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Assessment of Local Photovoltaic Inverter Control Strategies and transformer tap control for Voltage Regulation in Low-Voltage Distribution Networks

O. Abarrategi[1], E. Torres[1], D.M. Larruskain[1], V. Valverde[1], I. Zamora[1]

[1] Bilbao School of Engineering, EHU
C/ Rafael Moreno Pitxitxi 2. +34 94 601 4971, oihane.abarrategui@ehu.eus

Abstract. The increasing penetration of photovoltaic (PV) systems and electric vehicles in low-voltage distribution networks (LVDNs) has intensified voltage regulation challenges due to bidirectional power flows and limited network flexibility. Conventional solutions based on infrastructure reinforcement or centralized control are often costly and complex to deploy. This paper analyzes a local voltage control strategy that exploits the inherent capabilities of PV inverters to provide voltage support in LVDNs with high PV penetration. The proposed approach relies solely on local measurements, eliminating communication requirements, and employs reactive power control and, when necessary, active power modulation to maintain voltages within regulatory limits. Simulation results under representative operating conditions demonstrate the effectiveness of the proposed local control in mitigating overvoltages while reducing active power curtailment. The combination with transformer tap control enables performance of voltage regulation.

Key words. Low-voltage distribution networks, Photovoltaic inverters, Voltage control, Reactive power control, Active power curtailment, Distributed Energy Resources.

1. Introduction

The increasing electrification of society and the transition toward low-carbon energy systems have driven the large-scale integration of distributed renewable energy sources, particularly photovoltaic (PV) systems, together with the rapid adoption of electric vehicles (EVs). As a result, a significant share of both electricity generation and consumption has shifted toward low-voltage distribution networks (LVDNs), which were not originally designed to operate under these emerging conditions [1], [2], [3].

LVDNs exhibit distinctive electrical characteristics, including a high resistance-to-reactance (R/X) ratio, long radial feeders, and a high diversity of single-phase loads. Under these conditions, the increasing penetration of distributed generation introduces bidirectional power flows that significantly affect voltage profiles along the feeders. During periods of high PV generation and low demand, reverse power flow toward the substation can lead to overvoltage events [4]. Conversely, during evening or nighttime hours, the coincidence of residential demand and simultaneous EV charging may cause severe voltage drops, in some cases exceeding the limits established by the EN50160 standard [5], [6]. Several studies have identified uncoordinated EV charging as a major source of stress for LVDNs, particularly in urban areas with high user concentration [7], [8],[9].

Conventional voltage mitigation has relied on infrastructure reinforcement, including conductor upgrades, additional feeders, and transformer replacement [10], [11]. However, high investment costs, long implementation times, and environmental and social constraints have driven research toward more flexible solutions based on advanced control, power electronics, and active management of distributed energy resources [12].

Active Power Curtailment (APC) is widely used to mitigate overvoltages in networks with high PV and BESS penetration [13], but it introduces economic losses and fairness concerns, particularly for users at feeder ends [14]. To address these limitations, both centralized Optimal Power Flow (OPF)-based approaches [15], [16] and distributed, adaptive strategies have been proposed [17], [18]. Reactive Power Control (RPC), particularly through Volt/Var schemes, offers voltage regulation without reducing active power generation, although its effectiveness is limited by inverter capacity and the resistive nature of LVDNs [18], [19], [20]. Combined active–reactive power control (ARPC) schemes improve the trade-off between voltage regulation and curtailment losses when properly tuned [21], [22].

At the substation level, On-Load Tap Changers (OLTCs) remain widely used but face limitations under reverse power flows and phase unbalances [23],[24]. Coordinated schemes combining OLTCs with inverters, BESS, and EVs, as well as faster electronic OLTC variants, have been proposed to enhance performance [25].

Voltage control developed by smart inverters can be based on external control signals sent from a remote dispatch, or can use predefined and typically droop-based curves requiring only local measurements. Local voltage control does not require communications and contribute to increase hosting capacity without great investments.

The main objective of this work is to analyse the impact of high photovoltaic (PV) generation penetration on LVDNs and to evaluate how the application of local voltage control schemes based on different PV inverter control modes can mitigate overvoltage issues and affect renewable energy integration. To this end, a representative European LV distribution network has been used to assess the effectiveness and limitations of local inverter-based voltage control strategies. Simulations have been done using OpenDSS, while MATLAB has been employed for data processing, post-analysis, and result visualization. This co-simulation framework enables a detailed time-domain assessment of network behaviour under realistic operating conditions.

2. Methodology

The study has been conducted on the IEEE European Low Voltage Test Feeder, which represents a typical European LV distribution network. The feeder comprises 905 line segments, 50 single-phase loads, and a medium-voltage to low-voltage (MV/LV) transformer rated at 0.8 MVA. The selected test system allows the evaluation of voltage behaviour under realistic topology, impedance characteristics, and phase unbalance conditions.

Photovoltaic generation is integrated at each load connection point, resulting in a total of 55 PV units and a penetration level of 100%. Each PV system has a rated maximum power of 4kW, an inverter of 4.8 kVA and is modelled using realistic irradiance and temperature profiles, enabling accurate representation of PV output variability throughout the day.

OpenDSS has been controlled via a COM interface from MATLAB, allowing automated execution of time-series simulations and systematic modification of inverter control parameters. Daily simulations have been performed over a 24-hour horizon with a one-minute time resolution, capturing both steady-state and fast voltage variations caused by PV generation dynamics.

3. Inverter Control Strategies

Simulation results reveal several challenges associated with high PV penetration in LV distribution networks. These include significant voltage rise during periods of high solar irradiance, reverse power flow toward the distribution transformer, and pronounced voltage variability due to fast irradiance changes caused by cloud transients. Together, these phenomena impose technical limits on renewable energy integration and highlight the need for effective voltage control strategies.

In this section, the performance of several local PV inverter control mechanisms is assessed and compared. Consider the time scale represent a day and is set every 10 minutes, "0" being 00:00 and 144 corresponding to 23:59.

A. Volt/Var Control

Volt/Var control regulates voltage by absorbing or injecting reactive power as a function of the local voltage magnitude. This strategy reduces overvoltage conditions without curtailing active power generation; however, its effectiveness is limited by the available reactive power margin of the inverter, which may be insufficient under high PV penetration.

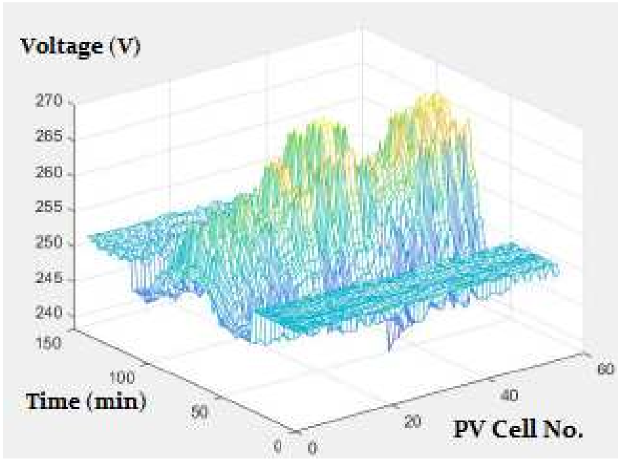

Fig. 1. Voltage of PVCells

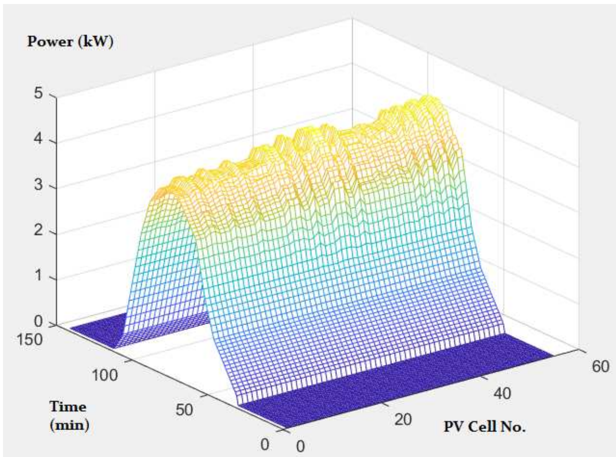

Fig 2. Active Power of the PV Cells

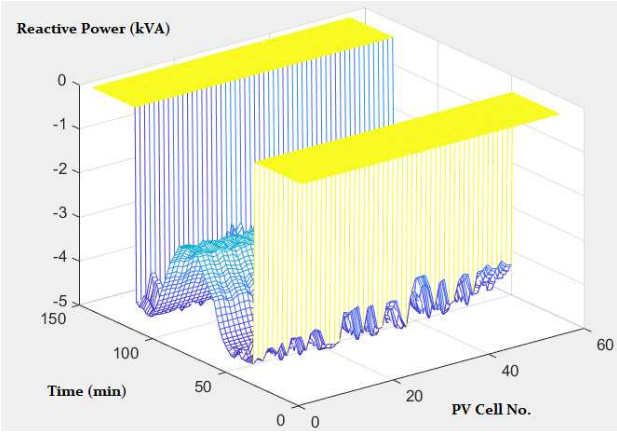

Fig 3. Reactive Power of the PV Cells

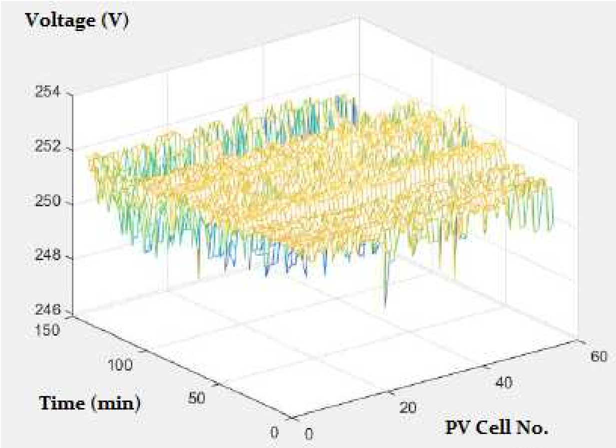

Fig 4. Voltage of the PV Cells

It is observed that photovoltaic generators consume reactive power in order to try to reduce the PV generator voltage, since priority is given to maintaining active power as a function of voltage. During the central hours of the day, when PV generation is higher and therefore voltages are higher, it is observed that reactive power consumption decreases. The reason is that, as can be seen in Fig.1-3, when the voltage rises to a defined value, the inverter control acts and reduces that voltage by increasing the consumption of generated reactive power. In this way, the value of the reverse power flow delivered to the grid is reduced, without modifying the generated active power.

Regarding the voltage at the different buses in the network, it decreases relative to the standard voltage but remains higher, reaching 264 V, and the voltage unbalance continues to be below 2%.

B. Volt/Watt Control

Volt/Watt control reduces active power output when the voltage exceeds a predefined threshold. This method is highly effective in mitigating overvoltages and ensuring compliance with voltage limits, but it directly penalizes renewable energy production by curtailing PV generation.

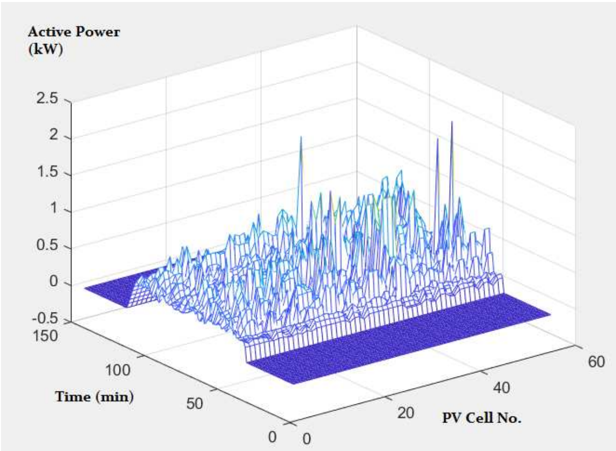

Fig 5. Active Power of the PV Cells

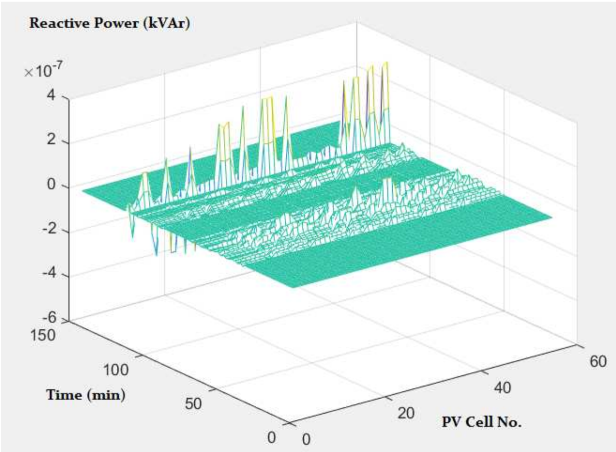

Fig 6. Reactive Power of the PV Cells

As can be seen on Fig.4-6, the voltage unbalance under this control mode is significantly reduced (0.02%), remaining well below the allowable limit (2%). Furthermore, the voltage magnitude at all buses stays within the permitted range, with the highest recorded value being 251 V (below the 253 V threshold).

C. Dynamic Reactive Current Control

Dynamic reactive current control responds to rapid voltage variations by injecting or absorbing reactive current as a function of the voltage change. While this strategy effectively reduces voltage oscillations and improves dynamic performance, it does not address sustained overvoltage conditions.

With this control mode, both the voltage unbalance and the voltage magnitude at each bus increase. Although the unbalance remains below 2%, reaching up to 0.6%, the voltages rise to as high as 265 V, exceeding the regulatory limit, as seen in Fig.7-9.

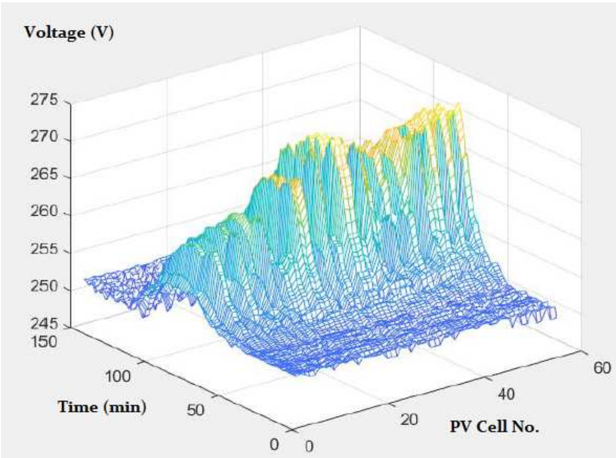

Fig 7. Voltage of the PV Cells

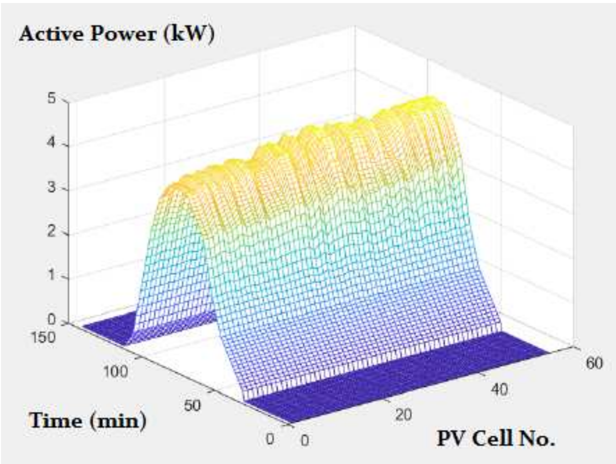

Fig 8. Active Power of the PV Cells

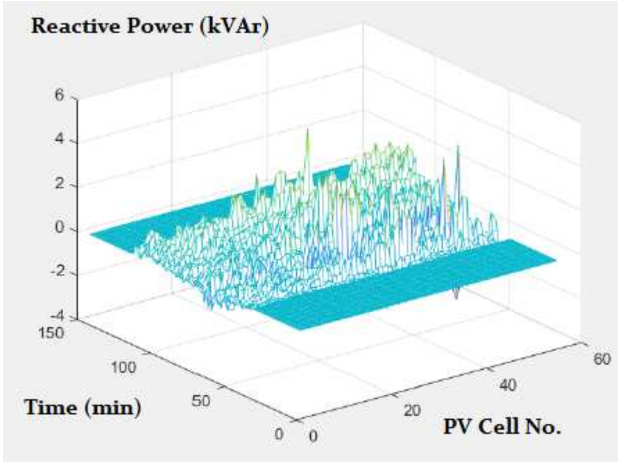

Fig 9. Reactive Power of the PV Cells

D. Watt/Power Factor (Watt/PF) Control

Watt/PF control adjusts the inverter power factor as a function of active power output, increasing reactive power consumption at high generation levels. Although this approach contributes to partial voltage reduction, it does not fully prevent overvoltages in scenarios with very high PV penetration.

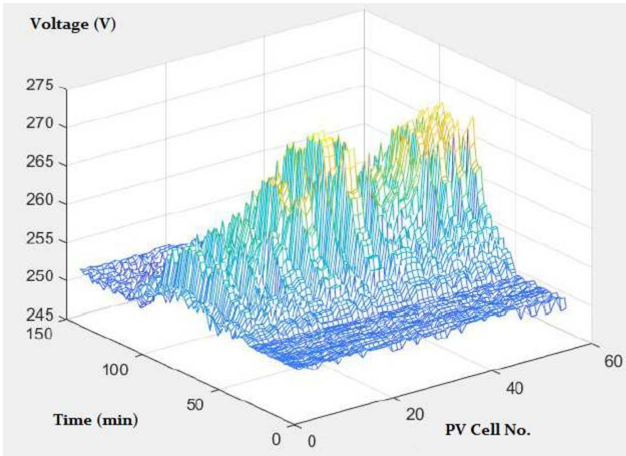

Fig 10. Voltage of the PV Cells

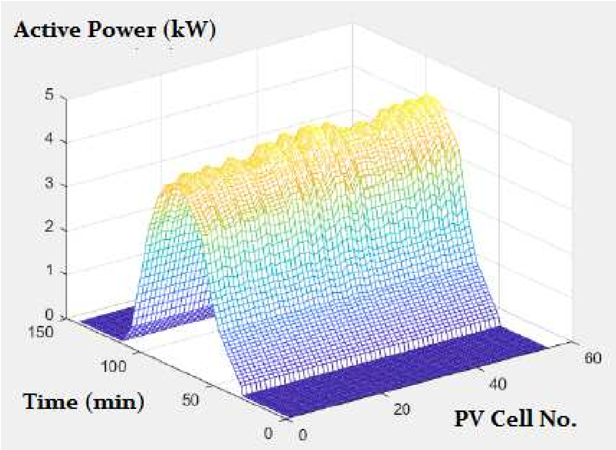

Fig 11. Active Power of the PV Cells

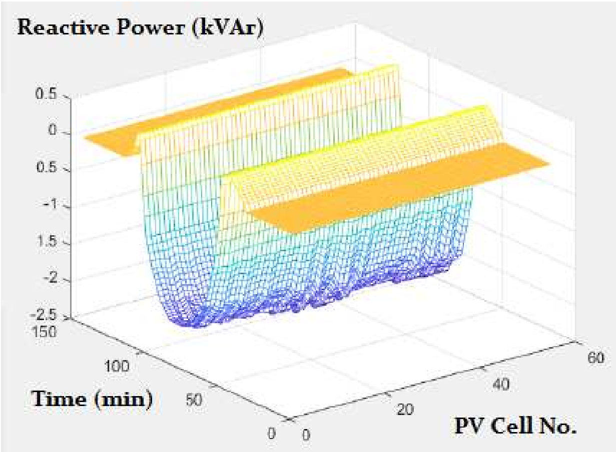

Fig 12. Reactive Power of the PV Cells

With this type of control, the reactive power is adjusted to maintain a power factor as a function of the generated active power. This strategy modifies the level of reactive power exchanged by the inverter: at low active power generation, a small amount of reactive power is injected, while beyond a certain active power threshold the inverter starts absorbing reactive power up to 1 pu.

However, since the inverter operates with active power priority, it cannot fully reach this limit, which explains the observed reduction in reactive power absorption during peak generation hours. Nevertheless, as can be observed in Fig.10-12, the voltages at all buses exceed the regulatory limits, with a maximum voltage of 266 V. The maximum voltage unbalance reaches 0.8%, which is still below the 2% threshold.

E. Watt/Var Control

Watt/Var control establishes a direct relationship between active and reactive power output. This strategy can reduce voltage levels more effectively than Watt/PF control but typically requires inverter oversizing to provide sufficient reactive power capability.

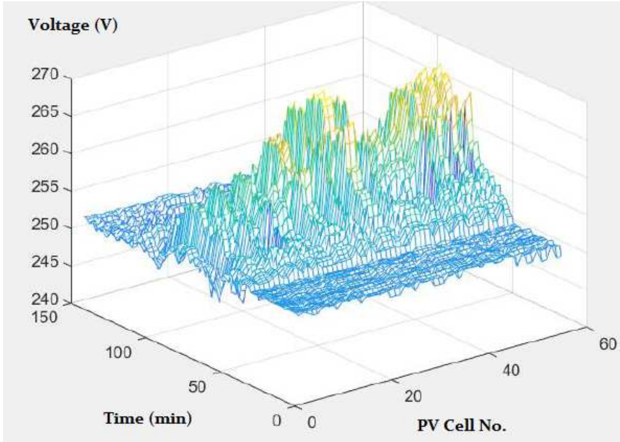

Fig 13. Voltage of the PV Cells

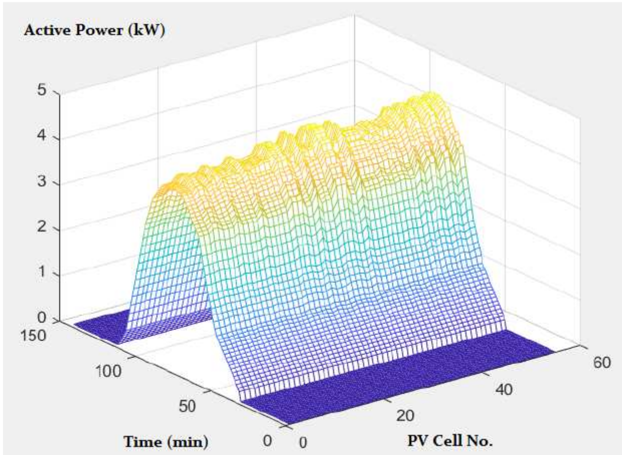

Fig 14. Active Power of the PV Cells

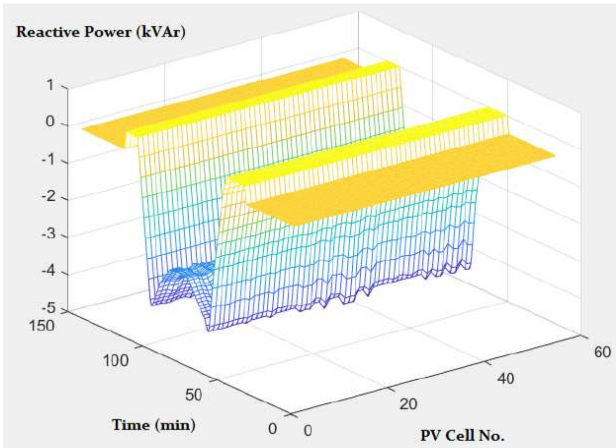

Fig 15. Reactive Power of the PV Cells

It can be observed in Fig.13-15, that under this control mode, modifying both active and reactive power reduces the voltage at the PV terminal. In this case, priority is given to active power production so a decrease in the reactive power is obtained during the middle hours of the day.

4. Combined Inverter and Transformer Tap Control Strategy

In low-voltage networks with high penetration of photovoltaic generation, the control performed of inverters may be insufficient and/or produce excessive curtailment of photovoltaic generation. However, the coordination with the tap control of the MV/LV transformer at the secondary substation provides enhanced voltage regulation along the whole feeder and reduces curtailed photovoltaic generation. In addition, the coordination between smart inverter control and transformer tap control will enable to take advantage of the local response of smart inverters and the overall voltage regulation obtained by changing the turns-ratio. In this section, the performance of the combination of transformer tap control with some of the local PV inverter control strategies is shown. With that purpose, a tap changer at the low voltage winding of the transformer has been considered, with five taps that enable changing the tap ratio from 0.95 to 1.05 p.u. in order to keep voltage at remote prosumer below the threshold of 253 V.

A. Volt/Var and OLTC control

In the case of Volt/Var strategy, the reduction in the transformer tap improves the voltage distribution in the whole network. As a result of the voltage improvement, the reactive power injection from inverters is also modified. In this case, the change in the reactive power is not much noticeable because a high-voltage scenario even without photovoltaic generation has been considered.

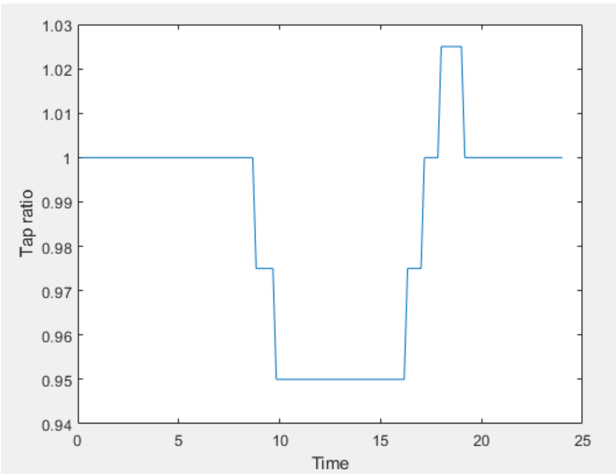

Fig 16. Tap ratio of the MV/LV transformer

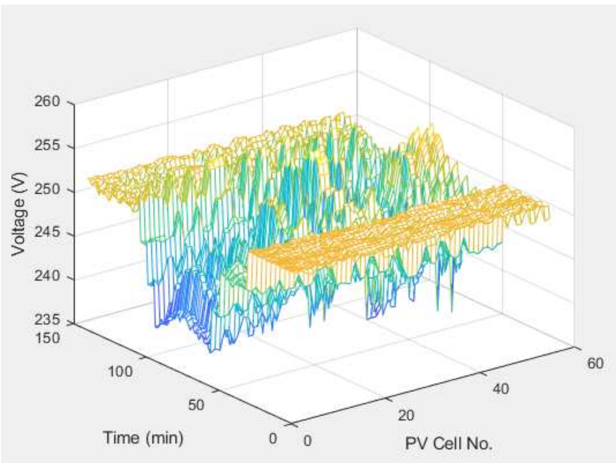

Fig 17. Voltage of the PV Cells

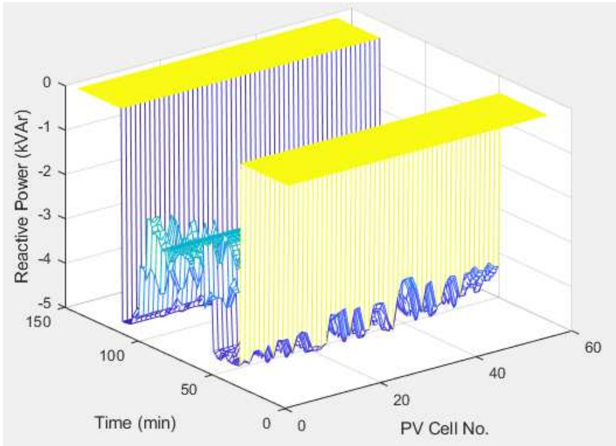

Fig 18. Reactive Power of the PV Cells

B. Volt/Watt and OLTC control

In the case of the Volt/Watt strategy, the inverter does not inject reactive power, but the curtailment in the active power from the inverter is now partially compensated by the action of the transformer tap control, which decreases a tap to decrease voltages in central hours. As a result, inverters inject more active power. However, in this case the improvement in the active power is moderate because a high-voltage scenario even without photovoltaic generation has been considered.

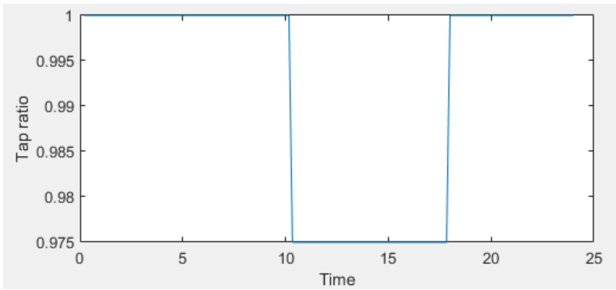

Fig 19. Tap ratio of the MV/LV transformer

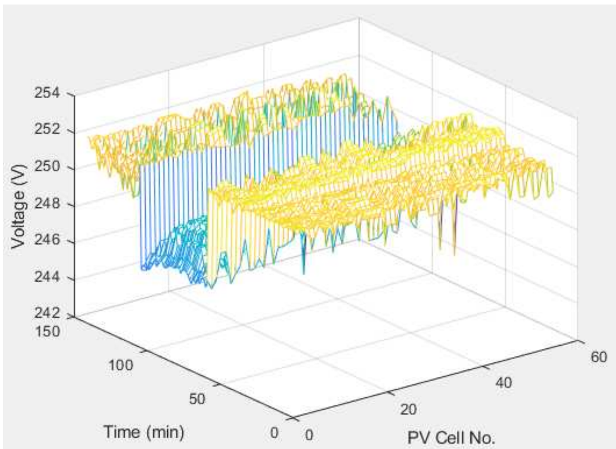

Fig 20. Voltage of the PV Cells

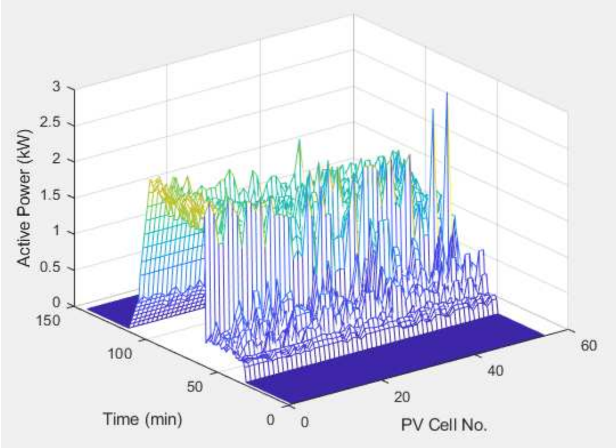

Fig 21. Active Power of the PV Cells

4. Conclusion

This paper has analyzed the effectiveness of different local PV inverter control strategies for voltage regulation in low-voltage distribution networks with high photovoltaic penetration. The results confirm that, in the absence of active control, LVDNs are unable to accommodate high levels of distributed generation without violating statutory voltage limits. Severe overvoltage conditions were observed, with phase voltages reaching up to 265 V, significantly exceeding the limits established by EN/UNE 50160, together with pronounced reverse power flows during periods of high PV generation.

Among the evaluated strategies, reactive power–based controls such as Volt/Var, Dynamic Reactive Current, Watt/PF, and Watt/Var contribute to partial voltage mitigation and reduced voltage fluctuations. These approaches alone are generally insufficient to ensure full compliance with voltage standards under peak generation conditions, particularly in networks with high R/X ratios and pronounced phase unbalance if priority is given to active power production and the inverter does not have enough capability to provide the required reactive power. In contrast, active power–based strategies, especially Volt/Watt control, proved effective in maintaining voltages within regulatory limits. Nevertheless, this improvement is achieved at the expense of active power curtailment, leading to reduced energy efficiency and limited renewable energy utilization.

The comparative analysis highlights a fundamental trade-off between voltage compliance and PV energy harvesting when relying exclusively on local inverter control. While reactive power modulation can delay the onset of overvoltages, active power curtailment remains necessary in heavily constrained scenarios. These findings indicate that no single local control strategy can provide an optimal solution across all operating conditions. Overall, the results emphasize the need for hybrid and adaptive control schemes that combine reactive and active power capabilities, potentially complemented by coordination among neighboring inverters. Furthermore, the optimal selection and tuning of control strategies must explicitly account for network topology, line impedances, and phase unbalance to ensure robust and efficient voltage regulation in future low-voltage distribution networks.

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