Effects of high penetration levels of residential photovoltaic generation

Observations from field data

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***Abstract*— Photovoltaic (PV) generation technologies, often deemed a viable solution for reducing greenhouse gases and decreasing electricity demand, have become increasingly prevalent in their deployment. Particular progress in their implementation has been evidenced in residential areas characterized by rooftop-mounted PV arrays. Aside from the known advantages provided by residential PV generation, one noteworthy disadvantage confronting the electric utility is the degradation of power factor when grid-tied PV sources are extensively integrated into the electrical distribution system. In this paper, the effect of PV sources on power factor is studied using recorded field data from a residential community that is part of a large-scale smart grid demonstration project in Austin, Texas.**

Keywords-Pecan Street; photovoltaic; power factor; PV; residential; solar; utility

I. Introduction

Fossil fuel scarcity and escalating environmental concerns have been instrumental in promoting power generation from renewable energy sources such as photovoltaic (PV) systems. Extensive integration of PVs into electric distribution systems has been a long-standing objective for realizing the next-generation electric grid.

Much attention in literature has been directed toward issues associated with high penetration levels of PVs in electrical distribution systems. The size and location of PV systems has been shown to be important in determining whether or not they may cause a significant impact on feeder voltage and power levels [1]. In [2], a load-flow analysis was performed using load and generation data to suggest that at very high penetrations of PVs, network voltage rises are small and unlikely to cause problems. Concerns related to the stability and security of the power system have also been explored, as models have been developed to reflect the dynamic behavior of PV generating units following either slow or sudden changes in both irradiance and ac grid voltage [3]-[6].

Renewable energy sources such as PVs may impose reliability challenges as well, for which methods have been proposed to evaluate the reliability of power systems containing renewable sources [7]-[9]. Particular attention in [10] is given to reactive power constraints in reliability evaluation techniques of such power systems, and findings suggest that PV sources in the network may reduce reactive power demand but only when they are placed in an adequate location. However, in most practical applications, utilities do not have the authority to decide where PV installations will occur. Hence, the question about the effect of high penetration PV deployments on the electric grid in terms of power factor remains. As a result, the objective of this paper is to observe power factor degradation resulting from high penetration levels of residential grid-tied PV systems.

A distinct aspect of this work is that the discussion is based entirely on recorded (i.e., real) residential power consumption and PV generation data. The data are obtained from a demonstration project in an urban development (Mueller) in Austin, Texas (TX) that is part of a large-scale smart grid initiative, called Pecan Street, Inc. [11]. Within the Mueller community, shown in Fig. 1, approximately one quarter of the nearly 800 homes have grid-tied PV systems. This is a large concentration of PV systems in a single urban area. In addition to the real data, this study is supported by a large computer model of the *entire* Mueller community distribution system in *MATLAB/Simulink*.

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Figure 1. Aerial view of a portion of the Mueller community showing many homes with rooftop PV arrays.

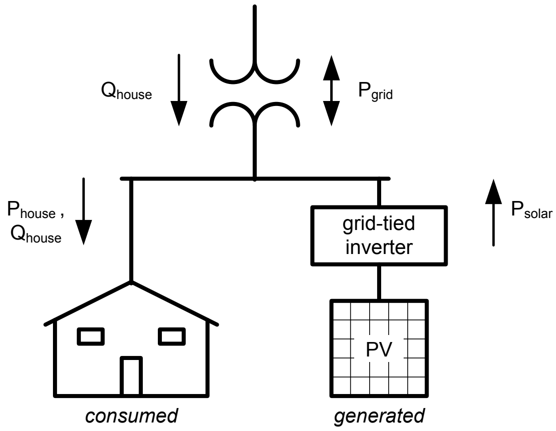


Figure 2. Aggregate power flow behind a residential distribution transformer in presence of PV generation. (All homes and PVs behind transformer are shown in aggregate form.)

II. Motivation

A depiction of the real (P) and reactive (Q) power flow in a residential setting with grid-tied PV installations is shown in Fig. 2. The household load and PV generation are aggregate representations of the assets downstream of a distribution transformer (i.e., at Mueller, there are typically eight homes behind each transformer, of which only a few have PVs). P_{house} represents the real power consumed by all homes together, Q_{house} the reactive power consumed by all homes, P_{solar} the power generated by all PVs, and P_{grid} the *net* power provided from the grid (i.e., $P_{grid} = P_{house} - P_{solar}$). It is important to note that when supplied PV power exceeds residential power demand ($P_{house} < P_{solar}$), the real power flows in the reverse direction: from the homes towards the grid. This bidirectional power flow is indicated by the double-headed arrows in Fig. 2.

Residential grid-tied PV inverters normally operate at unity power factor ($PF = P_{solar} \Big/ \sqrt{P_{solar}^2 + \left(Q_{solar}^2 = 0\right)} = 1$) as they only produce real power [2], [10], [12]. As a result, a large portion of the real power demanded by the households is provided from the PVs, whereas the reactive power is provided from the grid. Consequently, the utility experiences low power factors at the input side of distribution transformers in areas with high penetration of PV resources. It is relevant to point out that harmonic content injected by grid-tied PV inverters is typically small, and thus, harmonic content does not have a noticeable contribution to power factor measurements.

The Mueller site, which is continually expanding in both area and in number of residences, is currently fed from two 12.47 kV three-phase laterals emanating from two different substations. At the time of this study, there are 735 homes at Mueller—all of which were included in the computer model. Of these 735 homes, 178 are fitted with PV arrays. The 735 homes are supplied through 94 single-phase pad-mount distribution transformers of ratings 25, 50, 75, 100, or 167 kVA. These transformers have a 7.2 kV (line-to-ground) primary and a 240 V split-phase secondary voltage. The substations, cables (single-phase and three-phase), and distribution transformers were all modeled using the *SimPowerSystems* blockset in *MATLAB/Simulink*. The simulation *type* was a phasor-based simulation with a 1-minute time step interval to match the recorded data intervals. The simulation timespan was set to 24 hours or 1,440 minutes.

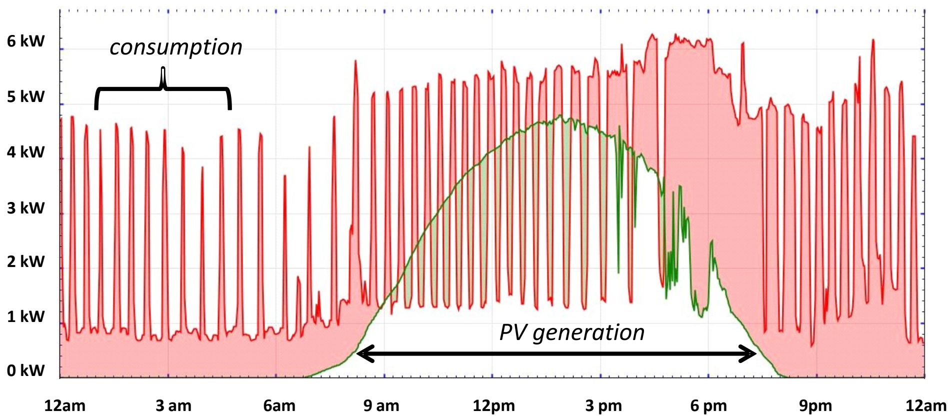


Figure 3. Household real power usage and generation for a single home on a summer day at Mueller. The time granularity is in one-minute intervals. (Source: Pecan Street, Inc.)

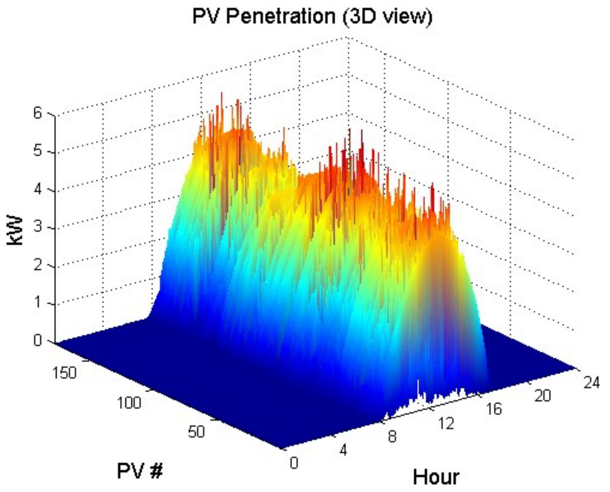


Figure 4. PV generation profiles of 178 homes. (The PV arrays, which vary in size, comprise a combination of west- and south-facing panels.)

III. DATA

Homes selected to be involved in this research project are fitted with monitoring equipment that capture power consumption and PV power generation in 1-minute intervals. (The equipment is located between the utility meter and a home's service panel.) An example of this data, which is readily available to Pecan Street researchers and consortium members, is shown in Fig. 3. For the day shown, consumption peaks near 6 kW, while generation near 5 kW. The recurring pulses in consumption behavior are attributed to air conditioning units cycling on and off. Additionally, PV generation is only available during daylight hours and is susceptible to fluctuations due to cloud passages. The data are used as inputs to the Mueller distribution system computer model developed in *MATLAB*/*Simulink*. Since power factor is not recorded by the installed equipment, at each time step of the simulation the power factor is estimated from [13]:

$$PF = \frac{I_1}{I_T}\cos\varphi = \frac{\cos\varphi}{\sqrt{1+THD^2}} \qquad (1)$$

where:

PF	power factor
I_1	fundamental current (rms Amps)
I_T	total line current (rms Amps)
THD	total harmonic distortion
φ	displacement angle between 240 V phasor and I_1

Equation (1) is computed for each home per each minute of data by assuming values for φ and *THD*. The power generation profiles for the 178 PV-bearing homes are depicted in Fig. 4.

IV. OBSERVATIONS

The aggregate consumption and generation of the entire Mueller community is shown in Fig. 5 for an arbitrary day, where *PF* is the power factor, and P_{house}, P_{solar}, and P_{grid} correspond to the nomenclature in Fig. 2. It is observed from Fig. 5 that high penetration levels of PV generation can significantly affect power factor, which in this case attains a value as low as 0.465. Equally notable, the power factor remains below 0.9 between 9:23 and 16:31. That is, although PV arrays contribute to reducing the peak power consumption during the critical daylight hours, they do so at the expense of reducing the power factor to levels too low to be compensated by conventional approaches.

Power quality phenomena such as power outages, voltage fluctuations, and steady-state disturbances cost the U.S. economy between \$120 billion and \$200 billion annually, according to studies conducted by the Electric Power Research Institute (EPRI) and the Department of Energy (DOE) [14]-

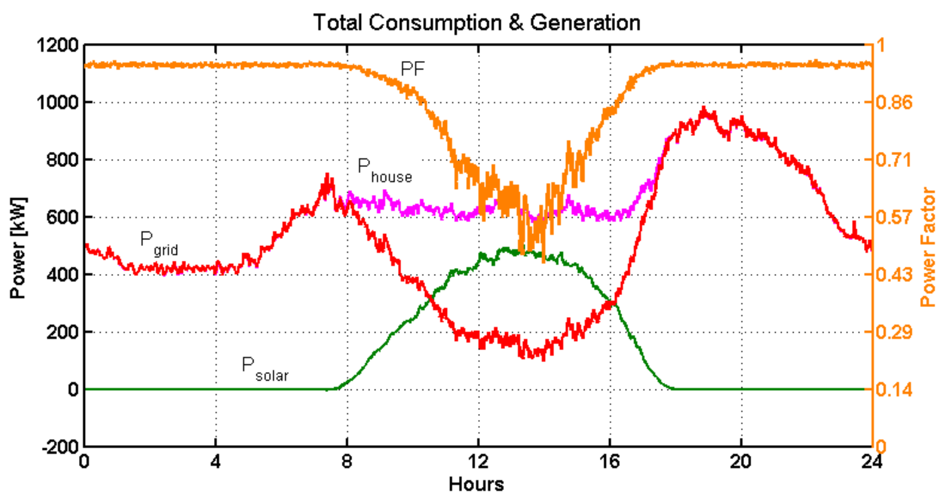


Figure 5. Total consumption and generation of Mueller community: 735 homes (178 homes with PV arrays).

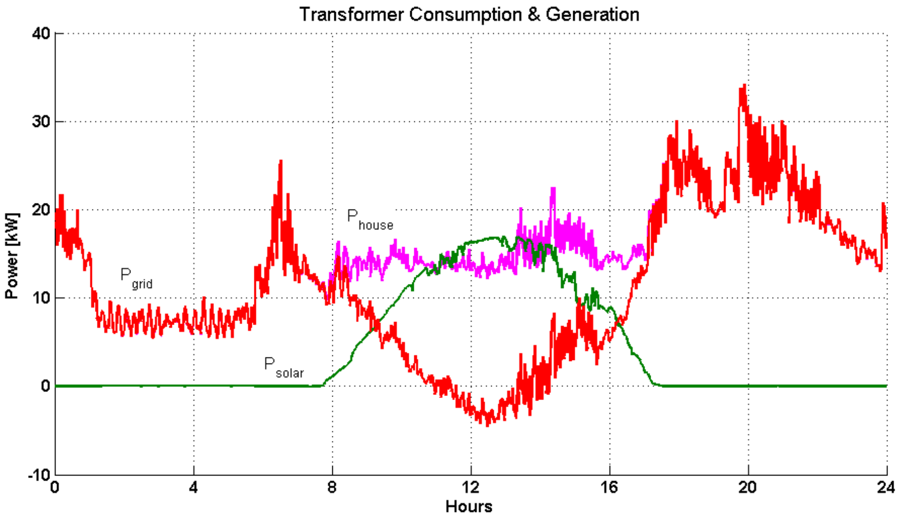


Figure 6. Reverse power flow experienced by a 75 kVA distribution transformer in Mueller serving 10 homes (4 homes with PV arrays).

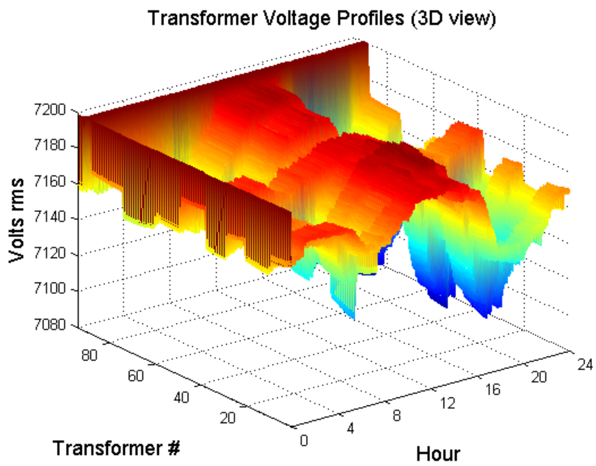
[17]. Furthermore, moderate penetration levels of distributed energy resources present interconnection issues for the electric power system, for which certain criteria and requirements are provided in accordance with [18]. When PV resources are integrated into a distribution system, the two-way power flow may, at times, be problematic for the utility as it inhibits the effectiveness of conventional voltage-regulating practices.

Within the Mueller area, several distribution transformers experience reverse power flow. When the ratio of PV-to-load is substantial, as observed in Fig. 6, the power generated by the PV arrays exceeds the demanded power. This causes real power to flow in the reverse direction between 10:57 and 14:17 up to a maximum value of 4.45 kW.

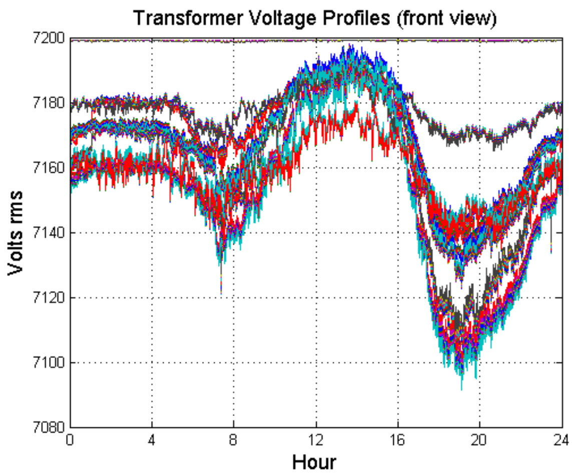
A particular consideration arising from widely deployed PV resources is to ensure that voltage levels are maintained within appropriate limits. The voltage supplied to consumers is an important metric as it indicates the service quality: a satisfactory voltage level is required for equipment such as lights and appliances in order to prevent inadequate operational characteristics. Higher voltage levels are undesirable because not only may they reduce equipment lifetime, but they may also increase power consumption without providing any noticeable improvement in performance. A voltage rise is to be expected when power is injected into a distribution system from the load side. This occurs because voltage drops along the power lines are reduced. Hence, it is possible that individual residential-scale PV systems adversely affect the voltage levels of other consumers.

The impact that PV arrays have on voltage levels in the Muller distribution system is depicted in Fig. 7. Although a voltage rise noticeably coincides with PV generation, voltage levels nevertheless satisfy the criteria prescribed by [19] in that they are within ±5% of nominal voltage (7.2 kV line-to-ground), and, therefore, do not warrant concern from a utility perspective.

Another issue deserving attention is the condition wherein the line voltages of a polyphase system are not equal,



(a)



(b)

Figure 7. Voltage profiles for all 94 transformers (primary sides). (a) 3D view. (b) Front view.

commonly referred to as a voltage unbalance. Voltage unbalance is primarily caused by the presence of single-phase loads on a three-phase system, particularly when the loads are distributed unevenly among the three phases. Since PV resources generate power on only one phase, they too can affect the balance between the three-phase voltages. Therefore, the combination of existing voltage unbalance in the system due to uneven single-phase load distribution, as well as uneven single-phase PV generation, contribute to an unacceptably high unbalance: a level specified as 2.5% to 3% or greater per [18] and [19]. The unbalance in voltage is obtained as the maximum deviation from the average of the three-phase line-to-ground voltages divided by the average of the three-phase voltages [19]:

$$V_{unb} = 100 \frac{\max(dV_a, dV_b, dV_c)}{V_{avg}} \% \qquad (2)$$

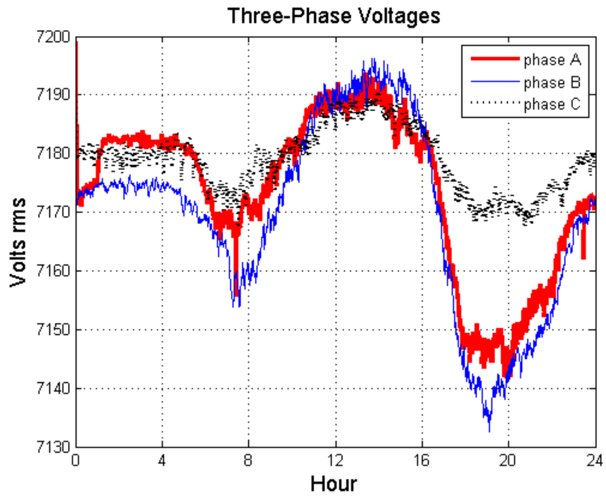
where:

V_{unb}	voltage unbalance
dV_a	deviation of phase *a* voltage from average voltage
dV_b	deviation of phase *b* voltage from average voltage
dV_c	deviation of phase *c* voltage from average voltage
V_{avg}	average of three-phase line-to-ground voltages

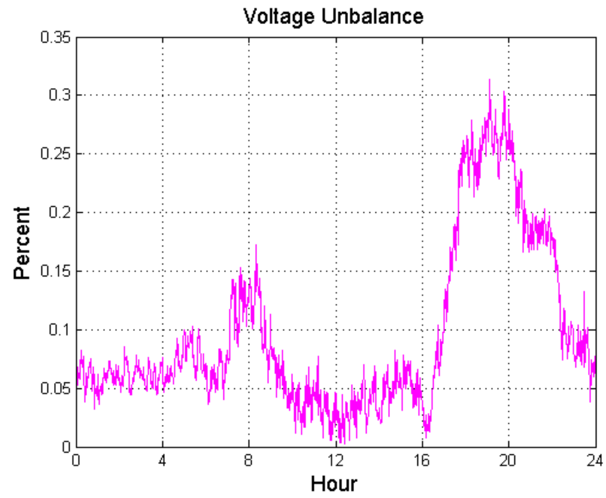
In order to prevent problems caused by unbalanced voltages, single-phase loads should be connected evenly across all three phases, i.e., future loads from the highest loaded phase should be planned for the other two phases. Furthermore, PV resources should—ideally—be interconnected to the highest loaded phase; however, utilities do not have the authority over residents to dictate this. The voltage unbalance observed in the Mueller community is plotted in Fig. 8, which conveys that the unbalance is well within the recommended range despite the high penetration of residential PV generation. This is an observation based on PV systems' relatively low impact on voltage in this neighborhood. (Voltage variations and phase unbalance effects may be more noticeable in "weak" power distribution areas such as in rural communities at the end of long feeders.)

V. Conclusion

This paper described the effects of residential grid-tied PV sources on a power distribution grid serving a residential area in the City of Austin. At this residential community (called Mueller), PV systems are installed in about one quarter of the homes. A computer model using *MATLAB/Simulink* was developed, with the capability to use recorded field data to estimate the phase voltages and branch currents everywhere in the electrical distribution system.



(a)



(b)

Figure 8. Voltage unbalance. (a) Three-phase rms voltage simulated at the feeder. (b) Percent voltage unbalance using ANSI C84.1 definition.

The descriptions presented herein are based on simulations conducted using real field data as inputs for a model representing Mueller, which is part of Austin's smart grid initiative known as Pecan Street. The descriptions consider observing the effects of basic power distribution variables such as power factor, voltage levels, and voltage unbalance. As expected, the real power generated by grid-tied PV arrays reduces the overall real power provided by the distribution utility to this neighborhood during daytime. However, at the same time, the power factor measured at the feeder level decreases to significantly low levels (as low as about 0.5). Even though the low power factor observed at Mueller is not necessarily a critical issue, if the observations from Mueller are extended to a widespread deployment in an entire city or country, the effects of conventional grid-tied PV sources could be severe.

Several distribution transformers in Mueller were noted to experience a reversal in the flow of real power during times when PV generation was abundant. Even though voltage rises were expected, the voltage levels in Mueller were maintained within appropriate limits. It was found that voltages restore themselves to nominal levels, which effectively counteracts the undesirable voltage drops.

Issues such as stability problems could be observed in microgrids operating isolated from the grid if conventional grid-tied PV inverters are used to supplement power generated by synchronous sources during islanded operation. These power factor issues, both in conventional grids and in microgrids, could be avoided if other types of inverters that allow for reactive power control are used instead of conventional grid-tied PV inverters, which are designed to provide power at unity power factor. Contrary to commonly believed concerns about the impact that high penetration levels of PV sources have on voltage levels and voltage unbalances, the discussion presented here does not corroborate major concerns about voltage rise or voltage unbalance for the Mueller area. However, these issues can be noticeable in areas with "weak" power grid feeders and laterals—i.e., areas served by feeders and laterals with a higher series impedance.

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