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

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

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Received: 03 Nov 2025 / Accepted: 15 Jan 2026

Abstract

The rapid growth of electrical demand and the increasing penetration of renewable energy sources have brought new challenges to the stability and reliability of modern power systems. Among various stability concerns, voltage stability has become a major issue, especially with the integration of large-scale photovoltaic (PV) power plants, whose output depends on solar irradiation. This thesis focuses on enhancing voltage stability in the INPS Eastern transmission system of Nepal by optimal integration of large-scale PV plants. Load flow studies and voltage stability analyses are carried out using Dig SILENT Power Factory. The research involves three main stages: (1) base case analysis without PV penetration, (2) system performance with PV integration at various bus locations, and (3) voltage profile improvement through the addition of reactive power support using capacitor banks. Optimal PV placement and capacity are determined based on their ability to improve bus voltages, enhance reactive power balance, and increase the system's voltage stability margin. Simulation results demonstrate that the strategic integration of PV plants at selected buses significantly improves the voltage profile and stability margin of the power system. The findings suggest that large-scale PV integration, when optimally located and sized, can contribute not only to cleaner energy generation but also to 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 landscape is undergoing a transformative shift toward cleaner, more sustainable sources. Among these, solar photovoltaic (PV) technology has emerged as a leading solution due to its scalability, low environmental impact, and declining costs. In 2023, solar PV accounted for 5.4% of global electricity generation, with a record 320 TWh increase. China led solar PV generation growth, followed by the European Union and the United States. The cost of solar PV modules has significantly decreased, and capacity additions have almost doubled due to low

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equipment prices and policy support. With the global aim of reducing the carbon footprint till 2045 AD, the world Energy trend shift toward to the renewable source, Solar power plant is key in the list (Qutaishat et al., 2016).

Voltage stability is critical for maintaining reliable power system operation, especially in countries like Nepal, where long transmission lines, weak grid infrastructures, and limited reactive power support are common. With the increasing penetration of renewable energy, particularly photovoltaic (PV) systems, there is a growing interest in their role in improving grid voltage profiles and stability. Photovoltaic power, if optimally integrated with proper control strategies and siting, can help manage reactive power flows and reduce stress on transmission systems. This thesis focuses on analyzing and enhancing voltage stability in Nepal Electricity Authority's (NEA) Eastern Transmission Network through the strategic deployment of PV plants. With the aim of shifting from fossil fuel energy to the environmentally friendly solar power plants, needs to synchronization the generated power from solar photovoltaic into the existing transmission grid. Thus, integration of high PV arises the problems in the existing grid like voltage instability, frequency instability, reactive power dip.

Voltage stability is the ability of the power system to maintain the voltage within the range after being disturbance in the system. While high penetration of PV in the system, the reactive power lacks, so the system voltage gets dip down which may collapse down the whole system voltage.

Scenario of Solar Power Plant in Nepal

Nepal's electricity sector is dominated by hydroelectric generation especially during the dry season creates a critical need for complementary renewable sources. However, the Eastern region of Nepal still faces voltage dips, line congestion, and reliability challenges. The national grid is expanding, and NEA is diversification of energy sources. Although Nepal has high solar potential (4.5-5.5 kWh/m2/day), the installed PV capacity is still relatively low. Policy support is increasing, and Independent Power Producers (IPPs) are showing growing interest in solar energy. The Eastern Grid, serving cities like Biratnagar, Dharan, and Itahari, is crucial for both industrial and residential demand. Voltage drops are frequent during peak hours due to long-distance transmission and unbalanced loading.

According to the recent Study from the investment Board Nepal (IBN), the study shows that Nepal has over 300 sunny days annually and solar radiation ranging from 3.6 to 6.2 kWh/m^2/day, Nepal holds immense potential for solar energy development. Recent Nepal Electricity Authority (NEA) had issued a call for a PPA for 800MW of solar power and the state-owned power utility received applications of 3600MW, more than four times (Investment Board Nepal, 2023). This indicates that there is huge potential and private sector are more interested in production of power from the solar plant. However, integrating large-scale PV systems into the national grid introduces technical challenges, particularly in maintaining voltage stability. This is especially relevant in the Eastern transmission network, where load growth and infrastructure limitations make the system more vulnerable to voltage fluctuations. This thesis investigates how optimal PV integration can enhance voltage stability in this region.

Dharel and Maharjan (2021) investigates voltage stability in Nepal's transmission network under high wind power penetration using DigSILENT PowerFactory. It evaluates three 132 kV buses Suichatar, Pokhara, and Middle Marshyangdi with various wind turbine technologies. Pokhara is identified as the weakest bus due to low penetration limits and high voltage sensitivity. Suichatar is deemed the most suitable for wind integration. High wind penetration leads to voltage dips and reduced reactive power support. The study also estimates feasible wind capacities at high-potential INPS locations.

Sultan et al. (2019) proposed a study on Evaluation of the Impact of High Penetration Levels of PV Power Plants on the Capacity, Frequency and Voltage Stability of Egypt's Unified Grid. The study examines the impact of high PV penetration on Egypt's national grid using load-flow analysis and Dig SILENT Power Factory simulations. It assesses grid capacity and required upgrades as PV integration increases. P–V curve results indicate that improved voltage control supports higher PV generation at various nodes. Both static and dynamic voltage stability are evaluated under large-scale PV integration.

Kamil et al. (2019) proposed on Analysis on the voltage stability on transmission network with PV interconnection. The study simulates power-flow conditions with and without PV integration using PSS/E to evaluate transmission-network behavior. Voltage Stability Indices are applied to assess system performance under varying PV output. Increasing PV generation reduces the active-power contribution from conventional generators. However, generators must supply additional reactive power to keep voltages within stable limits. A shortage of reactive power leads to voltage instability and potential system collapse.

Tiwari et al. (2023) proposed on Power System Voltage Stability Evaluation Considering Renewable Energy with Correlated Variabilities. This study assesses voltage stability under renewable integration using IEEE 9-bus and Lumbini's INPS system. A 1.46% power loss occurred at Bus 5, with load margin reaching 1.25×. Sensitivity analysis identified Butwal Grid as most critical. Solar projects showed strong intercorrelation, while wind generation varied by site. PV and QV curves revealed voltage drops under load, but RES penetration improved voltage profiles. High load margins confirmed system reliability.

2. Methodology

The methodology adopted in this study aims to assess how photovoltaic (PV) integration affects the voltage stability of the eastern transmission corridor of the Nepal Integrated Power System (INPS). The approach combines power system modeling, PV penetration analysis, and voltage stability assessment to evaluate improvements achieved through optimal PV placement and sizing.

This study follows a quantitative, case-study approach to investigate voltage stability enhancement in the eastern transmission corridor of the Nepal Integrated Power System (INPS) through the optimal integration of photovoltaic (PV) power plants.

The target population includes the electrical components and operational data of the eastern 132 kV, 220 kV, and 400 kV transmission network. A sample consisting of selected substations and transmission lines within the eastern corridor is chosen using purposive sampling, focusing on buses that are operationally significant or voltage-weak.

Data are collected through secondary technical sources, including Nepal Electricity Authority (NEA) system data, existing load-flow reports, transmission line parameters, transformer ratings, and PV plant specifications. System modeling and analysis are carried out using *DIgSILENT PowerFactory* to perform load-flow analysis, P–V and Q–V curve generation, and voltage stability assessment.

Ethical considerations, such as proper authorization for the use of NEA system data, data confidentiality, and accuracy of reporting, are maintained throughout the study. The limitations of this research include restricted access to complete system data, potential modeling assumptions, and simulation-based results that may not fully represent real-time system behavior.

The eastern Nepal INPS model consists of a 32-bus system comprising 19 transmission lines, 13 transformers, 9 load buses, 4 generators, and 1 diesel power plant. The nominal system frequency is 50 Hz, and the primary voltage level is 400 kV.

2.1 PV Integration

Photovoltaic (PV) integration at transmission-level buses provides local active power injection, which reduces transmission line loading, minimizes power losses, and improves the voltage profile along the transmission corridor. Modern PV inverters are also capable of supplying reactive power support, thereby enhancing voltage stability at voltage-weak buses.

The impact of PV integration on system perfor-

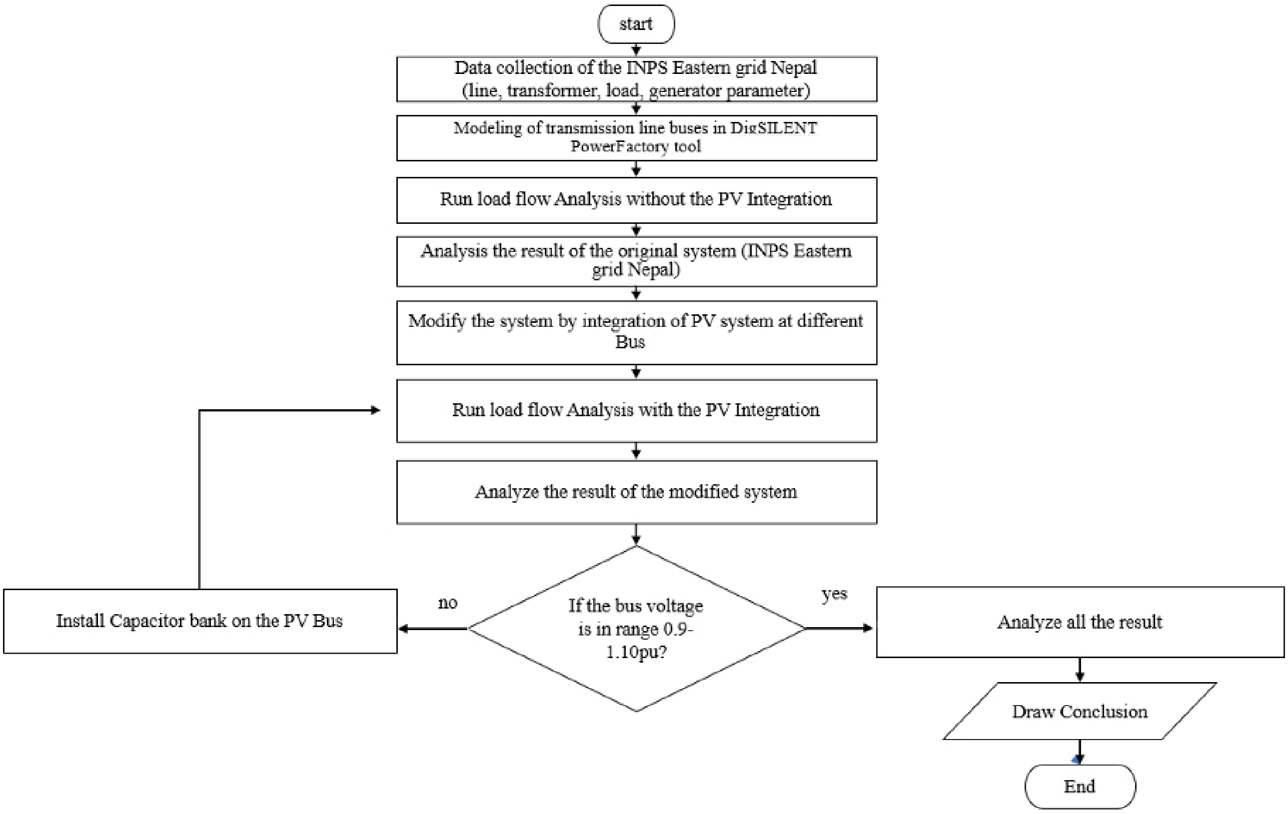

Figure 1: Flow chat of Load flow

mance depends strongly on the placement and sizing of the PV plants. Therefore, load-flow and voltage stability analyses are essential to determine optimal PV integration while ensuring that system operating limits are not violated.

2.2 Placement of PV

Load-flow analysis of the base system without PV integration reveals that three areas exhibit low voltage profiles and high reactive power demand. Based on the voltage profile analysis, optimal PV placement is considered at three different buses within the eastern grid of the Nepal Integrated Power System (INPS). The selected buses are:

- Lahan_132 kV (Bus 04)
- Rupani_132 kV (Bus 05)
- Tingla_132 kV (Bus 18)

These buses are identified as voltage-weak and operationally significant locations, making them suitable candidates for PV integration.

2.3 Load Flow Analysis

The load-flow analysis procedure adopted in this study consists of the following steps:

1. Collect system data, including transmission line parameters, transformer specifications, load profiles, and generator characteristics.
2. Model the transmission network in *DIgSILENT PowerFactory* using the collected data to develop an accurate single-line diagram.
3. Perform an initial load-flow analysis without PV integration to establish the baseline system performance.
4. Analyze the base-case results to identify bus voltage levels, voltage-weak buses, and reactive power requirements.

5. Modify the system model by integrating a PV system at different candidate buses within the transmission network.
6. Perform load-flow analysis with PV integration to assess its impact on voltage stability and overall system performance.
7. Evaluate the modified system results to verify whether bus voltages remain within the acceptable range of 0.9 to 1.0 per unit.
8. If bus voltages are within the acceptable range, analyze all results and draw conclusions regarding optimal PV placement.
9. If bus voltages fall outside the acceptable range, install capacitor banks at the PV-connected buses to provide reactive power support and repeat the load-flow analysis.

3. Results and Discussion

3.1 Bus Voltage and Angle Analysis

The load flow results indicate that buses located near major generation units, such as Bus 01, Bus 06, Bus 09, Bus 10, and Bus 12, maintain voltage magnitudes close to 1.0 p.u., reflecting strong voltage support and stable operation of the transmission network. In contrast, buses situated farther from the generation sources, particularly Bus 03, Bus 04, Bus 18, Bus 19, Bus 24, and Bus 25, exhibit voltage levels below 0.90 p.u., which lies outside the acceptable range for reliable system operation. This condition suggests increased line losses and inadequate reactive power support in those regions.

Furthermore, the voltage angle becomes increasingly negative as power flows toward load-centered areas, illustrating the natural effect of increased power transfer distance within the network. Overall, the voltage profile demonstrates that the system operates in a generally stable manner; however, voltage enhancement measures are required for buses experiencing low voltage levels, particularly in the distribution network.

Table 1: Density per hectare of *Olea europaea* in CFs of Bajura district

Bus	Voltage PU	Voltage angle	Voltage magnitude
Bus 01	1.0000	0.0000	400.0000
Bus 02	0.9132	-6.4543	120.5452
Bus 03	0.8898	-5.9173	117.4551
Bus 04	0.9053	-3.0904	119.5011
Bus 05	0.9687	-3.7461	127.8670
Bus 06	1.0000	-1.4825	132.0000
Bus 07	0.9982	2.1288	131.7675
Bus 08	0.9987	2.2694	131.8231
Bus 09	1.0000	4.8407	132.0000
Bus 10	1.0000	6.9699	132.0000
Bus 11	0.9998	-4.8069	131.9715
Bus 12	1.0000	7.6348	132.0000
Bus 13	0.9882	-1.7685	217.4112
Bus 14	0.9882	-1.7685	217.4112
Bus 15	0.9888	-1.5628	395.5382
Bus 16	0.9882	-1.7685	217.4112
Bus 17	0.9882	-1.7685	217.4112
Bus 18	0.8669	-7.4001	114.4347
Bus 19	0.8497	-8.8936	28.0397
Bus 20	0.9399	-3.2850	124.0705
Bus 21	0.9241	-4.5516	30.4958
Bus 22	0.9241	-4.5516	30.4958
Bus 23	0.9052	-5.4723	29.8718
Bus 24	0.8730	-7.8706	28.8105
Bus 25	0.8730	-7.8706	28.8105
Bus 26	0.8889	-7.2845	29.3322
Bus 27	0.9859	-4.8005	32.5354
Bus 28	0.9859	-4.8088	32.5353
Bus 29	0.9882	-1.7685	217.4112
Bus 30	0.9865	-2.3773	130.2177
Bus 31	0.9956	-0.2853	219.0427
Bus 32	0.9892	-0.7180	130.5703

3.2 Generator Active and Reactive Power Analysis

The generators connected at Bus 09, Bus 10, and Bus 12 operate at high power factors, close to unity, indicating efficient real power delivery with minimal reactive power demand. Conversely, the synchronous generator at Bus 06 supplies a significantly large amount of reactive power (178.48 MVar) while operating at a low power factor of 0.21. This behavior confirms its critical

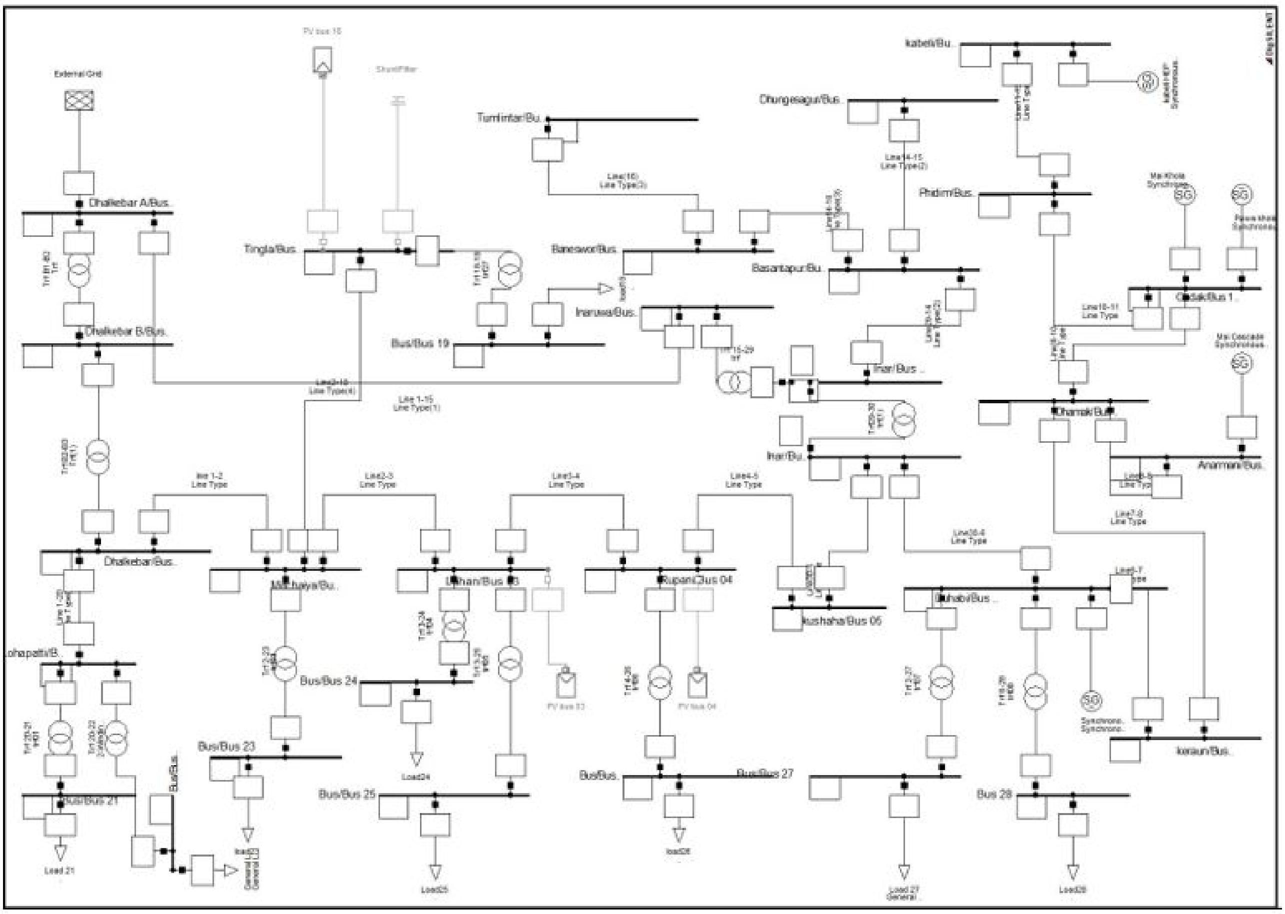

Figure 2: Single line diagram of 32 Bus INPS Eastern Transmission line

role in system voltage regulation but also indicates a substantial reactive power burden, which may lead to increased operational stress on the generator.

Additionally, the distributed hydropower plants contribute moderate levels of both active and reactive power, thereby supporting local voltage stability across the network. These findings emphasize the necessity for supplementary reactive power compensation devices, such as capacitor banks, to alleviate the reactive power demand on the synchronous generator and to enhance voltage profiles at weaker buses.

Based on the load flow analysis, the bus voltages, voltage angles, and generator active and reactive power outputs are summarized in Table 1.

3.3 Generator power output analysis

The generator performance data reveals that the hydropower plants connected at Bus 09, Bus 10, and Bus 12 operate efficiently with high power factors ranging from 0.94 to almost unity. Mai Cascade and Kabeli HEP provide both active and moderate reactive power support, contributing to voltage regulation in their respective areas. Mai Khola and Puwa Khola operate very close to unity power factor, indicating that their primary role is active power generation with negligible reactive intervention.

In contrast, the synchronous machine at Bus 06 supplies a large amount of reactive power, approximately 178.49 MVar, which is significantly higher than other units. This results in a very low power factor (0.21), showing that the machine is heavily utilized for voltage support and reactive power compensation in the network. Such a high

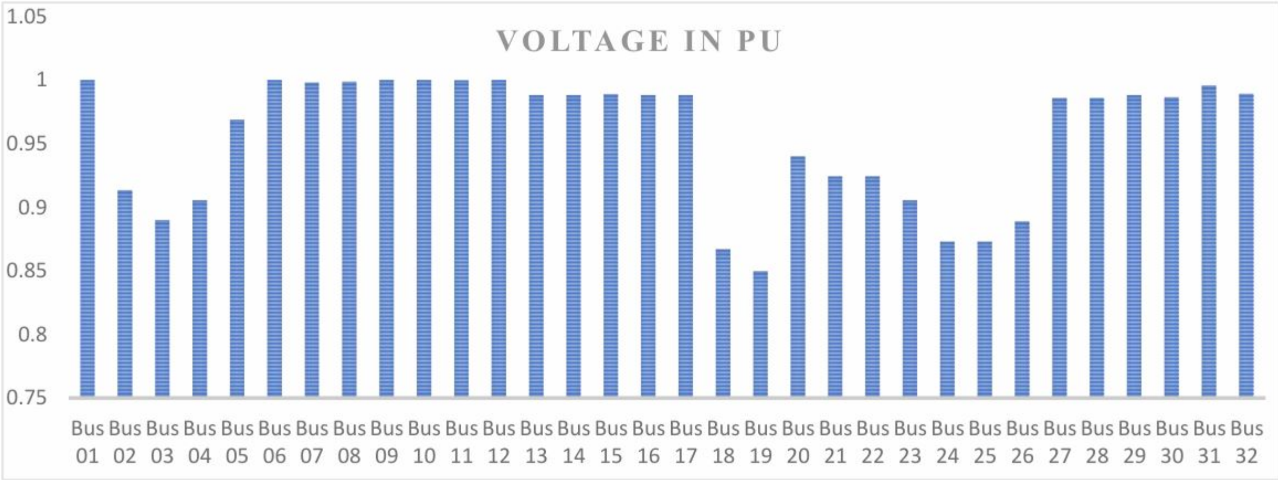

Figure 3: picture 3

reactive loading may lead to increased generator heating and stress on excitation systems if operated continuously under these conditions.

Overall, the results indicate that the distributed hydropower plants provide stable real power generation, while the synchronous machine plays a critical role in maintaining system voltage stability. The system would benefit from improving reactive power support in load-dominated areas — such as installing capacitor banks or synchronous condensers — to reduce the reactive burden on the generator at Bus 06 and enhance the overall voltage profile of the network.

3.4 Integration of PV in INPS Eastern Transmission System

The 32-bus INPS Eastern Grid, with a total load capacity of 361.22 MW and 271.44 MVAr, is considered in this study to investigate the impact of photovoltaic (PV) power penetration on system performance.

Bus 3 (Lahan 132 kV), Bus 4 (Rupani 132 kV), and Bus 18 (Tingla 132 kV) were selected as PV integration points due to their strategic locations within the transmission network and the availability of suitable land areas with high solar irradiation potential. The total PV capacity is distributed such that 50% is installed at Tingla (Bus 18), while 25% is allocated to each of Lahan (Bus 3) and Rupani (Bus 4). This allocation ensures balanced loading conditions and supports the maintenance of voltage stability across the network.

Table 3: Integration Level of PV

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

3.5 Voltage Profile due to 5% Integration of PV System

At the 5% penetration level, the total photovoltaic (PV) integration corresponds to 18.10 MW, which represents 5% of the total system generation capacity of 362 MW. This penetration level is considered the initial and lowest PV addition scenario and is intended to analyze the system behavior under minimum renewable power injection conditions.

At this level, the PV capacity is distributed across three major 132 kV substations as follows:

- Lahan 132 kV (Bus 3): 4.53 MW
- Rupani 132 kV (Bus 4): 4.53 MW
- Tingla 132 kV (Bus 18): 9.05 MW

Table 2: Different generator and their respective power

Generator Terminal	**Bus**	**Active Power (MW)**	**Reactive Power (MVar)**	**Apparent Power (MVA)**	**Power Factor**
Mai Cascade	09	4.20	1.45	4.44	0.95
Mai Khola	10	15.60	0.32	15.60	1.00
Puwa Khola	10	6.20	0.00	6.20	1.00
Synchronous Machine (1)	06	39.00	178.49	182.70	0.21
Kabeli HEP	12	37.00	-5.37	37.39	0.99

Table 4: Bus Voltage Magnitude Without PV and With 5% PV Integration

Bus	Voltage Magnitude without PV	Voltage Magnitude with 5% PV
Bus 01	400	400
Bus 02	120.5452	120.9850
Bus 03	117.4551	117.9322
Bus 04	119.5011	119.9139
Bus 05	127.8670	128.0195
Bus 06	132	132
Bus 07	131.7675	131.7675
Bus 08	131.8231	131.8231
Bus 09	132	132
Bus 10	132	132
Bus 11	131.9715	131.9715
Bus 12	132	132
Bus 13	217.4112	217.5201
Bus 14	217.4112	217.5201
Bus 15	395.5382	395.7324
Bus 16	217.4112	217.5201
Bus 17	217.4112	217.5201
Bus 18	114.4347	115.5129
Bus 19	28.03971	28.31495
Bus 20	124.0705	124.1047
Bus 21	30.49582	30.50452
Bus 22	30.49582	30.50452
Bus 23	29.87178	29.98273
Bus 24	28.81051	28.93217
Bus 25	28.81051	28.93217
Bus 26	29.33215	29.43735
Bus 27	32.53538	32.53538
Bus 28	32.53529	32.53529
Bus 29	217.4112	217.5201
Bus 30	130.2177	130.2856
Bus 31	219.0427	219.0648
Bus 32	130.5703	130.6025

Table 5: Line losses in the system

Loss without PV	Loss with 5% Integration
25MW	20MW
128.28 MV Ar	100 MV Ar

3.6 Voltage Profile due to 10% Integration of PV System

At the 10% penetration level, a total of 36.20 MW of photovoltaic (PV) generation is integrated into the system, which corresponds to 10% of the total system generation capacity of 362 MW. This penetration level represents an increased renewable energy injection scenario to evaluate its impact on the system voltage profile.

The installed PV capacity at this level is allocated to the selected 132 kV buses as follows:

- Lahan 132 kV (Bus 3): 9.05 MW
- Rupani 132 kV (Bus 4): 9.05 MW
- Tingla 132 kV (Bus 18): 18.10 MW

Table 6: Voltage magnitude of different penetration

Bus	Voltage magnitude without PV	Voltage magnitude with 5%	Voltage magnitude with 10%
Bus 01	400	400	400
Bus 02	120.5452	120.9850	121.3556
Bus 03	117.4551	117.9322	118.3482
Bus 04	119.5011	119.9139	120.2787
Bus 05	127.8670	128.0195	128.1534
Bus 06	132	132	132
Bus 07	131.7675	131.7675	131.7675
Bus 08	131.8231	131.8231	131.8231
Bus 09	132	132	132
Bus 10	132	132	132
Bus 11	131.9715	131.9715	131.9715
Bus 12	132	132	132
Bus 13	217.4112	217.5201	217.6179
Bus 14	217.4112	217.5201	217.6179
Bus 15	395.5382	395.7324	395.9083
Bus 16	217.4112	217.5201	217.6179
Bus 17	217.4112	217.5201	217.6179
Bus 18	114.4347	115.5129	116.4307
Bus 19	28.03971	28.31495	28.54918
Bus 20	124.0705	124.1047	124.1306
Bus 21	30.49582	30.50452	30.51112
Bus 22	30.49582	30.50452	30.51112
Bus 23	29.87178	29.98273	30.07621
Bus 24	28.81051	28.93217	29.03827
Bus 25	28.81051	28.93217	29.03827
Bus 26	29.33215	29.43735	29.53029
Bus 27	32.53538	32.53538	32.53538
Bus 28	32.53529	32.53529	32.53529
Bus 29	217.4112	217.5201	217.6179
Bus 30	130.2177	130.2856	130.3451
Bus 31	219.0427	219.0648	219.0816
Bus 32	130.5703	130.6025	130.6269

3.7 Voltage Profile due to 15% Integration of PV System

At the 15% penetration level, the total photovoltaic (PV) integration in the system reaches 54.30 MW, which corresponds to 15% of the total installed generation capacity of 362 MW. This penetration scenario is considered to further evaluate the impact of increased renewable energy penetration on the system voltage profile.

The installed PV capacity at this level is distributed across three major 132 kV buses as follows:

- Lahan 132 kV (Bus 3): 13.58 MW
- Rupani 132 kV (Bus 4): 13.58 MW
- Tingla 132 kV (Bus 18): 27.15 MW

Table 7: Voltage magnitude due 15% penetration of PV

Bus	Bus voltage without PV KV	Bus Voltage with 15% PV (KV)
Bus 01	400	400
Bus 02	120.5452	121.5814
Bus 03	117.4551	118.7466
Bus 04	119.5011	120.6431
Bus 05	127.8670	128.2856
Bus 06	132	132
Bus 07	131.7675	131.7675
Bus 08	131.8231	131.8231
Bus 09	132	132
Bus 10	132	132
Bus 11	131.9715	131.9715
Bus 12	132	132
Bus 13	217.4112	217.7166
Bus 14	217.4112	217.7166
Bus 15	395.5382	396.0873
Bus 16	217.4112	217.7166
Bus 17	217.4112	217.7166
Bus 18	114.4347	116.4963
Bus 19	28.03971	28.56593
Bus 20	124.0705	124.1463
Bus 21	30.49582	30.51512
Bus 22	30.49582	30.51512
Bus 23	29.87178	30.13318
Bus 24	28.81051	29.13983
Bus 25	28.81051	29.13983
Bus 26	29.33215	29.62315
Bus 27	32.53538	32.53538
Bus 28	32.53529	32.53529
Bus 29	217.4112	217.7166
Bus 30	130.2177	130.4034
Bus 31	219.0427	219.0918
Bus 32	130.5703	130.6417

The introduction of 15% PV penetration enhances the voltage profile across the system, especially at the buses where PV power is injected. Tingla (Bus 18) achieves the greatest improvement due to the highest share of PV capacity, demonstrating a significant reduction in voltage drops. Rupani (Bus 4) also exhibits a positive voltage rise, ensuring improved local stability. Meanwhile, buses not directly connected to PV sources experience small but beneficial improvements. Overall, 15% penetration supports better grid voltage regulation without exceeding operational limits.

Picture Damodar 5

Damodar 6 jpg

4. Conclusion

The load flow analysis of the INPS Eastern Transmission System demonstrates that the integration of photovoltaic (PV) generation significantly enhances the voltage profile and reduces system losses.

Voltage Profile Improvement

Without PV integration, several critical buses experience voltages below the acceptable operating range of 0.90–1.10 p.u., including Bus–03 (0.8699 p.u.), Bus–04 (0.8699 p.u.), and Bus–18 (0.8370 p.u.). With the integration of PV generation, the voltage profile improves progressively as the penetration level increases:

- **5% PV penetration:** Slight improvement in voltage magnitude is observed at all buses.
- **10% PV penetration:** Noticeable voltage improvement occurs, with values approaching acceptable operating limits.
- **15% PV penetration:** Significant enhancement is achieved; for instance, Bus–03 rises to 0.9258 p.u., Bus–04 to 0.9253 p.u., and Bus–18 to 0.8789 p.u.

4.1 System Loss Reduction

PV integration also reduces network losses by supplying power locally and decreasing stress on transmission lines:

- **5% PV penetration**: MW loss reduced from 25 to 20, MVAr loss from 128.8 to 100.
- **10% PV penetration**: MW loss reduced to 12, MVAr loss to 76.09.
- **15% PV penetration**: MW loss minimized to 7.087, MVAr loss to 61.09.

The study identifies **15% PV penetration** as the optimal integration level for the INPS Eastern Transmission System. At this level:

- Voltage profiles are significantly improved, bringing most buses closer to the acceptable range (0.90–1.10 pu).
- Both active and reactive power losses are substantially reduced, enhancing system efficiency and reliability.

Thus, integrating PV generation at 15% not only supports voltage regulation but also provides operational and technical benefits by minimizing losses, demonstrating the dual advantage of distributed renewable energy for the transmission network.

4.2 Recommendations

1. **Implement 15% PV Penetration**: Adopt 15% distributed PV integration in the INPS Eastern Transmission System to optimize voltage profiles and reduce system losses.
2. **Monitor Voltage Stability**: Continuously monitor critical buses to ensure voltages remain within the acceptable range (0.90–1.10 pu) under varying load conditions.

Table 8: Different generator and their respective power

Bus	**Voltage without PV in PU**	**5% Integration PV**	**10% Integration**	**15% Integration**
Bus–03 (Lahan)	0.869885	0.871173	0.879401	0.8975
Bus–04 (Rupani)	0.869885	0.8957	0.9258	–
Bus–18 (Tingla)	0.837008	0.857433	0.8789	0.9120

Table 9: Loss reduction due to PV integration

Bus	**Voltage without PV in PU**	**5% Integration PV**	**10% Integration**	**15% Integration**
MW loss	25	20	12	7.087
MVWr loss	128.8	100	76.09	61.09

3. **Reactive Power Support**: Incorporate reactive power control strategies in PV inverters to further improve voltage regulation and enhance system reliability.

4. **Expand PV Integration Studies**: Conduct detailed studies on higher PV penetration levels to evaluate potential benefits and limitations for future expansion.

5. **Dynamic Load Consideration**: Include load variability and seasonal changes in future analyses to ensure the network remains stable under different operating conditions.

6. **Advanced Control Strategies**: Implement intelligent control and coordination of PV systems with the grid to maximize efficiency, minimize losses, and support sustainable operation.

Acknowledgment

Acknowledgements The author gratefully acknowledges the guidance and support of Er. Md Zaid, Er. Sandeep Neupane, and Er. Tejraj Giri during this research, and sincerely thanks family and colleagues for their encouragement.

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