Integration of Behind-the-Meter Solar into Distribution Feeders: The Importance of Time Resolution on Model Results

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Abstract:

We investigate the impact of time resolution of solar data in modeling distribution grids with significant shares of distributed solar resources. As behind-the-meter solar grows in the United States, power system modelers are charged with understanding power quality implications in distribution systems. While analyses using high temporal resolution data are more realistic, data at this granularity is often not available and this high temporal resolution increases the computational burden significantly. On the other hand, while a low time resolution might be more feasible for these reasons, it might also lead to inaccurate results because of its inability to detect second-to-second dynamics in the solar profile. We model solar growth at different time granularities (from 4 seconds to 10 minutes) in a real-world distribution feeder. Results show that the model's ability to detect voltage flicker is highly affected by the changes in the temporal resolution of data considered. This highlights the importance of low-time resolution solar data in modeling power systems with significant solar penetration.

***Keywords**: Flicker; Power distribution network; Time resolution; Voltage rise.*

I. Introduction:

As of 2017 there is estimated to be more than 15,000 MW of net metered solar capacity over more than 1.7 million rooftops across the country.[1] This growth in behind-the-meter solar has raised questions on how to protect networks from potential power qualities issues such as voltage rise and flicker. For instance, the Louisiana Public Service Commission (LPSC) limited net-metered solar installations to 0.5% of a utility's retail peak load [1]. While this was likely a reasonable approach for a solar industry in its infancy, as penetration continues to grow policy makers need more information about how feeders are affected by solar penetration. To further complicate matters, the answer to this question is likely dependent on the specifics of the feeder's topology, load profile, and the pattern of solar generation in that area. Today, all Louisiana utilities have reached the 0.5% limit and the PSC is currently in a rulemaking process to determining the rate design regime moving forward. This is just one example of why it is important for policy makers and power system operators to understand the behind-the-meter penetration at which power quality problems might begin to arise.

Power distribution networks with significant solar penetration have been studied extensively. A review article published in 2013 [2] focused on issues regarding the integration of solar power in distribution grids; however, detailed technical analysis are not provided. [3] expands on this work and assesses the impact of transient cloud cover that can occur in a few seconds on a distribution network and [4,5] unsurprisingly find that excessive reverse power flow in distribution feeders is most likely to occur on sunny days. Both excess generation and quick drop-offs in solar generation can create significant changes to system frequency when with high solar penetration [6]. [7-9] analyze how power quality is affected by the solar power fluctuations, in lieu of excess generation.

The temporal resolution in prior solar studies has varied from a few seconds to one hour; however, a review of the literature reveals that a 1-hour time resolution is the most common, as high time resolution solar data is simply not available for many sites [10-12]. While this is the case, the potential importance of data granularity is discussed in a few analyses. In [13], energy matching indices are compared for simulation time resolutions ranging from 1 min to 1 hr. Considerable errors (from 15% to 60%) are observed with 1-hr resolution compared to 1-min resolution. We will further expand on [11] by investigated even shorter fluctuations at the granularity of just 4-seconds.

Our data comes from a 140W panel at Louisiana State University's Renewable Energy and Smart Grid Laboratory that records solar generation at 4-second intervals. The level of variability at this time resolution is significant. For instance, in April 8, 2016 we observed more than one hundred of 4-second intervals where the solar power changed more than 50%. Hourly, or even minute level, time resolution will simply not pick up on these second-to-second variations. This is illustrated in Figure 1. This variability is a particular concern for voltage flicker which depends on the number and magnitude of changes during a period of time [14]. Therefore, the smoothing of a voltage profile over the course of even minutes might yield a lower flicker at PCC which might result in an inaccurate measure of the solar impact on the flicker.

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[1] EIA 861.

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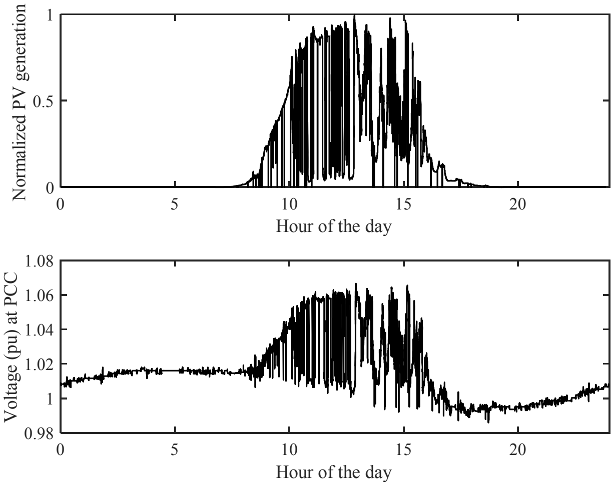

Figure 1. The solar generation pattern of April 8, 2016 (LSU's solar panel) along with the steady-state voltage measured at a selected node of a 23kV distribution feeder powered by Entergy

The goal of this paper is to address the importance of time resolution in the analysis of the impact of distributed solar on distribution networks by examining the sensitivity of results to changing the time granularity of solar data considered. In addition, while a number of recent academic literature focus on the scalability or renewable resources in a theoretical distribution grid [15-19], we will consider a real world feeder in Louisiana. While this system is not as not as "clean" as a theoretical system, we believe this will improve the accuracy of our results.

II. Simulation Layout and Data Preparation

A. *Case study*

Real distribution networks are not as "clean" and balanced as theoretical networks (e.g. IEEE 34-bus network). In different sets of literature those theoretical networks are widely studied due to both convenience and because data on real systems are simply not publicly available. In this study, a 24.9kV power distribution system operated by the Southwestern Electric Power Company (SWEPCO) is considered. This feeder has 595 load buses; 576 are single-phase loads and 9 and 10 are two-phase and three-phase loads respectively. SWEPCO has provided detailed information of this feeder including synthetic geographical coordination of buses, resistance (R), capacitance (C) and reactance (X) of all line segments along with phase configuration for all distribution lines, conductor types, and nameplates of active and reactive powers of all nodes. Also, the load profile of the feeder (at the substation transformer) is available with a time step of 15 minutes. A schematic is depicted in Figure 2. The total number of nodes in this network is 2,776 and the total number of power delivery lines is 2,793.

B. *Network Modeling*

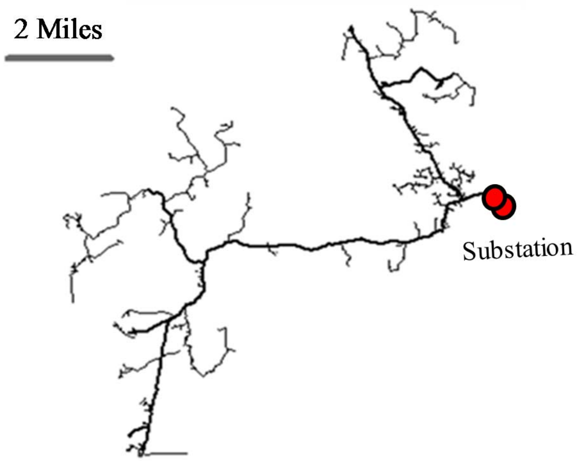

Figure 2. Layout of the radial distribution system powered by SWEPCO

Analysis is conducted in Open-source Distribution System Simulator (OpenDSS) software designed by the Electric Power Research Institute (EPRI). We chose this modeling tool for two reasons. OpenDSS is free, open source, publicly available and allows us to make modifications to ensure that the model results match the real-world data provided by SWEPCO. In addition, OpenDSS is capable of running a network in a timing loop. In a 2017 report released by the National Renewable Energy Laboratory (NREL), OpenDSS is recommended for modeling networks with fluctuating data in the order of a few seconds [20].

The time-series of solar generation and load are imported to OpenDSS through MATLAB software using the same temporal resolution. Using MATLAB, we then create timing loops inside the OpenDSS environment through the Component Object Model (COM) interface. When performing power flow, the feeder active and reactive powers are split among feeder nodes proportional to the nodes name plate powers, which are then superimposed to the nodal active power. The individual nodal active power capacities are proportional to the load nameplates and vary with the same pattern. Stochastic distributions of cloud cover and solar capacity are also considered to avoid concurrence of similar solar power variation across all nodes. In this study, the solar penetration is defined as the percentage of load buses with rooftop solar. For instance, for a feeder with 500 load buses, 10% penetration means that 50 of these load buses contain a 7-kW rooftop solar system. For each simulation, we randomly assign the solar to load buses. In real world systems, there is likely spatial correlation between solar installations. While spatial clustering will likely exacerbate voltage rise and flicker, thus, this is likely a conservative approach in this way.

C. *Solar Dataset Clustering*

Although the solar data is collected every 4 seconds over the course of an entire year, running the analysis at a 4-second interval for 365 days of the year is not computationally feasible, especially if the modeler wants to consider multiple feeders across multiple levels of solar penetration. In order to choose a representative sample of days, we cluster the days of the year into nine (9) categories based on the total load and the level of variability. For load, we sum the total MWhs of electricity consumed for the residential load profile provided by the utility. For variability, we subtract the solar generation from the four second interval solar data between each time step where, $\Delta s_t = s_t - s_{t-1}$, where $\mathrm{s_t}$ is the solar power (W) in time *t*. We take the standard deviation of $\Delta \mathrm{s_t}$. For both measures, we then calculate the 33.3rd and 66.6th percentile days and categorize each day into "high", "medium", or "low". We randomly choose one day from each of the nine categories as "representative days".[2]

It is important to note that this method will create two likely sources of potential bias to our variability. On one hand, scaling up data from a 140W panel to a 7kW system might overestimate the variability of the solar production data. On the other hand, load data is smoothed due to two factors. First, we only have the load for the entire feeder on a 15-minute interval—not each house. Thus, actual variability from node to node will be more than the aggregate. Second, linearly extrapolating this 15-minute load into 4-second intervals further smooths this data. We are unable to comment on the net effect of these two sources of bias.

III. Simulation Results

We then run our load flow analysis for ten (10) different time resolutions (4 sec, 10 sec, 20 sec, 30 sec, 40 sec, 50 sec, 1 min, 2 min, 5 min and 10 min). The starting time step (4 sec) is the minimum data acquisition rate at the measurement unit connected to the 140 W solar panel. The other time series of solar data are created by decreasing the sampling rate using integer factors.

We then choose a level of solar penetration for the analysis. We choose an 80% solar penetration, meaning that 80% of the households in the feeder install a 7-kW behind-the-meter solar system. We choose a high level of solar penetration as voltage rise and flicker might not be significant at low level of penetration and therefore mitigate our ability to observe the importance of time granularity, which is the purpose of this analysis. The voltage rise and flicker are observed based on the ANSI C84.1 standard and IEC-61000-15-4 standard respectively. We consider long-term flicker (in lieu of short-term flicker) as this is the relevant power quality issue in this context as short-term flicker is mostly used for product standardization [21] where the fluctuation of voltage is monitored in 10-minutes time windows. OpenDSS does not have the ability to monitor voltage flicker at all nodes unless monitors are manually defined for every single node, but does have the ability to monitor voltage level at each node bus. For this reason the flicker is calculated at samples nodes. The voltage rise and flicker observations for all 90 scenarios are summarized in Tables 1 and 2 and illustrated in Figures 3 and 4. Figure 3 shows that voltage rise is lightly affected by changes in the time resolution. With the exception of the second cluster, the error in the voltage rise observation will be less than 5% relative to the 4-second analysis. In the second cluster (low load-medium variability) the error is about 20%.

Table 1. Percent of voltage readings outside the permissible range for different time resolutions at 80% solar penetration

		Low Variability	**Medium Variability**	**High Variability**
		Percent of voltage readings outside the permissible range		
4 sec	**Low Load**	0	6.930%	16.696%
10 sec		0	6.963%	16.724%
20 sec		0	6.893%	16.710%
30 sec		0	6.856%	16.773%
40 sec		0	6.735%	16.468%
50 sec		0	7.085%	16.893%
1 min		0	6.733%	16.855%
2 min		0	6.272%	16.324%
5 min		0	6.000%	16.500%
10 min		0	5.535%	17.104%
4 sec	**Medium Load**	4.933%	3.882%	27.091%
10 sec		4.933%	3.855%	27.297%
%20 sec		4.929%	3.865%	27.354%
30 sec		4.925%	3.851%	26.861%
40 sec		4.945%	3.894%	27.256%
50 sec		4.943%	3.796%	27.106%
1 min		4.906%	3.861%	27.056%
2 min		4.866%	3.928%	26.817%
5 min		3.775%	4.000%	26.500%
10 min		4.920%	3.701%	26.264%
4 sec	**High Load**	0	0	0
10 sec		0	0	0
20 sec		0	0	0
30 sec		0	0	0
40 sec		0	0	0
50 sec		0	0	0
1 min		0	0	0
2 min		0	0	0
5 min		0	0	0
10 min		0	0	0

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[2] It should be noted that days of year do not add up to 365 because some days of solar generation data contained error and were therefore purged from the data. Some days technical errors occurred in the lab due to the computer freezing up, a student unhooking the panel accidentally, etc. In total we have sufficient data on 354 days of the year, thus are missing just 11 days associated with data issues.

Table 2. Long-term flicker observation at a sample bus for different time resolution

		Low Variability	Medium Variability	High Variability
		Maximum long-term flicker observed at a selected bus		
4 sec	Low Load	0.125	0.876	15.815
10 sec		0.018	0.446	6.341
20 sec		0.021	0.161	2.442
30 sec		0.005	0.069	1.285
40 sec		0.297	0.056	0.789
50 sec		0.192	0.071	0.542
1 min		0.108	0.062	0.380
2 min		0.107	0.013	0.094
5 min		0	0.001	0
10 min		0	0.001	0
4 sec	Medium Load	0.160	0.892	9.046
10 sec		0.023	0.073	1.280
20 sec		0.007	0.062	0.497
30 sec		0.007	0.141	0.165
40 sec		0.005	0.235	0.484
50 sec		0.001	0.057	0.109
1 min		0	0.064	0.383
2 min		0.022	0.059	0.168
5 min		0	0.001	0.001
10 min		0	0.001	0
4 sec	High Load	0.128	0.846	1.015
10 sec		0.342	0.341	0.274
20 sec		0.175	0.130	0.462
30 sec		0.062	0.025	0.247
40 sec		0.032	0.117	0.162
50 sec		0.006	0.027	0.113
1 min		0.004	0.045	0.082
2 min		0.045	0.024	0.076
5 min		0.001	0.001	0.001
10 min		0	0.001	0.001

Flicker, though, is highly affected by the changes in the time steps as indicated in Figure 4. In fact, increasing the time step from 4 sec to 10 minutes, will lead to flicker measurement errors ranging from 75% to 99%. This highlights the importance of low time resolutions, especially when considering voltage flicker.

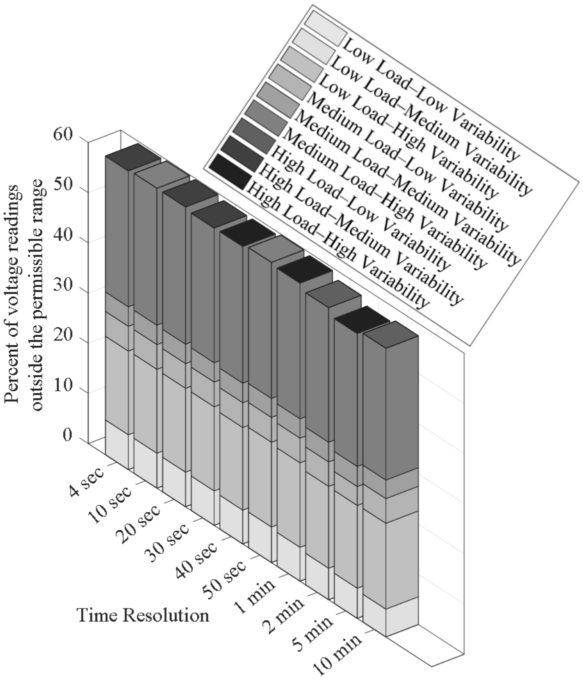

Figure 3. The voltage rise trend for different time steps

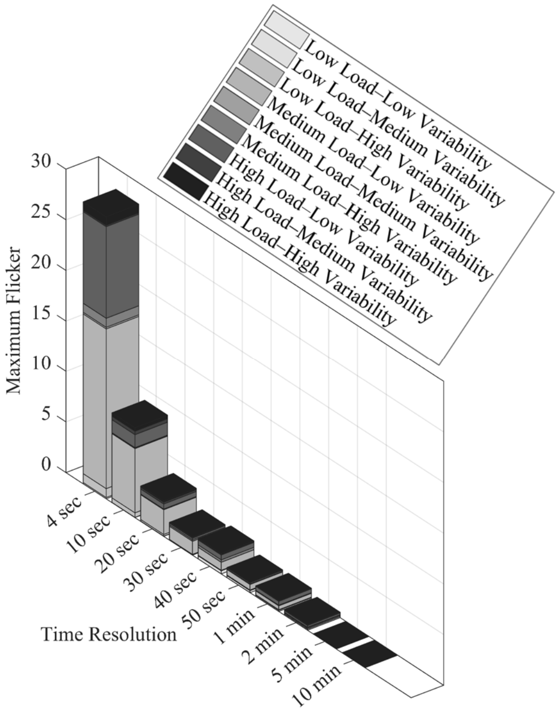

Figure 4. The flicker trend for different time steps

IV. Conclusion

As policies aimed at mitigating negative externalities of fossil fuel consumption [22] continue to drive renewable energy growth, both distributed [23] and utility scale [24], it will become increasingly important to understand the implications of this growth on electric markets [25] and power systems [26]. Long term cost trends of the renewable generation assets themselves need to be considered [27-29], but also cost implications on the grid itself. Understanding these implications will be increasingly important as policymakers grapple with citizens' preferences towards policies that subsidize these resources [30], [31]. This paper contributes to this effort by investigating how voltage rise and flicker modeling is affected by the time step of solar time series data. The steady-state behavior of a real 24.9kV power distribution feeder is observed for ten (10) different time resolutions from a few seconds to several minutes. Result show that time granularity is of particular importance, especially when considering voltage flicker. While we do find meaningful margins of error for voltage rise using lower time resolutions in one of the scenarios considered, it is less pronounced relative to voltage flicker. We find that using data sets with low time resolutions is likely not sufficient for understanding the implications of growth in solar PV on voltage flicker.

V. Acknowledgement

This study is supported by the Louisiana Board of Regent's Industrial Ties Research Subprogram (ITRS). LEQSF(2016-18)-RD-B-05.

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