

Network Reconfiguration for Power Loss Reduction on Distribution Feeder Using Particle Swarm Optimisation: Case study of 11kv Feeder in Ilorin, Nigeria

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ORIGINAL RESEARCH

Abstract- The distribution system is the largest segment of the electrical power system and the final stage in delivering electricity to consumers. It experiences power losses which could be technical or non-technical due to its radial configuration and connected components. Technical losses occur as energy dissipation in the form of heat in the system components, which is unavoidable. It affects the efficiency of the system and increases operational costs. Therefore, the reduction is essential for adequate power supply and improvement in utility revenue generation. This study focuses on reducing power losses on 11 kV Taiwo distribution feeder in Ilorin using the Network reconfiguration approach. The feeder was modelled, and its power losses were evaluated based on the Backward Forward Sweep method suitable for the radial network. The reconfigured network was optimised using the Particle Swarm Optimisation technique. The study shows that the values of feeder real power losses before and after reconfiguration are 176.883 kW and 121.972 kW, respectively. Further improvement was, however, achieved when PSO was used for the reconfiguration, as the power loss value stands at 98.465 kW. This is 44.33 % reduction compared to the initial power loss value and 19.273 % after reconfiguration. Furthermore, the values of the reactive power losses before and after reconfiguration are 9.474 kVar and 6.527 kVar, respectively, amounting to a 31.11 % reduction. However, PSO reduces the value to 3.101 kVar, which is 67.27 % of the initial value. Thus, radial distribution network reconfiguration using PSO has proven to be a robust method for reducing power loss in the distribution network.

Keywords- Power losses, Distribution feeder, Backward Forward Sweep, Network reconfiguration, Particle Swarm Optimisation.

1 INTRODUCTION

The availability of electric power systems is a substantial tool that drives technology growth and facilitates the economic development of any nation (Gonen, 2013; Nepal & Paija, 2019; Ruiz-Real, Uribe-Toril, De Pablo Valenciano, & Gázquez-Abad, 2018). Most developing countries face the challenges of poor quality and unreliable electricity supply, characterised by losses on the power system, financial constraints, and government policy (Fakih, Ghazalian, & Ghazzawi, 2020; Mena & García, 2012).

The distribution system is the largest portion of the electrical power system and the final stage in delivering electricity to consumers (Juma, Ngoo, & Muriithi, 2022). It consists of conductors, transformers, switchgear and customer substations (Mehta & Mehta, 2005) and is usually configured radially through the feeder to effectively coordinate the protective relays and switches (Nweke, Gusau, & Isah, 2020). However, the distribution network often experiences power interruption because of insufficient power generation and transmission and distribution system failures, which may be due to the ageing of equipment, mechanical damage and power losses in the networks (Fakih *et al.*, 2020).

Power loss in the distribution system is one of the challenges encountered in operating the electrical power system. It accounts for up to 70 % of the total losses in electric power system and consequently affects the efficiency and increase the system's operational costs (Akpojedje & Ogunjor, 2021; Hope, Simeon, Amuta, & Alashiri). About eight billion naira has been reported as the cost incurred due to power losses (Amadi, Okafor, & Izuegbunam, 2016). Power losses in countries such as China, the United Kingdom and the United States of America are rated 13 %, 7.4 % and 7.2 % of total losses, respectively. In addition, 22 %, 28 %, 18 % and 18 % of the total losses have been reported in India, Pakistan, Thailand and the Philippines, respectively (Bhatti *et al.*, 2015; Eseosa & Promise, 2015; Fakih *et al.*, 2020).

Power losses can be either technical or non-technical losses. Non-technical losses are due to external effects such as electricity theft, and effort has been made to eliminate them (Abdullateef, Salami, & Akorede, 2018; Abdullateef, Sulaiman, Issa, & Zakariyya, 2022; Agüero, 2012). However, technical losses occur in the form of heat dissipation in the components; hence, it is inevitable and can only be limited but not eliminated because of the internal configuration of electrical equipment on the power system. This loss is based on the amount of current flowing through the system and is at its highest during peak load. Low power factor, phase imbalance, and inappropriate joints are additional causes of technical loss (Amadi *et al.*, 2016).

The technical and financial implications of power loss on the power system have led to various studies and methods of reducing power losses. Such methods include distribution network reconfiguration (DNR), incorporation of distributed generation (DG), and

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capacitor placement (Diab & Rezk, 2019; Huy, Van Tran, Vo, & Nguyen, 2022; Prakash & Lakshminarayana, 2017; Wong et al., 2019). However, implementing these methods depends on the cost, and DNR has been adjudged to be the most economical (Mahdavi, Alhelou, Hatziaargyriou, & Al-Hinai, 2021). Several optimisation algorithms have been proposed to reduce power loss based on the proposed methods (Abdelaziz, Mohamed, Mekhamer, & Badr, 2010; Jeon & Kim, 2000; Nguyen & Truong, 2015; Raju & Bijwe, 2008). A mixed integer linear programming (MILP) model for distribution system reconfiguration considering load variations was proposed (Jabr, Singh, & Pal, 2012; Llorens-Iborra, Riquelme-Santos, & Romero-Ramos, 2012). However, the linear approximations model reduces the accuracy of the solution and limits the application to small-scale distribution systems. Moreover, global optimal solutions are not guaranteed; several parameters must be fine-tuned for proper performance and usually imply high computational cost.

Furthermore, heuristic algorithms have been widely proposed to find fast optimal solutions to overcome the shortcomings of linear programming. Ji, Shi, and O'Connell (2018) proposed an essential spanning tree based on an improved genetic algorithm for distribution system performance analysis. Raut and Mishra (2017) proposed a fast heuristic algorithm to minimise loss and improve the voltage profile for a smart power distribution system. For faster convergence, heuristic methods can be hybridised with meta-heuristic approaches and employed effectively for online applications. Heuristic algorithm solutions, however, might not be the best options and be challenging to apply to new circumstances (Tsai & Chen, 2014).

Furthermore, metaheuristic approaches have also been employed for power loss network reconfiguration. Computational intelligence models for solving optimisation problems to improve power quality and reliability in distribution systems have been proposed (Branch & Heris, 2016; Vaskantiras & You, 2016). Harmony Search Algorithm has been proposed for network reconfiguration and identification of optimal locations of distributed generation units in a distribution network (Rao, Ravindra, Satish, & Narasimham, 2012). Some authors have proposed using GA for reconfiguring the feeder distribution network (Ajenikoko, Eboda, & Adeyemi, 2017). In addition, PSO has been proposed in network reconfiguration for real power loss reduction using IEEE-33 and 69-node distribution systems (Akpojedje & Ogunjor, 2021; Kumar, Saw, & Bohre, 2020; Merzoug, Abdelkrim, & Larbi, 2020; Shetty & Ankaliki, 2019). The performance of PSO is effective and has a high convergence rate, making it suitable for real-time implementation. The algorithmic robustness and simplicity in coding made it easier to apply to the distribution network losses problems (Alberah, Olarinoye, & Jibril, 2019). This study proposed PSO for power distribution losses reduction on 11kV Taiwo feeder in Ilorin.

2 METHODOLOGY

2.1 DISTRIBUTION LINE MODEL

A single line diagram of a balanced distribution network assumed to have 'y' buses with bus 1 as slack bus and load buses of 'y - 1'. Considering a portion from bus 'u' to bus 'u + 1', as shown in Figure 1.

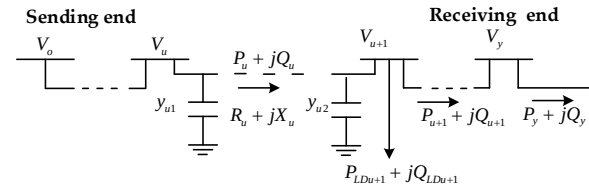


Fig. 1: A typical single line diagram of a distribution system (Rao et al., 2012)

The real and reactive power flow of the network from bus u to $u+1$ is expressed as:

$$P_{u+1} = P_u - P_{loss,u} - P_{LDu+1} \quad (1)$$

$$Q_{u+1} = Q_u - Q_{loss,u} - Q_{LDu+1} \quad (2)$$

where,

P_u is real power flowing out of bus u ;

Q_u is reactive power flowing out of bus u ;

P_{LDu+1} is real load power at bus $u + 1$;

Q_{LDu+1} is reactive load power at bus $u + 1$;

$P_{loss,k}$ is real power loss at bus u ;

$Q_{loss,u}$ is reactive power loss at bus $u + 1$;

V_u is voltage magnitude at bus u ;

V_{u+1} is voltage magnitude at bus $u + 1$ and

R_u, X_u are the resistance and reactance on the line connecting bus u to $u + 1$, respectively

The current in the line section connecting buses u and $u + 1$ is expressed as

$$I_u = \frac{P_u + jQ_u}{V_u} \quad (3)$$

Thus, the real and reactive power losses are

$$P_{loss}(u, u + 1) = R_u \frac{P_u^2 + Q_u^2}{V_u^2} \quad (4)$$

$$Q_{loss}(u, u + 1) = X_u \frac{P_u^2 + Q_u^2}{V_u^2} \quad (5)$$

The total power loss of the feeder, $P_{T,loss}$ is determined by summing up the losses of all sections of the feeder, which is given as equations 6 and 7.

$$P_{T,loss}(u, u + 1) = \sum_{u=1}^y P_{loss}(u, u + 1) \quad (6)$$

$$Q_{T,loss}(u, u + 1) = \sum_{u=1}^y Q_{loss}(u, u + 1) \quad (7)$$

where $P_{T,loss}(u, u + 1)$ - total real power loss in the line section; $Q_{T,loss}(u, u + 1)$ - total reactive power loss in the line section and y is the number of nodes in the network.

2.2 THE LOAD FLOW ANALYSIS

The load flow analysis was performed using the Backward Forward Sweep method. The real and reactive powers flowing through the line can be calculated backward from the last node given in (8) and (9).

$$P_u = P_{u+1} + R_u \left(\frac{P_{u+1}^2 + Q_{u+1}^2}{V_{u+1}^2} \right) \quad (8)$$

$$Q_u = Q_{u+1} + X_u \left(\frac{P_{u+1}^2 + Q_{u+1}^2}{V_{u+1}^2} \right) \quad (9)$$

The voltage magnitude and angle at each node are calculated in the forward direction. Initially, the voltage at the nodes is 1.0 pu and taken voltage $V_u \angle \delta_u$ at node 'u' and $V_{u+1} \angle \delta_{u+1}$ at node 'u + 1', the current flowing through the line connecting node 'u' and node 'u + 1' having an impedance $Z_u = R_u + jX_u$ is expressed as

$$I_u = \frac{V_u \angle \delta_u - V_{u+1} \angle \delta_{u+1}}{Z_u} \quad (10)$$

The line powers are computed iteratively with the updated voltages at each node, and the power summation is done in backward sweep, while voltages are calculated in the forward sweep as given by (Rupa & Ganesh, 2014); the detailed procedure is shown in Figure 2.

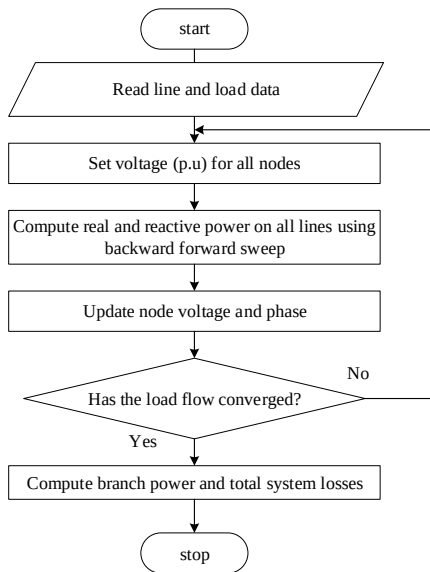


Fig. 2: Flowchart for backward forward sweep method (Rupa & Ganesh, 2014)

2.3 FORMULATION OF THE OBJECTIVE FUNCTION FOR DISTRIBUTION NETWORK LOSS

The objective of reconfiguring the distribution network is to reduce the line's real and reactive power losses. The real power loss for a line connected between buses u and $u + 1$, is expressed as

$$P_{loss(u,u+1)} = R_{u,u+1} \left(\frac{P_{u,u+1}^2 + Q_{u,u+1}^2}{|V_{u+1}|^2} \right) \quad (11)$$

Therefore, the total real power loss for all lines can be expressed as

$$P_{Tloss} = \sum_{u=1}^y P_{loss(u,u+1)} \quad (12)$$

Power loss after network reconfiguration can be calculated using 13 and the total real power loss for all lines after reconfiguration is expressed as (14).

$$P'_{loss(u,u+1)} = R_{u,u+1} \left(\frac{P_{u,u+1}'^2 + Q_{u,u+1}'^2}{|V_{u,u+1}'|^2} \right) \quad (13)$$

$$P'_{Tloss} = \sum_{u=1}^y P'_{loss(u,u+1)} \quad (14)$$

The difference in power loss before and after reconfiguration will give the net power loss reduction given by equation 15

$$\Delta P_{Tloss} = \sum_{u=1}^y P_{loss(u,u+1)} - \sum_{u=1}^y P'_{loss(u,u+1)} \quad (15)$$

$$\text{Max } f_1 = \text{total real power loss, } \Delta P_{Tloss} \quad (16)$$

$$\text{Max } f_2 = \text{total reactive power loss, } \Delta Q_{Tloss} \quad (17)$$

The objective functions in equations 16 and 17 are subjected to the following constraints;

$$V_{u_{\min}} \leq V_u \leq V_{u_{\max}} \quad u \in (1, 2, 3, \dots, y) \quad (18)$$

where,

$V_{u_{\min}}, V_{u_{\max}}$ are the minimum and maximum voltage limits of u th node, respectively

V_u = voltage at u th node; y = number of buses

Feeder capacity limits

$$|I_u| \leq I_{u_{\max}} \quad u = \{1, 2, 3, \dots, y\}_{\max} \quad (19)$$

where, $I_{u_{\max}}$ = Maximum current capacity of u branch

Bus isolation: All nodes or buses must be served after reconfiguration, meaning only one switch should be opened in a loop. The radial topology of the network must be maintained as in 20 and 21;

$$Sec_{sw} = (N_{bus} - 1) \quad (20)$$

$$Tie_{sw} = (N_b - 1) \quad (21)$$

where

Tie_{sw} is the total number of tie switches,

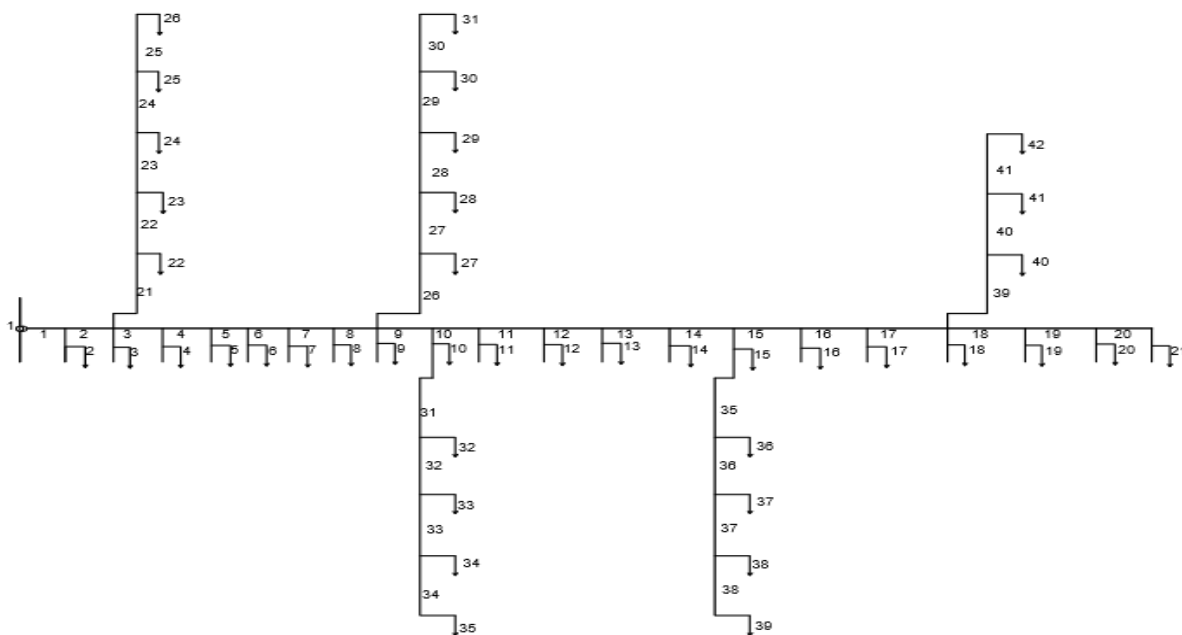
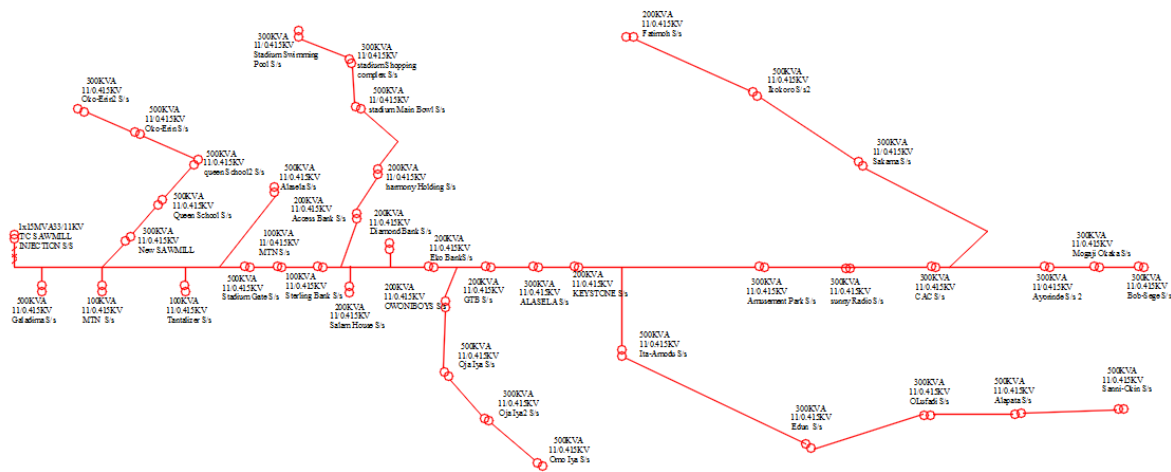
N_{bus} is the total number of buses,

N_b is Set of branches in the network,

Sec_{sw} is total number of sectionalising switches.

2.4 EXISTING TOPOLOGY

The 11kV distribution network of Taiwo feeder emanated from the sawmill sub-transmission station that supplies different consumers and has two voltage levels 132kV and 33kV. It comprises two (2) 30MVA transformers bays and a single 132kV incoming line from 330kV/132kV transmission station situated at Ganmo. There is another 15MVA, 132kV/33kV step-down transformer situated in the same station and has a separate 33/11 kV control station. There are four feeders emanating from it, among which is the Taiwo feeder. This feeder has forty-two distribution substations with a length of 19.88 km and covers four areas in Ilorin metropolis. Figure 3 shows the network layout diagram, while the redrawn single-line diagram is depicted in Figure 4.



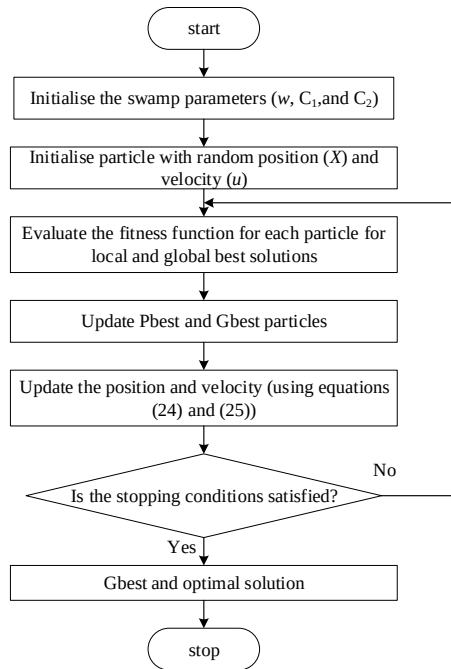


Fig. 5: Flowchart for PSO algorithm (El-Shorbagy & Hassanien, 2018)

2.5.1 Implementation of PSO for Optimal Reconfiguration

The PSO algorithm was implemented in MATLAB software 2018a with the necessary codes following the algorithm.

Step 1: Initialise a random population (X); velocity (U) within the bounds; inertia weight (w); acceleration coefficients (C_1) and (C_2); number of particles (n) and maximum iteration (T). X and U are matrices with the size number of particles (n) by number of possible lines.

Step 2: Evaluate the objective function (f) for each particle. The objective function is the total real power loss in the network for a particle in the population (X).

Step 3: Assign best individual solution (X_{best}) as X and best fitness function ($f_{X_{best}}$) as f .

Step 4: Assign best global solution (G_{best}) as the best of the fitness function ($f_{X_{best}}$) vector and the fitness of the global solution as $f_{G_{best}}$. Repeat from 1 to n

Determine the velocity of the particle using equation (25)

- Determine the new position of i^{th} particle using equation (24)
- Bound the new position such that line numbers are not less than 1 and not greater than the summation of sectional and tie lines.
- Evaluate the objective functions using equations (16 and 17) and update the population matrix and fitness function vector.
- Update the particle's best solution and its fitness function.
- Update the global best solution and its fitness function.

Step 5: Repeat from 1 to 5.

Figure 6 shows the implementation flowchart for the reconfiguration.

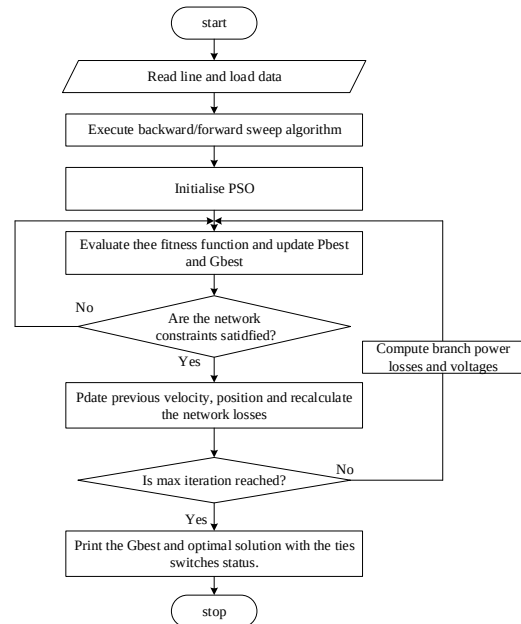


Fig. 6: Flowchart of optimal reconfiguration of distribution network

3 RESULTS AND DISCUSSION

The load flow analysis was performed using the BFS method to obtain the parameters used in determining the performance of the network system. Three cases were considered:

Case 1: Characteristics before Reconfiguration

The initial load flow analysis with the original network was used as a reference to show how other cases had improved from the original configuration of the system. Figure 7 shows the bus voltage value, where the minimum bus voltage is at bus 42 with 0.7079 p.u. This minimum value did not fall within the recommended range of 0.95 p.u. and 1.05 p.u. Therefore, the desired need for reconfiguration of the network is to improve the buses' voltage profile to fall within the recommended range.

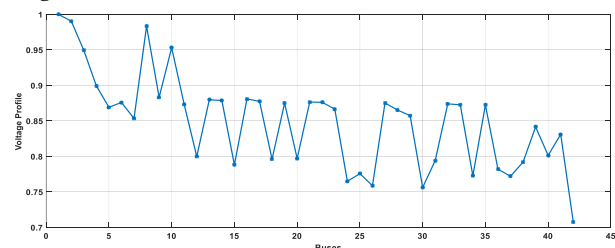


Fig. 7: Voltage profile before reconfiguration

Figures 8 and 9 show the graphical representation of the real and reactive power losses, which sum up to 176.883kW and 9.474kVar, respectively.

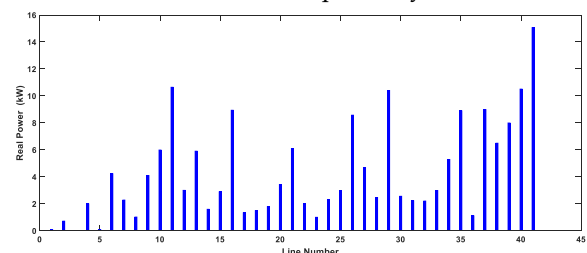


Fig. 8: Real power losses of the network before reconfiguration

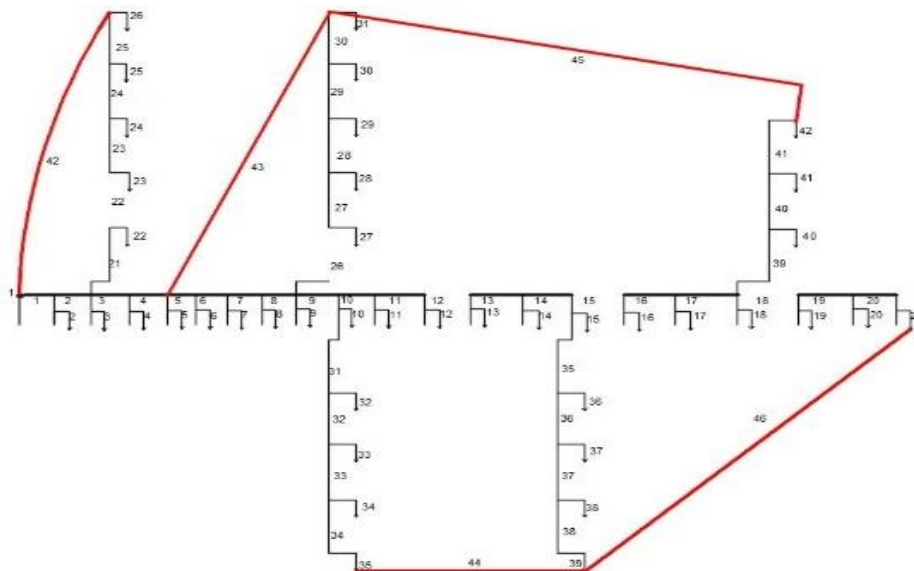


Fig. 10: 11 kV Distribution Taiwo Feeder Network, Ilorin after Reconfiguration.

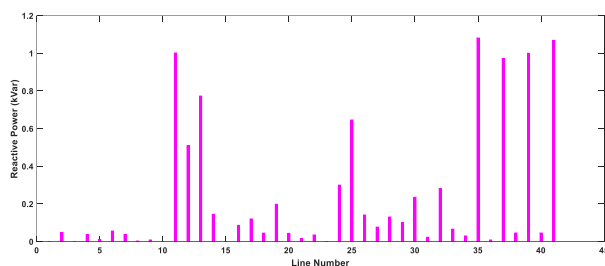


Fig. 9: Reactive power losses in the distribution lines before reconfiguration

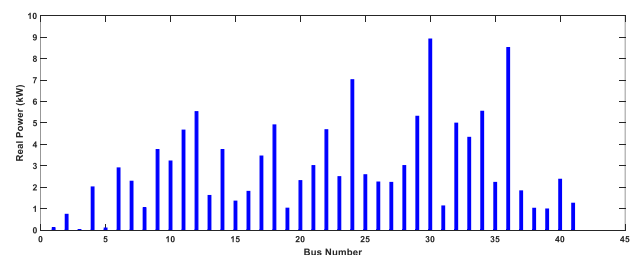


Fig. 11: Real power line losses after network reconfiguration without PSO

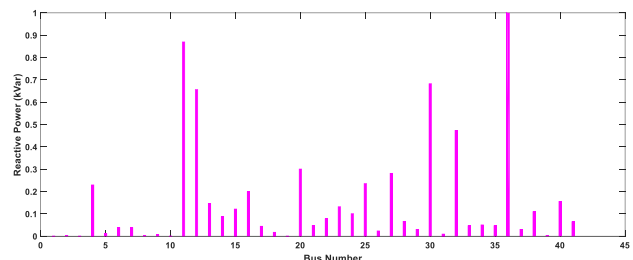


Fig. 12: Reactive power line losses after network reconfiguration without PSO

Case 2: Characteristics after reconfiguration

The distribution network is reconfigured by re-routing five existing lines using equations 20 and 21. Since the initial topology comprises 42 buses and 6 branches, there must always be 41 sectionalizing switches and 5 tie switches in the network. There will be no isolated nodes and the final configuration must be radial with all loads connected. Fig. 10 shows the network after the reconfiguration process with the following 67 sectionalizing switches opened 12th, 15th, 18th, 22nd and 26th. However, tie switches are proposed to connect the following buses because they experienced higher losses in the network. Line 42 connected bus 1 to bus 26, line 43 connected bus 5 to bus 31, line 44 connected bus 35 to bus 39, line 45 connected bus 31 to bus 42, line 46 connected bus 21 to bus 39 and they were all closed.

Figures 11 and 12 show the graphical representation of the real and reactive power losses after the reconfiguration of the network. The total real and reactive power losses are 121.972 kW and 6.527 kVar, respectively.

Case 3: Characteristics after PSO reconfiguration

After the reconfiguration using PSO, the following 67 sectionalizing switches are opened 12th, 18th, 23rd, 28th and 36th. However, tie switches are proposed to connect the following buses because those buses experienced higher losses in the network. Line 42 connects bus 1 to bus 26, line 43 connects bus 5 to bus 31, line 44 connects bus 35 to bus 39, line 45 connects bus 31 to bus 42, line 46 connects bus 21 to bus 39, as shown in Figure 13.

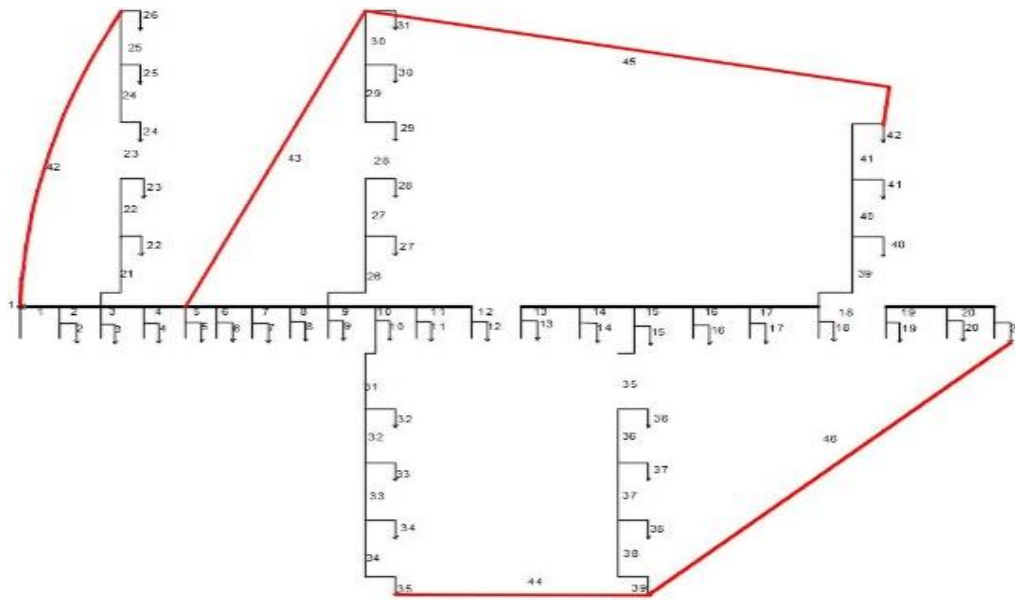


Fig. 13: 11 kV Distribution Taiwo Feeder Network, Ilorin after Optimal reconfiguration using PSO

Figures 14 and 15 show the graphical representation of the real and reactive losses after the network reconfiguration using PSO. It amounted to 98.465 kW and 3.101kVar, respectively. The convergence of the PSO algorithm occurred at 14th iteration, as shown in Fig. 16. This confirms the algorithm's effectiveness.

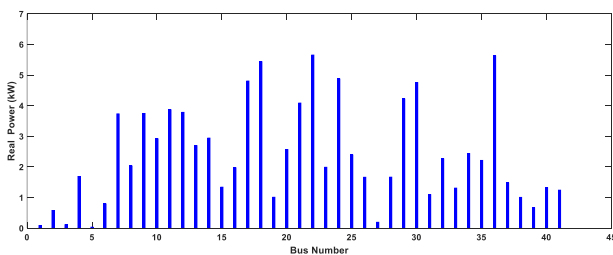


Fig. 14: Real power line losses after network reconfiguration using PSO.

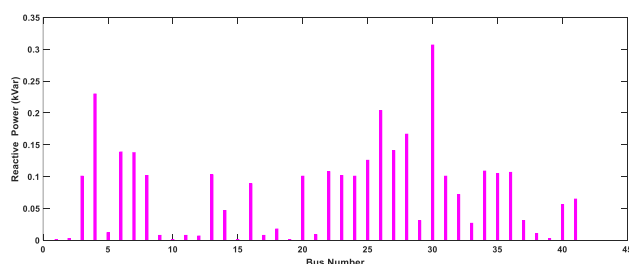


Fig. 15: Reactive power line losses after network reconfiguration using PSO

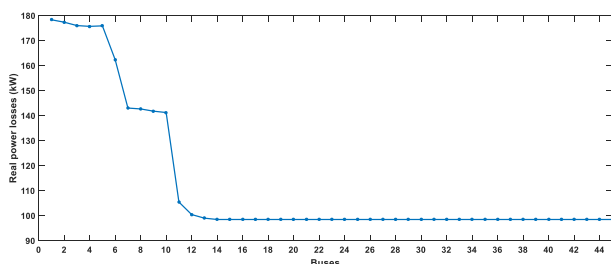


Fig. 16: PSO power reconfiguration convergence.

Figure 17 compares the bus voltages before and after reconfiguration, with and without PSO. The minimum bus voltage before reconfiguration is 0.7079. while the minimum bus voltage after reconfiguration with and without PSO are 0.8782 p.u. and 0.9800p.u, respectively.

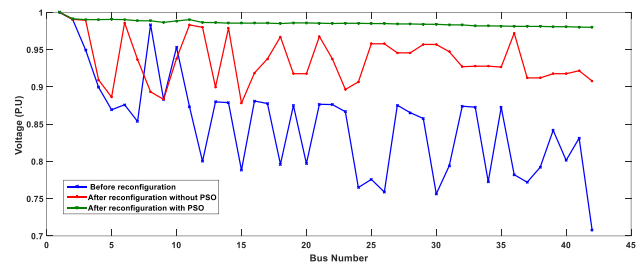


Fig.17: Voltage profile of the distribution network before and after reconfiguration

Figure 18 depicts the comparison of real and reactive power losses in the three cases.

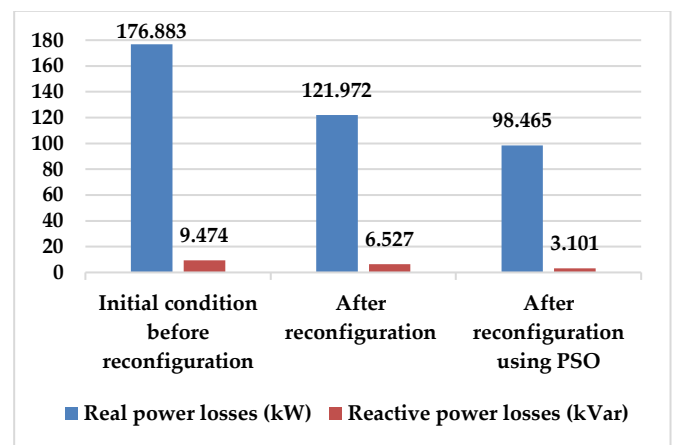


Fig. 18: Comparison of the losses at different cases

The values of real power losses for the three cases are 176.883 kW, 121.972 kW and 98.465 kW, respectively. There is 44.33 % and 31.04 % reduction in the real power losses in case 3 and case 2 compared with case 1. In

addition, further reduction in real power losses in case 3 compared with case 2 stands at 19.27 %. Furthermore, 9.474 kVar, 6.527 kVar and 3.101 kVar values were respectively obtained as reactive power losses in the three cases. The reduction in reactive power losses in cases 3 and 2 are 31.11 % and 67.27 %, respectively, compared to case 1. Also, the value of the reactive power loss in case 3 decreased by 52.49% compared to case 2.

Comparison of result with Genetic Algorithm

Genetic Algorithm (GA), another Metaheuristic technique as PSO was used to benchmark the effectiveness of PSO in this study. Both PSO and GA reduced the active power losses by 44.33 % and reactive power losses by 67.27 % compared with the initial framework. However, PSO reached the optimal solution after 15 iterations, while GA converged after 30 iterations, as indicated in Figure 19. This implies that PSO is effective since its computation time is faster than that of GA.

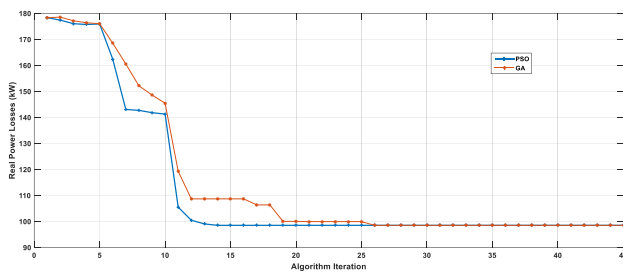


Fig. 19: Comparison of PSO and GA convergence

4 CONCLUSION

Power loss reduction on Taiwo 11kV distribution feeder was achieved in this study. Three cases of power loss estimation involving the initial network, reconfigured network and optimisation of the reconfigured network using PSO were carried out. The estimation of losses on the network was achieved in each case using backward forward sweep algorithm. The reconfiguration process includes 5 tie switches and 41 sectionalising switches. There were no isolated nodes, and the final configuration was radial, with all loads connected.

Sectionalising switches 12th, 15th, 18th, 22nd and 26th were opened while the following tie switches are proposed to connect the buses that experienced higher losses in the feeder, line 42 connected bus 1 to bus 26, line 43 connected bus 5 to bus 31, line 44 connected bus 35 to bus 39, line 45 connect to bus 31 to bus 42, line 46 connect bus 21 to bus 39 and they were all closed. After the reconfiguration process using PSO, the tie switches remained the same, but the following sectionalising switches were opened 12th, 18th, 23rd, 28th and 36th to ensure radial connection of the feeder. About 44.33% and 67.27% losses reduction in the real and reactive power, respectively, was achieved from the original network and PSO reconfigured network. Specifically, the power loss was reduced from 176.88 kW to 98.46 kW for the real power, while the reactive power reduces from 9.47 kVar to 3.10 kVar. This study will form a basis for distribution network reconfiguration of the case study for future expansion and operation planning.

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