Islamic University Journal of Applied Sciences (IUJAS)
https://journals.iu.edu.sa/jesc

Special Issue, December 2025, Pages 34-47

Advanced Network Voltage Control for Grid-Connected PV Systems Using Smart PV Inverter Capabilities

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Abstract

Photovoltaic (PV) systems integrated into low-voltage distribution networks (LVDNs) can induce voltage violations, raising concerns regarding their penetration limits. Although grid-connected PV systems (GCPV) offer advantages such as reduced production costs and enhanced efficiency, managing their voltage impact remains essential. To mitigate the need for grid reinforcements, distribution network operators must develop innovative control strategies that facilitate cost-effective PV integration. Advanced control techniques, including volt-watt control (VWC), volt-var control (VVC), and their coordinated combination (VWC-VVC), can effectively manage voltage violations by absorbing or injecting reactive power, or by curtailing active power output. This study evaluates inverter performance in GCPV systems subject to considerable voltage fluctuations due to high PV penetration. Real operational data from a GCPV system at the Centre for Renewable Energy Development (CDER) validate the proposed simulation methodology. Results demonstrate the effective application of PV inverters for LVDN integration and quantify the benefits of enhanced voltage management achieved through VWC and VVC functionalities.

Keywords: Advanced Control capabilities; Grid-connected PV system; Network voltage control; Smart PV inverters; Voltage violations.

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https://doi.org/10.63070/jesc.2025.038
Received 10 July 2025; Revised 08 November 2025; Accepted 09 December 2025;
Available online 24 December 2025.
Published by Islamic University of Madinah on behalf of *Islamic University Journal of Applied Sciences*.

1. Introduction

Several conventional resources face limitations or phase-out due to environmental issues. Renewable energy sources such as wind, solar, hydropower, and biomass will become increasingly crucial. In Algeria, solar energy is now increasingly available by solar plants connected to the medium voltage grid [1][2]. GCPV have an influence on: the protection policy, the energy quality, or the voltage violation due to a high PV penetration [3][4]. However, the characteristics, operation, and disturbances of the distribution network can affect the performance of PV systems. Depending on the capabilities and connection points of the PV generators and the network characteristics, the voltage at the node can fluctuate and may frequently exceed the acceptable limits (±10%) as defined by standards such as EN 50160, VDE 0126-1-1, and IEC 61727 [5][6][7]. A variety of approaches presented in the literature have successfully addressed the issue of voltage violation in LVDNs. Some suggest increasing cable diameter to lower line impedance, however this is not economically possible. Furthermore, these approaches are insufficient for responding to changing operational circumstances or external disruptions such cloud cover. On-load tap-changing transformers (OLTC) are a more practical option for changing tap positions and controlling voltage levels. The main limitation of these systems is that their control functions discretely and on a slower period of minutes, rendering them unsustainable in locations with high PV penetration and rapid cloud transients witnessed on a timescale of seconds[8][9]. To mitigate the issue, [10][11] propose integrating OLTC with fast-response devices including Battery Energy Storage (BES) and D-STATCOM. However, these approaches may improve system-wide performance, their real-time deployment and economic viability are uncertain due to the communication infrastructure requirements and the time necessary to tackle the majority of these issues. However, we focus on VWC and VVC capabilities, which are generally faster, easier to implement, and capable of responding to sudden external disturbances in GCPVs. Among the many functions of PV inverter, voltage reactive power control and voltage active power control have attracted attention due to their efficiency. We used these two advanced functionalities in this work to improve voltage violations in an LVDN. The advantages of improved voltage control in LVDN when PV inverters use new control strategies such as VWC and VVC are well known and have previously been investigated in the literature by works [8][9]. Consequently, this study focuses on the inherent capabilities of smart PV inverters, namely Volt-Watt Control (VWC) and Volt-Var Control (VVC). These functionalities are generally faster, easier to implement, and capable of responding to sudden external disturbances in GCPV systems. Among the many functions of a PV inverter, voltage-reactive power control and voltage-active power control have attracted significant attention due to their operational efficiency for local voltage management.

The main contribution of this work lies in the development and evaluation of a novel coordinated control strategy, combining the VWC and VVC functionalities of smart inverters. Unlike isolated applications of these controls, our generic VWC-VVC approach aims to orchestrate the entire fleet of inverters on the network to optimize voltage regulation. It is specifically designed for critical scenarios of high PV penetration and low demand, where overvoltage is most likely. The mechanism prioritizes reactive power adjustment VVC first; when this proves insufficient, it progressively activates active power curtailment VWC. This prioritization maximizes energy injection while ensuring compliance with voltage standards. The effectiveness of this strategy, as well as conventional VWC and VVC methods, is rigorously tested through simulations based on real load and solar profiles from Algeria, applied to a standard IEEE network model. Thus, this study proposes methodologies directly applicable to strengthening the integration of PV systems into Algerian low-voltage networks. The study aims to assess the effectiveness of PV inverters in mitigating voltage violations under high PV penetration. It focuses on an Algerian LV network context that faces significant voltage fluctuations and load demand variations. Real monitored data from the Centre de Développement des Energies Renouvelables (CDER) forms the basis of a detailed case study, with the LV distribution network modeled after the IEEE European test feeder in OpenDSS software.

2. Voltage sensitivity analysis

The power flow solution determines voltage amplitudes, phase angles, active and reactive power flows, and losses across all network buses, assuming balanced stability conditions and using phase analysis with a positive sequence system representation. This analysis is crucial for network planning, operation, economic scheduling, utility energy exchange, and various studies including stability and contingency analysis. Voltage sensitivity analysis helps identify the most efficient locations and amounts of reactive power support from solar inverters to maintain network voltage. Solving power flow requires formulating complex linear equations connecting bus voltages and currents through an admittance matrix, as depicted in equation (1).

$$[V_b us] = Y_b us^{(-1)}[I_b us] \tag{1}$$

The bus admittance matrix $[Y_b us] = [Z_b us]^{(-1)}$ is fundamental in electrical systems, representing the inverse of impedance. In practice, powers are more known than currents. Thus, replacing the current vector in equation (1) with power vectors forms nonlinear equations solved via the Newton-Raphson method. Solving for powers Eq (2) and (3) yields the voltage sensitivity matrix S. The Jacobian matrix is updated iteratively until convergence, and its inversion computes S [10]. Figure 1 illustrates a two-bus power flow.

$$P_i = |V_i| \sum_{j=1}^{N_{bus}} |V_j||Y_{ij}| \cos\left(\theta_{ij} - \delta_i + \delta_j\right) \quad (2)$$

$$Q_i = -|V_i| \sum_{j=1}^{N_{bus}} |V_j||Y_{ij}| \sin\left(\theta_{ij} - \delta_i + \delta_j\right) \quad (3)$$

$$\begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = \begin{bmatrix} S_{\theta P} & S_{\theta Q} \\ S_{VP} & S_{VQ} \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (4)$$

$$S = \begin{bmatrix} S_{\theta P} & S_{\theta Q} \\ S_{VP} & S_{VQ} \end{bmatrix} = J^{-1} \quad (5)$$

where i is the index of a three-phase bus in a balanced network, The green color denotes the nominal voltage zone (1.0 pu). The ANSI/IEEE-style diagram illustrates a simplified two-bus LV network

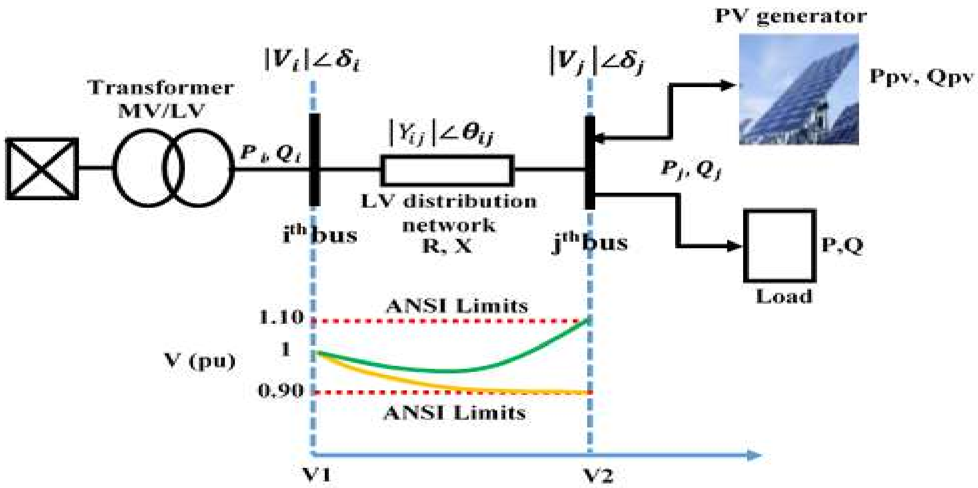


Figure 1. Effects of voltage increase in LVDN

3. Control capabilities of smart PV inverters

GCPV systems use inverters to convert DC power to AC for grid connection. These inverters can also control voltage at the point of common coupling (PCC) by altering reactive power or reducing active power [12]. Inverters' rated capacity limits their ability to inject or absorb reactive power, as determined by the following condition:

$$\sqrt{P_{out}^2 + Q_{inj}^2} \le S_{rated} \quad (6)$$

S_{rated}:: Inverter apparent power rating

3.1 Active power control

Active power curtailment reduces the inverter's generated active power, lowering the PV voltage at the PCC without actively altering the reactive power output. Users can set individual active power output points (x, y) for various voltage levels (see Figure 2). When the network's maximum voltage exceeds 10% of the nominal level as defined by EN50160, active power is limited to Pmax. This limit is determined by points (V1, P1) and (V2, P2) on a given curve:

$$P_{\max} = \begin{cases} P_1 & ; V < V_1 \\ P_1 - \dfrac{(V - V_1)(P_1 - V_2)}{(V_1 - V_2)} & ; V_1 < V < V_2 \\ P_2 & ; V < V_2 \end{cases} \tag{7}$$

The actual PV inverter operation is limited by available solar PV resources giving:

$$P_{out} \leq P_{APC} = \min\left(P_{\max}, P_{avail}\right) \tag{8}$$

VWC strategies are employed during high distribution-level penetration, when high PV output and low loads cause voltage to rise excessively.

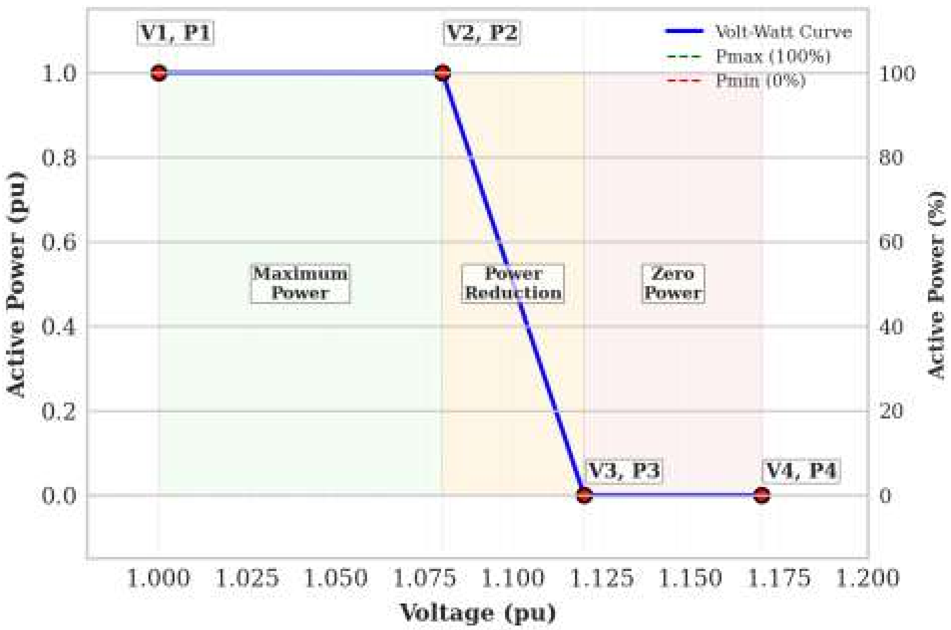


Figure 2. Typical curve of Volt-Watt voltage control

3.2 Reactive power control

The volt-var functionality ensures that the PV system voltage remains within EN50160 standards despite changing conditions. Reactive power exchange begins when the voltage exceeds a set upper limit (as shown in Figure 3). Conversely, if the voltage drops below the rated level, the inverter can inject reactive power into the distribution network to help stabilize them. Users can designate many points in a volt/var curve to select the angle points (V1, Q1), (V2, Q2), (V3, Q3), and (V4, Q4), (Qop) denotes reactive power exchange: negative for absorption, positive for injection Figure 3.:

$$Q_{op}=\begin{cases} Q_1 & V>V_1 \\ Q_1+\dfrac{(V-V_1)(Q_2-Q_1)}{(V_2-V_1)}; & V_2<V<V_1 \\ Q_2+\dfrac{(V-V_2)(Q_3-Q_2)}{(V_3-V_2)}; & V_3<V<V_2 \\ Q_3+\dfrac{(V-V_3)(Q_4-Q_3)}{(V_4-V_3)}; & V_4<V<V_3 \\ Q_4; & V>V_4 \end{cases} \tag{9}$$

Achieving desired reactive and active power operating points simultaneously may be limited by the inverter's rated apparent power, ensuring compliance with Eq (10).

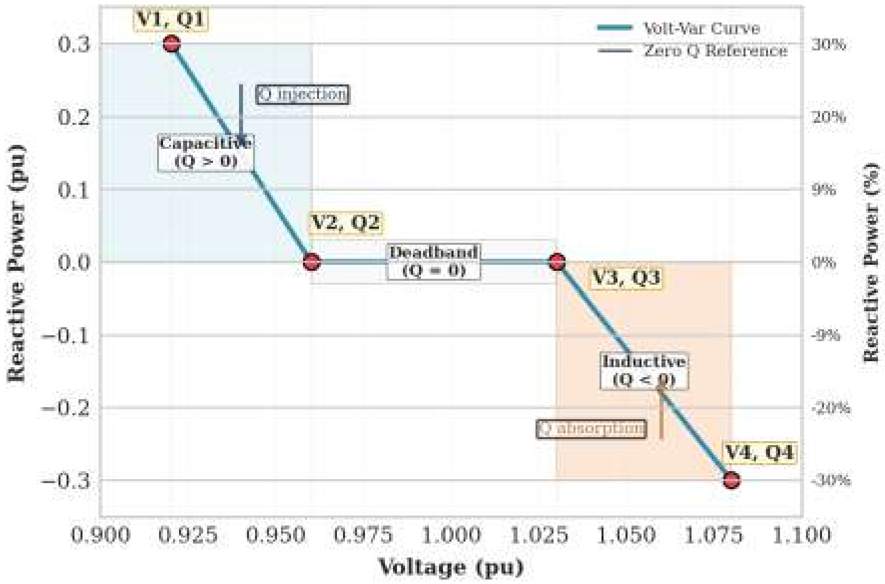


Figure 3. Typical curve of Volt-Var voltage control

3.3 Design of proposed coordination approach

The new approach investigates the interaction of two parameters: an active control voltage target level (V2) and an overvoltage threshold for Reactive Power Control (VVC) (V1). Using hierarchical control, separate sets of V1 and V2 are defined for various PV inverters along the feeder in a coordinated and efficient way. Figure 4. shows the suggested VWC-VVC control strategy for an inverter to solve overvoltage issues. According to references [13], the VVC algorithm may be ineffective for voltage control at the feeder's end when reactive power exchange is limited to specified voltage levels. In contrast, VWC improves voltage control methods. According to the proposed VWC-VVC algorithm: The inverter's reactive power is defined by the expression (10) and (11):

$$Q=\begin{cases} 0 & V\le V_1 \\ Q_0+\dfrac{(Q_{\max}-Q_0)(V-V_1)}{(V_2-V_1)}; & V_1<V\le V_2 \\ Change\_to \quad APC & V>V_2 \end{cases} \tag{10}$$

$$P=\begin{cases} P_{\max}+\dfrac{(P_{out}-P_{\max})(V-V_2)}{(V_3-V_2)}; & V_2\le V\le V_3 \\ P_{out}; & V>V_3 \end{cases} \tag{11}$$

$$\begin{cases} Q_{inj}=Q_0+\dfrac{(Q_{out}-Q_{\max})}{(V_3-V_1)} \\ P_{out}=\sqrt{S_{rated}^2-Q_{inj}^2} \end{cases} ;V>V_2 \tag{12}$$

According to, when line voltages exceed V2 and reactive power exchange is exhausted, the control strategy shifts from VVC to VWC. Reactive power injected to maintain voltages above V2 is calculated using equation (12). Adjustments in active power output follow based on the calculated injected reactive power. If line voltage drops below V2, the strategy reverts to VVC from VWC. This VWC-VVC approach enhances PCC level voltage control and enhances inverter capacity utilization across network points by managing injected reactive power for voltage control while curtailing active power.

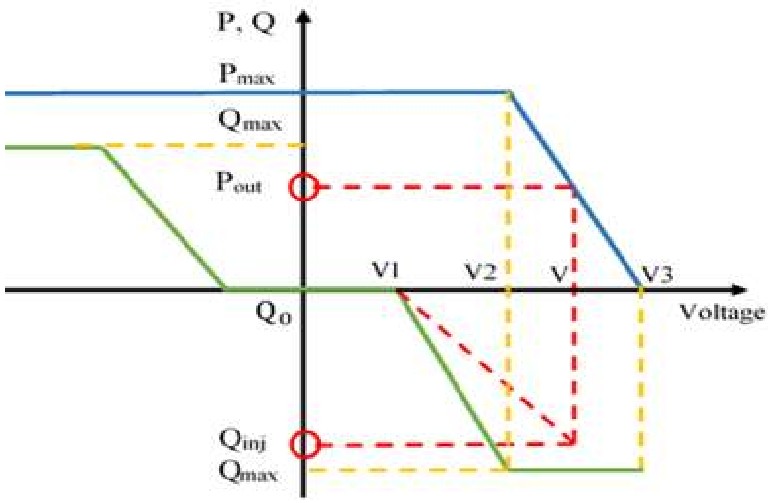


Figure 4. Typical curve of coordinate VWC-VVC voltage control

4. Voltage network control under integration of PV systems

An illustrative case study is presented to demonstrate how the advanced features of new PV inverters can be utilized to enhance the integration of a PV plant into an existing LVDN with high PV penetration.

4.1 Distribution network

To assess the PV system's impact on the LV distribution network, various power flow simulation tools are available, capable of solving both balanced and unbalanced distribution grids effectively. Standardization across platforms is crucial for comparative analysis. IEEE provides defined test feeders that include essential electrical components for analyzing voltage impacts in GCPV systems, usable across different software platforms.

Table 1. Summary of LV European test feeder left and right variables used in the simulations.

Grid characteristic	
Four-wire wye	Type of Feeder
residential	Type of settlement
906	Number of line
11, 0.416	Nominal voltage (kV)
800/800	Transformer rated power (kVA)
radial	Grid topology
1.5	Average distance between transformer and houses (km)
2c*007, 2c*0225, 2c*16, 35-SAC-XSC, 4c*06, 4c*1, 4c*35, 4c*185, 4c*70, 4c-95-SAC-XC	Feeder cable types

This study utilized the IEEE LV European Test Feeder, a three-phase radial grid with 0.416 kV nominal voltage and 50 Hz frequency, connected to an 11 kV medium voltage system via an 0.8 MVA step-down transformer [14]. Figure 5 depicts our representation of the IEEE network's single-line diagram. The network comprises 906 nodes and 55 single-phase loads distributed across three phases at 0.23 kV with a power factor of 0.95 in a Wye connection. The model was implemented using OpenDSS, an open-source software for electricity distribution systems developed by EPRI. Table. 1. show our variables used in simulations.

4.1 PV power and load profiles

Algerian data was used to create load profiles over a 24-hour period with 5-minute measurement intervals. Based on a day in July 2020, a specific type of load profile was generated (referring to July 7, 2020). This information is derived from the CDER monitoring system. The load profile and the power generated by the PV generator, are shown in Figure 6.

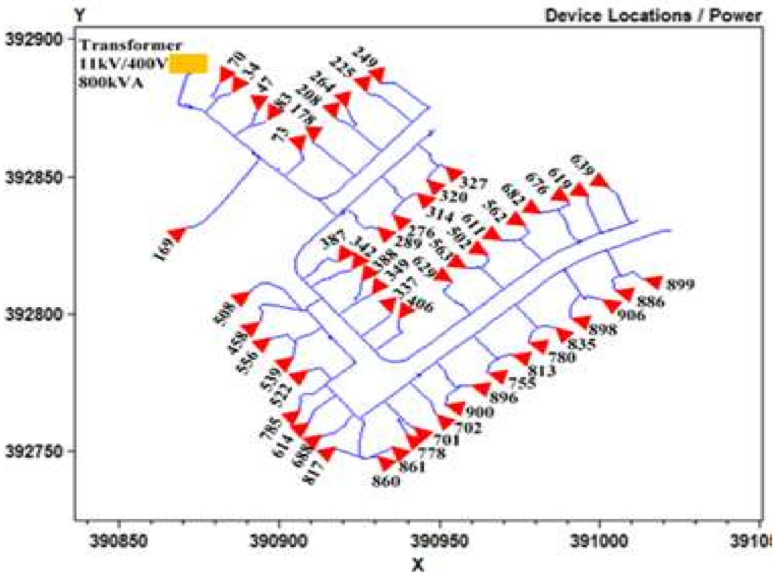


Figure 5. Single line diagram of the European LV test feeder

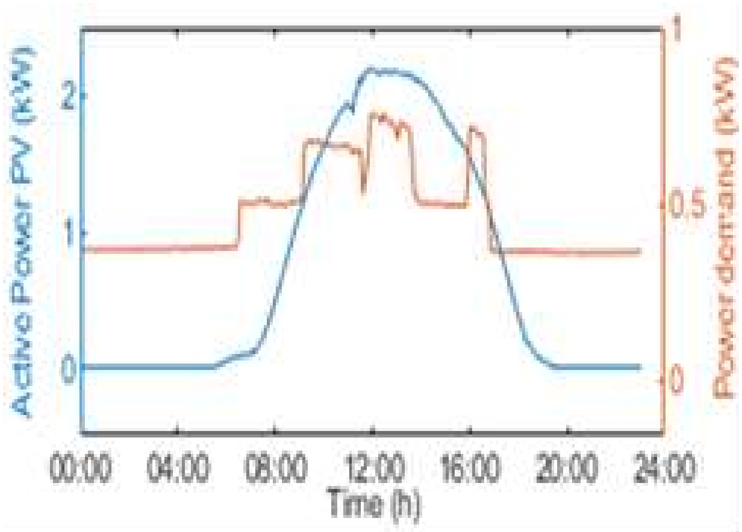


Figure 6. Daily load and PV profile

5. Results and discussions

To demonstrate the impact of GCPVs, the study used input data from the described demand load and PV generation for power-flow analysis of the test network. The stochastic nature of consumer load demand was simplified by using a generalized daily load curve for all consumers. Each GCPV system had a consistent output profile, with individual PV power limited to 2.16 kW. Figure 6 illustrates the PV output and generalized load demand curves. Scenarios included simulations with and without PV installations, and with/without voltage control. Increasing numbers of randomly connected GCPV generators were tested to identify voltage violations (voltage exceeding 1.10 pu). OpenDSS software performed successive 5-minute interval load flow calculations (288 intervals per day) on the LV network, using the Newton-Raphson algorithm to address flow problems.

5.1 PV system's impact on the LV test network

The study focused on an LV distribution network (LVDN) under extreme conditions, depicted in Figure 5. Details on the network modeling are in Section 4.

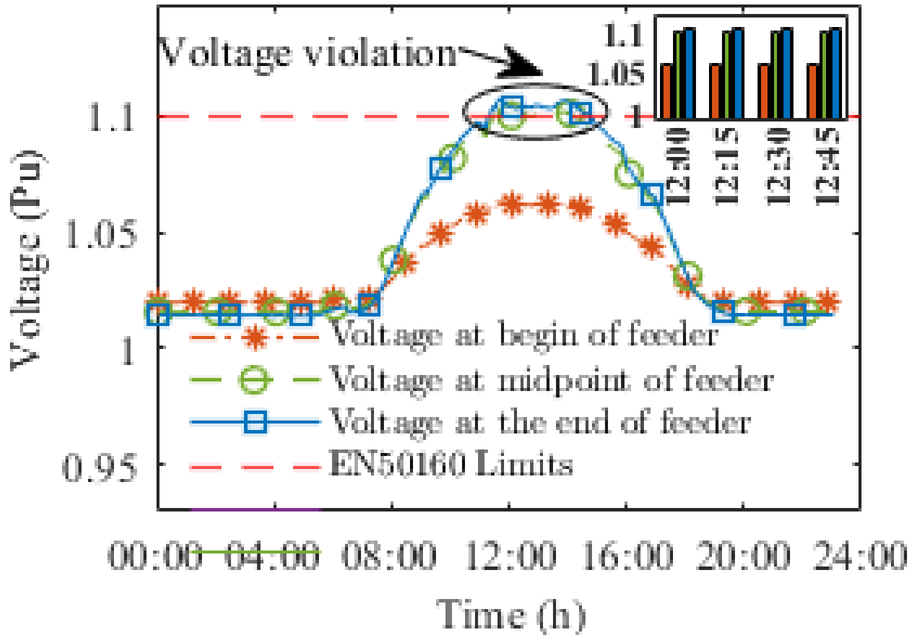


Figure 7. Daily voltage profile

Table. 2 summarizes the different voltage values at the different network PCCs.

Table 2. LV voltage variation under deferent PV penetration

Penetration (%)	Max LV Voltage at beginning of feeder (Pu)	Max LV Voltage at midpoint of feeder (Pu)	Max LV Voltage at the end of feeder (Pu)
0%	1,0198	1,0159	1,0145
10%	1,0206	1,0176	1,0163
25%	1,0226	1,0215	1,0202
35%	1,0243	1,0249	1,0238
50%	1,0268	1,0299	1,0293
100%	1,0350	1,0465	1,0472
200%	1,0507	1,0779	1,0808
280%	1,0628	1,1021	1,1068

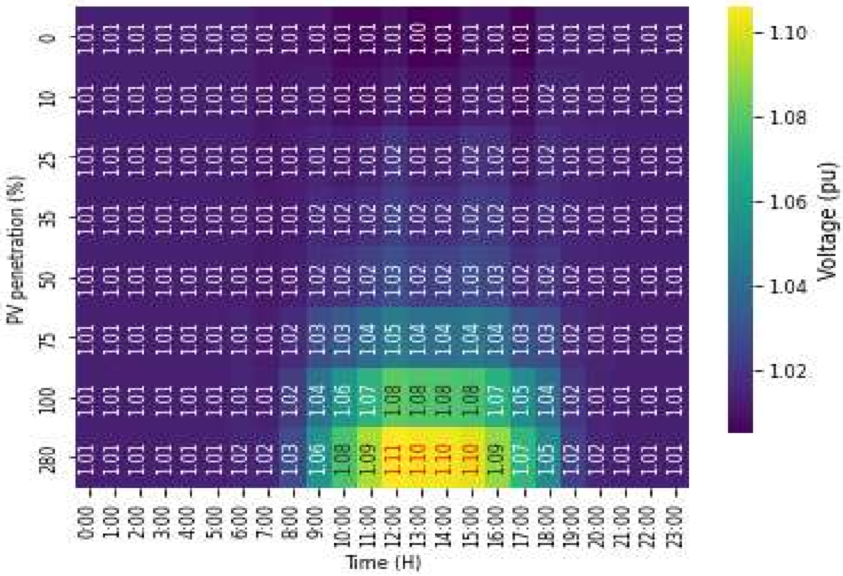


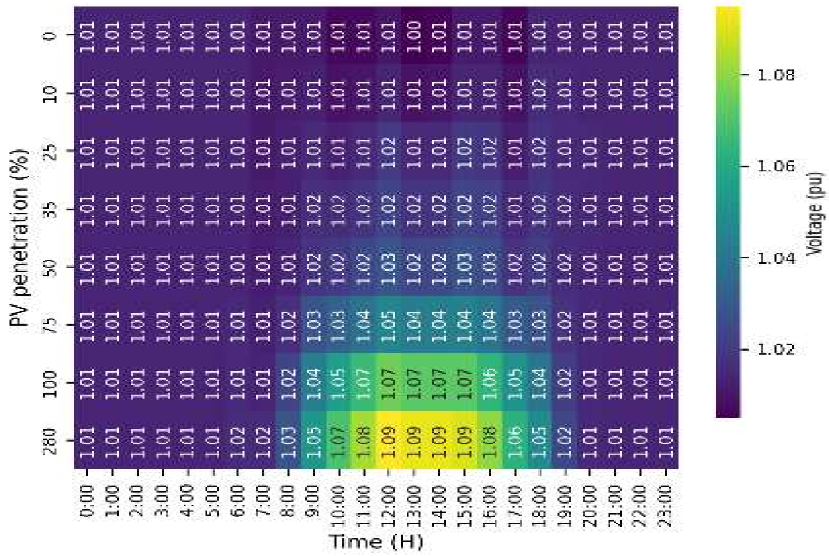
Figure 8. Heatmaps voltage violations at the end of feeder

The network includes a randomly dispersed set of single-phase PV systems connected to various customers. PV generator penetration levels were varied to assess their impact on voltage levels, guided by EN50160 standards. The transformer operates without an on-load tap-changer (OLTC), maintaining a fixed voltage configuration. Voltage profiles at different network nodes (start, middle, end) and voltage violation heatmaps at the PCC level are illustrated in Figure 7 and Figure 8. These figures highlight voltage violations occurring at maximum PV penetration levels, particularly at the feeder's end (Figure 7).

5.2 Mitigation of overvoltage

Therefore, to enhance the technical performance of GCPV systems using advanced photovoltaic inverter capabilities, this study incorporates the control strategies detailed in Section 4. These voltage control methods are applied to address voltage violations across the entire LV network, which is balanced with 55 GCPVs and 55 loads. By integrating of all PV arrays at maximum penetration causes voltage exceedances at the feeder end. For a detailed analysis of each method's effectiveness in mitigating PCC voltage violations, refer to Figure 9a, Figure 9b and Figure 9c. All three methods demonstrate significant improvements in local voltage control. Notably, the coordinated VVC and VWC-VVC strategies exhibit reduced voltage fluctuations compared to VWC approaches alone.

a



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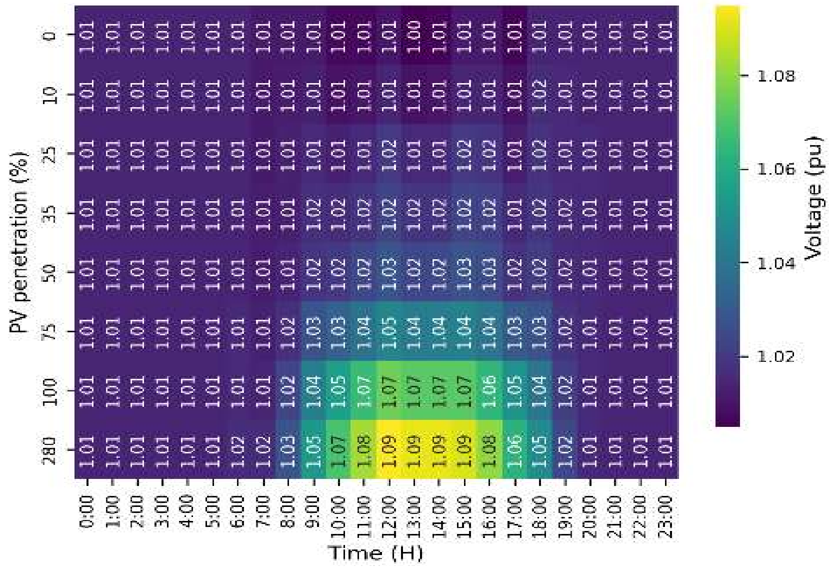

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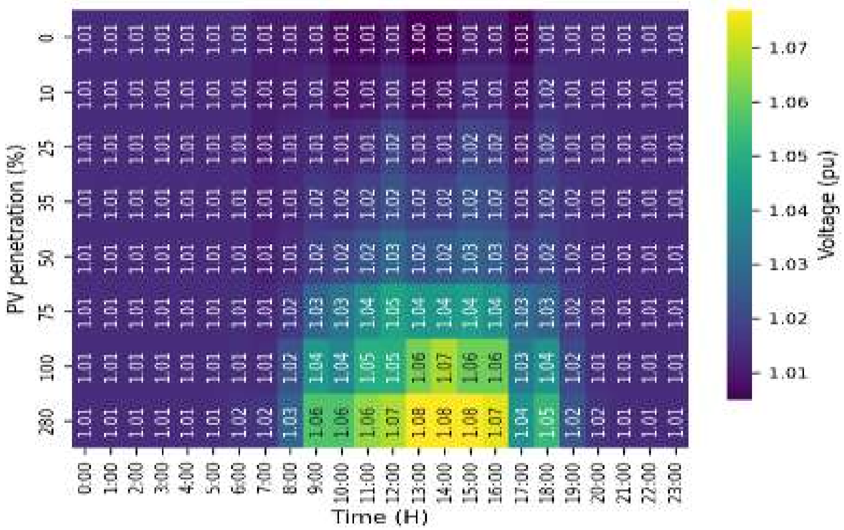

Figure 9. Mitigation of voltage violation a) Heatmaps of VWC control. b) Heatmaps of VVC control. c) Heatmaps of VWC-VVC control.

6. Conclusion

With the increased deployment of GCPVs, overvoltage at the PCC becomes a major issue. This study discusses voltage control enhancements for GCPVs with enhanced PV inverter capabilities. Three decentralized voltage control approaches VWC, VVC, and a proposed coordinated VWC-VVC strategy are used based on simulated models. When voltage violations detected, these methods cause reactive power absorption or injection while limiting active power injection to ensure conformity with EN50160 standards. However, a significant disadvantage is their potential inefficiency in using the full capacity of PV inverters, particularly those located further away from transformers working at higher capacities than those closer. The results of this study are useful for distribution system operators who are comparing the VWC-VVC approach to local control approaches. Proposals to standardize advanced PV inverter functionalities in the Algerian grid aim to improve existing systems.

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