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

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Abstract — **Distribution system analysis with high penetrations of distributed PV require quasi-static time-series (QSTS) analysis to model the variability introduced on the distribution system, but current QSTS algorithms are prohibitively burdensome and computationally intensive. This paper proposes a variable time-step algorithm to calculate the critical time periods when QSTS simulations should be solved at higher or lower time-resolution and to backtrack for any critical periods that were missed. This variable time-step solver is a new method of performing time-series simulations with high accuracy while performing the simulation more than 40 times faster. The scalability of the algorithm is demonstrated using a real utility distribution system model with thousands of buses.**

I. INTRODUCTION

Historically, distribution system analysis was performed using steady-state power flow simulations, harmonic analysis, and system protection studies. This was traditionally sufficient for distribution system engineers to design feeder layouts, plan expansions, consider upgrades, and determine the distribution system control settings. However, new smart grid technologies and high penetrations of distributed and renewable resources such as energy storage systems (ESS), electrical vehicles (EVs), distributed photovoltaic (PV) advanced inverters, demand response (DR), and the distributed energy management systems (DEMS) to control them are changing the paradigm for distribution system planning and operations. Quasi-static time-series (QSTS) simulation is a versatile study method used to understand equipment control operation, voltage regulation, and reactive power management for different DER, including solar PV [1-5]. QSTS solves a series of sequential steady-state power-flow solutions where the converged state of each iteration is used as the beginning state of the next. This creates a dependence where each power flow solution requires information from the previous ones. QSTS simulations specifically model the distribution system discrete controls and run the simulation as time-series to capture the time-varying parameters such as load, and the time-dependent states in the system, such as regulator tap positions. Without improved time-series analysis and tools, many potential impacts, like the duration of time with voltage violations and the increase in voltage regulator operations, cannot be analyzed.

Depending on the system being modelled and the type of impacts being studied, the required QSTS time-step resolution varies. For highly variable PV, in order to simulate the interaction voltage regulation controls, QSTS simulations are often performed at high time resolutions with time steps less than 10 seconds. To model control devices, the time resolution of the QSTS simulation should be below the fastest delay in any devices with discrete controls on the feeder to ensure accurate representation of the device's operation [6]. In [7], a 5-second resolution yearlong QSTS simulation is recommended to capture all distribution system analyses accurately.

High-resolution yearlong QSTS studies can take from 10 to 120 hours to run using existing methods [8]. Faster time-series analysis methods are needed for QSTS to be able to be used by utilities for distribution operation decisions and coordination. In this work, we focus on how to speed up the high resolution QSTS simulation to make it viable for both DER distribution impact studies and operational decision making.

In a typical power system simulation, small time-steps are necessary to capture the time-dependent, dynamic and transient behaviors of the system. However, the use of a small-time step is computationally intensive and leads to very similar power flow solutions for many consecutive iterations during steady-state conditions. Therefore, variable time-step algorithms have been commonly employed in power systems applications for dynamic analysis [9], transient analysis [10], and time domain simulation of large power systems [11]. One approach incorporated a variable time-step algorithm into the simulation of power-electronic-based systems [12]. More recently, a variable time-step algorithm was proposed for frequency-domain simulation of electromagnetic transients where the time window was divided into multiple subwindows, each with an independent time-step [10]. Jardim et al. coupled a transient stability program with an electromagnetic transients program based on variable time-step [13]. A co-simulation environment also used a variable time-step algorithm for the dynamic analysis of multi-area power systems [14]. This paper presents a new application to extended time-series simulations using a variable time-step solver for rapid QSTS simulations of distribution systems.

The contributions of this paper include:

- Development of a new variable time-step algorithm for rapid yearlong QSTS simulations
- Detailed comparison to existing variable time-step methods using the same circuit and simulation
- A new implementation of voltage-sensitivities to derive the key time points for higher resolution variable time-steps
- Demonstration of the scalability of the variable time-step algorithm using a utility feeder with thousands of buses.

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II. VARIABLE TIME-STEP ALGORITHM

Conventional QSTS simulations proceed throughout the duration of the simulation at a fixed time-step. This work expands on two previous rapid QSTS methods of predetermined time-step [15] and variable time-step with backtracking [16] to improve the speed even further. This novel algorithm provides improvements on each individual algorithm, and also combines both methods in a new way.

A. Predetermined Time-Step Solver [15]

The previously developed predetermined time-step (PT) solver is a deviation-based, variable time-step algorithm that improves the speed of QSTS by calculating the critical time periods when QSTS simulations should be solved at higher or lower time-resolution and focuses the computational effort during periods of the year when the system is rapidly changing [15]. During steady-state periods, the solver can step forward in time with large steps, and during highly variable times the solver operates at finer resolution. The algorithm is implemented using a deviation threshold that is applied to the input time-series data, jumping ahead until the load power consumption/injection has changed significantly from the previously solved time-step. The algorithm also includes a component to limit the maximum step size even during periods when very little is happening.

The PT solver demonstrated a 95.5% reduction in computational time (22.2 times faster), with a 3.3% error in estimated number of voltage regulator yearly tap changes [15].

B. New Voltage-Sensitivity-Based PT Solver

The original PT solver [15] applied a consistent threshold to each power injection in the circuit. Because of differing power factors of the power injections and the location, each power injection may affect the various controllers differently. For instance, the location of a PV system can impact the operation of a capacitor bank differently based on its proximity. Thus a voltage-based sensitivity analysis was proposed in [17] that quantifies the impact that each power injection profile has on the voltage at each controllable device. This is done by introducing a small disturbance in each profile individually and recording the controller input signals. Details of the perturb-and-observe sensitivity analysis can be seen in [17]. The resulting voltage sensitivity represents the input control voltage variation that a 0 to 1 per unit change in the profile would create in each controller. Because controllers are often programmed with deadbands to avoid oscillations, the voltage sensitivity is normalized with respect to the controller deadbands to determine how sensitive each controller is to a specific profile. The output of the voltage sensitivity is how much the voltage changes at the controller (in per unit of the deadband) per a kW injection of a given load or PV power profile.

In this voltage-sensitivity-based PT solver, a user can set a maximum allowable deviation as a percent of the deadband. Using the voltage sensitivities, a unique kW threshold is calculated for each profile, and then the same algorithm is applied as in [15]. The voltage-sensitivity-based PT solver is illustrated in Figure 1 with the deviation threshold of the load profile, the deviation threshold of the PV profile, and max time-step highlighted. Note that the load power deviation threshold is smaller than the PV power deviation threshold because it has a greater impact on the voltage regulation equipment, i.e. a larger voltage-sensitivity impact. The gridlines on the x-axis represent moments in time when the power flow is to be solved, and they show the increasing number of power flow simulations that occur during the variable periods. These moments are derived from deviations in load (blue squares), deviations in PV (yellow diamonds), or when the maximum time step is reached (pink triangles). One aspect of the proposed PT solver is that the length of the time-step is solely dependent on the input variables, so it can be predetermined. The output of the new voltage-sensitivity-based PT solver is simply a list of time points at which to solve the power flows.

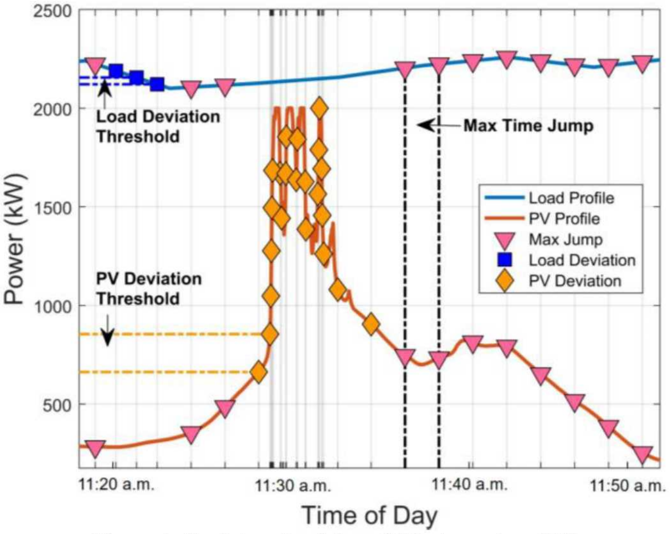


Figure 1. Predetermined time (PT) step solver [15]

C. Backtrack-Based Method [16]

The backtrack-based solver [16] uses a method wherein coarse time steps are taken until a system state change is detected. Then the solver backtracks to the previous large time-step instance and proceeds with small time steps for a period of time until large time-stepping is resumed. The solver uses a change in voltage regulator tap position to detect time periods when a higher resolution analysis is needed. This method yields higher accuracy in results in terms of determining the number of voltage regulator operations and the minimum and maximum voltages experienced on the circuit being studied. This type of algorithm can be more accurate than the PT solver because it can backtrack to catch all events, but it also requires additional power flow simulations and some interaction between the solver and time-step control.

The backtrack-based solver demonstrated a 91.3% reduction in computational time (11.5 times faster), with a 4.5% error in estimated number of voltage regulator year tap changes [16].

D. New Variable Resolution Backtrack-Based Method

A key component of the backtrack-based QSTS solver is the ability to backtrack and find the tap change event as quickly as possible. The original method backtracked and solved the entire timeframe at high-resolution 1-second time-steps. To avoid excessive computation effort, other algorithms such as a binary-search algorithm [16] or downsampling methods [18] were created. In this work, an alternative method is prposed that solves the backtrack timeframe at a variable resolution considering when the tap change event has begun. After backtracking to the previous PT solve point, the algorithm increments at "t_{step_medium}" resolution searching for the beginning of the event. Once the event has begun, meaning the voltage has gone outside the controller bandwidth and the controller delay period has begun, the algorithm proceeds at a time step of "t_{step_small}" until the queue is empty and the event has cleared. The finer resolution during the controller delay allows the algorithm to detect any times where the voltage came back in band and reset the controller delay. Once the algorithm has proceeded past the event, it again steps with an increment of "t_{step_medium}" until another event is found or until the next predetermined time step is reached.

Figure 2 shows a conceptual diagram of the proposed algorithm. The blue diamonds represent time points that belong to the set of points derived from the PT solver. Between these two predetermined solves, the algorithm detects that a higher resolution analysis is needed and backtracks, following the orange arrows to the previous predetermined time step. A medium resolution (in this case 10 seconds) is then used to find the moment that the regulator time delay is initiated, i.e. an event occurred. Once the start of the event is found, the algorithm proceeds at a small time-step (in this case 2 seconds) until the end of the regulator time delay is met.

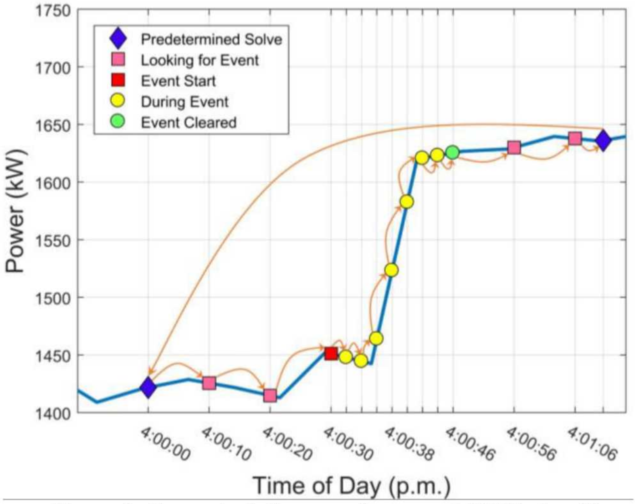


Figure 2. Conceptual diagram of proposed QSTS algorithm

E. Novel Combination of Variable Time-Step Methods

The proposed novel algorithm for QSTS simulation, specifically for 3-phase unbalanced power flow analysis of the distribution system, combines predetermined time-step [15] and variable time-step with backtracking [16] for additional speed. The general idea is to use the predetermined time-steps calculated by the PT solver as the coarse large step-size used in the backtrack-based solver. This allows the algorithm to take very large jumps during uneventful periods, and change the time-step length to a fine resolution when events may occur. This has the benefit that any backtracking is likely to be for a shorter period because the predetermined time-step are closer together during that period.

The flowchart shown in Figure 3 explains the algorithm in greater detail. The first step is to find all the predetermined time steps to be solved (PTS with index "k"). The algorithm then steps through each of these time points until some event occurs and populates the queue. The queue tracks the time delay of any of the controlled devices. For example, if the control voltage of a regulator rises above a certain threshold, that regulator will be added to the queue and remain there until the regulator operates or the voltage returns to an acceptable level. When the queue is populated, a backtrack event is initiated, as discussed in Section II.D.

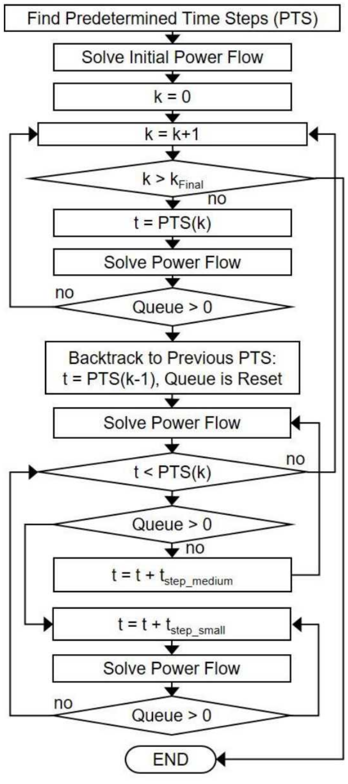


Figure 3. Flowchart of proposed QSTS algorithm

Because of the combination of the PT solver and the backtrack algorithm, time periods for backtrack events can widely vary in length: from 1 second to the max time jump defined in Section II.A. If an event is detected, but the previous PT solve was only a couple seconds before, there is no reason to initiate the backtrack process. If a backtrack is initiated, the time-step resolution of "t_{step_medium}" can be a variable to move faster through long backtrack time periods and slower through shorter backtrack time periods.

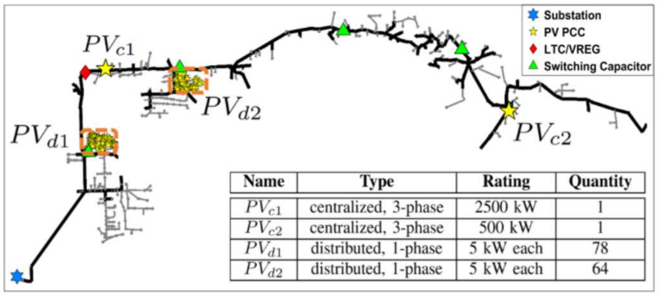
III. TEST SYSTEMS

A. *IEEE 13-bus Test Circuit*

The QSTS simulation is performed on a modified IEEE 13-bus test circuit that incorporates high penetration PV (~40% of peak load) and measured high-resolution load and PV data is used for the time-series profiles. The IEEE feeder was modified to be able to test high-resolution QSTS algorithms and was also used in [15] and [16]. See [15] for more details on the circuit.

B. *Large Utility Test Feeder*

Due to the computation time, many QSTS algorithms and analysis have been performed either for short time periods or on small systems like the IEEE 13-bus test circuit [19]. In order to demonstrate the scalability of the proposed variable time-step algorithm, a large utility test feeder is tested for a yearlong QSTS simulation. The model is based on an actual distribution feeder [20], with 2969 buses (5469 nodes) as shown in Figure 4. The length of the feeder is 21.37 km with a total of 9 controllable elements: a single three-phase substation load tap changing (LTC) transformer (30-second delay), 3 single-phase line voltage regulators (30-second delay),, 3 three-phase and 2 single-phase switching capacitor banks (60-180 second delays). There are 1,111 single-phase customers and 317 three-phase customers on the feeder, each modeled individually and connected on the low-voltage secondary networks. All three-phase loads are designated as commercial, while single-phase loads are assumed to be residential, accounting for 1.69 MW and 4.25 MW of the peak load respectively. Both load types are assigned a unique 1-second power injection profile generated from SCADA measurements of the feeder under consideration.



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

Figure 4. Large utility test feeder with centralized and distributed PV.

A total of 144 PV systems are installed on the feeder, which are grouped into four categories based on their geographical locations, as shown in Figure 4. Distributed PV systems are residential rooftop installations modeled on the low-voltage networks adjacent to the loads. The centralized PV systems are 3-phase utility-scale installations with their own inter connection transformer. Each category of PV system is also assigned a unique 1-second power injection profile based on solar irradiance data. More details about the test circuit can be found in [21]. The conventional brute-force QSTS simulation for a year at 1-second resolution takes approximately 30 hours to solve in OpenDSS!

C. *Simulation and Evaluation Criteria*

All QSTS simulations are performed in OpenDSS [22], and the speed improvements are compared to the sequential, yearlong 1-second resolution QSTS simulation. The accuracy of all methods is demonstrated using the total number of yearly tap changes from the voltage regulation equipment on the feeder. The purpose of the variable time-step solver is to reduce the time of QSTS simulations, so the main objective is computational speed. On the other hand, it is important that the QSTS simulation maintains the high-level of accuracy required when performing high-resolution time-series analysis using QSTS. The accuracy requirements are application-specific to what is being quantified: voltage regulation device operations (regulators and switching capacitors), line losses, and maximum and minimum voltages. Each of these will serve as the evaluation metrics for calculating the errors relative to the yearlong 1-second resolution QSTS simulation. For each evaluation criteria, maximum acceptable error thresholds have been set based on feedback from distribution system engineers on their expectations of the performance of QSTS simulations.

IV. COMPARISON TO PREVIOUS QSTS METHODS

Since the previous variable time-step QSTS algorithms [15, 16] were both tested on the IEEE 13-bus test feeder, the proposed algorithm is also used to perform a QSTS simulation on the same test system. This allows for a precise comparison of speed and error of each method, as shown in Table I. The root mean squared error (RMSE) is calculated for the error in total yearly tap changes for the three regulators in the circuit. For each of the three methods, the fastest times are shown that maintain the RMSE tap change error within the allowable 10% error threshold. The proposed algorithm is able to solve in half the time as the previous methods, and demonstrates a speed improvement of 43 times faster than the brute-force traditional QSTS simulation in OpenDSS.

TABLE I. COMPARISON OF RESULTS ON SMALL CIRCUIT

Method	**Regulator Error (RMSE)**	**Times Faster**
Backtrack [16]	4.54%	11.5
PT Solver [15]	3.30%	22.2
Proposed Algorithm	9.94%	43.0

One specifically new aspect of the proposed algorithm is applying the voltage-sensitivity based calculation from [17] into the predetermined time-step algorithm to calculate the appropriate deviation thresholds for each profile. In order to demonstrate the value of including new voltage-sensitivity-based PT solver, the proposed algorithm was run on the large utility circuit with the kW-based deviation and the voltage-sensitivity based deviations. Figure 5 shows that the voltage-sensitivity calculation improves both the error and the speed of the rapid variable time-step algorithm.

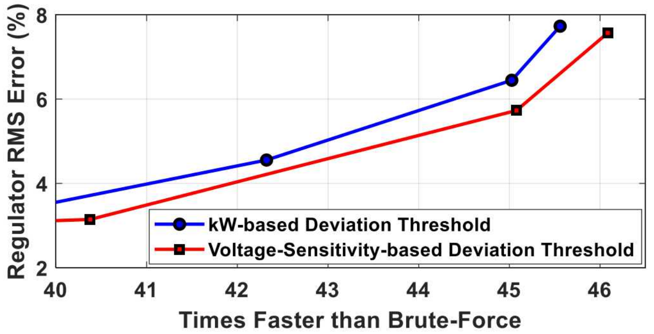


Figure 5. Comparison of deviation threshold methods for the large utility circuit with different thresholds calculated by the two deviation threshold methods with the maximum time-step set to 300 seconds.

V. SIMULATION RESULTS

In order to demonstrate the scalability of the proposed algorithm, all results in this section are for the yearlong large utility test feeder case described in Section III.B.

Figure 7 shows the correlations between error and computational time, with each dot representing a specific combination of deviation threshold and maximum time-step. The acceptable error threshold is shown with the dashed black line. The results demonstrate how the error generally increases as the speed of the QSTS simulation increases. By moving faster through time, some critical events are missed. The results demonstrate that a speed improvement of 45 times faster can easily be achieved with the proposed variable time-step solver.

In order to visualize the correlations between the deviation threshold and maximum time-step, Figure 8 shows the level of error for each combination of settings, with the color scale set based on the allowable error. The bottom plot in Figure 8 shows the increase in speed for each combination, in terms of times faster than the brute-force simulation. As the maximum time-step gets larger, there is trend towards higher levels of error.

Given the range of combinations of deviation threshold and maximum time-step, the best solutions can be found with the Pareto front for the regulator RMS error as shown in Figure 6. Along the Pareto front there is a tradeoff for selecting the higher speed or higher accuracy optimal solution. Some of the combinations along the Pareto front are shown in Table II for their specific levels of accuracy for each error metric and speed compared to the base case brute-force 1-second resolution yearlong QSTS simulation.

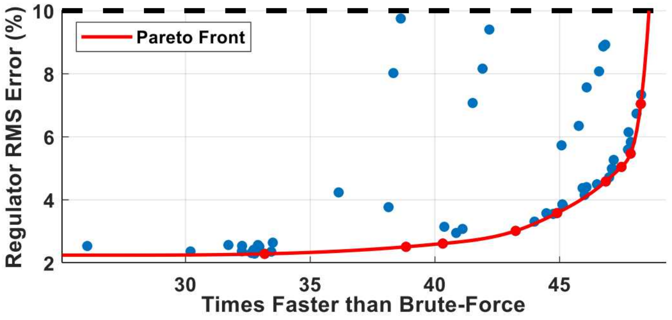


Figure 6. Pareto front for the most optimal variable time-step solutions.

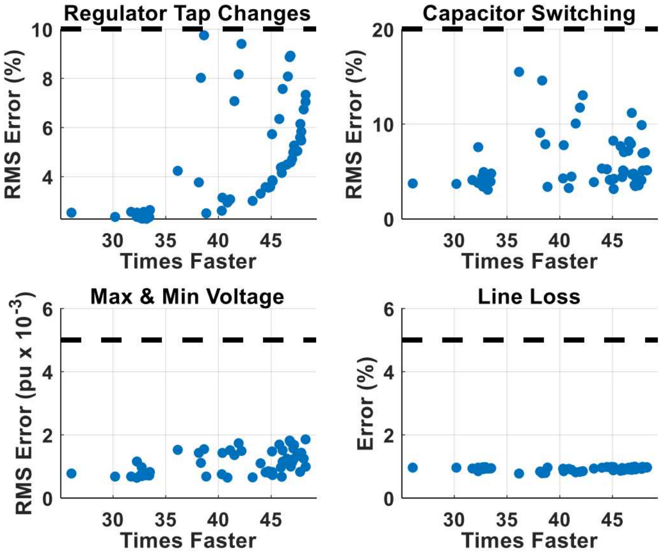


Figure 7. Correlations between error and computational time of the proposed variable time-step QSTS algorithm.

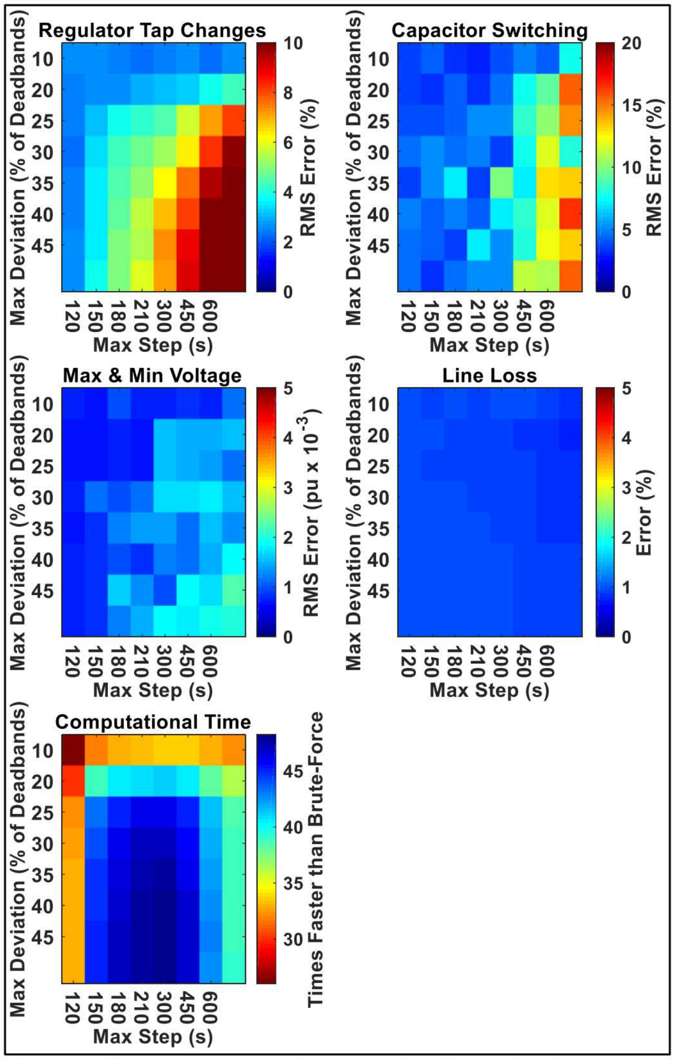


Figure 8. Simulation error and computational time for the proposed algorithm as a function of max voltage deviation and max step size.

TABLE II. ERROR AND PERCENT REDUCTION A RANGE OF SETTINGS ALONG THE PARETO FRONT

Deviation Threshold	Max Time Step (s)	Tap Changes Per Regulator	Capacitor 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	-1.2, -0.2, 3.4, -2.8 %	5.1, -3.7, 0.0, -2.6, -0.5 %	-0.0000pu	0.0010pu	0.93%	33.2
10%	120	-1.5, -0.9, 3.3, -3.4 %	7.4, 0.0, 0.0, -0.7, 1.4 %	0.0000pu	0.0010pu	0.97%	38.8
10%	150	-1.5, -1.5, 2.6, -4.0 %	8.0, -3.7, 0.0, -3.7, 0.5 %	0.0000pu	0.0011pu	0.93%	40.3
20%	120	-1.3, -2.6, 3.6, -3.8 %	7.4, -3.7, 0.0, -2.6, 0.0 %	0.0000pu	0.0009pu	0.93%	43.2
40%	120	-1.4, -4.8, 1.5, -5.0 %	7.4, -3.7, 0.0, -3.3, 1.9 %	0.0000pu	0.0011pu	0.98%	44.9
30%	180	-1.5, -6.9, 0.8, -7.2 %	7.4, 0.0, 0.0, -2.6, -1.1 %	-0.0010pu	0.0017pu	0.95%	47.5

IV. 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 demonstrates a new combination of predetermined time-step [15] and variable time-step with backtracking [16] that had previously demonstrated ~20x speed improvement and ~10x speed improvement, respectively. The new variable time-step algorithm dramatically improves this speed to over 40 times faster than conventional brute-force QSTS simulations, while maintaining the high accuracy that is expected from QSTS. The algorithms are scalable to any distribution feeder size, complexity, and control types.

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