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STEADY-STATE ANALYSIS OF NIGERIA 330 KV POWER NETWORK UNDER STATCOM AND SOLAR PV SUPPORT

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Abstract: **Nigeria's 330 kV transmission grid still grapples with operational issues like voltage instability and high transmission losses quite frequently nowadays. Integrating Static Synchronous Compensator and solar photovoltaic systems profoundly affects steady-state conditions on weak buses within Nigeria's 48-bus grid infrastructure. Simulations were run with MATLAB and Power System Analysis Toolbox under four distinct scenarios namely base case, STATCOM only, PV only, and combined STATCOM with PV. Results show combined deployment drastically improved bus voltages at Birnin Kebbi Akangba Lekki Aladja and Alaoji from as low as 0.89 pu. Line loading at weak buses decreased substantially from over 90 percent below 75 percent and available transfer capability rose sharply by nearly 29 percent. Total system power loss decreased substantially from 42.5 MW under base case conditions and settled at 28.6 MW with combined support. Hybrid STATCOM and solar PV integration remarkably bolsters voltage stability and system efficiency within Nigeria's transmission grid quite effectively.**

Keywords: **Available transfer capability, Nigeria transmission grid, solar photovoltaic, STATCOM, voltage stability.**

I. INTRODUCTION

Nigeria's electricity transmission network is dealing with some tough issues that make it hard to meet the rising energy demand [1, 2]. Even though there's a good amount of power generation capacity in the country, the actual electricity reaching consumers is still way below what's needed. This is mainly because of ongoing transmission problems, voltage issues, and the aged infrastructure not being used efficiently [3 – 5]. The 330 kV transmission grid, which is essential for moving power across the six geopolitical zones, often gets overloaded, especially during peak times [6, 7]. This results in frequent power outages, long stretches of low voltage, and unreliable supply for consumers [8]. To tackle these challenges, players in Nigeria's power sector are looking more towards new technology for support [9, 10]. One promising technology is the Static Synchronous Compensator (STATCOM), which helps manage reactive power quickly [11], improves voltage levels, and boosts how the system can be controlled without needing to expand capacity the traditional way [12 – 14]. Around the world, these devices are used to manage both temporary and steady problems with the power system, making them a good fit for Nigeria's needs [15 – 19]. Nigeria has a lot of potential when it comes to solar energy. With so much sunshine every day, setting up solar power systems could really help ease some of the transmission problems and create local energy sources [20 – 24]. These solar systems are not just about clean energy; they also help with voltage levels, reduce energy losses during transmission, and improve the system overall, especially in rural areas where the grid isn't as reliable [25 – 28].

While studies have looked at how STATCOM and solar PV systems work on their own in Nigeria, there hasn't been much research on how they perform together in the same simulation. Most existing studies focus on how to best place and size these systems but don't dive into direct evaluations of their performance. This study is set to address that gap. It will analyze the Nigerian transmission system to see how it behaves under different scenarios which are STATCOM alone, solar PV alone, and their combined application. The analysis will make use of the Power System Analysis Toolbox in MATLAB, looking specifically at five buses that have been identified as weak points due to voltage issues and sensitivity to load changes. The goal is to provide practical insights into how combining STATCOM with solar PV can boost Nigeria's ability to transfer power, keep bus voltages stable, and help the country push forward with its renewable energy goals.

There has been a growing interest in making power systems more flexible and reliable, especially with the rise of devices like FACTS and the push for renewable energy [29, 30]. One standout in this area is the Static Synchronous Compensator (STATCOM), which has become a go-to solution for things like voltage control and system stability. Lots of studies show its effectiveness in both steady and changing situations, especially in weak or heavily used transmission networks. According to [31], STATCOM can quickly respond to voltage changes, greatly boosting voltage stability in long transmission lines. It can add or reduce reactive power on the fly, helping to keep voltage levels steady at key points, even when loads change. In Nigeria, [32] found that placing STATCOMs at busy load points cuts down on voltage drops and helps move power more efficiently during peak times. At the same time, the global move towards renewable energy is driving research into how solar PV can be integrated into medium and high-voltage networks. These grid-tied solar systems, especially in developing nations, can help take pressure off main power stations and ease transmission issues if they're placed right. [33] showed that decentralized PV setups near load centers in Nigeria's North-Central and North-East regions can boost voltage levels and cut power losses from long transmission lines. But most studies in Nigeria so far have looked at either STATCOM or solar PV on their own. For example, Mohammed and [34] as well as [35, 36] focused on how solar PV affects power losses and voltage in part of the Nigerian grid, without looking at how it interacts with FACTS devices. Conversely, [37] examined STATCOMs in Nigeria's 330 kV grid using the IEEE 30-bus model, focusing on reactive power but not factoring in renewables. On a global scale, combining STATCOM and solar PV is seen as a strong strategy for making grids more flexible and resilient. Research by [38] in India showed that using both together helped stabilize voltage and supported higher power transfers during peak times, indicating this could work well for Nigeria too.

Despite these advancements elsewhere, there's a need for steady-state simulation studies that reflect Nigeria's actual 48-bus, 330 kV transmission network. Much of the existing research relies on simplified models or focuses on dynamic approaches. Plus, very few studies have looked at the combined effect of STATCOMs and solar PV on practical grid performance. This study aims to close that gap by analyzing how they work together in real-world conditions, focusing on voltage levels, line loading, transfer capability, and system losses.

II. METHODOLOGY

This study evaluates the steady-state performance of Nigeria's 330 kV transmission grid under the influence of STATCOM and solar PV integration using the Power System Analysis Toolbox (PSAT) in MATLAB. The analysis focuses on five strategically chosen buses known to experience voltage dips or congestion under normal and high-demand operating conditions. These buses include Birnin Kebbi (Bus 3), Akangba (Bus 16), Lekki (Bus 23), Aladja (Bus 27), and Alaoji (Bus 31) as shown in Figure 1 model.

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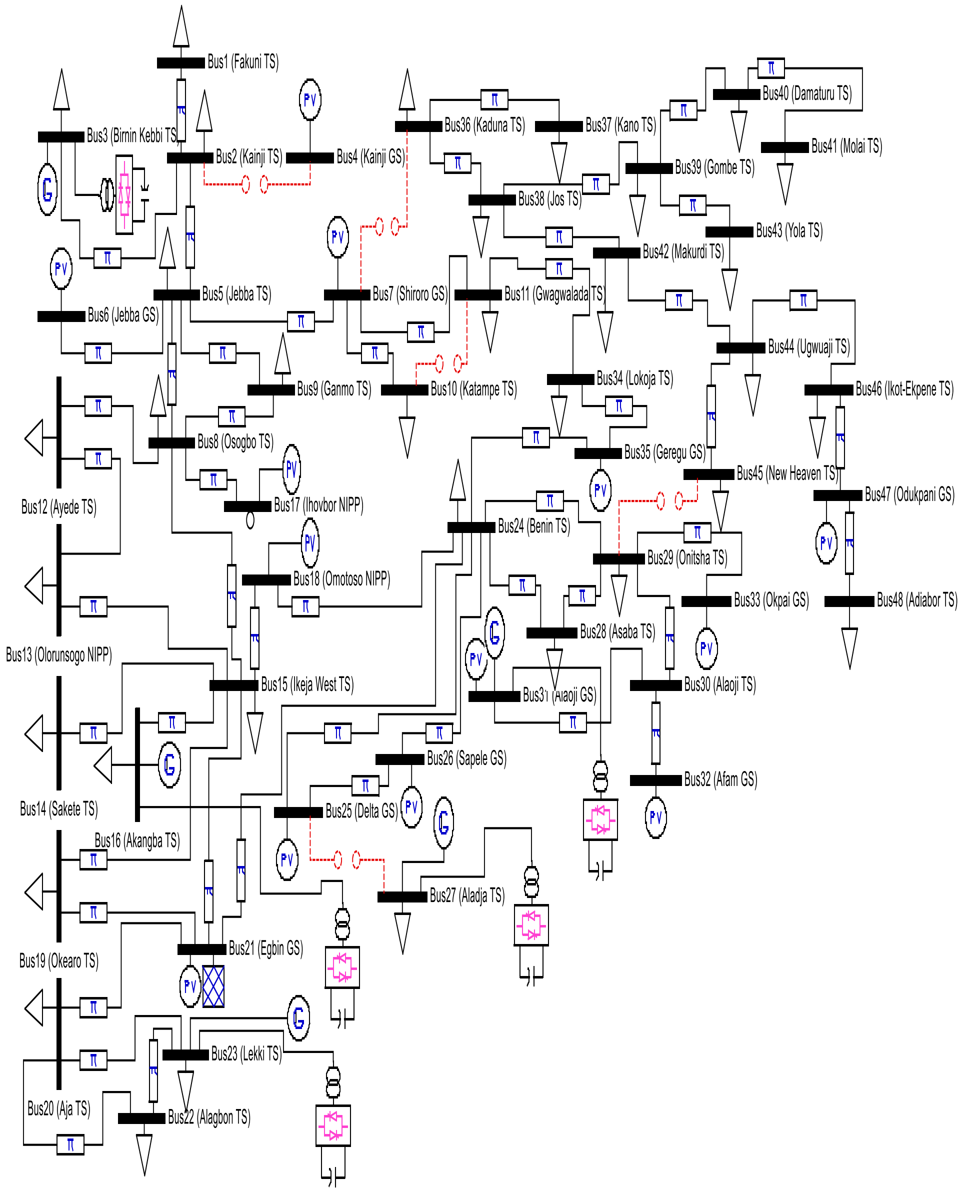

Figure 1: Network model of 48 bus system

2.1 System Description

The base system model is the 48-bus, 330 kV Nigerian transmission network, which includes major generation stations, transmission substations, and inter-zonal transmission lines are shown in Figure 1. The model is developed in accordance with publicly available grid data and adapted within PSAT for power flow analysis. Each bus is defined with its nominal voltage, load, and generation characteristics, while transmission lines are characterised by their impedance, thermal ratings, and length.

2.2 Scenario Development

To understand the impact of different interventions, four distinct simulation scenarios were developed:

Case 1: Base case: This scenario reflects the grid's performance without any FACTS device or solar PV support. It serves as a benchmark for voltage profiles, line flows, and transfer capability.

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Case 2: STATCOM only: A STATCOM unit rated at ±100 MVAr is placed individually at each of the five weak buses in separate sub-cases. The devices are tuned to inject or absorb reactive power to maintain bus voltage close to 1.0 pu.

Case 3: Solar PV only: A solar PV source with a maximum capacity of 80 MW is connected at each of the five target buses. The generation is modelled as a constant active power source during peak solar availability, without reactive power support.

Case 4: Combined STATCOM and PV: This scenario evaluates the combined deployment of STATCOM and solar PV systems at the same five weak buses. It simulates the coordinated effect of colocated reactive power compensation from STATCOM and active power injection from PV.

Each scenario is simulated under peak demand conditions, approximated using seasonal data from the Nigerian Electricity Regulatory Commission. A flat start Newton-Raphson power flow is executed for each case to evaluate key performance indices.

2.3 Evaluation Parameters

The following metrics are used to assess the impact of each intervention: Voltage magnitude at all buses, with focus on the five target buses; Line loading percentages across key corridors; Reactive power margin at generator and load buses; Available Transfer Capability (ATC) using a load-increase approach from generation-rich zones to demand centres.

The results are compared to determine whether the presence of STATCOM, solar PV, or both leads to improved voltage stability, reduced line congestion, and increased power transfer capability.

III. RESULTS AND DISCUSSION

This section shares the steady-state simulation results for Nigeria's 330 kV, 48-bus transmission network under different support conditions: the base case (no support), STATCOM only, solar PV only, and a mix of STATCOM with solar PV. We have looked at key factors like voltage levels, line loading, available transfer capability (ATC), reactive power injection, power loss reduction, and voltage deviation across all buses.

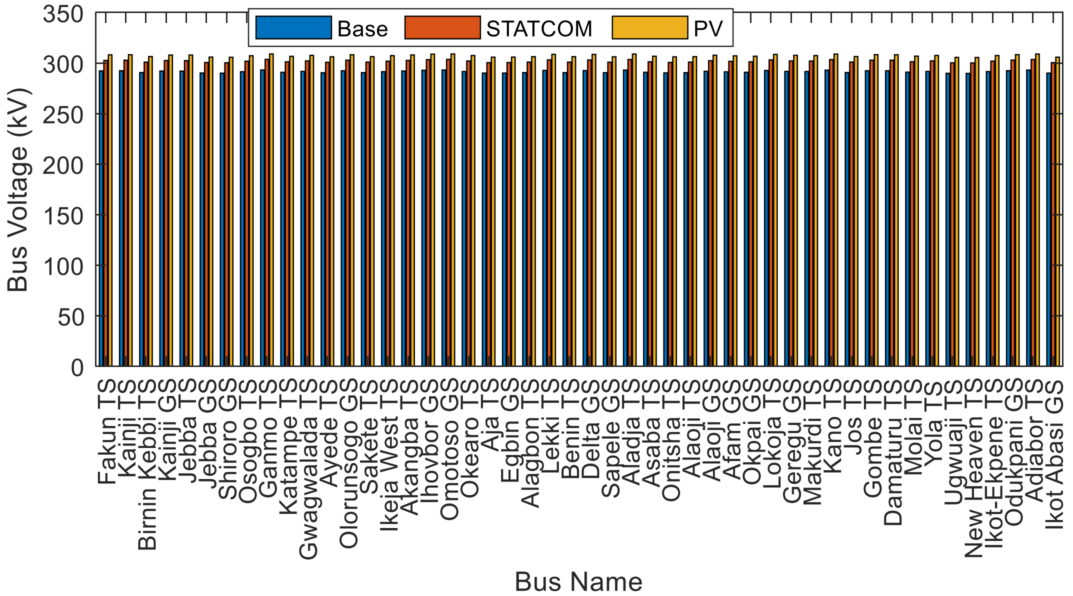

Figure 2: Voltage profile of all 48 buses under base case, STATCOM, and solar PV scenarios

Figure 2 shows how the voltage levels at all 48 buses look in the different scenarios. In the base case, many buses run below 295 kV. Adding STATCOM helps raise voltages across most of the network. Solar PV also helps improve voltage, especially at buses near the solar power sources. The best voltage results come from the combined scenario, where nearly all bus voltages get close to their target levels.

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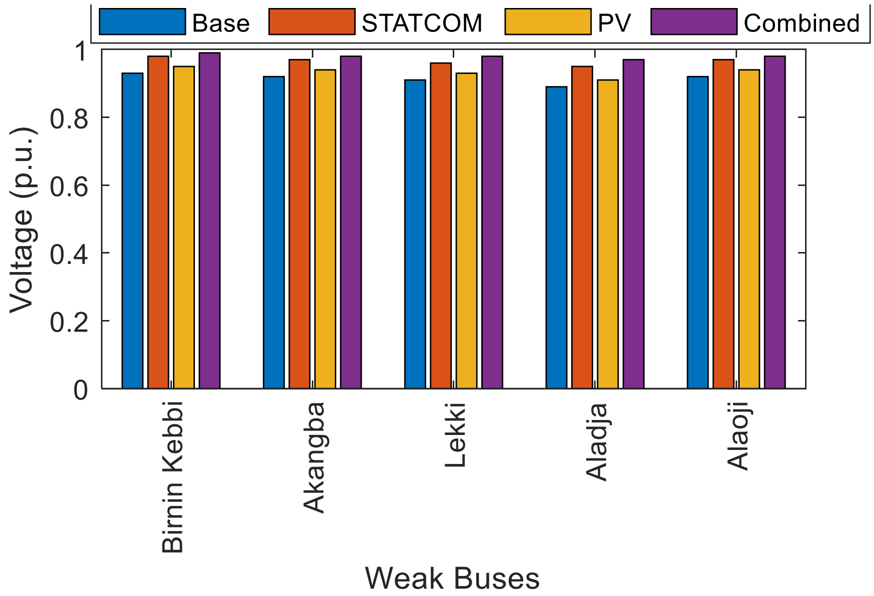

Figure 3: Voltage comparison at the five weakest buses under all four scenarios

To get a closer look at the critical points, Figure 3 shows the voltage profiles for the five weakest buses: Birnin Kebbi, Akangba, Lekki, Aladja, and Alaoji. In the base case, voltages drop below 0.93 per unit for all five, with Aladja being the most affected. Adding STATCOM raises the average voltage by about 0.05 per unit. Solar PV brings a small voltage increase too, particularly where it helps meet local power needs. The combined approach greatly stabilizes voltages across all five buses, getting them close to or above 0.98 per unit.

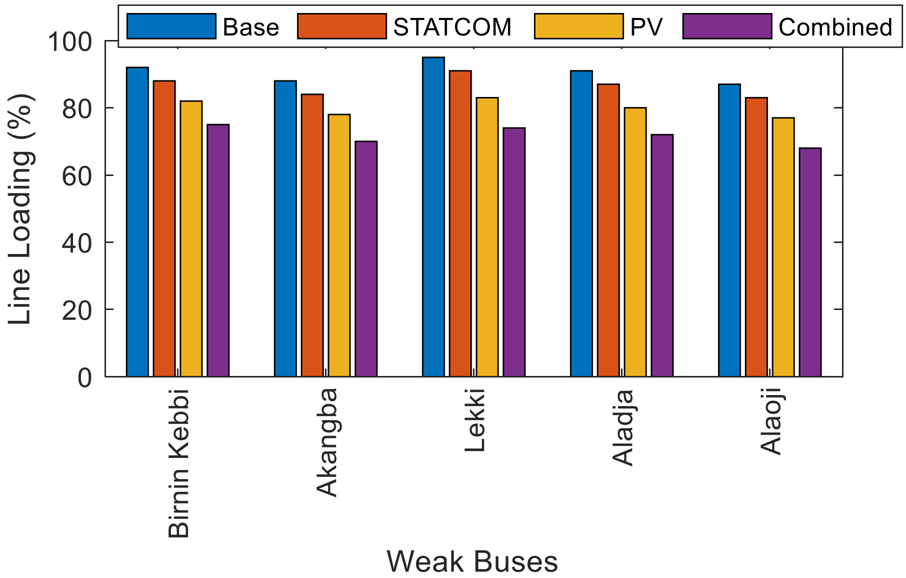

Figure 4: Line loading percentages at weak buses under base case, STATCOM, PV, and combined support conditions

Figure 4 displays the line loading at the five weak buses. In the base case, Lekki and Aladja show high line stress, with values over 90 percent of thermal capacity. STATCOM eases some of this pressure by improving voltage profiles. The solar PV scenario does a better job of reducing line loading since local generation takes some of the load off long transmission lines. The best loading levels are seen in the combined case, which shows a more balanced use of resources.

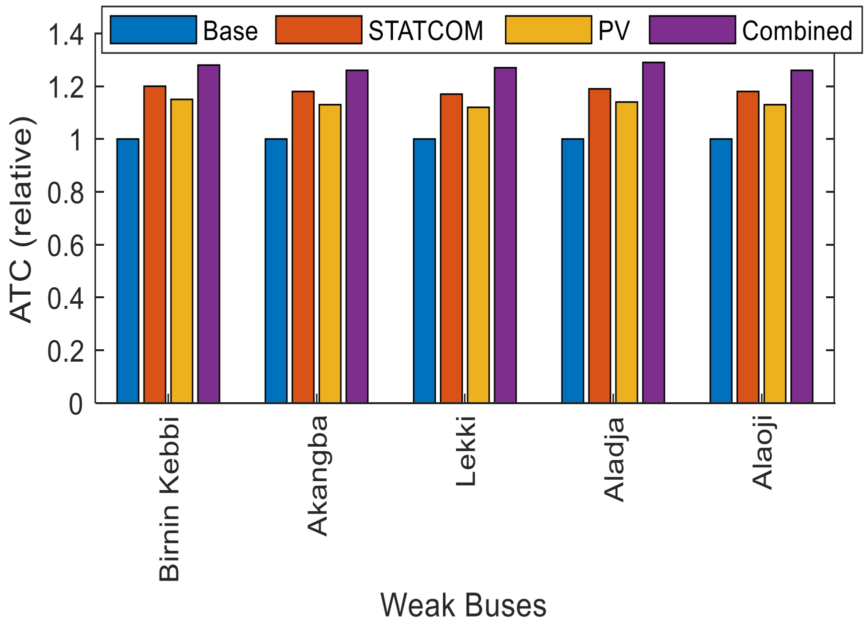

Figure 5: Relative available transfer capability (ATC) at weak buses across all operational scenarios

The boost in available transfer capability is shown in Figure 5, with the base scenario set at a relative ATC of 1.00. With STATCOM, ATC values rise to between 1.17 and 1.20. Solar PV also improves ATC to around 1.12 to 1.15. The biggest gains happen in the combined scenario, where ATC values hit up to 1.29, showing more ability to handle extra power transfers without causing issues.

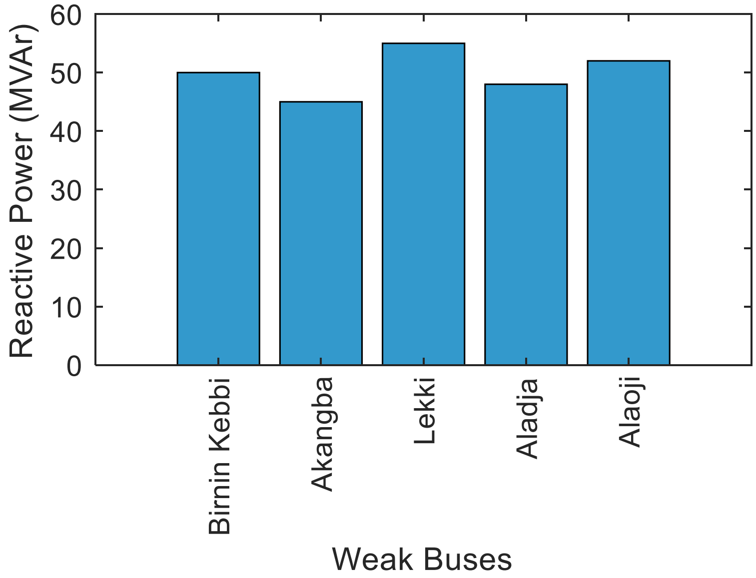

Figure 6: Reactive power injection by STATCOM at the five identified weak buses

Figure 6 outlines the reactive power injection by STATCOM at the weak buses, ranging from 45 to 55 MVAr. This shows that STATCOM plays a key role in providing local reactive power support, which helps maintain voltage levels and eases the load on central generators, improving stability.

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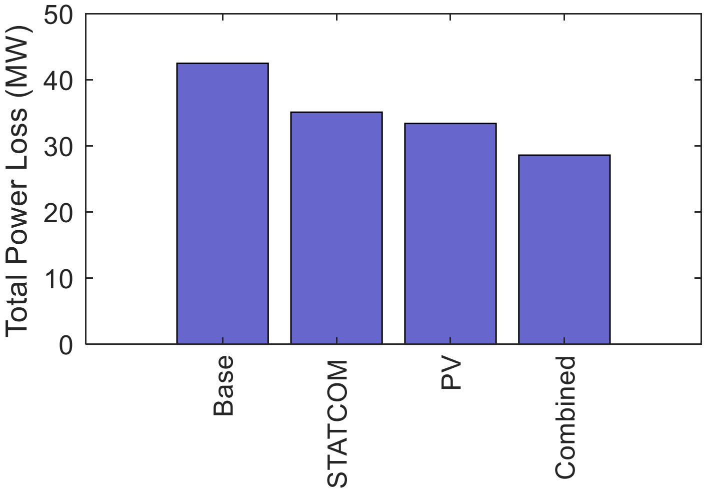

Figure 7: Comparison of total system power losses under base, STATCOM, PV, and combined support scenarios

Figure 7 compares total system power losses in different scenarios. The base case has the highest loss at 42.5 MW. With STATCOM, losses drop to 35.1 MW. Solar PV reduces losses even more, down to 33.4 MW. The least power loss occurs in the combined scenario, where total losses fall to 28.6 MW, showing a clear improvement in efficiency.

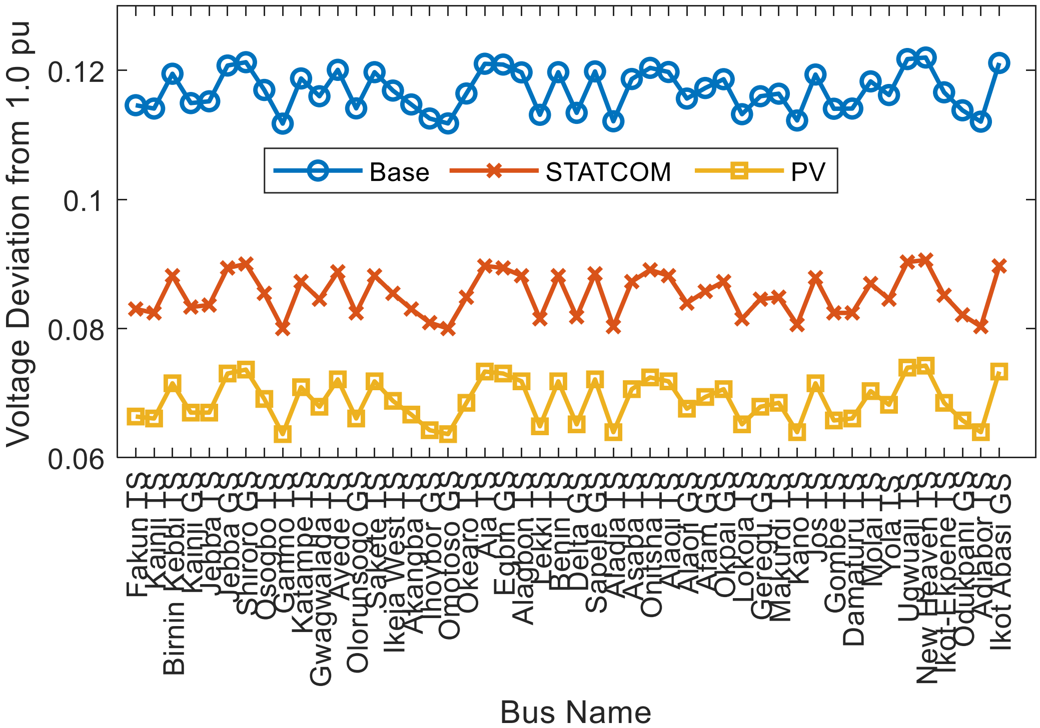

Figure 8: Voltage deviation from 1.0 per unit at all 48 buses for base, STATCOM, and PV scenarios

Figure 8 displays the voltage deviation from the nominal 1.0 per unit for all 48 buses. In the base case, many buses have deviations over 0.025 per unit, especially in the northwestern and southeastern areas. Both STATCOM and solar PV help to lessen this deviation, but the most uniform voltage regulation happens in the combined case. This consistency helps reduce outages related to voltage and keeps the network running smoothly.

IV. CONCLUSION

This study looked into how Nigeria's 330 kV transmission grid performs with the addition of STATCOM and solar PV systems, both separately and together. It focused on five weak areas that struggle with voltage issues and high line loads during normal operations. Using MATLAB and PSAT for simulations, the study checked how these technologies improved voltage levels, reduced line loading, boosted transfer capability, compensated for reactive power, and decreased power losses. The findings show that while STATCOM helps stabilize voltage by providing reactive power, solar PV adds active power to lower line loads. When both are used together, the effects are even better. With this combined approach, bus voltages stayed above 0.97 PU at all weak points, and line loading was cut down, making the system more reliable. It also led to the biggest boost in transfer capability and the least amount of power loss, proving that combining these systems really works well. Based on these results, it's recommended that Nigeria's transmission grid integrate STATCOM and solar PV systems at key spots to improve voltage stability, lessen line loading, and enhance transfer capability. Grid planners should focus on these hybrid setups in their future projects, and more studies should look into their dynamic and economic effects.

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