Impact of Solar Photovoltaic Generation (SPVG) on Distribution Networks: A case study of Minna town 33/11kV Injection substation

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***Abstract*—Distribution networks in Nigeria had suffered setbacks such as network losses and inadequate power injection into substations as compared with the net power delivered to load. This study examines the impact of solar photovoltaic generation on distribution networks of Minna Town 33/11kV injection substation. Distributed Generation (DG) is to minimize line losses and improve voltage profile of the network. Solar Photovoltaic Generation (SPVG) is one of the DGs that is capable of supplying real and reactive power into an existing distribution network to increase its overall efficiency. The SPVG was optimally placed in the network for case study by the use of Particle Swarm Optimization (PSO) technique. 11 kV Minna town distribution feeders of the Abuja Electricity Distribution Company (AEDC), used as case study was modelled and simulated in PSAT environment as a 17-node system. Results obtained showed reduction of overall active and reactive power losses to 63.7% and 64.1% respectively.**

Keywords— ***Distributed Generations, PSO, Reactive and active power compensation, PSAT software***

I. INTRODUCTION

Configuration of most distribution network (DN) systems are radial to ease their security. Every distribution feeder has a unique mix of industrial, commercial, and residential loads. The load demand patterns of these load categories vary, causing peak demand on feeder to occur at random intervals [1]. Loading the distribution system (installation) beyond it rated capacity can result in a variety of issues, ranging from branch disconnection due to protection device activation to a general voltage collapse, resulting in loss of revenue in the utility sector and electricity end users. It was computed in [2] that losses in the feeder at the distribution section consume approximately 5–13 percent of electricity generation. Every method of minimizing DN losses is worth looking into.

Distribution line losses can be mitigated using various technique: introduction of high voltage distribution system, load balancing, capacitor placement, and the network reconfigurations are just a few of the options available to reduce losses at the distribution level. As reported in [3], network reconfiguration, installation of capacitors, and the introduction of higher voltage levels are all linked to cost and reliability concerns. Therefore, installation of Distributed Generations (DGs) at an optimal point could effectively offset the above negative effects of line losses and voltage imbalance on the distribution network [4]. Electricity is distributed in Nigeria at 230V for single phase connections and 415V for three phase connections [5].

Particle Swarm Optimization (PSO) is an Artificial Intelligence (AI) techniques used for DG allocation in order to achieve optimal location on the distribution network [6]. Considering current line losses and subsequent impacts of DG were evaluated utilizing 11kV distribution feeders from the Abuja Electricity Distribution Company AEDC, Minna network. Simulation was carried out in MATLAB/PSAT environment.

II. REVIEW OF THE LITERATURE

Quite a number of researchers have worked on distribution network systems to proffer solutions that will mitigate power losses. The authors in [1] worked on the 32-bus, 69-bus, and 118-bus network reconfiguration problem using Hyper-Cube Ant Colony (HC-ACO) algorithm. Unlike probabilistic choice criterion, the study applied normal state transition rule to modify the localized heuristic rule. There was a 33.1 per cent reduction in power losses from 1.2947 MW to 0.8553 MW. In addition, based on a predefined line loss reduction level (up to 25%), the optimum capacity and site of DG-units (for future reference) were proposed in [7]. The method's goal was to get to that level for the least amount of net DG-unit expenditure (that is, the expenditure of a DG unit is deducted from the amount saved). The size of DG-units was found to be 40% of maximum loads demand. Sequential quadratic programming was used to arrive at the solution. The use of a DG-unit for voltage profile improvement in DN feeders was mentioned in

978-1-6654-7978-3/22/$31.00 ©2022 IEEE

[8]. The analysis uses voltage sensitivity index to find the best location for the DG-unit. The active and reactive powers of the DG-units were then tuned to obtain the best possible voltage support. Using Thevenin's theorem, the weakest bus was identified. The results showed that real and reactive power of the network was significantly improved.

In [9], optimal DG placement and sizing on IEEE 16-node system distribution feeder was used as a test network using the particle swarm algorithm approach to reduce active power loss. 47.35% loss reduction was achieved. The Particle Swarm Optimization Algorithm was employed in this research to locate the best DG-unit size and position for real and reactive power loss reduction. The results indicate that the PSO algorithm is efficient, has a high rate of convergence, requires less mathematical computation, and can handle difficult optimization problems. For modelling, the MATLAB/PSAT simulation package was employed, and the findings were then validated using the MATPOWER software package in MATLAB.

III. PARTICLE SWARM OPTIMAZATION ALGORITHM

In 1995, PSO was proposed by Doctor Kennedy and Eberhart as a global optimization technique. It is based on studies of flock movement behavior in birds and fish [10, 11] and is derived from swarm intelligence. The fundamental PSO algorithm comprised of "i" particles, with each particle's position representing a possible solution in dimensional space. The particles alter their state based on the following three principles:

(i) Maintain inertia
(ii) Change the condition based on its most optimistic position
(iii) Change the condition based on the swarm's most optimistic position.

Each particle's position in the swarm is affected by the most optimist position (individual experience) and the most optimist particle in its surroundings (near experience). The best optimist position of the environment is equivalent to the best optimist particle when the whole particle swarm is surrounding the particle; this algorithm is known as the PSO [10, 12]. Every one of the particles moves to updated position making use of velocity based on its own experience known as Pbest. Gbest is the best value that any particle in the population has obtained so far. The PSO is made up of velocity variations of each particle towards its Gbest over time. The distance of Pbest from current particles location as well as the distance between Gbest from current particle position [12], causes each particle to try to change its current position and velocity. The particles velocity and position are change according to the following equality after discovering the best values:

$$V_{id}^{k+1} = V_{id}^{k} + C_1 r_1^k \left(Pbest_{id}^k - x_{id}^k\right) + C_2 r_2^k (gbest_d^k - x_{id}^k)(1) \quad (1)$$

$$x_{id}^{k+1} = x_{id}^{k} + V_{id}^{k+1} \quad (2)$$

V_{id}^k and x_{id}^k denote particle speed, "i" and "k" are the location dimensions, $Pbest_{id}^k$ is the individual "i" dimension at best position, $gbest_d^k$ is the dimensional best position. C_1 represents the length when flying to the most particle in the entire swarm and C_2 represents the most optimistic individual particle while r_1 and r_2 are random conception. Therefore, this technique is employed to solve optimal DG location in this research.

A. Objective Function

As the primary aim of study is voltage profile improvement and power loss reduction across the distribution feeder. Net line losses on the base case network are represented with objective function written as branch resistance Ri, active and reactive power (Pi, Qi), and voltage.

1. Power losses reduction:

$$Losses_{with\ DG} \leq Losses_{without\ DG}$$

$$P_{Loss} = \sum_{k=1}^{n} R_i \frac{P_i^2 + Q_i^2}{V_i^2} \quad (3)$$

$$F_i = P_{loss} = \sum_{k=1}^{n} I^2 . R_i \quad (4)$$

Where;
P_i represents active power losses.
Q_i represents reactive power losses.
V_i represents voltage on the line.
R_i represents the line resistance.
n is the total number of buses in the network.
F_i represents power loss minimization objective function.

2. Subjected Constraints:

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (5)$$

$$I_i \leq I_i^{max} \quad (6)$$

$$V_{DG}^{min} \leq V_{DG} \leq V_{DG}^{max} \quad (7)$$

$$P_{DG}{}^{min} \leq P_{DG} \leq P_{DG} \quad (8)$$

Where;
P_{DG} denotes DG's real power generation.
V_i denotes magnitudes of voltage at bus *i.*
I_i denotes ith feeder current loading and
V_{DG} denotes DG voltage magnitudes at bus i

B. Constraints for Distributed Generator Optimization

In order to avoid system instability and unnecessary faults, active power supplied via DG to the network should be prevented from flowing back to the substation during a steady state operating condition. The maximum power output of Distributed Generations (DG) units is capped at 75% of PQ_{load} [13].

Power Injection Constraint:

$$\sum_{i=1}^{K} P_{DG} < P_{load} + P_{losses} \quad (9)$$

Total Power Balanced Constraint:

$$\sum_{i=1}^{K} P_{DG} + P_{substation} = P_{losses} + P_{load} \quad (10)$$

Where;

P_{DG} = DG's Power supply

supply power from substation

P_{load} = Power delivered to the network connected loads

P_{losses} = Network power losses

k = Number of connected distributed generators

3. Voltage deviations:

$$VD_i = | 1 - V_i | \quad (11)$$

Sum of voltage deviations

$$SVD_i = \sum_{i=1}^{n} | 1 - V_i | \quad (12)$$

Where V_i is the sum of voltage deviations at node i and n is the nodes no.

All node voltages should be within the accepted range of $\pm 5\%$ $(0.95 \leq V_i \leq 1.05)$ of nominal voltage.

IV. MINNA TOWN NETWORK DESCRIPTION

The Minna electricity network is comprised of a 132/33kV transmission substation in Niger State, Nigeria. The station is mesh-connected to the national grid by two high voltage circuits, Shiroro-Minna 132kV Line I and Shiroro-Minna 132kV Line II. Minna circuits (electrical network systems) emanate from Minna 132kV transmission sub-station connected to 330/132kV Shiroro transmission station at North-South Hydropower Generation Station Shiroro in Niger State. The Shiroro-Minna TS consists of 150MVA, 132/33kV transformers with total installed capacity of 150MVA. Table I provides detailed description of the 132/33kV substations in Minna town, as well as their installed capacity. Table II also shows the number of 33kV "feeder" lines as well as associated injection substations.

C. Modellling and Simulation of Test Network

The test networks under consideration necessitate a step-by-step strategy to achieving optimal distributed power with solar photovoltaic generators (SPVG). The MATLAB/PSAT software program was used to model the system using the network base-case data collected. The network's unknown parameters are computed using the Newton Raphson power flow method to determine node operating voltages and line current losses. In fact, the test networks rely solely on the available electricity from the grid supply. The use of Artificial Intelligence (AI) for optimal distributed generation location, on the other hand, would increase system voltage stability and network performance with proper power distribution.

TABLE I. SHIRORO-MINNA 132/33 KV TRANSMISSION SUBSTATION (TS)

Substation	***Rating***	***Total Capacity***	***Voltage***
Shiroro-Minna I	2×60MVA	120MVA	132/33kV
Shiroro-Minna II	30MVA	30MVA	132/33kV

TABLE II. THE 33/11KV INJECTION SUBSTATIONS (MINNA METROPOLIS)

Transformer Capacity	***Injection s/s Name***	***Capacity***	***No of Feeder***
15MVA	Power House	2×15MVA	4
15MVA	Zarumai	1×15MVA	4
7.5MVA	Maikunkele	2×7.5MVA	3

V. RESULTS

A. Simulation of Distributed Generator on 17-node System Minna Town Distribution Feeders

On the Minna Town distribution feeders, simulations with the Distributed Generator in place were implemented, and results were obtained. However, according to the PSO optimization results, node 9 was the best optimal location for DG deployment because it was the node having least power loss on the simulated network. The findings from Minna Town feeders with and without DG are shown in Table III, figure 2 and figure 3.

TABLE III. SUMMARY OF VOLTAGE DEVIATION ON TEST STSTEM BEFORE AND AFTER DG

S/N	**Node No.**	**VD (pu) without DG**	**VD (pu) with DG**
1	1	1.000	1.000
2	2	0.989	0.989
3	3	0.979	0.979
4	4	0.997	0.997
5	5	0.994	0.994
6	6	0.997	0.997
7	7	0.969	0.993
8	8	0.955	0.979
9	9	0.953	1.000
10	10	0.981	0.981
11	11	0.970	0.970
12	12	0.974	0.974
13	13	0.980	0.980
14	14	0.970	0.970
15	15	0.977	0.977
16	16	0.973	0.973
17	17	0.980	0.980

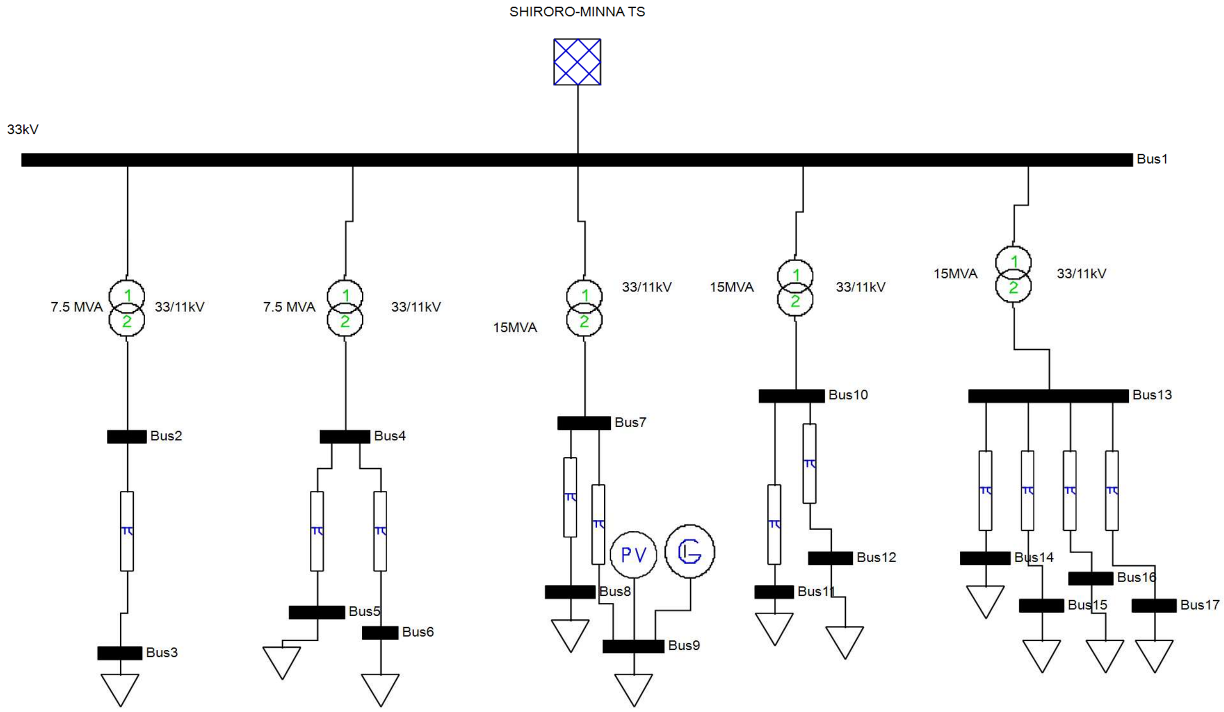

Fig. 1 PSAT model of test networ*k* with DG

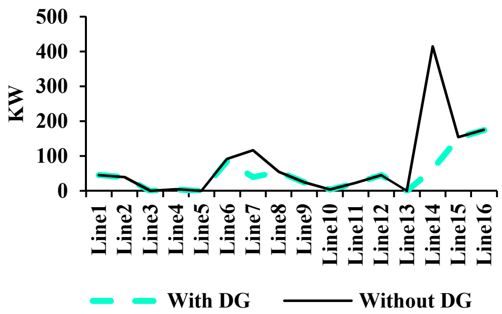

Fig. 2 Real line losses with and without DG on test system

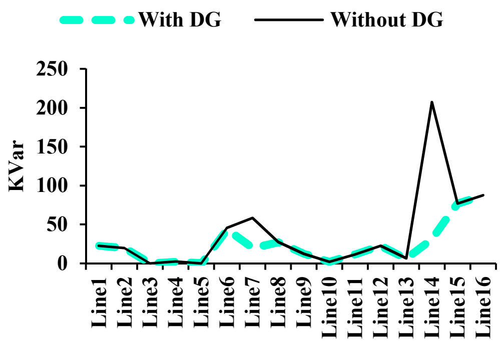

Fig. 3 Reactive line losses with and without DG on test network

VI. DISCUSSION OF RESULTS

The results of simulation indicate that the total generation and load of 11kV Minna Town distribution feeders of Abuja Electricity Distribution Company, Minna considered for case study are approximately 30920 kW and 29720 kW respectively. The total active and reactive power losses before DG are approximately 1197.4kW and 603.7kVar respectively while with DG is approximately 763kW (about 63.7% improvement). and 387.1kVar (about 64.1% improvement). Figures 2 and 3 show the real and reactive power losses before and after optimal placement of DG unit in an existing distribution network respectively. The following lines before DG unit (line 7 between node1 and node2, line 14 between node13 and node14, line 15 between node13 and node15 and line16 between node13 and node 17 suffers much line losses as result of power flow beyond capability. Having placed the DG, it injects additional inductive reactance to prevent power and loop flow since power flows towards less load. Thus, there is improvement of 437 kW active power on the network due to DG placement at node9. The weakest node (node9) suffers 5% voltage loss during load flow analysis on the test network with no DG. After DG placement, all the nodes show an improvement of at least 2% in voltage profile. As a result, the overall voltage drop following DG installation shows a significant impact and improvement across the entire network.

VII. CONCLUSION

There was reduction in the active and reactive power losses to 63.7% and 64.1% respectively after optimal placement of DG on the network under consideration. The PSO algorithm was employed effectively to determine the optimum DG placement on the test network to enhance voltage profile and reduce line losses.

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