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Application of Genetic Algorithm and Analytical Method to Determine the Appropriate Locations and Capacities for Distributed Energy System

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Abstract

In this study, the genetic algorithm (GA) and an analytical technique are used to properly connect the distributed energy system (DES) to the distribution network of the Federal Capital Territory (FCT). A power flow solution is used to obtain the losses and voltages assigned to the chromosomes as the fitness value for the GA to determine the best locations for the DES. Subsequently, the analytical method is used to calculate the capacities of the DES, corresponding to each location obtained using the GA. The effectiveness of the technique is examined on IEEE 33 and 69 buses, and the results demonstrate a loss reduction of 69.19%, the least voltage of 0.975 pu for the 33-node, and a 70.22% loss reduction with the least voltage of 0.985 pu for the 69-node. The suggested technique is applied to the FCT distribution network, and the results show a 70% voltage improvement and 14.05% loss reduction.

Keywords: analytical method, distributed energy system, distributed generation, genetic algorithm, voltage

1. Introduction

The distribution network of the Federal Capital Territory (FCT) of Nigeria is made up of critical loads that supply crucial establishments. However, due to limitations on the grid, the supply to these loads is not always achieved, and, worryingly, the distribution network is not isolated during periods of grid outages. Therefore, it is important to connect the distributed energy system (DES) to the distribution network of the FCT to enhance the supply of power to these loads when the supply from the grid is limited.

The DES is made up of distributed generation (DG), which is connected in propinquity to the load intended to supply. The DES comprises different types of DG, such as renewable and non-renewable types. Non-renewable includes gas turbines, reciprocating engines, combustion turbines, etc., while renewable includes wind, solar photovoltaic, tidal, geothermal, and biomass [1]. The introduction of DES offers related advantages apropos loss reduction, voltage improvement, efficiency, increased dependability of the system, enhancement of power quality, reduction in carbon emissions, and decreased operating costs [2-3]. Nonetheless, determining the proper DG capacity and the right location for its connection to the grid is notably signified, otherwise, more losses, poor voltage, reduced power quality, and deterioration of the protection system may incur as a consequence [4-6]. Researchers have applied several techniques to address the challenges, as stated above, to ensure the proper connection of DGs. The approaches to determine the best location and capacity of the DG can be grouped into analytical expressions (AEs), numerical methods (NM), metaheuristic methods, and hybrid-based methods [5, 7-8].

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The AEs are simple, reliable, require a short computation time, and provide optimum or near-optimum global solutions. Nevertheless, challenges of scalability emerge and hinder suitability for large-scale distribution networks [9]. As a result, to solve the optimization problem, the AEs yield various approximations to reduce the computational complexity. The NM includes linear, non-linear, dynamic, and sequential quadratic programming methods. One of the drawbacks of the method, however, lies in the uncertainty of whether the final solution obtained will be globally optimal. The meta-heuristic technique is a dynamic algorithm independent of solving problems towards achieving global optimum. The hybrid optimization approach combines two meta-heuristic methodologies, a numerical meta-heuristic, and an analytical meta-heuristic [7-8, 10-11].

Several studies have been carried out by applying different optimization techniques for the proper connection and sizing of DGs. Prakash et al. [12] focused on an analytical method for the optimal allocation of renewable energy sources in the distribution network. While the methodology was tested on the 33 and 69-node distribution systems, it can further be validated on a real distribution network. Mahmoud et al. [13] deployed the Salp swarm algorithm, grey wolf, and improved grey wolf to optimize the size of hybrid renewable energy. However, the study did not consider voltage improvement and loss reduction as objective functions. Furthermore, the study by Otuo-Acheampong et al. [14] considered a metaheuristic heap-based optimizer to improve voltage, minimize loss, reduce operation cost, and mitigate gas emissions, but it did not consider the connection of DGs to further reduce losses while providing reliable power.

Furthermore, the study's results were not applied to a larger standard test system or a real distribution system. Purlu and Turkay [15] utilized two heuristic techniques were used to optimize the capacity, location, and power factor of DGs to minimize losses and voltage deviation. Although the result obtained showed decent performance in the optimal allocation of DGs, further application concerning 69-bus or a distribution network for advanced investigation of the robustness is suggested. A modified shuffled frog leaping algorithm was developed by Lotfi [16] and applied to the 95 and 136 bus systems. The study showed that the method addressed the optimal DG allocation and shunt capacitors for varying demands. However, the optimization of the voltage was not considered to boost the performance of the distribution network. Similarly, Lofti et al. [17] formulated a multi-objective optimization for feeder reconfiguration and proper DG allocation. A modified gravitational search algorithm was used to optimize the reliability of the network and voltage security. Nevertheless, the losses can be further reduced, and the method can be tested on a real distribution network.

The proposed combination of the analytical technique and genetic algorithm (GA) is used to properly size and connect the DES in the 33 kV network of the FCT, which comprises 120 buses. First, the method is implemented using MATLAB R2022a and tested on the IEEE 33 and 69-node systems. Thereafter, the method is applied to the real distribution system of the FCT to determine the proper capacities and locations. Subsequently, the PowerFactory software is then used to connect DG capacities to their respective 33 kV bus locations. The voltage magnitude, network losses, and frequency stability results are determined and compared to the base-case scenario, before the connection.

The following contributions are made to this work:

(1) The technique coupled an analytical method with a GA for the optimal DES allocation. Notwithstanding the hindrance to rendering the scalability and ensuing inefficiency in large power systems, the analytical method is easy to implement, converges fast, and is computationally efficient. On the other hand, while the search space features and the ability of the GA to handle complex problems are advantageous, it suffers from premature convergence problems, thereby limiting its application in real distribution systems. Therefore, the strength of both methods was utilized.

(2) The proposed method was tested by applying it to the IEEE 33 and 69-node networks. The voltage profile and losses were compared to other related works. The results showed that for the optimal allocation of 4 DGs, the proposed method gave better results than other methods.

(3) The suggested method was validated by using it to determine the proper location and capacities of the real 120-bus FCT distribution network. The performance was compared to the base case scenario apropos voltage enhancement, reduced system losses, and acceptable frequency stability.

(4) The proposed method considered the frequency stability analysis and enables multiple considerations of up to four DES.

The remaining work is organized as follows: Section 2 introduces the problem formulation, while Section 3 covers the implementation of the GA and analytical method. Section 4 presents the result of the application of the suggested method to the standard IEEE system and the FCT distribution network. Eventually, Section 5 proffers a comprehensive conclusion of this study.

2. The Problem Formulation

(1) Objective function: The goal of this study is to reduce network losses and improve bus voltage in the distribution network.

(1-1) Loss reduction: The loss of the network of the distribution system is presented in the following formula [16]:

$$f_1(X)=\sum_{i=1}^{N} I_i^2 R_i \tag{1}$$

where: $X = P_{DG1}, P_{DG2}, \cdots, P_{DG,NDG}$, and P_{DG1} is the output power of the DG unit

(1-2) Voltage: The total voltage deviation (TVD)is the difference between the nominal voltage and the actual voltage, as shown in the formula below [18].

$$TVD=\sum_{i=1}^{N}\left|V_n - V_i\right|^2 \tag{2}$$

where N is the number of buses, V_n is the nominal voltage and V_i is the actual voltage.

(2) Operational constraint: The optimization issue considers the following operational limitations of a DG unit. The power injection constraints are given in the formulas below [18]:

$$\sum_{i=1}^{n} P_{DG} < P_{load} + P_{losses} \tag{3}$$

Total power balance constraint:

$$\sum_{i=1}^{n} P_{DG} + P_{substation} = P_{load} + P_{losses} \tag{4}$$

where P_{DG} means the DG power supply, $P_{substation}$ symbolizes the substation supply, P_{load} signifies the supply to connected loads, and P_{losses} refers to the power loss.

(2-1) Number of DG: The number of DG (N_{DG}) is lower than or equal to the maximum number of DG ($N_{DG/MAX}$)

$$N_{DG} = N_{DG/MAX} \tag{5}$$

(2-2) DG capacity constraint: The real power at each DG (P_{ga}), as shown in the formula below, is within the bounds [19]:

$$P_{ga}^{min} \le P_{ga} \le P_{ga}^{max} \tag{6}$$

(2-3) Voltage magnitude: The voltage magnitude should satisfy the allowable limit, given in (7) [13]:

$$V_{min} \le \left|V_i\right| \le V_{max} \tag{7}$$

where $|V_i|$ is the voltage magnitude, and V_{min} and V_{max} represent the minimum and maximum voltages.

(2-4) Line flow: The current in the line should be within the limits given in (8) [16]:

$$\left|I_j\right| \le I_{jmax} \tag{8}$$

where $|I_j|$ is the current magnitude of line j, and I_{jmax} is the maximum current limit of line j.

3. The Proposed Technique

The proposed technique utilized the search space features of the GA to determine the optimal location concerning complex problems. The simplicity and convergence speed of the analytical method was deployed to optimally determine the proper capacities of the DES, thereby connecting to the distribution network.

3.1. Genetic algorithm

The optimization problem aims to minimize the losses and improve voltage through the proper sizing and connection of the DES to the FCT distribution network. The capacity of the DG is determined using an analytical solution, while the location of the DG is determined using the GA. In the GA, the problem variables, which represent the locations of the DG, are encoded as chromosomes. Therefore, assuming that there are ng DGs, the length of the chromosomes would be 2 ng, which includes ng locations for the DG connections (D1, D2, ..., Dn). To initiate the GA process, a set of potential solutions, i.e., chromosomes, is generated randomly and assigned a numerical value based on its fitness. This value is determined by a fitness function that is optimized GA. Next, the GA selects certain chromosomes for crossover, mutation, and replacement operations using selection operators, considering their fitness. These operators generate a new population, and the process is repeated until the termination condition is met [20].

3.2. Analytical method

The loss for the distribution network is calculated using the formula below. The method is referred to as the exact loss formula [3, 21-22].

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j + P_iQ_j\right)\right] \tag{9}$$

where:

$$\alpha_{ij} = \frac{\gamma_{ij}}{v_i v_j}\cos\left(\delta_i - \delta_j\right) \tag{10}$$

$$\beta_{ij} = \frac{\gamma_{ij}}{v_i v_j}\sin\left(\delta_i - \delta_j\right) \tag{11}$$

where P_L is the power loss index, P_i and Q_i are power injections, and R_{ij} is the resistance from bus i to j. The loss formula is a function of α and β (the loss coefficients) and relies on the voltage magnitude and angle. The total power injected by the DG is presented as follows:

$$P_i = P_{DG} - P_{Di} \tag{12}$$

$$Q_i = Q_{DG} - Q_{Di} \tag{13}$$

where P_{DG} and Q_{DG} are the power injected by the DG, while P_{Di} and Q_{Di} are the active and reactive power loads. As stated by Muslimin et al. [3], the optimal size of the DG to minimize power loss is shown in the following formula

$$P_{Di} = \frac{1}{apf^2}\left[\alpha_{ij}\left(P_{Di} + apf.Q_{Di}\right) + \beta_{ij}\left(apf.P_{Di} - Q_{Di}\right) - X_i - apf.Y_i\right] \tag{14}$$

while renders the loss after the integration of DG as follows:

$$Loss\ Reduction = \frac{P_{loss} - P_{loss}^{DG}}{P_{loss}} \times 100\% \tag{15}$$

where $apf = \{sign\} \tan\{\cos^{-1}(PF_{DG})\}$. The $sign$ will be 1 if DG injects reactive power. In contrast, if the reactive power is absorbed by DG, the $sign$ will emerge as -1. PF_{DG} is the power factor of the DG.

3.3. The combined method

The GA and analytical techniques are combined and summarized through the process, as enumerated herein:

(1) GA opts for several certain chromosomes for crossover, mutation, and selection regarding its fitness function.

(2) The chromosomes generate a new population.

(3) The power flow solution is carried out to determine the losses and voltage assigned to a chromosome as its fitness value.

(4) The GA searches for the least value of the fitness function by varying the location of different DGs:

  (i) The total number of buses in the network is grouped into a subset of n (where n is the number of DG locations)

  (ii) For each iteration count, GA places the DGs in a given subset, and the fitness function is evaluated accordingly.

  (iii) The process is repeated until all the subsets are exhausted

  (iv) The subset (DG locations) with the least fitness value is opted as the optimal solution

(5) The analytical method is applied to determine the DG capacities, corresponding to each DG location obtained from the GA.

(6) The process is repeated until the number of iterations is reached.

A combination of the GA and analytical approach, illustrated in Fig. 1 was employed to find the proper connection points and sizes of DES for improved system performance. The method was developed to allow the integration of up to four DG units into the distribution network of the FCT.

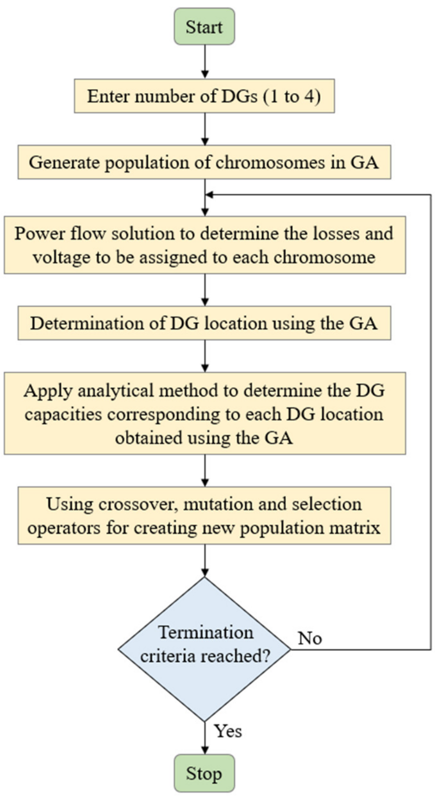

Fig. 1 Flow diagram for the optimal allocation of the DES

3.4. The standard IEEE node test network

The combined genetic algorithm and analytical method were tested on the IEEE standard 33 and 69-node systems before being applied to the real FCT 120-bus distribution network. The 33-node system is a 12.66 kV network comprising 33 nodes and 32 branches. The real power is 3.72 MW, and the reactive power is 2.3 MVar while the slack bus is located at node 1 [23]. On the other hand, the 69-node system is a 12.66 kV network that contains sixty-nine nodes and sixty-eight branches. The feeder has a power of 3.8907 MW and a reactive power of 2.6936 MVar [24].

3.5. Implementation of the algorithm on the FCT distribution network

The genetic algorithm and the analytical method were combined and implemented in MATLAB R2022b. First, the method was applied to the 33 and 69 IEEE distribution systems to test its efficacy. Thereafter, the method was implemented in the 120-bus distribution network of the FCT to obtain the proper location and sizes of the DES.

The FCT-Abuja power network is made up of two 330/132 kV substations and five 132/33 kV substations that supply power to the 33 kV FCT network. The source of power supply to the FCT distribution network from the grid is through the Gwagwalada and Katampe 330/132 kV substations as shown in Fig. 2 [25].

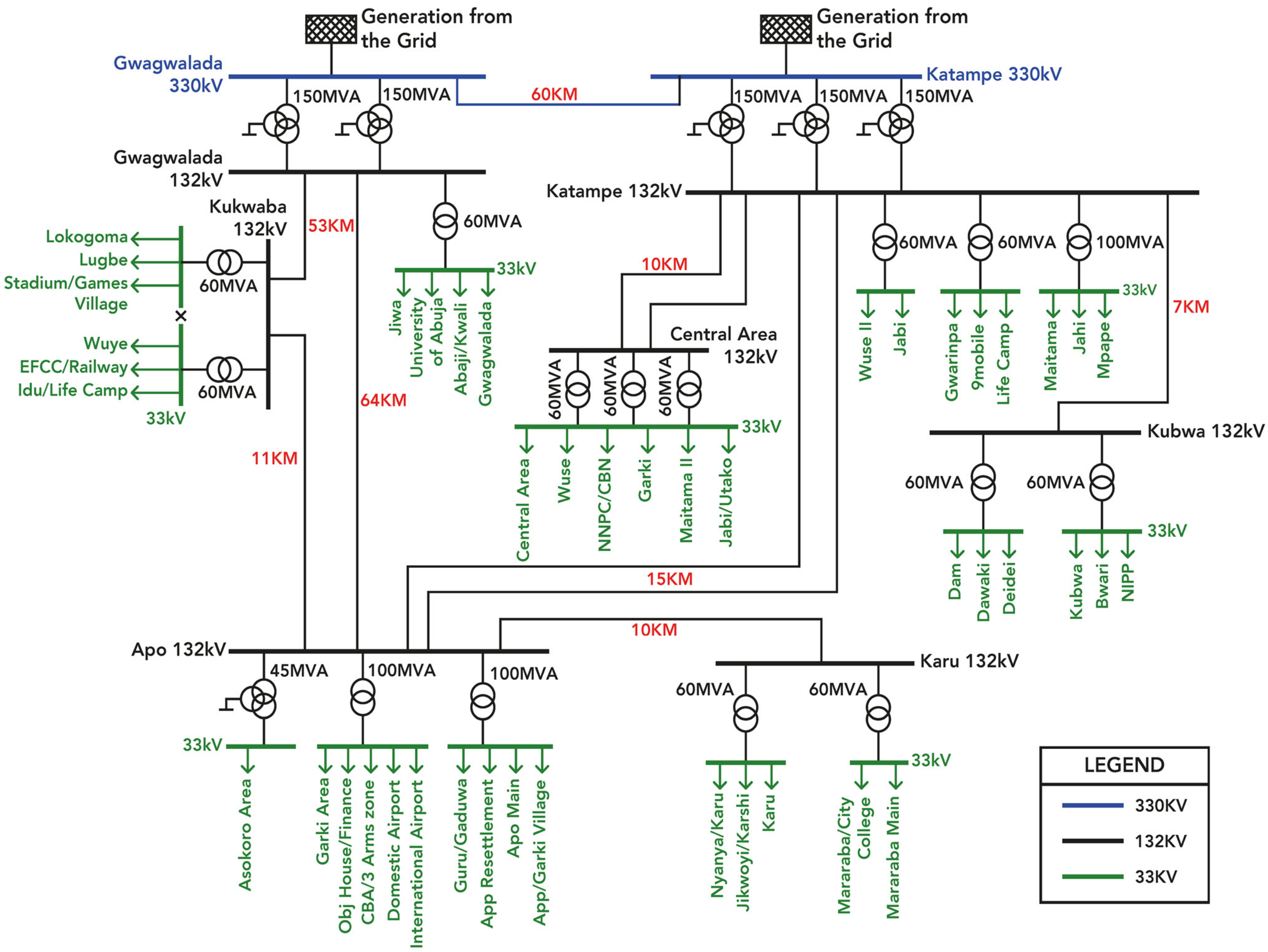

Fig. 2 The single-line diagram of the FCT distribution

4. Simulation Results and Discussion

The combined genetic algorithm and analytical (CGAA) method were used on the 33 and 69 bus systems, and the results were compared to other methods, such as multi-objective particle swarm optimization (MOPSO), white shark optimizer (WSO), improved grey wolf optimization with particle swarm optimization (I-GWOPSO), and dandelion optimizer (DO).

4.1. Results for the 33-node network

The results of the voltage and losses without and with the DG to the 33-bus are given in Fig. 3 and Fig. 4. The voltage magnitude for the standard 33-bus system, following the application of the suggested method, is shown in Fig. 3. The voltage profile associated with the DG allocation was compared to that of the 33-node network. The results indicate the minimum voltage stood at 0.975 pu with the connection of 4 DGs, and such a value is higher among other values recorded. In Fig. 4, the results show that with the connection of the DGs, the losses were lower than without DG allocation. Without DG, the highest loss was about 51 kW while with DGs, the highest recorded loss was approximately 14 kW. Table 1 shows the CGAA results compared to the results obtained by other algorithms.

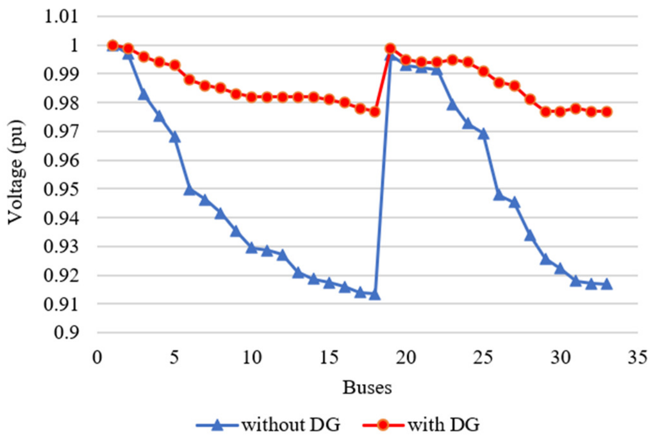

Fig. 3 Voltage magnitude for the 33-bus

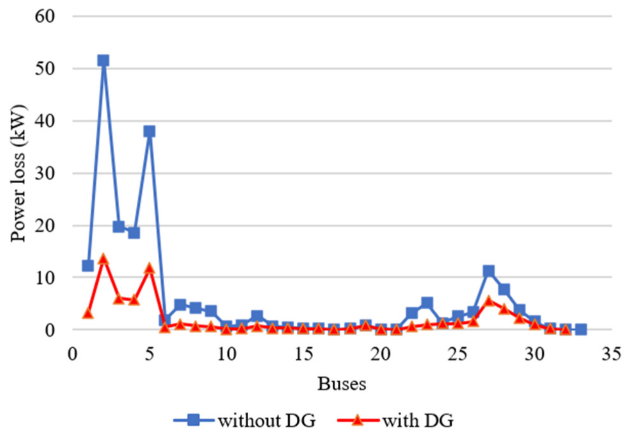

Fig. 4 Losses for the 33-bus

The IEEE 33-node was subjected to the combined GA and analytical method, as shown in Table 1. The results showed that with the connection of up to 4 DGs, the highest percentage loss reduction of 69.19% was recorded using the suggested algorithm.

Table 1 Comparative analysis of the 33-bus system with other methods

DGs	Method	Optimal bus location	DG power (kW)	Power loss (kW)	Percentage improvement in power loss (%)
1	WSO [24]	6	2600	102.79	51.28
	PSO [26]	6	2600	111.3	-------
	DO [27]	6	------	111.03	-------
	Proposed	6	2664	103.0	51.18
2	WSO [24]	13, 30	850, 1191.1	82.6	60.85
	PSO [26]	13, 30	849, 1152	87.2	-------
	Proposed	13, 30	873, 1212	83.0	60.66
3	WSO [24]	13, 24, 30	790, 1070, 1080	69.48	67.07
	PSO [26]	9, 24, 30	1062, 1045, 952	75.8	-------
	I_GWOPSO [18]	14, 24, 30	786, 1032, 1094	70.64	66.37
	Proposed	14, 24, 30	780, 1075, 1120	69.00	67.30
4	Proposed	31, 14, 24, 7	761, 622, 965, 863	65.00	69.19

4.2. Results for the 69-node network

Furthermore, the technique was applied to the 69-node standard system, and the voltage magnitude and losses were determined without and with the connection of DG. The result of the voltage without and with the DG is depicted in Fig. 5, while the loss results without and with the DG are illustrated in Fig. 6.

The voltage magnitude for the IEEE 69-bus, following the application of the algorithm, is presented in Fig. 5. The voltage magnitude associated with the allocation of DG was compared to that of the 69-node network. The results indicate the minimum voltage stood at 0.985 pu with the connection of 4 DGs, and such a value is higher among other values recorded. In

Fig. 6, the results show that with the connection of the DGs, the losses were lower than without DG allocation. Without DG, the highest loss was about 49 kW while with DGs, 14 kW was recorded as the highest loss. Table 2 shows the proposed algorithm results in comparison with the results obtained by other algorithms.

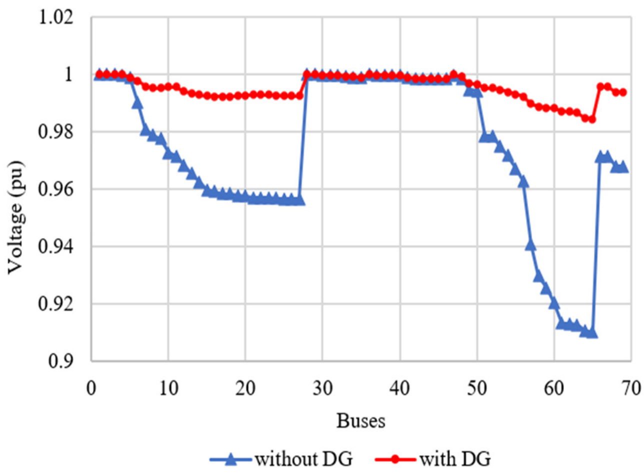

Fig. 5 Voltage magnitude for the 69-bus

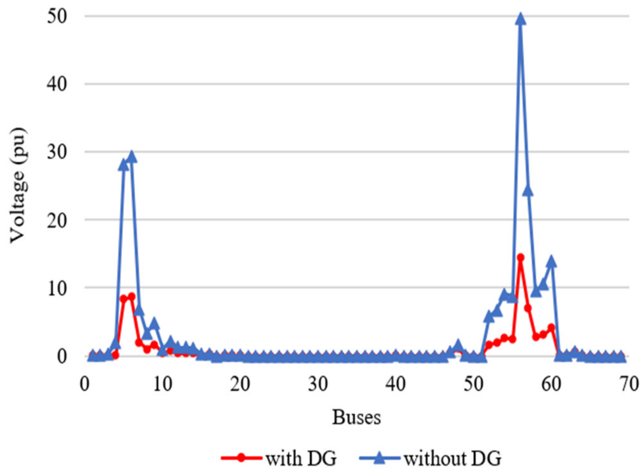

Fig. 6 Losses for the 69-bus

The values in Table 2 compare the result of the proposed algorithm with other related algorithms. The results show that with the connection of up to four DGs, the highest percentage loss reduction of 70.22% was recorded using the suggested algorithm. Therefore, the suggested method cogently outperforms other algorithms.

Table 2 Comparative analysis of the 69-bus system with other approaches

No. of DG	Method	Optimal bus location	DG power (kW)	Power loss (kW)	Percentage improvement in power loss (%)
1	WSO [24] Proposed	61 61	1890 1913	81.50 82.00	63.77 63.56
2	WSO [24] Proposed	61,17 61,17	1775,525 1810,540	70.46 70.00	68.68 68.89
3	WSO [21] I_GWOPSO [18] Proposed	61, 17, 11 61, 21, 11 61, 18, 11	1740, 380, 480 1738, 301, 508 1781, 429, 384	68.69 68.59 69.00	69.46 69.46 69.33
4	Proposed	61, 50, 21, 12	1784, 661, 275, 519	67.00	70.22

4.3. Results for the FCT distribution system

The algorithm was used to properly size and locate DES in the FCT distribution system. Following this, the results presented in this section compare the base-case scenario with the proper connection and sizing of DES in the FCT distribution system.

4.3.1. Base case scenario

The result for this scenario was obtained by modeling and simulation of the FCT distribution network using PowerFactory software. From the results of the base case in Fig. 7, a generation of 147.7 MW and 378.6 MW were supplied to Gwagwalada 330 kV and Katampe 330 kV buses, for the supply to the FCT distribution network. Following the steady-state power flow and transient stability analysis, the voltage profile, network losses, and frequency stability were determined. The result of the per unit voltage magnitudes for the 33kV buses is depicted in Fig. 8, where the values are between 0.82 pu – 0.995 pu.

According to the grid code [28], the normal voltage limit for 33 kV is 0.94 pu – 1.06 pu. As observed from Fig. 1, about 88 bus voltages are between 0.89 pu – 1.0 pu. The low voltages can be attributed to the fact that the study assumed all 33kV feeders to be in service. In reality, however, all the 33 kV feeders are usually not in service simultaneously due to different limitations, e.g., generation constraints, load shedding, loading levels, and planned and unplanned outages.

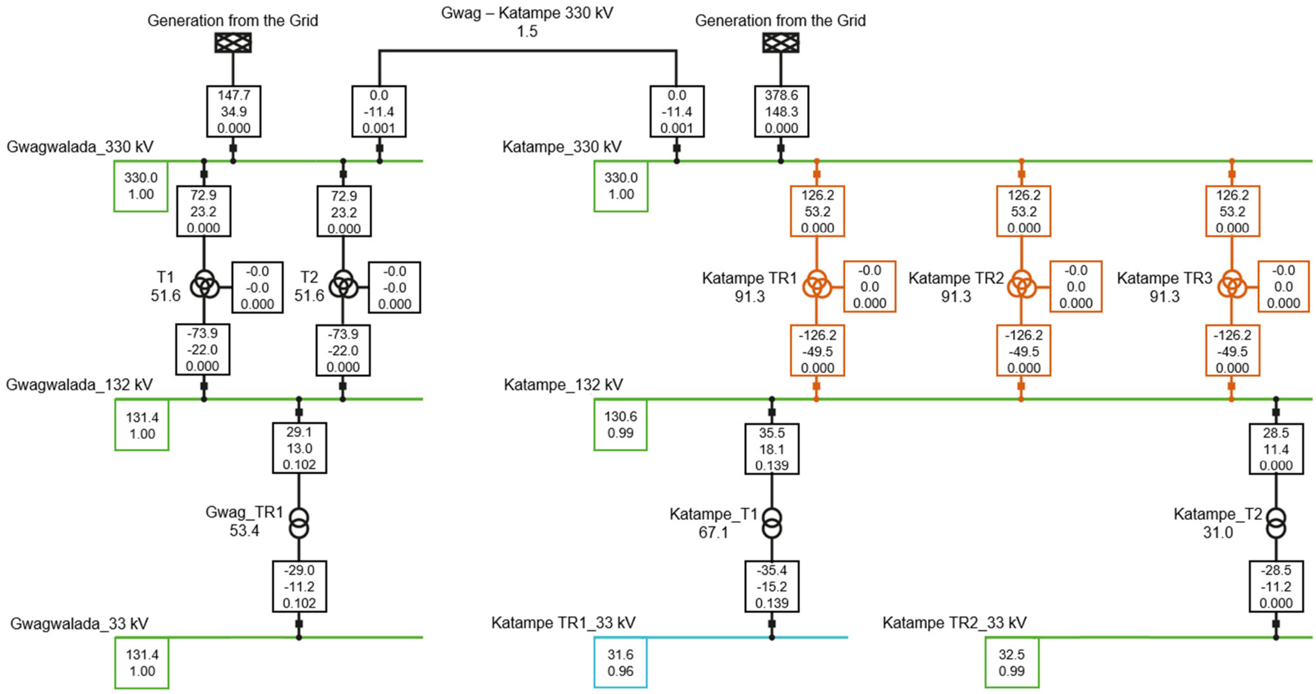

Fig. 7 The base case power flow diagram

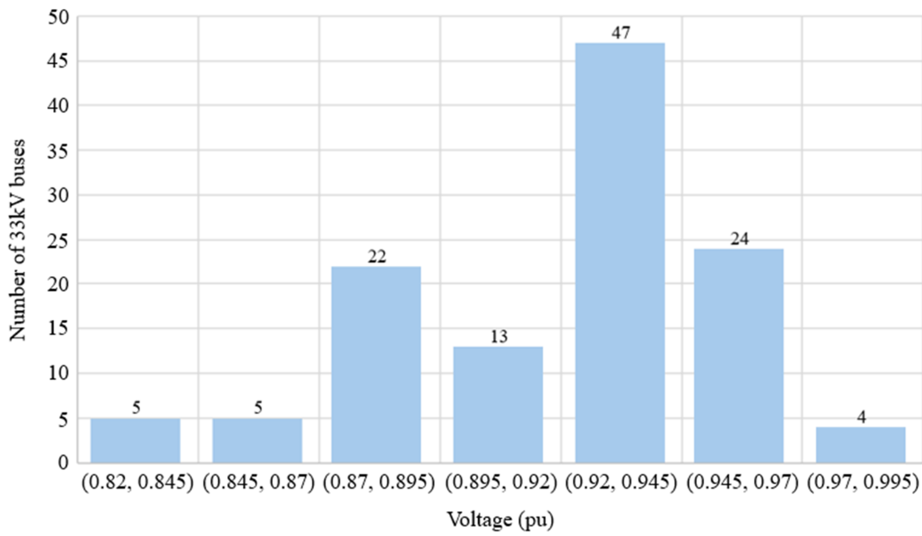

Fig. 8 The base case voltage profile

4.3.2. *Result for the optimal allocation of DES*

After the successful testing of the algorithm in IEEE bus systems, the CGAA was implemented in the MATLAB/Simulink program and applied to the Abuja 120-bus distribution. The appropriate location of the DG bus for four DGs with their capacity to supply the entire load in the network is given below.

(1) Bus 13 (Katampe 33kV): 130.0 MW

(2) Bus 120 (Karu 33kV): 129.0 MW

(3) Bus 72 (Apo_T3 33kV): 121.0 MW

(4) Bus 46 (Central Area 33kV): 129.0 MW

The above results yield the proper allocation of the DGs that were connected to the FCT distribution network. As indicated in the grid code, the reactive power supplied by generators was based on a power factor of between 0.85 – 0.95. Subsequently, the values were used to place the 130.0 MW, 129.0 MW, 121.0 MW, and 129.0 MW capacity generators on the respective 33 kV buses in the FCT distribution network developed in the PowerFactory software. After determining the proper allocation of the DES to the FCT distribution network, the following study scenarios were considered.

(1) Connection of DG only, without a power supply from the grid

(2) Connection of DG with reduced grid power from both Gwagwalada and Katampe 330kV buses

(3) Connection of DG with power supply only from Gwagwalada

(4) Connection of DG with power supply only from Katampe

The results of the DG allocation for the different scenarios were obtained and compared to the base case scenario, as depicted in Fig. 9.

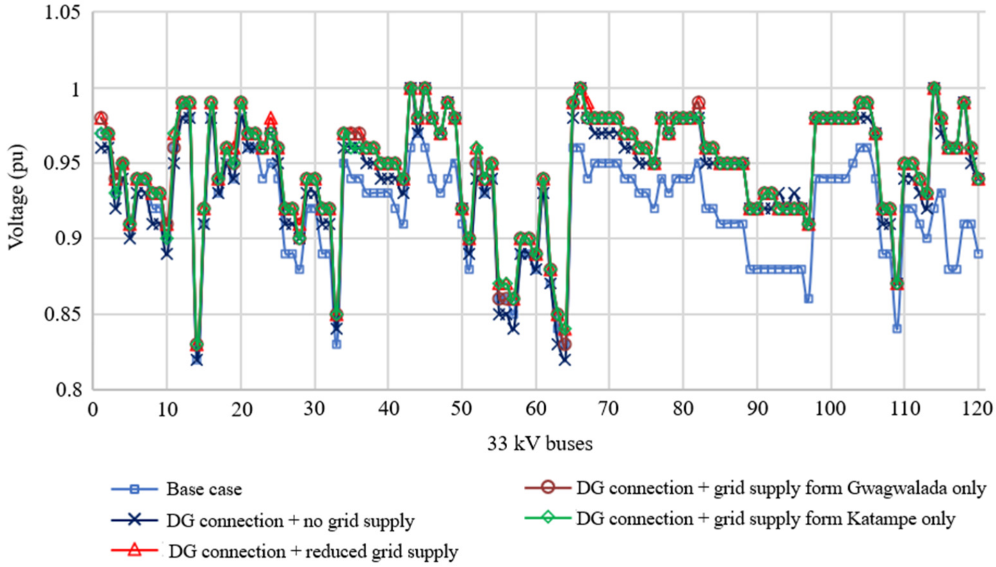

Fig. 9 Base-case voltage profile vs. voltage profile after DG connection

As observed from Fig. 9, the voltages associated with the connection of the DGs outperformed those of the base case. The percentage of voltage improvement for individual buses was 70% for the connection of only the DG, 95% for the connection of the DG plus reduced grid supply, 90% for the connection of the DG plus the supply in Gwagwalada, and 92.5% for the connection of the DG plus the supply in Katampe. Concerning network losses for the base case and DG allocation scenarios, the results are illustrated in Fig. 10.

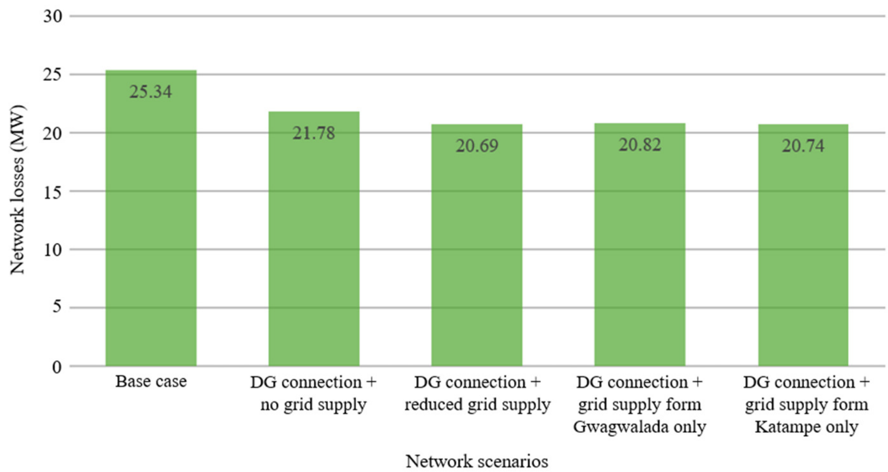

Fig. 10 Comparative analysis of network losses with DG Connection

As indicated from the losses shown in Fig. 10, the percentage loss reduction for the DG scenarios compared to the base case was 14.05%, 18.35%, 17.83%, and 18.15 %, respectively. The result of the transient stability analysis is summarized in Table 3.

Table 3 Summary of the results of the frequency stability

S/N	Study Scenarios	Fluctuation (Hz)	Remarks
1	Connection of DES + zero grid supply	49.898 – 50.429	(i) Upper-frequency fluctuation outside limits but final frequency acceptable (ii) Stability was achieved at 7.9641 seconds
2	Connection of DES + reduced grid supply	49.930 – 50.102	(i) Fluctuation within limits and final frequency acceptable (ii) Stability was achieved at 5.9481 seconds
3	Connection of DES + grid power at Gwagwalada 330kV	49.867 – 50.330	(i) Upper-frequency fluctuation outside limits but final frequency acceptable (ii) Stability was achieved at 7.9641 seconds
4	Connection of DES + grid power at Katampe 330kV	49.883 – 50.162	(i) Fluctuation within limits and final frequency acceptable (ii) Stability was achieved at 5.9481 seconds

As observed from the results in Table 3, the frequency stability results were obtained from the connection of DES under different scenarios and compared with the base case scenario. The results showed that the final frequency attained was stable after the fluctuations dampened.

5. Conclusions

The FCT of Nigeria houses profuse important government establishments requiring a constant and adequate power supply. However, due to limitations on the grid, the supply to the loads within the FCT does not correspond as always. The worst scenario is that during periods of system collapse, the distribution network is not isolated, as the supply to the loads is interrupted. Therefore, to address these challenges, this study proposes the connection of a DES to enhance the supply of power to the distribution network of the FCT. The GA and analytical methods were used to determine the appropriate sizes and connection points for DES in the real FCT 120-bus 33 kV distribution network.

First, the method was tested on the standard 33 and 69-node IEEE network, and the results were compared with other techniques. Specifically, the results showed a 69.19% reduction in losses and the least voltage of 0.975 pu for the 33-node system; and a 70.22% reduction in losses and the least voltage of 0.985 pu for the 69-bus system. Thereafter, the suggested method was tested on the 120-bus FCT distribution network, and the results obtained showed at least a 70% voltage improvement and 14.05 loss reduction, for all the scenarios considered. The results of the study showed that the suggested method was effective in properly connecting DES to the distribution network. Future work should consider utilizing the DES to determine the controlled islanding of the distribution network to improve the power supply to critical loads during system collapse.

Conflicts of Interest

The authors declare no conflict of interest.

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