

PAPER 154 – THE IMPLICATIONS OF LOW SHORT-CIRCUIT CAPACITY ON THE STRENGTH OF POWER GRID: A NIGERIAN CASE STUDY

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ABSTRACT

The quest to integrate renewable energy sources (RES) into power grids arises from the need to adopt a sustainable source of energy while achieving energy security. RES such as solar photovoltaic (PV) and wind energy systems are also called inverter-based generators (IBGs) because of their inverter-interfaced connections with the grid. The inverter's quick dynamic response and low short-circuit capacity (SCC) can cause distress to the grid and potentially result in power system stability problems. This paper has assessed the SCC and system strength of the Nigerian grid based on proposed IBG integrations in the northern part of the country. A short-circuit study was conducted, system strength was evaluated using the Network Response Short Circuit Ratio (NRSCR), and a dynamic voltage stability analysis was performed. These studies revealed that most of the proposed points on the grid have low SCC but suitable for the size of IBG integration; however, some identified weak points may affect the stability of the grid. The results of this investigation provide valuable insights on the impact of IBG integration in renewable energy-rich, SCC-deficient areas of a grid.

KEYWORDS: Renewable energy resources; Inverter-based generators, Short-circuit capacity; Solar PV; System strength; Wind energy system; Voltage stability

1. INTRODUCTION

The Nigerian power grid, like many others around the world, is struggling to meet the increasing demand for energy due to inadequate generation. But then, the adoption of renewable energy sources (RES) has provided an alternative source, largely owing to its reduced marginal costs and a drive for low-carbon generation (Gordon et al., 2022). RES popularity has been further supported by government incentives and advancements in technological breakthroughs, and it is projected that Nigeria's energy mix will increasingly incorporate renewable energy sources, as shown in Figure 1 (International Renewable Energy Agency, 2023).

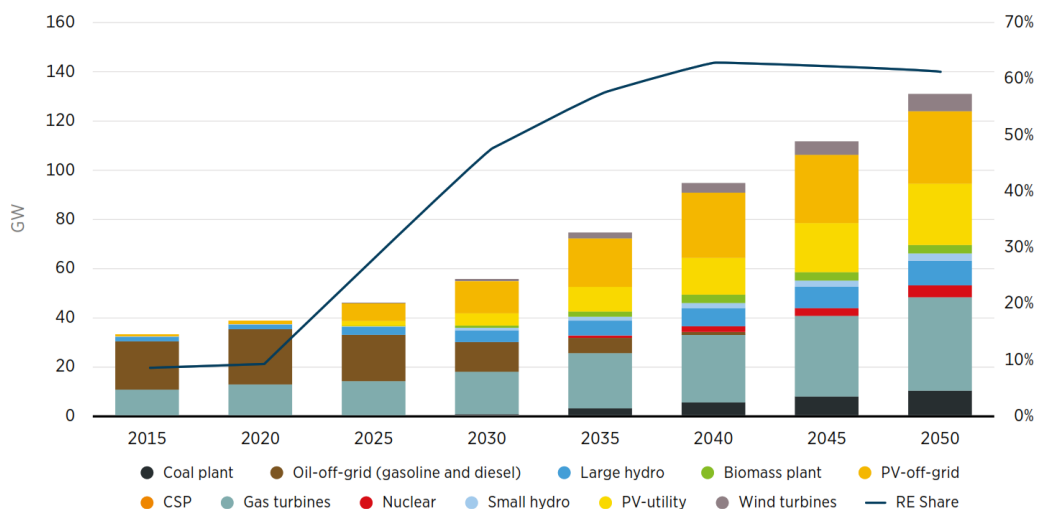


Fig. 1. Electricity generation based on generation technology under current plans and policies

Although RES technologies such as solar photovoltaic and wind energy systems, which are within a larger group of generators known as inverter-based generators (IBGs), are the most prevalent, their power electronics inverter interface may pose a challenge to the stable operation of power grids. Traditionally, synchronous generators (SGs) are the primary sources of short-circuit current, which ensures power grid resilience during system disturbances.

The large-scale integration and preference of IBGs over SGs in power systems, however, leads to low short-circuit current, which can make a power grid vulnerable. The strength of the grid at a specific point in the network is one such vulnerability and is characterized by the size of the short-circuit capacity (SCC). IBGs are typically located in remote regions of an electric power grid, where they are connected to the main grid by long transmission lines and are not supported by SGs, which provide short-circuit services (Ekic et al., 2018). As the penetration level of IBGs increases in some areas and the commitment to synchronous resources falls, these areas become weak. The weakness is aggravated by the rapid dynamic response of the inverter controller, which responds quickly to any slight deviation from normal operating conditions (Mohammed et al., 2019). Moreover, having a large concentration of these IBGs within an area will allow them to interact with each other, causing significant weak grid issues.

System strength assessment is an essential requirement for power system operators and planners to provide adequate understanding of potential weak grid areas prior to the integration of an IBG. The system strength of a power grid with IBG is quantified by the short-circuit ratio (SCR) (North American Electric Reliability Corporation, 2017). It estimates how rigid the grid is to disruptions such as changing power injection or equipment switching. Although SCR's computation is based on the steady state parameter, it is an indicator of a bus's resilience to disturbance during dynamic conditions (Goud et al., 2019). SCR computation, however, does not consider the impact of interactions between IBGs, which can lead to inaccurate estimates of the grid's strength at the PoIs for IBG (North American Electric Reliability Corporation, 2017; Zhang et al., 2014). Other available methods, such as the weighted short-circuit ratio (WSCR) developed by ERCOT (Zhang et al., 2014) and the composite short-circuit ratio (CSCR) developed by GE (GE Energy, 2014), do consider the effects of IBG interactions on grid strength but fail to account for the electrical connections between IBGs, which can result in an inaccurate representation of the grid's strength at PoIs. Moreover, both the CSCR and WSCR methods mainly provide the combined strength of a power grid in the area where the IBGs are interconnected, but they do not compute the strength of the grid at each individual PoI within an area (Aldaoudeyeh et al., 2019). The network response short-circuit ratio (NRSCR) proposed by Sanni et al. (2022) addresses these limitations and provides a more accurate assessment of the grid's strength at PoIs by accounting for both the interactions among IBGs and their electrical connections.

This paper presents an investigation into the impact of low SCC on system strength at the PoI when IBGs are integrated. The Nigerian transmission grid is used as the case study based on the proposed integration of IBGs in the grid.

2. METHODOLOGY

2.1 Power System model

The Nigerian transmission grid system being studied is presented in Figure 2. It comprises 71 buses, including 19 conventional generators, 43 loads, and 79 overhead transmission lines. Power transmission occurs at two voltage levels: 330 kV and 132 kV. Thermal power plants serve as the primary sources of conventional generation in the southern part of the country, whereas hydroelectric power plants dominate the northern part. The northern region also has abundant renewable energy resources, such as wind and solar, with available land for utility-scale deployment. In 2016, Nigerian Electricity Bulk Trading (NBET) Plc signed a power purchase agreement (PPA) with several investors (see Table 1) interested in harnessing this resource for utility-scale systems. Accordingly, this study incorporates renewable generation, which includes nine solar PV plants and one type III wind turbine generator, based on the NBET's PPA.

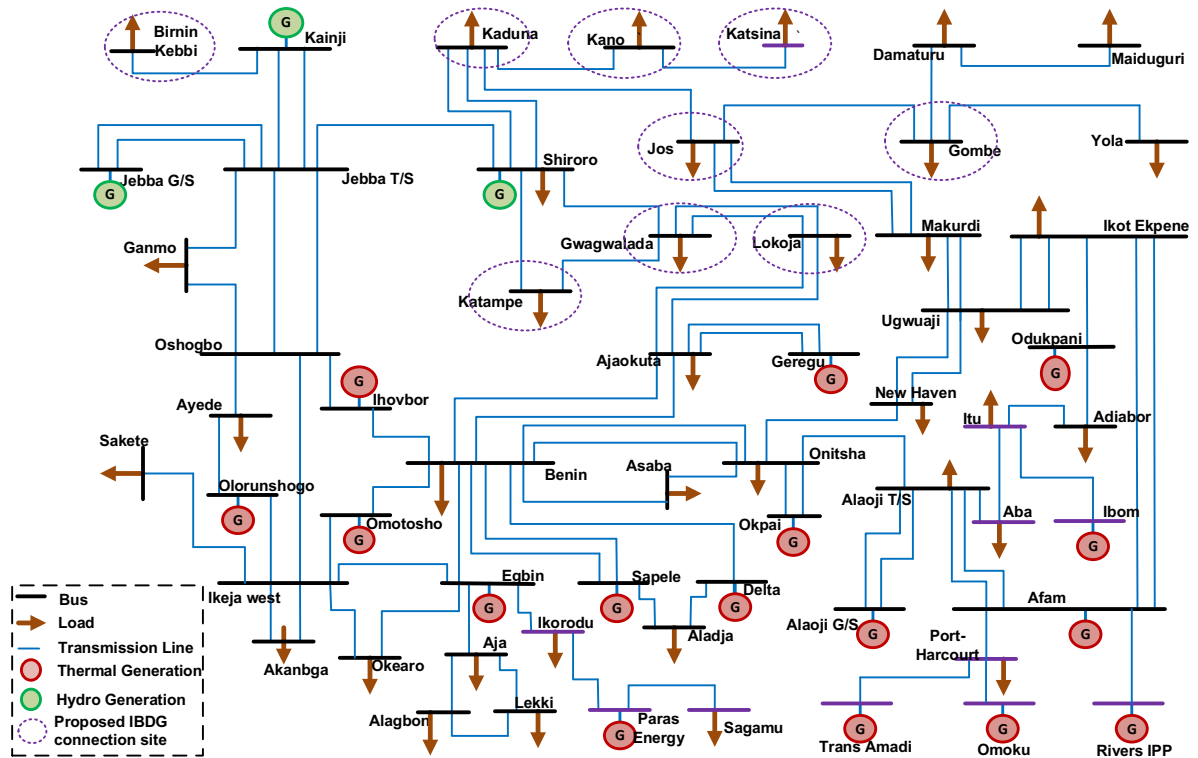


Fig. 2. Single-line diagram of case study Nigerian transmission network.

Table 1. Proposed solar PV and wind energy projects in northern Nigeria

Project / Project Company	Type	PoI	Equivalent Capacity (MW)
KVK Power Limited	Solar	Birnin Kebbi	55
Nigerian Solar Capital Partners	Solar	Gombe	100
LR Aaron Power	Solar	Gwagwalada	100
CT Cosmos	Solar		
Quaint Abiba Power	Solar	Jos	220
Anjeed Innova Group	Solar		
EN Africa	Solar	Kaduna	50
Novia Scotia Power Development Company	Solar	Kano	130
Oriental Renewable Solutions	Solar	Katampe	50
Afrinegia Power Limited	Solar	Katsina	175
Pan Africa Solar	Solar		
Nova Solar 5 Farm Limited	Solar		
Vergnet	Wind (Type 3)	Katsina	10
Middle Band Solar One	Solar	Lokoja	100
Total			990

b. Short-circuit studies

The short-circuit current is the current at a given point in the power system during a short-circuit fault based on the equivalent source impedance and nearby sources of fault current. Short-circuit studies use static computational methods involving various factors to model the contribution of synchronous and asynchronous machines. The short-circuit capacity (SCC) at a bus is the short-circuit current expressed as power (Urdal et al., 2015). This information is also used to classify power grids without IBGs as either weak or strong. In fact, the terms “SCC” and “system strength” are sometimes used interchangeably (Gordon et al., 2022). Although there is no predefined threshold for SCC, 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 shown in equation (1). It involves applying a balanced three-phase fault to the bus of interest first, and thereafter computing short-circuit capacity based on the symmetrical short-circuit current and pre-fault voltage of the bus.

$$S_i'' = \sqrt{3}V_n I_i'' \quad (1)$$

where S_i'' is the short-circuit capacity to be computed for bus i , I_i'' and V_n are the short-circuit current and the bus nominal voltage, respectively.

c. Grid Strength Assessment

When IBGs are integrated into a power grid, the short circuit ratio (SCR) given by equation (2) is a common measure used to assess the strength of the Pol and to evaluate its ability to operate under different system conditions. A lower SCR is associated with a weaker system, while a higher SCR indicates a strong system that can easily recover from major disturbances. It is defined as the ratio of the short-circuit capacity at the Pol to the rated capacity of the IBG. It is mathematically expressed as given in Equation (2) (Sanni et al., 2022).

$$SCR_i = \frac{|S_i''|}{P_{IBG,i}} \quad (2)$$

where $P_{IBG,i}$ is the rated power of the IBG.

However, the accuracy of the SCR only applies to a single IBG in a single Pol, as it does not account for the effects of interactions caused by close-by IBGs (Fernandes et al., 2015; Kim et al., 2020; Wu et al., 2018). To address this, a previous work by the author proposed the network response short-circuit ratio (NRSCR) (Sanni et al., 2022), which captures the interactions among IBGs to evaluate system strength. Equation (3) shows the expression for computing NRSCR.

$$NRSCR_i = \frac{S_i''}{\left(P_{DG,i} + \sum_{j \in D, j \neq i} [P_{DG}^C]_{j,i} \right)} \quad (3)$$

Where S_i'' is the short-circuit capacity at the i^{th} Pol; $P_{DG,i}$ is the rated capacity of the IBG connected at bus i ; $[P_{DG}^C]_{j,i}$ is the fraction of neighbouring IBG injection at bus j interacting with the IBG at bus i ; and D is the total number of IBG in the network. Typically, system strength evaluated either with SCR or NRSCR classifies a system as strong for value greater than 3, weak for value between 2 and 3, and very weak for value less than 2.

Although this study involves multiple IBG integrations, both the SCR and NRSCR measures are evaluated to provide a proper perspective on the accuracy of the latter.

d. Dynamic analysis

This study conducts dynamic simulation studies to assess how the IBGs respond to a sudden disturbance at the Pols with different system strength values. To achieve this objective, a solid three-phase short circuit fault is simulated in this test network, which lasts for 0.3 seconds before clearing. The response of the IBG during and after fault clearance is then evaluated with respect to the NRSCR values in the Pols. This study utilized the industry-standard Power System Simulation for Engineering (PSS/E) software to model and simulate the Nigeria 330 kV network.

3. RESULTS AND DISCUSSION

This section describes the results of short-circuit studies, system strength evaluation, and dynamic analysis of the system response to disturbance.

Figure 3 presents the results of the short-circuit studies conducted on the Nigerian transmission grid to assess the strength of the network without any IBG integration using the IEC 60909 standard. It was observed that buses in the southern part of the grid had significantly higher SCC values than buses in the northern region. The highest SCC value of 19,888 MVA was recorded at the Benin bus, while the lowest value of 378 MVA was at the Maiduguri bus. The reason is due to the higher concentration of synchronous generators in the south than in the north. Selected buses in the northern region (coloured red), including Birnin Kebbi, Gombe, Jos, Kano, and Katsina, are the proposed Pol for IBG integration based on the NBET PPA agreement. It is observed that these Pols have very low SCC compared to most buses in the grid. This should be of concern for future integration of IBG into the grid in this region.

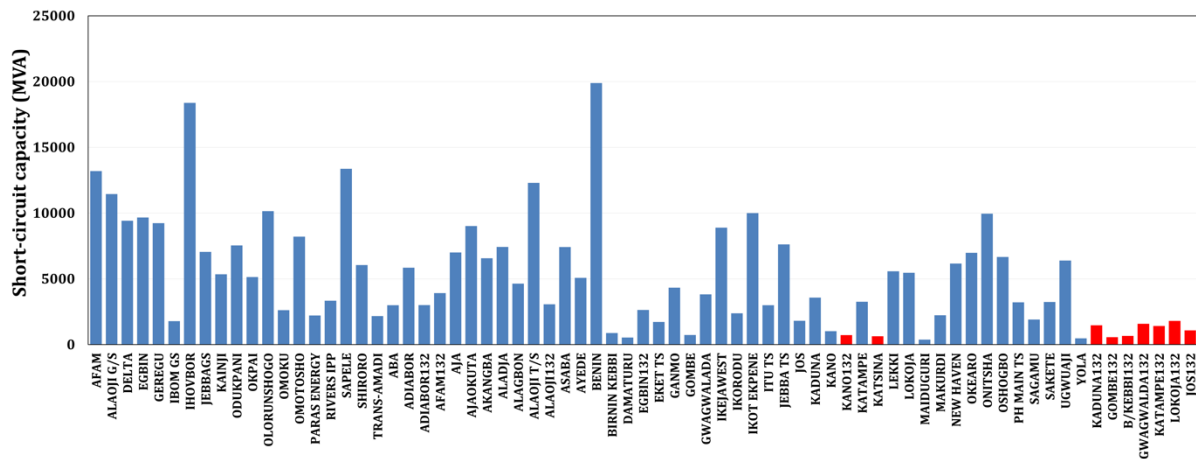


Fig. 2. Short-circuit capacity profile of the Nigerian transmission grid.

The SCC value at the proposed Pols shows that it ranges from 571.77 MVA at Gombe to 1805.67 MVA at Lokoja. These SCC values are used to evaluate the system's strength using SCR and NRSCR metrics. Table 1 presents the results of the SCR and NRSCR values computed using Equation (2) and (3), respectively, with the rated power output of the IBGs. It is observed that the result of the SCR estimates is generally higher than that produced by NRSCR. While the rated power at the Pols ranges from a minimum of 50 MW at Kaduna and Katampe to 220 MW at Jos, SCR identified all the Pols as strong (i.e., > 3), with Kaduna (SCR = 29.44) as the strongest. This is contrary to the NRSCR measure which suggests Katampe (NRSCR = 19.01) as the strongest, while the buses at Kano (NRSCR = 2.05) and Katsina (NRSCR = 1.93) are identified as weak and very weak, respectively. Moreover, both measures identified Katsina as the weakest Pol. This confirms the suggestion that the SCR metric is unsuitable as a metric of choice in a multi-IBG-penetrated power grid. Furthermore, the Pols at Kano, Katsina, Kaduna, Gombe, and Jos all have NRSCR values less than 10, with Kano and Katsina posing a potential concern for the grid due to their closeness and interaction between the two Pols. All other buses have NRSCR values greater than 10 and may not be of concern to the grid.

Table 4. System strength evaluation result for IBG integrated Nigerian transmission grid

Pol	Short-circuit power at Pol (MVA)	Rated Power injection of IBG (MW)	SCR	NRSCR
Kano	735.01	130	5.65	2.09
Katsina	650.33	185	3.51	1.96
Kaduna	1472.13	50	29.44	7.31
Gombe	567.77	100	5.68	2.94
Birnin kebbi	664.41	55	12.08	12.08
Gwagwalada	1581.97	100	15.82	13.48
Katampe	1415.51	50	28.31	19.01

Lokoja	1805.67	100	18.06	16.49
Jos	1085.71	220	4.94	3.23

To confirm the validity of result and presence of interaction based on the system strength values indicated in Table 1, a dynamic simulation is conducted to assess the dynamic voltage stability of the Nigerian power grid. A credible disturbance by way of a three-phase fault is simulated at the Shiroro bus for 300 ms, and the Shiroro-Jebba transmission line is tripped to clear the fault. Figure 4 illustrates the voltage response of the Pols in relation to the system strength, which is evaluated using NRSCR. The simulation is conducted first with all the IBGs connected (Scenario A). Thereafter, the simulation is repeated by disconnecting the IBG at Kano (scenario B). For scenario A, it is observed that the bus voltages in Kano, Katsina, Kaduna, Gombe and Jos displayed some transients during fault conditions. The response can be attributed, among other things, to the proximity of the two weakest buses (Kano and Katsina), to the fact that the short-circuit power of these buses is low in comparison to the rated capacities of the IBGs, and to the fact that the control action of the IBG power electronic systems at these Pols interacts with one another in an attempt to maintain a stable system operation. This demonstrates that the IBG voltage controller's quick dynamic response has a significant impact on grid stability in locations with low SCC. In contrast, Birnin Kebbi, Gwagwalada, Katampe, and Lokoja buses' voltage responses did not experience similar transients, despite Katampe and Gwagwalada's nearness to the fault location. In scenario B, where the generator at Kano was disconnected, none of the Pols experienced any transients during the fault as recorded in scenario A. This confirms that the absence of interactions among multiple IBGs at a weak Pol is will not impact grid operation negatively.

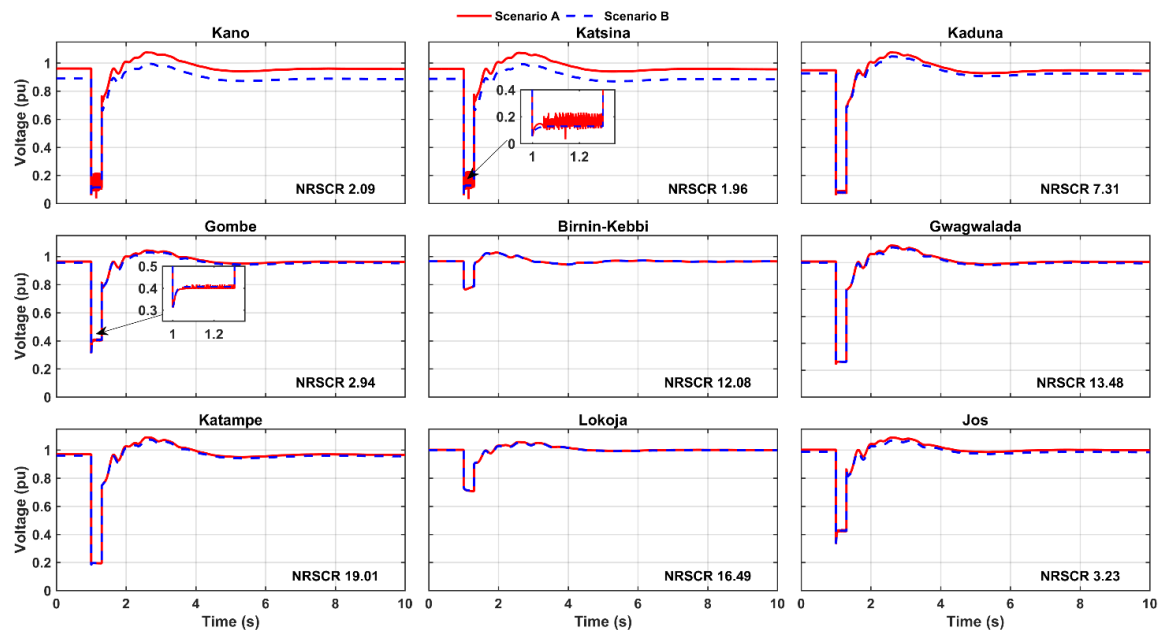


Fig. 3. voltage response to system disturbance

4. CONCLUSION

The existence of low SCC in the Nigerian transmission grid and its impact on system strength when integrated with IBGs has been examined. Without IBG, the short circuit studies indicates that the most buses in the northern part of the grid are weak. With the integration of IBGs, the system strength measured by NRSCR shows that some of the proposed Pol based on the NBET PPA are not entirely weak, with some strong Pols. However, the presence of few buses with NRSCR value less than 3 may be a source of concern in ensuring operational stability. Dynamic voltage stability analysis shows that Pols with system strength less than 10 may require close attention and adequate planning to integrate IBGs. In this regard, this study will help the system operators and the concern stakeholders to have the knowledge of the system strength for immediate and future system planning. Nevertheless, additional studies will be required to establish a threshold NRSCR value to differentiate a weak

grid condition and a strong grid. Future studies will investigate the impact of IBG integration on frequency stability of the grid.

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