N I S T Smart Grid Program

Flexibility at the grid edge

Research capabilities around campus for power systems research

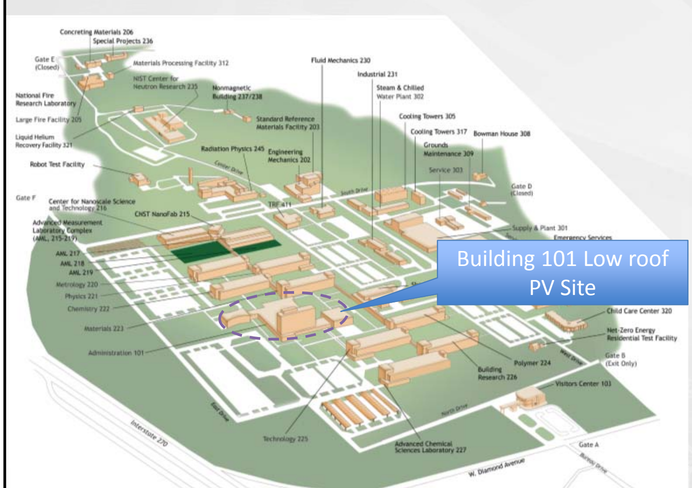
NIST
National Institute of Standards and Technology
U.S. Department of Commerce

1

Validation using NIST campus' distribution circuit

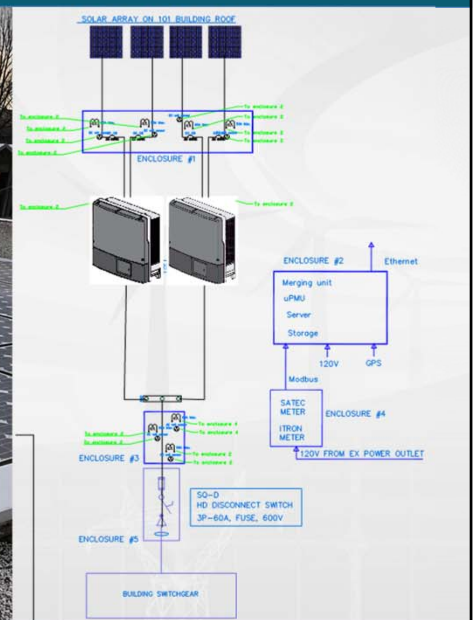
Supporting a variety active projects:

- Modeling low voltage circuits
- Uncertainty propagation
- Inverter control



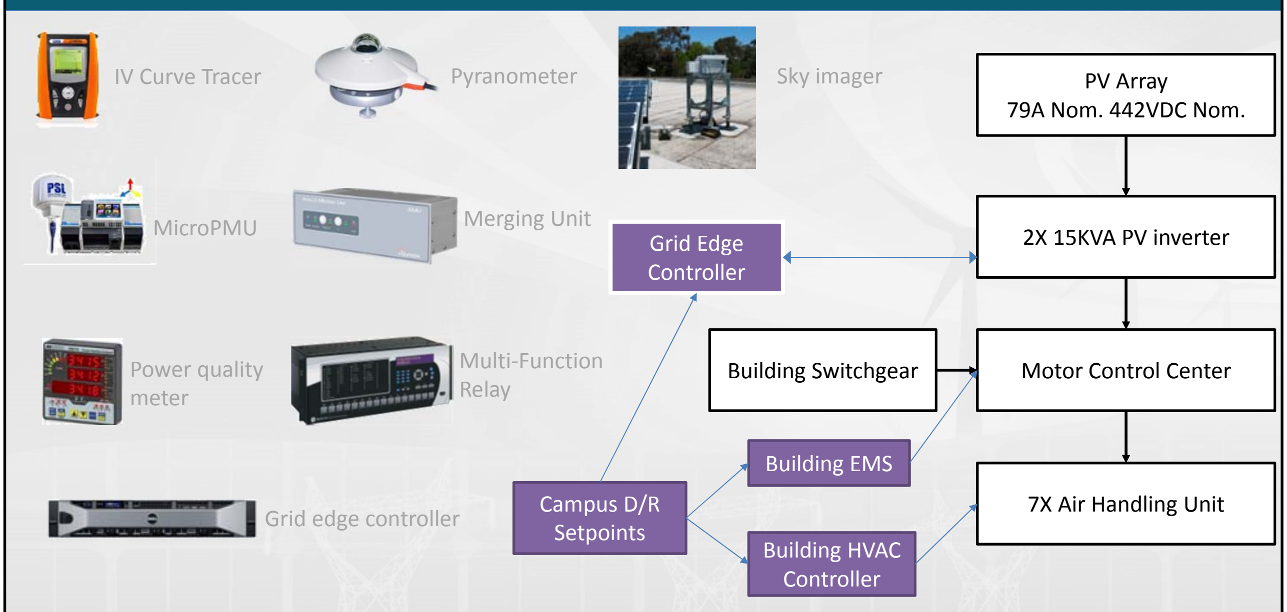
N I S T smart grid program 2

101 Low Roof



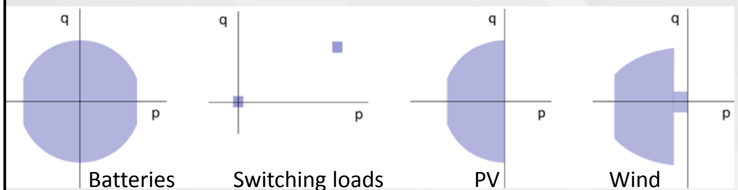
N I S T smart grid program 3

30 KVA PV Generator, 480VAC 3PH-3W HVAC circuit



N I S T smart grid program 4

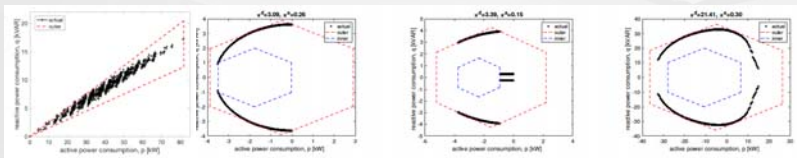
Estimating flexibility margins for heterogenous DERs



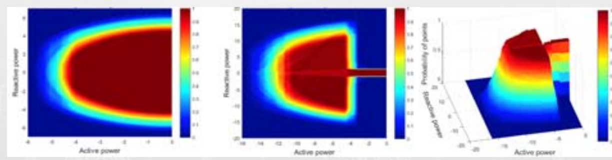
DERs have different (possibly non-convex) flexibility domains

Aggregate flexibility is the Minkowski sum of individual domains

Homothetic transformation (scaling and translation) to approximate (homogenize) DER flexibility



Set point tracking probability within flexibility domains. Need to explore belief maintenance in Bayesian networks to homogenize stochastic DERs.



Zhao, Lin, et al. "A geometric approach to aggregate flexibility modeling of thermostatically controlled loads." *IEEE Transactions on Power Systems* 32.6 (2017): 4721-4731.

Kundu, Soumya, Karanjit Kalsi, and Scott Backhaus. "Approximating Flexibility in Distributed Energy Resources: A Geometric Approach." *arXiv preprint arXiv:1803.06921* (2018).

The cutting edge at the grid edge

- Estimating flexibility of grid edge resources (beyond dispatchability)
  - Do we have data quality, secure communication capacity and robust algorithms?

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- Estimating flexibility of grid edge resources (beyond dispatchability)
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  - Evaluate control implications
  - Hardware-in-the-loop Simulation
  - Validated Emulations
  - Calibration of interfaces

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The cutting edge at the grid edge

now

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this afternoon

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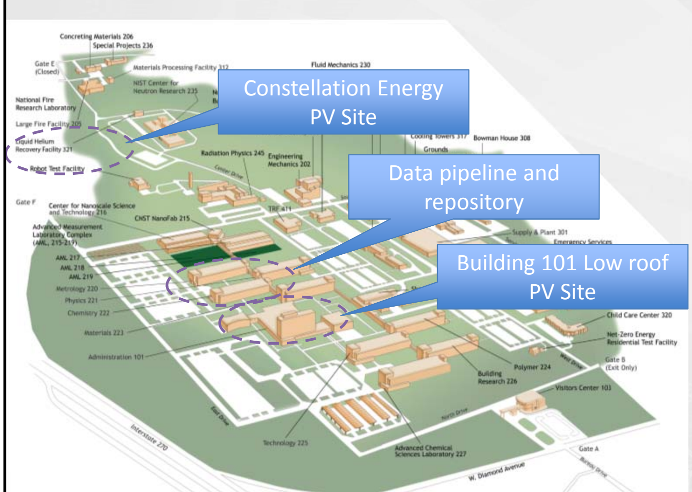
N I S T s m a r t g r i d p r o g r a m 9

Validation using NIST campus' distribution circuit



Supporting a variety active projects:

- Modeling low voltage circuits
- Uncertainty propagation
- Composition of models, data and inference
- Communication considerations
- Lightweight crypto
- Low power wide area comms
- Quasi-linear control/ Model-free optimization

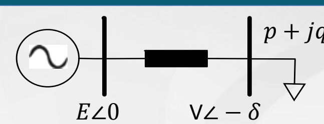
Designed for a lot more:

General purpose grid edge compute
Integrated with NIST data repositories/ infrastructure

N I S T s m a r t g r i d p r o g r a m 10

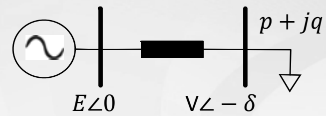
A Short-Term Voltage Instability Scenario

A Short-Term Voltage Instability ~~Scenario~~ Nightmare



- Your distribution system is operating in a stressed condition during hot weather with a high level of air conditioning load
- The triggering event is a multi-phase fault near a load center
  - Causes voltage dips at distribution buses
  - Compressor motors decelerate, drawing high current
- Following fault clearing motors draw very high reacceleration current

A Short-Term Voltage Instability Scenario



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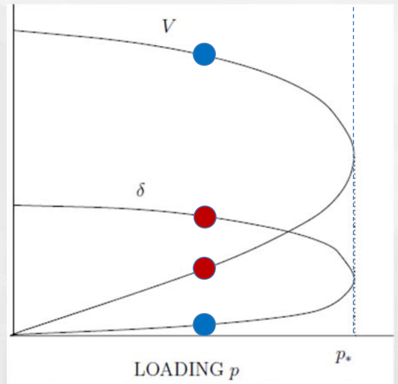
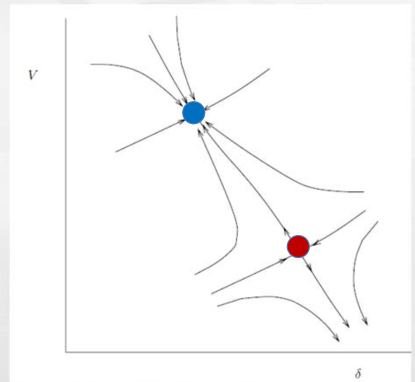
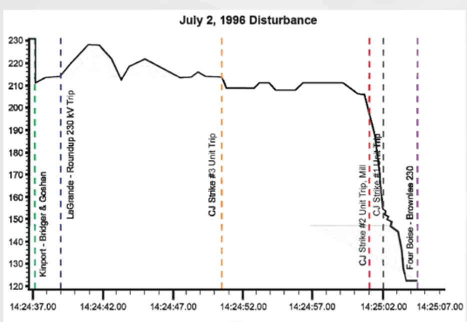
- The triggering event is a multi-phase fault near a load center
  - Causes voltage dips at distribution buses
  - Compressor motors decelerate, drawing high current
- Following fault clearing motors draw very high reacceleration current
  - Under-voltage load rejection not be fast enough to be effective
  - Voltage collapse reached -loss of the area load.

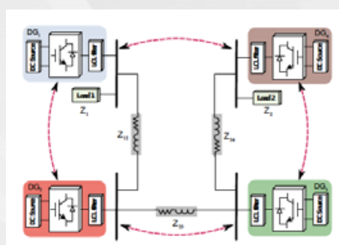


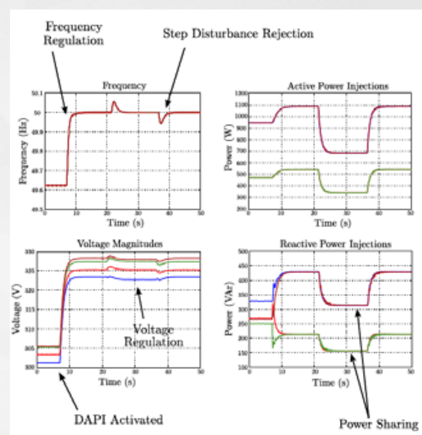


Flexibility for control



NERC report on July 2,3 WSCC Disturbance :
Boise 230kV Voltage Collapse





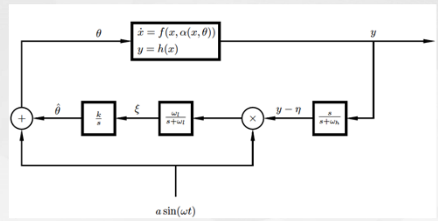
Control of network voltage and generator reactive output
– Improvement on AVRs, e.g. adding load (or line drop) compensation
– Coordinated voltage control (e.g. hierarchical, automatic 2-3 layers voltage control)
Coordination of protections/controls
– Ensure adequate coordination based on dynamic simulation studies
– Tripping of equipment to protect from overloaded conditions should be the last resort.

J. W. Simpson-Porco, F. Dorfler, and F. Bullo. Voltage stabilization in microgrids via quadratic droop control. IEEE Transactions on Automatic Control, May 2015.
J. W. Simpson-Porco, F. Dorfler, and F. Bullo. Voltage Collapse in Complex Power Grids. February 2015

Optimization and Control in Uncertain Environments

Online gradient estimation

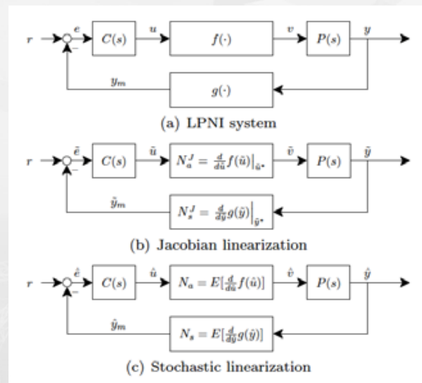
- Perturb the plant with a periodic signal $a\sin(\omega t)$
- High-pass filter the performance variable: $(y - \eta)$
- Multiply with $a\sin(\omega t)$
- Low-pass filter to estimate the gradient $\xi \approx \frac{\delta y}{\delta \theta}$
- $\hat{\theta} \approx \theta^*$ when $\xi = 0$ until then $\hat{\theta}$ is the best estimate



Linear plant/ Non-linear instrumentation

$$sat_\alpha(u) = \begin{cases} \alpha, & u > \alpha \\ u, & -\alpha \le u \le \alpha \\ -\alpha, & u < -\alpha \end{cases}$$

- The Jacobian linearization of $sat_\alpha(u)$ is independent of α
- When α is large Jacobian linearization may be sufficiently accurate
- Stochastic linearization accounts for the non-linearity $sat_\alpha(u)$



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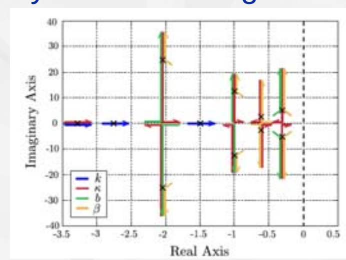

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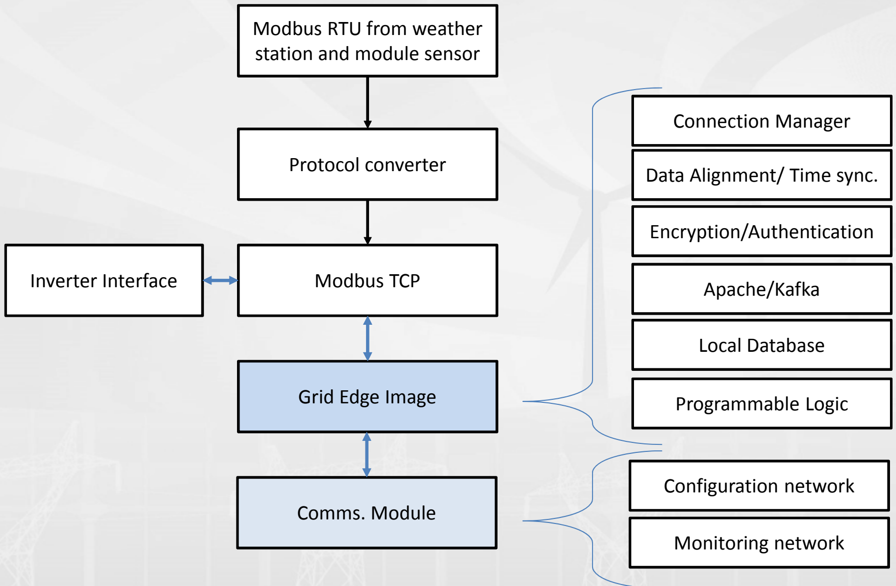
5 MW Solar Field

N I S T smart grid program 18

General purpose grid edge controller

- IP67 & IP69K Compliant
- M12 Input/output Connectors
- Intel Bay Trail N2930 1.83GHz SoC CPU
- 6.3W Consumption
- Ethernet X2, Wireless X3
- Serial X3, USB
- NIST Ubuntu Image
- PSK L3 Security



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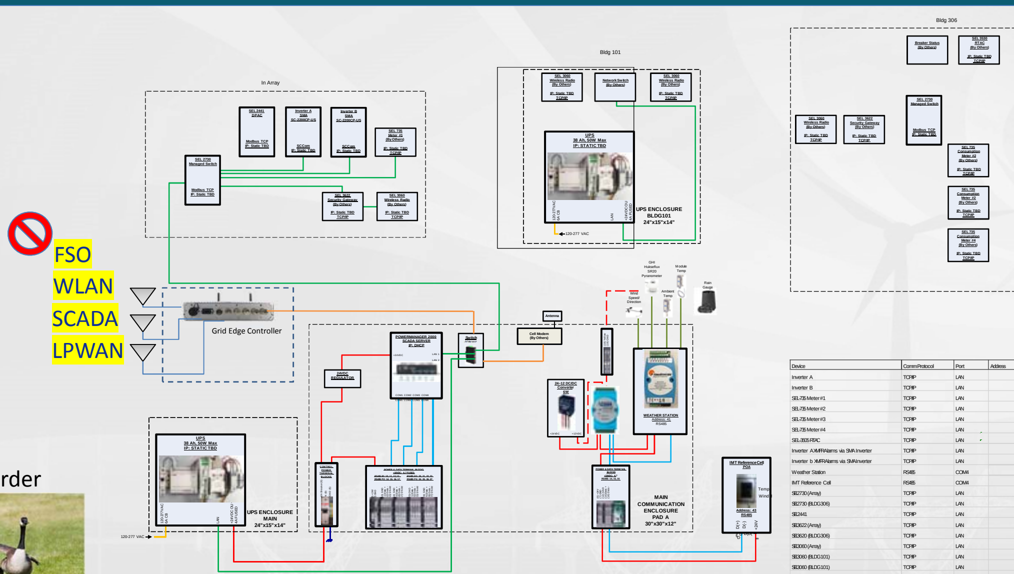
5MW PV site ~140 data points every 10ms



Device	CommProtocol	Port	Address
Inverter A	TCPIP	LAN	
Inverter B	TCPIP	LAN	
SEL-735 Meter#1	TCPIP	LAN	
SEL-735 Meter#2	TCPIP	LAN	
SEL-735 Meter#3	TCPIP	LAN	
SEL-735 Meter#4	TCPIP	LAN	
SEL-3505 RTAC	TCPIP	LAN	
Inverter A XMFRAlarms via SMA Inverter	TCPIP	LAN	
Inverter b XMFRAlarms via SMAInverter	TCPIP	LAN	
Weather Station	RS485	COM4	
IMT Reference Cell	RS485	COM4	
SEL2730 (Array)	TCPIP	LAN	
SEL2730 (BLDG306)	TCPIP	LAN	
SEL2441	TCPIP	LAN	
SEL3622 (Array)	TCPIP	LAN	
SEL3620 (BLDG306)	TCPIP	LAN	
SEL3060 (Array)	TCPIP	LAN	
SEL3060 (BLDG101)	TCPIP	LAN	
SEL3060 (BLDG101)	TCPIP	LAN	
SEL3060 (BLDG306)	TCPIP	LAN	
UPSMain	TCPIP	LAN	
UPSBLDG101	TCPIP	LAN	

by order

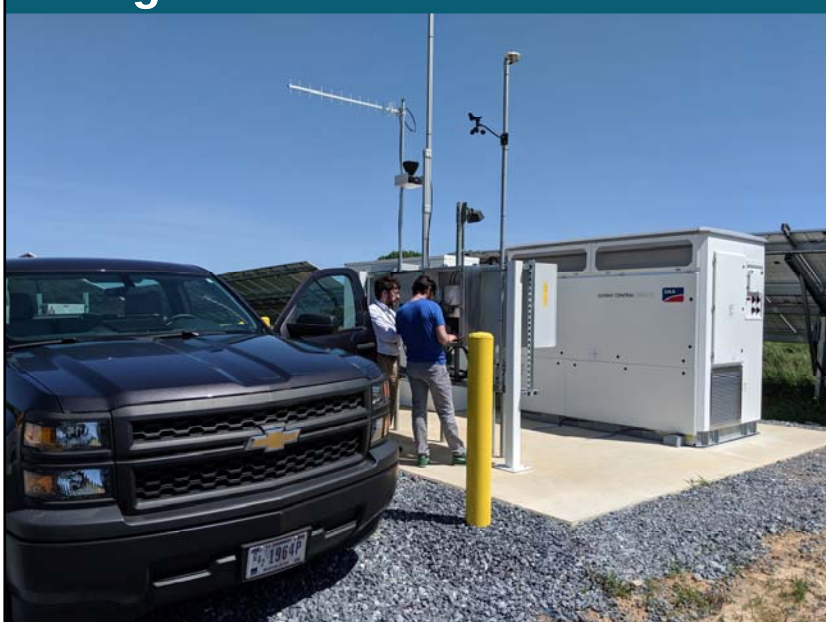
N I S T s m a r t g r i d p r o g r a m

Progress since October 2018

Progress since October 2018

Progress since October 2018

Progress since October 2018



5 MW Solar Field

WLAN	SCADA	LPWAN
100m	500m	10E3m
450 Mb/s	120 Kb/s	4 Kb/s
20 dBm	16 dBm	20 dBm
256-bit WPA2-PSK (AES)	128-bit AES	128-bit AES
2.4 GHz	900 MHz (NB)	900 MHz (WB)

Synchronized composition of data at varying time scales requires planning at every step of the data pipeline.

Low Power WAN is particularly challenging but has a large payoff.

Smart Grid test pilot in Argentina

The Smart Grid Sub Group of the Argentina-U.S. Binational Energy Working Group (BewG) is deploying a Smart Grid Test Pilot in Armstrong, Argentina.

A small town with 12000 inhabitants.

~1000 smart meters have been deployed by INTI (Argentina's NMI)

Their interests include:

- AMI for AVR
- Lightweight security for LPWANs
- Data pipelines for high data rate links vs aggregated information over low data rate link
- Comparison between Wi-SUN and LoRaWAN

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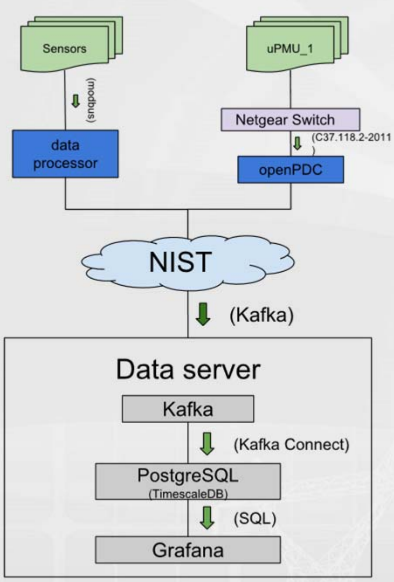
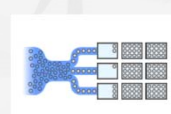
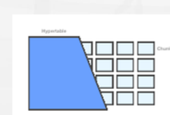
Data pipeline



- **uPMU/modbus**
  - High speed, high volume data sources
  - 100 ~ 1000 datapoints per second
  - 10s ~ 100s of sensor measurements
- **Kafka Streaming Platform**
  - Publish/subscribe streams of records
  - Store streams of records
  - Process streams of records
  - Move data between systems/applications
  - <https://kafka.apache.org/>

- **TimescaleDB time-series database**
  - Easy to use
  - Scaleable
  - Reliable (based on PostgreSQL)
  - <https://www.timescale.com/>

- **Grafana Dashboard**
  - Fast and flexible visualizations
  - Alert notifications
  - Dynamic dashboards
  - Data sources
  - <https://grafana.com/>

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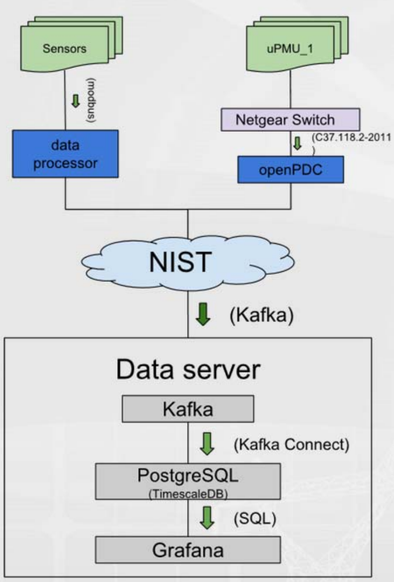
Inverter Data Acquisition System demo

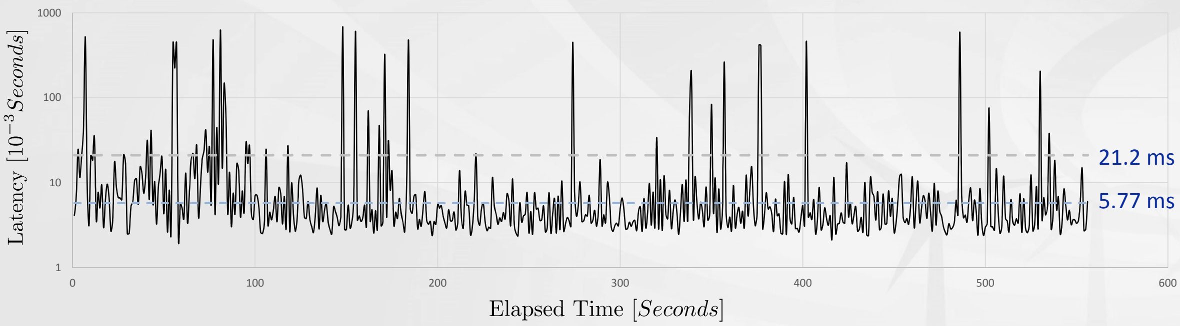
- Phasor data at 120 measurements/s
- Inverter data at 100 measurements/s
- Flexibility monitoring
- LPWAN optimized communications

Data pipeline



- **Field servers**
  - Five installed sites
  - hardy.campus.nist.gov (5MW)
  - laurel.campus.nist.gov (A19)
  - curly.campus.nist.gov (101 roof)
  - moe.campus.nist.gov (101 mezz)
  - larry.campus.nist.gov (224)
- **Data servers**
  - Ceph Storage cluster (Three sites managed by ELDST)
  - Frontend fileserver: CentOS 7 VM (NFS/Samba)
  - KVM (libvirt/QEMU) Hypervisor
  - **chaplin.el.nist.gov (224) (Grafana)**
  - **voltaic.el.nist.gov (226) (5 years of PV Data)**
  - **mission.el.nist.gov (220) (~7TB sky images)**

5 MW Solar Field: Pipeline performance



Upgrade planned for WLAN system to switch to P2P Layer 2 encryption instead of Layer 3 IPSec currently used

Thank you

NIST Smart Grid Program

Quantifying Operational Resilience Benefits of the Smart Grid
A Case Study of the Florida Electric Grid and Hurricane Irma

Cheyney O'Fallon, Ph.D.
Applied Economics Office
Engineering Laboratory

Federal Advisory Committee Meeting
June 5th, 2019

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Motivation

Interoperability

- "The capability of two or more networks, systems, devices, applications, or components to work together, and to exchange and readily use information—securely, effectively, and with little or no inconvenience to the user".

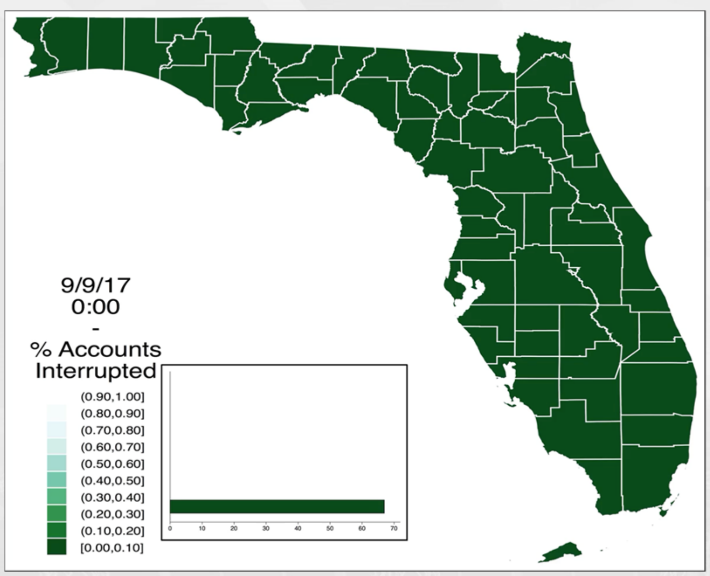
  SOURCE: NIST Special Publication 1108r3

- Interoperability is foundational to many resilience enhancing smart grid applications, yet it remains a challenge for stakeholders across the electric power sector.

Motivation

- Public Utility Commissions (PUCs) want to see tangible evidence supporting the prudence of investments.
- Interoperability value propositions are challenging to estimate and examples for PUCs are limited.
- Florida's recent experience with Hurricane Irma (September 2017) presents an opportunity to evaluate the benefits to operational resilience that the state's grid experienced due to improved interoperability.
- **Focal Point**: Service interruptions are critical outcomes for customers.

Hurricane Irma Service Interruptions



How can we measure or proxy for Interoperability?

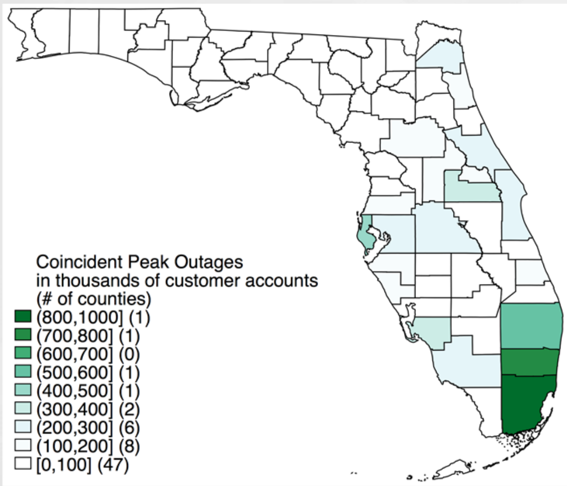
- A simple proxy for utility interoperability is the share of customers within each market segment that are served through advanced metering infrastructure (AMI).
- Let this proxy be denoted **AMI Share**.
- How did segments of the grid with varying levels of **AMI Share** differ in their operational resilience with respect to sustaining customer account interruptions from Hurricane Irma?
- What performance benefits can we attribute to greater interoperability?

Empirical Strategy

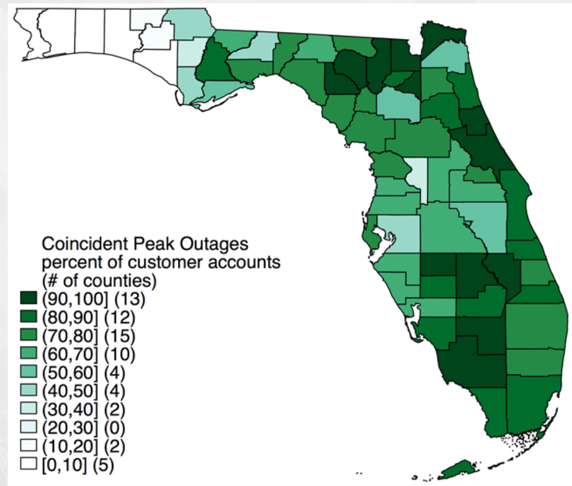
- Obtain data on time-invariant factors impacting resilience including AMI Share and proxies of distribution grid topology.
- Build an hourly longitudinal dataset of customer account interruptions and wind stress levels at the county and county-utility level.
- Employ **Conditional Fixed Effects Poisson Regression** of hourly change in customer interruptions on wind stress, AMI Share, and control variables.

Hurricane Irma – Customer Interruptions

Peak Outages (Count)

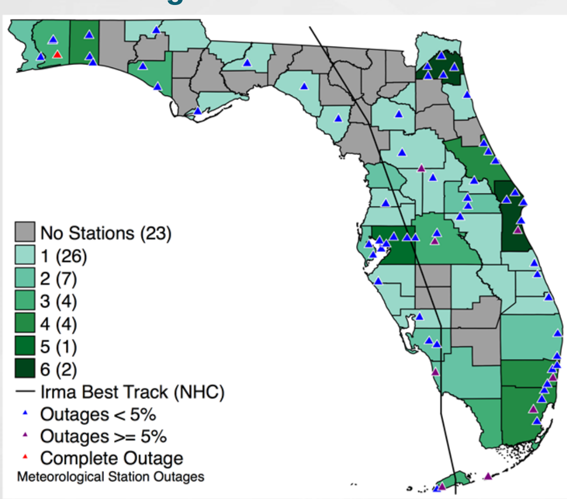


Peak Outages (Percent)

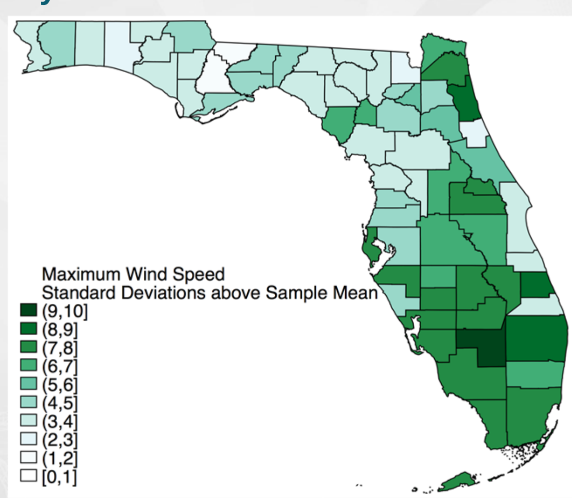


Wind Stress Data

Meteorological Stations



Synthetic Wind Series

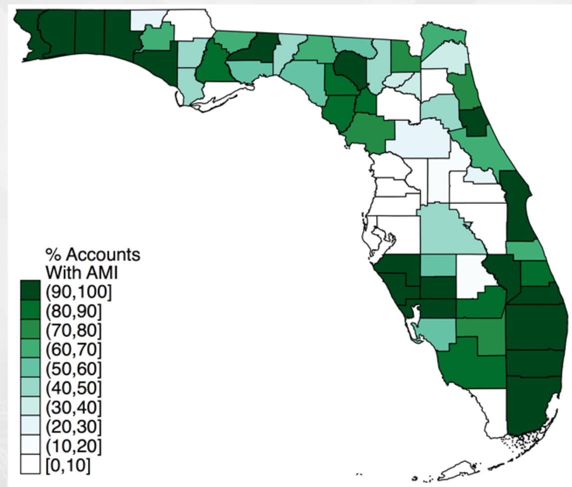


Advanced Metering Data

SOURCE: EIA Form 861

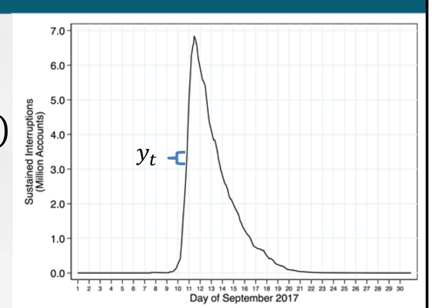
- Data reported as the count of customers with advanced metering infrastructure at the utility level.
- County-level AMI-share data is constructed as a linear combination of AMI-shares for each utility operating in the county.

Advanced Metering Infrastructure



Core Regression Specification

- $E[y_{it}|\theta_i, \boldsymbol{x}_{it}] = \theta_i \, exp(\boldsymbol{\beta}_1 x_{1it} + \boldsymbol{\beta}_2 x_{1it} x_{2i} + \epsilon_{it})$



- Where:
- i and t are indices for region and hour
- y_{it} number of new sustained interruptions to customers
- x_{1it} square of our synthetic wind speed metric
- x_{2i} time invariant measure of AMI Share
- θ_i region-level fixed effect

Expected Value of Customer Interruptions

DepVar: Δ Interruptions	County-Utility	County
Wind Speed (W^2)	1.589***	1.595***
	(0.000)	(0.000)
W^2 × AMI Share	0.905**	0.904**
	(0.012)	(0.021)
Observations	144 877	48 172
χ^2	1047.6	857.0

Coefficients reported as Incident Rate Ratios (IRR)
p-values reported in parentheses
Significance Denoted: * 0.1 ** 0.05 *** 0.01

Topological Concerns

- Some segments of the grid are built stronger than others.
- Densely populated areas may contain more resilient buildings.
- Wealthier areas may enjoy a stronger distribution grid.

Population Density, Median Household Income, New Building Share, and AMI Share (County)

County Level Analysis Dependent Variable: Δ Interruptions	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Wind Speed Squared (W^2)	1.595***	1.482***	1.547***	1.534***	1.604***	1.619***	1.625***	1.639***	1.651***	1.502***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
W^2 × AMI Share	0.904**				0.900*	0.919*	0.904**	0.858***	0.889**	1.082
	(0.021)				(0.088)	(0.064)	(0.030)	(0.008)	(0.046)	(0.499)
W^2 × Population Density		1.010			0.998			0.989		
		(0.145)			(0.849)			(0.224)		
W^2 × Median Household Income			0.957***			0.964**			0.924*	
			(0.010)			(0.014)			(0.082)	
W^2 × New Building Share				0.909			0.919			1.425
				(0.617)			(0.659)			(0.123)
W^2 × AMI Share × Population Density								1.038		
								(0.395)		
W^2 × AMI Share × Median Household Income									1.065	
									(0.301)	
W^2 × AMI Share × New Building Share										0.390*
										(0.076)
N = 48 172										
χ^2	857.2	470.7	493.7	433.9	901.3	1019.8	867.8	2386.1	950.9	1339.2

Wind speed squared, population density, and median household income are normalized within sample.
New building share records the percent of buildings that have been built after 2000.
Coefficients reported as Incident Rate Ratios (IRR)
p-values reported in parentheses
Significance Denoted: * 0.1 ** 0.05 *** 0.01

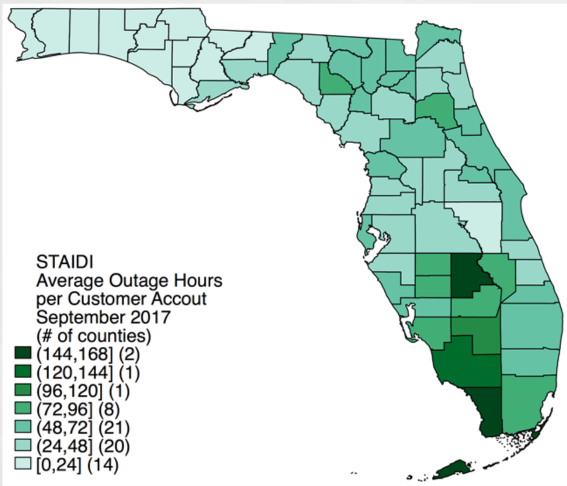
Population Density, Median Household Income, New Building Share, and AMI Share (County-Utility)

County-Utility Level Analysis Dependent Variable: Δ Interruptions	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Wind Speed Squared (W^2)	1.589***	1.475***	1.542***	1.532***	1.591***	1.613***	1.622***	1.624***	1.647***	1.500***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
W^2 × AMI Share	0.905**				0.904*	0.921**	0.905**	0.863***	0.888**	1.082
	(0.012)				(0.072)	(0.049)	(0.019)	(0.002)	(0.023)	(0.480)
W^2 × Population Density		1.011*			0.999			0.991		
		(0.059)			(0.949)			(0.175)		
W^2 × Median Household Income			0.956***			0.964***			0.921**	
			(0.002)			(0.004)			(0.021)	
W^2 × New Building Share				0.900			0.911			1.406**
				(0.575)			(0.622)			(0.047)
W^2 × AMI Share × Population Density								1.037		
								(0.390)		
W^2 × AMI Share × Median Household Income									1.069	
									(0.183)	
W^2 × AMI Share × New Building Share										0.395**
										(0.049)
N = 144 877										
χ^2	1047.8	515.4	557.9	496.2	1078.1	1190.9	952.2	2686.0	1094.3	1577.6

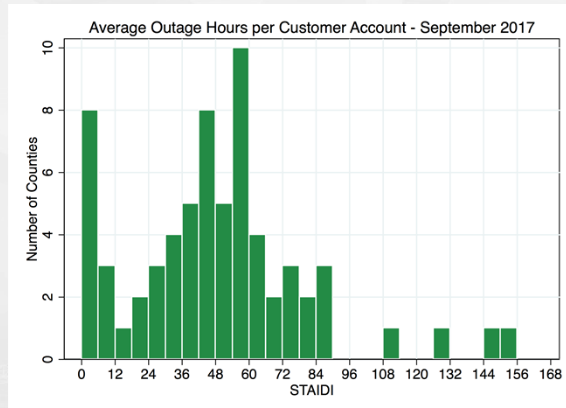
Wind speed squared, population density, and median household income are normalized within sample.
New building share records the percent of buildings that have been built after 2000.
Coefficients reported as Incident Rate Ratios (IRR)
p-values reported in parentheses
Significance Denoted: * 0.1 ** 0.05 *** 0.01

Storm Average Interruption Duration Index (STAIDI)

Spatial Distribution of County STAIDI



Distribution of County STAIDI



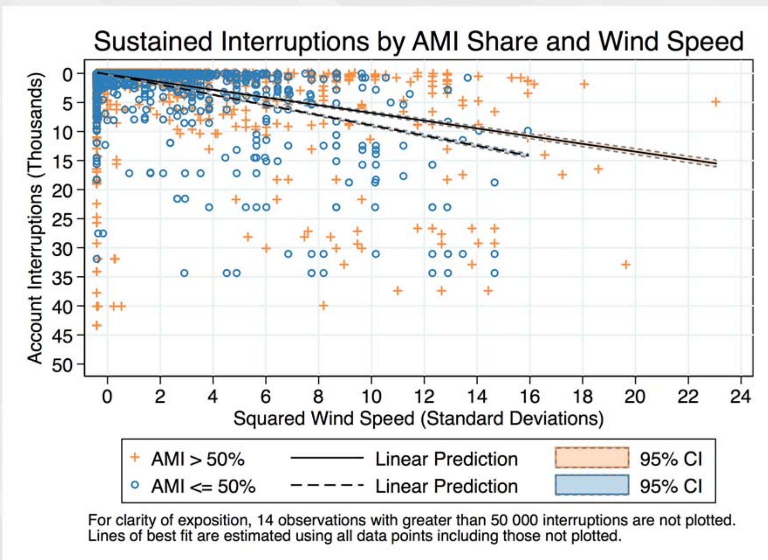
Counterfactual Scenarios

- We investigate three counterfactual scenarios to characterize some of the resilience benefits already coming from interoperability improvements and the additional opportunities still available to stakeholders.
- Estimate Counterfactuals interruptions, I_{it}^{CF}, for scenarios in which the entire grid performs commensurate with a uniform distribution of AMI penetration:
- CF_M: at the state-level average, 57.4 %.
- CF_0: at an AMI share of 0 %.
- CF_1: at an AMI share of 100 %.

Counterfactual Scenarios

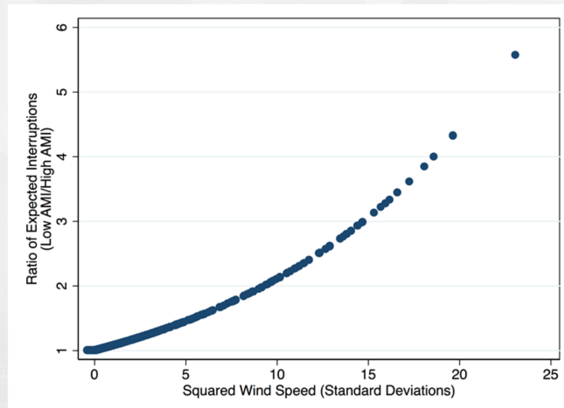
- We observe that:
- The partial derivative of expected sustained interruptions with respect to wind speed is positive.
- The cross partial derivative of sustained interruptions with respect to wind speed and AMI penetration is negative.
- The core regression model is fit separately to two subsamples.
- The first subsample contains counties with greater than 50 % AMI penetration and the second subsample contains all other counties in Florida.

Performance Wedge



Counterfactual Method

- Let R_{it} be the ratio of expected interruptions between the low AMI and high AMI cases for a given level of wind speed.
- $I_{it}^{CF} = (I_{it}^{A})(R_{it}^{G_i})$
- $G_i = (M_i - \widehat{M})/\text{H}$
- M_i is the actual AMI share
- $\widehat{M}$ is the counterfactual AMI share
- H is the gap between average AMI share in the two samples
- $G_i \in [-0.90, 0.67]$



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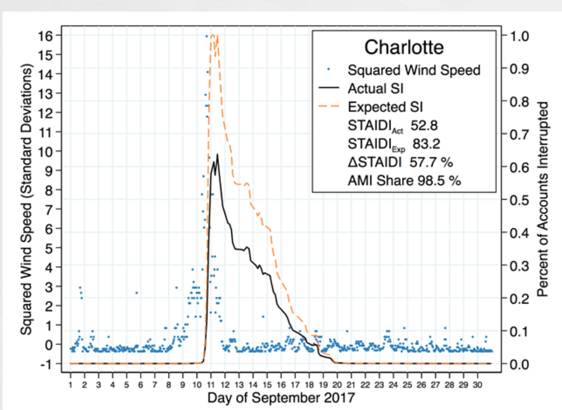
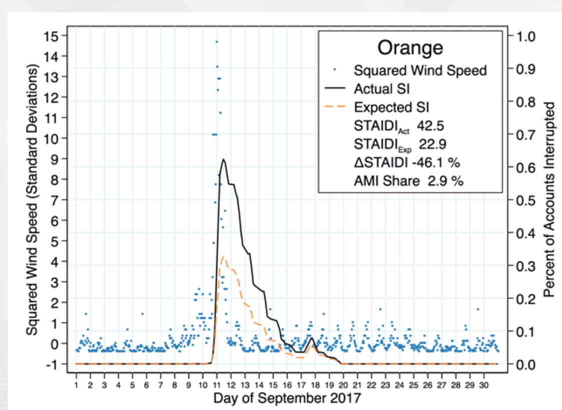
Counterfactual Series

High AMI County



Low AMI County



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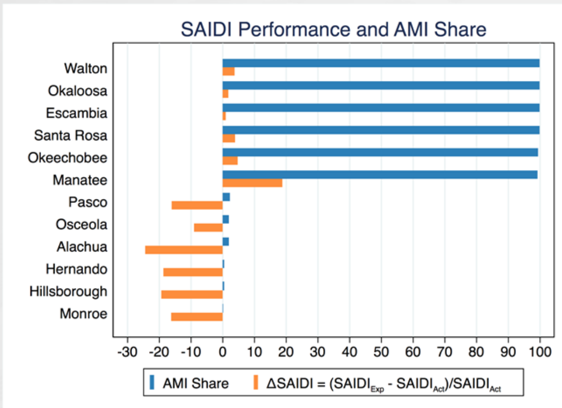
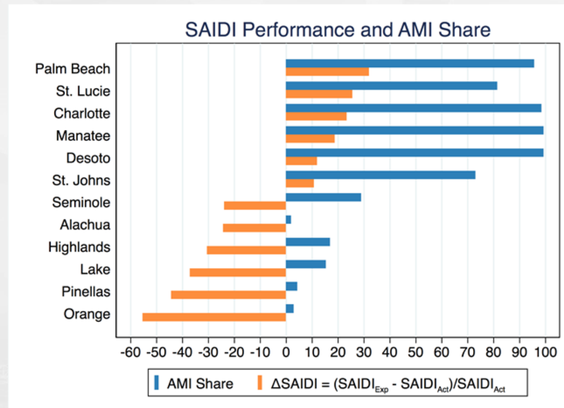
SAIDI Performance and AMI Share

AMI Share Ranking



Performance Ranking



Actual and Counterfactual Outcomes

	Interruption Costs ($/hour)	Actual	CF0	CFM	CF1
Total Interruption Hours		556 636 224	668 625 344	569 795 392	464 152 384
Florida SAIDI (Hours in 9.2017)		52.9	63.6	54.2	44.1
Total Interruption Costs	0.50	278 318 112	334 312 672	284 897 696	232 076 192
($ millions)	5.00	2 783 181 056	3 343 126 784	2 848 976 896	2 320 761 856
	15.00	8 349 543 424	10 029 380 608	8 546 930 688	6 962 285 568
	45.00	25 048 629 248	30 088 140 800	25 640 792 064	20 886 857 728
	75.00	41 747 718 144	50 146 902 016	42 734 653 440	34 811 428 864
Customer Average	0.50	26	32	27	22
($/customer)	5.00	265	318	271	221
	15.00	794	953	812	662
	45.00	2381	2860	2437	1985
	75.00	3968	4767	4062	3309

Interruption costs range drawn from Woo, C.-K. et al. "Residential outage cost estimation: Hong Kong." Energy policy 72, 204-210 (2014).

Comparison of Actual and Counterfactual Outcomes

	Interruption Costs ($/hour)	Actual	Actual-CF0	Actual-CFM	Actual-CF1
Total Interruption Hours		556 636 224	-111 989 120	-13 159 168	92 483 840
Florida SAIDI (Hours in 9.2017)		52.9	-10.6	-1.3	8.8
Total Interruption Costs	0.50	278 318 112	-55 994 560	-6 579 584	46 241 920
($ millions)	5.00	2 783 181 056	-559 945 728	-65 795 840	462 419 200
	15.00	8 349 543 424	-1 679 837 184	-197 387 264	1 387 257 856
	45.00	25 048 629 248	-5 039 511 552	-592 162 816	4 161 771 520
	75.00	41 747 718 144	-8 399 183 872	-986 935 296	6 936 289 280
Customer Average	0.50	26	-5	-1	4
($/customer)	5.00	265	-53	-6	44
	15.00	794	-160	-19	132
	45.00	2381	-479	-56	396
	75.00	3968	-798	-94	659

Interruption costs range drawn from Woo, C.-K. et al. "Residential outage cost estimation: Hong Kong." Energy policy 72, 204-210 (2014).

For Context: 2017 Florida GDP was $976 billion ($2.7 billion/day)

ICE Calculator Results (Actual - CF_0)

Sector	# of Customers	Cost Per Event	Cost Per Avg kW	Cost Per Unserved kWh	Total Cost
Residential	9 398 000	23.94	15.20	1.43	224 965 812.38
Small C&I	1 053 391	6592.87	3824.74	359.13	6 944 875 179.91
Medium and Large C&I	267 609	29 095.94	598.87	56.23	7 786 334 838.82
Total	10 719 000	1395.30	504.89	47.41	14 956 175 831.11

SOURCE: Values produced using the Interruption Cost Estimates (ICE) Calculator, found at https://icecalculator.com/interruption-cost

NOTE: Results presented incorporate default settings for Florida with a SAIDI equal to 639 minutes ($SAIDI_{CF0} - SAIDI_{Act}$) and a SAIFI of 1.0. Customer counts are for December 31, 2017 and are drawn from "Statistics of the Florida Electric Utility Industry" (Florida Public Service Commission) http://www.floridapsc.com/Files/PDF/Publications/Reports/Electricgas/Statistics/2017.pdf

Conclusions

- The expected value of customer account interruptions is moderated by AMI share.
- A standard deviation shock to the square of wind speed is associated with approximately of 10 % fewer interruptions per hour when AMI is fully deployed.
- The operational resilience benefits from improved system interoperability for Florida during Hurricane Irma are on the order of $1.6 billion.

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THANK YOU

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NIST Transactive Energy Challenge

Modeling and Simulation for the Transactive Smart Grid

Phase II Results

June 4, 2019

David Holmberg

NIST TRANSACTIVE ENERGY CHALLENGE
Modeling and Simulation for Grid Challenges

NIST National Institute of Standards and Technology U.S. Department of Commerce

https://doi.org/10.6028/NIST.SP.1900-603

Overview

- The TE Challenge Phase II team research finished in late 2018. https://doi.org/10.6028/NIST.SP.1900-603
- Effort involved 5 research teams: PNNL, NREL, Tata Consultancy Services (TCS), MIT and Vanderbilt.
- Teams worked together to define a common weather scenario and common electric grid that would be shared by all.
- The goal was to use different transactive methods to manage voltage swings on the grid, while the common scenario would allow comparability among results.
- This presentation will review the common scenario, summarize team transactive approaches and results.

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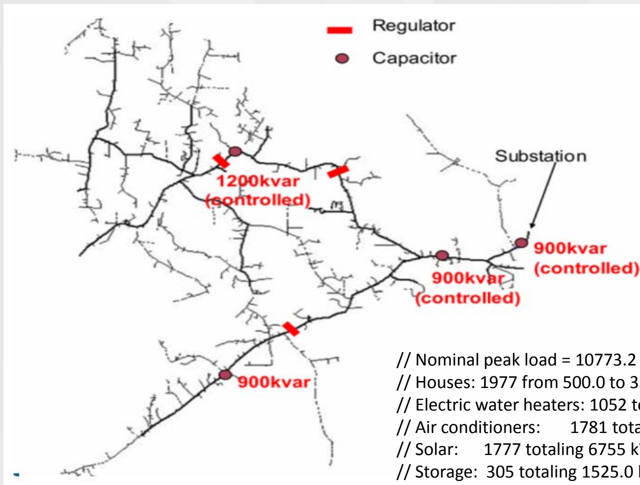
IEEE 8500 grid



Final grid specification in agreed-on [scenario]

// Nominal peak load = 10773.2 + j2700.0 kVA
// Houses: 1977 from 500.0 to 3500.0 sq feet, total area 3960179.6 sq ft
// Electric water heaters: 1052 totaling 4741.5 kW
// Air conditioners: 1781 totaling 23734.5 kW
// Solar: 1777 totaling 6755 kW
// Storage: 305 totaling 1525.0 kW
// Water heater load is resistive
// HVAC load ZIP=0.2,0.0,0.8 with variable power factor as input
// (the fan load ZIP=0.2534,0.7332,0.0135 and pf=0.96)
// The non-responsive ZIP load is input all constant current, pf=0.95

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Challenge Scenario Narrative

- *Electric feeder with high penetration of PV. At mid-day on sunny day, the feeder has reverse power flows and over-voltage conditions. At 2:30pm, a storm front overspreads the feeder and PV power production drops from full sun to 10% sun in a period of 10 min. Temperature drops 5F. This is followed by a ramp back up to full sun from 4:00 – 4:30 pm. Transactive methods are used to incentivize load generation or storage response as needed throughout the day, and the transactive signals are localized to the feeder level to respond to voltage levels.*
- Focus on distribution grid and challenge of DER integration (PV, batteries)
- Based on Scenario #3 in [SGIP TE Application Landscape Scenario white paper]

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Common Metrics

- Line voltages and frequency, real and reactive power flows, and line losses
  - at each load or node (meter)
  - at each DER (PV or battery inverter)—real and reactive power
  - one minute time step for common reporting.
  - separate PV generation from aggregated loads
- Reliability indices: utility metrics on out-of-band events and outages, but also measures of voltage excursions even if in limits, and capacitor bank and voltage regulator action counts.
- Economic metrics:
  - market transactions and prices
  - Billing data (customer energy cost monthly or minutely)
  - Total cost of energy at feeder level
- Comfort metrics
  - House air temps, setpoint deviations—average comfort scale over occupied period
  - Water temps and deviations
- Utilization of local green energy (PV or battery sourced on the feeder vs. from transmission sub-station)

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Research Summary-PNNL

- PNNL provided the grid definition and metrics.
- Simulations were performed in Gridlab-D on the PNNL TE Simulation Platform (TESP).
- PNNL examined the use of inverter Volt-VAR and Volt-Watt controls and HVAC temperature setbacks to manage distribution grid voltage violations.
- Volt-VAR control on all PV inverters proved to reduce voltage violation duration by 61 %. Volt-Watt by 4 %, HVAC control by 19 %.

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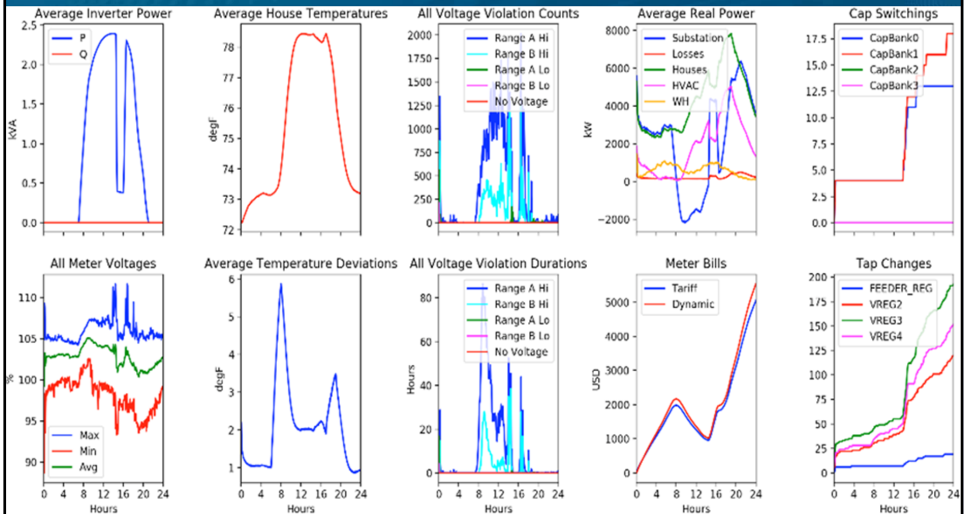
Base Case Simulation Results



Volt-VAR and Volt-Watt functions

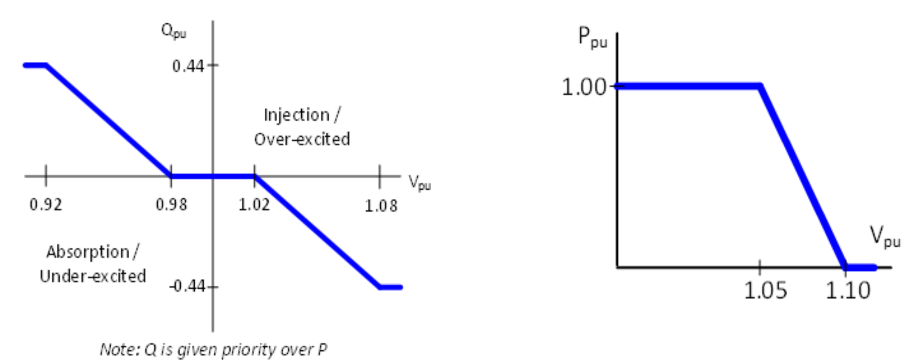


Figure PNNL-11 Applied Volt-Var (left) and Volt-Watt (Right) functions; these are the defaults for category B ("high penetration") in IEEE 1547-2018.

Research Summary-NREL

- Used the TOU price as input, and then overlay incentive prices unique to each meter, based on voltage. Both real and reactive prices.
- If voltage is high, incentive price is negative to encourage consumption.
- Voltage violations reduced by 80 % compared to the simple TOU rate with the same weather scenario.
- Average temps changed less than 2 F, capacitor banks and voltage regulator operations reduced.
- Average cost not increased. But some houses saw significant change in energy bill.

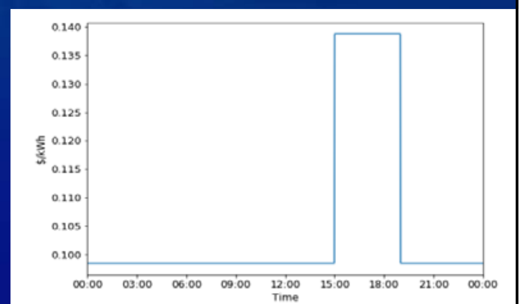


Figure NREL-6 The TOU rate used for simulations.

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Average voltages across day

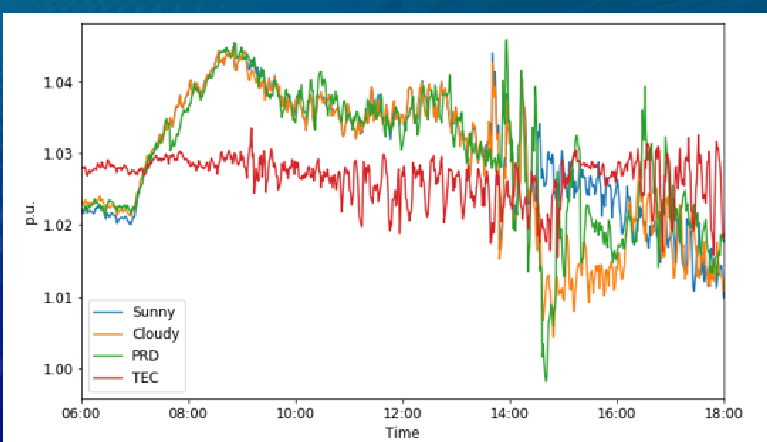

Figure NREL-7 Average voltages for all houses.

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Real and Reactive incentive prices

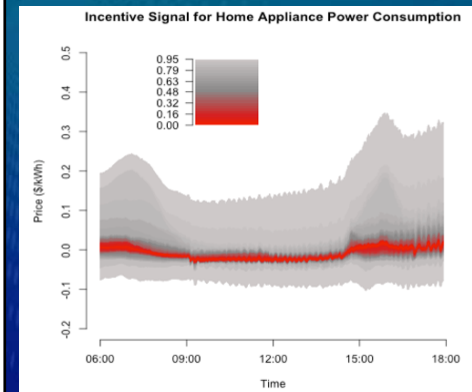

Figure NREL-12 Incentive prices for active power generated by the network-level control.

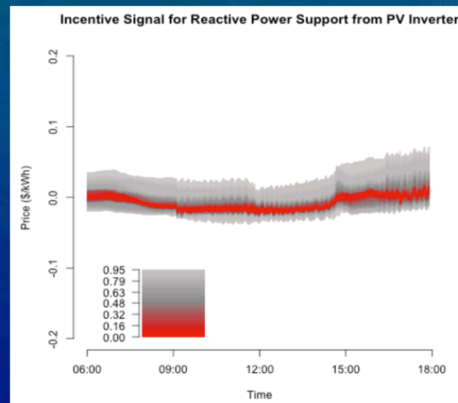

Figure NREL-13 Incentive prices for reactive power generated by the network-level control.

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Capacitor bank and voltage regulator actions

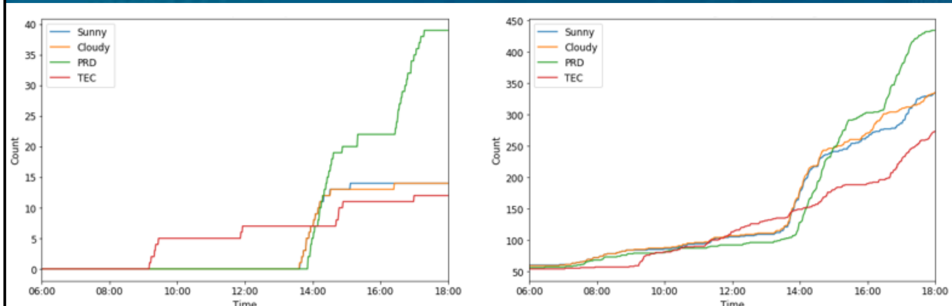

Figure NREL-21 Number of capacitor operations (left) and number of voltage regulator tap changes (right).

- 2:30pm clouds move in, 4:30pm sun back out
- 3pm TOU price increase

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Customer energy bill

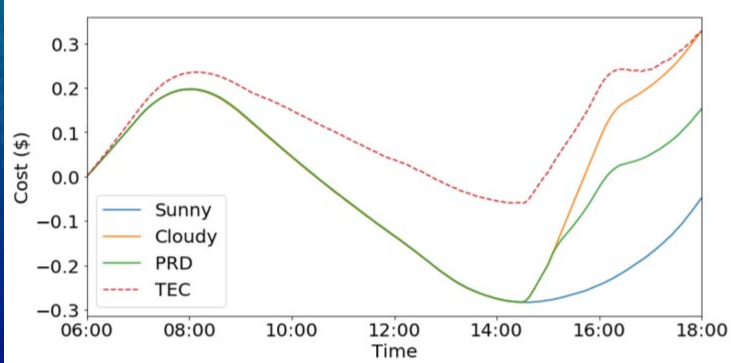


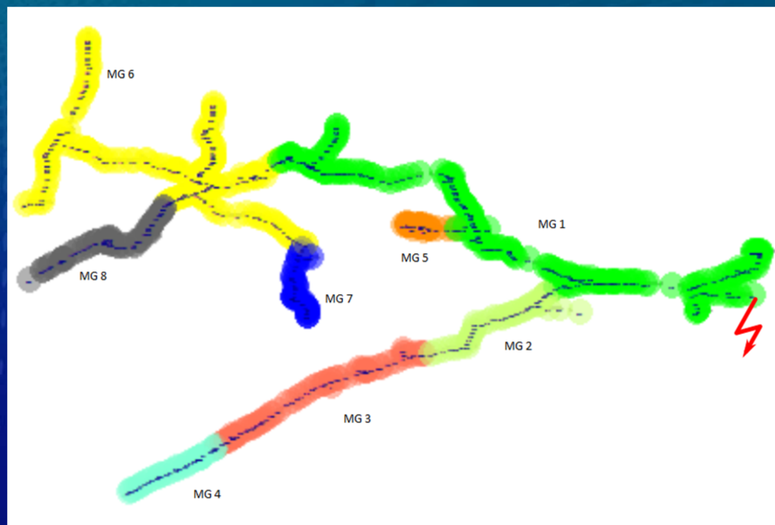
Figure NREL-18 Cumulative average energy cost for houses.

- TEC reduces PV output in morning, but comparable to PRD in afternoon.

Research Summary - TCS

- Modified the 8500 grid to reduce to 3-phase nodes, and aggregated all house loads up to these nodes.
- Two separate research components:
  - Ran the GridLAB-D double-auction market with this grid.
  - Studied dynamic microgrid reconfiguration in the face of faults.
  - Had hoped to combine the two concepts for this report.
- A dynamic microgrid configurator (DMC) was created that continuously monitors grid topology, load conditions and renewable generation at each instant to plan for segmented microgrid operations.
- Key variables: utilization of green power, reduction of losses, and percentage of load served
- 3 faults studied: (1) at substation, (2) between two microgrids, and (3) within a microgrid
- In the first two fault cases they observed increased use of renewable energy resulting in greater load served.

TCS 3-phase grid with MG configuration for the substation fault case



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Three Fault Cases with DMC

Table TCS-5 Comparison of Load Interruptions without and with DMC

Case	Amount of load interrupted	
	Business-as-usual	DMC
1: Substation outage	15,694 kW	7944 kW (allowing DERs to energize the microgrids)
2: Fault on line 509-645 (between MG2 and MG3)	15,694 kW (momentary*) 34.65 kW (sustained)	0 (MG3 is supply adequate)
3: Fault on line 32-35 (within MG5)	15,694 kW (momentary*) 26.43 kW (sustained)	26.43 kW (MG5 islanded. Interruption until fault is isolated)

* Momentary interruption until switching is done to isolate faults. Assuming there are no tie-switches present in the entire network

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Research Summary - MIT

- Modified the 8500 grid to reduce to 3-phase nodes, and connected all houses at these nodes.
- DER use model predictive control (MPC) to estimate power usage and submit cost sensitivity curves as bids for real and reactive power.
- Distribution grid controller uses AC OPF to model grid voltage to make sure that distribution voltage stays in limits.
- The MIT approach seeks to maximize DER participation and minimize grid losses through:
  - relaxations on comfort requirements (temp deviation not reported)
  - use of batteries (with resulting 20 % reduction in grid losses)
  - use of inverters for reactive power (reducing reactive power flow to grid by 15 % contributing to grid loss reduction)
  - substation voltage adjustment
- End result was 30 % reduction in cost of energy to customers

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Shunt reactor competition with DER

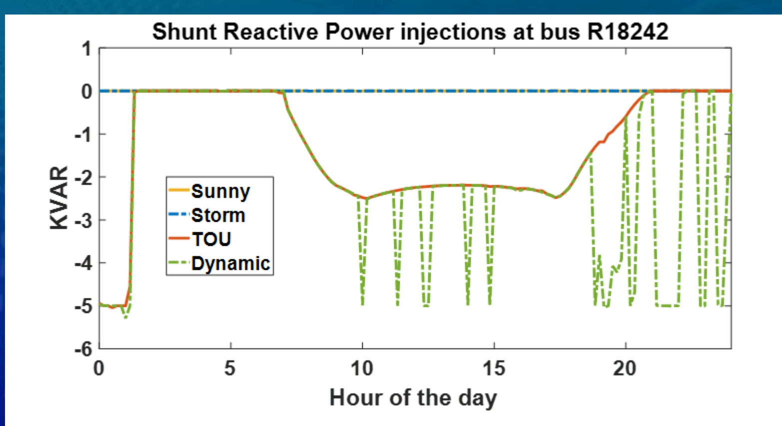

Figure MIT-12 Shunt capacitor reactive power injections at node 'R18242'

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Dynamic LMP-based tariff is lower cost that TOU

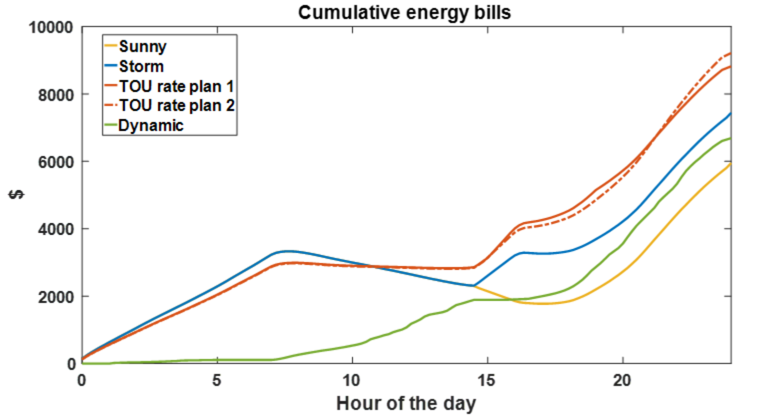

Figure MIT-17 Cumulative energy bills of all the houses

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Research Summary - Vanderbilt

- Developed a web-based generic co-simulation platform, called CPSWT-TE, that can be customized and augmented to support a variety of heterogeneous simulations.
- CPSWT-TE is based on the IEEE distributed simulation standard called High-Level Architecture (HLA).
- HLA provides services that support co-simulation: time-management, distributed object management, distributed simulation management, and support for real-time components.
- CPSWT-TE is online.

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What we learned

1. Volt-VAR control of inverters led to a 60 % decrease in voltage violation duration.
2. Power flow modeling of grid with per-meter adjustment of prices for real and reactive power led to 80 % reduction in voltage violation duration.
3. Dynamic microgrid reconfiguration improves fault tolerance and balancing and enables use of renewable resources in fault conditions.
4. Energy bills for customers can be lowered with dynamic prices.
5. A dynamic TE tariff based on substation LMP is more efficient than a TOU tariff for managing energy balance and voltage.

What we learned (cont)

6. TE can result in fewer control actions for distribution grid equipment.
7. Grid line losses with PV systems may be reduced by using TE. Batteries were effective to reduce reverse power flows.
8. Customer inverter reactive power control can be useful for real voltage management and loss reduction.

Comparing team TE approaches

- PNNL did not implement a TE market, but rather evaluated specific voltage control approaches.
- NREL used comfort adjustment, and real and reactive incentive prices on top of TOU tariff to manage voltages with very significant reduction in voltage violations.
- MIT added to this the use of batteries and substation voltage adjustment, as well as basing their real power market price on the CAISO LMP price provided with the Challenge Scenario.
- NREL varied the price per-meter, but ran into the fairness question.
- All teams show the disconnect between bulk grid prices and distribution voltage, requiring other means to manage voltage.
- MIT was successful in completely eliminating voltage violations.
- Vanderbilt focused on platform development.

TE Challenge Key Accomplishments

1. Developed a foundational TE co-simulation component model. This model provides a common vocabulary for TE co-simulation and a foundation for interoperable TE simulations.
2. Advanced co-simulation modeling tools and platforms that can support industry needs for TE system performance analysis.
3. Developed a reference TE Scenario that can support ongoing comparative simulations.
4. Tested various TE approaches for integrating distribution grid DER while managing voltage. The results help industry to understand the potential for TE methods to support DER integration.

Thank You!

NIST Smart Grid Program

Collaboration with National Renewable Energy Laboratory

Characterization of power hardware-in-the-loop systems

Instrumentation design for High-Z Fault Localization

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The cutting edge at the grid edge

- Estimating flexibility of grid edge resources (beyond dispatchability)
  - Do we have data quality, secure communication capacity and robust algorithms?
- Composing this flexibility
  - Evaluate control implications
  - Hardware-in-the-loop Simulation
  - Validated Emulations
  - Calibration of interfaces

  (Hardware-in-the-loop Simulation, Validated Emulations, Calibration of interfaces → Characterization of power hardware-in-the-loop systems)
- Characterizing these compositions as metrology problems
  - How good do micro-scale measurements need to be to provide good macro-scale state estimates for control? → Instrumentation design for High-Z Fault Localization
  - Can we decompose macro scale measurements to observe micro scale dynamics?

NREL Energy Systems Integration Facility

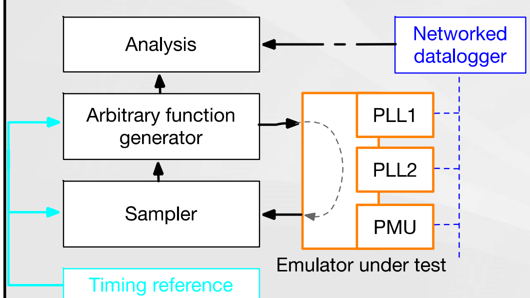
Power Hardware in the loop

Metrology best practices for HiL validation

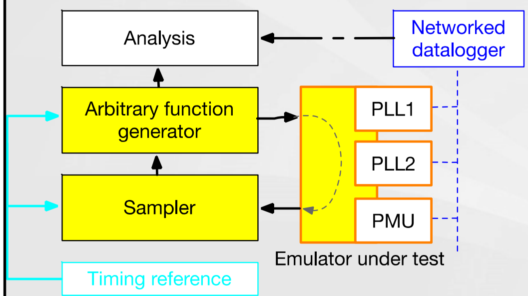
Characterize and calibrate interfaces, transducers, amplifiers and filters.

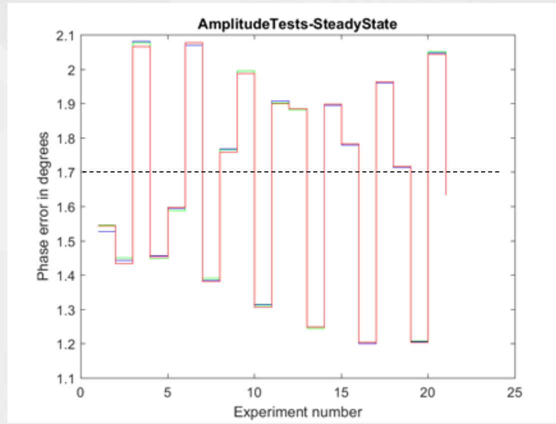
Explicitly define uncertainty terms, limits of validity on the model and control over both model and simulation parameters

Emulator interface characterization



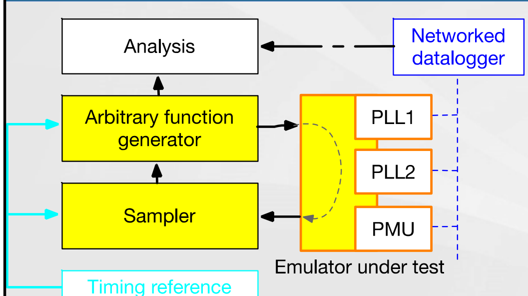
Vector error in nominal operating states

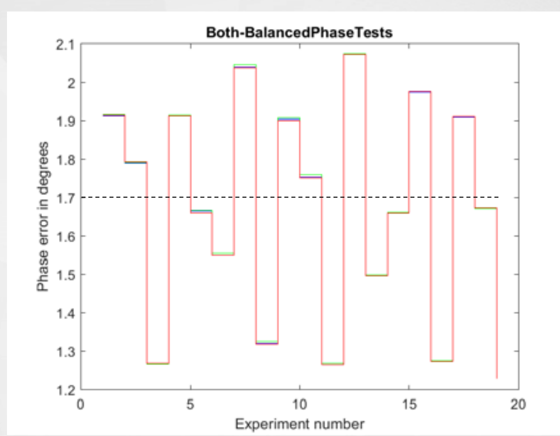




Line compensated Phase difference computed using a 5E4 sample DFT – Amplitude steps $[1{:}\,0.3{:}\,7]\ V_{rms}$

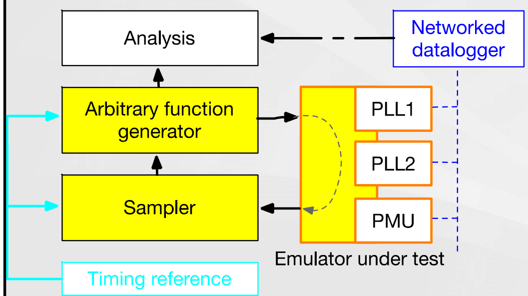
Vector error in nominal operating states

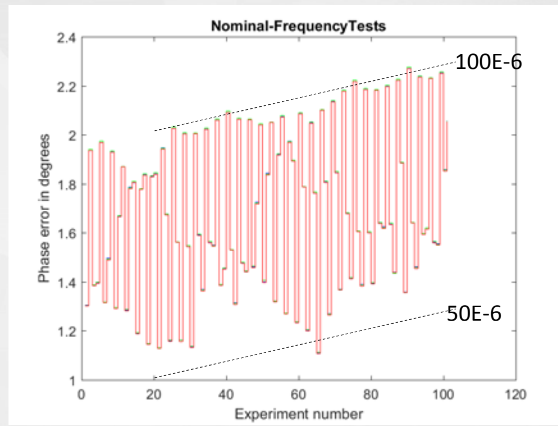




Line compensated Phase difference computed using a 5E4 sample DFT – Phase steps $[0{:}\,\pi]\ rad$

Vector error in nominal operating states





$55 - 65\ Hz$

Compensator design

Lumped CLTF

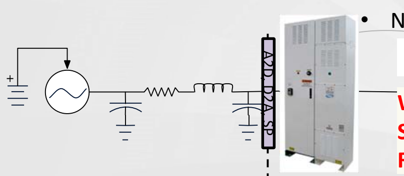
- Parasitic resonance: Emulator-Inverter.
- Phantom impedances affecting tracking.
- Negative gain margin due to time delays.

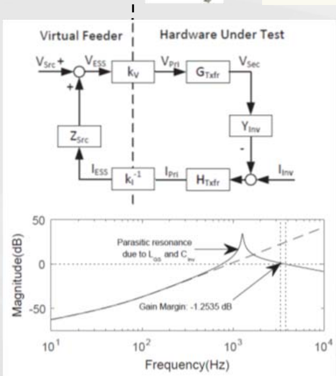
$$G_{OL,Uncomp} = \frac{k_V k_I^{-1} Z_{Src}}{(\frac{s}{2\pi f_{GS}}+1)(Z_L+Z_{GS})} e^{-s(T_{RTS}+T_{GS})}$$

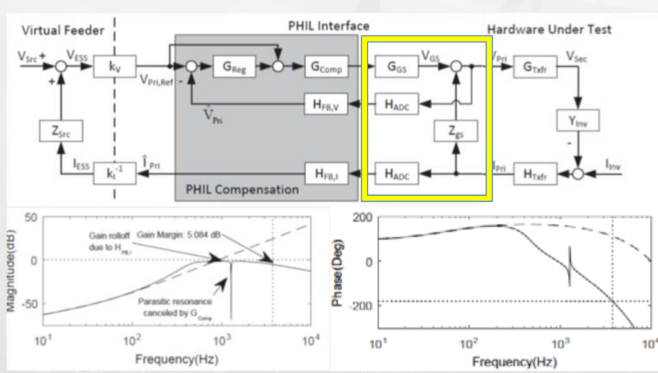
Wideband characterization of interfaces.
Self-calibration.
Robustness guarantees.

Interface compensation

- Resonance mitigation
- Narrowband gain $60 \pm 0.5\ Hz$
- Low pass filtering







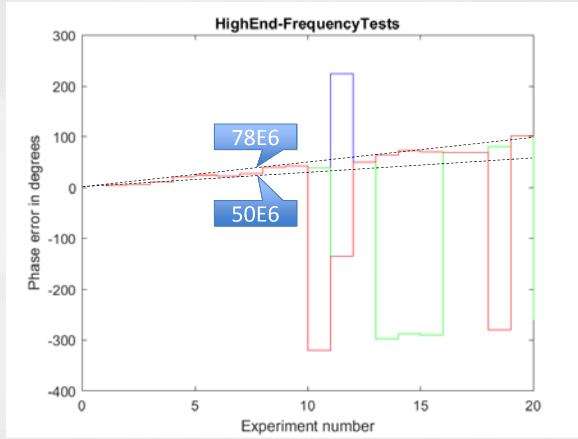
Frequency tests at higher frequencies

Frequency sweep from 150 Hz to 3KHz.

DFT over 2E5 samples (2secs)

With 50E-6 deterministic delay, @3KHz phase diff.= 54 deg.
With 78E-6 deterministic delay, @3KHz phase diff.= 84 deg.

While the trend line for phase error is mostly consistent with observed delay, unfiltered DFT results show phase errors that are not modulo 360.



Time domain analysis

Time domain expression for error:

$$\epsilon(t) := \alpha\sin(\omega t) - \beta\sin(\omega t + \phi) = \gamma\sin(\omega t + \delta)$$

$$\gamma = \sqrt[2]{\alpha^2 + \beta^2 - \alpha\beta\cos(\phi)}$$

Gain bias:

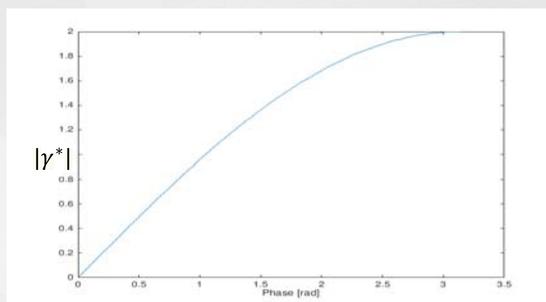
$$\boldsymbol{\gamma^* = 2\sin(\frac{\phi}{2})}$$

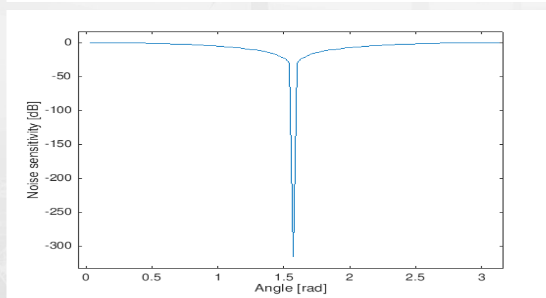
Phase bias:

$$\delta = atan2(-\beta\sin(\phi), \alpha - \beta\cos(\phi))$$

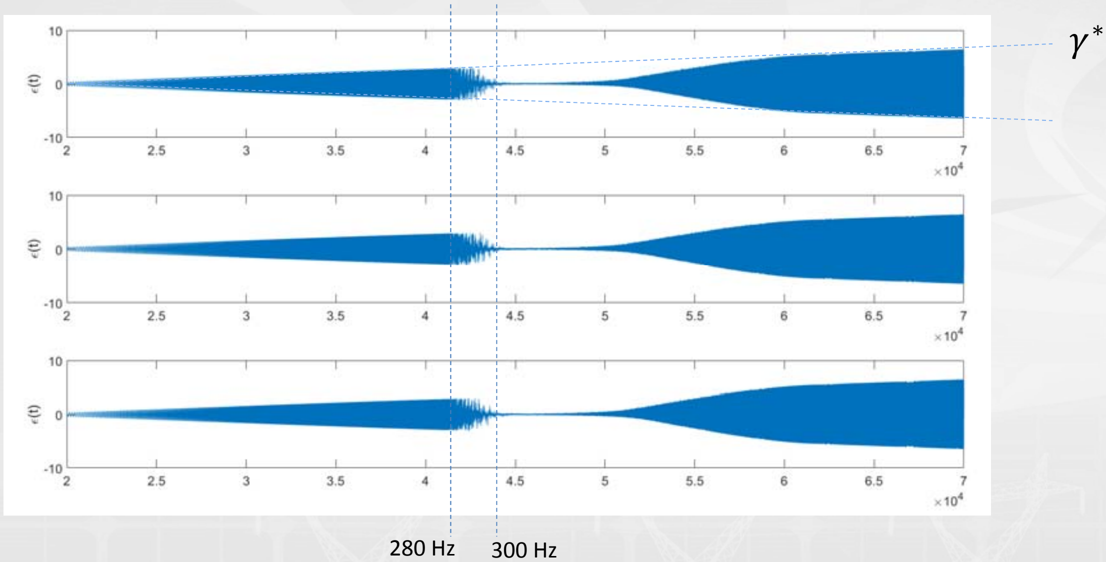
Broad spectrum sensitivity to latency variation:

$$\frac{\partial}{\partial\phi}(\alpha\sin(\omega t) - \beta\sin(\omega t + \phi)) = -\beta\cos(\omega t + \phi)$$

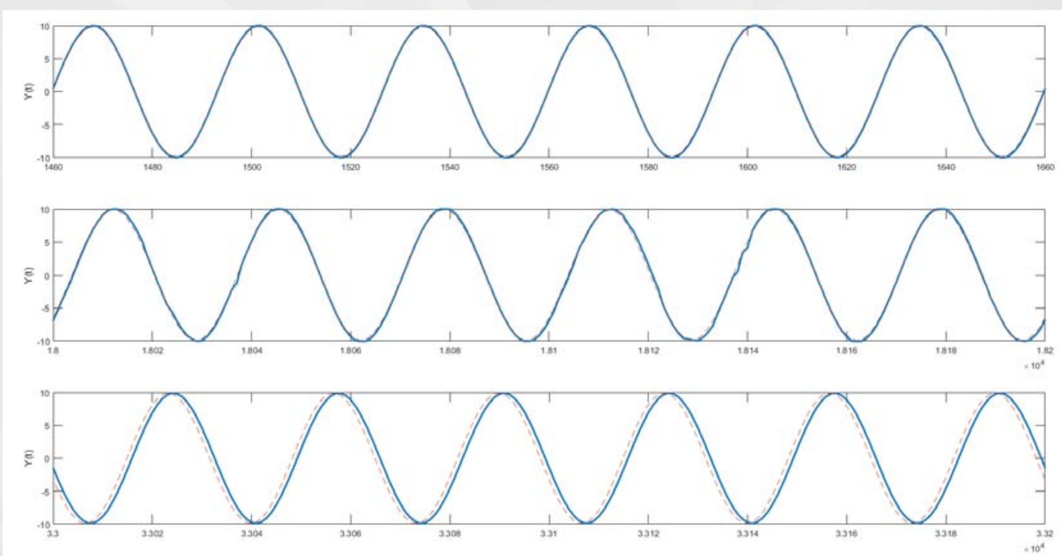




Time domain error - Frequency sweep 100Hz/S



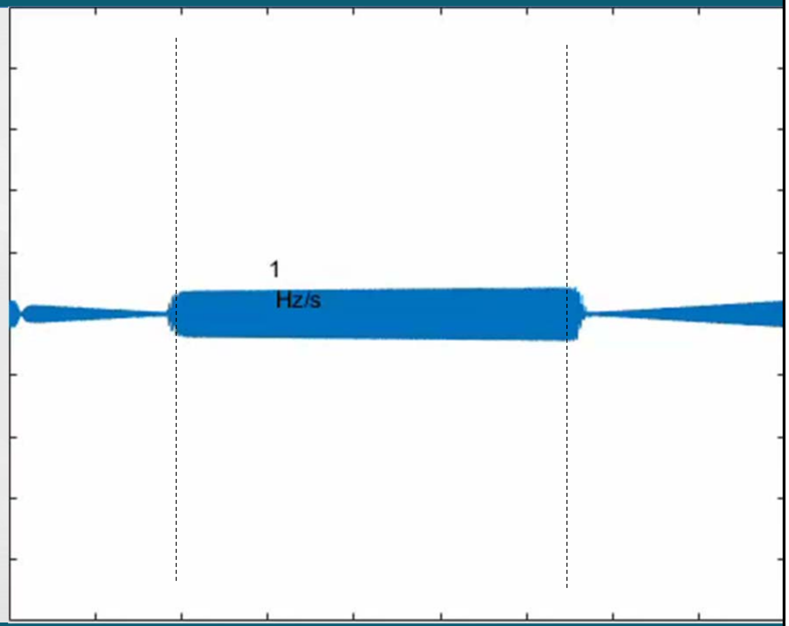
Buffer purge events – software issue manifested as electrical artifacts



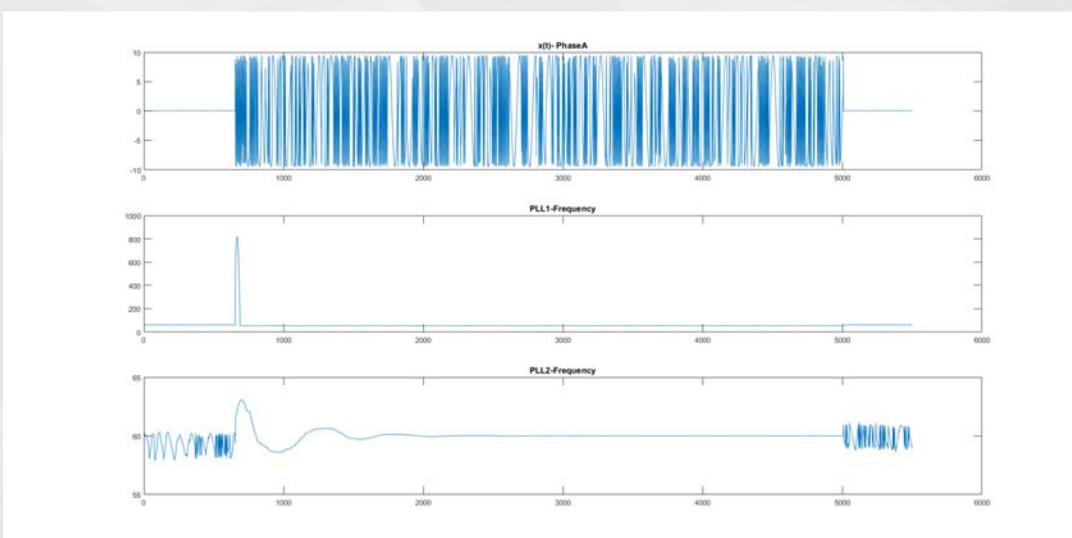
Time derivative of sensitivity

$$-\beta \frac{d}{d\omega} \cos(\omega t + \phi) = t\beta \sin(\omega t + \phi)$$

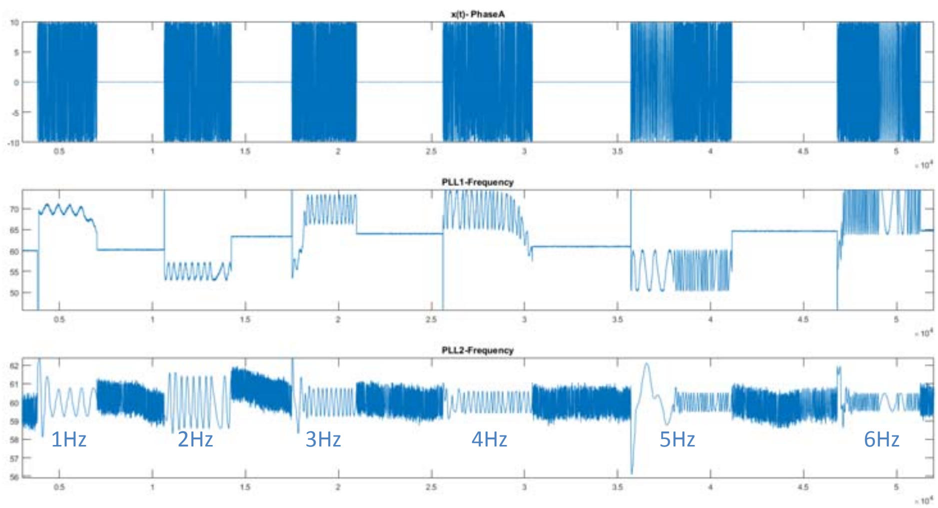
$$-\beta \frac{d}{dt} \frac{d}{d\omega} \cos(\omega t + \phi) = t\omega\beta \cos(\omega t + \phi)$$



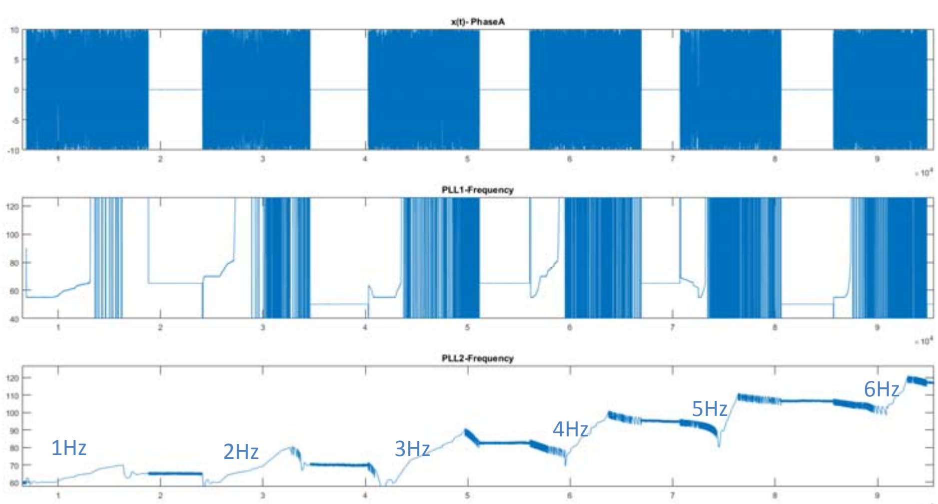
Input filter performance – amplitude step



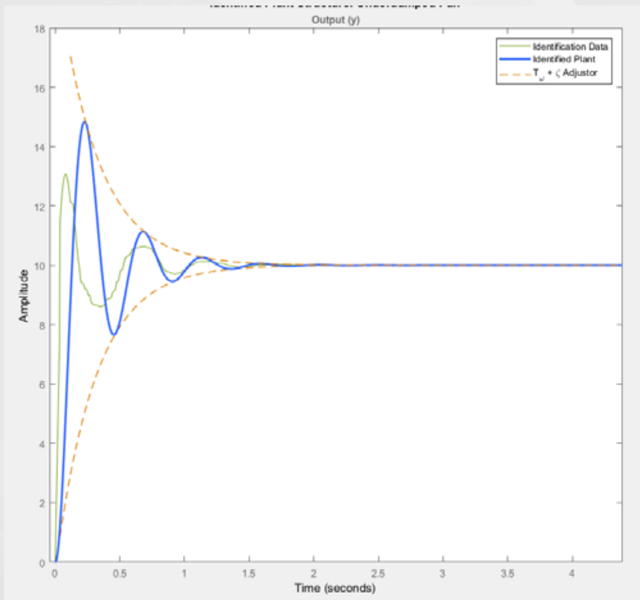
Tracking test FM 1Hz- 6Hz

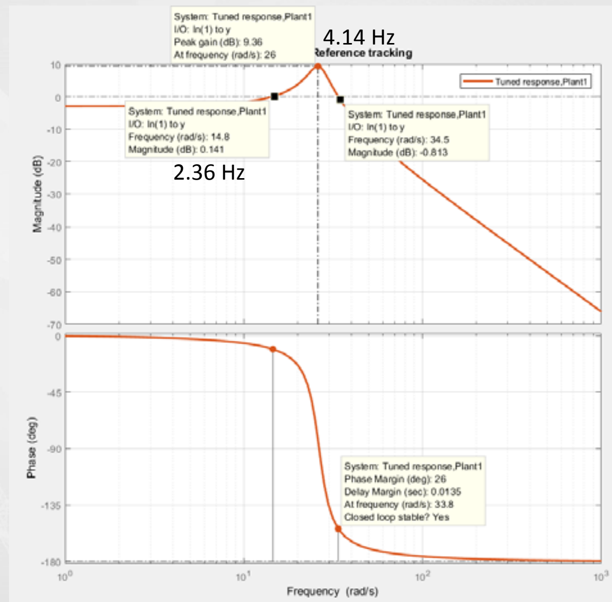


Tracking test F_ramp 1Hz/s- 6Hz/s

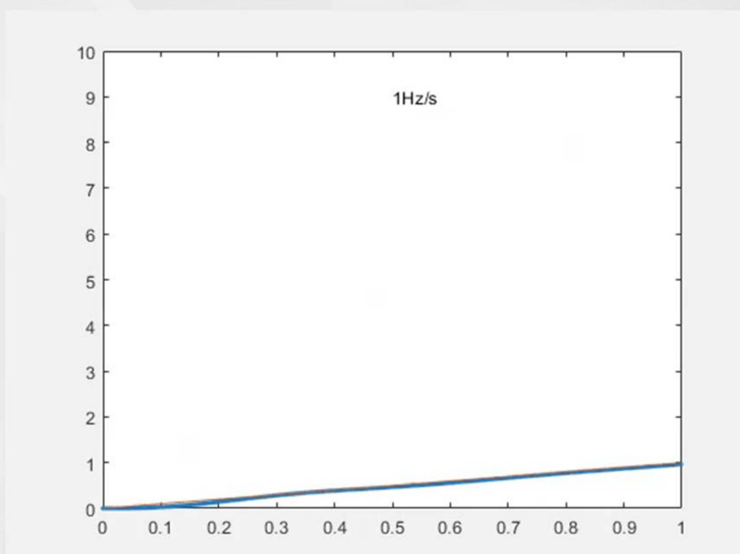


Estimating dynamic model of PLL2 - N4SID model

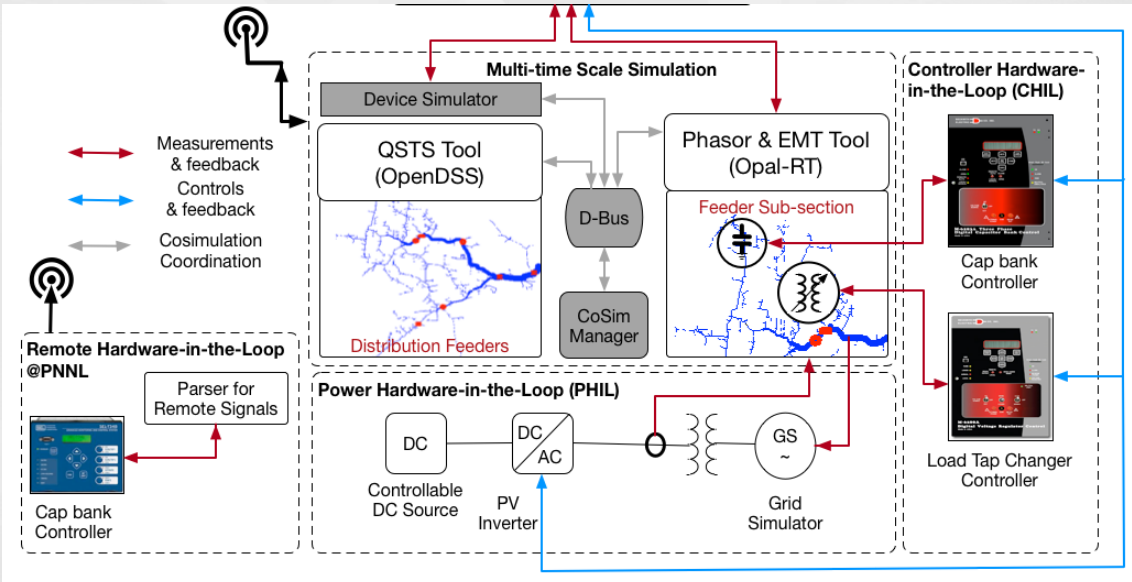




Finite tracking error for ramps per PLL model



HiL validation for systems that are multiscale and remote



NIST/NREL HIL Phase II – recover dynamic coefficients

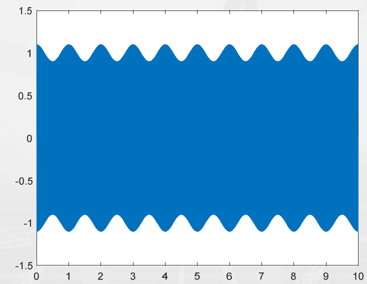
- Systems of the form: $\dot{X} = AX + Bu(t),\ Y = CX + Du(t)$
- Single band oscillator: $A = \begin{bmatrix} 0 & 1 \\ -\omega^2 & D \end{bmatrix}$ (ω = angular frequency, D = damping factor)
- 3-Band oscillator: $A = \begin{bmatrix} [Sideband] & \cdot & \cdot \\ \cdot \quad \omega & [Fundamental] & \cdot \\ \cdot & \cdot & [Sideband] \end{bmatrix}$

Example: Amplitude Modulation to estimate "virtual damping"

- A = 3-band oscillator from previous page
- C =

$$\begin{bmatrix} \frac{kx}{2}\cos\phi_x & -\frac{kx}{2}\frac{\sin\phi_x}{(\omega_0-\omega_a)} & X_m\cos\theta & X_m\frac{\sin\theta}{\omega_0} & \frac{kx}{2}\cos\phi_x & \frac{kx}{2}\frac{\sin\phi_x}{(\omega_0+\omega_a)} \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

- Where:
  - k_x = index of modulation
  - ϕ = phase of the modulation
  - X_m = Amplitude of the fundamental
  - ω_0 = fundamental frequency
  - ω_a = modulation frequency



$f_0 = 60, f_a = 1, k_x = 0.1, no\ damping$

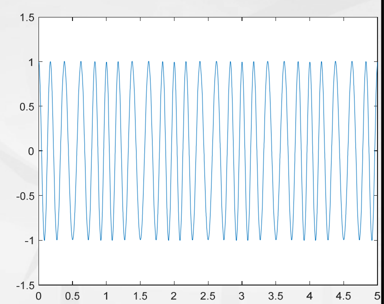
Example: Phase Modulation to estimate "synthetic inertia"

- A =

$$\begin{bmatrix} [\text{sideband21}] & & & & \\ & [\text{sideband11}] & & & \\ & & [\text{fundamental}] & & \\ & & & [\text{sideband12}] & \\ & & & & [\text{sideband22}] \end{bmatrix}$$

- C =

$$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ J_2(k_a) & 0 & -J_1(k_a) & 0 & X_m J_0(k_a) & 0 & J_1(k_a) & 0 & J_2(k_a) \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$



For visibility:
$f_0 = 5, f_a = 1, k_a = 1, no\ damping$

- $J_n(k_a)$ =

$$J_0(k_a) \cong 1 - \frac{k_a^2}{2^2}, \quad J_1(k_a) \cong \frac{k_a}{1!2!}$$
$$J_2(k_a) \cong \frac{k_a^2}{2!2^2}, \quad J_3(k_a) \cong \frac{k_a^3}{3!2^3}, \quad etc!$$

(n^{th} order Bessel function)

The cutting edge at the grid edge

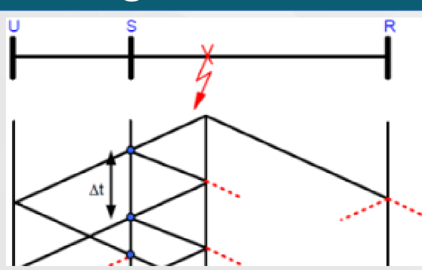
- Estimating flexibility of grid edge resources (beyond dispatchability)
  - Do we have data quality, secure communication capacity and robust algorithms?
- Composing this flexibility
  - Evaluate control implications
  - ~~Hardware-in-the-loop Simulation~~
  - ~~Validated Emulations~~
  - ~~Calibration of interfaces~~
- Characterizing these compositions as metrology problems
  - How good do micro-scale measurements need to be to provide good macro-scale state estimates for control?
  - Can we decompose macro scale measurements to observe micro scale dynamics?

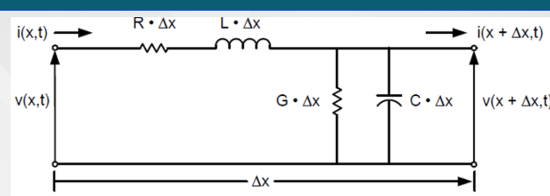
N I S T smart grid program 25

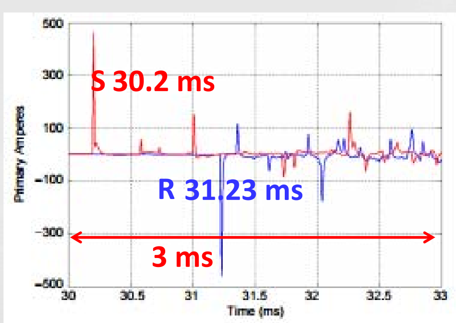
Project Objectives

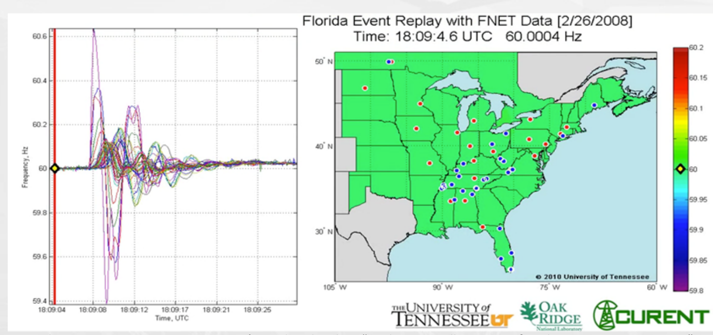
- Develop a high frequency signature based protection devices for a distribution system with high PV penetration
- Infer fault location using time domain information (moving away from phasor domain)
- Emulate traveling wave phenomenon in software and hardware

Background on traveling waves





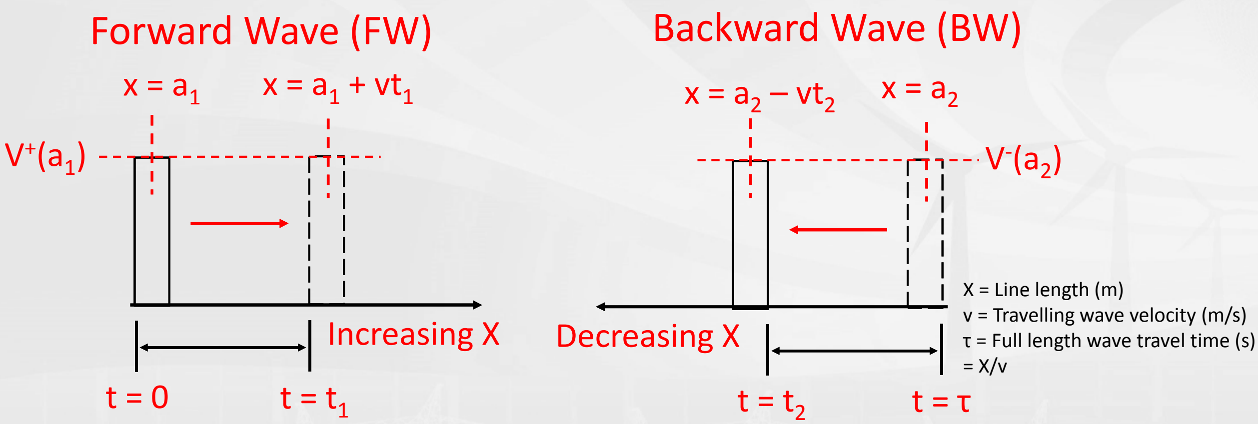




E. O. Schweitzer III, B. Kasztenny, A. Guzmán, and V. Skendzic, "Applying Travelling Waves for Ultra-Fast Line Protection."

S. K. Salman and I. M. Rida, "Investigating the impact of embedded generation on relay settings of utilities electrical feeders," in IEEE Transactions on Power Delivery, vol. 16, no. 2, pp. 246-251, Apr 2001.

Telegrapher's Equation



$$V(x,t) = V^{+} f_1(x - vt) + V^{-} f_1(x + vt)$$

$$I(x,t) = I^{+} f_1(x - vt) - I^{-} f_1(x + vt)$$

$$I^{+} = \frac{V}{Z}$$

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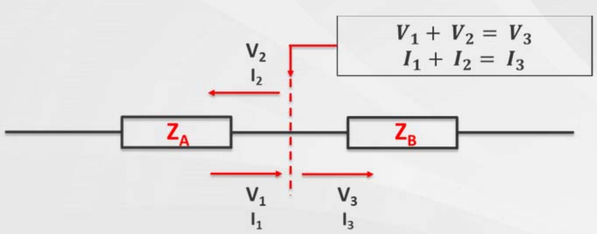
Reflection and Refraction



$$\boldsymbol{I_1 + I_2 = I_3}$$

$$\frac{\boldsymbol{V_1}}{\boldsymbol{Z_A}} - \frac{\boldsymbol{V_2}}{\boldsymbol{Z_A}} = \frac{\boldsymbol{V_3}}{\boldsymbol{Z_B}}$$

Reflection Coefficient (α_V) = $\frac{Z_B - Z_A}{Z_B + Z_A}$ $(-1 \le \alpha_V \le 1)$

Refraction Coefficient (β_V) = $\frac{2Z_B}{Z_B + Z_A}$ $(0 \le \beta_V \le 2)$

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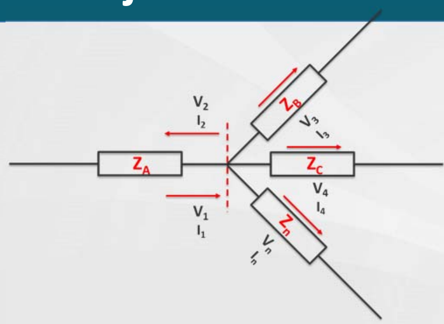
Multi-junction Reflection and Refraction



$$Z_{eq}^{T} = \frac{1}{Z_B} + \frac{1}{Z_C} + \ldots. + \frac{1}{Z_n}$$

$$\alpha_I = \frac{Z_A - Z_{eq}^T}{Z_A + Z_{eq}^T} \qquad \beta_I = \frac{2Z_A}{Z_A + Z_{eq}^T}$$

Reflected current = $\alpha_I * I_1$ **Total transmitted current =** $\beta_I * I_1$

Transmitted current in each branch = $I_n^T = \frac{Z_{eq}^T}{Z_n} * \beta_I * I_1$

N I S T s m a r t g r i d p r o g r a m

Wave velocity

$$\gamma = \sqrt{ZY} = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta$$

ω → $2\pi f$

R, L, G, C **= Modal Parameters**

α **= Attenuation Constant** β **= Wavelength Constant**

$$\text{Velocity} = f\lambda = \frac{2\pi f}{\beta}$$

f → **wave frequency**

N I S T s m a r t g r i d p r o g r a m

Wave velocity

Example#1 (Lossless Line):

L = 3.0823 mH/Km, C = 3.6097 * 10^-3 µF/Km

$$\text{Calculated Velocity} = 2.997967995 \ * 10\text{^}5 \ Km/sec$$

$$\text{EMTP Velocity} = 2.9980 \ * 10\text{^}5 \ Km/sec$$

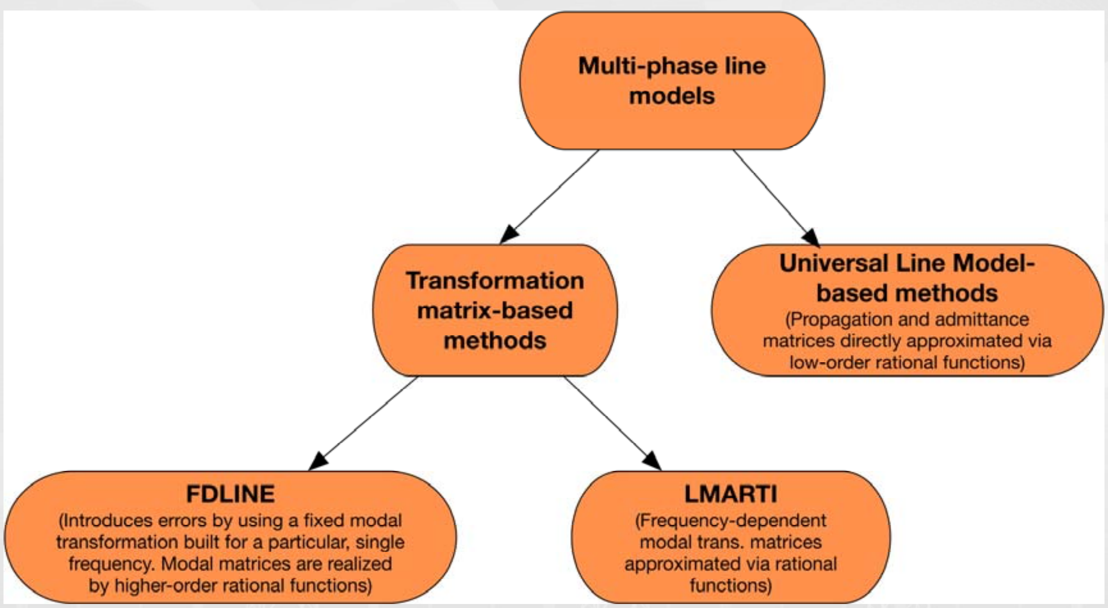
Example#2:

R = 1100.2Ω, L = 3.2636 mH/Km, G = 2.0171 * 10^-10 MH/Km, C = 3.66 * 10^-3 µF/Km, f = 10^6 Hz

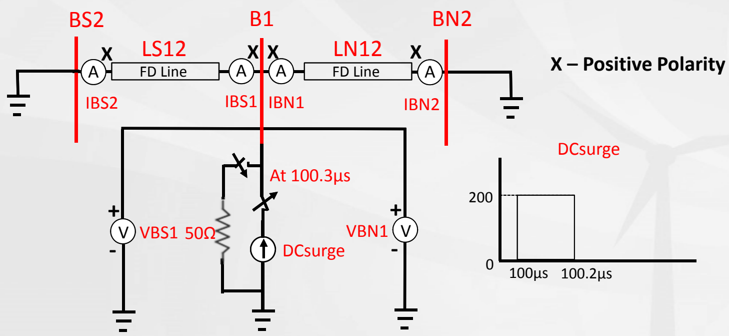
$$\text{Calculated Velocity} = 2.892376941 \ * 10\text{^}5 \ Km/sec$$

$$\text{EMTP Velocity} = 2.8924 \ * 10\text{^}5 \ Km/sec$$

Modeling considerations for distribution lines



Simulation study: Single line case



Line	Length (Km)	Surge Impedance (Ω)	Velocity (Km/sec)	Wave Travel (µs)
LN12	0.75	924	3*10^5	2.5
LS12	0.25	924	3*10^5	0.83

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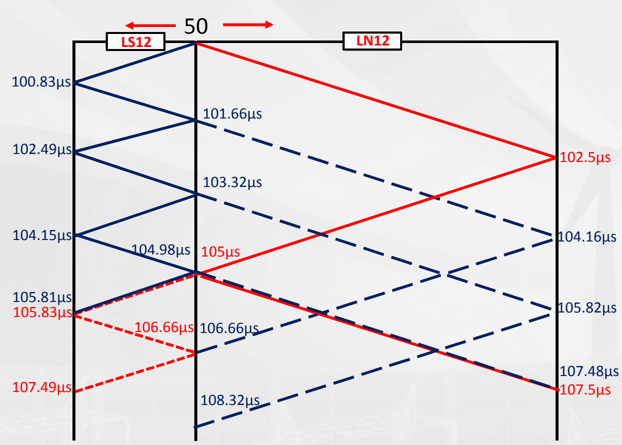
Lattice diagram: Single line case



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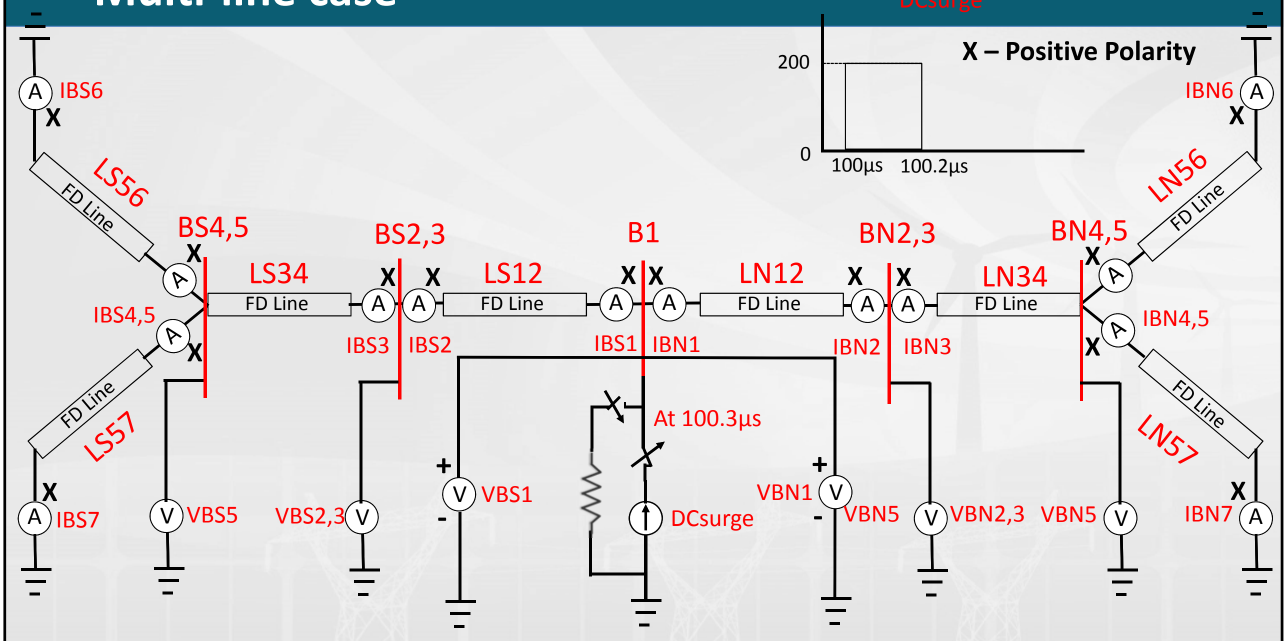
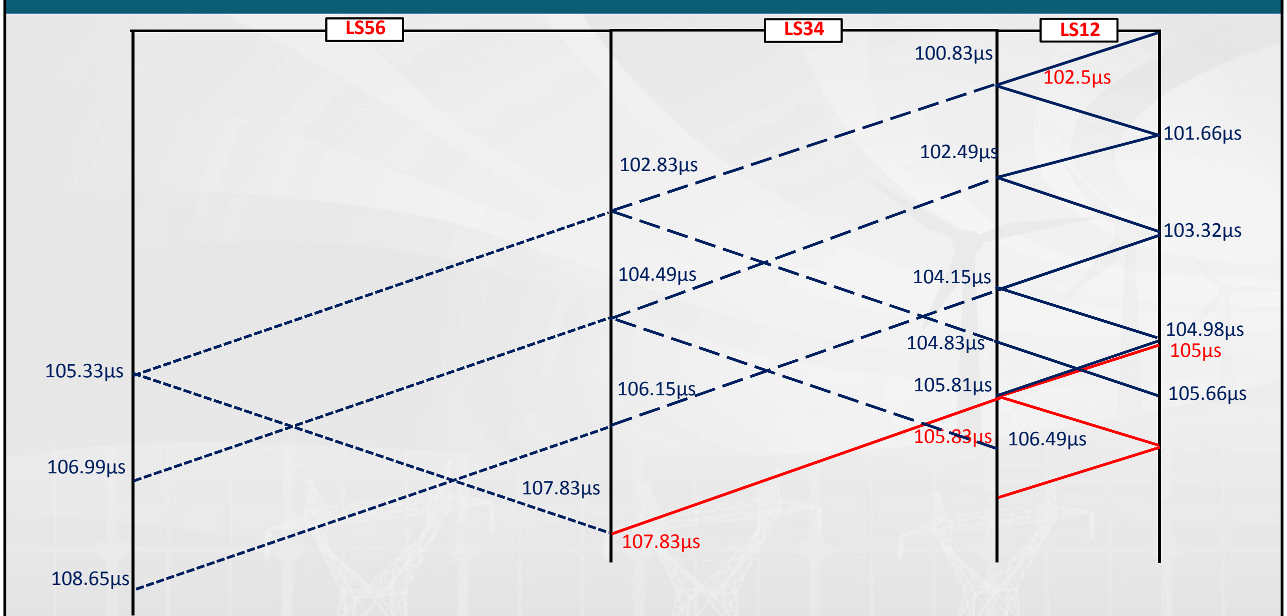
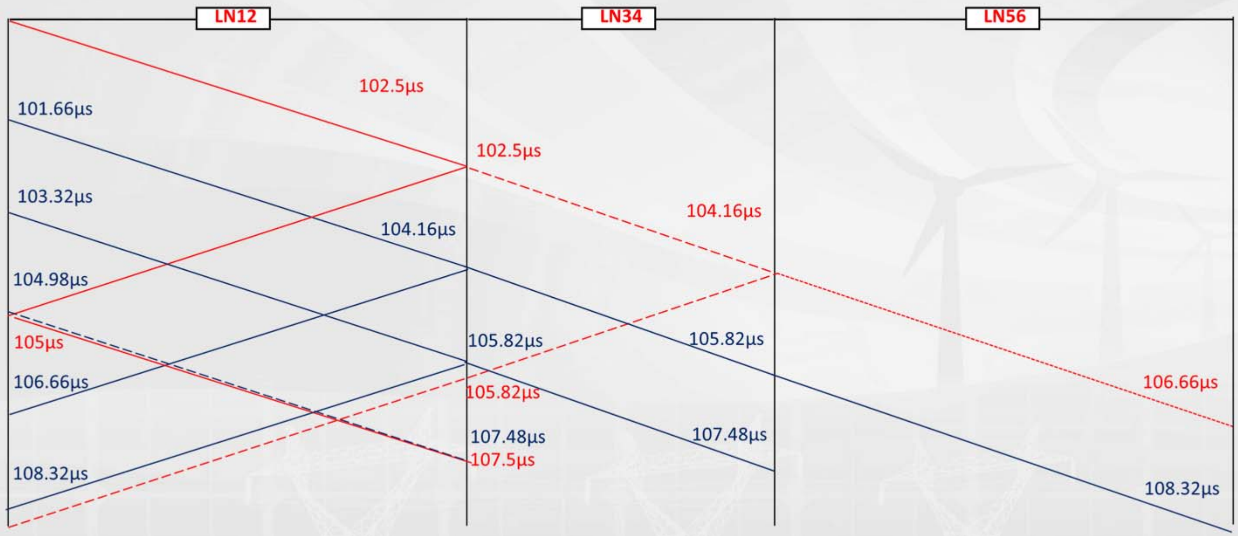
Multi-line case



South Lattice



North Lattice



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Leveraging ESIF capabilities

- Leveraging MVOTA capabilities to show travelling wave characteristics in distribution lines.
- Challenges in MVOTA testing
  - Short line length
  - (travel time =16 ns)
  - Data acquisition resolution

ESIF's medium voltage test facility MVOTA used for tests

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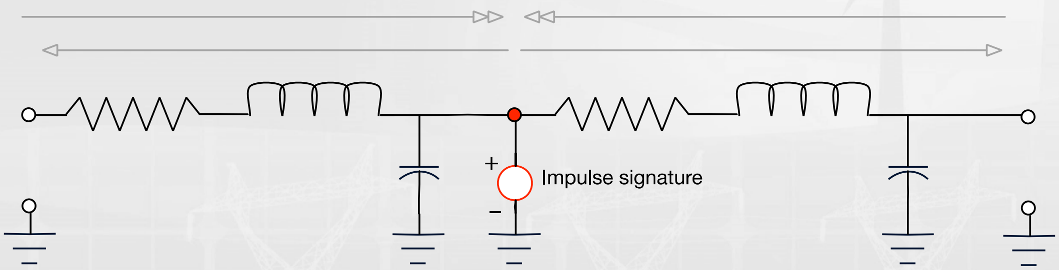
Challenges with injecting impulses

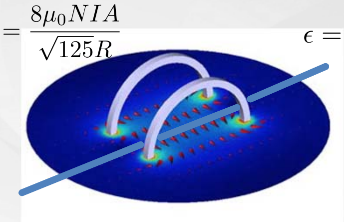
- Parasitic impedances, coupling artifacts and transients at the output buffer.
- Even if matched carefully, impedance at injection point is time varying.
- Energy is limited for commercial impulse generators, at low circuit impedances induced voltage magnitudes are low – introducing sensing challenges.

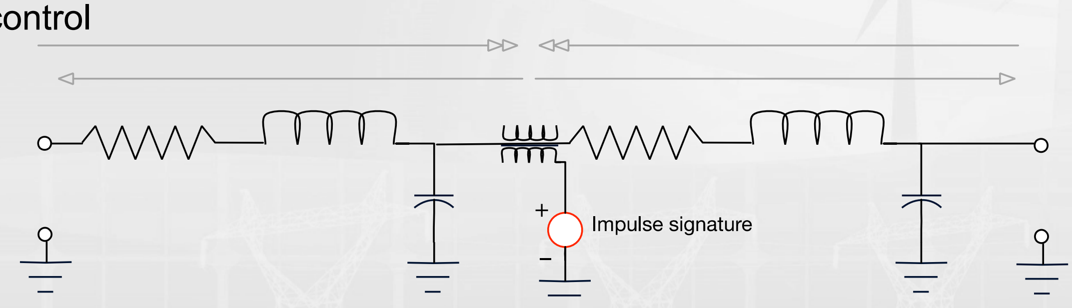


Electromagnetic impulse injection

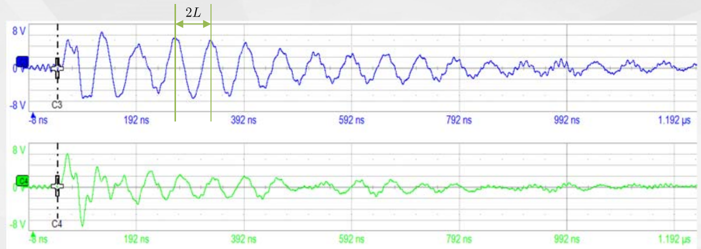
- A Helmholtz coil produces a uniform magnetic field with the primary component parallel to the axis of the coils.
- The induced voltage is only proportional to the rate of change of magnetic field -which we can control

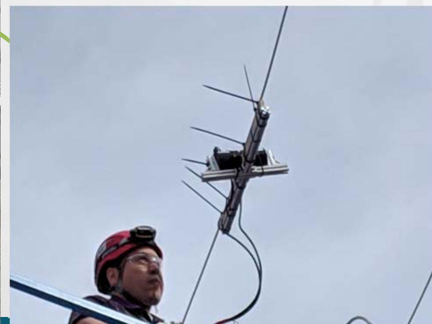
$$\Phi = \frac{8\mu_0 N I A}{\sqrt{125}R} \qquad \epsilon = -\frac{d\Phi}{dt}$$

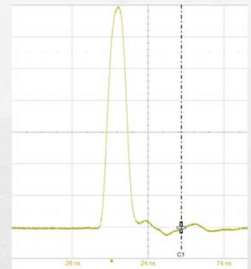




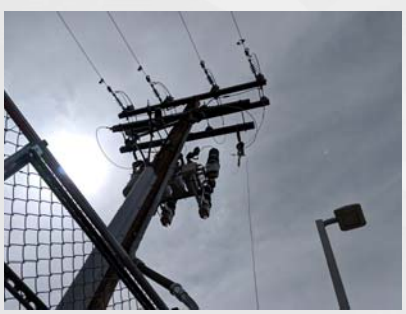
Electromagnetic impulse test on the MVOTA



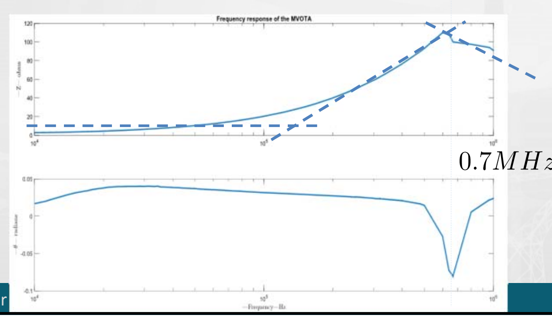


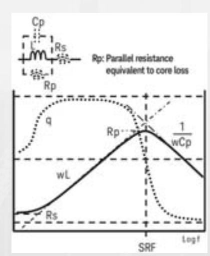


Identifying model parameters for the MVOTA



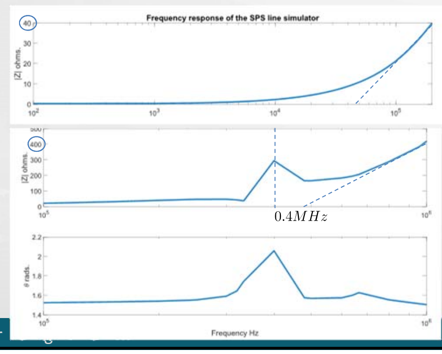
- All line models require discretized RLC elements to be defined, these parameters may be frequency dependent.
- 4 port impedance analysis was performed to identify these parameters for the MVOTA.
- Clear changes in impedance regime in the 10E4 -10E6 MHz interval.

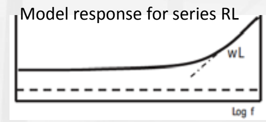




Identifying model parameters for the line simulator

- Simulates a line as series RL circuit; enabling us to validate data acquisition instrumentation at realistic power and voltage levels.
- Will help us characterize a key unknown; the interaction between PV inverters and electromagnetic transients.





Close to model response <200KHz, parasitic capacitances introduce self resonance at ~400KHz

Sensing and Data Acquisition

Current Transformer
- High current rating (100A pulse)
- High frequency range (up to 500MHz)

NIST characterized

Voltage Transformer
- Rated for medium voltage application

(20kV rms)
- High bandwidth (120 MHz)

NIST characterized

DAQ
- High bandwidth (4GHz max.)
- High resolution (12 bits)
- High sampling rate

(20 GS/s)
- Precise time sync. NIST T&F

Thank you