Renewable Energy, Environment, and Power Quality Journal (REE&PQJ)
ISSN:3020-531X
Volume 26, July 2026

Impact of PV Inverter Reactive Power Control on Local Voltage and Real Power Generation

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Abstract. Behind-the-meter smart photovoltaic inverters are known to have the ability to generate or absorb reactive power for local voltage regulation/support, in addition to their main task of converting DC to AC power. This paper presents field tests on the impact of inverter reactive power on the local voltage at two customer sites with rooftop PV systems. Two inverter control approaches were tested: Volt-VAR control, and direct reactive power dispatch. The latter reveals not only the amount of additional power loss in the inverter, but also a measurable change in local voltage that can be utilized to estimate the Tevenin impedance of the network.

Key words. Smart PV inverters, Volt-VAR control, direct reactive power dispatch, voltage regulation.

1. Introduction

Traditionally, electric utilities utilize a combination of voltage regulating devices including on-load tap changers, step-voltage regulators and shunt capacitors, to maintain the voltage at the service entrance within the acceptable range of ± 5% of the nominal values as defined by ANSI C84.1 Standard [1]. The increasing integration of distributed photovoltaic (PV) generation resources into low-voltage distribution networks can lead to over-voltages due to reverse power flow and voltage fluctuations because of variability in solar irradiance on cloudy days. These challenges have led to a need to update voltage regulation strategies.

Photovoltaic (PV) inverters were initially operated to inject only active power into the system (i.e., unity power factor). The increase in PV penetration over the past two decades has led to the revision of IEEE Std. 1547-2018 [2], which now allows advanced inverters to directly manage reactive power Q by adjusting the phase angle between voltage and current on the AC side, independent of DC power. Consequently, the aggregation of inverter- based distributed resources, is an emerging solution for end-user reactive power dispatch [3].

Utilities are increasing their efforts in studying the impact of autonomous Volt/VAR and Volt/Watt functions of PV inverters in voltage regulating strategies, as well as impacts on energy production for customers [4]. Reference [5] showed that inverters' reactive power absorption can mitigate overvoltage in low-voltage networks without requiring costly network upgrades. However, reactive power compensation alone may not be as effective as active power in mitigating over-voltages due to the high R/X ratio of distribution networks [6]. Other authors proposed Smart inverter controls to mitigate voltage fluctuation caused by solar variability on cloudy days [7]. References [8]-[10] pointed out that non-unity power factor operation of PV inverters comes at a cost as this creates more losses in the inverter, thus resulting in lower energy production and reduced lifecycle. Recent studies have explored advanced inverter control strategies for smart inverters to enhance voltage regulation and reduce distribution network losses using either de-centralized or centralized control schemes [11], [12].

The authors believe that the extended literature above is largely based on simulations or laboratory experiments, and more field demonstrations are needed to validate the effectiveness of the voltage regulation grid service using smart PV inverters. In addition, the two common control methods of PV inverters that are analyzed in the literature, i.e., constant power factor (PF) mode Volt-VAR mode, do not show a clear impact on the local voltage and additional power loss in the inverter. The authors propose to analyze the response to direct reactive power dispatch in order to shed light on the above information, in addition to estimating the magnitude of the Thevenin impedance of the distribution network (seen from the point of common coupling).

This paper presents field measurements at two customer sites with rooftop PV systems and smart inverters through the execution of two inverter control approaches: Volt-VAR control and direct reactive power dispatch. The rest of the paper is as follows: Section 2 reviews the reactive power limits of PV inverters. Section 3 provides a theoretical framework that describes the effect of PV real and reactive power on the local voltage. Section 4 describes the field demonstration set-up, followed by the results and discussion in Section 5. Section 6 draws conclusions and future work.

2. Reactive Power availability from PV Inverters.

Modern smart PV inverters are compliant with IEEE 1547-2018, thus allowing the common control functions which are autonomous and are typically remotely adjusted to achieve the desired dynamic grid support. These include, (a) Volt-Watt function (used only in case of over-voltages outside of ANSI C84.1 ranges which can occur under high penetration and light load condition), (b) Volt-VAR function where the inverter monitors the local voltage and responds by either injecting or absorbing reactive power to flatten the voltage profile, (c) non-unity power factor operation (either leading or lagging) where the inverter adjusts its reactive power to maintain a specific power factor.

The amount of Q_{pv} (kVARs) that is available from a particular PV inverter depends on the inverter apparent power rating S_{pv} (kVA) and PV power production P_{pv} (kW). An inverter that is 10% oversized allows up to 40% of the rating as reactive power (Q_{max}) at all times. Even when the kVA rating is matched to the maximum expected real power, this occurs only during the noon hours of clear days and when the sun is perpendicular to the array surface. So, the inverter often operates below maximum power – allowing more room for reactive power. Certain modern, utility-scale, and some advanced string PV inverters can generate or absorb reactive power at night to support grid voltage, provided they have specific, enabled firmware [13]. The two inverters that were tested in this study do not have such features, i.e., they remain dormant and start operation only after sensing the presence of sun power on the DC side.

The Volt-VAR function is represented by the Q-V curve in Figure 1 below which shows the local voltage (in per-unit) and reactive power based on Q_{max}. A deadband 1 % or 2% is often added around nominal line voltage to enable the operator to define a target operating voltage range within which VAR support is not needed.

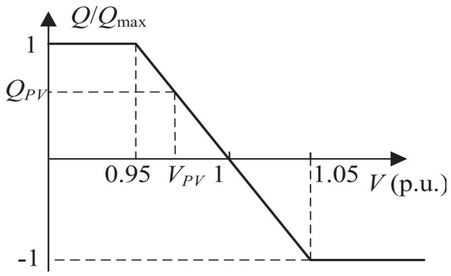


Figure 1: Typical Volt/VAR Control Curve.

Two cases are considered in this study: (a) the autonomous Volt-VAR Control described above, and (b) Direct Reactive Power Dispatch. This latter case is generally needed in emergency situations where VAR support is critical, e.g., under severe voltage violations due to failure of conventional voltage regulation equipment.

3. Impact of PV Real and Reactive Power on Local Voltage

The voltage V_{PCC} at the point of coupling between the utility and customer varies in a complex way as it depends on numerous parameters including the voltage at the substation, the feeder (including laterals and sub-laterals if any) impedance and loading, the distribution transformer impedance and the load it serves, secondary feeder impedance, customer net load (PV power minus native load). For simplicity, V_{PCC} can be approximated by

$$V_{PCC} = V_{th} - Z_{th} I, \tag{1}$$

where,

$$Z_{th} = R_{th} + jX_{th}, \tag{2}$$

V_{th} and Z_{th} represent the Thevenin equivalent circuit looking from the PCC into the grid, and I is the current flowing from the source to the customer site. Herein, Z_{th} consists of the sum of the secondary feeder, distribution transformer, lateral and main feeder (all the way to the substation) impedances. It is worth pointing out that R_{th} is largely dominated by secondary feeder resistance, especially for underground cables, while X_{th} mostly consists of the distribution transformer reactance [11]. The voltage difference between the Thevenin source and the voltage at the terminals of the PV inverter can be approximated by

$$\Delta V = V_{th} - V_{PCC} \approx \{R_{th}(P_L - P_{pv}) + X_{th}(Q_L - Q_{PV})\}/V_o \tag{3}$$

where (P_L, Q_L) and (P_{pv}, Q_{pv}) respectively represent the real and reactive power consumed by the customer load, and real and reactive power generated by the PV inverter, while V_o is the nominal value of the local voltage. Note that real and/or reactive power generation by the PV inverter tends to increase voltage, while reactive power absorption by the PV inverter tends to lower the voltage.

4. Field Demonstration

The goal is to assess the impact of smart inverter support of the local voltage through reactive power generation or absorption. Two customers with roof-top solar PV systems that are located on two different feeders and supplied by the same distribution substation were considered in this study. The inverter sizes of Customer A and B are respectively equal to 10 kVA, and 6 kVA.

The following measurements were recorded with eGauge meters that were installed at the breaker panel of each home at 1-second time intervals during the testing: PV inverter real and reactive power *(P_{pv}, Q_{pv})*, real and reactive power *(P_L, Q_L)* consumed by the home appliances, and local voltage *(V_{PCC})*. The inverter settings were remotely controlled via the manufacturer Application Programming Interface (API).

A. Baseline

Herein, the inverters were kept at their default settings, i.e., unity power factor operation, and the above variables were recorded over a 24-hour period.

B. Volt-VAR Control

After examining the magnitude of the local voltage and maximum PV power generation at each site, it was determined that setting Q_{max} to 80% of each in inverter rating would not result in power curtailment. VVC curves shown in Fig. 1 were implemented in each inverter with the above maximum reactive power. Measurements were again taken over 24-hour period, and the local voltage variation is compared with that of the Baseline.

C. Direct Reactive Power Dispatch

In here, sudden demands of specific blocks of reactive power (up to the full inverter rating) that last 5 minutes were implemented to provide a clearer picture of drop or rise in the local voltage and power production. In this case, VAR priority function under which the requested reactive power is delivered regardless of real power curtailment.

5. Results and Discussion

For base case, Figure 2 below displays the variations in local voltage (in per-unit based on 240 V), load active and reactive powers, PV inverter active and reactive power of Customer A (with 10 kVA inverter) and Customer B (with 6 kVA inverter) over the course of 24-hour day. The graphs show that the local voltage at both sites remains above 1 p.u., and this is a common practice for utilities to maintain a higher voltage to handle voltage drops caused by the load. Note this was a clear day (8/13/2025) that is characterized by smooth solar power curves that peaked at 9.1 kW and 4.3 kW, and the PV reactive power in near zero, indicating unity power factor operation. The load swings are largely due to the on-off cycling of air conditioning and refrigeration. Customer A shows a load exceeding 12 kW in the evening hours due to EV charging that resulted in a noticeable voltage dip.

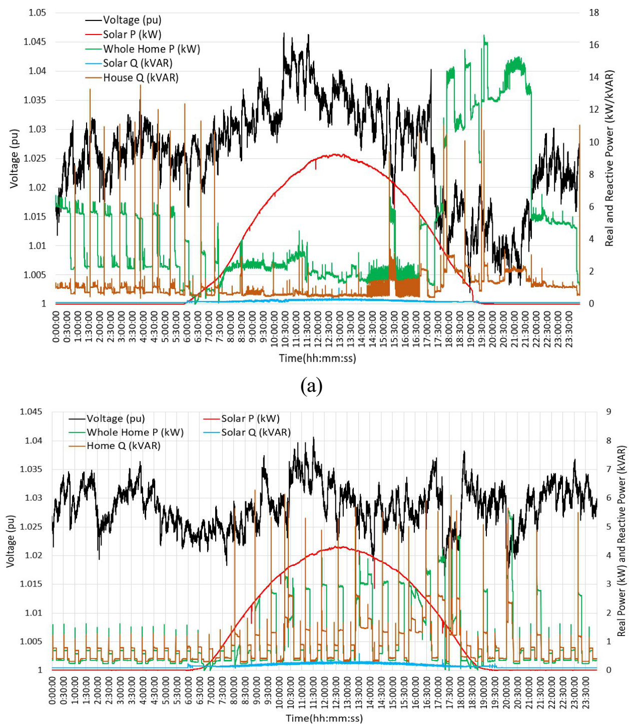


Figure 2: Base Case - local voltage, PV inverter and load real and reactive power over 24 hours (a) 10 kVA, (b) 6 kVA.

Figure 3 shows the variation in local voltage, generated real power, and absorbed reactive power by the PV inverters upon the implementation VVC function. The test day (8/21/2025) happened to be partly cloudy in the afternoon hours as indicated by the dips in solar power. Herein, the inverters reacted to the local voltage changes by absorbing reactive power since the voltage was higher than the nominal value. The graphs show that the inverters spent the entire daylight hours reacting to fast voltage changes by absorbing VARs at the same pace. Figure 4 shows the reactive powers absorbed by the inverters as a function of the local voltages. These linear relations mirror the bottom part of VVC curves described in Fig. 1.

Assessing the impact of the absorbed reactive power on the local voltage is difficult due to the small inverter sizes relative to the strength of an electrical grid at the connection point (stiff short circuit ratio). One way to approach this is to compare the voltage profiles in Fig. 3 with those recorded without activating VCC by selecting the same day of the week and assuming that loading remains generally consistent [14]. Figure 5 displays the local voltage with and without VVC (i.e., default setting) at both customer sites during the daylight hours. It is worth noting that Volt-VAR activation resulted in average voltage reduction by 0.43% at Customer A, and 0.27% at Customer B.

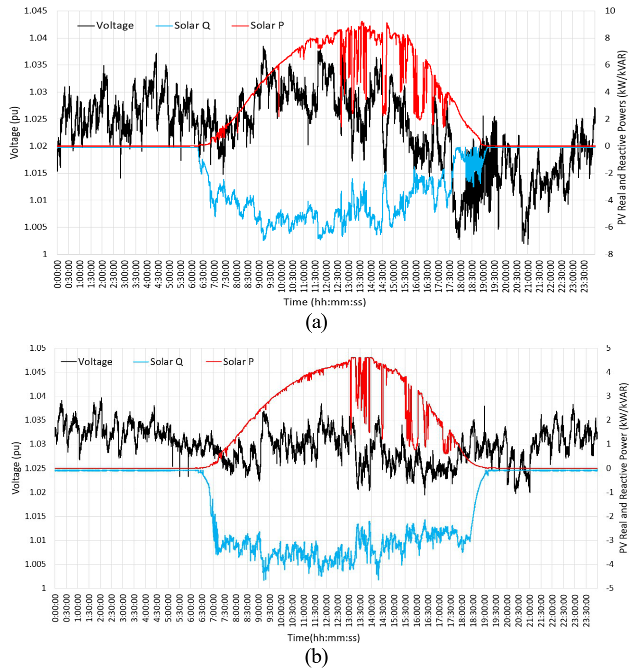


Figure 3: Local voltage, PV inverter real and reactive power over 24 hours under Volt/Var mode (a) 10 kVA, (b) 6 kVA.

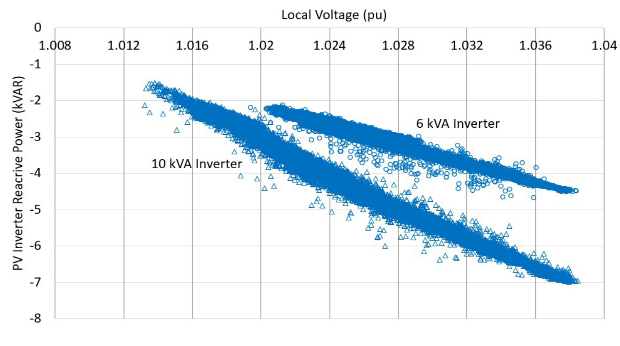
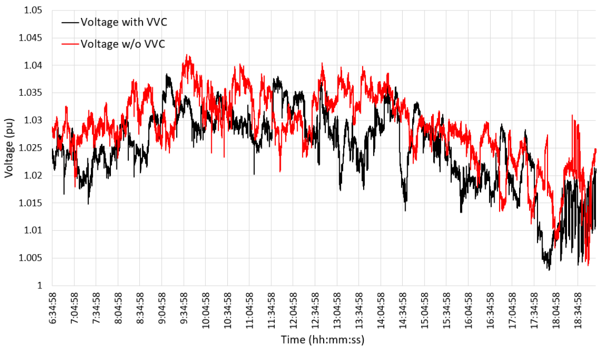


Figure 4: PV inverter reactive power as function of local voltage.

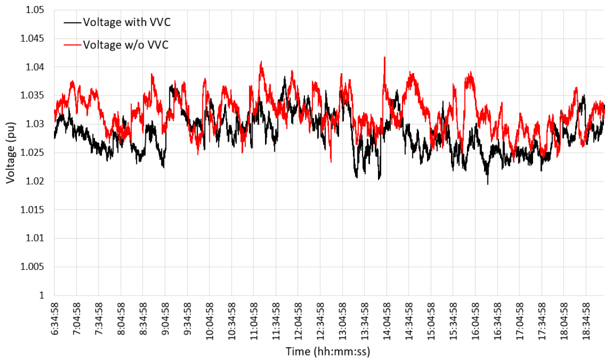
Figure 6 shows a direct reactive power dispatch of blocks of 4 kVAR, 6 kVAR, 8 kVAR and 10 kVAR absorption from the 10 kVA inverter (each lasting 5 minutes) while it was generating nearly 7.3 kW of solar power at 10:25 am up to just over 8 kW at 11:05 am.

The following remarks can be made:

- A dispatch of 4 kVAR between 10:30 am and 10:35 am is below the available reactive power, so the real power is not curtailed as expected. The slight dip in real power is due to the additional inverter losses caused by the increase in current and apparent power output. The instantaneous decrease/increase in voltage during the positive/negative step in reactive power is also noticeable.



(a)



(b)

Figure 5: local voltage variation with and without activation of Inverter Volt/Var function.

- A demand of 6 kVAR is also below the available reactive power and resulted in a noticeable decrease in real power that is approximately equal to 140 W. This additional power loss tends to increase with the square value of the inverter reactive power. The resulting voltage drop is more noticeable (≃ 0.003 p.u. or 0.72 V) when compared to that caused by the 4 kVAR demand. Knowing that the load reactive power was negligible during the 6 VAR dispatch, Eqn. (3) can be used to estimate the reactive component X_{th} of the Thevenin impedance as follows:

$$X_{th} = \Delta V . \frac{V_o}{Q_{pv}} \simeq 0.03\ \Omega. \quad (4)$$

- A demand of 8 kVAR resulted in power curtailment of nearly 2 kW in order not to exceed the inverter maximum kVA capacity, and in a voltage drop of nearly 0.005 pu.
- A demand of 10 kVAR that is equal to the full inverter KVA rating resulted in nearly the entire real power curtailment as expected. The voltage drop of over 0.01 p.u. (0r 2.4 V) is due to both the drop in real power and the substantial increase in reactive power absorption. Once more, knowing that the load demand was 4.5 kW with a negligible amount of kVAR during this dispatch, Eqn. (3) can be applied to estimate the resistive part R_{th} of the Thevenin impedance:

$$R_{th} = \frac{\{\Delta V . V_o - X_{th}(Q_L - Q_{pv})\}}{(P_L - P_{pv})} \simeq 0.07\ \Omega \quad (5)$$

Figure 7 shows the results of the test conducted on the 6 kVA inverter while it generated nearly 3.5 kW. Similar effects on both local voltage drop and real power curtailment can be observed, but at a proportional scale.

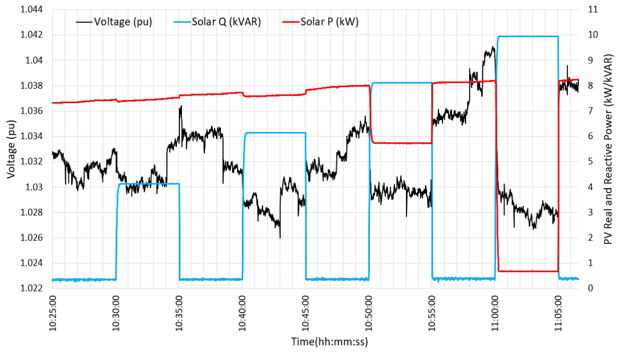


Fig. 6: Direct reactive power dispatch from 10 kVA inverter.

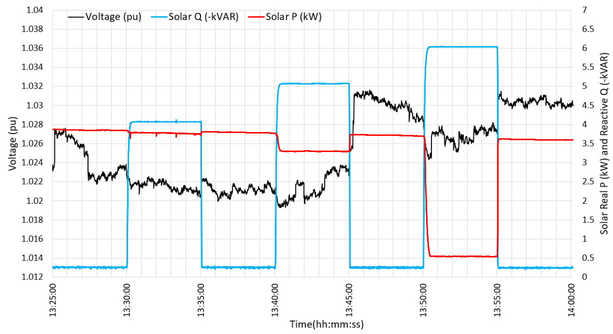


Fig. 7: Direct reactive power dispatch from 6 kVA inverter.

6. Conclusion

This paper presented the results of a field test on smart PV inverter voltage support by means Volt-VAR control and direct reactive power dispatch at two customer sites. The impact of Volt-VAR control function on the local voltage is difficult to measure due to the stiffness of the distribution network relative to the inverter ratings. Direct reactive power dispatch shows clear changes in local voltage, and a reduction in real power generation due to additional power losses and curtailment. These changes allow one to estimate both the resistive in reactive components of the Thevenin impedance. Since distributed PV resources are generally owned by customers, some form of compensation mechanism is needed to cover the cost associated with inverter reduced Lifecyle and additional energy losses caused by reactive power absorption or generation. Future work includes gathering seasonal local voltage variations followed by the development of a framework to estimate additional yearly losses on specific inverters when operating in autonomous Volt-VAR mode.

Acknowledgement

This work is supported in Part by the Solar Energy Technology Office of the U.S. Department of Energy (DOE) under Grant No. DE-EE000902.

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