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NETWORK VOLTAGE PROFILE IMPROVEMENT USING GEOTHERMAL DISTRIBUTED GENERATION

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ABSTRACT

voltage instability in Electrical Distribution Networks (EDNs) is a pressing concern, particularly in Old Umuahia Distribution System (OUDS). The OUDS is one of the 33KV lines of the Owerri Distribution System (ODS), located at Egbu Owerri in Imo State. The network is prone to Under Voltage (UV) issues, due to insufficient supply and inadequate reactive power compensation. The UV problem has led to equipment damage, reduced efficiency, and increased losses. The research deals with Network Voltage Profile (NVP) enhancement of OUDS (33/11/0.415KV network), using Geothermal Distribution Generation (GDG). The data of the network wete gathered through Enugu Electricity Distribution Company (EEDC), using Field Survey (FS). The modeling and simulation of the network were performed using MATLAB (2020a) software. The network data, one line diagram of the network, and Particle Swarm Optimization (PSO), were incorporated in the simulation. The simulation was done with and without GDG. The results of the simulation done without GDG showed that out of the 9 buses of the case study network, 6 buses were violated, 3 buses were non-violated, and the value of he active loss obtained yields 0.053 PU. Also the results of the simulation done with GDG indicated 9 non-violated buses, zero (0) violated bus, 6 healed buses, 0.140 PU optimal size of DG, and the magnitude of active loss obtained gives 0.031PU. The percentage of the active loss reduction yields 36.9%.. The research demonstrates the potential of GDG to address voltage instability in Electrical Distribution Systems (EDSs). The research contributes to the development of sustainable and reliable Power Systems (PSs), supporting economic growth and social development.

KEYWORDS: Geothermal Distribution Generation, Distribution Network, Network Voltage Profile, Voltage Regulation and Power Quality.

1.0 INTRODUCTION

The increasing demand for electricity in Nigeria has put pressure for on the existing distribution infrastructure, leading to Voltage Instability (VI) and Under Voltage (UV) issues. A recent incident where a cable fault led to the removal of a critical cable in a Distribution Network (DN), highlights the vulnerability of the network. The removal of the cable resulted in a significant under voltage condition, affecting the network's performance and reliability. This incident underscores the need to innovative solutions to improve voltage profile and reduce power losses in EDNs. The GDG offers a promising solution to address these challenges. Thus, by injecting power into the grid, geothermal DG can improve NVP, reduce power losses, and enhance network (system) stability. The integration of GDG into DN can also enhance reliability and resilience, particularly in areas prone to cable faults and other disruptions.

This study focuses on the application of GDG to improve the voltage profile and reduce Power Losses (PLs), in EDN affected by fault. The research aims to develop a strategy for optimal placement and sizing of GDG units, to regulate voltage levels and minimize power losses.

2.0 LITERATURE REVIEW

2.1 Overview of Embedded Generation

The Embedded Generation (EG) or Distributed Generation (DG), is Electrical Power (EP) generation technology used to provide small Capacity Power (CP) units, and the EG is situated nearer to (electricity) end-users Akbari *et al.*, 2024). The researchers stated that on-site generation (embedded generation or distributed or decentralized generation), is integrated on the grid through EDSs. The generation unit (i.e., decentralized generation) maintained power which range from KW to MW.

Many EG technologies can be used to solve the Voltage Instability (VI) problem. (Akpan *et al.*, 2023) in their research work identified Solar Photovoltaic System (SPS), Wind Turbine (WT), Fuel Cell (FC), Gas Turbine (GT), Micro Turbine (MT), Hydroelectric Power (HEP), biomass, and geothermal (power plant), as technologies which can be deployed on Electrical Distribution System (EDS), to solve voltage instability challenges. They are mainly essential for voltage regulation in the Power System (PS). (Akhavanhejazi, 2024) maintained that geothermal (power plant) specifically, leverages heat from the earth's core to generate electricity (often using steam turbines or binary cycle systems). It is a reliable, Renewable Energy Source (RES) with a small environmental footprint. In Nigeria, geothermal potential is estimated at 600MW, mainly in the Benue trough and Jos plateau (Badreddine *et al.*, 2024). Studies have shown that GDG can improve NVP and reduce losses in the Distribution System (DS). According to the researchers, the placement and sizing of geothermal DG (units) are critical factors in achieving optimal Voltage Regulation (VR). Various optimization techniques, like Genetic Algorithm (GA), have been applied to determine the optimal location and sizing of geothermal DG units (Daziga and Fujii, 2024).

Indeed, the control of GDG units is crucial in regulating the voltage level in EDS. Different control strategies, such as Reactive Power (RP) control and voltage control, have been proposed to manage GDG. Also, the use of advanced control techniques (such as model predictive control and fuzzy logic), has been explored to optimize the performance of GDG units (Enrico and Chicco, 2024). In Nigeria, according to Fettah *et al.*, 2024, the application of GDG to address UV (Under Voltage) issues in EDS is still in its infancy. However, studies have shown that geothermal energy can be a viable option for power generation in the country. The integration of the GDG units in EDS improve NVP and reduce Power Losses (PLs) in Distribution System (DSs). A case study of the Ogba 33KV injection substation in Rivers State, revealed that GDG improved the NVP from 0.88PU to 0.96PU, and reduced total Active Power Loss (APL) by 78.2% (9). Figure 1 shows Geothermal Power Plant (GPP).

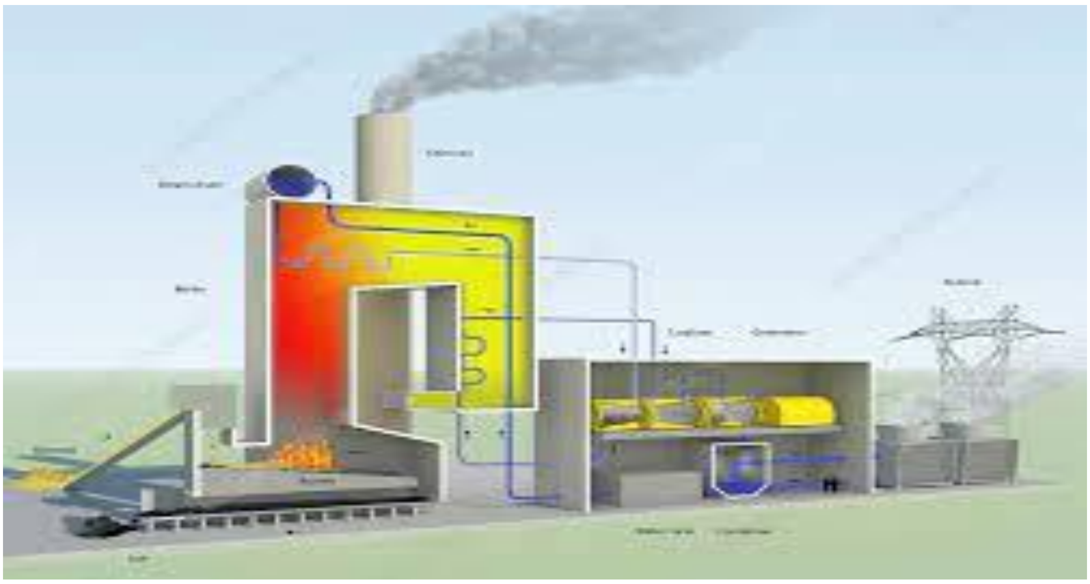

Figure 1: Geothermal power plant.

2.2 Overview of Electrical Distribution System

The distribution system (DS) provides the final link between the HV (High Voltage) transmission system (network) and the end-users (Geev, 2024). Hossen *et al.* (2023 viewed the distribution system as a measure of stepping down High Electricity Voltage (HEV) to Smaller Electricity Voltages (SEVs) for possible consumption by end-users (consumers).

In Nigeria, voltages (currently) applied by the Transmission Company of Nigeria (TCN) and Distribution Company of Nigeria (DCN) are 330KV, 132KV, 33KV, 11KV, 0.415KV (or 4.15KV), 415V, and 240V (Hyun *et al.*, 2024). In the stepping down process of the voltages, 330KV is stepped down to 132KV (i.e., 330/132KV), 132KV is stepped down to 33KV (i.e., 132/33KV), 33KV is stepped down to 11KV (i.e, 33/11KV), 11KV is stepped down to 0.415KV or 4.15KV (i.e., 11/0.415KV or 11/4.15KV), and 415V is stepped down to 240V (i.e., 415V/240V), (13). The stepping down linkage of the voltage is given in equations (1) and (2), (Javed and Zeeshan, 2023).

330/132KV - 132/33KV - 33/11KV - 11/0.416KV (1)

Or the stepping down linkage of the voltages occurs as:

330/132KV - 132/33KV - 33/11KV - 11KV/415V - 415V/240V (2)

The 33KV (directly) supplies industries which are heavy, 11KV (directly) supplies industries that are light, 415V supplies Towns, Villages and Farms (TVF), while 240V (directly) supplies homes.

Distribution system (or EDS) is a complex system comprising various components like substations, transformers, distribution lines, and protection devices (circuit breakers, isolators and protection relays). Transformers are used to step down voltage from one voltage level to another. Circuit breakers and isolators are used to control the flow of electricity and isolate faulty sections of EDS. Protection relays detect faults and trigger circuit breakers to isolate the faulted section (13).According to (Leo and Erone, 2024), The EDS also includes Distribution Lines (DLs), which can be either Overhead (OH) or Underground (UG). The OH lines are more common and consist of conductors suspended from poles, while UG lines are used in areas where OH lines are not feasible. The DLs are designed to withstand various environmental conditions like extreme weather and temperature fluctuations (Paes, 2023).

The EDS begins at the transmission substation, where HV (High Voltage) electricity is stepped down to 33KV. This voltage is then transmitted to primary distribution substations, where it is further reduced to 11KV. The 11KV feeders distribute electricity to secondary substations, which transform the voltage to 0.415KV for final delivery to consumers (Reza *et al.*, 2023).

The EDS is beneficial as it ensures a reliable and efficient power supply to Residential, Commercial and Industrial (RCI) consumers (Reza et *al.*, 2023). It aid to transform HV electricity to LV electricity levels, making it safe for consumption. The EDS plays vital role in supporting economic growth, social development, and improving the quality of life (Yusuf, 2024).

One of the key challenges facing EDS is a high level of technical losses, which occur due to the resistance of power lines (distribution lines) and transformers. The increasing electricity demand, which puts pressure on the EDS infrastructure pose another challenge (Yusuf, 2024).

2.3 Distribution System Faults

Distribution System Fault (DSF) according to Vunda *et al.* (2025) is an abnormal condition that disrupts the normal flow of electric current, potentially causing damage to equipment and affect power supply reliability. The researchers disclosed that a fault in Power Distribution System (PDS) originate through vandalism, lightning, tree falling across lines, small animals entering switchgears, wind damage, and vehicles colliding with lines (Vinod and Satish, 2022). The researchers classified PDS faults into two forms as symmetrical (balanced) faults and unsymmetrical (unbalanced) faults.

2.3.1 Symmetrical (balanced) faults

Symmetrical Fault (SF) is a fault in the Power System (PS) that give rise to SF current. That is equal Fault Currents (FCs) in the Power lines with 120^0 displacement. When the three conductors of three phase line are brought together (simultaneously) into a short-circuit situation, SF occurs. This SF is severe, and it imposes too much on the Circuit Breaker (CB) (Wenshu *et al.*, 2023). The example of SF is three phase fault (either to earth or clear of earth).

2.3.2 Unsymmetrical (unbalanced) faults

The Unsymmetrical Faults (UFs) are faults on the PDS that give rise to the UFs current. That is unequal FCs in the Power Lines (PLs) with Unequal Phase (UP) displacement. The examples of the UFs are (Xiaohua *et al.*, 2024):

Line - to - line fault (L - L).

Single line - to - ground fault (L - G).

Double line - to - ground fault (L - L - G).

Again combination of any two (2) of the stated faults forms Unsymmetrical Fault (UF) condition. Figures 2 to 4 shows the UFs.

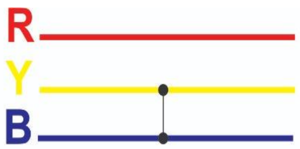

Fig. 2. L-L Fault

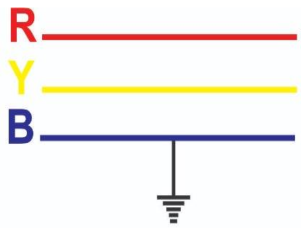

Fig. 3. L-G Fault

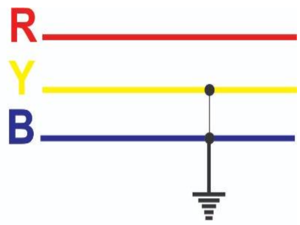

Fig. 4. L-L-G Fault

2.3.3 Benefits of fault analysis

Fault Studies (FSs) on PDS is performed to determine the magnitudes of system (network) current (I) and Voltage (V), during fault situations. The determination of V and I during the fault situations is vital, so that Protective Devices (PDs) may be set to detect (and minimize) the harmful effects of such contingences.

2.4 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a heuristic optimization algorithm inspired by the social behaviour of birds or fishes. The algorithm was first introduced by Kennedy and Eberhart in 1995, and has since been widely used to solved complex optimization problems. PSO is a population based algorithm that search space (Zaro, 2023)/

In PSO, a swarm of particle is randomly initialized, each representing a potential solution to the problem. Thus, each particle has a position and velocity which are updated iteratively based on its own experience, and the experience of its neighbors. The position of a particle represents a point in the search space, and the velocity determines the direction and speed of the particle's movement (Enrico and Chicco, 2024)..

The PSO algorithm evaluates the fitness of each position using a fitness function, which is problem specific. The fitness function maps the particle's position to a real number, indicating the quality of the solution. The particles communicate with ach other and share their best positions, which are used to update their velocities and positions (Akpan *et al.*, 2023).

The PSO process starts with the initialization of particles and their velocities. The fitness of each particle is evaluated, and the particle best (pbest) and global best (gbest) positions are updated. The pbest is the best position found by a particle so far, while the gbest is the best position found by the entire swarm (Daziga and Fujii, 2024)/ The PSO has benefit of fast convergence an flexibility. PSO computation is very easy. It is suitable for large scale optimization problems. The PSO can handle non-linear and non-convex problems (Daziga and Fujii, 2024).

2.5 Network Voltage Profile Enhancement

The System Operator (SO) in EDS, is obligated to ensure proper maintenance of Voltage Level (VL), of network nodes within the required limit. Indeed, different standard are established to give recommendation (stipulations) in EDS. Example, the ANSI (American National Standard Institute) standard-C84.1, maintained that Voltage Violations (VVs) in EDS should be checked (controlled), within the limit of -13% - 7% (Hyun *et al.*, 2024).Normally, many Electricity Companies (ECs) try to control VVs within the limit of ±6%. Therefore, the basic upcoming (widely) adopted techniques for enhancing NVP of EDS is the introduction of distributed generation. Distributed Generation (DG) enhances NVP by injecting power to the distribution system (Paes, 2023). The location and size of the DG are vital impact on NVP enhancement (Paes, 2023). The power losses reduction on the hand are arrested easily with aid of DGs (Vunda *et al.*, 2023).

3.0 METHODOLOGY

3.1 Research Design

The research employed simulation based research design. MATLAB (2020a) software and Particle Swarm Optimization (PSO) were applied in the study.

3.2 The Existing Old Umuahia (Line) Network

The Old Umuahia (Line) Network (OULN) is one of the 33KV feeders of Owerri distribution system in Imo State. The network has nine nodes, transformers, and other essential equipment.The one line diagram of the network is given below.

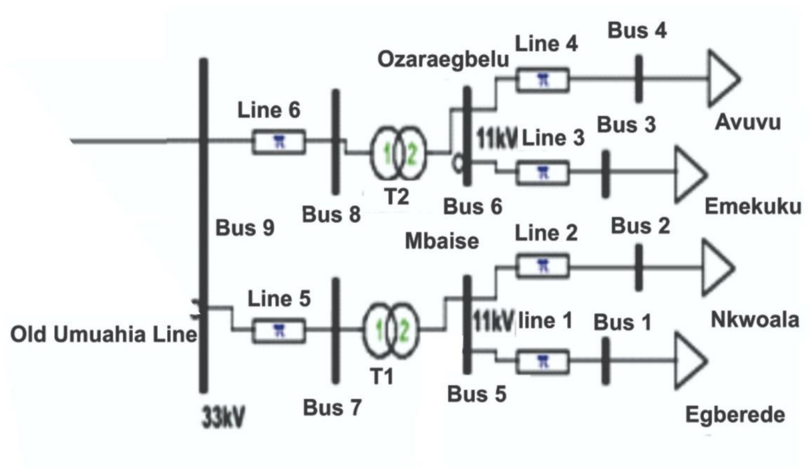

Figure. 5: One line diagram of Old Umuahia line network.

The data of the network was obtained from Enugu Electricity Distribution Company (EEDC).

Table 1: Node distance an load of Old Umuahia line Network.

S/N	Node Name	Load (MW)	Distance (KM)
1	Egberede	6.20	9.60
2	Nkwoala	5,80	14.00
3	Emekuku	6.20	4.40
4	Avuvu	5.40	13.20
5	Mbaise	22.10	23.20
6	Ozaraegbelu	18.90	13.60
7	Okpuala	14.10	10.80
8	Onuimo	13.10	12.80
9	Old Umuahia	12.60	16.00

Table 2: Old Umuahia line network equipment data.

S/N	PARTICULARS	STATUS
1	Incoming Feeder	1
2	Outgoing Feeder	2
3	Nodes	9
4	Transformers	Greater than 2
5	Generators	0
6	Conductors	Alominiom
7	Cross-sectional area of conductor	150mm^2
8	Conductor resistance	0.1825Ω
9		

3.3 Problem formulation

3.3.1 Voltage improvement index (VII)

The violated voltage needs to be healed. The healing makes it easy for the voltage at each bus, to remain within the acceptable range, and the line flows within the limits. The VII mathematically is given by:

$$VII = \int_{i=1}^{n} 1 \sqrt{\left[\frac{Viref - Vi}{Viref}\right] 2} \quad (3)$$

Where: n is number buses, Viref is reference voltage at bus i, Vi is actual voltage at bus i.

3.3.2 Generator Constraint

The DG capacity of each unit should be defined around its nominal value. So that each DG is maintained within an acceptable limit. This includes: the upper and lower, true and reactive power generation limits of DG, connected at bus, i. The capacity of DG is given by:

$P_{DG}^{min} \leq P_{DGI} \leq p_{DG}^{max}$ (3.19)

$Q_{DG}^{min} \leq P_{DGi} \leq P_{DG}^{max}$ (3.20)

Where: P_{DG}^{min} is lower true power of DG, Q_{DG}^{max} is upper reactive power of DG, Q_{DG}^{min} is lower reactive power of DG, p_{DG}^{max} is the upper true power of DG, P_{DGi} is the real power of DG at bus, i; and Q_{DGi} is the reactive power of DG at bus, i.

3.3.3 Bus voltage constraint

This includes the upper and lower voltage magnitude limits (V_{min} and V_{max}), at bus, i. Bus voltage value is to be kept within acceptable operating limits throughout the optimization process. The bus voltage limit is given by:

$V_{min} \leq V_i \leq V_{max}$(3.21)

Where: V_{min} is the lower voltage limit, V_{max} is the upper voltage limit, and V_i is voltage of bus, i. V_{min} is 0.95PU and V_{max} is 1.05PU.

3.4 Simulation

The simulation o the base case load flow is performed with MATLAB 2020a software. The network voltage profiles were noted. This is followed by identification of voltage sensitivity nodes using exhaustive simulation of 20% in each of the 11KV and 33KV nodes. The PSO was applied for the sizing and location of the DG. Bus with the least bus voltage deviation after installing DG is selected as the best GDG placement. Then, the running of the load flow with optimal size of DG integrated at the optimum is carried out. The comparison of the GDG impact in the steady system voltage profile with the base case simulation is done. Figure 5 shows the simulation diagram of the Old Umuahia line network.

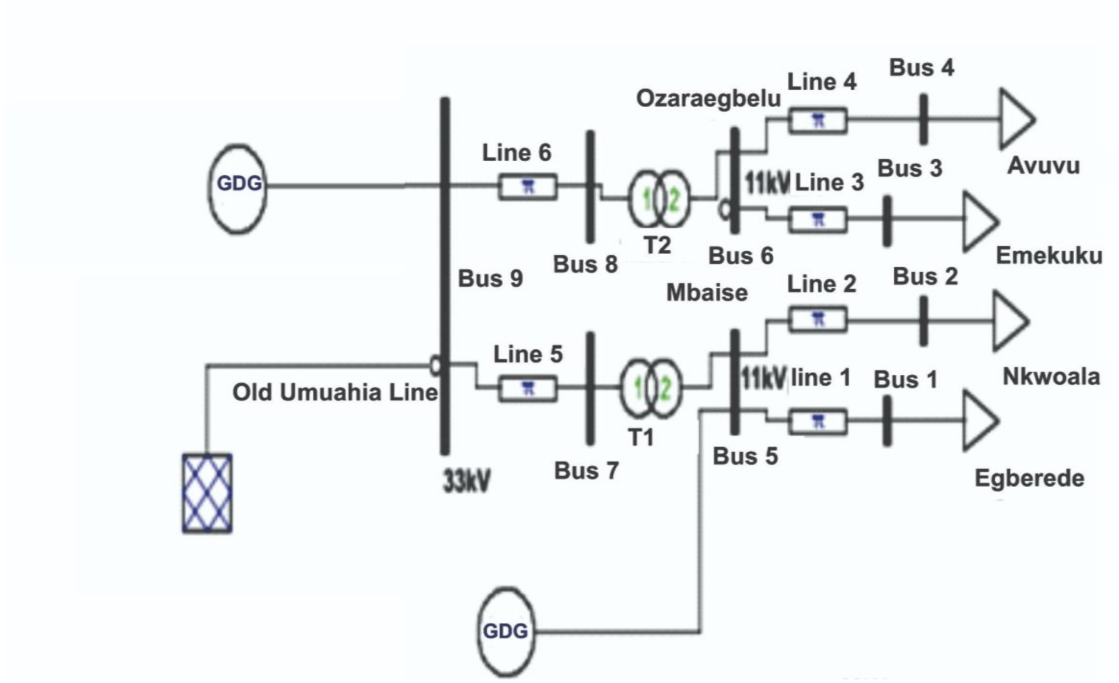

Figure 5: Simulation diagram of the Old Umuahia line network.

4.0 RESULTS AND ANALYSIS

Table 3: Power flow result of the base case system.

Bus Number	Bus Name	Voltage (PU)	Phase (rad)	P-Gen (PU)	Q-Gen (PU)	Bus (PU)	V (PU)
1	Egberede	0.98316	-0.29026	-4.3E-16	1.88E-15	0.062	0.00
2	Nkwoala	0.89064	-0.29083	5.83E-16	5.98E-16	0.058	0.00
3	Emekuku	1.00126	-0.28169	7.08E-15	-6.6E-17	0.062	0.00
4	Avuvu	0.99592	-0.28269	0.00000	-6.4E-17	0.054	0.00
5	Mbaise	0.80022	-0.28873	9.49E-16	-1.9E-15	0.000	0.00
6	Ozaraegbelu	0.98841	-0.28099	-4.4E-15	-1.2E-15	0.000	0.00
7	Okpuala	0.96671	-0.81067	0.00000	0.00000	0.000	0.00
8	Onuimo	0.81067	-0.10971	-1.4E-14	-1.9E-15	0.000	0.00
9	Old Umuahia	0.97075	-0.97075	-1.2E-14	3.9E-15	0.000	0.00

Table 5: Line flow result of the base case system.

From Bus	To Bus	Bus Name-Bus Name	Line	P-Flow (PU)	Q-Flow (PU)	P-Loss (PU)	Q-Loss (PU)
1	5	Egberede-Mbaise	1	-0.062	1.88E-15	0.00046	9.57E-05
2	5	Nkwoala-Mbaise	2	-0.058	5.93E-16	0.00058	0.000123
3	6	Emekuku-Ozaraegbelu	3	-0.062	-6.6E-17	0.00020	4.31E-05
4	6	Avuvu-Ozaraegbelu	4	-0.054	-6.7E-17	0.00047	9.93E-05
5	9	Okpuala-Old Umuahia	5	-0.223	-0.02232	0.00056	0.000117
6	9	Onuimo-Old Umuahia	6	0.118	-0.02051	0.00025	5.21E-05
7	5	Okpuala-Mbaise	7	0.122	0.02233	0.00111	0.022106
8	6	Onuimo-Ozaraegbelu	8	0.118	0.02051	0.00102	0.020640

Table 6: Optimal position placement ranking.

Bus No	Bus Voltage Level (KV)	PLRI	QLRI	VSI	Ranking Criteria	Achieved Rank
5	11	0.0416	0.0636	0.0953	High PLRI, QLRI, &Low VSI	1
6	11	0.0356	0.0581	0.0955	High PLRI, QLRI, &Low VSI	2

Table 7: The 20% GDG penetration in the 33KV and 11KV nodes of the base case system.

Bus No	BVL (KV)	APL (PU)	QPL (PU)	PLRI (PU)	QLRI (PU)	VSI (PU)	No of NVB	No of VB	No of HB	BVII
-	-	0.050	0.555	0.000	0.000	0.098	3.000	6.000	0.000	0.000

Table 8: The 20% GDG penetration in the 33KV and 11KV nodes of the proposed system.

Bus No	BVL (KV)	APL (PU)	QPL (PU)	PLRI (PU)	QLRI (PU)	VSI (PU)	No of NVB	No of VB	No of HB	BVII
9	33	0.0484	0.5244	0.0344	0.0561	0.0954	9.000	0.000	6.000	0.1500
5	11	0.0451	0.5202	0.0416	0.0636	0.0953	9.000	0.000	6.000	0.1500
6	11	0.0484	0.5232	0.0358	0.0581	0.0955	9.000	0.000	6.000	0.1500

Table 9: Summary of the study simulation result.

Case	Feeder Voltage (PU)	Type of Simulation Performed	No of Non-Violated Buses	No of Violated Buses	No of Healed Buses	Optimal Size of GDG	Optimal System Active Loss (PU)	% Active Loss Reduction
1	1.00	Base System Sinulation	3.000	6.000	0.000	-	0.053	-
2	1.04	GDG Placed at bus 5	9.000	0.000	6.000	0.140	0.031	36.9

The results presented showed the outcome of the research carried out**.** Figure 6: is a simple bar chart showing the voltage profile of the Old Umuahia network. Where: APL is active power loss, QPL is reactive power loss, QPLRI is reactive power loss reduction index, PLRI ir real power loss reduction index, VSI is voltage stability index, NVB is number of violated buses, VB is violated buses, HB is healed buses, and BVII is bus voltage improvement index.

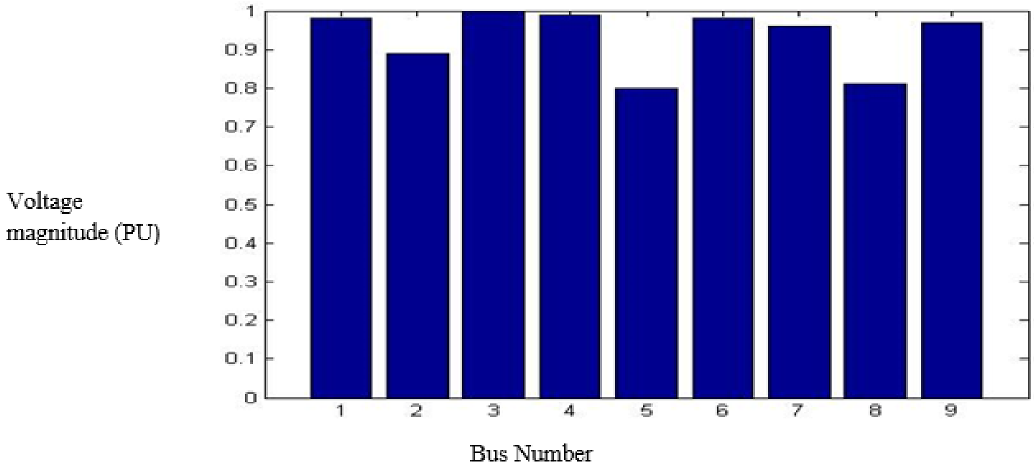

Figure 6: Simple bar chart showing the voltage profile of the Old Umuahia network.

In figure 6, the voltage profile of the case study network shows that out of the nine buses of the network, three buses were violated while six buses were non-violated. The violation resulted due insufficient supply and fault issue. A cable was incidentally removed from the existing network. The removal of the cable from the existing network causes fault challenge. The buses which did not maintain the acceptable of 0.95 - 1.05PU are Nkwoala bus 2, Mbaise bus 5, and Onuimo bus 8.

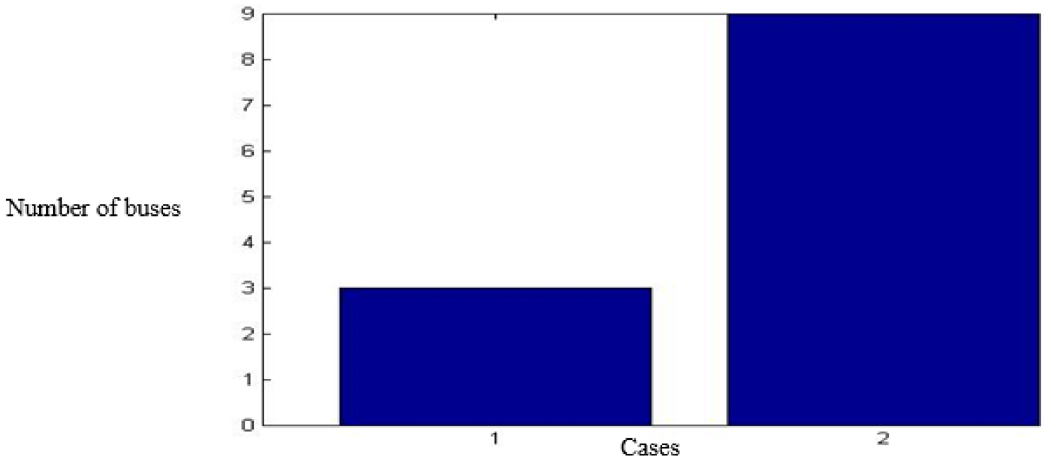

Figure 7: Bar chart showing number of the non-violated buses in the base case simulation and simulation done with GDG.

The first bar indicated as one in the case axis represent number obtained from the base case simulation, and the number is 3. The second bar shows 9 (nine), which is total number obtained from the simulation done with GDG. The results shows that GDG can enhance voltage profile positively.

Figure 8: is a bar chart representing the number of violated buses (which is 6) in the existing network simulation, and the proposed network simulation. The bar indicated as 1, shows 6 voltage buses that were violated due to insufficient supply and fault. The bar indicated as 2, shows that the 6 buses were healed with the aid of GDG. The healing also attained well with the help of the feeder voltage (i.e., 1.04PU) applied.

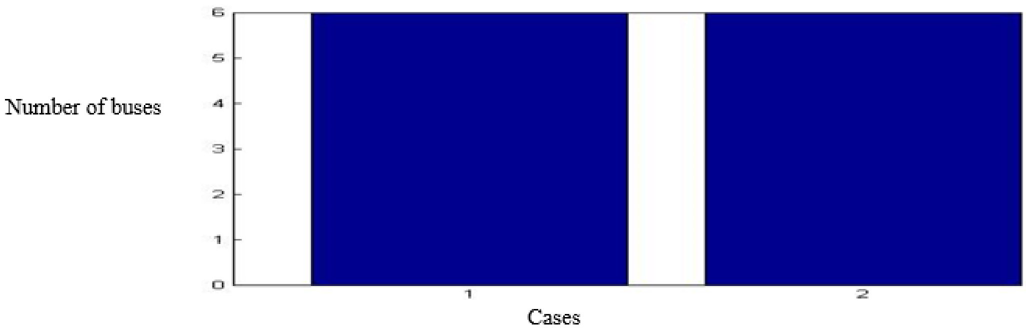

Figure 8: Bar chart represent the number of violated buses (which is 6) in the existing network simulation, and the proposed network simulation.

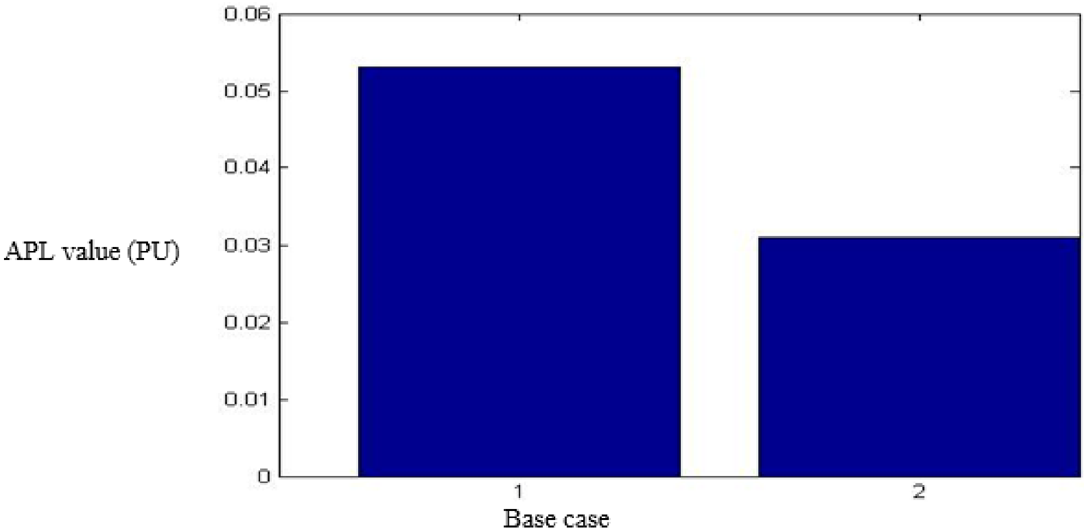

Figure 9: Bart chart showing the active power loss results.

In figure 9, bar number 1, shows the magnitude of active loss obtained through the base case simulation. The value of the active power loss is 0.053 PU. The second bar shows reduction of the active power loss achieved through the aid of GDG. The second bar is indicated as 2, and its magnitude is 0.031 PU.

5.0 CONCLUSION

The study deals with the enhancement of voltage profile of Old Umuahia line network. The simulation of the study was done with MATLAB software, while GDG and PSO were incorporated in the simulation. The simulation is performed with and without GDG in the case study network. The base case simulation results showed that out of the 9 buses of the case study network, 6 buses were violated, 3 buses were non-violated, and the value of he active loss obtained yields 0.053 PU. This results occurred due to insufficient power supply in the network and fault issue. The results of the simulation carried out with GDG revealed 9 non-violated buses, zero (0) violated bus, 6 healed buses, 0.140 PU optimal size of DG, and the magnitude of active loss obtained gives 0.031PU. The percentage of the active loss reduction yields 36.9%. The results show that GDG can enhance the network voltage profile of a distribution network.

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