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Impact of On-Load Tap Changer Operation on Voltage Control in Distribution Networks with High PV Penetration

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Abstract. High photovoltaic (PV) penetration in distribution networks creates increasing voltage regulation challenges due to the variability of generation and demand. Overvoltages during periods of high PV production and undervoltages during peak demand can compromise voltage quality compliance. Traditional voltage regulation based on fixed or off-load tap changers lacks flexibility and often requires planned outages.
This paper analyses the impact of on-load tap changer (OLTC) operation on voltage control in a distribution network. Time-series simulations are carried out on a representative feeder using synthetic load and PV profiles. Scenarios with and without OLTC are compared, and different OLTC control strategies are evaluated. Key performance indicators include voltage limit compliance and the effectiveness of tap operations.
Results show that OLTC operation significantly improves voltage regulation and mitigates voltage violations without supply interruptions. OLTCs are therefore confirmed as an effective solution for PV-rich distribution networks.

Key words. On-load tap changer, voltage regulation, photovoltaic integration, active distribution networks.

1. Introduction

The increasing penetration of distributed photovoltaic (PV) generation is reshaping distribution network operation. In low- and medium-voltage feeders, PV variability and its mismatch with demand can lead to voltage rise (high PV output, low demand) and voltage drop (peak demand, negligible PV). Maintaining voltage compliance under these conditions is therefore a key concern for distribution network operators (DNOs).

In Europe, power-quality standards require the supply voltage to remain within ±10% of nominal under normal operating conditions [1,2]. Conventional voltage regulation in distribution systems relies on fixed settings and off-load tap changes, which offer limited adaptability and typically require planned outages to adjust set-points. At high PV penetrations, compliance may otherwise require curtailment or network reinforcement.

On-load tap changers (OLTCs) address these limitations by enabling tap adjustments under load, allowing adaptive regulation of feeder voltages. Prior studies report improved voltage profiles and increased PV hosting capacity with OLTC deployment [3,4], and European field trials have demonstrated mitigation of PV-driven overvoltages and improved voltage quality [5].

OLTC operation also entails trade-offs: tap changes affect voltages, currents, and losses, while frequent operations accelerate mechanical wear. Different control strategies can therefore lead to different compromises between voltage compliance, hosting capacity, losses, and operational effort [6,7].

This paper evaluates OLTC-based voltage control in a high-PV distribution feeder using time-series power-flow simulations driven by synthetic load and PV profiles. A baseline without OLTC is compared with alternative OLTC control strategies, focusing on voltage compliance and control performance.

2. Voltage Regulation Challenges

Voltage regulation in distribution networks was traditionally designed for passive operation with predominantly unidirectional power flows. Under these conditions, fixed transformer set-points and infrequent tap adjustments were generally sufficient to keep customer voltages within statutory limits.

High penetrations of distributed photovoltaic (PV) generation change this operating regime. PV connected at LV and MV levels introduces bidirectional power flows and strong intra-day variability. During high irradiance and low local demand, reverse power flows can cause voltage rise, particularly at the end of long or weak feeders. In the evening, when PV output is low and demand increases, voltage drop can become critical. These effects can lead to voltage excursions beyond admissible ranges defined by relevant standards [1,2].

Voltage compliance is therefore a key factor limiting further PV integration. When limits are exceeded, additional PV typically requires measures such as curtailment, reactive power control, reinforcement, or restrictive connection agreements. This constraint is commonly discussed in terms of PV hosting capacity, and voltage limits are often more restrictive than thermal limits in LV networks [3,4].

Active voltage regulation is needed to cope with these operating conditions. OLTCs at the MV/LV interface provide a practical actuator by adapting the LV voltage set-point through discrete tap changes in response to load and generation variability.

Standards define the compliance band and influence the operating margin. In Europe, EN 50160 is commonly interpreted using a ±10% band for 95% of 10-minute values over one week, whereas ANSI C84.1 uses a tighter normal operating range of approximately ±5% [1,8].

3. OLTC Operation and Control Strategies

On-load tap changers (OLTCs) regulate transformer secondary voltage by adjusting the turns ratio under load, thereby enabling discrete voltage set-point changes without interrupting supply. In distribution networks, OLTCs are typically installed at primary substations and at MV/LV interfaces to accommodate variations in demand and distributed generation.

Tap position changes directly affect voltage profiles along LV feeders. During periods of high photovoltaic (PV) generation, reducing the LV-side voltage set-point can mitigate voltage rise associated with reverse power flows, whereas during peak demand periods an increased set-point can help prevent undervoltage. This makes OLTCs a practical and widely deployed actuator for voltage management in active distribution networks with high PV penetration.

In this work, OLTC behaviour is assessed through time-series AC power-flow simulations under high PV penetration, comparing three operating modes: (i) fixed tap operation (baseline), (ii) a standard local voltage deadband controller acting on the transformer LV busbar, and (iii) a dual-bus, priority-based strategy that preserves a hard voltage constraint at the transformer LV busbar while seeking, on a best-effort basis, to improve the voltage at a downstream load bus. The latter is implemented as a model-assisted controller with a one-step feasibility check to ensure that secondary improvements do not compromise the primary constraint, and includes anti-hunting measures (hysteresis, persistence, and lockout) to limit unnecessary tap operations. The analysis focuses on the resulting trade-offs between voltage compliance at key buses and tap operation effort, without invoking centralised optimisation or extensive communication infrastructure.

4. Methodology

This work follows a simulation-based methodology to evaluate the impact of on-load tap changer (OLTC) operation. The simulation is designed to enable a controlled comparison between conventional operation without OLTC and active voltage control using OLTC under identical network and operating conditions. Time-series power flow simulations are used to capture the interaction between load demand, PV generation, and transformer tap operation.

The methodological approach consists of four main steps: (i) definition of a representative distribution network model based on real data, (ii) generation of synthetic time-dependent load and PV profiles, (iii) definition of operating scenarios with and without OLTC operation, and (iv) evaluation of performance indicators.

A. Distribution Network Model

The analysed network is based on data provided by a distribution network operator (DNO) from a real low-voltage feeder located in Northern Spain (Palencia). To preserve confidentiality while retaining technical representativeness, the original feeder was synthesised into an equivalent reduced model, summarised in Table I.

Table I. Modelled distribution network elements

Element	Description	Value
MV bus	Nominal voltage, V_{MV}	12 kV
LV buses	Nominal voltage, V_{LV}	0.4 kV
Transformer	Rated power, S_N	0.25 MVA
	Voltage ratio, V_{MV} / V_{LV}	12 / 0.4 kV
	Short-circuit voltage, y_k	6%
	Resistive component, y_{kr}	1.425%
	No-load losses, p_{fe}	1.35 kW
	Magnetizing current, i_0	0.2375%
	OLTC position side	MV
	Tap step	2.0%
	Tap range [%] (min/max)	-4, +12
Line01	NAYY 4 × 50 SE	0.1 km
Line02	NAYY 4 × 50 SE	0.1 km
PV unit	Rated active power, P	0.10 MW
	Rated apparent power S_N	0.12 MVA
Load	Active power, P	0.12 MW
	Reactive power, Q	0.05 MVAr

The network consists of a 12 kV medium-voltage supply connected to a 400 V low-voltage feeder through a 250 kVA MV/LV transformer equipped with an on-load tap changer (OLTC). The transformer electrical parameters are taken directly from the DNO dataset and correspond to the transformer model reported in [9]. The OLTC is modelled with nine tap positions, a 2% step size, and a tap range from -4 to +12.

On the low-voltage side, two short radial feeders supply a residential load aggregation and a distributed PV generator connected at separate buses. Underground cable sections are modelled using typical parameters for residential networks. A normally open sectionalizing switch is included to reflect the operational topology of the original feeder. The single-line diagram of the modelled network is shown in Fig. 1.

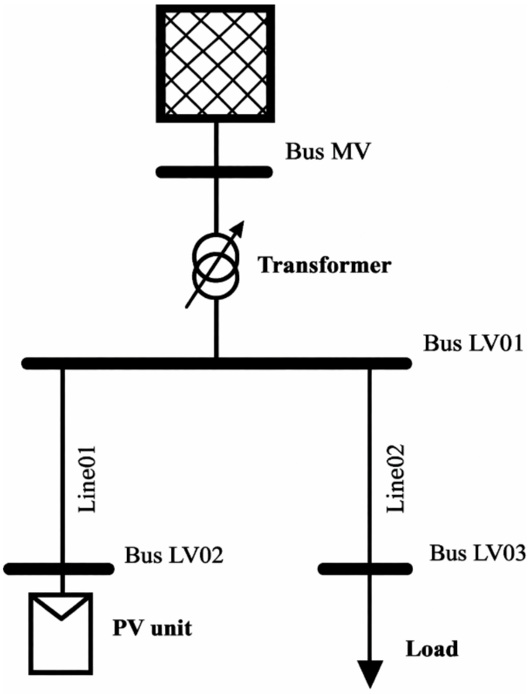

Figure 1. Distribution Network

B. Load and Generation Profiles

Feeder-level time-series measurements were not available due to data confidentiality constraints with the network owner. Operating scenarios are therefore generated using synthetic load and PV profiles designed to be representative of the feeder conditions. The normalised profiles used to drive the power-flow simulation are shown in Fig. 2, and the main parameters are summarised in Table II.

PV production is modelled as a daylight-limited diurnal curve with a midday peak. To reflect non-ideal conditions, the clear-sky profile is clipped and perturbed by stochastic cloud attenuation, then smoothed to avoid step changes.

Load demand is represented as a residential and commercial mixture with morning and evening residential peaks and daytime commercial activity. Small random variability is added and smoothed, and the same normalised shape is applied to both active and reactive power before scaling.

Independent scaling of load and PV represents a high-PV penetration condition in which peak PV injection exceeds peak load demand.

C. Simulation Framework

Power flow simulations are carried out using the open-source *Pandapower* framework [10] for Python. This tool allows detailed modelling of distribution networks, including transformer tap changers and time-dependent operating conditions, and has been identified as a suitable tool for power quality and grid-integration studies [11]. All simulations are performed assuming balanced steady-state conditions.

Table II. Synthetic PV and load profile parameters.

Category	Parameter	Value
	Time resolution	15 min
	Horizon	2 days
PV gen.	Daylight window	06:00-20:00
	Base shape	Sine
	Clear-sky clipping	0.85 p.u.
	Cloud factor (uniform)	[0.6, 1]
	Cloud smoothing	3 samples
	Scaling factor	2.5
Load	Commercial window	07:30-18:00
	Residential peaks	07:00, 20:00
	Peak widths (std. dev.), σ	1 h and 2.5 h
	Mix (commercial/residential)	25% / 75%
	Additive noise, σ	0.02 p.u.
	Load smoothing	5 samples
	Scaling factor	2.0

D. Operating Scenarios

Three operating scenarios are considered. In all cases, the same time-series of load demand and PV generation is applied (Fig. 2), and an AC power flow is solved at each time step.

1) *Baseline*: The MV/LV transformer tap position is held fixed (initialised at the neutral tap), representing conventional operation without on-load voltage regulation.

2) *Standard OLTC*: OLTC operation is enabled using a local, voltage-based strategy on the LV side of the MV/LV transformer. Tap changes are commanded solely from the measured voltage magnitude at the transformer LV busbar (LV01), aiming to keep it within ±3% of the reference value.

3) *Priority-based OLTC*: A hierarchical controller is applied with a hard primary constraint and a best-effort secondary objective. The primary objective is to regulate LV01 within ±3%. If LV01 is compliant, the controller may attempt to improve the voltage at a downstream bus (LV03) within ±5%, without compromising the primary constraint. Candidate secondary tap actions are screened with a one-step look-ahead: the tap is applied temporarily, the network is re-solved, and the action is accepted only if LV01 remains within ±3%; otherwise, it is rejected and the original tap is restored.

To avoid tap hunting (rapid back-and-forth switching) and to preserve real-time feasibility, the controller uses: (i) deadband hysteresis around the voltage limits, (ii) a persistence rule requiring violations to last for one timestep before acting, (iii) a post-action lockout interval, and (iv) a limit of one tap change per time step. The internal control loop is also capped by a maximum number of iterations per time step.

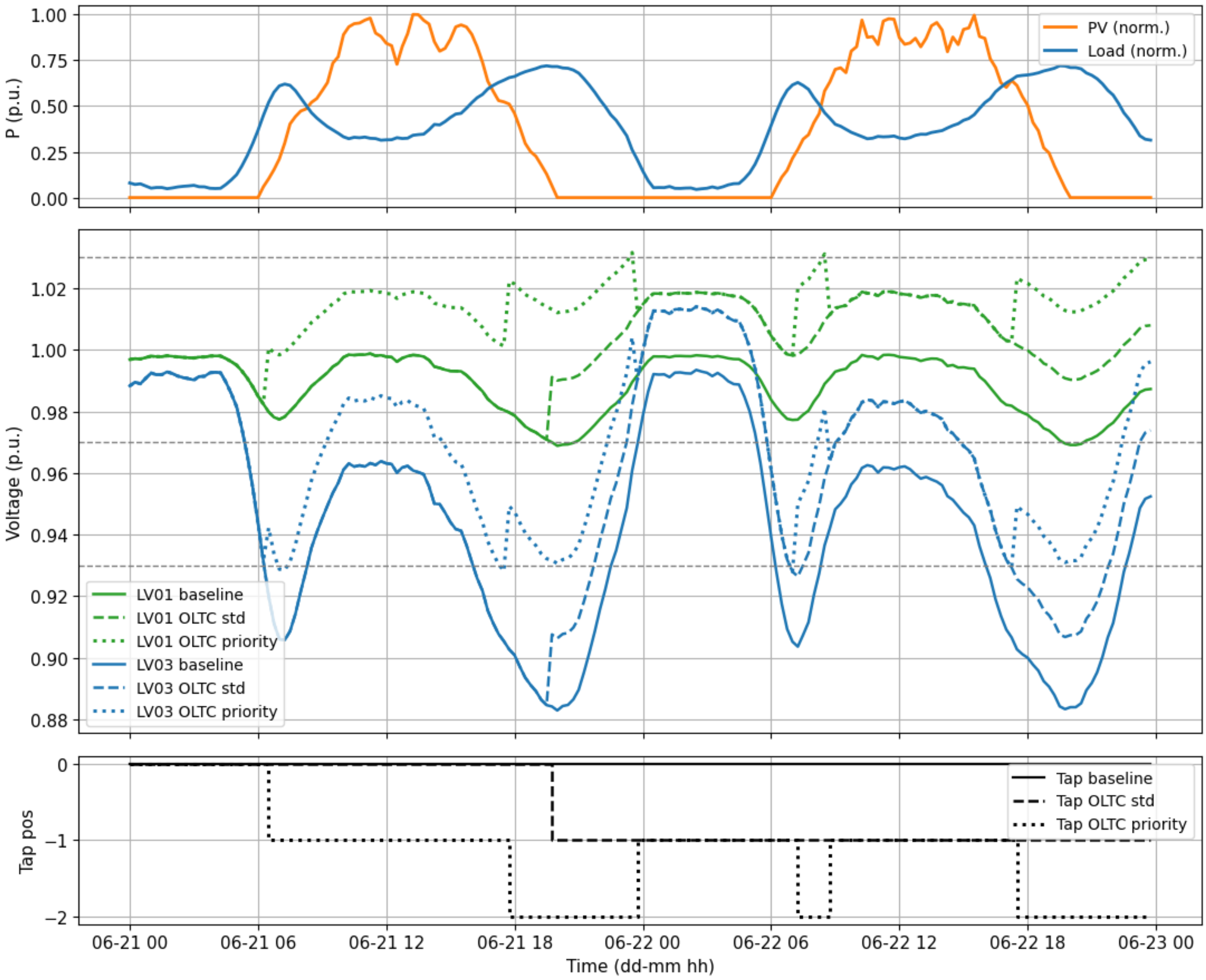

Figure 2. Time series of PV and loa active power, LV bus voltajes at transformer and load buses, and the corresponding OLTC tap position for the analysed scenarios.

E. Performance Indicators

For each scenario, performance is quantified using: (i) the fraction of time steps with voltage limit violations at LV01 and LV03, (ii) the corresponding total violation duration over the simulated horizon, and (iii) the total number of OLTC tap operations. These indicators support a consistent comparison between voltage-quality improvements and actuation effort across the analysed control strategies.

5. Results

Results are reported for three operating scenarios (baseline, standard OLTC, and priority-based OLTC), evaluating voltages at LV01 and LV03 and the corresponding OLTC tap actions.

Table III. Performance indicators for different scenarios

Scenario	**LV01 [%]**	**LV01 [h]**	**LV03 [%]**	**LV03 [h]**	**Tap Ops**
Baseline	4.68	2.25	35.94	17.25	0
Standard OLTC	0.00	0.00	26.56	12.75	1
Priority-based OLTC	1.04	0.50	2.60	1.25	6

Figure 2 compares the voltages at LV01 and LV03 with the OLTC tap position. In the baseline case (fixed tap), voltage limit violations occur already during the first day, mainly during peak demand. PV generation provides partial voltage support but does not prevent sustained violations at LV03.

Table III quantifies these outcomes. The baseline scenario shows violations during 4.68% of the horizon at LV01 (2.25 h) and 35.94% at LV03 (17.25 h), with no tap operations. With standard OLTC control, regulation at LV01 removes LV01 violations (0%, 0 h) with a single tap change, but LV03 remains frequently outside limits (26.56%, 12.75 h), particularly during high-load periods.

Priority-based OLTC control shifts the regulation objective to LV03 and substantially reduces downstream violations to 2.60% (1.25 h) using six tap operations. LV01 remains compliant for almost the entire horizon, with only brief excursions of 1.04% (0.50 h). These LV01 violations correspond to two 15-minute steps and occur during a rapid voltage rise following a load decrease; the controller corrects at the next step and restores voltages within limits.

6. Conclusions

Fixed-tap operation is inadequate in distribution networks with high photovoltaic (PV) penetration. In the simulations, static settings do not track intra-day PV and demand changes, which leads to repeated voltage violations, most clearly at electrically remote buses where loading dominate.

Standard OLTC control improves regulation at the transformer LV bus (LV01), but downstream violations at the load bus (LV03) can persist when the controller uses a single local reference. The proposed priority-based OLTC strategy addresses this by including LV03 constraints in the tap decision. This reduces downstream violations while keeping LV01 within limits for almost the full horizon.

The approach remains effective under tightened voltage envelopes. With limits of ±3% at LV01 and ±5% at LV03, the priority-based strategy maintains compliance for more than 97% of the simulated horizon. This indicates a practical margin for meeting statutory requirements while improving voltage quality at the customer connection point.

Overall, the results support advanced OLTC strategies as an effective and scalable enabler for active distribution network operation under high PV penetration. By aligning tap-changer logic with voltage limits at the customer connection point, distribution network operators (DNOs) can increase PV hosting capacity without immediate reinforcement. Automation also reduces reliance on manual seasonal tap adjustments, providing operational benefits beyond PV-driven voltage management.

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