Analysis of the Impacts of Distribution-Connected PV Using High-Speed Data Sets

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Analysis of the Impacts of Distribution-Connected PV Using High-Speed Data Sets

Jason Bank, *IEEE Member*, Barry Mather, *IEEE Member*

Abstract -- **High penetrations of distribution-connected photovoltaic (PV) systems are becoming more common. However, the impact of these variable generators on system voltage and automatic voltage regulation equipment is not well quantified. In contrast to load, which generally has some diversity, PV systems are often non-diverse over small geographic areas. Variability caused by PV can range from relatively slow changes in system voltage to high-frequency impacts on real and reactive power. These changes have the ability to impact the operation of a distribution circuit from a protection, voltage control, and load prediction/modeling point of view.**

This paper utilizes information from high resolution data acquisition systems developed at the National Renewable Energy Laboratory and deployed on a high-penetration PV distribution system to analyze the variability of different electrical parameters. High-resolution solar irradiance data is also available in the same area which is used to characterize the available resource and how it affects the electrical characteristics of the study circuit. This paper takes a data-driven look at the variability caused by load and compares those results against times when significant PV production is present. Comparisons between the variability in system load and the variability of distributed PV generation are made. Additionally, the potential impacts of high-penetration PV on voltage regulation equipment such as capacitor banks and load tap changing transformers are quantified.

I. Introduction

The Anatolia SolarSmart Community is a neighborhood southeast of Sacramento, California. It is an area in which each house has been built with highly energy efficient home features and an average of 2.5 kW of PV on each house. Because of this high concentration of PV generation the Sacramento Municipal Utility District (SMUD) has several ongoing research projects in this neighborhood and distribution circuit. In order to support these research efforts the National Renewable Energy Laboratory (NREL) has been developing measurement devices and a supporting data collection network specifically targeted at distribution systems. This measurement network is designed to apply real-time and high-speed (sub-second) measurement principles to distribution systems that are already common for the transmission level in the form of phasor measurement units (PMU) and related technologies. Twelve of these meters have been installed on distribution transformers in the Anatolia neighborhood and voltage, current, and power measurements have been collected at a resolution of one second, covering almost two years. This paper aims to mine these extensive data sets to investigate some of the impacts high-penetration PV has been having on this distribution circuit; specifically, the relative diversity factors of load on the circuit and PV generation at various points of aggregation and the impact on automatic voltage regulation equipment, both at the distribution and sub-transmission level.

II. Metering Devices and Source Data

A. Distribution Transformer Metering

Over the past few years NREL has been developing high-speed, real-time metering hardware targeted specifically for installation at the distribution level [1],[2],[3]. These meters implement phasor calculations and communications architecture similar to that of PMUs [4],[5]. Additionally, these units include support for several power quality calculations. These meters are referred to as Distribution Monitoring Units (DMU) throughout this paper.

Design of the DMUs has been specifically targeted for installation at remote and disparate points within a distribution circuit, particularly at customer service voltage levels. The DMUs are equipped with a cellular modem that provides an Internet connection through the network of a cellular provider. Data is collected on a point-by-point basis in real time through this Internet connection. Servers at NREL are responsible for aggregating, correlating, and storing all of these data sets.

A picture of a DMU installed on the secondary of a transformer in Anatolia is shown in Fig. 1. Each of the voltage clips has been attached to the two hot and the neutral Z-bars, and the current sensors are attached around the conductors going out to the homes. The DMU also requires an antenna for its GPS and cellular connections. In this case, a black hockey-puck style combination antenna was mounted to the top of the transformer case.

NREL in conjunction with SMUD has deployed 12 DMUs on the secondary side of 50 kVA and 75 kVA pad mount, split-phase residential transformers in the Anatolia neighborhood. DMU installation in this community began in March 2011, with installations taking place in several waves since that time. The DMUs have been collecting one-second data since their install dates, all of which has been stored on the NREL servers and made available for project team members. The distribution transformers in the Anatolia community generally feed between 8 and 12 single-family homes.

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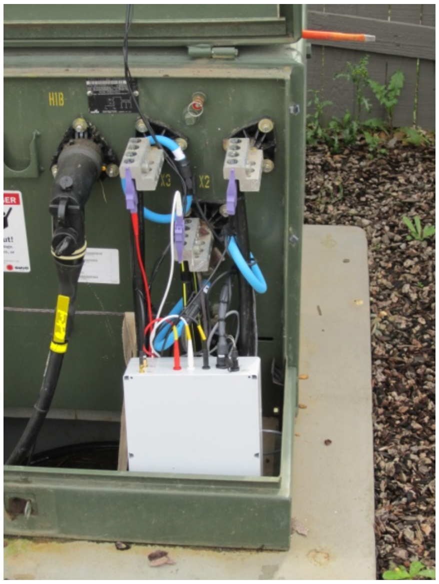

Fig. 1: DMU installed on a transformer secondary
Photo credit Jason Bank, NREL

B. Solar Resource Measurments

In addition to the above electrical metering, NREL has deployed a Global Horizontal Irradiance (GHI) sensor, weather station, and rotating shadow band radiometer (RSR) in the area of the Anatolia community. The GHI sensor provides one-second irradiance data and is situated at the north side of the neighborhood. The weather station and RSR provide one-minute data across several irradiance and environmental factors and are located about a mile to the northwest of the neighborhood in the Anatolia-Chrysanthy substation. Both of these units are part of the Measurement and Instrumentation Data Center (MIDC); more information on MIDC and publically-available data from several projects are available at *www.nrel.gov/midc*.

C. SCADA Data

Furthermore, data is being collected and stored through SMUD's SCADA system. The SCADA data used here is taken at the feeder level where it enters the Anatolia neighborhood. Three-phase RMS voltage, RMS current, and real power and reactive power measurements are available at five-second resolution at this point.

III. Power Spectral Density Analysis

The high-resolution metering which has been installed at the distribution transformer level in the Anatolia neighborhood gives valuable insight in the nature of the loads and PV generation in the area. The available one-second resolution on the power measurements gives incredible detail into the variable nature of both the load and PV. Many of these variable features are periodic in nature due to the cycling of household loads. The interaction of these elements determines the total load seen by the utility and is thus important for advanced load modeling and assessment of the impacts of variable distributed generation.

Previous works have applied the concepts of Fourier Transforms and Power Spectral Density (PSD) to assess the variable nature of load and renewable generation [6],[7],[8]. These methods are utilized in the analysis detailed in this paper.

This method was applied to a set of DMU data to provide an example of how to use this analysis and to demonstrate the results. The one-second real and reactive power measurements on August 16, 2012 from a transformer were used as the input data set. This transformer serves 10 single-family homes, so the measurements represent the summation of 10 residential customers. The results of the spectral analysis of this data are presented in Fig. 2. Here the higher order frequency terms from the Fourier Transform are truncated as they are of extremely low magnitude and primarily represent sampling and windowing error and show no discernible features.

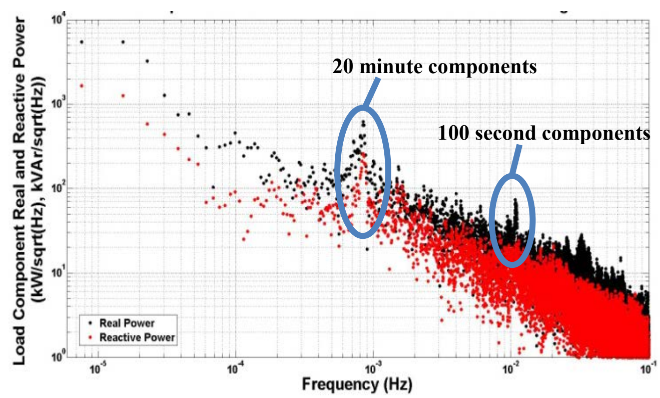

Fig. 2: Power spectra of transformer power measurements

The points to the far left of Fig. 2 represent the lower order, higher magnitude components of the load waveform, i.e. the daily load profile. There are few points in this region because of the limited size of the input data set (a single day). Points further to the right on the x-axis represent periodic loads of successively higher switching frequencies. The y-axis gives the power drawn by the corresponding load component. Here the real power components are plotted in black, and the reactive power in red. The thick band running diagonally through Fig. 2 represents components resulting from measurement noise, windowing error, and aperiodic load elements. Periodic components of the measurement waveform show up as spikes above this band at the appropriate frequency value.

Inspection of this plot reveals two distinct spikes below the daily load and PV profiles. The first of these represents periodic loads that switch at a period of about 20 minutes ($f \approx 8.5*10^{-4}$ Hz); both the real and reactive power demonstrate this behavior. The second feature is components with switching periods on the order of 100 seconds ($f \approx 1*10^{-2}$ Hz); in this case, only the real power demonstrates this spike with the reactive power remaining relatively consistent in this frequency span. Examples of the load components which are driving these features of the spectral density are given in Fig. 3 and Fig. 4.

Fig. 3 gives an example of the load behavior which is driving the frequency components with a 20-minute period. This time series plot is a subset of the data set used to construct the power spectra of Fig. 2. A 4 kW, 2 kVAr load is switching on and off throughout the 2-hour window with a period on the order of 20 minutes as expected. Given the time of year, the size of the load, and the period, this is most likely residential air conditioning loads.

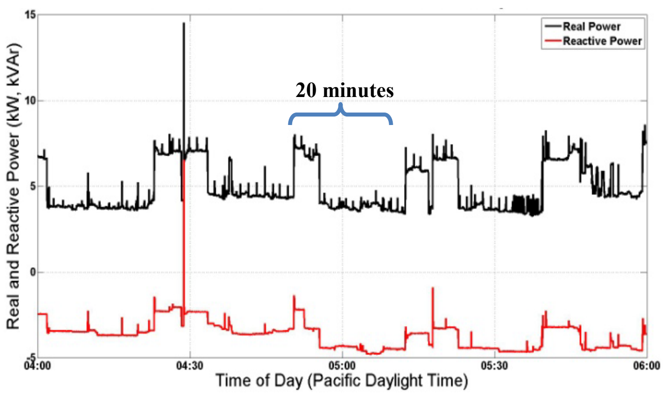

Fig. 3: Load component with 19-minute switching period

The other prominent component identified in Fig. 2 is a real power load switching at a period of about 100 seconds. Some of this behavior is demonstrated in the time series plot of Fig. 4. Over this 10-minute span, a load of about 5 kW is switching on and off on at a 100-second interval. Additionally the reactive power over this span is relatively constant with little correlation to the switching in real power, indicating that the load in question has no reactive component. Once again this reflects the results of Fig. 2 which showed a load switching with a 100-second period that draws real power but not reactive.

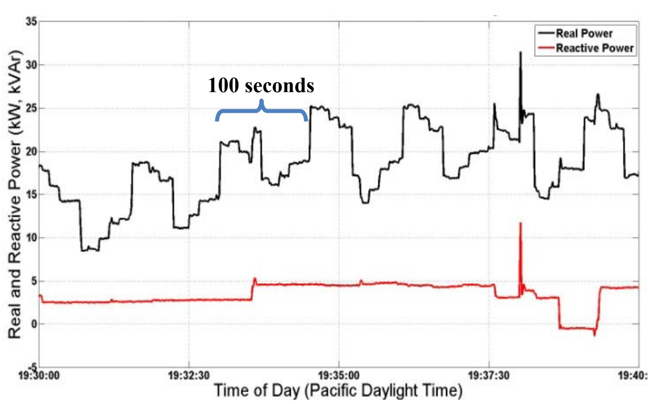

Fig. 4: Load component with 100 sec switching period

The frequency domain analysis, as demonstrated in Fig. 2, will be used throughout this paper to identify periodic features in the load and solar resource measurements. It is important to note that these load measurements represent the aggregation of 10 residential customers, so the periodic waveforms of Fig. 3 and Fig. 4 may not necessarily be one particular load but up to 10 similar loads switching in the same time frame. For example, the waveform of Fig. 3 may actually be up to 10 air conditioning units switching in the same time frame with each of the 'on' periods representing a different piece of physical equipment.

IV. Periodic Loads and Aggregation

The example data set demonstrated some of the periodic loads and how they are reflected in the power spectra. In that case, 1 transformer was considered which served 10 houses. In order to assess the effects of these components at the system level, several successively higher load aggregation levels were considered.

A set of data ranging from July 2 to July 8 2012 was chosen as the input. This particular set of days was selected because, during this time, the solar resource measurements demonstrated very little variability. The low variability in irradiance should give a consistent PV output in the area and limit the short term variability to only effects caused by loads.

Data from 10 of the distribution transformers and the SCADA measurement point are available from this time span. The measured real power waveforms for all for these locations are used as the input data for the following power spectral analysis. The power spectra were computed for four different load waveforms representing different aggregation points of the load. These power spectra are given in Fig. 5. The black trace in Fig. 5 is the power spectra of a single transformer. The red trace is the power spectra of five transformers, with their power measurements summed on a point-by-point basis to produce the input for the Fourier Transform. The power from 10 transformers is summed to produce the spectra given by the green trace. Finally, the blue trace gives the power spectra for the entire Anatolia neighborhood, as measured by the SCADA point, representing about 70 transformers. In order to put these results on the same vertical scale, all of the measurement data was normalized before performing the Fourier Transform. Thus, in Fig. 5 the vertical axis does not give the absolute power of the component, but its value as a percentage of the total power of the source signal.

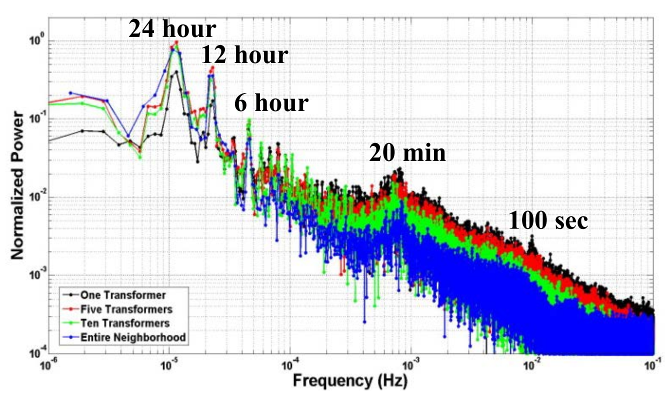

Fig. 5: Power spectra of load at multiple aggregation levels

Several prominent load components are prevalent in the power spectra of Fig. 5. The lower frequency components include load characteristics with 24, 12 and 6 hour periods. These represent the daily load profile, the daily PV production curves and other hourly trends. These components contain most of the power in the data set. The next major components are centered on a 20-minute period; these are the air conditioning loads discussed previously. While all 4 of the spectra demonstrate the 20-minute periodic load, they have a noticeable decrease in magnitude for larger aggregation levels. Finally, a 100-second periodic load is also present but is only noticeable in the single transformer data set.

The results of Fig. 5 demonstrate some of the effects of load diversity. The longer term load characteristics in the 24, 12 and 6 hour regions have successively higher magnitudes for larger aggregations of load. On the other end of the scale, the single transformer demonstrates that more of its power is concentrated in shorter term, more variable load components. As more and more transformers are included, the effects of smaller, variable loads are less prominent. Additionally, similar periodic loads may be out of phase with each other, effectively offsetting each other as more loads are included.

V. SEASONAL LOAD DIFFERENCES

Throughout the data sets presented so far, a 20-minute periodic load has been observed. Based on the size of the loads, the way they switch, and that the data has been from the summer months, it was claimed that these were residential air conditioning loads. In order to verify this, the power spectra for a set of real power SCADA data from January 2012 was computed. Once again, this data covered a week of clear days in order to limit the variability effects of the PV generation. This power spectrum is plotted in red on Fig. 6 against the previously-used spectra for the July SCADA data in black.

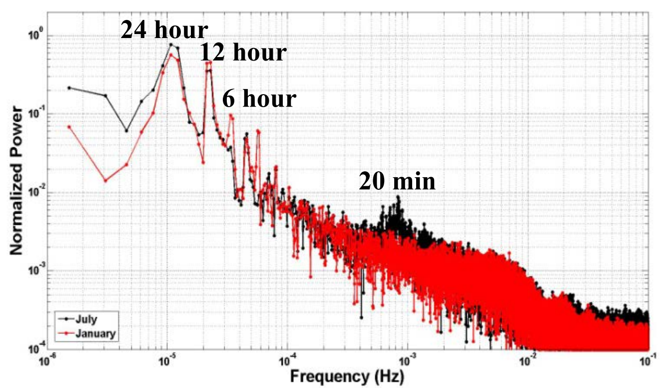

Fig. 6: Total load spectra in winter and summer

These two spectra track each other extremely closely and the only sizable difference occurs in the 20-minute region. The January measurement data shows no discernible spike at 20 minutes as the results in that region fall into the noise band. This is as expected, since there should be no air conditioning load running in January.

VI. EFFECTS OF PV VARIABILITY

The Anatolia neighborhood incorporates a large amount of rooftop PV generation. Each house in the community is built and sold with integrated solar panels. On average throughout the community, each home has 2.5 kW of PV. Across the community of 343 houses, a total of 867 kW of PV capacity is installed. The variable nature of the solar resource introduces another level of variability into this circuit through the PV generation.

Since the PV is installed on the customer rooftop level, both the distribution transformer and SCADA power measurements include the PV generation and the load netted together. To this point, clear sky days have been used for the analysis of load data to limit the impacts of solar resource variability on the results. In order to assess the impacts of solar resource variability, cloudy and clear days are compared. Here data sets from January are used because the winter months were found to contain the least variable load characteristics.

Seven clear days and seven cloudy days from between January 1 and January 18, 2012 were selected for analysis. One-second global horizontal irradiance measurements from the north side of the neighborhood were compiled and the resulting power spectra were computed for this data. Fig. 7 presents these results, with the clear days plotted in red and the cloudy days in black.

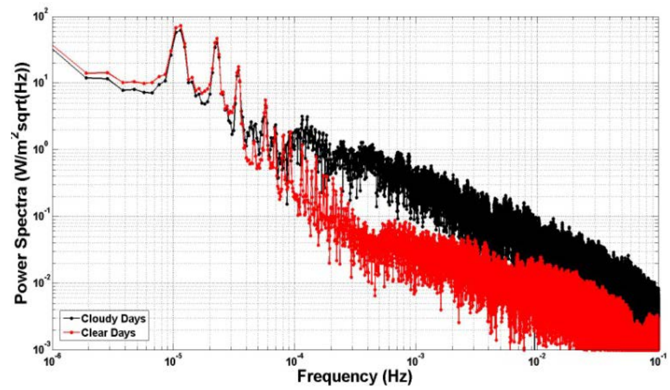

Fig. 7: Solar resource spectra for clear and cloudy days

As before, the 24, 12 and 6 hour components are prevalent in both trends and contain most of the power in the signal. To the right of these points, the two spectra become markedly different though. The cloudy day demonstrates significantly higher power throughout the 2.7 hour ($f \approx 10^{-4}$ Hz) to 10 sec ($f \approx 10^{-1}$ Hz) band. This indicates significantly higher resource variability on the cloudy and overcast days as expected. Neither spectrum has any prominent spikes in this region though, indicating the random, aperiodic nature of the cloud passage through this area.

The effect of the PV variability can be seen at the neighborhood level through the SCADA measurements. In Fig. 8, the spectra of the SCADA real power measurements is plotted in black for the cloudy days and in red for the clear days. The cloudy days demonstrate more power in the 2.7 hour ($f \approx 10^{-4}$ Hz) to 20 sec ($f \approx 5*10^{-2}$ Hz) band than the clear days do.

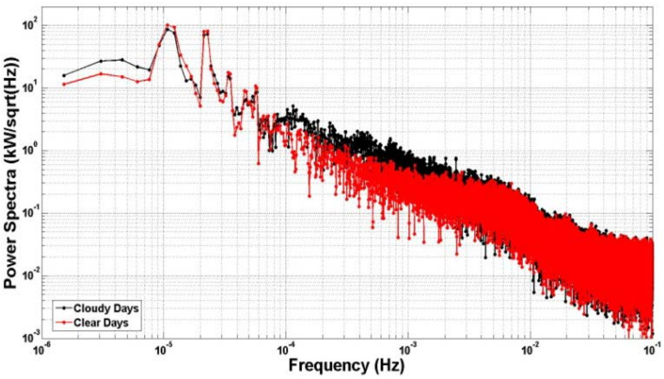

Fig. 8: Power spectra of SCADA data on clear and cloudy days

Given the small area covered by this neighborhood, less than half a square mile, the irradiance throughout should be highly correlated and non-diverse. With all the PV panels experiencing very similar solar resource, the variability in irradiance should be well correlated with the variability in total power of the neighborhood. Up to a point, this is seen in Fig. 7 and Fig. 8; while the clear (low PV variability) and cloudy (high PV variability) days show drastic difference between the irradiances in Fig. 7, these differences are still present in Fig. 8 but are not as pronounced.

While the available resource is non-diverse across the neighborhood, several other factors are at play which can serve to limit the variability of the PV seen at the system level. The solar panels throughout the area are all roof-mounted on the homes and thus do not all have the same orientation, with most ranging from southeast facing to southwest. This diversity in PV panel orientation serves to lessen the impacts of non-diverse global horizontal irradiance as each panel is receiving slightly different incident irradiance. Additionally, the load in the neighborhood is being netted against the PV generation before the measurement point and thus makes up a smaller percentage of the total signal power, reducing its prominence in the spectra of Fig. 8.

VII. Effects on Voltage Control Elements

The impact on automatic voltage regulation equipment such as voltage regulators located on a distribution circuit, as well as load tap changing transformers and switched capacitors located at a distribution substation, has been previously studied through the simulation of circuit operation [9]. In this section, analysis of the high-quality data sets from the Anatolia neighborhood is used to gain an insight into how the variable nature of PV systems' generation profiles impact the automatic voltage regulation equipment used to regulate the voltage on the distribution circuit. The analysis, described below, aims at developing a proxy for the general control profile of the load tap changing transformer and switched capacitor banks located at the Anatolia-Chrysanthy substation. The distribution circuit does not have a voltage regulator or switched capacitors located on the distribution circuit itself.

A. Description of Data Analysis used to Approximate the Impact of PV Variability on Automatic Voltage Regulation Equipment

Data was available for a total of 12 distribution transformers located in the Anatolia neighborhood. Each of these distribution transformers is connect to a single phase of the medium voltage three-phase system, and of the 12 units, 6 are connected to phase A, 5 are connected to phase B, and 1 unit is connected to phase C. Note – these phase assignments are somewhat arbitrary relative to the rest of the utility distribution system but will be used in the description of this analysis for simplicity.

The goal of the data analysis was to develop an approximate waveform representing the control actions taken by automatic voltage regulation equipment. The analysis started with the determination of relatively large instantaneous voltage changes for each of the 12 DMUs. Fig. 9 shows an example of an instantaneous voltage change that occurred on all three phases on September 26, 2011 at about 11:47 p.m. This voltage change magnitude is approximately 2 V_{AC} across the 240 V_{AC} secondary winding on the split-phase distribution transformer. It is likely that this voltage step is due to a capacitor bank switching off at the substation, as the circuit load decreases in the late evening and voltage support from the capacitor bank is no longer needed. To determine voltage changes, the secondary winding voltage for the DMUs was processed using a forward-looking and backward-looking, 5-second box-car moving average. One of the 5-second moving averages processed the past 5 seconds of voltage data, whereas the other averaged the subsequent 5 seconds of data. This data was then analyzed point-by-point, and if a voltage difference greater than 1 V_{AC} was observed between the two 5-second averages, then a significant voltage regulation action may have occurred and an event was recorded noting the time at which the event occurred and the magnitude of the event.

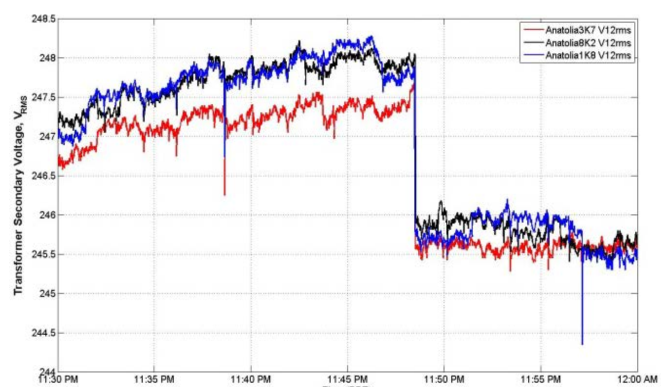

Fig. 9: Plot of the three-phase voltage on the Anatolia distribution system for an instantaneous voltage step

In order to separate normal load events causing significant voltage changes on the measured distribution transformer, such as AC units cycling off and on from the voltage changes expected due to the action of an automatic voltage regulation device, it was necessary to correlate instantaneous voltage change events between various DMUs on the circuit. In this study, the data was processed such that a significant automatic voltage regulation control action was "detected" if 4 of the 6 phase A units, 3 of the 5 phase B units and the sole phase C unit all experienced an instantaneous voltage change within three seconds of each other. It was necessary to allow some variation in event timing due to the five-second backward- and forward-looking moving averaging used to detect significant voltage changes, which added some time skew to the analysis.

The data analysis steps described above identify voltage regulation actions that take place on all three phases at the same time. The types of devices in which control actions would likely be recorded by this type of analysis are the switched capacitors at the substation and gang-operated, load tap changing transformers. As the circuit being studied has a non-ganged (single-phase voltage control) load tap changer, the only control action that should be detected on the circuit is the switched capacitor banks located at the substation. The control of these capacitor banks is described in [10]. Generally speaking, the capacitors are switched to support the VAr requirements of the local loads and to support the sub-transmission voltage.

B. Results from Automatic Voltage Regulation Equipment PV Impact Analysis

The analysis completed attempts to compare the three-phase control action of the automatic voltage regulation equipment on the circuit for both clear days, when PV systems would be generating a predictable amount of energy, and cloudy days when the impacts of variable power generation due to PV would be noticeable. Fig. 10 shows the relative amount of voltage regulation, for all three phases, for a very clear weather week from July 2-8, 2012. The daily voltage control action due to both the daily load curve of the neighborhood along with the smooth PV generation profile is evident. There is a small uptrend in the voltage regulation control waveform, meaning that the data analysis captures more positive voltage step changes than negative voltage step changes over the week. This small trend does not significantly affect the frequency of this signal for the frequencies of interest.

Fig. 11 shows the relative voltage regulation waveform for a comprised week of cloudy days. The weather in Sacramento in the summer is generally clear so an entire week of cloudy weather data was not available. Instead, individual cloudy days were merged into a single week long data set. The days included in the analysis include days from June 4 through August 14, 2012. The relative voltage regulation actions during the cloudy days are markedly different than in the clear days shown in Fig. 10. Some days show more erratic control behavior as would be expected due to relatively high-frequency PV variability across the neighborhood. The entire week shows that the range of voltage control, as measured by the data analysis method described above, is lower than the week of clear data analyzed. No long-term trend is present in this waveform as each day, since they are not contiguous, starts at a relative voltage regulation of 0 V_{AC} at 12:00:01 a.m.

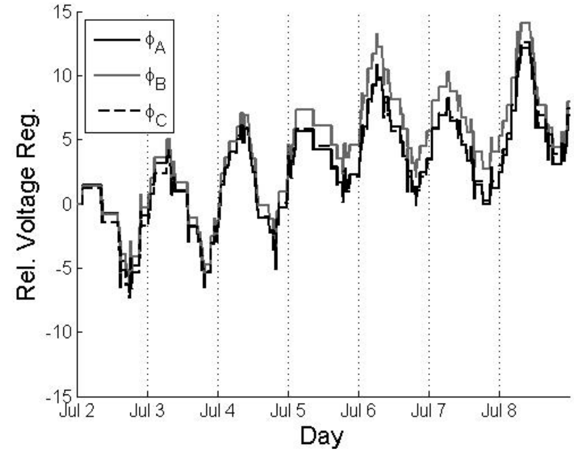

Fig. 10: Relative voltage regulation control waveform for a week of clear weather from July 2-8, 2012

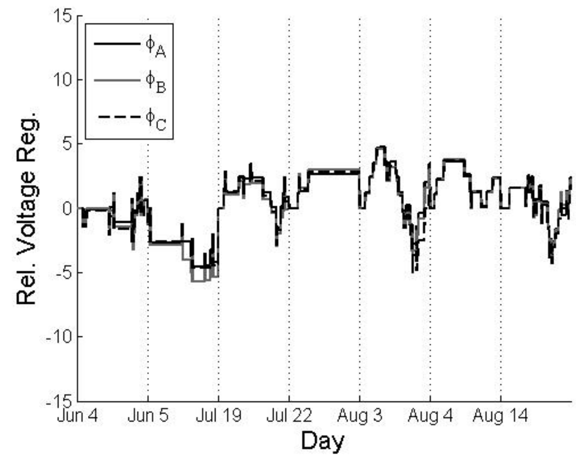

Fig. 11: Relative voltage regulation control waveform for seven days of cloudy weather that occurred between June 4 and August 14, 2012

As described in Section III, a power spectral density analysis was completed for the weekly relative voltage regulation waveforms shown in Fig. 10 and Fig. 11. The result of this power spectral density analysis is shown in Fig. 12. Additionally, in order to investigate the frequency components of a single cloudy day more accurately, a power spectral density of a typical cloudy day (August 3, 2012) was calculated and is shown in Fig. 12. As expected, more power is distributed at higher frequencies for the automatic voltage regulation equipment's actions on cloudy days than for the clear days. This means that automatic control equipment is switching more often during these times due to PV variability or other load variability due to weather, which was not taken into account in this analysis. Additionally, the typical cloudy day represented by August 3, 2012 shows again that the power at higher frequencies and even at some relatively lower frequencies around $5*10^{-5}$ Hz are increased. Also, the variability of the power of the voltage regulation action is broadened at higher frequencies.

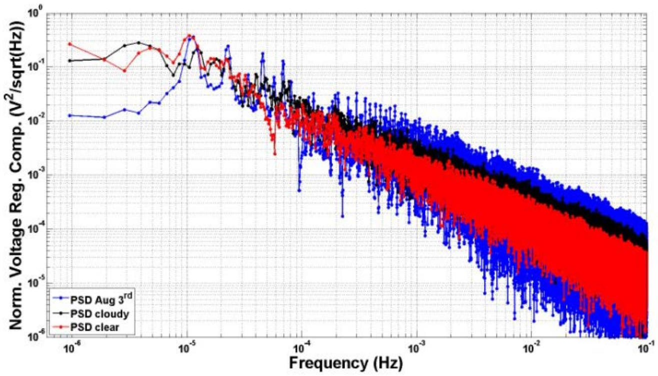

Fig. 12: Power spectra of the relative voltage regulation control waveforms

VIII. Conclusions and Future Work

High-resolution data has been and continues to be collected in SMUD's Anatolia distribution circuit. This community represents an area with high penetrations of distributed rooftop PV generation. The detailed nature of the data sets, both spatially and temporally, provides an excellent resource for assessing the grid impacts of distributed, variable generation. In this paper, power spectral density analysis has been applied to load and irradiance data in order to assess the nature of their variability from a frequency domain perspective. Using PSD analysis, several system characteristics have been identified. These include the identification of specific periodic loads, the spectral density of solar resource variability, and how that affects the net load seen by the utility. Finally, the effect of added PV variability on voltage regulation equipment was analyzed.

Several ongoing related works are underway for this particular distribution circuit. Data collection in this area continues and new data sets are being compiled and processed. More complete spectral density analysis is being performed covering the entire data set as opposed to the few weeks covered in this analysis. This includes breakdowns for both seasonal and weather-related changes as they relate to both load and PV variability. This circuit also contains battery installations at the residential and distribution transformer levels as part of an ongoing demonstration project [11]. Future work with the power spectral analysis aims to quantify the effects that the battery firming algorithms are having on reducing the overall system variability.

IX. Acknowledgment

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XI. Biographies

Jason Bank received his B.S., M.S., and Ph.D. degrees in Electrical Engineering from Virginia Tech in 2004, 2006, and 2009 respectively. Graduate research topics in the power systems field included transmission-level dynamics, electromechanical wave propagation, wide-area measurements, data collection, and analysis. Work experience in these areas includes positions at ABB corporate research, and Oak Ridge National Laboratory.

He began working at the National Renewable Energy Laboratory in February 2010. Current research efforts focus on the continuing development of high-speed, real-time, distribution-level data collection networks. Of particular study interest are those circuits containing high penetrations of distributed generation, PV, and smart grid technologies. He is an IEEE member.

Barry Mather earned the B.S. degree in Electrical Engineering in 2001 from the University of Wyoming, and M.S. and Ph.D. degrees, also in Electrical Engineering, in 2008 and 2010 respectively from the University of Colorado Boulder. Since March 2010, Barry has worked in the Distributed Energy Systems Integration Group at the National Renewable Energy Laboratory in Golden, Colorado where he researches the impacts of high-penetration PV integration on distribution systems and leads the Southern California Edison High-Penetration PV Integration Project.