Impact of Solar Photovoltaic Penetration on the Power-Flow Performance of the IEEE 30-Bus Transmission Network

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ABSTRACT

The growing penetration of renewable energy sources, driven by global decarbonization goals, has increased the integration of solar photovoltaic (PV) systems into transmission networks. Although PV generation supports cleaner energy production, high penetration levels introduce variability and alter conventional power-flow patterns. Poorly planned integration may therefore cause voltage deviations, reverse power flow, increased losses, line overloading, and system instability. This study evaluated the impact of solar PV penetration on the power-flow performance of the IEEE 30-bus transmission network. PV was integrated at Bus 8 under unity power factor, 0.95 lagging power factor, and 0.95 leading power factor scenarios. Newton-Raphson load-flow analysis was performed using MATLAB/Simulink and MATPOWER. The results showed that moderate PV penetration improved the minimum bus voltage, reduced active and reactive power losses, and relieved transmission-line loading. However, excessive penetration increased losses, branch loading, and operating-limit violations because of reverse power flow. The best overall performance was achieved at 30% PV penetration, equivalent to 56.76 MW, with 0.95 lagging power factor operation. At this level, the minimum voltage was 0.96788 p.u., maximum branch loading was 86.06%, and no network violations occurred. The study concludes that controlled PV deployment, appropriate siting, and reactive power support are essential for reliable and efficient grid operation.

KEYWORDS

Solar photovoltaic penetration, IEEE 30-bus system, power-flow analysis, voltage profile, transmission-network performance

I. INTRODUCTION

A. Background to the Study

The global energy sector is undergoing a significant transformation as countries seek cleaner and more sustainable alternatives to conventional fossil fuel-based electricity generation. The increasing concerns surrounding climate change, energy security, and environmental degradation have encouraged the adoption of renewable energy technologies, particularly solar photovoltaic (PV) systems. Renewable energy sources are becoming essential components of modern power systems due to their ability to reduce greenhouse gas emissions and support long-term energy sustainability (International Energy Agency [IEA], 2023).

Solar photovoltaic generation has emerged as one of the fastest-growing renewable energy technologies because of its scalability, declining installation costs, and suitability for both small-scale and large-scale electricity generation. The continuous advancement of PV technology has increased its integration into power networks, allowing utilities to diversify generation sources, reduce dependence on fossil fuels, and improve energy security (IRENA, 2023). Unlike conventional power plants that rely on centralized generation, PV systems can be deployed closer to demand centres, potentially reducing transmission losses and improving system efficiency. Despite these benefits, the increasing penetration of solar PV introduces new operational challenges for conventional power systems. Since solar generation depends on weather conditions and solar irradiance, its output is naturally variable and intermittent. These fluctuations can affect the balance between electricity generation and demand, creating difficulties in maintaining stable grid operation (Luo et al., 2021). High levels of PV penetration may also contribute to voltage fluctuations, reverse power flow, changes in generation dispatch patterns, and transmission network congestion. The integration of large amounts of renewable generation requires careful assessment of power system performance to ensure reliability and stability. Power-flow analysis remains one of the most important tools for evaluating the steady-state behaviour of electrical networks. It provides information about bus voltages, power losses, transmission line loading, and overall network operating conditions under different generation scenarios (Kundur et al., 2020). Therefore, evaluating the impact of solar PV penetration on transmission networks is essential for identifying suitable integration levels and developing effective planning strategies.

The IEEE 30-bus transmission network is widely used as a benchmark system for power system studies because it represents a practical medium-sized transmission network suitable for evaluating operational changes caused by renewable energy integration. Investigating PV penetration within this network provides valuable insights into how increasing solar generation affects voltage profiles, power losses, and power-flow performance. This study therefore examines the impact of solar photovoltaic penetration on the power-flow characteristics of the IEEE 30-bus transmission system to support reliable renewable energy integration.

B. Statement of the Problem

The increasing adoption of solar photovoltaic (PV) generation has introduced new operational challenges for conventional power systems. Traditional transmission networks were primarily designed around centralized power generation, where electricity flows in a predictable direction from large generating stations to consumers. However, the growing integration of renewable energy sources is changing these traditional operating patterns and creating new requirements for transmission system planning and management (Blaabjerg et al., 2017).

High PV penetration can significantly influence the steady-state performance of transmission networks by affecting voltage magnitude, reactive power requirements, transmission losses, and power flow direction. Since solar PV generation varies with environmental conditions, sudden changes in output can create voltage instability and operational uncertainties. Additionally, excessive PV integration may result in reverse power flow and increased stress on transmission components if the network is not properly prepared (Adefarati & Bansal, 2016). Although several studies have investigated the effects of renewable energy integration, much of the existing research has concentrated on distribution networks due to their direct connection with distributed generation systems. Comparatively fewer studies have examined the impact of high PV penetration on transmission-level networks, particularly regarding changes in power-flow behaviour, voltage performance, and transmission line utilization. This creates a need for further investigation using standard transmission test systems such as the IEEE 30-bus network.

Therefore, this study addresses the existing research gap by evaluating how different levels of solar PV penetration affect the power-flow performance of the IEEE 30-bus transmission network. The findings will provide useful information for improving renewable energy integration strategies and ensuring reliable operation of future power systems.

C. Aim and Objectives of the study

The main aim of this study is to assess the impact of solar photovoltaic penetration on the power-flow performance of the IEEE 30-bus transmission network. To achieve this aim, the study will pursue the following specific objectives:

- To develop a power-flow model of the IEEE 30-bus transmission network for renewable energy integration analysis.
- To evaluate the base-case operating performance of the network without solar photovoltaic generation.
- To integrate solar photovoltaic generation at selected buses and analyze different levels of PV penetration.
- To examine the effect of increasing solar photovoltaic penetration on bus voltage profiles across the transmission network.
- To assess the changes in active and reactive power losses resulting from different PV penetration scenarios.
- To investigate the influence of solar photovoltaic integration on transmission line and transformer loading conditions.
- To determine the maximum PV penetration level that can be accommodated while maintaining acceptable network operating limits.
- To analyze the effects of PV placement location and power-factor control strategies on overall network performance.
- To recommend suitable strategies for improving solar photovoltaic hosting capacity and maintaining reliable transmission system operation.

II. LITERATURE REVIEW

A. Overview of Solar Photovoltaic Systems

Solar photovoltaic (PV) systems convert sunlight directly into electrical energy through semiconductor materials that generate direct current when exposed to solar radiation. The amount of electricity produced depends mainly on solar irradiance, temperature, and the characteristics of the PV modules (Green et al., 2022). Through power electronic converters, the generated electricity can be converted into a suitable form for connection to the electrical grid. Grid-connected PV systems are increasingly used in modern power networks because they provide clean energy while reducing dependence on conventional fossil fuel generation. PV penetration refers to the proportion of solar generation integrated into an electrical network relative to the total system generation or demand. As penetration levels increase, the influence of PV generation on network operation becomes more significant.

B. Renewable Energy Integration into Power Systems

Renewable energy integration involves incorporating generation sources such as solar and wind energy into existing power networks. Distributed generation allows renewable sources to be located close to consumers, reducing transmission losses and improving energy efficiency. In contrast, centralized renewable generation involves large-scale renewable plants connected directly to transmission networks. The increasing integration of renewable energy requires grid modernization through improved monitoring, advanced control systems, energy storage, and flexible network operation. These developments help address challenges associated with renewable variability and maintain reliable electricity supply (International Energy Agency [IEA], 2023).

C. Power Flow Analysis in Electrical Networks

Power-flow analysis is a fundamental technique used to determine the steady-state operating condition of electrical power systems. It provides important information about bus voltages, power losses, transmission line flows, and system security, making it essential for network planning and operation (Saadat, 2011).

D. Newton-Raphson Method

The Newton-Raphson method is a widely applied numerical technique for solving nonlinear power-flow equations. It determines system voltage magnitudes and phase angles through an iterative process that updates solutions until convergence is achieved. Due to its fast convergence and high accuracy, the method is commonly used for transmission network analysis, including large-scale systems (Grainger & Stevenson, 1994).

E. Impact of PV Penetration on Power Systems

Voltage Profile: Solar PV integration can improve voltage levels by supplying power closer to demand locations and reducing voltage drops. However, excessive PV penetration may cause voltage rise problems, particularly during periods of high solar generation and low demand (Adefarati & Bansal, 2016).

III. MATERIALS AND METHODS

A. Research Design

This study employs a simulation-based methodology to investigate the effect of solar photovoltaic (PV) penetration on the steady-state performance of the IEEE 30-bus transmission network. The analysis is conducted using AC power-flow simulations implemented in MATLAB with the MATPOWER simulation environment. The developed model evaluates the influence of different PV penetration levels and inverter power-factor conditions on voltage stability, power losses, transmission loading, and renewable hosting capacity.

B. IEEE 30-Bus Transmission Network Model

The IEEE 30-bus test system is adopted as the reference transmission network for this study. The system consists of 30 buses, 6 generators, 41 transmission branches, and 21 load points with a base power rating of 100 MVA. The network data are obtained from the MATPOWER case30 model and used as the base system for PV integration analysis.
The nodal power balance equation used in the power-flow analysis is expressed as:

$$P_i = V_i \sum_{j=1}^{n} V_j \left(G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij} \quad , \quad Q_i = V_i \sum_{j=1}^{n} V_j \left(G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij}\right)\right.$$

where:
P_i= active power injection at bus *i*
Q_i = reactive power injection at bus *i*
V_i, V_j= voltage magnitude at buses *i* and *j*
G_{ij} = conductance of the transmission network
B_{ij}= susceptance of the transmission network
θ_{ij} = voltage angle difference between buses *i* and *j*

C. Solar PV Integration Model

A solar PV generator is incorporated into the IEEE 30-bus system by adding a fixed active and reactive power injection at the selected connection bus. The PV location is determined by identifying the bus with the highest active power demand, representing the major load centre of the network. The PV penetration level is defined as:

$PV_{pen}(\%) = \frac{P_{PV}}{P_{Load}} \times 100$ where:

PV_{pen} = PV penetration level %
P_{PV} = active power generated by the PV plant MW
P_{Load} = total base-case system load MW

The PV active power output for each penetration level is calculated as:

$$P_{PV} = \frac{PV_{pen} \times P_{Load}}{100}$$

D. PV Power Factor and Reactive Power Control

The PV system is evaluated under three inverter operating conditions:

1. Unity power factor (PF = 1.0)
2. 0.95 lagging power factor (reactive power injection)
3. 0.95 leading power factor (reactive power absorption)

The reactive power contribution of the PV inverter is calculated using

$Q_{PV} = P_{PV} \tan(cos^{-1}(PF))$ where:

Q_{PV} = PV reactive power output (MVAr)
P_{PV} = PV active power output (MW)
PF = inverter power factor

For unity power factor operation: $Q_{PV} = 0$, For lagging and leading power factor conditions, reactive power is either injected into or absorbed from the network depending on the selected operating mode.

E. AC Power-Flow Solution Method

The Newton-Raphson method is applied to solve the nonlinear power-flow equations. The iterative solution is represented as:

$X^{k+1} = X^k + \Delta X$, where:

X represents the vector of voltage magnitudes and phase angles, and ΔX represents the correction vector obtained from:

$J(X)\Delta X = \Delta S$, where:

J(X) = Jacobian matrix
ΔS = mismatch between calculated and specified power values

The Newton-Raphson method is selected because of its fast convergence and suitability for transmission-level power-flow studies.

F. *Simulation Scenarios*

The simulation process consists of the following cases:

Case 1: Base System
The IEEE 30-bus network is simulated without PV integration to establish the reference operating condition.

Case 2: PV Penetration Analysis
PV generation is introduced at different penetration levels, and the resulting changes in network performance are evaluated.

Case 3: Power Factor Analysis
Each PV penetration level is tested under different inverter power-factor conditions to determine the influence of reactive power control.

Case 4: PV Location Assessment
The selected PV installation bus is compared with neighbouring candidate buses to evaluate the effect of PV placement on system performance.

G. *Performance Evaluation Indicators*

The impact of PV penetration is assessed using the following performance indicators:

Voltage Profile Analysis: The voltage deviation is evaluated by comparing bus voltage magnitudes with acceptable operating limits.

The voltage deviation index is expressed as:

$VD = \sum_{i=1}^{n} \left| V_i - V_{ref} \right|$, where:

V_i= voltage magnitude at bus *i*
V_{ref}= reference voltage 1.0 p.u.

Active and Reactive Power Losses: Transmission losses are calculated from the difference between generated and consumed power.

Active power loss:
$P_{loss} = P_G - P_L$

Reactive power loss:

$Q_{loss} = Q_G - Q_L$, where:

P_G, Q_G= total generated active and reactive power
P_L, Q_L = total load active and reactive power

Transmission Line and Transformer Loading
Branch loading is calculated as:

$$Loading(\%) = \frac{S_{actual}}{S_{rated}} \times 100$$

S_{actual}= apparent power flow through the branch
S_{rated} = rated capacity of the transmission component

A loading value above 100% represents a thermal limit violation.

H. Operating Limit Assessment

The acceptable PV penetration level is determined by checking:

- Bus voltage limits.
- Transmission line thermal limits.
- Reactive power capability limits.
- Power-flow convergence.

A penetration level is considered feasible when:

$V_{min} \leq V_i \leq V_{max}$ and $\text{Loading} \leq 100\%$
The maximum hosting capacity is therefore defined as the highest PV penetration level that satisfies all operating constraints without violations.

I. Data Analysis and Presentation

The simulation results are analysed by comparing the performance of the network before and after solar PV integration. The findings are presented using tables and graphs showing the relationships between PV penetration and minimum bus voltage, active power losses, reactive power losses, maximum transmission loading, voltage profiles, and operating-limit violations. These results are used to evaluate the influence of increasing solar PV penetration on the transmission network and to recommend suitable strategies for improving renewable energy hosting capacity

IV. RESULT DISCUSSION

A. Introduction

This chapter presents the results obtained from the MATLAB/MATPOWER simulation of solar photovoltaic (PV) penetration on the IEEE 30-bus transmission network. The analysis evaluates the impact of PV integration on key power-flow performance parameters, including voltage profile, power losses, transmission loading, operating-limit violations, hosting capacity, PV location, and power-factor control strategies. The IEEE 30-bus system was simulated with PV generation integrated at Bus 8, identified as the major load centre. Three operating strategies were examined: unity power factor (PF = 1.0), 0.95 lagging power factor (reactive power injection), and 0.95 leading power factor (reactive power absorption). The results were used to determine the maximum PV penetration level that can be accommodated while maintaining acceptable network operating conditions.

B. Base-Case Performance of IEEE 30-Bus Transmission Network without PV Integration

The initial performance of the IEEE 30-bus transmission network without solar PV integration is presented in Table 1. The base-case simulation represents the existing operating condition of the network before renewable energy integration.

Table 1: Base-Case Performance of IEEE 30-Bus Transmission Network Without PV Integration

Parameter	**Base Case Value**
PV Penetration Level (%)	0
PV Capacity (MW)	0
PV Location (Bus)	8
Minimum Bus Voltage (p.u.)	0.96062
Active Power Loss (MW)	2.4438
Reactive Power Loss (MVAr)	8.9899
Maximum Branch Loading (%)	108.83
Voltage Violations	0
Thermal Violations	1
Generator P Violations	0
Generator Q Violations	0
Total Violations	1
Power Flow Convergence	Yes

The base-case results indicate that the IEEE 30-bus network operates with a minimum bus voltage of 0.96062 p.u., which is within an acceptable voltage range. However, the system experiences a thermal loading violation, with the maximum branch loading reaching 108.83%. This indicates that although the network power flow converges successfully, some transmission elements are operating beyond their specified thermal limits. The presence of this initial operating constraint highlights the importance of carefully planning renewable energy integration. Properly located PV generation has the potential to reduce power transfer requirements through heavily loaded transmission paths and improve overall network performance.

C. Selection of PV Integration Location

The PV integration location was determined based on the load distribution characteristics of the IEEE 30-bus network. Table 4.2 presents the network demand characteristics and selected PV location.

Table 2: IEEE 30-Bus Network Base Demand Characteristics

Parameter	**Value**
Total Active Power Demand (MW)	189.20
Total Reactive Power Demand (MVAr)	107.20
Major Load Centre	Bus 8

Adjacent Candidate Bus 1	Bus 6
Adjacent Candidate Bus 2	Bus 28
Selected PV Integration Bus	Bus 8
Reason for Selection	Located at/near major load centre

representation from obstetrics and gynaecology, nursing and midwifery, clinical psychology or psychiatry, medical social work, hospital chaplaincy, and, if the facility wishes to include this dimension, a person trusted in the local community. The coordinator's role would be to ensure that ward staff continues to have a Tier 1 training programme, to ensure that offers made in the Tier 2 pathway to specialist services are made and recorded and not assumed, to monitor referrals into Tier 3 specialist services and to be the Tier 4 point of contact for community and faith based partnerships within the facility.

Bus 8 was selected as the PV integration point because it represents the major load centre of the system. Locating distributed generation close to a major demand centre reduces the distance between generation and consumption, thereby reducing transmission stress and improving voltage performance.

The sensitivity analysis of alternative PV locations is presented in Table 3.

Table 3: PV Placement Location Sensitivity Analysis under Unity Power Factor

PV Location (Bus)	**Location Description**	**Maximum Hosting Capacity (%)**	**Minimum Voltage at Maximum Hosting (p.u.)**	**Maximum Loading at Maximum Hosting (%)**		**Assessment**
8	Major load centre	25	0.96661	91.205		Best location
6	Adjacent to major load centre	Not achieved	Not available	Not available		Unsuitable
28	Adjacent to major load centre	20	0.96590	94.660		Acceptable

The results show that Bus 8 provides the highest hosting capacity of 25% under unity power factor operation. Bus 28 achieved a lower hosting capacity of 20%, while Bus 6 could not satisfy the required operating limits. This confirms that PV placement significantly influences network performance, and locating PV generation near major load centres provides better system benefits.

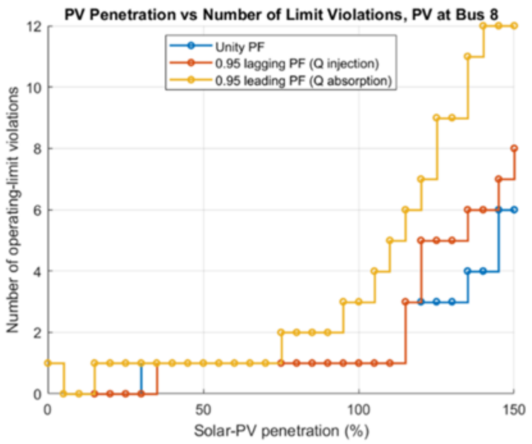
D. Effect of Solar PV Penetration on Network Performance

The impact of increasing PV penetration under unity power factor operation is presented in Table 4.

Table 4: Effect of Solar PV Penetration on Network Performance under Unity Power Factor

PV Penetration (%)	PV Capacity (MW)	Minimum Voltage (p.u.)	Active Loss (MW)	Reactive Loss (MVAr)	Max Branch Loading (%)	Total Violations
0	0	0.96062	2.4438	8.9899	108.83	1
5	9.46	0.96303	2.1628	8.0200	94.43	0
10	18.92	0.96535	1.9600	7.3211	93.56	0
15	28.38	0.96612	1.8342	6.8885	92.73	0
20	37.84	0.96637	1.7841	6.7175	91.95	0
25	47.30	0.96661	1.8084	6.8038	91.21	0
30	56.76	0.96683	1.9061	7.1433	107.76	1
50	94.60	0.96761	3.0110	10.9620	194.73	1
100	189.20	0.96788	10.5070	36.7770	441.32	1
150	283.80	0.96788	24.4030	84.5370	694.96	6

The results demonstrate that increasing PV penetration initially improves the operating condition of the transmission network. Between 5% and 25% PV penetration, the minimum bus voltage gradually increases from 0.96303 p.u. to 0.96661 p.u., while maximum branch loading reduces from 94.43% to 91.21%. The improvement occurs because PV generation supplies part of the local demand, reducing the amount of power transmitted through existing network corridors. Consequently, voltage support improves and transmission congestion is reduced. However, beyond the optimal penetration range, additional PV generation begins to create operational challenges. At 30% penetration, although voltage continues to improve slightly, the maximum branch loading increases to 107.76%, resulting in a network violation. This indicates that excessive PV penetration can introduce reverse power flow and increase stress on transmission components. Figure 1 illustrates the relationship between PV penetration and the number of operating-limit violations. The number of violations remains low at moderate penetration levels but increases significantly when PV penetration exceeds the hosting capacity limit.



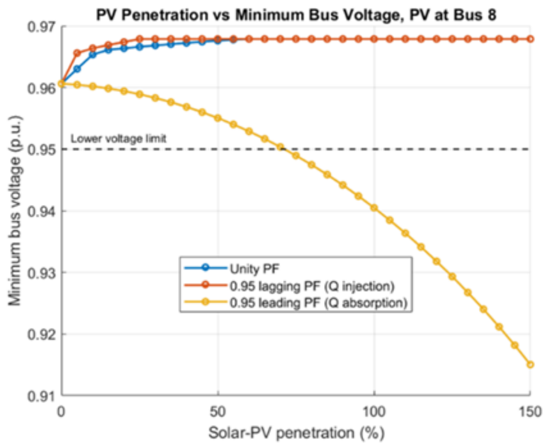


Figure 1: PV Penetration vs number of operating-limit violation
Figure 2: PV Penetration vs minimum bus voltage

E. Impact of PV Penetration on Voltage Profile

The variation of minimum bus voltage with increasing PV penetration is shown in Figure 4.2, while the detailed voltage improvement is presented in Table 4.5.

Table 5: Voltage Profile Improvement with Increasing PV Penetration (Unity PF)

PV Penetration (%)	Minimum Bus Voltage (p.u.)	Voltage Improvement Compared with Base Case (%)
0	0.96062	-
5	0.96303	0.25
10	0.96535	0.49
15	0.96612	0.57
20	0.96637	0.60
25	0.96661	0.62
30	0.96683	0.65
50	0.96761	0.73
100	0.96788	0.76
150	0.96788	0.76

The voltage profile results indicate that PV integration improves voltage conditions throughout the network. The minimum voltage increased from 0.96062 p.u. in the base case to approximately 0.96788 p.u. at higher PV penetration levels. Figure 3 further shows the voltage profile variation across all buses for different PV penetration scenarios. The results indicate that buses located near the load centre experience improved voltage performance as PV penetration increases. Although voltage improvement continues with increasing PV penetration, voltage alone cannot determine hosting capacity because excessive PV generation introduces other constraints such as thermal overload and increased losses.

F. Effect of PV Penetration on Active and Reactive Power Losses

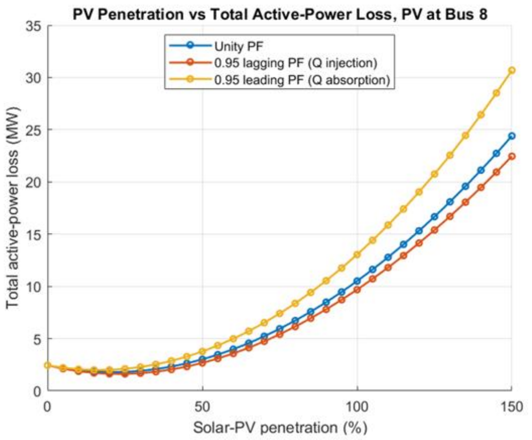
The influence of PV integration on network losses is presented in Table 6 and Figures 3 and 4.

Table 6: Active and Reactive Power Loss Variation under Unity Power Factor

PV Penetration (%)	PV Capacity (MW)	Active Power Loss (MW)	Reduction from Base Case (%)	Reactive Power Loss (MVAr)
0	0	2.4438	-	8.9899
5	9.46	2.1628	11.49	8.0200
10	18.92	1.9600	19.80	7.3211
15	28.38	1.8342	24.94	6.8885
20	37.84	1.7841	27.00	6.7175
25	47.30	1.8084	25.99	6.8038

30	56.76	1.9061	22.00	7.1433
50	94.60	3.0110	-23.21	10.9620

The results show that PV integration reduces both active and reactive power losses at moderate penetration levels. The lowest active power loss occurs at approximately 20% PV penetration, reducing from 2.4438 MW to 1.7841 MW. Similarly, reactive power losses decrease from 8.9899 MVAr in the base case to 6.7175 MVAr at 20% PV penetration. This indicates improved power transfer efficiency due to reduced transmission distance between generation and demand. However, beyond the optimal penetration level, losses begin to increase. At 50% PV penetration, active power loss increases to 3.011 MW. This behaviour is associated with excessive power injection, which causes additional network circulation and higher current flow.



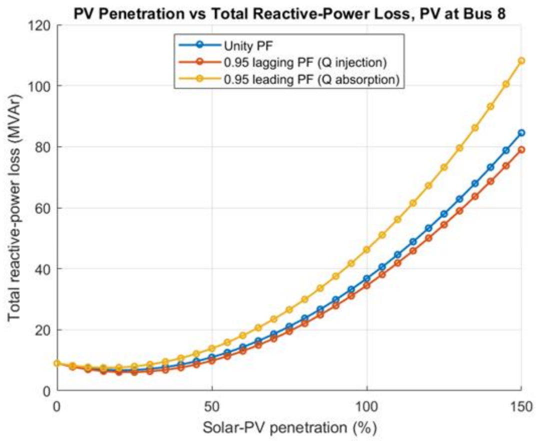


Figure 3: PV Penetration vs active power loss
Figure 4: PV Penetration vs reactive power loss

G. Effect of PV Integration on Transmission Line and Transformer Loading

The effect of PV integration on network loading is presented in Table 7 and Figure 2.

Table 7: PV Hosting Capacity Assessment Based on Network Constraints

PV Penetration (%)	**PV Capacity (MW)**	**Maximum Branch Loading (%)**	**Total Violations**	**Hosting Status**
0	0	108.83	1	Not acceptable
5	9.46	94.43	0	Acceptable
10	18.92	93.56	0	Acceptable
15	28.38	92.73	0	Acceptable
20	37.	91.95	0	Acceptable
25	47.30	91.21	0	Acceptable

30	56.76	107.76	1	Limit exceeded
50	94.60	194.73	1	Not acceptable
100	189.20	441.32	1	Highly overloaded

PV integration reduces transmission loading up to the optimal penetration level. The maximum loading decreases from 108.83% in the base case to 91.21% at 25% penetration. Figure 5 confirms that PV integration reduces loading on several transmission elements. However, excessive PV penetration causes increased loading due to reverse power flow conditions.

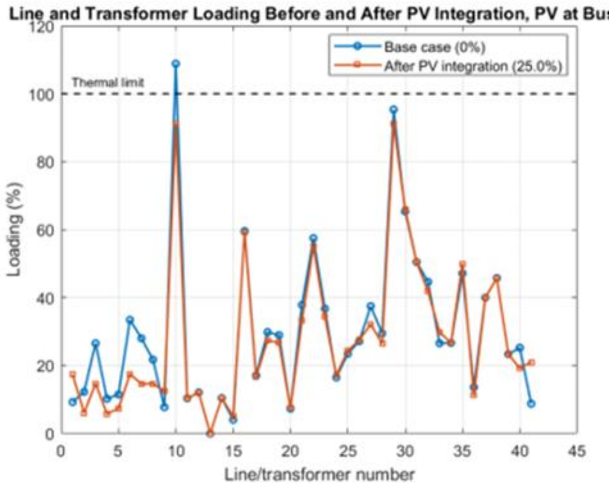


Figure 5: PV Penetration vs minimum bus voltage

H. Influence of Power Factor Control Strategy on PV Hosting Capacity

The hosting capability of different PV control strategies is summarized in Table 8.

Table 4.8: Maximum PV Hosting Capacity under Different Power-Factor Strategies

PV Control Strategy	Power Factor Mode	Maximum Hosting Level (%)	Corresponding PV Capacity (MW)	Hosting Capacity Assessment
Unity PF	PF = 1.0	25	47.30	Acceptable
Lagging PF	0.95 lagging (Q injection)	30	56.76	Highest hosting capability
Leading PF	0.95 leading (Q absorption)	10	18.92	Limited hosting capability

The results demonstrate that reactive power control significantly influences PV hosting capacity. The 0.95 lagging power factor strategy achieved the highest hosting capability of 30%, equivalent to 56.76 MW.

This improvement occurs because reactive power injection provides additional voltage support, allowing higher PV penetration without violating operating limits. Conversely, the leading power factor strategy achieved only 10% hosting capacity because reactive power absorption reduces voltage support and increases operating constraints. Figure 5 shows that leading power factor operation causes voltage reduction as PV penetration increases, confirming the limitation of excessive reactive power absorption.

I. Recommended PV Integration Strategy

Based on the combined analysis of voltage performance, losses, loading conditions, and operating violations, the recommended PV integration strategy is presented in Table 4.16.

Table 9: Recommended PV Integration Strategy

Evaluation Criterion	**Recommended Condition**
PV Installation Bus	Bus 8
Preferred Power Factor Control	0.95 Lagging PF (Reactive Power Injection)
Maximum Recommended PV Penetration	30%
PV Capacity	56.76 MW
Minimum Voltage	0.96788 p.u.
Maximum Branch Loading	86.06%
Active Loss	1.6865 MW
Reactive Loss	6.3328 MVAr
Network Violations	None

The results indicate that integrating PV generation at Bus 8 with reactive power support provides the best overall performance. The optimal configuration improves voltage stability, reduces power losses, lowers transmission loading, and eliminates network violations.

V. CONCLUSION

The study concludes that solar PV integration can improve the power-flow performance of the IEEE 30-bus transmission network when appropriately located and controlled. Moderate PV penetration improved the minimum bus voltage, reduced active and reactive power losses, relieved transmission loading, and eliminated the thermal violation observed in the base case. However, excessive PV penetration increased power losses, branch loading, and operating-limit violations because of reverse power flow and additional network stress.

Among the assessed configurations, PV integration at Bus 8 using a 0.95 lagging power factor produced the best overall performance. This strategy achieved a maximum acceptable penetration of 30%, equivalent to 56.76 MW, with no operating violations, a minimum voltage of 0.96788 p.u., maximum branch loading of 86.06%, active power loss of 1.6865 MW, and reactive power loss of 6.3328 MVAr. The findings therefore confirm that PV hosting capacity depends strongly on installation location, penetration level, and reactive power control strategy.

RECOMMENDATIONS

Solar PV generation should be installed at or near major load centres, with Bus 8 recommended for the studied network. The PV system should operate at 0.95 lagging power factor to provide reactive power support and improve its hosting capacity. Under the investigated conditions, PV penetration should be limited to approximately 30%, or 56.76 MW, unless additional network reinforcement or control measures are introduced.

Network voltage, line loading, losses, and reverse power flow should be continuously monitored as PV penetration increases. Further studies should also examine solar variability, protection coordination, transient stability, energy storage, and alternative PV locations before large-scale practical implementation.

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