

Power quality considerations for embedded generation integration in Nigeria: A case study of ogba 33 kV injection substation

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ABSTRACT

The deregulation of the Nigerian power sector has resulted in the quest to explore power generation options for power quality improvement. One of such options is the pattern shift from central power generation to embedded power generation. Network integration of embedded generators (EGs) causes several regulatory, technical and economic issues. This research focuses on power quality challenges that may arise as a result of network integration of embedded generation in a weak electricity networks using Ogba 33 kV injection substation as case study. The embedded generators considered comprised of gas turbine and diesel generators. NEPLAN software was used to perform the load flow analysis with and without EGs connection on the network. This was necessary so as to ascertain the healthiness of the existing distribution network for EGs integration. The power quality issues considered in the study were bus voltage profiles and the total line losses. Simulation results showed that EGs connection improved the voltage profile, for example, bus voltage at PTC 11 kV, improved from 0.881 pu to 0.958 pu while the total active power loss was reduced by 78.16%. The results obtained suggest that the grid is healthy enough to accommodate the EGs with no quality issues.

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1. INTRODUCTION

Modern civilization and technological development in recent times have led to increasing demand for electrical energy [1, 2]. As at present, Nigeria is in deep energy crisis [3]. All the efforts being made by the government to stabilize the Nigerian power system so far has yielded little or no significant result. Though the country is endowed with abundance of renewable energy sources, about 60-70% of the over 70 million Nigerian have no access to the grid electricity [4]. The 30-40% that are connected to the grid have the number of hours of outages to be more than the number of access hours [3].

Nigeria operates a centralized power system with distinct generation, transmission and distribution units with the supply chain having the consumers at its end [5, 6]. It is the distribution sector that is in touch with the consumers as it steps down and distributes the energy at the required voltage to the consumers. This study is focused on power quality improvement at the distribution section of the power network.

In general, there are two types of electricity distribution networks: radial or interconnected. In radial distribution networks, no alternative supply route is provided and as a result the outage of any branch would interrupt service delivery to the consumers supplied via the branch [7, 8]. It is typically made up of long rural lines with load centres that are isolated in nature. An interconnected network is one in which several distributed generation units are integrated [9].

The interconnected model is adjudged to be better than the radial model as provisions are made such that a portion of the network can be disengaged in the event of fault or scheduled maintenance, while the remainder kept on delivery power to the consumers [10, 11]. Due to the increasing level of modern civilization resulting in increasing demand for electrical power, the central power generation is facing several challenges resulting in the search for viable options of meeting the demand of the end-users [12]. One such option is the generation and supply of power at the distribution level.

The generation of power in close proximity to the distribution network or load node is termed distributed or embedded power generation [13-16]. Distributed or embedded generation (EG) is often used to refer to electricity generation on a small-scale [17, 18]. The survey carried out by CIRED and authors in [19] show that there is no consensus on the exact meaning of EG as at present [20].

EG was described as generating units, whose capacity ranges from 50 to 100 MW, which are connected to the distribution network but not planned or dispatched centrally in [20-22]. EG is also considered as generating units connected to the local network directly by the international energy agency (IEA) with no reference made to the generation capacity. Most distributed generation systems have several characteristics in common. These include [14]:

- Small ratings compared to regular power plants;
- Mostly owned by private individuals or bodies;
- Not dispatched centrally;
- Connected to medium voltage or low voltage distribution networks

The inclusion of EGs in the existing networks has advantages of cost savings and transmission and distribution losses reduction as power is generated on-site [14, 23]. These advantages have made EG a feasible option in the modern power network. EG inclusion in the distribution network also improves power quality, reliability and stability [24, 25]. Peak shaving capability, standby and cogeneration as well as power systems efficiency improvement are other benefits of EGs [26].

However, there are several technical, economical and regulatory issues when EGs are connected to the grid [27]. In terms of physical integration, power quality is one of the issues to be considered [28]. Protection is also an issue, as new protection schemes would have to be developed for both embedded generators and utility distribution networks.

Embedded Generation remains one of the alternative options available to ramp up power capacity on the Nigerian electricity grid. Many companies and industries have shut down operation in this country due to this erratic nature of the power supply. It is therefore important to embrace embedded generation in order to improve power quality.

It is not just sufficient to say that embedded generators should be connected to the distribution network because we have enough gas to fire generators. Adequate consideration will have to be given to the integrability of EGs into the existing grid. This paper therefore looked into power quality considerations for Embedded Generation integration in Nigeria. The power quality issues considered here are bus voltage profiles and the total power loss in the the network.

In EG penetration studies, determination of network's voltage is adjudged the most time consuming module [29]. Many of the studies estimated the bus voltages by running distribution power flow, which is more complex than power flow in transmission networks for reasons such as: larger number of buses/nodes, radial topology in normal operation and greater ratio of resistance to reactance of the distribution system. According to [30-34], load-flow Studies are conducted to determine:

- Power system's steady-state operation (calculation of bus voltages, voltage drops and the power-flow in all branches and feeders circuits).
- Whether the bus voltages fall within the acceptable limits under several contingency conditions, as well as the loading condition of transformers, conductors and other network equipment.
- Whether there be need for increased generation capacity, inductive or capacitive VAR support, or the optimal placement of VAR compensators, in order to stabilize the system's voltage.

The traditional load-flow methods (e.g. Newton-Raphson, Gauss Siedel and fast-decoupled) cannot be used for most cases of power flow analysis in distribution system as a result of its radial or weak meshed nature, high resistance to reactance ratio and unbalanced operation in the network [35, 36]. The conventional methods are very efficient in solving power flow problems in transmission network, but are inefficient for distribution networks as the solution may not converge. Hence in this research work, NEPLAN software which is capable of solving power flow problems via simulation was used.

Electrical power systems are designed to operate within a set of boundaries with clearly defined lower and upper limits. The quality of any power system network is measured in terms of its ability to function effectively within the pre-set boundaries. Power quality could be defined as the provision of voltage, frequency or current and system design of electric power systems such that the consumers can utilize the electrical energy from the distribution system without interference or interruption while maintaining near sinusoidal bus voltages at rated magnitude and frequency [37, 38].

A number of measurable parameters are used for power quality assessment. The most common parameters, according to [39] are voltage swells, voltage increase, harmonics, frequency variations, transient, unbalance, rapid voltage change, flicker, frequency deviation, protection system etc. The above are some of the technical issues worthy of consideration when integrating embedded power generation units into an existing system according to the authors in [40].

Electrical distribution network distributes electrical power to the consumers. It has the responsibility of ensuring that the power meet certain requirement. In order to achieve the above, the network make use of different network configurations, protection, control and monitoring equipment. Poor power quality has adverse effect on the consumers' loads and can have serious consequences and costs for users and energy providers [41]. The quality of power system's voltage is affected by all the interconnected parties: power generation, transmission and distribution, and consumers.

Nonlinear loads such as computers, switching power supplies, compact florescent lamps, electric arc furnaces, frequency converters, etc are the major sources of harmonics in power systems [42, 43]. The effects of harmonics include: impaired efficiency in engines, overheating of motors, increased energy losses, transformers and other equipment overloading, resonance resulting in over-voltage or over-current, disturbance with electronics and control systems

The presence of power electronics equipment in most EGs is one of the major causes of harmonics. Many EGs like renewable energy sources are integrated into the grid using power electronics converters which may introduce harmonics into the grid [41]. Consequently, the integration of embedded generators into the sub-transmission or distribution networks result in lots of technical challenges such as [43]:

- Inclusion of embedded generator may result in voltage rise in the networks that could result from reverse flow of power
- Increased loading levels of individual elements (transformers and lines) that could result to the thermal ratings being exceeded.
- Inrush currents cause step voltage changes. This may occur when induction generators and /or transformers are energized from the power network. Disconnection of a generator from the network could also result in sudden change in voltage
- When embedded generator is connected to a distribution network, the fault level in parts of the network closer to the point of connection may increase.
- Network instability resulting from the interconnection of multiple generators.
- The ability of local EGs to improve the network performance is depended on its ability to island and supply customers' loads in the event of failure.
- The integration of embedded generators into a weak network may increase losses as power is being forced through the network.

In reality, Power system quality, reliability and stability studies are necessary to predict the possible effects of connecting embedded generators to the distribution network. Several literatures reviewed argued that the connection of inclusion of EGs in the electric grid affect the system's quality, reliability and or stability due to the random characteristics of some EGs. Because of the reasons above, it is important to predict the effect of EGs on the distribution network before they are connected to it.

One of the most important concern when interconnecting EG to distribution grid is Steady state voltage influence or profile at all buses [33]. This study considers the bus voltage profiles and the total loss on the line with and without EG integration into the network.

Normally, distribution networks are passive in design [44-47]. That means no design provision is made to accommodate any other source of generation. Connections of EGs of difference sizes and types convert the distribution network from passive to active. This will significantly impact the power flow in the grid and the voltage condition of the customers' end. These impacts can either be negative or positive depending on the distribution system operating condition and the embedded generator characteristics. So, injection of EGs to power grid, according to [48] can affect the voltage quality of the existing network. Therefore, steady state flow (load flow) needs to be carried out on the existing distribution network to which the embedded generation is to be connected to ascertain if it could accommodate the new generation units [49].

If EGs are carefully sizes and placed on the distribution network, it can improve and support the voltage profile of the system [50]. It is worth mentioning that connection of embedded generators to the

distribution network is bringing about two major issues, which are power quality (like voltage regulation, flicker, harmonics) and protection coordination problems because the integration of EGs increases the short circuit current of the existing network which in turn will affect the protection of the network [22]. In this research work, voltage profile at each bus, power losses and short circuit currents would be considered. This is because the subject of voltage profile and losses are of great importance to the consumers that are fed by the network. They want to have fair quality, reliable and stable power supply from the grid at all times.

2. RESEARCH METHOD

The distribution network used for the study was modeled using the schematic diagram obtained from the Ikeja electricity distribution company (IKEDC) which is one of the largest of the eleven (11) electricity distribution networks in Nigeria. The Ogba injection sub-station has been chosen as the site for the erection of the proposed EG, which comprises of gas turbine and diesel generators, because of its closeness to gas station and also because of the current energy deficit and evacuation capacity of the designated injection substation. The Injection Substation has the under listed accessories;

- 13 numbers of Bus bar
- The grid infeed = 106,604 MVA
- Ogba local transformer is 3 units of 15 MVA, 33/11 kV
- Agege Bye pass transformer is 15 MVA, 33/11 kV
- Universal steel transformer is 15 MVA, 33/11 kV
- PCT transformer is 2 units of 15 MVA 33/11 kV
- Embedded generator (EG) 1 is 57.162 MVA
- Embedded generator (EG) 2 is 33.169 MVA
- Embedded generator (EG) 3 is 13.264 MVA

EG 1, 2 and 3 locations on the network were determined using the NEPLAN software. The distribution network under study is a typical radial network. The cable impedance (Z) was $Z = R + jX = 0.4110 + j0.1070$ thereby giving a high resistance to reactance ratio of 3.8411. The conventional load flow analysis will not converge for distribution network due to high resistance to reactance ratio. Hence load flow analysis in this work was carried out using the dedicated NEPLAN software. The schematic layout of Ogba 33 kV injection substation modeled the NEPLAN software with the embedded generators integrated is as shown in Figure 1.

3.1. Modeling of diesel generator

Diesel generator set modeling was the first to be considered in the test distribution grid modeling. The model of diesel generator set in NEPLAN comprises of three important components which are the diesel combustion engine plus governor, synchronous generator, and the excitation system. It is assumed that the diesel engine and the synchronous generator rotate at the same mechanical speed, i.e. 1800 rpm; this implies that gearbox was not used.

Synchronous Generators are used for converting mechanical energy into electrical energy. The mathematical description of the generator can be obtained using Park's transformation. For Synchronous Generators, electrical frequency is proportional to the mechanical speed and could be obtained using (1):

$$\omega_e = \frac{p}{2} \omega_m \quad (1)$$

where: p is the number of poles, and ω_e and ω_m are the generator's electrical and mechanical speeds respectively.

Among other dynamic calculations, the model determined the torque using (2):

$$\Delta\dot{\omega} = \frac{T_m - T_e - D\Delta\omega}{J} \quad (2)$$

where;

T_m = mechanical torque

T_e = electrical torque

D = generator damping factor

ω = shaft speed and

J = moment of inertia

The synchronous generator (SG) model was implemented using the already built-in SG in NEPLAN software.

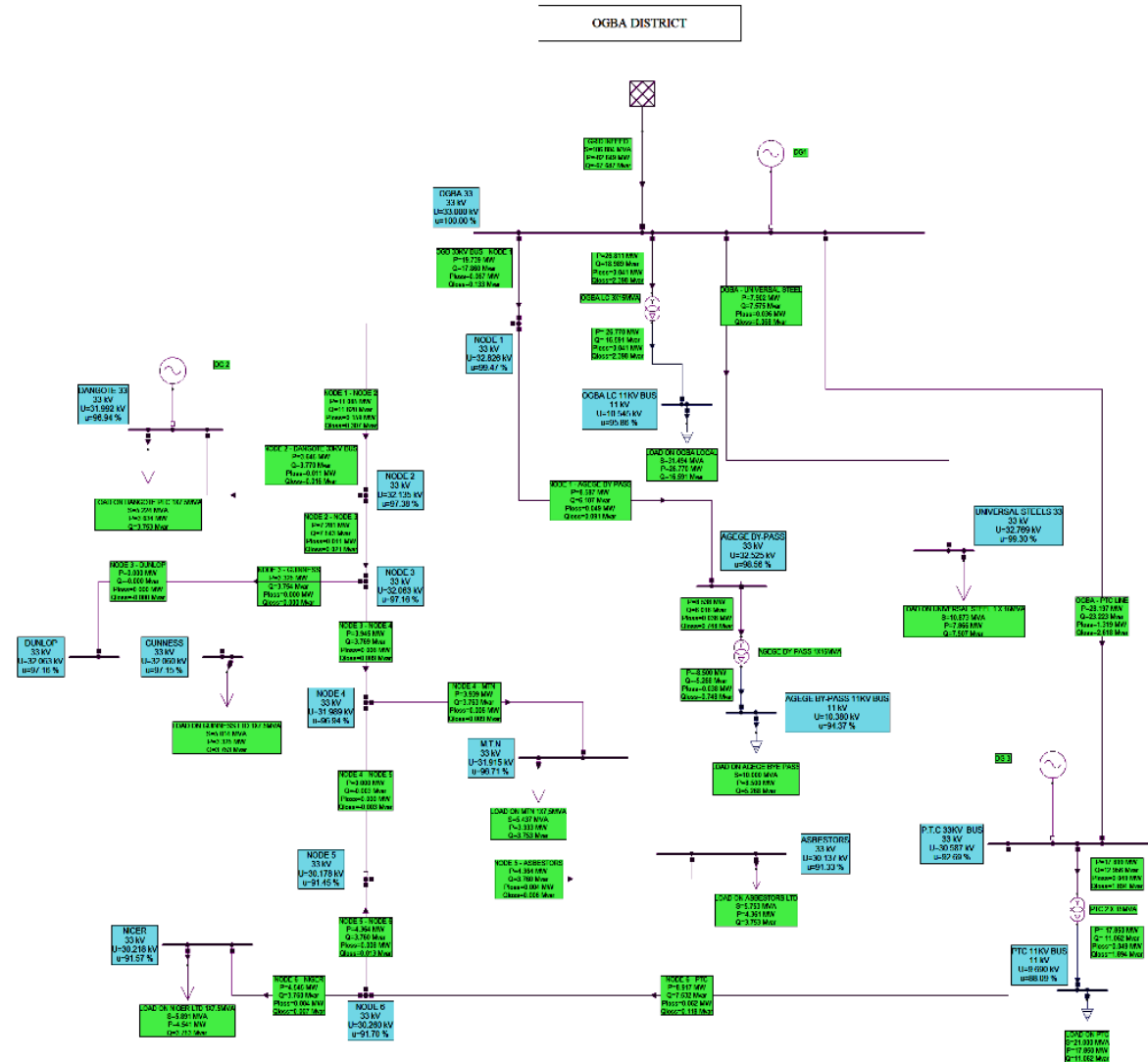


Figure 1. Modeling of the test distribution grid with EGs in NEPLAN

3.2. Internal combustion engine model

The diesel engine provides power to the generator and controls the speed of its shaft by means of a governor. An Internal Combustion Engine is available in NEPLAN Library and was used directly in this work. The NEPLAN software is very flexible such that the engine parameters could easily be entered. The input parameters used for the Internal Combustion Engine is as shown in Table 1

Table 1. Input parameters of the internal combustion engine

Machine rating	Engine Speed Rating	Number of Cylinders	Number of Engine Cycles	Misfired cylinders
57 MVA, 33 MVA and 13 MVA	1800 rpm	6	Four stroke	None

3.3. Gas turbine modeling

The gas turbine engine is an assembly of components which are designed on the basis of aero thermodynamic laws. A gas turbine plant is designed to converts the chemical energy content of fuels into heat energy, which is in turn converted into mechanical and then to electrical energy. Gas turbines are known to have lower greenhouse emission and higher efficiency compare to others.

A simple gas turbine power generation plant is made up of three main blocks including: the compressor, the combustor, and the turbine. The compressor unit which is either a centrifugal or axial flow type is normally mounted on the same shaft with the turbine. The turbine operates on the Brayton cycle

principle in which compressed air is mixed with fuel, and combusted under at constant pressure. The hot gas produced expands through the turbine to produce mechanical rotation. For the purpose of this work, the gas turbine generator was modeled as a synchronous generator which is available in the NEPLAN environment. The dynamic model of a synchronous generator was completed using (3);

$$\frac{Jd^2\theta_m(t)}{dt^2} = T_m - T_e \quad (3)$$

where: J is the rotor moment of inertia, T_m , and T_e are defined for (2) above and $\theta_m(t)$ is the rotor position.

The mechanical torque T_m is determined by the prime mover while the electrical torque is determined by the amount of power converted from mechanical into electrical. For steady state model for one axis,

$$V_a = rI_a - jXI_a + E \quad (4)$$

where: $X = X_d = X_q$

$$P_e = \frac{V_a E}{X} \sin \quad (5)$$

where: P_e is the electrical power of the machine, and V_a is the voltage across a-axis of the machine.

High number of poles makes most Synchronous generator to be large in size. A frequency converter is required to connect the generator to the grid in order to creat room for variable speed operation. The parameters of the simulated synchronous generators and transformers are as shown in Tables 2 and 3 respectively.

Table 2. Parameters of the simulated synchronous generators

Rated Powers (MVA)	57
	33
	13
Stator-Rotor turns ratio	0.38
Stator Voltage	575 V
Resistance of the Rotor, R_r (p.u)	0.005
Stator Resistance R_s (p.u)	0.00706
Rotor Leakage Inductance of the L_r (p.u)	0.156
Stator leakage Inductance L_s (p.u)	0.171
Inertia Constant (Lumped)	5.04
Magnetizing Inductance L_m (p.u)	2.9

Table 3. Parameters of the (33/11kV) 15MVA transformer

Rated Power (MVA)	15
Resistance of the Primary Winding, R_1	0.01
Primary Winding Reactance, X_1 (p.u)	0.05
Secondary Winding Resistance, R_2 (p.u)	0.01
Secondary Winding Reactance, X_2 (p.u)	0.05
Resistance, R_m (Magnetizing) (p.u)	1,000
Reactance, X_m (Magnetizing) (p.u)	1,000

3.4. Line model

The short line model which represented the distribution lines sections as series impedance was used in this study as shown in (6) and (7):

$$Z = (r + j\omega L) \quad (6)$$

$$Z = R + jX \quad (7)$$

where ℓ is the line length, r is thr resistance per-phase, per-unit length L is the inductance per-phase, per unit length.

3.5 Load model

A constant impedance load model, according to [51] can be used for voltage computation and voltage stability analysis of a radial distribution networks. The type of load in the network includes; lighting or heating, computers and a water pump. These loads can be divided into static load (lighting or heating,

computers) and dynamic load which includes induction machines (water pump). The static load of the network could be represented by the expression in (8). The total maximum load on the network was 135 kVA.

$$P_L = P_{EXP} = P_{LO} \left(\frac{U_L}{U_{LO}} \right)^{mp} \quad (8)$$

$$Q_L = Q_{EXP} = Q_{LO} \left(\frac{U_L}{U_{LO}} \right)^{mq} \quad (9)$$

The exponent's mp and mq were the parameters of this model defined as follows:

$mp = mq = 0$ for constant power characteristic

$mp = mq = 1$ for constant current characteristic

$mp = mq = 2$ for constant impedance characteristic

0.9 Power factor was used for both constant power and constant impedance with the lower and upper voltage limits set in the load flow program to 0.90 and 1.04 pu respectively. All the test distribution components or parameters were modeled in the NEPLAN environment to see if the system could be healthy enough to accommodate the connection of the generators.

3. RESULTS AND DISCUSSIONS

The distribution grid under investigation was modeled with embedded generators using NEPLAN software as shown in Figure 1. The network was simulated first without EGs' integration and then with EGs integrated to obtain the line losses and bus voltages for each case. This was done so as to study the impact of the inclusion of EGs on the line losses and bus voltages of the existing network. Result of the bus voltages for the network without and with EGs included is as shown in Table 4 and the associated graph shown in Figure 2 while Table 5 shows the total line losses with the associated chart shown in Figure 3.

It could be seen from the Table 4 that all the nodes voltages fall within the voltage limit except PTC 11 kV bus that has the lowest voltage of 0.881 pu which is slightly below the minimum voltage (0.90 pu). This shows that PTC 11 kV bus is experiencing low voltage without the connection of embedded generators. It was observed that all bus voltages are within the voltage limits (0.90 pu and 1.04 pu) indicating improvement on the voltage profile at all buses. For example, bus voltage at PTC 11kV, which was 0.881 pu when EG was not connected, improved to 0.958 pu when EG was connected.

Comparing the results in Tables 4 and 5, it can be seen that inclusion of embedded generators improved the voltage profile at each bus of the network. Similarly, Table 5 showed a total active power loss of 3.09 MW and 0.675 MW for the network without and with EGs connected respectively. The table also showed a total reactive power loss of 27.129 MVar and 10.216 MVar for the network without and with EGs connected respectively. From the results, it could be inferred that inclusion of embedded generators into the power distribution network would improve the bus voltages and reduce the line losses.

Table 4. Result of bus voltage profile with and without eg

S/N	Name	Nominal Voltage (kV)	With Grid Infeed Only		With EGs integrated	
			Node Voltage (kV)	Node Voltage (p.u)	Node Voltage (kV)	Node Voltage (p.u)
1	PTC 11 kV BUS	11	9.69	0.881	10.538	0.958
2	AGEGE BY-PASS 11KV BUS	11	10.38	0.944	10.419	0.947
3	OGBA LC 11 kV BUS	11	10.545	0.959	10.545	0.959
4	ASBESTORS	33	30.137	0.913	32.584	0.987
5	NODE 5	33	30.178	0.915	32.622	0.989
6	NICER	33	30.218	0.916	32.659	0.990
7	NODE 6	33	30.26	0.917	32.697	0.991
8	P.T.C 33 kV BUS	33	30.587	0.927	33	1.000
9	M.T.N	33	31.915	0.967	32.502	0.985
10	DANGOTE 33	33	31.992	0.969	33	1.000
11	NODE 4	33	31.989	0.969	32.574	0.987
12	GUNNESS	33	32.06	0.972	32.644	0.989
13	DUNLOP	33	32.063	0.972	32.647	0.989
14	NODE 3	33	32.063	0.972	32.647	0.989
15	NODE 2	33	32.135	0.974	32.718	0.991
16	AGEGE BY-PASS	33	32.525	0.986	32.635	0.990
17	UNIVERSAL STEELS 33	33	32.769	0.993	32.769	0.993
18	NODE 1	33	32.826	0.995	32.935	0.998
19	OGBA 33	33	33	1.000	33	1.000

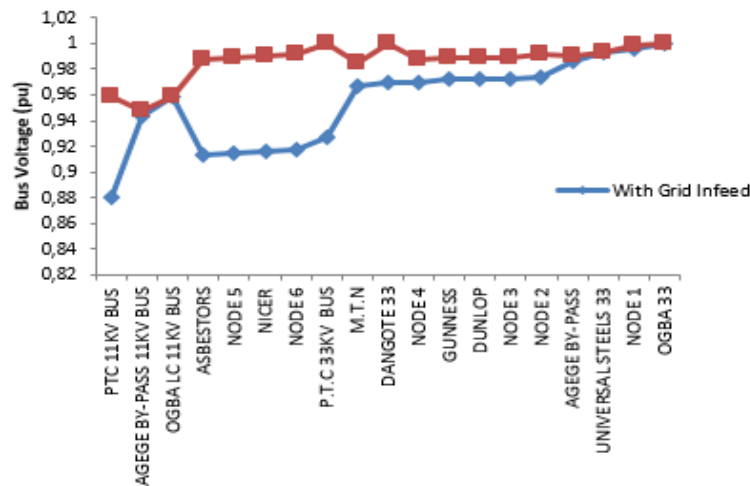


Figure 2. Graphical representation of the network voltage profiles without and with EG

Table 5. Total real and reactive powers of the line

	Active Power (MW)	Reactive Power (Mvar)
Line Losses with Grid Infeed	3.09	27.129
Line Losses with EGs	0.675	10.216
% Reduction in Losses	78.16	62.34

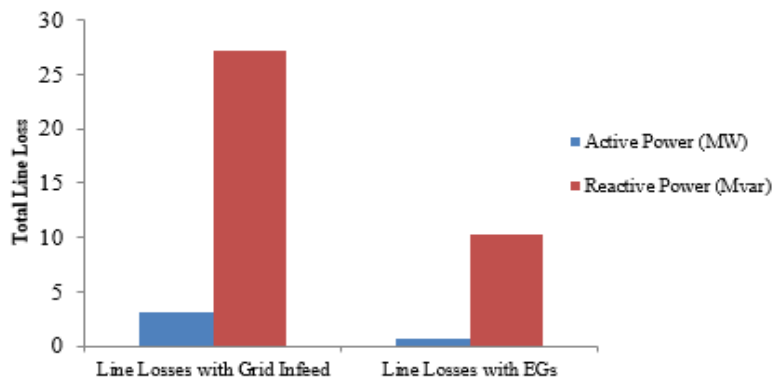


Figure 3. network line losses without and with EGs

4. CONCLUSION

Nigeria has several energy sources that could be harnessed for embedded power generation. However the healthiness of the existing distribution networks to accommodate embedded generation is of great concern due to several technical issues that are associated their integration into the existing networks. In order to be more certain of the healthiness of EGs connection to the existing grid, load flow analysis was performed on the test distribution system to consider the voltage profiles, short circuit current, and losses in the network with and without EGs connection. Simulation results showed that EGs connection improved the voltage profile, for example, bus voltage at PTC 11 kV, was improved from 0.881 pu to 0.958 pu while the total active power loss was reduced by 78.16%. The results obtained suggest that the grid is healthy enough to accommodate the EGs with no quality issues.

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