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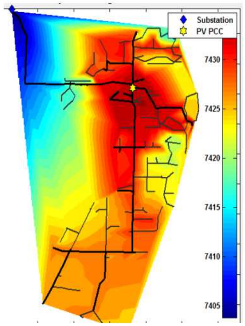

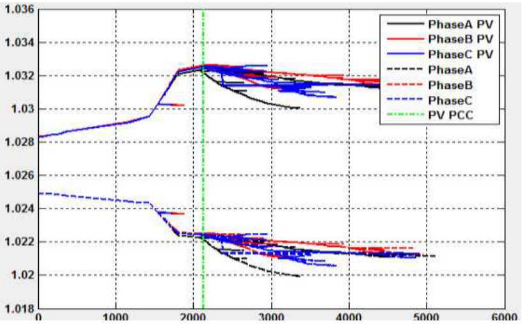

Variable Time-Step Implementation for Rapid Quasi-Static Time-Series (QSTS) Simulations of Distributed PV

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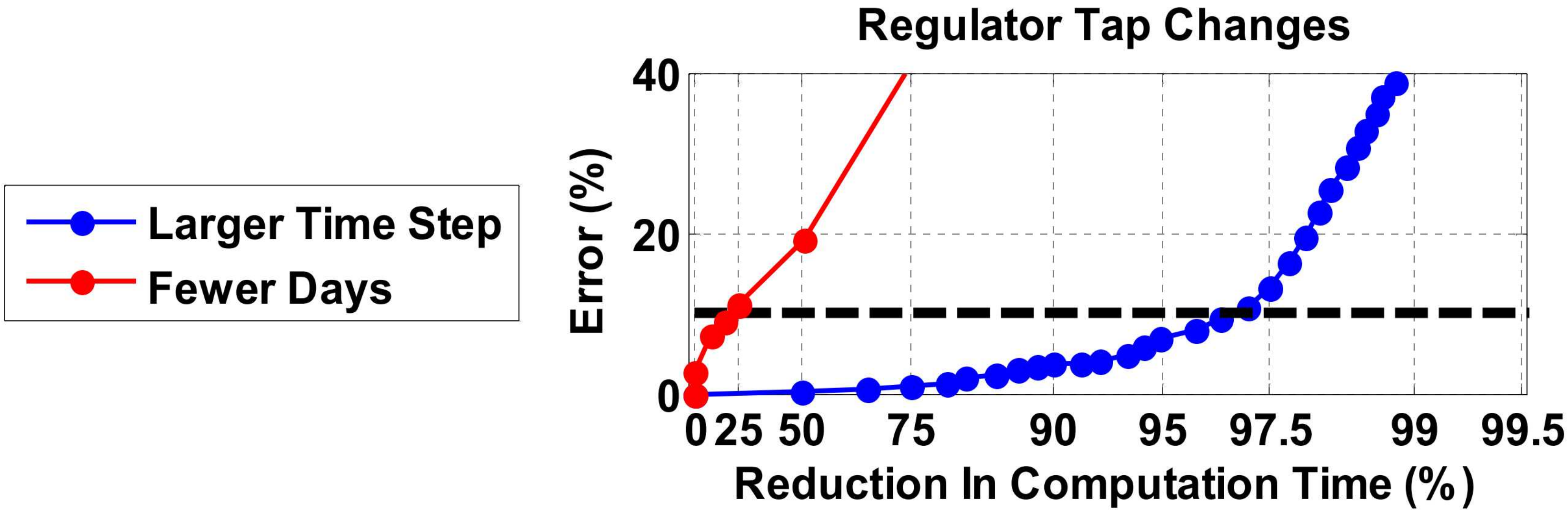
Introduction

- Distribution system analysis with high penetrations of distributed PV requires **quasi-static time-series (QSTS)** analysis to capture the time-varying and time-dependent aspects of the system
- Current QSTS algorithms are prohibitively burdensome and computationally intensive.
- New timeseries analysis methods are needed for QSTS to be used by utilities for distribution operation decisions and coordination

Background

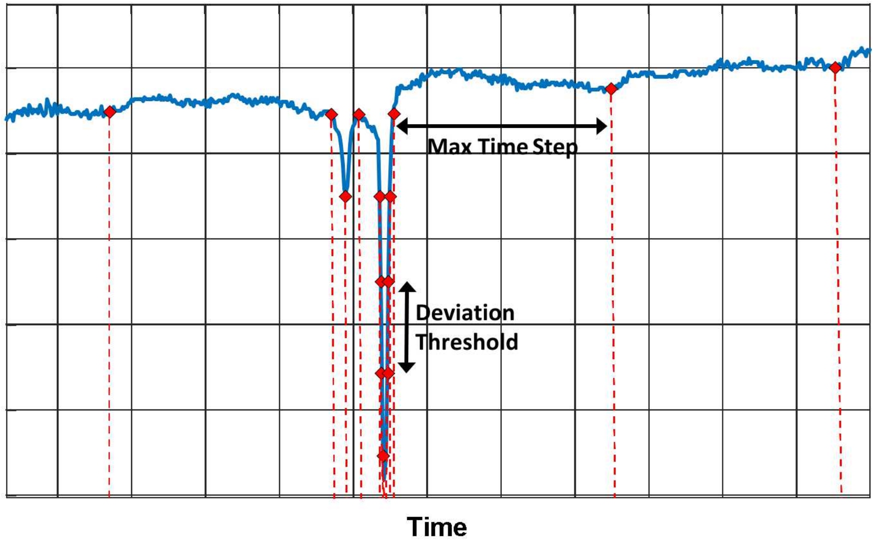
- The computational time for yearlong high-resolution QSTS simulations takes 10 to 120 hours for realistic-sized distribution feeders
- Two main ways to reduce the number of power flows in a yearlong 1-second time-step QSTS simulation
  1. Skipping through time (larger time step)
  2. Shorter duration simulation (fewer days)

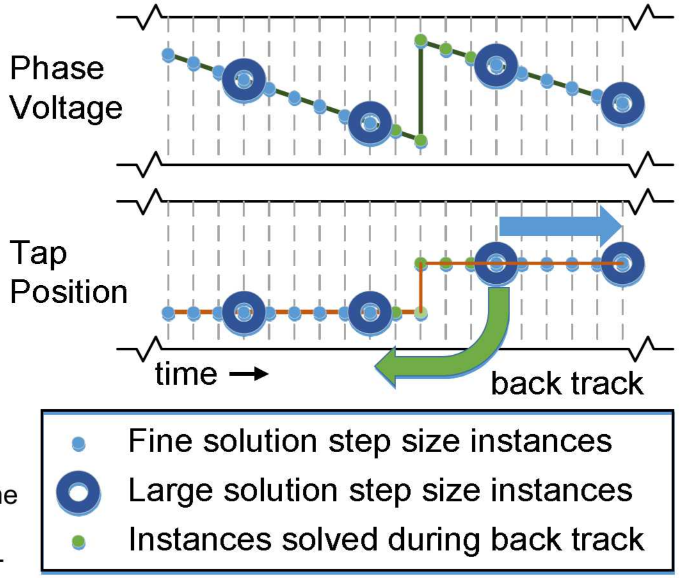


Previous QSTS Variable Time-Step Methods

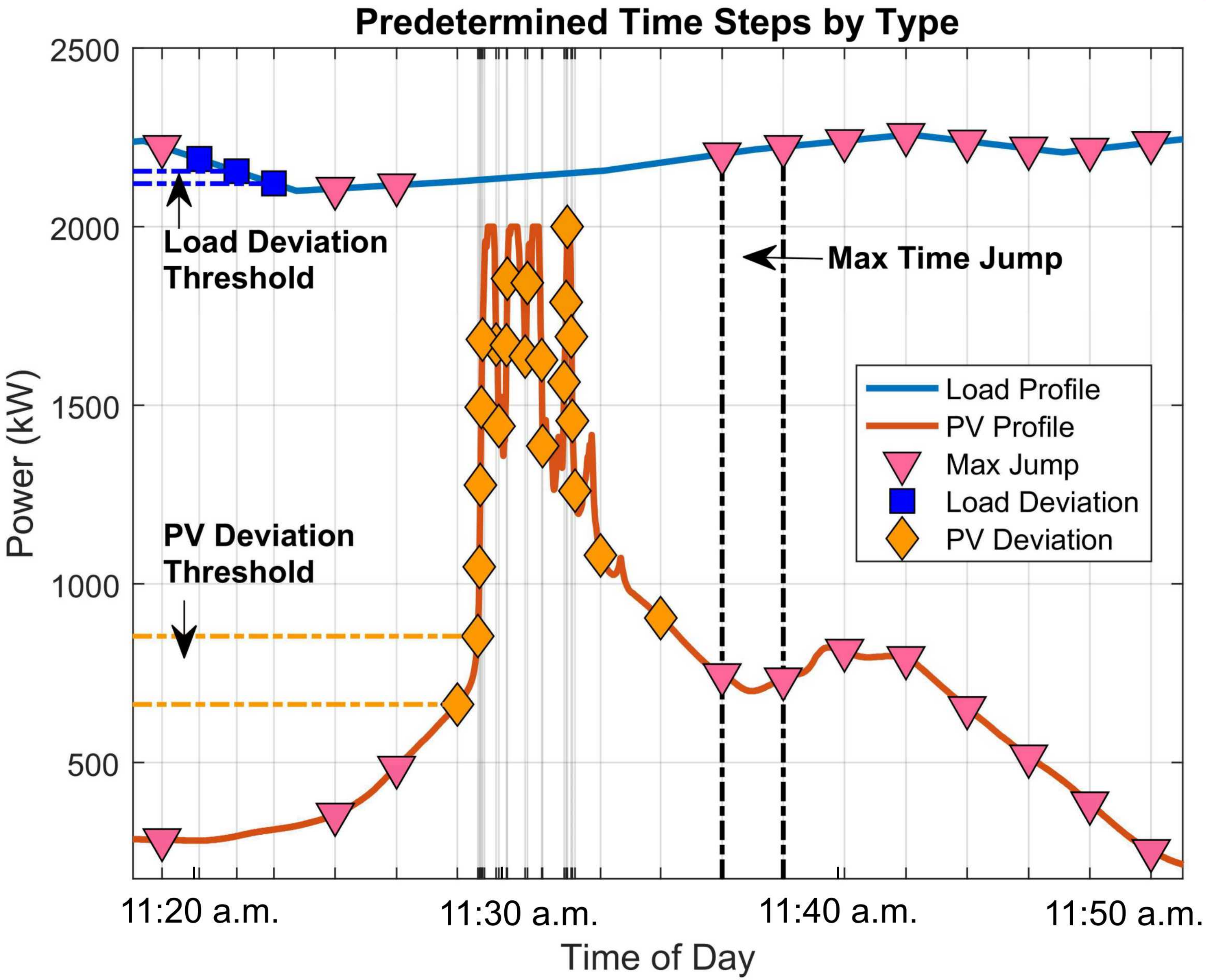
Variable time-step solvers do not solve every time-step and skip forward to time points of interest, advancing through the QSTS analysis with varying time-steps

- The predetermined time-step (PT) solver is a deviation-based variable time-step algorithm that preprocesses the load and generation data in order to define the time-steps [1]
- The backtrack-based solver uses coarse time steps until a system state change is detected, and then backtracks to the previous large time-step instance and proceeds with small time steps [2]



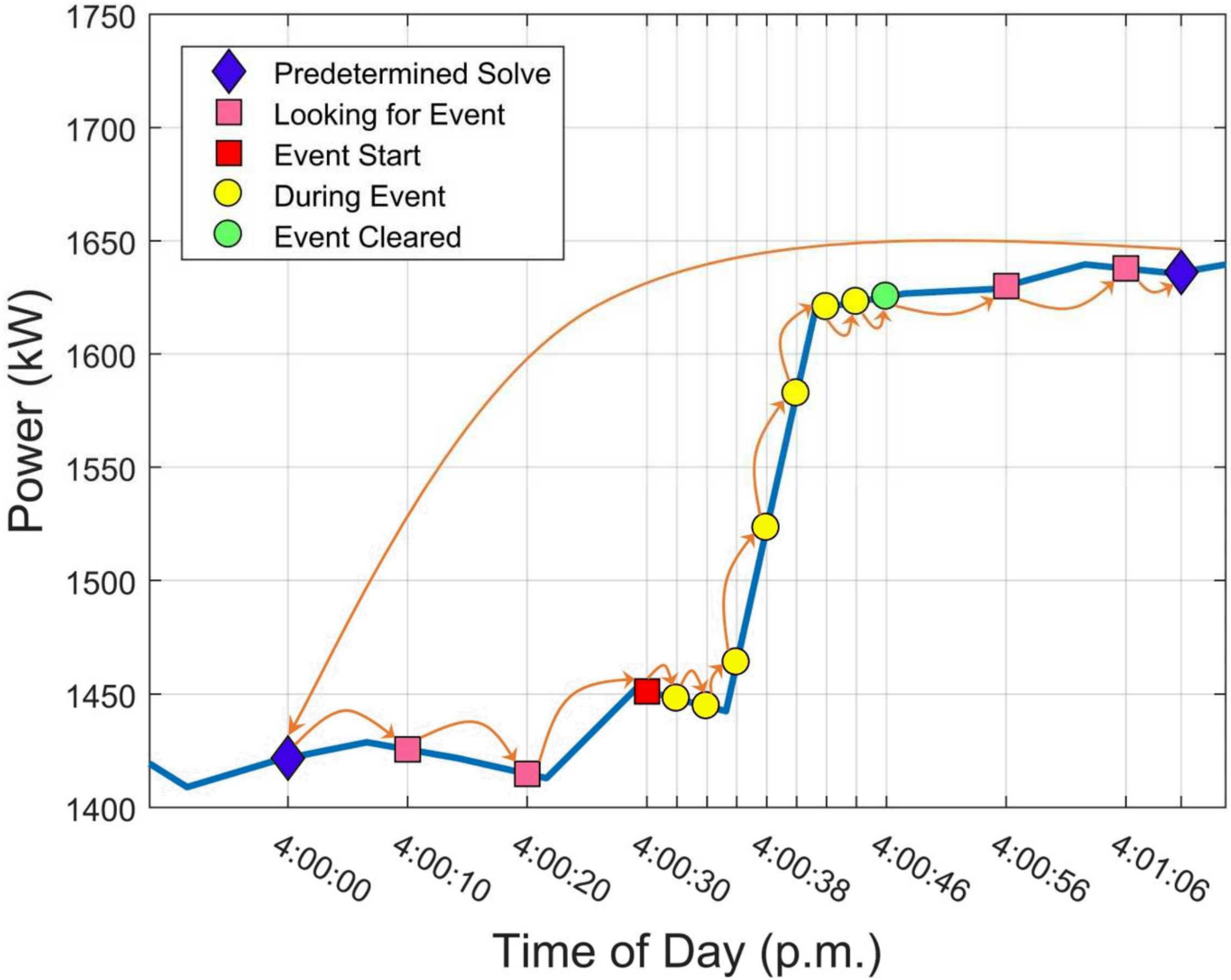


[1] M. J. Reno and R. J. Broderick, "Predetermined Time-Step Solver for Rapid Quasi-Static Time Series (QSTS) of Distribution Systems," *IEEE Innovative Smart Grid Technologies*, 2017.
[2] B. Mather, "Fast Determination of Distribution-Connected PV Impacts Using a Variable Time-Step Quasi-Static Time-Series Approach," *IEEE Photovoltaic Specialists Conference*, 2017.



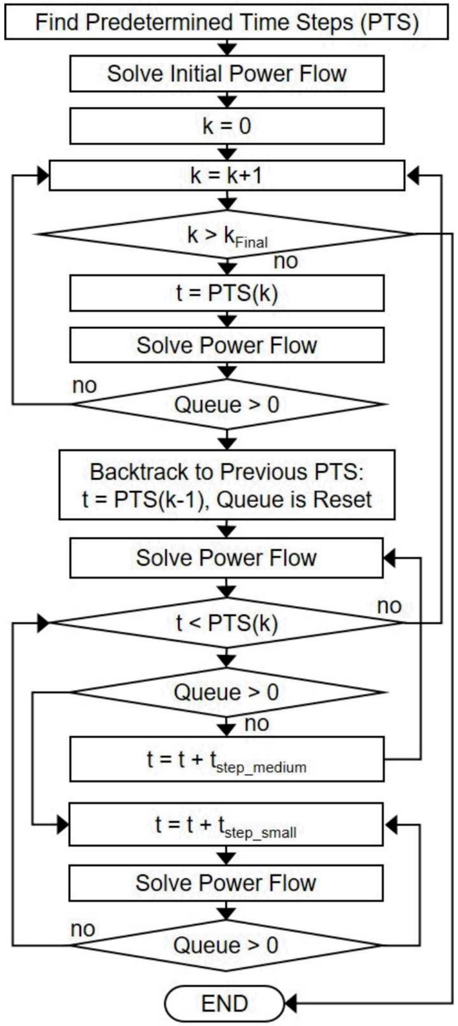
Predetermined Time Steps by Type
2500
2000
1500
1000
500
Power (kW)
11:20 a.m.
11:30 a.m.
11:40 a.m.
11:50 a.m.
Time of Day
Load Deviation
Threshold
PV Deviation
Threshold
Max Time Jump
Load Profile
PV Profile
Max Jump
Load Deviation
PV Deviation

Backtrack and Search for Tap Change



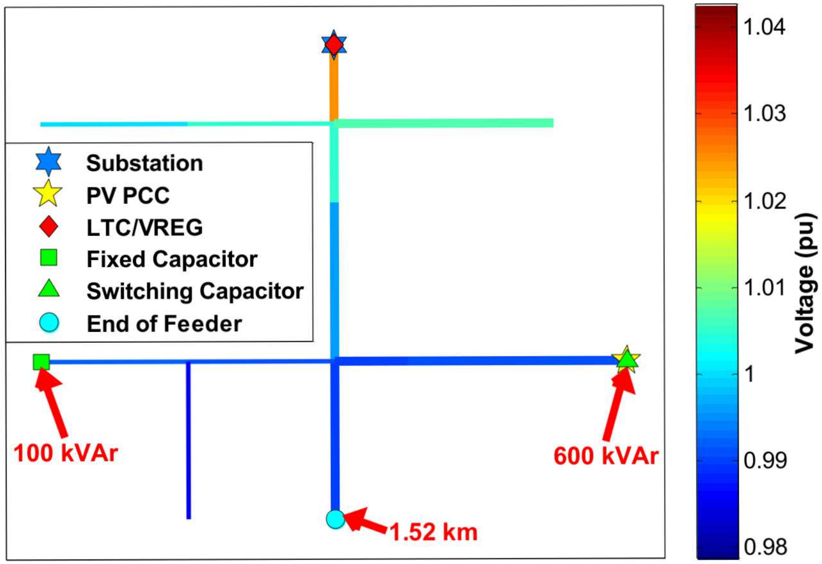
Proposed Variable Time-Step Algorithm

- Combines predetermined time-step and variable time-step with backtracking for additional speed
- First the predetermined time-step algorithm determines the time-steps to be solved. Second, as the QSTS progresses through the points, if an event is detected, the backtrack algorithm reverses time to solve that period in more detail.
- The benefit is that the simulation progresses through non-variable periods quickly, and then during events, the backtrack is for shorter periods because the predetermined time-steps are closer together
- Two main settings in the proposed algorithm:
  1. Deviation threshold in % of controller deadband
  2. Maximum allowed time-step



Comparison To Previous Methods

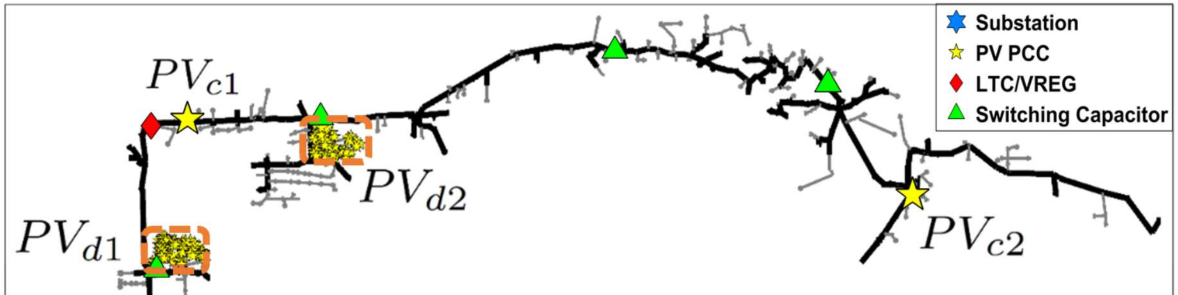
- Previous variable time-step algorithms were run on a modified IEEE 13-node test circuit
- The circuit has three single-phase voltage regulators at the feeder head and a large 3-phase 2MW PV system (~40% penetration of peak load) at the end of the feeder
- QSTS simulations performed in OpenDSS
- The simulation results and computational time is compared to a brute-force yearlong QSTS simulation at 1-second resolution



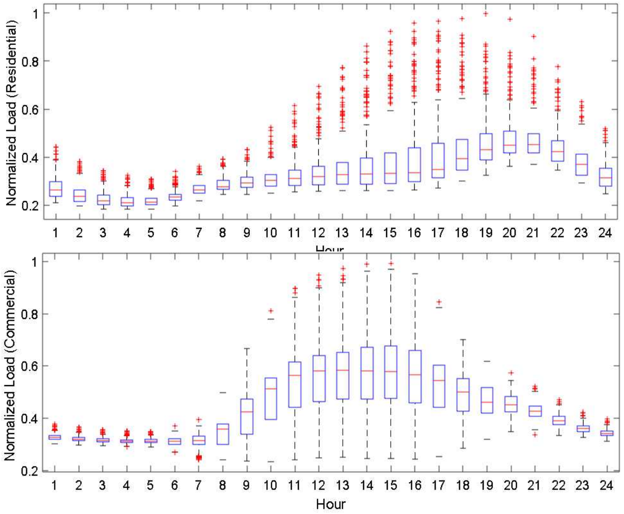
Method	Regulator Error (RMSE)	Times Faster
Backtrack [2]	4.54%	11.5
PT Solver [1]	3.30%	22.2
Proposed Algorithm	9.94%	**43.0**

Simulation Test Setup

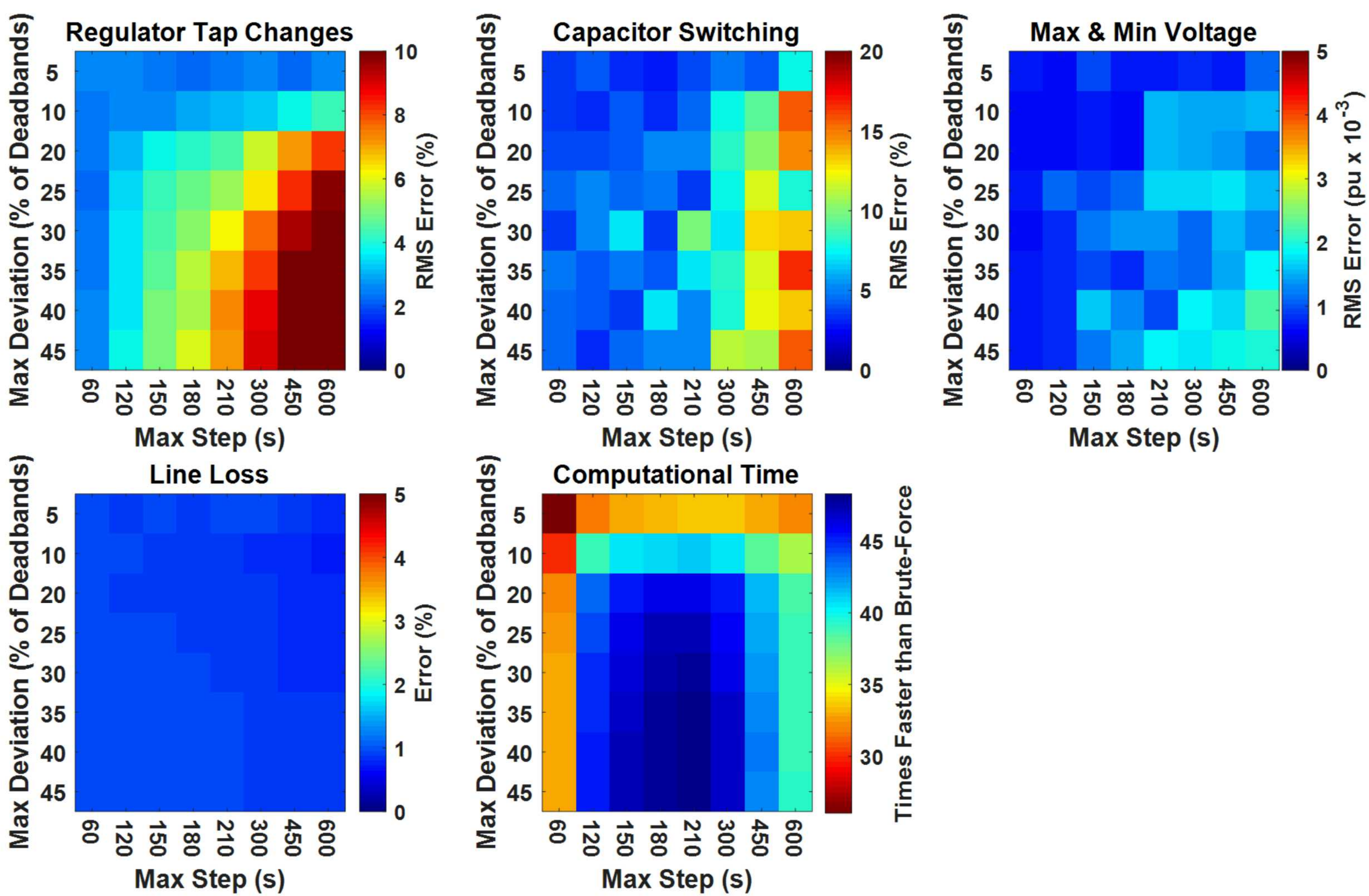
- In order to test the scalability of the proposed variable time-step algorithm, a large real distribution system feeder with ~3000 buses (~5000 nodes) is used
  - 5 voltage-controlled capacitor banks
  - 3 single-phase line voltage-regulating tap changers
  - 1 three-phase substation load tap changer (LTC)
- Combinations of distributed and centralized PV systems (4 profiles)
- Multiple load profiles for customer classes



Name	Type	Rating	Quantity
PV_{c1}	centralized, 3-phase	2500 kW	1
PV_{c2}	centralized, 3-phase	500 kW	1
PV_{d1}	distributed, 1-phase	5 kW each	78
PV_{d2}	distributed, 1-phase	5 kW each	64

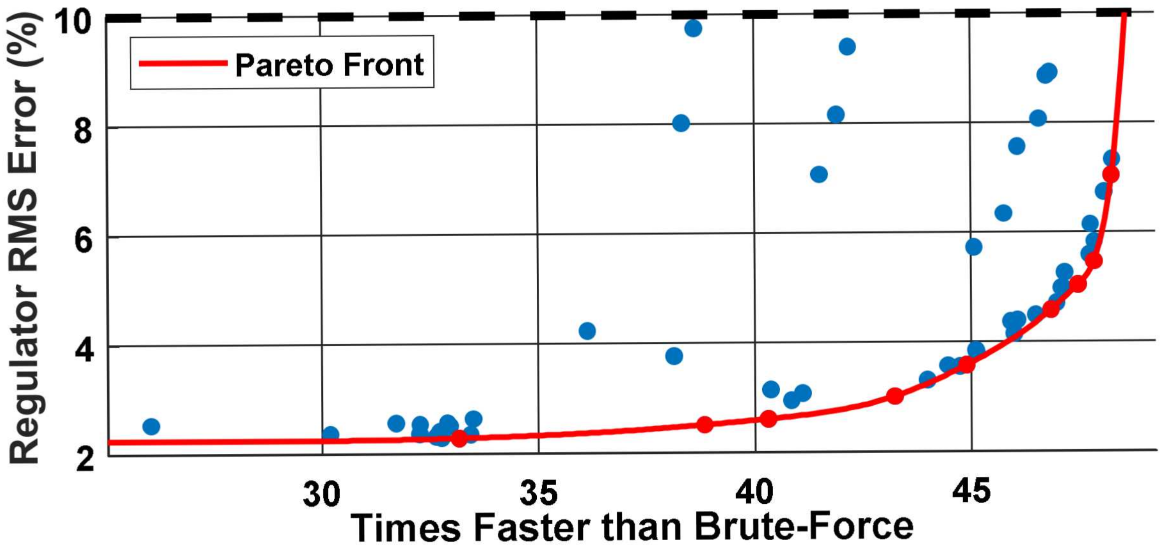


Variable Time-Step Solver Results



Variable Time-Step Solver Results

Optimal models are along the Pareto front of the trade-off between accuracy and speed



Error and Percent Reduction for different settings

Deviation Threshold	Max Time Step (s)	Taps Per Reg	Cap Switches	Max Voltage	Min Voltage	Total Line Losses	Times Faster
Base Case		2746, 5515, 5055, 5274	352, 54, 30, 544, 740	1.0607pu	0.9673pu	146.0 MWh	
5%	180	2.3%	3.1%	0.0000pu	0.0010pu	0.93%	33.2
10%	120	2.5%	3.4%	0.0000pu	0.0010pu	0.97%	38.8
10%	150	2.6%	4.3%	0.0000pu	0.0011pu	0.93%	40.3
20%	120	3.0%	3.9%	0.0000pu	0.0009pu	0.93%	43.2
40%	120	3.6%	4.1%	0.0000pu	0.0011pu	0.98%	44.9
30%	180	5.1%	3.5%	-0.0010pu	0.0017pu	0.95%	47.5

Conclusions

- QSTS simulation will be a critical aspect of future power system analysis with high penetration of renewable energy and increasing number of smart grid controls.
- This paper proposes a new combination of predetermined time-step and variable time-step with backtracking
- A new voltage sensitivity-based deviation threshold is proposed for predetermining the best time-steps
- The proposed variable time-step algorithm dramatically improves the speed to 50 times faster than conventional brute-force QSTS simulations, while maintaining the high accuracy that is expected from QSTS
- The algorithms are demonstrated to be scalable for large distribution feeders, complexity, and control types

QUESTIONS?

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