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International Journal of
Electrical and Electronics Research (IJEER)
Research Article | Volume 12, Issue 4 | Pages 1440-1448 | e-ISSN: 2347-470X

# Voltage and Reactive Power Control Approach to Address Over-Voltage Issues in High PV Penetration Networks

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**ABSTRACT-** High energy penetration through photovoltaic (PV) panels poses a significant challenge due to over-voltage problems. This article presents a new approach for controlling the rise of voltage in low voltage Micro-grids (LVMg) with relatively high PV penetration (HPVP) named voltage/reactive power control (VRPC). The control is set via an inverter that uses the point of common coupling (PCC) voltage and returns it to its reference voltage via controlling of reactive power. Furthermore, the network in which the proposed method is considered have a high X/R ratio to emulate the LVMg. The proposed approach was implemented using MATLAB/Simulink environment and OpenDSS co-simulation. The simulations demonstrated that the VRPC/BESS technique has proven effective and robust in regulating voltage under HPVP operating conditions at various levels, where the rate of voltage rise was reduced by 5.6776% during 90% of HPVP. The proposed method can be considered fully robust and ready for widespread implementation.

**Keywords:** photovoltaic; reactive power control; micro-grids; high penetration; over-voltage.

**ARTICLE INFORMATION**

**Author(s)**: Mohammed Kdair Abd, Rasool M. Imran, Layth F. Kamal, Farhad E. Mahmood and Firas M. F. Flaih;
**Received**: 16/08/2024; **Accepted**: 04/11/2024; **Published**: 30/12/2024;
**e-ISSN**: 2347-470X;
**Paper Id**: IJEER 1608-12;
**Citation:** 10.37391/IJEER.120438
**Webpage-link**:
https://ijeer.forexjournal.co.in/archive/volume-12/ijeer-120438.html

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## 1. INTRODUCTION

There is a growing trend toward using renewable energy sources (RESs), e.g., PV-based units, instead of traditional generation units to address the energy shortage. PV-based units are the most popular RESs that have witnessed significant growth due to the gradual decrease in their price [1]. The International Energy Agency (IEA) reports that grid-connected PV units have recently experienced massive growth worldwide. However, HPVP can impact current, voltage, and frequency on networks designed before this increase in PV penetration. With the growing PV energy penetration in distribution networks, new strategies are necessary to regulate over-voltage problems in unbalanced distribution networks. Low voltage distribution networks (LVDNs) have a higher *X*-over-*R* ratio than medium-voltage networks and have more susceptible to voltage breakdowns. Additionally, typical PV generation peaks at midday when load demand is low, causing voltage levels on LVMg to exceed their grid code voltage limits (0.96 – 1.06 p.u.).

Several techniques have been proposed to mitigate this voltage rise. Efficient voltage control and reactive power control can help mitigate over-voltage in HPVP networks. In article [2], the authors apply experimental studies on a local Saudi power Micro-grid to compare different control techniques for mitigating the issue of over voltage caused by HPVP. These techniques are reactive power injection, active power restriction, and the hybrid mode of the former two techniques. Their results found that the hybrid mode provides the most effective method to decrease the voltage rising in the network. The article [3] proposed another way to mitigate the voltage rising issue via adding energy storage system (ESS) to store extra energy. Appropriate management has been used for charging and discharging the battery based on the amount of penetration, which is set to range from 0% to 100%. Their system focuses on the dangerous part, which is from 81% to 100%, to get an acceptable voltage of no more than 1.01 p.u. The article in [4] examines the impact of various reactive power regulation approaches on the low-voltage Malaysian Micro-grid associated with PV systems. The examined techniques include constant power-factor control, schedule power-factor control, active injection of power, and voltage-based RPC. These techniques were evaluated based on their effects on reactive power compensation, voltage violation, and total network losses across a number of active customers. In [5], the researchers investigate different solutions to handle voltage violations caused by PV integration into a typical LVMg with a three-phase, four-wire line configuration. The examined solutions encompass feeder augmentation, on-load tap changers (OLTC), demand management, RPC, and other approaches. OLTC is one of the major voltage regulators that plays an important role in maintaining load voltage, especially for relatively slow load changes. Another method for managing both overvoltage during peak PV generation and voltage drops during peak demand was presented in [6].

In [7], a method is presented to mitigate the over-voltage by distributing it evenly among different ESSs. Article [8] introduced a method of decentralized control, which coordinates between OLTC and PV Systems, eliminating the need for communication links for voltage range control. The authors in [9] introduced a multi-objective mixed integer non-linear programming model with a novel time-varying decision design to execute centralized voltage control. The article [10] proposed a methodology for controlling reactive power and voltage regulation at residential PV inverters to address unbalanced voltages in distribution networks. The results showed that the Volt/Var control mitigates voltage violations in unbalanced active distribution networks and minimizes the reactive power burden on the substation [11]. In addition, in the case of voltage violations, smart inverters are categorized into two groups: one group addresses voltage violations directly. At the same time, the other minimizes the reactive power burden on the substation. The authors of [12] proposed a synchronized control technique for managing ESS and OLTC, ensuring optimal voltage levels throughout the distribution feeder. The optimization problem presented aims to minimize voltage deviation from specified values while reducing the frequency of tap position adjustments and maximizing the battery's longevity.

The authors in [13,14] proposed a voltage regulation method for a distribution network based on PV reactive power and OLTC transformers in each bus-bar. A distributed reactive power-sharing algorithm is designed to achieve voltage regulation according to the reactive power rating [15]. The article [16] analysed the mechanism of voltage over-limit and proposed an active/reactive power control strategy to meet voltage requirements. When violations occur in the electrical grid, maintaining active and reactive powers simultaneously with voltage and frequency control of PV systems is difficult [17]. The authors in [18] proposed a virtual inertia control scheme based on the dynamic equations of the synchronous generator for a two-stage transformer-less PV grid system to maintain the system's active and reactive power while changing system voltage under variable irradiance conditions [19]. In [20], the authors presented two-stage Volt/Var control blueprints using the affinely adjustable-robust counterpart (AA-RC) approach. The AA-RC works to mitigate the over-voltage problems caused by integrating PV panels in micro-grids. Simulation results demonstrated reductions in active power loss, reactive power use, and line congestion.

The rapid growth of HPVP may lead to other power quality issues, such as severe voltage fluctuations and imbalance, which may restrict further PV integrations into the grid [21,22]. The article [23] proposed using single-phase PV inverters arbitrarily connected among different phases. The effectiveness of the proposed strategy in regulating voltage imbalances and reducing energy losses is demonstrated through 24-hour simulations on three-phase, four-wire unbalanced LVDNs using realistic data. Article [24] proposed a real-time voltage control method to address the unfair active power curtailment issue in LVDNs with residence PV plants. Additionally, the article introduces a simplified method to compute the voltage sensitivity matrix for applications in unbalanced LVDNs. Other techniques have been presented in [25-30] to overcome the issue of overvoltage due to high PV penetration.

In view of what has been reviewed in the literature, in LVDNs with HPVP, it is difficult to avoid the nodal voltage fluctuation due to intermittent, stochastic, and fluctuating characteristics of PV unit output without using ESS. This article proposes a supervisory VRPC-based strategic approach for multi-string PV inverters to effectively improve voltage profile and voltage imbalance using advanced step control methodology and local voltage measurements to address the mentioned limitations and reduce the reliance on ESS. The main contributions of this article can be summarized as follows:

(1) This study proposes a VRPC approach for monitoring the voltage at the PCC to control reactive power injection or absorption based on the control of reactive power.

(2) The control aims to maintain the voltage balance within the specified grid code voltage limits while preventing the PV inverter from aging.

(3) The proposed approach is tested on LVMg containing seven bus-bars with HPVP and battery energy storage system (BESS).

(4) The efficacy of the VRPC/BESS approach is demonstrated on an unbalanced LVMg developed using actual metered PV and micro-grid data.

(5) Our search contributes to developing sustainable energy infrastructure. The results of this paper emphasize the importance of proactive voltage management in PV systems and provide practical insights to enhance the reliability and efficiency of renewable energy integration within power distribution networks.

This paper is structured as follows: *Section 2* describes the problem formulation. *Section 3* proposed the method. *Section 4* presents the model simulation and its related results. Finally, *Section 5* presents the conclusions and Future works.

## 2. PROBLEM FORMULATION

### 2.1 Impact of PV Penetration

*Figure 1* illustrates the PV penetration and reactive power adjustment on the LVMg. For the sake of simplicity, the distribution system is connected to a single customer with the power of $P_L$ and the reactive power of $Q_L$ demand through an impedance wire represented by R+ jX.

A solar cell system supplying active power $P_{pv}$ and reactive power $Q_{pv}$ is also connected to the same customer's connection point. MV/LV means medium-voltage to low-voltage transformer. $U_1$ and $U_2$ are the voltages on the two opposite sides of the bus line [4].

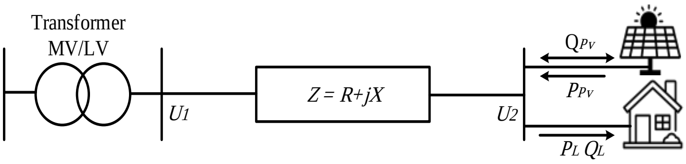

**Figure 1.** A typical power network scheme with the connection of the PV to the Micro-grid

The potential difference between the terminals of the bus can be calculated as:

$$\Delta U = U_1 - U_2 = I^* Z \tag{1}$$

$$I^* = \left(\frac{(P_L - P_{Pv}) + j\,(Q_L - Q_{Pv})}{U_2}\right)^* \tag{2}$$

By substituting *equation (2)* in *equation (1)*, we get:

$$\Delta U = \left(\frac{(P_L - P_{Pv}) + j\,(Q_L - Q_{Pv})}{U_2}\right) * Z \tag{3}$$

Then we have;

$$\Delta U = \Delta U_d + j\Delta U_q = \left(\frac{(P_L - P_{PV})R + (Q_L - Q_{PV})X}{U_2}\right) + j\left(\frac{(P_L - P_{PV})X - (Q_L - Q_{PV})R}{U_2}\right) \tag{4}$$

Where $\Delta U_d$ and $\Delta U_q$ represented the real and imaginary components; as a result, the magnitude of the voltage at point $U_1$ in *figure 1* can be computed as follows:

$$U_1 = \sqrt{(U_2 + \Delta U_d)^2 + \Delta U_q^2} \tag{5}$$

Where the voltage at point $U_2$ can be simplified since the reactance X /resistance R ratio of LVMg is so little $\Delta U_q \approx 0$, hence, we can write:

$$U_2 = U_1 - \Delta U_d \tag{6}$$

Furthermore, $\Delta U_d$ can be approximated by replacing $U_2$ with $U_1$:

$$\Delta U_d \approx \left(\frac{(P_L - P_{Pv})R + (Q_L - Q_{Pv})X}{U_1}\right) \tag{7}$$

The voltage $U_2$ is expressed as follows at the PCC:

$$U_2 \approx U_1 - \left(\frac{(P_L - P_{Pv})R + (Q_L - Q_{Pv})X}{U_1}\right) \tag{8}$$

From *equation (8)*, when demand exceeds generation, a voltage drop occurs along the feeder. Conversely, when PV generation exceeds demand, power flows to the substation, resulting in a voltage rise at the PCC, as shown in *equation (9).*

$$U_2 \approx U_1 + \left(\frac{(P_{pv} - P_L)R + (Q_{pv} - Q_L)X}{U_1}\right) \tag{9}$$

As the voltage exceeds the regulatory limits owing to rising PV penetration ($P_{pv}$ of $P_L$), the problem worsens. The combination of both reactive powers generated by the PV load and the associated inverter can have models depicted in *equations (8)* and *equation (9)*, respectively. These two powers heavily impact the voltage of PCC. Therefore, to keep the level of PCC voltage in a legitimate range, the reactive power output of the PV inverter needs to be appropriately managed.

## 2.2 Control of Reactive Power (Q(U))

Based on the voltage or PV active power level, the intelligent inverter in the PV system can either absorb or inject reactive power into the network. The following algorithm explains the proposed steps to overcome the high-level voltage in PV, as follows:

1. *Start*
2. *Read PCC voltage*
3. *Read the lower and upper voltage limits*

4. *If* $U_{pcc} < U_{lower}$
    - *Calculate the amount of reactive power needed to compensate* $Q_{compensate}$.
    - *Set the PV inverter to be ready to inject reactive power =* $Q_{compensate}$.
    - *Go to step 7.*
5. *If* $U_{pcc} > U_{upper}$
    - *Calculate the excess voltage amount* $U_{excess}$.
    - *Set PV inverter to absorb reactive power proportional* $U_{excess}$
    - *Go to 7.*
6. *If* $U_{lower} < U_{pcc} < U_{upper}$
    - *Set the PV inverter reactive power to 0.*
    - *Go to 7.*

7. *End*

The VRPC approach has been used to mitigate the voltage elevation problem in LVMg with PV integration. The level of Q(U) will be determined at the voltage of the PCC, and its interaction with the line voltage is depicted in *figure 2.*

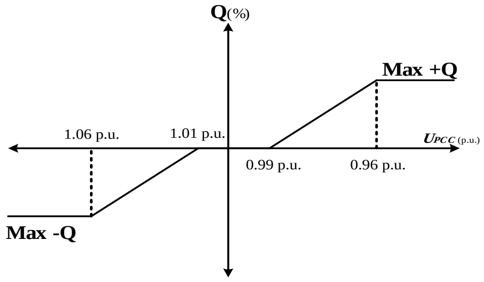

**Figure 2.** Q(U) graph supported by PV inverters based on proposed VRPC

The ESS stores surplus energy and feeds it back to the system during high load demand. In the case of HPVP, the high PV active power injection causes the voltage rise. Consequently, numerous researchers have recommended implementing ESSs, such as pumped hydro storage, flywheels, batteries, etc., to store excess energy during periods of high PV generation and low load demand [4, 29]. This approach helps prevent voltage rise issues in the Micro-grid.

### 2.3 Control of Power Factor

The PV inverter's power factor is usually set to a constant value. Producing a lead in the power factor allows the reactive power to be absorbed to contract the voltage surge resulting from active power generation. The controlling of the power factor method ensures the consumption of reactive power is balanced with the generation of active power.

## 3. PROPOSED METHOD

The algorithm presented in *section (2.2)* is associated with *Q(U)* to address the voltage level rising in the LVMg. The algorithm monitors the voltage at the PCC to control reactive power injection or absorption based on the voltage levels. Given that *Q(U)* had a high dependence on the line voltage sensitivity analysis, as revealed in *figure 3* and *equation (10).* Where *Q*, *P*, and *S* refer to the inverter's reactive power regulation capability, active power injected by the *PV*, and inverter size, respectively.

$$Q = \sqrt{S^2 - P^2} \tag{10}$$

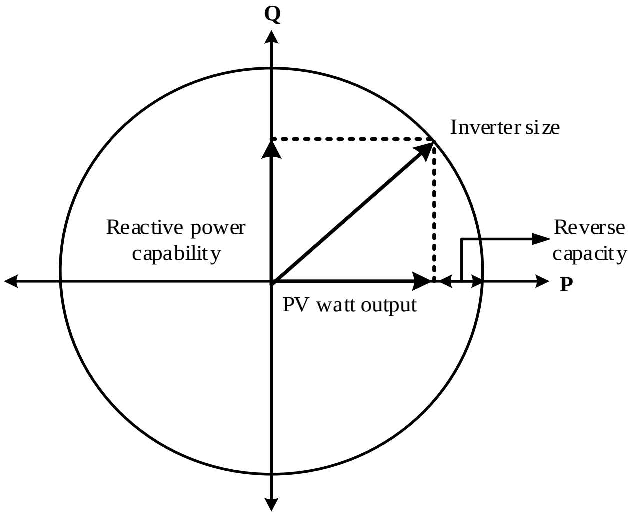

**Figure 3.** Power capability circuit of the PV inverter

Since the PV inverter's capacity to control voltage levels is limited, the risk of voltage rise is proportional to the active power production of the PV system. In the case of maximum PV generation and minimum load demand, especially when PV penetration is over 90%, the reactive power is insufficient to maintain the voltage within the limit (0.96 – 1.06 p.u.). Therefore, the control algorithm proposed a second stage to keep the voltage within the allowed limits and monitor both the voltage on the inverter terminal and the reactive power capacity utilized by the inverter.

In case the PV inverter reaches its maximum size with a terminal voltage out of the allowed limit, the ESS charging control will charge the battery with PV active power in the amount that keeps the voltage within the permitted limit.

*Figure 4* shows the proposed flowchart for this study. A microgrid model was developed for the LVMg specified in the OpenDSS Software [31]. In the next step, power flow simulations were performed to examine potential voltage rise issues with HPVP. Then, the VRPC approach for PV inverters was implemented and certified to ensure legal voltage limits for the LVMg.

The voltage profiles continuously vary from bus to bus, which may lead to an increase, decrease, or sustain of their values. This comes from many reasons, such as the availability of renewable energy sources (HPVP, ESS, etc.). For this reason, and to make a valuable comparison, a new index was used to manage voltage profiles by determining the voltage restoration index (*Ures.*) as the following equation:

$$\mathrm{U_{res.}}\% = \left|\frac{(\mathrm{U_{rate}})_{\mathrm{without}} - (\mathrm{U_{rate}})_{\mathrm{with}}}{(\mathrm{U_{rate}})_{\mathrm{without}}}\right| \mathrm{X}100\% \tag{11}$$

Where, $$\mathrm{U_{rate}} = \sum\nolimits_{\mathrm{k}}^{\mathrm{No.}} \mathrm{U_k} \Big/ \mathrm{No.} \tag{12}$$

Where $U_{rate}$ is the voltage rate with/without BESS; $U_k$ is the value of the voltage at bus *k*; No. is the number of LVMg buses.

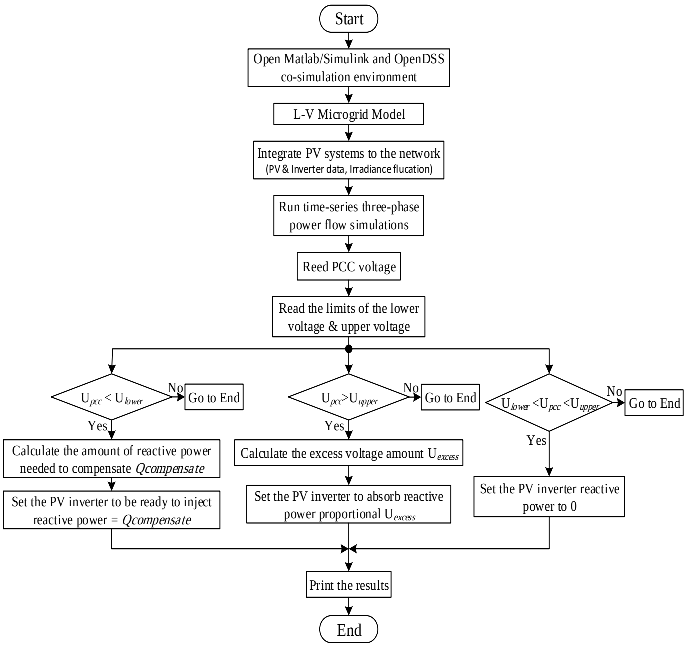

**Figure 4.** Flowchart of the proposed approach

## 4. SIMULATION AND RESULTS

Distribution network analysis is based on power flow at specific snapshots in time, and the PV generation is variable because of the weather conditions and changes in load demands, where the conventional simulation techniques will not be able to provide the appropriate analysis to verify the HPVP control performance. The OpenDSS [31] offers capabilities for timeseries analysis of voltage profiles over-long periods compared to MATLAB/Simulink.

The system has been simulated using MATLAB/Simulink and OpenDSS co-simulation. A model of a seven bus-bars system in an Iraqi distribution network was used as a test model to implement the proposed approach. In this study, five cases of HPVP in the micro-grid were taken, namely (10%, 30%, 50%, 70%, and 90%). The LVMg data are mentioned in *table 1*. *Figure 5* shows the proposed model in this article.

**Table 1. The features of the Iraqi tested distribution network**

| Characteristic | Quantity |
|---|---|
| Number of customers | 42 |
| Transformer rating (kVA) | 400 |
| Peak load demand (kW) | 273 |
| Microgrid (km) | 1.425 |

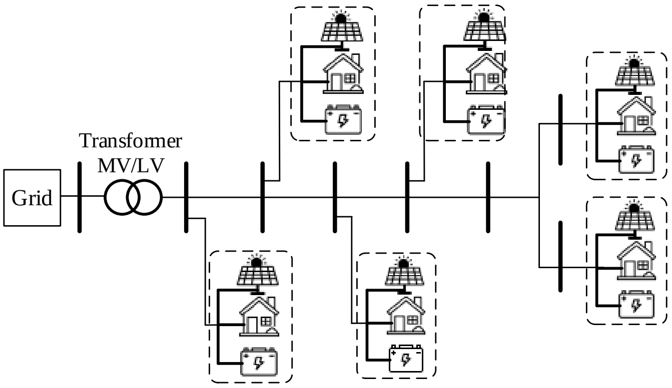

**Figure 5.** The LVMg seven Bus-bar with HPVP and battery system

### 4.1 Voltage Increase Problem

The system penetration level is up to 90% from the distributed generator, which is considered penetration of the system. The penetration level of PV can be calculated as flows:

$$\mathrm{PV}_{\mathrm{penetration}} = \frac{\text{maximum PV generation}}{\text{maximum load demand}} \times 100\% \qquad (13)$$

When the amount of PV generation is increased, the PV penetration is increased. Accordingly, increasing the grid demand reduces the dangerous impact of PV penetration on the power system, which causes voltage increase levels.

The proposed approach was tested under the worst case, typically during the midday when generation reaches its maximum and load demand is minimal.

*Figure 6* shows the typical voltage graph of the LVMg had a high voltage breakdown due to the high X/R ratio that characterizes the LVMg. Therefore, only in the case of HPVP did the power have a reverse flow, as the PV generation was higher than the load demand, where the LVMg is not designed for such distribution generators. Therefore, a voltage rise will occur among different buses in the micro-grid, as shown in *figure 6*.

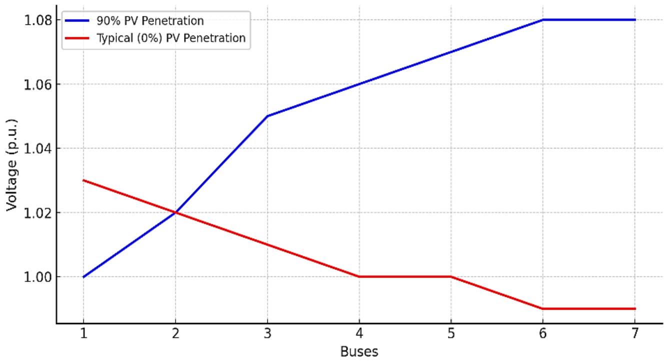

**Figure 6.** Micro-grid voltage vs. number of buses without voltage control

*Table 2* shows the bus voltage before executing the VRPC with/without BESS at different penetration levels. At 10% and 30% of HPVP levels, the voltage level is within the range, except for 50%, which is close to the permissible voltage limit. At HPVP levels of 70% and 90%, the bus voltage level is 1.068 p.u. and 1.092 p.u. respectively, and both are violating the voltage level limit. So, it is possible to determine an HPVP starting from 70% and above.

**Table 2. Bus voltage at HPVP level (%).**

| Case | HPVP level (%) | Bus Voltage |
|---|---|---|
| 1 | 10 | 1.004 |
| 2 | 30 | 1.011 |
| 3 | 50 | 1.044 |
| 4 | 70 | 1.068 |
| 5 | 90 | 1.092 |

*Figure 7* reveals the voltage rise in a particular bus during 24 hours. This voltage operates within the allowed voltage level limit, starting from 0.96 p.u. up to 1.06 p.u. with the breakdown in the direction of the last customer. On the other hand, a voltage rise occurred at midday for the network with HPVP, and reverse power flow occurred.

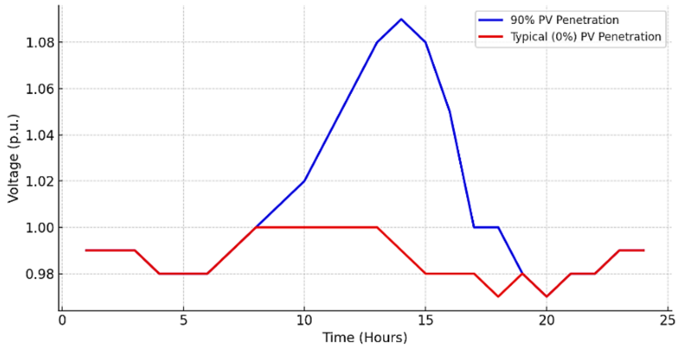

**Figure 7.** Voltage on one bus for 24 hours without voltage control.

### 4.2 Improve Voltage Levels using VRPC with/without BESS

As explained in the previous section, the PV inverter has limited reactive power and response capacity to verify the PCC voltage. *Figure 8* shows the response reactive power of the PV inverter following the rise of PV generation during midday. The inverter's limited capacity prevents the voltage from being maintained within the limit.

Therefore, this article supports the VRPC technique with a BESS that charges only when reactive power reaches its maximum to keep the voltage at the PCC within the permissible limit. *Figure 9* shows the battery charging current within 24 hours.

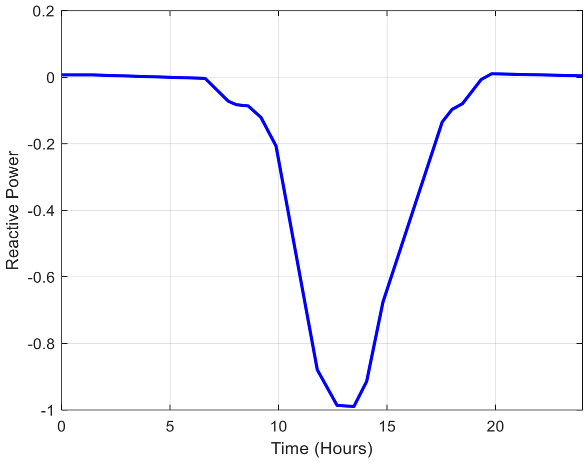

**Figure 8.** Reactive power of PV inverter with time

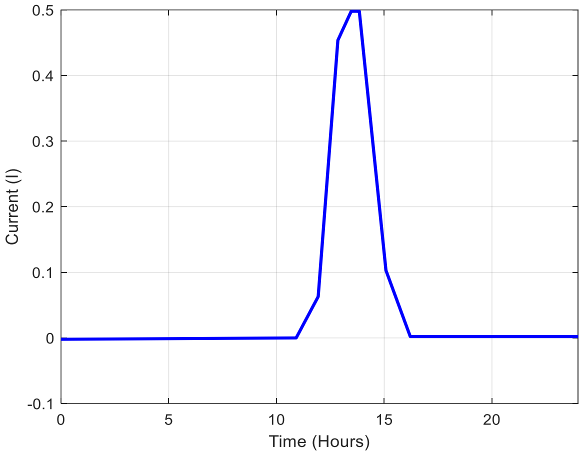

**Figure 9.** Charging current of ESS for one day (p.u.)

*Table 3* and *table 4* show the bus voltage for the proposed system after executing the VRPC technique without BESS at a penetration level of 70% and 90%. We notice the voltage levels (V1, V2, V3, and V4) are within the range, except for V5, which is close to the permissible voltage limit. At the same time, V6 and V7 violate the voltage level limit. In addition, *table 3* and *table 4* show that when using the VRPC technique with BESS, all voltages are within the permissible voltage.

Moreover, for comparison, a new index was used to manage voltage profiles by determining the voltage restoration index (Ures.), as shown in *equation (11)*. A lower voltage rise rate of 2.8816% and 3.203% was observed for HPVP levels of 70% and 90%, respectively, using the VRPC technique compared with/without BESS.

░ **Table 3. Bus voltage at 70% HPVP using VRPC with/without BESS**

| No. of bus | Voltage (p.u.) Implementing VRPC | Voltage (p.u.) Implementing VRPC/BESS | Ures% |
|---|---|---|---|
| 1 | 1.001 | 1.001 | 0 |
| 2 | 1.02 | 1.020 | 0 |
| 3 | 1.025 | 1.0224 | 0.254 |
| 4 | 1.037 | 1.0267 | 0.9932 |
| 5 | 1.049 | 1.028 | 2.0019 |
| 6 | 1.0604 | 1.03 | 2.8668 |
| 7 | 1.0619 | 1.0313 | 2.8816 |

░ **Table 4. Bus voltage at 90% HPVP using VRPC with/without BESS**

| No. of bus | Voltage (p.u.) Implementing VRPC | Voltage (p.u.) Implementing VRPC/BESS | Ures% |
|---|---|---|---|
| 1 | 1.003 | 1.003 | 0 |
| 2 | 1.021 | 1.021 | 0 |
| 3 | 1.04 | 1.021 | 1.83 |
| 4 | 1.05 | 1.021 | 2.762 |
| 5 | 1.0504 | 1.021 | 2.799 |
| 6 | 1.062 | 1.032 | 2.825 |
| 7 | 1.063 | 1.03 | 3.203 |

*Figure 10* depicts a one-day voltage graph using the VRPC technique with/without BESS. The figure shows that the VRPC technique cannot keep the voltage within the limit; nevertheless, the VRPC/BESS technique keeps the voltage within the limit by charging the battery with surplus energy to give it back to the system during high load demand periods.

The simulation results show that the VRPC/BESS technique is proven effective and robust in regulating the voltage at operating conditions of various HPVP levels, and the proposed method can be considered fully robust and ready for widespread implementation.

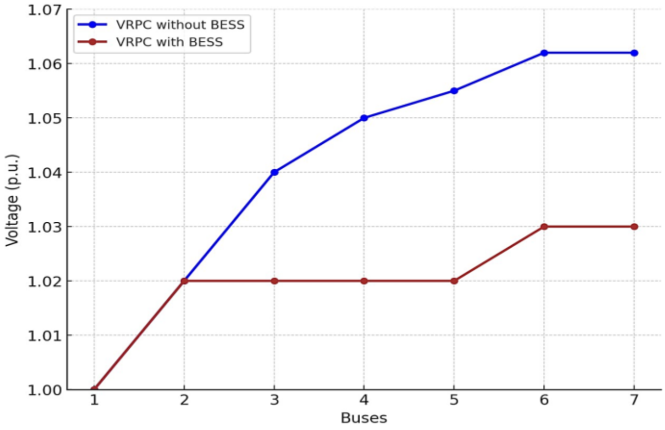

**Figure 10.** Voltage vs. number of buses using VRPC with/without BESS

### 4.3 Sensitivity analysis

This section aims to evaluate the impact of varying levels of HPVP, VRPC, BESSs, and control techniques on voltage levels and reactive power for an LVMg with 42 customers. The following scenarios were simulated to assess how different control mechanisms affect the performance of an LVMg under HPVP conditions. *Table 5* shows the parameters considered for the sensitivity analysis.

**Table 5. The parameters considered for the sensitivity analysis**

| Parameter | Value |
|---|---|
| PV Penetration Levels | 10%, 30%, 50%, 70%, and 90%, with each customer having a maximum PV generation capacity of 4 kW. |
| Load Conditions | A minimum load of 550 W per customer, resulting in a total minimum load of 23.1 kW and a maximum load of 273 kW for 42 customers. The difference between maximum PV generation and minimum load is 3.45 kW per customer, resulting in a total PV generation of 144.9 kW for 100% HPVP. |
| Battery Energy Storage System (BESS) | The presence and absence of BESS (100 Ah, 51.4V) were analyzed to determine its effect on voltage levels regulation. |
| Control of Reactive Power *Q(U)* | The effectiveness of *Q(U)* was evaluated with and without BESS. |
| Control Strategies | • VRPC: This control strategy manages reactive power by adjusting the reactive power output from PV inverters to maintain voltage levels within permissible limits. VRPC is crucial in reducing over-voltage issues caused by HPVP, as it has proven effective and robust in regulating the voltage by injecting or absorbing reactive power as needed.<br>• BESS Integration: BESS provides an effective means of absorbing excess energy during periods of high PV generation and releasing it during periods of high demand or low generation. BESS plays a key role in managing voltage fastness by balancing supply and demand, reducing the need for active power curtailment, and providing reactive power support. |

**Scenario 1: Minimum Load and No PV Generation**
The total load of 23.1 kW and no PV generation resulted in voltage levels across all buses remained stable at approximately 1.00 p.u., reactive power requirements were minimal, with no significant voltage deviations. The system remains within nominal operating limits with a balanced load and no PV contribution.

**Scenario 2: HPVP (90%) and Minimum Load**
The total PV generation of (144.9 kW x 0.9), with load remaining at 23.1 kW resulted in voltage levels rising significantly, particularly at end buses, reaching up to 1.08 p.u., reactive power dipped to -1.0 p.u. during midday due to high PV output and limited compensation capability. Here, HPVP led to over-voltage issues, particularly at buses farther from the transformer, indicating a need for additional voltage control measures.

**Scenario 3: HPVP with VRPC**
The HPVP generation with VRPC-enabled resulted in voltage levels being reduced compared to Scenario 2, with end buses reaching around 1.06 p.u., reactive power compensation improved, with dips reduced to -0.8 p.u. Here, VRPC helped mitigate over-voltage issues, but it was not sufficient to fully stabilize voltage across all buses under HPVP conditions.

**Scenario 4: HPVP with VRPC/ESS**
The HPVP generation with VRPC/ESS enabled resulted in voltage levels across all buses remaining within the permissible range, around 1.03 to 1.05 p.u., the reactive power profile was more stable, with values staying closer to 0 p.u. throughout the day. A significant improvement in the voltage restoration index (*Ures%*) was observed, with up to 5.6776% reduction in voltage rise at critical buses during 90% HPVP compared to scenarios 2 and 3. Here, the combination of VRPC/BESS provided effective voltage regulation, preventing over-voltage and ensuring reactive power stability.

The simulations demonstrated that the VRPC/BESS technique is effective and robust in regulating voltage under HPVP conditions, making the proposed method suitable for widespread implementation. The boxplot in *figure 11* shows the voltage levels for different scenarios. A heat map of voltage levels across buses over 24 hours for Scenario 4 is shown in *figure 12.* It illustrates the consistency of voltage across the buses throughout the day, with minimal deviations from the target range.

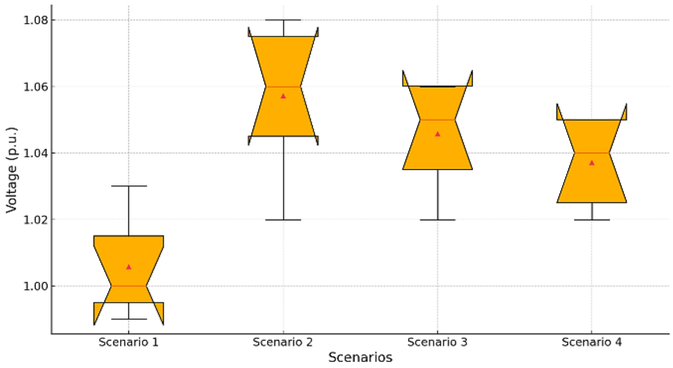

**Figure 11.** Voltage levels for different scenarios.

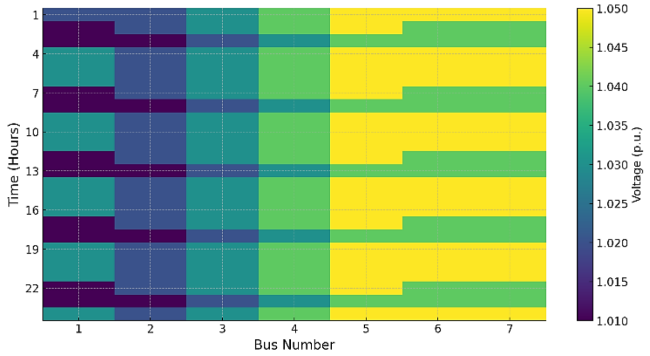

**Figure 12.** Voltage levels across buses over 24 hours for Scenario 4.

*Figure 12* shows the effectiveness of the VRPC/BESS technique in maintaining voltage levels. The voltage levels are predominantly within the permissible limits (between 1.03 and 1.05 p.u.), indicating the ability of the VRPC/BESS technique to mitigate fluctuations caused by HPVP generation. The heat map also highlights the periods of HPVP output and how the system responded to maintain stability.

## 5. CONCLUSION

This article aims to find a way to support *Q(U)* when PV generation penetration is high. The VRPC/BESS technique is proposed to be implemented in an LVMg, where the system voltage interacts rapidly with any change of reactive power. The algorithm monitors the voltage on the common coupling point to *Q(U)* injection or absorption based on the *Q(U)* control. As illustrated in the simulation results, the VRPC/BESS technique is proven to regulate the transient and steady state of voltage at various HPVP levels. Meanwhile, the rate of voltage rise was reduced by 5.6776% during HPVP by 90% using the VRPC/BESS technique compared to scenarios 2 and 3. The simulations demonstrated that the VRPC/BESS technique is proven effective and robust in regulating the voltage under various HPVP operating conditions, and the proposed method can be considered fully robust and ready for widespread implementation. The future work will focus on:

1. Develop intelligent control and regulation techniques under HPVP and assess these techniques' performance under various disturbances and uncertainties.
2. Improve the power quality level through quality improvement techniques such as harmonic filters and voltage regulators.

### Author Contributions

“Conceptualization, Rasool M. Imran and Mohammed Kdair Abd; methodology, Mohammed Kdair Abd; software, Rasool M. Imran and Farhad E. Mahmood; validation, Firas M. F. Flaih, Rasool M. Imran, and Layth F. Kamal; formal analysis, Rasool M. Imran and Mohammed Kdair Abd; investigation, Rasool M. Imran; resources, Mohammed Kdair Abd; data curation, Farhad E. Mahmood; writing—original draft preparation, Firas M. F. Flaih; writing—review and editing, Mohammed Kdair Abd; visualization, Layth F. Kamal; supervision, Mohammed Kdair Abd”.

### Conflicts of Interest

“All authors affirm that there is no conflict of interest to disclose regarding the publication of this paper”.

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