Quasi-Static Time Series PV Hosting Capacity Methodology and Metrics

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Quasi-Static Time-Series PV Hosting Capacity Methodology and Metrics

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***Abstract*— Distributed photovoltaic systems (DPV) can cause adverse grid impacts, including voltage or thermal violations. The installed capacity at which violations first occur and above which would require system upgrades is called the hosting capacity. Current methods for determining hosting capacity tend to be conservative by either only considering infrequent worst-case snapshots in time and/or only capturing coarse time and spatial resolution. Additionally, current hosting capacity methods do not accurately capture the time-dependence making them unable to capture the behavior of voltage regulating equipment and of some advanced controls mitigations. This can trigger delays from unnecessary engineering analysis or deter solar installations in areas that are actually suitable. We propose a quasi-static-time-series (QSTS) based PV hosting capacity methodology to address these issues. With this approach, we conduct power flow analysis over the course of a full year, to capture time-varying parameters and control device actions explicitly. We show that this approach can more fully capture grid impacts of DPV than traditional methods.**

***Index Terms*- PV Hosting Capacity, Quasi-Static Time-Series Simulation, System Impact Studies**

I. INTRODUCTION

The widely used practice for determining a feeder's photovoltaic (PV) hosting capacity, or the amount of PV the feeder can host without adverse grid impacts that might require changes or upgrades to the distribution system, tries to find the minimum limits for a given spatial deployment of Distributed photovoltaic systems (DPVs) [1]-[3]. The analysis is historically conducted at worst-case time points (snapshots) of maximum or minimum load or the maximum PV to load ratio. We refer to these as "static, snapshot hosting capacity" methods. In this approach, the first parameter violated determines the hosting capacity and is often the upper voltage limit as per ANSI standard C84.1-2016, Range A [4]. However, this ANSI standard also allows infrequent violations of the voltage limit as long as they are corrected [4]. Operation of voltage control devices, such as capacitors and regulators, can bring the voltages within limits in a short time span. However, static hosting capacity metrics cannot capture such changes in the control device operations, a potential limit to hosting capacity, and therefore use proxy metrics, such as not allowing any equipment operations.

Thus, the resulting estimates of hosting capacity using static, snapshot methods provide a conservative estimate of how much DPV could be hosted on a given system without upgrades. Additionally, the use of snapshot analyses does not allow for one to capture how certain system changes that may be lower cost, for example dynamically changing the set points of PV inverters for voltage regulation or selective curtailment, that can be used to expand the hosting capacity.

Quasi-static time-series simulation (QSTS) is one option to better reflect the behavior of PV, grid devices, or loads to more accurately capture potential system impacts and hosting capacities. QSTS analysis has been previously used for conducting impact studies of control schemes for smart inverters and voltage regulating devices [5]-[7].

Recently, "iterative" hosting capacity techniques have introduced some time-varying simulation, such as the use of two representative 24-hour periods, that begin to address these issues [8,9]. However, the computational challenges have limited the efforts to use long (e.g. hourly) timesteps that may not accurately capture cloud-induced variability or corresponding regulator and capacitor control responses, which typically require 1 minute or faster analysis for lower errors [7]. Such efforts also tend to resort to reduced representations (e.g. only 3-phase lines) of the distribution feeder that can also miss some phenomena, particularly for smaller DPV.

This paper overcomes these gaps by proposing a full QSTS-based hosting capacity approach. Recent algorithmic advances promise to drastically speed QSTS simulations (e.g. [10]) , so we focus on describing key considerations for using QSTS for hosting capacity, defining candidate metrics, and comparisons to traditional static methods. It can be difficult to provide a single set of metrics for QSTS hosting capacity, since it will be determined by the comfort level of utilities in allowing voltage deviations or thermal violations on their system for small periods of time, and also because the preferences or practices vary significantly between utilities. However, exploring potential definitions of QSTS hosting capacity and carefully analyzing the time-series impacts of DPV on distribution networks can help in achieving a more sophisticated understanding of hosting capacity and how it may be expanded to incorporate increased DPV penetration in the future.

This paper aims to provide initial insights into these issues by exploring QSTS hosting capacity. Section II introduces a QSTS hosting capacity methodology, and an example set of metrics that could be used to understand hosting capacity in a QSTS world. Section III compares results between snapshot PV hosting capacity and QSTS PV hosting capacity on a real distribution feeder in the United States using 1-minute resolution load and PV profiles simulated for a one-year period.

II. QSTS PV HOSTING CAPACITY

Per the draft IEEE guide, QSTS 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." [11]

Thus, to get the most accurate PV hosting capacity results, the QSTS simulations should be conducted at a time resolution that can adequately capture the time delays of the voltage control devices (typically about 30 seconds) for at least one full year. However, in practice this can be difficult to achieve.

First, annual load and PV profiles for a distribution feeder at second or minute time resolution are difficult to obtain and are often not available. The increasing use of advanced metering infrastructure by utilities has allowed for more data to be available than before, but data integrity and availability issues remain in many cases. Secondly, once the finer time resolution load profiles are available, the analysis itself poses major computational challenges. For a real distribution model with thousands of nodes and 1 second resolution load and PV data, an annual simulation could take a few days. In order to achieve realistic PV hosting capacity results, multiple deployments at each PV penetration level must be analyzed. This could easily push the analysis duration to several years. A variable time step (VTS) solver proposed in [10] can be used to narrow down the number of time points to be analyzed by using a larger and a finer resolution step size. The solver has been shown to reduce the simulation time by up to 90% with 1-second resolution data in some cases [10]. The various deployment and penetration scenarios can be simulated using the VTS solver in parallel on a high-performance computing system, potentially reducing the simulation time to a few days even with 1-second resolution data. However, the VTS solver was not used in the case study discussed in this paper as the finest time resolution available for the load and PV profiles was 1-minute and all data points could be analyzed in a relatively short duration.

Defining a set of rules or metrics for determining the QSTS PV hosting capacity poses its own unique challenges. Applying static PV hosting capacity metrics, such as instantaneous voltage and thermal violations, to a QSTS simulation would counter the very purpose of performing a QSTS study, because the results would be the same as the snapshot hosting capacity case, and the fact that in practice, for example, the voltage is allowed to be outside of ANSI A limits for a short duration of time will not be captured. So, a new set of metrics will have to be defined that conform more closely with the established standards and can allow infrequent parameter violations, provided they are corrected in a timely manner.

A. QSTS PV hosting capacity metrics

The proposed metrics for evaluating QSTS PV hosting capacity are based on common standards and try to accommodate infrequent limit violations. These metrics can be applied independently to each PV deployment scenario. The amount of PV in the deployment scenario where any of these metrics are violated would be the feeder's quasi-static PV hosting capacity. These metrics focus on the impact of time varying parameters on grid operations and not solely on the instantaneous values. The results in this section are for a day long simulation on a detailed distribution feeder model using 1-minute resolution data. To bring out the differences in the metrics clearly, three utility scale DPV units are deployed on the three phase primary nodes near the feeder extremities, as shown in Fig. 1. This feeder model has about 3500 nodes and includes secondaries. The capacity of the deployed PV units is varied to highlight the limiting conditions of each metric.

1) Voltage Metrics: ANSI standard C84.1-2016 defines two voltage ranges, A and B [4]. It allows infrequent, short-term voltages outside both ranges. However, during Range B violations, equipment might not operate satisfactorily and protective devices might operate to protect the equipment. Considering these issues two separate metrics were created:

a) Moving n-minute average voltage: In this metric bus voltages are monitored using a *n*-minute moving window, the window length used here is 10 minutes and can be modified by a utility based on operational requirements. The moving average voltage of each bus for a 10 minute duration is determined and the maximum and minimum of these averages are stored for all the analyzed time points. If these values are outside Range A limits, the current time point t_c is stored in a vector as summarized in algorithm 1. If the violations continue until time point t_f, the time violation would be $t_f - t_c$, as shown in Fig. 2. We assume that the total time violation should not be 2 hours more than that in the base case for the entire year.

Figure 3.a shows the maximum instantaneous and average voltages observed in a day long QSTS simulation of the test feeder of Fig. 1, with three utility scale PV units of 1 MW each. The results in the blue boxes show how the 10 minute moving average allows short term voltage violations, but captures the violations in a time vector (shown in green on the secondary axis) if the violations persist. The total time for which the moving 10 minute average voltages were outside range A was 169 minutes, thereby violating this metric.

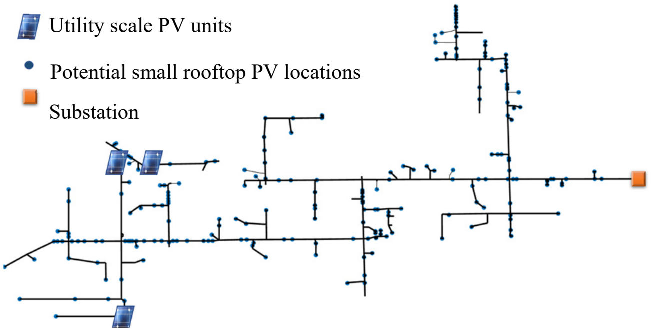

Figure 1. Test Feeder topology and PV unit locations

a) Instantaneous maximum voltages: The instantaneous voltages at any time point should not be outside Range B or, if Range B is exceeded in the base, no PV case, then the number of these instantaneous violations with PV should never be more than those in the base case. There are a couple of overvoltage violations in Fig. 3.a, so this metric is also violated assuming base scenario did not have Range B violations.

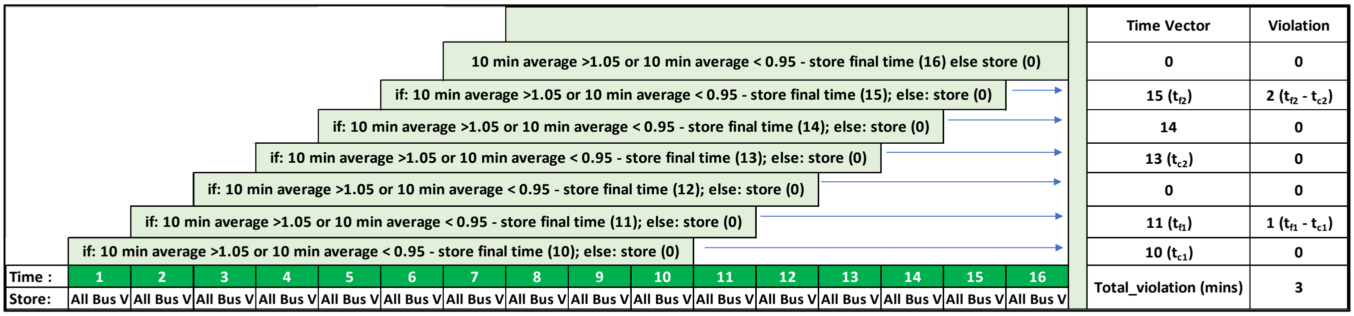

Figure 2. Moving *n*-minute average voltage metric

```
Initialize total time = 1 year (525,600 minutes);
B = set of all feeder buses;
$T_w$ = Window length (10 minutes);
while (time < total time) do
    for b ϵ B do
        $V_b = \frac{1}{T_w} \sum_{t=time-T_w}^{time} V_{b,t}$
    end
    $V_{max}$ = Max ($V_b, \forall b \in B$)
    $V_{min}$ = Min ($V_b, \forall b \in B$)
    if $V_{max}$ or $V_{min}$ outside Range A do
        Store time in vector
    end
end
```

Algorithm 1: Moving 10-minute average voltage metric

2) Loading Metrics: The ampere rating of the lines and cables and kVA ratings of the distribution transformers are determined based on the load demand to be met. These ratings may be exceeded in feeders with high PV. The following two metrics are defined for quantifying the total thermal violations in a QSTS simulation, using a similar methodology as for voltages:

a) Moving n-hour average loading: It has been suggested that an air-cooled transformer could be operated for up to 2 hours at 120% of its rated capacity following an initial loading of 90% [12]. To comply closely with this rule, a 2 hour moving average of each transformer's loading as a percentage of its rated capacity is calculated. If the maximum average loading exceeds 120%, the time vector is updated in a similar manner as the moving *n*-minute average voltage metric. The total time violation should not be more than that in the base, no PV, scenario. For over-load conditions on lines a similar methodology is used, however the 2 hour average loading is not allowed to exceed 100% of the rated capacity as lines do not have any additional cooling mechanism. Fig. 3.b shows the maximum instantaneous and average line loadings observed when three, 2.5 MW utility scale PV units were deployed in the test feeder of Fig. 1. The results in the blue box show that using a 2-hour moving average allows short term over-loading, but captures long term violations. It can also be seen that similar to the voltage metric, the time vector is updated only when the loading exceeds the threshold.

b) Instantaneous over-loading: The instantaneous loading of the transformers should not exceed 150% of their rated capacity, whereas for lines the maximum instantaneous loading threshold is 120%, or might be even lesser at 100% for some utilities. In Fig. 3.b, both of the line loading metrics are violated.

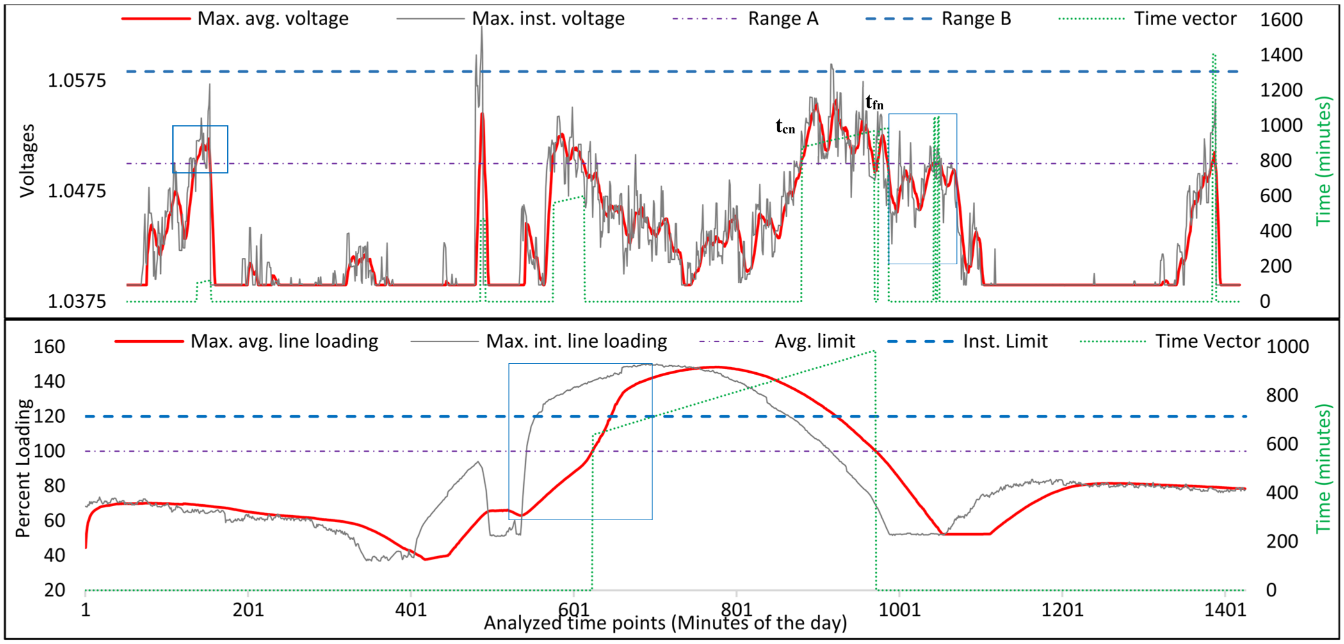

Figure 3.a (top) Maximum instantaneous and average voltages, and violations captured in a time vector
Figure 3.b (bottom) Maximum instantaneous and average percentage line loading, and violations captured in a time vector

Control Equipment Operations: High PV penetration can lead to frequent changes in the feeder voltages, potentially leading to increased state changes of the voltage control equipment such as voltage regulators and switched capacitors. These increased mechanical movements of the control equipment can reduce their life span. Thus, it is necessary to ensure that the control device operations are not increased significantly. Number of device movements can not be determined in the snapshot hosting capacity analysis, and thus this further highlights the need for conducting QSTS PV hosting capacity studies.

Future work is still needed to detemine how significant the issue of device movements is and what the implications are in terms of device lifetime and associated operation and maintenance (O&M) costs. Utilities may not use number of device movements as a metric for determining when a distribution upgrade is required, and thus this may not represent a hard limit on hosting capacity in practice. In this paper, we track the number of control device (regulators and capacitors) operations with PV compared to the base case in order to help provide additional insights on this topic. To analyze the impact of PV units on the operations of different types of voltage control devices, a substation load tap changer (LTC) and a voltage regulator were added to the feeder model shown in Fig. 1, in addition to the 5 existing capacitor banks. The number of regulator tap changes increased 62.5% and capacitor state changes increased 25% over the base scenario, for a day long simulation with 3, 1 MW PV units.

III. Snapshot vs QSTS PV Hosting Capacity

For conducting the snapshot PV hosting capacity analysis on the original feeder model of Figure 1, the added voltage regulator and substation LTC were removed. PV deployment scenarios were generated based on Monte Carlo simulation [3]. The potential locations where a small rooftop PV unit may be deployed are shown in Fig. 1. The type of the PV unit, residential or commercial, is determined based on the type of the randomly chosen customer load. Random sampling from probability density functions of both residential and commercial PV maximum powers acquired from the California solar PV statistics data was used to determine the PV unit size. This widely used methodology is described in [1]. All the PV inverters are operating in constant power factor mode, with a fixed set point of 0.95 inductive. The procedure is repeated to generate PV deployment scenarios covering 5% to 100% of the customers on the feeder, in a 5% step size. The study is repeated 10 times for each of these percentage penetration levels. Thus, a total of 200 scenarios were analyzed at the peak and minimum loading time points.

The minimum loading condition occurred during the solar peak hours (between 11 am – 1 pm) when there is a high PV to load ratio, leading to overvoltage violations as shown in Fig. 4. ANSI Range A was used as the conservative threshold because the snapshot PV hosting capacity methodology doesn't provide any information about the time for which the violations might continue. The PV hosting capacity limit was reached for deployment 8 at 65 percent PV penetration as highlighted in Fig. 4, where the maximum instantaneous voltages of each PV deployment scenario are plotted. Even though 65% of the customers were deployed with a PV unit, the net generation was about 22% of the peak feeder load of 7.6 MVA.

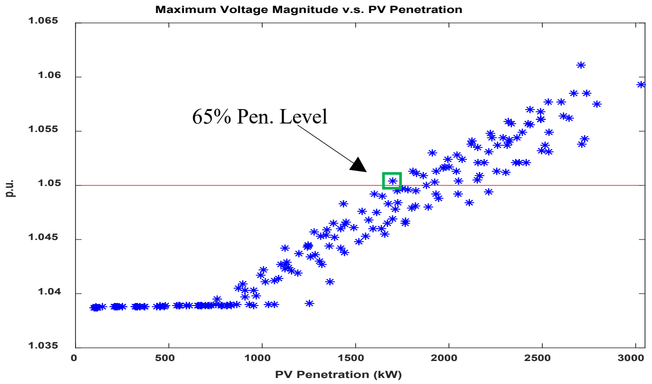

Figure 4. Maximum instantaneous voltage observed in each deployment and PV penetration scenario of the snapshot PV hosting capacity study

To compare the results of the snapshot PV hosting capacity study with QSTS PV hosting capacity, all the penetration levels for deployment 8 were analyzed using a yearlong QSTS PV hosting capacity study with 1-minute resolution load and PV profiles. As can be seen in Fig. 4, the results for different deployments are closely clustered. Thus, the QSTS PV hosting capacity value obtained from a single deployment, can be expected to be very close to the actual hosting capacity value. To test the impact of a different window length, a 5-minute moving average was used for the voltage metric while the remaining metric parameters and thresholds were kept the same as described in section II.A.

After significant code optimization in python, a single year-long simulation took about 65 minutes on a Core i5-7300U processor operating at 2.60 GHz. Analyzing all 20 penetration levels necessary to compute the QSTS hosting capacity value in series would have taken more than a day. To overcome this issue, the different penetration levels were simulated in parallel on a high-performance computing system, and the QSTS PV hosting capacity results were obtained within a couple of hours.

The results from these year-long QSTS PV hosting capacity studies are shown in Fig. 5. Even when 100% of the customer locations were deployed with a PV unit, which have an aggregate rating of about 35% of the peak feeder load, no undervoltage or thermal violations were observed. The increase in the number of capacitor state changes is also well within the metric thresholds. The base scenario had Range A overvoltage violations (>1.05 p.u.) for about 0.73% of the time points analyzed (3,868/525,600). However, these were only marginally above the threshold as only about 0.0057% of the time points were outside Range B (> 1.058 p.u.). The reason for Range B violations was sudden load drops as shown in Fig.6, which are not captured in the snapshot PV hosting capacity study. These events can cause a sudden spike in voltage, but it is quickly regulated by the voltage control devices. For the event shown in Fig. 6, the voltage spike was mitigated by the opening of a capacitor bank after its time delay setting of four minutes. The reduction in overvoltages in some of the PV scenarios from the base case is because of the reactive power support from the inverters operating at 0.95 inductive power factor setting. The role of reactive power support in mitigating overvoltages was evident from a yearlong simulation of the 65% penetration scenario with all inverters operating at unity power factor, as it resulted in an increase in the overvoltages by about 134% from the base scenario.

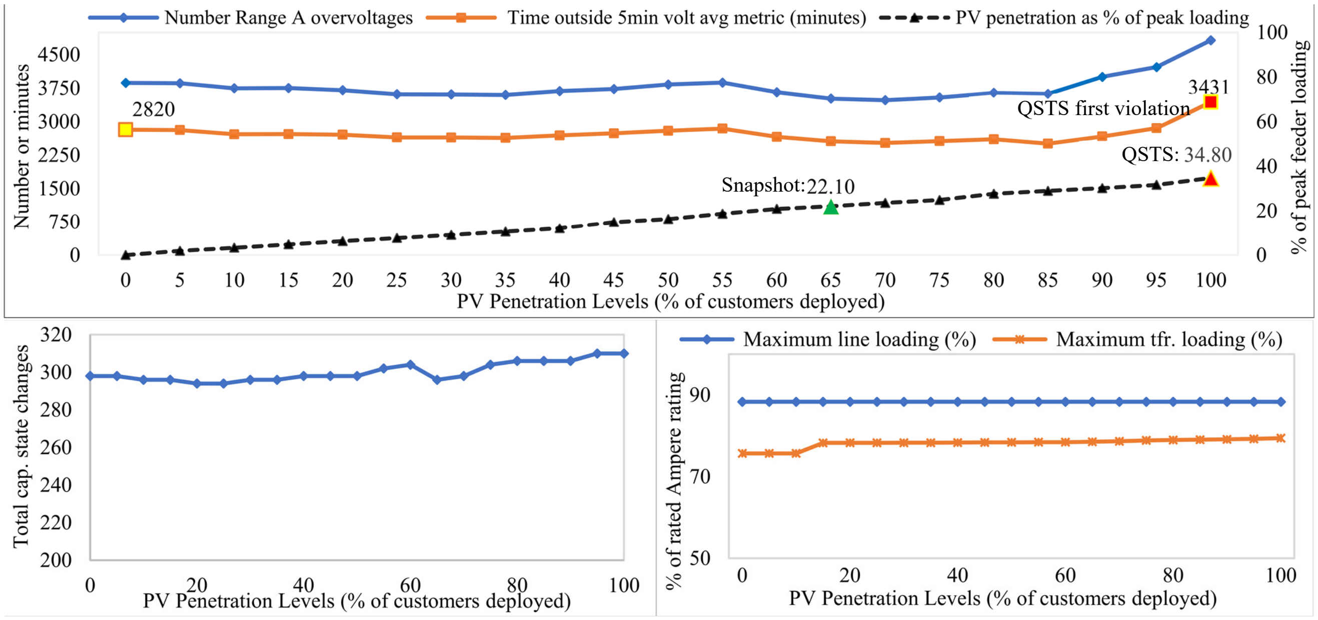

Figure 5. QSTS Results: (Top (a)) Number of overvoltage violations and total time for which the 5-minute average voltage was outside ANSI Range A; (Bottom left (b)) Sum of state changes of all capacitor banks; (Bottom right (c)) Maximum line and transformer loading observed at each PV penetration

The first metric to be violated was the 5-minute moving voltage average, when the total time violation was 2 hours more than that in the base case for the entire year. However, this violation occurred at 100% PV penetration scenario, suggesting the possibility of deploying 35% more customer locations with PV units than the snapshot study proposed, without adversely affecting the grid or the need for system upgrades.

IV. CONCLUSIONS

This paper presented a QSTS PV hosting capacity methodology and metrics. The methodology tries to conform more closely with the standards, by allowing infrequent short-term parameter violations while capturing all long-term violations. This study methodology can give a better estimate of the feeder's PV hosting capacity by considering the effect of voltage control device operations and their time delays. We have demonstrated this new methodology on a real feeder in the United States in this paper. While the snapshot PV hosting capacity gave a conservative estimate, the quasi-static PV hosting capacity suggested the possibility of going to a higher PV penetration level. Although this paper focuses on the methodology itself, future work will delve on a more thorough validation of this approach by using a larger number of feeder test cases as well as running more scenarios in parallel.

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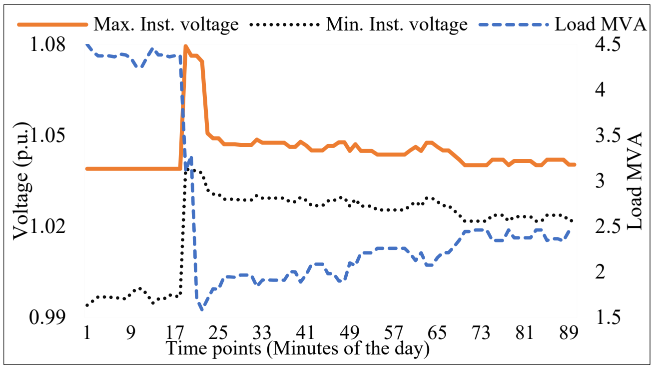

Figure 6. Voltage peak because of sudden load drop, quickly regulated