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DISTRIBUTED GENERATION PLANNING IN AN UNBALANCED THREE-PHASE DISTRIBUTION NETWORK USING FIREFLY ALGORITHM AND VOLTAGE STABILITY INDEX METHODS

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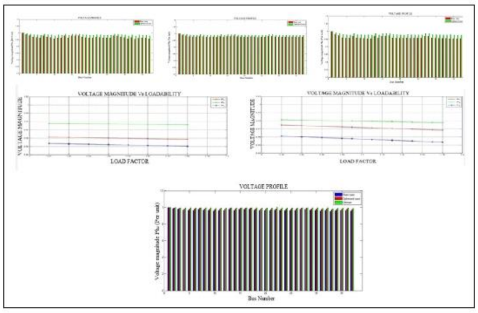
Graphical abstract



Abstract

This research presents the use of the Firefly Algorithm (FA) and the Voltage Stability Index (VSI) for optimizing Distributed Generation (DG) planning within an unbalanced three-phase distribution network. The VSI was employed to identify the optimal DG location, while the FA determined the appropriate sizing of the generators. The methodologies were applied to the standard IEEE 37-bus radial distribution network and a localized 19-bus Mahuta feeder. The results show that, in the IEEE 37-bus network, the total power losses were 31.3543 kW for active power and 15.2829kVAr for reactive power without DG. After implementing the proposed method, the optimal DG location was identified at bus 34, with a size of 356 kW for active power and 170kVAr for reactive power, resulting in losses of 19.8329 kW and 10.0014kVAr, respectively. This reflects a loss reduction of 36.75% for active power and 34.56% for reactive power compared to the base case. The maximum load ability increased to 18% of initial loading with DG. For the 19-bus Mahuta feeder, the optimal DG location was at bus 17, with sizes of 201.58 kW for active power and 115kVAr for reactive power. This setup achieved power loss reductions of 4.48% for active power and 5.62% for reactive power. The maximum load ability for both approaches were found to be 119% of initial loading. Compared to similar studies, the proposed method achieved loss reductions of 8.14% for active power and 30.42% for reactive power.

Keywords: Distributed Generation, Firefly Algorithm, Load ability, Voltage Stability Index, Unbalanced three-phase, Distribution Network

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1. Introduction

The electric power system majorly includes a generating plant, a transmission system, and a distribution network. In modern power systems, users get supply (electricity) from smaller generating units that are situated close to the demand site [1,15]. The continuous increase in penetration of distributed generation (DG) in distribution networks has changed the distribution network from a passive network to an active network where the voltages and power flow are determined by the structure of the network generation sources and loads [7]. DG can serve as an alternative for commercial, residential, and industrial applications [4]. Due to the continuous integration of DGs into the network, significant growth is expected in the electrical distribution systems (EDS) soon [14]. As such, this will add additional complexity to the system, it is of paramount importance that the performance of these systems should be continuously improved to ensure increasing levels of power quality to the customers [25]. It is well-known that most DG is considerably unbalanced, and in high-density load areas such as city centers, the network topology can be highly meshed [16]. Under these circumstances, the three-phase four-conductor configuration with multiple neutral grounding has been largely adopted, due to low installation costs and better sensitivity for fault protection, when compared with the three-phase three-conductor configuration. However, the presence of neutral conductors and grounding negatively affects the system operation and human safety [25]. Factors such as conductor bundles, single- and double-phase 'radial spurs' on primary feeders, un-transposed feeders, and single-phase loads are the major causes of unbalanced structure in the distribution system [11,28]. As such, there is a need for efficient analysis of the distribution system employing a detailed component model to avoid significant errors. Load flow techniques such as Newton-Raphson, Gauss-Siedel, and fast decoupled approach are therefore not suitable or encouraged in solving such networks [21,26]. Non-symmetrical conductor spacing of 3-phase underground and overhead line segments and the significant presence of unequal single-phase loads are the major reasons why distribution feeder loading is unbalanced. In a transmission system, the single-phase representation of the three-phase system is normally used for power flow studies because the system is assumed to be balanced. However, recently, researchers/ operators have now used the three-phase power flow analysis for both transmission networks and distribution systems. The three-phase power flow analysis can be carried out in two different reference frames namely phase frame and sequence frame. The phase frame deals directly with unbalanced quantities while the sequence frame deals with three separate phasor systems which, when superimposed, give the unbalanced conditions in the circuit [5,13].

Different methodologies and approaches have been employed in literature for the optimal sizing and location of DGs. [9,17] developed optimal sizing and placement of DG in a radial distribution system using loss sensitivity factor and firefly. In the work, the loss sensitivity factor is used for optimal DG location and the firefly algorithm is used for DG sizing. [13] presented a Thevenin-based impedance-stability index for the sizing and location of the DG in the distribution system. [3] also developed a multi-objective technique to help minimize power loss in the distribution system. [2] used particle swarm optimization technique for optimal placement to ensure effective power loss minimization. [7,8,20,28] and a lot of researchers have shown that DG placement on the unbalanced system has a significant effect on the voltage and the power flowing in the system.

To ensure a balance between generation and consumption with a minimum power loss in an unbalanced distribution system, this introduces the voltage stability index and firefly algorithm method for optimal location and sizing of DG in the network. Also, the Backward-Forward Sweep (BFS) based method will be used to achieve a convergence guaranteed of power flow analysis. The BFS method is the most suitable method for solving power flow problems due to its simplicity and better convergence performance compared to Gauss-Siedel and Newton-Raphson-based methods under the assumption of radial network structures [10].

2. Material and Method

2.1. Distribution Network Parameters

To evaluate the proposed method, two radial distribution network feeders were adopted in this work. These are a standard IEEE-37 node test feeder and a 19-node Mahuta distribution feeder located in the Kaduna metropolitan city distribution network. However, due to limited line data for the three-phase line of the 19-bus Mahuta feeder, the impedance of all the three-phase is assumed to be the same.

2.2. Development of Three-Phase Power Flow Based on Backward and Forward Sweep Technique

In developing the three-phase power flow based on the BFS technique for the unbalanced distribution network, the following three steps are involved: nodal current injection was first carried out. This was done by first assigning the initial phase voltage at each bus to each phase in p.u. The backward sweep technique was then introduced to update the current values towards the source node. For this technique, the current in each branch is calculated using Kirchoff's current law. Lastly, the forward sweep approach was incorporated to calculate the voltage at each node, starting from the source node to the last or receiving end node.

2.3. Power Flow Analysis

The power flow analysis was carried out using the steps highlighted below:

a. Read the network parameters
b. Formation of line and bus matrix, and assign a base voltage (p.u) and deviation error limit (∈ = 0.0001)
c. Calculate the three-phase bus current injection and three-phase branch currents.
d. Set iteration count k = 1
e. Calculate the current injections for each branch
f. For Backward Sweep: calculate the branch current starting from the far end node
g. For Forward Sweep: calculate and update the bus voltages starting from the source node to the end node
h. Calculate and check for voltage mismatch using the equation
i. If ΔVmax ≤ ∈ go to step x, else, set k = k+1 and go to step v
j. Print the voltage magnitude, phase angle, and total power losses
k. Stop.

2.4. Voltage Stability Index (VSI) Application

The value of the parameters obtained from the power flow analysis such as active power, reactive power, and voltage with the reactance of the line are used in evaluating the VSI of the network using the method presented by [16,17]. Once the VSI of the network was obtained, the VSI was ranked in descending order after which the location of the DG was obtained.

2.5. Model of the Distributed Generation Planning

The DGs are capable of supplying active, reactive power or both depending on the type of DG used. In most cases, the DG is modeled as a PQ or PV bus depending on the purpose to which it is made to be served. Modeling the DG as a PV bus provides a means for reactive power control which is a function of a voltage and this helps in evaluating the maximum loading of the network. Also, modeling DG as a PQ bus provides a means for reducing the active power losses of the network and it also helps in controlling the reactive power flow of the line by serving as a negative load. The type III DG model is adopted in this work, with the following characteristics: 0<PFDG<1, Sign = +1 and is constant.

2.6. Firefly algorithm (FA) for Optimal DG Sizing

After obtaining the location of the DG using the VSI, the FA was then used in finding the optimal DG size that is suitable for the location with a minimum power loss and the steps involved in the application of FA for optimal DG size are as follows:

a. Generate an initial Firefly based on the location obtained by the VSI and define the FA parameters.
b. Consider the fitness function (brightness) as the objective function.
c. Calculate the objective function from equations based on [29] that correspond to all the initial fireflies obtained in (i) above.
d. Select the best DG size that achieved a minimum power loss and maximum system load ability, and keep the best DG size and system load ability as a new firefly (system variables).
e. If the convergence criteria are met, go to step (vi) else, repeat steps (iii and iv) for the iteration counter.
f. Display the results with the brightest firefly**,** and The parameters used are given in table 1.

Table 1. Firefly parameter definition, notation and value

Parameter	Notation	Value
Brightness	Objective function	
Alpha (α)	Randomization parameter	0.25
Beta (β)	Attractiveness	0.20
Gamma (γ)	Absorption coefficient	1
Number of generation (i)	Iterations	50
Number of fireflies (N)	Populations	10

These parameters are selected based on [30], and are applied, to achieve a fast convergence and reliable solution.

2.7. Proposed Method for DG Planning

The proposed method involved the combination of the VSI and Firefly algorithms for the location and sizing of the DG respectively. The steps involved in carrying out the proposed method are as follows:

a. Input the network parameter (line and bus data) and Firefly parameter
b. Run the base case three-phase power flow and calculate the bus voltage, branch current, and power losses of the network.
c. Calculate the VSI for each bus of the network
d. Make the list of the VSI in descending order and select the bus with the highest value of VSI as the DG location.
e. Generate a random Firefly as the DG size based on the location obtained from step IV above.
f. Compute the objective function and display the result.

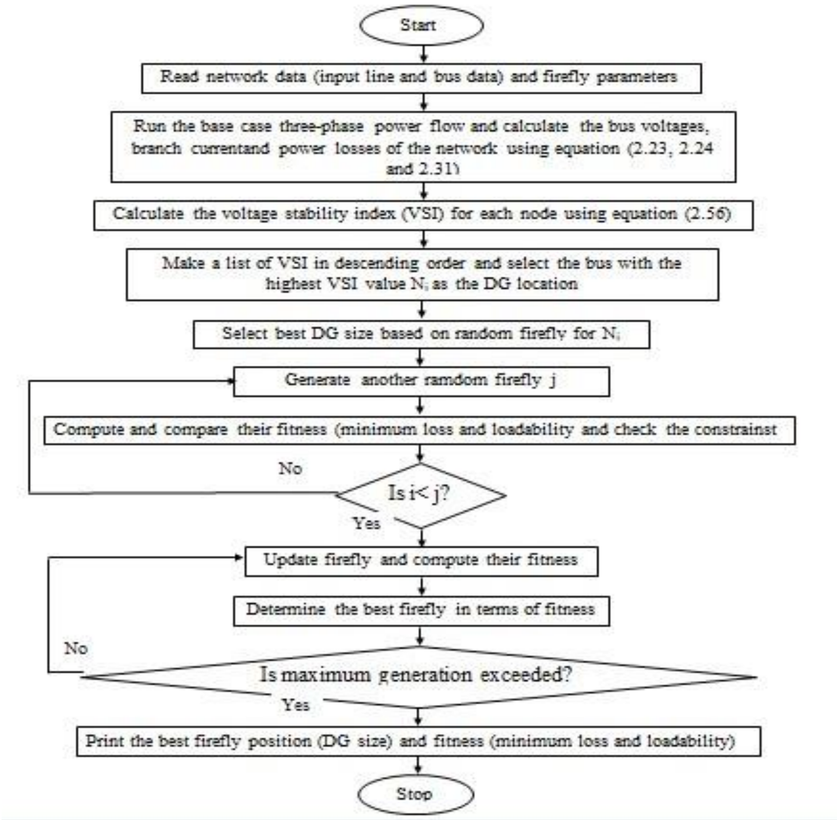

Figure 1. Flowchart of the proposed method

2.8. The Network Maximum Load ability

The maximum load ability of the network is carried out using the formulation from [12]. This is done by increasing the load by 1% of the present state load until the constraints given by [6] are violated. The point at which the constraint can no longer hold is taken as the maximum loading factor of the network. At that point, it is assumed that the maximum load ability of the network has been reached.

3. Results and Discussion

This section presents the results obtained and the discussion of the results. The results included the base case (network without DG) and the case with DG and also the maximum load ability of the network are evaluated. The implementation of the work is done on the IEEE 37-bus and 19-bus Mahuta feeder. The comparison between the developed method with the work of [20] is also presented in this chapter.

3.1. The IEEE 37-Bus Unbalanced Radial Distribution Test System

The proposed method implemented on the IEE 37 were done on two case scenarios, which are network without DG and network with DG.

3.1.1 Case I: Network without DG (Base Case)

For the base case, power flow analysis is carried out without DG on the network. The power flow analyses are performed using a three-phase power flow based on (the BFS) technique where the steady state of the network is determined. From the result obtained, it is observed that each phase voltage magnitude and phase angle differ except bus 1 which is the slack bus. At the slack bus, the value of the voltage magnitude is taken to be 1p.u with a displacement of 120º between the phases. Phase A has a minimum voltage magnitude of 0.9543p.u at bus 33, phase B has a minimum voltage magnitude of 0.9734p.u at bus 24 and phase C has a minimum voltage magnitude of 0.9541 located at bus 36. Phase C has the highest voltage drop due to the heavy load on it as compared to phases A and B. Also, the phase angle between the phases is not equally displaced due to the unbalanced loading between the phases. Maximum voltage magnitudes of 0.9884, 0.9908, and 0.9827p.u for phases A, B, and C respectively are observed except the slack bus which is shown in Table 2 and are all located at bus 2 due to its closeness to the grid supply. The active and reactive power losses for phases A, B, and C are found to be 12.2816 kW, 7.7743 kW 11.3297 kW, and 5.8341kVAr, 3.6227kVAr, and 5.8261kVAr respectively. The losses are calculated using the current loss formulae from [29]. It was observed that phase B has the lowest power loss because of the low load connected to it as compared to phases A and C. The average voltage magnitude for phases A, B and C obtained are 0.9694, 0.9788 and 0.9616 p.u. The total active and reactive power loss for the base case is found to be 31.3543 kW and 15.2829kVAr respectively.

3.1.2 Network with DG

After running the three-phase power flow, the value of the voltage and the power obtained from the base case are used to obtain the DG location using the VSI from equation established by [19]. Figure 2 shows the VSI graph for the IEEE 37-bus URDN.

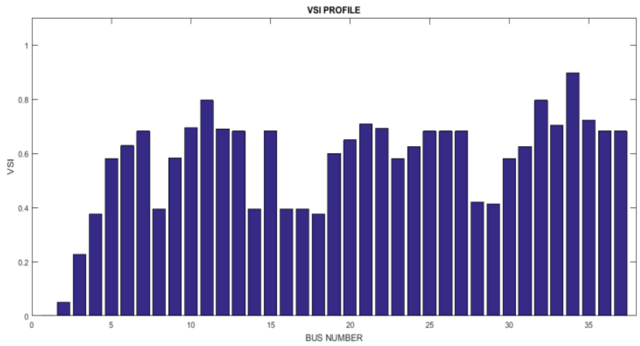

Figure 2. Voltage stability index (VSI) for IEEE 37-bus URDN

From Figure 2, it is observed that bus 34 has the highest value of VSI. Therefore, it is selected as the optimal DG location. The firefly algorithm is then used to find the DG size that gives the minimum power loss based on the location obtained by the VSI. From the simulation results obtained in MatLab, the optimal DG size of 356 kW and 170kVAr for active and reactive power are obtained respectively. After the DG placement, power flow analysis and the real power losses are calculated. From the results obtained, the line losses on each phase of the network are different, with phases A, B, and C having an active power loss of 7.3717 kW, 3.5443 kW, and 8.9169 kW and reactive power losses of 3.5601kVAr, 1.7464kVAr, and 4.6949kVAr respectively. The total power loss for the entire network is found to be 19.8329 kW and 10.0014kVAr for both active and reactive power respectively.

From the result obtained, a minimum voltage magnitude of 0.9764, 0.9865, and 0.9762p.u was observed at bus 33, 24, and 36 for phases A, B, and C respectively. Phase C has the lowest voltage magnitude due to the heavy load connected to it. The average voltage magnitude for phases A, B, and C obtained are 0.9861, 0.9902 and 0.9808p.u respectively for the entire network.

3.1.3 Network Voltage Profile with and without DG

The base case and the proposed method's voltage magnitude are plotted against their respective buses from the numerical values given. Figures 3, 4, and 5 show the voltage magnitude for the base case and the optimized case for phases A, B, and C.

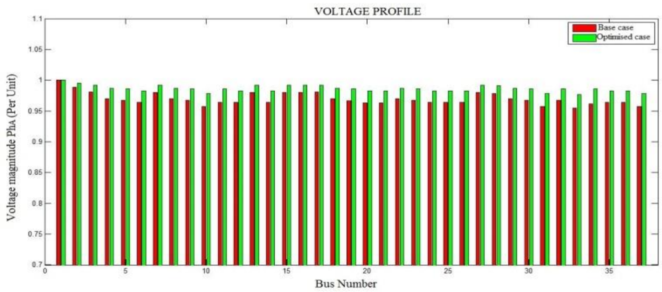

Figure 3. Voltage profile for the developed method and the base case for IEEE 37-bus URDN phase A

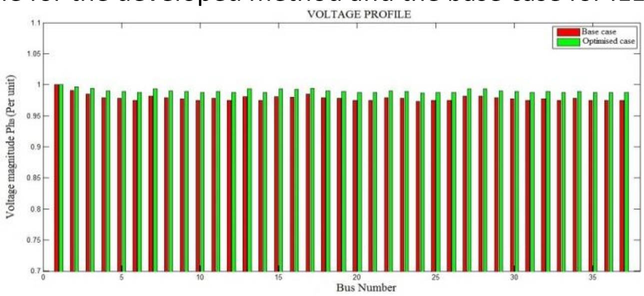

Figure 4. Voltage Profile for the developed method and the base case for IEEE 37-bus URDN phase B

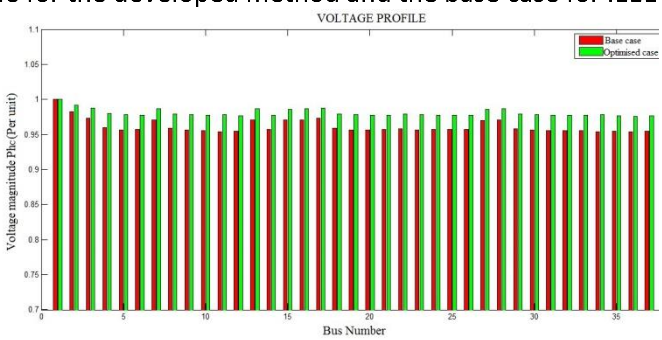

Figure 5. Voltage profile for the developed method and the base case for IEEE 37-bus URDN phase C

From Figures 3, 4, and 5, a voltage profile improvement is observed from a minimum voltage of 0.9543, 0.9734, and 0.9541p.u to 0.9764, 0.9865, and 0.9762p.u for phases A, B, and C respectively. This shows a 2.32%, 1.35%, and 2.32% minimum voltage profile improvement for phases A, B, and C respectively.

3.1.4 IEEE 37-Bus Load ability

Figures 6 and 7 show the plot of voltage magnitude against the loading factor for the base case and the developed method for the IEEE 37-Bus network respectively.

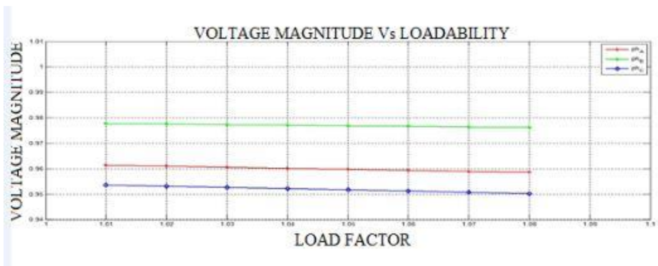

Figure 6. IEEE 37-bus URDN maximum load ability for base case

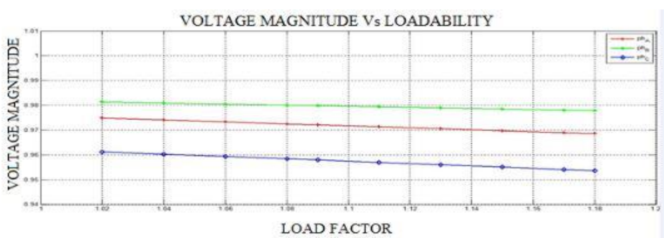

Figure 7. IEEE 37-bus URDN maximum load ability with DG

From Figures 6 and 7, it can be seen that the maximum load ability of the network for both the base case and the developed method are 1.08 (8%) and 1.18 (18%) respectively over the initial loading of the network. Phase A has a better loading factor as compared to Phase B and C, with Phase C having the least load ability. This implies that the addition of an equal amount of load to all the phases will cause phase C to violate the network constraints, which may result in network collapse. The maximum load ability improvement of the network is found to be 9.26%. Table 2 shows the summary of the results obtained for the IEEE 37-bus URDN.

Table 2. Summary of test result for IEEE 37-bus unbalance radial distribution network

Description	Case I (without DG)			Case II (with DG)		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
DG location				34		
DG size (P&Q)				356kW and 170kVAr		
Minimum voltage (p.u)	0.9543	0.9734	0.9541	0.9764	0.9865	0.9762
Voltage profile improvement				1.72%	1.16%	2%
Active Power loss (kW)	12.2816,	7.7743,	11.3297,	7.3717,	3.5443,	8.9169,
% active power reduction	-	-	-	39.98%	54.41%	21.29%
Reactive power loss	5.8341	3.6227	5.8261	3.5601	1.7464	4.6949
% reactive power loss reduction	-	-	-	38.98%	51.79%	19.42%
Loading factor	1.08 (8%)			1.18 (18%)		
% loading factor improvement	9.26%					

3.2. 19-Bus Mahuta Radial Distribution Network Feeder

Two case scenarios are considered in carrying out the test on this feeder which are discussed below.

3.2.1 Case I: Network without DG (Base Case)

For the base case, the three-phase power flow is performed on the feeder to obtain the steady state voltage magnitude and phase angle of the network without the DG.

From the results obtained, it is observed that the voltage magnitude and phase angle in all the buses differ in each phase due to the different loading in the network with a minimum voltage of 0.9962p.u, 0.9963p.u and 0.9967p.u and a maximum voltage of 0.9993p.u, 0.9993p.u, and 0.9994p.u for Phase A, B and C respectively. But except for the slack bus, which value is based on the initial operating point given. The minimum voltage magnitude of all the phases is found at the far end of the network due to the line voltage drop because of the distance and impedance of the line. The active and reactive power loss for phases A, B, and C are found to be 0.5392 kW, 0.4986 kW, 0.4108 kW, and 0.3852kVAr, 0.3419kVAr, and 0.2841kVAr respectively. The total active and reactive power loss of the network are 1.4486 kW and 1.0112kVAr respectively. The average voltage magnitude of the base case for phases A, B, and C of the entire network is found to be 0.9968p.u, 0.9969p.u, and 0.9973p.u respectively.

3.2.2 Case II: Network with DG

After running the three-phase power flow, the value of the voltage and power obtained from the base case power flow are used to obtain the DG location. Figure 8 shows the VSI graph for the 19-bus feeder. From Figure 8, it can be seen that the bus with the highest value of VSI is bus 17 and is therefore, taken as the optimal location of the DG. The firefly algorithm is then used to find the DG size that gives the minimum power loss based on the location obtained by the VSI. From the simulation results obtained using a Matlab environment, the size of the DG active and reactive power obtained are 201.58 kW and 115kVAr respectively.

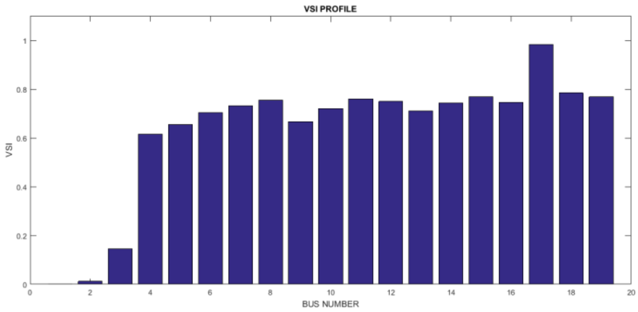

Figure 8. Voltage stability index (VSI) for 19-bus Mahuta distribution network feeder

The result obtained shows that, the minimum voltage magnitude for phases A, B, and C are found to be 0.9987p. u, 0.9988p.u, and 0.9989p.u as compared to the base case which is 0.9962p.u, 0.9963p.u and 0.9967p.u. Like the base case scenario, the minimum voltage magnitude is found at the far end of the network (at bus 19) due to the almost balanced nature of the feeder and the assumption made. Also, a power loss for phase A as 0.5167 kW and 0.3664kVAr, phase B as 0.4659 kW and 0.3145kVAr, and 0.3997 kW and 0.2749kVAr for phase C are obtained, which give a total network loss of 1.4123 kW and 0.9558kVAr for both active and reactive power respectively. The average voltage magnitude of the network when DG is installed is found to be 0.9990, 0.9990, and 0.9991p.u for phases A, B, and C respectively.

3.2.3 19-Bus Mahuta Feeder Network Voltage Profile

Based on the analysis and the result obtained, the voltage magnitude for both the base case and the optimized case are plotted against their respective buses which are shown in the figures 9, figure 10 and figure 11 for each phase on the network.

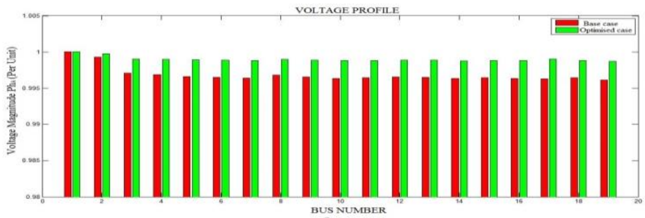

Figure 9. Voltage Profile for the base case the developed method for 19-bus Mahuta distribution network Feeder Phase A

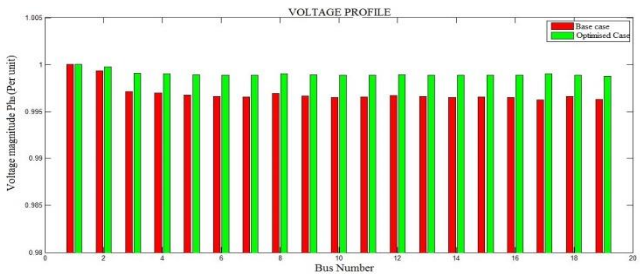

Figure 10. Voltage Profile for the base case and the developed method for 19-bus Mahuta distribution network feeder phase B

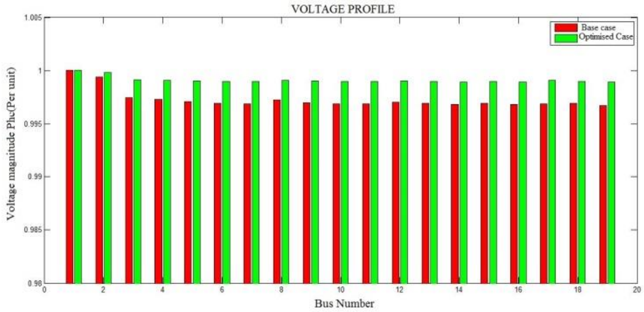

Figure 11. Voltage Profile for the base case and the developed method for 19-bus Mahuta distribution network feeder phase C

From Figures 9, 10, and 11, a voltage profile improvement from a minimum voltage of 0.9962, 0.9962, and 0.9967p.u of the base case to a minimum voltage of 0.9987, 0.9988, and 0.9989p.u for the optimized case was observed. This shows that the placement of DG in the network affects the voltage profile.

3.2.4. 19-Bus Mahuta Feeder Load ability

The maximum load ability of the Mahuta feeder is evaluated to know the amount of load which when added to the network may result in the network steady state violation. Figures 12 and 13 show the plot of voltage magnitude against the loading factor for both the base case and the developed method respectively for the 19-Bus Mahuta Distribution network Feeder.

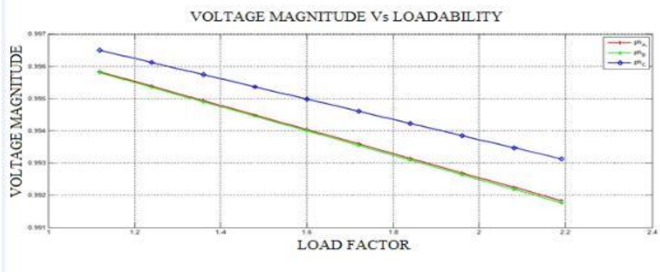

Figure 12. 19-bus Mahuta distribution network feeder maximum load ability without DG (base case)

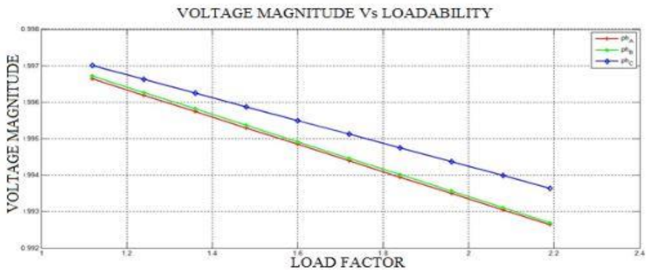

Figure 13. 19-bus Mahuta distribution network feeder maximum load ability with DG

From Figures 12 and 13, it is observed that the maximum load ability for the 19-bus Mahuta feeder for both the base case and the developed method is the same, which is 2.19 (119%). This implies that the network will violate the network constraints only when the load is increased twice the existing load on the network with an additional 19% of the load. The indifferent between the developed method and the base case is due to current carrying capacity of the line. When the load is increased beyond this loading factor, it results in voltage collapse (melting of the line) of the network. The summary of the test result obtained for the 19-Bus Mahuta DN Feeder is shown in Table 3.

Table 3. Summary of test result for 19-bus Mahuta distribution network feeder

Description	Case I (without DG)			Case II (with DG)		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
DG location				17		
DG size (P&Q)				210.58 kW	115kVAr	
Minimum voltage (p.u)	0.9962	0.9963	0.9967	0.9987	0.9988	0.9989
Active Power loss (kW)	0.5392	0.4986	0.4108	0.5167	0.4659	0.3997
% active power loss reduction	-	-	-	4.17%	6.56%	2.70%
Reactive power loss kVAr	0.3882	0.3419	0.2841	0.3664	0.3145	0.2749
% reactive power loss reduction	-	-	-	5.62%	8.01%	3.24%
Loading factor	2.19 (119%)			2.19 (119%)		

3.3. Validation of the Optimized Method

The results of the optimized method (proposed method) are compared with the work of [22]. The performance metrics used for the comparison are power loss and voltage profile and the comparison is done on standard IEEE 37-Bus URDN.

In the optimized method, the optimal DG location obtained is bus 34 and the DG size is 356 kW and 170kVAr for active and reactive respectively. The active and reactive power loss of the network is found to be 19.8329 kW and 10.0014kVAr as compared to the base case of 31.3543 kW and 15.2829kVAr respectively. This shows a percentage loss reduction of 36.75% and 34.56% for active and reactive power respectively.

For [20], the optimal location at which the DG is placed is bus 22 of the network and the size of the DG is 1502.25 kW and 730.1kVAr for active and reactive power respectively. The power loss obtained by [22] is 21.5911 kW and 14.3730kVAr for active and reactive power as compared to the base of 31.3543 kW and 15.2829kVAr respectively. This showed a percentage loss reduction of 31.14% and 5.95% for both active and reactive power respectively.

However, in the comparison between the optimized method and [22] method, the optimized method showed a percentage loss reduction of 8.14% and 30.42% for active and reactive power respectively over the work of [22]. Figure 14 shows the voltage profile of the base case, optimized method (optimized method), and [22].

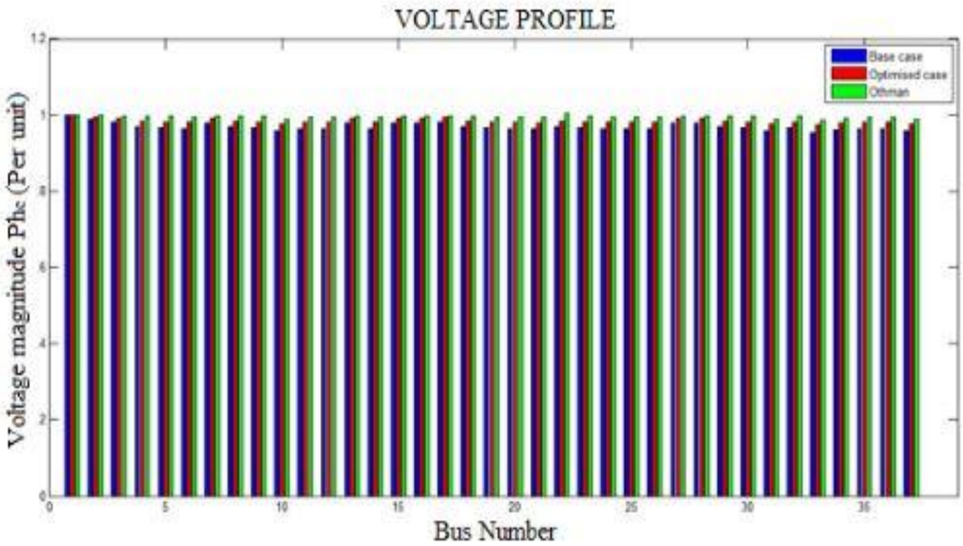

Figure 14. Voltage profile for the base case, optimized method, and othman et al (2016)

As can be seen from Figure 14, the blue line represents the base case, the red line represents the optimized case, and the green line represents the [22]. The [22] method has a better voltage profile as compared to the optimized method and the base case. This is due to the large size of DG placed in the network which causes a significant difference in the voltage profile of the network.

Table 4. Summary of results from [22] and optimized method

Descriptions	[22]	Optimized method
Optimal DG location	22	34
Optimal DG active power	1502.25kW	356kW
Optimal DG reactive power	730.1kVAr	170kVAr
Active power loss	21.5911kW	19.8328kW
Reactive power loss	14.3730kVAr	10.014kVAr
% loss reduction of active and reactive power	-	8.14% & 30.42%

The percentage average voltage profile for [22] and the optimized method over the base case are 2.6862% and 1.5615% respectively. However, in terms of power loss reduction, the optimized method had a better loss reduction than that of [22] when compared with the base case. The optimized method gave a percentage loss reduction of 36.75% and 34.56% for active and reactive power while [22] gave a percentage loss reduction of 31.14% and 5.95% for active and reactive power respectively over the base case. Table 4 shows the summary of the comparison between [22] results and the optimized results.

4. Conclusion

This work presents the use of the firefly algorithm-based method and voltage stability index for distributed generation planning in an unbalanced three-phase network. The VSI is used to determine the DG location while the FA is used for the DG sizing. A three-phase power flow was carried out to determine the initial steady-state operating condition of the network. Two test systems are used in implementing the work, the standard IEEE 37-bus URDN and a local 19-bus Mahuta feeder. The developed method is validated using a paper presented by [20] and is done on the standard IEEE 37-bus test system.

For the standard IEEE 37-bus URDN, the total power loss obtained is 31.3543 kW and 15.2829kVAr for active and reactive power respectively without DG in the network. When the developed method is applied, a DG optimal location is found at bus 34 and a DG size of 356 kW and 170kVAr for active and reactive are obtained respectively. The active and reactive power loss obtained when DG was placed in the network are 19.8329 kW and 10.0014kVAr respectively, the developed method recorded a loss reduction of 36.75% and 34.56% for both active and reactive power respectively over the base case. Also, the maximum load ability of the network is determined. It was discovered that the network can only carry an additional 8% of the initial loading without DG and 18% of the load when DG was incorporated without violating the network constraints (such as line and voltage limit).

For the 19-bus Mahuta feeder, the location found for the DG is bus 17 and the DG size of 201.58 kW and 115kVAr are obtained for active and reactive power respectively. A power loss reduction of 4.48% and 5.62% for active and reactive power are recorded over the base case respectively. The maximum load ability of the network is found to be 2.19 (119%) over the initial loading of the network for both the developed method and the base case.

For the validation with the work of Othman et al., (2016), DG size of 356 kW and 170kVAr for active and reactive power is obtained as against the 1502.25 kW and 730kVAr obtained by [20] respectively. A loss reduction of 8.14% and 30.42% for active and reactive power are recorded when compared to the work of [20]. However, Othman et al., had a better voltage profile when compared to the optimized method due to the large size of DG used but the optimized method's voltage profile is still within the voltage limit. From the results obtained, it is evident that the proposed method has a better performance in terms of power loss reduction than the work of [20].

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