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RESEARCH ARTICLE

On the Choice of System Strength Metrics for the Allocation and Sizing of Synchronous Condensers in Power Grids

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ABSTRACT The integration of high levels of inverter-based generation (IBG) into power grids requires meticulous planning, especially as IBGs lack the inherent short-circuit capacity of conventional generators, potentially weakening system strength. To mitigate this, synchronous condensers (SCs) are deployed in weak areas to enhance fault current and voltage support. Traditional SC allocation methods use the short-circuit ratio (SCR) as a key metric, but this may not account for control interactions in grids with significant IBG penetration. This study compares two approaches for optimizing SC placement and sizing: SCR-based and network-response short-circuit ratio (NRSCR)-based, a metric that captures dynamic IBG interactions. Applying a genetic algorithm (GA) to the Nigerian power grid as a case study, the SCR-based approach identified two critical points of interconnection (PoIs) requiring 68 MVA of SC capacity, while the NRSCR-based method identified four PoIs, requiring a total of 674 MVA. Although the NRSCR-based method significantly improved system performance during faults—offering faster voltage recovery post-fault and higher fault current contributions—it resulted in a cost increase of approximately 7 times. This highlights the trade-off between cost and performance, underscoring the need for utilities to balance economic and technical considerations when deploying SCs in IBG-dominated grids.

INDEX TERMS Control interactions, synchronous condensers, inverter-based generation, system strength, short-circuit ratio.

I. INTRODUCTION

The growing integration of renewable energy sources (RES) like wind and solar is driven by both their sustainability credentials and significant contributions to reducing greenhouse gas emissions from power generation [1]. In 2023 alone, the global capacity of RES-based generators grew by 536 GW,

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a 54% increase from previous levels, with solar photovoltaic (PV) and wind energy being the primary contributors. Solar PV accounted for 407 GW (34%), while wind power contributed 117 GW (13%) of this growth [2]. This transition is particularly appealing to countries with established power grids, as it enables a gradual shift to cleaner energy through the phaseout of conventional power-generating units [3]. For nations seeking to address energy deficits, RES emerges as a key alternative to meet their needs [4]. Despite the diverse

motivations for adopting RES, their integration presents unique challenges for power grids. These challenges stem from the reliance of RES on electronic converters, leading to the classification of such sources as inverter-based generation (IBG).

IBGs are rapidly changing the landscape of power grids. Due to their remote locations and inherent lack of short-circuit capacity, they can weaken grid strength, especially in areas far from synchronous generators. Given this consideration, system strength at the point of interconnection (PoI) becomes a primary concern. Key system variables, including voltage stability and fault response, are directly affected by the grid's ability to handle disturbances at this specific location [5]. Traditionally, the short-circuit ratio (SCR) has been used to quantify this strength, providing an indication of how well the grid can accommodate the IBG's power output relative to its short-circuit capacity [6], [7].

As the deployment of IBGs increases, concerns arise about potential instability issues in weak grids, particularly due to control system interactions [8], [9], [10]. These interactions arising from the inverter's fast-acting electronics can trigger unwanted oscillations that threaten grid stability. In this scenario, simply relying on the SCR for strength assessment is insufficient. This stems from SCR's inability to capture these interactions, which may lead to an underestimation of the actual risks [11]. Alternative methods like the weighted SCR (WSCR) [12], composite SCR (CSCR) [13], site-dependent SCR (SDSCR) [11], and network-response SCR (NRSCR) [14] have been proposed to address this limitation. While WSCR and CSCR assume full interaction between all IBGs, they ignore actual electrical network connections between IBGs and may potentially misrepresent system strength except for areas with very close IBGs [11], [13], [14], [15]. In contrast, SDSCR and NRSCR, consider network connections, providing more accurate strength estimates. In any case, it has been established that large numbers of IBGs in close proximity experience interactions which have a negative impact on network operation [16]. Therefore, power grids need to be equipped to handle potential problems arising from such scenarios for enhanced system strength.

Weak grid characteristics such as low short-circuit current and poor voltage regulation can be improved through transmission line reinforcement and the deployment of discrete compensating devices such as static var compensators (SVCs), static synchronous compensators (STATCOMs), battery energy storage systems (BESSs), variable frequency transformers (VFTs), and synchronous condensers (SCs) [17], [18], [19], [20], [21], [22], [23]. However, each of these technology presents unique challenges. For large-scale transmission networks, SCs are identified as the most suitable solution to enhance system strength, provide dynamic reactive support and addressing voltage stability issues [23]. Additionally, the need for transmission line upgrades is emphasized, along with potential contributions for SVCs and VFTs in similar contexts. However, the implementation of

these solutions may present cost challenges. As an alternative, STATCOM technology provides essential grid support functions, enhancing voltage stability and reducing reliance on traditional reactive power compensators. Nonetheless, critical challenges remain, including integration issues, frequency regulation concerns, and the need for adaptive regulatory frameworks to accommodate these advanced grid functionalities [19]. BESS on the other hand can effectively provide inertia support during power system contingencies, playing a crucial role in stabilizing system frequency. However, its main limitation is its inability to provide additional inertia support once the converter's maximum output power is reached [18]. Moreover, BESSs are prone to undesired oscillations if not properly tuned. In essence, SCs are recognized for their inherent ability to provide grid support with respect to reactive power, inertia, voltage control, and short-circuit current at a relatively lower cost when compared to VFTs [24], [25]. For effective results, SCs are located at the required PoI where system strength enhancement is needed. However, optimal allocation of SCs is necessary to minimize the cost implications and ensure adequate grid support.

The significance of cost in the allocation of SC for grid support has been highlighted by [26]. It emphasized that a synchronous condenser is cost-effective compared to other reactive power-generating equipment. However, cost could be further reduced by retrofitting an existing synchronous generator as a condenser and optimizing its size for an effective result. The use of decommissioned synchronous generators as condensers for enhanced inertia and short-circuit power in a RES-dominated power system is therefore recommended for cost effectiveness [3]. This could be further enhanced by optimally allocating dynamic reactive power support in large-scale RES-integrated power systems [27]. The use of this approach for mitigating system strength problems has been widely reported [28], [29], [30], [31]. Marrazi et al. [29] proposed a genetic algorithm (GA)-based optimization model to evaluate and optimize the need for synchronous condensers in weak power systems with renewable generation. Results suggest prioritizing SC allocation for buses with the lowest SCR. This suggestion can be effectively used to allocate and size synchronous condensers in weak power systems with renewable energy penetration. In addition, it ensures that the SCR at the weak PoIs exceeds pre-defined values and is able to withstand disturbances and adhere to grid codes [28]. The long-term techno-economic implications of synchronous condenser installation for system strength enhancement have been investigated [30], [31]. It was apparent that the net present value (NPV) remains positive even with internal synchronous condenser losses greater than 3 % [30]. A comparative study of SC with SVC by Masood et al. [31] indicates that an SVC does not always guarantee long-term financial benefits, except if wind generation curtailment reduction is substantial. At even moderate reductions, synchronous condensers significantly outperform SVCs in both net profit and NPV, making them the preferred option across all sce-

TABLE 1. Summary of selected relevant references on synchronous condenser sizing.

Ref	Optimization Method	Test Network	System Strength Metric	Interaction Effects Demonstrated?
[28]	Bat Algorithm Hyper Spherical Search Genetic Algorithm	Modified IEEE 39-bus system	SCR	No
[29]	Genetic Algorithm	Western Danish transmission system 2012 DK1 model	SCR	No
[31]	Genetic Algorithm	IEEE 39-bus system	SCR	No
[30]	Genetic Algorithm	Australian South-East 14-Generator model	SCR	No
[12]	Iterative process	ERCOT Panhandle area	SCR, WSCR	No
[38]	Genetic Algorithm	IEEE 33-bus system	SCR	No
[39]	Improved Genetic Algorithm	Not specified	SCR	No
[32]	Basin Hopping Algorithm (BHA) with Nelder-Mead Algorithm (NMA)	Modified IEEE 39-bus system	ESCR	No
This study	Genetic Algorithm	Nigerian 72-bus transmission system	SCR, NRSCR	Yes

narios. Reference [32] proposed optimizing SC size and location using the Effective Short-Circuit Ratio (ESCR) to consider IBG interactions in weak grids. However, it lacks explicit analysis demonstrating how these interactions affect system behavior, such as voltage response or dynamic performance, leaving the practical impact of interactions underexplored.

Table 1 summarizes previous efforts that mostly utilized the SCR metric to optimize SC size, often overlooking interaction issues among IBGs. This limitation underscores the need for assessment of alternative metrics, such as the network-response short-circuit ratio (NRSCR), developed by the authors in [14], which this study explores for more effective grid reinforcement.

It is apparent that existing research predominantly relies on the basic SCR metric to determine optimal SC sizes for enhancing power grid strength. However, SCR's effectiveness is limited as it fails to account for interactions with nearby IBGs during large-scale integration. Reports of control interaction problems in practical power grids with multiple IBGs further emphasize this concern [33], [34], [35]. Consequently, SCR-based sizing may not provide sufficient grid reinforcement. To address this gap, the present study compares the performance of the basic SCR and NRSCR metric, which considers these interactions. This study aims to support power system planners in choosing suitable system strength metrics, a critical step for ensuring reliable integration of IBGs into power grids. The key contributions of this paper are summarized as follows:

- Formulated an optimization framework to determine the optimal sizing and allocation of SCs for enhancing system strength in weak grids with high IBG penetration.
- Incorporated IBG interaction effects into the optimization process, addressing a gap in existing literature where traditional strength metric (SCR) overlooks coupling between multiple IBGs.

- Compared system strength metrics (SCR vs. NRSCR) by evaluating their impact on post-disturbance dynamic behaviour, highlighting the importance of metric choice in mitigating instability due to IBG control interactions.
- Demonstrated practical applicability and scalability by applying the proposed method to the real-world Nigerian 72-bus transmission system.
- Evaluated the dynamic performance of the optimized network under a fault scenario, validating the effectiveness of the proposed planning method in suppressing oscillatory behaviour and improving overall system stability.

The remaining sections of this paper are organized as follows: Section II describes the problem formulation, including the optimization algorithms used. Section III offers an overview of the test network along with the implementation process. Section IV describes the optimization results and analysis. Section V presents the key findings and future work.

II. PROBLEM FORMULATION

Numerous system strength measures have been proposed in the literature, two of which are considered in this study; the short-circuit ratio (SCR) and the network-response short-circuit ratio (NRSCR). An overview of both measurements is given in this section. Thereafter, the problem posed by the sizing of the synchronous condenser with consideration of the strength constraint is formulated.

A. SHORT-CIRCUIT RATIO (SCR)

System strength measure as defined by the SCR is the ratio of short-circuit power to the rated IBG active power at the PoI is the generally accepted metric for evaluating the strength at the PoI is expressed as [36] and [37]:

$$SCR_i = \frac{|S''_i|}{P_{\max,i}} \quad (1)$$

where S_i'' is the short-circuit capacity of the i^{th} PoI and $P_{max,i}$ is the rated active power of the IBG connected to the that PoI. The SCC is determined from a three-phase short-circuit fault analysis and expressed in (2) as:

$$S_i'' = \sqrt{3} V_n I_i'' \quad (2)$$

where I_i'' and V_n are the short-circuit fault current and the bus nominal voltage, respectively.

The SCR metric has been utilized as the sole criterion for optimal sizing of SCs to enhance system strength in power grids [28], [29], [30], [31]. However, SCR suitability in evaluating system strength has been established to be limited since it does not account for interaction with close-by IBG in large-scale integration [11], [12], [14]. Considering that more IBGs are being deployed worldwide, the proximity between them will become narrower; thus, an optimally sized SC using the SCR results in a simplistic outcome that may not be adequate for grid reinforcement.

B. NETWORK-RESPONSE SHORT-CIRCUIT RATIO (NRSCR)

The NRSCR is an alternative metric that addresses the lack of consideration for interactions and provides a more accurate method to evaluate system strength. It reflects the interaction among IBGs at different PoIs based on the electrical interconnections in the network. An optimally sized IBG using the NRSCR is expected to adequately provide the necessary enhancement for the power grid. The NRSCR at the i^{th} PoI is given in equation (3) as:

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

where $P_{max,i}$ denotes the rated capacity of the IBG at bus i , D represents the total number of IBGs in the network, and $\sum_{j \in D, j \neq i} [P_{max}^C]_{j,i}$ quantifies the influence of IBG injections from neighboring buses. This influence is defined as a fraction of the rated capacity of the IBG at bus j , capturing its interaction with the IBG at bus i , and is expressed as:

$$\sum_{j \in D, j \neq i} [P_{max}^C]_{j,i} = \sum_{j \in D, j \neq i} [F_{ji} \times P_j] \quad (4)$$

F_{ji} is derived the elements of the F_{LG} matrix derived from the network's admittance matrix. Details of the computation procedure is presented in [14]. A key advantage of the NRSCR approach is its adaptability across different grid configurations, as it inherently accounts for the structural characteristics of the network. Unlike conventional metrics, NRSCR dynamically reflects changes in grid topology, ensuring that variations in system configuration, IBG penetration levels, and network interconnections are effectively captured. This makes it a robust and scalable method for assessing system strength across diverse power networks [40].

While evaluating system strength, a common recommendation is to classify grids as follows: strong for SCR above 3,

weak between 2 and 3, and very weak below 2 [11], [23], [37]. However, individual grid characteristics can necessitate different threshold ranges [41].

C. IBG INTERACTIONS AND SYSTEM STRENGTH IN WEAK GRIDS

In interconnected power systems, components interact dynamically through various control systems [42]. For grids with high penetration of IBGs, these interactions become more complex, especially when involving other power-electronic devices like FACTS devices [43]. The impact of such control interactions is more significant in weak grids, characterized by low system strength, where even small disturbances can cause substantial changes in network conditions. In contrast, strong grids with higher system strength experience less severe effects from these interactions [44]. The voltage sensitivity response to a reactive power injection at an IBG's PoI is defined by Equation (5) [45]:

$$\frac{dV_{PoI}}{dQ} = \frac{X_l}{2V_{PoI} - 1} \quad (5)$$

where V_{poi} represents the voltage at the PoI, Q is the reactive power, and X_l is the reactance of the transmission line connecting the IBG to the grid.

The implication of system response using (4) is illustrated by analyzing the dynamic response of a simple power grid with weak grid conditions. Figure 1 shows a sample 5-bus system, where IBGs are connected at buses 1-3, which are considered weak PoIs. These IBGs maintain voltage stability through reactive power injection in voltage control mode. Buses 4 and 5, on the other hand, are conventional generation buses with stronger voltage regulation capabilities but are located farther from the IBG cluster.

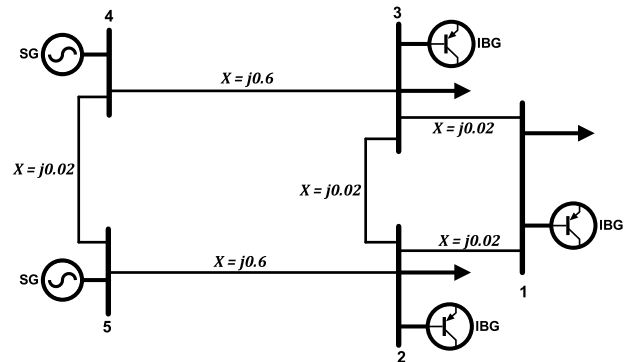


FIGURE 1. A sample 5-bus power system integrated with IBG.

When a voltage change occurs at weak bus 1, the IBG compensates by injecting or absorbing reactive power to stabilize the voltage. However, due to the high sensitivity and rapid response of the inverter, this action may result in an overshoot or undershoot, leading to further fluctuations in voltage. The action induces oscillations which propagate to

nearby buses 2 and 3, which are electrically close to bus 1, triggering similar control actions at these buses. This creates a cascading effect, where sustained voltage oscillations impact multiple buses. The feedback mechanisms among IBGs exacerbate the grid's vulnerability, particularly in weak areas. Thus, understanding and evaluating system strength in weak grids requires critical consideration of these IBG interactions, especially as large-scale IBG integration becomes prevalent.

D. THE OPTIMIZATION PROBLEM

The integration of IBGs in power systems may be constrained by limited short-circuit strength. Synchronous condensers are well-known for providing the essential short-circuit capacity necessary to support the grid in the large-scale integration of IBGs. The question that arises as a result is; what size of SC will offer such support? Consequently, the problem posed by this scenario is to reduce the installation cost of a synchronous condenser while improving the system's strength. The objective function of the optimization problem can thus be represented using (6) and (7)

$$\text{Min } C_T(S_{SC}, k) \quad (6)$$

$$C_T = \sum_{k \in N_{POI}} (C_f + C_v(S_{SC}(k))) \quad (7)$$

where C_f and C_v denotes the fixed and variable cost associated with installing synchronous condenser in \$ and \$/MVA respectively. N_{POI} is the number of PoIs considered for synchronous condenser installation, S_{SC} is the size of installed synchronous condenser at the k^{th} PoI.

This minimization problem requires that the system strength must be maintained above a set minimum level at all PoIs. Thus, the following constraint applies:

$$SCR_k \text{ (or } NRSCR_k) \geq S_{min}, \forall k \in N_{POI} \quad (8)$$

S_{min} is the minimum acceptable system strength value defined in this study as 5.

E. OPTIMIZATION ALGORITHM

The formulated optimization problem is a mixed-integer non-linear programming (MINLP) problem, characterized by discrete variables representing the presence of an IBG and non-linear system strength computations. To solve this, the Genetic Algorithm (GA) is adopted due to its demonstrated suitability for non-convex, discrete, and constraint-intensive problems. GA has been widely used in power system studies for its ability to efficiently explore large solution spaces and avoid local optima through stochastic search processes inspired by natural selection. It has also been extensively applied in similar optimization contexts, providing a strong basis for comparison with previous studies. Its population-based structure enables flexible constraint handling, making it particularly well-suited for system strength optimization in power grids [46], [47]. While alternative metaheuristics have emerged in recent literature, GA remains a widely adopted method due to its consistent performance and adaptability.

The GA, is based on a biological science theory and operates through computational mechanisms that mimic the human evolution cycle. The process starts with the creation of an initial population of potential solutions made up of several chromosomes. This will represent the parent having n genes with the i^{th} generation and k^{th} chromosomes given as:

$$g_i = (S_1, S_2, S_3, S_4, \dots, S_{N_{pop}}), i \in G \quad (9)$$

$$S_k = [z_{1,k}, z_{2,k}, z_{3,k}, \dots, z_{n,k}], \quad (10)$$

$$s \in n; k \in N_{POI}; z_k \in [S_{SC}, \overline{S_{SC}}]$$

The total number of generations is denoted by G , minimum and maximum synchronous condenser sizes is given as S_{SC} and $\overline{S_{SC}}$ respectively.

The fittest individuals in this population, determined by the objective function, are selected to form the next generation. A new set of solutions is created by crossing over selected pairs of parents and mutating the genes in the chromosomes of the preceding generation, as shown in equations (11) and (12).

$$C_j^{xy} = [z_{c1,j}, z_{c2,j}, z_{c3,j}, \dots, z_{cn,j}], \quad (11)$$

$$x \neq y; x, y \in N_{pop}; s \in n;$$

$$M_j^{xy} = [z_{m1,j}, z_{m2,j}, z_{m3,j}, \dots, z_{mn,j}], \quad (12)$$

where $z_{ms,j} = z_{cs,j} \pm \Delta z; \Delta z \sim \text{random}; z_{ms,j} \in [S_{SC}, \overline{S_{SC}}]$

After crossover and mutation, the system strength constraint is checked with the new children. Eligible children who meet the minimum system strength criteria are selected, and their fitness is evaluated. The set of children with the best fitness score becomes the parents for the next generation. This process continues until the last generation, when the best chromosome that minimizes the objective function is obtained.

III. PROPOSED APPROACH AND CASE STUDY

A. GENETIC ALGORITHM IMPLEMENTATION

The proposed solution was implemented with the power system simulation for engineering (PSS/E) software and script written in Python. Figure 2 illustrates the computational framework of the GA optimization approach employed in this study. All the relevant inputs, such as the number of iterations, size of the population, mutations, selection, and crossover criteria, are well-defined for the GA execution. The algorithm starts with a short-circuit capacity assessment, which is then utilized to assess system strength (SCR or NRSCR). The objective is to identify the PoIs whose strength is below the minimum threshold set for the system. The next step is to generate an initial population of solutions for the identified PoIs by randomly allocating different sizes of SCs that satisfy the constraint. The solutions were transmitted to the PSS/E software, where they are connected to their respective PoIs to obtain the power flow solution for the system. The system strength constraint is verified again for every individual, and the best fit is identified from the population. A new generation formed after crossover and

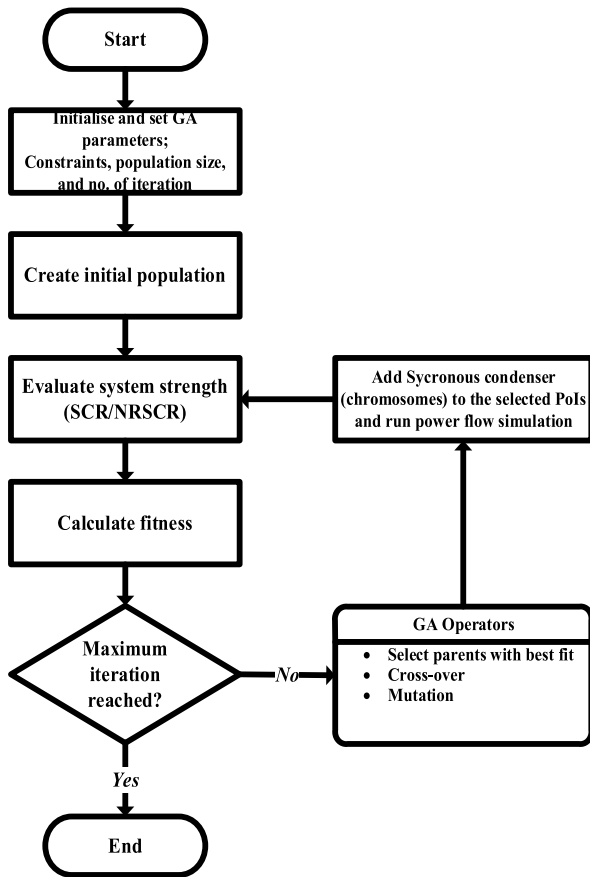


FIGURE 2. Implementation framework of the genetic algorithm.

mutation is also returned to the PSS/E software, and the cycle continues until the best solution for all the chromosomes is established. The whole process is automated using the application program interface (API) features of PSS/E. The proposed approach terminates once the maximum number of generations is exceeded, as illustrated in Figure 2.

The studied power system is based on the Nigerian grid model, representing the high-voltage transmission network with integrated IBGs, as described in [48]. Figure 3 illustrates the network, which consists of a 72-bus system with an IBG-installed generation capacity of 990 MW, primarily from solar and wind sources in the northern region, as detailed in Table 2. This region is characterized by long transmission lines, low short-circuit power, and a significant distance from adequate synchronous generation, which could negatively impact IBG operation [48]. Furthermore, a preliminary assessment of the network reveals that the IBGs are clustered closely together, increasing the likelihood of mutual interactions. This potential interaction suggests that the studied network section, as shown in Figure 3, is at risk of experiencing low system strength at the PoI. This scenario presents a picture of a weak grid condition, necessitating additional short-circuit power to be provided by a synchronous condenser. In addition, the grid's unique challenges—particularly the interaction of IBGs and the

resulting low system strength, along with related issues within the Nigerian grid as demonstrated in previous studies such as [48], [49]—make it an ideal candidate for testing and validating the effectiveness of the proposed methodologies in enhancing system strength. All IBGs in this study are modeled using grid-following voltage control mode.

IV. RESULTS AND DISCUSSION

This study examined two optimization approaches. The first approach utilized an SCR-based metric to optimally size and SCs, while the second relied on an NRSCR-based measure for the same purpose. In both cases, SCs were connected to candidate PoIs where the SCR or NRSCR values fell below the minimum value of 5 set for this study. Using the implementation framework outlined in Figure 2, the optimal sizes of SCs determined are chosen to provide the acceptable SCR/NRSCR threshold value on all PoI buses. A 50% random uniform crossover rate and a 5% mutation rate are used when running GA. Furthermore, we set the maximum number of generations and population size to 50 and 150, respectively, while retaining the best individuals from ten simulations. These individuals yielded the lowest total installation cost and were selected as the best and final outcome. The cost parameters assigned to the synchronous condensers are determined by the average installation cost for refurbished units reported in [50]. Equation (5) incorporates a fixed cost parameter (C_f) set to zero and a variable cost parameter (C_v) set to \$35,000/MVA

TABLE 2. IBG integration details in northern Nigeria.

PoI	Type	IBG Capacity (MW)
Birnin Kebbi	Solar	55
Gombe	Solar	100
Gwagwalada	Solar	100
Jos	Solar	220
Kaduna	Solar	50
Kano	Solar	130
Katampe	Solar	50
Katsina	Solar	175
Katsina	Wind (Type 3)	10
Lokoja	Solar	100

A. CASE-1: SCR-BASED INVESTIGATION

1) OPTIMIZING SYNCHRONOUS CONDENSER SIZE

The system's strength at the PoI buses is assessed by initially calculating the SCR values, without installing any SC. Table 3 shows that only the PoI buses at Katsina and Jos violated the minimum defined threshold of 5, having SCR values of 3.46 and 4.94, respectively. These two buses are the candidate PoIs for connecting SC. Consequently, SC was attached to them, and GA optimization was applied to the system. The optimal sizes were found to be 67 MVA and 1 MVA at Katsina and Jos, which resulted in SCR values of 5.05 and 5.00, respectively. Moreover, except for the PoI at Kano and Katsina, no other PoI in the system experienced a significant improvement in the SCR values. The rationale for this

becomes clearer when by analyzing the short-circuit current profiles at the PoIs, as depicted in Figure 4. It is apparent that SC placement will not always lead to uniform improvements across all PoIs. For example, at Birnin Kebbi and Lokoja, the unchanged short-circuit current values suggest that these locations are structurally constrained in their response to the addition of SCs in the identified weak points network. A comparable trend is later seen in Figure 6 under NRSCR-based allocation, highlighting the necessity of a grid-sensitive approach when optimizing SC placement for enhanced stability.

2) PERFORMANCE EVALUATION OF OPTIMALLY SIZED SYNCHRONOUS CONDENSER WITH SCR

The effectiveness of the optimally sized SC on the Nigerian power grid is evaluated through time-domain analysis performed using PSS/E simulation studies. This part of the study aimed to examine the impact of the SCR-based optimally sized SC on system strength, based on the post-fault voltage response to unstable control actions initiated by balanced three-phase fault conditions at Jebba. Therefore, two scenarios were compared in the analysis: one without SCs, where Katsina and Jos had SCR values below 5, and one with optimally sized SCs at each location, increasing their SCRs to 5.05 and 5.00, respectively. Figure 5 reveals that both scenarios exhibited oscillatory responses during the fault, with bus voltages dropping to around 0.2 pu and 0.45 pu at Katsina and Jos, respectively. Katsina, having a lower SCR value, experienced a more severe dip. Additionally, while the SC improved post-fault voltage recovery at Katsina to 3.2 seconds, its impact on Jos was minimal. This suggests that the small size of the SC (1 MVA) at Jos also implied limited fault current contribution, hindering its ability to significantly strengthen voltage response at Jos.

TABLE 3. Optimal synchronous condenser sizes and SCR result.

Bus Name	Prated (MW)	Optimal size of SC (MVA)	SCR	
			Without SC	With SC
Kano	130	-	5.58	7.73
Katsina	185.18	67	3.46	5.05
Kaduna	50	-	29.42	30.11
Gombe	100	-	5.68	5.71
Birnin kebbi	55	-	12.08	12.08
Gwagwalada	100	-	15.82	15.89
Katampe	50	-	28.31	28.43
Lokoja	100	-	18.06	18.07
Jos	220	1	4.94	5.00

B. CASE-2: NRSCR-BASED INVESTIGATION

1) OPTIMIZING SYNCHRONOUS CONDENSER SIZE

To determine the optimal size of SCs, the evaluation of the NRSCR at the PoIs was initially conducted without any SCs in place. As shown in Table 4, four PoIs at Kano, Katsina, Gombe, and Jos had NRSCR values of 2.1, 1.96, 3.02, and 3.33, respectively, all falling short of the pre-defined

minimum threshold of 5. Implementing the optimal sizing algorithm led to significant improvements in NRSCR for these identified weak buses. The NRSCR values at these PoIs increased to 5.32, 5.13, 5.92, and 5.05, respectively. Table 4 clearly illustrates this improvement, with the optimal SC sizes for each PoI being 159 MVA (Kano), 245 MVA (Katsina), 152 MVA (Gombe), and 118 MVA (Jos). The integration of SCs led to a noticeable increase in short-circuit current levels at these PoIs, as evidenced by the rise in

TABLE 4. Optimal synchronous condenser sizes and NRSCR result.

Bus Name	Prated (MW)	Optimal size of SC (MVA)	NRSCR	
			Without SC	With SC
Kano	130	159	2.1	5.32
Katsina	185.18	245	1.96	5.13
Kaduna	50	-	7.6	8.18
Gombe	100	152	3.02	5.92
Birnin kebbi	55	-	12.08	12.09
Gwagwalada	100	-	13.54	13.72
Katampe	50	-	19.02	19.29
Lokoja	100	-	16.52	16.55
Jos	220	118	3.33	5.05

NRSCR values. Among the PoIs where SCs were installed, Kano exhibited the most significant increase in short-circuit current rising from 3.19 kA to 8.1 kA, while Gombe experienced the smallest increase, from 2.5 kA to 4.9 kA. This enhancement is visually depicted in Figure 6. In contrast, PoIs such as Birnin Kebbi, Gwagwalada, Katampe, and Lokoja showed minimal changes in NRSCR values after SC integration, as their short-circuit currents remained nearly unchanged. This indicates that the impact of SC integration at the weaker PoIs had little effect on these unaffected PoIs.

2) PERFORMANCE EVALUATION OF OPTIMALLY SIZED SYNCHRONOUS CONDENSER WITH NRSCR

Dynamic simulations were also conducted to evaluate the performance of optimally sized SCs selected using the NRSCR metric. The simulations involved a three-phase fault initiated at the Jebba bus, followed by an unstable control action triggered by the IBG at Kaduna.

Without any SCs in place, the bus voltage responses at the four PoIs; Kano, Katsina, Gombe, and Jos, mirrored those observed in the SCR-based optimal sizing scenario. Figure 7 shows that these PoIs recorded significant voltage drops during the fault: approximately 0.2 pu at Kano and Katsina, 0.38 pu at Gombe, and 0.45 pu at Jos. These voltage deviations are primarily due to the limited short-circuit current available at these locations. Furthermore, none of the PoIs regained their pre-fault voltage levels within the observed post-fault period.

Upon connecting the optimally sized SCs based on NRSCR criteria, all PoIs exhibited successful post-fault recovery of bus voltages to pre-fault values within 2.9 seconds. The fault-induced voltage drops at the PoIs improved to around 0.75 pu for all the PoIs with the SCs

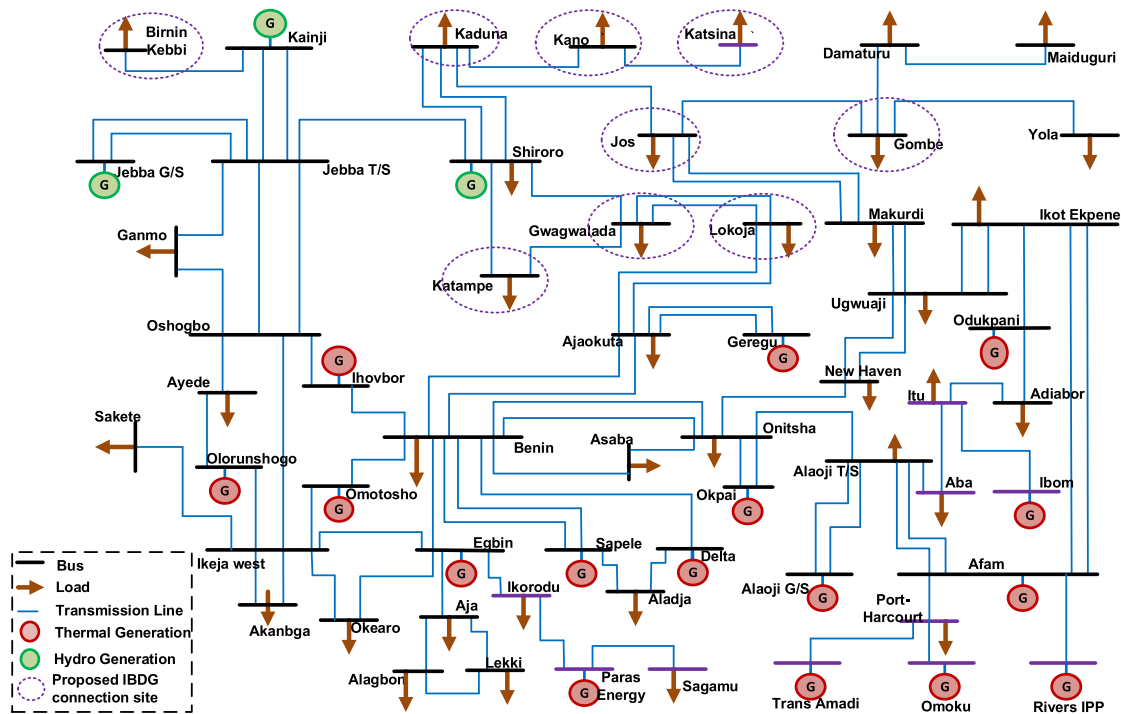


FIGURE 3. Single-line diagram of case study Nigerian transmission network.

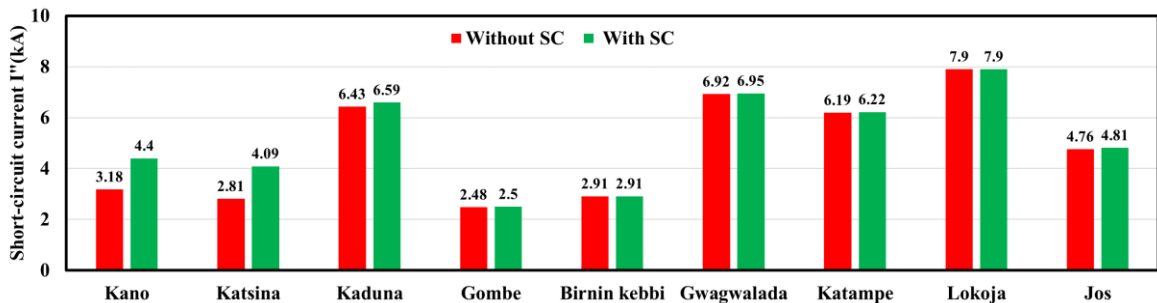


FIGURE 4. Short-circuit current with and without synchronous condenser sized with SCR-based metric.

in place. Additionally, the oscillations observed in the system without SCs were eliminated, owing to the increased short-circuit current contributed by the SCs during faults.

More specifically, the observed differences in voltage profiles at Katsina and Kano reflect the structural characteristics of the network, where electrical proximity influences voltage dynamics. Compared to the SCR-based optimally sized system, these results highlight the critical importance of selecting an appropriate system strength metric when sizing SCs for improving system strength. This case demonstrates the effectiveness of enhanced metrics that account for interactions among multiple IBGs in achieving robust system strength improvements. Moreover, the applicability of the NRSCR method is reinforced by its foundation in the structural characteristics of the power grid, making it adaptable to various network configurations and enabling more effective strength enhancement under diverse grid conditions.

C. IMPACT OF SYSTEM STRENGTH METRICS ON SHORT-CIRCUIT CURRENT DISTRIBUTION

The contour maps in Figure 8 illustrate the spatial distribution of short-circuit current across the geographical locations of the PoIs under three scenarios: (i) without SC installation, (ii) SC allocation based on the SCR metric, and (iii) SC allocation based on the NRSCR metric. The interpolated results reveal spatial variations in short-circuit current levels across the renewable energy (RE)-rich region where the IBGs are situated, with the color gradient representing the magnitude of the short-circuit current. In the no SC scenario (leftmost subplot), a wide range of short-circuit current values is observed. The lowest levels appear in areas extending from Gombe to Birnin Kebbi, while locations such as Lokoja, Gwagwalada, and Katampe exhibit relatively higher values. Under the SCR-based SC allocation (middle subplot), a noticeable redistribution of short-circuit current occurs. Most locations

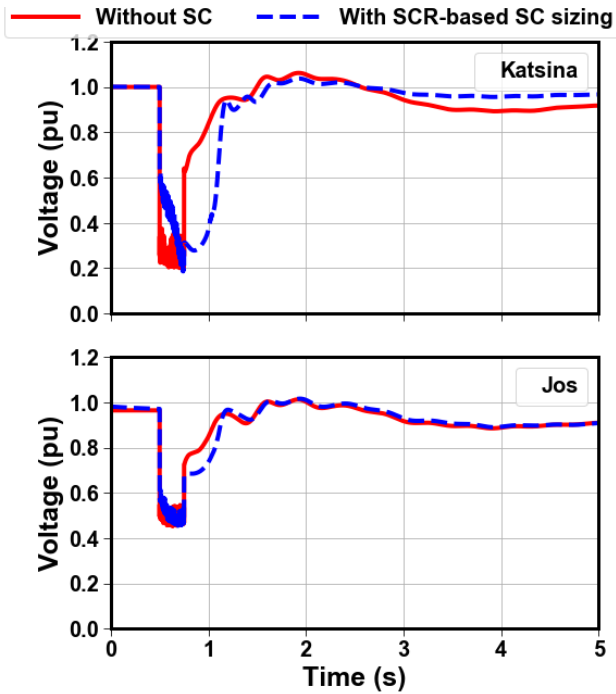


FIGURE 5. Performance evaluation of SCR-based sizing of Synchronous condenser.

experience a moderate increase, particularly in previously low-level areas, indicating improved short-circuit support. However, regions such as Gombe and Birnin Kebbi continue to show low values, suggesting that the SCR method—while beneficial—delivers non-uniform improvements due to its lack of consideration for IBG interactions. In contrast, the NRSCR-based compensation (rightmost subplot) results in a more significant and uniform increase in short-circuit levels across all locations. Unlike the SCR-based approach, which yields localized enhancements, the NRSCR method accounts for the electrical interactions among IBGs, thereby offering a more holistic improvement. These findings demonstrate that NRSCR-based compensation provides a robust and geographically consistent solution for enhancing short-circuit capacity and overall system strength.

D. COST-BENEFIT ANALYSIS OF SYSTEM STRENGTH METRICS FOR SC DEPLOYMENT

The primary objective of the optimization is to determine the optimal size of SCs that effectively enhance the system's strength while minimizing the total installation cost. Therefore the investment cost associated with the optimally sized SCs, evaluated using both SCR and NRSCR metrics, is outlined in Table 4. It is observed that an aggregate SC size of 68 MVA is required to enhance the system strength at all PoIs to a minimum of 5, employing the SCR metric. This incurs a total cost of \$2,380,000. In contrast, ensuring sufficient system strength based on the NRSCR metric entails a substantial SC size totaling 674 MVA, necessitating a cost outlay of \$23,590,000.00. This discrepancy highlights

that the cost associated with augmenting system strength, as measured by NRSCR, is approximately 7 times greater than that of SCR. A clear trade-off emerges between cost and performance based on the choice of system strength metric.

While the initial costs associated with the NRSCR-based approach are significantly higher, the long-term benefits must be considered, as the increased system strength achieved through this method enhances network stability and reliability, particularly during contingencies. Additionally, larger SCs can reduce maintenance costs by mitigating the risk of grid collapse through improved operational conditions, potentially offsetting some of the higher initial investments and providing long-term value in terms of system reliability and reduced operational risks. The number of SCs required also depends on IBG penetration levels and the grid's short-circuit capacity: at lower IBG penetration levels, fewer SCs are generally needed, reducing costs while maintaining stability, whereas at higher penetration levels, more SCs may be required to compensate for reduced short-circuit strength, increasing costs but significantly improving reliability. This trade-off between cost and reliability is influenced by system conditions and economic factors.

TABLE 5. Comparing size and investment costs for each system strength metric.

System strength metric	Total size (MVA)	Total investment cost (\$)
SCR	68	2,380,000.00
NRSCR	674	23,590,000.00

It is important to note that the effectiveness of the system strength metrics used in this study is not influenced by the level of IBG penetration. Both NRSCR and SCR are based on the rated power of IBGs and the grid's short-circuit capacity, and since IBGs do not contribute to short-circuit current, penetration level does not affect these metrics. Moreover, this study considers the addition of IBGs to an existing system without displacing synchronous generators; therefore, cost-performance trade-offs related to grid-strengthening measures, such as SC allocation under high IBG penetration scenarios involving synchronous generator replacement, are beyond its scope. Nevertheless, the NRSCR method remains a valuable tool for assessing grid strength and identifying potential stability challenges in systems with growing IBG integration, providing a foundation for future research into scenarios involving the replacement of synchronous generation.

To achieve an optimal balance between cost and performance, utilities must align system strength enhancement strategies with broader operational and financial priorities. Factors such as grid topology, load growth forecasts, regulatory requirements, budgetary constraints, and evolving renewable energy penetration play a crucial role in this decision-making process. A structured evaluation

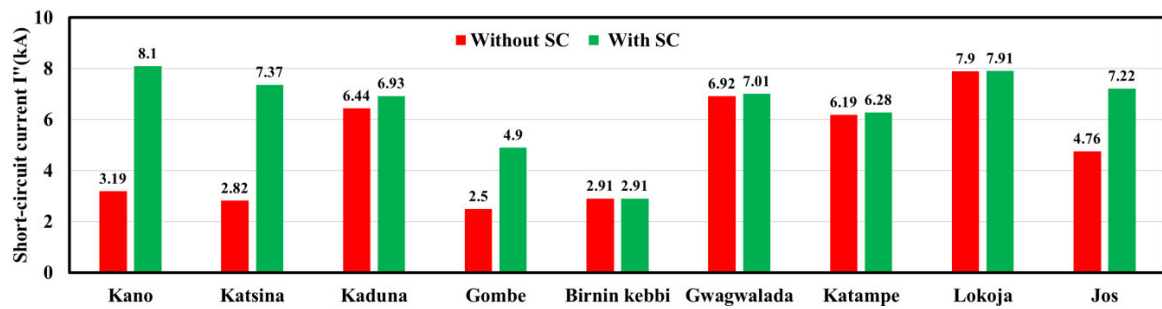


FIGURE 6. Short-circuit current with and without synchronous condenser sized with NRSCR-based metric.

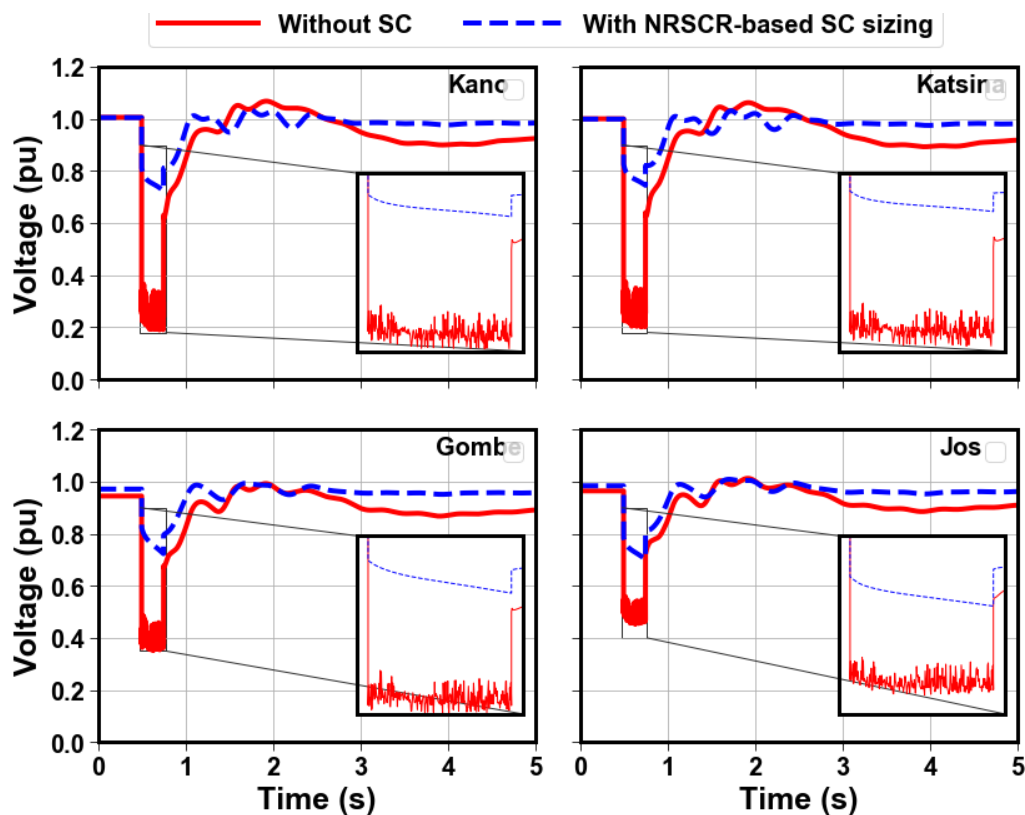


FIGURE 7. Performance results of NRSCR-based sizing of synchronous condenser.

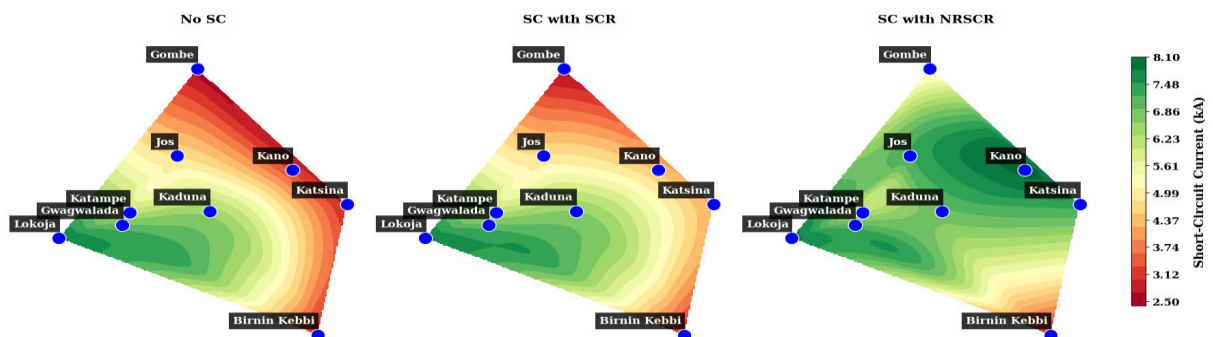


FIGURE 8. Contour maps illustrating short-circuit current distribution across Pols for scenarios without SC and with SC allocation based on SCR and NRSCR methods.

framework that incorporates both short-term financial feasibility and long-term grid resilience can aid in selecting the most effective approach. Furthermore, integrating real-world case studies and historical grid performance data can provide valuable insights into how different system strength metrics influence practical implementation outcomes. Therefore, careful evaluation of both upfront costs and long-term operational savings is necessary when deciding between the basic SCR and interaction-based metrics like NRSCR.

V. CONCLUSION

This paper investigated the implications of the choice of system strength metrics for determining the size of synchronous condensers in power grids with high penetration of inverter-based generation. A GA-based optimization approach is developed to find the optimal SC size while minimizing installation costs and maintaining system strength above a threshold of 5. Employing the Nigerian transmission grid model with 9 IBGs, both SCR and NRSCR metrics are considered to account for the effect of IBG interactions. While the SCR-based metric identified two PoIs for SC placement, the NRSCR identified four potential vulnerable PoIs. Consequently, the SCR-based approach yielded a total synchronous condenser size of 68 MVA, whereas the NRSCR-based approach resulted in a larger capacity of 674 MVA, a 7.5-fold cost increase. However, the NRSCR approach offered better system response during disturbances, with a higher fault current contribution and faster post-fault voltage recovery. Overall, the results suggest that NRSCR-based SC sizing outperforms the SCR-based approach in technical performance, though at a higher cost. System strength improvement thus requires balancing performance with the economic realities of the utility operator.

Applying the NRSCR-based method to large power systems might be challenging due to its computational demands and data requirements; calculating NRSCR across numerous PoIs and obtaining accurate dynamic models of IBGs and synchronous generators can be resource-intensive. However, advancements in parallel processing, cloud computing, and reduced-order modeling can mitigate these issues. Despite its complexity, the method remains viable, leveraging fundamental grid characteristics available to system operators to identify weak areas and guide grid-strengthening measures like synchronous condensers or advanced inverter controls.

While the GA utilized in this study is an effective choice, alternative optimization techniques such as Particle Swarm Optimization and Differential Evolution could also be explored for this type of problem in the future. These methods have demonstrated advantages in terms of convergence speed and computational efficiency, particularly for large-scale systems. Benchmarking these alternatives against GA to further evaluate their suitability for SC sizing in IBG-integrated power grids can be considered. Additionally, given the study's assumptions regarding the non-replacement of synchronous generators and idealized IBG behavior, future

research could incorporate more detailed system dynamics. This includes assessing the impact of IBG penetration levels on system strength in real-world operational scenarios to enhance the generalizability of the findings. Expanding the methodology to different network topologies and regulatory environments beyond the Nigerian grid would further validate the robustness of the proposed approach.

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