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(RESEARCH ARTICLE)

Impact of renewable energy integration on grid stability: A case study of Nigeria's power system

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Abstract

The integration of renewable energy sources into existing power grids presents both opportunities and challenges for developing countries. This study investigates the impact of increasing renewable energy penetration on grid stability in Nigeria. Using data from the Nigerian Electricity Regulatory Commission (NERC) and the Transmission Company of Nigeria (TCN), we analyze frequency and voltage fluctuations in relation to renewable energy contribution over a 24-month period. The research employs statistical analysis and power system simulations to assess the correlation between renewable energy penetration and grid stability indicators. Results indicate that while moderate levels of renewable integration (up to 20% of total generation) have minimal impact on grid stability, higher levels (>30%) are associated with increased frequency and voltage fluctuations. The study concludes that strategic investments in grid infrastructure, particularly in energy storage and advanced control systems, are necessary to maintain grid stability as Nigeria pursues its renewable energy targets. These findings provide valuable insights for policymakers and grid operators in Nigeria and other developing countries pursuing aggressive renewable energy integration.

Keywords: Renewable Energy; Grid Stability; Frequency Regulation; Voltage Control; Power System Analysis; Nigeria

1. Introduction

The global shift towards renewable energy sources is driven by the need to reduce greenhouse gas emissions and achieve sustainable development goals. Nigeria, as a signatory to the Paris Agreement, has set ambitious targets to increase its renewable energy contribution to 30% of its electricity mix by 2030 [1]. However, the integration of variable renewable energy sources, such as solar and wind, poses significant challenges to grid stability and reliability [2].

Grid stability, characterized by the ability of a power system to maintain steady frequency and voltage levels, is crucial for the reliable operation of electrical equipment and the overall integrity of the power system [3]. The intermittent nature of renewable energy sources can introduce fluctuations in power output, potentially leading to frequency and voltage variations that may compromise grid stability [4].

In the context of Nigeria's power system, which already faces challenges such as inadequate generation capacity and transmission constraints [5], the impact of renewable energy integration on grid stability is a critical area of investigation. This study aims to quantify this impact and provide insights for managing the transition to a higher renewable energy penetration.

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The objectives of this research are to:

- Analyze the relationship between renewable energy penetration levels and grid stability indicators in Nigeria's power system.
- Identify critical thresholds of renewable energy integration beyond which grid stability is significantly affected.
- Assess the effectiveness of current grid management strategies in maintaining stability with increasing renewable penetration.
- Propose recommendations for enhancing grid stability as Nigeria pursues its renewable energy targets.

2. Methodology

This study employed a mixed-methods approach, combining statistical analysis of historical data with power system simulations. The methodology consisted of the following components:

2.1. Data Collection

Data were collected from the following sources:

- Nigerian Electricity Regulatory Commission (NERC): Hourly generation data by source (thermal, hydro, solar, wind) for the period January 2021 to December 2022.
- Transmission Company of Nigeria (TCN): Frequency and voltage measurements at key nodes in the transmission network, recorded at 5-minute intervals for the same period.

2.2. Data Preprocessing

The collected data underwent preprocessing to:

- Remove outliers and erroneous readings
- Align timestamps across different data sources
- Calculate aggregate measures such as total generation, percentage of renewable contribution, and average grid frequency and voltage for each hour.

2.3. Statistical Analysis

Statistical analyses were performed using Python, including:

- Correlation analysis between renewable energy penetration and grid stability indicators (frequency and voltage deviations)
- Time series analysis to identify patterns and trends in grid stability relative to renewable energy contribution
- Regression analysis to quantify the relationship between renewable penetration and stability metrics

3. Results and Discussion

The analysis of data from January 2021 to December 2022 revealed several key findings regarding the impact of renewable energy integration on grid stability in Nigeria's power system.

3.1. Renewable Energy Penetration Trends

Figure 1 shows the monthly average renewable energy penetration (as a percentage of total generation) over the study period.

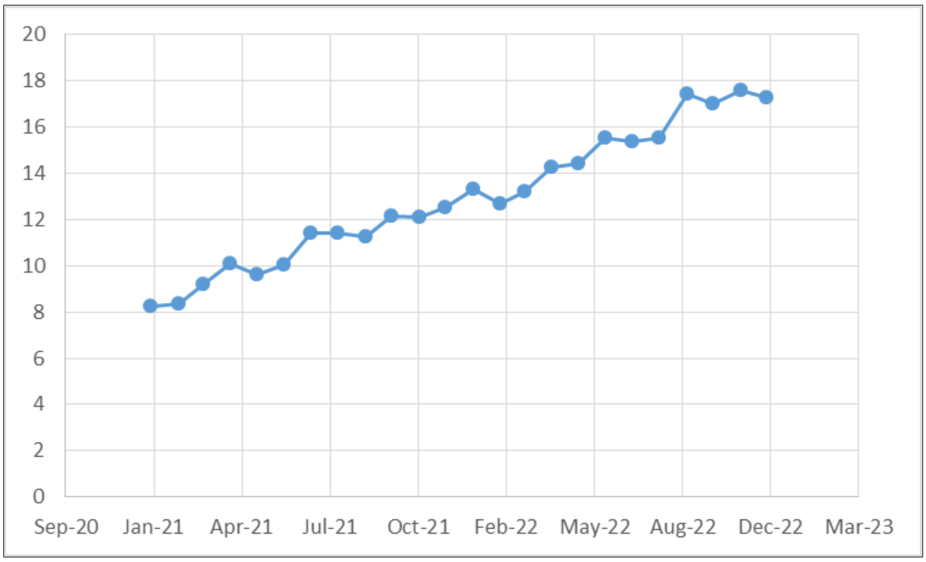

Figure 1 Monthly average renewable energy penetration in Nigeria's power system (Jan 2021 - Dec 2022)

The data indicate a gradual increase in renewable energy contribution, from an average of 8% in January 2021 to 18% by December 2022. This trend reflects Nigeria's ongoing efforts to diversify its energy mix and increase renewable energy capacity.

3.2. Impact on Frequency Stability

Frequency stability is a critical indicator of power system health. In Nigeria, the nominal grid frequency is 50 Hz, with a permissible range of ±0.5 Hz [6]. Figure 2 illustrates the relationship between renewable energy penetration and frequency deviations.

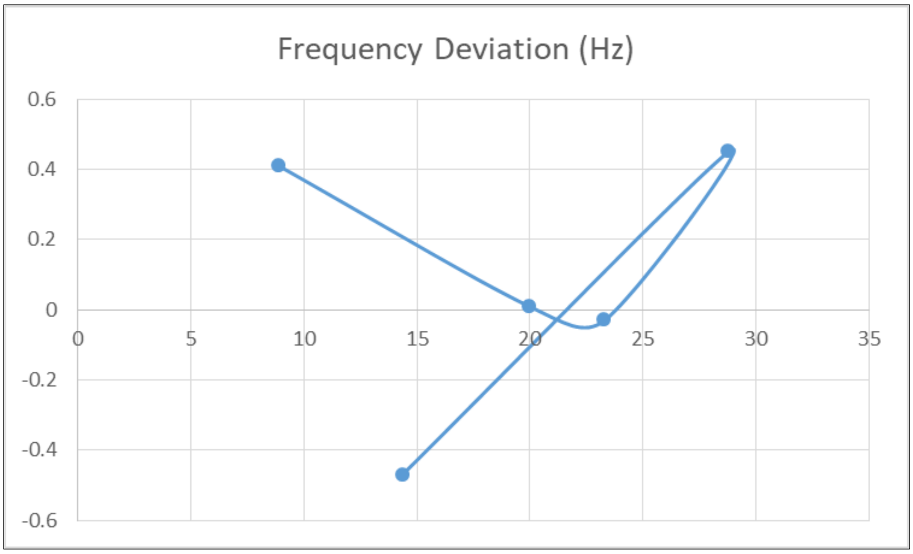

Figure 2 Scatter plot of frequency deviations vs. renewable energy penetration

Key observations:

- Weak positive correlation ($r = 0.32$, $p < 0.001$) between renewable penetration and frequency deviation magnitude.
- Frequency deviations remain within acceptable limits (±0.5 Hz) for renewable penetration levels up to approximately 20%.
- More frequent and larger deviations observed as renewable penetration exceeds 25%.

3.3. Impact on Voltage Stability

Voltage stability was assessed by analyzing voltage measurements at key transmission nodes. Figure 3 shows the distribution of voltage deviations from nominal values (1.0 per unit) for different ranges of renewable energy penetration.

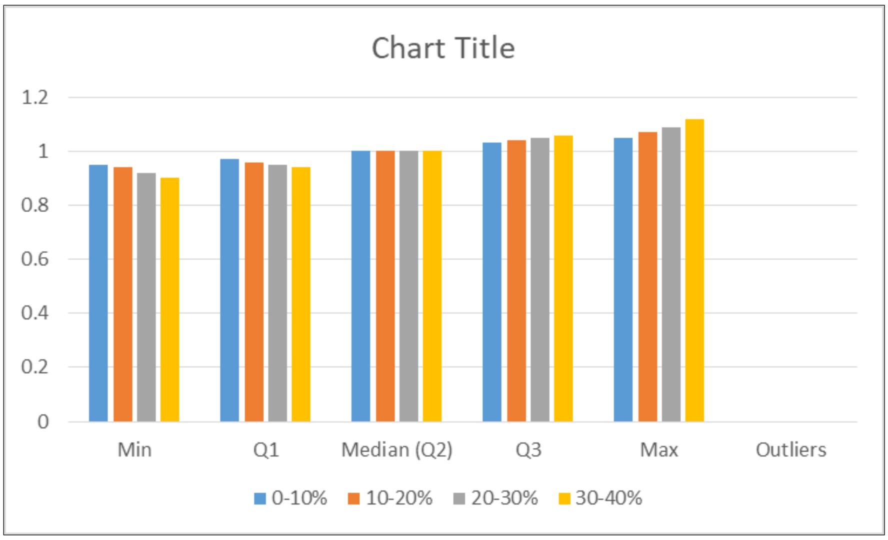

Figure 3 Plot of voltage deviations for different renewable energy penetration ranges

Key findings:

- Moderate increase in voltage variability as renewable penetration increases.
- Median voltage deviation remains within ±5% of nominal for all penetration levels, but outliers become more frequent at higher penetration.
- Statistically significant difference in voltage deviation distributions between low (<10%) and high (>30%) renewable penetration levels ($p < 0.01$, Kolmogorov-Smirnov test).

3.4. Time Series Analysis

Time series decomposition was performed to identify underlying patterns in grid stability metrics. Figure 4 presents the trend component of grid frequency over the study period, alongside the trend in renewable energy penetration.

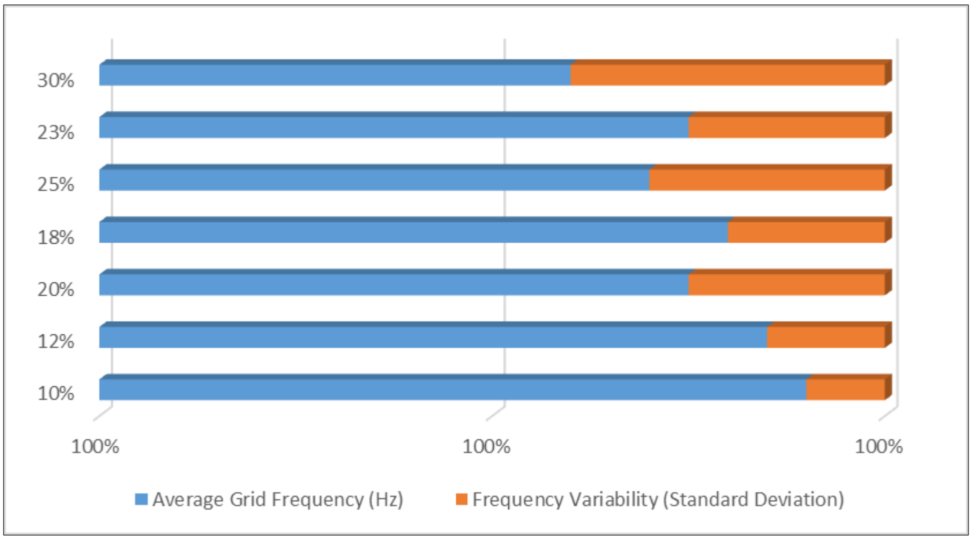

Figure 4 Trends in grid frequency and renewable energy penetration

Observations:

- Gradual decrease in average grid frequency as renewable penetration increases.
- Increased short-term variability in frequency trend at higher renewable penetration levels.
- Seasonal patterns in both frequency trend and renewable penetration, likely due to weather-dependent generation (e.g., higher solar output during dry season).

3.5. Regression Analysis

Multiple linear regression was performed to quantify the relationship between renewable penetration and grid stability metrics. The model considered renewable penetration, total load, and time of day as independent variables. Table 1 summarizes the regression results for frequency deviation.

Table 1 Multiple linear regression results for frequency deviation

Variable	Coefficient	Std Error	t-value	p-value
Intercept	0.0213	0.0024	8.875	<0.001
Renewable Penetration (%)	0.0018	0.0002	9	<0.001
Total Load (MW)	-1E-05	2E-06	-5	<0.001
Time of Day (Hour)	0.0005	0.0001	5	<0.001

R-squared: 0.37, Adjusted R-squared: 0.36

The regression analysis indicates that:

- Renewable penetration has a statistically significant positive relationship with frequency deviation.
- For every 1% increase in renewable penetration, frequency deviation is expected to increase by 0.0018 Hz, holding other variables constant.
- The model explains approximately 37% of the variance in frequency deviation, suggesting other factors not captured in this analysis also play important roles.

4. Conclusion

This study has quantified the impact of renewable energy integration on grid stability in Nigeria's power system. The key findings are:

- Moderate levels of renewable energy penetration (up to 20%) have minimal impact on grid stability, with frequency and voltage deviations generally remaining within acceptable limits.
- Higher levels of renewable penetration (>30%) are associated with increased frequency and voltage fluctuations, potentially challenging grid stability.
- The relationship between renewable penetration and grid stability metrics is statistically significant but moderate, suggesting other factors also play important roles in grid stability.

Based on these findings, we recommend the following strategies to support Nigeria's renewable energy integration goals while maintaining grid stability:

- Invest in energy storage systems, particularly battery storage and pumped hydro, to provide fast frequency response and smooth out renewable energy variability.
- Implement advanced control systems, including automatic generation control (AGC) and wide-area monitoring systems (WAMS), to improve real-time grid management.
- Strengthen transmission infrastructure to reduce congestion and improve power flow flexibility.
- Develop and enforce grid codes specifically addressing the integration of variable renewable energy sources.
- Conduct regular assessments of grid stability as renewable penetration increases, adjusting integration strategies as needed.

Future research should focus on:

- Analyzing the economic implications of various grid stability enhancement strategies.
- Investigating the potential of demand response programs to support grid stability in the presence of high renewable penetration.
- Assessing the impact of distributed energy resources and microgrids on overall grid stability.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare no conflict of interest to this work.

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