

Research Paper

Identifying interaction boundary of inverter-based generation in assessing system strength of power grids using relative electrical distance concept

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ABSTRACT

The increasing use of inverter-based generation (IBG) in power grids raises concern about system strength. This is partly due to the inherent interactions among multiple IBGs in close proximity to one another. This paper proposes an approach to identifying the existential boundary of interaction in a network using the relative electrical distance (RED) concept. The mathematical formulation of the RED concept to address the interaction problem among the IBGs involved utilising the power system network's admittance matrix to capture its structural characteristics. An interaction matrix derived from the RED values of all IBG pairs was then developed to identify the interacting IBG groups. The proposed approach was demonstrated using the IEEE 39-bus system and a practical 72-bus Nigerian power grid. Results showed that RED values effectively group interacting IBGs, with values closer to 0 signifying higher interaction levels, values closer to 1 indicating lower interaction, and a value of 1 denoting no interaction. Time-domain simulations confirmed the accuracy of the approach, demonstrating that the effect of control interaction propagates proportionally to neighbouring IBGs based on RED values. However, fault currents can influence the impact of control interactions. This approach, which requires less computational effort, provides a quick identification tool for potential areas of concern based on the degree of interaction, enhancing the reliability of power grids with high IBG penetration.

1. Introduction

The adoption of renewable energy sources (RES) by power grids across the world is driven by the need to reduce carbon emissions contributed by the power sector [1]. However, this uptake is introducing new challenges for system operators, largely due to the intermittent nature of required resources such as wind and solar radiation. Also, the characteristic use of inverter interfaces adds another layer of complexity when integrating them into power grids. This often results in them being referred to as inverter-based generation (IBG). The dispersed nature of the IBGs also means that they are located in weak and remote areas since they are far from the rest of the grid with synchronous generators [2,3]. For this reason, system strength at the point of interconnection (PoI) is a prevalent concern for most power grids as several power system variables depend on the strength of the grid [4]. Traditionally, system strength at the PoI is measured by the short-circuit ratio (SCR) [5], which indicates the strength at the PoI with respect to the rated power of

the IBG [6].

In large-scale deployments, IBGs will get closer to each other and certain operating conditions may lead to possible stability issues arising from control system interactions of the converter systems [7]. Such interactions can potentially trigger undesirable dynamic oscillations, which may threaten the grid stability in a weak grid scenario [8]. Moreover, system strength evaluated in such a scenario using the SCR becomes inadequate since it does not account for this interaction. If adopted, the result produced by the SCR metric will be too optimistic, thus misrepresenting the actual state of the grid and the appropriate actions required to mitigate potential problems. While there is currently no exact guide on the acceptable metric to measure system strength, several other methods that capture the interaction among IBGs have been suggested, including the weighted short-circuit ratio (WSCR) [9], the composite short-circuit ratio (CSCR) [10], the site-dependent short-circuit ratio (SDSCR) [11], and the network response short-circuit ratio (NRSCR) [12]. WSCR and CSCR methods assume full interaction exists

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between IBGs, ignoring the actual electrical connections within a network, and may also not indicate the real strength of the system at the PoI except for locations where IBGs are really closer to each other [13]. In contrast, however, the SDSCR and NRSCR methods account for interactions based on the electrical connections within a network to accurately estimate system strength. Moreover, all these metrics established that interaction among large numbers of IBGs within an area in close proximity to each other has a negative influence on network operation. Thus, there is a need for a network to withstand potential problems that may arise during operations.

Power grids are vast infrastructures, encompassing thousands of interconnected points (buses) spread across expansive regions. This vastness limits the interaction between multiple IBGs within the network, even if they are electrically connected. Consequently, existing methods for estimating system strength lack guidance on defining the interaction boundaries within the grid. This is further underscored by the recommendation from system operators, like the Australian Energy Market Operator (AEMO), to limit interaction-based strength evaluation to a localised area of just three buses around the PoI being assessed [14]. Nevertheless, it did not provide guidance on how to determine which of the candidate buses should be given preference with respect to the degree of interaction amongst the three buses to be considered. ERCOT has also determined that boundaries of interaction are becoming more complicated as the number of IBG in a network increase [8]. A power flow tracing scheme for identifying the boundary of interaction was presented by [13]. The result of the proposed system applied to the Korea Electric Power Corporation (KEPCO) network produces the same boundaries regardless of the change in the PoI of interest. However, the direction of power flow within a network can change dynamically due to uncertainties arising from changing network configurations, system loads, generator outages, and weather variability, which may result in shifting identified boundaries [15]. It is therefore essential to identify clear boundaries that truly defines how IBGs interact with each other in order to accurately estimate system strength.

A number of power system problems are related to the structural configuration of the network. The theory behind the concept of structure as proposed by [16] is reported to have been used to solve network problems largely related to the nodes [17]. These approaches are grounded in computations based on the network's admittance matrix which do not require the solution of the power flow problem. System strength estimations and related issue is a node-based problem that can be addressed using this theory [12]. Aldaoudeyeh et al. [18] and Ekic et al. [19] demonstrated this by using the power network's structural characteristics to identify the transmission line components required for system strength improvement. Results confirmed that power flow solution is not necessary when the network topology changes since this structural change are captured in the system's admittance matrix. The concept of relative electrical distance (RED) proposed by Visakha et al. [20] provided another application of this theory. In the study, RED-based transmission charge allocation shows that reduced transmission loss, improved transmission tariffs and better system stability margins could be achieved. A similar work by Thukaram & Vyjayanthi, [21] indicates that the RED concept can also be used to compute reactive power contributions from several reactive power sources within a network to meet system demands. The "T-index" approach which is based on the RED concept also demonstrates that suitable location for new generation could be determined in a restructured power system [22]. Other studies based on this theory have outlined solutions to identifying the critical transmission lines and weak nodes [17], defining each generator contribution to the line flows and line losses in a network [23], and generation to load allocation [24].

Large-scale penetration of IBGs introduces complexities in power grid analysis. While electrical connections determine the level of interaction between IBGs, ultimately impacting system strength at a specific PoI, existing research highlights a significant gap: a clear definition of the interaction boundaries among multiple IBGs within a grid. To

address this gap, this paper proposes a computationally efficient approach for defining these boundaries using the RED concept. The RED method uses network topology and transmission line parameters, which remain constant regardless of changing network conditions. This approach establishes the existence and strength of a relationship between any two PoIs based on their electrical connectivity.

The primary objective of this research is to develop an effective method for identifying IBG interaction boundaries within a power grid penetrated with IBGs. This approach aims to provide clarity for existing system strength estimation methods, accounting for the inherent interaction among IBGs in power grids.

The proposed approach offers several advantages that contribute to the ongoing research on RES integration in power grids, including:

1. The development of an interaction matrix based on RED provides a quantitative and easily interpretable way to map IBG interaction boundaries.
2. Leveraging the network's structural characteristics through RED, the approach avoids complex power flow analysis and repetitive calculations, leading to significant computational time savings and reduced memory requirements.
3. Validation on benchmark power grids such as the IEEE 39-bus and the practical Nigerian 72-bus systems showcases the effectiveness of the approach and its applicability in large-scale IBG penetration scenarios.
4. The approach serves as a fast and efficient tool for identifying potential areas of concern in large-scale IBG integration scenarios, allowing for proactive planning and mitigation strategies.

This paper is structured as follows: Section 2 provides a brief overview of control system interactions and presents the mathematical formulation of the proposed scheme. The implementation approach is detailed in section 3. The technical and policy implications, along with the conclusions, are presented in Sections 5 and 6, respectively.

2. Control Interactions in IBGs

Power system components in interconnected networks interact through the actions of the different control systems [25]. For networks, with high penetration RES, this interaction is particularly substantial between IBGs and with other power electronic-based components, such as FACTS devices [26]. Control interactions are greater in weak grid areas which is characterised by low system strength, causing significant changes in network conditions. The impact of interactions is minimal in a strong ("stiff") grid area, so this changing condition is less pronounced [27].

Fig. 1 depicts an example of simple power grid of a remotely located IBG like a solar photovoltaic (PV) or wind power plant connected to a "stiff" grid (constant voltage) with synchronous generators through a long transmission line.

An IBG can operate in voltage-control mode to provide voltage support in a network by injecting/absorbing reactive power into the grid almost instantaneously in response to changes in voltage at the PoI [28]. The reactive power injection can be expressed as [29]:

$$Q = \frac{V_{PoI}^2 - V_{PoI}V_g\cos\delta}{X_l} \quad (1)$$

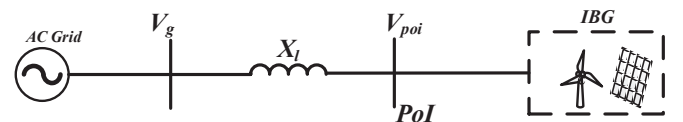


Fig. 1. Simple representation of an IBG-grid system

$$\frac{dQ}{dV_{pol}} = \frac{2V_{pol} - V_g \cos \delta}{X_l} \quad (2)$$

Assuming a grid voltage of $V_g = 1.0$ pu and $\delta = 0$, the dV_{pol}/dQ sensitivity of the PoI is expressed as:

$$\frac{dV_{pol}}{dQ} = \frac{X_l}{2V_{pol} - 1} \quad (3)$$

Equation (3) therefore indicates that the voltage sensitivity (dV/dQ) at the PoI is proportional to the electrical distance between it and the supporting grid. Thus, a high grid impedance will lead to a high sensitivity (large changes) of the PoI voltage due to a small change in reactive power. In other words, the network topology and impedances are critical factors in determining the effect of changing voltage at one PoI over the others [30].

In a typical scenario with multiple IBGs having fast acting controllers and electrically close PoIs having high sensitivity, a change in voltage at one PoI will be corrected with reactive power injection by the associated IBG. Nevertheless, the high sensitivity means that the voltage will rise significantly, which will trigger an absorption of reactive power by the IBG controller. This will also lead to a significant drop in voltage, and the reactive power injection/absorption cycle will continue. Other nearby IBGs will also sense these changes and initiate similar control actions in an attempt to maintain the voltage at the respective PoIs. This interaction among neighbouring IBGs will lead to sustained oscillations, which may lead to instability [26].

3. Methodology

The increasing deployment of IBGs often relies on renewable energy resources like solar or wind. These resources are often located in remote areas, leading to clusters of geographically close IBGs. While this physical proximity might suggest strong electrical interconnection between these IBGs, the actual level of interaction can be more complex, which may pose potential stability challenges from interactions. The RED concept, derived from the network's admittance matrix, conventionally offers an indication on the relative position of a load bus to a synchronous generator bus for proportional resource allocation [20]. In this section, the approach is extended to identify the boundaries of interaction between IBGs in power grids.

3.1. Mathematical formulation of RED concept

Considering an interconnected power system with IBG integration, made up of n buses, out of which $1, 2, 3, 4, \dots, g$, buses are conventional synchronous generator buses and $g+1, g+2, \dots, n$, remaining $(n - g)$ composite load buses. These composite load buses consist of actual loads and IBG PoI. The network equation is given by:

$$\begin{bmatrix} I_g \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_g \\ V_L \end{bmatrix} \quad (4)$$

Where $[I_g] = [I_1, \dots, I_g]^T$ and $[V_g] = [V_1, \dots, V_g]^T$ are the vector of injected current and voltage of synchronous generators; $[I_L] = [I_{g+1}, \dots, I_n]^T$ and $[V_L] = [V_{g+1}, \dots, V_n]^T$ are the vector of injected current from the composite load buses. $[Y_{GG}]$, $[Y_{GL}]$, $[Y_{LG}]$, and $[Y_{LL}]$ are the corresponding part of Y-bus admittance matrix. Separating (4) into Eqs. (5) and (6), we get,

$$[I_g] = [Y_{GG}][V_g] + [Y_{GL}][V_L] \quad (5)$$

$$[I_L] = [Y_{LG}][V_g] + [Y_{LL}][V_L] \quad (6)$$

From Eq. (6),

$$[Y_{LL}]^{-1}[I_L] = [Y_{LL}]^{-1}[Y_{LG}][V_g] + [V_L] \quad (7)$$

$$[V_L] = [Y_{LL}]^{-1}[I_L] - [Y_{LL}]^{-1}[Y_{LG}][V_g] \quad (8)$$

Substituting for $[V_L]$ in Eq. (5), we obtain,

$$[I_g] = [Y_{GG}][V_g] + [Y_{GL}][Y_{LL}]^{-1}[I_L] - [Y_{GL}][Y_{LL}]^{-1}[Y_{LG}][V_g] \quad (9)$$

Equations (8) and (9) can be expressed in matrix form as:

$$\begin{bmatrix} V_L \\ I_g \end{bmatrix} = \begin{bmatrix} Y_{LL}^{-1} & -Y_{LL}^{-1}Y_{LG} \\ Y_{GL}Y_{LL}^{-1} & Y_{GG} - Y_{GL}Y_{LL}^{-1}Y_{LG} \end{bmatrix} \begin{bmatrix} I_L \\ V_g \end{bmatrix} \quad (10)$$

Re-writing equation (10), we obtain equation (11) as follows:

$$\begin{bmatrix} V_L \\ I_g \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & H_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_g \end{bmatrix} \quad (11)$$

where:

$$[Z_{LL}] = [Y_{LL}]^{-1}, [F_{LG}] = -[Y_{LL}]^{-1}[Y_{LG}], K_{GL} = [Y_{GL}][Y_{LL}]^{-1}, \text{ and } [H_{GG}] = \{[Y_{GG}] - [Y_{GL}][Y_{LL}]^{-1}[Y_{LG}]\}.$$

The proposed approach presented in this study is centred around the F_{LG} sub-matrix, which is a complex matrix whose columns represent synchronous generator bus numbers and rows represent composite load bus numbers. It captures the relation between the composite load bus voltages and synchronous generator bus voltages. In addition, it shows the relative electrical distance between composite load nodes and synchronous generator nodes and it is given as [20]:

$$[RED] = [U] - abs[F_{LG}] \quad (12)$$

Where U is a unity matrix of size L number of rows (composite load buses) and G number of columns (synchronous generator buses). The characteristics and applicability of the $[F_{LG}]$ and $[RED]$ matrices as a solution to several power system problems is well documented in [22,24,31,32].

Equation (11) allows for the expression of the voltage of the composite load buses given as:

$$[V_L] = [Z_{LL}][I_L] + [F_{LG}][V_g] \quad (13)$$

The column vector for voltage is given as $V_L = [V_D \quad V_\Omega]^T$ while that of the current expressed as $I_L = [I_D \quad I_\Omega]^T$. The subscripts, D specify IBG PoI while Ω represent the load buses. Considering the IBG PoI buses only,

$$[V_D] = [Z_{LL}][I_D] + [F_{LG}][V_g] \quad (14)$$

Pre-multiplying (14) by the conjugate of the diagonal load current matrix $[I_D^*]$, we have,

$$[I_D^*][V_D] = [I_D^*][Z_{LL}][I_D] + [I_D^*][F_{LG}][V_g] \quad (15)$$

Interpreting Eq. (15) with respect to complex power injection as:

$$[S_{DG}] = [S_{DG}^L] + [S_{DG}^C] \quad (16)$$

Where $[S_{DG}]$ is the apparent power provided by the IBG, $[S_{DG}^L]$ accounts for transmission line losses and $[S_{DG}^C]$ is the fraction of IBG injected power interacting with the synchronous generator buses. From the real part of Eq. (16), we have:

$$[P_{DG}] = [P_{DG}^L] + [P_{DG}^C] \quad (14)$$

The ideal contribution of IBG injection interacting with synchronous generator buses is provided by $[P_{DG}^C]$.

3.2. Illustrative example of the proposed RED concept

The RED concept is illustrated with the sample system shown in fig. 2 which is modified from [20]. It includes two synchronous generators at

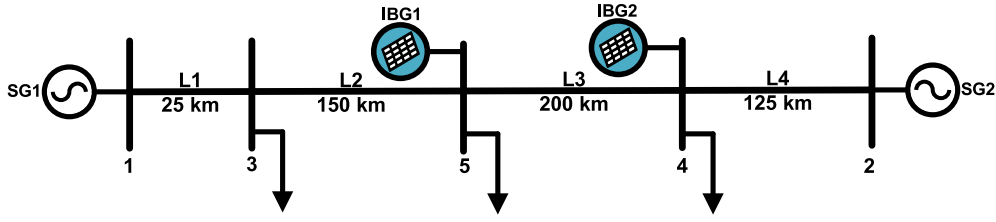


Fig. 2. A 5-bus sample power system illustrating the RED concept

buses 1 and 2, while buses 3, 4, and 5 are composite load buses. The lengths of the transmission lines are as indicated on the figure with the following line parameters: $R = 0.00165$, $X = 0.02059$ per unit per 100 km. The $[F_{LG}]$ matrix indicating the relationship between corresponding composite load buses and synchronous generator buses for the sample network is given as:

$$[F_{LG}] = \begin{bmatrix} 0.95 + j0 & 0.05 + j0 \\ 0.25 + j0 & 0.75 + j0 \\ 0.65 + j0 & 0.35 + j0 \end{bmatrix}, \text{abs}\{[F_{LG}]\} = \begin{bmatrix} 0.95 & 0.05 \\ 0.25 & 0.75 \\ 0.65 & 0.35 \end{bmatrix}$$

The columns of the $[F_{LG}]$ matrix represent buses with synchronous generators at buses 1 and 2, while the rows indicate the composite load buses without IBG (bus 3) and with IBG (buses 4 and 5). The row-wise summation of the elements of this matrix is close to 1.0.

The relative electrical distances of the composite load buses with respect to the synchronous generator buses are computed using equation (9) and given as:

$$[RED] = \begin{bmatrix} 0.05 & 0.95 \\ 0.75 & 0.25 \\ 0.35 & 0.65 \end{bmatrix}$$

For the buses with IBGs, the elements of this matrix indicate if any interaction will exist and the degree to which any two buses at that location interact with one another. In this sample system, for instance, IBG1 at bus 5 is 175 km from SG1 and 325 km from SG2, which correspond to 0.35 and 0.65, respectively, in the RED matrix. This reveals that bus 5 is electrically closer to bus 1 than bus 2; hence, IBG1 will interact more with SG1 than SG2. Also, IBG2 is 375 km from bus 1 and 125 km from bus 2, corresponding to 0.75 and 0.25 in the RED matrix, respectively. Likewise, load bus 3 is 25 km from SG1 and 475 km from SG2, which is 19 times the 25 km, with the corresponding elements of the RED matrix being 0.05 and 0.95, respectively. Accordingly, an RED value of 1 indicates no connection between the corresponding buses, thus no interaction exists. These values, which represent the REDs, will be used to identifying the boundary of interaction among IBGs in large-scale penetration.

3.3. Identifying the Boundary of Interaction of IBG

The relative electrical distance between a composite load bus and a synchronous generator bus indicates the likelihood that a composite load bus (specifically, an IBG PoI) will be supported by a synchronous generator. However, if the synchronous generator bus is seen as an IBG PoI, then the RED between this PoI and other PoIs can be determined. Therefore, this study theorised that determining the relative electrical distance between a PoI for which system strength is to be evaluated and all other PoIs will possibly indicate which of the PoIs will interact with each other depending on their location as determined by the RED. To achieve this, each PoI bus is converted into a synchronous generator bus, one at a time, and RED is computed using (12). This will increase the number of synchronous generator buses by one, resulting in a reduction in the number of composite load buses by one as well. Consequently, the last column of the new RED matrix gives the relative electrical distance between the PoI converted to a synchronous generator bus and all other PoI buses. This last column is extracted for each conversion scenario to

build an “interaction matrix” of the network under consideration. The salient steps involved in the boundary of interaction identification process are described in algorithm 1 and illustrated with the flow chart in Fig. 3.

Algorithm for Identification of the boundary of interaction

Input: Network data, Synchronous generator list, PoI list.

Output: Interaction matrix of size PoI list.

1. Initialise an empty interaction matrix of size PoI list to store interactions between PoIs.
2. Partition the network based on number of synchronous generators and composite load bus using equation (Eq. (4)).
3. Calculate the $[F_{LG}]$ and $[RED]$ matrix as reference case.
4. For each PoI in the PoI list:
5. Convert the PoI to a synchronous generator bus.
6. Recalculate the $[F_{LG}]$ matrix after repartitioning the system equation (Eq. (4)) to include the converted the PoI bus as a synchronous generator
7. Compute the $[RED]$ matrix from the new $[F_{LG}]$ matrix.
8. Extract the last column of the new $[RED]$ matrix and store in the interaction matrix.
9. End for.
10. For each column j in the interaction matrix:
11. If the RED value at row (i, j) of interaction matrix is less than 1 (indicating interaction):
12. Add PoI i and PoI j to the same interaction group.
13. End if.
14. End for.

4. Case Study and Results

This section demonstrates the proposed concept and examine its effectiveness in identifying the boundaries of interaction among multiple IBG deployed in power grids. Two test systems were used to verify the approach: the IEEE 39 bus system and the practical Nigerian transmission network. In both systems, identified IBG locations were investigated to determine if and which of the IBG would interact with each other based on the RED concept. The simulations were performed with power system simulation for engineering (PSS/E) software and scripts written with Python programming.

4.1. Case 1: Modified IEEE 39 Bus System

The single-line diagram of the modified IEEE 39 bus test system, comprising 39 buses with 6 conventional generators, 4 IBGs, and 17 loads, is shown in Fig. 4. Other detailed parameters of the IEEE 39 bus system are available in [33] and [12]. The algorithm described in section 3.3 is applied to the test system, and the result of the interaction matrix is illustrated with the heat map correlation plot shown in figure 5. This matrix reveals that all RED values between IBGs are less than 1, indicating a likelihood of interaction among them. This suggests that the IBGs can be considered a single cohesive group, with a high degree of mutual influence. This finding aligns with theoretical foundation, which demonstrated that geographically close IBGs tend to exhibit strong electrical interaction within a power grid. This aligns with earlier findings on system strength in power grids with IBG integration [11,12], where IBGs located close to each other exhibited strong mutual influence due to low electrical impedance, potentially limiting the system's power transfer capability. However, it is important to acknowledge that this initial observation only considers the network topology and may not fully capture the impact of dynamic factors like fault severity and

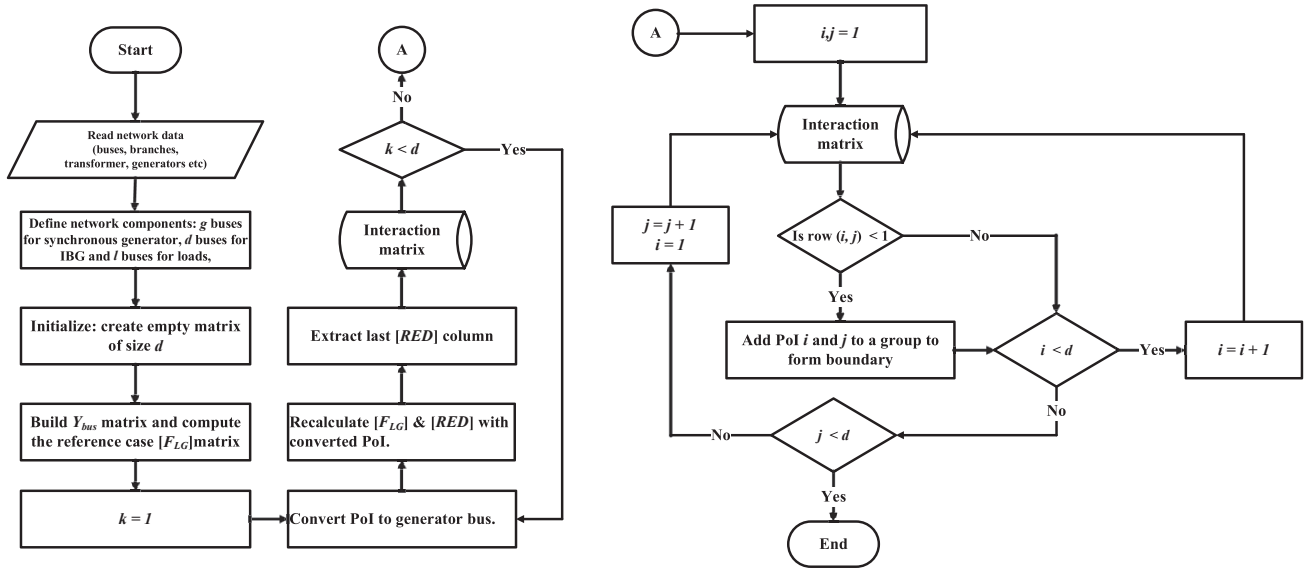


Fig. 3. Flowchart for identifying interaction boundary of IBGs.

location.

In terms of the degree of interaction, it is observed that bus 37, which has the least RED value of 0.488, is closer to bus 30 and will interact more with it as shown in column 1. In column 2, buses 30, and 37 appear to have similar values, which suggests that they will have identical levels of interaction with bus 35, although bus 38 will tend to interact more since its RED value is lesser at 0.791. Similarly, buses 30 and 38 will have comparable degree of interaction with bus 37 when compared with bus 35 as indicated in column 3. From column 4, the greatest influence on bus 38 will come from bus 37.

The validity of the identified boundary and the observed level of interaction between each IBG is further investigated using time-domain simulations. As system strength is related to voltage [34,35,36] and interaction is largely associated with the IBG control actions, whose effectiveness depends on the network characteristics [30], the test network is simulated with a fault on bus 17. Additionally, an abnormal control action is initiated at the IBG on bus 37 during the fault condition, and the response of the bus voltage at each PoI is reviewed. Figure 6 shows that the effect of the abnormal control action at bus 37 is proportionally propagated to buses 30 and 38 based on the RED values, while bus 35 remains unaffected. This indicates that the impact of control interaction may be suppressed by other factors. To this end, the fault current level at each IBG PoI as shown in figure 7 reveals that bus 35 may not have been affected by the abnormal control action due to its high fault current, but the combination of low fault current, lower RED values, and an aberrant control action is responsible for the effect shown at other buses. Nevertheless, the system response during disturbances indicates that the boundaries of interaction among the IBGs in a network have been adequately identified using the proposed method. However, other factors are responsible for the observed effects of interaction.

These results underscore the importance of considering multiple factors, such as fault current levels, RED values, and control strategies, in understanding IBG interactions. While the proposed method effectively identifies interaction boundaries, the observed effects of interaction are influenced by additional factors, as suggested by [37]. This emphasises the need for further investigation into the complex dynamics of IBG interactions within power grids.

4.2. Case 2: The Nigerian Transmission Network

In practical power grids, IBGs are usually dispersed across wider area and connected by long transmission lines. Thus, this section

demonstrates the applicability of the proposed approach to such scenario. Fig. 8 shows the practical Nigerian transmission network, which consists of 76 buses at the 330 kV and 132 kV levels. The northern region which is remote from most synchronous generators and the load centres is also rich in RES, leading to the siting of nine IBG plants. An assessment of this part of the system indicates a high prospect of interaction amongst IBGs. The boundaries of interaction of the IBGs becomes blurry and may be difficult to determine in large-scale penetration. Thus, identifying the boundary of interaction in such a network will provide an understanding of potential risk areas of the grid. Having applied the proposed method to the network, the heat map correlation plot of the RED interaction matrix is given in figure 9. From the figure, three groups of boundaries can be identified: group 1, which includes the IBGs at Kano, Katsina, Kaduna, Gombe, and Jos; group 2, consists of Gwagwalada, Katampe, and Lokoja; and group 3, which is made up of Birnin Kebbi as the only IBG.

The wider geographical area and long transmission lines in the Nigerian network contribute to generally higher RED values within group 1 compared to the previous, more compact test case. This indicates weaker electrical connections between IBGs in this scenario. Interestingly, Kano (column 1) exhibits the strongest interaction within the group with Katsina (RED = 0.002), which aligns with their geographical proximity and strengthens the theoretical foundation of the RED method. Lower RED values, as observed here, correspond to stronger electrical connections and hence, more significant interaction. This finding is further supported by previous research on IBG integration on the Nigerian grid [38], where the relationship between the proximity of IBGs, system interaction, and stability was established and identified as a potential concern at these locations. However, the RED values between Kano and Kaduna (0.893) and Kano and Jos (0.916) suggest a weaker interaction compared to Kano-Katsina. This difference could be attributed to variations in transmission line impedances or the presence of additional network elements in the paths between Kano and these other IBGs, leading to an increased overall electrical distance.

In a similar manner, Kano, having an RED value of 0.121, will have the strongest interaction impact on Katsina as the PoI (column 2). Other IBG in the group will have a similar degree of interaction with Katsina, albeit with lesser influence. With Kaduna as a PoI (column 3), the IBGs at Kano and Katsina show an equal degree of impact when interacting, while those at Jos and Gombe have a slightly different but similar degree of impact. When either Gombe or Jos are considered a PoI, the trio of Kano, Katsina, and Kaduna indicate a fairly equal degree of interaction

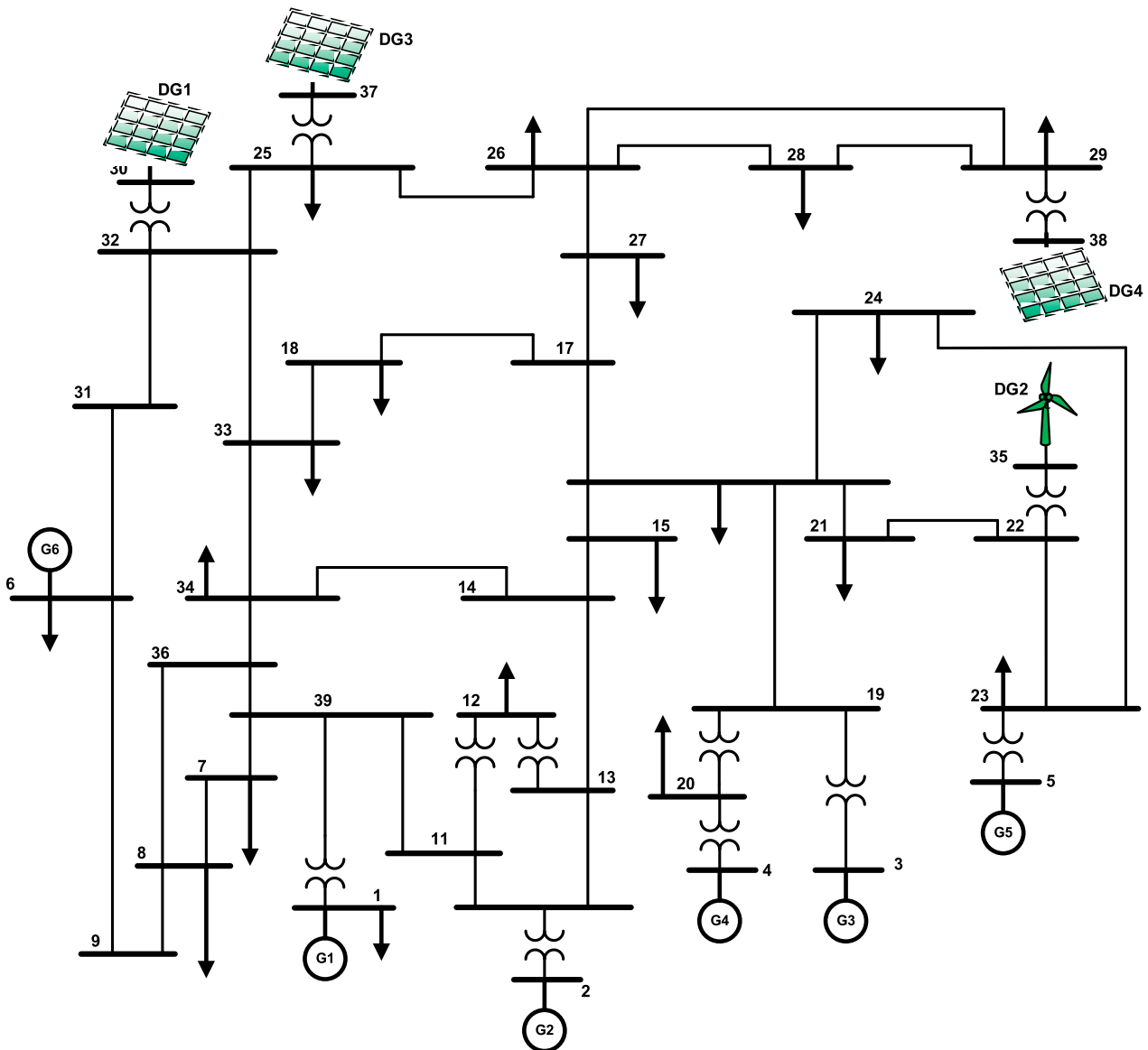


Fig. 4. Single-line diagram of the modified IEEE 39-bus test system

will be experienced on either. In addition, the close proximity of Gombe and Jos to each other means that they will interact with each other more, as indicated by the RED values of 0.701 and 0.377 in columns 5 and 10, respectively. In group two, the IBG at Gwagwalada and Katampe, which have similar RED values of 0.783 (column 6) and 0.798 (column 7), will interact with each other to a similar degree. While Lokoja IBG is also within this group, its RED values of 0.932 (0.939) and 0.949 (0.957) to (from) Gwagwalada and Katampe, respectively, suggest an identical influence from these buses. A review of column 5 for Birnin Kebbi shows that all the RED values are 1. This implies that none of the IBG PoI buses in the network will interact with it, hence the reason for being the only bus in group three.

In a similar approach to case 1, time-domain simulation is carried out to examine how the system's PoI voltage reacts to abnormal control triggered by a fault. This is to understand if the identified boundary of interactions will be apparent in actual scenario during system operation. A three-phase fault is initiated at the Jebba bus while the abnormal control action is simulated on the IBG at Jos to observe the response on other PoIs in the network. Figure 10 shows that the effect of this control action is also propagated to the other PoIs within group 1, as identified by the proposed method. In addition, it is observed that the degree of

impact of the control action is higher for the PoI at Gombe, with the buses at Kaduna, Kano, and Katsina showing similar degree of response. This aligns with the RED value captured under the Jos column in the boundary of interaction matrix. Note that other PoIs within this group show similar response if the abnormal control action is initiated at any other PoI bus during post-fault voltage recovery. The IBG at Gwagwalada (from group 2) is simulated with similar control actions, and the system response is depicted in Figure 11. It is observed that while Katampe is impacted more, Lokoja is lightly affected based on the identification already provided by the proposed approach in Figure 9. The effect is also noticeable on all the PoIs in group 1, albeit to a lesser degree. The low short-circuit current at most of these PoI as shown in Figure 13, suggests that the fault current, also plays a significant role in determining the impact of control interaction among IBGs. Figure 12 show the voltage response of all the PoIs when the only IBG (Birnin Kebbi) in group 3 is initiated with the abnormal control action. It is evident that no other PoI is affected by the control action, thus confirming the suitability of the proposed method in identifying the boundary of interactions among multiple IBGs in a power grid.

Analysis of the interaction matrices in this case study and the previous one reveals a unique property: asymmetry. While Katsina strongly

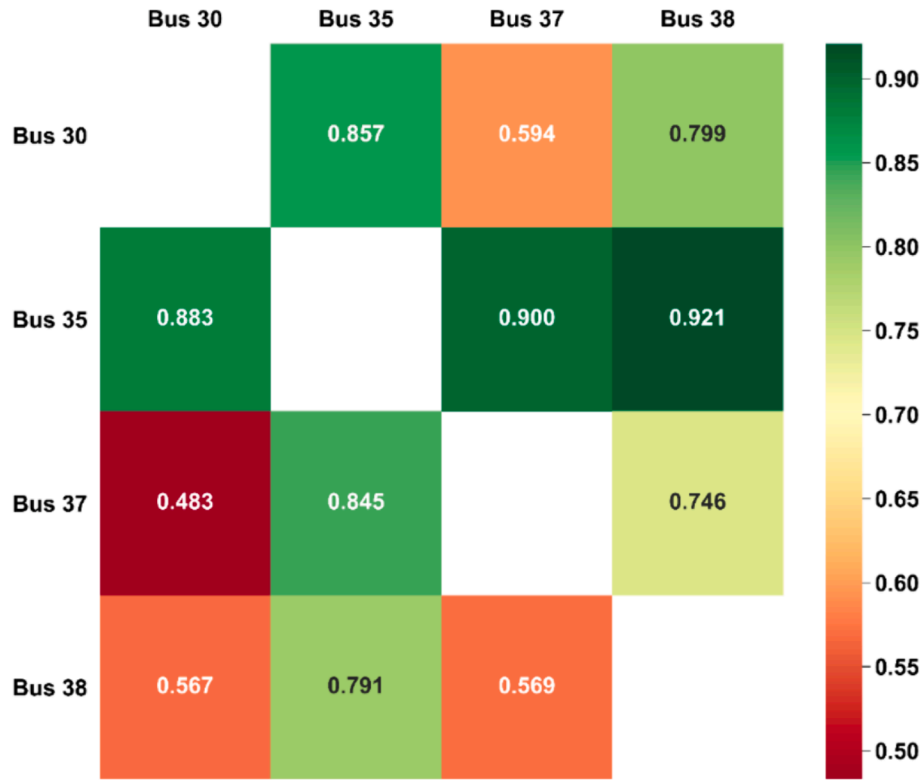


Fig. 5. IEEE 39 bus system heatmap correlation of the RED interaction matrix

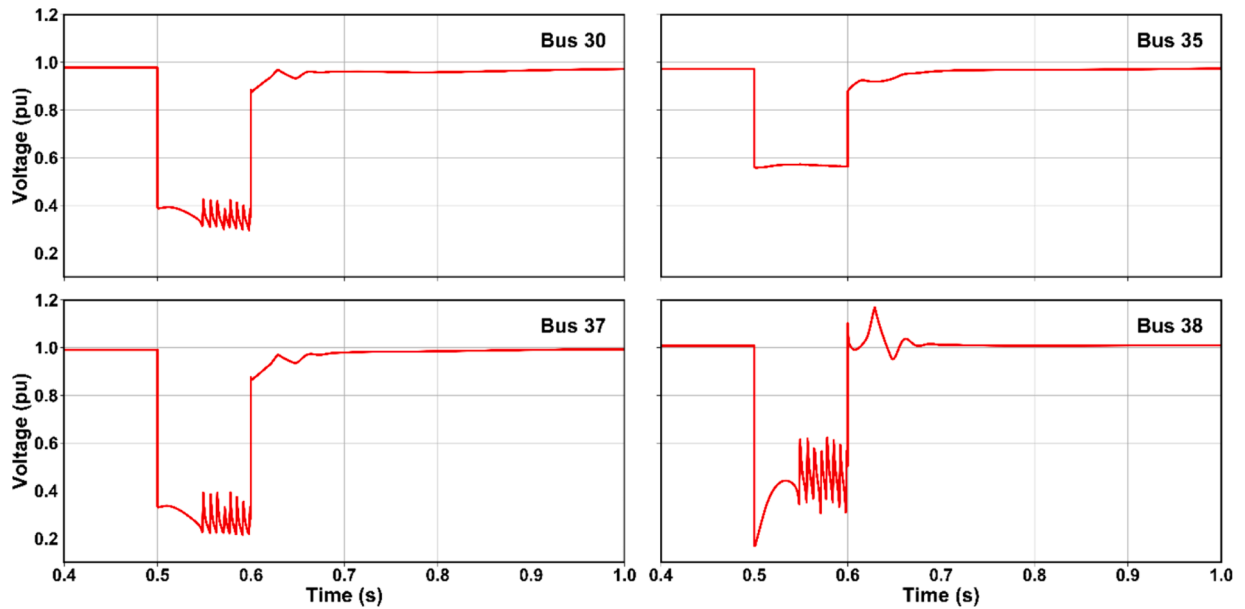


Fig. 6. PoI voltage response showing interaction due to abnormal control of the IBG at bus 37

influences Kano (RED = 0.002, column 1), the reverse influence is weaker (RED = 0.121, column 2). This pattern is evident when comparing other IBGs within the different identified groups. This asymmetry highlights that an IBG can significantly impact another, but the reverse effect may not be reciprocal. This has important implications for understanding and managing IBG interactions within a power system.

4.3. Comparison with Existing Method

To fully understand the perspective of the proposed RED-based method, it is crucial to compare it with an existing approach. Table 1 offers a comparison with the power flow tracing strategy proposed in [42]. By comparing the reported performance results of this method with our proposed RED-based method, we strengthen the growing trend of IBG integration's impact on the system strength of power grids and underscore the importance of understanding the potential effects of interaction and how it can support planning decisions.

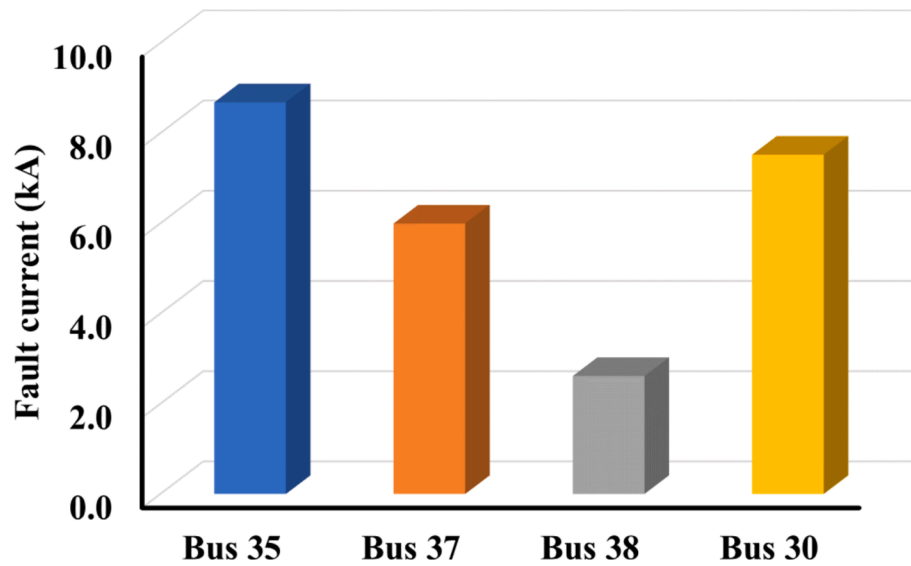


Fig. 7. Fault current profile at the PoIs of the modified IEEE 39 bus system

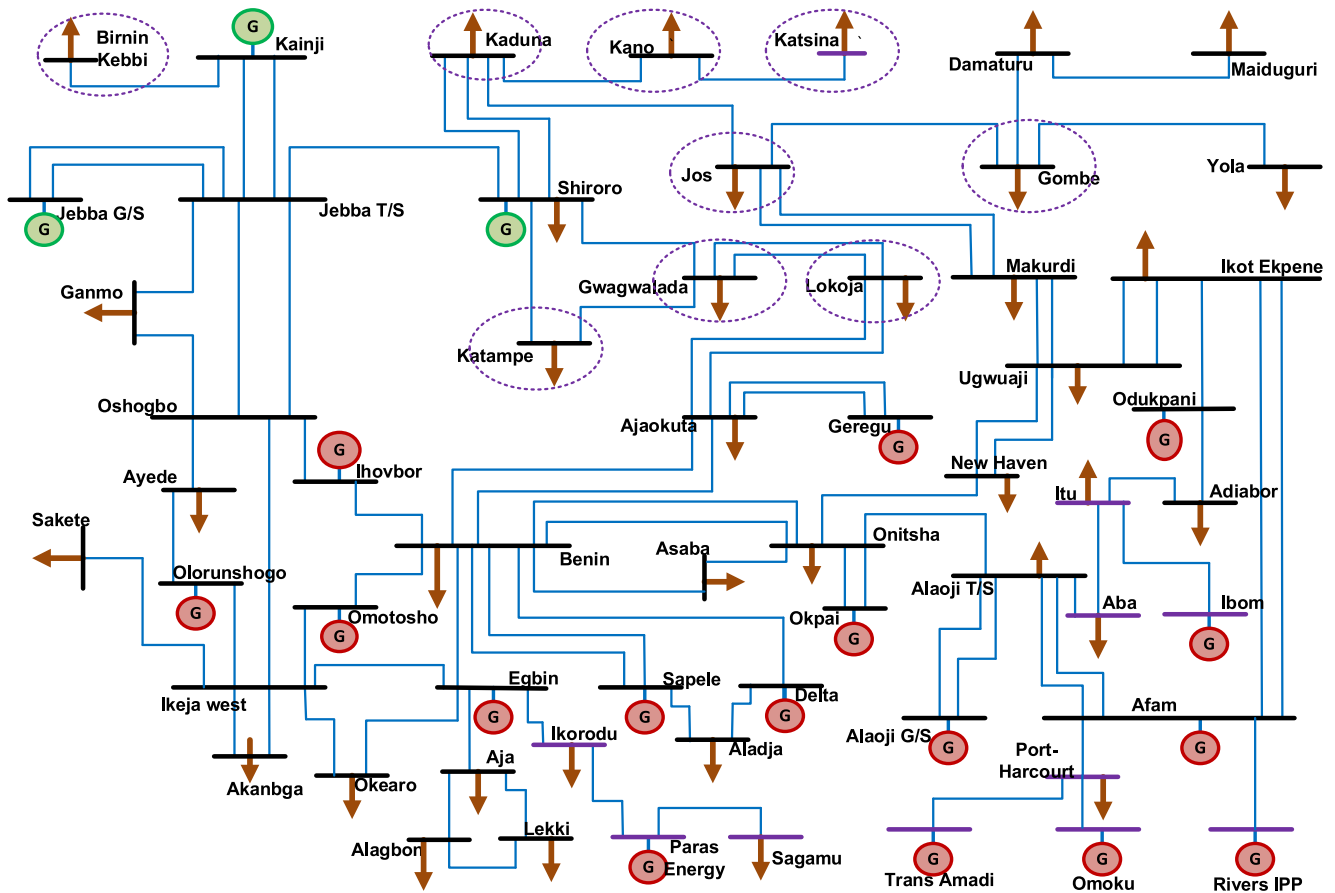


Fig. 8. Single-line diagram of the Nigerian transmission network

5. Technical and Policy Implications

The objective of this study aligns with current industry trends geared towards addressing the broad challenges of maintaining adequate system strength in power grids with large-scale integration of IBG. It offers an innovative approach for identifying IBG interaction when estimating system strength using the proposed RED concept. The method has

significant implications for both technical grid management and policy development in large-scale IBG integration scenarios. The RED-based interaction matrix equips system operators and planners with a clear understanding of IBG interaction levels, enabling more accurate system strength estimation during grid planning and expansion. It also informs IBG integration regulatory frameworks. For example, the RED concept complements the recommendations from the AEMO [14] to focus on

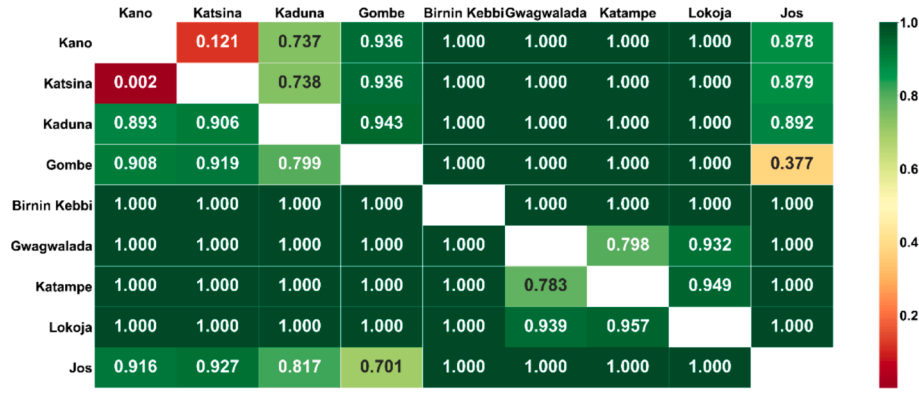


Fig. 9. Nigerian transmission system heatmap correlation of the RED interaction matrix

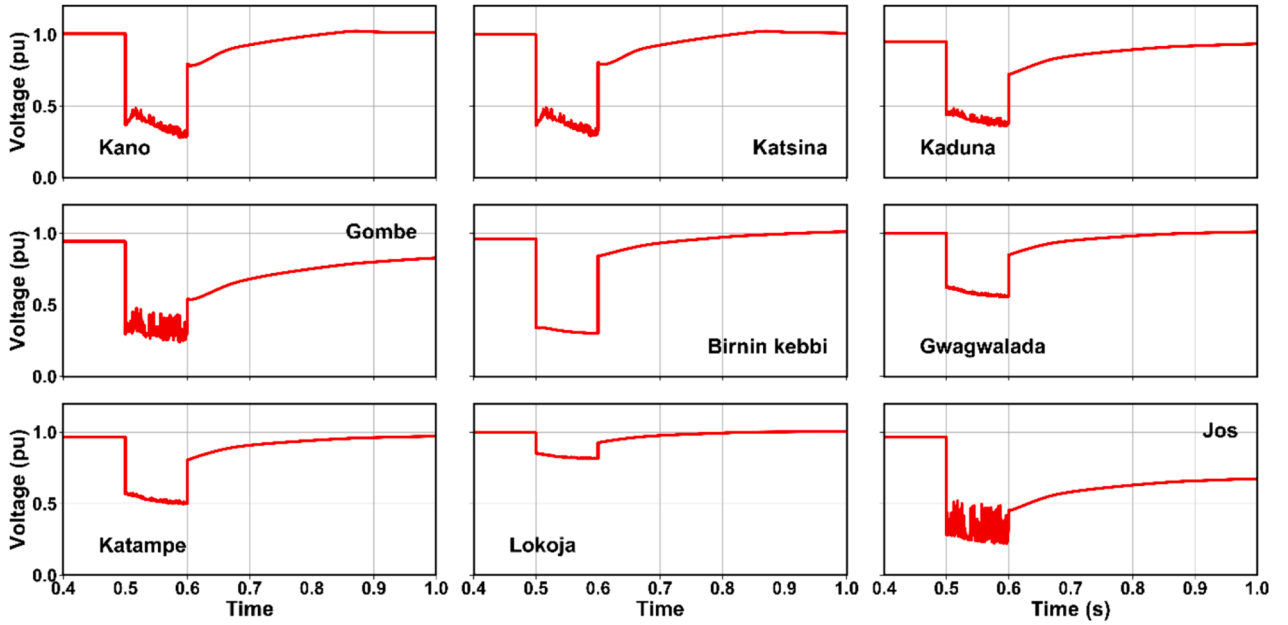


Fig. 10. PoI voltage response showing interaction among IBGs within group 1

localised interactions (within three buses) for system strength evaluations, offering a practical tool for system operators. By utilising the RED values, decisions on specific buses to be considered in system strength estimation can be data-driven.

Building on this, regulatory bodies can establish guidelines for interconnection studies, stability requirements, and grid code compliance based on the interaction boundaries defined by the RED concept. This approach can also be translated into standardised practices for IBG interaction and system strength assessment, ensuring consistency in grid performance evaluation and planning. Policymakers can further utilise this method to develop incentive programmes that encourage investments in grid infrastructure upgrades and the deployment of technologies that enhance system strength in areas identified with potential interaction issues. Additionally, the RED approach can facilitate targeted, and cost-effective solution for grid reinforcements while serving as a practical tool for identifying potential areas of concern and enabling proactive system strength enhancement strategies.

The RED values provide quantitative information representing IBG interaction level, crucial for decision-making and system planning. This data can be incorporated into system planning tools, leading to more accurate and reliable outcomes. By identifying areas with limited interaction, grid planners can prioritise rapid uptake of IBGs for increased grid capacity, particularly in electricity-strapped grids like the

Nigerian power network. Ultimately, understanding and managing IBG interactions will contribute to improved system performance, including improved system strength, enhanced voltage stability, and increased reliability for power consumers.

6. Conclusion

This study presents a method for identifying the boundaries of interaction among IBGs, a critical aspect of evaluating system strength in power grids with large-scale IBG integration. The method is based on the concept of relative electrical distance (RED), which illustrates the relationship between any two buses in a network. An interaction matrix, composed of the relative electrical distances between all the Points of Interconnection (PoIs) in the network, is designed and validated through simulations on the standard IEEE 39-bus system and the practical Nigerian transmission system.

The simulation results confirmed the effectiveness of the proposed method in identifying the boundaries of interaction. The different groups of boundaries identified indicate that electrical connectivity is not absolute and that varying degrees of interaction exist between several PoIs. In the context of these interactions, the fault current level at a PoI significantly influences both the magnitude and effect of interactions among IBGs. Moreover, the presence of multiple IBGs with a

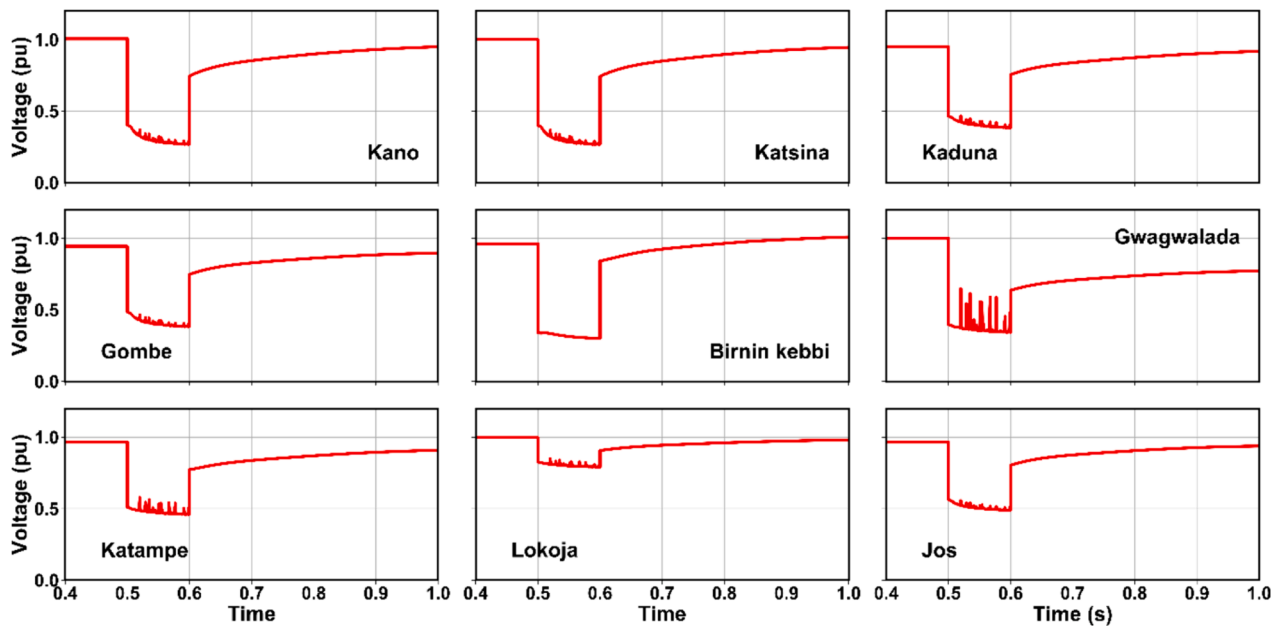


Fig. 11. PoI voltage response showing interaction among IBGs within group 2

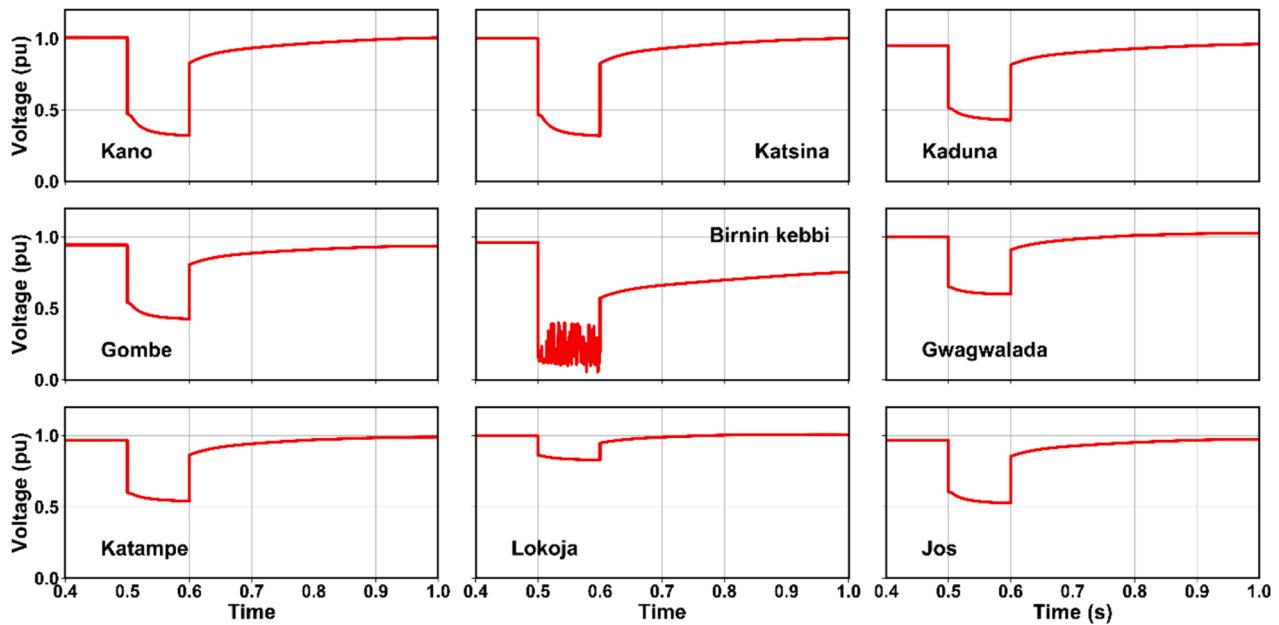


Fig. 12. PoI voltage response showing interaction among IBGs within group 3

RED value closer to zero (i.e., in close proximity) interacting with each other may be detrimental to system operation, though this impact diminishes as the RED value approaches unity. While the method offers significant benefits in terms of computational efficiency, accuracy, and applicability to large-scale systems, it is reliant on accurate network data, and discrepancies could affect the results' accuracy. Furthermore, its effectiveness in highly dynamic grid conditions and in grids with extensive additional network equipment, such as reactors, capacitors, and FACTS devices, may require further investigation. Despite these limitations, the results suggest that system strength assessment methods based on actual electrical connections will provide more reliable estimates of grid strength at the PoIs.

The findings of this study contribute to the broader literature on grid stability and IBG integration by providing a straightforward method for quantifying interaction levels among IBGs. Unlike traditional methods

that rely heavily on power flow analysis and time-consuming time-domain simulations, the RED-based approach offers a computationally efficient alternative that captures the inherent structural characteristics of the grid. This method is a valuable tool for power system planners and operators, enabling the initial screening of potential areas of concern in grid design and network operation. Its reliance on network topology and electrical parameters eliminates the need for complex system modelling and mathematical formulation. Future research will focus on identifying the threshold of RED values beyond which interaction effects may be considered negligible, further enhancing the method's applicability and precision in diverse grid conditions.

CRediT authorship contribution statement

Shereefdeen Oladapo Sanni: Writing – review & editing, Writing –

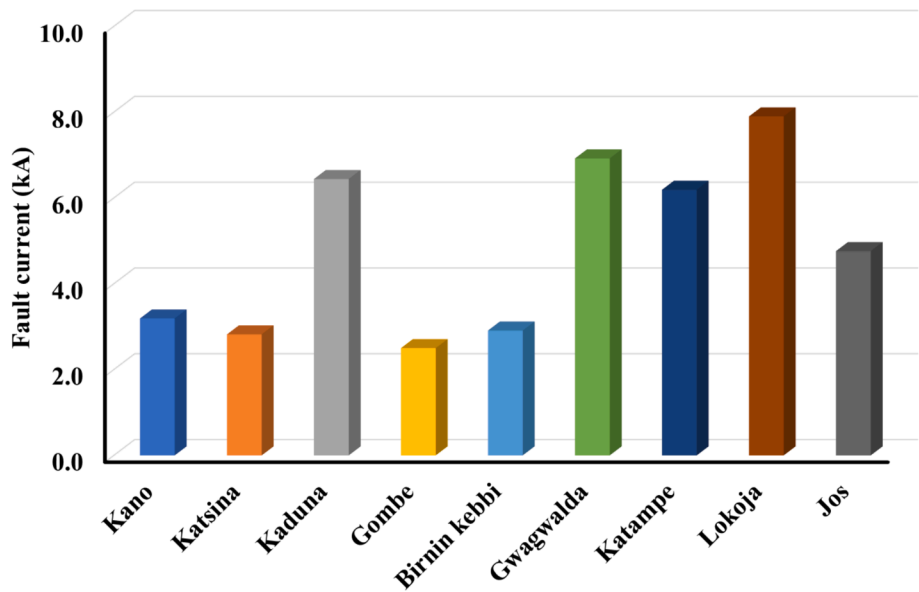


Fig. 13. Fault current profile at the PoIs of the Nigerian transmission system

Table 1
Comparison of power flow tracing and RED-Based methods for defining interaction boundaries among IBGs

Method	Power Flow Tracing Strategy [13]	Relative Electrical Distance Concept (Current Study)
Objective	To determine actual interaction boundaries of RESs using the power flow tracing method.	To identify interaction boundaries among IBGs using the relative electrical distance concept.
Data Requirements	Requires detailed power flow data, including power generation, load demand, etc, which may not always be readily available.	Uses the power system network's admittance matrix which is obtained from the transmission line data.
Strengths	- Provides detailed insights into power flow paths. - Useful for understanding the contribution of each IBG source to overall system strength.	- Based on electrical connectivity. - Efficient and less computationally demanding, suitable for large-scale grids. - Empirically driven, providing clear, insights based on RED values.
Weaknesses	Computationally intensive, especially for large-scale grids.	Simplifies network representation for computational efficiency, potentially limiting the capture of complex system dynamics.
Test System	Korea Electric Power Corporation (KEPCO) systems.	IEEE 39-Bus System,Nigerian 72-Bus System.
Consideration of System Dynamics	Focuses on static condition.	Accounts for both static and dynamics condition.
Key Findings	Demonstrates that full interaction between IBGs is not always present, identifying distinct interaction groups.	- Quantifies interaction levels using RED values, revealing varying degrees of influence between IBGs. - Highlights the impact of fault current levels and control strategies on IBG interactions.

original draft, Validation, Software, Methodology, Formal analysis, Conceptualization. **Olatunji Obalowu Mohammed:** Writing – review & editing, Writing – original draft, Supervision. **Ayodele Isqeel**

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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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