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Stochastic Overvoltage-Limited Hosting Capacity Assessment of Photovoltaic Generation in an Egyptian Medium-Voltage Substation Network

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Research Article

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Abstract

The rapid growth of photovoltaic (PV) installations under Egypt's net-metering scheme raises the question of how much PV a distribution network can host before operating limits are violated. This paper presents a stochastic, overvoltage-limited hosting capacity (HC) assessment of two medium-voltage (MV) distribution networks: the IEEE 33-bus 12.66 kV benchmark and a real 59-bus 22 kV substation network in Cairo, Egypt, modeled from published data and validated against published base-case results. For each network, randomized Monte Carlo placement scenarios are solved by full AC load flow at penetration levels from 0% to 150% of peak load under a critical-hour condition (25% loading, maximum PV output, unity power factor), using common random numbers across levels and Wilson score confidence intervals. With a 1.05 p.u. limit, the IEEE 33-bus feeder shows zero violations in 500 scenarios up to 40% penetration (95% upper bound 0.8%) and a 50.8% violation probability at 100%; the Cairo 59-bus network shows zero violations up to 100% penetration and 1.6% at 150%. Because the assessment is voltage-constrained only, HC is reported as overvoltage-limited: at 100% penetration the Cairo network exports up to 37.7 MW against a 12.6 MW critical-hour load, so transformer and conductor thermal limits, not published for either network, would bind before overvoltage in practice. Sensitivity analysis shows the overvoltage-limited HC depends strongly on the substation voltage setpoint (the zero-violation level falls from 100% to 30% as the setpoint rises from 1.00 to 1.04 p.u.). Losses are minimized near 10-20% penetration in both networks. All code, data and results are openly reproducible.

I. Introduction

Rooftop PV systems below 500 kW connect to low- and medium-voltage distribution networks in Egypt under the small-scale PV (ssPV) connection code and the Electricity Distribution Code (EDC) [1], [2]. As penetration grows, reverse power flow can raise feeder voltages above statutory limits and increase losses. The maximum PV capacity a network can host without violating planning limits is its hosting capacity (HC) [3]. Because HC depends on network topology, loading, and national voltage limits, international reviews conclude that it must be assessed case by case [4]. For Egyptian networks, prior studies assessed PV impacts deterministically [5], by short-circuit-impedance analysis [6], by optimal placement with harmonic analysis for the Tala network [7], and by a stochastic multi-objective optimization framework (Tianji's Horse Racing Optimization) that coordinates the dispatch of PV and wind generation, vehicle-to-grid PEV aggregators, and STATCOMs to maximize HC under uncertainty on this same Cairo network [12]. What has not been reported is a direct Monte Carlo quantification of the baseline - uncontrolled, overvoltage-limited - HC of an Egyptian MV network under randomized PV placement. This paper fills that gap and complements the optimization-oriented result of [12].

Contributions: (i) an openly reproducible pandapower model of the 59-bus 22 kV Cairo network validated to published base-case values; (ii) stochastic HC curves (violation probability versus penetration) for both

networks under a critical hour; (iii) loss-versus-penetration curves identifying the loss-optimal penetration; and (iv) a fully reproducible code and data package.

II. Related Work

HC quantification methods are reviewed in [3] (deterministic, time-series and stochastic) and benchmarked in [8]. Torquato et al. applied Monte Carlo assessment to 50,000 real Brazilian LV systems and found overvoltage the most restrictive impact [9]; a 2020 review showed HC values are network- and code-specific and must be assessed per case [4]. For Egypt, the ssPV connection code and EDC set connection requirements and voltage limits [1], [2], and practical compliance measurements of a 200 kW station were reported at MEPCON 2019 [2]. The 59-bus Cairo network used here is documented in [12] with base-case results in [13]. Egyptian prior work [5]-[7], [12] is summarized in the Introduction.

III. Methodology

Load flows are solved with pandapower [10] (Newton-Raphson, full AC). Penetration is defined as total installed PV active power divided by peak load. Following critical-hour practice [9], base scenarios use 25% of peak load with maximum PV output at unity power factor, a conservative minimum-load assumption for overvoltage; a 50% loading case is studied as sensitivity. PV units represent aggregate PV capacity as seen at MV buses (MW-scale plants or aggregated net-metered rooftop fleets); LV-level effects are out of scope. At each penetration level (0% to 150% in 10% steps), 500 scenarios place 5-20 units at uniformly sampled load buses with squared-uniform random sizes. Common random numbers are used: each scenario (unit locations and relative sizes) is identical across all levels and settings, so level-to-level differences are paired rather than sampling noise, and the worst-case curves are monotone by construction. Violation probabilities are reported with Wilson score 95% confidence intervals; for a level with zero violations in n scenarios the 95% upper bound is about 3/n (0.8% for n = 500). Sensitivity cases vary the substation voltage setpoint (1.00, 1.02, 1.04 p.u., the realistic operating range) and the loading (25%, 50%) with 150 scenarios each. A scenario violates when any bus voltage exceeds 1.05 p.u. The Egyptian Electricity Distribution Code sets the operating voltage range at +/-5% for LV and MV cable networks and +/-10% for MV aerial networks (code text at [1]; values as reviewed in [11]); the 0.95-1.05 p.u. band used here is the conservative limit. Thermal line limits and transformer ratings are not published for either network, so HC is quantified as overvoltage-limited only, and the reverse power flow to the substation is reported separately to show where thermal constraints would bind first. Metrics per level: mean, 95th-percentile and worst-case maximum voltage, violation probability with confidence interval, total losses, and substation power.

IV. Test Networks and Validation

Two radial MV networks are studied. The IEEE 33-bus 12.66 kV benchmark (peak load 3.715 MW) is taken from pandapower's library. The Cairo 59-bus 22 kV network (peak load 50.344 MW; a substation supplying eight feeders from one busbar, not a single feeder) is built from the branch data published in the appendix of [12]; its six tie lines are kept open (radial operation). Table I shows that both models reproduce published base-case quantities, which validates the implementation before any HC result is drawn.

Network	Ploss computed	Ploss published	Vmin computed	Vmin published
IEEE 33-bus	202.68 kW	202.67 kW [14]	0.91309 p.u.	0.9131 p.u. [14]
Cairo 59-bus	218.91 kW	218.9 kW [13]	0.98646 p.u.	0.98646 p.u. [13]
Note	Cairo totals:			

	computed load 50.344 MW vs 50.348 MW published (source-data rounding).			

Table I. Base-case validation of both network models.

V. Results and Discussion

A. Voltage-constrained hosting capacity

Fig. 1 and Fig. 2 show the maximum bus voltage statistics versus penetration under the base critical hour; Fig. 6 shows the violation probabilities with Wilson 95% confidence intervals. On the IEEE 33-bus feeder, no violation occurs in 500 scenarios up to 40% penetration (95% upper bound 0.8%); the first violations appear at 50% (1.2%; 95% CI 0.6-2.6%), rising to 50.8% at 100% (95% CI 46.4-55.2%) and 90.6% at 150%, with a worst-case voltage of 1.196 p.u. On the Cairo 59-bus substation network, no violation occurs up to 100% penetration; the violation probability is 0.6% (3 of 500; 95% CI 0.2-1.8%) at 110%, 1.0-1.2% at 120-140%, and 1.6% at 150%, with a worst case of 1.074 p.u. With common random numbers the worst-case curves are monotone non-decreasing for both networks. Under a zero-violation criterion the deterministic overvoltage-limited HC is 40% (IEEE 33) and 100% (Cairo 59) of peak load. The Cairo result needs a caveat. The network is a substation supplying eight feeders from one 22 kV busbar, not a single feeder, and the study is voltage-constrained only. At 100% penetration the Cairo network exports up to 37.7 MW to the substation against a 12.6 MW critical-hour load (Fig. 7), so a substation transformer rated below the export power becomes the binding constraint before overvoltage; conductor ampacities, likewise unpublished, could bind earlier still. The 100% figure is therefore an overvoltage-limited HC, not a practical connection limit. Its lower per-unit losses relative to the IEEE 33-bus feeder follow from its published branch impedances and are not a like-for-like comparison of the two systems. Under the aerial +/-10% EDC limit the Cairo network would show no violation at any studied level (worst case 1.074 p.u.).

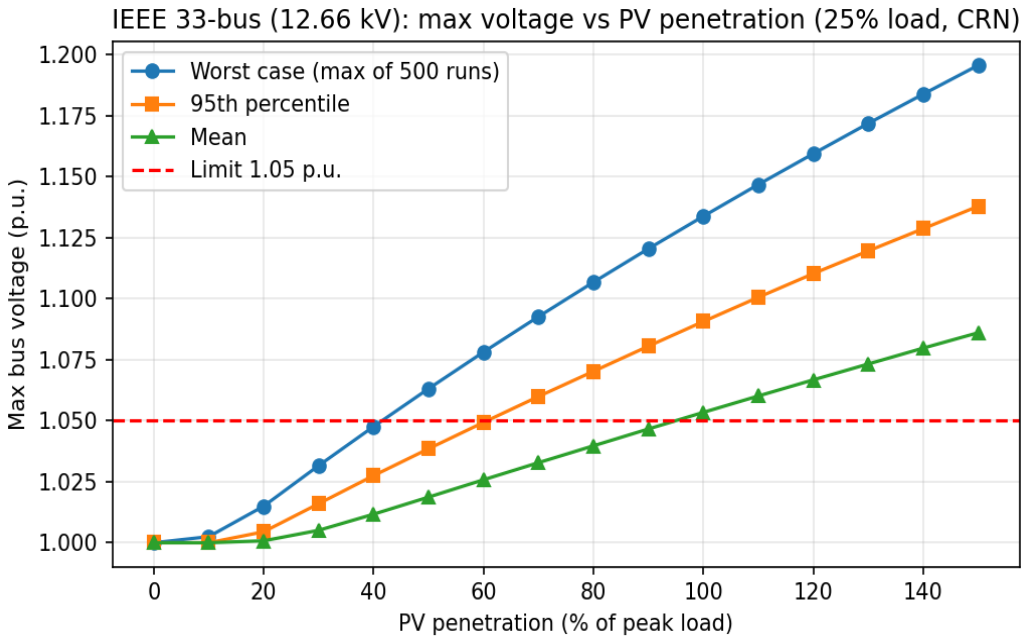

Fig. 1. IEEE 33-bus: maximum bus voltage vs PV penetration (500 Monte Carlo scenarios per level, 25% loading).

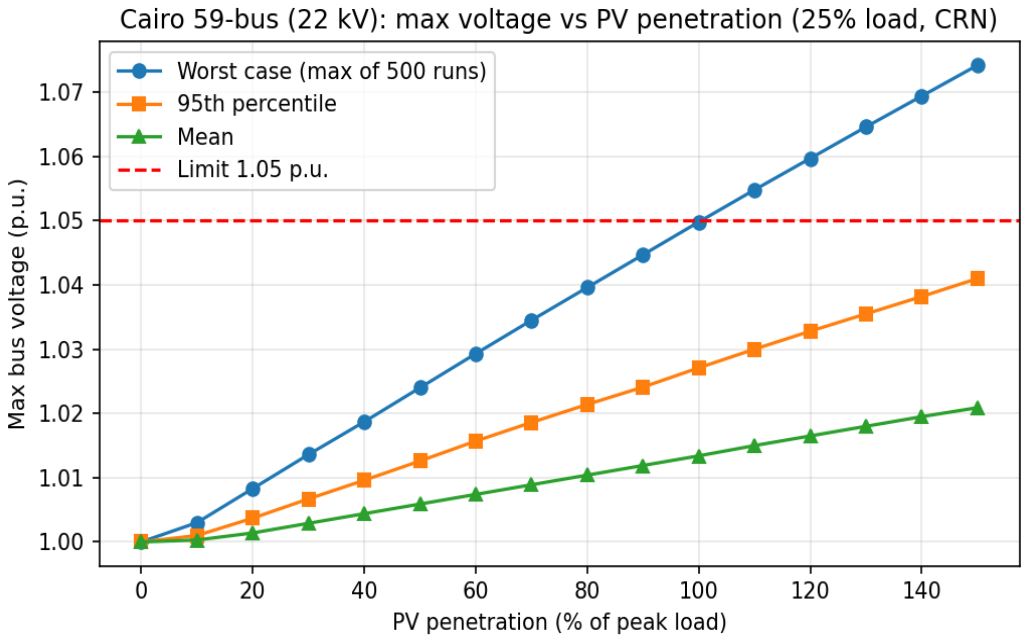

Fig. 2. Cairo 59-bus: maximum bus voltage vs PV penetration (500 scenarios per level, 25% loading).

B. Network losses

Fig. 3 and Fig. 4 show mean total losses versus penetration. Losses fall from 11.4 kW (0% PV) to a minimum of 5.4 kW at 20% penetration on the IEEE 33-bus (a 53% reduction), and from 13.5 kW to 8.6 kW at 10% on the Cairo network (a 36% reduction), then rise steeply as reverse power flow grows: mean losses reach 109.3 kW and 331.8 kW at 100% penetration, and 262.3 kW and 784.7 kW at 150%. The loss-optimal penetration (10-20%) is far below the voltage-limited HC, which matters for loss-reduction planning.

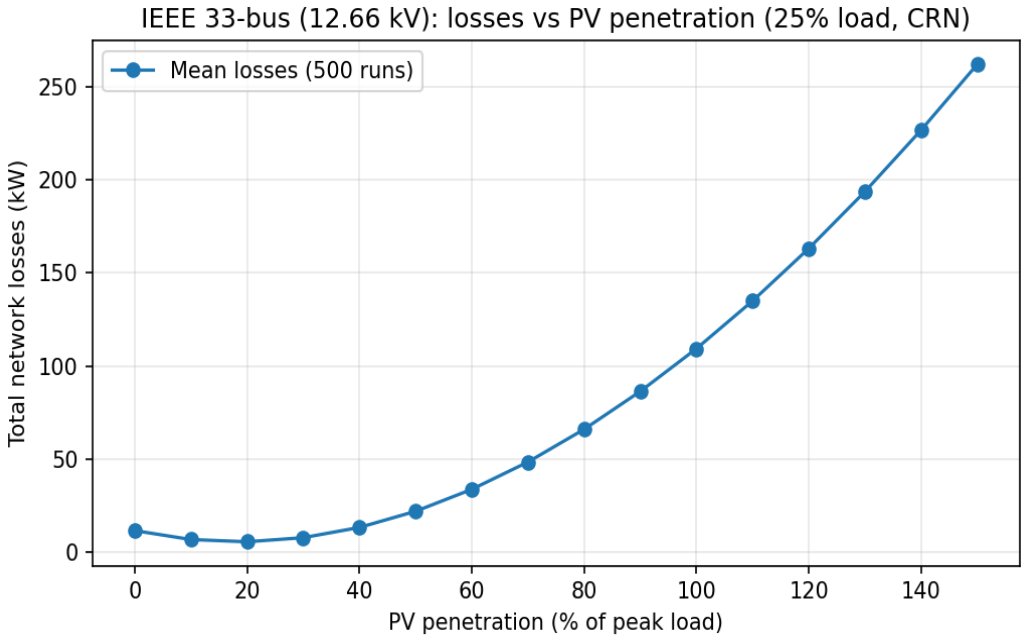

Fig. 3. IEEE 33-bus: total losses vs PV penetration (mean and range of 500 scenarios).

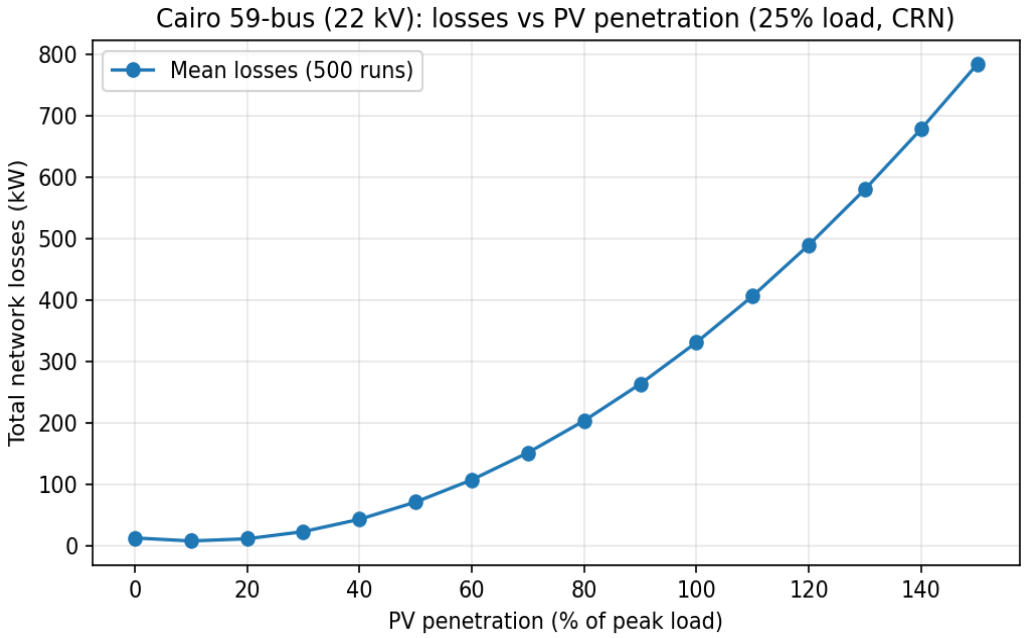

Fig. 4. Cairo 59-bus: total losses vs PV penetration (mean and range of 500 scenarios).

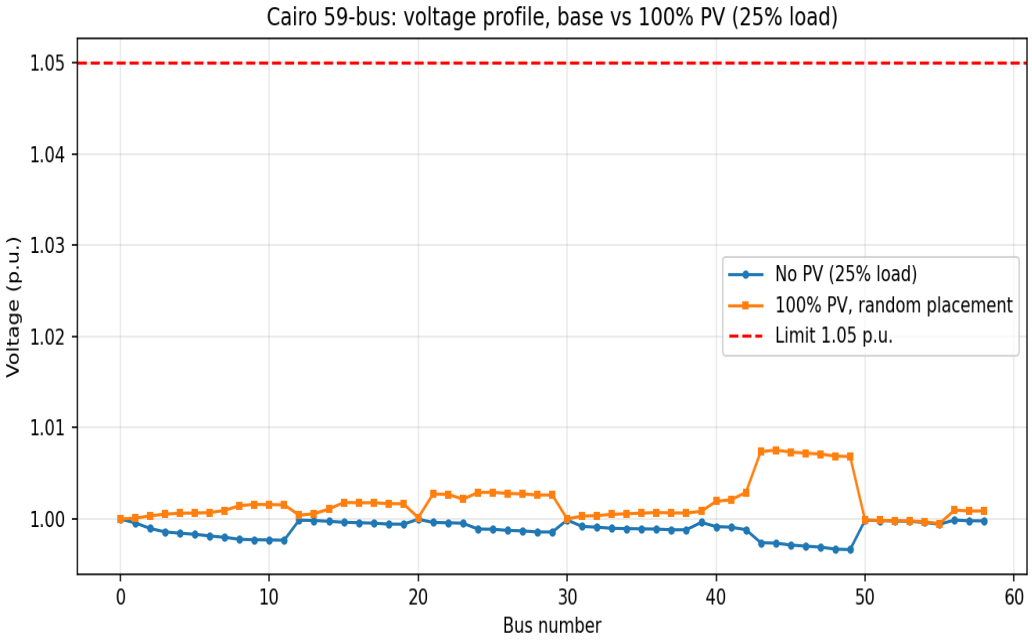

Fig. 5. Cairo 59-bus voltage profile: no-PV base case versus one 100%-penetration scenario (25% loading).

C. Sensitivity to loading and substation voltage

Fig. 8 and Fig. 9 vary the critical-hour assumptions. Raising the substation voltage setpoint from 1.00 to 1.02 and 1.04 p.u. lowers the zero-violation level on the Cairo network from 100% to 90% and 30%, and on the IEEE 33-bus feeder from 40% to 30% and 20%; at 150% penetration and 1.04 p.u. the violation probabilities reach 96.0% (Cairo) and 100% (IEEE 33). Raising the loading from 25% to 50% raises the zero-violation level to 60% on the IEEE 33-bus feeder, while the Cairo network shows no violation even at 150%. The overvoltage-limited HC is therefore sensitive to the substation voltage setpoint, which utilities control, and is conservative under the minimum-load assumption. The 25% loading follows international critical-hour practice [9]; Egyptian feeder-specific minimum-load measurements are not published. Fig. 6 collects the base-case violation probabilities with Wilson intervals, and Fig. 7 shows the maximum reverse power flow to the substation.

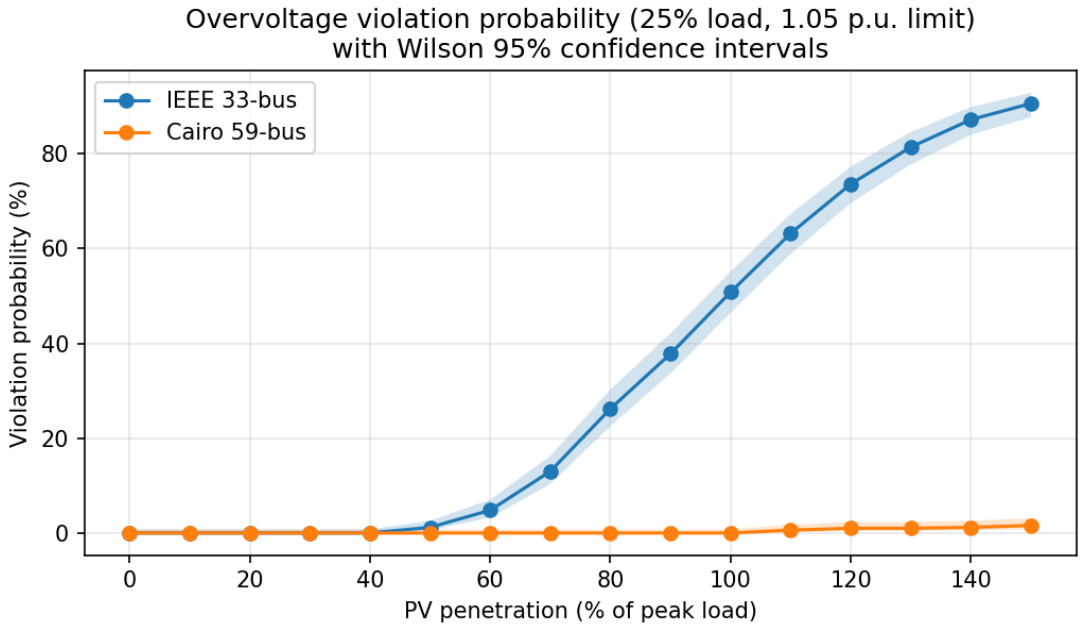

Fig. 6. Overvoltage violation probability with Wilson 95% confidence intervals (base critical hour).

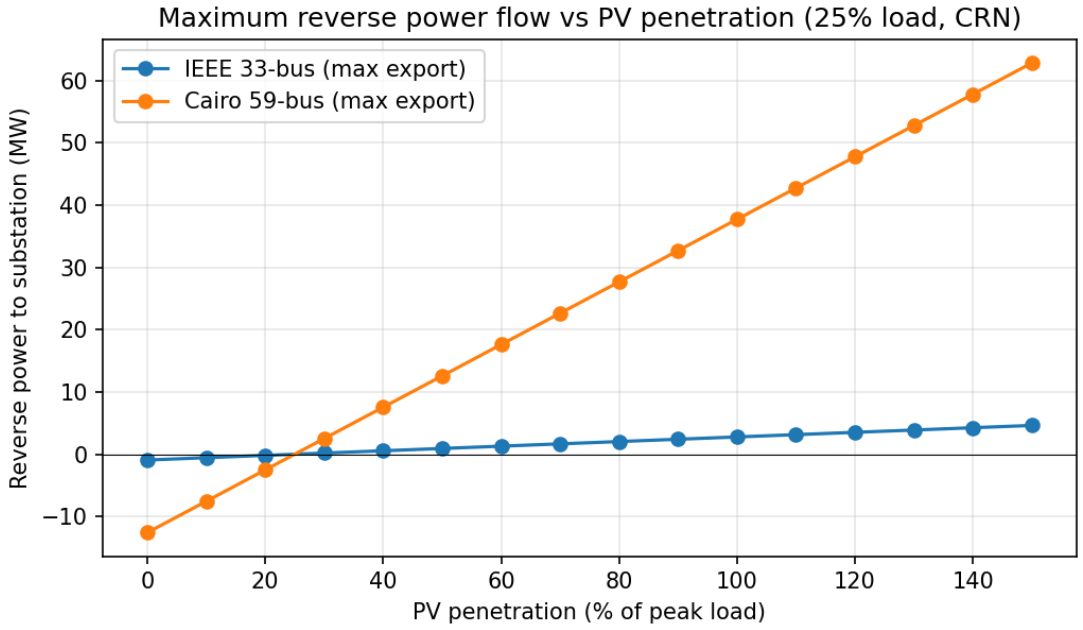

Fig. 7. Maximum reverse power flow to the substation versus PV penetration (base critical hour).

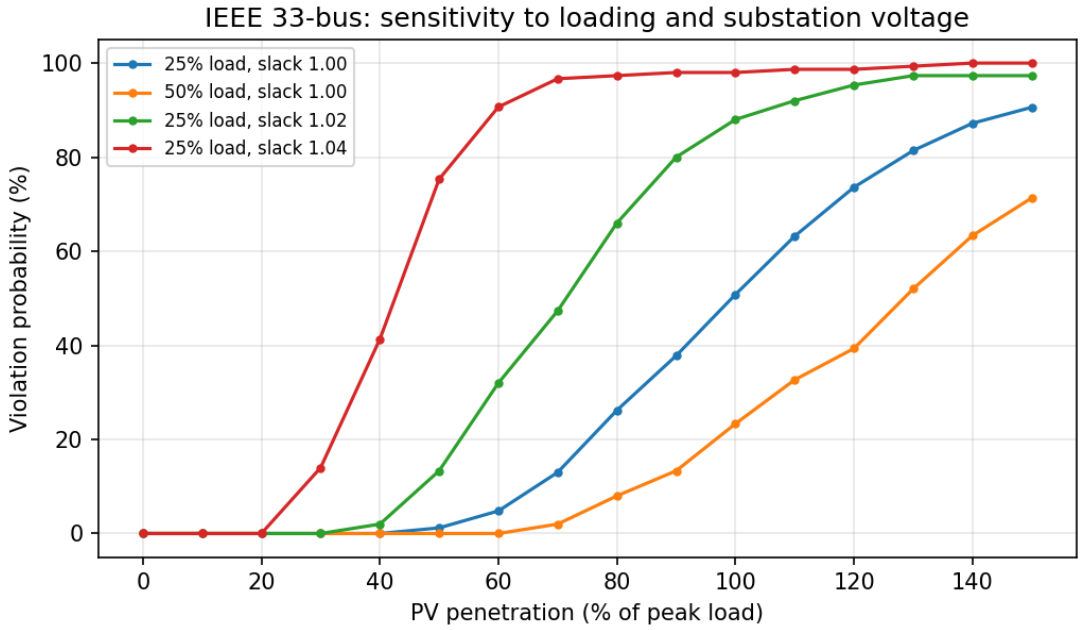

Fig. 8. IEEE 33-bus: sensitivity of violation probability to loading and substation voltage.

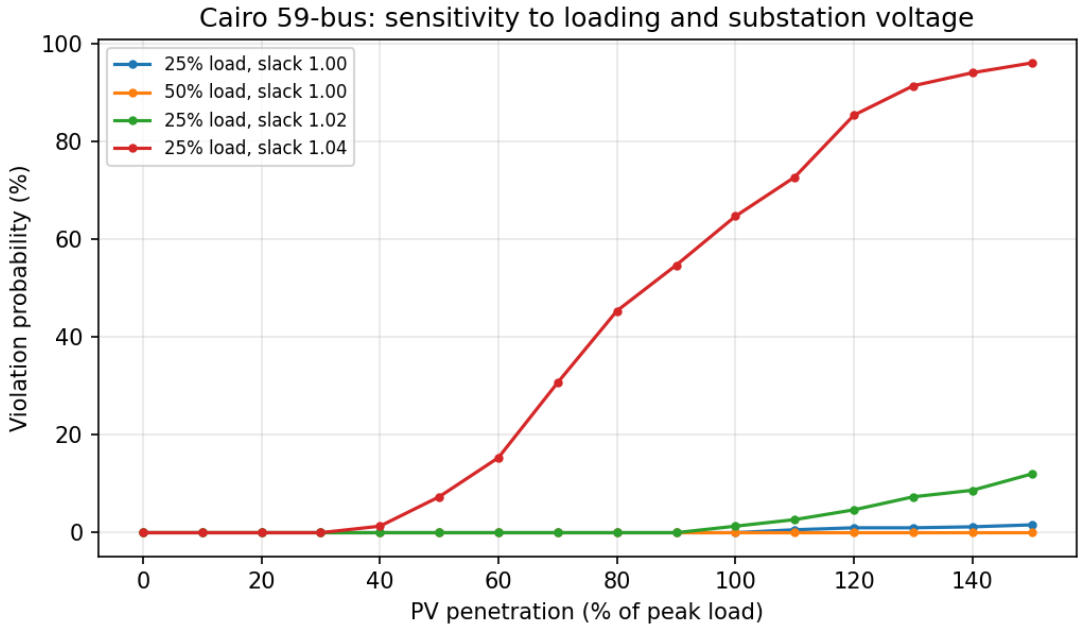

Fig. 9. Cairo 59-bus: sensitivity of violation probability to loading and substation voltage.

D. Limitations

The study is voltage-constrained only; conductor thermal ratings and transformer ratings are not published for either network, and the reverse-power analysis shows they would bind first on the Cairo network. The base-case validation against [13] verifies the model and data entry against values computed from the same published data; it does not validate the network against field measurements. A single critical hour (25%

load, clear-sky noon) and unity power factor are assumed in the base case, with loading and substation-voltage sensitivity analyzed separately; smart-inverter reactive support would raise HC further. PV units are placed at MV buses, whereas most Egyptian rooftop PV connects at LV; LV networks behind distribution transformers are expected to bind earlier and are the direct next step.

E. Summary

Quantity	IEEE 33-bus	Cairo 59-bus	Note
Zero-violation HC	40% of peak	100% of peak	500 scenarios; 95% upper bound 0.8% where zero
Violation prob. at 100%	50.8% (95% CI 46.4-55.2%)	0% (95% upper 0.8%)	Wilson score interval
Loss-optimal penetration	20% (5.4 kW)	10% (8.6 kW)	from 11.4 / 13.5 kW at 0%
Max reverse power at 100%	2.8 MW	37.7 MW	critical-hour load 0.93 / 12.6 MW

Table II. Hosting capacity and loss summary (25% loading, 1.05 p.u. limit).

VI. Conclusion

A reproducible Monte Carlo load-flow assessment quantified the overvoltage-limited PV hosting capacity of the IEEE 33-bus benchmark and a validated real 59-bus 22 kV Cairo substation network. Under a 1.05 p.u. limit and a 25%-loading critical hour, the Cairo network hosts 100% of peak load in PV without a single violation in 500 scenarios, versus 40% for the benchmark, while losses are minimized near 10-20% penetration in both. The result is strongly sensitive to the substation voltage setpoint, and in practice transformer and conductor thermal limits, not modeled here for lack of published data, would bind before overvoltage at high penetration. Future work: LV-level assessment with ssPV-code limits, smart-inverter volt-var control, time-series profiles from measured Egyptian irradiance, and thermal constraints once conductor and transformer data are available.

Data availability and reproducibility

All simulations use pandapower (open source). Network data, scripts, seeds, raw results (CSV) and figures are included in the accompanying package; running study_crn.py and summarize_crn.py reproduces every figure and number. Cairo 59-bus data are republished from the appendix of [12].

Acknowledgment

Drafting, code and figures of this article were prepared with an AI assistant under the author's direction. All simulations were executed with the disclosed open-source scripts, and all data sources are cited. The author re-ran the released code and confirmed that it reproduces the reported numbers.

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