
11kV Pama Distribution Feeder Reconfiguration for Power Loss Minimization and Reliability Improvement

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ABSTRACT

A method of distribution network reconfiguration using Particle Swarm Optimization (PSO) for active power loss minimization and reliability improvement is proposed in this paper. The PSO based reconfiguration algorithm is used to determine the optimum positions of the tie and sectionalizing switches of the network leading to power loss minimization and increase in reliability. The proposed method was applied to the IEEE 33 test bus system. Thereafter, the method was applied to the 11kV Pama distribution feeder in Ungwan Boro Injection sub-station located in the southern part of Kaduna State, Nigeria. For the standard IEEE 33 test bus system, the proposed method produced a power loss reduction of 49.12 %. The system average interruption frequency index (SAIFI) increased by 5.69%. The optimal location of the tie switches were found to be positions (4-5), (11-12), (16-17), (19-20), and (21-22). A power loss reduction of 57.15% was achieved for the 11kV Pama distribution feeder, a case study. SAIFI increased by 25.19% while the optimal location of tie switches were found to be positions (6-7), (14-15) and (17-20) for the 11kV Pama distribution feeder.

Keywords: Distribution, Reconfiguration, Particle Swarm Optimization, Power loss minimization, Reliability.

INTRODUCTION

Distribution system losses constitute a significant part of the total electrical power losses (Sehgal *et al.*, 2012). Various techniques, such as injection of distributed generations in the grid, load balancing, upgrading of conductors and installation of capacitors have been developed to reduce losses in power systems (Ramesh *et al.*, 2009). The major concerns about the methods of minimizing power losses are the technical and financial implications of their application to power system networks.

Distribution Network Reconfiguration (DNR) can be defined as the process of altering the topological structures of distribution network by changing the open/close status of the sectionalizing and tie switches with the aim of avoiding transformer overload, feeder thermal overloads, and abnormal voltages while simultaneously minimizing real power losses (Abdelaziz, 2017). DNR is one of the effective methods of loss reduction in distribution systems (Willis *et al.*, 1995).

In addition to power loss reduction, reliability improvement of a power system enhances the delivery of better power quality. By definition, the reliability of an electrical network is described as the ability of the power system to supply consumers uninterruptedly with adequate quality electricity supply (Allan, 2013). The distribution systems are located close to the consumers and as such, the quality and reliability of electrical services supplied is being affected

(Etemadi & Fotuhi-Firuzabad, 2008). Some of the methods for reliability enhancement are (1) adding new devices for protection (2) utilization of more reliable equipment to avoid contingencies (3) fast switching and reclosing schemes (4) accurate precise fault allocation techniques (5) fast crew to speed up the repair process and (6) system topology reconfiguration (Djavid & Jalilian, 2010). However, one of the most effective strategies which can improve the reliability of the power system is the system topology reconfiguration (Niknam *et al.*, 2012). The reliability index considered to measure the reliability of the networks utilized in this work is the System Average Interruption Frequency index (SAIFI). This is the average number of interruptions that the customer may experience in the system in a year. SAIFI indicates how frequently average users suffer from a sustained interruption in a year, in terms of faults per year (López *et al.*, 2016).

A system's topology can be altered by performing the action of opening/closing on the sectionalizing and tie switches. Since the number of switches are relatively high in practical systems, it is almost impossible for the operator to find the best topology without an optimization study (Ahmadi & Martí, 2015). DNR problem for minimizing power loss was first solved by (Merlin & Back, 1975). Since then many algorithms have been developed for power loss reduction in distribution networks such as: cuckoo search algorithm (Nguyen & Truong, 2015), genetic algorithms (Prasad *et al.*, 2005; Mazza *et al.*, 2014), and ant colony optimization (Daniel *et al.*, 2005).

Distribution network reconfiguration is preferred to other methods because of the dynamic nature of the distribution loads, where the network topology at a specific operating condition may no longer be optimal under changed operating conditions. Souifi *et al.*, (2019) performed an optimal reconfiguration of a power distribution network using genetic algorithm (GA) based on graph theory. The reconfiguration problem was addressed as a multi-criteria one with low investment cost and reduced active power loss objectives. The method was tested on IEEE 10-bus system. In (Bai *et al.*, 2018), an hourly network reconfiguration was conducted in a distribution network to optimize power flow by changing network topology. A mixed-integer second-order cone programming model was formulated to optimally determine the locations and energy capacities of distributed energy storage systems. The proposed model was verified on a modified IEEE-33 node distribution network. Wu and Liu (2018) presented a distribution reconfiguration framework to adapt to the IEEE 33 and 69 bus distribution systems, considering the power loss reduction and voltage stability. A modified particle swarm optimization (MPSO) algorithm based on Kruskal algorithm was introduced to determine the optimal network topology. This work is an effort to reconfigure the topology of the standard IEEE 33 Bus test system and the existing 11kV Pama distribution feeder using PSO algorithm with a view to improving the system performances.

METHODS

This section describes the approach use to achieve performance improvement via network reconfiguration.

Model of the Network Reconfiguration

The objective functions for the network reconfiguration considered in this work are the active power loss and reliability index. The real power loss model is discussed in the following subsection.

Real Power Loss Model

The first of the two objective functions implemented is the real power loss. The significance of power loss reduction is the reduction in operating cost of utilities and increase in the loading capacity of the network. The total power loss of the *K*-th radial configuration is determined by the summation of losses in all line section. This is expressed as follows;

$$P_{li} = \sum_{j=1}^N R_j \times \left(\frac{P_j^2 + Q_j^2}{V_j^2} \right) K_j \tag{1}$$

Where,

K_j is the switch state of *j*-th branch, with 0 indicating switch open and 1 indicating switch closed.

Nbr is the number of the buses

R_j is the resistance of the *j*-th branch

P_j is the active power flowing through the terminal of *j*-th branch

Q_j is the reactive power flowing through the terminal of *j*-th branch

V_j is the terminal node voltage of the *j*-th branch

Equation (1) gives the total power loss of the distribution network.

Reliability Index

The System Average Interruption Frequency index (SAIFI) is the second objective function. It was used to measure the reliability of the distribution network. SAIFI is the average number of times a customer experiences power interruption for specific duration of time and is described by the following equation (Mendoza *et al.*, 2009):

$$S = \frac{\sum_{j=1}^N (P_j + Q_j) \lambda_j K_j}{\sum_{j=1}^N (P_j + Q_j)} \tag{2}$$

Where λ_j is the failure rate of branch *j*. The other terms retain their definitions provided in the previous section. A

Lower SAIFI, indicate a higher reliability of the distribution network.

Aggregate Objective Function

An Aggregate Objective Function (AOF), is a function that combines the two objectives into a scalar function. The AOF typically contains parameters to be selected. These parameters reflect the relative importance of each objective. An objective with higher importance will be given priority during the optimization process. The AOF is simply a weighted linear combination of all the objective functions (Messac, 2015).

The Aggregate Objective Function proposed in this work can be described by the equations provided as follows;

$$f = (w_1 f_1 + w_2 f_2) \times K_j \tag{3}$$

$$Cost = \min(\sum_{j=1}^N f_i) \tag{4}$$

Where f_1 is real power loss reduction function given in equation (1) and f_2 is SAIFI function given in equation (2). w_1 is the weight assigned to f_1 and w_2 is the weight assigned to f_2 . These objective functions are subject to constraints which must be satisfied. These constraints are listed as follows;

I. Node voltage constraint

$$V_m(j) \leq V(j) \leq V_m(j)$$

II. Branch Power constraint

$$P_j \leq P_j$$

$$Q_j \leq Q_j$$

III. Radial Network constraint

$$\sum_{i=1}^n \sum_{j=1}^n a_{ij} = 1 \text{ or } -1 \tag{5}$$

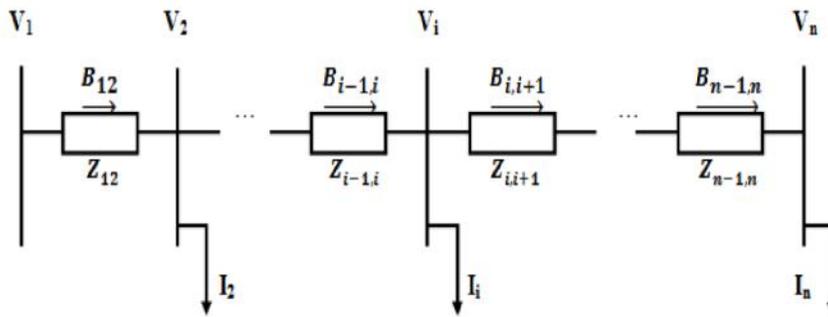
Where nbus is the number of total buses and a_{ij} is the elements of the incidence matrix A which has dimension of $n \times n$.

IV. No islanding in the distribution network

Backward-Forward Sweep (BFS) Technique for Power Flow Analysis.

A radial distribution system is considered having ‘n’ buses as shown in Figure 1.

Figure 1: Single Line Diagram of n-bus Radial Distribution System



The system is assumed to be a balanced one, with (n-1) load buses which are treated as load buses and bus 1 as slack/swing bus. The general bus ‘i’ current injection at the kth iteration is given by the following equation (Alhaddad & El-Hawary, 2014):

$$I_i^k = \left(\frac{S_i^{s,n}}{V_i^k} \right) \tag{6}$$

Where $S_i^{s,n}$ is the scheduled complex power at bus i, V_i^k is the bus ‘i’ voltage at the kth iteration. Kirchhoff’s current law (KCL) is applied by backward current sweep starting from the last bus ‘n’ to the source bus 1 to obtain the branch currents. The relevant equation is provided as follows;

$$\begin{bmatrix} B_1 \\ \vdots \\ B_{i-2,i-1} \\ B_{i-1,i} \\ B_{i,i-1} \\ \vdots \\ B_{n-1,n} \end{bmatrix} = \begin{bmatrix} 1 & \dots & 1 & 1 & 1 & \dots & 1 \\ \vdots & \dots & \dots & \dots & \dots & \dots & \vdots \\ 0 & \dots & 1 & 1 & 1 & \dots & 1 \\ 0 & \dots & 0 & 1 & 1 & \dots & 1 \\ 0 & \dots & 0 & 0 & 1 & \dots & 1 \\ \vdots & \dots & \dots & \dots & \dots & \dots & \vdots \\ 0 & \dots & 0 & 0 & 0 & \dots & 1 \end{bmatrix} \begin{bmatrix} I_1 \\ \vdots \\ I_{i-1} \\ I_i \\ I_{i+1} \\ \vdots \\ I_n \end{bmatrix} \tag{7}$$

Equation (7) may be written in compact form as follows;

$$[B] = [B] [I] \tag{8}$$

Where [B] is the relationship matrix between branch currents and bus current injections. In the forward voltage sweep, Kirchhoff’s voltage law (KVL) is applied to obtain the bus voltages and is given by:

$$\begin{bmatrix} V_2 \\ \vdots \\ V_{i-1} \\ V_i \\ V_{i+1} \\ \vdots \\ V_n \end{bmatrix} = \begin{bmatrix} V_1 \\ \vdots \\ V_1 \\ V_1 \\ \vdots \\ V_1 \end{bmatrix} - \begin{bmatrix} 1 \dots 1 \ 1 \ 1 \dots 1 \\ \vdots \dots \dots \dots \vdots \\ 0 \dots 1 \ 1 \ 1 \dots 1 \\ 0 \dots 0 \ 1 \ 1 \dots 1 \\ 0 \dots 0 \ 0 \ 1 \dots 1 \\ \vdots \dots \dots \dots \vdots \\ 0 \dots 0 \ 0 \ 0 \dots 1 \end{bmatrix} \begin{bmatrix} B_1 \\ \vdots \\ B_{1-2,1-1} \\ B_{i-1,i} \\ B_{i,i-1} \\ \vdots \\ B_{n-1,n} \end{bmatrix} \tag{9}$$

The change in voltage vector $[\Delta V]$ is obtained as follows:

$$[\Delta V] = [B] [I] \tag{10}$$

Where $[B]$ is the relationship matrix between bus voltages and branch currents. In addition,

$$[\Delta V] = [B] [I]$$

$$[\Delta V] = [D] [I] \tag{11}$$

Where $[D]$ is the relationship matrix between voltage drops and bus current injections. The Radial Distribution Power Flow (RDPF) solution is achieved by employing KCL and KVL respectively to form the matrices [BIBC] and [BCBV] and performing matrix multiplications. The following equations are solved iteratively to get the power flow solution

$$I_i^k = \left(\frac{P^{s \ h} + j \ Q^{s \ h}}{V_i^k} \right) \tag{12}$$

$$[\Delta V^{k+1}] = [D] [I^k] \tag{13}$$

$$[V^{k+1}] = [V_0] - [\Delta V^{k+1}] \tag{14}$$

Where $[V_0]$ is initial bus voltage vector. The iterative process stops when the absolute of difference between previous bus current injection and most recent bus current injection is less than or equal to a prescribed tolerance, ϵ given as follows;

$$|I_i^{k+1} - I_i^k| \leq \epsilon \tag{15}$$

Application of Particle Swarm Optimization for Network Reconfiguration.

Particle swarm optimization (PSO) was introduced by Edward and Kennedy in 1995. This is a population based stochastic algorithm that imitates the dynamics and social psychological principles of swarm behavior observed in nature. It can be seen in the social behavior and swarm intelligence of bird, swarm of bees and fish flock movement. The Particle Swarm does not use selection. Typically, all population members survive from the beginning of a trial to the end. Their interaction result in iterative improvement of the quality of solution over time (Kennedy, 2011). The main reason behind the choice of PSO is its wide spread use in power systems, simplicity and its ability to generate high quality solutions within a very short duration. It also has the flexibility to control the balance between the global and local exploration of the search space. This unique features overcomes the premature convergence problem and enhance the search capacity (Ramesh *et al.*, 2009). The algorithm implemented to solve the optimization problem is provided as follows;

1. Input the network line data, load data and PSO parameters.
2. Randomly initialize a population of particles (switches in this case) with position and velocity of the particle.
3. Check for constraint and calculate the fitness function.
4. Calculate the velocity and new position of each particle.
5. Compare the current position with particle's previous best experience, in terms of fitness values and hence update pbest for each particle in the population.

6. After updating the position, choose the best value among all the particles in pbest and set as global best, i.e. gbest.
7. Set iteration as iteration + 1
8. Calculate velocity of each particle and update if constraints get violated.
9. Then calculate new position of each particle.
10. For each particle calculate fitness function.
11. Then go to step II until the maximum iteration is reached.
12. Finally the optimal location of tie and sectionalizing switches can be evaluated by tracing the gbest particle and the optimized values of power loss and SAIFI are obtained.

Parameters used in PSO algorithm for the simulation are as follows: $C_1 = 2$, $C_2 = 2$, $W_m = 0.9$, $W_m = 0.4$, Number of particles = 20, r_1 = Random number between 0 and 1, r_2 = Random number between 0 and 1, and $it_m = 20$.

RESULTS AND DISCUSSION

This section discusses the results obtained when the proposed method was applied to the 33 – Bus distribution test system and the 11kV Pama distribution Feeder.

33-Bus Test System

The proposed method is applied on 33-bus test system. The maximum bus voltage of the system is considered as 1pu, while the minimum bus voltage is assumed to be 0.8pu. This system consists of 33 buses, 1 main feeder, 3 laterals, 37 branches of 32 sectionalizing switches and 5 tie switches. The substation voltage is 12.66kV and the base power is 10MVA (Zhu, 2002). The single line diagram of the test bus system is shown in Figure 2 and the bus data is given in (Gupta *et al.*, 2014) and (Zhu, 2002). The total active power loss, voltage profile and SAIFI of the re-configured network is compared with the corresponding results of the existing network also known as the base case. The total active power loss of the reconfigured network was computed to give 102.2592 kW. The base case total active power loss is calculated as 202.2592 kW indicating that a 49.12% reduction in distribution network power loss was achieved by reconfiguring the network using the proposed method.

The lowest bus voltage magnitude after reconfiguration was found to be 0.94751pu while the corresponding value for the base case is 0.85661pu. The SAIFI before and after reconfiguration is 0.32118 and 0.30290 respectively indicating a 5.69% improvement in network reliability. After the reconfiguration process, the optimal locations of tie switches are positions (4-5), (11-12), (16-17), (19-20), and (21-22). These have changed from their original positions given as (8-21), (9-15), (12-22), (18-33) and (25-29) for the base case. Figure 3 shows the power loss profile of both the reconfigured distribution network and the original network. Figure 4 shows the voltage profile of the 33-Bus distribution network before and after reconfiguration Table 1 gives the summary of the performance results obtained before and after reconfiguration of the 33 bus test system.

11kV Pama Feeder

The 11kV Pama Feeder consists of 24 buses, with 23 sectionalizing and 3 tie switch, which is fed from Ungwan Boro Injection substation. The Injection substation network consists of a single 33/11kV transformer which is being fed from a 132/33kV Kaduna Town 1 Transmission Station located in the southern part of Kaduna State Nigeria. The schematic diagram of Pama

Feeder is shown in Figure 5. The total active power loss, lowest bus voltage and SAIFI obtained before reconfiguration are 4.7088kW, 0.99181pu and 0.00025413 respectively. After reconfiguration, these performance indices have improved to 2.0176kW, 0.99632pu and 0.00019009 respectively. Clearly, there is a 57.15% reduction in power loss and a 25.19% improvement in reliability with respect to SAIFI. After the reconfiguration process, the optimal arrangement of the tie switches is (6-7), (14-15) and (17-20) which has changed from (2-24), (17-20) and (12-17) in the base case. Figure 6 shows the power loss profile for the distribution network before and after reconfiguration. Figure 7, on the other hand, shows the voltage profile for the same network before and after the re-configuration process. Table 2 gives the network data for the 11kV Pama Feeder.

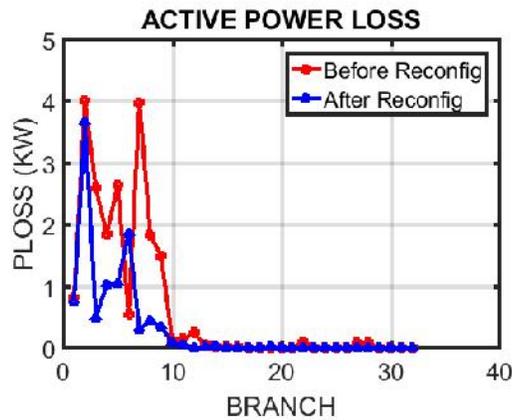


Figure 2: Single Line Diagram of IEEE 33-Bus Test Feeder

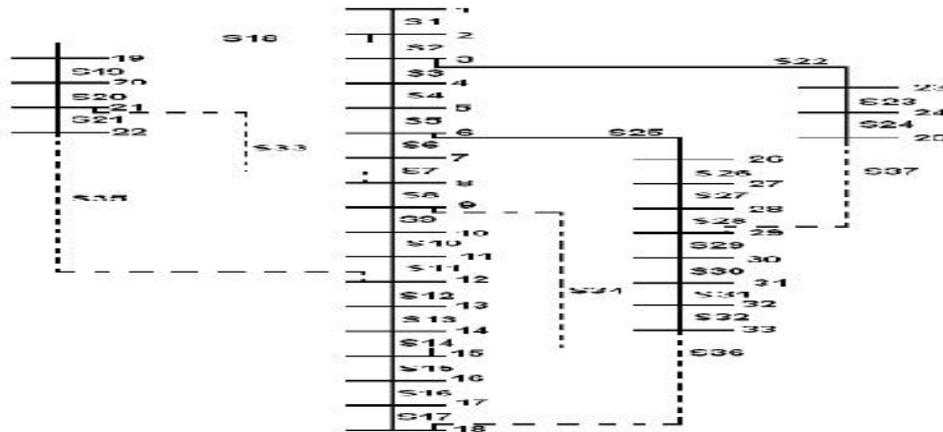


Figure 3: Power Loss Profile of the 33 Bus System.

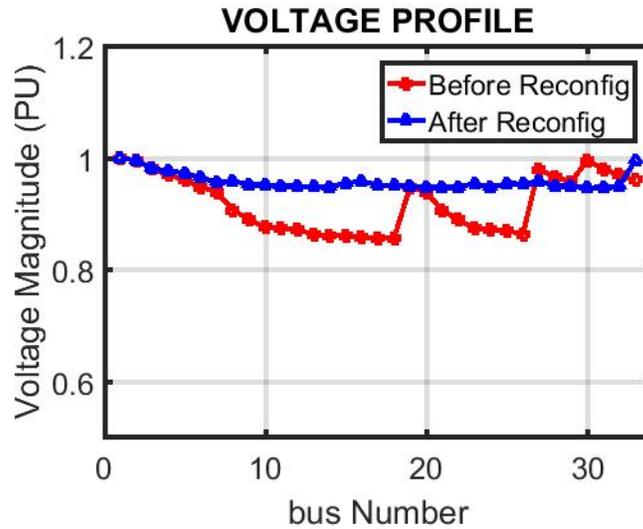


Figure 4: Voltage Profile of the 33 Bus System.

Table 1: Summary of Performance Results of the 33 Bus Test System.

Parameters Description	Case I	Case II
Active Power Loss(kW)	202.2592	102.2592
Minimum Voltage(pu)	0.85661	0.94751
SAIFI	0.32118	0.30290
Percentage Reduction In Power Loss (%)	-	49.12
Percentage Improvement In Reliability (%)	-	5.69
Tie Switches	(8-21), (9-15), (12-22), (18-33) & (25-29)	(4-5), (11-12), (16-17), (19-20), & (21-22)

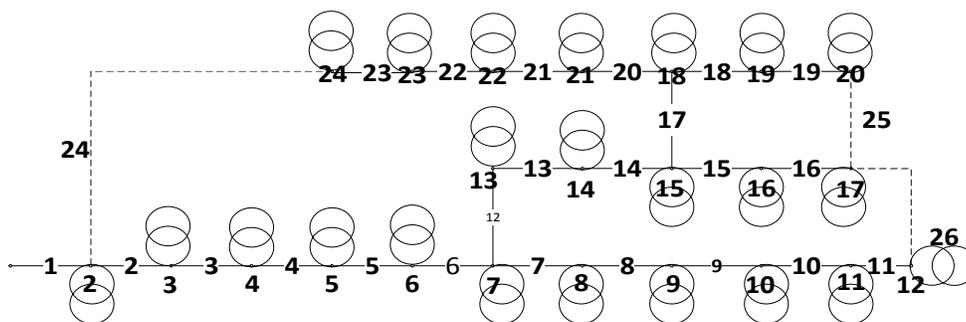


Figure 5: Single Line Diagram of Pama Feeder.

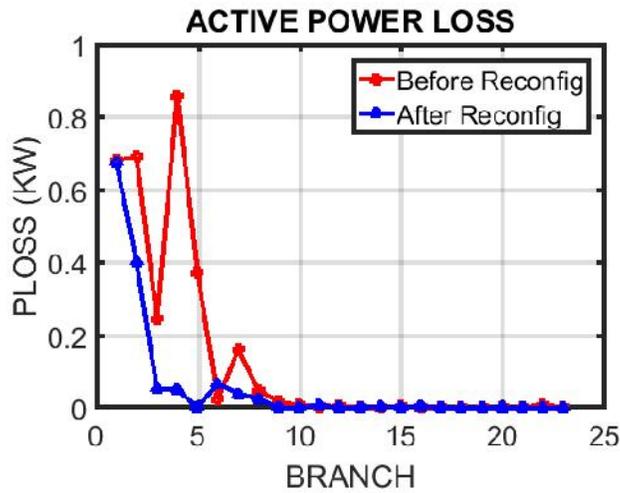


Figure 6: Power Loss profile for 11kV Pama Feeder.

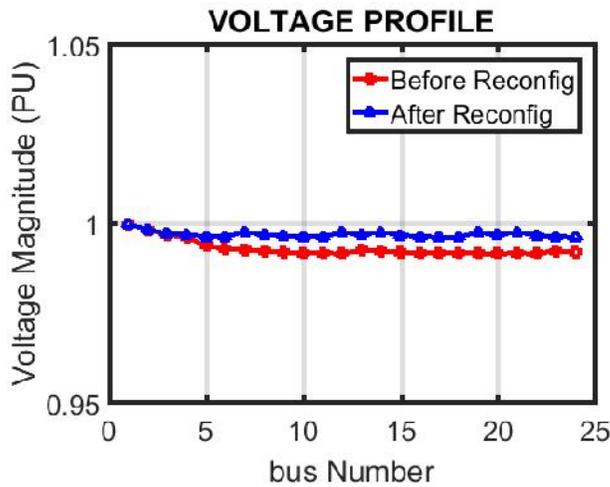


Figure 7: Voltage Profile for 11kV Pama Feeder.

Figure 8 illustrates the single line diagram of the re-configured layout of the 11kV Pama distribution network.

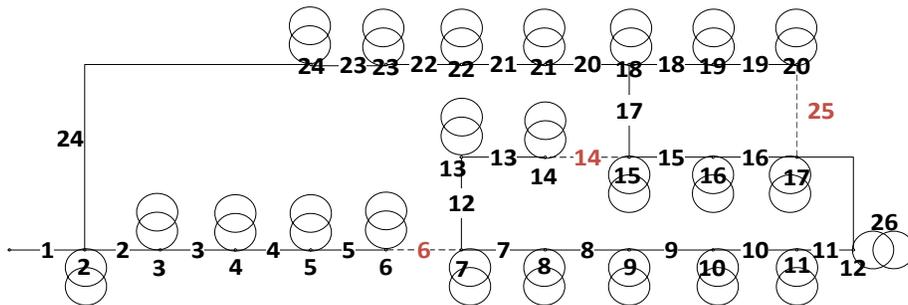


Figure 8: Reconfigured 11kV Pama Feeder.

CONCLUSION

This paper demonstrates a method of minimization of real power losses and improvement of network reliability. The aggregate objective function that combines the network active power loss and reliability performances was formulated. The BSF technique was used for the power flow analysis while the SAIFI was used for evaluation of the reliability of the network. The analysis is applied on the 33-bus test system and subsequently on the 11kV Pama distribution network located in southern Kaduna, Nigeria. The PSO based reconfiguration solution proposed in this paper provides significant improvements in total active power loss and reliability of the distribution networks tested

Table 2: Network Data for Pama Feeder

LINE No.	FRM BUS	TO BUS	LENGTH (KM)	CSA (M ²)	R(ohms) 75	X(ohms) 75	FAILURE RATE(λ) (F/year)	P(kW)	Q(kVAR)
								AT RECEIVING BUS	
1	1	2	0.3169	150	0.0083395	0.0513666	0.00000	32	24
2	2	3	0.327	"	0.0086053	0.053004	0.00000	320	240
3	3	4	0.138	"	0.00036316	0.0223685	0.00034	320	240
4	4	5	0.5854	"	0.0154100	0.0948880	0.00034	192	144
5	5	6	0.2875	"	0.0075659	0.046601	0.00034	192	144
6	6	7	0.0211	"	0.00055527	0.0034212	0.00034	0	0
7	7	8	0.1863	"	0.00490267	0.0301975	0.00000	320	240
8	8	9	0.1297	"	0.00341318	0.0210232	0.00046	320	240
9	9	10	0.0759	"	0.0019974	0.012303	0.00159	192	144
10	10	11	0.0772	"	0.00203159	0.0125134	0.00000	32	24
11	11	12	0.372	"	0.0097896	0.0602978	0.00000	0	0
12	7	13	0.2358	"	0.0062053	0.0382210	0.00000	32	24
13	13	14	0.0372	"	0.00097896	0.00602978	0.00000	320	240
14	14	15	0.2131	"	0.00560794	0.034542	0.00091	0	0
15	8	16	0.3131	"	0.0082395	0.050751	0.00000	320	240
16	16	17	0.341	"	0.00897376	0.055273	0.00046	192	144
17	17	18	0.1381	"	0.00363424	0.022385	0.00011	0	0
18	18	19	0.4004	"	0.0105369	0.0649012	0.00000	192	144
19	19	20	0.0152	"	0.00040003	0.0024638	0.00000	0	0
20	18	21	0.04	"	0.00105264	0.00648364	0.00000	32	24
21	21	22	0.0759	"	0.00199738	0.0123027	0.00000	320	240
22	22	23	0.6005	"	0.015803	0.09733559	0.00034	320	240
23	23	24	0.2922	"	0.0076895	0.0473629	0.00079	190	144
24	2	24	0.5854	"	0.0154100	0.0948880	0.00011		
25	17	20	0.04	"	0.0010526	0.0064836	0.00079		
26	12	17	0.5854	"	0.0154100	0.0948880	0.00000		

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