Advances in Distribution System Time-Series Analysis for Studying DER Impacts

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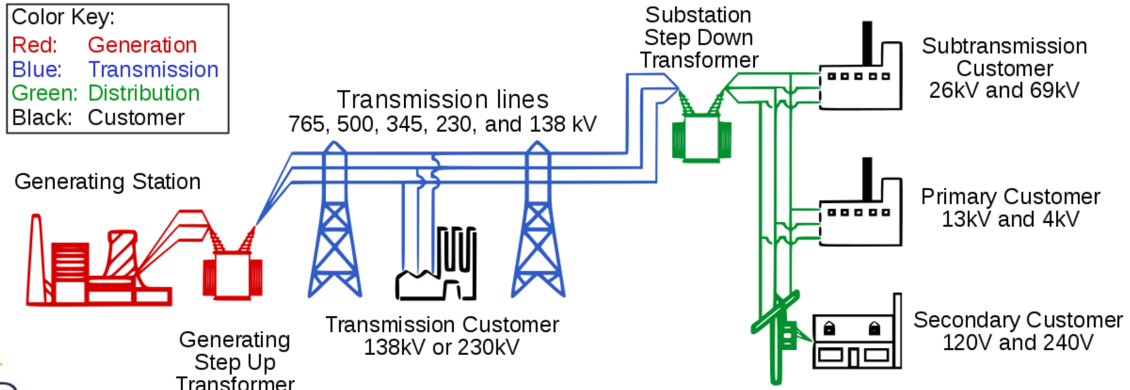
Electric Power Distribution Systems

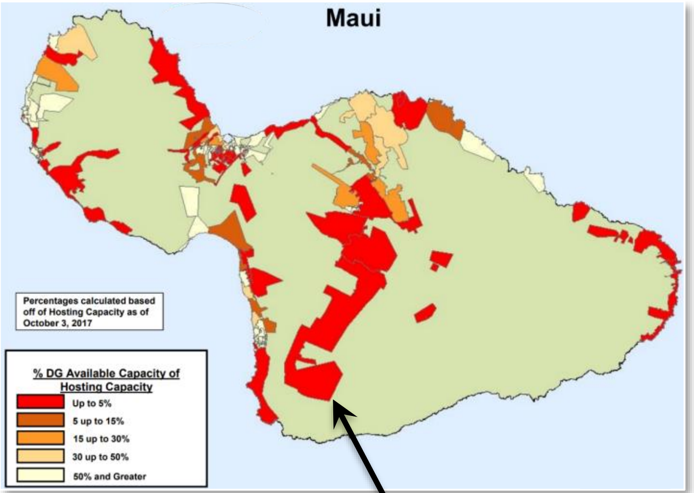
- Many of the recent advances in smart grid technologies, proliferation of distributed energy resources (DER), and new control strategies are on the medium-voltage distribution system between the transmission system and the customer
- Distribution system analysis and design has experienced a gradual development over the last couple of decades
  - Large volumes of data and computational processing of three-phase unbalanced systems, including low-voltage secondary networks
  - Analysis commonly performed in frequency domain without dynamics
  - Typically models assess power delivery at one point in time



http://www.ferc.gov/industries/electric/indus-act/reliability/blackout/ch1-3.pdf

Distribution System Networks

- Emerging technologies are creating significant changes to:
  - the energy mix
  - the traditional methods for planning and operation of distribution systems
- Growing demand for rooftop solar photovoltaic (PV)
  - U.S. Department of Energy is working to decrease PV interconnection cost and time
- Existing practices can conservatively limit the number of PV interconnections



Saturation of distributed generation at the local level

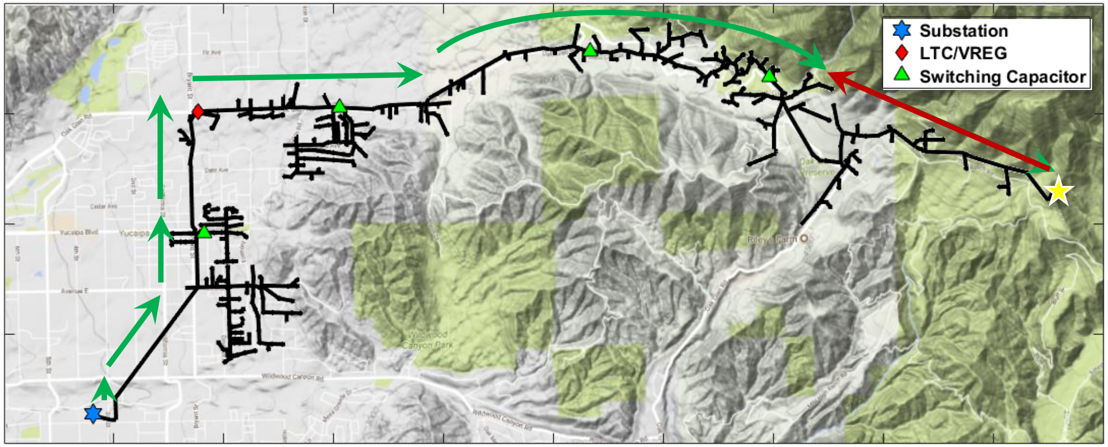
PV Grid Integration

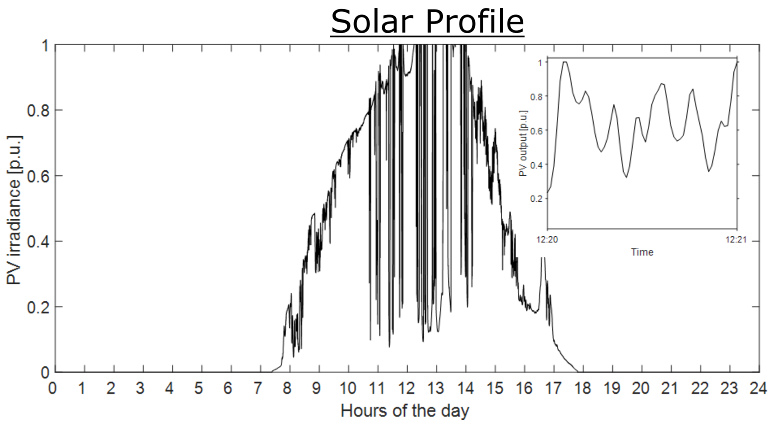
PV systems can cause negative impacts on a distribution system feeder

1. Designed for radial flow in one direction from the substation
2. Designed for aggregated loads with little short-term variability

Distribution System Impacts:

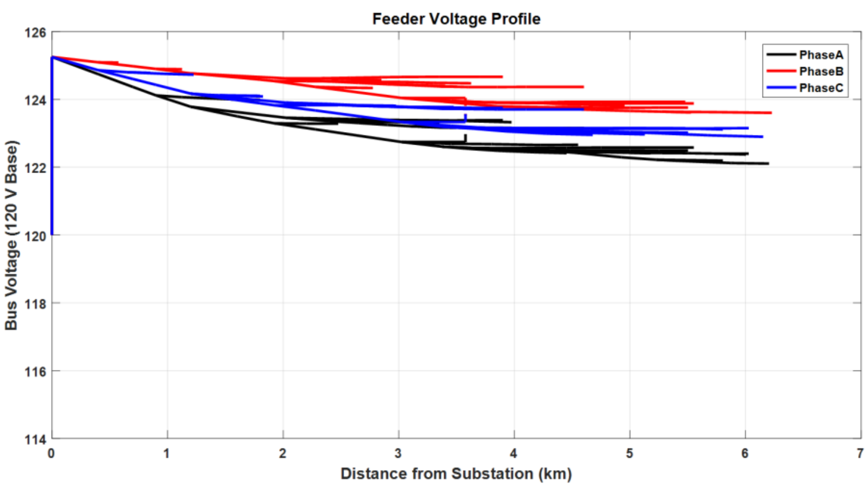
- Over/under-voltage conditions, thermal limit violations, reverse power flow, rapid power fluctuations, excessive voltage controller actions, etc.



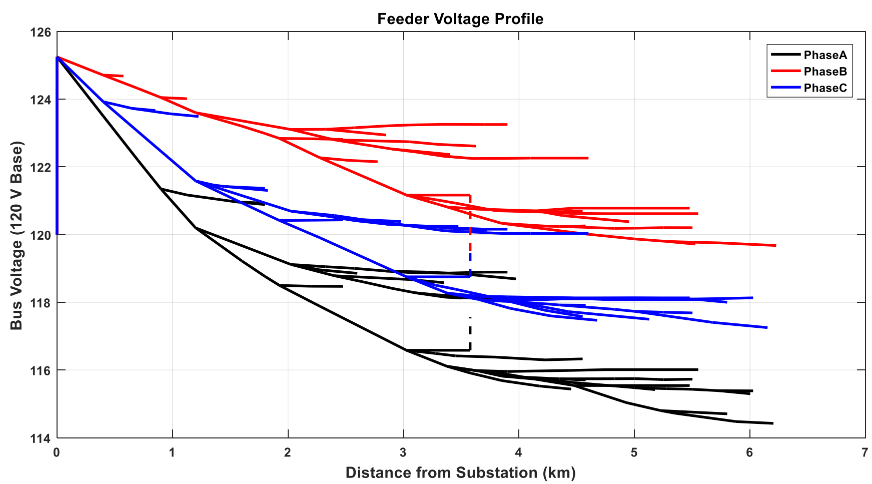


Conventional Interconnection Study

- <u>Snapshot simulation</u>:
  - Steady-state power flow simulations of particular scenarios
  - <u>Peak load conditions</u> to capture any under-voltage conditions
  - <u>Minimum load conditions</u> to capture any over-voltage conditions
  - Simple and quick tool used in the industry by system planners



Min. Load



Max. Load

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Snapshot Analysis

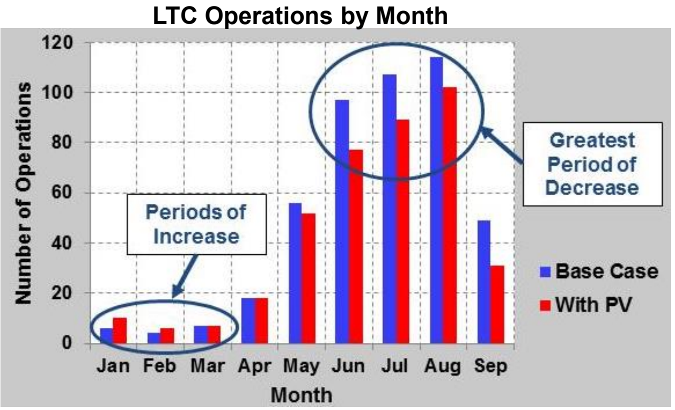
	Extreme Voltages	Thermal Loading	Regulators Tap Changes	Capacitor Switching	Time outside ANSI	Losses	Computation Time[1]
Snapshot	Good	Good	-	-	-	-	<1 sec

- Snapshot simulations are good at identifying extremes, especially for simple systems without DER or complex controls
- Snapshot simulations cannot measure the impact to controllers (such as regulators or capacitors), time the feeder is outside allowable ANSI voltage limits, or energy losses.

[1]Simulations in OpenDSS for a single unbalanced radial utility distribution feeder with >3000 buses, 4 voltage regulators, high penetration of distributed and utility-scale PV, and secondary system modelled.

Timeseries Simulations

- Timeseries simulations capture time-dependent characteristics of the power flow, including the interaction between the daily changes and seasonal correlation of load and PV production
- Yearlong analysis is typically performed at hourly resolution using **independent static** steady-state power flows (8760)
- Hosting capacity analysis and other such tools that only use snapshot analyses to investigate specific time periods are overly conservative about PV impacts because they do not include the geographic and temporal diversity



R. J. Broderick, J. E. Quiroz, M. J. Reno, A. Ellis, J. Smith, and R. Dugan, "Time Series Power Flow Analysis for Distributed Connected PV Generation," Sandia National Laboratories, SAND2013-0537, 2013.

Planning Using Timeseries Simulations

- Timeseries for simulations are used for power system planning by using historical measurements of load and PV production to study potential scenarios
- Distribution system analysis typically uses power consumption/injection profiles, and does not include OPF
- Solving individual steady-state timeseries power flows is becoming more common in industry due to DER
- “Steady State Analysis with Load Profiles” module in CYME
- California has begun including timeseries analysis in the Integration Capacity Analysis for Distribution Resources Plans

Hourly Timeseries Simulation

	Extreme Voltages	Thermal Loading	Regulators Tap Changes	Capacitor Switching	Time outside ANSI	Losses	Computation Time[1]
Snapshot	Good	Good	-	-	-	-	<1 sec
Hourly Timeseries	Great	Great	-	-	Good	Great	5 sec

- Hourly timeseries for a year ensures that the correct correlations between loads and DER are analyzed to determine the extreme voltages and thermal loadings
- Hourly timeseries provides good estimates of the time variables
- Hourly timeseries cannot measure the impact of controllers (such as regulators or capacitors) that operate inside the hourly timeframe

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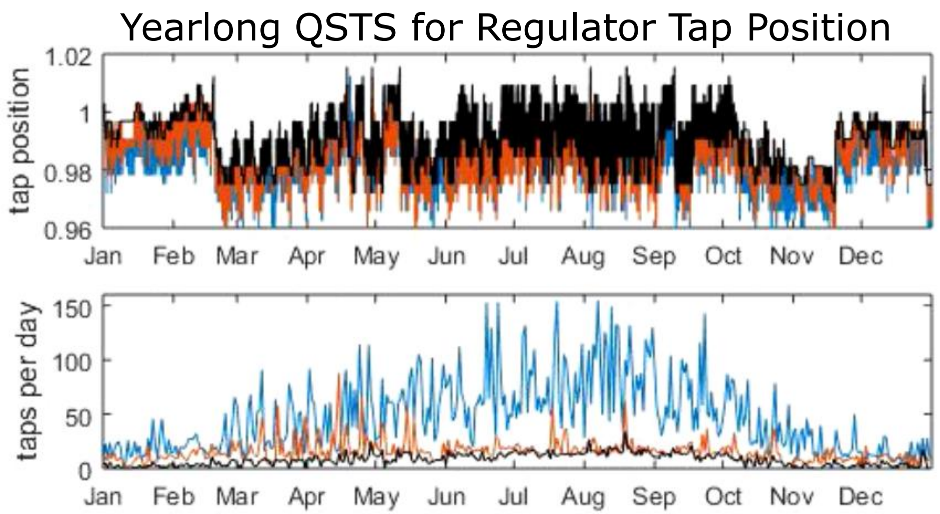
Quasi-Static Time-Series Simulations

- Quasi-static time series (QSTS) analysis is defined by the IEEE guide for *conducting distribution impact studies for distributed resource interconnection* (P1547.7):
  - *"Quasi-static simulation refers to a sequence of steady-state power flow, conducted at a time step of no less than 1 second but that can use a time step of up to one hour. Discrete controls, such as capacitor switch controllers, transformer tap changers, automatic switches, and relays, may change their state from one step to the next."*
- QSTS power flows use the information from the previous time-steps



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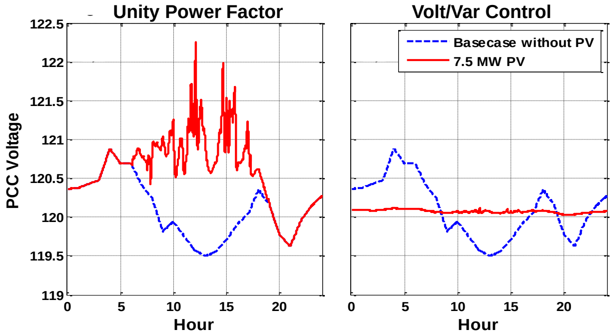
Quasi-Static Time-Series (QSTS)

- QSTS analysis captures higher-frequency time-dependent characteristics of power flows, including the interaction between controllers and advanced inverters
- QSTS simulations are needed today to understand:
  - Rapid fluctuations due to highly variable PV
  - Impact to voltage regulators and switch capacitors
  - Temporary extreme conditions before controls reach steady-state
- The need will continue to increase in the future:
  - Study interactions between advanced inverters with volt-var
  - Simulate fast operating FACTS devices
  - Research new distribution control strategies



M. J. Reno, R. J. Broderick, and S. Grijalva, "Smart Inverter Capabilities for Mitigating Over-Voltage on Distribution Systems with High Penetrations of PV," in IEEE Photovoltaic Specialists Conference, 2013.

Simple Comparison of Distribution Simulation Methods

Steady-state (snapshot)

- Follow traditional planning practices
- Require relatively low-resolution input data (multiple time points)
- Are inherently conservative

Quasi-Static Time-Series

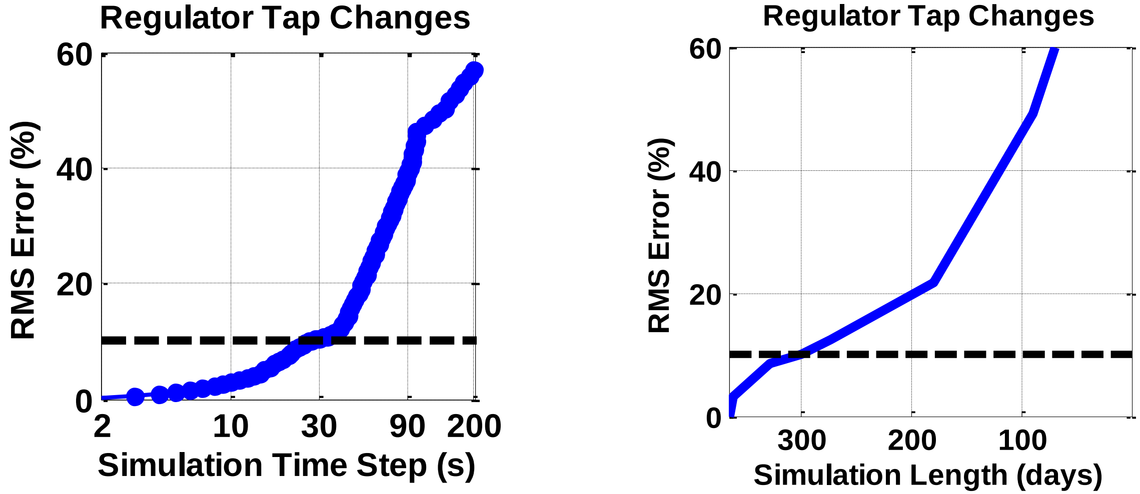
- Require new tools, new experience
- Require high-resolution input data (temporal and spatial)
- Are inherently realistic and more informative
  - Calculate automatic voltage regulation equipment operations, time durations of voltage excursions, etc.

In future hi-pen PV scenarios (or other types of DER) conservative, worst-case analysis, will unnecessarily limit PV integration – thus we need to improve the PV impact study methods

QSTS Requirements

- QSTS simulations need to be:
  - High resolution simulation to capture solar variability (time step less than 10 seconds)
  - Extended-term simulations (year-long)

Error for Time-Step and Simulation Length Compared to Yearlong 1-second Resolution QSTS



M. J. Reno, J. Deboever, and B. Mather, "Motivation and Requirements for Quasi-Static Time Series (QSTS) for Distribution System Analysis," IEEE PES General Meeting, 2017.

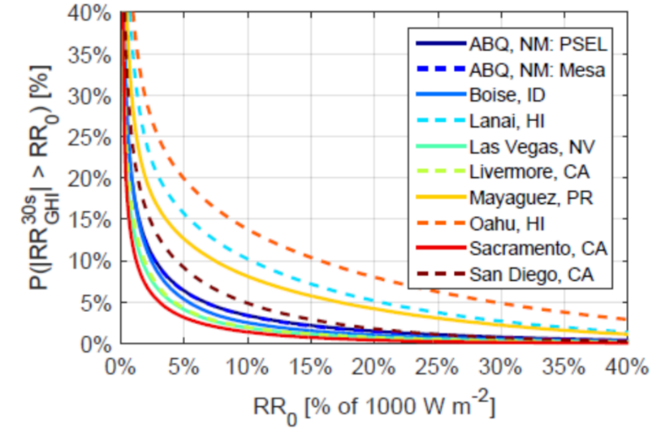
QSTS Simulation Tradeoff

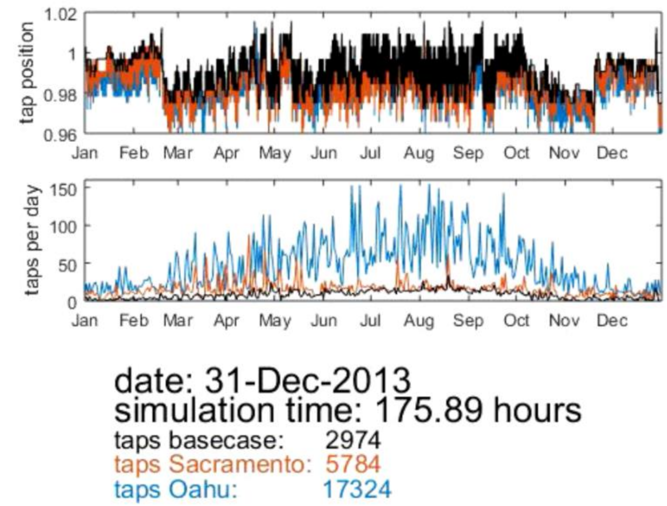
	Extreme Voltages	Thermal Loading	Regulators Tap Changes	Capacitor Switching	Time outside ANSI	Losses	Computation Time[1]
Snapshot	Good	Good	-	-	-	-	<1 sec
Hourly Timeseries	Great	Great	-	-	Good	Great	5 sec
1 day QSTS	Poor	Poor	Decent	Decent	Poor	Poor	5 minutes
1 year QSTS	Great	Great	Great	Great	Great	Great	36 hours

- Single-day QSTS does not capture the full seasonal variations
- Identifying key periods for QSTS simulation is difficult and error does not converge until simulation of more than 100 days
- QSTS simulation of an entire year is too computational intensive

Current Limitations for QSTS Adoption

- Lack of High-Resolution Data
  - Load/PV generation profiles need to be high-resolution, time synchronized, spatially correlated, and measured locally
- Computational Speed
  - Yearlong QSTS at 1-second resolution requires 31 million power flow solutions – it can take days of computational time to solve, but there are new interconnection requests daily





M. Lave, M. J. Reno, and R. J. Broderick, "Characterizing Local High-Frequency Solar Variability and its Impact to Distribution Studies," in Solar Energy, 2015.

Rapid QSTS Simulations for High-Resolution Assessment of Distributed PV

Funded by: U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Objectives
  1. Develop load/PV models for QSTS
     - Accurate, location-specific, models that reflect variability and geographic diversity
  2. Enable year-long QSTS distribution simulations by reducing analysis time from days to minutes
     - Speed up power flow solutions and timeseries analysis methods

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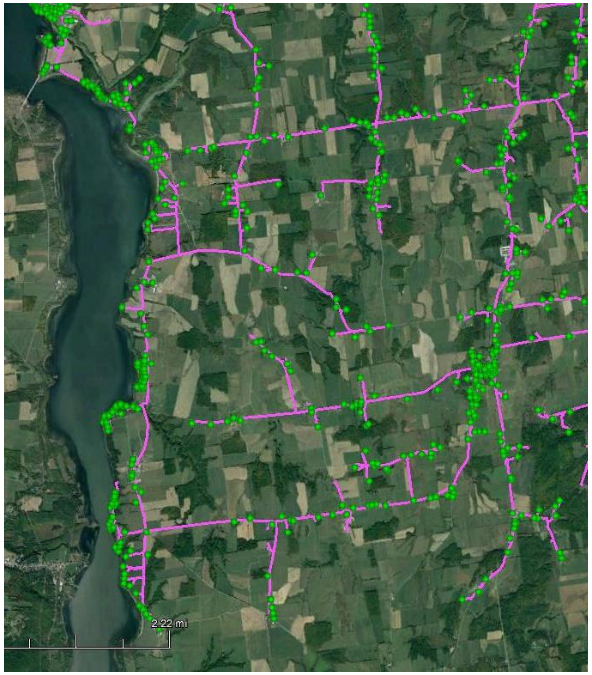
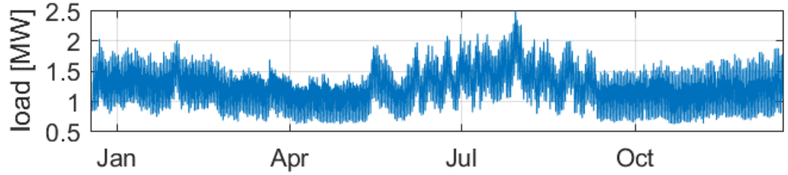
High-Frequency Data for QSTS

- QSTS requires data to represent the time-varying PV output coincident with time-varying load. High-frequency load and solar measurements are scarce.
- New database structures and memory management strategies are required. Data I/O becomes a bottleneck.
- Requires high-frequency (temporally and spatially) historical measurements

- Objective: Develop methods to create accurate high-resolution proxy data sets for QSTS analysis from lower-resolution data
- Produce unique profiles to model the spatial correlations and geographic diversity





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Cloud Fields for Distribution Simulations

Challenge: Modeling PV power from several potential PV interconnection points on a distribution feeder

- Current spatial resolution of satellite imagery is not fine enough to model individual distributed PV
- Installing sky imagers at all feeders for a year of video is expensive and computational intensive

PV locations are actual irradiance sensors in Oahu, HI

Options:

Single Sensor

- Measurements taken from a single PV system, satellite pixel, or local irradiance sensor
- Point measurements from single sensor applied to all PV locations
- PV power timeseries perfectly correlated

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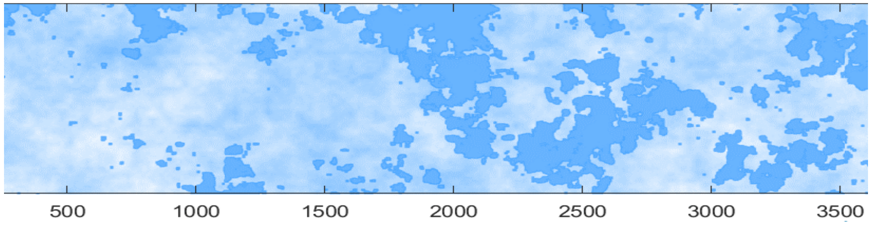
Unique Power Profiles

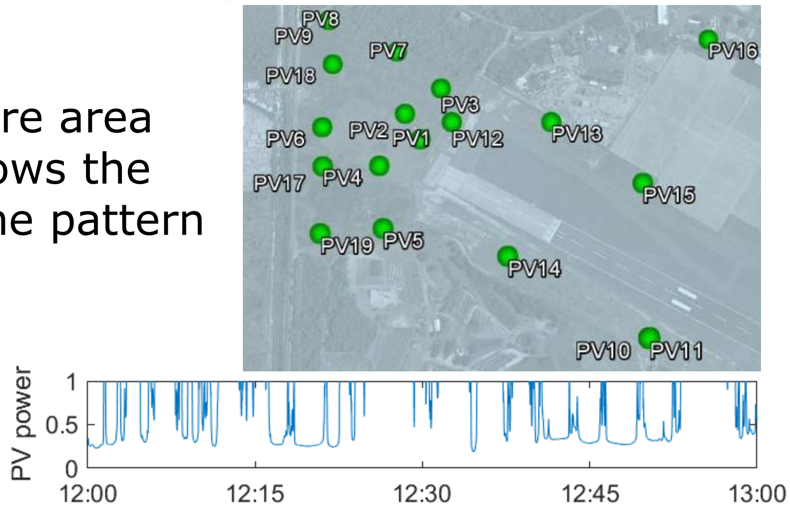
- Using a sky imager or simulated cloud formations
- Create unique PV power timeseries at each interconnection point using cloud field and cloud speed



Cloud Fields for Distribution Simulations

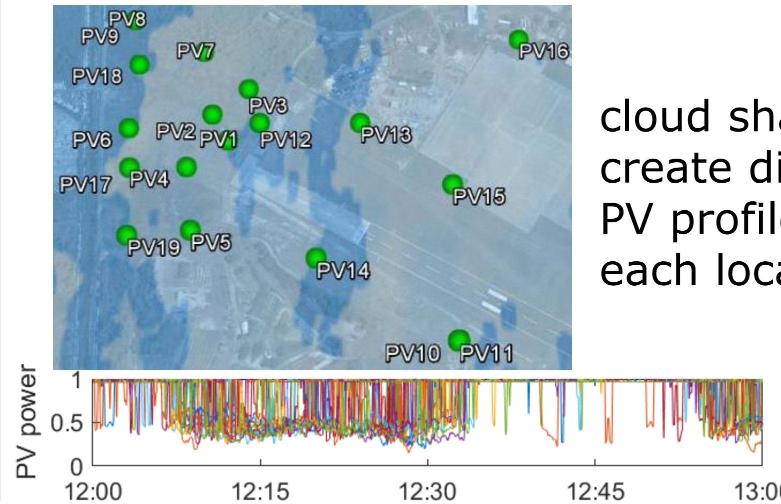
Single Sensor

entire area follows the same pattern

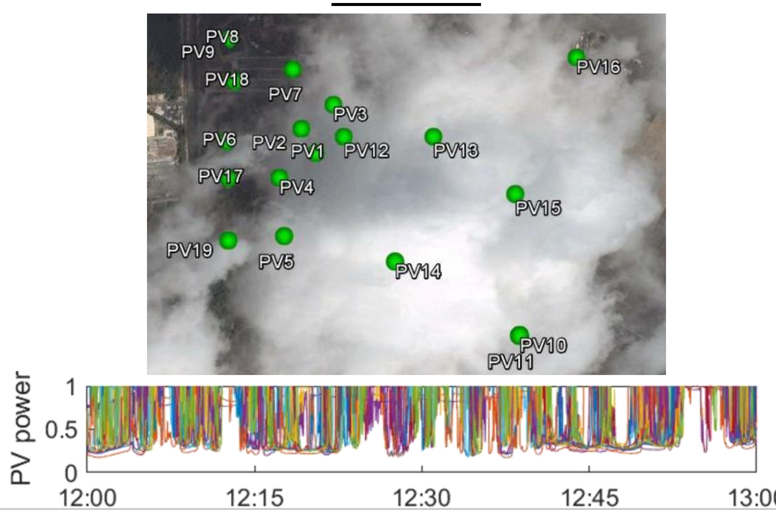


Synthetic Cloud Fields

cloud shapes create different PV profiles at each locations



Actual



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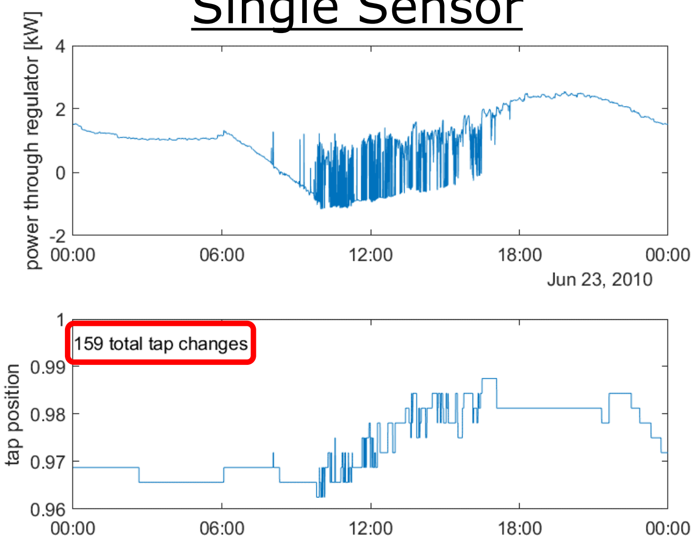
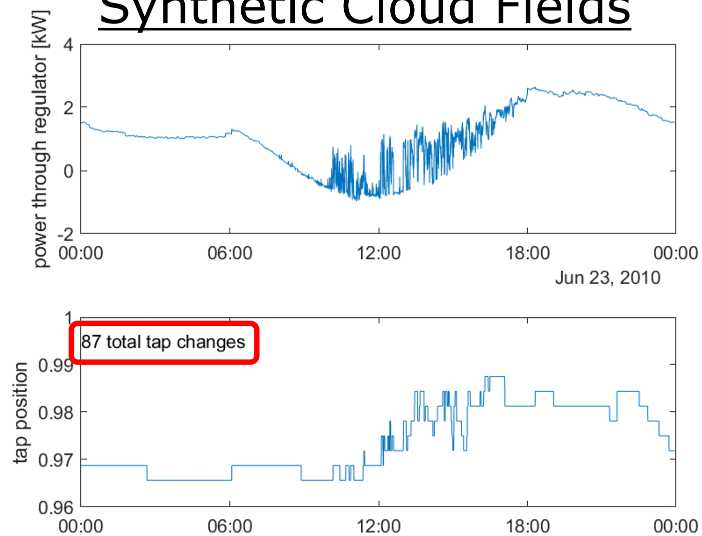
Cloud Fields for Distribution Simulations

Single Sensor



Synthetic Cloud Fields



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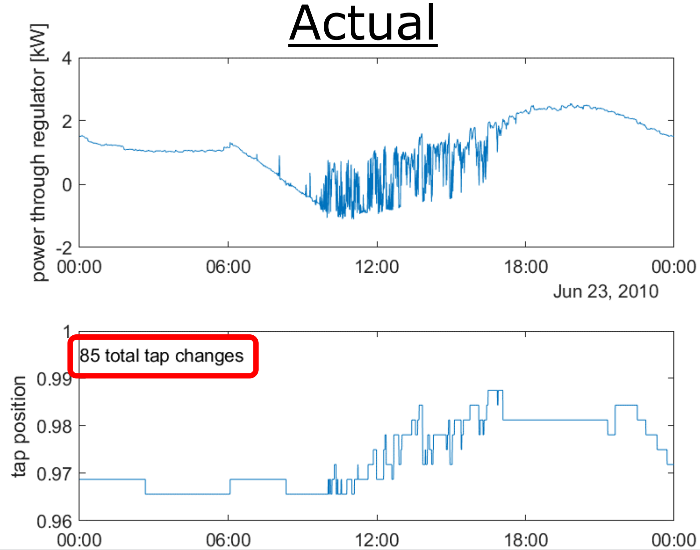

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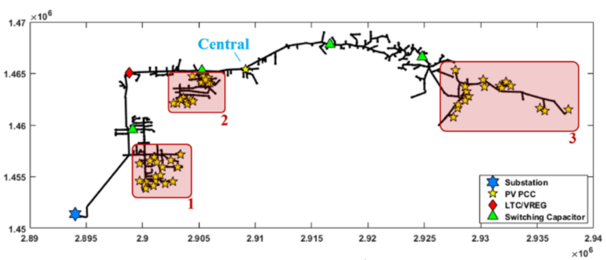
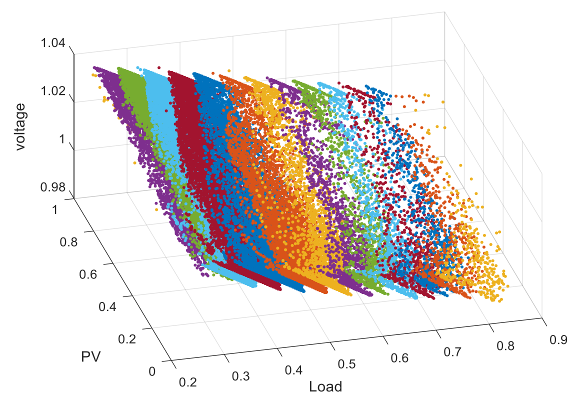
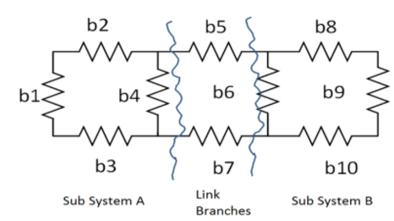
Computational Time of QSTS

- Address the limitation of QSTS due to the speed
- **Objective**: Reduce the computational time (10-120 hours) and complexity of QSTS analysis to achieve year-long time-series solutions that can be run in less than 5 minutes
- There are several ways to improve the speed of QSTS
  1) Fast Time-Series Approximations
  2) Improved Power Flow Solution Algorithms
  3) Circuit Reduction
  4) Parallelization of QSTS (Temporally or Spatially)







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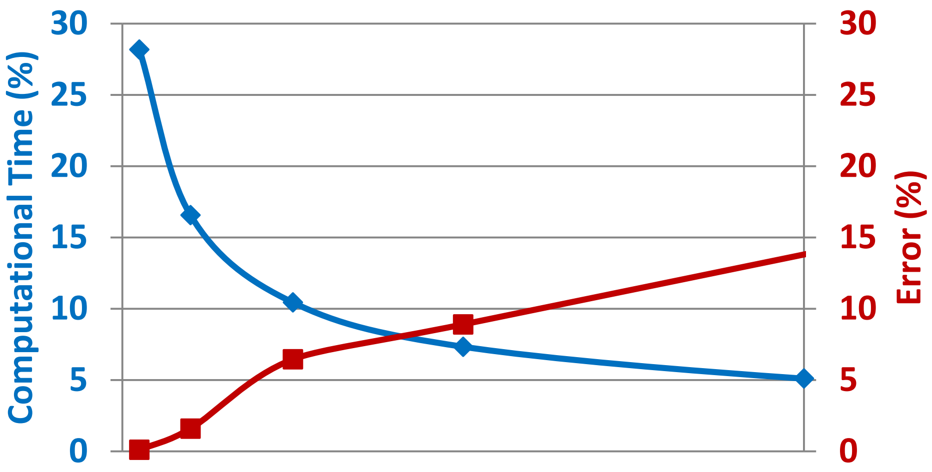
Challenges to Increasing Speed of QSTS

1. An individual power flow is often very fast, but a QSTS simulation requires solving the power flow 31 million times
2. Distribution systems are unbalanced nonlinear discontinuous system with thousands of buses
3. Power flow solutions are dependent on the previous time-steps
4. Discrete voltage controllers with hysteresis and deadbands
5. Controllable element interactions and cascading errors
6. Fast control elements that respond in seconds

J. Deboever, X. Zhang, M. J. Reno, et al. "Challenges in reducing the computational time of QSTS simulations for distribution system analysis," Sandia National Laboratories, SAND2017-5743, 2017.

Evaluating Speed and Accuracy

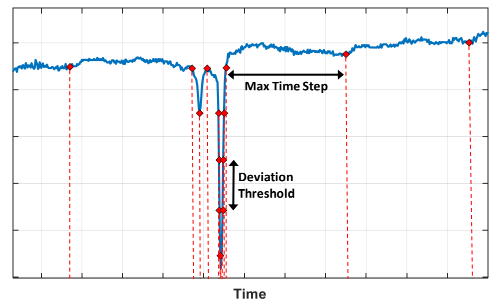
- Speed improvements may come at the expense of accuracy

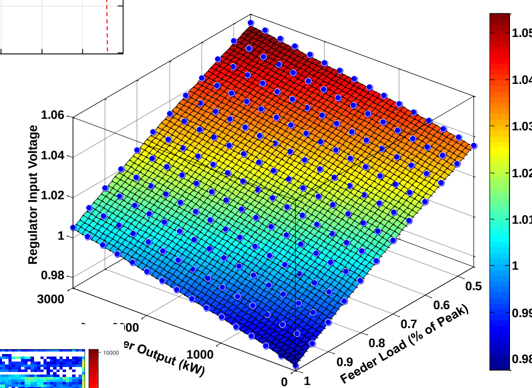


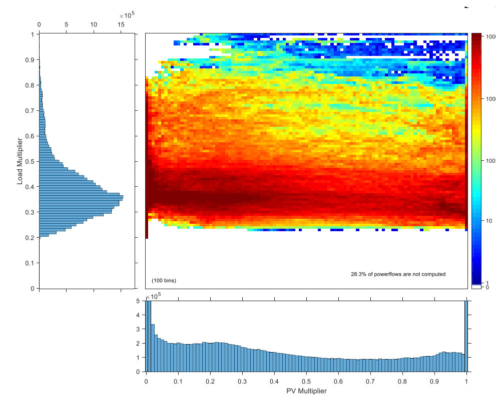
- All new algorithms are tested extensively and validated against yearlong 1-second resolution QSTS results
  - Regulator tap changes, capacitor switching operations
  - Bus voltages, hours per year with ANSI violations
  - Thermal loading (worst overloads and time overloaded)
  - Yearly line losses

1) Fast Time Series Approximations

- Objective: Dramatically speed up the computational process using innovative methods to progress through the timeseries simulation
- Variable Time-Step
  - Reduce the computational burden by adjusting the QSTS time-step to solve fewer load flows, skipping forward to time points of interest
- Event-Based Simulation
  - Detect discrete system events using voltage sensitivities and jump from event to the next
- Vector Quantization
  - Take advantage of repeated power flow computations using a quantized lookup table to bypass the power flow solver







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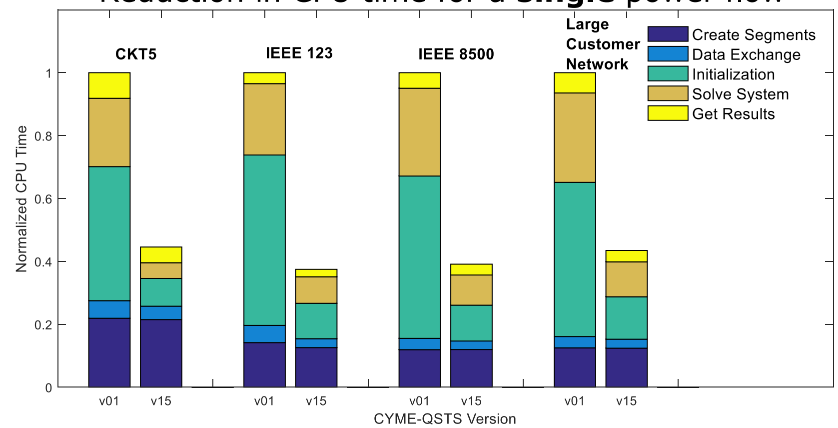
2) Improved Power Flow Algorithms

Objective: Speed up single power flow solutions through improved algorithms, data handling, and memory management

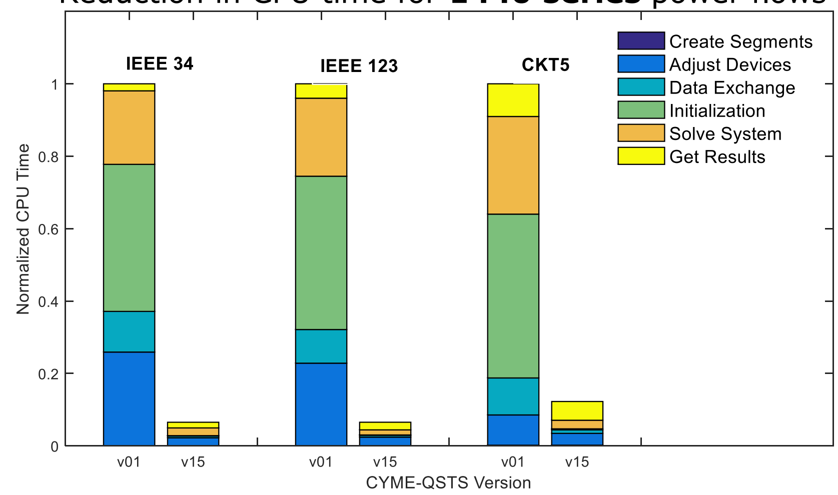
Solutions:

- Initialization using previous solution
- Focused data recording and offloading
- Improve memory management
- Investigate different power flow algorithms
- Decrease controller convergence time

Reduction in CPU time for a **single** power flow



Reduction in CPU time for **1440 series** power flows

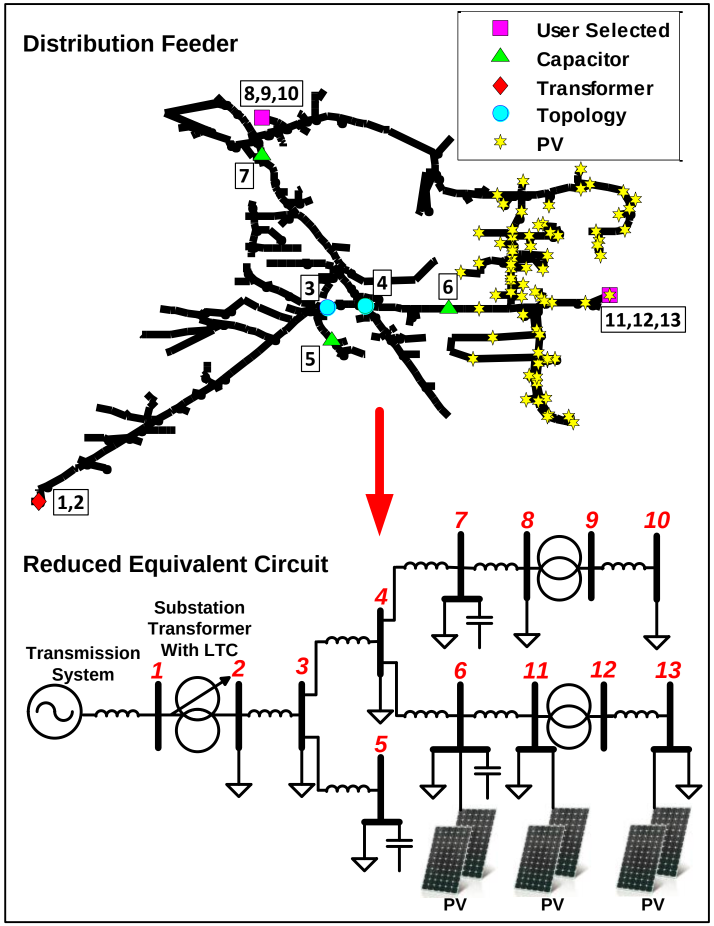


3) Circuit Reduction

<u>Objective</u>: Use an equivalent reduced circuit with fewer buses to decrease the power flow simulation time.

<u>Solutions:</u>

- Many buses can be removed or aggregated into nearby buses, while keeping the results for the remaining buses equivalent
- Reduction algorithms can handle unbalanced loads and PV, unbalanced and unsymmetrical wire impedance, mutual coupling, shunt capacitance, transformer magnetizing currents, and multiple different load profiles and PV power profiles.



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4) Parallelization of QSTS

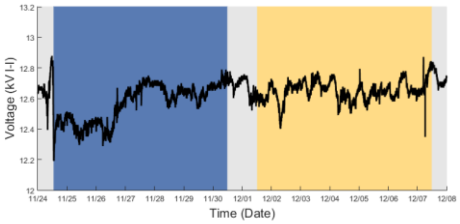
Objective: Solving QSTS is inherently sequential (single-core), but the speed can be improved with more computational power

Solutions:

- Intelligently divide the solution to allow for parallelization (multi-core)
- Many personal computers have multiple cores
- Small clusters or servers can be used for processing (CYME Server)

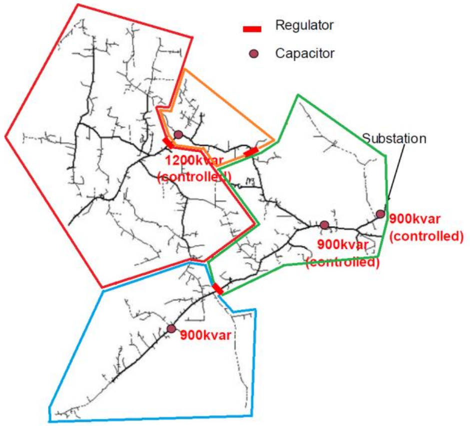
Temporal Decomposition

- Yearlong QSTS is split into individual solutions and computed via multiple cores
- Solutions are "stitched" together after processing



Diakoptics

- Circuit is intelligently divided and power flows for division calculated (multi-core)



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Rapid QSTS Algorithms

	Extreme Voltages	Thermal Loading	Regulators Tap Changes	Capacitor Switching	Time outside ANSI	Losses	Computation Time[1]
Snapshot	Good	Good	-	-	-	-	<1 sec
Hourly Timeseries	Great	Great	-	-	Good	Great	5 sec
1 day QSTS	Poor	Poor	Decent	Decent	Poor	Poor	5 minutes
1 year QSTS	Great	Great	Great	Great	Great	Great	36 hours
New Rapid QSTS Algorithms	Great	Great	Great	Great	Great	Great	30 sec

- New 1-year rapid QSTS algorithms maintain the accuracy of high-resolution yearlong QSTS simulations while solving in a fraction of the time

Rapid QSTS Summary

- We have developed a collection of rapid QSTS algorithms, each demonstrating significant speed improvements
- Algorithms can be combined for additional speed:
  - For example, a reduced circuit can be simulated with a variable time-step separated onto several parallel cores
- The project was targeting 1400x speed improvement:

$$\frac{\mathbf{120\ hours}}{\underset{\text{Fast Timeseries}}{\mathbf{10}} \times \underset{\text{Improved Power Flow Solution}}{\mathbf{2}} \times \underset{\text{Circuit Reduction}}{\mathbf{10}} \times \underset{\text{Parallelization}}{\mathbf{7}}} = \mathbf{5\ minutes}$$

- Project has been extremely successful, and in research settings, we may be able to achieve even faster speeds reaching 100,000x faster

$$\underset{\text{Fast Timeseries}}{\mathbf{200}} \times \underset{\text{Improved Power Flow Solution}}{\mathbf{5}} \times \underset{\text{Circuit Reduction}}{\mathbf{20}} \times \underset{\text{Parallelization}}{\mathbf{7}}$$

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Conclusions

- Timeseries analysis is important for distribution system planning with high penetrations of DER, and high-resolution QSTS is needed to model the impacts to voltage regulators and controls
- Several rapid QSTS algorithms have been implemented into software
  - Temporal parallelization and diakoptics have been fully implemented and integrated in OpenDSS-PM
  - CYME improved QSTS speeds up to 10x faster
- Ongoing and future work
  - Combining rapid QSTS algorithms to demonstrate full potential
  - Implementing rapid QSTS into analysis software packages for researchers and industry to use

QUESTIONS?

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