EVALUATING VOLTAGE STABILITY AND LOSS MINIMIZATION IN POWER SYSTEMS THROUGH PV INTEGRATION AT THE DISTRIBUTION ENDS: A CASE STUDY OF THE IEEE 9-BUS NETWORK

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Abstract

This project investigates the effects of photovoltaic (PV) integration on voltage stability and power loss minimization within the IEEE 9-bus system. Utilizing MATPOWER version 8.0, the study simulates multiple scenarios, including stressed load conditions and PV integration at various buses. Results indicate that PV systems effectively maintain voltage stability, notably at Bus 8, and reduce system losses when strategically placed, such as at Bus 5. Compared to conventional Static Var Systems (SVS), PV integration offers superior voltage support, although its impact on losses depends on placement and capacity. These findings provide valuable insights for optimizing PV deployment in power systems.

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1. Introduction

The IEEE 9-bus system serves as a standard test network for power system analysis due to its compact size and well-defined parameters. It comprises 9 buses, 3 generators, 3 transformers, and 6 transmission lines, operating at base voltage levels of 13.8 kV, 16.5 kV, 18.45 kV, and 230 kV. The system includes 3 generator buses (PV nodes), 3 load buses (PQ nodes), and 1 slack bus, making it an excellent platform for studying voltage profiles and power losses.

Voltage stability and loss minimization are pivotal for reliable and efficient power system operation. This study aims to:

- Assess voltage support and power losses across various scenarios using MATPOWER simulations.
- Evaluate the impact of PV systems on voltage profiles and losses in the IEEE 9-bus system.
- Compare PV integration with traditional SVS solutions for voltage support.

By integrating PV systems at the distribution ends, this project explores their potential to enhance system performance over conventional reactive power compensation methods.

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2. Methodology

The simulations were performed using MATPOWER version 8.0, a robust tool for power flow analysis. The base case was established using a modified case9_1.m file, adapted to simulate different scenarios. The Newton-Raphson method was employed to solve the power flow equations:

$P_k = \Sigma |Y_{ki} V_i V_k| \cos(\theta_{ki} + \delta_i - \delta_k)$
$Q_k = -\Sigma |Y_{ki} V_i V_k| \sin(\theta_{ki} + \delta_i - \delta_k)$

The following scenarios were analyzed:

1. **Unmodified IEEE 9-Bus System**: Standard system without modifications.
2. **Stressed Load at Bus 8 (Base Case)**: Load increased by 50% to 150 MW and 52.5 MVAr at Bus 8
3. **Stressed Load with SVS**: Added a 0.5 pu shunt compensator at Bus 8.

   Under Stressed Load at Bus 8
4. **PV at Bus 8 (50 MW)**: Integrated a 50 MW PV system at Bus 8.

   Under Stressed Load at Bus 8
5. **PV at Bus 5 (50 MW)**: Integrated a 50 MW PV system at Bus 5.

   Under Stressed Load at Bus 8
6. **PV at Bus 6 (50 MW)**: Integrated a 50 MW PV system at Bus 6.

   Under Stressed Load at Bus 8
7. **Distributed PV**: PV systems distributed across multiple buses.

   Under Stressed Load at Bus 8
8. **High PV at Bus 8 (75 MW)**: 75 MW PV system at Bus 8.

   Under Stressed Load at Bus 8
9. **Low PV at Bus 8 (25 MW)**: 25 MW PV system at Bus 8.

   Under Stressed Load at Bus 8
10. **Stressed Load at Bus 6**: Load increased by 50% to135 MW and 45 MVAr at Bus 6.

    Under with stressed load at bus 8
11. **PV at Bus 8 with High Load**: Load at Bus 8 set to 200 MW and 70 MVAr with 50 MW PV.
12. **Relaxed Voltage Limits**: Voltage limits adjusted to 0.85-1.15 pu .

    under stressed load at Bus 8.

For each scenario, bus voltage magnitudes (in per unit, pu) and total system losses (in MW) were recorded, with a particular focus on Bus 8 as a critical node.

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3. Results and Discussion

The simulation results are summarized below, detailing total system losses and Bus 8 voltage for each scenario:

Case No.	Scenario	Total Losses (MW)	Bus 8 Voltage (pu)
0	Unmodified IEEE 9-Bus Case	4.64	1.000
1	Stressed Load (Bus 8) - Base Case	3.85	0.998
2	Stressed with SVS	3.843	0.998
3	PV at Bus 8 (50 MW)	4.779	1.000
4	PV at Bus 5 (50 MW)	3.375	0.998
5	PV at Bus 6 (50 MW)	3.477	0.995
6	Distributed PV	3.481	1.000
7	High PV at Bus 8 (75 MW)	5.795	1.000
8	Low PV at Bus 8 (25 MW)	4.122	1.000
9	Stressed Load (Bus 6)	5.50	1.012
10	PV at Bus 8 with High Load	3.826	1.000
11	Relaxed Voltage Limits	3.85	0.998

3.1 Unmodified IEEE 9-Bus System

- **Total Losses**: 4.64 MW
- **Bus 8 Voltage**: 1.000 pu
- **Observation**: we use this case only to understand basic behaviour like voltage and losses. however all cases are compared Stressed load at bus 8 (Base case) only for reference

3.2 Stressed Load at Bus 8 (Base Case)

- **Total Losses**: 3.85 MW

- **Bus 8 Voltage**: 0.998 pu

Observation: With increased load, Bus 8 voltage decrease from 1.016 pu 0.998 as compared to unmodified case and losses decrease from 4.64 MW to 3.85 compared to the Unmodified case, "Stressed Load at Bus 8 (Base Case)**"** serving as a reference for subsequent comparisons.

3.3 Stressed Load with SVS

- **Total Losses**: 3.843 MW
- **Bus 8 Voltage**: 0.998 pu
- **Observation**: The 0.5 pu shunt compensator has negligible impact on voltage and losses when compared to Stressed Load at Bus 8 (Base Case) suggesting limited effectiveness.

3.4 PV Integration Scenarios

- **PV at Bus 8 (50 MW)**:
  - **Total Losses**: 4.779 MW
  - **Bus 8 Voltage**: 1.000 pu
  - **Observation**: PV maintains voltage at 1.000 pu but increases losses compared to the stressed load case.
- **PV at Bus 5 (50 MW)**:
  - **Total Losses**: 3.375 MW
  - **Bus 8 Voltage**: 0.998 pu
  - **Observation**: This placement yields the lowest losses (3.375 MW), underscoring the importance of optimal PV siting.
- **PV at Bus 6 (50 MW)**:
  - **Total Losses**: 3.477 MW
  - **Bus 8 Voltage**: 0.995 pu
  - **Observation**: Moderate effects on losses and voltage, less effective than Bus 5 placement.
- **High PV at Bus 8 (75 MW)**:
  - **Total Losses**: 5.795 MW
  - **Bus 8 Voltage**: 1.000 pu
  - **Observation**: Increased PV capacity significantly raises losses while maintaining voltage stability.

- **Low PV at Bus 8 (25 MW)**:
    - **Total Losses**: 4.122 MW
    - **Bus 8 Voltage**: 1.000 pu
    - **Observation**: Reduced PV capacity lowers losses compared to higher capacities but remains above the stressed load case.

3.5 Distributed PV

- **Total Losses**: 3.481 MW
- **Bus 8 Voltage**: 1.000 pu
- **Observation**: Distributed PV ensures balanced voltage support with moderate loss reduction.

3.6 Stressed Load at Bus 6

- **Total Losses**: 5.50 MW
- **Bus 8 Voltage**: 1.012 pu
- **Observation**: Stressing Bus 6 increases losses and slightly elevates Bus 8 voltage, revealing system vulnerabilities.

3.7 PV at Bus 8 with High Load

- **Total Losses**: 3.826 MW
- **Bus 8 Voltage**: 1.000 pu
- **Observation**: Under extreme load (200 MW, 70 MVAr), 50 MW PV at Bus 8 prevents voltage collapse while keeping losses comparable to the stressed load case.

3.8 Relaxed Voltage Limits

- **Total Losses**: 3.85 MW
- **Bus 8 Voltage**: 0.998 pu
- **Observation**: Adjusting voltage limits to 0.85-1.15 pu shows no significant deviation from the stressed load case, indicating operation within tighter constraints.

3.9 Discussion

- **Voltage Stability**: PV integration at Optimal location or distributed location stabilize Bus 8 voltage consistently achieves 1.000 pu, outperforming SVS, which shows minimal effect.
- **Loss Minimization**: PV at Bus 5 minimizes losses (3.375 MW), while high PV at Bus 8 maximizes them (5.795 MW), illustrating a trade-off between voltage support and loss reduction.

- **System Resilience**: PV integration under high load conditions mitigates voltage collapse, acting as a peak-shaving mechanism where net demand is reduced ($P_{net} = P_{load} - P_{PV}$)

These results emphasize the critical role of PV placement in optimizing system performance.

4. Conclusion

This study confirms that PV integration enhances voltage stability in the IEEE 9-bus system, particularly at Bus 8, and reduces losses when optimally positioned, such as at Bus 5. Distributed PV provides balanced voltage regulation across the system. Compared to SVS, PV systems offer superior voltage support, though their impact on losses varies with placement and capacity. Future research could explore optimizing PV sizing and placement or conducting dynamic stability analyses

($dV/dt = f(P, Q, t)$,) to further enhance system understanding.

5. References

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