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A Fast Quasi-Static Time Series (QSTS) Simulation Method for PV Impact Studies Using Voltage Sensitivities of Controllable Elements

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***Abstract* — Yearlong quasi-static time series (QSTS) simulations at second-level granularity are required to accurately model controller devices and determine the impact of PV resources on distribution systems. However, the computational time for running such simulations takes 10 to 120 hours for a realistic-sized distribution feeder. This long simulation time is preventing widespread adoption of QSTS simulation for PV impact studies and more generally impact studies needed for all types of distributed energy resources (DERs). This paper proposes a fast QSTS simulation approach by substantially reducing the number of power flow solutions used during the simulation. The proposed method uses voltage sensitivities to model the control logic and behavior of system regulators and capacitors, accurately predicting the control actions of system controllers without having to solve all the power flows through time. The effectiveness and efficiency of the proposed method is demonstrated on the IEEE 13-bus test case with 100 times faster computational time.**

***Index Terms* — power system simulation, smart grid, power system planning, photovoltaic systems.**

I. Introduction

Scenario-based simulation is an approximate approach that has been used in the industry to evaluate the PV integration impacts on distribution circuits. In this method, a few scenarios representing worst-case conditions during a year, are explored through independent power flow analyses. However, scenario-based simulations cannot capture the complex behavior of voltage controllers with thresholds and time delays. Capturing this behavior is critical with variable PV production to determine for instance the number of tap changing actions during a year [1].

The state-of-the-art method to evaluate the impact of new distributed resources such as PV systems is quasi-static time series (QSTS) simulation analysis. QSTS simulation takes the time series load and PV temporal profiles as inputs and solves power flow chronologically. Each solution, uses the previous power flow results and takes into account time delays and thresholds of all the control devices [2]-[3].

According to [4], yearlong high-resolution QSTS simulations are required to analyze the impact of PV integrations for seasonal trends and the highly variable PV outputs. This volatile energy output may cause system voltage violations and potential regulator and capacitor status oscillations. Moreover, these voltage violations and system controllable element actions may occur in a few seconds and cannot be identified without higher granularity QSTS simulation. In order to capture these control actions and potential controller oscillations, a 5-second or higher time resolution QSTS simulation is required. According to [5], a yearlong high- resolution QSTS simulation can take between 10 to 120 hours to run for realistic feeders. Fast QSTS simulations is necessary to ensure distribution system reliability and safety in the face of numerous distributed resources and controllable elements. Therefore, enhanced QSTS approaches that can maintain high accuracy and reduce computational time are highly needed.

This paper describes a voltage sensitivity-based model that can drastically increase the speed of QSTS simulations. The model also provides new insight into the operation of controllable devices in distribution systems. There are many challenges [6] in reducing the computational time of QSTS simulation, including:

a) Presence of multiple valid power flow solutions,
b) Interaction of controllable elements interactions, and
c) Time dependency of the time-series simulation.

In the "brute force" QSTS simulation, the full AC 3-phase unbalanced power flow is solved in chronological order. Using the proposed model with an event-based simulation, we can safely skip the process of solving power flows for many time-points, without missing any controller transition event. The increased in speed is expected to make QSTS simulation a practical approach for high-fidelity PV and DER hosting capacity analysis. In addition, the proposed method provides new insight that will help researchers to understand the state transition process of power system distribution networks due to discrete controller actions.

The remainder of this paper is structured as follows: Section II discusses the sensitivity-based model of distribution system controllable elements including regulators and capacitors. Section III introduces a solution to estimate power system state transitions using the sensitivity-based model and geometric analysis. Section IV provides an iterative method for the sensitivity-based model parameter estimation and proposes a detailed implementation of the fast QSTS simulation approach. Section V tests the proposed method on a test case distribution system with realistic load and PV measurements. Section VI concludes the paper and discusses the potential applications of the proposed sensitivity-based model and fast QSTS simulation method.

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II. A Discrete Sensitivity-Based State-Transition Model of Controllable Elements

A. Bus Voltage Sensitivity Linear Approximation

In this section, we introduce a sensitivity-based state-transition model (sensitivity model) for controllable elements on a distribution feeder. The sensitivity model is based on the linear approximation between bus voltage and power injections from load or PV. The model explains various distribution system transition behaviors and can be used for speeding up QSTS simulations.

The control logic of most system controllable elements, such as regulators and capacitors, depends on the system bus voltage. Due to the nonlinear physical property of the distribution network, bus voltages are not strictly linearly-correlated with system loads. However, in most distribution systems and for small changes in the load, we can assume a linear approximation. This linearized assumption is further supported by reference [7], where the authors mathematically derive a tight upper error bound of the linearization assumption.

B. Sensitivity-Based Model for System Regulators

A regulator aims at maintaining the bus voltages within a specific band. Let $V_{regCtrl}$ denote the input control voltage of a regulator. The regulator control keeps $V_{regCtrl}$ within a voltage band (V_{regMin}, V_{regMax}) by changing the tap position. When $V_{regCtrl}$ moves above V_{regMax}, the regulator control will trigger a tap switch event to move the tap to a lower position; similarly, when $V_{regCtrl}$ drops lower than V_{regMin}, regulator will trigger a tap switch event to move the tap to the adjacent higher position. In other words, when $V_{regCtrl}$ moves outside the voltage band, the regulator control will keep adjusting tap position until the $V_{regCtrl}$ falls back in the band, unless the tap is already at extreme positions.

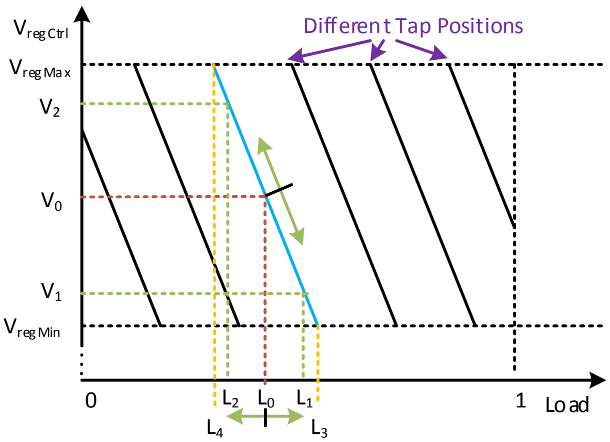

Fig. 1. Regulator control input voltage vs. system load.

Since $V_{regCtrl}$ increases as the system load increases and decreases as the system load decreases, we introduce a graphical representation of the regulator control, as shown in Fig. 1. When the load increases from L_0 to L_1, $V_{regCtrl}$ will drop from V_0 to V_1, similarly, when the load decreases from L_0 to L_2, $V_{regCtrl}$ will increase from V_0 to V_2. As long as the load remains within L_3 and L_4, no tap event will be triggered. However, when the system load moves beyond the L_3 and L_4, $V_{regCtrl}$ will moves outside the voltage band (V_{regMin}, V_{regMax}) and triggers a tap action. The regulator tap will move to the adjacent tap position, which corresponds to the adjacent lines in the graphical model.

Let us now also incorporate the PV output profile for PV interconnection studies. The PV production can move much faster compared to the load and can have a larger impact. The PV output profile can be modeled as a fast-varying negative load. In the proposed sensitivity-based model, we add one more dimension of PV output onto the single load profile plot and form a multiple-plane-shaped model as shown in Fig. 2.

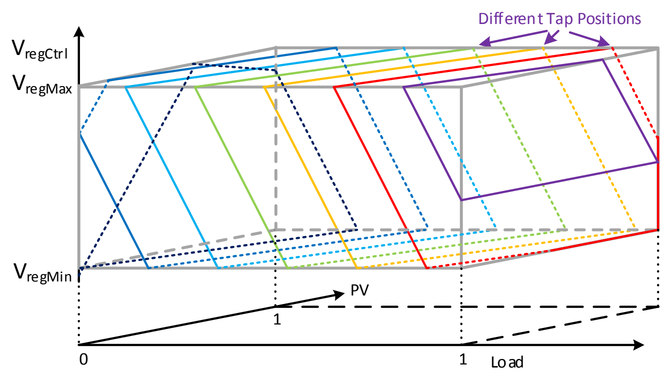

Fig. 2. Multiple-plane model for different regulator tap positions.

In addition to the abovementioned graphic model, the discrete linear model for a regulator with n load profiles can be mathematically presented as equation (1).

$$V_{regCtrl,i} = \boldsymbol{\beta}_i \boldsymbol{U} \qquad i = 1,2,\ldots,m \tag{1}$$

where $V_{regCtrl,i}$ stands for the regulator control input voltage at tap position i; m stands for the total number of tap positions; $\boldsymbol{U}$ is a $(n+1)\times 1$ vector consists of all input load profiles. For example, in Fig. 1, $\boldsymbol{U}^T = [load, 1]$; similarly, in Fig. 2, $\boldsymbol{U}^T = [load, PV, 1]$. $\boldsymbol{\beta}_i$ is a $1\times(n+1)$ vector stands for the coefficients of the linear model.

We can easily apply the model to systems with 3 or more load profiles. In those cases, the sensitivity-based model can be represented by a hyper plane. As long as the linear voltage sensitivity assumption holds, the proposed method does not have limitation on the number of load profiles. This property is very appealing, because it allows for multiple PV output profiles in the system and new load measurements, such as smart meter data can be incorporated into the QSTS simulation.

C. Linear Model for Capacitors

Similar to a regulator, a common voltage controlled capacitor maintains the system bus voltages by switching the capacitor banks on and off based on the regulated bus voltage. When the capacitor is on and the voltage rises above the switch-off threshold V_{capOff}, the capacitor will switch off; when the capacitor is off and the voltage falls below the switch-on threshold V_{capOn}, the capacitor will switch on.

Similar sensitivity-based model applies to capacitors, as shown in Fig. 3. The red plane represents the operational plane when the capacitor is off, and the blue plane the capacitor is on. The decision boundary for the capacitor to switch on can be derived by the intersection of the plane $ABCD$ and V_{capOn}. Similarly, the other decision boundary for the capacitor to switch off can be derived by the intersection of the plane $EFGH$ and V_{capOff}.

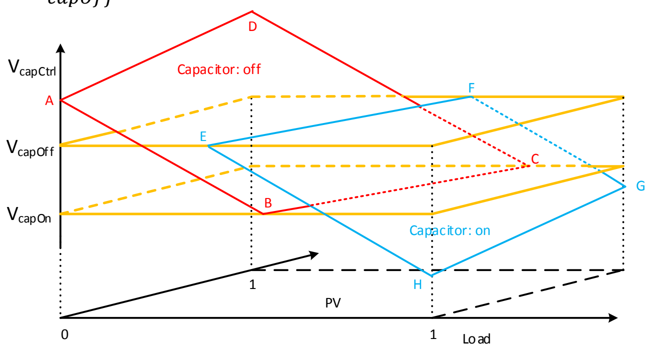

Fig. 3. Capacitor control input voltage vs. load and PV output.

III. System State Transition Estimation Using the Sensitivity-based Model

One of the most important reasons for conducting yearlong high time resolution QSTS simulation is estimating the interactions between the existing system controllable elements and the renewable energy resources. Moreover, if the state of the system controllable elements is given, the relationship between system bus voltage and load becomes a continuous function and is much easier to extrapolate. This section, we show how to predict system controller state transitions without relying on solving power flows, after establishing the proposed model.

A. Use of Sensitivity-based Model to Predict Transitions

According to the proposed sensitivity-based model, for a given regulator tap position, the correlation between $V_{regCtrl}$ and individual power injection (in this case load and PV variables) can be represented as a linearized plane as shown in Fig. 4. Line AB corresponds to $V_{regCtrl} = V_{regMin}$ and line DC corresponds to $V_{regCtrl} = V_{regMax}$. If we project the blue plane $ABCD$ down to the load-PV space, we get a red parallelogram $A'B'C'D'$. $A'B'C'D'$ is also the decision boundary of the current regulator tap position. For example, if the load and PV input combination moves to the right of the red parallelogram, then we have $V_{regCtrl} < V_{regMin}$, which will cause a regulator tap switch-up action. Similarly, if the load and PV combination moves to the left of the red parallelogram, a regulator tap switch-down action will be triggered. In other words, if we get the decision boundary of a tap position on the load-PV plane, we no longer need to solve $V_{regCtrl}$ to predict tap switch actions. Instead, we only need to check whether the load and PV input locates within the decision boundary.

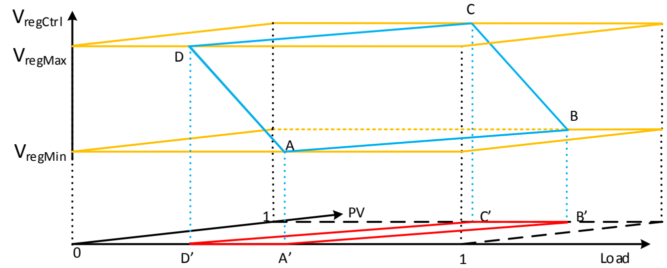

Fig. 4. Decision boundary for a given regulator tap position.

As shown in Fig. 2, multiple tap positions of a regulator can be represented as multiple planes. Projecting these planes down to the load-PV space will produce a series of overlapping decision boundaries. Fig. 5 shows two adjacent decision boundaries: $A'B'C'D'$ and $E'F'G'H'$. To further illustrate how to use decision boundaries to predict system events, let us assume the load and PV inputs follow the trajectory *a-b-c-d-e* through time as shown in Figure 5. The load and PV input starts at point a with the regulator tap on the red position. The regulator stays stationary (likely for hundreds or thousands of seconds) until the load and PV inputs move to point b, when the $V_{regCtrl}$ equals to V_{regMin}. Since the load continues to increase after point b, $V_{regCtrl}$ becomes smaller than V_{regMin}. A tap switch action is triggered, which boosts $V_{regCtrl}$ to be above V_{regMin}, and the system now operates on the adjacent green plane. Similarly, when the load moves from c to e, $V_{regCtrl}$ becomes greater than V_{regMax} after point d. This will trigger a tap switch action at point d, and the system jumps from the green plane back on the red plane. In this example, should we know the decision boundary $E'F'$ and $D'C'$, we can predict the system transitions at point b and d without solving time series-power flows for voltages through the entire trajectory.

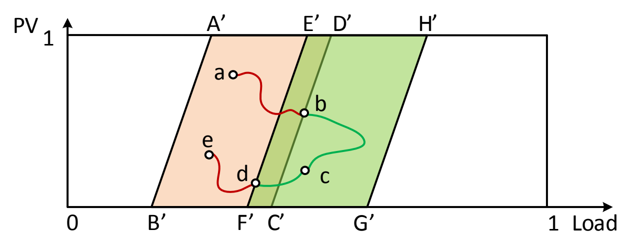

Fig. 5. Predict regulator actions through decision boundaries.

B. Multiple-Controller Model

In most distribution systems, multiple system controllable elements are presented. The proposed model also applies to systems with multiple regulators and capacitors. Due to the correlation among different controllers, any action of a controller will have impacts on all other controllers. Thus, we need to update the plane model for each controller whenever a controller takes action and changes the system state.

Let us consider an example of a distribution network with three regulators and one capacitor. We first build up the sensitivity-based models for each of the controllers. Then, we combine the decision boundaries of all controllers as shown in Fig. 6. The final decision boundary for the system state is the cut or common area of all decision boundaries, shown as the black dashed lines. If the combination of load and PV moves out of the black decision boundary, a system controller action will be triggered, and the system will move to another state with new decision boundaries.

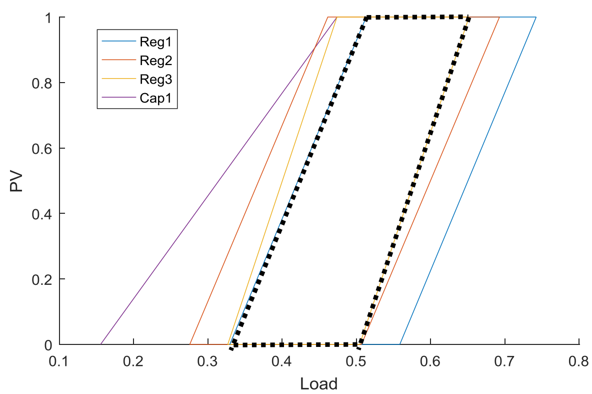

Fig. 6. Decision boundary for multiple system controllers.

IV. Fast QSTS Simulation Using a Sensitivity-based Model

This section discusses the implementation of the proposed sensitivity-based model for fast QSTS simulation, including model parameter estimation.

A. Iterative Method for Model Accuracy

The key for implementing the proposed sensitivity-based model is the estimation of the red decision boundary $A'B'C'D'$ or equivalently the blue plane $ABCD$ shown in Fig. 4. Line AD and line BC are determined by the PV output range (0~1). Line AB and line CD are derived from the regulator settings V_{regMin} and V_{regMax}, which are known. Since the function of the plane $ABCD$ can be found, the decision boundary can also be determined.

In order to uniquely identify a hyper-plane with n-dimensions (n load profiles), we need to solve for $\boldsymbol{\beta}_i$ in equation (1). Mathematically, we only need n points, which is equivalent to solving $n+1$ different power flows under the given system controller state.In practice, bus voltage and system load are not strictly linear-correlated. Hence, to increase the accuracy of the estimated plane, we use $2n$ distinct power flow solutions instead of $n+1$ to estimate the plane. Moreover, an iterative approach is developed to make sure the four power flows are solved close to the edges of the decision boundary. This minimize the error caused by the linearization approximation.

The closer the power flow solutions are to the true decision boundary edges, the more accurate the estimated decision boundary will be. The iterative method keeps updating the $2n$ power flow solutions to make sure the estimated plane is at least accurate at the decision boundary. Fig. 7 shows the flow chart of the iterative method, where a certain iteration number is used as a stopping criteria.

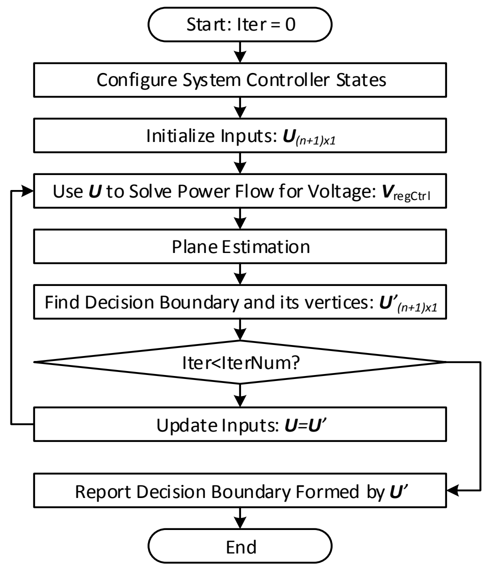

Fig. 7. Decision boundary estimation using the iterative method.

We further illustrate the iterative method in Fig. 8, where we estimate the decision boundary of a regulator using two iterations. In the initial iteration, we pick four points with two random load levels, combined with two PV scenarios, where the outputs are 0 and 1 pu. These points may not be actual states the system will ever experience, but they define the voltage sensitivity plane. After solving the four power flows, we obtain the four points A1, B1, C1, and D1. From these points we derive the equation of the plane. The boundaries of the voltage sensitivity plane are constrained to the decision boundary by calculating A2-B2-C2-D2 using the voltage thresholds of the voltage regulator and the min and max PV levels as discussed earlier. In the second iteration, we use the load and PV values at A2, B2, C2, and D2 to calculate and update the boundary plane. In the second iteration, the updated plane boundary A3-B3-C3-D3 is drawn using the plane estimated by power flow solutions at A2, B2, C2, and D2.

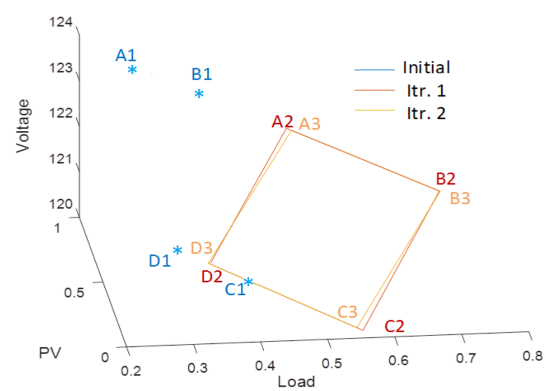

Fig. 8. Graphic illustration of the iterative estimation method.

B. Flow Chart for Fast QSTS Simulation

Finally, we piece the previous building blocks together and provide the whole flow chart of the proposed sensitivity-based model for fast QSTS simulation. As shown in Fig. 9, the method starts with model initialization where the circuit is compiled. We store the computed plane models in a look-up table. Let $SimLength$ stand for the total simulation length. The only building block that requires solving power flow is the green portion of the flow chart, where a system event occurs and the plane model of the new system state has not been solved before. No power flow solve is involved if the simulation stays in the blue block, where no system event occurs or the system state transits to a previously computed plane model.

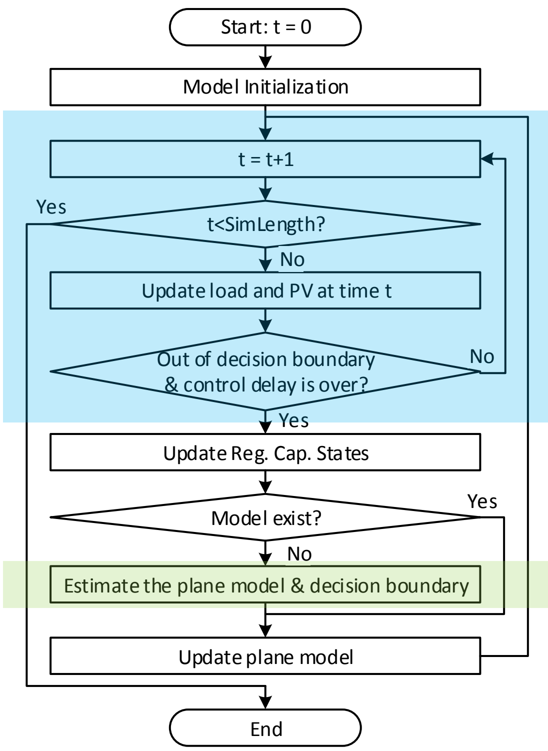

Fig. 9. Flow chart of the proposed fast QSTS simulation method.

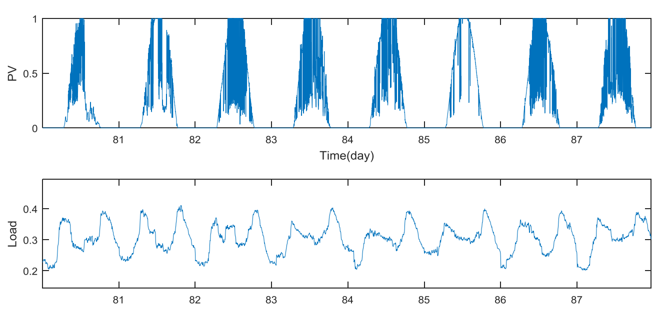

Fig. 10. Sample PV output and load profiles.

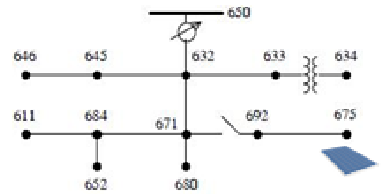

Fig. 11. IEEE 13-bus system with a PV system installed on bus 675.

V. Test Result Analysis

The proposed fast QSTS simulation algorithm is tested on an IEEE 13 bus system for hosting capacity analysis. The tested system has one load time-series profile (measured from the substation SCADA) and one PV profile (1-second measured irradiance). Fig. 10 shows sample load and PV output profiles for 8 days. The test system is a modified IEEE 13-bus system, which has three independent single-phase regulators at the substation and one capacitor at the end of the feeder, where a PV system is installed, as shown in Fig. 11. The PV penetration of the network is set as 40 percent.

In order to acquire the baseline simulation results, we first run a yearlong 1-second QSTS simulation using the brute force method with the abovementioned one load profile and one PV output profile. For the 13-bus small system, the brute force simulation took 13 minutes and 27 seconds. Fig. 12 shows single-phase voltages at bus 675 in per unit with respect to load and PV profiles. Each dot represents a power flow solution for a specific time instance t in the QSTS simulation. We color each dot based on different regulator tap positions. All the dots associated with each tap position lay on separate surfaces which verified our voltage linearization assumption. Since all these surfaces are approximately flat, combined with the previous linear assumption, we refer to them as “planes”. As the PV and load change in the system and the solution points forms a trajectory on the given plane. When the controller state changes the operating point “jumps” from one plane to another to continue with a trajectory in the new plane.

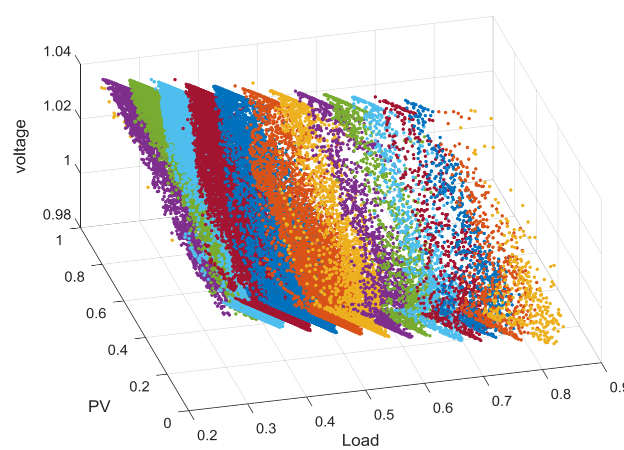

Fig. 12. Bus 675 voltages for over 31 million power flows in the brute force QSTS simulation.

To test the accuracy of the proposed method, we run the same yearlong 1-second resolution QSTS simulation using the proposed sensitivity-based model, and compare the simulation results. Fig. 13 shows the system controllers' states from both the brute force method and the proposed method for 90 days. Since the states of all system controllable elements are overlapping for both methods, we have demonstrated that the proposed method serves the purpose of predicting system state transitions very well.

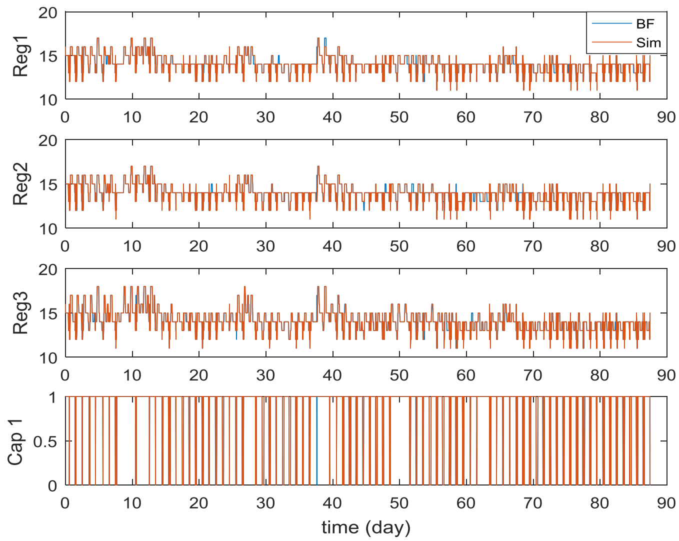

Fig. 13. System controller state comparison for two methods.

TABLE I MODEL ACCURACY AND EFFICIENCY TRADE-OFFS

Num. of Iterations	Reg. Avg. Err (%)	Cap. Avg. Err (%)	Comp. Time (sec)	Comp. Time Reduction (%)
0	3.22	2.35	6.34	99.21
1	2.24	-5.19	6.47	99.20
2	1.91	-4.94	6.57	99.19
3	1.91	-4.94	6.75	99.16
4	1.91	-4.94	6.96	99.14

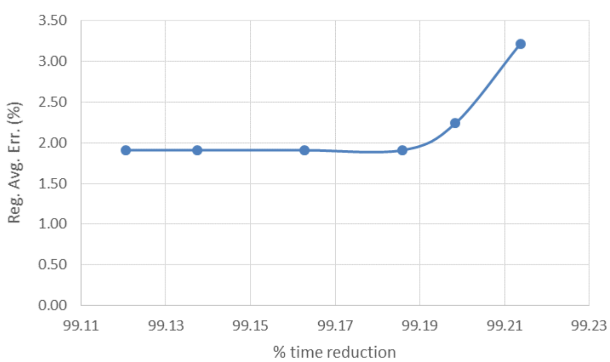

Fig. 14. Model accuracy and computational time trade-off.

The annual QSTS simulation results of the proposed method are shown in TABLE I with percentage error and computational time. TABLE I illustrates how the iterative method helps to improve the accuracy of the algorithm. When we increase the number of iterations in estimating the decision boundary of the plane model, the simulation error decreases but the computational time increases slightly. The simulation error stabilized after just two iterations. This is because the estimated decision boundary converges very fast, which just takes roughly two iterations in this test case. This also provides additional support for the linear voltage sensitivity assumption. Fig. 14 is a more illustrative figure demonstrates the trade-off between model accuracy and efficiency.

VI. CONCLUSION

QSTS simulation is the state-of-the-art distribution system analysis method, which provides a comprehensive and thorough evaluation of possible PV impacts. The major barrier that prevents the pervasive adoption of QSTS simulation is the long computational time for a yearlong high resolution QSTS simulation. In order to speed up QSTS simulation, we proposed a sensitivity-based and discrete transition state model that can capture distribution controller actions with a minimum number of power flow solutions. The proposed fast QSTS simulation method is based on the sensitivity model and has been tested with real load and PV profiles and has demonstrated high simulation accuracy with significant computational time reduction.

The proposed fast QSTS simulation has the potential to make yearlong high resolution QSTS simulation more effective and applicable to PV hosting capacity analysis and distribution system planning. Moreover, the proposed model provides new insight into behaviors of controlling devices and uses voltage sensitivities to vastly speed up the analysis of their operation in distribution networks.

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