

Investigating the impact of solar PV and wind energy systems on the strength of a longitudinal power grid

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ABSTRACT

The integration of inverter-based generation (IBG), such as solar photovoltaic (PV) and wind systems, presents unique challenges for power grid strength, especially in regions with limited conventional generation capacity. This study investigates the impact of such integration on the strength of Nigeria's power grid, focusing on sparsely connected northern region with abundant renewable resources. Using the network response short-circuit ratio (NRSCR) metric, which accounts for interactions between IBGs, we assess grid strength in three case studies. Simulations were conducted with the Power System Simulation for Engineering (PSS®E) software. Static analysis reveals inherent weakness in the northern region, characterized by low short-circuit capacity. Integrating IBGs at nine strategic locations shows varying responses: strong buses (NRSCR > 10) adapt well, while weak buses (NRSCR < 10), particularly in Kano and Katsina, constrain the operational capacity of the IBGs. Furthermore, close interaction among IBGs at these locations significantly impacts the system's dynamic response, although planned addition of conventional generators offers marginal improvement. This work highlights the potential of renewable resources to address energy shortages but also underscores the crucial need for detailed design studies at each point of interconnection (PoI), considering the longitudinal grid layout in the northern region and potential limitations imposed by IBG interactions. The findings also offer a structured approach that can be applied to power grids with comparable IBG integration levels, similar to the energy landscape of Nigeria.

1. Introduction

Power grids worldwide are mostly dominated by synchronous generators (SGs) powered by fossil-based fuels. However, rising energy demands and the need to reduce pollution from greenhouse gas emissions from these power plants are propelling utilities around the world to adopt inverter-based generation (IBG) driven by wind and solar renewable energy (RE) resources [1]. Traditionally, SGs have been the primary source of short-circuit current in power grids, maintaining voltage stability during system faults [2]. These short-circuit currents can be as high as 5 to 10 per unit depending on the SG size. In contrast, IBGs, often located in remote areas, inherently produce lower short-circuit currents, typically ranging from 1 to 2 per unit, with variations depending on specific IBG technology and control strategies [3, 4]. In essence, low short-circuit current is a direct consequence of the

large-scale penetration of IBG in power systems and may result in weak grid conditions with a greater risk of voltage instability. In such a scenario, the lack of sufficient system strength is detrimental to the efficient operation of power grids. Thus, the viability of utility-scale deployment requires an adequate understanding of IBG's response to different operating conditions.

The strength of power systems with SGs is measured by their ability to provide sufficient short-circuit current during faults [5]. As a result, a strong grid has a high short-circuit capacity (SCC), whereas a weak grid has a low SCC, owing to high impedance [2,6]. In a power system with IBG, the short-circuit ratio (SCR) is used to measure the strength of the grid. It is traditionally used to assess the influence of AC/DC system interaction on the AC-side system strength in power grids with both AC and DC systems [7]. The SCR index is used to develop an understanding of reliability implications and quantify the risks associated with high

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penetration of IBGs at a given point of interconnection (PoI) given that all IBGs are not interacting with each other [8]. Increased penetration of IBG in power grids will limit the influence of existing SGs due to low SCC and inertia. Consequently, SCR values at such PoIs are reduced, leading to stability problems. For large-scale deployments of IBG, quasi SCR-based measures such as weighted short-circuit ratio (WSCR) and composite short-circuit ratio (CSCR) provide estimates of system strength that capture the interactions that occur among the IBGs [9,10]. While CSCR assumes full interaction exists among IBGs, WSCR captures interaction weighted by the average of the SCC at the IBG PoIs within a cluster. Essentially, the interaction of IBGs is critical for adequate system strength evaluation to enable system planners to identify a system's weaknesses when IBGs are incorporated [11,12].

Studies have shown that voltage stability is one of the most important technical challenges that may limit the operational capacity of IBG in high penetration scenarios [13]. This challenge manifests in the form of voltage fluctuation/variation during steady-state operation and outright instability during dynamic conditions [14]. In a power network penetrated by wind generation, voltage variation at a PoI and the system strength are strongly coupled [15], i.e., a PoI with lower SCR values (weak bus) exhibits higher variations, whereas a strong bus indicates less changes in bus voltage [16]. Similarly, voltage variations at the PoIs with low SCC are more detrimental than at PoIs with high SCC [17]. Moreover, it has been shown that maintaining stable bus voltage within an acceptable range may limit the IBG plant's capacity [18]. In addition, the allowable active power operating range of doubly-fed induction generators (DFIGs) and full-scale converter (FSC) wind turbine generators (WTG) is greatly reduced with decreased SCR value. This can, however, be improved with reactive power compensation, albeit marginally, as excessive compensation may reduce active power output capability and cause sustained voltage oscillations in a weak grid [18, 19].

High penetration of utility-scale IBGs on power grids remains a point of attraction for researchers worldwide. Within North Africa and the Middle East, the performance of grid-tied solar PV plants has been studied, with notable examples from Tunisia [20], Algeria [21], and Saudi Arabia [22]. In [23], a RE integration study for the 2030 Japanese power system is reported. The effect of wind penetration levels, electrical distance, and grid configuration on the initial rate of change of frequency (RoCoF) values on the Croatian power system was investigated in [24]. In [25], an investigation into the impact of solar PV and wind systems on the Lesotho national electricity grid revealed that increased penetration may lead to voltage violations for wind systems, while solar PV integration results in rotor angle instability. Comparative results on the effect of different penetration levels of solar PV systems on Ontario's power system stability reveal that voltage and transient stability improved for distributed PV as compared to centralized PV [26]. The authors in [27] and [28] investigated the impact of solar PV and wind generation penetration levels on voltage, frequency, and power of the Jordanian and Egyptian national grids, respectively. In [29], large-scale offshore wind farm integration for a renewable-rich area of the Korean power grid is considered. The result showed that system strength evaluation with consideration of the actual interaction of offshore wind farms and other IBGs is necessary for accurate assessment.

In Nigeria, generation planning and viability of utility-scale solar PV and wind generation have been reported in [30]. [31] demonstrated the ability of DFIG to mitigate overvoltage issues in the northern part of the Nigerian grid. [32] showed that dispersed large-scale deployment of solar PV can enhance the voltage stability of the grid when compared with centralized solar PV. However, the idea of replacing the existing shunt reactors with solar PV may not be an attractive proposition due to the intermittent nature of solar resources. While these studies have highlighted the importance of utility-scale IBGs (solar PV and wind) on the Nigerian grid, works specifically related to system strength are limited and scarce. This paper, therefore, assesses the impact of large-scale solar PV and wind energy system integration on the strength

of the Nigerian 330 kV grid. The system's strength is estimated using the network response short-circuit ratio (NRSCR), a metric that considers interaction among IBGs and its relation to static and dynamic voltage stability while adhering to the requirements of the Nigerian grid code. No prior research has documented the impact of IBGs on the strength of the Nigerian grid, making this study a pioneering contribution to the field. The key contributions of this paper can be summarized as follows:

- Scenario-based static analysis to evaluate the strength of the Nigerian grid in terms of short-circuit capacity and voltage response to increasing demand.
- Utilizing the NRSCR measure to evaluate the grid's strength with multiple IBGs. The relationship between this index and power transfer in the network is compared across different case studies.
- Evaluating the dynamic response of the IBGs to system disturbances to determine their impact on the voltage stability of the Point of Interconnection (PoI).

The rest of the paper is organized as follows: [Section 2](#) elucidates a description of the Nigerian 330 kV grid under study, and the prospects of solar PV and wind integration as determined by the availability of resources are described in [Section 3](#). The system modeling and simulation process is presented in [Section 4](#). [Section 5](#) presents the results of the strength assessment for three different cases and two scenarios. Conclusions are deduced in [Section 6](#).

2. Background

This section describes the existing Nigerian national grid along with the prospects for RE integration.

2.1. Overview of the Nigerian power system

Deregulation of the Nigerian power sector in 2005 led to the creation of six generation companies (GenCos), one transmission company (TCN), and eleven distribution companies (DisCos). Since then, it has undertaken a rapid expansion program that has increased the number of GenCos to 23 through independent power producers (IPPs) and the National Integrated Power Project (NIPP) scheme of the government. Currently, the System Operation (SO) reports that the installed generation capacity is 13,014 MW while the available capacity is 7653 MW as of 2020. Although the transmission network has also been expanded to increase its capacity, the transmission wheeling capacity of the grid is still limited to 7300 MW [33]. The identified factors responsible for these inadequacies include inadequate and aging transmission and distribution equipment; disruptions in gas supply for thermal generators; and unpredictable weather patterns for hydro generation. Thus, the available power is rationed among the DisCos through load shedding, thereby leaving most consumers without electricity.

2.2. Prospects of solar and wind energy in Nigeria

Nigeria's location along the equator with tropical climatic conditions makes it strategically placed for high solar radiation. Sunshine hours range from about 3.5 h/day along the coast in the south to about 9 h/day in the north. Based on Nigeria's total land mass of $924 \times 10^3 \text{ km}^2$, which translates to an average of $1.804 \times 10^{15} \text{ kWh}$ of incident solar energy per annum with a daily average irradiance of $5.535 \text{ kWh/m}^2/\text{day}$ [34]. The wind energy potential for Nigeria is also adequate, with reports of average wind speeds hitting 3 m/s. Although it could be as low as 1.77 m/s in the south, reports also show that it may well increase to 9.5 m/s in the north [35]. This makes northern region of Nigeria the most energy-rich in terms of wind speed and solar radiation potential. The region is also not short of available land for utility-scale deployments if required. To this end, the Nigerian Bulk Electricity Trading (NBET) Plc

Table 1
Solar PV and wind energy projects in Northern Nigeria with signed PPA.

S/N	Project / Project Company	State	Type	Capacity (MW)	Connecting Transmission Bus	Equivalent Capacity (MW)
1	KVK Power Limited	Sokoto	Solar	55	Birnin Kebbi	55
2	Nigerian Solar Capital Partners	Bauchi	Solar	100	Gombe	100
3	LR Aaron Power	Abuja	Solar	100	Gwagwalada	100
4	CT Cosmos	Plateau	Solar	70	Jos	220
5	Quaint Abiba Power	Kaduna	Solar	50		
6	Anjeed Innova Group	Kaduna	Solar	100		
7	EN Africa	Kaduna	Solar	50	Kaduna	50
8	Novia Scotia Power Development Company	Jigawa	Solar	80	Kano	130
9	Oriental Renewable Solutions	Jigawa	Solar	50		
10	Afrinergia Power Limited	Nasarawa	Solar	50	Katampe	50
11	Pan Africa Solar	Katsina	Solar	75	Katsina	175
12	Nova Solar 5 Farm Limited	Katsina	Solar	100		
13	Vergnet	Katsina	Wind (Type 3)	10	Katsina	10
14	Middle Band Solar One	Kogi	Solar	100	Lokoja	100
Total						990

in 2016 signed a power purchase agreement (PPA) with a number of investors (Table 1) willing to harness this resource for utility-scale systems [36].

3. System under study

3.1. System description

The single-line diagram of the Nigerian national grid system under study is shown in Fig. 1. It is a 72-bus system comprising of 19 conventional generators, 43 loads, and 79 overhead transmission lines. Power transmission is at voltage levels of 330 kV and 132 kV. Conventional generation in the southern part of the grid is mainly thermal power plants (gas turbines, steam turbines, and combined cycle) while the northern part of the grid, which is largely longitudinal is dominated by hydro generation. This region also has enormous RE resources such as wind and solar. Based on NBET PPA, renewable generation consisting of nine solar PV plants and 1 WTG (DFIG) plant, included in this study.

3.2. Modeling of IBG systems

This section presents the modelling of the solar PV system and DFIG systems, which are considered in this work.

3.2.1. Solar PV model

A solar PV generation system, as depicted in Fig. 2(a), comprises of a PV array, converter system, transformers, and associated connecting transmission lines. The fundamental circuit, illustrated in Fig. 2(b), represents how incident solar irradiance induces current flow. It features a solar cell modelled by a current source (I_{sc}), an anti-parallel diode carrying the current (I_D), and an inherent series-parallel resistance combinations contributing to the flow of I_{cell} and I_{sh} , respectively. The resulting cell output current can be described by Eq. (1) [37]:

$$I_{cell} = I_{sc} - I_D - I_{sh}, \quad (1)$$

By substituting the expressions for the shunt and diode currents, Eq. (2) provides the output current of a cell as follows [37]:

$$I_{cell} = I_{sc} - I_0 \left[\exp \left(\frac{q(V + IR_{se})}{nKT} - 1 \right) \right] - \frac{V + IR_{se}}{R_{sh}}, \quad (2)$$

Here, n is the constant representing an ideal diode condition, the Boltzmann constant is given as $k = 1.3806503 \times 10^{-23}$ J/K, the cell temperature is represented by T , q is the charge constant given as 1.602×10^{-19} C, I_0 is the saturation current of the diode, and R_{se} and R_{sh} represent the series and shunt resistance, respectively. Depending on the required size of the PV array, several series/parallel combinations of modules can be interconnected. The DC-AC inverters in this system provide physical isolation of the PV system from the grid. Moreover, they can inject active

power into the grid while providing controllable reactive power support. The inverter models represented by the q-d transformation can be expressed as [38]:

$$\begin{cases} V_q = RI_q + LpI_q + \omega LI_d + e_q \\ V_d = RI_d + LpI_d - \omega LI_q + e_d \end{cases} \quad (3)$$

where V_d , V_q , I_d , and I_q are respectively the d-q inverter voltages and currents; e_q and e_d are the grid voltages.

3.2.2. DFIG model

The structure of a grid-connected DFIG, shown in Fig. 3, includes both the stator and rotor connected to the grid, making it a variable-speed wind energy system. The stator enables direct grid connection, while additional power is extracted from the rotor through a back-to-back converter system. The DFIG's variable-speed capability, combined with maximum power point tracking, allows it to harness the maximum power regardless of wind speeds. Furthermore, the converter control system ensures a rapid dynamic response, maintaining a desired terminal voltage and minimizing power fluctuations caused by changing wind speeds or system disturbances [31]. The model for DFIG dynamics after the reference frame transformation (q-d frame) are expressed in Eqs. (4) – (7) [39,40].

$$V_{qs} = -r_s I_{qs} + \omega \lambda_{ds} + p \lambda_{qs} \quad (4)$$

$$V_{ds} = -r_s I_{ds} - \omega \lambda_{qs} + p \lambda_{ds} \quad (5)$$

$$V_{qr} = -r_r I_{qr} + (\omega - \omega_r) \lambda_{dr} + p \lambda_{qr} \quad (6)$$

$$V_{dr} = -r_r I_{dr} - (\omega - \omega_r) \lambda_{qr} + p \lambda_{dr} \quad (7)$$

where V_{qs} (I_{qs}), V_{ds} (I_{ds}), V_{qr} (I_{qr}), V_{dr} (I_{dr}) are the q and d-axis stator and rotor voltages (currents), respectively. ω and ω_r represent the synchronous and rotor speed, while r_s and r_r are the stator and rotor resistances, respectively. λ_{qs} , λ_{ds} , λ_{qr} , λ_{dr} are the q-axis and d-axis stator and rotor flux linkage, which are defined as follows [40]:

$$\lambda_{qs} = -[(L_{ls} + L_M)I_{qs} + L_M I_{qr}] \quad (8)$$

$$\lambda_{ds} = -[(L_{ls} + L_M)I_{ds} + L_M I_{dr}] \quad (9)$$

$$\lambda_{qr} = -[L_M I_{qs} + (L_{lr} + L_M)I_{qr}] \quad (10)$$

$$\lambda_{dr} = -[L_M I_{ds} + (L_{lr} + L_M)I_{dr}] \quad (11)$$

where L_{ls} , and L_{lr} is the stator and rotor self-inductances, respectively, and L_M denotes the mutual inductance. The active (P_s , P_r) and reactive (Q_s , Q_r) power supplied and extracted from the stator and rotor are given as [41]:

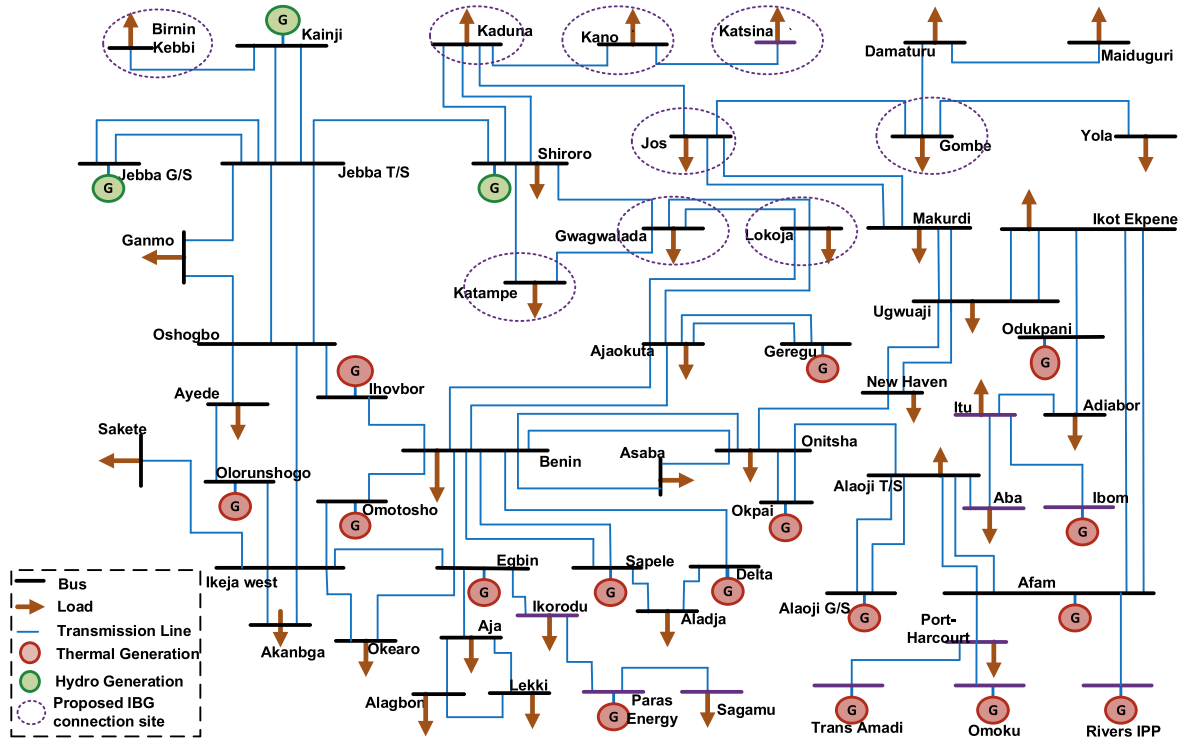


Fig. 1. Single-line diagram of the system under study.

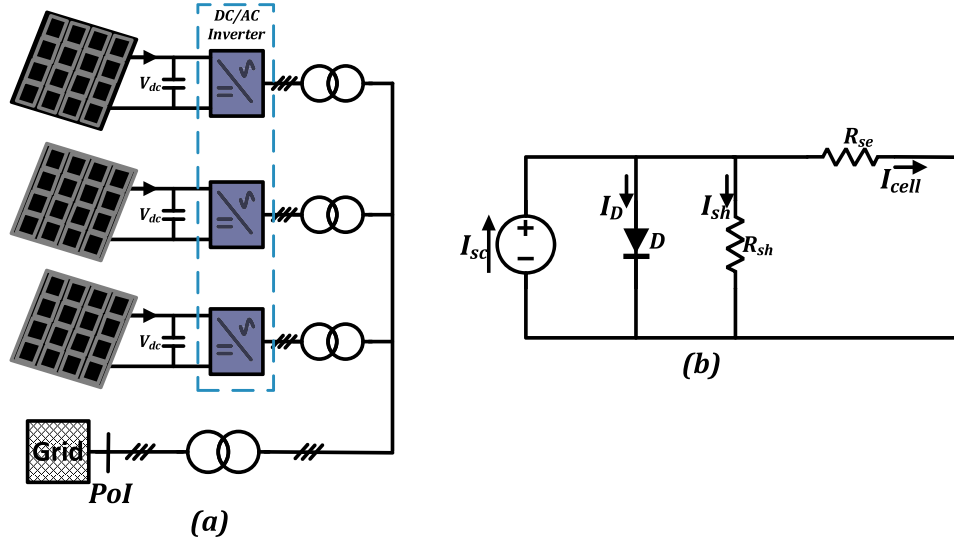


Fig. 2. (a) Schematic diagram of a grid-connected PV generation system, (b) Equivalent circuit of a PV cell.

$$P_s = \frac{3}{2} [V_{qs}I_{qs} + V_{ds}I_{ds}] \quad (12)$$

$$Q_s = \frac{3}{2} [V_{qs}I_{ds} - V_{ds}I_{qs}] \quad (13)$$

$$P_r = \frac{3}{2} [V_{qr}I_{qr} + V_{dr}I_{dr}] \quad (14)$$

$$Q_r = \frac{3}{2} [V_{qr}I_{dr} - V_{dr}I_{qr}] \quad (15)$$

Total active and reactive power available at the terminal of the DFIG is: $P_T = P_s + P_r$ and $Q_T = Q_s + Q_r$.

4. Methodology

In this section, the key tools for system strength assessment in power grids with and without IBGs are described, followed by a description of the complete approach. The SCC computation based on the IEC 60909 standard is used to examine the strength of the grid without IBG. The network response short-circuit ratio (NRSCR) estimates the strength at the PoI after IBG integration, while the power-voltage (P-V) analysis tool provides an assessment of the bus voltage response to increasing power demand in the network to identify the weak bus.

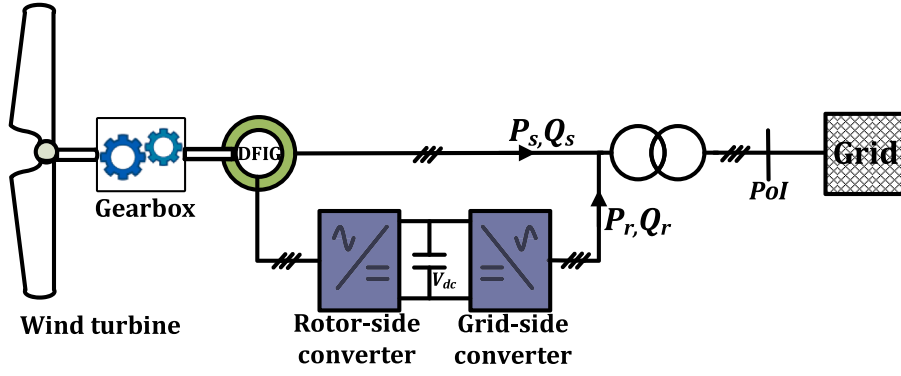


Fig. 3. Configuration of a grid-connected DFIG wind system [41].

4.1. Short-Circuit analysis

Short-circuit analysis is carried out to determine the currents that flow in a power system under fault conditions. Typically, short-circuit calculations are primarily used to determine the ratings of network equipment at the planning stage. If the SCC of the system exceeds the capacity of the protective device, a dangerous situation exists. Note that the SCC of a bus is the short-circuit current expressed as a power [6]. This information is also used to classify power grids as either weak or strong. In fact, the terms “SCC” and “system strength” are sometimes used interchangeably [42]. The higher the SCC of a bus, the stronger the bus. Short-circuit analysis was conducted in this study using the IEC 60909 standard, which expresses the short-circuit power as:

$$S'_k = \sqrt{3} \times V_n \times I'_k, \quad (16)$$

where S'_k is the short-circuit power to be computed, I'_k and V_n are the short-circuit current and the bus nominal voltage, respectively.

4.2. System strength assessment

Traditionally, the system strength of power grids with renewable energy resources (RER) is measured by the short-circuit ratio (SCR). It is defined as the ratio of the short-circuit capacity at the PoI to the rated capacity of the IBG. It is mathematically expressed as [43].

$$SCR_i = \frac{|S_{MVA,i}|}{P_{IBG,i}}, \quad (17)$$

where $S_{MVA,i}$ is the short-circuit capacity at bus i and; $P_{IBG,i}$ is the rated power of the IBG.

However, for multiple IBGs in a network in close proximity to each other, the SCR metric may not provide an adequate estimation because it ignores interactions that exist among multiple IBGs in large-scale deployments. To address this, a study by the authors in [43] proposed the network response short-circuit ratio (NRSCR), which captures the interactions among IBGs for evaluating system strength using the network structural characteristics of a power grid. Eq. (9) shows the expression for computing the NRSCR.

$$NRSCR_i = \frac{S_{SCC,i}}{\left(P_{IBG,i} + \sum_{j \in D, j \neq i} [P_{IBG}^C]_{ji} \right)}, \quad (18)$$

where $S_{SCC,i}$ is the short-circuit capacity at the i^{th} IBG bus prior to the connection of the IBG, $P_{IBG,i}$ is the rated capacity or active power injection of the IBG connected at bus i , $[P_{IBG}^C]_{ji}$ is the fraction of neighboring IBG injection at bus j interacting with the IBG at bus i , and D is the total number of IBGs in the network.

The conventional guideline for assessing system strength through SCR-based metrics suggests categorizing grids as strong when SCR

exceeds 3, weak for SCR values ranging between 2 and 3, and very weak when SCR falls below 2 [7,12,19]. Nevertheless, variations in SCR thresholds may exist to accommodate the unique characteristics of specific grids [36,44].

4.3. P-V curve analysis

P-V curve analysis is typically used to perform static voltage stability analyses in power systems. The concept is well documented in the literature [45]. It offers a useful way to determine the maximum power transferable from generation to the load demand (as it increases). Fig. 4 shows a typical plot of this load increase with respect to variations in bus voltages. It is obtained through a series of power flow solutions by increasing the power injection at generators in response to load increases while monitoring its impact on the bus voltage profile. The point where the power flow solution no longer converges gives the maximum active power (P_{max}) transmitted to the load and it is identified as the “voltage collapse point”. A stronger system ($SCR = 4$) allows for greater power transfer compared to a weaker one ($SCR < 4$). Thus, a P-V curve can indicate if the system’s strength is weak or strong [11]. This study also employs the use of P-V curve analysis to evaluate the impact of system strength on the maximum active power transferable in a power grid and its impact on voltage stability.

4.4. System modelling and simulation

This study involves a detailed evaluation of system strength for three scenarios including both steady-state and dynamic conditions. The aim is to provide a comprehensive understanding of system response following the integration of IBGs. The steady-state analysis includes short-circuit computation and P-V analysis while the system response based on the strength estimates is used to conduct dynamic analysis. Bus voltage, and reactive power outputs of IBGs are observed during the dynamic simulations. The proposed methodology is implemented in a step-wise framework using the Power System Simulation for Engineering (PSS®E) software and Python programming language through the application program interface (API). This framework, illustrated in Fig. 5, leverages PSS®E’s capabilities for analyzing the performance of a power system transmission network and generation under both steady-state and dynamic conditions, while Python facilitates data manipulation and custom visualizations. The simulations were performed on a computer with a 2.5 GHz core i5 processor and Windows 10 64-bit OS. In this paper, the required data with respect to the transmission network, including bus location, branches, transformers, machines, load and shunt devices, was obtained from the TCN and used to create a static and dynamic network model of the Nigeria 330 kV network in this study.

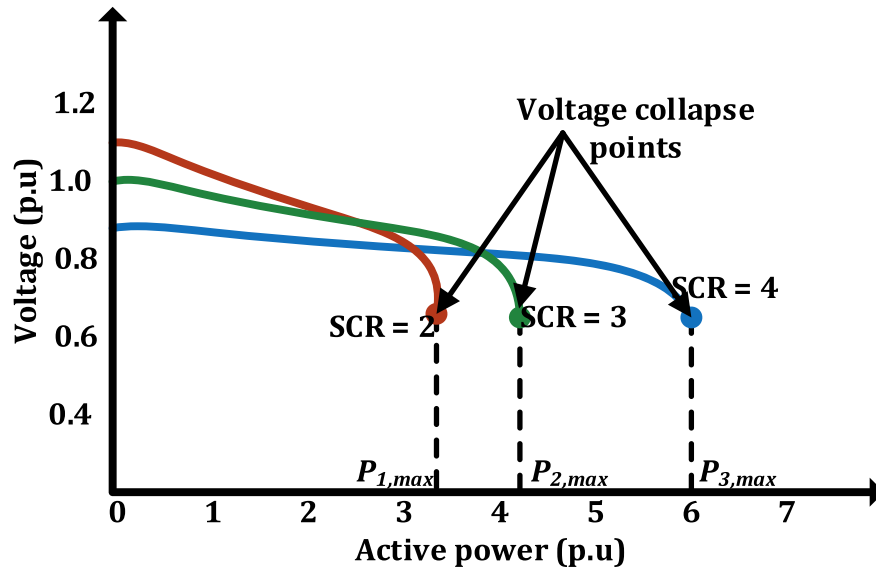


Fig. 4. P-V curves showing the maximum power transfer points for different strength [7,11].

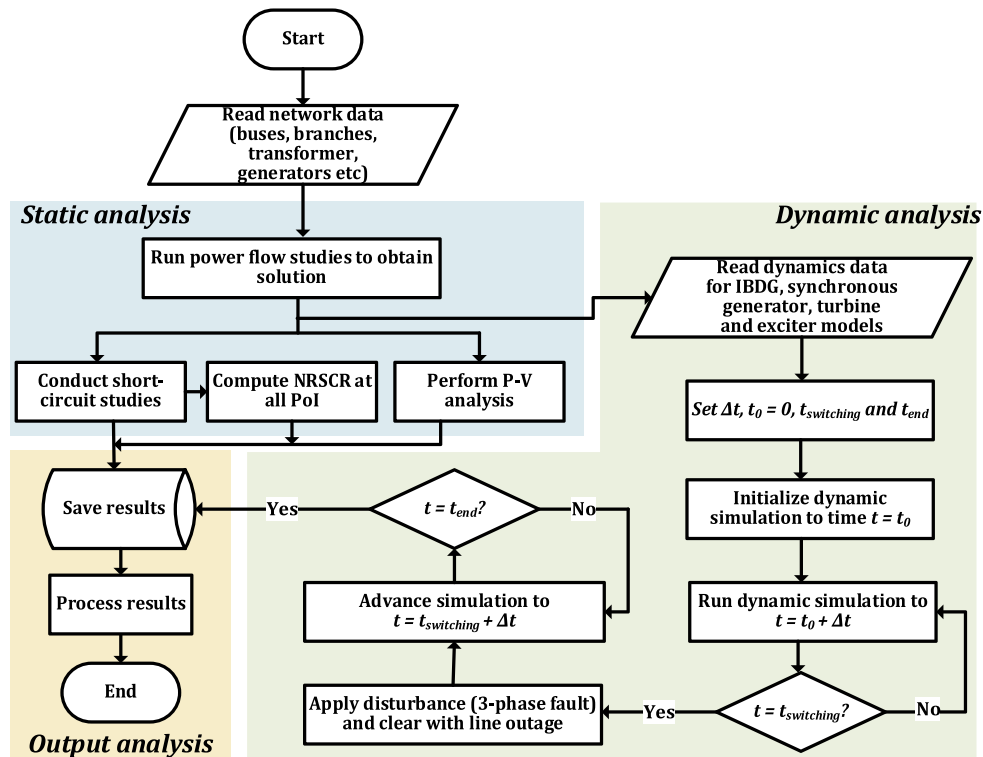


Fig. 5. Flowchart of the proposed methodology for each case study.

5. Results and discussion

Three case studies are examined in this paper. Case 1 is the base case scenario which captures the existing Nigerian grid without any RE generators. Short-circuit studies and P-V analysis were conducted to identify the weak buses in the network. This is to provide an understanding of the current state of the network. The second case (case 2) involves the integration of the proposed solar PV and wind power plant on selected buses based on the existing NBET PPA. The aim here is to investigate the impact of these integrations on system operations based on system strength at the PoI. Case 3 is built upon case 2 by integrating completed and soon to be completed power plants with synchronous

generators into the network. These new generators are expected to reinforce the network and provide insight of their impact on the

Table 2
Summary of case studies.

Case study	Total load (MW)	Total synchronous generation (MW)	Total RE generation (MW)	Penetration level (%)
Case 1	4842.75	4913.77	0.0	0.0
Case 2	4842.75	3923.60	990.18	20.15
Case 3	4842.75	3923.60	990.18	20.15

operation of the IBGs integrated in case 2. In this paper, we adopt the grid-following, voltage control mode for all IBGs. Moreover, solar PV generators operate at unity power factor while the DFIG plant operates at 0.95 power factor. Table 2 provides a summary of the case studies considered in this paper.

5.1. Steady-state analysis

Steady-state analysis of the Nigerian 330 kV network is carried out in this section through short-circuit analysis, and P-V curve analysis. We also demonstrate the impact of system strength on voltage stability and power transfer in this section.

5.1.1. Case 1: existing Nigerian grid (base case)

The strength of the grid without the IBGs is defined by its fault level and quantified by the available short-circuit current at a particular bus in the network. A short-circuit study is conducted on the network using the IEC 60909 standard and fault current is determined for each bus as described in section II. Fig. 6 shows that the largest short-circuit current in the network is 35 kA at Benin, while the least is 0.66 kA at Maiduguri. It is observed that 50 % of the buses have a short-circuit current of less than 10 kA, with the buses in the northern longitudinal part of the grid forming the majority. Some of these buses, including Birnin Kebbi, Gombe, Jos, Kano and Katsina, are proposed for IBG integration based on the NBET agreement. This should be of concern for the future integration of IBGs into the grid in this region.

The base case system is also subjected to P-V analysis to determine weak buses with poor response to increasing loads in the network. The P-V curve shown in Fig. 7 reveals that the buses at Maiduguri, Damaturu, Gombe, and Yola are the weakest with respect to voltage response to increasing power transfer. This case shows that the maximum power transferable by the system is 807 MW.

5.1.2. Case 2: integration of the proposed IBG systems

This case integrates the NBET's proposed IBGs (solar PV and wind systems) into the existing Nigerian 330 kV grid, presented in case 1. The aim is to evaluate the system strength at the PoIs of renewable energy sources (RES) and investigate its impact on the operational capacity of the grid. Based on an NBET PPA with some investors, the buses at Kano, Katsina, Kaduna, Gombe, Birnin Kebbi, Gwagwalada, Katampe, Lokoja, and Jos have been identified as the PoI for the IBGs. The SCC at these PoIs as obtained in case 1 (without IBG) is shown in Fig. 8. It is observed that most of the PoIs exhibit low short-circuit power, with Lokoja having the maximum at 1805.67 MVA, while the PoI at Gombe has the least SCC of 567.77 MVA. Given the rated power output of the IBGs at the PoI,

system strength is evaluated using NRSCR and computed with Eq. (18). Table 3 presents the results of the system strength evaluation for this case. It is observed that the buses at Kano, Katsina, Kaduna, Gombe and Jos all have NRSCR values of less than 10. In particular, the values for the buses at Kano (2.10) and Katsina (1.97) indicate a very weak condition and a potential source of concern for the grid. All other buses have NRSCR value greater than 10 and are identified as strong.

P-V analysis is conducted by dispatching all the IBGs only to supply the load increase in the network indicates that a power transfer of 516 MW is allowed in this case. As shown in Fig. 9, the P-V curve indicates that the strong buses at Birnin Kebbi, Gwagwalada, Katampe, and Lokoja experience little or no deviation from the initial values. Other buses in the network experienced different levels of deviation, with the bus at Gombe exhibiting the highest voltage sensitivity to increasing system load in both scenarios. This is similar to the response obtained in case 1, showing that integrating an IBG at Gombe may not be sufficient to improve its poor voltage response and may require a supplementary reactive power source. This is in line with the base case results, i.e., the buses in the northern part are mostly weak and should be a matter of concern to system operators limiting the size of the IBG to be incorporated corresponding to these weak points.

5.1.3. Case 3: integration of future generations in northern Nigeria

In this section, the addition of soon to be completed synchronous generation systems in the northern part of the Nigerian grid is considered. Table 4 outlines these generations, that are at various levels of completion. The procedures implemented in case 2 are repeated in this case. Hence, short-circuit analysis, system strength evaluation, and P-V curve analysis is carried out with solar PV and wind power systems incorporated into the same buses as in case 2 for the Nigeria 330 kV Power Grid.

Comparative results of the short-circuit analysis for the buses with IBG connections following the integration of additional synchronous generators in the northern region are illustrated in Fig. 10. Except for the bus at Kaduna, it is observed that all other buses experienced little or no increase in SCC. This is largely due to the small size of the new generator being added, the long line between these buses and the new generations and the longitudinal grid structure, resulting in limited short-circuit contributions.

The result of system strength computed for this case, as presented in Table 5, indicates a system-wide improvement for all the buses. NRSCR at Kano and Katsina buses improved to 2.25 and 2.10 from 2.10 and 1.97, respectively, when compared to the same scenario in case 2. Nevertheless, these values are still low and do not indicate a significant improvement in the system strength at these locations. Moreover,

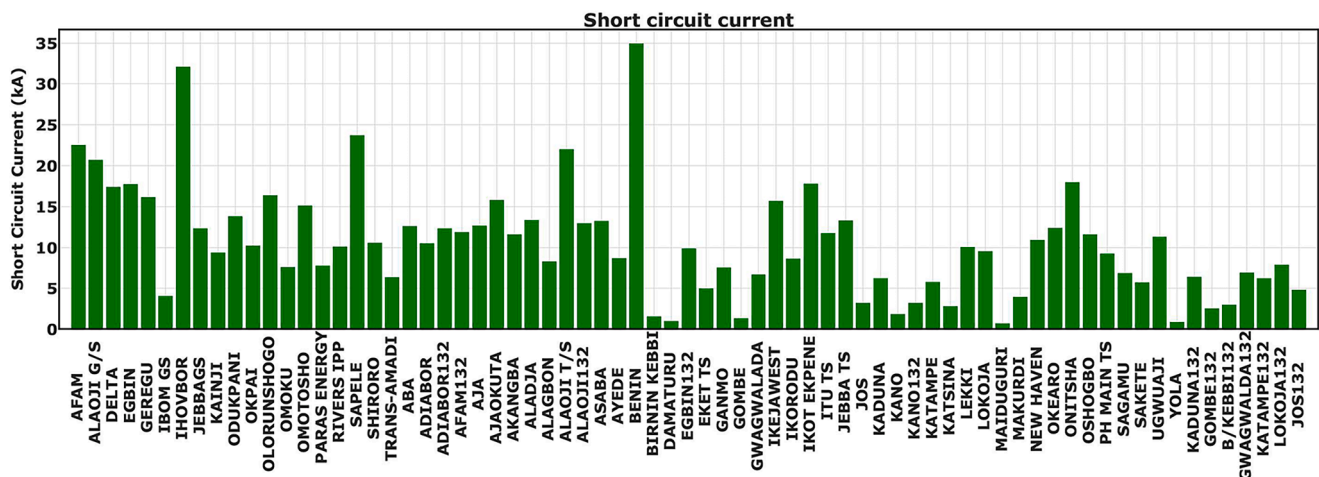


Fig. 6. Short-circuit current profile for case 1.

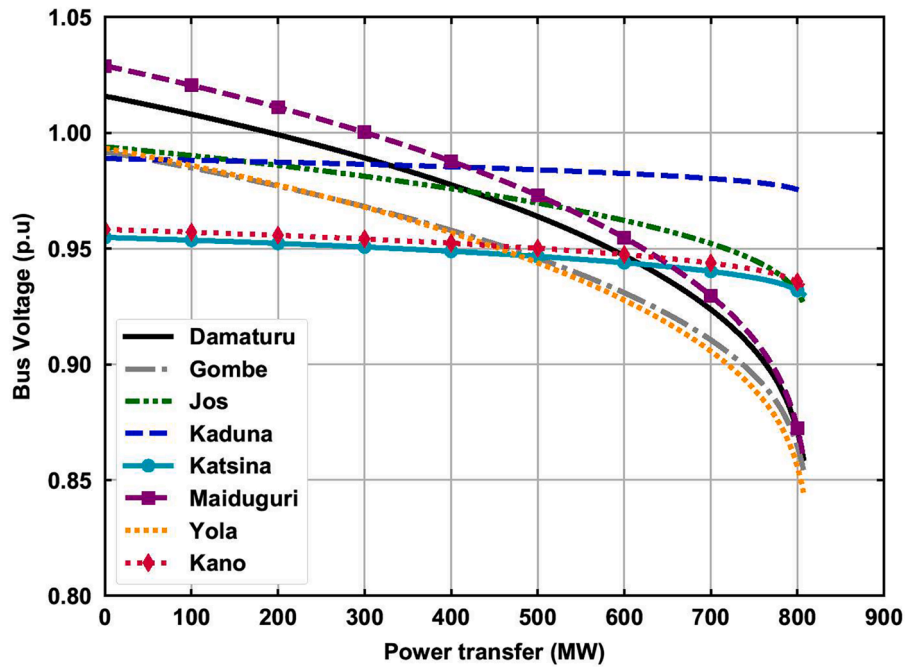


Fig. 7. P-V curves for selected Northern buses in case 1.

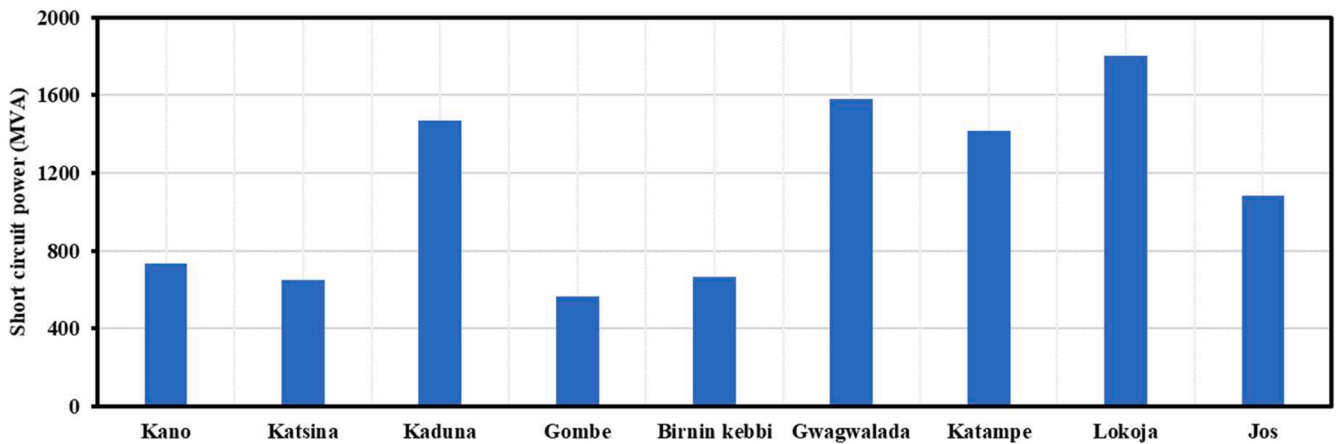


Fig. 8. Short-circuit capacity at the PoI prior to the IBG connection.

Table 3

System strength evaluation result for case 2.

PoI	Short-circuit power (MVA)	IBG Power injection (MW)	NRSCR
Kano	735.01	130	2.10
Katsina	650.33	185	1.97
Kaduna	1472.13	200	7.43
Gombe	571.77	100	3.00
Birnin kebbi	664.41	55	12.08
Gwagwalada	1581.97	100	13.48
Katampe	1415.51	50	19.01
Lokoja	1805.67	100	16.49
Jos	1085.71	70	3.26

Kaduna now has an NRSCR value of 10.31, representing a 39 % increase when compared with case 2. This improvement results from the additional synchronous generator at Kudenda and Gurara bus, which increased the short-circuit power at Kaduna.

The P-V curve response for case 3 is shown in Fig. 11. Power transfer improved from 520 MW in case 2 to 1600 MW in case 3. This shows that

the additional synchronous generation systems increase the power transfer capability of the IBGs in the network. The buses at Birnin Kebbi, Gwagwalada, Katampe, and Lokoja are still able to maintain a constant voltage profile with increasing load demand for the two scenarios. It is also observed that the voltage response to increasing demand has improved for Gombe due to the availability of reactive power support from the new generator at Dadin-Kowa, which is closer to Gombe. While Kano and Katsina exhibited the worst voltage response to increasing demand which confirms the inherent weakness of these buses.

5.2. Dynamic voltage stability analysis

The dynamic voltage stability of the Nigerian power grid with IBGs is examined by assessing the response to a disturbance. Cases 2 and 3 presented in the previous section are subjected to a credible disturbance to examine the dynamic response of bus voltage and reactive power injection at the PoI. A disturbance is simulated by applying a three-phase fault at the Shiroro bus for 300 ms, that is then cleared by tripping the Shiroro–Jebba transmission line. The response of the IBG with respect to system strength evaluated with NRSCR is examined.

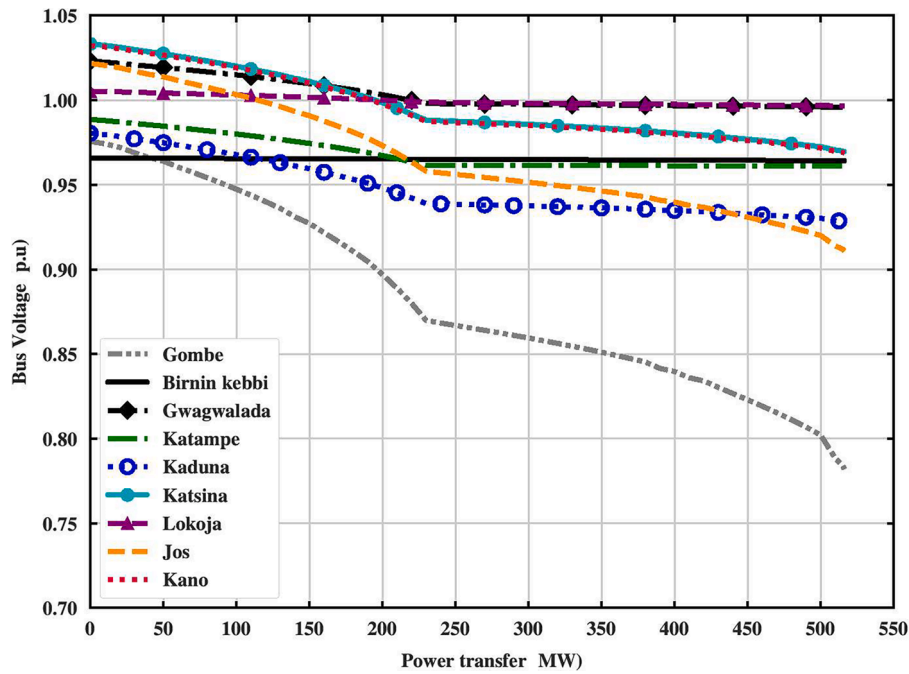


Fig. 9. P-V curves for PoI in case 2.

Table 4

Future additional generation planned for integration into the Nigeria grid.

Generation plant	State	Type	Capacity (MW)
Kashimbilla	Taraba	Hydro	40
Dadin-kowa	Gombe	Hydro	39
Gurara	Kaduna	Hydro	30
Zungeru	Niger	Hydro	700
Kudenda	Kaduna	Thermal	215

5.2.1. Case 2: integration of proposed IBG generation systems

Fig. 12 shows bus voltage responses to the disturbance at all the PoIs. It is observed that the bus voltages at Kano, Katsina, Kaduna, Gombe, and Jos exhibit some transients, while the fault lasts when the NRSCR values are less than 10. A reason attributed to this response is the closeness of the two weakest buses, Kano and Katsina, to each other; low short-circuit power relative to the size of IBGs on these buses; and the control action of the power electronic systems of the IBGs interacting with each other to ensure that steady-state operation of the system is restored. This confirms that the rapid dynamic response of IBG voltage controllers has a considerable impact on grid stability. In addition,

system strength as measured by NRSCR is also indicative of areas where additional studies will be required to understand the system response during dynamic conditions. The voltage response of the buses at Birnin Kebbi, Gwagwalada, Katampe, and Lokoja did not experience this transient behavior, even though Katampe and Gwagwalada are closer to the fault location. A comparative review of the NRSCR value for these buses shows that it is greater than 10, indicating that they are strong buses. In addition, the IBG power output at Birnin Kebbi, Gwagwalada, Katampe, and Lokoja is small when compared with the buses that experience transients. Fig. 13 shows the reactive power output from IBGs at all the PoIs. The high frequency oscillation observed in the response for the buses at Kano, Katsina, Kaduna, Gombe, and Jos apparently explains the voltage response for these buses. Moreover, the reactive power and voltages at these buses have a high correlation, hence the transients observed at these buses during fault conditions. In contrast, reactive power injection at Birnin Kebbi, Gwagwalada, Katampe, and Lokoja did not demonstrate any aggressive control action from the power electronics, largely due to the strong grid conditions at the respective PoIs.

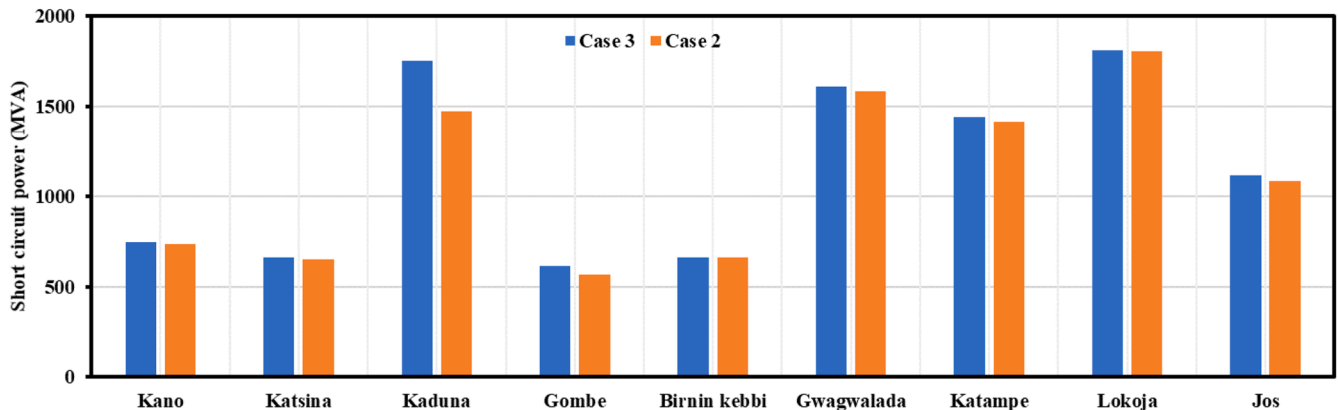


Fig. 10. Comparison of short-circuit capacity for cases 2 and 3.

Table 5
System strength evaluation result for case 3.

PoI	Short-circuit power (MVA)	IBG Power injection (MW)	NRSCR
Kano	750.26	130	2.25
Katsina	662.19	185	2.10
Kaduna	1750.63	200	10.31
Gombe	616.98	100	3.30
Birnin kebbi	665.39	55	12.10
Gwagwalada	1608.43	100	13.70
Katampe	1439.79	50	19.34
Lokoja	1809.81	100	16.53
Jos	1118.14	70	4.06

5.2.2. Case 3: integration of future generations in northern Nigeria

Simulations performed under case 2 are repeated on the network with additional conventional generators in the northern region. Fig. 14 shows the voltage profiles at the PoIs for this case. It is observed that the voltage transients exhibited at Kano, Katsina, Kaduna, Jos, and Gombe in case 2 are no longer present in this case. Specifically, Kaduna, which now has an NRSCR value exceeding 10, did not exhibit the severe voltage dip previously observed at Kano, Katsina, Gombe, and Jos. The additional short-circuit capacity from the new synchronous generators at Kudenda, Gurara, and Dadin-Kowa, which are close to these buses, is responsible. Also, post-fault oscillations observed for most buses in case 2 have either been eliminated or reduced in this case. This shows that

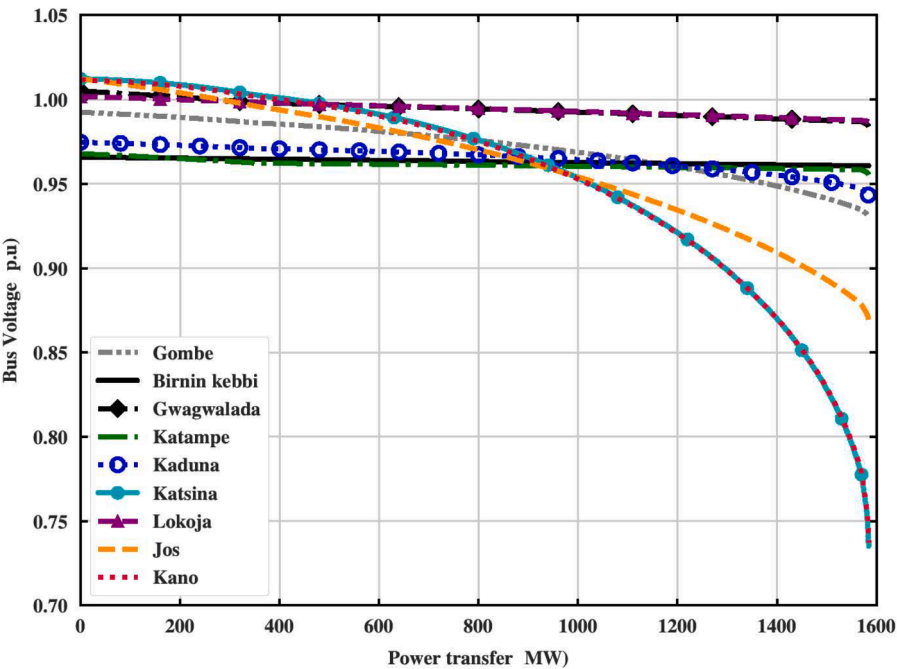


Fig. 11. P-V curves for the PoIs in case 3.

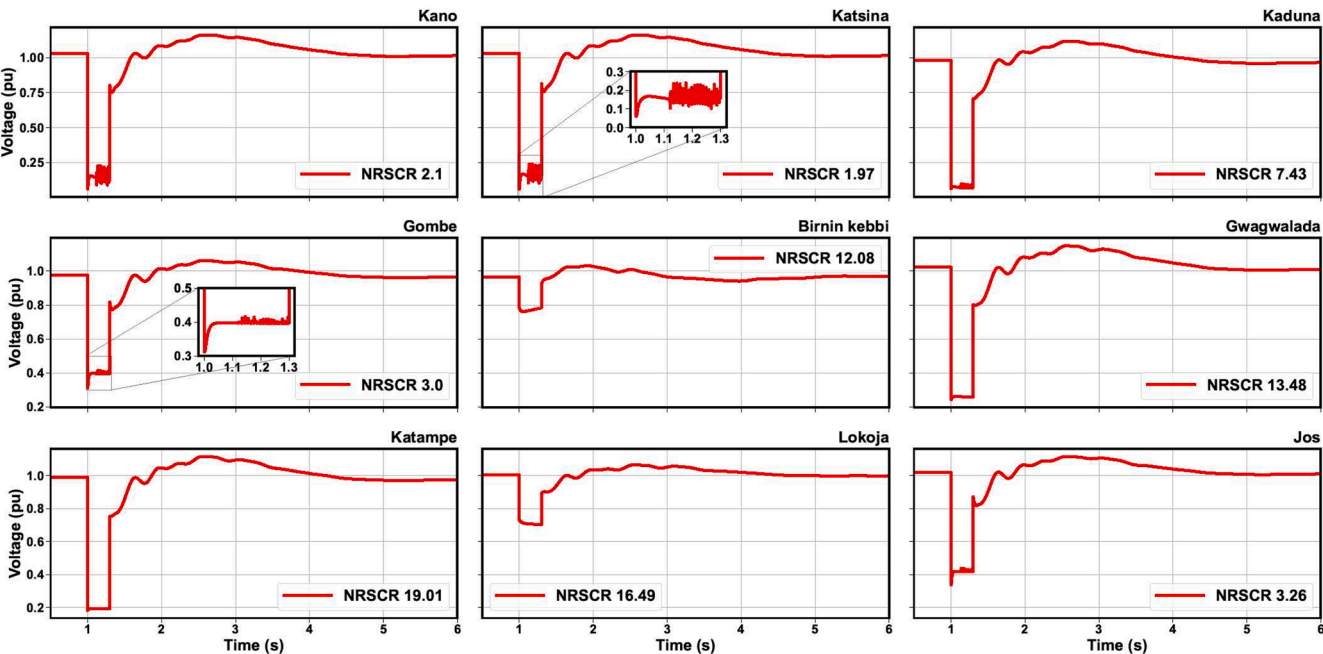


Fig. 12. Dynamic voltage response after introducing a disturbance in case 2.

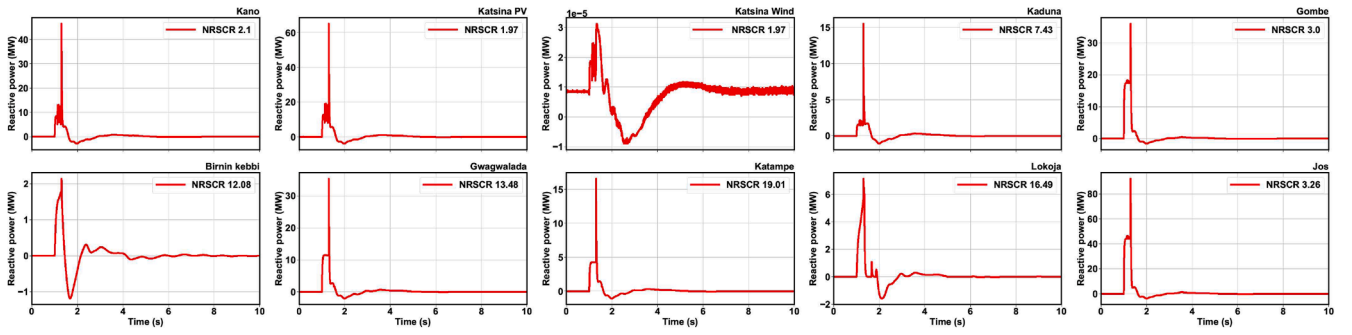


Fig. 13. Reactive power response after introducing a disturbance in case 2.

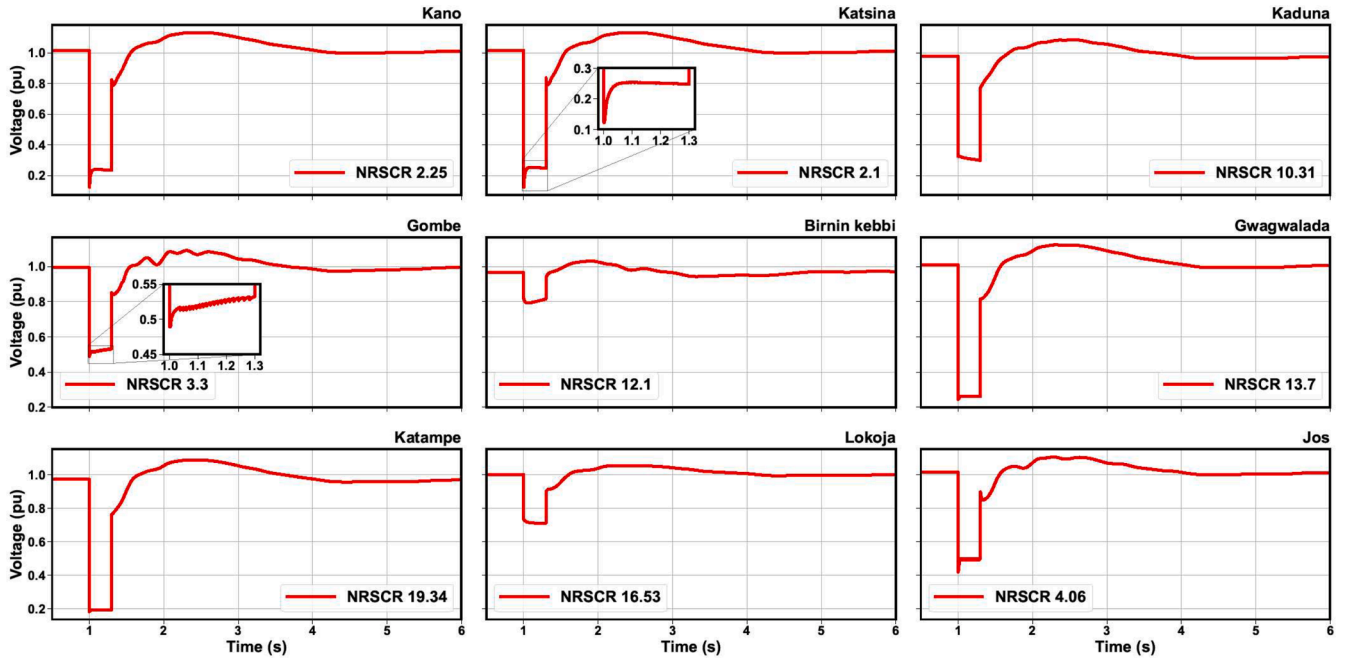


Fig. 14. Dynamic voltage response after introducing a disturbance in case 3.

the new generators in northern Nigeria can provide stability and support for the grid. The reactive power response at the PoI illustrated in Fig. 15 shows that the persistent oscillations encountered at the buses in Kano, Katsina, Kaduna, Gombe, and Jos are the result of interactions among the IBGs and the control actions of the converters due to the high dv/dq sensitivity of the solar PV plants. There is no significant difference in the reactive power response at the other PoIs when compared to case 2.

5.3. Comparison with similar national grids

This section presents a comparative analysis of the impact of IBG integration on national grids, drawing insights from other similar studies of power systems in Nigeria, Lesotho, and Tunisia (Table 6). It highlights the growing trend of IBG integration efforts in Africa and underscores the importance of understanding their potential effects on grid stability and operational integrity.

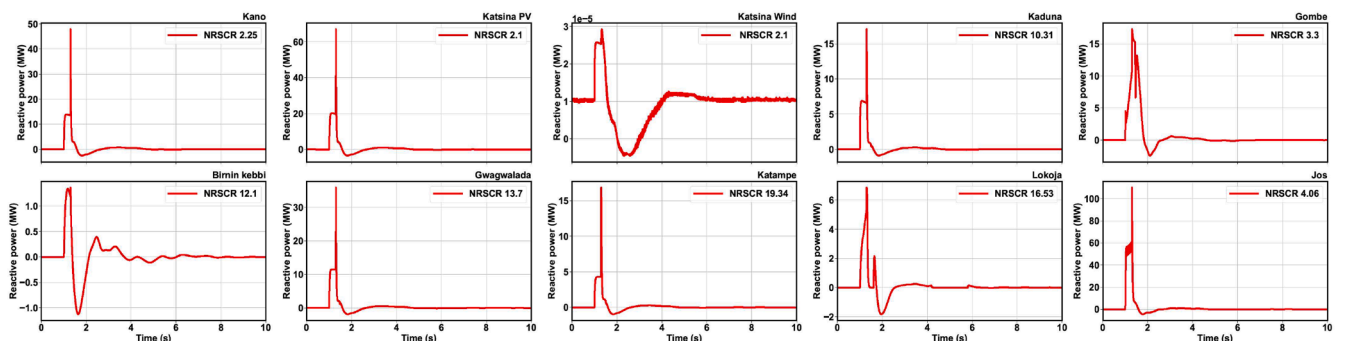


Fig. 15. Reactive power response after introducing a disturbance in case 3.

Table 6
Comparison of national grids with similar experiences.

Reference	IBG type	Location/Grid Characteristics	Methodology	Key Findings
Current study	Solar PV and Wind energy system (DFIG)	Nigeria, 72-bus, 330 kV power grid with abundant renewables in the weak northern region.	Static (short-circuit studies and PV curve analysis) and dynamic voltage analyses using PSS®E software. Evaluated grid strength with the NRSCR metric for different case studies.	Integrating IBGs has varying effects on grid strength across different locations. While strong grid connection points (NRSCR > 10) can adapt well to these IBGs, weak points (NRSCR < 10), particularly evident in Kano and Katsina, struggle. Highlights a key issue: high levels of renewable energy can negatively impact grid stability in regions with weak infrastructure and longitudinal layout.
[32]	Solar PV	Nigeria, 52-bus, 330 kV power grid with overvoltage issues in northern region.	Used static P-V and Q-V analyses with simulations conducted in DigSILENT PowerFactory and MATLAB.	Integration of centralized solar PV systems maintains acceptable voltage limits up to a 26.29 % penetration level (1000 MW), while dispersed systems achieve this at a lower penetration level of 21.44 % (800 MW). Additionally, dispersed system demonstrates superior voltage stability improvement.
[31]	Wind energy system (DFIG)	Nigeria, 52-bus, 330 kV 330 kV power grid with overvoltage issues in Northern Nigeria.	Voltage stability was analyzed using PV and QV curves, with simulations implemented in DigSILENT PowerFactory and MATLAB.	Incorporation of DFIG-based wind systems enhances voltage stability in weak grids, with an optimal penetration level of 35 % ensuring acceptable voltage levels, reduced equipment loading, and effective mitigation of overvoltage issues, particularly in the Northern region.
[25]	Solar PV and Wind energy system (DFIG)	Lesotho, 132 kV power grid.	Dynamic and steady state impacts on voltages were examined using DigSILENT PowerFactory.	Solar PV and wind power penetration of 35 MW and 50 MW respectively is achievable without causing voltage instability. However, increased wind integration can lead to voltage issues at neighboring substations, highlighting the need for further analysis as the grid expands.
[20]	Solar PV	Tunisia, 400 kV, 225-bus power grid.	Static PV-curve analysis and dynamic analysis were implemented using the MATLAB/PSAT toolbox.	PV-curve analysis suggests a maximum grid capacity of 2185 MW for solar PV. While short-circuit capability at the PoI impacts voltage stability, increased solar power generation with additional reactive power supply can improve voltage regulation and dynamic grid performance.

6. Conclusion

This study examined the impact of integrating solar PV and wind energy systems on the strength of the Nigerian 330 kV power grid. Grid strength was evaluated using the NRSCR metric, which accounts for interaction among IBGs. Static and dynamic voltage analyses were conducted for three case studies. Initial assessment of the grid’s base case without IBG integration through short-circuit studies and P-V analysis revealed that the buses in the northern (longitudinal) region are the weakest. This region is characterized by high RER but low short-circuit capacity and poor voltage response to increasing load demand. System strength evaluated based on the proposed integration of IBGs on nine different buses showed that the PoIs with NRSCR > 10 demonstrate a strong response to changing operating conditions. However, PoIs with NRSCR < 10 display weak system response, and the existence of some very weak buses in Kano and Katsina affects the operational capacity of the strong buses to support system operation.

Adding conventional generators in the northern region marginally improved short-circuit capacity, system strength, and operational margins. Dynamic analysis showed that the NRSCR index essentially indicates buses where additional studies will be required as the power electronic control system and the number of IBGs closely interacting with each other determine the system response during dynamic conditions. This work highlights the potential of Nigeria’s northern RER to address energy shortages but also underscores the limitations imposed by low short-circuit capacity and weak operational capacity. Therefore, detailed design studies are crucial to assess system strength and its impact on IBGs at individual PoIs. Further research is recommended to validate the proposed NRSCR threshold for the Nigerian grid through additional comprehensive studies. Also, investigating the transient stability of the grid under large-scale integration of both solar PV and wind generation is necessary.

CRediT authorship contribution statement

Shereefdeen Oladapo Sanni: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Ayodele Isqeel Abdullateef:** Writing – review & editing, Writing – original draft, Supervision, Project administration. **Olatunji Obalowu Mohammed:** Writing – review & editing, Writing – original draft, Supervision, Project administration. **Muhammad Naveed Aman:** Writing – review & editing, Writing – original draft. **Atanda Kamoru Raji:** Writing – review & editing, Writing – original draft. **Ibukun Damilola Fajuke:** Writing – review & editing, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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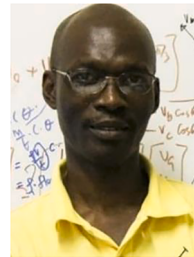
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