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Impact of Grid-Scale Solar Photovoltaic Integration on Power System Performance

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ABSTRACT

The impact of SPV integration on grid performance is a topic of ongoing debate, with conflicting reports on its effects. This study employs modal analysis, Newton-Raphson power flow, and time-domain simulations to assess the impact of SPV integration on voltage profiles, active power loss, and system stability in the IEEE 4-machine and Nigerian 50-bus power systems. The findings reveal that SPV integration impacts power systems differently, emphasizing the need for a comprehensive approach considering voltage stability, power losses, and stability constraints. While SPV integration can improve voltage levels and reduce power losses, it may also compromise transient stability, highlighting the importance of careful planning and grid reinforcement. For the IEEE 4-machine system, SPV integration is feasible up to 25% based on power loss, but transient stability constraints limit it to 0%. The Nigerian grid, achieves optimal SPV integration at 10% based on power loss and voltage profile, while transient stability constraints limit integration to 5%. This study underscores the necessity of a multi-metric approach to defining SPV penetration limits, considering the trade-offs between voltage performance, power loss, and system stability.

1. INTRODUCTION

Renewable energy (RE) sources, including solar, wind, and hydro, have the potential to become leading global energy sources, with targets to reduce CO2 emissions by 45% by 2030 and achieve net zero by 2050 [1]–[6]. Despite this potential, countries like Nigeria underutilize RE, especially solar. Advances have made solar energy more affordable, encouraging consideration of main grid integration as photovoltaic (PV) systems expand beyond distribution networks [7]. Optimal Distributed Generation (DG) placement has been shown to reduce technical losses and enhance voltage and power quality [8]–[11].

The effects of large-scale solar photovoltaic (SPV) integration on power system security and reliability remain debated [12]–[16]. Kumar et al. suggest integrating grid-tied SPV with energy storage and MPPT control to enhance stability and cut generation costs [17], while Patnaik et al. advocate for innovative management systems to stabilize the grid and reduce fossil fuel use [18]. Hossain et al. highlight the need for better control strategies for high PV penetration in low-voltage systems [19]. Peprah et al. find that rooftop PV can significantly lower distribution losses while maintaining standard voltage levels [20]. Adewumi et al. note that integrating Energy Storage Systems (ESSs) can improve voltage compliance with grid codes [21], while Sanni et al. point to grid weaknesses when integrating inverter-based generation in Nigeria [22].

Saidi [23] and Ugwuanyi et al. [24] recommend using STATCOM-based strategies to address voltage stability in high-PV systems. Although SPV has been linked to improvements in transient and voltage stability [25][26], studies primarily focus on small-signal analysis, leaving the broader impacts on stability uncertain. Varying reports on RE impacts arise from different case studies and inappropriate integration, with most

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research centering on losses and voltage profiles rather than assessing rotor angle stability [27]–[32]. SPV integration can change power system dynamics, potentially interacting with existing oscillatory modes and affecting overall stability, which might necessitate limiting SPV penetration [33].

In Nigeria, while various studies have explored solar-grid integration [34]–[40]. There is limited focus on the technical implications for grid performance. This paper evaluates the effects of large-scale SPV on voltage profiles, power loss, and both small- and large-signal stability in the Nigerian grid. Our work provides a comprehensive analysis typical of developing power systems, considering the nation's energy challenges and increasing investments in SPV. Key contributions of this research include:

- **Holistic Evaluation Framework:** This study evaluates voltage profiles, power losses, and both small- and large-signal stability simultaneously, providing a holistic analysis of solar photovoltaic (SPV) integration. This approach contrasts with previous studies that focused on isolated metrics.
- **Clarity on Penetration Limits**: The research defines the penetration limits of SPVs by examining various trade-offs among multiple parameters (voltage, power, and losses). This analysis reveals how these limits can vary depending on the parameter considered.
- **Context-Specific Insights**: This study offers the first detailed examination of SPV impacts on the stability and performance of Nigeria's grid. It addresses practical challenges often overlooked in earlier studies, primarily focusing on technical losses or voltage profiles.

The paper is structured as follows: Section 2 provides theoretical background on SPV integration and an overview of the studied cases, Section 3 presents the results and discussion, and Section 4 concludes with suggestions for future research.

2. METHOD

2.1. Solar-grid integration

Figure 1 illustrates SPV connected to the grid via two-stage converters, DC-DC and DC-AC. Two main models are used in load flow studies: PQ-controlled and PV-controlled. The choice of model depends on the designer's objectives. This work uses the PV-controlled mode, which allows voltage regulation.

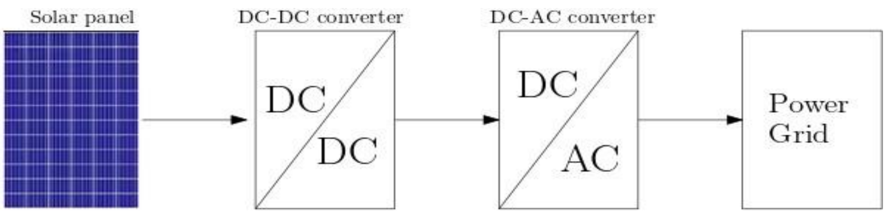

Figure 1. Schematic diagram of SPV connected to the grid

2.2. Small-signal stability

For simplicity, this section focuses on the dynamics of a PV array under a constant power load, neglecting resistive losses. The simplified equivalent circuit, illustrating this configuration, is presented in Figure 2.

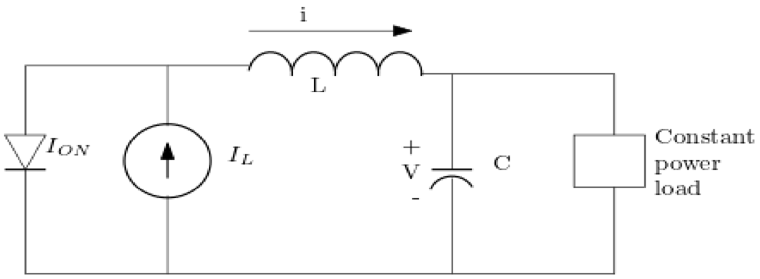

Figure 2. Simplified PV array with output elements

Kirchhoff's laws at both nodes yield

$$I_L \quad - I_s\left\{exp\left[\alpha\left(v + L\frac{di}{dt}\right)\right] - 1\right\} - i = 0, \tag{1}$$

.

$$i - C\frac{dv}{dt} - \frac{p}{v} = 0 \tag{2}$$

where I_s is the saturation current of the diode and p is the constant power load.

Therefore, the dynamics of the systems are given by

$$\frac{di}{dt} = \frac{1}{L}\left[\frac{1}{\alpha} ln\left(\frac{I_L - i}{I_s} + 1\right) - v\right] \tag{3}$$

$$\frac{dv}{dt} = \frac{1}{C}\left[i - \frac{p}{v}\right] \tag{4}$$

Where thermal diffusion, α = q/nskT, k = 1.3807 x 10^{-23} JK^{-1} is Boltzmann's constant, q = 1.6022 x 10^{-19} C is the electronic charge, T = 298K is the temperature, n = electron density, and s = surface recombination velocity.

The differential equation can model power system dynamics:

$$\dot{x} = f(x, u), \tag{5}$$

where x is a vector of state variables in Eq. 3 and Eq. 4 together with other state variables in the system, while u is a vector of input variables. The linearization of Eq. 5 gives

$$\Delta\dot{x} = A\Delta x + B\Delta u. \tag{6}$$

The eigenvalues can be complex, real, or zero. For complex eigenvalues, it appears in the complex conjugate pair. A system is said to be stable in all operations if all the eigenvalues $\lambda = \sigma \pm j\omega$ of A are at the left plane. The eigenvalues in power systems are usually referred to as oscillation modes. Therefore, the damping ratio, time constant, and the frequency are given as $\varsigma = \frac{-\sigma}{\sqrt{\sigma^2+\omega^2}}$, $f = \frac{\omega}{2\pi}$, where ς is the damping ratio, f is the frequency, ω is the angular frequency. In this paper, 5% and above are considered sufficient damping.

2.3. Definition of solar photovoltaic penetration

This study defines penetration as the proportion of SPV generation in the total active power generation. As the SPV share increases, the generation from conventional generators decreases.

$$\text{Penetration (\%)} = \frac{P_{\text{spv}}}{P_{\text{spv}} + P_g} \times 100 \tag{7}$$

Here, P_{spv} represents the active power generation from SPV, and P_g denotes the combined generation from all synchronous generators in the system. The generation of individual conventional generators is adjusted based on their respective capacities.

2.4. The IEEE 4-Machine power system

The IEEE 4-Machine system is a widely recognized benchmark for investigating inter-area oscillations in power systems [41]–[44]. It comprises two areas, four generators (two in each region), and eleven transmission lines. Figure 3 is the single-line diagram of the power system. The total connected load on the system is 2,734 MW, with generators equipped with Automatic Voltage Regulators (AVR).

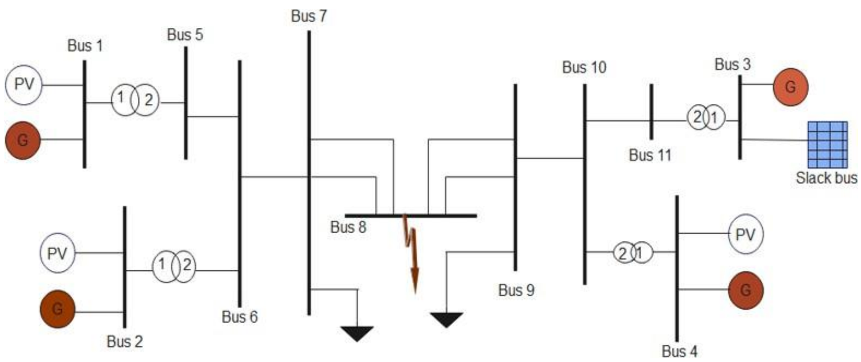

Figure 3. Single-line diagram of the IEEE 4-machine system

The system's configuration facilitates the study of inter-area oscillations by initiating a disturbance at the central bus (i.e., Bus 8). Its relatively compact size enables convenient testing and comparison of various scenarios. The analytical insights from studying this system can be extrapolated to larger grids, such as the Nigeria 50-bus power system, which will be elaborated on subsequently.

2.5. Nigerian 50-bus power system

Figure 4 is the single-line diagram of Nigeria's 50-bus, 330kV power system as of 2022. It includes 14 generators, three hydro-powered (Kainji, Shiroro, and Jebba) in the north and gas-fired generators in the south. This study assumes a practical load demand of 4,300 MW, using modeling data from [45].

2.6. Case studies

Case 1 represents the system without SPV, serving as the base case for comparison. Case 2 includes SPV, which will be compared to the base case across various penetration levels. Simulations were conducted using PSAT® software, considering the SPV's reactive power limit per the guidelines in [46].

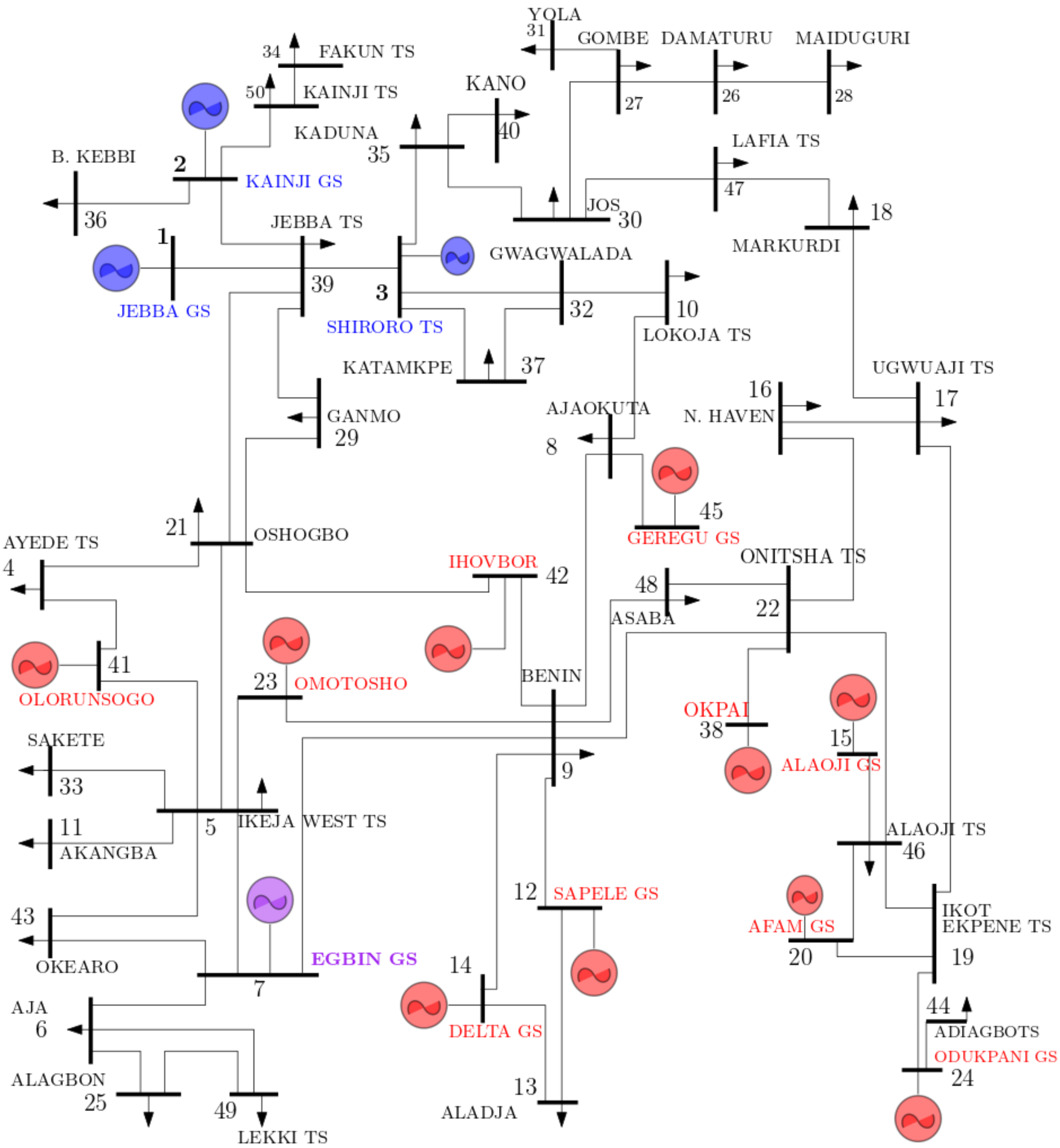

Figure 4. Single-line diagram of the Nigerian 50-bus power system [32]

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3. RESULTS AND DISCUSSION

3.1. Analysis of the IEEE 4-Machine Power System

We integrated SPV at Bus 9 and conducted load flow analysis to evaluate active power loss and voltage profile, followed by small-signal analysis focusing on damping ratios of oscillatory modes, especially inter-area oscillations. Three-phase faults were simulated at buses 8 and 11 to trigger inter-area and local oscillations and assess critical clearing time. The SPV share was varied according to Eq. 7, and the analysis was repeated for each penetration level. In the base case small-signal analysis, three slow electromechanical modes were identified with frequencies of 0.98 Hz, 0.95 Hz, and 0.48 Hz, with Mode 1, an inter-area mode, exhibiting poor damping (1.87%).

Figures 5a–5d illustrate the effects of increasing SPV share on power loss, voltage profile, small-signal stability, and large-signal stability of the IEEE 4-machine system. As SPV penetration increases, active power loss decreases, as shown by the negative gradient in the power loss curve (Figure 5a). The voltage profile (Figure 5b) indicates that bus 8, with a 0.95V, meets the ±5% tolerance. However, voltage profiles for all buses improve with higher SPV shares, suggesting enhanced voltage stability. This indicates the system can accommodate up to 25% SPV as active power loss and voltage profile improve.

The damping ratio shown in Figure 5c improves with higher SPV share, indicating enhanced small-signal stability, though this analysis only provides a steady-state assessment. Figure 5d shows a decreased critical clearing time (CCT) with higher SPV shares, suggesting reduced transient stability. These results indicate that the system cannot sustain SPV integration without compromising generator angle stability. The system had both AVR and PSS, and all eigenvalues were negative. Instability likely arose from interactions between SPV and conventional generators under stress, as modal interactions can destabilize power systems.

These findings emphasize the need for a holistic approach to determining SPV integration levels. While robust control design could facilitate significant penetration, this is beyond the scope of this paper.

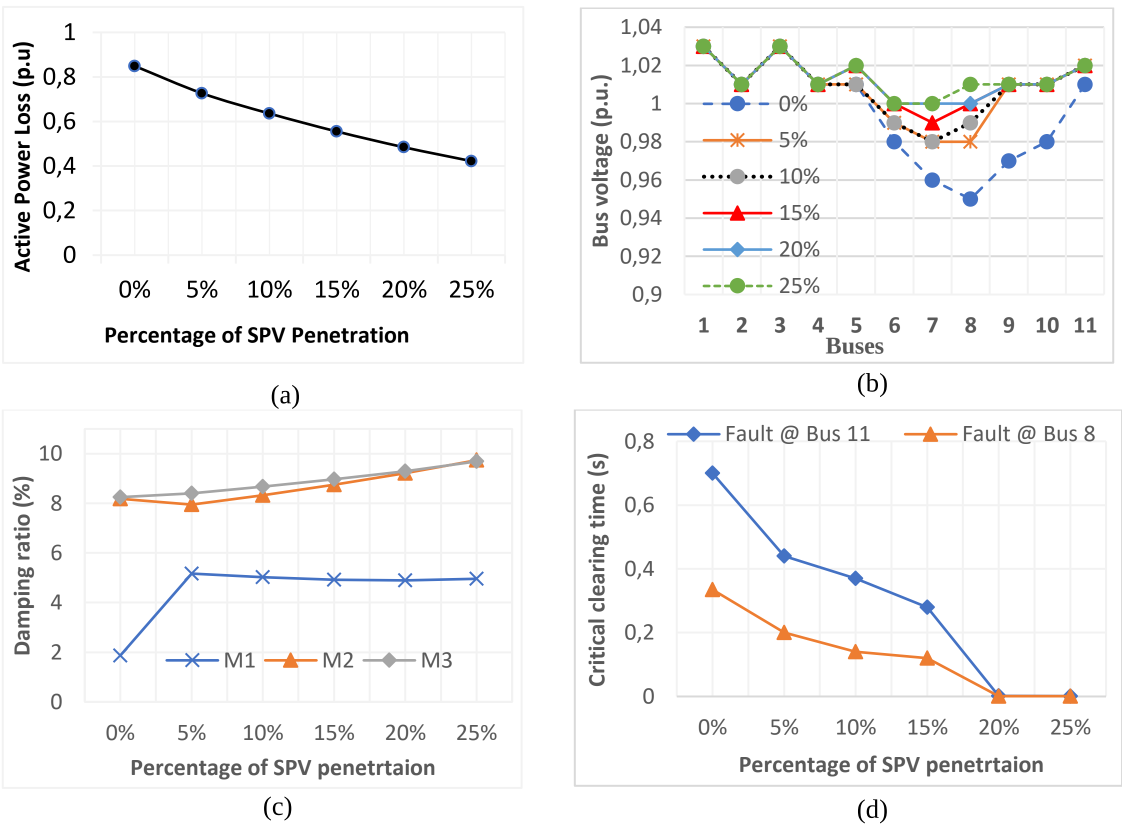

Figure 5. Large-scale SPV improves (a) active power loss, (b) voltage profile, (c) small-signal stability, but worsens (d) enormous signal stability

3.2. Analysis of Nigeria's 50-bus power system

Figures 6b–6d illustrate the effects of grid-scale SPV on active power loss, voltage profile, and both small- and large-signal stability. Seven buses in northern Nigeria violated the ±5% voltage tolerance; however, the region is suitable for solar farms due to high solar irradiation. Testing revealed that Damaturu exhibited the most excellent angle stability. Thus, SPV was installed at Damaturu. Two faults were sequentially introduced at Osogbo and Kainji buses, based on prior research identifying significant nonlinear modal interactions at these locations. Figure 6a shows that active power loss is at least at 10% SPV integration, indicating a penetration limit (optimal penetration).

Figure 6b demonstrates improved voltage profiles with SPV integration, yet some buses did not meet tolerance requirements. Specifically, the voltage levels of Damaturu, Gombe, Maiduguri, Jos, Yola, B/Kebbi, and Kano improved significantly at 10% SPV integration. Figure 6c shows stable damping ratios for three modes as SPV share increases, focusing on modes with the lowest damping. Figure 6d indicates that critical clearing times for faults increase at 5% penetration before declining, suggesting that SPV integration beyond this level risks grid destabilization.

The RE converter (power converter) synchronizes output voltage and frequency with the grid, protects against overvoltage and overcurrent to ensure system safety, and enables secure disconnection during outages or maintenance. Typically, RE converter protection systems disconnect the converter during significant faults, particularly those near the converter. Our tests simulated fault clearance under less stressed conditions, allowing the SPV to remain connected. The rotor angle dynamics for Generator 2 of the IEEE 4-machine system and the Kainji generator with a 10% SPV share (see Figures 7a and 7b) show reduced stability with 10% integration, revealing that oscillations are more effectively dampened without SPV.

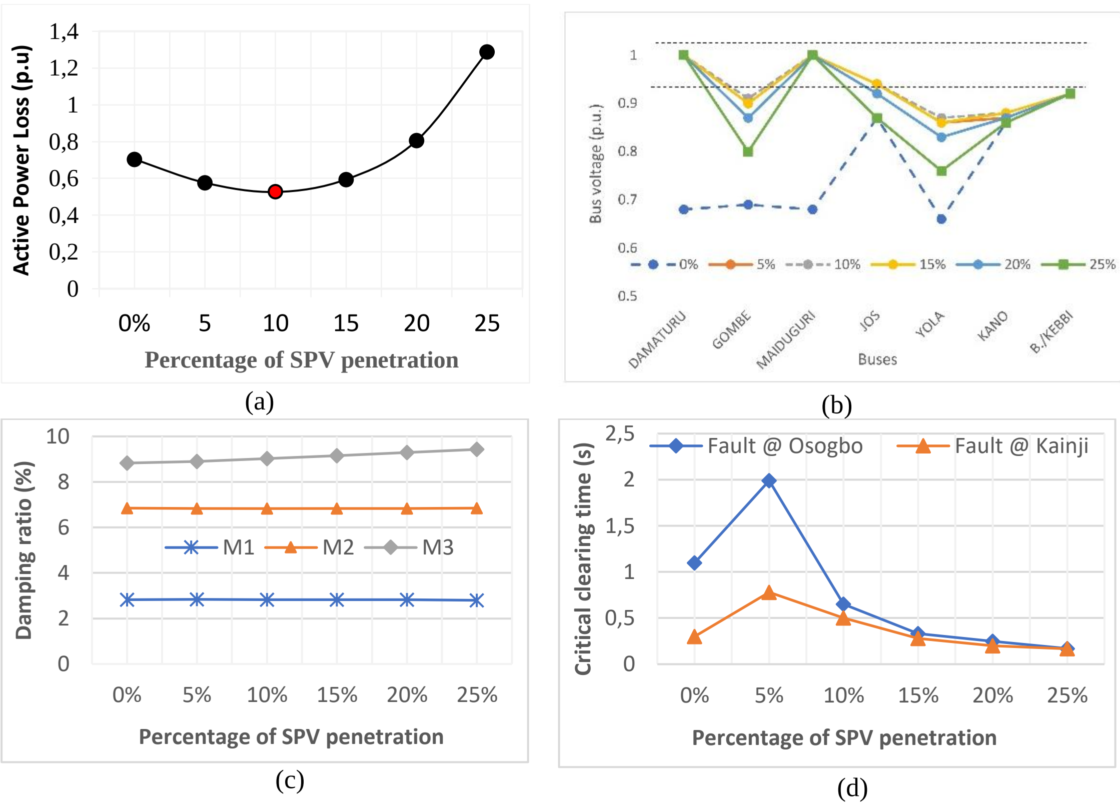

Figure 6. Large-scale SPV improves (a) active power loss, (b) voltage profile, (c) small-signal stability, but worsens (d) large signal stability

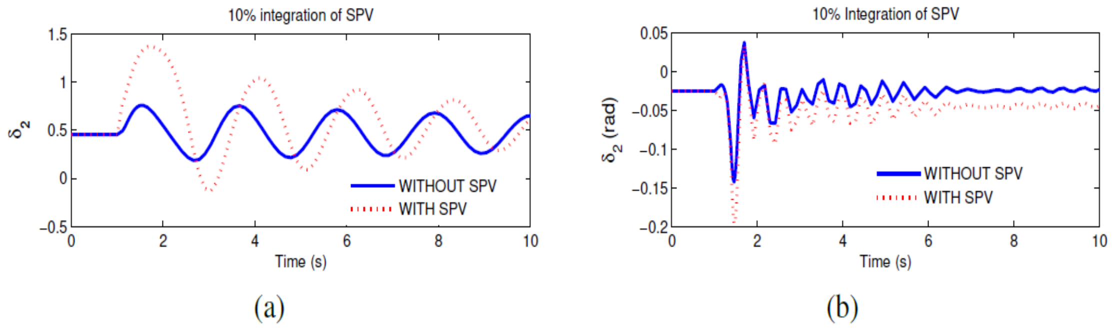

Figure 7: Impact of 10% SPV on Rotor Angle Stability - (a) Generator 2 in IEEE 4-Machine System and (b) Kainji Generator in Nigerian Grid Following Minor Fault.

3.3. Discussions

From our study, we analyzed that the current grid infrastructure may not be capable of supporting such integration levels, indicating the need for a more comprehensive approach. While both systems exhibited improvements in power loss reduction and voltage profile, the IEEE 4-machine system consistently benefited up to 25% SPV integration, whereas the Nigerian grid showed notable gains only up to 10%. These results underscore the context-dependent impacts of SPV, where benefits are achievable if stability issues are addressed.

Despite favorable small-signal analysis, transient stability challenges remain, as SPV integration may weaken the grid's ability to handle significant faults, necessitating careful trade-offs. Identifying vulnerable grid areas based on SPV placement can guide testing. While large-scale SPV is feasible, some networks like Nigeria's require infrastructure upgrades and advanced control systems for successful renewable energy integration.

The analyses presented are summarized in Table 1, highlighting the necessary trade-offs in defining the penetration level of solar photovoltaic (SPV) systems by evaluating system limits based on various metrics. Figures 5 and 6 show that the IEEE 4-machine system can accommodate over 25% SPV integration when assessed based on power loss criteria (see Table 1, column 2). However, it cannot support SPV integration when evaluated against transient stability criteria (see Table 1, column 3). The best voltage profile is notably observed at a 20% SPV penetration level. Although it may be more economical to accept higher power losses, the consequences of instability are far more significant, suggesting that the optimal trade-off is 0% SPV integration.

Table 1: SPV Penetration Limits by Various Metrics

System	Limit by power loss	Limit by stability	Limit by voltage profile	Trade-off Limit
IEEE 4-machine Power System	> 25 %	0 %	20%	0 %
Nigerian 50-Bus 330 kV Power System	10%	5%	10%	5%

Similarly, the optimum penetration level for the Nigerian grid is 10% based on power loss and the voltage profile. However, transient stability constraints limit the optimal penetration to 5%. A reasonable trade-off would involve restricting SPV integration to 5% to maintain system stability. This multi-metric approach to defining penetration limits contrasts with much of the existing literature, which often considers only power loss as the primary metric.

This analysis also highlights that the impact of SPV on grid performance must be evaluated on a case-by-case basis, as results can vary significantly across different systems. It is important to note that the systems studied here can be reconfigured through robust control strategies, grid strengthening, improved planning, and other interventions—factors not addressed in this work. The key conclusion is the importance of adopting a multi-metric approach to define SPV penetration limits, ensuring a comprehensive assessment of overall system performance.

4. CONCLUSION AND LIMITATION

This paper investigates integrating grid-scale solar photovoltaic (SPV) energy into power systems, focusing on the IEEE 4-machine and Nigerian 50-bus networks. Key findings are: i) SPV-conventional generator interactions can destabilize the grid; ii) Optimal SPV penetration varies by system, with the current Nigerian grid struggling to support significant SPV without performance issues; iii) While SPV injection improves voltage and reduces losses, it does not always enhance transient stability, requiring trade-offs; iv) Strengthening grid infrastructure and control is crucial, especially in developing countries.

Future research should consider the stochastic nature of solar irradiation and explore alternative SPV control methods beyond PSAT software for better integration.

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