EuroSun2026

PV AND EV HOSTING INTERACTIONS IN LOW-VOLTAGE DISTRIBUTION NETWORKS: EFFECTS OF PHOTOVOLTAIC ORIENTATION AND TILT

Summary

Increasing residential photovoltaic (PV) and electric vehicle (EV) penetration creates competing power flow challenges in low-voltage (LV) distribution networks. In Malta, predominantly south-facing residential PV concentrate generation around midday, while low-tilt configurations permit greater rooftop utilisation and deployable PV capacity. Both characteristics can increase PV-induced network stress. This study applies Monte Carlo time-series analysis to a synthetic Maltese LV feeder for PV penetration of 25%, 50% and 100%, two tilt angles (10° and 35°), uniform south-facing and mixed south-east-west orientations, and EV charging penetration from 0% to 200%. The 35° configurations consistently produce lower overvoltage than the 10° cases, although this partly reflects their 0.7 rooftop coverage factor and approximately 30% lower deployable active PV area. Orientation diversity provides smaller, less consistent benefits. Uncontrolled EV charging offers little systematic mitigation of overvoltages because charging demand is not sufficiently coincident with peak PV generation. At intermediate EV penetration, some coincident charging reduces reverse feeder current, but at higher penetration EV demand becomes dominant. Beyond approximately 110 to 120% EV penetration, undervoltage emerges as a distinct constraint, affecting up to about 13% of buses at 200%. Coordinated PV planning and managed EV charging are therefore required as network constraints transition from PV-driven overvoltage towards EV-driven loading and undervoltage.

Keywords: *photovoltaics, electric vehicles, low-voltage distribution networks, PV orientation, PV tilt, voltage violations, Monte Carlo analysis*

Field of application for the findings: *Planning and operation of low-voltage distribution networks with high photovoltaic and electric vehicle penetration*

Addressed audience: *Distribution system operators, energy regulators, network planners, PV and EV researchers, and power-system engineers*

1. Introduction

High distributed photovoltaic (PV) penetration can create reverse power flows, voltage rises and increased feeder utilisation in low-voltage (LV) networks. In Malta, high solar availability and constrained rooftops have driven widespread PV deployment, shown to cause reverse power flow and voltage rise in Maltese LV feeders [1]. Uncontrolled electric-vehicle (EV) charging introduces a complementary stochastic demand that can increase peak loading and undervoltage risk [2], and the combined integration of PV and EV penetration does not necessarily eliminate these constraints [3]. Previous work showed that diversifying PV orientation and tilt can mitigate PV-driven voltage rise in a synthetic Maltese LV feeder [4], but did not consider whether these benefits persist as EV charging penetration increases. This study extends that framework by jointly assessing PV orientation, tilt and rooftop coverage alongside EV penetration from 0% to 200%, to identify the point at which the dominant network constraint shifts from PV-driven overvoltage to EV-driven undervoltage.

2. Methodology

The methodology extends a Monte Carlo time-series framework previously developed for PV orientation and tilt in Maltese LV networks [4]. A synthetic radial LV feeder representing a compact Maltese urban block (36 buses, 35 lines) is combined with real daily residential demand profiles (4,980 single-phase and 1,807 three-phase), experimentally measured plane-of-array irradiance and module temperature data from the Malta PV Living Laboratories, and 1,751 stochastic 7.2 kW EV charging profiles. PV generation is calculated from irradiance and temperature using a linear, temperature-corrected model referenced to standard test conditions. Three PV penetration levels, two orientation strategies and two tilt configurations define 12 PV deployment scenarios, each evaluated at 21 EV penetration levels from 0% to 200% in steps of 10%, summarized in table 1. For every combination, 100 Monte Carlo runs randomise residential demand, PV allocation and EV charging, and OpenDSS performs 15-minute time-series power-flow simulations. Network performance is quantified using the maximum feeder utilisation factor and the percentage of buses experiencing voltage violations, with violations further split into overvoltage (>253 V) and undervoltage (<207 V) to distinguish PV-driven and EV-driven constraints.

Table 1. PV and EV deployment scenarios considered in the simulations.

Scenario	PV orientation	PV penetration	Tilt	C	EV penetration
S1	South (100% S)	25%	10° (coverage 100%)	1.0	0–200%
S2	Mixed (~50% S/25% E/25% W)	25%	10° (coverage 100%)	1.0	0–200%
S3	South (100% S)	25%	35° (coverage 70%)	0.7	0–200%
S4	Mixed (~50% S/25% E/25% W)	25%	35° (coverage 70%)	0.7	0–200%
S5	South (100% S)	50%	10° (coverage 100%)	1.0	0–200%
S6	Mixed (~50% S/25% E/25% W)	50%	10° (coverage 100%)	1.0	0–200%
S7	South (100% S)	50%	35° (coverage 70%)	0.7	0–200%
S8	Mixed (~50% S/25% E/25% W)	50%	35° (coverage 70%)	0.7	0–200%
S9	South (100% S)	100%	10° (coverage 100%)	1.0	0–200%
S10	Mixed (~50% S/25% E/25% W)	100%	10° (coverage 100%)	1.0	0–200%
S11	South (100% S)	100%	35° (coverage 70%)	0.7	0–200%
S12	Mixed (~50% S/25% E/25% W)	100%	35° (coverage 70%)	0.7	0–200%

3. Results and Discussion

At 25% PV penetration (representative of current Maltese urban deployment), PV-related constraints are limited and EV penetration dominates. Maximum feeder utilisation exceeds 100% at ~80% EV penetration, with significant undervoltage from ~110-120% EV penetration (Fig. 1). At 50% and 100% PV, the network starts in a PV-dominated regime with high utilisation and overvoltage, especially for the 10° configurations. Rising EV penetration initially lowers maximum utilisation as some charging demand coincides with PV generation, but this passive balancing is limited. At higher EV uptake, charging establishes a new forward-loading peak and utilisation rises again. Across all scenarios, total voltage violations track this PV to EV transition (Fig. 2). Overvoltage dominates initially (Fig. 3), undervoltage increasingly dominates at high EV penetration (Fig. 4). Undervoltage is essentially absent below ~110-120% EV penetration in all 12 scenarios, then rises sharply to ~9-13% of buses at 200% EV, with little dependence on PV orientation or tilt. The 35° configurations show consistently lower overvoltage than the 10° cases, though this reflects their ~30% lower deployable PV capacity combined with generation profile, not tilt alone. Orientation diversity offers a further but less consistent benefit as EV charging increasingly sets the timing of peak feeder demand [4].

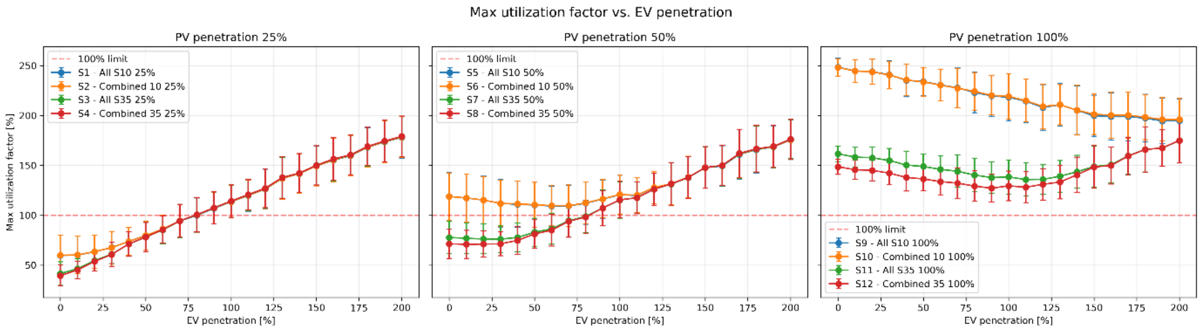

Fig. 1: The maximum utilization factor against EV penetration (mean±standard deviation) for scenarios S1-S4 (left), S5-S8 (middle) and S9-S12 (right)

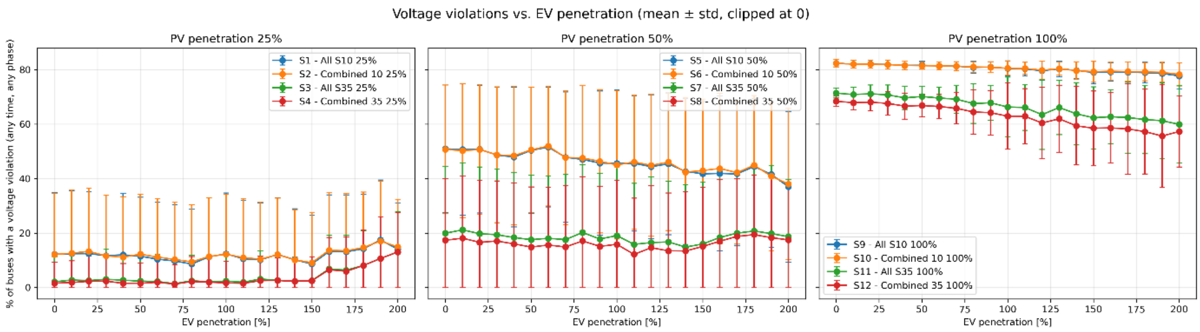

Fig. 2: The number of buses (%) experiencing voltage violations against EV penetration (mean±standard deviation) for scenarios S1-S4 (left), S5-S8 (middle) and S9-S12 (right); the standard deviation is clipped to 0 at the lower end

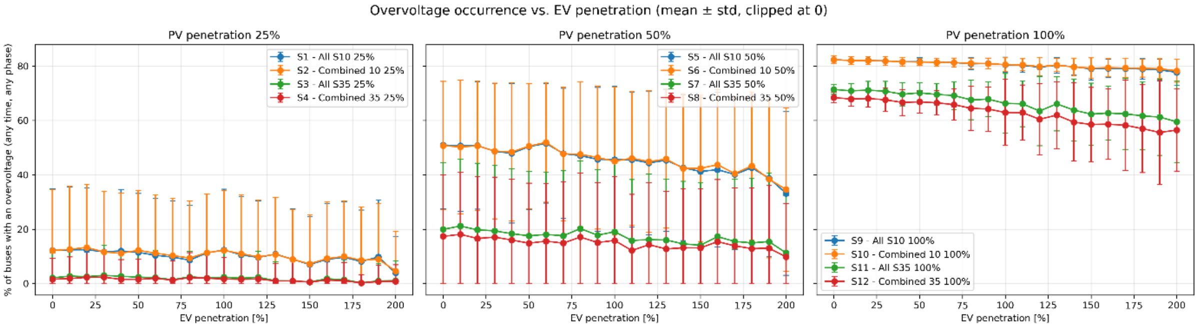

Fig. 3: The number of buses (%) experiencing overvoltage issues against EV penetration (mean±standard deviation) for scenarios S1-S4 (left), S5-S8 (middle) and S9-S12 (right); the standard deviation is clipped to 0 at the lower end

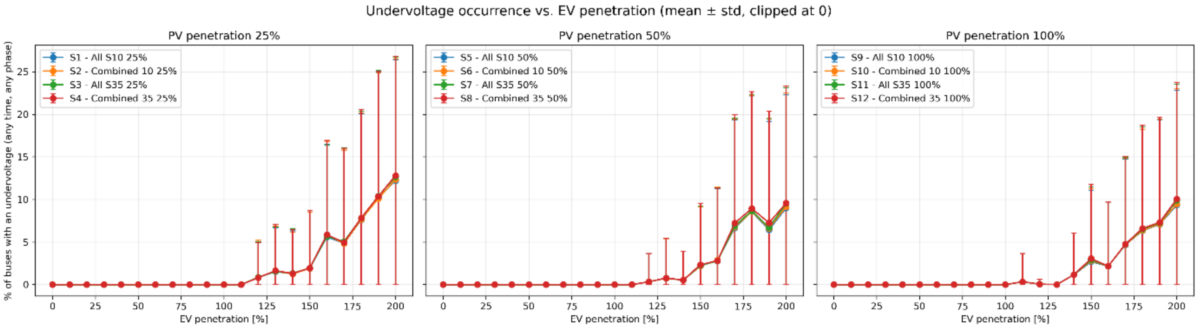

Fig. 4: The number of buses (%) experiencing undervoltage issues against EV penetration (mean±standard deviation) for scenarios S1-S4 (left), S5-S8 (middle) and S9-S12 (right); the standard deviation is clipped to 0 at the lower end

4. Conclusions

This study shows that the network condition limiting LV feeder operation shifts as PV and EV penetration jointly increase: EV charging drives feeder loading and undervoltage at low PV penetration, while PV generation drives overvoltage and reverse power flow at higher PV penetration, with EV charging providing only limited passive mitigation. PV rooftop configuration remains important: lower-tilt PV maximises deployable capacity but increases network stress at high penetration, while higher-tilt and mixed-orientation strategies reduce stress partly at the cost of deployable capacity and with less consistent benefit once EV charging dominates peak demand. Passive PV design alone cannot address the full range of constraints introduced by simultaneously high PV and EV penetration; coordinated PV planning together with managed or PV-responsive EV charging is likely to become increasingly necessary as both technologies are adopted at scale in constrained urban LV networks such as those in Malta.

References

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