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Optimal Network Reconfiguration of Electric Power Distribution System for Power Loss Reduction and Voltage Profile Improvement

[1]France O. Akpojedje, and [2]Emmanuel A. Ogujor

[1]Department of Electrical/Electronic Engineering Technology, National Institute of Construction Technology and Management (NICTM), Uromi, Nigeria.

[2]Department of Electrical/ Electronic Engineering, University of Benin, Benin City, Nigeria.

Corresponding Authors Email: francetech007@yahoo.com, emma.ogujor@uniben.edu

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Abstract

The aim of reconfiguring electric power distribution network under normal operating conditions is to reduce the total power losses of the network or to balance the load of the system's feeders which is an important part of the distribution network operation to improve system availability, reliability and stability. However, the three main objectives of the distribution network engineers are power losses minimization, maintenance of good voltage profile and minimum feeders' current levels. This paper proposed optimal network reconfiguration (ONR) for the Ugbowo 2x15MVA, 33/11kV distribution network to reduce the high system power losses, balance the feeders' load and improve the voltage profiles. The binary version of the particle swarm optimization (BPSO) algorithm was used to optimally select the switches and it was programmed in MATPOWER and ran in MATLAB 2017a version. The simulation results revealed that the proposed technique optimally select the switches that produce the best configuration which gives minimum power losses, reduce the load balance index, balance the feeders' load and improve the system's voltage profile in most of the buses within acceptable limits of ±6%.

1.0 Introduction

In recent past and even currently, the frequent power interruptions in the Nigerian electric power distribution network have become a recurrent decimal and this is tagged as one of the biggest obstacles to be tackled in the distribution network of Nigeria power systems [1]. The reasons for the frequent power interruptions are not far fetch from scheduled and unscheduled outages [1]. The unscheduled outages are the outages that occur due to system faults on the power system such as lightning, earth failure, breaking of conductor etc., while the scheduled outages are carried out mostly due to inadequate or poor generation and equipment limitations which has caused the Nigeria's utility companies to carry out energy management in the network such as load shedding. Also, scheduled outages are carried out for routine and preventive maintenance. This energy management system is implemented to manage the available supply with the ever-growing demand of electric energy which has resulted to overload in the system [1]. [2] opined that the demand for electricity is elevating day by day and this leads the field experts, environmentalists and economists to identify the possible solution to overcome the energy shortfall.

Despite the current poor generation, high power losses occur in the power lines of the Nigerian power system. According to [3, 4 & 5] 13% of the total power generated is wasted in the form of line losses at the distribution level. Also, [6] opined that 40% of the power generated is lost in the transmission and distribution lines of the Nigeria's power systems. The problem of power losses in the distribution network is enormous. According to [7] stated that the power losses in distribution networks can account for up to seventy (70%) percent of the total power losses in the power systems. Thus, seventy (70%) percent power loss in the distribution network is enormous to give optimal output to consumers. In other words, power losses in the distribution network significantly affect the quality and quantity of power delivered to the consumers, most especially when the distribution system is large. The problem of reducing distribution network losses has been one of major focus for researchers and utility companies with the view of giving better quality of service and better utilization of the available electric energy.

"Over the last three decades, researchers and utility companies in the area of distribution systems automation and control have developed and utilized different techniques for power loss reduction within the electric power distribution system. These techniques include load balancing, capacitor placement, introduction of higher voltage level, reconductoring, reconfiguration, distributed generation (DG), etc. [8 & 9]. Though, the techniques use in reducing power losses in electric distribution system is enormous but the major concern when adopted is about their technical implications on the network both in engineering terms and financial perspectives [10]. Most methods of reducing power losses in the network cause tremendous financial burden and time consuming on the utilities such as introduction of new equipment and high voltage level, fixed compensators, reconductoring, etc.

Therefore, the application of optimal network reconfiguration (ONR) to solve power loss, load balancing and voltage profile improvement in the distribution system is timing and cost efficient compared to others. Consequently, optimal network reconfiguration is one of the best ways of reducing power losses, maximizing load balancing, enhancement of voltage profile and increase in reliability of the network [1]. [11] opined that distribution network reconfiguration has been shown to be a feasible approach, often involving computational intelligence algorithm to optimize power delivery by reducing power losses, balancing loads, increasing power quality and improve reliability.

Network reconfiguration (NR) of a power distribution system is an operation that alters the topological structure of the distribution feeders by changing open/closed status of sectionalizing and ties switches [12]. According to [13], network reconfiguration is a process of changing the switch states of the network. The switch can be opened, where it is called (tie switches) or closed, where it is called (sectionalizing switches)." Consequently, network reconfiguration involves two fundamental steps:

i. varying network topology by changing the status of normally open/closed switches of the system and
ii. subsequent execution of power flow analysis to determine the operational characteristics of the modified system [e.g power loss levels, bus and line voltage, load levels in the power lines, etc.] [14].

Hence, this paper attempts to use optimal network reconfiguration which is a robust method in reducing distribution feeders' losses as well as improving the system voltage profile.

2. Methodology

2.1 Problem Formulation of Optimal Network Reconfiguration for Power Loss Reduction and Voltage Profile Improvement

The core objective of optimal network reconfiguration in the distribution system is to reduce power losses in the lines and invariably increase the bus voltages. Although power losses occur in various sections that make up the distribution system, but the losses in the power line segments and bus sections of the transformer devices form the major share of the overall power losses in the network. Hence, this paper considered the power losses in the line segments of the transformers' feeders and the voltage profile improvement of the Ugbowo 2x15MVA, 33/11kV of the distribution network and associated bus voltages. The feeder line between bus i and bus i+1 is given in Figure 1 which connects the buses and is calculated as [15]:

$$P_L(i,i+1) = R_i\left[\frac{P_i^2 + Q_i^2}{|V_i|^2}\right] \tag{1}$$

Where P_i and Q_i are the active and reactive power flow at bus i respectively while R_i is the resistance of the line segment in bus i and V_i is the voltage of bus i. The total power loss of the distribution network can be obtained by summation of the power losses in all of the line segments of the distribution network and is given as:

$$P_{L_T} = \sum_{i=1}^{N_{PL}} R_i\left[\frac{P_i^2 + Q_i^2}{|V_i|^2}\right] \tag{2}$$

Where N_{PL} is the number of power line segments in the distribution network and the number of power line segments in the network is given as:

$$N_{PL} = N_b - 1 \tag{3}$$

Where N_b is the total number of buses in the distribution network. The optimal network reconfiguration (ONR) performance is determined by the loss reduction index which is defined as the ratio of power loss before and after the reconfiguration processes. The power loss reduction index is given as:

$$\Delta P_L^{ratio} = \frac{P_L^{rec}}{P_L^{init}} \tag{4}$$

Where P_L^{rec} and P_L^{init} are the power losses after reconfiguration and the initial power losses before reconfiguration of the distribution network respectively.

As a result of altering the topology of the network, loading of the line segments may vary. Upon that, the voltage of the load buses may be altered. The indicator of deviation in voltage levels after network reconfiguration is given as:

$$\Delta V_D = \max_{i=1 \dots N_b}\left[\frac{V_1 - V_i}{V_1}\right] \tag{5}$$

Where V_1 is the nominal voltage of the source bus and V_i is the load bus voltage level.

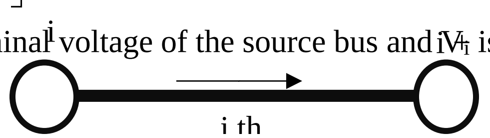

Figure 1: Schematic Representation of a Feeder Line Connecting Two Adjoining Buses

As espouse of the standard approach by [16 & 17] the optimal network reconfiguration process attempts to minimize the voltage deviation and power loss reduction index subject to the voltage and reactive power limits of the network. Hence, the objective function is given as:

Minimize F = $\Delta P_L^{rec} + \Delta V_D$ (6)

Subject to the following Constraints:

i. Voltage Deviation

$$V_{i\min} \le V_i \le V_{i\max} \tag{7}$$

ii. Branch Current Limit

$$I_{i\min} \le I_i \le I_{i\max} \tag{8}$$

The minimum voltage is 0.94pu and maximum voltage is 1.06pu (±6% of the nominal voltage)

iii. Power Flow Constraints

$$S_i \le S_{i\max} \tag{9}$$

iv. Radial Structure Limit

$$J \in P \tag{10}$$

Where:

J is the topology structure after optimal network reconfiguration

P is the set of all feasible topology structures.

v. Feeder Capacity Limit

$$|I_i| \le I_{i\max} \tag{11}$$

vi. Node Constraints

The Load Centre (Node) must not be isolated without supply from any feeder.

2.1.1 Objective Function of Optimal Network Reconfiguration

The main objective function of the optimal network reconfiguration (ONR) problem is to minimize the total system losses by reducing the active (real) power losses thereby improving the bus voltage profiles since there is a correlation between power loss and voltage drop in a network.

2.2 Binary Particle Swarm Optimization (BPSO) Algorithm

Particle swarm optimization (PSO) is one of the swarm intelligence (SI) algorithms that function based on random search of swarms and it simulates the nature of evolutionary based processes which has the characteristics of memory. In optimal problems, any variable provides a new solution that is represent as a particle and its limit will call a search of D-dimension space. Its basic principle is as follows: every particle represents a solution of the problem being optimized; which its fitness function is determined by the optimal function algorithm. Therefore, in relation to the cognitive memory, all the particles can adjust their position moving toward their global best position or their neighbour’s local best position [18]. Consequently, the optimal solutions or near optimal solutions with fast convergent speed is realized. Particles’ velocity and position are updated with the help of Equations 12 & 13 and the process continues till the criteria for stoppage are met.

$$V_{id}^{k+1} = \omega v_{id}^{k} + c_1 r_1 \left(P_{best} - x_{id}^{k}\right) + c_2 r_2 \left(g_{best} - x_{id}^{k}\right) \tag{12}$$

$$x_{id}^{k+1} = x_{id}^{k} + V_{id}^{k+1} \tag{13}$$

Where:

V_{id}^{k+1} is the new value of the particle velocity
i is the particle number
d is the selected search space number
x_{id}^{k+1} is the new value of the particle position
P_{best} and g_{best} respectively represent each particle's previous (local) best position remembered and the globally best position in the whole swarm
ω is the inertia
c_1,c_2 are the learning factor
r_1,r_2 are respectively a random number between 0 and 1.
The basic PSO invented by [19] was not originally designed for pure discrete binary combinatorial problem. But most engineering problems are combinatorial in nature. To handle this kind of problem, Kennedy and Eberhart proposed binary version of particle swarm optimization (BPSO) algorithm [20] to adequately handle engineering and related problems that are discrete in nature. In this improved PSO called BPSO, the particle takes the values of binary vectors of length n and a discrete problem is solved with the idea of using probability of being '1' and '0' in binary search space instead of position value being updated. Equation 14 is used for updating each bit x_{ij} of a particle.

$$S\left(V_{id}^{k+1}\right)=\frac{1}{1+e^{-V_{id}^{k+1}}} \tag{14}$$

The iterative equation of particle is given as:

$$x_{id}^{k+1}=\begin{cases}1, & rand(\ )\lhd S\left(V_{id}^{k+1}\right)\\ 0, & Others\end{cases} \tag{15}$$

If $\left(rand(\ )\lhd S\left(V_{id}^{k+1}\right)\right)$ then $x_{id}^{k+1}=1$
else $x_{id}^{k+1}=0,$
Where the value of $rand(\ )$ is a random number between 0 and 1 range and the $S(V_d)$ is the Sigmoid limiting transformation. The Sigmoid limiting transformation of the velocity component in Equation 14 is applied to squash the velocities into a range of [0, or 0.5 or 1] and force the component values of the locations of the particles to be 0's and 1's. Using Equation 15 in the optimal network reconfiguration problem, the closed switch represents 1, while the open switch represents 0.

2.2.1 Implementation of Binary Version of Particle Swarm Optimization (BPSO)

Solving the optimal network reconfiguration (ONR) problem by BPSO can be categories into three steps as follows and the flow chart of the algorithm is shown in Figure 2:

a. Determine the number of dimensions
b. Finding the search space for each dimension
c. Using BPSO to select the optimal solution from the search spaces

2.3 System Description

The original PSO is modified based on unique characteristics of the distribution network feeder operations. The Ugbowo 2x15MVA, 33/11kV distribution system with one hundred and forty-two (142) buses were implemented using the binary version of PSO for the optimal network reconfiguration. The distribution network has four (4) feeders with one hundred and forty-two (142) active associated load buses operating on three (3) phase system with nominal voltage of 415V and the base apparent power is 30MVA. The real-time system was used for the optimal network reconfiguration (ONR) which is programmed in MATPOWER and ran in MATLAB2017a using the Intel Dual Core Processor, CPU 1.6 GHz PC with 6GB of RAM.

The system performances were evaluated by carrying out power flow studies of the network under investigation and all relevant information revealing the performance was retrieved with case study implemented as all the various branches and nodes of the network connected to supply. Subsequently, the binary version of particle swarm optimization (BPSO) algorithm was applied to the network to see the effect of the proposed approach in optimizing the network and how the suggested approach work effectively in minimizing the high power losses in the network under investigation and also; the extent of voltage profile improvement by the method. The existing configuration and optimal configuration results were depicted in a form of tables and graphs. Consequently, the graphs were discussed extensively and deductions were drawn.

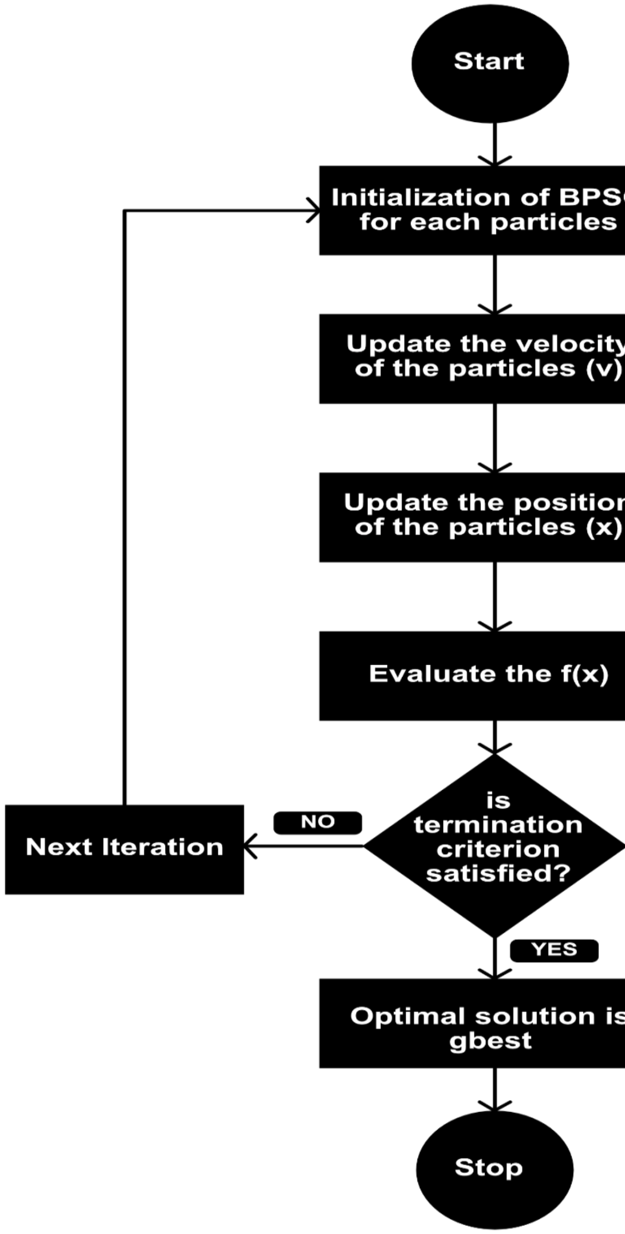

Figure 2: The Flow Chart of BPSO for Optimal Network Reconfiguration of Distribution System

3.0 Results and Discussion

Figures 3 and 4 shows the existing and optimal configurations of the Ugbowo 2x15MVA, 33/11kV electric distribution network without and with tie & sectionalizing switches incorporated, while Table 1 shows the optimal results of the Ugbowo buses distribution network using BPSO. Figures 5, 6,7 & 8 shows the power losses before and after ONR for peak and off peak period respectively. Also, Figures 9, 10,11 & 12 shows the bar chart representation of the power losses in the network for peak and off peak periods respectively, while Figures 13 & 14 shows the voltage profiles of the network for peak and off peak periods for both before and after optimal network reconfiguration.

Figures 5,6 7,8,9, 10, 11 & 12 shows the power loss reduction for peak and off peak period after optimal network reconfiguration technique has been deployed, while Figures 13 & 14 shows the voltage profile improvement in the proposed network after the application of the suggested method.

Table 1: Optimal Results of the Ugbowo One Hundred and Forty-Two (142) Buses Distribution Network using BPSO

Description of Items	**Before Optimal Network Reconfiguration**		**After Optimal Network Reconfiguration**	
	Peak Period	**Off Peak Period**	**Peak Period**	**Off Peak Period**
Power Losses (kW)	3606	1723	1527	791
Power Losses (kVAr)	2137	1012	985	456
% of Power loss reduction (kW)	-----------	-----------	57.654	54.09
% of Power loss reduction (kVAr)	-----------	------------	53.91	54.94
Power loss reduction Index (kW)	-----------	------------	0.4235	0.4591
Power loss reduction Index (kVAr)	-----------	-----------	0.4609	0.4506
Maximum Voltage (PU)	0.8023	0.8614	0.9596	0.9776
Minimum Voltage (PU)	0.6387	0.7390	0.8391	0.8486
Total Load Demand (MW)	18.843	11.734	19.629	12.645
Total Load Demand (MVAr)	11.306	7.040	11.119	6.123
System Load Balancing Index (LBI_{Syst})	0.9564		0.5294	
Percentage Reduction of LBI_{Syst}	-------------		44.6466	
Tie Switches	15 16 19 33 42 52 64 104 105 131		15 16 33 42 52 104 105 131 142 163	

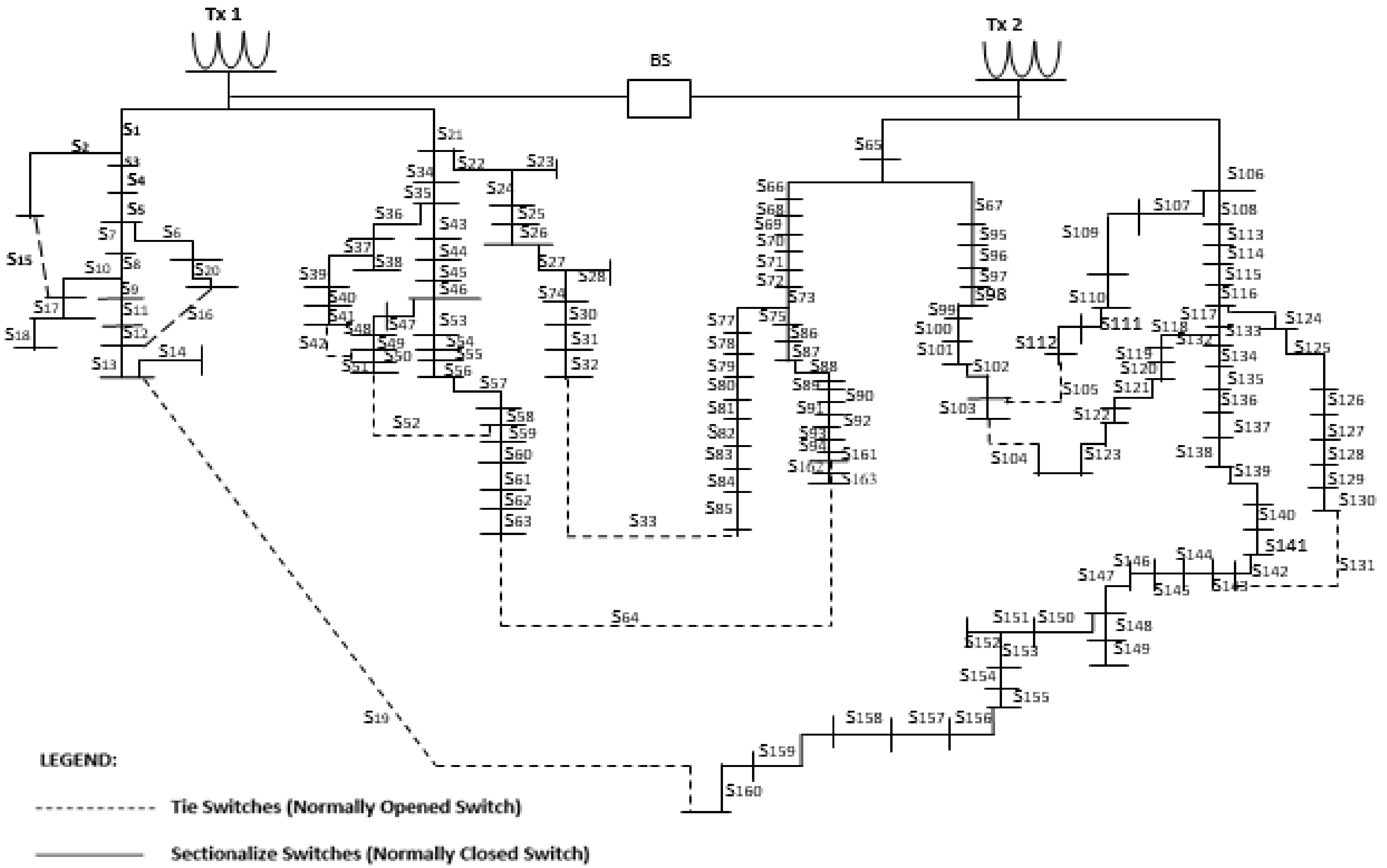

Figure 3: The Existing Configuration of the Ugbowo 2x15MVA, 33/11kV Distribution Network

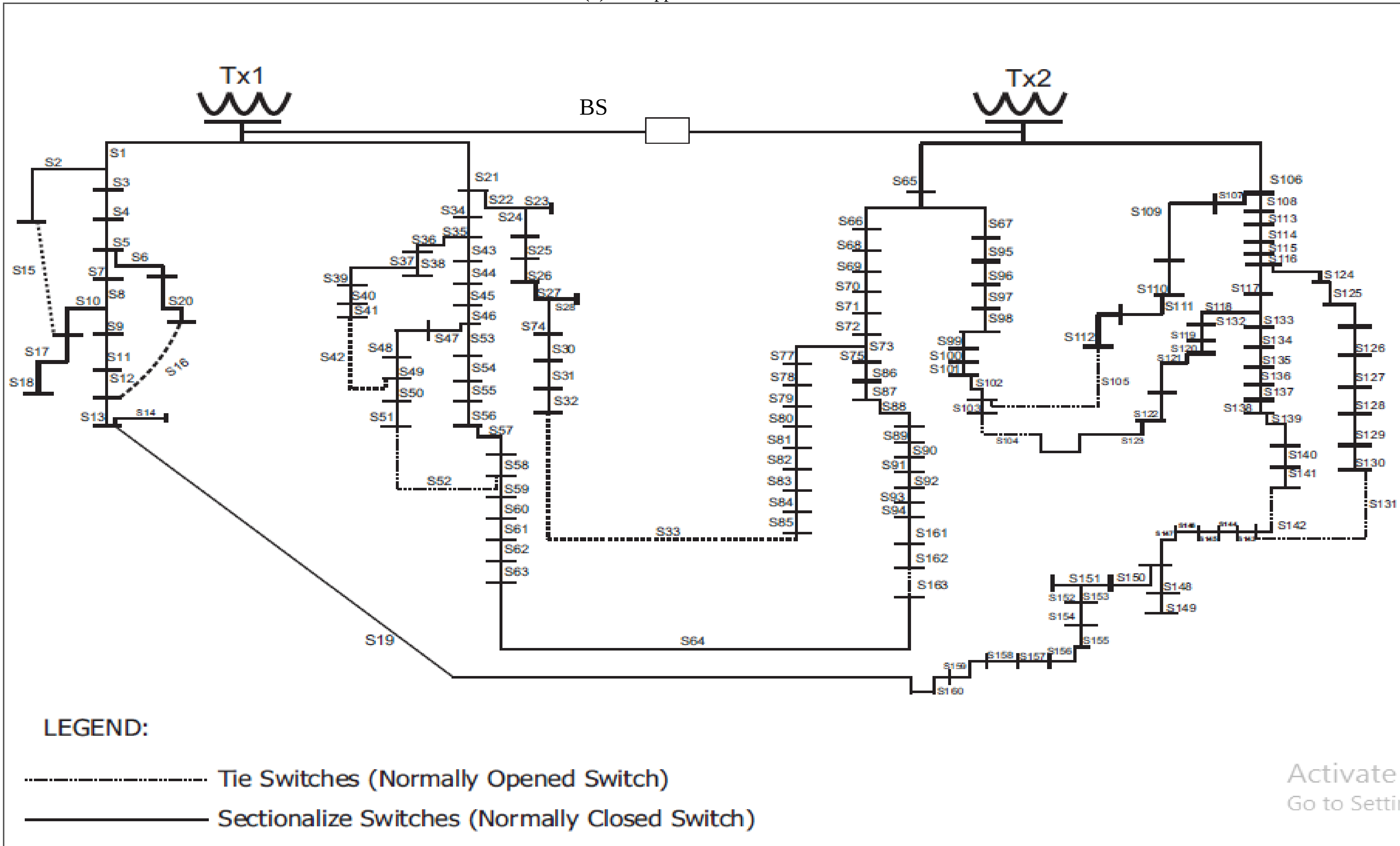

Figure 4: The Proposed Optimal Configuration of the Ugbowo 2x15MVA, 33/11kV Distribution Network

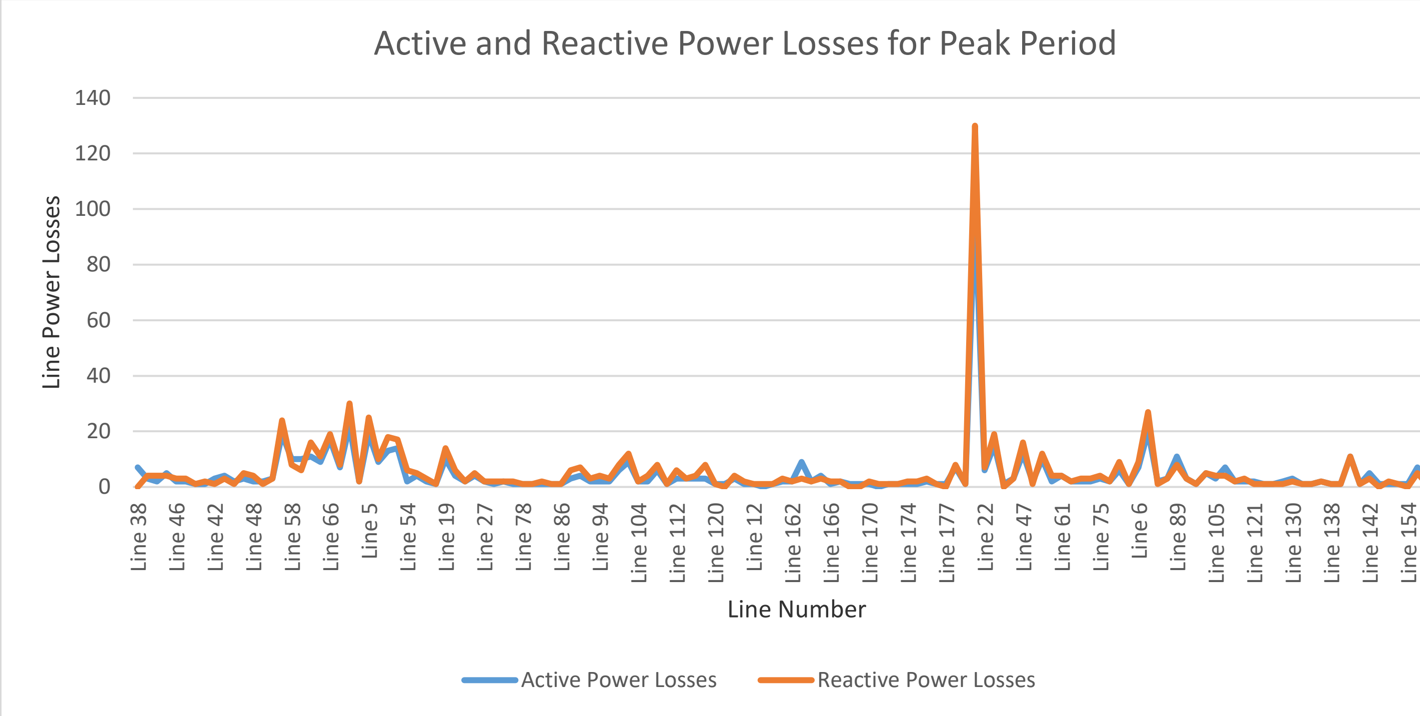

Figure 5: Active and Reactive Line Losses for each Connected Bus for Peak Period Before Optimal Network Reconfiguration.

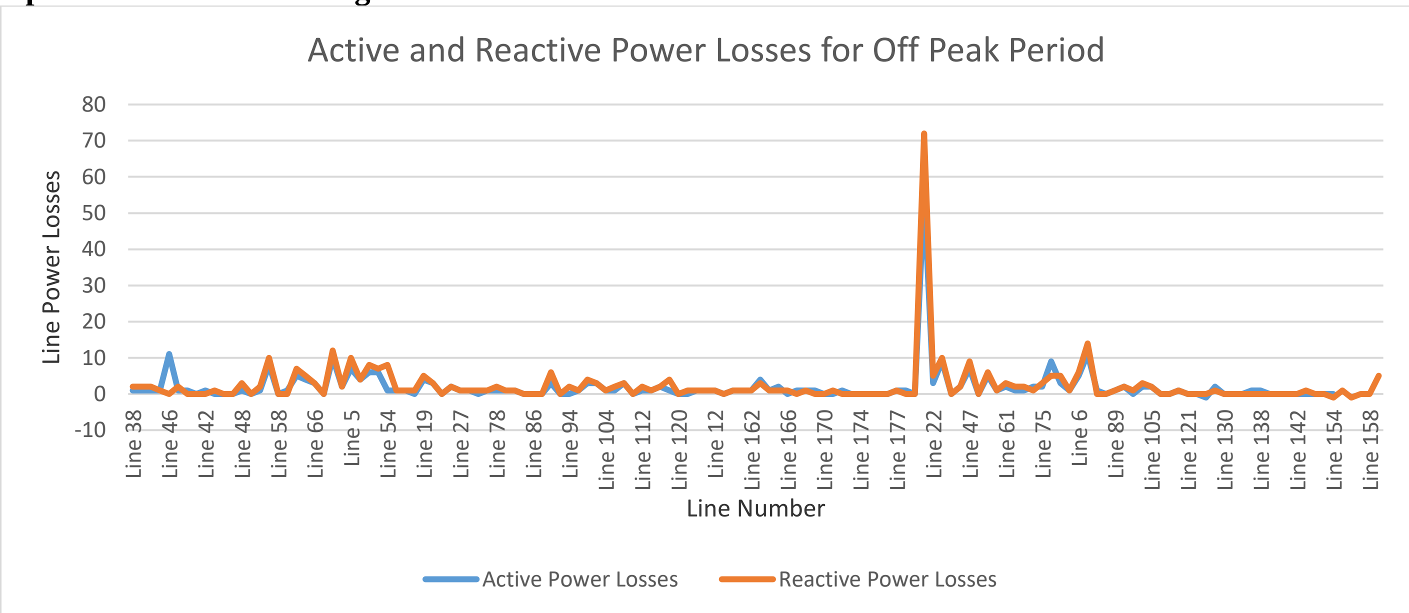

Figure 6: Active and Reactive Line Losses for each Connected Bus for Off Peak Period Before Optimal Network Reconfiguration.

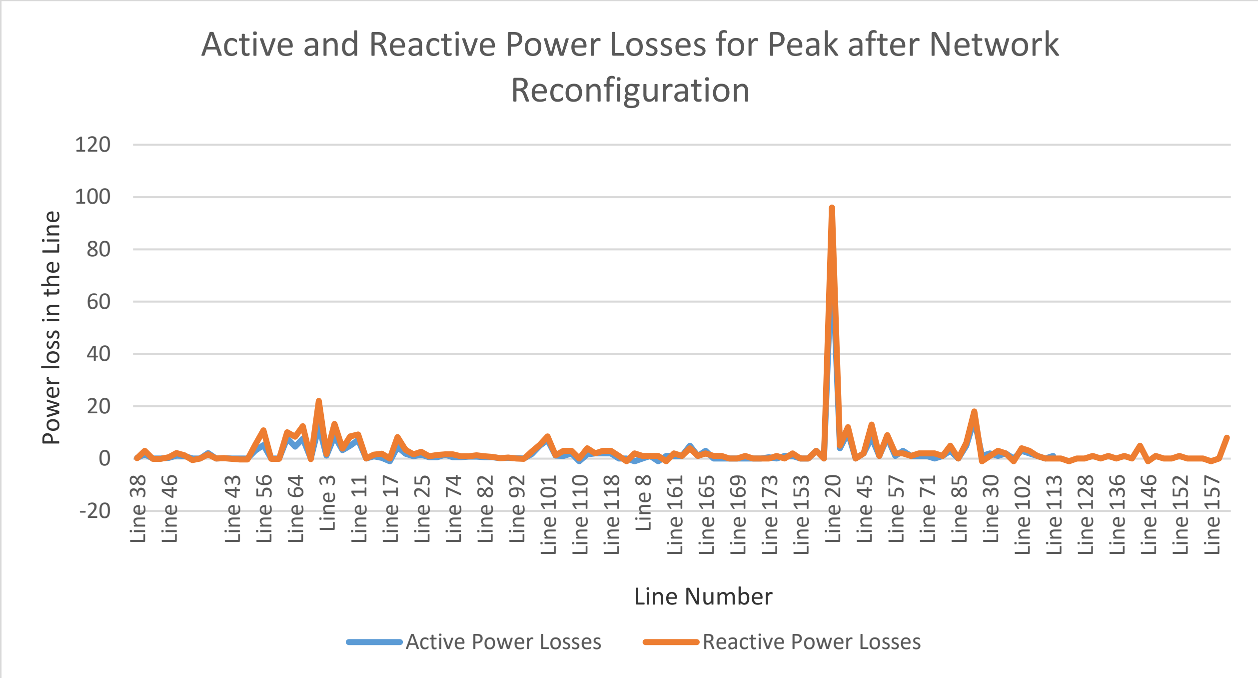

Figure. 7: Active and Reactive Line Losses for each Connected Bus for Peak Period after Optimal Network Reconfiguration.

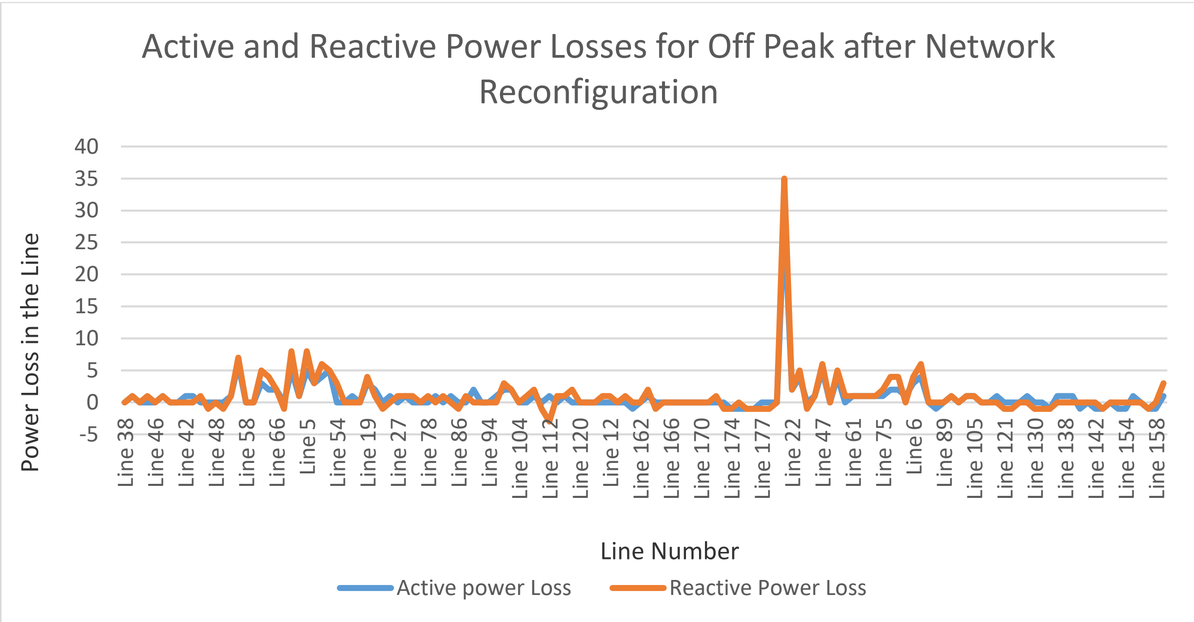

Figure 8: Active and Reactive Line Losses for each Connected Bus for Off Peak Period after Optimal Network Reconfiguration.

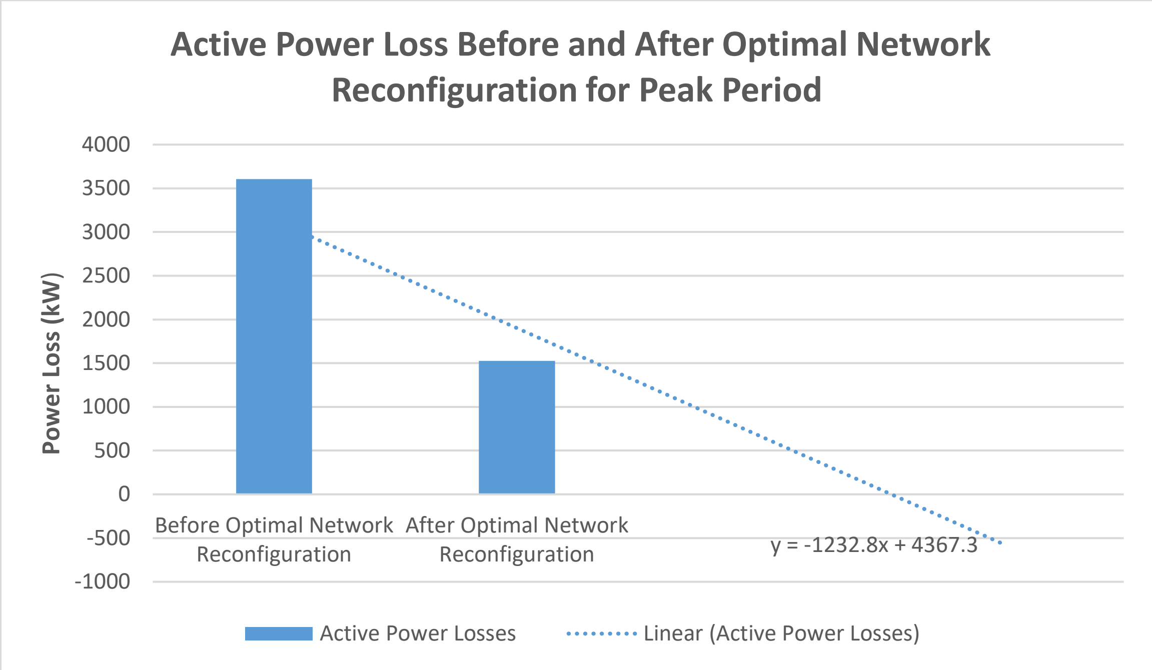

Figure 9: Active Power Loss Before and After Optimal Network Reconfiguration for Peak Period

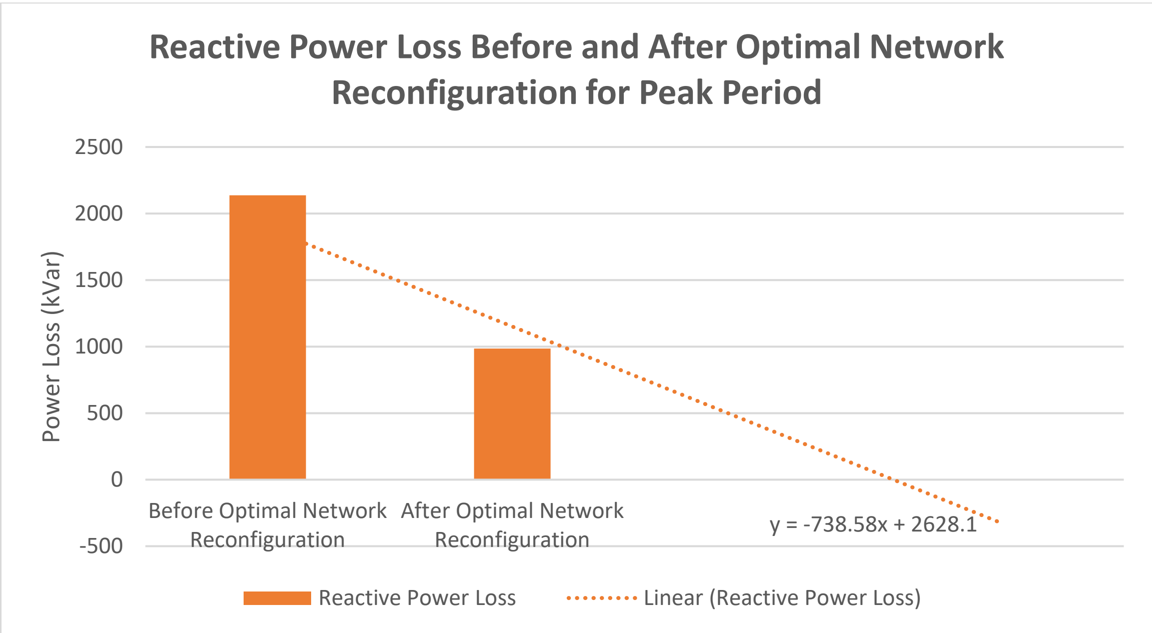

Figure 10: Reactive Power Loss Before and After Optimal Network Reconfiguration for Peak Period

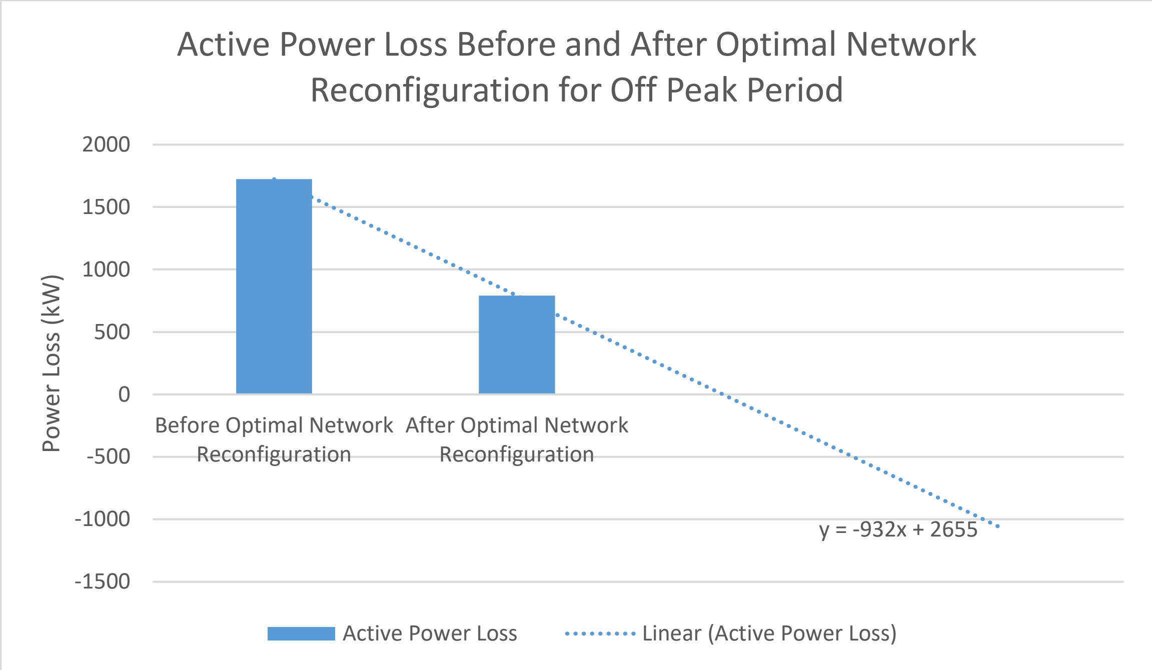

Figure 11: Active Power Loss Before and After Optimal Network Reconfiguration for Off Peak Period

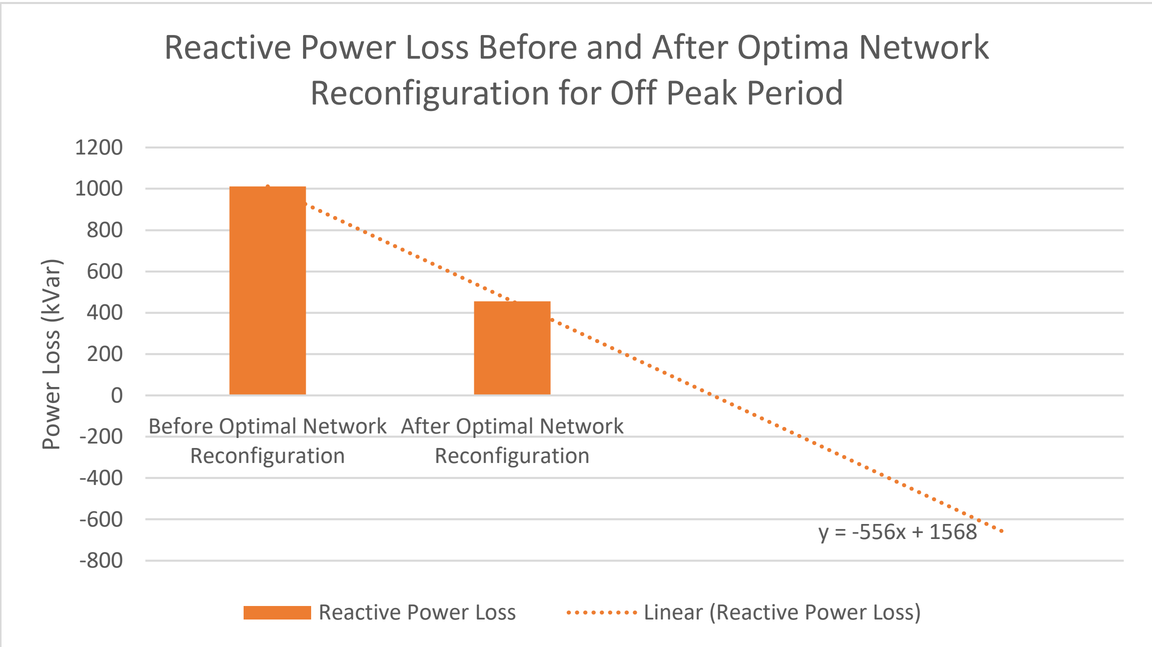

Figure 12: Reactive Power Loss Before and After Optimal Network Reconfiguration for Off Peak Period

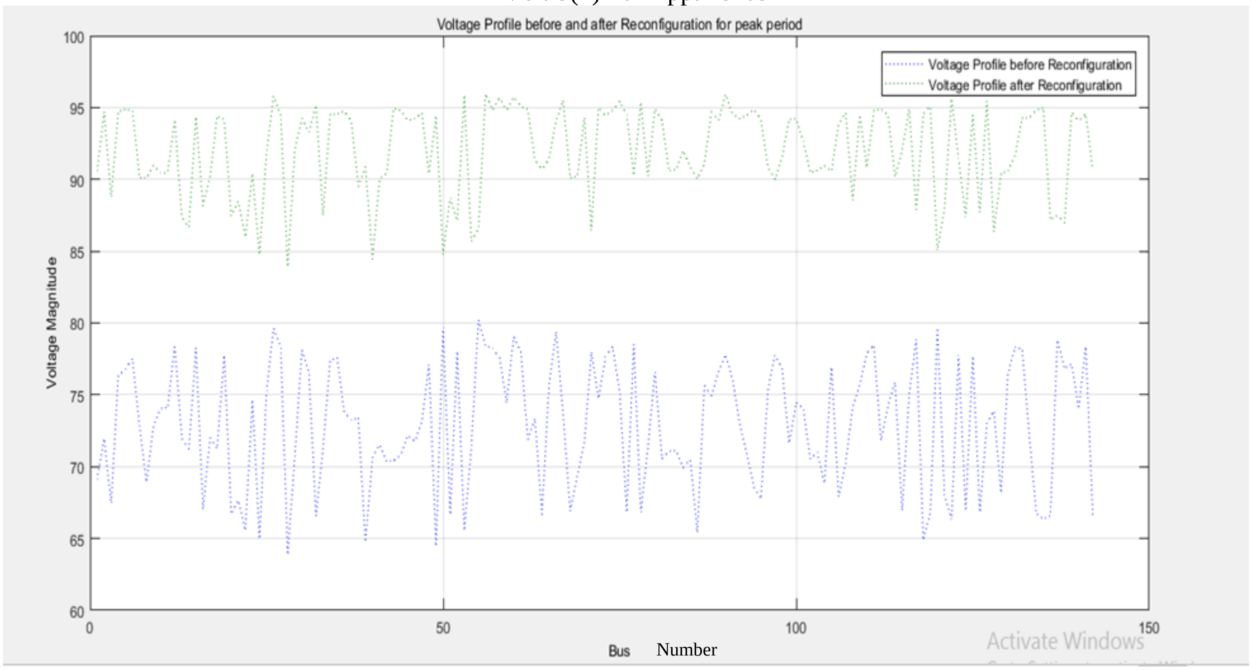

Figure 13: Voltage Profile of the Existing and the Proposed Configuration of the Ugbowo 2x15MVA, 33/11kV Power Distribution Network for Peak Period

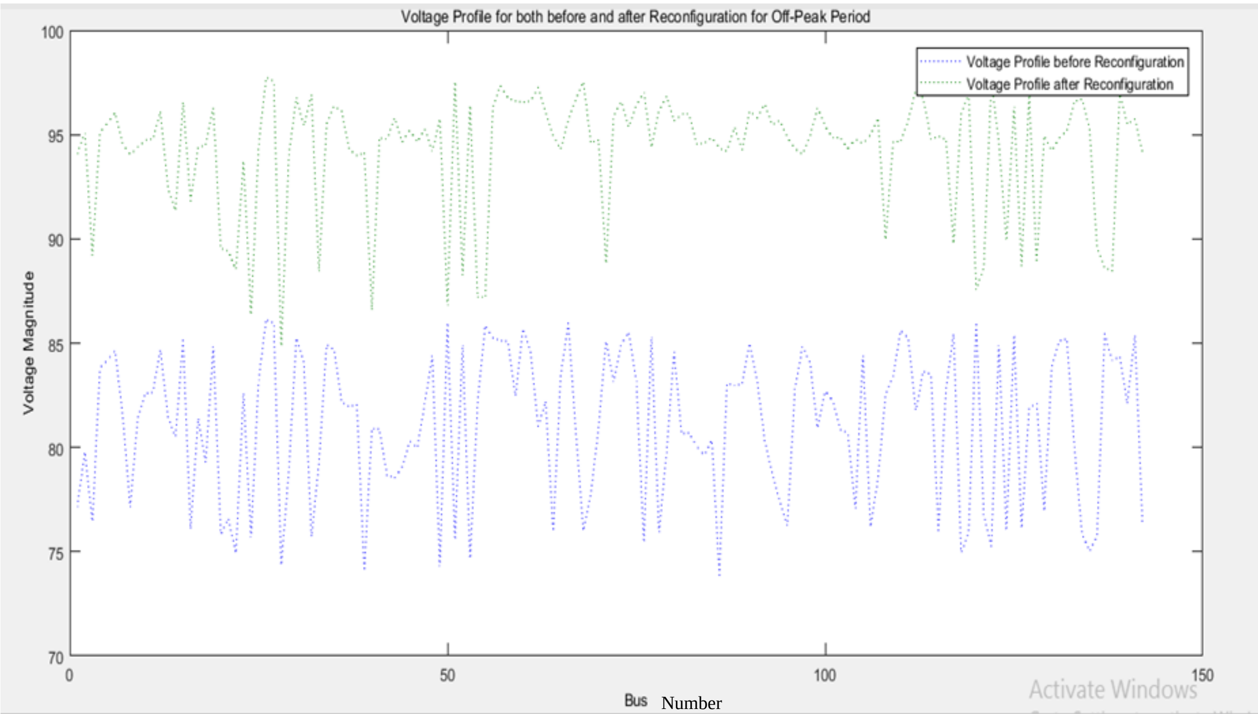

Figure 14: Voltage Profile of the Existing and the Proposed Configuration of the Ugbowo 2x15MVA, 33/11kV Power Distribution Network for Off Peak Period

From the graphs depicted in Figures 5, 6 and the result in Table 1, the network under investigation was on red alert with high power losses which reveals the under voltage system, poor power quality and frequent power outages occurring in the distribution network before the application of optimal network reconfiguration (ONR), while Figures 7, 8, 9, 10, 11 and 12 showed the power loss reduction for peak and off peak period after the application of optimal network reconfiguration. Also, Figures 13 and 14 showed the voltage profile improvement in the distribution network under investigation. Consequently, the method demonstrates its validity in power loss reduction, feeders' load balancing and voltage profile improvement.

4.0 Conclusion

The capacity of the optimization tool for power loss reduction, feeders' load balancing and voltage profile improvement in the Ugbowo 142-bus distribution network using BPSO algorithm for the optimal network reconfiguration has been successfully demonstrated in this work using MATLAB Vr2017a. The power loss was reduced by 57.65% for peak period and 54.09% for off peak period; while the voltage is increased from 0.8022pu to 0.9596pu for peak period and 0.8614pu to 0.9776pu for off peak period. The validity of the suggested algorithm is achieved by altering the parameters that stimulates the system power losses reduction and voltage profiles improvement. These parameters of the algorithm that were controlled are the particles velocities and positions, whereby the resultant effects showed that the BPSO algorithm have the capacity in reducing power losses, optimal feeders' load balancing and voltage profile improvement was optimal. The BPSO algorithm results demonstrated higher capacity of power loss reduction, feeders' load balancing and a better voltage profile improvement when compared to other heuristic algorithms from literature surveyed.

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