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Measurement-based voltage sensitivity analysis of LV distribution networks for PV integration in Uzbekistan

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Abstract. This study analyzes the impact of residential photovoltaic (PV) plants on voltage levels in low-voltage (LV) distribution networks based on real operational data obtained from PV installations located in Tashkent. The analysis employs monitoring system measurements followed by data processing using Ordinary Least Squares (OLS) linear regression and event-based (ΔP – ΔU) analysis. The results demonstrate a clear relationship between the active power output of PV plants and voltage rise in LV distribution networks. The calculated voltage sensitivity coefficients enable the estimation of voltage deviations under different PV generation levels. The findings confirm that a high penetration of distributed single-phase PV systems can cause significant voltage deviations and phase imbalance in LV distribution networks, highlighting the need for systematic network assessment, the development and mandatory implementation of a national Grid Code adapted to the conditions of Uzbekistan, the establishment of dedicated technical requirements for PV integration, and the adoption of effective voltage regulation measures.

INTRODUCTION

In recent decades, the global power sector has been undergoing a profound transition driven by efforts to reduce dependence on fossil fuels, enhance energy security, and mitigate greenhouse gas emissions. This transition is characterized by the rapid deployment of solar, wind and other renewable energy technologies, the expansion of distributed generation, and stricter requirements for energy efficiency [1]. Within this global context, Uzbekistan is actively shaping its own green agenda, which targets an increase in the share of renewable energy sources to 40% of the national energy mix by 2030 [2]. PV power plants play a key role in achieving these goals, with their total installed capacity planned to exceed 8 GW by 2030.

In parallel with the development of utility-scale and commercial–industrial PV plants, Uzbekistan has introduced a set of measures to stimulate the adoption of small-scale PV systems by residential customers, with connection to 0.4 kV low-voltage (LV) distribution networks [3]. According to the Ministry of Energy of the Republic of Uzbekistan, as of 1 August 2025 a total of 129,826 small-scale PV systems with a combined capacity of 1,650 MW had been commissioned nationwide, including 78,140 residential PV plants with an aggregate capacity of 361.1 MW [4].

The integration of PV systems affects power quality in LV networks, with voltage level being one of the most sensitive indicators. If the installed PV capacity is not aligned with the hosting capability of the LV feeder, the resulting reverse power flow may cause excessive voltage rise, particularly in situations where end users modify the factory-set voltage protection thresholds of inverters. Resolution No. 610 of the Cabinet of Ministers of the Republic of Uzbekistan, dated 22 July 2019, establishes a simplified procedure for connecting PV systems to 0.4-kV LV distribution networks, under which residential customers are allowed to install systems up to 20 kW without a detailed network impact assessment [5].

Numerous studies have shown that single-phase PV systems tend to cause more pronounced voltage rise and higher voltage unbalance in LV distribution networks than three-phase PV systems of the same installed capacity [6–9]. In Uzbekistan, despite the absence of explicit regulatory limits for single-phase PV capacity, the practical upper bound is determined by the technical ratings of single-phase electricity meters, the characteristics of switching and protection equipment, the cross-section of the incoming supply cable from the LV feeder, and the maximum nominal rating of single-phase grid-tied inverters available on the domestic market.

In practice, the product range of single-phase inverters offered in Uzbekistan is typically limited to units with a maximum output of 10 kW. Together with the aforementioned technical constraints, this effectively defines the upper realistic capacity of single-phase PV systems at this voltage level. It should also be emphasized that, among consumers supplied via single-phase connections, 10-kW grid-tied PV systems have become one of the most common and widely adopted configurations.

For these reasons, the present study focuses on assessing the impact of 10-kW single-phase grid-tied PV systems on voltage levels in LV distribution networks, as such systems exert the most significant influence on their operating conditions [7].

EXPERIMENTAL RESEARCH

A large number of studies have investigated the impact of PV systems on power quality in LV distribution networks. In most of these works [7–9], deterministic modelling approaches are employed, which require detailed information on network topology, line electrical parameters, phase load distribution and consumer characteristics. In practice, however, such data are often incomplete or only partially available. Moreover, developing detailed models for each individual LV network is time-consuming and, even when sufficient data are available, still involves uncertainties, since it is practically impossible to accurately represent the behaviour of every single consumer.

Under conditions of large-scale PV deployment in Uzbekistan, a more practical solution is not purely theoretical modelling, but a measurement-based assessment of how PV systems affect voltage levels in LV distribution networks. This can be achieved using readily available operational data and electrical parameters obtained directly from solar inverters, without additional field measurements. In this context, remote monitoring tools play a key role, enabling continuous collection and analysis of network performance indicators without on-site visits. Access to monitoring platforms significantly broadens the scope of analysis, as it allows a large number of LV networks to be studied under real operating conditions.

The emergence of modern communication modems and cloud platforms capable of transmitting and storing data at 5–10 second intervals, instead of the conventional 300-second interval, has further strengthened this measurement-based approach. High-resolution data make it possible to build more detailed datasets, improve the accuracy of assessing the impact of PV generation on network parameters, and substantially reduce the time required for experimental campaigns and subsequent analysis.

Although the relationship between voltage and active power is generally nonlinear, linear approximation is widely used in engineering practice for practical, measurement-based evaluation [10,11]. Within this framework, the change in voltage at the point of common coupling caused by a change in PV generation is described by:

$$\Delta U_i \approx k_p \cdot \Delta P_i + k_Q \cdot \Delta Q_i \quad (1)$$

where k_p and k_Q are the voltage sensitivity coefficients to active and reactive power, respectively.

However, in this study only the impact of active power from PV systems on the network voltage level is considered. This is due to the fact that in Uzbekistan there are no requirements for reactive power compensation for residential customers, and electricity billing for both consumption and export is based solely on active energy. As a result, under real operating conditions grid-tied inverters almost always operate at (or very close to) unity power factor, supplying only active power. Therefore, the assessment of reactive power influence on voltage is not of practical relevance in this work, since the reactive component in the generated power of the PV systems is effectively negligible.

It should also be emphasized that LV distribution networks are characterized by a pronounced dominance of line resistance over reactance ($R/X \gg 1$). For example, for LV aerial bundled conductors (LV-ABC), which currently represent the main type of conductor used in LV distribution networks in Uzbekistan, typical R/X ratios are in the range of approximately 8–15. Consequently, in LV networks the impact of active power on voltage levels is significantly stronger than that of reactive power. This is clearly reflected in the widely used engineering formula for estimating voltage variation along a radial distribution feeder:

$$\Delta U \approx \frac{P \cdot R + Q \cdot X}{U} \quad (2)$$

where ΔU is the voltage change along the line section under consideration, V; P is the active power, W; Q - is the reactive power, var; R - is the line resistance, Ω ; X - is the line reactance, Ω ; U - is the voltage at one end of the line (either sending or receiving end, depending on the problem formulation), V.

In this study, the objects of investigation are 10 kW single-phase grid-tied PV systems connected to various LV distribution feeders in Tashkent. In all examined installations, the inverters are located very close to the main LV feeder; therefore, the voltage drop along the cable section between the inverter and the feeder can be neglected.

During the experiment, a control command is sent to the inverter to limit its active power output to 5% of the rated value, i.e., to 0.5 kW. Once this limit is removed, the inverter output increases to a level determined by the instantaneous solar irradiance. To improve the robustness of the results, this procedure is repeated several times. The active power ramp rate is defined by the manufacturer's control algorithm and is equal to 0.5% of the rated power per second, i.e., 50 W/s for a 10 kW inverter. Data are collected via the built-in monitoring system with a sampling interval of 10 seconds.

The experimental data are processed using linear regression, in particular the ordinary least squares (OLS) method, as well as an event-based ΔP - ΔU sensitivity analysis. In the OLS-based linear regression approach, the relationship between the voltage and the active power of the PV plant is approximated by a linear model of the form:

$$U(t) = a + b \cdot P(t) + \varepsilon(t) \quad (3)$$

where $U(t)$ is the voltage at the PV system point of connection to LV network, V; $P(t)$ is the active power on the AC side of the inverter, kW; a is the intercept (the voltage level at $P=0$ kW), V; b is the slope coefficient, i.e., the voltage sensitivity to active power ($b=\Delta U/\Delta P$), V/kW; and $\varepsilon(t)$ is the random error term (noise) accounting for the impact of other loads and background network fluctuations.

The slope coefficient b and the intercept a are calculated using the following expressions:

$$b = \frac{\sum_{i=1}^N (P_i - \bar{P}) \cdot (U_i - \bar{U})}{\sum_{i=1}^N (P_i - \bar{P})^2} \quad (4)$$

$$a = \bar{U} - b \cdot \bar{P} \quad (5)$$

where P_i and U_i are the measured active power and voltage at the i -th time instant; \bar{P} and \bar{U} are their mean values over the observation interval; and N is the total number of measurements.

The standard deviation of the noise, which characterizes the level of random voltage fluctuations caused by unpredictable load variations, switching events, and measurement errors, is determined as follows:

$$\sigma_\varepsilon = \sqrt{\frac{1}{N-2} \cdot \sum_{i=1}^N (U_i - (a + b \cdot P_i))^2} \quad (6)$$

This method has the advantage of being able to use an extended set of experimental data, including time intervals during which the PV output power remains nearly constant. This, in turn, enables a more reliable statistical estimation of the random component (noise) caused by the influence of other loads and network operating fluctuations. This aspect is particularly important for low-voltage distribution networks, which are characterized by a high degree of load stochasticity and significant short-term voltage variations.

The event-based ΔP - ΔU sensitivity analysis considers only those time instants at which a distinct change in the inverter active power (an event ΔP) is observed, accompanied by a corresponding change in voltage (ΔU):

$$\Delta U = (k \pm \sigma_k) \cdot \Delta P \quad (7)$$

where k is the mean voltage sensitivity to active power (V/kW), indicating the average change in the voltage for a 1 kW change in the PV active power; and σ_k is the standard deviation of the mean voltage sensitivity (V/kW), which characterizes the dispersion of local sensitivity estimates around the mean value k and quantitatively reflects the influence of other loads, network operating fluctuations, and measurement errors.

The values of the coefficient k and the corresponding standard deviation σ_k are calculated using the following expressions:

$$k = \frac{1}{N} \sum_{i=1}^N \frac{\Delta U_i}{\Delta P_i} \quad (8)$$

$$\sigma_k = \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^N (\Delta U_i / \Delta P_i - k)^2} \quad (9)$$

where P_i and U_i are the measured active power and voltage at the i -th event, and N is the total number of identified power-change events used for the statistical analysis.

In most cases, this method is preferable because it focuses solely on the system response at the moments when the PV power output changes. This is particularly important in situations where the inverter reports data only once every 300 seconds, which severely limits the applicability of classical regression-based approaches. Under such conditions, the informativeness of the measurements can be enhanced by deliberately introducing large power perturbations: the

inverter is periodically switched between the mode of maximum PV generation (without power limitation) and a low-power mode (for example, at 5% of the rated power) in the intervals between successive data transmissions.

The data obtained during these switching events can be effectively processed using the event-based ΔP - ΔU analysis method. To achieve a more accurate estimate of the sensitivity coefficient, the experiment is repeated multiple times, which improves the robustness of the resulting estimate and reduces the impact of random factors.

RESEARCH RESULTS

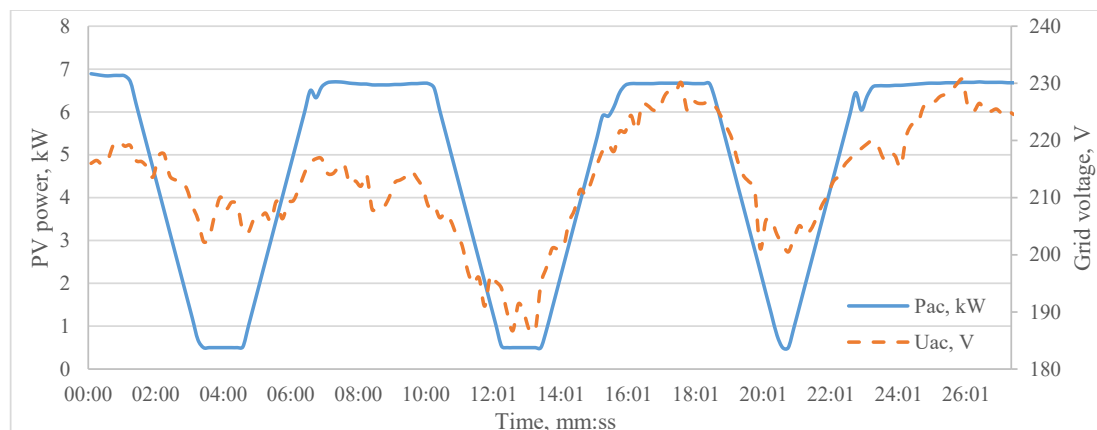


FIGURE 1. Dependence of grid voltage on the output active power of PV system No. 1

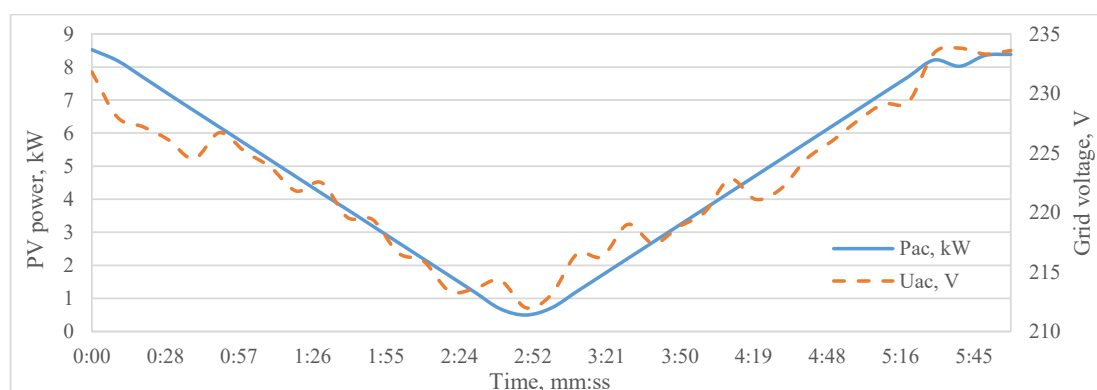


FIGURE 2. Dependence of grid voltage on the output active power of PV system No. 2

The analysis of the measurement data for PV system No. 1 (Figure 1) and PV system No. 2 (Figure 2) revealed a pronounced dependence of the LV distribution network voltage on the active power generated by the PV systems. For PV system No. 1, the voltage sensitivity coefficient was 3.45 V/kW when evaluated using linear regression and 2.64 V/kW when using the event-based ΔP - ΔU sensitivity analysis. For PV system No. 2, the corresponding values were 2.38 V/kW and 2.27 V/kW, respectively.

It is noteworthy that the standard deviations of the estimated sensitivity coefficients are comparable to, or even higher than, the coefficients themselves. This indicates a significant contribution of the random load component, driven by unpredictable variations in the operating modes of residential consumers, switching events, and external voltage fluctuations in the LV network. This effect highlights the high degree of stochasticity in the voltage behavior of the studied distribution networks and confirms the need for statistical methods in the analysis of measurement data.

TABLE 1. Voltage Sensitivity Results for the Studied PV Plants

PV Plant	Least-squares method (OLS)			Event-based ΔP – ΔU method	
	a, V	b, V/kW	σ_e , V	k, V/kW	σ_k , V/kW
PV Plant №1	213,3	3,45	6,18	2,64	3,65
PV Plant №2	211,4	2,38	1,56	2,27	3,10

CONCLUSIONS

A measurement-based assessment of the impact of PV systems on LV distribution networks, carried out using real operational data obtained from grid-tied inverters, makes it possible to estimate the voltage sensitivity to PV active power quickly and with accuracy sufficient for engineering analysis, without the need to build a detailed network model, reconstruct the full topology, or explicitly represent individual load characteristics. This approach significantly simplifies the practical evaluation of the effects of distributed generation and enables analysis directly under real operating conditions.

For the LV distribution networks and 10 kW single-phase PV systems considered in this study, the voltage sensitivity coefficients with respect to active power were found to be no less than 2.2 V/kW. This implies that operation of a 10 kW PV system at rated power may lead to a voltage rise of more than 22 V, i.e., an increase exceeding 10% of the nominal 220 V phase voltage adopted in Uzbekistan, which may conflict with existing power quality standards [12].

The connection of several similar single-phase PV systems to the same phase within one LV network further increases the voltage on that phase and results in a pronounced phase voltage imbalance. This confirms the need for a systematic approach to managing the integration of distributed solar generation.

The obtained results highlight the necessity of comprehensive regulation of distributed PV integration and the development of technical requirements that ensure safe and reliable operation of LV distribution networks under increasing shares of solar generation. To maintain adequate power quality and improve LV network robustness, the following measures are recommended:

1. Develop and implement a national regulatory document—a Grid Code governing the parallel operation of PV power plants with the electrical network—taking into account the large-scale deployment of PV systems in the Republic of Uzbekistan.
2. Include in the Grid Code specific requirements for the P–U (volt–watt) function in inverters, providing for automatic active power reduction as voltage increases, as well as defining an upper voltage threshold at which PV generation must be curtailed.
3. Ensure that single-phase PV systems are distributed as evenly as possible across the phases of LV feeders.
4. Plan for the reinforcement of LV lines or the installation of dedicated feeders from PV systems directly to the LV busbars of transformer substations.
5. Promote the deployment of smart load management systems (Smart Home / HEMS — Home Energy Management Systems) to align consumption patterns with periods of peak solar generation.
6. Encourage the use of hybrid PV systems with energy storage, capable of absorbing surplus PV power during daytime hours and supplying energy during evening peak demand periods.

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