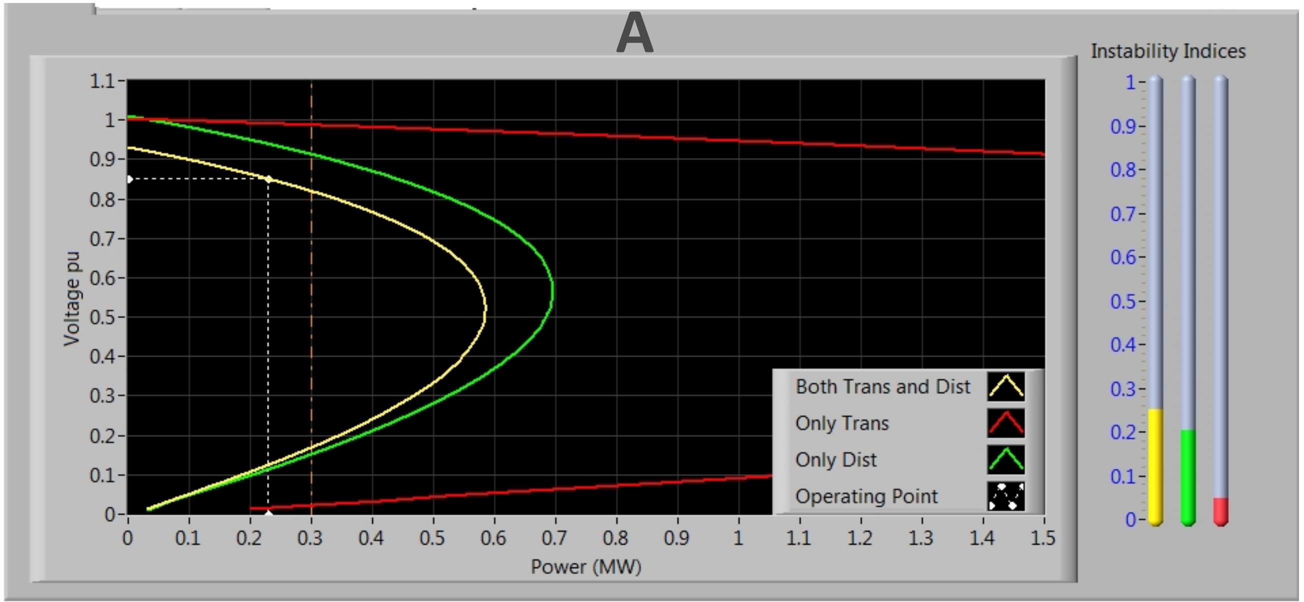
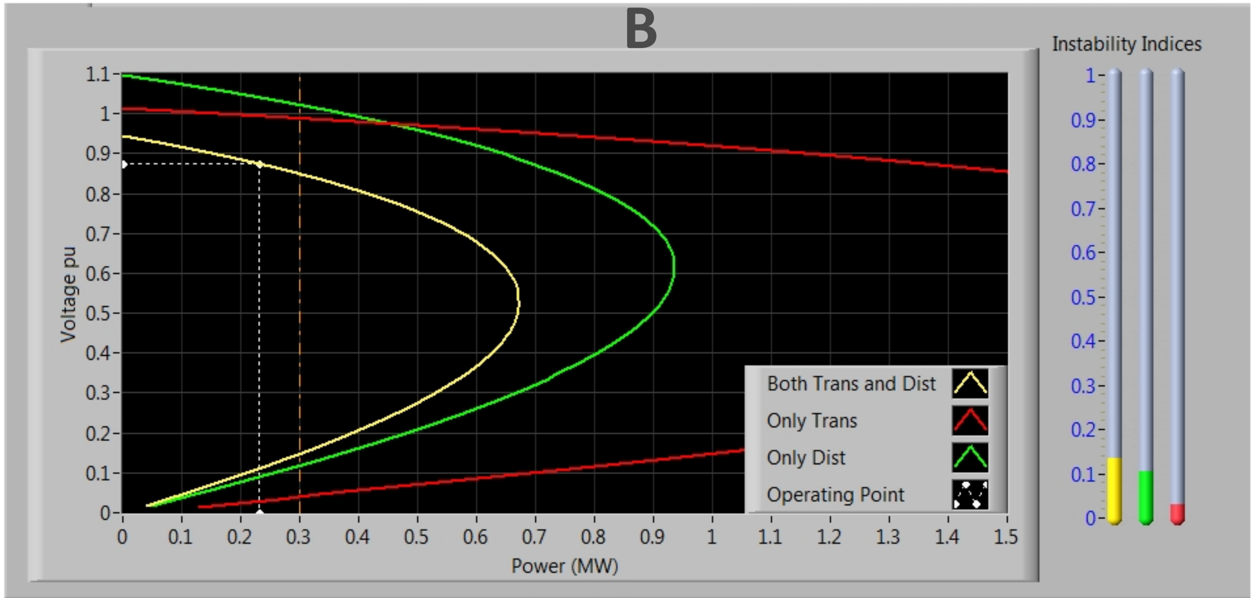
App. 3: Real-Time HIL Testing

- Real-time simulations results:
  - o Observation point at LV network, i.e. PV curves seen from PMU22:
- Cases:
  A. All distributed generation inside MV network is disconnected
  B. All distributed generation inside MV network is connected

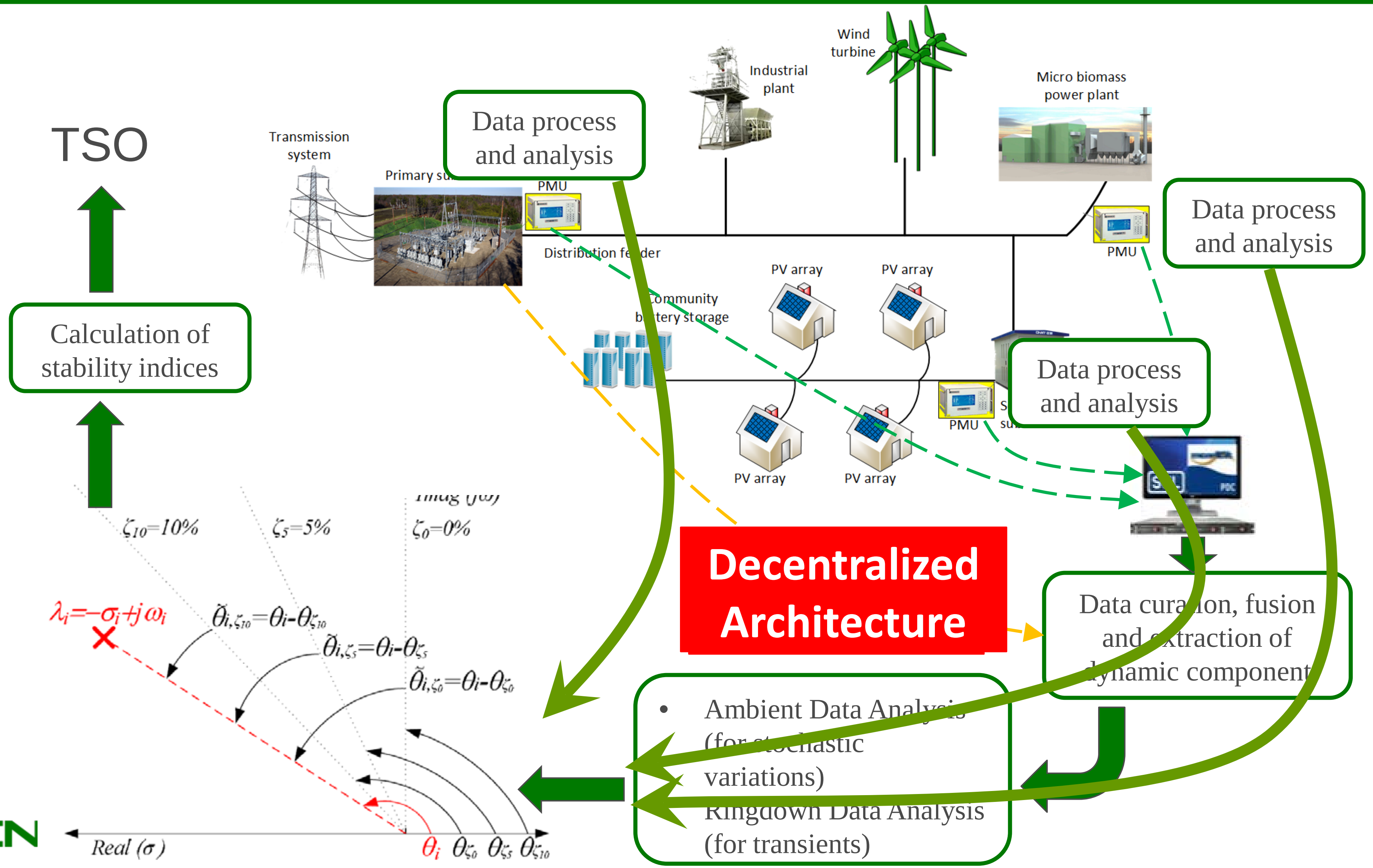






App. 4: Distributed Mode Estimation

Real-Time Oscillation Detection and Monitoring in Local Active Distribution Networks



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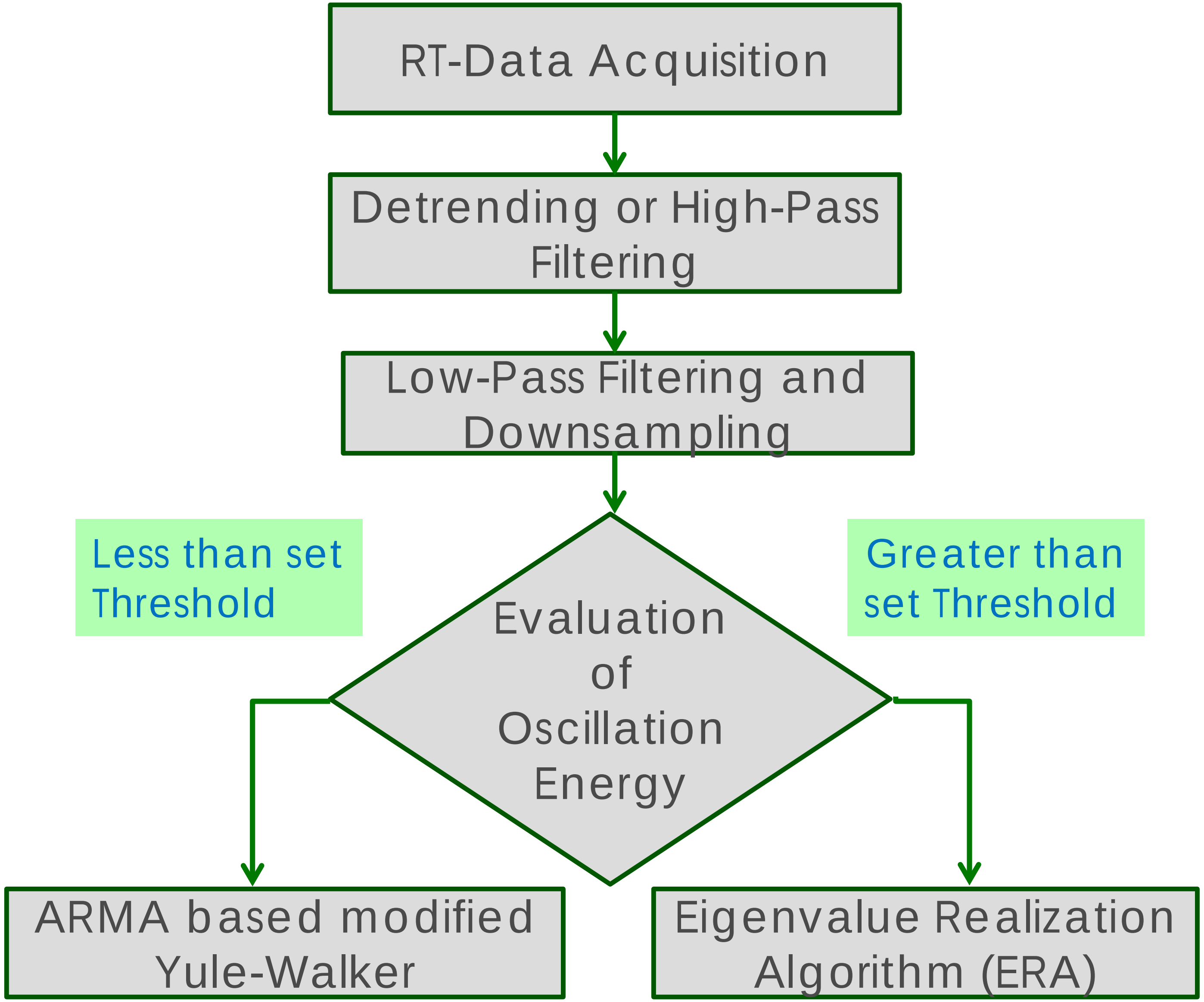
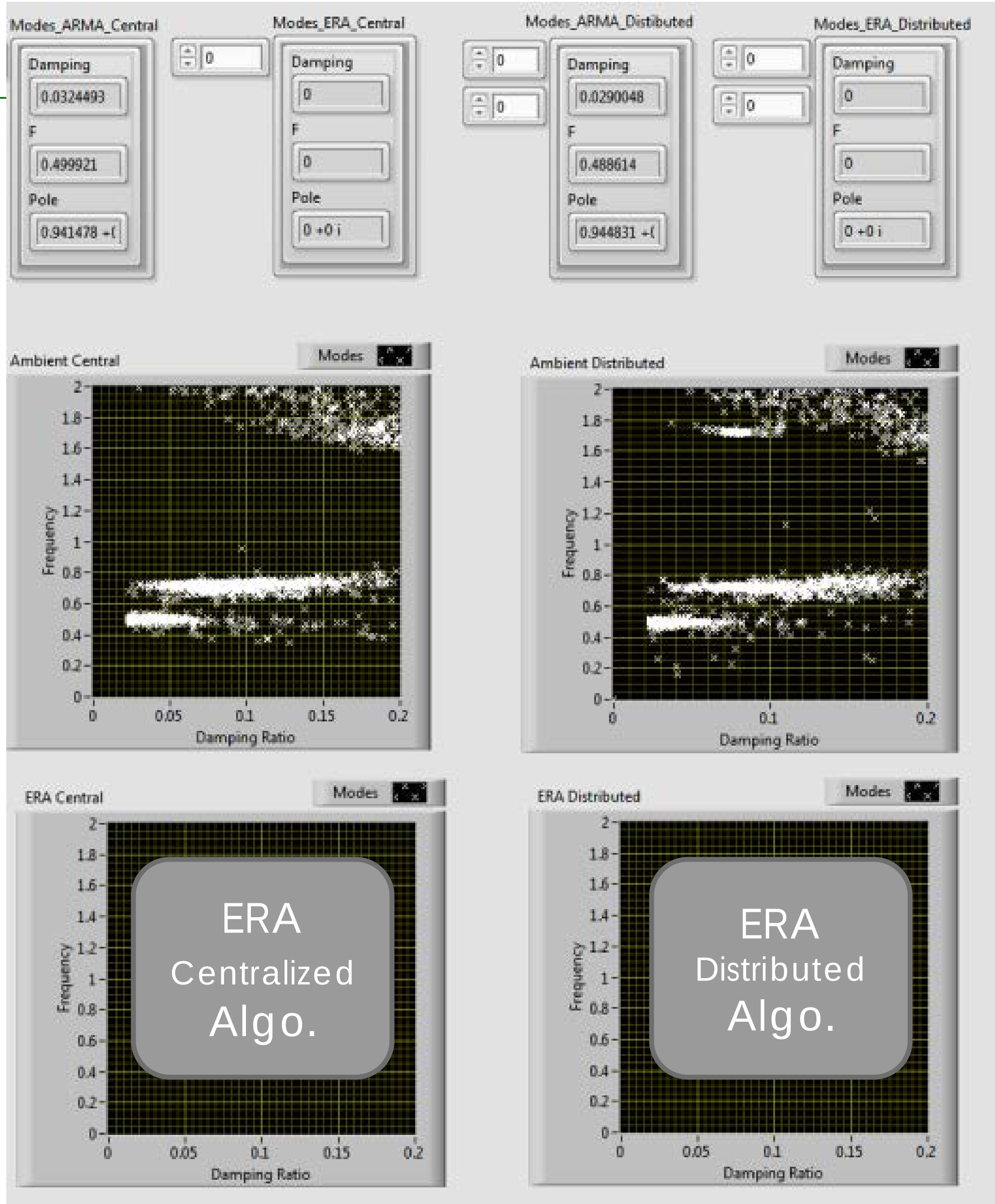
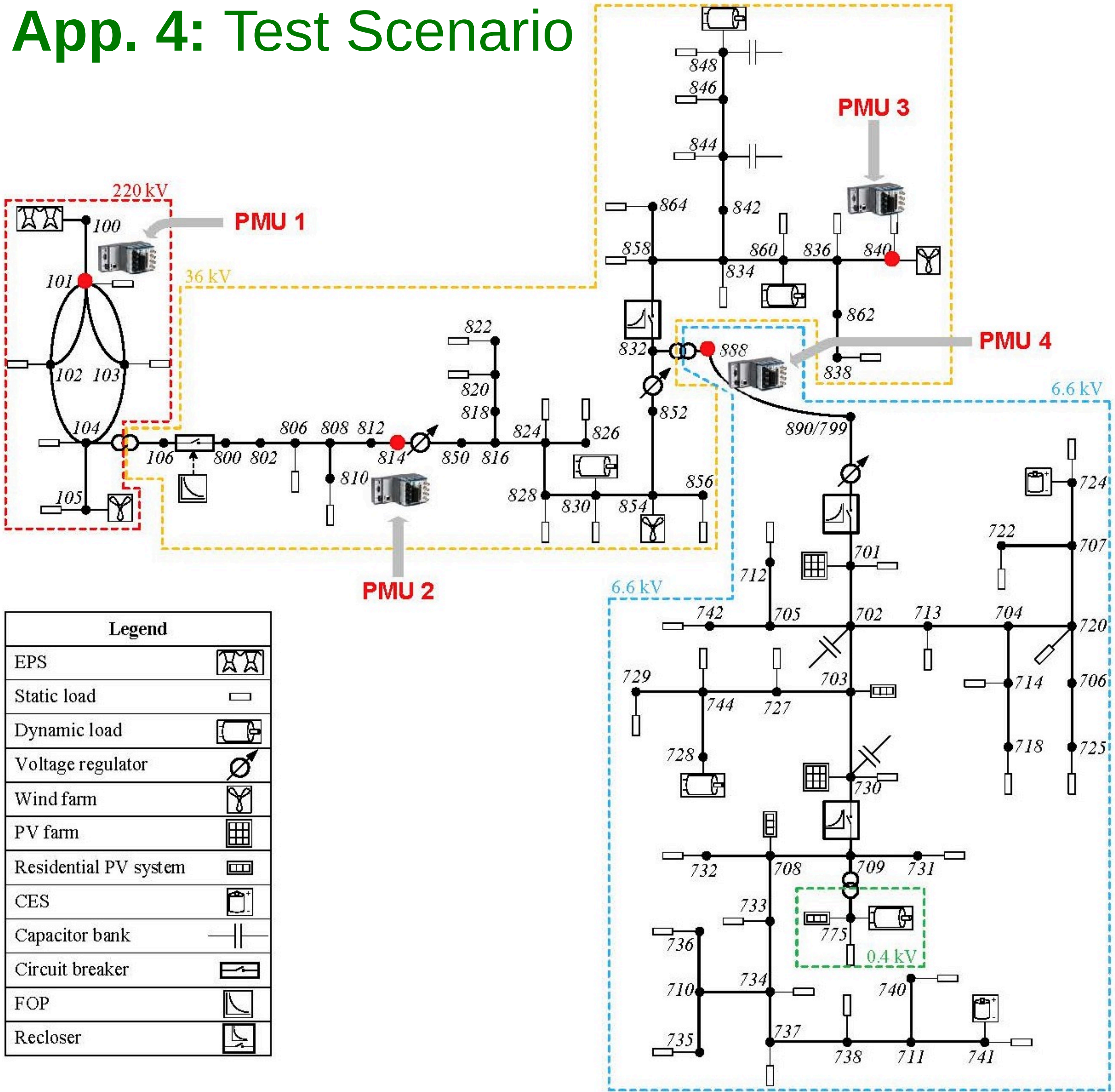
App. 4: Mode Estimation Algorithm(s) Implemented



LabView Implementation Monitor



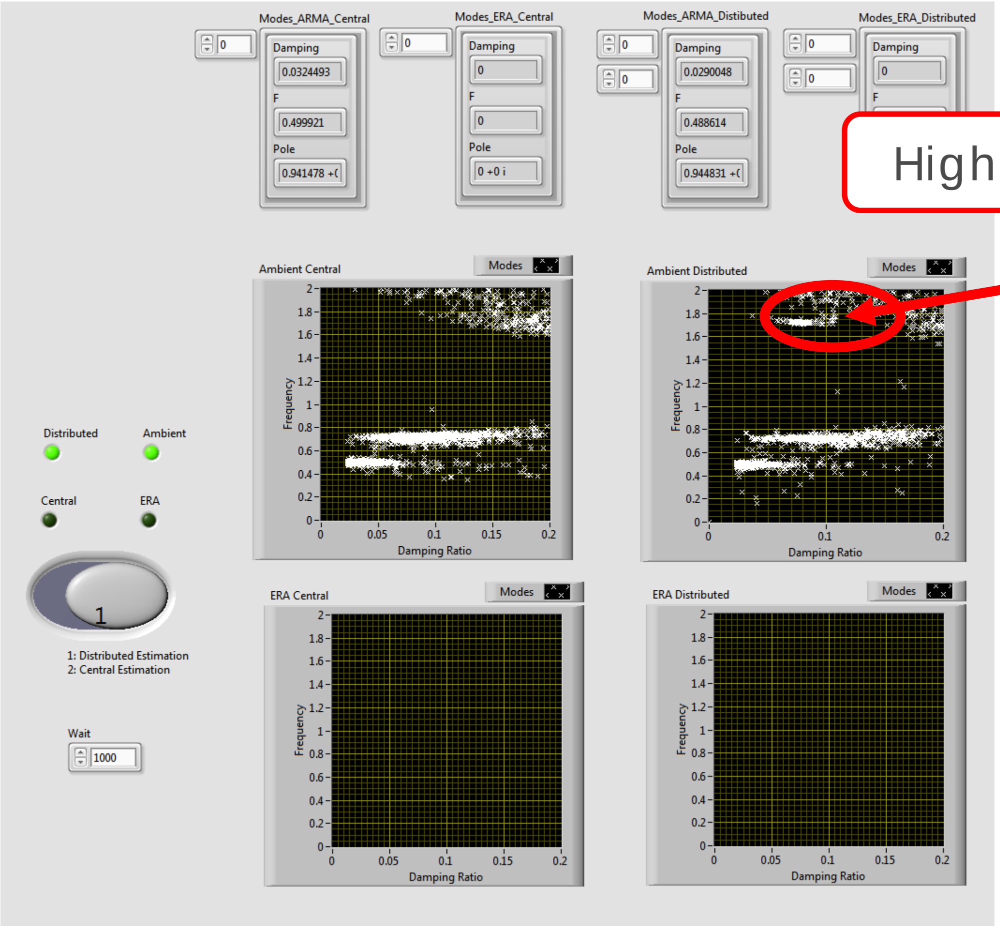
App. 4: Test Scenario

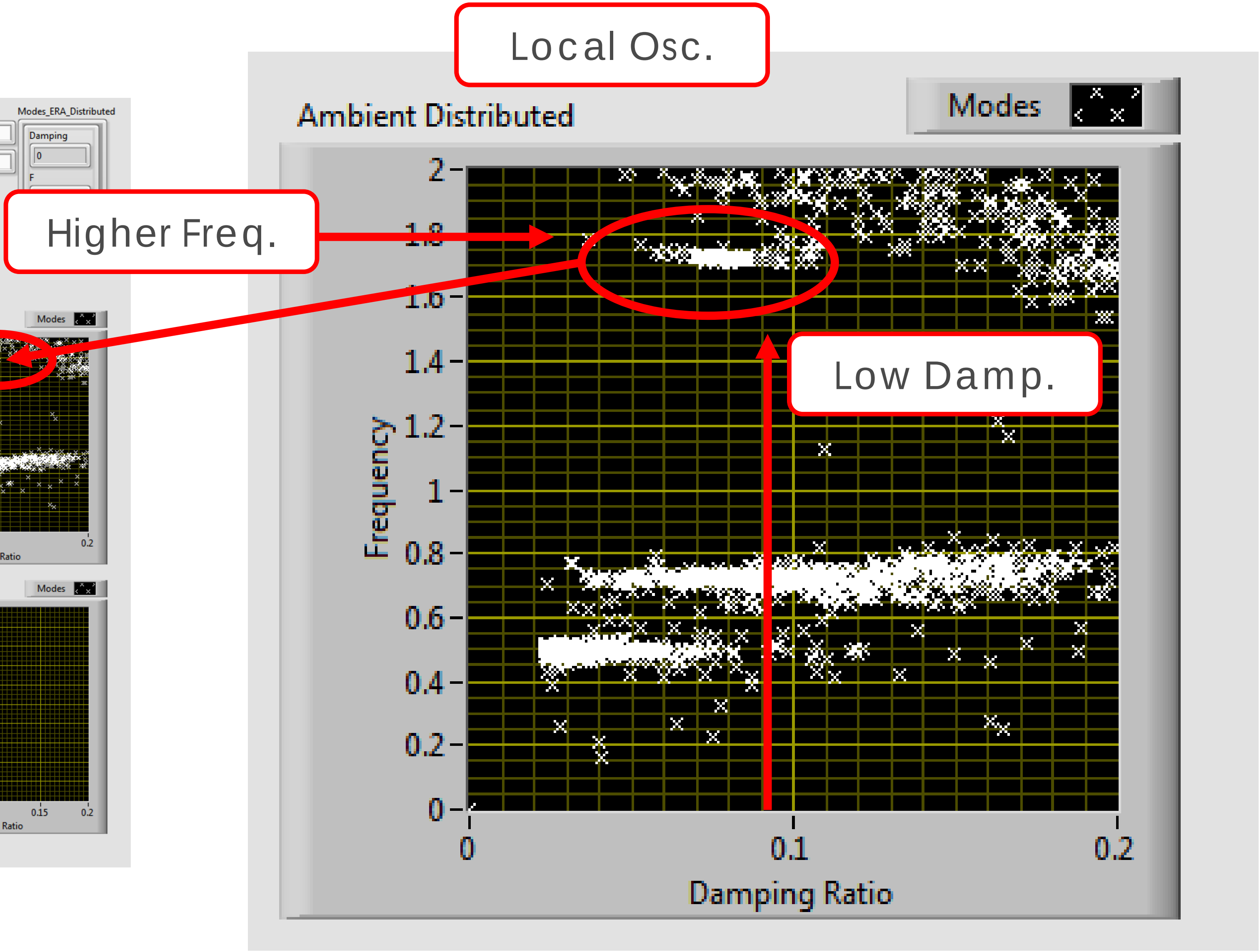


- 4 PMUs placed at nodes 101, 814, 840 and 888 (PMU1, PMU2, PMU3 and PMU4 respectively).
- Inter-Area oscillation (mode) present throughout the network. A low-level, local oscillation was forced at node 888 in the LV section.
- In decentralized architecture, Synchrophasor data is processed separately for each PMU. Each processor give mode-estimates based on individual PMU data.
- Voltage Magnitude and Voltage Angle difference Signals were used to identify the modes.

Mode	Frequency
Mode 1 (inter-area)	0.41 Hz
Mode 2 (forced local)	1.70 Hz

App. 4: RT-HIL Testing under Ambient Conditions
Centralized vs decentralized architecture in local mode visibility





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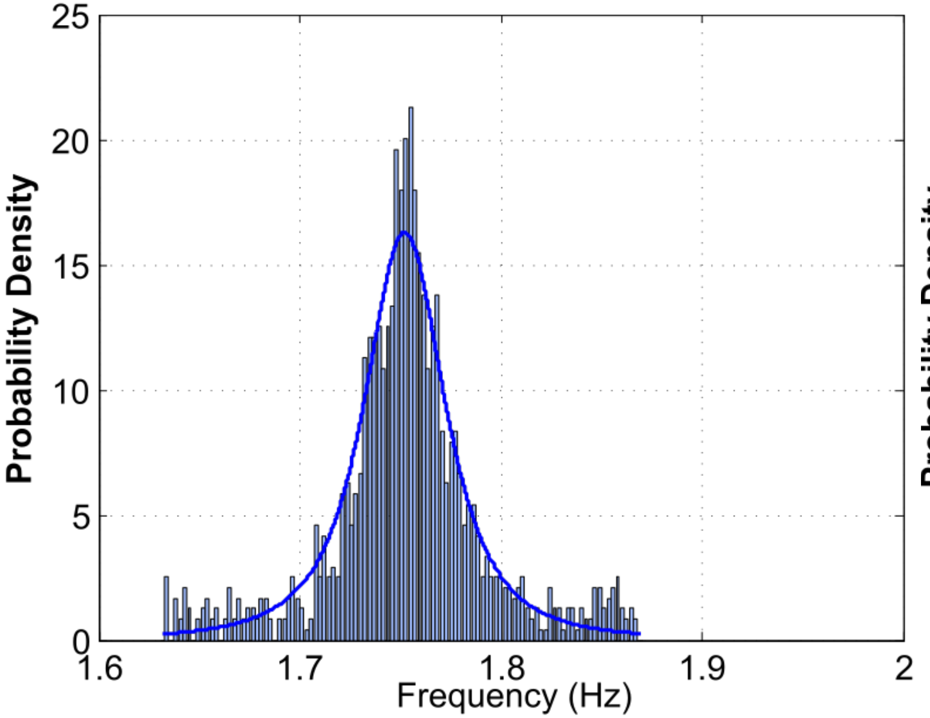
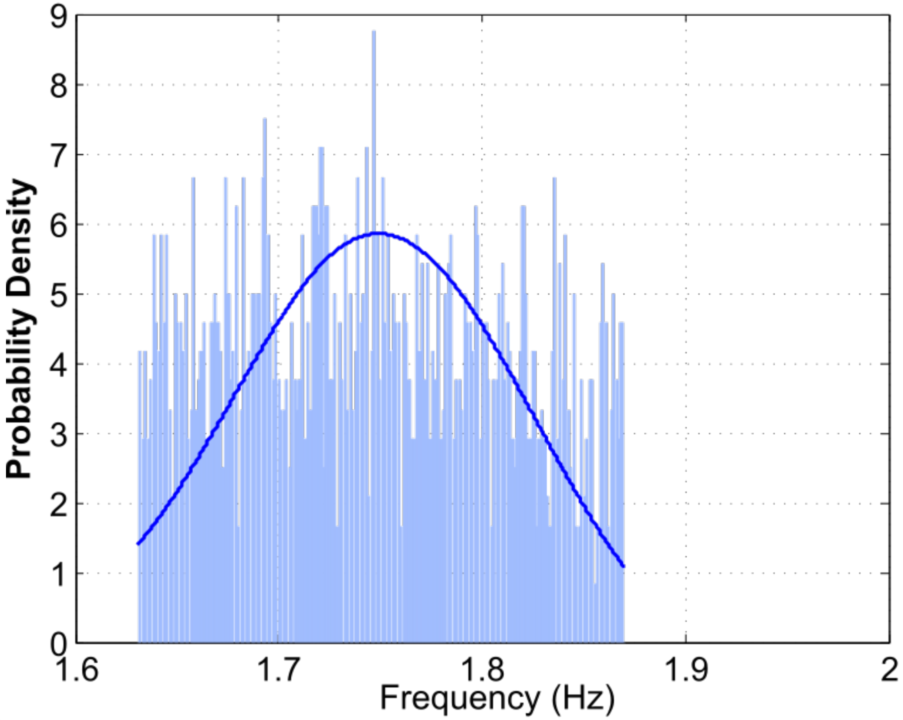
App. 4: Statistical Analysis

Decentralized Approach also provides better accuracy!

Forced local oscillatory mode detectable in decentralized architecture



Decentralized Mode Estimation (PMU ID: 4)



Centralized Mode Estimation (4 PMUs)

Inter-area oscillatory mode between HV section and rest of the grid

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Conclusions

- The increase of intermittent renewable sources bring ***technical challenges*** for network operation.
- Synchrophasor measurements have a great potential to support the technical operation of distribution networks with DER.
- Applications can play an important role of synthesizing (extracting) key information about the operation of the grid.

- TSOs-to-DSOs interaction in operations through PMU Apps.
  - DSOs can enhance the way they operate by having better knowledge of the system's performance in near real-time
  - TSOs can gain visibility of the phenomena at lower voltage levels, and device actions

- Real-time automatic control and protection is the next big step
  - Existing architecture, automation and system level technology needs (urgently) to mature…

- Interoperability and Standardization:
  - Need to develop and support a truly open market of products and services – an efficient electricity market requires and efficient technological market → we need to create competition!
  - Open standards **and open source software with the standard implementation** would help establishing such markets by providing the basic building blocks for a **quantitative and technical** comparison.

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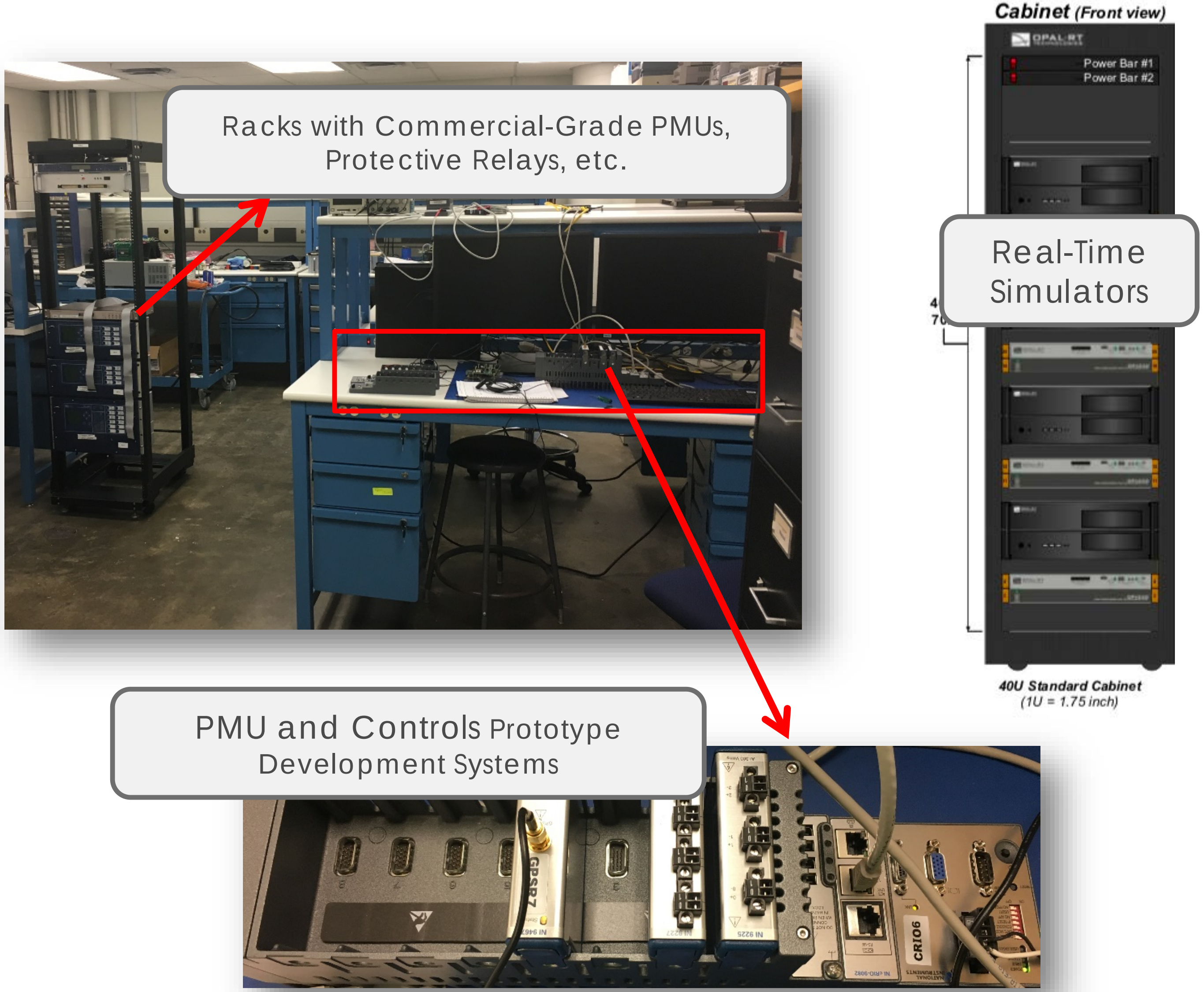
Future Work

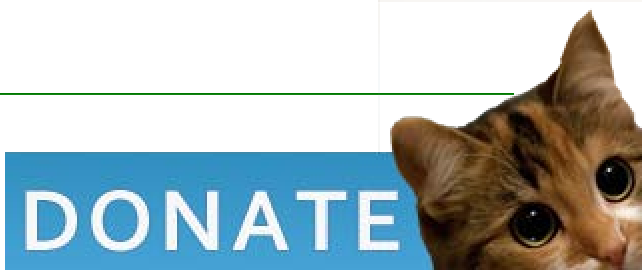
- We have now started to build a new real-time hardware-in-the-loop simulation lab at RPI for PMU R&D

- **ALSETLab** is being developed to solve real-world grid problems!
  - We want to work with you!

- Lab Development Status:
  - Laboratory space preparation
    - 6 work stations
  - Equipment being shipped.
  - Opal-RT Simulator in production.
  - In operation ~ Summer ’18.



ALSETLab
Needs your help!



Follow our donors example!

- ***Platinum Contributors:***

  Dominion Energy

  SEL SCHWEITZER ENGINEERING LABORATORIES

- Gold: GE Global Research

- Silver: GitHub

References and Resources (1/2)

- Github repositories for software:
  - General: https://github.com/ALSETLab
  - STRONgrid Real-time PMU data mediation library: https://github.com/ALSETLab/S3DK-STRONGgrid
  - Toolkit for PMU applications implementation: https://github.com/ALSETLab/S3DK
- Work related to the motivation and goals: (Wind Turbine SSCI Interaction Detection App)

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- Work related to modeling for RT Model and Tooling:

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  - R. S. Singh, H. Hooshyar and L. Vanfretti, "Testing and analysis of centralized and decentralized mode estimation architectures for active distribution network monitoring," 2017 IEEE Manchester PowerTech, Manchester, 2017, pp. 1-6. DOI: https://doi.org/10.1109/PTC.2017.7981163
- Overview Papers and Architecture of Information Exchage:
  - H. Hooshyar and L. Vanfretti, "A SGAM-based architecture for synchrophasor applications facilitating TSO/DSO interactions," *2017 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, 2017, pp. 1-5. https://doi.org/10.1109/ISGT.2017.8085977
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