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Predetermined Time-Step Solver for Rapid Quasi-Static Time Series (QSTS) of Distribution Systems

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***Abstract* — Distribution system analysis with high penetrations of distributed energy resources (DER) requires quasi-static time-series (QSTS) analysis to capture the time-varying and time-dependent aspects of the system, but current QSTS algorithms are prohibitively burdensome and computationally intensive. This paper proposes a novel deviation-based algorithm to calculate the critical time periods when QSTS simulations should be solved at higher or lower time-resolution. This predetermined time-step (PT) solver is a new method of performing variable time-step simulations based solely on the input data. The PT solver demonstrates high accuracy while performing the simulation up to 20 times faster.**

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

I. INTRODUCTION

Distribution system analysis using steady-state power flow simulations, harmonic analysis, and system protection studies has traditionally been sufficient for distribution system engineers to design feeder layouts, plan expansions, consider upgrades, and determine the distribution system control settings. However, emerging 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. Traditional snapshot tools and methods may not be adequate to accurately analyze the fast variability and complex interactions of high levels of distributed energy resources (DER) being interconnected, and snapshot study methods that only analyze peak periods or a peak variability day often lead to over-estimation of normal operating issues. Transactive energy system and other control strategies for grid edge devices will require time-series analysis to full understand their capabilities.

Quasi-static time-series (QSTS) simulation is a versatile study method used to understand equipment control operation, power protection coordination, and voltage regulation and reactive power management for different DER, including solar PV [1-4], wind [5], electrical vehicles [6], and ESS [7]. 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, so each power flow solution is dependent on 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.

There is a great need for fast accurate tools and methods to study the penetration of DER on the distribution system and determine grid impacts and mitigation solutions. 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. In order to coordinate integration of renewables, grid edge devices, and new distribution management systems (DMS), time-series analysis will be required.

To fully simulate the interaction between devices and controls, QSTS simulations are often performed at high time resolutions with time steps less than 10 seconds. 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 [8] [9]. In [10], 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. The speed of the simulation tools and algorithms is matching the high rate of interconnections and high penetrations of distributed and renewable resources. New 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 quasi-static time-series (QSTS) simulation to make this method viable for both DER distribution impact studies and operational decision making.

In this paper, we propose a predetermined time-step (PT) solver for rapid QSTS simulations of distribution systems. The paper is organized as follows. Previous work on QSTS analysis and improving the speed is discussed in Section II. Section III describes the test feeder for this work. The PT solver algorithm and description is given in Section IV, and the results for accuracy and speed of the PT solver are in Section V. Discussions, recommendations, and conclusions based on the simulation results are presented in Section VI and VII.

II. BACKGROUND

A one-year QSTS simulation at one-second time-step represents 31.5 million chronological power flows. The computational burden of this limits the adoption of QSTS and the user's capability to rapidly simulate different devices or control strategies. There has been extremely little research investigating ideas for improving the speed of QSTS analysis. In [11], some circuit reduction methods were presented to use a simpler equivalent circuit in QSTS. This method reduced the computational time for each power flow solution and the overall QSTS time by 98%, but the same number of power flows had to be solved. Similarly, A-Diakoptics methodology for multicore power flow simulation was presented in [12] to divide large distribution grids into subnetworks and solve each in parallel. Parallelizing the power flow solution reduced the computational time with minimal error. In [13], non-uniform vector quantization of load profiles, PV profiles and slack voltage profile was investigated to shortened time-series power flow simulation, with a simple circuit demonstrating time savings between 50%-70%. Similarly, clustering of load and production profiles was proposed in [14] to reduce the number of load flow calculations.

The previous QSTS work has focused on reducing the computational time of solving power flows or grouping time periods together. The predetermined time-step (PT) solver proposed in this paper is a novel approach to improve the speed of distribution system analysis by solving fewer power flows. The PT solver is a variable time-step algorithm that decreases the computational time by focusing the computational effort during periods of the year when the system is rapidly changing.

Variable time-step algorithms have been commonly employed in power systems applications for dynamic [15] and transient analysis [16] and analysis of power electronic switching [17], but this paper presents a new application to extended time-series simulations. The proposed PT solver is a novel algorithm for QSTS simulation, specifically for 3-phase unbalanced power flow analysis of the distribution system. The proposed PT solver is also unique compared to most variable time-step solvers because it is not dependent on the simulation results or the accuracy of the solution convergence.

III. Test System

The QSTS simulation is 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, one 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 some 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 is converted to plane-of-array (POA) irradiance using the DIRINT decomposition model and the Hay/Davies transposition model [18]. The Sandia Array Performance model and Sandia Inverter models are used to convert the POA irradiance into PV power output time-series [19]. The circuit is modeled in OpenDSS and the algorithm is coded in MATLAB using the GridPV toolbox to interact with OpenDSS [20]. The simulation is a year at one-second resolution.

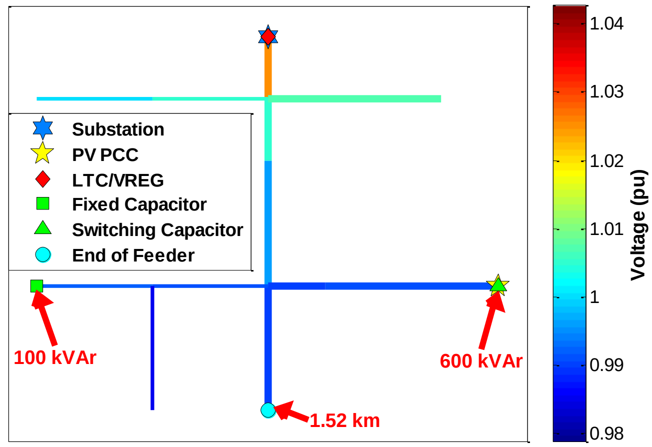

Figure 1. Diagram of the modified IEEE 13-node feeder colored by voltage.

IV. Predetermined Time-Step (PT) Solver

The novel predetermined time-step (PT) solver algorithm proposed in this paper improves distribution system analysis by focusing the computational effort during periods of the year when the system is rapidly changing. During fixed time-step QSTS analysis, the power flow solution can be very similar (if not the exact same) for many time-steps in a row. For example, at night the load is fairly low and constant, so from one second to the next, little has changed. This is the motivation for the proposed PT solver that treats the time-step as a variable that is continually changing based on the variability of the distribution system. During steady-state periods, the solver can jump forward in time, skipping the unvarying smooth periods, and during highly variable times the resolution can get down to 1-second time-step. The simulation time-step is essentially the derivative of the system inputs.

The algorithm is implemented using a deviation threshold that is applied to the input time-series data. For example, the predetermined time-step solver jumps ahead until the load has changed at least 10 kW from the previously solved time-step. The deviation threshold is a variable that can be adjusted to include more or less power flow solutions for a given kW change in the input time-series data. The deviation threshold easily allows for times when the load is quickly changing to be solved at higher resolution. The deviation threshold is the first variable in the solver.

The algorithm also includes a component to limit the maximum step size. Even during periods when very little is happening and everything is within the deviation threshold, the solver will max out to not skip ahead more than a certain at a time. The maximum allowable time-step is important to still maintain some information of what is happening in the system during the constant periods. The max time-step is the second variable in the solver.

The predetermined time-step solver is illustrated in Figure 2 with the deviation threshold and max time-step highlighted. The red points and red dashed lines represent the moments in time when the power flow is solved. Note the increasing number of power flow simulations that occur during the variable periods that is very beneficial for improving accuracy of the method.

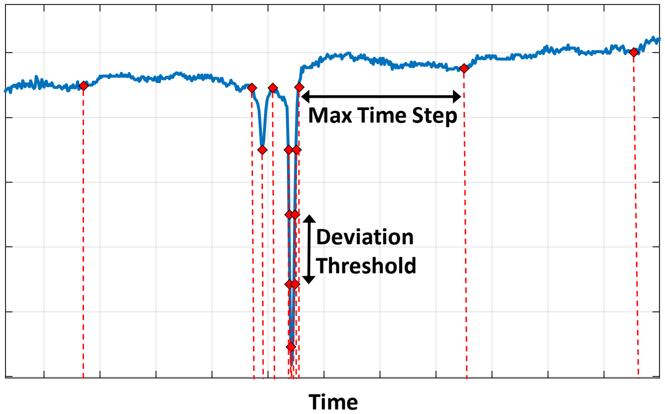

Figure 2. Predetermined time (PT) step solver.

One unique aspect of the proposed PT solver compared to algorithms in other fields is that the length of the time-step is solely dependent on the input variables. Variable time-step solvers commonly use the simulation results to modify the time resolution if the change in the output has exceeded a specific threshold. The proposed PT solver is not sensitive to voltage changes, regulator or capacitors switching states, or any simulation results. This has the advantage that the time-step lengths can be predetermined. There is no computational slow down to interact with the outputs from the power flow simulation. Some other variable time-step solvers can also reverse time to backtrack to perform higher time-resolution simulations depending on the output. While these types of algorithms can be more accurate, they also require additional power flow simulations, interactions between the solver and time-step control, and real-time calculations of sensitivities.

V. Simulation Results

A. Evaluation Criteria

The purpose of the predetermined time-step 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), power quality analysis, time outside normal operations, and line losses. Each of these will serve as the evaluation metrics for calculating the errors of the PT solver relative to the yearlong 1-second resolution QSTS 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.

B. Comparison of Simulation Speed vs. Error

By applying different thresholds for the deviation and maximum time-step, many different PT solver solutions can be created. Figure 3 shows over 100 different combinations of the predetermined time-step that all perform within the established error thresholds for each evaluation metric. In Figure 3, 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 bottom plots are 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.

The results demonstrate how the error generally increases as the speed of the PT solver increases. By moving faster though time, some critical events begin to be missed. Some evaluation criteria very easily fall within the allowable error thresholds (e.g. voltage, line loss, and time outside ANSI), while other criteria (e.g. regulator and capacitor switching) are much harder to accurately simulate. Figure 3 demonstrates that a 90% reduction can easily be achieved with the PT solver.

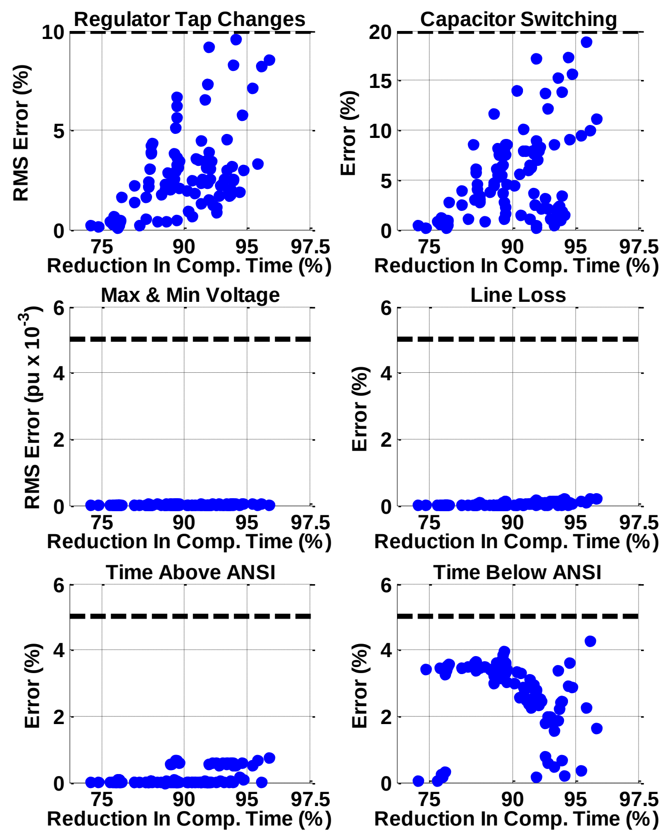

Figure 3. PT solver simulation results.

C. Tuning the PT Solver

While Figure 3 shows the correlations between error and computational time, each dot represents a specific combination of the PT solver variables of deviation threshold and maximum time-step. In order to visualize the correlations between the deviation threshold and maximum time-step, Figure 5 shows the level of error for each combination of settings. The color scale is set such that any error above the allowed thresholds is dark red. The bottom right plot in Figure 5 also shows the reduction in computational time for each combination. As the predetermined time-step simulation gets faster, there is trend towards higher levels of error. Also note that a maximum time-step greater than 20-seconds generally has significant error. There are some points like 100 kW deviation and 5-minute max step that are outside the allowable error and are not represented in Figure 3 for this reason.

Given the range of possible PT solver algorithms and settings, the best solutions from Figure 5 can be found with the Pareto front for the regulator RMS error as shown in Figure 4. These 8 solutions with different combinations of deviation threshold and maximum time-step represent the most optimal results (based on regulator RMS error). Along the Pareto front there is a tradeoff for selecting the higher speed or higher accuracy optimal solution. The 8 PT solvers along the Pareto front are shown in Table I 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.

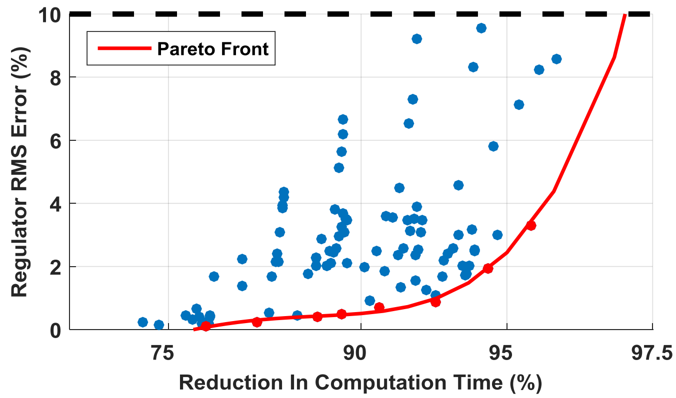

Figure 4. Pareto front for the most optimal PT solver solutions.

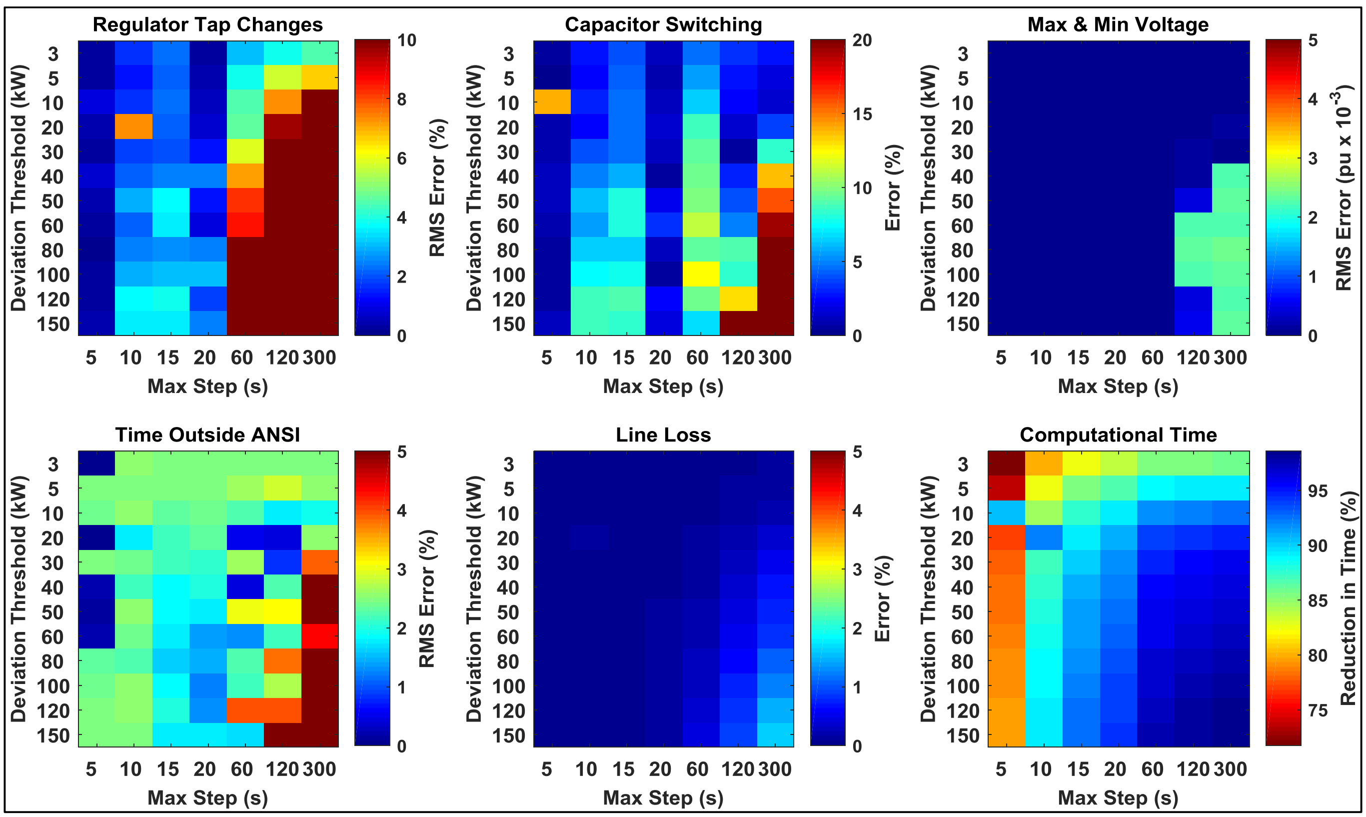

Figure 5. Simulation error and computational time for the PT solver variables of deviation threshold and maximum time-step

TABLE I. ERROR AND PERCENT REDUCTION FOR THE MOST OPTIMIAL PT SOLVERS ALONG THE PARETO FRONT

Deviation Threshold (kW)	Max Time Step (s)	Tap Changes Per Regulator	Capacitor Switches	Max Voltage	Min Voltage	Hours Above ANSI	Hours Below ANSI	Total Line Losses	Percent Reduction
Base Case		7048,7222,8449	2504	1.0607pu	0.9673pu	22.1h	11.5h	146.0 MWh	
90	5	0.1%,0.1%,-0.2%	0.6%	-0.0000pu	0.0000pu	-0.1%	3.3%	-0.04%	79.1%
3	20	-0.0%,0.2%,-0.4%	1.0%	-0.0000pu	0.0000pu	0.0%	3.5%	-0.03%	83.6%
5	30	0.2%,0.7%,0.0%	11.7%	-0.0000pu	0.0001pu	0.0%	3.4%	0.01%	87.7%
10	20	-0.2%,-0.2%,-0.8%	1.1%	-0.0000pu	0.0000pu	0.0%	3.4%	-0.03%	89.0%
20	20	-0.6%,-0.5%,-0.9%	1.4%	-0.0000pu	-0.0000pu	0.0%	3.3%	-0.04%	90.8%
60	20	-0.2%,-0.1%,-1.5%	3.2%	-0.0000pu	0.0000pu	-0.6%	1.8%	-0.11%	93.0%
40	40	-1.6%,-1.4%,-2.6%	17.4%	-0.0000pu	-0.0000pu	-0.2%	2.9%	-0.03%	94.5%
60	45	-3.2%,-2.7%,-3.9%	18.8%	-0.0000pu	0.0000pu	-0.7%	2.2%	-0.11%	95.5%

VI. DISCUSSION

The proposed PT solver was demonstrated using a single deviation threshold applied to all input time-series data. Due to the location of the injection, a kW deviation in load may not have the same system impact as a kW deviation in PV. The system sensitivity to each input time-series profile is based on the magnitude of the injection, distance to the substation, voltage level, and many other things. Because of this diversity, the optimal deviation threshold may vary for each input profile individually. Future work will investigate methods to determine the appropriate individual deviation thresholds using voltage sensitivities and effects on regulation equipment. In Figure 6, we demonstrate kW deviation thresholds applied separately to the system load and PV power time-series profiles. A load deviation threshold above 4 kW starts to introduce significant error in the number of regulator tap changes during the year, but there are no error problems with PV output deviations three times that size as long as the load deviation threshold stays small. As mentioned previously, the sensitivity of a kW change is dependent on many things. Additionally, the PV system is only injecting power during daylight hours, so higher resolution deviation thresholds on the load are required.

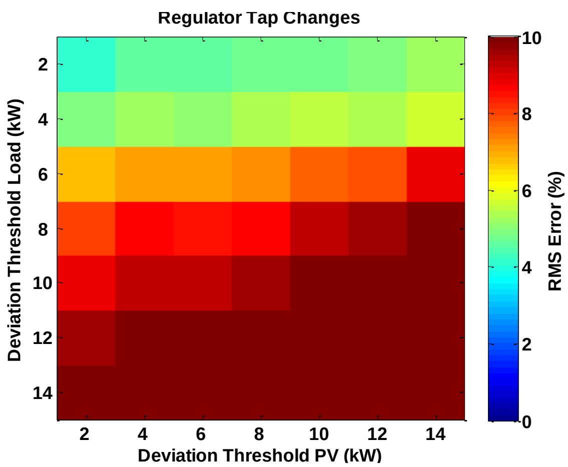

Figure 6. Regulator tap changes root-mean-squared (RMS) error for a yearlong QSTS simulation with the PT solver and a max step of 300 seconds.

VII. CONCLUSIONS

Yearlong high-resolution QSTS analysis is required to adequately model DER impacts on the distribution system, but currently QSTS simulations are too computational burdensome to be widely applied. There is very little research on methods to improve the computational speed of QSTS. This paper proposed a novel rapid QSTS algorithm to reduce the computational time of a yearlong distribution system analysis using a predetermined time-step solver. The PT solver is based solely on the input data profiles and does not require any interaction with the power flow engine. Results for a yearlong QSTS simulation with the PT solver demonstrate up to a 95% reduction in computational time compared to the base case simulation. The PT solver is validated against the base case and is shown to be highly accurate for all evaluation metrics. The proposed algorithm is easy to apply, and work is ongoing to make QSTS more accessible through implementing the PT solver into open-source and commercial tools.

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