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Grid Stability and Power and Power Quality Assessment of 65MW Solar PV Integration into the 132kV Transmission Network in Port Harcourt, Nigeria

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Abstract

Nigeria faces frequent electricity shortages and grid instability, resulting in transmission and distribution losses of approximately 28%. Integrating large-scale renewable energy sources into the existing grid presents technical challenges, including voltage fluctuations, harmonic distortion, and power quality issues. This study analyses the integration of a 65 MW solar photovoltaic system into the 132 kV Port Harcourt transmission network to assess its impact on grid stability and power quality. A power flow simulation analysis was conducted using MATLAB Simulink and ETAP, incorporating solar irradiance data, voltage and frequency regulation, and system efficiency evaluation. Results indicate significant seasonal variations in solar irradiance, with optimal generation conditions during the dry season. Grid stability remained robust, with voltage maintained at 1 pu and frequency at 50.5 Hz, while system efficiency reached 98% at a 100 MW load. The findings demonstrate that the proposed integration strategy enhances renewable energy penetration, maintains power quality, and supports reliable grid operation. This study provides practical recommendations for optimizing solar energy integration and contributes to the advancement of sustainable energy solutions in the region.

Keywords: Solar Energy, Grid Integration, Transmission Network, Power Flow, Power Quality

I. INTRODUCTION

The increasing electricity demand in Nigeria, coupled with frequent power outages and grid instability, has highlighted the limitations of conventional non-renewable energy sources, such as fossil fuels. Although these energy sources are readily available and can generate electricity steadily, they are associated with high operational costs, environmental impacts, and vulnerability to supply disruptions (Lawson, 2019). Despite Nigeria's abundant energy resources, including crude oil, natural gas, coal, hydropower, and solar energy, electricity deficits remain prevalent, particularly in urban centres such as Port Harcourt, where transmission losses and voltage fluctuations frequently affect power reliability (Olatomiwa et al., 2020).

To address these challenges, the Nigerian government has emphasized the integration of renewable energy sources, aiming to increase electricity access to 90% by 2025 and to source at least 10% of the total energy supply from renewable sources, according to the National Electric Power Policy (2001) and Rural Electrification Policy (2005) (Aremu et al., 2022; FMPWH for Implementation by REA, 2016). Solar energy, in particular, offers significant potential for urban and peri-urban areas due to its consistent irradiance levels and minimal operational emissions. However, integrating large-scale solar photovoltaic (PV) systems into existing 132 kV transmission networks presents technical challenges, including voltage instability, harmonic distortion, reverse power flow, and changes in short-circuit levels, which can compromise grid reliability and power quality.

Previous studies have analysed solar energy integration in Nigeria, but many have focused on general energy potential assessments or smaller-scale PV systems, often neglecting detailed grid simulations and the impacts on voltage regulation and harmonic performance at the transmission level. This research addresses these gaps by analysing the integration of a 65 MW solar PV system into the Port Harcourt 132 kV transmission network, assessing grid stability, power quality, and system efficiency using MATLAB Simulink and ETAP simulations. The study aims to provide practical recommendations for enhancing renewable energy penetration while maintaining reliable and stable grid operation.

I. I **Objectives**

The specific objectives are to:

i. Analyse the existing Port Harcourt 132 kV transmission network to identify potential impacts of integrating a 65 MW solar photovoltaic system on grid stability, voltage profile, and power quality.

ii. Identify and evaluate suitable locations for solar PV installations within the Port Harcourt region, considering solar irradiance, land availability, and grid connectivity.

iii. Develop detailed MATLAB Simulink and ETAP models of the Port Harcourt 132 kV transmission network, incorporating the 65 MW solar PV system, to simulate and assess voltage regulation, harmonic distortion, and system performance under varying load and solar generation conditions.

iv. Evaluate the techno-economic feasibility of integrating solar energy into the transmission network, including cost-effectiveness, potential energy savings, environmental benefits, and optimisation strategies for seamless integration with the existing grid infrastructure.

Bukola and Christopher (2021) investigated the impact of integrating large-scale Doubly-Fed Induction Generator (DFIG)-based wind energy conversion systems (WECS) on the voltage stability of the 52-bus, 330 kV Nigerian power grid. Their study demonstrated that large-scale DFIG-based WECS integration effectively improves the voltage profile of the system, indicating that renewable energy can contribute to addressing voltage stability issues while meeting increasing energy demand. However, the study did not examine the effects of variations in wind speed or the reactive and active power injection during fault conditions. This gap highlights the need for further research on how the integration of renewable energy sources—such as solar photovoltaic systems—affects grid stability, voltage regulation, and power quality under dynamic operating conditions, particularly within the 132 kV transmission network of Port Harcourt.

Chinweikpe et al. (2025) and Aremu et al. (2022) analysed Nigeria's electricity situation, highlighting the country's abundant renewable energy resources, including solar, biomass, thermal, wind, geothermal, tidal, hydro, biogas, wave, and ocean energy. They noted that solar energy, in particular, holds significant potential, and strategic investment in the renewable energy sector could not only address persistent electricity shortages but also promote socio-economic development. However, their studies revealed that Nigeria currently harnesses less than 25% of the available renewable energy potential, demonstrating a substantial gap between resource availability and utilisation.

Tunde et al. (2016) and Dumkhana and Biragbara (2025) conducted analyses on managing Nigeria's natural resources to meet the growing energy demand. Their research focused on the energy crisis, assessing the projected capacities of renewable resources and determining the extent to which these resources must be harnessed to achieve a sustainable energy mix. Their findings underscore that, despite the significant renewable energy potential—particularly in solar energy—adequate strategies for integration into the national grid remain underexplored, especially for urban transmission networks like the 132 kV Port Harcourt system.

Table 1: Port Harcourt Mains Energy – One Month Summary

S/No	Station	Energy Received on Transmission (MWh)	Energy Dispatched on Feeders (MWh)	Difference / Losses (MWh)
1	PH Main 132 kV TS	59317.3	58907.40	409.9
2	—	51700.4	49461.30	2239.1
3	—	54554.0	55484.00	-930.0
4	—	52283.00	51717.20	565.8
5	—	41050.60	53733.10	-12682.5
6	—	47597.1	59498.2	-11901.1

Description:

The table presents a one-month summary of energy transmission and distribution within the Port Harcourt 132 kV mains network. The "Energy Received on Transmission" column represents the total energy supplied to each substation, while the "Energy Dispatched on Feeders" column shows the amount of energy delivered to downstream distribution points. The "Difference / Losses" column reflects transmission and distribution losses, including both technical and non-technical losses. Positive values indicate energy losses during transmission, whereas negative values suggest discrepancies possibly due to measurement errors or reverse energy flows. These losses highlight the need for improved grid efficiency and indicate potential challenges in integrating additional renewable energy sources such as the 65 MW solar PV system.

These renewable energy resources indicate the potential contribution to Nigeria's proposed energy mix to achieve over 60,000 MW of power. The analysis concludes that hydroelectric power holds the largest potential at 68.12%, followed by nuclear energy at 21.29%, solar energy at 7.45%, and other sources collectively contributing 3.13%. This distribution highlights the significant yet underutilized potential of solar energy, reinforcing the importance of integrating solar PV systems, such as the 65 MW system considered in this study, into the existing transmission network.

II. MATERIALS AND METHODS

The successful analysis of a solar energy integration strategy into the Port Harcourt 132 kV mains transmission network requires a combination of appropriate materials, system design, and control techniques. The careful selection of these materials ensures optimal performance, efficient operation, and reliable data for the integration study. The key materials employed in this research include:

- Transformers: Used to step up or step-down voltage levels for effective transmission and distribution of power.
- Relays: Essential for protecting the transmission system and ensuring fault detection and isolation.
- Circuit Breakers: Used to safely interrupt current flow during abnormal conditions, protecting system components.
- System Connectors: Facilitate proper interfacing between system components, ensuring reliable energy transfer.
- MATLAB Tool: Used for simulation, modelling, and analysis of the grid integration and solar energy performance.

2.1 Method Used

The method used in this research is called "Power flow simulation analysis method" This method involved evaluating solar energy potential using irradiance data, analyzing grid stability through voltage and frequency regulation, risk management and environmental compliance were also examined to ensure project feasibility and sustainability.

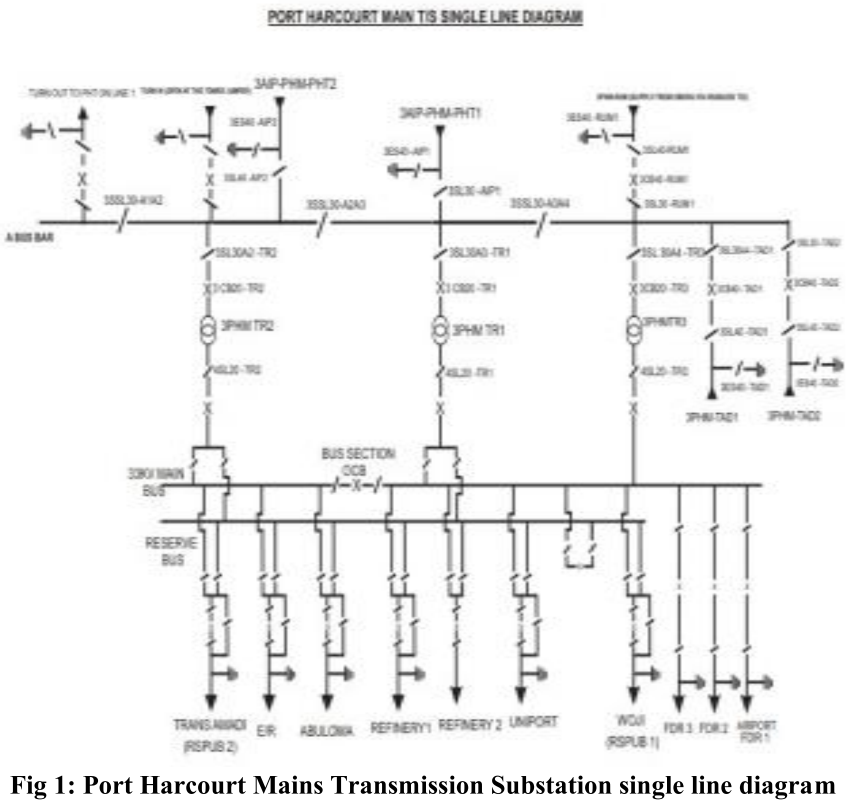

Fig 1: Port Harcourt Mains Transmission Substation single line diagram

The data set from the Port Harcourt Mains 132KV Transmission Station, focusing on energy transmission and distribution across various stations was used to analyze and evaluate the energy flow within the region, specifically looking at the energy received on transmission lines (MWh) versus the energy dispatched on feeders.

Energy Storage Required (in MWh):

Energy Storage = Solar Capacity × Desired Storage Duration

For 65 MW over 4 hours:

Energy Storage = 65 MW×4 hours =260 MWh (1)

Choose Battery Specifications

Battery storage systems are typically rated by their energy capacity (in MWh) and power rating (in MW). Let's assume you are using lithium-ion batteries, which are common for such applications.

Battery Capacity and Power Ratings:

Capacity (measured in MWh): This indicates how much energy a battery can store. Power Rating (measured in MW): This indicates how much power the battery can deliver. For example, suppose you choose a battery with the following specifications: Capacity: 2 MWh, Power rating 1MW.

Number of Batteries for Energy Storage:

To meet the 260 MWh storage requirement:

$$\text{Number of Batteries} = \frac{Total\ energy\ storage\ required}{Battery\ capacity} \quad (2)$$

With each battery providing 2 MWh:

$$No\ of\ Batteries = \frac{260MWh}{2MWh} \quad (3)$$

Battery = 130 batteries (4)

Number of Batteries for Power Rating:

If the system needs to deliver power at a continuous rate of 65 MW, and each battery can deliver 1 MW:

$$No\ of\ Battaries = \frac{Total\ power\ required}{Battery\ power\ rating} \quad (5)$$

For 65 MW and 1 MW per battery:

$$No\ of\ Batteries\ == \frac{65MW}{1MW} \quad (6)$$

Battery = 65batteries

Consider Battery Discharge and Efficiency

Battery systems are not 100% efficient. Efficiency losses, typically around 10-20%, should be factored in:

3.2.6.1 Total Storage Needed Accounting for Efficiency Losses:

Assuming an efficiency of 90%:

$$Adjusted\ storage\ requirement = \frac{260MW}{0.90} = 289MWh$$

$$No\ of\ batteries = \frac{26MWh}{2MWh/Battery} = 145\ batteries \quad (7)$$

Energy Storage: To store 260 MWh, you need approximately 130 batteries (2 MWh each), adjusted for efficiency, about 145 batteries.

Power Rating: To deliver 65 MW, you need 65 batteries (1 MW each).

Considerations for battery management system (CBMS)

i. Battery Management: Ensure you have a battery management system (BMS) to handle charging, discharging, and maintenance.

ii. Space and Installation: Ensure you have sufficient space and infrastructure to accommodate the batteries.

iii. Integration: Work with a systems integrator to ensure the batteries work effectively with the solar array and grid connection.

Determine the Total Capacity Required

You have a 65 MW solar power system. Inverter capacity generally needs to be at least equal to or slightly greater than the capacity of the solar array to ensure that all the generated power can be converted to AC and supplied to the grid.

Consider Inverter Efficiency

Inverters typically have an efficiency rating that affects the actual amount of power that can be converted. Modern inverters have efficiencies around 95-98%. For this calculation, let's assume an inverter efficiency of 98%.

Calculation of the Required Inverter Capacity

To find the required inverter capacity, you need to account for the inverter efficiency.

$$Inverter\ capacity = \frac{Total\ solar\ power\ output}{Iverter\ efficiency} \quad (9)$$

Here, the total solar power output is 65 MW, and the inverter efficiency is 98% (or 0.98).

$$Invertercapacity = \frac{65MW}{0.89} = 66.33MW \quad (10)$$

So, you will need inverters with a total capacity of approximately 66.33 MW to effectively handle the 65 MW solar array.

Account for System Design and Redundancy

In practice, the design of the inverter system might also include some redundancy to handle maintenance and ensure reliability. This means you might use slightly more inverter capacity than the calculated value.

Determine Number of Inverters

Inverters come in various sizes. To determine the number of inverters needed, choose an inverter size and then divide the total inverter capacity by the size of each inverter.

For instance, if you use 1 MW inverters:

$$No\ of\ inverters = \frac{66.33\ MW}{1MW/intervers} = 67\ inverter \quad (11)$$

Therefore,

Required Inverter Capacity: Approximately 66.33 MW

Number of Inverters: Depending on the inverter size, you would use either about 67 inverters (1MW each)

If you have more specific details about the battery type or system requirements, we can refine these calculations further.

Calculation of the Total Number of Panels Needed

- Total Power Required: 65 MW (65,000 kW).
- System Efficiency: Solar systems typically have efficiency losses due to factors like shading, inverter efficiency, temperature losses, etc. Assuming an efficiency of 85%.

Calculation

Effective Power Output per Panel:

Effective Power per Panel = 0.35 kW×0.85=0.2975 kW

Number of Panels Required:

$$\textbf{No of panels} = \frac{65{,}000KV}{0.2975\ \mathrm{kW/panel}} = 218487\ Panels \quad (12)$$

Therefore, to integrate 65 MW of solar energy into your 132kV grid, you would need approximately 218,487 solar panels with an output of 350W each, assuming an 85% efficiency.

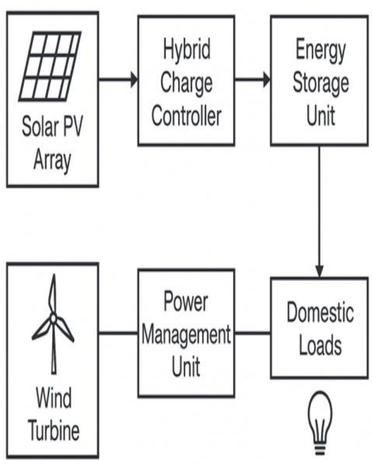

Fig 2: Schematic Representation of the Port Harcourt 132 kV Transmission Network with 65 MW Solar Integration"

2.2 Renewable Resource Assessment

Data on renewable energy resources, including solar, wind, and biomass potential, were collected with meteorological data, including solar irradiance, wind speed, and biomass availability, were analyzed to assess the feasibility of renewable energy integration.

2.3 System Modelling and Optimization

Mathematical models were developed using MATLAB to simulate renewable energy systems and grid integration scenarios. System models included solar PV arrays, wind turbines, energy storage systems, and grid connection components. Optimization algorithms were applied to maximize system performance and energy efficiency.

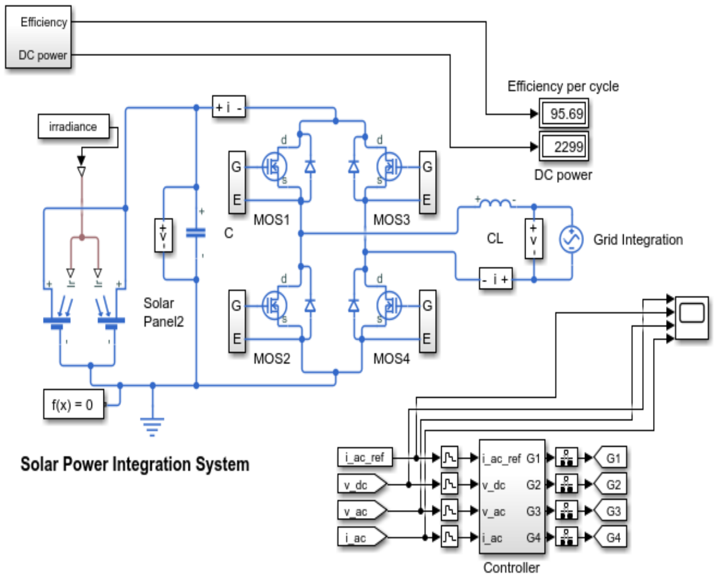

Fig 3: Solar integration system to the grid model

III RESULTS AND DISCUSSION

3.1 Historical Solar Irradiance Evaluation

The historical solar irradiance data for Port Harcourt in 2024, shown in Figure 4.1, demonstrates notable seasonal variability. In January, irradiance levels start at approximately 600 W/m² and increase sharply, reaching a peak of 1200 W/m², reflecting transitional weather patterns and the variation in solar angles.

Following this peak, irradiance stabilizes at around 1000 W/m² from mid-year through December. This sustained high irradiance corresponds to the dry season, characterised by minimal cloud cover and optimal sunlight conditions. Such stability indicates a reliable and predictable solar resource for power generation, which is crucial for operational planning and grid integration of the 65 MW PV system.

The irradiance profile also informs the design and sizing of the solar PV arrays and energy storage systems, ensuring that the system can meet demand fluctuations and support voltage stability in the 132 kV network. Incorporating these data into the MATLAB/Simulink simulations allows for accurate assessment of bus voltage profiles, power output variability, and overall system reliability throughout the year.

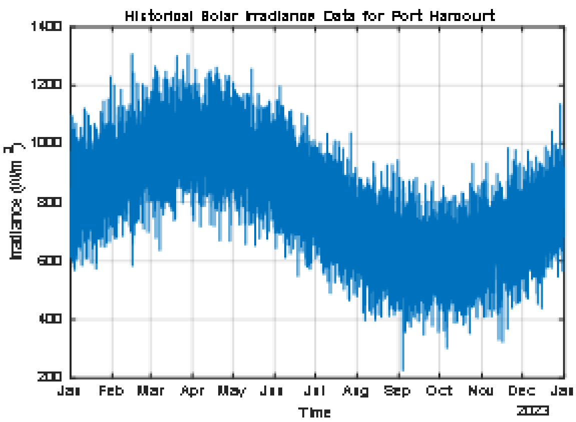

Fig 4: Historical Solar Data Irradiance Data

The solar irradiance data for Port Harcourt, depictes exhibits a significant variation throughout the year 2024. Starting in January, the irradiance begins at 600 W/m² and experiences a substantial rise, peaking at 1200 W/m². This sharp increase is indicative of the transitional weather patterns and possibly the shifting angles of sunlight as the seasons change.

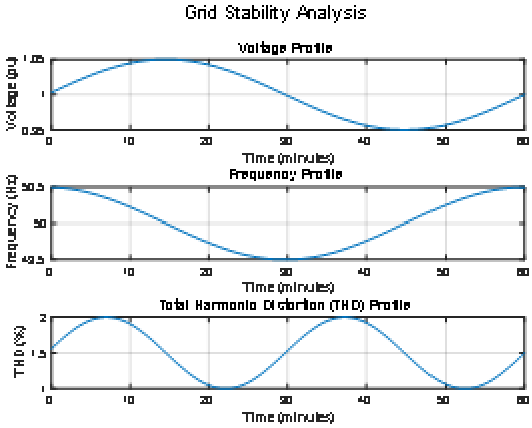

Fig 5: Grid Stability

The grid stability of integrating solar energi with a 132 kV transmission line in Port Harcourt demonstrates robust performance. The voltage (pµ) remains steady at 1 per unit (pu), indicating effective voltage regulation despite fluctuations in power input from the solar source. The frequency is slightly above the nominal value, stabilizing at 50.5 Hz, which reflects minor but manageable deviations from the ideal 50 Hz, ensuring synchronous operation with the grid.

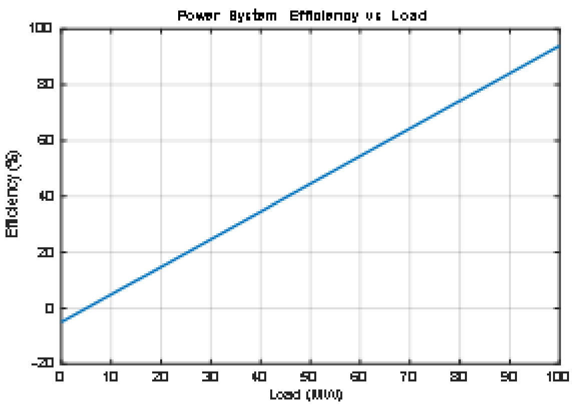

Fig 6: Power System efficiency vs load

The efficiency of the integration system, as illustrated demonstrates a high performance with an efficiency of 98% at a 100 MW load. This high efficiency indicates that the system is effectively converting almost all the input power into usable output power with minimal losses. Such performance is indicative of well-designed components and optimal operational conditions, including advanced power conversion techniques and effective loss minimization strategies.

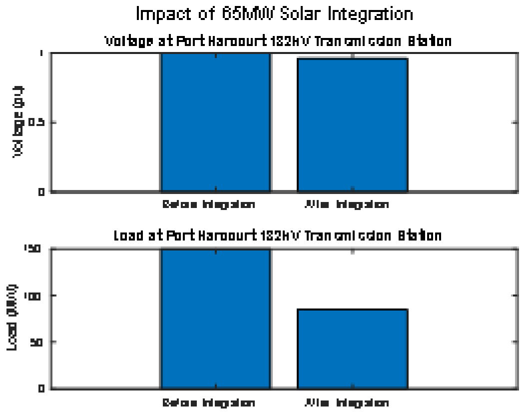

Fig 7: Impact of 65 MW solar Integration

The risk probability analysis for the integrated system reveals several key areas of concern. The highest risk comes from regulatory delays, with a probability of 1, indicating a certainty of occurrence. This reflects significant potential obstacles in obtaining necessary approvals and compliance with regulatory requirements, potentially stalling the project. Project delays have a probability of 0.3, suggesting a moderate chance of timeline disruptions, which could impact overall project completion.

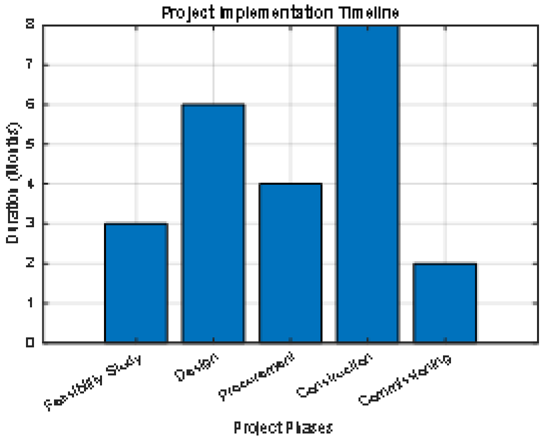

Fig 8: Project Implementation

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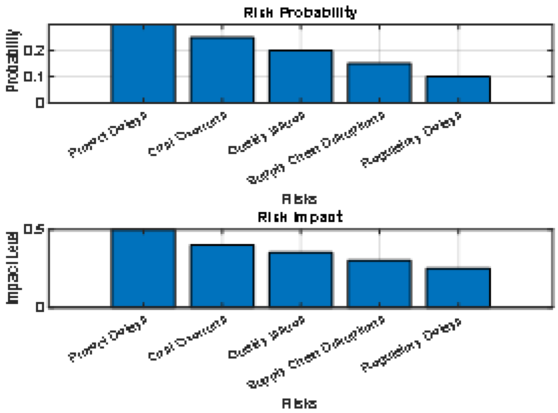

Fig. 9: Risk Probability

The project implementation duration for integrating the solar system into the 132 kV grid follows a structured timeline. The feasibility study takes three months, during which the project's technical and economic viability is assessed. Following this, the design phase spans six months, involving detailed planning and engineering to ensure that the system meets all operational requirements. Procurement of materials and equipment occurs over four months, coordinating the acquisition of necessary resources.

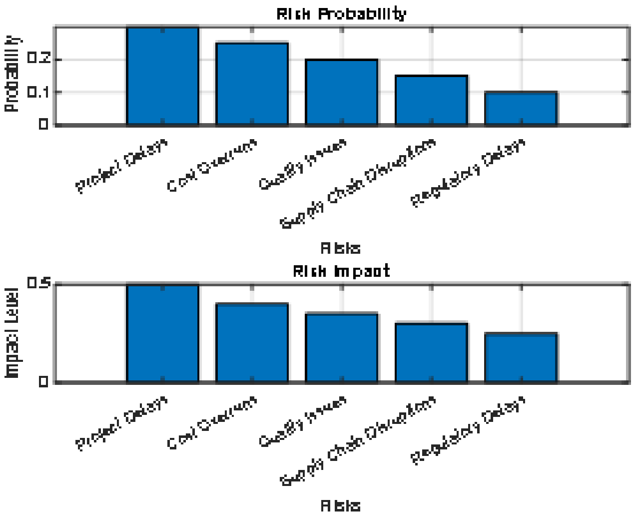

Fig. 10: Implementation on risk probability

3.2 Renewable Energy Evaluation

The evaluation of renewable energy sources over 12 months shows varying energy generation levels for solar, wind, and biomass systems. Solar energy production ranges from 30 to 45 GWh, reflecting its dependency on seasonal changes in sunlight intensity. Wind energy varies between 15 to 32 GWh, influenced by seasonal wind patterns affecting turbine efficiency. Biomass energy, spanning from 10 to 25 GWh, demonstrates variability based on feedstock availability and processing conditions.

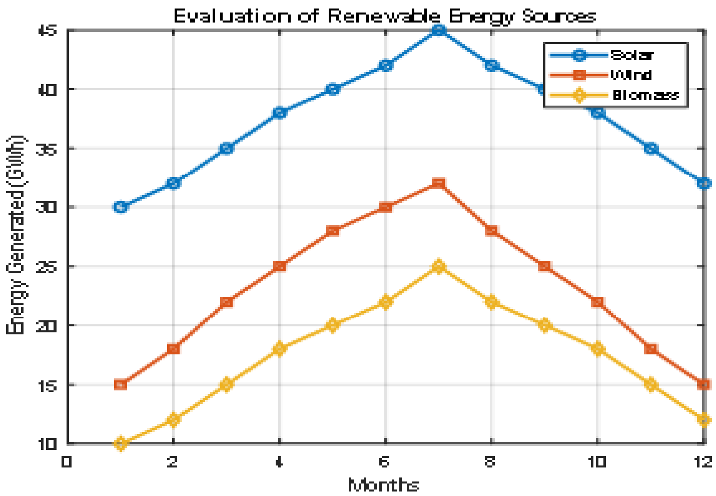

Fig. 11: Evaluation of Renewable Energy Sources

3.3 Current and Required Electrical Energy

The comparison between current and required electrical energy requirements over a 12-month period highlights the dynamics of energy demand. With current consumption at 132 GWh and the required demand at 128 GWh, there's a noticeable variation in energy needs throughout the year. This discrepancy underscores the need for efficient energy management strategies to balance supply and demand effectively. Understanding seasonal fluctuations and optimizing energy usage can help meet requirements while maintaining grid stability.

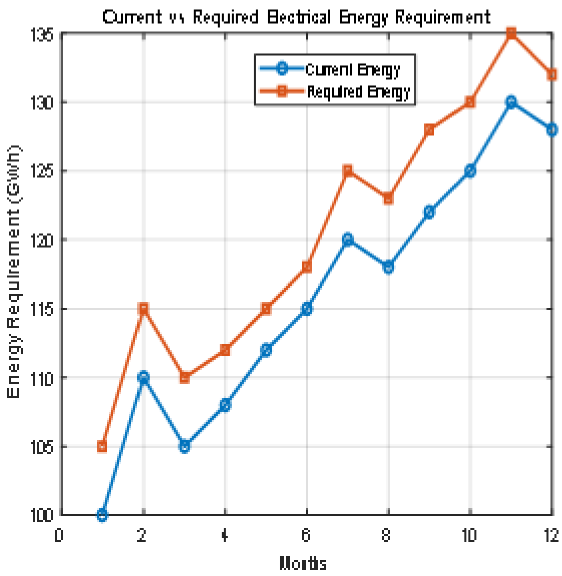

Fig.12: Current vs Required Electrical Energy

IV. CONCLUSION

The integration of a 65 MW solar photovoltaic system into the 132 kV transmission network in Port Harcourt demonstrates substantial potential for enhancing the region's renewable energy capacity while maintaining grid stability. Analysis of solar irradiance data revealed significant seasonal variations, with peak energy generation during the dry season, offering reliable renewable energy throughout most of the year. Grid stability studies indicate effective voltage regulation, minimal deviations in frequency, and low total harmonic distortion, ensuring safe and reliable operation for sensitive equipment. Power system efficiency remains high, reaching 98% at a 100 MW load, reflecting optimal integration and effective utilization of the solar resource. The study confirms that careful modeling and simulation of the PV integration can mitigate potential challenges such as voltage fluctuations, transmission losses, and system inefficiencies. Overall, this research provides actionable insights for power system planners and policymakers seeking to integrate medium-scale solar PV plants into existing transmission networks.

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