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Impact Analysis of Photovoltaic Penetration in Radial Distribution System - A Case Study of Bazar Feeder in Dhulabari DC

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Abstract

The increasing integration of photovoltaic (PV) systems in distribution networks has significantly influenced system performance in terms of the voltage profile and power losses. This study analyzed PV penetration in the 38-bus bazar feeder at the Dhulabari distribution center using Dig SILENT Power Factory. Load flow analyses were conducted under various PV penetration levels, with PV systems integrated near the source (Bus 4), middle (Bus 19), and end (Bus 38) of the feeders. The results show that at a low penetration level (10%), power loss reduction is more effective when the PV system is installed at the end bus (Bus 38), whereas at higher penetration levels, PV placement at the middle of the network (Bus 19) minimizes losses. At 40% PV penetration (2160 kW), the system showed improved voltage regulation and reduced power losses, with PV installation at Bus 19 minimizing the active and reactive losses by 40% and 44.83%, respectively. The lowest bus voltage (Bus 38) increased to only 9.80 kV under this configuration. To improve the voltage profile, an 840 kVAr capacitor bank was introduced at Bus 34 (the weak bus) alongside 40% PV penetration at Bus 19. This combination yielded a 54% reduction in active power loss and a 58.62% reduction in reactive power loss, significantly improving the system performance. This study demonstrates that the coordinated placement of PV units and capacitor banks can enhance voltage stability and network efficiency in radial distribution systems.

Keywords: Photovoltaic (PV) integration • power loss reduction • voltage profile • capacitor bank • Dig SILENT PowerFactory • PV penetration level

1. Introduction

The growing global demand for electrical energy and the increasing concern over environmental impacts have accelerated the adoption of renewable energy sources. Among these, photovoltaic (PV) systems have gained significant attention due to their clean, sustainable, and decentralized nature. Integrating PV generation into existing power distribution networks not only supports the transition toward green energy but also introduces new operational challenges in maintaining power quality and reliability.

Distribution networks are typically designed for unidirectional power flow from the substation to the end consumers. However, the integration of distributed PV generation leads to bidirectional power flow, which can affect the voltage profiles, system losses, and overall feeder stability. Therefore, a detailed study of PV penetration at

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various levels and locations within the network is essential to understand its technical impact and optimize the system performance.

This project focuses on the Bazar Feeder of the Dhulabari Distribution Center, where the effect of PV integration on the voltage profile and power loss was analyzed using the Dig SILENT Power Factory software. Different penetration levels of PV were considered at three strategic positions—near the source, at the midpoint, and at the end of the feeder—to determine the optimal configuration of the feeder. This study also includes reactive power compensation using capacitor banks to further enhance the network performance. The outcomes provide valuable insights into the effective planning and operation of PV-integrated radial distribution systems.

2. Literature Review

The integration of photovoltaic (PV) systems into radial distribution networks has been widely studied because of the increasing penetration of renewable energy and the operational challenges it poses. Several researchers have focused on understanding the effects of PV penetration on voltage profiles, power losses, and system stability, as well as on methods for the optimal placement and sizing of PV units.

2.1 Impact of PV Integration on Distribution Systems

When PV systems are connected to distribution networks, they can introduce bidirectional power flow, voltage fluctuations, and changes in power loss. According to Hatziargyriou et al. (2017), high PV penetration can improve energy efficiency but may also lead to voltage rise issues at buses located near PV installation points. Similarly, Tripathy and Mishra (2015) observed that the strategic placement of PV units can reduce technical losses, enhance voltage stability, and mitigate the adverse effects of intermittent generation.

2.2 PV Penetration Levels and Placement Strategies

The effect of PV integration strongly depends on its penetration level and the location within the feeder. Studies by Kumar et al. (2016) demonstrated that low-to-moderate PV penetration near the substation has minimal impact on voltage deviations, whereas high PV penetration at the end of the feeder may lead to over-voltage conditions. Research by Singh and Goel (2018) highlighted that mid-feeder placements often provide a balance between loss reduction and voltage profile improvement.

2.3 Reactive Power Compensation and Voltage Regulation

Reactive power support through capacitor banks or PV inverters with reactive power control has been proposed to address voltage rise and maintain system stability. Ahmed et al. (2019) indicated that combining PV systems with properly sized capacitor banks can significantly improve voltage profiles and further reduce active and reactive power losses in the network.

2.4 Simulation and Analytical Studies

Dig SILENT Power Factory and MATLAB/Simulink are commonly used tools for evaluating the effects of PV integration. Simulation-based studies allow for the detailed modelling of feeder characteristics, load profiles, and PV generation patterns. For example, Yadav et al. (2020) conducted a case study on a radial 33-bus distribution system, concluding that optimal PV placement with reactive power compensation improved voltage levels and reduced system losses, similar to the findings of the present study.

2.5 Summary

The reviewed literature emphasizes that both the penetration level and location of PV units critically influence distribution system performance. Incorporating reactive power compensation strategies further enhances voltage stability and reduces losses. These collective insights provide a foundation for the present study, which analyzes PV integration on the Bazar Feeder of the Dhulabari Distribution Center using Dig SILENT Power Factory, considering various PV penetration levels and strategic placement points.

3. Methodology

The methodology adopted in this study aims to analyses the impact of photovoltaic (PV) penetration on the voltage profile and power losses in a radial distribution system, specifically the Bazar feeder of the Dhulabari distribution center. This approach combines simulation modelling, PV placement analysis, and reactive power compensation to evaluate the system performance.

3.1 Study System Description

The study was conducted on the Bazar Feeder, a radial distribution feeder comprising 38 buses. The feeder supplies power to various residential, commercial, and industrial facilities. Its electrical parameters, including the line resistances, reactance's, and bus load data, were collected from the distribution center. The feeder was modelled in Dig SILENT Power Factory for a detailed load flow analysis.

3.2 PV Penetration Levels

To assess the impact of PV integration, multiple penetration levels were considered: 10%, 20%, 30%, and 40% of the feeder peak load. PV units are injected at specific buses.

3.3 PV Placement Locations

Three strategic locations were selected for PV placement:

- **Near the source (Bus 2–Bus 5):** To evaluate the effect of PV close to the substation.
- **Midpoint of the feeder (Bus 18–Bus 19):** To examine balanced impact on feeder losses and voltage profile.
- **End of the feeder (Bus 34–Bus 38):** To analyze potential voltage rise and over-voltage issues at the far end.

3.4 Load Flow Analysis

Load flow simulations were conducted using Dig SILENT Power Factory. The backward/forward sweep method was employed for radial systems, considering both active and reactive power flows in the system. The simulation objectives were as follows:

- To determine the voltage profile at each bus under different PV penetration levels.
- To calculate real (kW) and reactive (kVAR) power losses in the feeder.

3.5 Reactive Power Compensation

Capacitor banks were strategically placed at selected buses to provide reactive power support and improve voltage profile. The combination of PV generation and capacitor banks was tested to identify configurations that minimize power losses and maintain voltage within permissible limits.

3.6 Performance Evaluation Metrics

The impact of PV penetration was evaluated using the following metrics:

- **Bus voltage magnitude:** To ensure compliance with standard voltage limits (±5% of nominal voltage).
- **Real and reactive power losses:** To quantify efficiency improvements due to PV integration.

3.7 Simulation Procedure

- Model the Bazar Feeder in Dig SILENT PowerFactory with line and load data.
- Conduct base case load flow analysis without PV to establish reference voltage and losses.
- Integrate PV units at three location near source, middle of network and end of network for each penetration level.
- Load flow simulations were performed to evaluate the voltage profile and losses for each scenario.
- Capacitor banks were introduced to the selected buses, and the simulations were repeated.
- The results were compared and analyzed.

This methodology ensures a systematic assessment of the technical impact of PV penetration and provides insights into optimal planning and operational strategies for PV-integrated radial distribution networks.

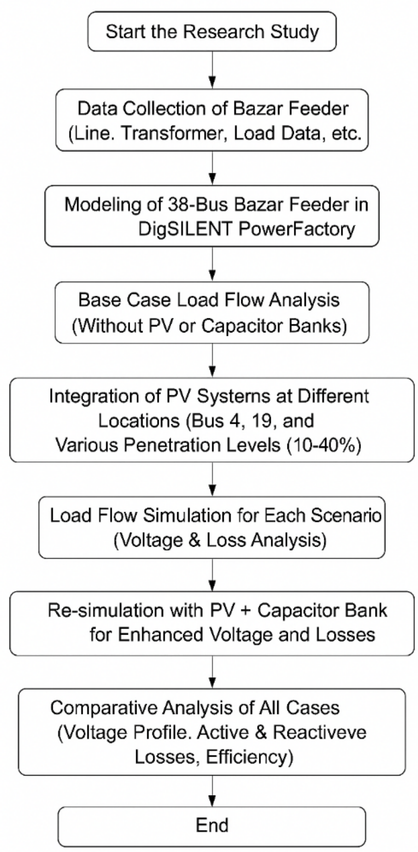

Figure 1: Methodology Flow Chart

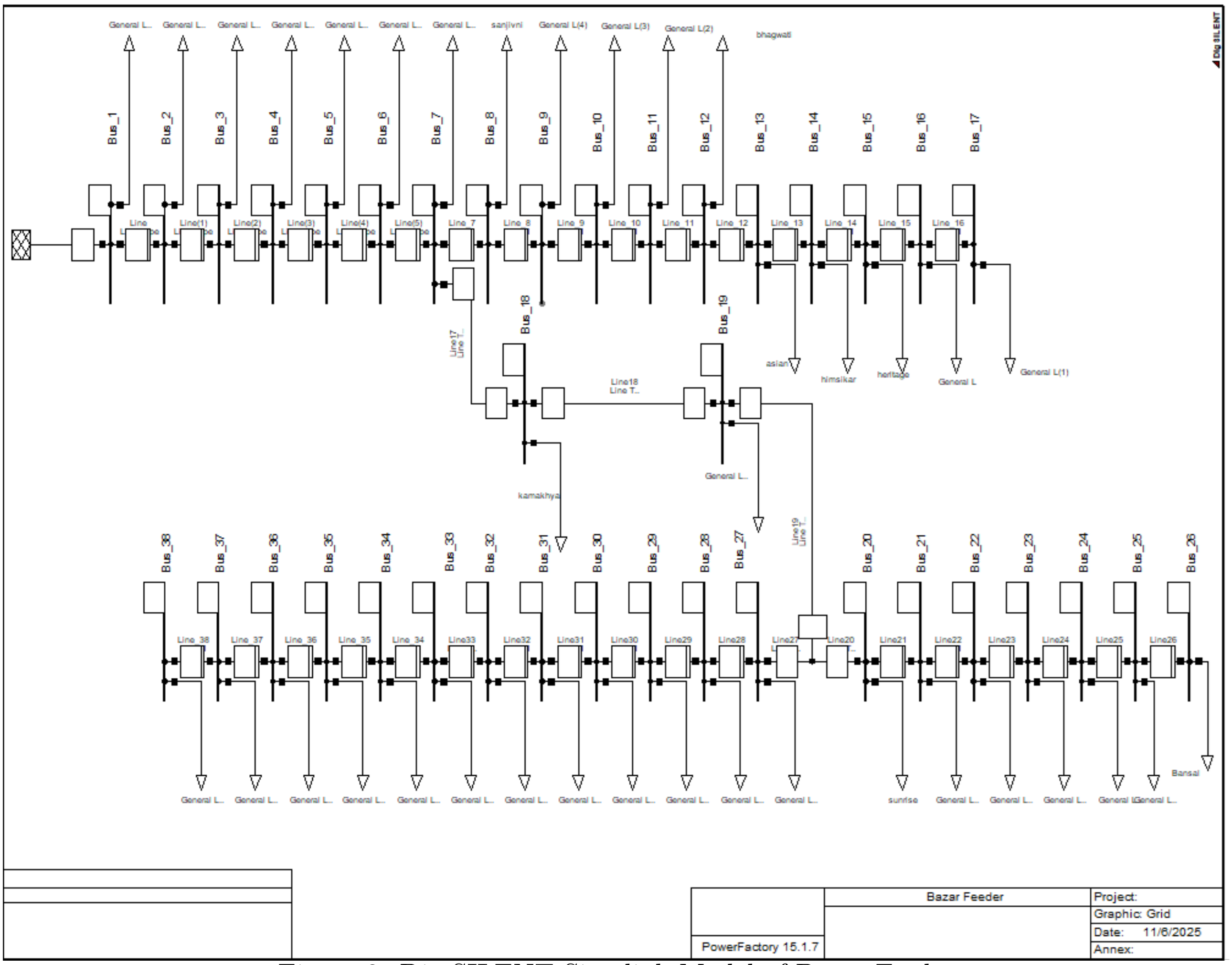

Figure 2: Dig SILENT Simulink Model of Bazar Feeder

4. Results and Discussion

The Bazar Feeder is a 38-bus radial distribution system operating at 11 kV with a total load of 6145 kVA. Transformer peak loads were considered for NEA transformers, whereas 80% loading at 0.8 pf lagging was assumed for industrial transformers. The system includes branching connections and uses 100 MVA and 11 kV as the base values for per-unit calculations. Without PV or DG integration, the active and reactive power losses are 500 kW and 580 kVAR, respectively, with bus 1 at 1.0 p.u. and a minimum voltage of 0.86 p.u. at bus 38.

4.1 Voltage and Loss Profile at 10% penetration

With 10% PV penetration (540 kW), the distribution network showed notable improvement in voltage profile and power loss (Table 1, Figures 3–5). The PV unit was integrated at different buses to assess system performance. At Bus 4, active and reactive losses decreased by 4% and 5.17%, respectively; at Bus 19, by 12% and 13.79%; and at Bus 38, by 16% and 17.24%. The minimum bus voltage (Bus 38) improved from 9.41 kV to 9.82 kV with PV at Bus 38. All simulations were performed in Dig SILENT Power Factory.

Table 1: Voltage Profile with 10% PV Penetration at Bazar Feeder

S.N	**BUS**	**Without PV (kV)**	**10% PV Pen at Bus 4 (kV)**	**10% PV Pen at Bus 19 (kV)**	**10% PV Pen at Bus 38 (kV)**
1	Bus_1	11	11	11	11
2	Bus_2	10.84406	10.85301	10.85468	10.85517
3	Bus_3	10.69057	10.70842	10.71175	10.71272
4	Bus_4	10.53839	10.56507	10.57007	10.57153
5	Bus_5	10.38874	10.41586	10.43085	10.43279
6	Bus_6	10.24165	10.26922	10.29411	10.29654
7	Bus_7	10.09717	10.12516	10.15990	10.16281
8	Bus_8	10.02221	10.05042	10.08543	10.08836
9	Bus_9	9.966476	9.994859	10.03006	10.03302
10	Bus_10	9.901425	9.930000	9.965442	9.968414
11	Bus_11	9.848745	9.877475	9.913109	9.916097
12	Bus_12	9.797600	9.826482	9.862302	9.865305
13	Bus_13	9.771041	9.800002	9.835919	9.838930
14	Bus_14	9.751878	9.780896	9.816883	9.819900
15	Bus_15	9.742594	9.771640	9.807661	9.810681
16	Bus_16	9.724012	9.753113	9.789203	9.792229
17	Bus_17	9.717817	9.746936	9.783048	9.786076
18	Bus_18	10.06670	10.09479	10.13273	10.13579
19	Bus_19	9.815866	9.844735	9.914315	9.918928
20	Bus_20	9.607647	9.637161	9.708278	9.736255
21	Bus_21	9.583746	9.613335	9.684630	9.712676
22	Bus_22	9.562046	9.591702	9.663159	9.691268
23	Bus_23	9.544754	9.574465	9.646050	9.674210
24	Bus_24	9.523207	9.552985	9.624732	9.652954
25	Bus_25	9.510338	9.540156	9.611999	9.640259
26	Bus_26	9.495120	9.524986	9.596942	9.625246
27	Bus_27	9.616721	9.646208	9.717260	9.751258
28	Bus_28	9.588197	9.617774	9.689039	9.738186
29	Bus_29	9.562816	9.592472	9.663928	9.728221
30	Bus_30	9.540584	9.570310	9.641933	9.721364
31	Bus_31	9.508745	9.538572	9.610434	9.720073
32	Bus_32	9.483241	9.513148	9.585203	9.725019
33	Bus_33	9.467606	9.497564	9.569737	9.724696
34	Bus_34	9.448456	9.478474	9.550792	9.735900
35	Bus_35	9.435678	9.465737	9.538152	9.753322
36	Bus_36	9.426091	9.456181	9.528669	9.773861
37	Bus_37	9.419699	9.449808	9.522345	9.797509
38	Bus_38	9.416502	9.446621	9.519182	9.824256

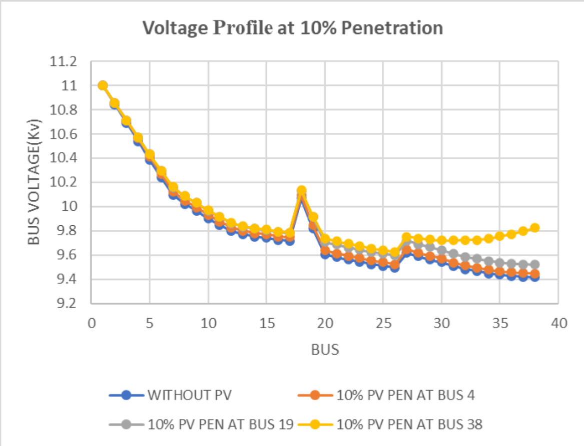

Figure 3: Voltage profile at 10% penetration

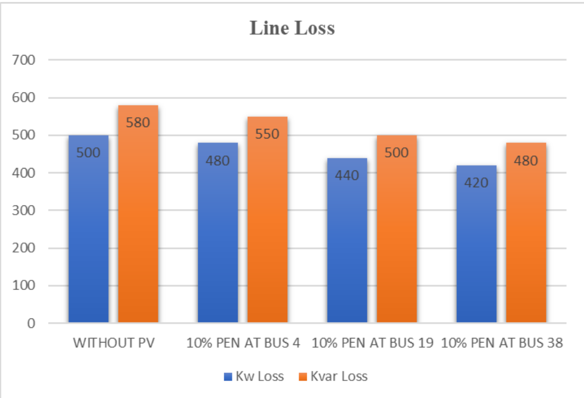

Figure 4: Line loss at 10% penetration

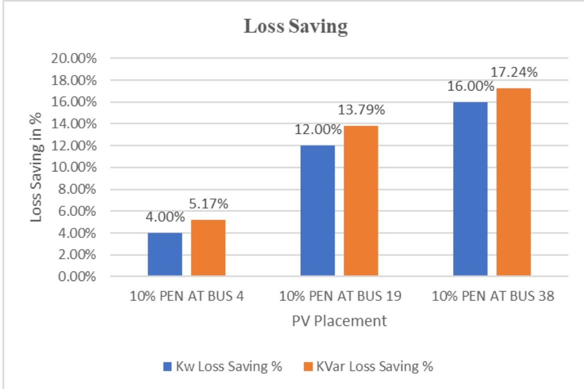

Figure 5: Loss saving % at 10% penetration

4.2 Voltage and Loss Profile at 20% penetration

At 20% PV penetration (1080 kW), the system showed significant improvement in performance (Table 2, Figures 6–8). Installing PV at Bus 4 reduced active and reactive losses by 8% and 10.34%, respectively; at Bus 19, by 24% and 27.59%; and at Bus 38, by 22% and 27.59%. The minimum bus voltage (Bus 38) increased from 9.41 kV to 10.19 kV with PV at Bus 38.

Table 2: Voltage profile, with 20% PV penetration at Bazar feeder

S.N	**Bus**	**Without PV (kV)**	**20% PV at Bus 4 (kV)**	**20% PV at Bus 19 (kV)**	**20% PV at Bus 38 (kV)**
1	Bus_1	11	11	11	11
2	Bus_2	10.84406	10.86186	10.86485	10.86477
3	Bus_3	10.69057	10.72608	10.73206	10.73189
4	Bus_4	10.53839	10.59150	10.60047	10.60021
5	Bus_5	10.38874	10.44274	10.47128	10.47095
6	Bus_6	10.24165	10.29653	10.34454	10.34412
7	Bus_7	10.09717	10.15291	10.22026	10.21976
8	Bus_8	10.02221	10.07838	10.14625	10.14575
9	Bus_9	9.96648	10.02298	10.09124	10.09074
10	Bus_10	9.90143	9.95831	10.02703	10.02652
11	Bus_11	9.84875	9.90594	9.97502	9.97451
12	Bus_12	9.79760	9.85509	9.92454	9.92402
13	Bus_13	9.77104	9.82869	9.89832	9.89781
14	Bus_14	9.75188	9.80964	9.87941	9.87889
15	Bus_15	9.74259	9.80041	9.87024	9.86973
16	Bus_16	9.72401	9.78194	9.85190	9.85139
17	Bus_17	9.71782	9.77578	9.84579	9.84527
18	Bus_18	10.06670	10.12262	10.19628	10.19576

19	Bus_19	9.81587	9.87333	10.00945	10.00867
20	Bus_20	9.60765	9.66639	9.80548	9.84854
21	Bus_21	9.58375	9.64264	9.78207	9.82524
22	Bus_22	9.56205	9.62108	9.76081	9.80408
23	Bus_23	9.54475	9.60389	9.74388	9.78722
24	Bus_24	9.52321	9.58248	9.72278	9.76621
25	Bus_25	9.51034	9.56969	9.71017	9.75366
26	Bus_26	9.49512	9.55456	9.69527	9.73883
27	Bus_27	9.61672	9.67541	9.81437	9.86883
28	Bus_28	9.58820	9.64707	9.78644	9.86983
29	Bus_29	9.56282	9.62184	9.76158	9.87392
30	Bus_30	9.54058	9.59975	9.73981	9.88109
31	Bus_31	9.50875	9.56811	9.70863	9.90773
32	Bus_32	9.48324	9.54277	9.68366	9.94057
33	Bus_33	9.46761	9.52723	9.66835	9.95412
34	Bus_34	9.44846	9.50820	9.64960	9.99324
35	Bus_35	9.43568	9.49551	9.63709	10.03849
36	Bus_36	9.42609	9.48598	9.62771	10.08684
37	Bus_37	9.41970	9.47963	9.62145	10.13827
38	Bus_38	9.41650	9.47645	9.61832	10.19277

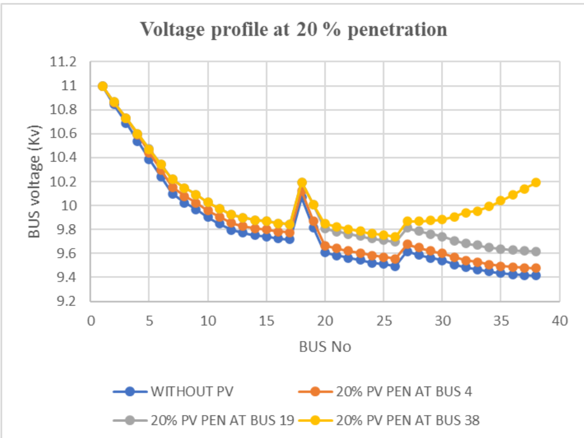

Figure 6: Voltage profile at 20% penetration

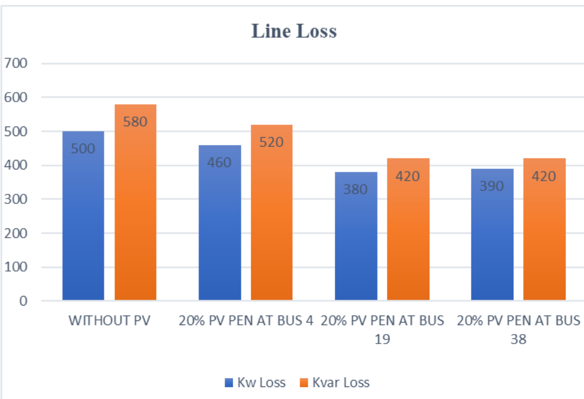

Figure 7: Line loss at 20% penetration

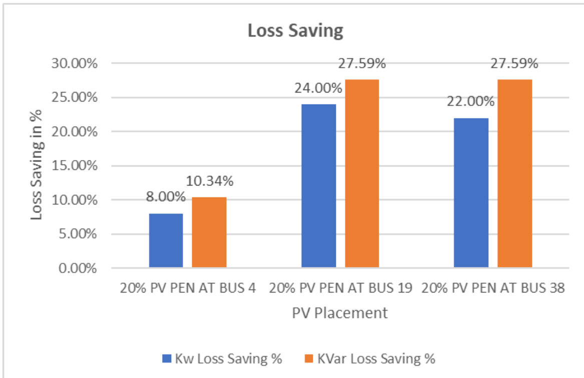

Figure 8: Loss saving % at 20% penetration

4.3 Voltage and Loss Profile at 30% penetration

At 30% PV penetration (1620 kW), system performance improved significantly in terms of voltage profile and loss reduction (Table 3, Figures 9–11). With PV at Bus 4, active and reactive losses dropped by 12% and 13.79%, respectively. At Bus 19, losses decreased by 34% and 36.21%, while at Bus 38, by 22% and 32.76%. The minimum voltage (Bus 38) rose from 9.41 kV to 10.53 kV after PV installation at Bus 38.

Table 3: Voltage profile, with 30% PV penetration at Bazar feeder

S.N	**Bus**	**Without PV (kV)**	**30% PV at Bus 4 (kV)**	**30% PV at Bus 19 (kV)**	**30% PV at Bus 38 (kV)**
1	Bus_1	11	11	11	11
2	Bus_2	10.84406	10.87062	10.87461	10.87317
3	Bus_3	10.69057	10.74357	10.75155	10.74866
4	Bus_4	10.53839	10.61770	10.62966	10.62534
5	Bus_5	10.38874	10.46938	10.51016	10.50440
6	Bus_6	10.24165	10.32360	10.39307	10.38588
7	Bus_7	10.09717	10.18039	10.27841	10.26979
8	Bus_8	10.02221	10.10608	10.20485	10.19616
9	Bus_9	9.96648	10.05084	10.15017	10.14143
10	Bus_10	9.90143	9.98636	10.08635	10.07755
11	Bus_11	9.84875	9.93414	10.03466	10.02581
12	Bus_12	9.79760	9.88344	9.98447	9.97559
13	Bus_13	9.77104	9.85711	9.95842	9.94950
14	Bus_14	9.75188	9.83812	9.93962	9.93069
15	Bus_15	9.74259	9.82892	9.93051	9.92157
16	Bus_16	9.72401	9.81050	9.91228	9.90333
17	Bus_17	9.71782	9.80436	9.90620	9.89724
18	Bus_18	10.06670	10.15020	10.25754	10.24845
19	Bus_19	9.81587	9.90167	10.10151	10.08783
20	Bus_20	9.60765	9.69535	9.89949	9.94789
21	Bus_21	9.58375	9.67167	9.87631	9.92482
22	Bus_22	9.56205	9.65017	9.85526	9.90388
23	Bus_23	9.54475	9.63304	9.83849	9.88719
24	Bus_24	9.52321	9.61169	9.81759	9.86640
25	Bus_25	9.51034	9.59894	9.80511	9.85398
26	Bus_26	9.49512	9.58386	9.79035	9.83929
27	Bus_27	9.61672	9.70434	9.90830	9.97296
28	Bus_28	9.58820	9.67609	9.88064	9.98694
29	Bus_29	9.56282	9.65094	9.85603	10.00401
30	Bus_30	9.54058	9.62891	9.83447	10.02417
31	Bus_31	9.50875	9.59737	9.80360	10.07668
32	Bus_32	9.48324	9.57211	9.77887	10.13541
33	Bus_33	9.46761	9.55662	9.76371	10.16172
34	Bus_34	9.44846	9.53765	9.74515	10.22685
35	Bus_35	9.43568	9.52499	9.73276	10.29808
36	Bus_36	9.42609	9.51549	9.72347	10.37244
37	Bus_37	9.41970	9.50916	9.71727	10.44990
38	Bus_38	9.41650	9.50599	9.71417	10.53042

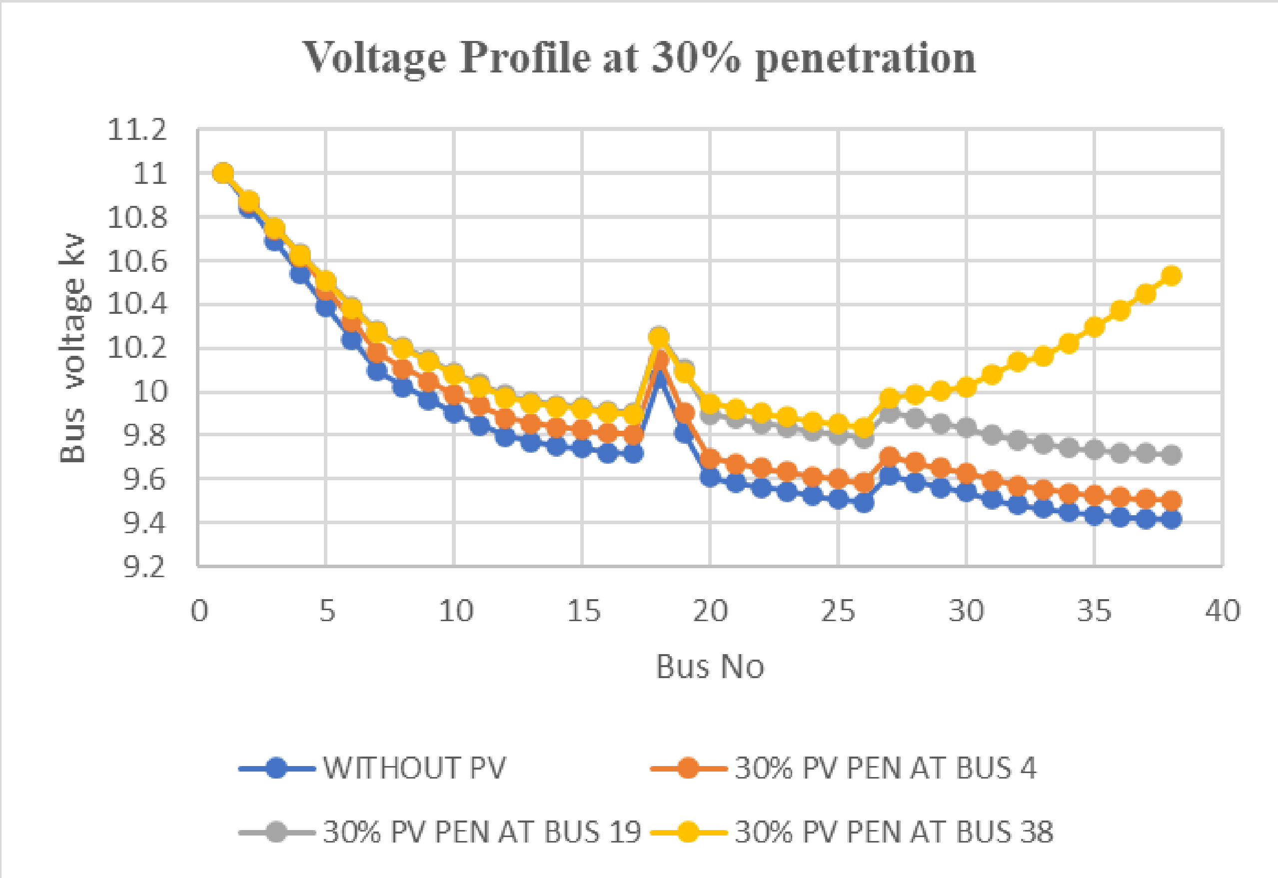

Figure 9: Voltage profile at 30% penetration

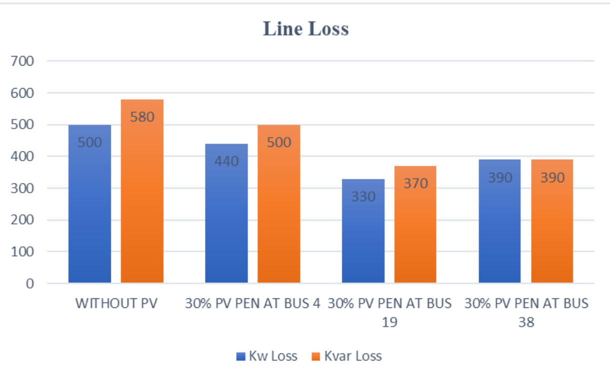

Figure 10: Line loss at 30% penetration

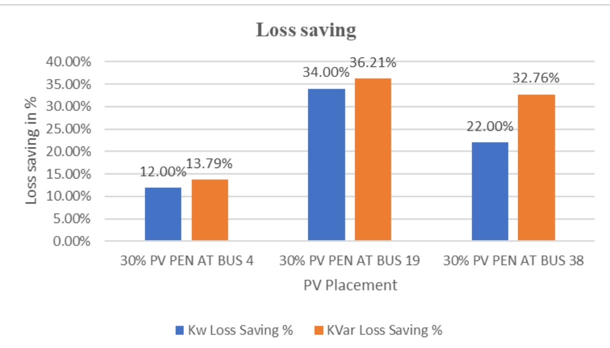

Figure 11: Loss saving % at 30% penetration

4.4 Voltage and Loss Profile at 40% penetration

At 40% PV penetration (2160 kW), the distribution network demonstrated a substantial enhancement in both the voltage profile and reduction of power losses, as presented in Table 4 and Figures 12, 13, and 14. When the PV system was installed at Bus 4, the active and reactive power losses decreased by 16% and 17.24%, respectively. The most significant improvement was observed when the PV was integrated at Bus 19, resulting in 40% and 44.83% reductions in active and reactive power losses, respectively. Similarly, PV installation at Bus 38 led to decreases of 14% in active power loss and 31.03% in reactive power loss. Moreover, the voltage of the lowest-voltage bus (Bus 38) increased from 9.41 to 10.84 kV with PV penetration at Bus 38.

Table 4: Voltage profile, with 40% PV penetration at Bazar feeder

S.N	**Bus**	**Without PV (kV)**	**40% PV at Bus 4 (kV)**	**40% PV at Bus 19 (kV)**	**40% PV at Bus 38 (kV)**
1	Bus_1	11	11	11	11
2	Bus_2	10.84406	10.87928	10.88397	10.88057
3	Bus_3	10.69057	10.76089	10.77027	10.76346
4	Bus_4	10.53839	10.64368	10.65774	10.64753
5	Bus_5	10.38874	10.49578	10.54759	10.53397
6	Bus_6	10.24165	10.35042	10.43984	10.42282
7	Bus_7	10.09717	10.20763	10.33451	10.31410
8	Bus_8	10.02221	10.13353	10.26138	10.24081
9	Bus_9	9.96648	10.07845	10.20701	10.18633
10	Bus_10	9.90143	10.01415	10.14355	10.12273
11	Bus_11	9.84875	9.96208	10.09216	10.07124
12	Bus_12	9.79760	9.91152	10.04227	10.02124
13	Bus_13	9.77104	9.88527	10.01636	9.99528
14	Bus_14	9.75188	9.86633	9.99767	9.97655
15	Bus_15	9.74259	9.85716	9.98862	9.96747
16	Bus_16	9.72401	9.83879	9.97050	9.94931
17	Bus_17	9.71782	9.83267	9.96445	9.94326
18	Bus_18	10.06670	10.17753	10.31665	10.29514
19	Bus_19	9.81587	9.92974	10.19070	10.15827
20	Bus_20	9.60765	9.72404	9.99054	10.03661
21	Bus_21	9.58375	9.70043	9.96757	10.01375
22	Bus_22	9.56205	9.67899	9.94672	9.99299
23	Bus_23	9.54475	9.66191	9.93010	9.97645
24	Bus_24	9.52321	9.64063	9.90940	9.95585
25	Bus_25	9.51034	9.62792	9.89704	9.94354
26	Bus_26	9.49512	9.61288	9.88241	9.92899
27	Bus_27	9.61672	9.73300	9.99928	10.06603
28	Bus_28	9.58820	9.70483	9.97187	10.09212
29	Bus_29	9.56282	9.67976	9.94748	10.12131
30	Bus_30	9.54058	9.65780	9.92613	10.15359
31	Bus_31	9.50875	9.62636	9.89555	10.23032
32	Bus_32	9.48324	9.60117	9.87105	10.31333
33	Bus_33	9.46761	9.58573	9.85604	10.35149
34	Bus_34	9.44846	9.56681	9.83765	10.44110
35	Bus_35	9.43568	9.55420	9.82538	10.53683
36	Bus_36	9.42609	9.54473	9.81617	10.63574
37	Bus_37	9.41970	9.53842	9.81003	10.73780
38	Bus_38	9.41650	9.53526	9.80696	10.84297

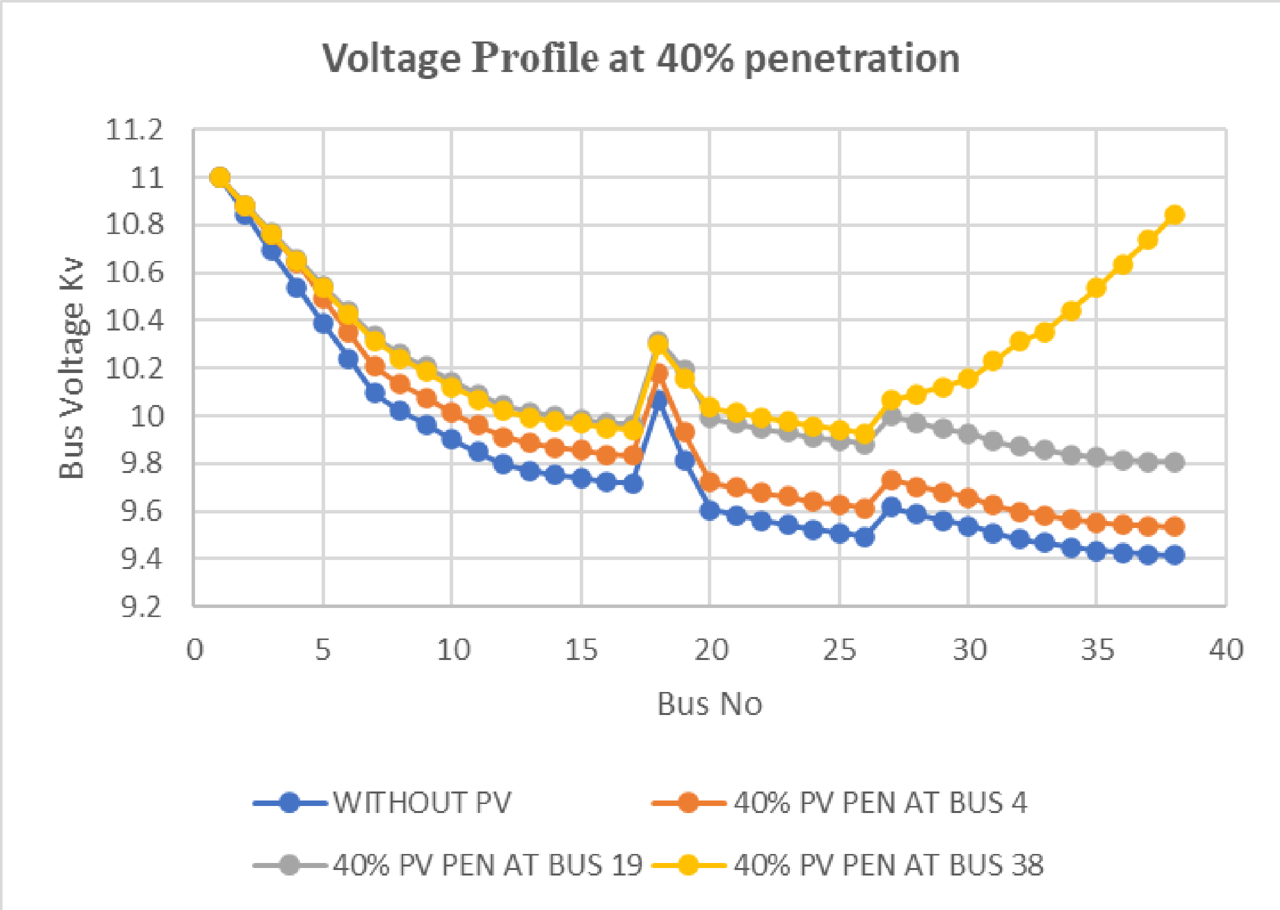

Figure 12: Voltage profile at 40% penetration

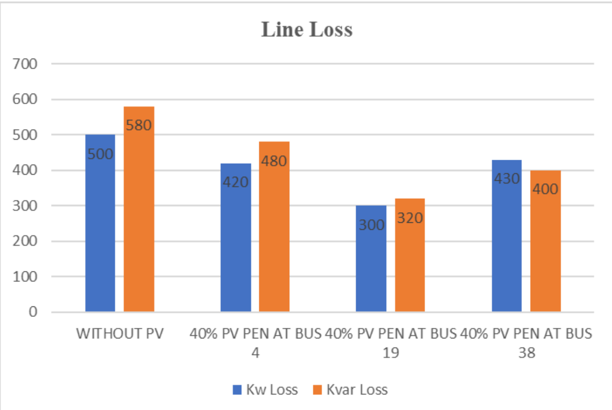

Figure 13: Line loss at 40% penetration

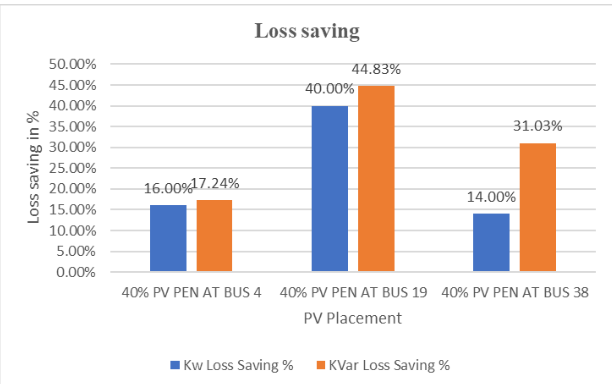

Figure 14: Loss saving % at 40% penetration

4.5 Voltage and Loss Profile at 40% penetration and 420kvar cap bank

With 40% PV penetration (2160 kW), the distribution system showed significant improvements in power losses, as presented in Table 4 and Figures 12, 13, and 14. Among the different bus locations evaluated, PV installation at Bus 19 provided the greatest reduction in losses. In this configuration, the active and reactive power losses decreased by 40% and 44.83%, respectively, while the lowest bus voltage (Bus 38) increased from 9.41 kV to 9.80 kV. Although the lowest bus voltage is higher when PV is installed at Bus 38, Bus 19 was chosen because it achieves the maximum loss reduction, providing the best compromise between minimizing losses and improving voltage profile.

To further enhance the system performance, a 420 kVAr capacitor bank was installed at the weak Bus 34 in combination with PV at Bus 19. This setup further reduced active and reactive power losses by 50% and 53.45%, respectively, and improved voltage magnitude across the system, as shown in Table 5 and Figures 15, 16, and 17.

Table 5: Voltage profile, with 40% PV penetration and Cap bank at Bazar feeder

S.N	**Bus**	**Without PV (kV)**	**40% PV Pen at Bus 19 (kV)**	**40% PV Pen at Bus 19 and Cap 420 kvar at Bus 34 (kV)**
1	Bus_1	11	11	11
2	Bus_2	10.84406	10.88397	10.89195
3	Bus_3	10.69057	10.77027	10.78623
4	Bus_4	10.53839	10.65774	10.68167
5	Bus_5	10.38874	10.54759	10.57949
6	Bus_6	10.24165	10.43984	10.47970
7	Bus_7	10.09717	10.33451	10.38232
8	Bus_8	10.02221	10.26138	10.30958
9	Bus_9	9.96648	10.20701	10.25552
10	Bus_10	9.90143	10.14355	10.19242
11	Bus_11	9.84875	10.09216	10.14131
12	Bus_12	9.79760	10.04227	10.09170
13	Bus_13	9.77104	10.01636	10.06594
14	Bus_14	9.75188	9.99767	10.04736
15	Bus_15	9.74259	9.98862	10.03835
16	Bus_16	9.72401	9.97050	10.02033
17	Bus_17	9.71782	9.96445	10.01433
18	Bus_18	10.06670	10.31665	10.36701
19	Bus_19	9.81587	10.19070	10.26615
20	Bus_20	9.60765	9.99054	10.08567
21	Bus_21	9.58375	9.96757	10.06294
22	Bus_22	9.56205	9.94672	10.04230
23	Bus_23	9.54475	9.93010	10.02586
24	Bus_24	9.52321	9.90940	10.00538
25	Bus_25	9.51034	9.89704	9.99314
26	Bus_26	9.49512	9.88241	9.97867
27	Bus_27	9.61672	9.99928	10.09904
28	Bus_28	9.58820	9.97187	10.07682
29	Bus_29	9.56282	9.94748	10.05760
30	Bus_30	9.54058	9.92613	10.04137
31	Bus_31	9.50875	9.89555	10.02090
32	Bus_32	9.48324	9.87105	10.00645
33	Bus_33	9.46761	9.85604	10.00344
34	Bus_34	9.44846	9.83765	9.99506
35	Bus_35	9.43568	9.82538	9.98299
36	Bus_36	9.42609	9.81617	9.97394
37	Bus_37	9.41970	9.81003	9.96790
38	Bus_38	9.41650	9.80696	9.96488

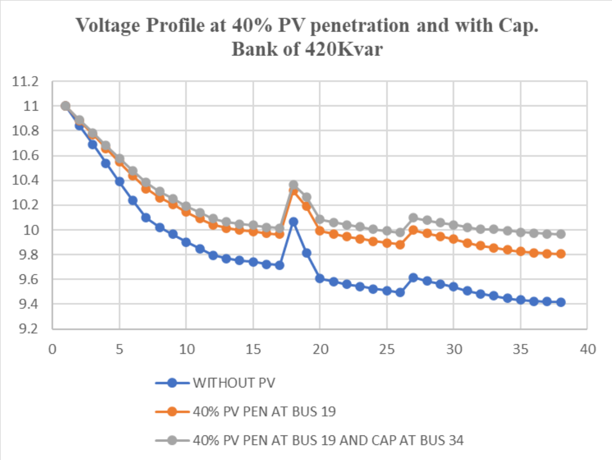

Figure 15: Voltage profile at 40% penetration and cap bank of 420kvar at bus 34

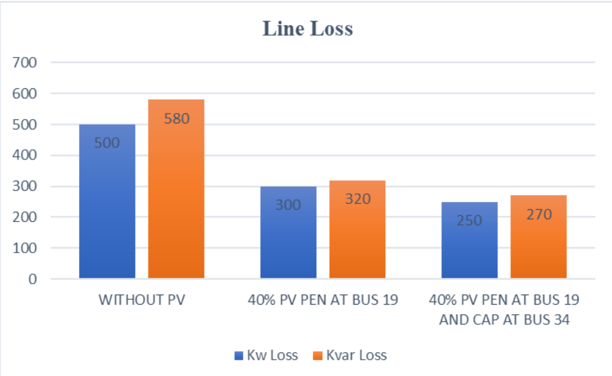

Figure 16: Line loss at 40% penetration and 420kvar cap bank

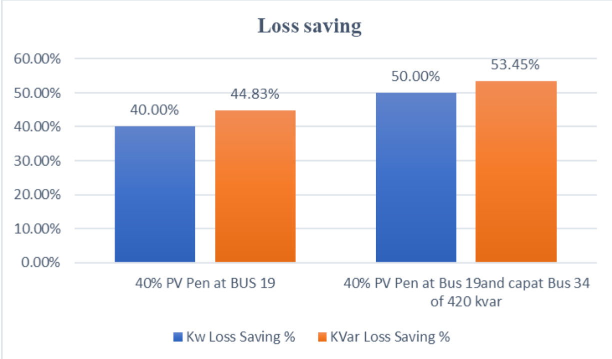

Figure 17: Loss saving % at 40% penetration and 420kvar cap bank

4.6 Voltage and Loss Profile at 40% penetration and cap bank of 840kvar

Furthermore, by injecting an 840 kvAr capacitor bank at the weak Bus 34 along with 40% PV penetration (2160 kW) at Bus 19, the active and reactive power losses were further reduced by 54% and 58.62%, respectively, while significantly enhancing the overall voltage profile, as presented in Table 6 and Figures 18, 19, and 20.

Table 6: Voltage profile, with 40% PV penetration and Cap bank of 840 kvar at Bazar feeder

S.N	**Bus**	**Without PV (kV)**	**40% PV at Bus 19 + Cap 420 kvar at Bus 34 (kV)**	**40% PV at Bus 19 + Cap 840 kvar at Bus 34 (kV)**
1	Bus_1	11	11	11
2	Bus_2	10.84406	10.89195	10.89987
3	Bus_3	10.69057	10.78623	10.80206
4	Bus_4	10.53839	10.68167	10.70543
5	Bus_5	10.38874	10.57949	10.61116
6	Bus_6	10.24165	10.47970	10.51928
7	Bus_7	10.09717	10.38232	10.42980
8	Bus_8	10.02221	10.30958	10.35741
9	Bus_9	9.96648	10.25552	10.30360
10	Bus_10	9.90143	10.19242	10.24080
11	Bus_11	9.84875	10.14131	10.18994
12	Bus_12	9.79760	10.09170	10.14056
13	Bus_13	9.77104	10.06594	10.11492
14	Bus_14	9.75188	10.04736	10.09643
15	Bus_15	9.74259	10.03835	10.08747
16	Bus_16	9.72401	10.02033	10.06953

17	Bus_17	9.71782	10.01433	10.06355
18	Bus_18	10.06670	10.36701	10.41704
19	Bus_19	9.81587	10.26615	10.34137
20	Bus_20	9.60765	10.08567	10.18059
21	Bus_21	9.58375	10.06294	10.15807
22	Bus_22	9.56205	10.04230	10.13763
23	Bus_23	9.54475	10.02586	10.12134
24	Bus_24	9.52321	10.00538	10.10104
25	Bus_25	9.51034	9.99314	10.08892
26	Bus_26	9.49512	9.97867	10.07459
27	Bus_27	9.61672	10.09904	10.19868
28	Bus_28	9.58820	10.07682	10.18160
29	Bus_29	9.56282	10.05760	10.16750
30	Bus_30	9.54058	10.04137	10.15639
31	Bus_31	9.50875	10.02090	10.14608
32	Bus_32	9.48324	10.00645	10.14182
33	Bus_33	9.46761	10.00344	10.15113
34	Bus_34	9.44846	9.99506	10.15300
35	Bus_35	9.43568	9.98299	10.14112
36	Bus_36	9.42609	9.97394	10.13221
37	Bus_37	9.41970	9.96790	10.12626
38	Bus_38	9.41650	9.96488	10.12329

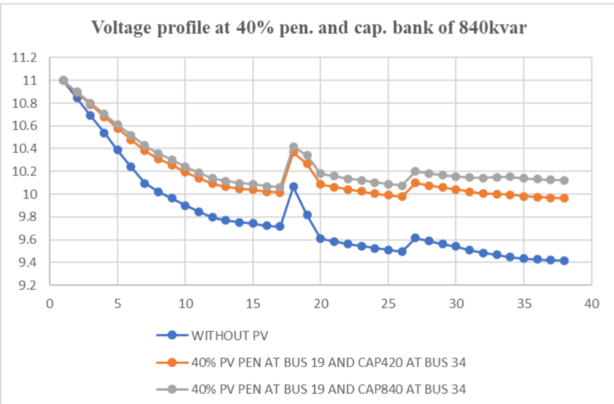

Figure 18: Voltage profile at 40% penetration and cap bank 840kvar

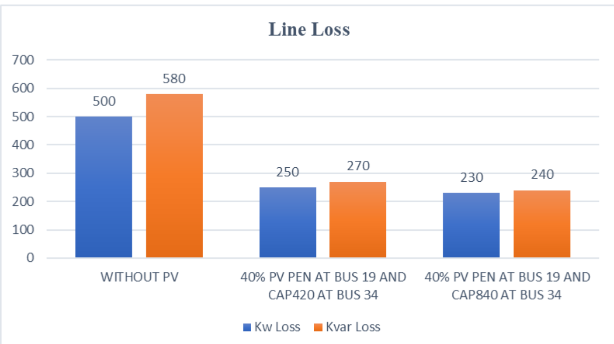

Figure 19: Line loss at 40% penetration and 840kvar cap bank

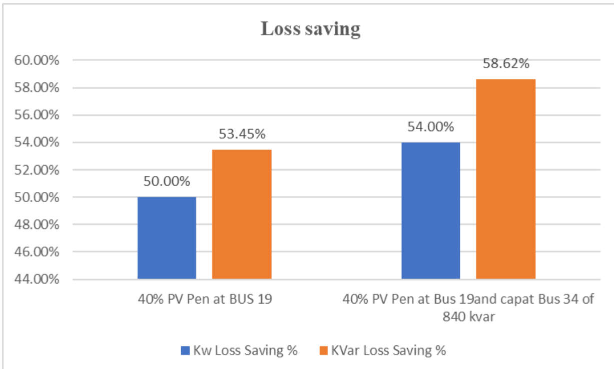

Figure 20: Loss saving % at 40% penetration and 840kvar cap bank

Conclusion and Recommendations

This study analyzed the impact of photovoltaic (PV) system integration on the performance of the 11 kV Bazar Feeder, a 38-bus radial distribution network. Load flow analyses were conducted under various PV penetration levels, with PV systems strategically integrated near the source (Bus 4), middle (Bus 19), and end (Bus 38) of the feeder. Simulations were performed in DIgSILENT PowerFactory to evaluate improvements in voltage profile and power loss.

The results demonstrated that PV integration significantly enhanced the overall system performance. At 10%, 20%, 30%, and 40% PV penetration levels, both active and reactive power losses were progressively reduced, and bus voltages improved accordingly. Results show that at a low penetration level (10%), power loss reduction is more effective when the PV system is installed at the end bus (Bus 38). However, as the penetration level increases, PV placement at the middle of the network (Bus 19) becomes more effective in minimizing losses. Among the tested buses, PV integration at Bus 19 consistently provided the maximum reduction in losses, achieving up to 40% reduction in active power loss and 44.83% in reactive power loss at the 40% penetration level. However, despite the minimum losses, the lowest bus voltage (Bus 38) remained relatively low at 9.80 kV.

To address this, reactive power compensation was introduced. The installation of a 420 kVAr capacitor bank at the weak Bus 34 improved the voltage profile while maintaining reduced losses. Furthermore, by increasing the capacitor bank capacity to 840 kVAr along with 40% PV penetration at Bus 19, the system achieved a substantial 54% reduction in active power loss and a 58.62% reduction in reactive power loss, with a notable improvement in the overall voltage profile across the feeder.

Recommendations:

For optimal performance in radial distribution systems, PV units should be strategically placed at the middle of the network at higher penetration levels, while lower penetration levels may benefit from placement near the feeder end. Additionally, coordinated integration of capacitor banks with PV systems is recommended to enhance voltage stability, reduce power losses, and improve overall system efficiency.

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