

(RESEARCH ARTICLE)



OPTIMUM SIZING AND SITING FOR SOLAR PV INTEGRATION INTO THE 33KV PORT HARCOURT DISTRIBUTION NETWORK

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ABSTRACT

The increasing demand for reliable and sustainable electricity in Nigeria has created a need for alternative generation technologies that can be integrated directly into existing distribution networks. Solar photovoltaic (PV) generation is particularly attractive for the Port Harcourt electricity distribution system because of the availability of solar resources, the modular nature of PV systems, and the potential to reduce dependence on conventional generation. However, inappropriate sizing and placement of PV units can result in reverse power flow, overvoltage, increased losses, protection challenges, and poor voltage regulation. This paper investigates the optimum sizing and siting of solar PV integration into the Port Harcourt Distribution Network. The 132/33 kV, 40-bus single-line diagram of the Port Harcourt electricity distribution network is considered, with the optimization objective of minimizing active and reactive power losses while improving the network voltage profile. Particle Swarm Optimization (PSO) is adopted to determine appropriate PV locations and capacities subject to network operating constraints. The case-study results indicate that strategic placement of six 500kW PV units can substantially improve network performance, reducing active power losses from approximately 42,606.8 kW to 10,140.42 kW and reactive power losses from 120,286.1kVAr to 23,515.93 kVAr. The optimal installation of the six PV units also results in an improvement of the average bus voltage from 0.90 p.u. to 0.95 p.u., while also raising the minimum system voltage from 0.836 p.u. to 0.88 p.u. The study demonstrates that optimal PV allocation can improve voltage performance, reduce feeder loading, and enhance the technical efficiency of the PHED system.

Keywords: Distributed Generation, Solar Photovoltaic, Optimal Sizing, Optimal Placement, PHED 33 kV Network, Particle Swarm Optimization, Power Loss, Voltage Profile.

1 INTRODUCTION

Renewable generation is the most viable strategy for improving the sustainability of conventional distribution grids, given that its installation, production, and maintenance costs are now competitive with diesel-based generation. [1] The integration of distributed generation (DG) into distribution networks provides an opportunity to address some of these

challenges. Rather than relying exclusively on large centralized generating stations, DG allows electrical power to be generated close to the load centres. Solar photovoltaic generation is particularly suitable because PV systems are modular, have relatively low operating requirements and can be deployed at different points within a distribution network.[2] However, the benefits of solar PV integration depend strongly on where the PV systems are connected and how large they are. A small PV plant installed at a weak bus may provide substantial voltage support and reduce feeder losses, whereas a large PV plant at an inappropriate location may cause excessive voltage rise and reverse power flow. Consequently, optimal sizing and placement constitute important planning problems.[3] Previous studies have established that optimally located DG can reduce active and reactive power losses, improve voltage profiles, increase loadability, and improve overall network performance. Metaheuristic optimization techniques are increasingly used because the DG placement problem is nonlinear, non-convex and contains both discrete variables, such as bus location, and continuous variables, such as generator capacity. [4] The study investigates how the location of distributed generation impacts the voltage profile and power losses in a radial distribution network. Similarly, Ding examines various factors influencing voltage fluctuation levels following the integration of solar PV systems into the grid.[5]. They propose accounting for uncertainties within the distribution network and utilizing probabilistic load flow analysis to assess voltage levels across the system buses.

In a review paper by [6], having identified a gap in the literature on the use of heuristic methods for addressing reactive power support challenges in the Nigerian power grid, this study proposes an optimal sizing and siting approach for solar PV systems aimed at improving the voltage profile and minimizing active power losses in a radial distribution network. Particle Swarm Optimization (PSO) to determine suitable allocations and capacities, and with the Port Harcourt 132/33kV electricity distribution network employed as a case study.

2 LITERATURE REVIEW

In recent decades, Distributed Generation (DG) integration into power grids has increased considerably, owing to its potential for power loss reduction, voltage profile improvement, and enhanced reliability.. In [7], for loss minimization in a balanced radial distribution network, an analytical method for DG sizing and siting was implemented and tested on the IEEE 15-bus system, yielding about 42% loss reduction. It was observed that a more robust technique could achieve further loss reduction and better system performance. Consequently, a constructive reconfiguration algorithm was proposed for simultaneous reconfiguration and DG allocation to ensure steady voltage distribution and maximal loss reduction. [8]. Authors in [9] considered different load models to minimize cost, power loss, and voltage deviation using a proposed Shuffled Bat Algorithm (SBA). However, the convergence criteria were less favorable compared to the Shuffled Frog Leaping Algorithm (SFLA). [10] A Lightning Search Algorithm (LSA) was used for the simultaneous allocation of DG and DSTATCOM to solve a multi-objective problem under varying feeder loads, but without addressing optimal sizing. Cuckoo Search Algorithm was therefore employed to determine the optimal sizes of the compensators in [11] The study investigated the individual and simultaneous placement of shunt capacitor banks and DG in a distribution network to evaluate network performance, with objectives of power loss minimization and voltage stability maximization. Furthermore, the advantages of the backward/forward sweep method over Gauss-Seidel and Newton-Raphson methods were emphasized. Authors in [12] proposed a Phasor Particle Swarm Optimization technique for a practical radial distribution feeder, focusing on power loss reduction as the objective function instead of annual energy loss optimization. Nonetheless, critical aspects such as system stability, reliability, and power quality were not considered. In [13], the authors addressed a multi-objective problem considering the economic, environmental, and technical benefits of optimal DG and capacitor bank sizing in distribution systems by emulating the water cycle from streams and rivers to the sea (Water Cycle Algorithm). The approach yielded more flexible results when using DGs with controllable power factor compared to those with fixed power factor. However, the objective was achieved primarily from an economic perspective by reducing production cost. In a hybrid approach, the elitism phase of the Ant Lion Optimizer (ALO) was improved using Particle Swarm Optimization (PSO), while the Fuzzy Logic Controller (FLC) was employed to train parameters and datasets for optimal DG placement. In [14], a Mixed-Integer Second-Order Cone Programming (MI-SOCP) methodology was developed by combining branch and bound and classical methods for siting with second-order cone relaxation of optimal power flow for sizing. However, the approach was inadequate for optimal sizing and siting of battery storage in AC distribution networks. In [15], the Firefly Algorithm (FA), a swarm-based optimization technique, was employed for optimal DG placement and sizing for loss reduction and voltage profile enhancement in radial distribution networks.

3 MATERIALS AND METHODOLOGY

3.1 Research Design

I. Development of the Port Harcourt Electricity Distribution Network model. II. Base-case load-flow analysis. III. Identification of candidate PV buses. IV. Formulation of the PV sizing and placement optimization problem. V.

Application of Particle Swarm Optimization (PSO). VI. Load-flow evaluation of each candidate solution. VII. Selection of the optimum solution; and VIII. Comparison of network performance before and after PV integration.

3.2 Development of the PHED Network Model

The single-line diagram of the 132/33kV 40 bus sub transmission-network of Port Harcourt Electricity Distribution Work Station and its loading capacity is shown in figure 1 & 2 [16]

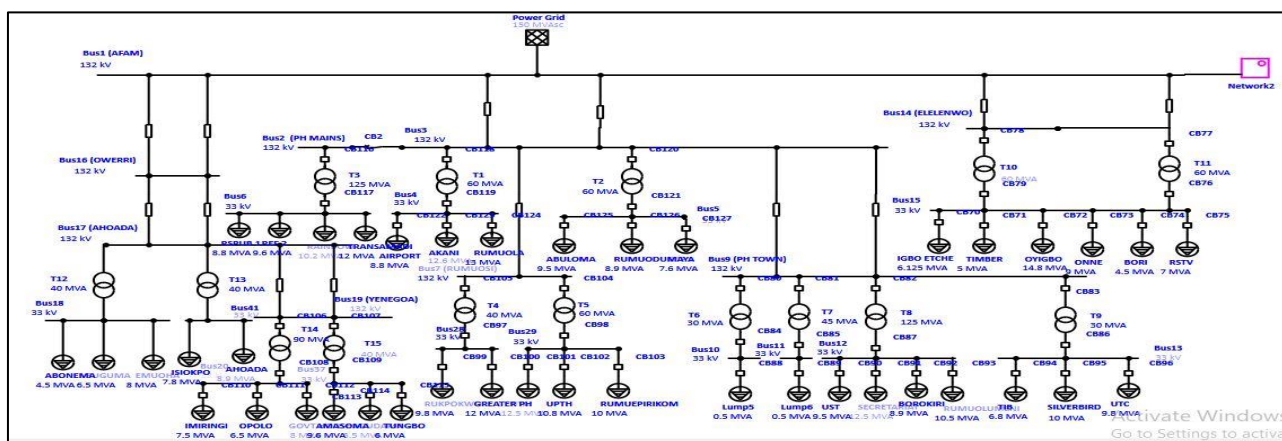


Figure 1: Single Line Diagram of Port Harcourt 40-Bus 132/33 kV Distribution System of Port Harcourt Electricity Primary Distribution Network. (Network 1)

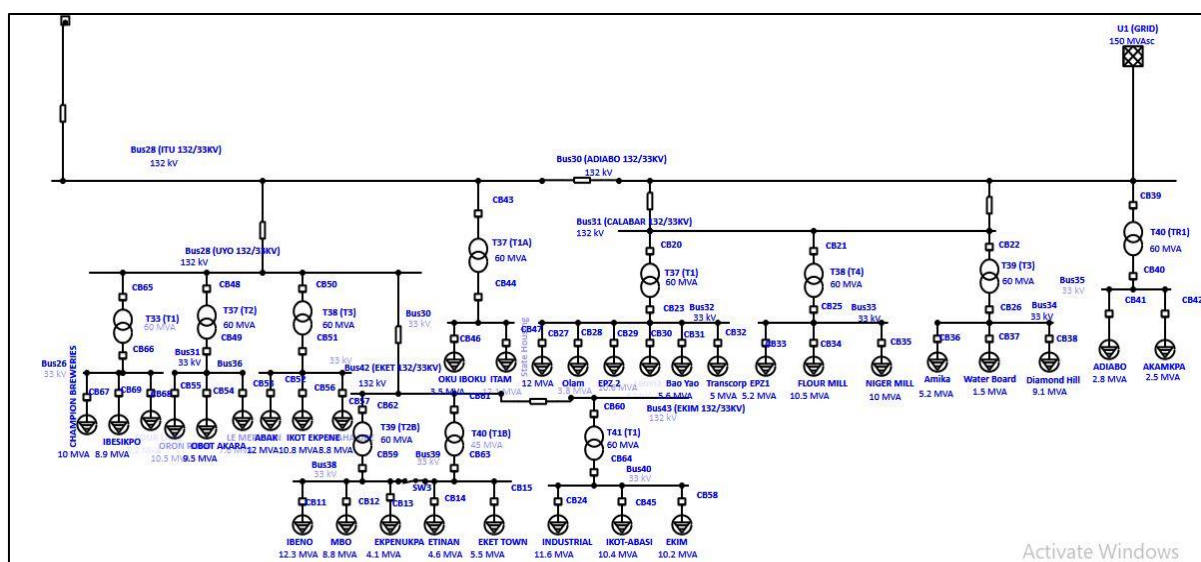


Figure 2: Single Line Diagram of Port Harcourt 40-Bus 132/33 kV Distribution System of Port Harcourt Electricity Primary Distribution Network (Network 2) [16]

3.3 Base Case Load Flow and Identification of Candidate Buses

Fig 3 & 4 shows the base case load flow simulation result of Port Harcourt Electricity 132/33kV 40 Bus Primary Distribution Network. Bus 5, bus 8, bus 10, bus 31, bus 36 and bus 40 of the Port Harcourt 132/33kV sub-transmission network were identified weak and were operating under a critical under voltage conditions.

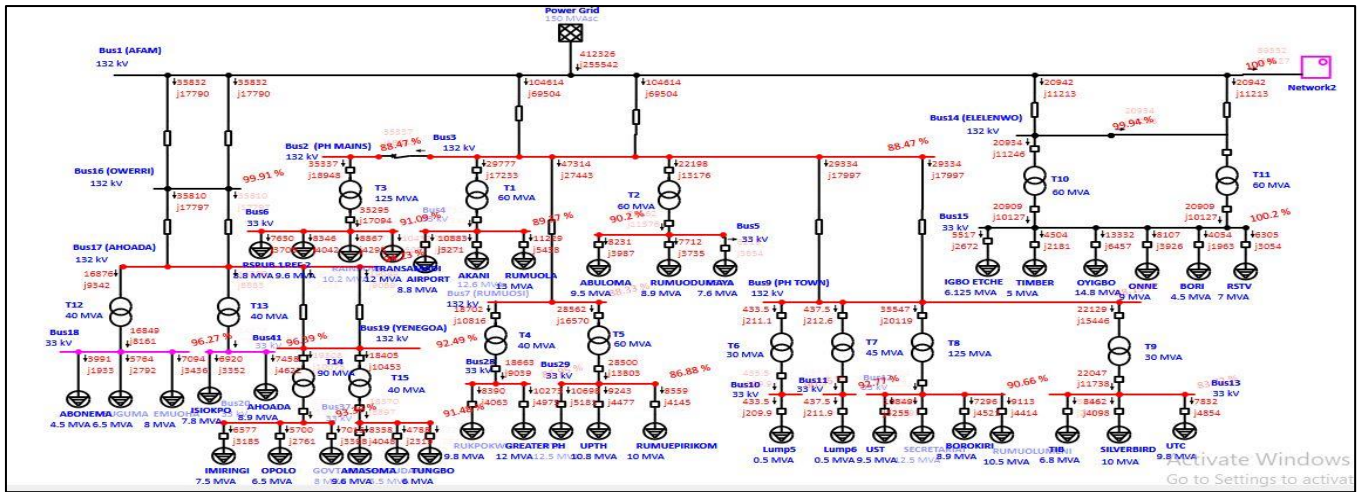


Figure 3: Load Flow Simulation Result of Port Harcourt Electricity 132/33kV 40 Bus Primary Distribution Network. (Network 1)

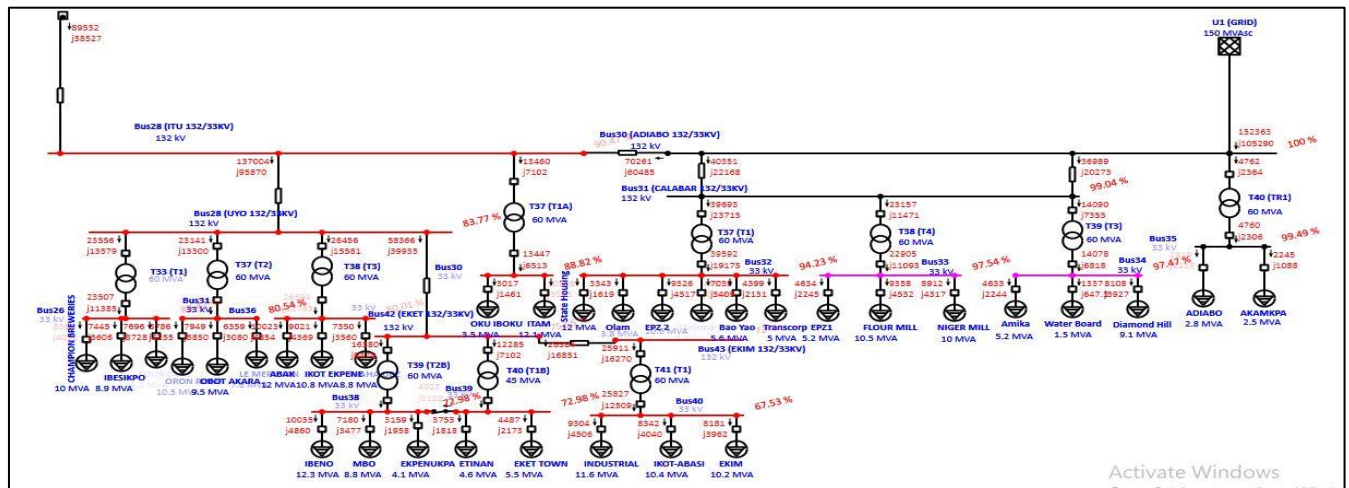


Figure 4: Load Flow Simulation Result of Port Harcourt Electricity 132/33kV 40 Bus Primary Distribution Network. (Network 2)

3.4 Primary Objective Function: Active Power Loss Minimization

The primary objective of the optimization is to minimize active power losses. The various electrical parameters are computed using backward-forward power flow analysis. As illustrated in Figure 5 below, each receiving bus in a radial distribution network is supplied by a single sending bus.

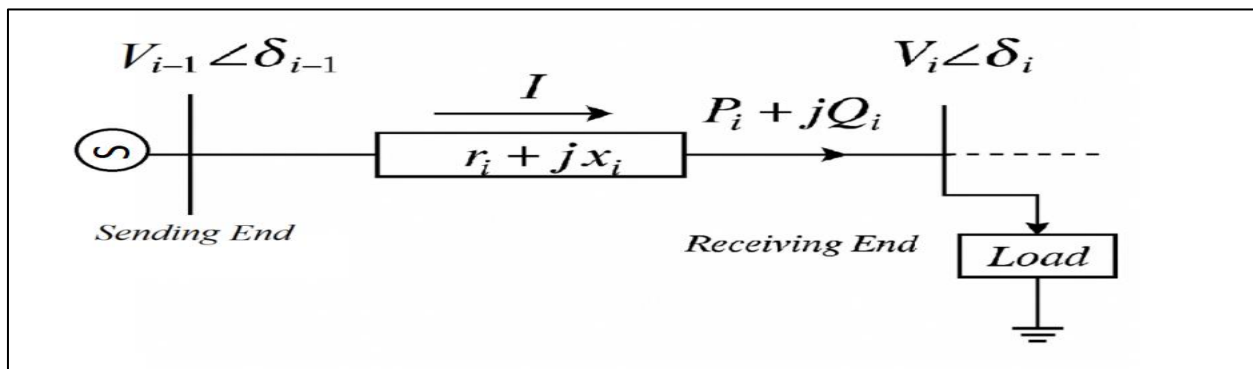


Figure 5: Single Line Representation of a Two-Bus Power System

The power loss, $P_{loss}(i)$, between the sending and receiving ends in Figure 5 is given by Equation (1):

$$P_{Loss}(i) = r_i \frac{P_i^2 + Q_i^2}{V_i^2} \quad (1)$$

Considering the system operating conditions, the active and reactive power losses in the distribution network can be computed using Equation (2). The precise power loss formula can be straightforwardly derived from basic power flow relationships.

$$P_L = \sum_{i=1}^n \sum_{j=1}^n [A_{ij} (P_i P_j + Q_i Q_j) + B_{ij} (Q_i P_j - P_i Q_j)] \quad (2)$$

The primary objective of the DG placement strategy is to minimize the total active power losses. Mathematically, this objective function is expressed as:

$$f_1 = \text{Minimize } P_L = \sum_{i=1}^{N_{bus}} [P_{Loss}(i)] \quad (3)$$

Subject to the power balance constraints:

$$\sum_{i=1}^N (PDGi) = \sum_{i=1}^N (PDi + P_L) \quad (4)$$

The active and reactive power output of each DG unit must not exceed the total active and reactive load demand of the system. This constraint is expressed mathematically as follows:

$$P_{DG} \leq \sum P_{load} \quad (5)$$

$$Q_{DG} \leq \sum Q_{load} \quad (6)$$

Voltage constraints:

$$|V_i|^{min} \leq |V_i| \leq |V_i|^{max} \quad (7)$$

Current limits:

$$|I_{ij}|^{min} \leq |I_{ij}|^{max} \quad (8)$$

3.5 Second Optimization Objective: Voltage Profile Enhancement

Voltage stability refers to the capability of a power system to maintain acceptable voltage levels at all buses under normal and post-disturbance conditions, ensuring that load power increases as load admittance increases, with both power and voltage being controllable. From Figure 5,;

$$V_{i-1} < \delta_{i-1} - V_i < \delta_i = I(r_i + jx_i) \quad (9)$$

$$(V_i < \delta_i) * I = (P_i - jQ_i) \quad (10)$$

Where 'I' denotes the current magnitude and '*' represents the complex conjugate operator. From Equations (9) and (10), we have:

$$V_i^2 - V_i \cdot V_i - 1 + [(P_i^2 + Q_i^2) \cdot (r_i^2 + x_i^2)]^{\frac{1}{2}} = 0 \quad (11)$$

Equation (11) roots are real if:

$$V(i-1)^2 - 4 \cdot [(P_i^2 + Q_i^2) \cdot (r_i^2 + x_i^2)]^{\frac{1}{2}} \geq 0 \quad (12)$$

Therefore, the voltage stability index for the bus i (Sli) is formulated as:

$$Sli = V(i-1)^4 - 4(P_i x_i - Q_i r_i)^2 - 4(P_i r_i + Q_i x_i)^2 \cdot V(i-1)^2 \geq 0 \quad (13)$$

For stable system operation, the value of SI must be greater than zero for all buses, i.e., Sli > 0 for $i = 2, 3, \dots, N_{bus}$. The stability of a bus improves as its SI value approaches unity. The bus with the lowest SI value is the most susceptible

to voltage collapse. In the proposed algorithm, an SI value is computed for each bus in the network. Accordingly, the second objective function is formulated as follows:

$$F_2 = \frac{1}{1 + SI_{min}} \quad (14)$$

Where;

SI_{min} = The minimum SI value among all buses

Equations (1)–(8) show that the decision variables consist of the DG capacities and locations at candidate buses, denoted as $[P_{DG1}, P_{DG2}, \dots, P_{DGNbus}]$, while the state variables comprising bus voltage, active and reactive power are determined through power flow computation. $P_{DGi} = 0, (i = 2, 3, \dots, N_{bus})$ signifies that bus i is not allocated a DG unit. The decision variable corresponds to the optimal DG capacity for a fixed location, and to the optimal location for a fixed capacity. To determine the power flow:

$$P_{n+1} = P_n - P_{loss, n} - PL_{n+1} \quad (15)$$

$$Q_{n+1} = Q_n - Q_{loss, n} - QL_{n+1} \quad (16)$$

P_n = Real power flow out of bus

Q_n = Reactive power out of bus

PL_{n+1} = Power loss at $n + 1$ bus

QL_{n+1} = Reactive power loss at $n + 1$

3.6 The Adaptive Multi-Objective Particle Swarm Optimization (PSO) Algorithm

The MPSO algorithm initializes with a swarm of random particles that iteratively search for the optimal solution. Each particle adjusts its position based on its own experience and that of its neighboring particles. The best positions are denoted as P_{best} and G_{best} respectively, respectively. The particle's movement can be described by Equations (17) and (18) below can be used to explain how the particle's location changes.

$$V_i^{k+1} = wv_i^k + c_1 r_1 (P_{besti} - S_i^k) + c_2 r_2 (G_{best} - S_i^k) \quad (17)$$

$$S_i^{k+1} = S_i^k + V_i^{k+1} \quad (18)$$

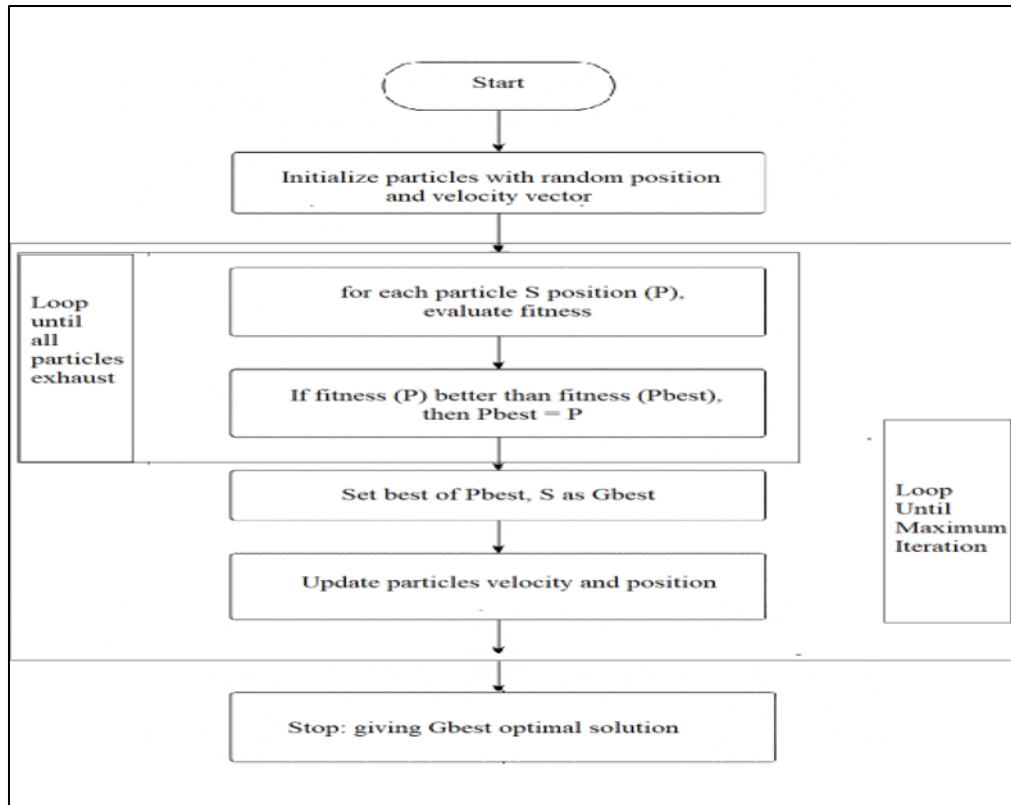


Figure 6: Particle Swarm Optimization (PSO) Implementation Algorithm Flowchart

4 RESULTS AND DISCUSSIONS

4.1 Simulation Results and Analysis of the Base Case

Load flow analysis of Port Harcourt Electricity 132/33kV 40 Bus Primary Distribution Network was carried out in Electrical Transient Analyzer Program (ETAP) using the Newton Raphson Method. The results of the analysis are shown in figure 3 and figure 4. The results shows that bus 5 (PH Main 132/33kV), bus 8 (PH Town 132/33kV), bus 10 (Rumuosi 132/33kV), bus 31 (Adiabo 132/33kV), bus 36 (Uyo 132/33kV) and bus 40 (Ekim 132/33kV) were operating under a critical under voltage conditions. The base-case simulation results also indicate substantial active and reactive power losses as shown in table 1

Table 1: Base-Case Total Active and Reactive Power Losses

S/N	Performance Parameters	Base - Case
1	Number of Bus	40
2	PV Units	0
3	Active Power Losses	42,606.80 kW
4	Reactive Power Losses	120,286.10 kVAr
5	Solar PV Penetration	0%

4.2 Simulation Results and Analysis Following the Integration of Solar PV Units

The voltage profiles and power losses before and after optimal placement and sizing of one to six solar PV units in the Port Harcourt 132/33 kV, 40-bus distribution network were compared.

Table 2: Total Active and Reactive Power Losses After the Optimum Placement of Solar PV

S/N	Performance Parameters	Before Solar PV	With Optimized Solar PV
1	Number of PV Units	0	6
2	Active Power Losses	42,606.80 kW	10,140.42 kW
3	Reactive Power Losses	120,286.10 kVAr	23,515.93 kVAr

Thus, the optimized PV configuration produces approximately 76.2% reduction in active power losses and 80.45% reduction in reactive power losses.

4.3 Comparative Analysis of Voltage Profiles and Power Losses Before and After Placement of Solar PV Units Across Six Scenarios

By comparing with the network without PV units, the optimal installation of six PV units at bus 5, bus 8, bus 10, bus 31, bus 36 and bus 40 results in an improved average bus voltage of 0.955 p.u. compared to 0.90 p.u., and increases the minimum system voltage from 0.836 p.u. to 0.885 p.u. Likewise, the optimal placement of the six PV units reduced the total active and reactive power losses. by (42606.8kW, 120286.1kvar) to (10140.42kW, 23515.93kvar) respectively, amounting to 76.2% and 80.45% reduction in the overall real and reactive power losses respectively.

Bus Voltage Profiles Before and After Optimal Placement of Six PV Units Across Six Cases

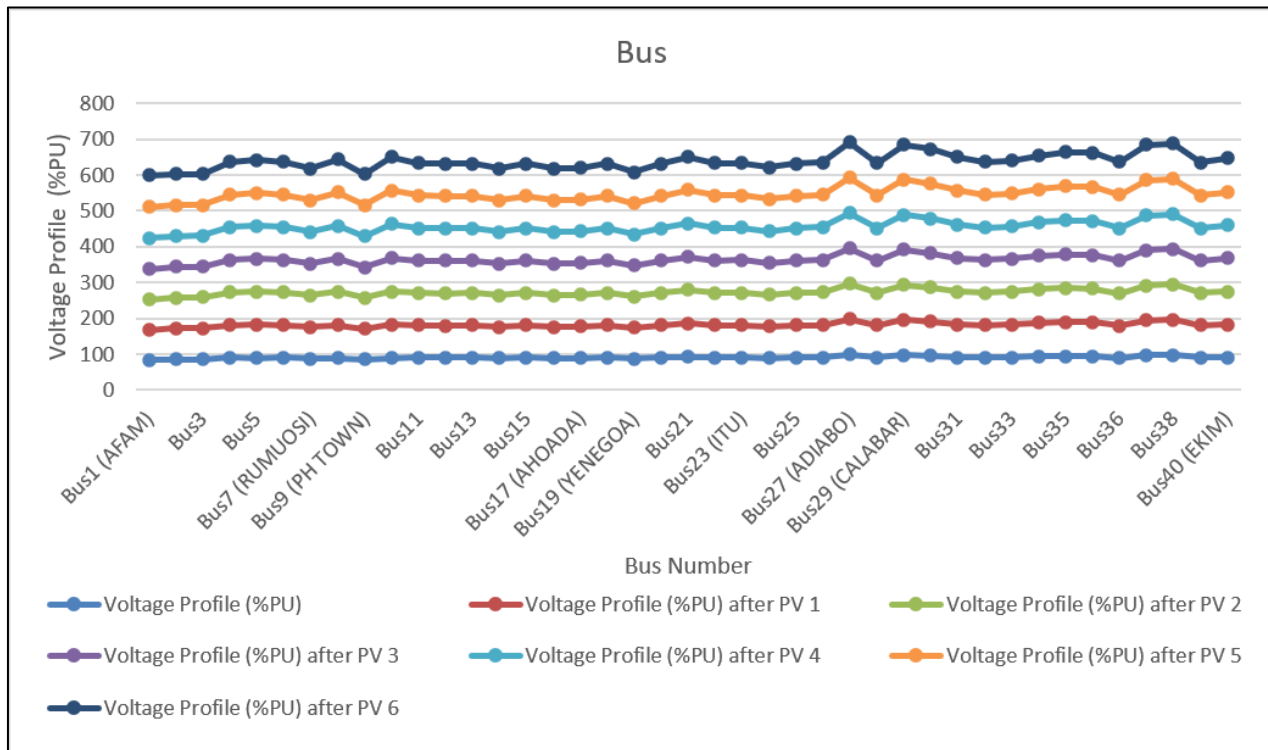


Figure 7: Bus Voltage Profiles Before and After Optimal Placement of Six PV Units Across Six Cases in the Port Harcourt 132/33kV, 40-bus distribution system.

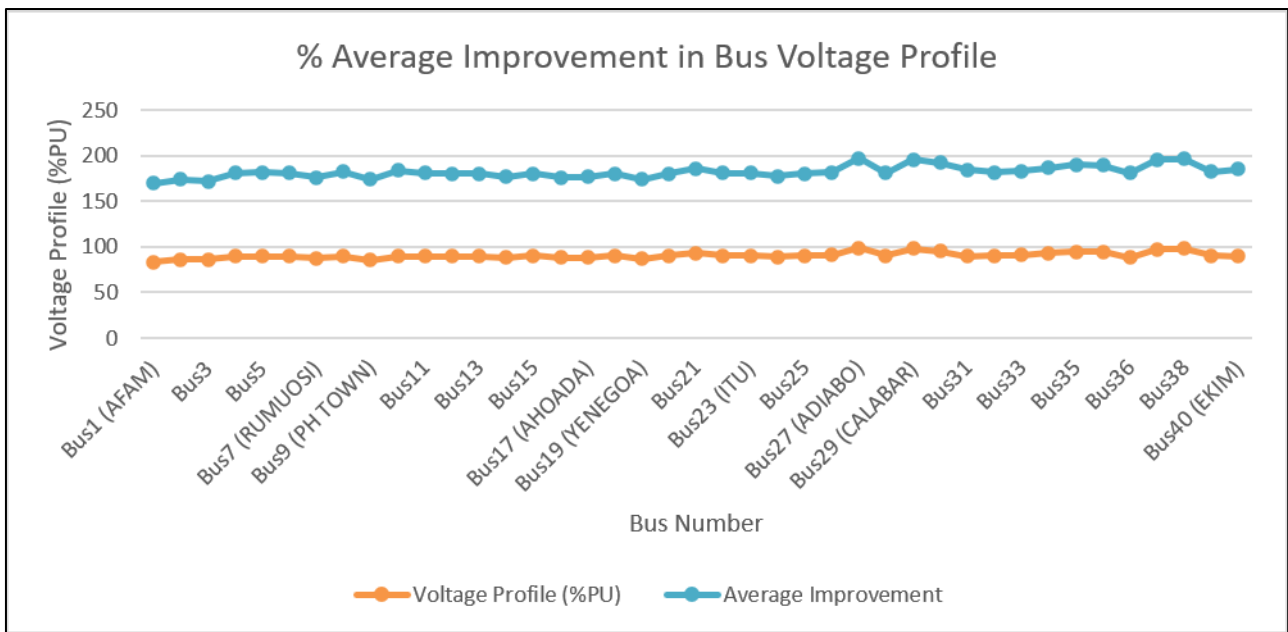


Figure 8: Plot of % average improvement in bus voltage profiles across all six PV placement cases

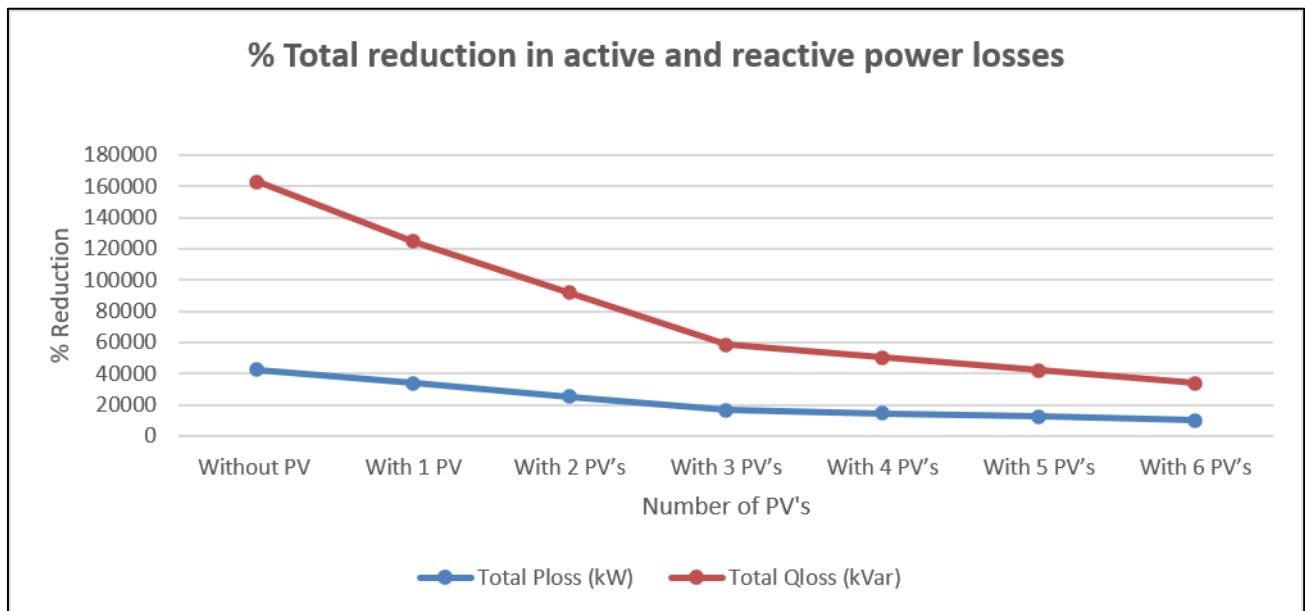


Figure 9: Plot of percentage reduction in total active and reactive power losses for all six optimal PV placement cases

5 CONCLUSION

This study investigated the optimum sizing and placement of solar PV distributed generation on the Port Harcourt 132/33 kV distribution network using a multi-objective optimization framework based on Particle Swarm Optimization. The study demonstrates that the location and size of PV systems have a significant effect on distribution-network performance. Rather than distributing PV capacity arbitrarily, optimization allows generation to be concentrated at electrically beneficial locations.

For the investigated 40-bus Port Harcourt network, the optimized configuration consists of six strategically placed PV units at bus 5, bus 8, bus 10, bus 31, bus 36 and bus 40 of the Port Harcourt 132/33kV sub-transmission network having been observed to be operating under a critical under voltage condition. After obtaining the simulation results for the six different PV placement cases, a comprehensive comparison of bus voltage profiles and power losses before and after PV

integration was conducted. The resulting system performance shows a reduction in active power losses from 42,606.80 kW to 10,140.42 kW, representing approximately 76.20% reduction. Reactive power losses decrease from 120,286.10 kVAr to 23,515.93 kVAr, representing approximately 80.45% reduction. These results demonstrate the significant technical potential of properly planned solar PV integration into the Port Harcourt distribution system. The principal benefits are reduced network losses, improved voltage performance, reduced upstream power requirements and increased renewable-energy utilization. This study provides a comprehensive framework for assessing and improving solar PV integration, offering valuable insights for stakeholders. By addressing technical, regulatory, and infrastructural challenges, PHED can effectively harness the potential of solar PV systems, paving the way for a resilient and sustainable energy future.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript.

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