High Temporal Resolution Load Variability Compared to PV Variability

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***Abstract* — While solar variability has often been quantified and its impact to distribution grids simulated, load variability, especially high-frequency (e.g., 1-second) load variability, has been given less attention. The assumption has often been made that high-frequency load variability is much smaller than PV variability, but with little evidence. Here, we compare load and PV variability using 1-second measurements of each. The impact on voltage regulator tap change operations of using low-resolution (e.g., 15- or 30-minute) interpolated load profiles instead of 1-second is quantified. Our results generally support the assumption that distribution feeder aggregate PV variability is much greater than aggregate load variability.**

I. INTRODUCTION

Many studies (e.g., [1-3]) have demonstrated the impact of PV variability to voltage fluctuations on distribution feeders and hence voltage regulator tap change operations. The spatial smoothing due to geographic diversity of PV modules has been well documented (e.g., [4-6]) and modeled (e.g., [7-9]). Additionally, the importance of using high-frequency PV samples for distribution grid studies was shown in Lave, et al. [2], where errors in simulated tap change operations of 20% or more resulted from using low-frequency (5-minute or 15-minute) PV power samples instead of sub-minute.

However, comparatively little analysis of load variability exists. Historically, load measurements have been low-frequency (e.g., 15-minute resolution), sparse (e.g., only measured at the distribution substation), and low quality (e.g., low accuracy and reliability due to lack of maintenance), but recently load data availability (e.g. AMI data) and resolution have been improving. So far the assumption in most PV integration studies has been that high-resolution load data is not necessary because the PV variability is much larger than load variability, but this has not been directly verified.

In this work, we present a direct comparison of the variability of both PV and load on a distribution feeder using measured data from Ota City, Japan. Additionally, we investigate the impact of using low resolution load, PV, or both on distribution simulation accuracy.

II. DATA

1-second load and PV power output data from nearly 500 homes in Ota City, Japan with PV was used for this analysis. The maximum load of all houses was 1.0MW and the installed capacity of PV was 1.9MW. The data is described in detail in [10]. Figure 1 shows the load and PV profiles for the aggregate of all houses, binned into averages by month of year and hour of day.

The Ota City load had both a morning and an evening peak, due in part to household heating demands. These peaks are largest in the winter; in the summer, loads are low. Houses in Ota City do not typically have air conditioning. This load profile is different from many United States load profiles. In the Southwestern United States, for example, loads tend to have a single daily peak, with maximums in summer afternoons.

The PV profile generally follows seasonal solar cycles, but suffers from reduced power output in July due to many cloudy days. In this way, it may be similar to locations in the United States that experience summer cloud cover/fog, such as coastal San Diego or San Francisco.

III. PV VS. LOAD VARIABILITY

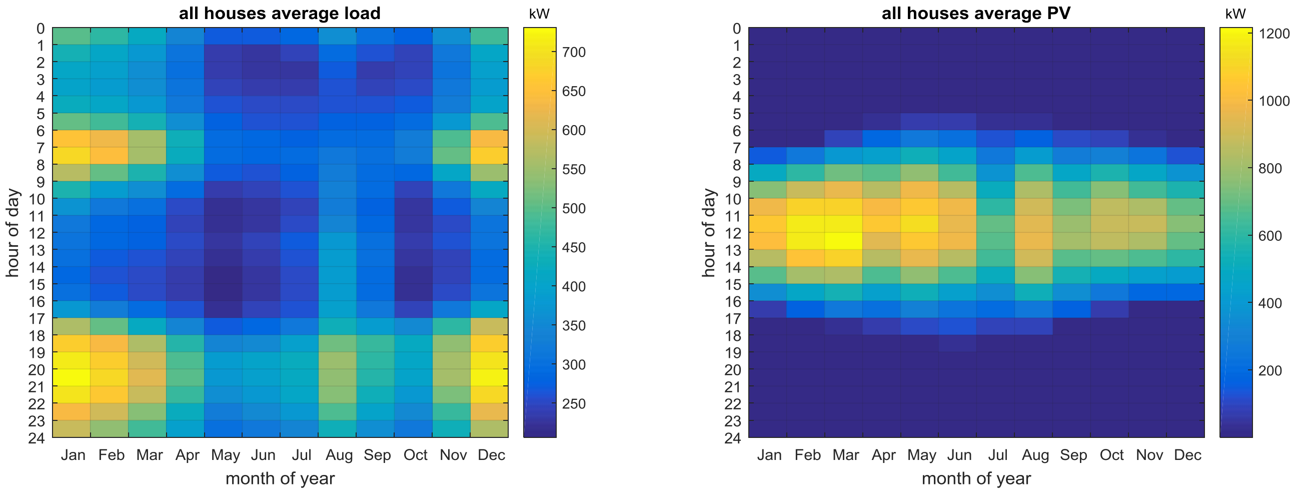


Figure 1: Average load and PV power output values for each month of year/hour of day combination for the aggregate of 483 houses in Ota City, Japan.

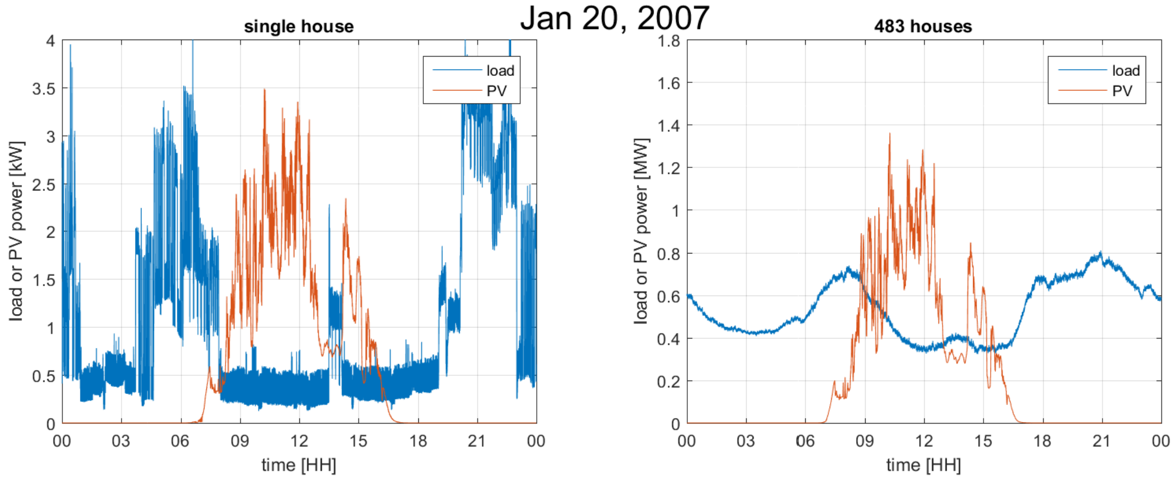


Figure 2: Comparison of load and PV timeseries for a single house and the aggregate of 483 houses in Ota City, Japan.

PV and load variability were compared directly for a single house and for the aggregate of all houses. Figure 2 shows the timeseries comparison. For a single house, PV and load variability are comparable. Quantitative comparison revealed that the load timeseries actually had much larger 1-second ramps (max 1-sec load ramp 1.80 kW, max 1-sec PV ramp 0.19 kW). This is likely due to electric loads which can be turned on or off at the flick of a switch, while PV power generation is increased or decreased by cloud shadows which gradually shade the module (i.e., cloud shadows are not fully opaque with sharp edges).

When aggregated, the total PV power output of all houses is smoothed slightly compared to a single house. The houses at Ota City with measurements are all collected in a small area – ~0.4 km^2 – leading to the relatively small spatial smoothing. The load of the aggregate, however, is significantly smoothed compared to the load of the single house. This significant smoothing is caused by the load of each house being uncorrelated: one house may turn a heater on, another house may do the same a few second later, etc., but *all* houses will not turn their heaters on at exactly the same second.

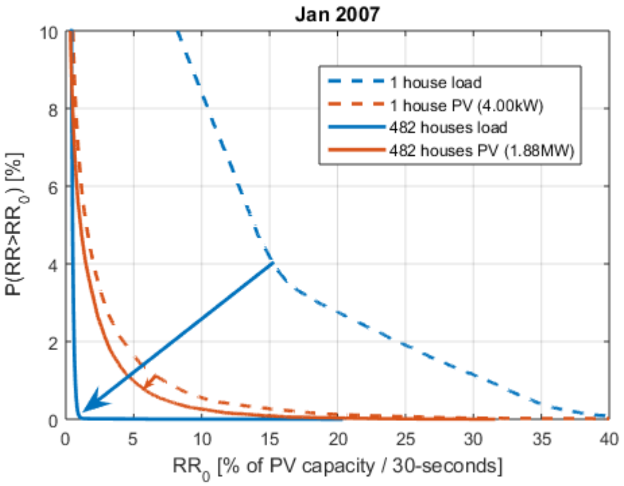


Figure 3: Ramp rate distributions for load and PV ramps for a single house and the aggregate of 482 houses in the month of January 2007 in Ota City, Japan. The arrows illustrate the reduction in variability due to aggregation.

To further explore the reduction due to aggregation, Figure 3 shows the 30-second ramp distributions of both PV and load during January 2007 for a single house and for the aggregate of 482 houses. Note that one house that had data on January 20th (Figure 2) did not have data for every other day in January and so is not included in Figure 3 (hence the difference between 483 and 482 houses considered). The variability of the single-house load is seen to be much larger than the variability of the single-house PV, as seen by many large magnitude (far to the right), high probability (far to the top) load ramps. For example, a 15% of capacity 30-second load ramp (equivalent to a 0.6kW ramp for a 4kW system) has a ~4% probability of occurrence, while the same magnitude PV ramp has less than a 0.3% probability.

In looking at the ramps for the aggregate of 482 houses, we again see the benefit of aggregation. The arrows illustrate these reductions in variability due to aggregation: the reduction in load variability (blue arrow) is much more significant than the reduction in PV variability (red arrow). 30-second aggregate load ramps almost never exceed 1% of capacity, while 30-second aggregate PV ramps larger than 5% of capacity still occur about 1% of the time.

Thus, at least for Ota City in January, single-house load ramps are larger than single-house PV ramps, but aggregate load ramps are much smaller than aggregate PV ramps.

IV. LOAD AND PV TIMESCALE IMPORTANCE TO DISTRIBUTION STUDIES

As mentioned previously, most distribution grid studies have used low frequency-resolution load data (e.g., 15- or 30-minute resolution). Many have also used low-frequency PV data (e.g., 1-minute resolution ground measurements or 30-minute resolution satellite measurements). In this section, we test the sensitivity of voltage regulator tap change operations to varying resolutions of input load and PV data.

To quantify the impact of using varying temporal resolutions, we used the GridPV [11] MATLAB toolbox to run OpenDSS (a quasi-static time series simulation program) and compute voltage regulator tap change operations on the test feeder mentioned in Section II. Simulations were run at five-second resolution for one year. A 12kV agricultural feeder in California was used as our test feeder, the same feeder that has been used for previous studies of solar variability impact to voltage regulator operations [2]. The feeder layout is shown in Figure 4.

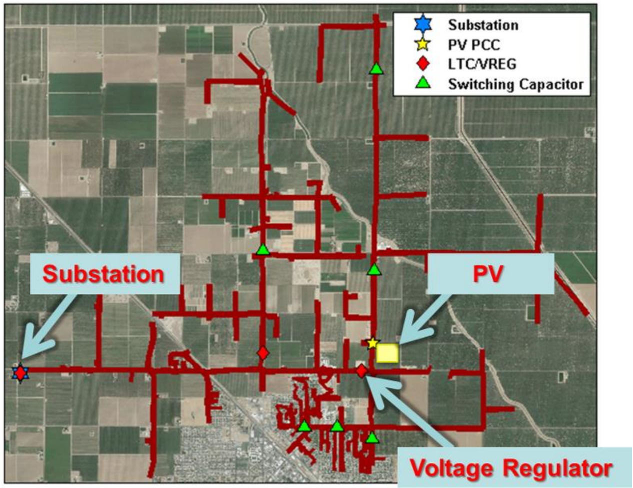


Figure 4: Layout of study feeder showing the location of the substation, the voltage regulator considered, and the PV connection location.

For all simulations (except those without any PV), we used a single PV interconnection point just downstream of the voltage regulator representing 3.6MW of PV. However, PV profiles were created two different ways:

1. Using the aggregate power output of the nearly 500 houses in Ota City.
2. Using the power output from only a single house.

The aggregate PV power from all houses in Ota City (Case 1) totaled approximately 1.8MW and so was multiplied by a factor of 2 to create the 3.6MW simulated PV output. The single house PV power (Case 2) was also linearly scaled to 3.6MW (using a scaling factor of approximately 900). This represents an unrealistic case, since in truth 3.6MW of PV would have significant smoothing over a single house. We present this scenario (Case 2), thus, as an extreme example of PV variability.

Load profiles measured at each house in Ota City were used. The aggregate load of all houses was used as the load profile at all points across the feeder. Ota City loads were multiplied by a factor of approximately 8.5 to match the actual maximum load of the agricultural feeder used. To better balance changes to PV and load timescales, all load upstream of the voltage regulator (peak load 3.6MW) was fixed at 15-minute resolution. Timescales of load downstream of the regulator (peak load 5.0MW) were varied.

All load and PV data was measured at 1-second resolution. To simulate lower resolutions, the 1-second data was averaged and then linearly interpolated, representing the case where a utility SCADA system logs a time-average (e.g., 15-minute or 30-minute) of load, or a PV inverter logs only the time-average of its output.

A. Load Only

Figure 5 shows the number of voltage regulator tap change operations found with varying load timescales but no PV on the feeder. 5s, 30s, and 60s resolution load timeseries produce almost identical numbers of tap changes: all match to within 1%. This makes sense since the voltage regulator's time constant is 45s. For resolutions worse than 60s, differences from the 5s case become larger. The longest timescale resolution, 3600s (1-hour), results in a 13% underestimation of the number of tap changes.

The high number of tap changes found for Ota City (average of more than 20 per day) is due to the load profile having both a morning and an afternoon peak (Figure 1). The voltage regulator follows the load up and down twice per day.

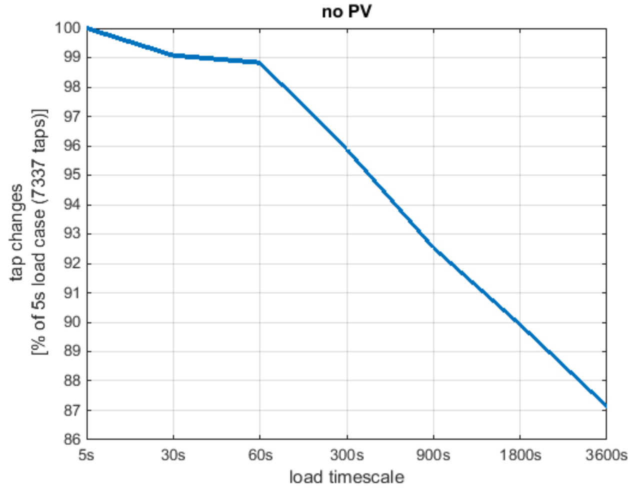


Figure 5: Voltage regulator tap change operations as a function of load resolution, normalized by the number of taps for 5-second load.

The underestimation of tap changes when using lower resolution (longer timescale) data is caused by the smoothing of the data. Extreme values (local maximums and minimums) in the 5-second data are less extreme when longer timescale averages are used. This is seen visually in Figure 6, which shows the power through the regulator and the regulator tap position for the two hours surrounding the annual peak load on the feeder. The maximum power through the regulator is 4.955MW for 5-second resolution load but only 4.484MW for 1-hour resolution load. This results in several fewer tap changes up and then back down to follow the load.

This smoothing of the data occurs because we assumed that low-frequency data was created by sampling at high frequency and then averaging to record a low-frequency value. If instead instantaneous (rather than average) values were collected at low-frequency, more tap change operations would be found. However, due to aliasing effects, this may result in too many tap changes being simulated, as a short (e.g., 5-second duration) excursion may be sampled and result in a tap change, even though the duration of the excursion is shorted than the voltage regulator time constant and would not have actually caused a tap operation.

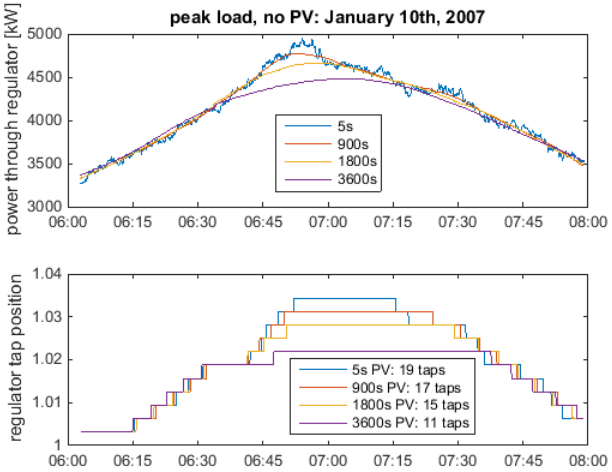


Figure 6: [Top] Power through voltage regulator and [Bottom] regulator tap position for different resolutions of load data, with no PV.

B. *Impact of PV*

When PV is considered, the simulated number of tap change operations depends on both the resolution of load and the resolution of PV data used. Figure 7 shows how PV timescale can impact simulated voltage regulator operations. Both Case 1 (PV data based on aggregate of all houses) and Case 2 (PV data based on a single house) are presented in Figure 7. The 5-second PV in Case 1 is smoother than in Case 2 due to the spatial smoothing that occurs when aggregating over all house. However, for this example day, there is little difference in tap change operations between Case 1 and Case 2. The significant difference in tap changes observed for 5-second PV data versus 900-second PV data on a variable day is evident for both Case 1 and Case 2 in Figure 7.

Compared to load, PV variability has the ability to cause more tap changes in a short time period. The taps caused by changes in load (Figure 6) generally slowly move in the same direction, with a few inflections per day corresponding to morning and evening load peaks. PV variability, though, can cause many taps up and down and back up over a short period (<1 hour). However, the impact of PV variability by (a) clear days when there is little PV variability and (b) nighttime when there is no solar resource and hence no solar variability.

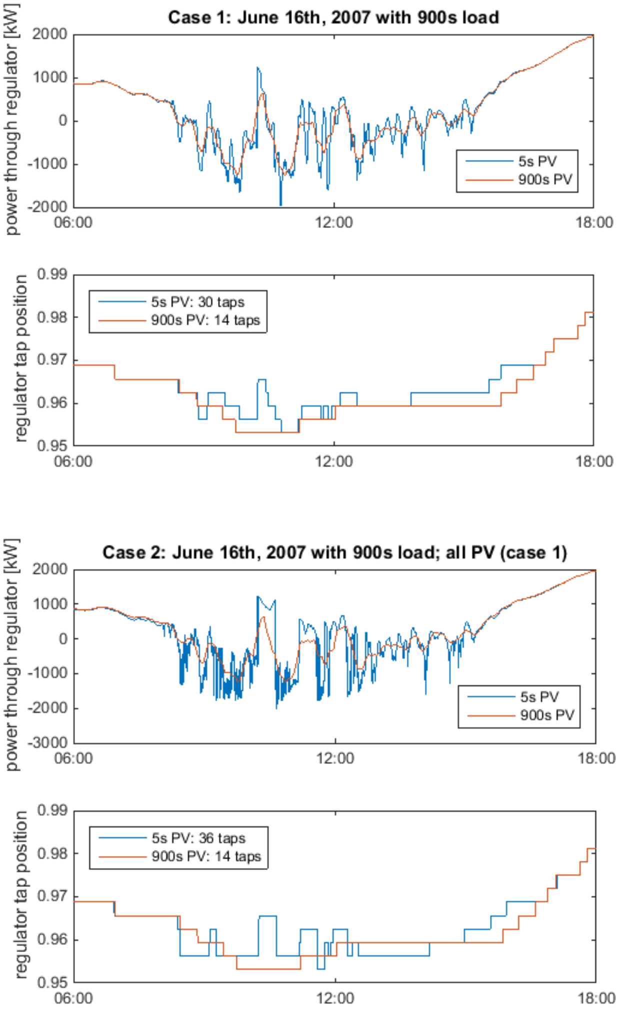
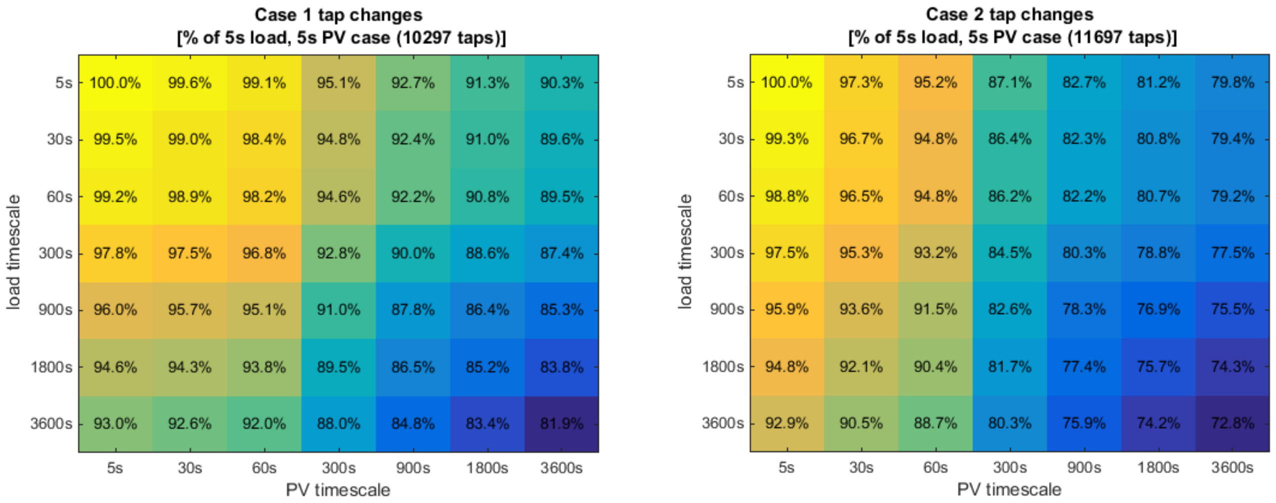


Figure 7: Power through voltage regulator and regulator tap position for different resolutions of PV data, all using 900-second load data. [Top two plots] Case 1 based on aggregate PV at all houses in Ota City and [Bottom two plots] Case 2 based on PV output at a single house.

C. *Load and PV Interdependence*

The coupled impact of PV and load data resolution on number of simulated tap changes in shown in Figure 8, for both Case 1 with PV based on the aggregate of all houses in Ota City, and for Case 2 where PV is based on a single house. The number of tap changes for the 5-second load, 5-second PV case was 13.5% larger for Case 2 compared to Case 1. This difference is due to PV smoothing from spatial diversity, and shows the importance of accounting for spatial smoothing of PV in distribution grid studies. This is consistent with previous studies (e.g., [7, 12]). .

In Case 1, there is a similar impact from using-low resolution PV data as from using low-resolution load data. When load data is fixed at 5-second resolution, 9.7% less taps are simulated for 5-second PV data versus 3600-second PV



Case 1 tap changes [% of 5s load, 5s PV case (10297 taps)]

load timescale \ PV timescale	5s	30s	60s	300s	900s	1800s	3600s
5s	100.0%	99.6%	99.1%	95.1%	92.7%	91.3%	90.3%
30s	99.5%	99.0%	98.4%	94.8%	92.4%	91.0%	89.6%
60s	99.2%	98.9%	98.2%	94.6%	92.2%	90.8%	89.5%
300s	97.8%	97.5%	96.8%	92.8%	90.0%	88.6%	87.4%
900s	96.0%	95.7%	95.1%	91.0%	87.8%	86.4%	85.3%
1800s	94.6%	94.3%	93.8%	89.5%	86.5%	85.2%	83.8%
3600s	93.0%	92.6%	92.0%	88.0%	84.8%	83.4%	81.9%

Case 2 tap changes [% of 5s load, 5s PV case (11697 taps)]

load timescale \ PV timescale	5s	30s	60s	300s	900s	1800s	3600s
5s	100.0%	97.3%	95.2%	87.1%	82.7%	81.2%	79.8%
30s	99.3%	96.7%	94.8%	86.4%	82.3%	80.8%	79.4%
60s	98.8%	96.5%	94.8%	86.2%	82.2%	80.7%	79.2%
300s	97.5%	95.3%	93.2%	84.5%	80.3%	78.8%	77.5%
900s	95.9%	93.6%	91.5%	82.6%	78.3%	76.9%	75.5%
1800s	94.8%	92.1%	90.4%	81.7%	77.4%	75.7%	74.3%
3600s	92.9%	90.5%	88.7%	80.3%	75.9%	74.2%	72.8%

Figure 8: Voltage regulator tap change operations as a function of load and PV data resolution, normalized by the number of taps for 5-second load, 5-second PV, for [Left] Case 1 where PV is simulated based on aggregate PV output of all houses in Ota City and [Right] Case 2 where PV is simulated based on PV output from a single house.

data. Similarly, when PV data is fixed at 5-second resolution, there is a 7% difference in taps simulated for 5-second versus 3600-second load resolution. Note this 7% (721 tap) difference is smaller than the 13% (954 tap) difference between 5-second and 3600-second load data found for the no PV case. This may be explained by slight correlation in load and PV production, especially in spring and fall months when PV can help reduce the evening load peak.

Overall, differences from the base 5-second load, 5-second PV case are small. Using 15-minute load with 5-second PV only results in a 4% “error” (difference from base case) in tap changes. Using 15-minute load and 15-minute PV still capture 87.8% of the base case taps. This may be comparable with other errors expected in distribution grid simulations (e.g., magnitude of load, predicted amount of PV, etc.).

Case 2 shows more impact from changing PV resolution, since Case 2 has more PV variability. When load is fixed at 5-second resolution, a greater than 20% difference is found between 5-second and 3600-second resolution PV data. Load resolution dependencies are more modest, having only a 7% difference between 5-second and 3600-second resolution, and are consistent with Case 1. Using 15-minute load with 5-second PV again results in only a modest (4.1%) difference versus using 5-second load. However, using 15-minute PV data with 15-minute load data results only capturing 78.3% of the higher resolution tap changes. This difference may be significant and shows that high-frequency data can be important to accurate distribution grid simulations.

V. CONCLUSION

High-frequency (1-second) load and PV power output measurements from Ota City, Japan were used to compare the impact of load and PV variability on distribution grid operations, specifically voltage regulator tap changes operations. Load variability was found to be larger than PV variability at a single house, but when aggregated over many houses, load variability was much smaller than PV variability. Aggregate PV variably is smoothed by spatial decorrelation of cloud edges; houses next to one another will be highly correlated, while houses further away will be less correlated. Aggregate load variability is smoothed since there is essentially no correlation in timing of loads in different houses turning on or off; neighboring houses are likely entirely uncorrelated. The lack of correlation of loads among houses leads to the larger reduction in variability when aggregated.

Load variability and two samples of PV variability (one based on aggregate PV output of all houses, the other based on PV output of a single house) were used as input to quasi-static time series (QSTS) distribution grid simulations. The resolution of the inputs was varied between 5-second and 1-hour. A small sensitivity to load timescale was found. In most cases, a load resolution of 15-minutes resulted in modest (<10%) differences from high resolution load. Similarly, modest differences were found when using low-resolution PV data based on the aggregate of all houses, though differences were aggregated and exceeded 10% when using both low-resolution load and low-resolution PV data. However, when using PV based on measurements from a single house (i.e., more PV variability), the impact of using low-resolution PV data is more significant: differences when using 15-minute or lower resolution PV data exceeded 17%.

Overall, this work shows that using low-resolution load or PV data can lead to errors in distribution grid simulations. The daily double-peak load profile seen at Ota City is expected to have emphasized the importance of load resolution. For single-peak daily load profiles, we expect PV resolution to have a larger impact on simulated number of tap change operations.

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