SAND2019-2357PE

Rapid QSTS Simulations for High-Resolution Comprehensive Assessment of Distributed PV

Robert Broderick and Matthew J. Reno
Sandia National Laboratories

SunShot
U.S. Department of Energy

Key Lessons from the California Integrated Capacity Analysis

> "Hosting capacity analysis certainly warrants the full attention of stakeholders, policymakers and regulators working to transform the electricity grid. IREC observes that hosting capacity analyses are building blocks with which the grid of the future will be built."
>
> - *Sky Stanfield representing IREC in regulatory proceedings. In Key Lessons from the California Integrated Capacity Analysis, Posted on October 16, 2018.*

What is Integrated Capacity Analysis (ICA)?

The passage of California's AB 327 (2013) required investor owned utilities to prepare Distributed Resources Plans that identify optimal locations for distributed energy resources on the grid. CPUC required utilities to prepare a hosting capacity analysis of their system.

Types of hosting capacity analysis demonstrated by CA utilities:

The iterative method is based on iterations of successive power flow simulations at each node on the distribution system, whereas the streamlined method uses a set of equations and algorithms to evaluate power system criteria at each node on the distribution system."

What is resolution of the existing methods?

Utilizes load profiles with 576 hours of data: peak and min day for each month of the year (2X24X12)

What are the 5 main issues?

1) Accuracy, 2) computation speed for huge number of data points and scenarios, 3) does not model single phase system , 4) does not address advanced inverter functionality and 5) does not address interconnection of other DER systems such as PV plus storage.

Rapid QSTS Simulations for High-Resolution Comprehensive Assessment of Distributed PV

Sandia National Laboratories

DOE Award

Year 3 – QTR4

February 15, 2019

Principal Investigator: Robert Broderick (Sandia) and Barry Mather (NREL)

Quasi-Static Time-Series (QSTS)

What is QSTS?

Quasi-static time series (QSTS) analysis captures time-dependent aspects of power flow, including the interaction between the daily changes in load and PV output and control actions by feeder devices and advanced inverters.

What is the problem with today's tools?

Snapshot analyses and other methods that only investigate specific and limited time periods can be <u>overly pessimistic</u> about PV impacts. They do not include the geographic and temporal diversity in PV production and load and the interaction with control systems may not be adequately analyzed.

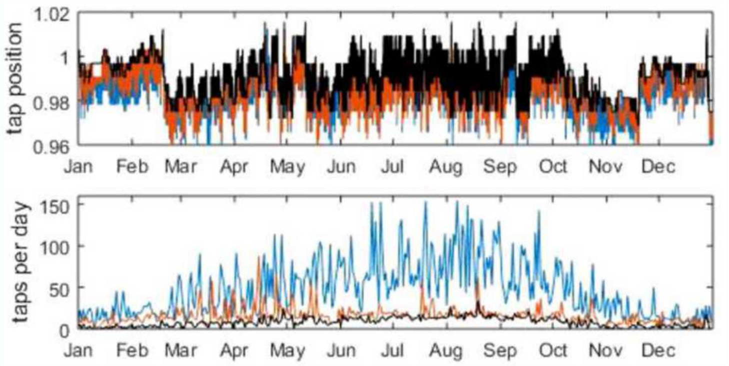
Why do we need QSTS?

QSTS simulations are needed today to understand:

- Rapid fluctuations due to high variable PV
- Impact to voltage regulators and switch capacitors
- Temporary extreme conditions before controls react

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



Yearlong QSTS for Regulator Tap Position

> *"You can't manage what you can't measure"*
>
> *-P. Drucker*

QSTS – Motivation

- Accurate modelling of high penetration PV requires understanding the time varying impacts of variable generation on the distribution system
- QSTS also plays a major role in analysis and planning of many other smart grid technologies, control schemes, ADMS function, energy storage, etc.

Steady-state (snapshot)	**Quasi-Static Time-Series**
Follow traditional planning practices	Require new tools, new experience
Require relatively low-resolution input data (multiple time points)	Require high-resolution input data (temporal and spatial)
Are inherently conservative	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

Project Objectives

- Accelerate QSTS simulation capabilities through use of new and innovative methods for advanced time-series analysis
- Seamlessly integrate equivalent reduced-order feeder models
- Reduce the current QSTS analysis computational time (10-120 hours) that is not possible for utilities in order to make QSTS the industry preferred PV impact assessment method
- Develop high-resolution proxy data sets that will be statistically representative of existing measured load and PV plant data for an accurate representation of PV impacts

- Year 3 Milestone: Implement accelerated QSTS analysis into CYME Long-Term Dynamics commercial distribution system analysis software package and OpenDSS and demonstrate solution times of 5 minutes or less for year-long simulations using at least three complex feeder types.

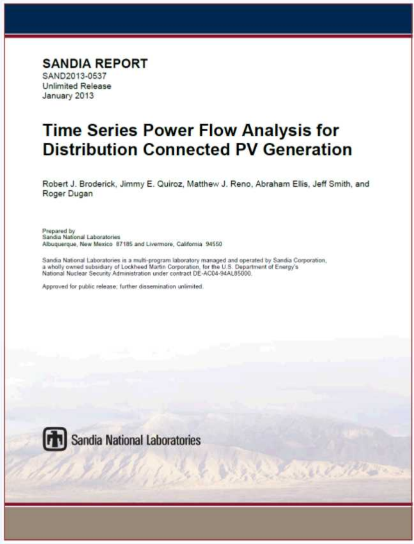
Task Summary

- Task Structure
  - ✓ Task 1: Fast Time-Series Approximations
  - ✓ Task 2: Improved Power Flow Solution Algorithms
  - ✓ Task 3: Circuit Reduction
  - ✓ Task 4: Parallelization of QSTS
  - ✓ Task 5: Implementation
  - ✓ Task 6: High-Resolution Input Data

- Year 3 focus is on parallelization and implementation

QSTS – How far we have come

- In 2012/2013, SNL, NREL, and EPRI collaborated to establish the benefits of QSTS
  - State of the art at the time was one 9-month long simulation
  - It took forever to run (weeks) and crashed many times before being able to complete it
  - Limited access to data
  - No standardized test circuits for analysis
- At the end of this project:
  - We have run hundreds of yearlong QSTS simulations
  - Simulation times only take minutes
  - Better high-resolution data methods have been developed
  - Publishing standardized QSTS test circuits with data and results



SANDIA REPORT
SAND2013-0537
Unlimited Release
January 2013

Time Series Power Flow Analysis for Distribution Connected PV Generation

Robert J. Broderick, Jimmy E. Quiroz, Matthew J. Reno, Abraham Ellis, Jeff Smith, and Roger Dugan

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

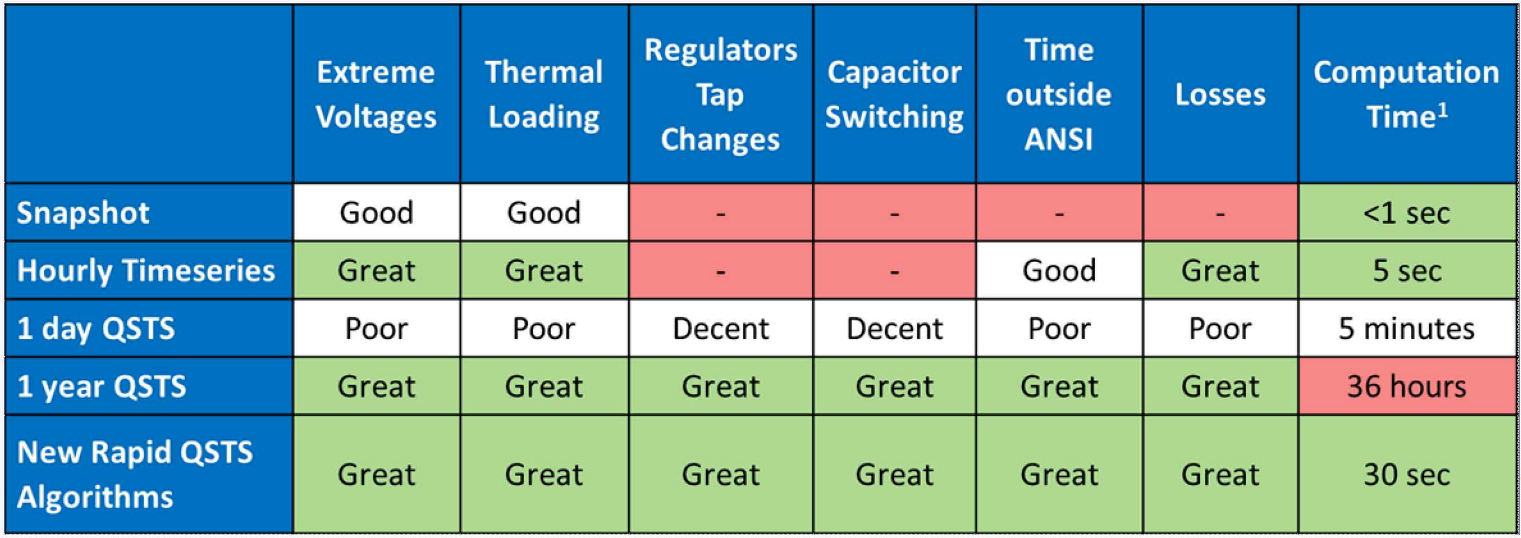
Approved for public release; further dissemination unlimited.

QSTS Test Circuits

- Developed 5 test circuits that we have used to test the algorithms throughout the project
- QSTS test circuits will be publicly released for others to test their algorithms

	IEEE 13 Bus	IEEE 123 Bus	Feeder CO1	Feeder CO1_VV	J1
Buses	13	123	2969	2969	3433
PV systems	Single 3-ph (unity PF)	Single 3-ph (-0.98 PF)	144 systems (3-ph + 1-ph)	144 systems (3-ph + 1-ph)	10 systems (3-ph + 1-ph)
Total Profiles	1 Load, 1 PV	4 Load, 1 PV	2 Load, 4 PV	2 Load, 4 PV	3 Load, 7 PV
Challenges	Fast regulator and cap interactions	Feeder reconfiguration, Phase profiles, non unity PF	Size, Total profiles, LV modeled	Volt VAR for 3-ph PV systems	Size, multiple VREGs in series, LV secondary

Progression of Impact Study Methods and Tools



	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

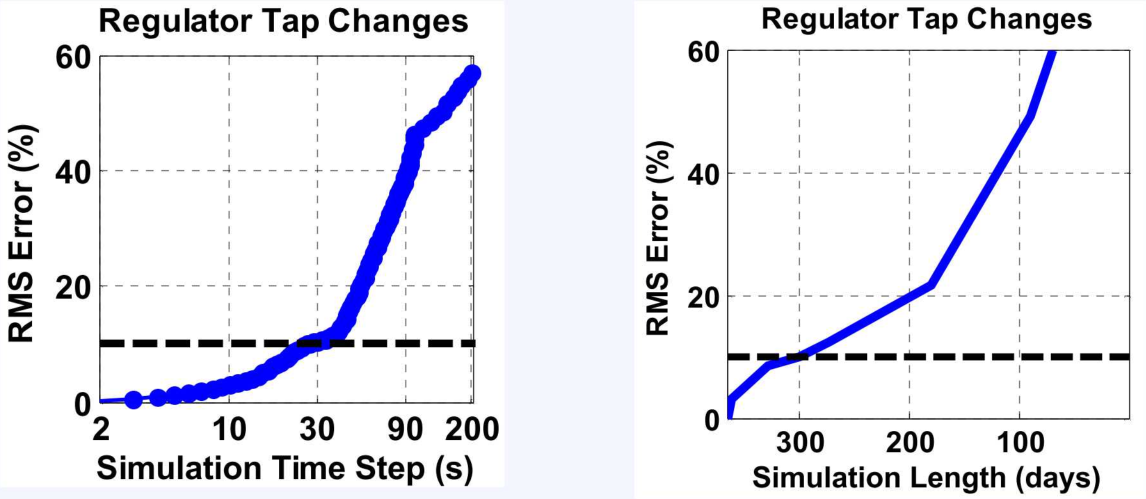
Our new rapid QSTS algorithms maintain the accuracy of high-resolution yearlong QSTS simulations

…..while solving in a fraction of the time

Quasi-Static Time Series (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)

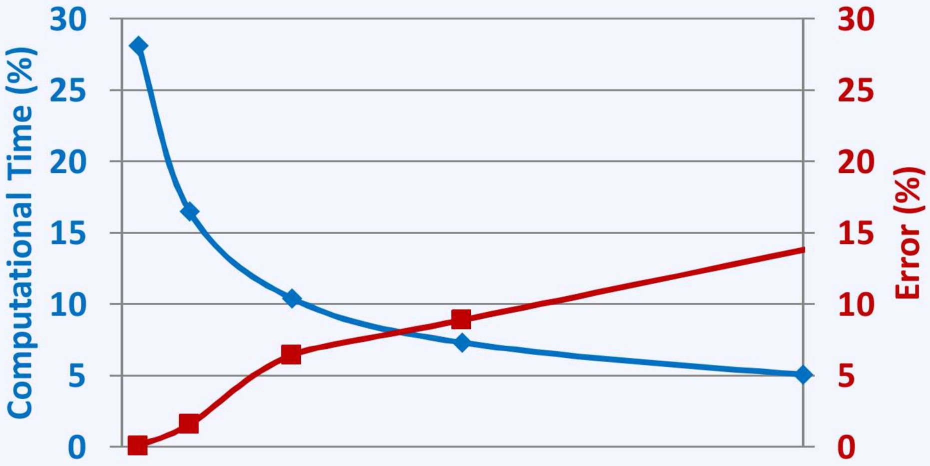
Error for Time-Step and Simulation Length Compared to Yearlong 1-second Resolution QSTS



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.

Evaluating Speed and Accuracy

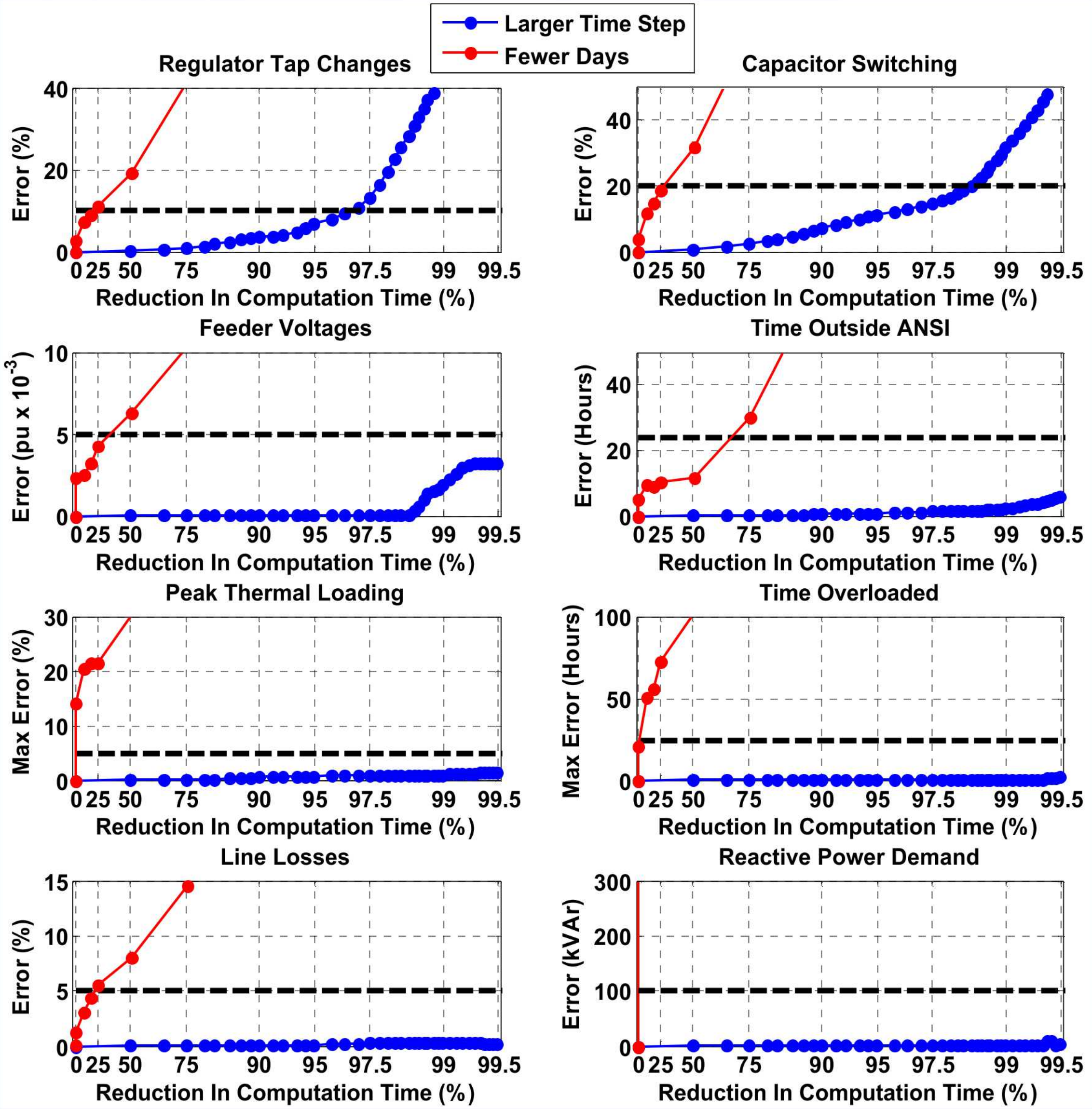
- Speed improvements may come at the expense of accuracy



- 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

QSTS Standards and Requirements

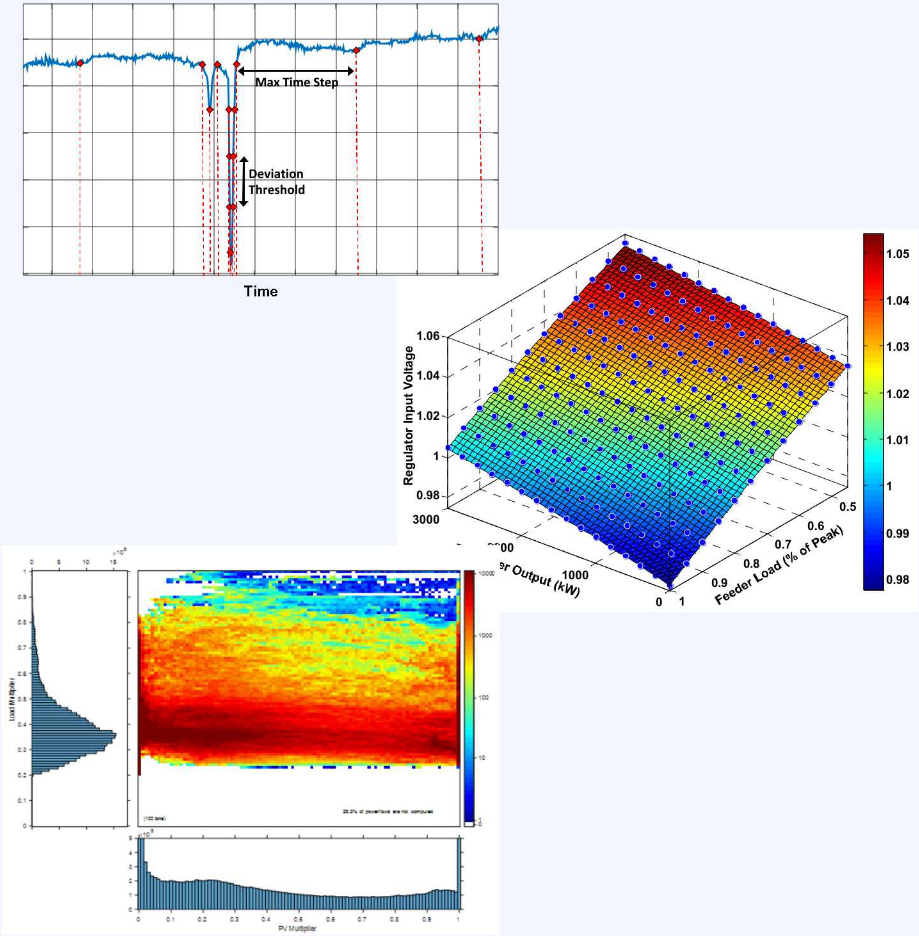
- QSTS simulations need to be:
  - High resolution simulation to capture solar variability (time step less than 10 seconds)
  - Extended-term simulations (year-long)
- The QSTS requirements are application-specific: voltage regulation device operations, power quality, time outside normal operations, and 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



Task 1: Fast Time-Series Approximation

	Metric Definition (From Measurement)	Success Value	Measured Value
Evaluation Criteria 2.1	Refine rapid QSTS algorithms to improve speed and scalability	At least 90% reduction in computational time. Mean Absolute error (MAE) is less than 10% for tap operations.	3 algorithms have shown >90% reduction

- Approach:
  - Event-Based Simulation
  - Vector Quantization
  - Combination of variable time-steps

Speed Improvement Comparison

	IEEE 13 Bus	IEEE 123 Bus	Feeder CO1	Feeder CO1_VV	J1
Buses	13	123	2969	2969	3433
PV systems	Single 3-ph (unity PF)	Single 3-ph (-0.98 PF)	144 systems (3-ph + 1-ph)	144 systems (3-ph + 1-ph)	10 systems (3-ph + 1-ph)
Total Profiles	1 Load, 1 PV	4 Load, 1 PV	2 Load, 4 PV	2 Load, 4 PV	3 Load, 7 PV
Challenges	Fast regulator and cap interactions	Feeder reconfiguration, Phase profiles, non unity PF	Size, Total profiles, LV modeled	Volt VAR for 3-ph PV systems	Size, multiple VREGs in series, LV secondary

Algorithm	Times Faster				
Event-Based	100x	288x	300x	111x	115x
VTS	41x	-	53x	56x	42x
VQ	243x	-	169x	243x	-

All QSTS Metrics satisfied with errors under the established thresholds for all the test cases!

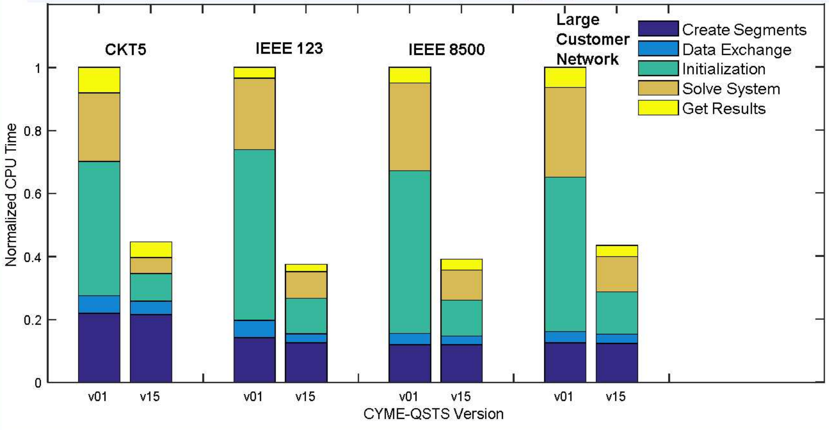
2) Improved Power Flow Algorithms

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

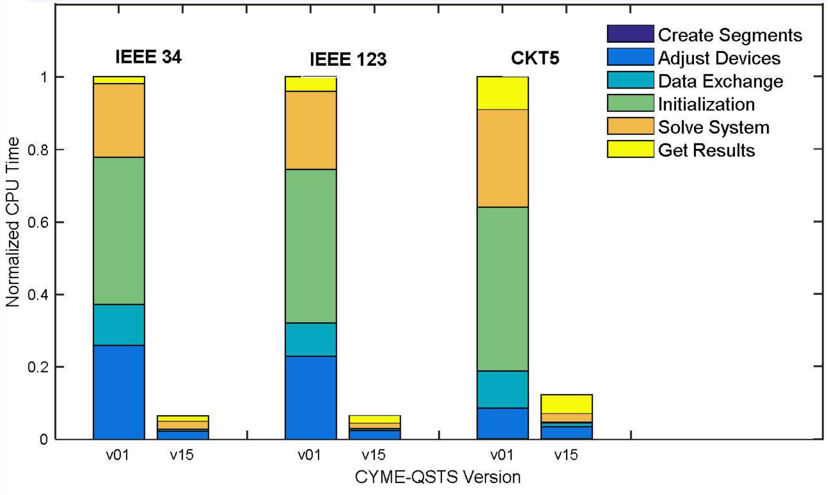
Solutions:

- 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

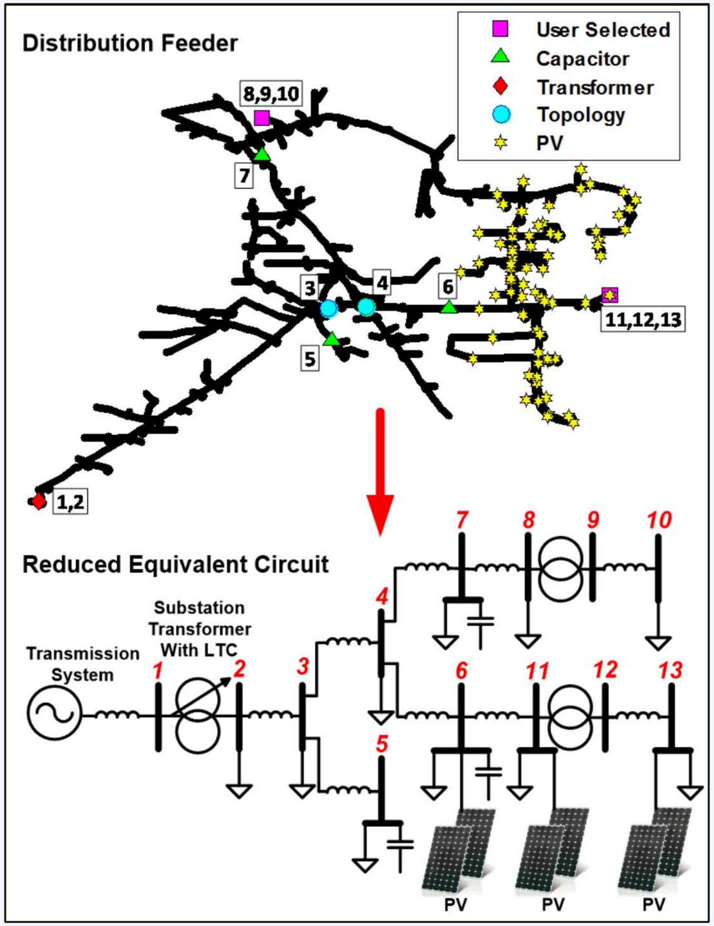


3) Circuit Reduction

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

Solutions:

- 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.



4) Parallelization of QSTS

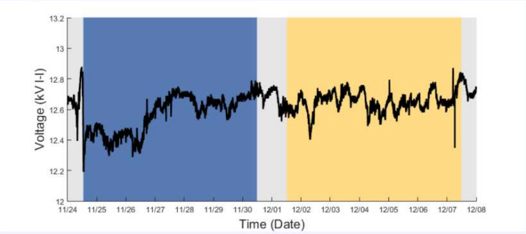
Objective: Solving QSTS is inherently sequential (single-core), but the speed can be improved with more computational power

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)

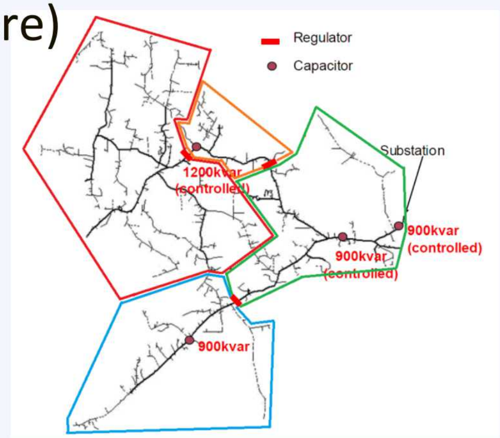
Temporal Decomposition

- 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)



Task 5: Implementation

Open Source Matlab Release

- Variable Time-Step
- Vector Quantization
- Event-based Simulation
- Detailed Equivalent Circuit Reduction
- Irradiance Modelling

OpenDSS Integrated

- Faster Power Flow Solver
- Multi-Rate Time-Step
- Reduction of Switches and Lateral
- Temporal Parallelization
- Diakoptics

CYME Integrated

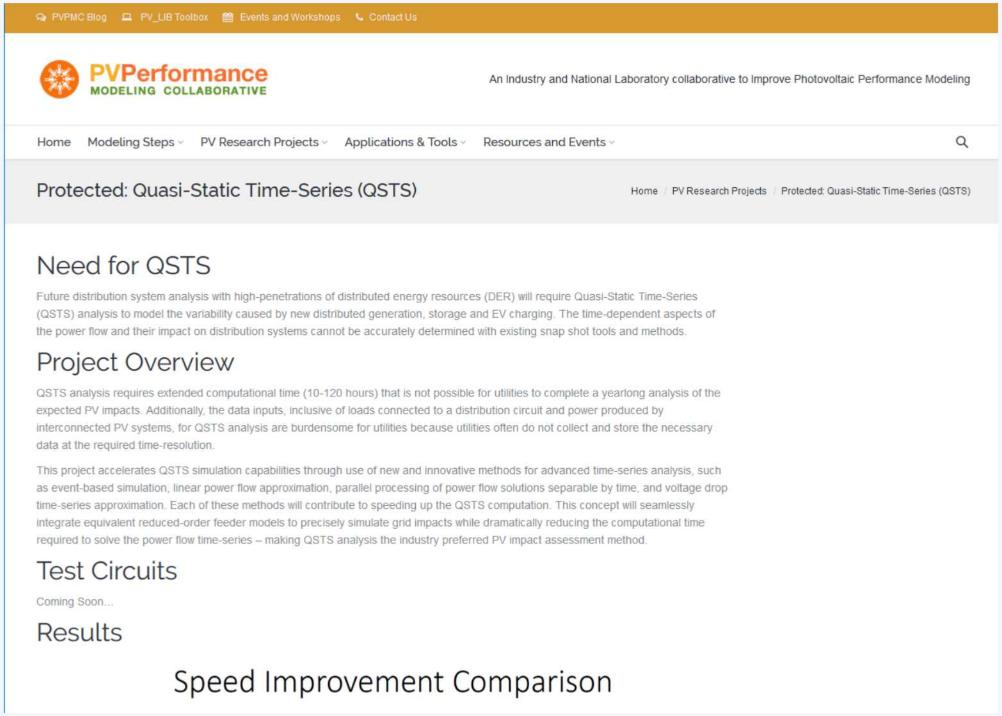
- QSTS Long-Term High-Resolution Study Capable
- Faster Power Flow Solver
- Circuit Reduction, including GUI
- Detailed Variable Time-Step
- Dynamic Data Pull

	MATLAB	OpenDSS	CYME
Variable Time-Step	✓	✓	✓
Vector Quantization	✓		
Event-based Simulation	✓		
Circuit Reduction	✓	Simple	✓
Temporal Parallelization	✓	✓	✓
Diakoptics		✓	

QSTS Website

All project results will be published on a website hosted by the PV Performance Modeling Collaborative (PVPMC)

- QSTS Test Circuits, Data, and Results
- Rapid QSTS Algorithms
- Project Publications



An Industry and National Laboratory collaborative to Improve Photovoltaic Performance Modeling

Protected: Quasi-Static Time-Series (QSTS)

Need for QSTS

Future distribution system analysis with high-penetrations of distributed energy resources (DER) will require Quasi-Static Time-Series (QSTS) analysis to model the variability caused by new distributed generation, storage and EV charging. The time-dependent aspects of the power flow and their impact on distribution systems cannot be accurately determined with existing snap shot tools and methods.

Project Overview

QSTS analysis requires extended computational time (10-120 hours) that is not possible for utilities to complete a yearlong analysis of the expected PV impacts. Additionally, the data inputs, inclusive of loads connected to a distribution circuit and power produced by interconnected PV systems, for QSTS analysis are burdensome for utilities because utilities often do not collect and store the necessary data at the required time-resolution.

This project accelerates QSTS simulation capabilities through use of new and innovative methods for advanced time-series analysis, such as event-based simulation, linear power flow approximation, parallel processing of power flow solutions separable by time, and voltage drop time-series approximation. Each of these methods will contribute to speeding up the QSTS computation. This concept will seamlessly integrate equivalent reduced-order feeder models to precisely simulate grid impacts while dramatically reducing the computational time required to solve the power flow time-series – making QSTS analysis the industry preferred PV impact assessment method.

Test Circuits

Coming Soon...

Results

Speed Improvement Comparison

Accomplishments

- Publications
  - 7 journal publications
  - 26 conference publications
- 19 Panels presentations
- Developed 5 QSTS Test circuits
- Implemented Rapid QSTS methods for faster solution times in MATLAB (up to 500000x faster), OpenDSS (up to 10000x faster), and CYME (up to 10000x faster) for much faster

Questions?

Task 5: MATLAB Implementation

- Releasing in Sandia’s GridPV MATLAB Toolbox for OpenDSS
  - Rapid QSTS (Task 1) - Variable Time-Step, Vector Quantization, Event-based Simulation
  - Detailed Equivalent Circuit Reduction (Task 3)
  - Irradiance Modelling (Task 6)
  - Standardized QSTS Data Structures
  - QSTS Test Circuits and Examples

QSTS.Results

Field	Type/Size	Required?	Description
DataLogging	Structure	Yes	From inputs of what data we were recording in the QSTS
TimePoints	Int Array [1,numTimepoints]	Yes	Array of time points in seconds for when the power flow was solved. These values correspond to the timepoints for all timeseries measurements.
AlgorithmOutputs	Structure	Optional	Any particular outputs from the specific QSTS algorithm. For example, QSTS.Results.AlgorithmOutput.NumRewinds for variable time-step simulations
QSTS.Results.Voltage			
NodeNames	Cell array of strings [numNodes,1]	Required	Names of the nodes corresponding to the node voltage arrays in QSTS.Results. Buses filtered to only look at distribution level voltages (<43kV LL)
MonitoredNodes	Cell array of strings [numMonitoredNodes,1]	Optional	Names of the nodes to record timeseries voltage in QSTS.Results.VoltageTimeseries. Defaults not to record any nodes. Names come from DataLogging.MonitoredNodes
MonitoredNodesIndex	Int Array [numMonitoredNodes,1]	Optional	Index of MonitoredNodes in NodeNames
FeederMaxVpu	Float	Yes, if DataLogging.Voltage is TRUE	Max voltage on any phase of any bus any time during the simulation
FeederMaxVpuNode	String		Name of the node that had the max voltage during the QSTS simulation
FeederMaxVpuTimeIndex	Int		Time index of when the max voltage on the feeder occurred
FeederMinVpu	Float		Min voltage on any phase of any bus any time during the simulation
FeederMinVpuNode	String		Name of the node that had the min voltage during the QSTS simulation
FeederMinVpuTimeIndex	Int		Time index of when the min voltage on the feeder occurred
NodesMaxVpu	Float Array [numNodes,1]		Max voltage (pu) at each node for any time during the simulation
NodesMinVpu	Float Array [numNodes,1]		Min voltage (pu) at each node for any time during the simulation
NodesAvgVpu	Float Array [numNodes,1]		Average voltage (pu) at each node for the entire time period of the simulation
FeederHoursAboveANSI	Float		Total time in hours that anywhere on the feeder was above ANSI C84.1 voltage limits
FeederHoursBelowANSI	Float		Total time in hours that anywhere on the feeder was below ANSI C84.1 voltage limits
NodesHoursAboveANSI	Float Array [numNodes,1]		Total time in hours that each node spent above the ANSI C84.1 voltage limits
NodesHoursBelowANSI	Float Array [numNodes,1]		Total time in hours that each node spent below the ANSI C84.1 voltage limits
FeederMaxVpuTimeseries	Float [1,numTimepoints]	Yes, if DataLogging.VoltageTimeseries is TRUE	Timeseries of the max voltage (pu) on any phase of any bus at each time point in the simulation
FeederMinVpuTimeseries	Float [1,numTimepoints]		Timeseries of the min voltage (pu) on any phase of any bus at each time point in the simulation
NodesMaxVpuDailyTimeseries	Float [numNodes,numDays]		Timeseries of the max voltage (pu) at each node for each day in the simulation (due to memory)
NodesMinVpuDailyTimeseries	Float [numNodes,numDays]		Timeseries of the min voltage (pu) at each node for each day in the simulation (due to memory)
NodesAvgVpuDailyTimeseries	Float [numNodes,numDays]		Timeseries of the average voltage (pu) at each node for each day in the simulation (due to memory)
MonitoredNodesVpuTimeseries	Float [numMonitoredNodes,numTimepoints]	Yes, if DataLogging.VoltageTimeseries is TRUE AND MonitoredNodes is not empty	Timeseries of the voltage (pu) at any monitored node in QSTS.CircuitInfo.MonitoredNodes for each time point in the simulation
QSTS.Results.Controllers			
RegulatorNames	Cell array of strings [numRegulators,1]	Required	Names of the regulators corresponding to the tap arrays in QSTS.Results
CapacitorNames	Cell array of strings [numSwitchingCaps,1]	Required	Names of the capacitors corresponding to the cap arrays in QSTS.Results
CurrentTap	Float Array [numRegulators,1]	Yes, if DataLogging.Controllers is TRUE	Current tap of the voltage regulators corresponding to QSTS.CircuitInfo.RegulatorNames
TapChanges	Int Array [numRegulators,1]		Number of times that the voltage regulators corresponding to QSTS.CircuitInfo.RegulatorNames switched taps
CurrentCap	Int Array [numSwitchingCaps,1]		Current status of the capacitors corresponding to QSTS.CircuitInfo.CapacitorNames
CapChanges	Int Array [numSwitchingCaps,1]		Number of times that the capacitors corresponding to QSTS.CircuitInfo.CapacitorNames switched states
TapPositionTimeseries	Float Array [numRegulators,numTimepoints]	Yes, if	Timeseries of tap position of each voltage regulators at each time point in the simulation

Circuit	Buses, Nodes	kV	Peak Load (MW)	Length of feeder	Controllable Elements	PV Penetration	Number of Profiles	Interesting	Reconfigurations	Advanced Inverters
IEEE 13	16, 41	4	4.3	1.5 km	4	40%	2	Fast oscilations between reg and cap, LDC in substation regs		
IEEE 123	132, 278	4	3.6	6.2 km	7	50%	5	load profile for each phases, LDC all regulators PV system with 0.98 power factor	Yes	
CO1	2969, 5466	12	6.4	21.4 km	9	62%	6	Large feeder PV upstream/downstream of regs		
CO1 VV	2969, 5466	12	6.4	21.4 km	9	62%	6	Two different volt-var curves on each of the large PV plants		Yes
J1	3433, 4242	12	6.3	18.1 km	12	28%	10	Multiple regulators in series, LTC has larger tap distance		

Demonstration of MATLAB Algorithms

- Function to run Brute Force
- Functions to run Rapid QSTS
- QSTS output data structure
- Help files and documentation
- QSTS Visualization functions

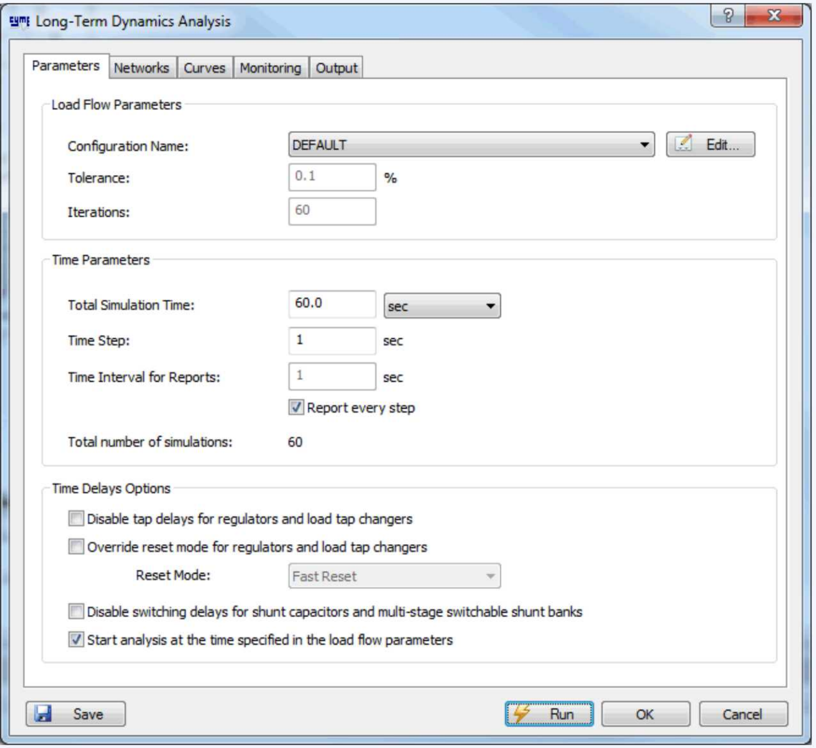
Task 5: Implementation (CYME)

CYME's Implementation Milestone Table

	Metric Definition (From Measurement)	Success Value	Measured Value
Evaluation Criteria 3.5	Implement accelerated QSTS analysis into CYME distribution system analysis software	Combination of the best methods from fast time-series, improved power flow, circuit reduction, and parallelization demonstrate solution times of 5 minutes or less. Mean Absolute error (MAE) is less than 10% for tap operations.	~90%

- Circuit reduction Python prototype adapted to preserve main line if needed
- Two variable time-step methods implemented in CYME
- More quality assurance test cases completed for the variable time-step methods
- Ability to read profiles from binary files and run long-term QSTS simulations in CYME (e.g., 1 year)

Task 5: Implementation (CYME)



Long-Term Dynamics Analysis

Load Flow Parameters

Configuration Name: DEFAULT

Tolerance: 0.1 %

Iterations: 60

Time Parameters

Total Simulation Time: 60.0 sec

Time Step: 1 sec

Time Interval for Reports: 1 sec

☑ Report every step

Total number of simulations: 60

Time Delays Options

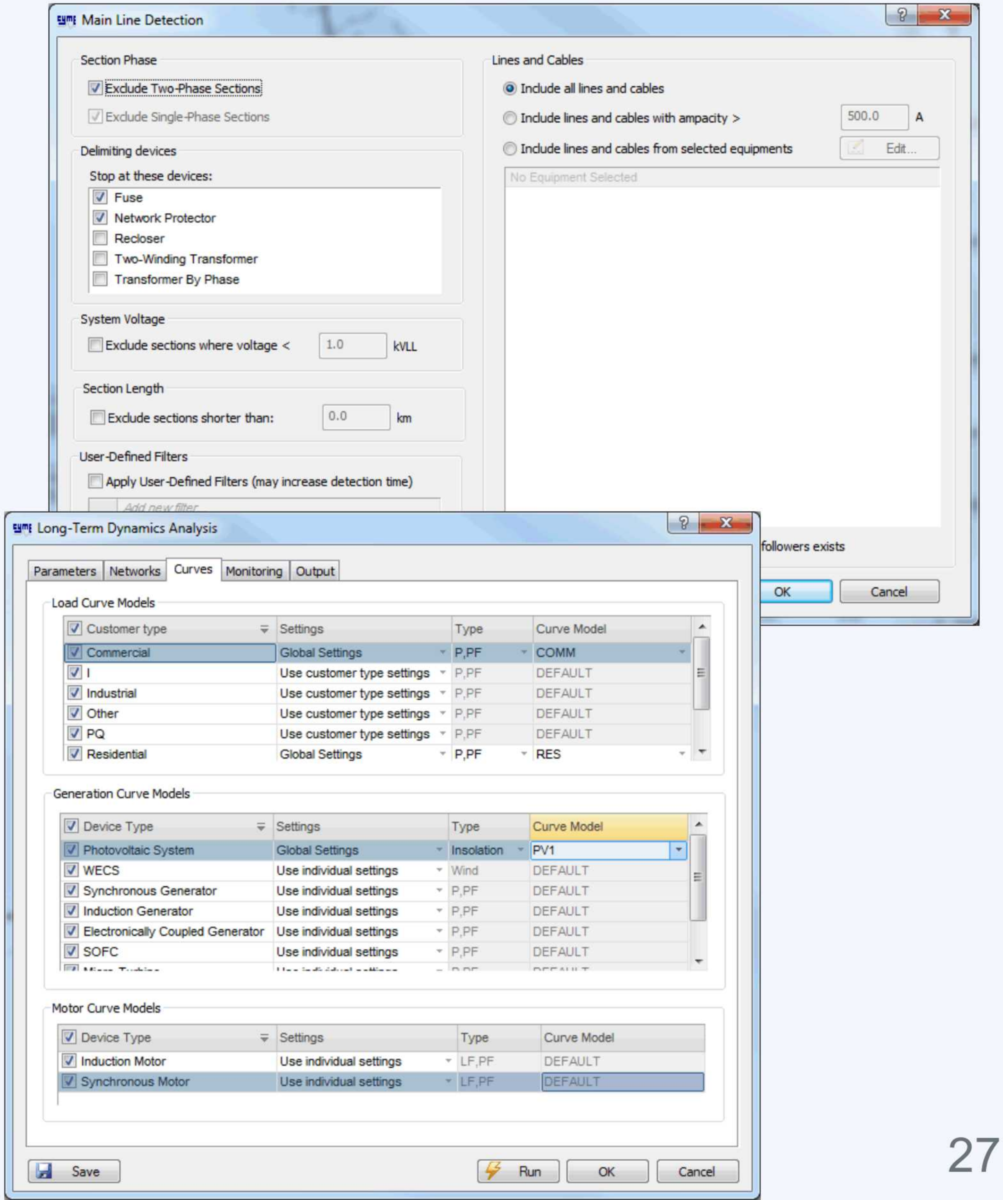
☐ Disable tap delays for regulators and load tap changers

☐ Override reset mode for regulators and load tap changers

Reset Mode: Fast Reset

☐ Disable switching delays for shunt capacitors and multi-stage switchable shunt banks

☑ Start analysis at the time specified in the load flow parameters



Main Line Detection

Section Phase

☑ Exclude Two-Phase Sections

☑ Exclude Single-Phase Sections

Delimiting devices

Stop at these devices:

☑ Fuse

☑ Network Protector

☐ Recloser

☐ Two-Winding Transformer

☐ Transformer By Phase

System Voltage

☐ Exclude sections where voltage < 1.0 kVLL

Section Length

☐ Exclude sections shorter than: 0.0 km

User-Defined Filters

☐ Apply User-Defined Filters (may increase detection time)

Add new filter

Lines and Cables

● Include all lines and cables

○ Include lines and cables with ampacity > 500.0 A

○ Include lines and cables from selected equipments

No Equipment Selected

followers exists

Long-Term Dynamics Analysis

Load Curve Models

☑ Customer type	Settings	Type	Curve Model
☑ Commercial	Global Settings	P,PF	COMM
☑ I	Use customer type settings	P,PF	DEFAULT
☑ Industrial	Use customer type settings	P,PF	DEFAULT
☑ Other	Use customer type settings	P,PF	DEFAULT
☑ PQ	Use customer type settings	P,PF	DEFAULT
☑ Residential	Global Settings	P,PF	RES

Generation Curve Models

☑ Device Type	Settings	Type	Curve Model
☑ Photovoltaic System	Global Settings	Insolation	PV1
☑ WECS	Use individual settings	Wind	DEFAULT
☑ Synchronous Generator	Use individual settings	P,PF	DEFAULT
☑ Induction Generator	Use individual settings	P,PF	DEFAULT
☑ Electronically Coupled Generator	Use individual settings	P,PF	DEFAULT
☑ SOFC	Use individual settings	P,PF	DEFAULT

Motor Curve Models

☑ Device Type	Settings	Type	Curve Model
☑ Induction Motor	Use individual settings	LF,PF	DEFAULT
☑ Synchronous Motor	Use individual settings	LF,PF	DEFAULT

SunShot
U.S. Department of Energy