PU Journal of Science and Engineering
Purbanchal University Science and Engineering Campus
Biratnagar
ISSN: XXXX-XXXX

Enhancing the Impact of Photovoltaic Integration in the Integrated Nepal Power System in the Eastern Transmission System of Nepal

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Received: 03 Nov 2025 / Accepted: 15 Jan 2026

Abstract

The rapid increase in electrical demand and the growing integration of renewable energy sources have introduced significant challenges to the stability and reliability of modern power systems globally. Among these challenges, voltage stability has emerged as a critical concern, particularly with the deployment of large-scale photovoltaic (PV) power plants whose output is dependent on solar irradiation. This study aims to enhance the voltage stability in Nepal's INPS Eastern transmission system by optimally integrating large-scale PV power plants. Load-flow studies and voltage stability analyses were conducted using the DigSILENT PowerFactory. The research methodology comprises three primary stages: (i) base case analysis without PV penetration, (ii) assessment of system performance with PV integration at various bus locations, and (iii) improvement of voltage profiles through the addition of reactive power support using capacitor banks. Optimal PV placement and capacity were identified based on their effectiveness in improving bus voltages, enhancing reactive power balance, and increasing the voltage stability margin of the system. The simulation results indicate that strategically integrating PV plants at selected buses significantly improves the voltage profile and stability margin of the power system. These findings demonstrate that large-scale PV integration, when optimally located and sized, can contribute to cleaner energy generation and a more stable and reliable power grid.

Keywords: Voltage Stability • INPS Eastern Grid • Photovoltaic (PV) Integration • Optimal Placement • Load Flow Analysis

1. Introduction

The global energy sector is shifting toward cleaner and more sustainable energy sources. Solar photovoltaic (PV) technology is attracting attention because it can be scaled up, has a low environmental impact, and its costs are rapidly decreasing. In 2023, solar PV accounted for approximately 5.4% of global electricity generation, with a record increase of 320 TWh. China led this growth, followed by the European Union and the United States. Over the past ten years, solar PV module costs have decreased significantly, and installed capacity has nearly doubled ow-

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ing to lower equipment prices and strong policy support. As the world focuses more on reducing carbon emissions by 2045, the energy sector is shifting toward renewable sources, and solar power plants are key contributors.Qutaishat et al. (2021) Transitioning from fossil fuel energy systems to solar power requires careful coordination of PV-generated electricity with current transmission grids. The addition of large-scale PV systems presents challenges, such as voltage instability, frequency changes, and insufficient reactive power. Voltage stability refers to the ability of a power system to maintain stable voltage levels after disruptions. High PV generation can result in weak reactive power support, leading to voltage drops and, potentially, voltage collapse.

Voltage stability is particularly important for reliable power in developing countries such as Nepal, where long transmission lines, weak grid infrastructure, and limited reactive power are common. As more renewable energy, especially from photovoltaic (PV) systems, is added, there is growing interest in how this affects grid voltage and stability. Integrating PV systems well with good control strategies and site choices can help manage reactive power and reduce grid stress. Nepal mainly uses hydroelectric power; however, during the dry season, low water necessitates the use of other renewable sources. Although Nepal has significant solar potential, its installed PV capacity is still low. The eastern region, which supplies cities such as Biratnagar, Dharan, and Itahari, often faces voltage dips, congestion, and reliability problems because of long transmission distances and uneven load. Although the national grid is growing and the Nepal Electricity Authority (NEA) is adding more energy sources, voltage stability remains a significant challenge. A recent study by the Investment Board Nepal (IBN) shows that Nepal receives over 300 sunny days annually and solar radiation levels between 3.6 and 6.2 kWh/m^2/day, indicating strong potential for solar energy. The Nepal Electricity Authority recently requested power purchase agreement (PPA) proposals for 800 MW of solar power and received approximately 3,600 MW in project submissions, more than four times the planned amount.(Adhikari et al., 2025) This strong response demonstrates growing private-sector interest in solar power and highlights the potential for increased PV integration into the national grid.

Many studies have examined voltage stability in the presence of a high amount of renewable energy. One study of Nepal's transmission network examined voltage stability with high wind power integration using DigSILENT PowerFactory to assess three 132 kV buses: Suichatar, Pokhara, and Middle Marshyangdi. The results showed that Pokhara was the weakest bus because of its low penetration limits and high voltage sensitivity, whereas Suichatar was the best for wind power integration. High wind penetration is linked to voltage dips and low reactive power support in the system.(Dharel and Maharjan, 2021) Another study investigated the effects of high levels of PV power plants on the capacity, frequency, and voltage stability of Egypt's unified grid.(El-Sattar et al., 2022, 2021) The researchers used load-flow analysis and DigSILENT PowerFactory simulations to verify the grid capacity requirements and system upgrades as the PV integration increased. A P-V curve analysis revealed that the improved voltage control could handle more PV generation at different points in the grid. The study assessed both static and dynamic voltage stability with large-scale PV integration.(Adrianti et al., 2023)

Karmila Kamil and Muhammad Amirul also studied voltage stability in transmission networks with PV connections using PSS/E simulations. They compared the performance of systems with and without PV integration using voltage stability indices. The results showed that increased PV generation lowers the active power output of conventional generators, which must then provide more reactive power to maintain voltage stability. Insufficient reactive power support can lead to voltage instability and possible system collapse.(Kamil et al., 2019; Gu and Cañizares, 2007) Another study examined voltage stability with renewable energy variability using the IEEE 9-bus and Lumbini Integrated Nepal Power System (INPS). The analysis revealed a power loss of 1.46% at bus 5 and a load margin of 1.25 times. Sensitivity analysis showed that the Butwal grid was the most critical point in the network.(Halarou et al., 2026) Although PV and QV curve analyses showed voltage drops with higher loads, more renewable energy helped improve voltage profiles and made the system more reliable.(Bu et al., 2012; Huang et al., 2019)

Despite these studies, there has been little research on how optimal photovoltaic integration affects voltage stability in Nepal's eastern transmission network. This study aims to analyze and improve the voltage stability in the Nepal Electricity Authority's eastern transmission network by strategically adding photovoltaic power plants.

2. Methodology

A. Study System Description

This study uses a simulation-based approach to analyze voltage reliability improvements in the eastern transmission corridor of Nepal by integrating photovoltaic (PV) power plants. It focuses on the eastern part of the Integrated Nepal Power System (INPS), which operates at 132, 220, and 400 kV. System data were collected from technical reports and the operational data of the Nepal Electricity Authority (Figure 2). These include transmission-line parameters, transformer ratings, generator data, and load information. The eastern INPS network in this study has 32 buses, 19 transmission lines, 13 transformers, nine load buses, four generators, and one diesel power plant. The nominal frequency is 50 Hz, and the highest voltage level is 400 kV. The entire network was modelled using DigSILENT PowerFactory. Analyses, such as load-flow, P-V, and Q-V curves, were performed to evaluate the voltage profile and system stability. Assumptions were made during the modelling because of limited detailed system data.

B. PV Integration

Integrating PV plants into transmission buses can improve power system performance. PV plants supply active power locally, reducing transmission-line loading and system losses. Modern photovoltaic (PV) inverters also provide reactive power. This helps improve the voltage profile and maintain voltage regulation, particularly at weak buses. However, the benefits of PV integration depend on the location and size of PV plants. Therefore, an analysis is required to determine suitable buses for PV installation.

C. PV Placement

First, a load-flow analysis was performed without PV integration to identify buses with low voltage and high reactive power demand. Based on the voltage profile, three buses were selected as potential locations for PV installation. The buses selected in the eastern INPS network were as follows:

- Lahan 132 kV (Bus 04)
- Rupani 132 kV (Bus 05)
- Tingla 132 kV (Bus 18)

These buses were chosen because they have lower voltages than other buses in the system.

D. Load Flow Analysis Procedure

A load-flow analysis was performed (see Figure 1) using the following steps:

1. System data, such as line parameters, transformer ratings, generator data, and load demand, were collected.
2. The transmission network was modelled in DigSILENT PowerFactory using a single-line diagram.
3. A base-case load-flow analysis was performed without PV integration to assess the voltage profile and identify weak buses.
4. The PV plants were connected to the selected buses, and the load-flow analysis was repeated to observe the changes in the system voltage and performance.
5. The bus voltages were checked to ensure that they remained within the acceptable range of 0.9-1.0 per unit (PU). If the values were outside this range, capacitor banks were added at the PV buses to provide reactive power support, and the analysis was repeated.

3. Results and Discussion

A. Base Case Voltage Analysis

First, a load-flow analysis was performed without PV integration to understand the initial conditions of the eastern transmission corridor of the integrated Nepal Power System (INPS). The results indicate that buses located close to major generation sources maintained voltages close to 1.0 PU, indicating stable system operation (Table 1). These buses included buses 01, 06, 09, 10, and 12. However, some buses located away from the generation sources exhibited lower voltage values. Buses 03, 04, 18, 19, 24, and 25 had voltage levels below 0.90 PU, which indicates weak voltage conditions in these areas. This occurs mainly because of higher transmission-line loading and limited reactive-power support in load-dominated regions. The voltage angle also becomes more negative as power flows toward the load centers, thereby indicating the direction of power flow in the system.[12] Although the system operates within a stable range, the voltage profiles of some buses require improvement. The results also show that the generators at Buses 09, 10, and 12 operate with high power factors, indicating that they efficiently supply active power. In contrast, the synchronous machine at Bus 06 provides a large amount of reactive power, approximately 178.48 MVar, and operates with a low power factor of 0.21. This indicates that the machine plays an important role in network voltage control. However, continuously supplying high reactive power may create stress on the generator and its excitation system.(Shrestha et al., 2024)

B. Generator Power Output Analysis

The generator performance results show that hydropower plants connected at buses 09, 10, and 12 operate efficiently under normal system conditions. These generators maintain power factors between approximately 0.94 and unity. Hydropower plants, such as Mai Cascade and Kabeli, provide both active power and moderate reactive power support, helping to maintain voltage levels in the nearby areas of the network (Table 2). Similarly, the Mai Khola and Puwa Khola hydropower plants operate close to unity power factor. This implies that they mainly supply active power and provide only a small amount of reactive power support. Their operation helps maintain the balance between generation and system demand. In contrast, the synchronous machine at Bus 06 supplies significantly more reactive power than the other generators (Figure 3). It produces approximately 178.49 MVar of reactive power and operates with a low power factor of approximately 0.21. This indicates that the generator is heavily used for voltage support in the system. Prolonged operation under this condition may increase generator heating and place additional stress on the excitation system.

Overall, the results demonstrate that hydropower plants primarily supply active power, whereas the synchronous machine helps control the system voltage. Therefore, additional reactive power support, such as capacitor banks, in load-dominated areas can help reduce the reactive power burden on the generator at Bus 06 and improve the system voltage profile.

C. Integration of PV in the INPS Eastern Transmission System

Study System and PV Distribution Strategy

The eastern grid of the integrated Nepal power system, with 32 buses, was used to study the impact of PV integration. The total system load considered in this study was 361.22 MW and 271.44 MVAr. Three buses were selected for PV installation: Bus 03 (Lahan 132 kV), Bus 04 (Rupani 132 kV), and Bus 18 (Tingla 132 kV). These buses were selected for their location within the network and for the availability of suitable land areas with good solar radiation (Table 3). To maintain a balanced system operation, the PV capacity was distributed among the three buses. In this study, 50% of the total PV capacity was connected to Tingla (Bus 18), with the remaining 50% shared equally between Lahan (Bus 03) and Rupani (Bus 04), each receiving 25% of the total PV capacity. This distribution helps to improve voltage conditions in the eastern transmission corridor.

Voltage Profile with 5% PV Integration

At the 5% PV penetration level, a total of 18.10 MW of PV power was added to the system. This represented 5% of the total system generation capacity of 362 MW. The PV power was distributed as 4.53 MW at Lahan (Bus 03), 4.53 MW at Rupani (Bus 04), and 9.05 MW at Tingla (Bus 18). The results show that the voltage profile improved slightly after PV integration. In addition, system losses were reduced because a portion of the power was generated locally. Without PV integration, the system losses were approximately 25 MW and 128.8 MVAr. After 5% PV integration, the losses were reduced to approximately 20 MW and 100 MVAr (Table 4).

Voltage Profile with 10% PV Integration At the 10% PV penetration level, the PV capacity increased to 36.20 MW. The PV power was distributed as 9.05 MW at Lahan (Bus 03), 9.05 MW at Rupani (Bus 04), and 18.10 MW at Tingla (Bus 18). The results demonstrate further improvement in the voltage profile compared with those of the base case and the 5% PV case (Table 4). The additional PV generation provides local power support and helps reduce voltage drops in the transmission lines. Consequently, the overall voltage stability of the system improved (Figure 4).

Voltage Profile with 15% PV Integration

At the 15% PV penetration level, the total PV capacity increased to 54.30 MW. The PV capacity was distributed as 13.58 MW at Lahan (Bus 03), 13.58 MW at Rupani (Bus 04), and 27.15 MW at Tingla (Bus 18). The results show that the voltage at the selected buses gradually increased as the PV penetration increased. In the base case without PV, Bus 18 had the lowest voltage among the three buses. After adding PV at 5%, 10%, and 15%, the voltage levels at Buses 03, 04, and 18 improved in steps. This shows that PV integration helps reduce voltage drop and support voltage stability in the transmission network (Figure 5).

Loss Reduction Due to PV Integration

The effect of PV integration on system losses was also analyzed. In the base case without PV, the system losses were approximately 25 MW and 128.8 MVar. When PV was integrated into the system, the losses decreased significantly. At PV penetration levels of 5%, 10%, and 15%, the active power losses were reduced to 20, 12, and 7.087 MW, respectively. The reactive power losses also decreased to 100, 76.09, and 61.09 MVAr, respectively. These results demonstrate that increasing the PV penetration reduces system losses. Overall, PV integration improves the voltage profile, reduces transmission losses, and enhances the voltage stability of the eastern transmission network (Figure 6).

4. Table and Figure

Table 1: Load flow analysis results of bus voltage, voltage angle, and generator power outputs in the system.

Bus	Voltage PU	Voltage Angle	Voltage Magnitude (kV)
Bus 01	1.00	0.00	400.00
Bus 02	0.92	-4.81	120.55
Bus 03	0.89	-6.46	117.46
Bus 04	0.91	-5.92	119.51
Bus 05	0.97	-3.10	127.87
Bus 06	1.00	-3.75	132.00
Bus 07	0.99	-1.48	131.77
Bus 08	0.99	2.13	131.83
Bus 09	1.00	2.27	132.00
Bus 10	1.00	4.85	132.00
Bus 11	0.99	6.97	131.98
Bus 12	1.00	7.64	132.00
Bus 13	0.99	-1.77	217.42
Bus 14	0.99	-1.77	217.42
Bus 15	0.99	-1.57	395.54
Bus 16	0.99	-1.77	217.42
Bus 17	0.99	-1.77	217.42
Bus 18	0.87	-7.41	114.44
Bus 19	0.85	-8.89	28.04
Bus 20	0.94	-3.28	124.08
Bus 21	0.93	-4.56	30.50
Bus 22	0.93	-4.56	30.50
Bus 23	0.91	-5.48	29.88
Bus 24	0.88	-7.88	28.82
Bus 25	0.88	-7.88	28.82
Bus 26	0.89	-7.29	29.34
Bus 27	0.99	-4.80	32.54
Bus 28	0.99	-4.81	32.54
Bus 29	0.99	-1.77	217.42

Bus	Voltage PU	Voltage Angle	Voltage Magnitude (kV)
Bus 30	0.99	-2.38	130.22
Bus 31	0.99	-0.29	219.05
Bus 32	0.99	-0.72	130.58

Table 2: Different Generators and Their Respective Power

Generator	**Terminal Station**	**Active Power (MW)**	**Reactive Power (MVar)**	**Apparent Power**	**Power Factor**
Mai Cascade	Bus 09	4.2	1.456	4.45	0.95
Mai Khola	Bus 10	15.6	0.33	15.61	0.99
Puwa Khola	Bus 10	6.2	-0.001	6.2	1.00
Synchronous Machine (1)	Bus 06	39.001	178.49	182.71	0.214
Kabeli HEP	Bus 12	37	-5.37	37.39	0.99

Table 3: Integration Level of PV

Level	**Total PV Installed (MW)**	**Bus 3 (25%)**	**Bus 4 (25%)**	**Bus 18 (50%)**
5%	18.10 MW	4.53 MW	4.53 MW	9.05 MW
10%	36.20 MW	9.05 MW	9.05 MW	18.10 MW
15%	54.30 MW	13.58 MW	13.58 MW	27.15 MW

Table 4: Comparison of Bus Voltage Magnitude Profiles Without PV and With 5% and 10% PV Penetration Levels

Bus No.	**Voltage Magnitude Without PV**	**Voltage Magnitude With 5% PV**	**Voltage Magnitude With 10% PV**
Bus 01	400.00	400.00	400.00
Bus 02	120.55	120.99	121.36
Bus 03	117.46	117.94	118.35
Bus 04	119.51	119.92	120.28
Bus 05	127.87	128.02	128.16
Bus 06	132.00	132.00	132.00
Bus 07	131.77	131.77	131.77
Bus 08	131.83	131.83	131.83
Bus 09	132.00	132.00	132.00
Bus 10	132.00	132.00	132.00
Bus 11	131.98	131.98	131.98
Bus 12	132.00	132.00	132.00
Bus 13	217.42	217.53	217.62
Bus 14	217.42	217.53	217.62
Bus 15	395.54	395.74	395.91
Bus 16	217.42	217.53	217.62
Bus 17	217.42	217.53	217.62
Bus 18	114.44	115.52	116.44

Bus No.	**Voltage Magnitude Without PV**	**Voltage Magnitude With 5% PV**	**Voltage Magnitude With 10% PV**
Bus 19	28.04	28.32	28.55
Bus 20	124.08	124.11	124.14
Bus 21	30.50	30.51	30.52
Bus 22	30.50	30.51	30.52
Bus 23	29.88	29.99	30.08
Bus 24	28.82	28.94	29.10
Bus 25	28.82	28.94	29.10
Bus 26	29.34	29.44	29.54
Bus 27	32.54	32.54	32.54
Bus 28	32.54	32.54	32.54
Bus 29	217.42	217.53	217.62
Bus 30	130.22	130.29	130.35
Bus 31	219.05	219.07	219.10
Bus 32	130.58	130.61	130.63

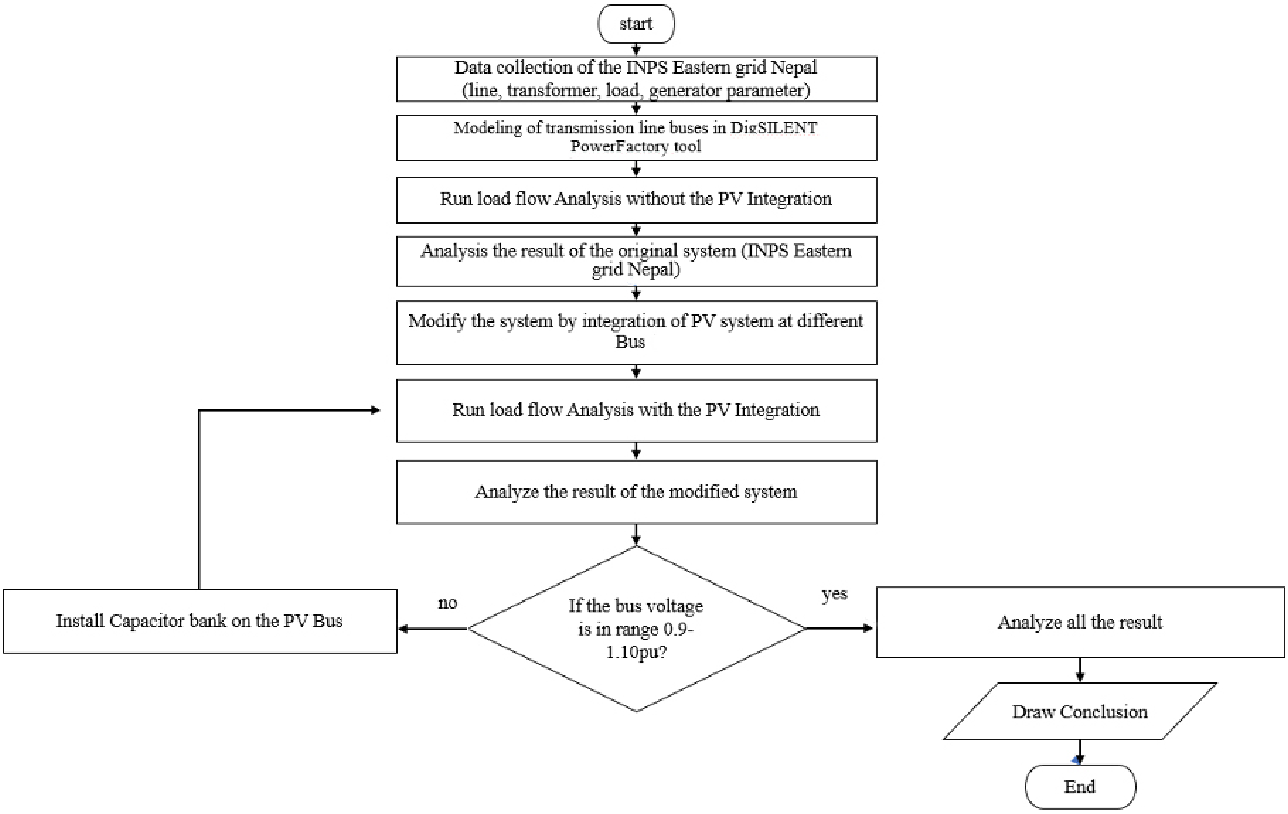

Figure 1: Flow chart of Load flow

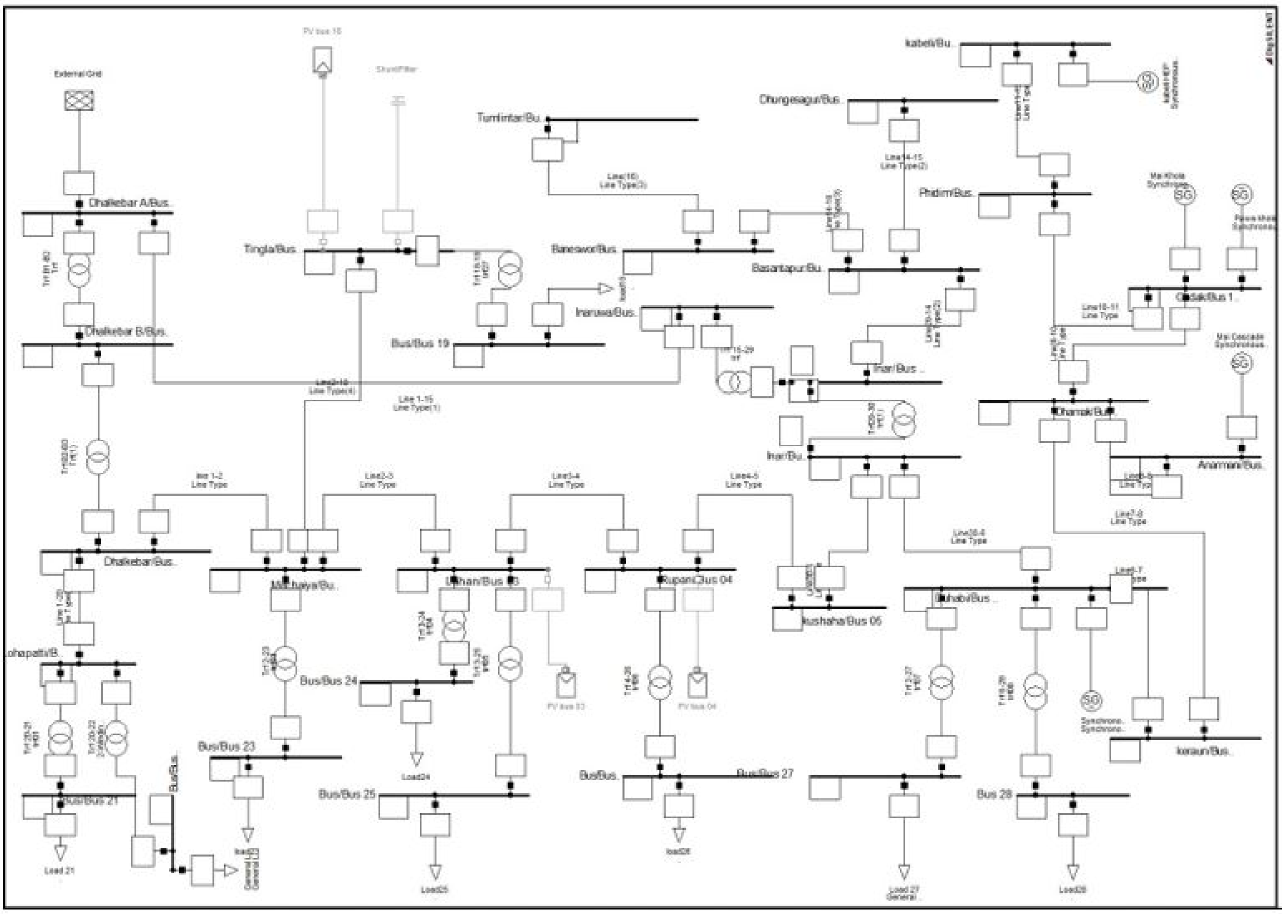

Figure 2: Single line diagram of 32 Bus INPS Eastern Transmission line

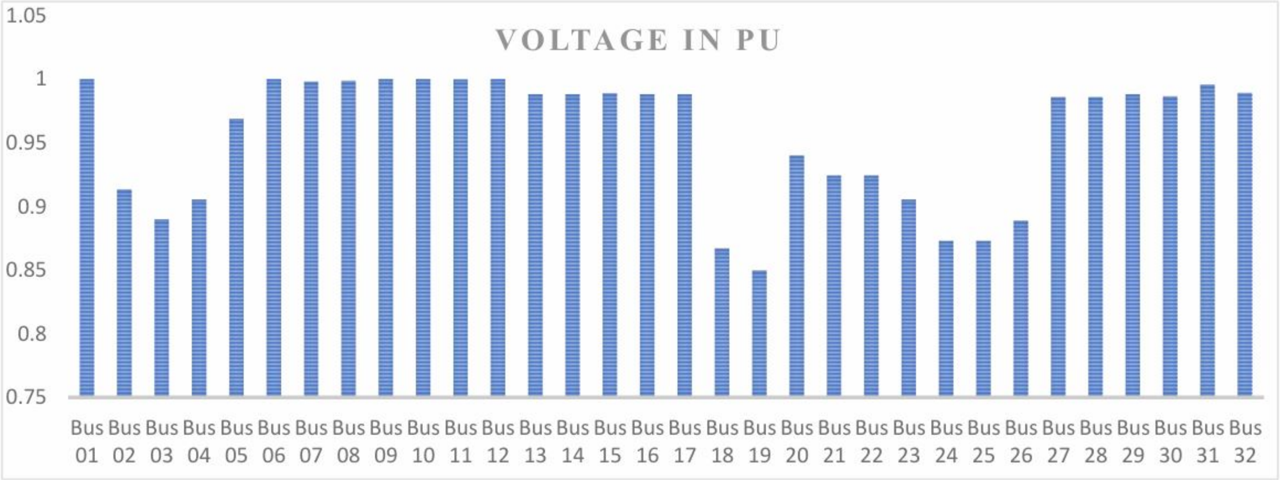

Figure 3: Voltage input diagram showing bus voltage distribution in the system.

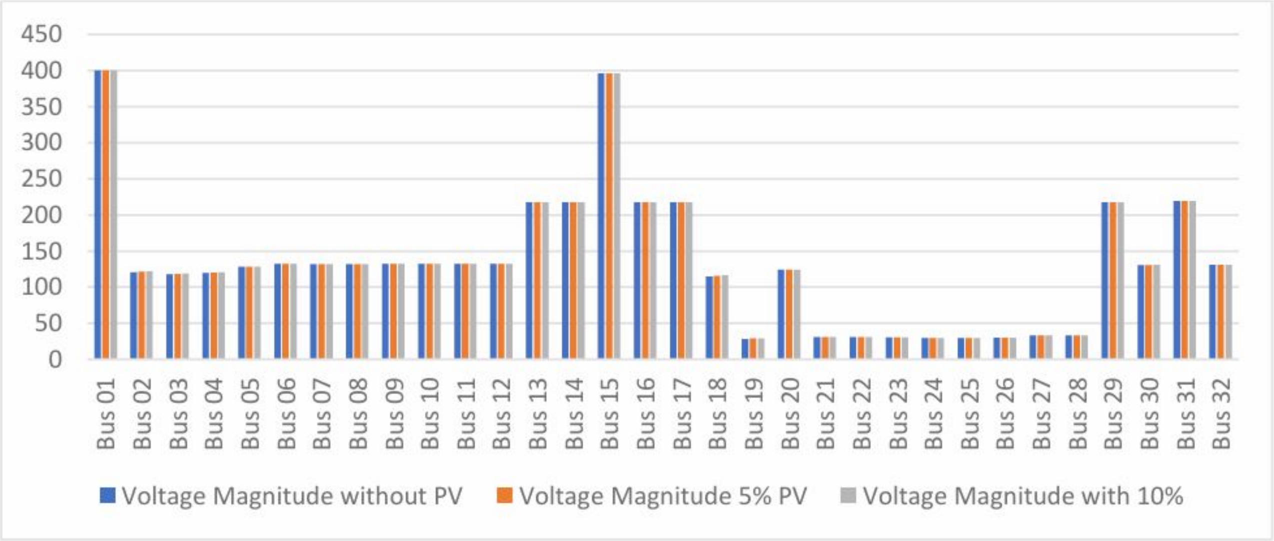

Figure 4: Voltage magnitude of different penetration.

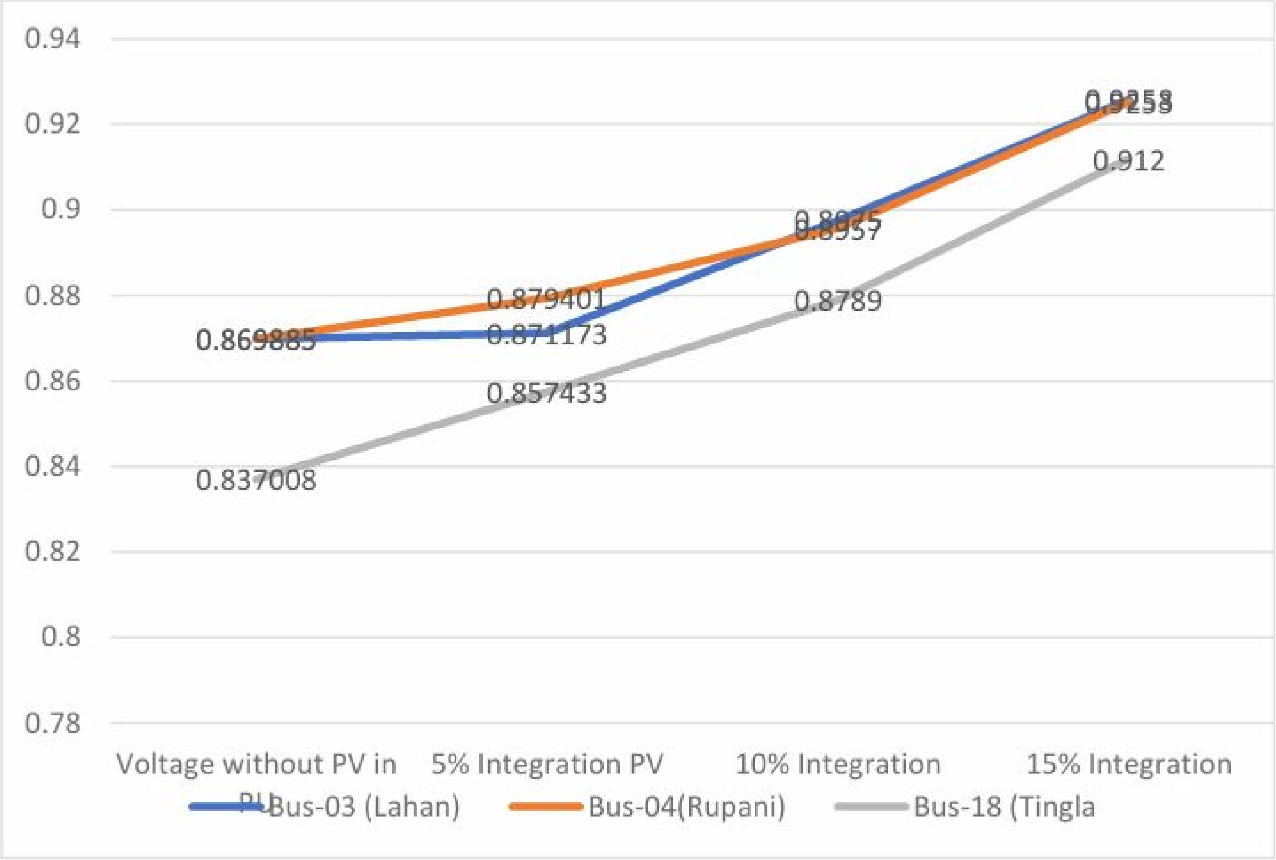

Figure 5: Voltage profile comparison of Bus-03 (Lahan), Bus-04 (Rupani), and Bus-18 (Tingla) under 5%, 10%, and 15% PV penetration levels.

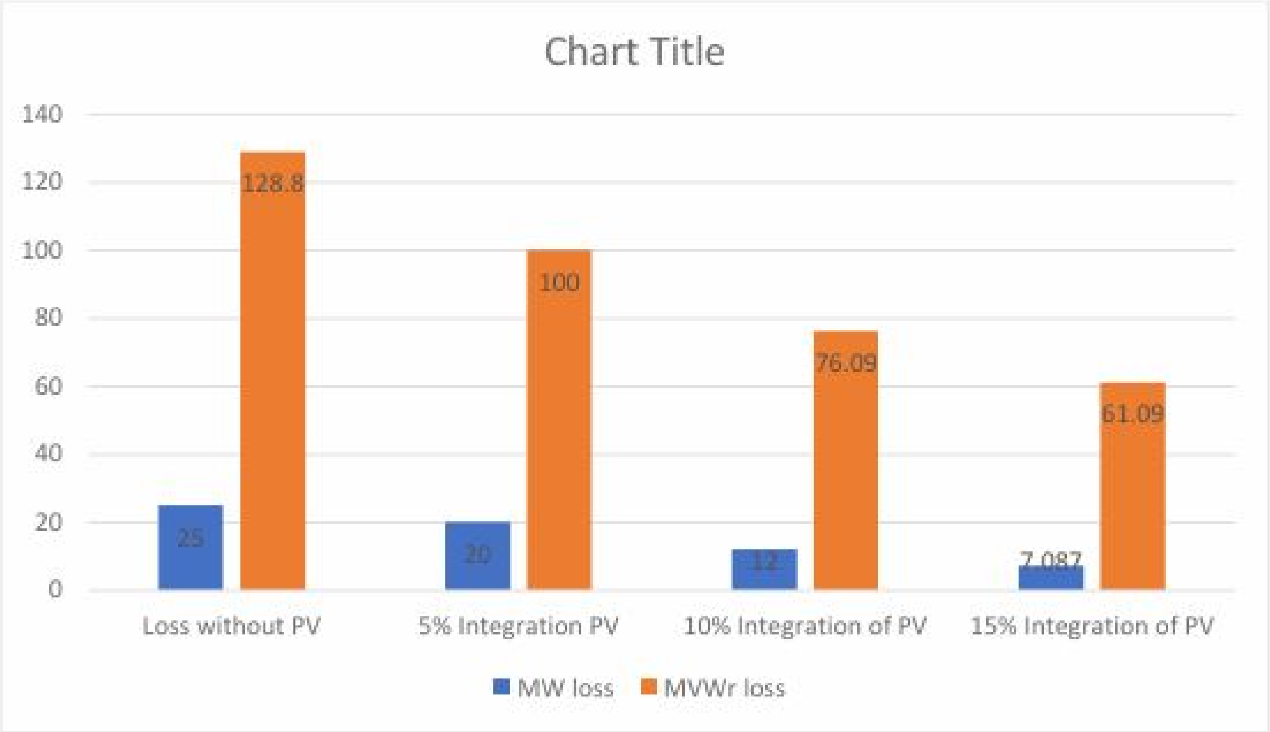

Figure 6: Comparison of Power Loss in different Integration level.

5. Conclusion and Recommendation

A load-flow analysis of the INPS Eastern Transmission System demonstrated that integrating PV generation significantly enhanced the voltage profile and reduced system losses.

Voltage Profile Improvement

In the absence of PV integration, several critical buses operated below the permissible voltage range (0.90-1.10 PU), with buses 3 and 4 at 0.8699 PU and bus 18 at 0.8370 PU, reflecting significant under voltage conditions. Progressive PV penetration led to systematic voltage enhancement across the network, with incremental improvements at the 5% and 10% levels and substantial recovery at 15% penetration. Notably, the voltage increased to 0.9258 PU (bus 3), 0.9253 PU (bus 4), and 0.8789 PU (bus 18), demonstrating the effectiveness of higher PV integration in strengthening voltage stability and overall system performance.

System Loss Reduction The integration of photovoltaic (PV) generation reduces network losses by supplying power closer to load centers, lowering line loading, and reducing resistive and reactive power losses. At 5% PV penetration, the active power loss decreased from 25 to 20 MW, whereas the reactive power loss decreased from 128.8 to 100 MVar. At 10% penetration, the losses were further reduced to 12 MW and 76.09 MVar, respectively. The best performance occurred at 15% PV penetration, with an active power loss minimized to 7.087 MW and a reactive power loss of 61.09 MVar. This 15% penetration level was identified as optimal for the INPS Eastern Transmission System, providing improved voltage profiles and significantly reducing power losses while supporting reliable system performance.

Recommendation

1. Implement 15% PV penetration: Adopt distributed PV integration in the INPS Eastern System to optimize voltage and reduce losses.

2. Monitor voltage stability: Monitor critical buses to maintain voltages within the range (0.90–1.10 PU) under varying loads.

3. Reactive power support: PV inverter reactive power control is used to improve voltage regulation and reliability.

4. Expand PV integration studies: Conduct studies with higher PV penetration levels to assess future expansion potential.
5. Dynamic load consideration: Load variability should be included in the analyses to ensure network stability under different conditions.
6. Advanced control strategies: Intelligent PV system coordination should be implemented to maximize efficiency and support operations.

Author's declaration

The authors declare no conflicts of interest regarding the publication of this research paper. All contributors agreed to the final draft of the manuscript.

Declaration of the conflict of interest

The authors declare that there are no irreconcilable circumstances. All authors contributed to the preparation of the final manuscript.

Acknowledgement

I would like to thank the Director of the M.Sc. EPE Program, Er. Tejraj Giri, for enhancing the paper's quality. Finally, I express my appreciation to my family, friends, and well-wishers for their support throughout this endeavor.

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