Motivation and Requirements for Quasi-Static Time Series (QSTS) for Distribution System Analysis

Matthew J. Reno
Electric Power Systems Research
Sandia National Laboratories
Albuquerque, NM, USA

Jeremiah Deboever
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, GA, USA

Barry Mather
Power System Engineering Center
National Renewable Energy Labortory
Golden, CO, USA

***Abstract* — Distribution system analysis with ever increasing numbers of distributed energy resources (DER) requires quasi-static time-series (QSTS) analysis to capture the time-varying and time-dependent aspects of the system. Previous literature has demonstrated the benefits of QSTS, but there is limited information available for the requirements and standards for performing QSTS simulations. This paper provides a novel analysis of the QSTS requirements for the input data time-resolution, the simulation time-step resolution, and the length of the simulation. Detailed simulations quantify the specific errors introduced by not performing yearlong high-resolution QSTS simulations.**

***Index Terms* -- distributed power generation, photovoltaic systems, power distribution, power system interconnection**

I. Introduction

Conventionally, distribution system analysis has focused on steady-state power flow simulations, harmonic analysis, and system protection studies. These types of studies have traditionally been sufficient for distribution system engineer's planning needs such as designing feeder layouts, planning expansions and upgrades, and determining control settings. However, emerging technologies and capabilities such as energy storage systems (ESS), electrical vehicles (EVs), distributed photovoltaic (PV) advanced inverters, demand response (DR), and Advanced Distribution Management Systems (ADMS) are changing the paradigm for distribution system planning and operations. Commercial circuit analysis tools have provided the capability to perform steady state power at snapshots in time, such as the peak load period that was historically the most extreme condition. Traditional snapshot tools and methods may not be adequate to accurately analyze the interactions of new distributed energy resources (DER) being interconnected.

A draft of the IEEE guide on conducting DER distribution impact studies for distributed resource interconnection discusses four types of special system impact studies: (1) dynamic simulation, (2) electromagnetic transient (EMT) simulation, (3) harmonic and flicker study, and (4) quasi-static simulation [1]. Dynamic simulation is practical to simulate stability issues or voltage and frequency ride-through [1]. EMT simulation is often used for protection design and fault analysis [1]. Harmonic and flicker studies provide insights on the feeder's power quality [1]. Last, quasi-static simulation is a versatile study used to understand equipment control operation, power protection coordination, and voltage regulation and reactive power management [1]. In this work, we focus on the quasi-static time-series (QSTS) simulation to study the impact of various DERs. 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 captures time-varying parameters such as load, and the time-dependent states in the system such as regulator tap positions. QSTS simulation is best defined by the IEEE draft guide:

"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. However, there is no numerical integration of differential equations between time steps." [1]

QSTS involves steady-state power flows, but it is distinguished by the dependence on the previous power flow solution. Each time step of the solution cannot be solved independently because it relies on the information from the previous time step about the feeder state, regulator taps, control delays, etc. QSTS simulations specifically model these discrete controls and run the simulation as a time-series to capture the time-dependent states of any controllable elements. QSTS helps to understand the impact of a new DER and offers many practical advantages and uses over conventional tools:

1) Analysis is not limited to specific time periods, such as peak load, which may no longer be the most critical times with high penetrations of DER
2) Enables the study of control algorithms, such as energy storage or ADMS control, and interactions between control equipment, such as between PV advanced inverter volt-var and distribution voltage regulators
3) Simulates impacts like voltage fluctuations that are caused by variable resources such as distributed PV
4) Calculates the interaction between the daily changes in load and PV output and perform energy and loss evaluations over actual profiles of load and generation
5) Determines the steady-state voltage conditions for quickly changing circuit load and or generation
6) Calculates the time duration of extreme conditions, such as the number of hours a customer is expected to see an over-voltage condition or the amount of time a conductor or transformer is overloaded each year

Without time-series analysis, many potential impacts of new DER, like the duration of time with voltage violations and the increase in voltage regulator operations, cannot be accurately analyzed. Understanding the voltage regulator

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operations is essential to determine the impact of DER on these expensive pieces of utility equipment. Furthermore, snapshot study methods that only analyze peak periods or a peak variability day often lead to over-estimation of normal operating issues. Paired with accurate load and generation time-series data or models, a QSTS can accurately quantify the magnitude, frequency, and duration of an impact [1].

In this paper, we discuss the motivation and requirements of QSTS for distribution system analysis. The paper is organized as follows. Previous work using QSTS analysis is discussed in Section II. Section III describes the test feeder for this work. The time-step resolution and time horizon requirements for QSTS analysis are analyzed in Section IV. Discussions, recommendations, and conclusions based on the simulation results are presented in Section V and VI.

II. Background

The notion of time-series power flow simulations is discussed in the literature for impact studies of different DER: solar PV [2]–[14], wind [15], [16], electrical vehicles [17], [18], and ESS [19]. QSTS simulation is also used for impact studies of control schemes in different power equipment: smart inverters [7], [12], [13], [20], and voltage regulating devices [10], [21]–[24]. The common objective for using QSTS analysis is to capture the time-dependent effects and controller actions on a feeder. QSTS analysis can be used to perform various types of studies on a feeder, such as studying the impact of DERs or control schemes on the voltage quality [2]–[12], [18], [20]–[22]. The sequential time-series simulation can determine the range of voltage magnitude as well as the duration of any voltage violations on the circuit. QSTS simulation is also used to study the operation of voltage regulating devices [2]–[5], [8], [10], [11], [13], [18] caused by large power flow fluctuation that certain DER creates. Other types of studies performed with QSTS analysis includes: equipment loading assessment [15], [19], system losses [4], [11], [14], [17], [19], [21], [23], or power flow direction [2].

The time-step resolution and time horizon of the QSTS analysis varies based on the type of study performed and the DER studied. The need of high resolution (seconds) to study the impact of PV systems based on its highly variable nature is described in [8]. On the other hand, wind, EVs, and ESS impact studies have a minutes-to-hour resolution due to the slower variation in power injection of wind farms and periodic charging schedule of storage. In addition, 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 [9]. The type of study is also a factor in the time-step resolution used for QSTS. [11] discusses a general recommendation of hourly resolution for energy impact analyses, minutes for steady-state overvoltage studies, and seconds to minutes for voltage fluctuations. However, the requirements for the time-step resolution and time horizon of QSTS simulations have not been quantitatively studied in the literature. The contributions of this paper include detailed studies to measure the errors caused by QSTS simulation time-step resolution, input data resolution, the simulation time horizon. Recommendations are provided for the QSTS requirements to yield accurate results and adequately capture DER impacts.

III. Test System

The analysis of the QSTS simulation requirements is analyzed on a modified IEEE 13-bus test circuit that incorporates a centralized PV system at the end of the feeder, shown in Figure 1. The circuit has three single-phase voltage regulators at the feeder head, a single-phase capacitor, and a 3-phase capacitor bank. The voltage regulators are modified to provide ±5% regulation and a voltage switching control is added to the 3-phase capacitor. The phase of some loads are changed to slightly balance the feeder, and all loads were increased by 20% to create more extreme conditions. The load time-series is a 5-minute resolution normalized profile based on substation SCADA measurements from a feeder in California in 2013. A large 3-phase latitude-tilt 2MW PV system (~40% penetration of peak load) is added at the end of the feeder. The global horizontal irradiance (GHI) time-series measured at 1-second resolution in Oahu [25] is converted to plane-of-array (POA) irradiance using the DIRINT decomposition model and the Hay/Davies transposition model [26]. The Sandia Array Performance model and Sandia Inverter models are used to convert the POA irradiance into PV power output time-series [27]. The circuit is modeled in OpenDSS and the algorithm is coded in Matlab using the GridPV toolbox to interact with OpenDSS [28]. The time horizon of the simulation is one year at one second resolution.

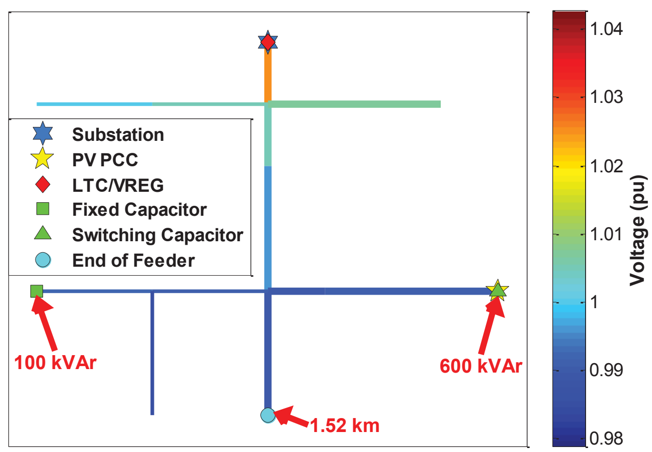

Figure 1. Diagram of the modified IEEE 13-node feeder colored by voltage.

IV. QSTS Requirements

Many motivations and applications for QSTS are discussed in the previous section, but there is very little information available for the requirements and standards for performing QSTS simulations. This paper provides a novel analysis of the QSTS requirements for the input data time-resolution, the simulation time-step resolution, and the length of the simulation. The requirements are application-specific to what is being quantified: voltage regulation device operations (regulators and switching capacitors), power quality analysis, time outside normal operations, and line losses. Each of these applications will serve as the evaluation metrics for calculating the errors of QSTS simulations relative to the yearlong 1-second resolution simulation described in Section III. 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.

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A. Input Data Time-Resolution

QSTS simulations require the availability of historical time series data that is often not easily available at the required time resolution. It is common for utilities to record load data at 15-minute or 1-hour resolution, which may be too low to analyze some distribution system impacts that function on the order of seconds. The most ideal input for PV QSTS simulations is high resolution irradiance data locally measured at the feeder time-coincident to the load data measurements, but there are very few 1-second resolution irradiance data sources. Some previous work has shown that high-resolution data (sampled at <1-minute resolution) is more critical for modelling PV than load in distribution system simulations [29], and that using 1-minute resolution PV data instead of 1-second resolution can result in up to 18% error in the number of voltage regulator tap changes [30]. Here we perform a similar study for the errors introduced by using lower resolution input data in QSTS simulations on the test feeder. The 1-second irradiance data is averaged over the larger sample periods to represent a standard datalogger and then the QSTS resamples it back to the 1-second time-step resolution with linear interpolation.

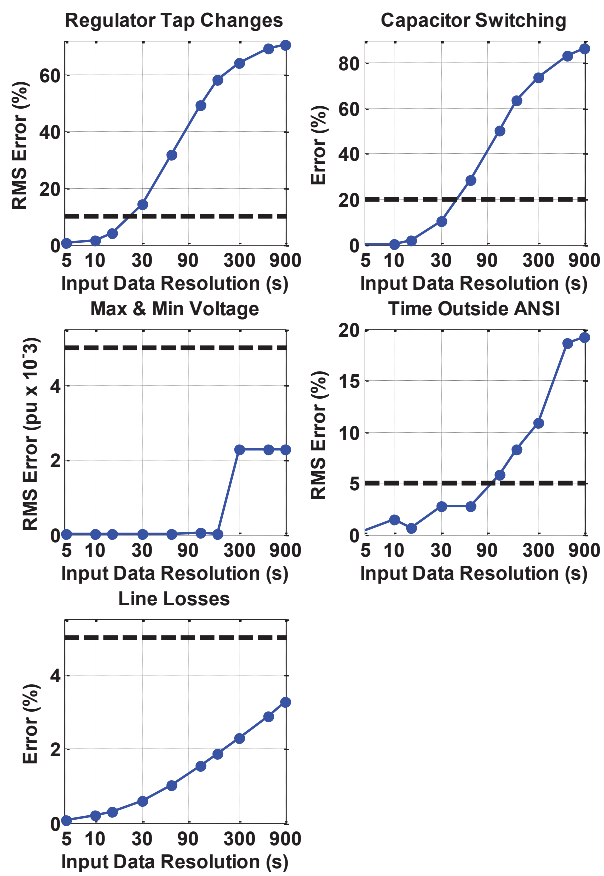

Figure 2. Errors in a yearlong QSTS simulation by using input data at lower resolution than 1-second.

Figure 2 shows the errors for using lower resolution PV irradiance input data. The root-mean squared (RMS) error of the number of tap changes for the three regulators is shown in the top left. The maximum and minimum voltages that occur anywhere on the feeder at any time of the year are shown in the middle left plot. The middle right plot is the RMS error of both the time below and time above the ANSI C84.1 allowable voltage ranges. The error for the yearly number of capacitor switches and total line losses are also shown. For each evaluation metric, the acceptable error threshold is shown with the dashed black line.

B. Simulation Time-Step Resolution

Voltage regulation equipment includes a controller action delay (typically around 30-seconds) where the voltage must remain out of a specified band during the delay period before regulation equipment will initiate an action. This delay function keeps the voltage regulation equipment from reacting to voltage transients. To capture the response of typical distribution equipment, QSTS simulations should have time steps of 1–60 seconds to simulate times when the voltage came back in band during the delay to reset the counter [9]. For any time step longer than the delay, the QSTS simulation will not take the control action until the next power flow is solved and the controller delay has expired. If the simulation time is long, the state of the system is less likely to still be out of band when the system is next solved, so the number of operations decreases as the time step lengths are increased. In [8], it is recommended that the simulation time step should be shorter than the shortest time variable in the system (e.g. 30-second time step if the time delays are 30-second).

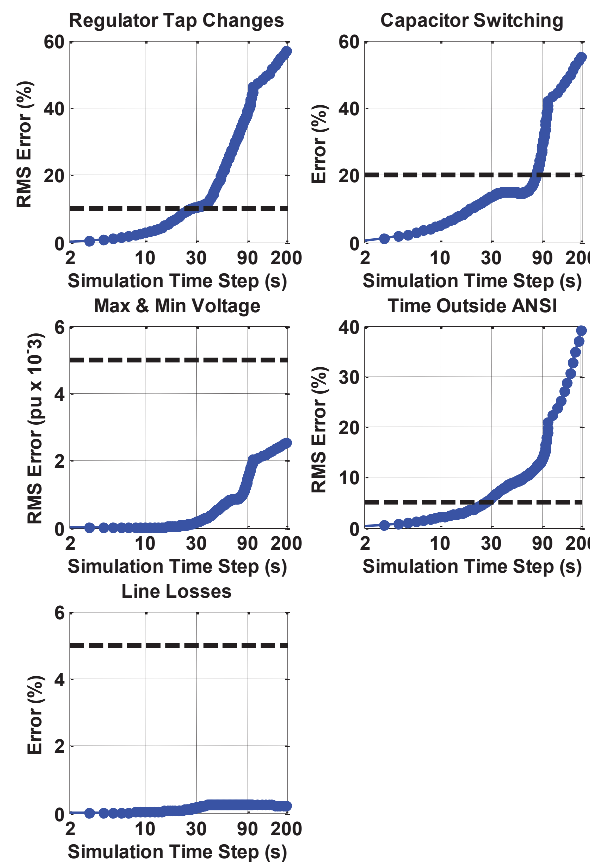

Figure 3. Errors introduced by performing a yearlong QSTS simulation at time step resolutions greater than 1-second.

The requirements for QSTS time-step are studied quantitatively in this paper by performing a yearlong QSTS of the test feeder at various time steps, and the errors for time-steps longer than 1-second are shown in Figure 3. The results demonstrate that high-resolution QSTS simulations are not required to estimate the line losses or extreme voltages, but voltage regulation equipment operations have a noticeable error at time-steps greater than 5-second resolution and significant error at greater than 20-second time steps.

C. Length of Simulation

Distribution system analysis depends on the system load and other input data, all of which are heavily seasonally dependent. In [8], distributed PV was shown to reduce the number of voltage regulator tap changes some times of year and increase it during others. In order to capture the seasonally variations, an extended yearlong QSTS simulation is often required. The necessary length of time for a QSTS simulation is studied in this paper by performing 1-second resolution QSTS simulations of the test feeder for a subset of the number of days in the year. To study possible different sampling methods, a Monte Carlo analysis was performed with a random sampling of the 365 days of the year. The Monte Carlo analysis is performed 100,000 times for each number of sampled days to create a distribution of error, which is shown in the box plots in Figure 4. The resulting range of errors demonstrate that there may be some promising methods to select the best days of the year and be at the bottom of error bars, but the median value (black dot) is generally consistently high for only doing a simulation for part of the year. Figure 4 also shows that time the feeder will be outside the allowable ANSI voltage range during the year cannot be estimated by only solving part of the year.

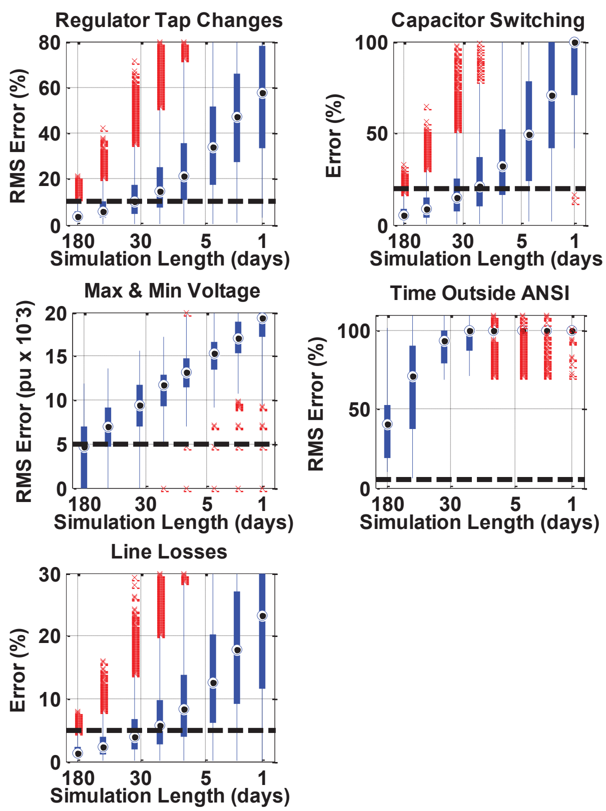

Figure 4. Errors in estimating a yearlong QSTS simulation when only solving a subset of the days.

V. Discussion

In general, it is more important to do longer simulations than higher resolution simulations if limited by computational power. This is especially true for estimating worst case voltages and time outside of ANSI. To demonstrate this, Figure 5 shows the previous error graphs plotted on the same axis of percent reduction in computational time. For example, a 2-second yearlong simulation (half of the computational time) has 0% error for time outside ANSI, while a 1-second time-step simulation of half the days in the year has a 40% error.

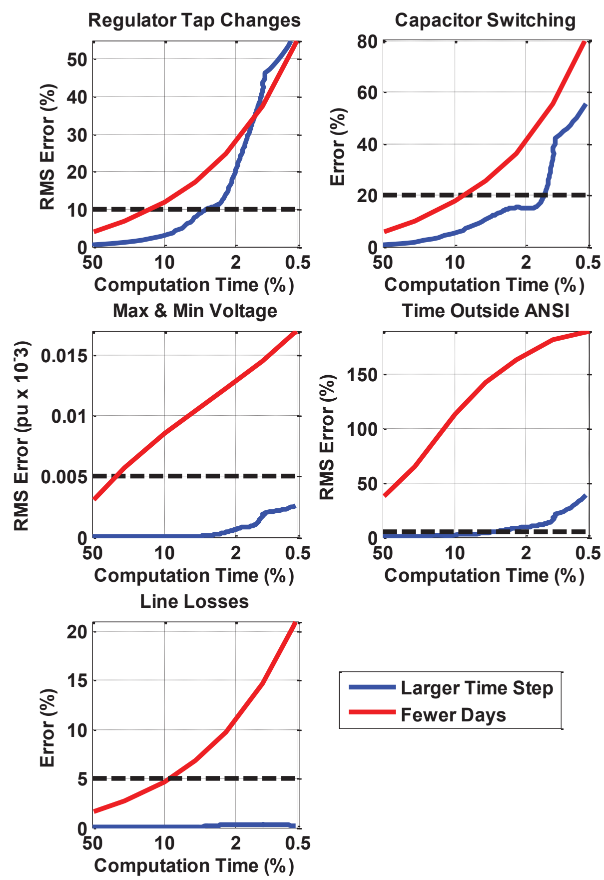

Figure 5. Comparison of error introduced by doing either larger time-steps or fewer days (mean error) than a yearlong 1-second resolution QSTS simulation.

Using the established acceptable error thresholds, Table I shows the minimum requirements for QSTS simulation time-step and length of time for each QSTS analysis type. These error results and QSTS requirements can vary depending on the distribution system configuration, input time-series data, voltage regulation controls, error thresholds, and other system parameters. Thus, Table I should be viewed as rough minimum requirements for having acceptable error for each analysis. On the other hand, based on the simulation results, Table II shows the requirements for accurate high-resolution QSTS simulations with minimal error in each analysis metric. For this analysis, performing higher-resolution or longer simulations than Table II will not provide additional accuracy benefit.

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TABLE I. QSTS REQUIREMENTS FOR SIMULATION TIME-STEP AND LENGTH OF TIME TO BE WITHIN AN ACCEPTABLE ERROR WITHIN THE THRESHOLDS

Analysis Metric	Required Time-Step (sec)	Required Length of Time (% of year)
Voltage Regulation Equipment Operations	≤20-second	≥20%
Extreme Max / Min Voltages	~15-minute	≥50%
Time outside ANSI	≤30-second	≥90%
Line Losses	~60-minute	≥10%

TABLE II. QSTS REQUIREMENTS FOR SIMULATION TIME-STEP AND LENGTH OF TIME TO HAVE MINIMAL ERROR

Analysis Metric	Required Time-Step (sec)	Required Length of Time (% of year)
Voltage Regulation Equipment Operations	≤5-second	≥50%
Extreme Max / Min Voltages	≤1-minute	≥90%
Time outside ANSI	≤5-second	100%
Line Losses	≤5-minute	≥80%

VI. CONCLUSIONS

Yearlong high-resolution QSTS analysis is required to adequately model DER impacts on the distribution system. The total line losses for the year can be fairly well estimated using shorter low-resolution simulations. However, shortening the simulation to even half of the year can result in extremely high errors for estimating the worst case voltage magnitudes and hours the feeder will be outside the ANSI voltage range during the year. The interactions and number of actions taken by voltage regulation equipment can be modeled with QSTS simulations with a time-step resolution up to 5-seconds, but time-step resolution of 20-seconds or greater begin to demonstrate large errors. In order to be able to capture all distribution system analysis metrics together accurately, a time-step resolution less than 5-seconds and a time horizon of an entire year is recommended.

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