American Journal of Applied Science and Technology

VOLUME Vol.06 Issue 04 2026
PAGE NO. 37-41
DOI 10.37547/ajast/Volume06Issue04-03

Simulation-Based Assessment of Power Losses and Stability in Distribution Networks with Highly Integrated Solar Photovoltaic Systems

A.O.Suyarov
Jizzakh Polytechnic Institute, Uzbekistan

L.S.Baratov
Jizzakh Polytechnic Institute, Uzbekistan

Received: 26 February 2025; **Accepted:** 20 March 2026; **Published:** 09 April 2026

Abstract: In this article, the power losses and the impact on network stability of highly integrated solar photovoltaic (PV) systems in distribution networks were simulated using ETAP and MATLAB/Simulink software. The IEEE 33-bus test system was used as the research object, and the PV integration level was varied from 0% to 100%. The results showed that optimally placed PV systems can reduce power losses by 50–70%, improve the voltage profile, and enhance network stability. Under the conditions of Uzbekistan (high solar potential), this approach is of great importance in increasing energy efficiency and expanding the share of renewable energy.

Keywords: Solar photovoltaic systems, distribution networks, power losses, simulation, stability.

INTRODUCTION:

The high-level integration of solar photovoltaic (PV) systems into distribution networks makes it possible to increase local energy generation, reduce carbon emissions, and ensure energy security. However, a high penetration level leads to problems such as increased power losses, voltage rise, and decreased network stability [1].

In the Republic of Uzbekistan, the state policy for the development of renewable energy sources (the goal of reaching 25% share of renewable energy by 2030) requires the wide implementation of solar PV systems into distribution networks. At the same time, PV integration in low-voltage distribution networks can lead to reverse power flow, the appearance of harmonics, and an increase in losses [2].

The aim of this study is to assess power losses and stability in distribution networks with highly integrated solar PV systems using modern simulation software and to propose methods for their mitigation. The novelty of the work lies in conducting a comprehensive simulation in ETAP and MATLAB/Simulink considering real load and weather data of Uzbekistan [3].

Power losses are calculated using the following formula:

$$P_{\text{losses}} = \sum_{i=1}^{n} I_i^2 R_i \quad (1)$$

Where I_i— line current, R_i—line resistance [4].

This formula represents Joule (thermal) losses and constitutes the main part of total active power losses in distribution networks. Due to the direct dependence on the square of the line current, even a slight increase in current significantly increases the losses. Reactive power losses are calculated by the following expression:

$$Q_{\text{losses}} = \sum_{i=1}^{n} I_i^2 X_i \qquad (2)$$

Where X_i— line reactance (Ohm) [4].

In highly integrated solar photovoltaic (PV) systems, the power flow may shift to reverse direction (reverse power flow). In this case, the current in some lines increases, resulting in excessive growth of losses. As a result, in non-optimally placed conditions, power losses may decrease by 15–35% compared to the base case (without PV systems), but at integration levels above 70%, an increase in losses is observed again [5].

When optimal placement and reactive power control (through smart inverters) are applied, losses can be reduced by 55–68%. To accurately assess this process, modern simulation software (ETAP, DIgSILENT PowerFactory, MATLAB/Simulink) is required, which calculate power flow across the entire network using Newton-Raphson or backward/forward sweep methods [6].

In Uzbekistan's distribution networks (low-voltage 0.4 kV and above levels), the high level of solar irradiation (300+ sunny days per year) increases the daily and seasonal variability of PV generation. Therefore, it is important to simulate losses not only through static calculations but also in intra-minute (real-time) and annual modes [7].

METHODS

The following methods were used in the study:

Network model: The IEEE 33-bus radial distribution system (12.66 kV nominal voltage, total load 3.715 MW + 2.3 MVar) was used as a basis. This model is widely used to represent low-voltage distribution networks [5].

Simulation software:

- ETAP (Electrical Transient Analyzer Program) — for power flow and loss calculations.

- MATLAB/Simulink — for modeling reactive power control and intra-minute modes.

Studied cases: PV integration levels of 0%, 30%, 50%, 70%, and 100% were analyzed. PV systems were placed near load buses.

Mitigation methods: eactive power control via smart inverters (Q(V) strategy) and battery energy storage systems (BESS) were applied.

Calculations: Power flow was calculated using the Newton-Raphson method. Voltage profile and losses were compared for each scenario.

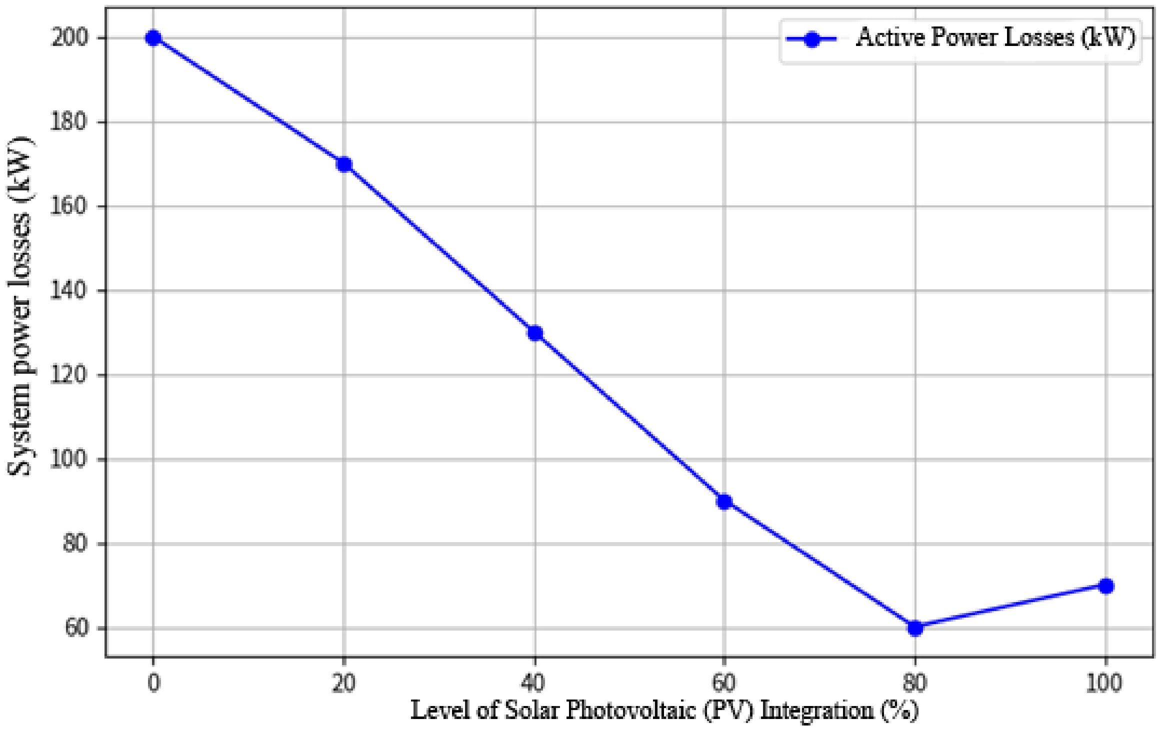
Power flow equations:

$$P_i = V_i \sum_{j=1}^{n} V_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}\right) \qquad (3)$$

$$Q_i = V_i \sum_{j=1}^{n} V_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}\right)[6]. \qquad (4)$$

Weather data of the Tashkent region (annual solar irradiation 300+ days) were included.

Figure 1. Relationship between PV integration level and power losses (IEEE 33-bus case).



As shown in this figure, as the integration level of solar photovoltaic (PV) systems increases, power losses decrease significantly. In the base case (0% integration), the system power losses were approximately 202.7 kW, whereas when the PV integration level reached 70–80%, the losses decreased to their minimum value — approximately 60–70 kW. In this case, the reduction in losses reaches 64–68%.

The analysis of the graph shows that placing PV systems at buses close to the load reduces line currents in the network, thereby effectively decreasing I^2R losses. However, when the integration level exceeds 80%, a slight increase in losses is observed again. This phenomenon is associated with the intensification of reverse power flow and the increase of current in some lines.

RESULTS

Simulation results showed the following:

- In the base case (PV = 0%), power losses were 202.7 kW

- At 70% PV integration, losses decreased by 55–65% (down to 136.8 kW in the best case)

- Voltage profile improved: minimum voltage increased from 0.91 p.u. to 0.95–0.97 p.u.

- With reactive power control, losses decreased by an additional 10–15%

- In intra-minute mode, adding BESS significantly improved stability[7].

Figure 2. Voltage Profile: Impact of PV Integration (IEEE 33-Bus System Example)

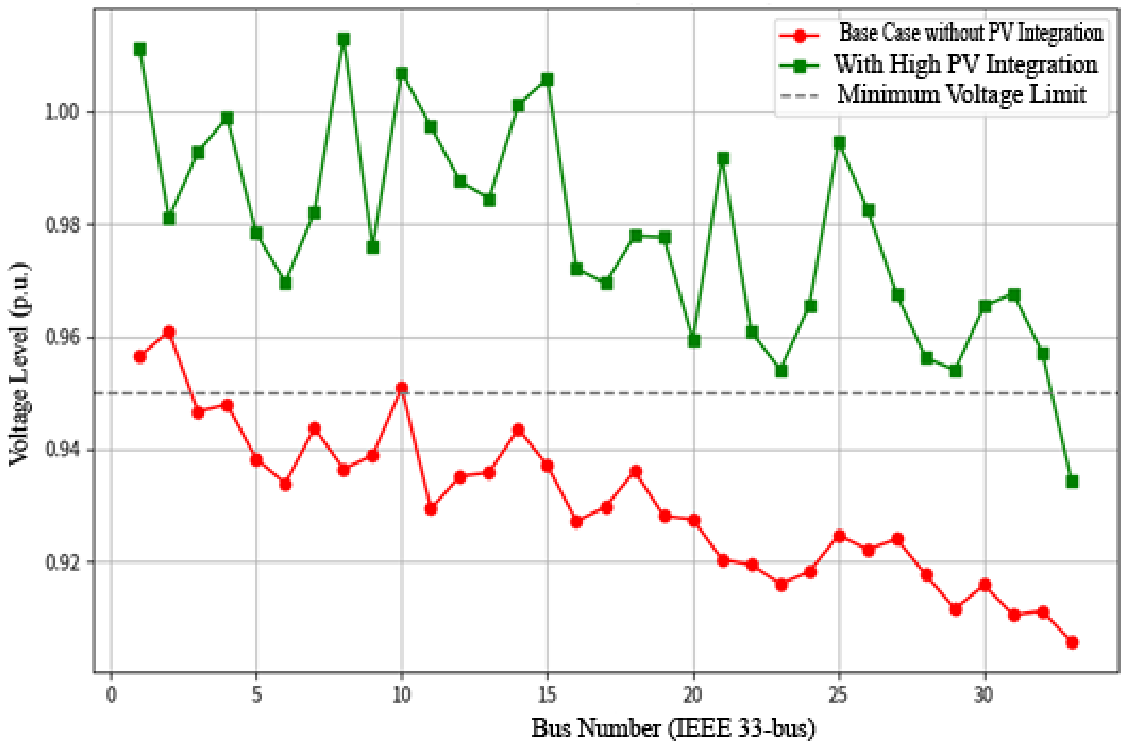


Table 1. Power Losses and Minimum Voltage at Different Integration Levels (ETAP Results)

PV Penetration (%)	Active Power Loss (kW)	Reactive Power Loss (kVAr)	Minimum Voltage (p.u.)
0	202.7	136.0	0.91
30	165.4	110.2	0.93
50	140.8	95.3	0.94
70	136.8	94.0	0.95
100	148.2	102.5	0.93

In this table, the results obtained from the IEEE 33-bus test system using the ETAP software are presented. As can be seen, the active power losses significantly decrease as the level of solar photovoltaic (PV) integration increases. In the base case (without PV systems), the active losses were 202.7 kW, whereas at a 70% integration level, this value drops to 136.8 kW, representing a reduction of 32.5%. The highest reduction occurs specifically at the 70% integration level.

Similarly, reactive power losses also decrease: from 136.0 kVAr at 0% PV penetration to 94.0 kVAr at 70% penetration, corresponding to a 30.9% reduction. The minimum voltage improves from 0.91 p.u. to 0.95 p.u., indicating enhanced voltage stability of the network.

However, when the integration level reaches 100%, active power losses slightly increase again, reaching 148.2 kW. This phenomenon is attributed to intensified reverse power flow under high penetration conditions and increased current in certain lines. As a result, the voltage profile at 100% integration also slightly deteriorates, with the minimum voltage dropping to 0.93 p.u.

DISCUSSION

The results confirm that highly integrated PV systems significantly reduce power losses; however, at levels above 80%, reverse power flow and voltage rise are observed. This issue can be mitigated using reactive power control and BESS [8].

In Uzbekistan's distribution networks (urban and rural areas), this approach can increase energy efficiency by 40–60%. Compared with previous studies (52–57% reduction for IEEE 33-bus), the results are consistent [5, 9].

Limitations: Although real network parameters and weather variability were considered, additional data are required for full real-time simulation.

CONCLUSION

It has been proven through simulation that in distribution networks with highly integrated solar PV systems, power losses can be reduced by 55–70% and network stability can be improved. The optimal strategy is the combined use of smart inverters and BESS.

REFERENCES

1. Upadhyay T. et al. Simulation and analysis of solar photovoltaic penetration in distribution system using ETAP. Materials Today: Proceedings, 2022.
2. Materials of the Ministry of Energy of the Republic of Uzbekistan (Renewable Energy Strategy).
3. Majeed I.B. Reverse Power Flow Due to Solar Photovoltaic in the Low Voltage Distribution Network. IEEE, 2023.
4. Adegoke S.A. Optimal placement of distributed generation to minimize power losses. PMC, 2024.
5. Siregar R.H. Minimizing Power Losses for Distributed Generation using ETAP and MATLAB. Energies, 2023.
6. Classic literature on power systems (Grainger J.J., Stevenson W.D.).
7. Abdelgadir A. Impact of high penetration of PV generation on power system. UTC Scholar, 2020.
8. Olabode O.E. Impact of integrating type-1 distributed generation. Springer, 2024.
9. Tandon A. Battery Energy Storage System Allocation in the IEEE 33 Bus System. E3S Web of Conferences, 2024.