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The Sway of Optimal Network Reconfiguration and Contingency Analysis on Electric Power Distribution System

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Abstract: *The aim of carrying out optimal network reconfiguration and contingency analysis of electric power distribution system under normal operating conditions is to reduce the total power losses of the network or to balance the load of the system's feeders. This is an important part of the distribution network operation to improve the system availability, reliability, stability and also, to see its effects when applied. However, the main objectives of the distribution network engineers are power losses minimization, maintenance of good voltage profile, minimum feeders' current levels and stability of the network. Therefore, this paper proposed the sway of optimal network reconfiguration (ONR) and contingency analysis (CA) of the Ugbowo 2x15 MVA, 33/11 kV distribution network for high system power loss reduction, feeders' load balancing and voltage profile improvement. The binary version of the particle swarm optimization (BPSO) algorithm was used to optimally select the switches in the network and it was programmed in MATPOWER and ran in MATLAB R2017a version. Line contingency analysis was also done and the simulation of the power flow was run again to see it impact. The simulations result revealed that the proposed techniques optimally selected the switches that produced the best configuration and stable network which resulted in minimum power loss, reduction of the load balancing index, balancing of the feeders' load and improving the system's voltage profile in most of the buses of the network within tolerance levels of ±6%.*

Keywords: *BPSO algorithm, contingency analysis, distribution network, optimal network reconfiguration, power loss, voltage profile.*

1. INTRODUCTION

Stable electricity supply plays a very significant and impactful role in socio-economic and technological development of every nation [1]. Besides, the amount of electric energy supply per capita in a country and its reliability also play an important role as well in the socio-economic and technological advancement. But in recent times and even now, the frequent power interruptions in the Nigeria electric power distribution network has become a recurrent decimal and it is tagged as one of the biggest obstacles to be tackled in the distribution network of the power systems [2]. This frequent interruption is as a result of unscheduled and scheduled outages currently occurring in the distribution network. The reasons for the frequent power interruptions are due to inadequate generation capacity, equipment limitations and systems fault. This has resulted to poor availability in the supply of electricity in the network.

Despite the current poor generation, high power losses occur in the power lines of the Nigerian power system. According to [3,4 & 5] up to 13% of the total power generated is wasted in the form of line losses at the distribution level as indicated and stated in recent studies. Also, [6] opined that 40% of the power generated is lost in the transmission and distribution lines of the Nigeria power systems. The problem of power losses in the distribution network is enormous. According to [7], the power losses in the distribution networks can account for up to seventy (70%) percent of the total power losses in the power systems. 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. In the words of [8], power losses in the distribution network cause limitations of the system loadability. Therefore, the problem of reducing distribution network power losses, voltage profile improvement and power quality have been one of the 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. [9 & 10]. Though, the techniques use in reducing power losses in electric distribution system is numerous but the major concern when adopted is about their technical implications on the network both in engineering terms and financial perspectives [11]. 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, etc. Therefore, the impact of optimal network reconfiguration and contingency analysis to solve the power problem of high line losses, load balancing and voltage profile improvement in the distribution network is timely and cost efficient, compared to other methods. According to [2] the importance of optimal network reconfiguration and contingency analysis can't be overemphasized in power loss reduction, maximizing load balancing, improvement of voltage profile and reliability enhancement in the distribution network. Also, [12] 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 reliability. Hence, optimal network reconfiguration is defined as operations that alters the topological structure of the distribution feeders by changing open/closed status of sectionalizing and tie switches. According to [13], network reconfiguration is a process of changing the switch states of the network. Therefore, optimal network reconfiguration is defined as the best way of selecting and altering the open/closed statuses of switches in the system for optimum configuration of the network that will bring about power loss reduction, load balancing and voltage profile improvement. To carry out optimal network reconfiguration, it involves two fundamental steps:

a. varying network topology by optimally selecting and changing the status of normally open/closed switches of the system by using an algorithm and,
b. subsequent execution of power flow analysis to determine the operational characteristics of the modified system [e.g power loss level, bus and line voltages, load level in the power lines, etc.] [14].

1.1 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, 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 2x15 MVA, 33/11 kV distribution network and associated bus voltages. The feeder line between bus i and bus i+1 is given in Figure 1 which connect the buses and is calculated as [15]:

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

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 obtain by summation of the power losses in all of the line segments of the distribution network and is given as:

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

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:

$$N_{PL} = N_b - 1 \quad (3)$$

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:

$$\Delta P_L^{ratio} = \frac{P_L^{rec}}{P_L^{init}} \quad (4)$$

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:

$$\Delta V_D = \max_{i=1....N_b}\left[\frac{V_1 - V_i}{V_1}\right] \quad (5)$$

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

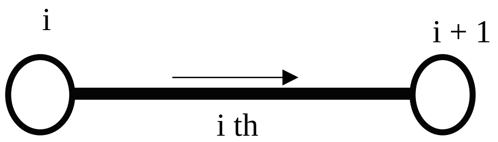

Figure 1: Schematic Representation of a Feeder Line Connecting Two Adjoining Buses

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

$$V_{i\min} \le V_i \le V_{i\max} \quad (7)$$

ii. Branch Current Limit

$$I_{i\min} \le I_i \le I_{i\max} \quad (8)$$

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

iii. Power Flow Constraints

$$S_i \le S_{i\max} \quad (9)$$

iv. Radial Structure Limit

$$J \in P \quad (10)$$

Where:
J is the topology structure after optimal network reconfiguration
P is the set of all feasible topology structures.

v. Feeder Capacity Limit

$$|I_i| \le I_{i\max} \quad (11)$$

vi. Node Constraints

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

1.1.1 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.

1.2 Binary Version of 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 represented 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 and the process continues till the criteria for stoppage are met.

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

Solving the optimal network reconfiguration (ONR) problem by BPSO can be categorized into three steps as follows:

a. determine the number of dimensions;
b. find the search space for each dimension; and
c. using BPSO technique to select the optimal solution from the search spaces

The flow chart of the algorithm is shown in Figure 2:

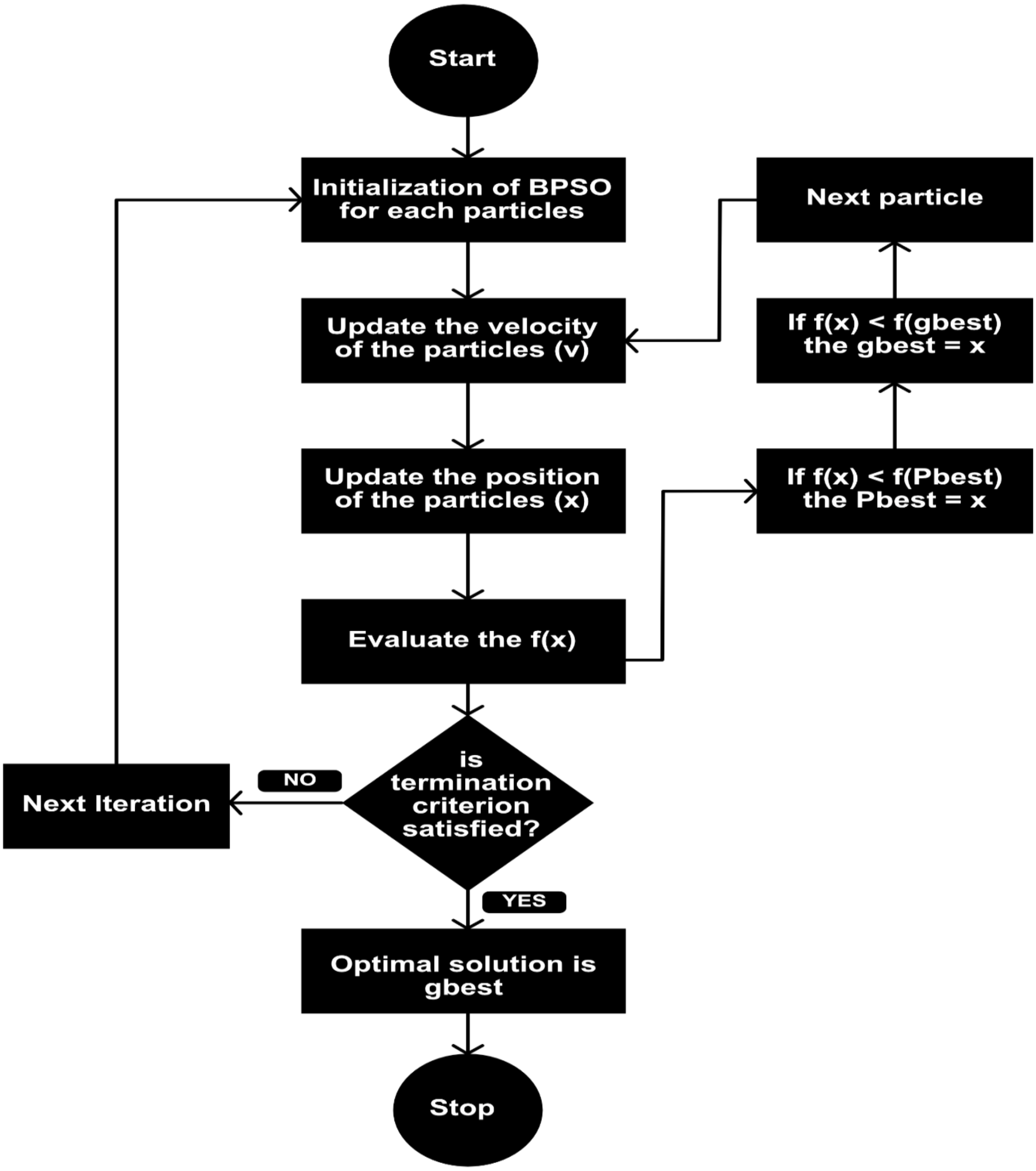

Figure 2: The Flow Chart of BPSO for Optimal Network Reconfiguration of Distribution System

1.3 Contingency Analysis (CA) Procedure

An electric power system comprises of various components such as alternators, transformers, transmission lines, buses, circuit breakers, etc., and the stability/security of these components are very important to the operation of the power system [19]. Therefore, contingency analysis (CA) is the study of the outage of components such as generators, power lines, transformers, buses, circuit breakers, etc., and the investigation of the resulting effects on electric line power flows and bus voltage of the remaining components of the electric power system [20]. It can also be defined as the non-functional of a device in the power system such as generators, transformers, power lines, etc., or the changes of the device state which include changing the size of the power line conductor sizes, sudden removal of generator, breakage of line, etc. The purpose of contingency analysis is to check and simulate the effect of the changes that have occurred on the functionality and sustainability of the power system. Generally, contingency analysis provides the medium for creating, analyzing, managing and describing the various events and its associated violations.

1.3.1 Line Contingency Analysis

Line and generator contingencies are the most common types of contingency. These contingencies mainly cause two types of violations which are: Line Mega Volts Ampere (MVA) limits violations and low voltage violations. The line MVA limits contingency violations occur in a system when the MVA rating of the line exceeds a given rating. The power lines are designed in such a way that should be able to withstand 125% of their MVA limit and based on utility practices, if the current crosses 80 – 90% of the limit, it is declared as an alarming situation [21]. But low voltage type of violation occurs at the various buses are less than the statutory limit ±6%.

The Ugbowo 2 x 15 MVA, 33/11 kV distribution network is modeled and simulated in the based configuration that comprises of 100mm^2 and 150mm^2 feeder conductor sizes and all the feeder conductor sizes of 150mm^2 only to see the effect of the changes of the conductor size on the distribution network.

2. MATERIALS AND METHODS

This section deal with the materials and methods deployed to achieve our results.

2.1 MATERIALS

The data was collected from the Ugbowo 2 x 15 MVA, 33/11 kV distribution network which comprises of one hundred and fifty-nine (159) buses, out of which one hundred and forty-two (142) buses were in service as at the time of writing. The Ugbowo electric power distribution network comprises of conductors of cross sectional area 100mm^2 and 150mm^2 respectively. All the conductors are of Aluminum Conductor Steel Reinforced (ACRS). The load and transformers data as well as the feeders' length were taken. The load of the associated substation was classified into peak and off peak periods in the network under investigation. The peak period was between 6:00am to 8:00am and 6:00pm to 9:00pm, while the remaining time was taken as off peak period in our study. Although intermediate period does exist in the network, it was not taken into consideration in this study.

2.2 METHODS

The distribution network under investigation was modeled in Electrical Transient and Analysis Programme (ETAP 16.0) and the Newton-Raphson (NR) technique was deployed for the power flow studies. The original PSO was modified based on the unique characteristics of the distribution network feeder operations and the Ugbowo 2 x 15 MVA, 33/11 kV distribution system with one hundred forty-two (142) buses. They 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 the three (3) phase system with a nominal voltage of 415 V and the base apparent power of 30 MVA. The real-time system was used for the optimal network reconfiguration (ONR) which was programmed in MATPOWER and ran in MATLAB R2017a 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. The relevant information revealing the performance was retrieved with case study implemented as all the various branches and nodes of the network connected to supply. The Figure 3 showed the base configuration of the network under study and subsequently, the binary version of particle swarm optimization (BPSO) algorithm was applied to the network to see the effect of the proposed approach. Also, in optimizing the network and how the suggested approach worked effectively in minimizing the high power losses in the network under investigation. The extent of voltage profile improvement by the method was showed as well. 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 4 showed the single line diagram of the Ugbowo 2 x 15 MVA, 33/11 kV distribution network modelled in ETAP environment.

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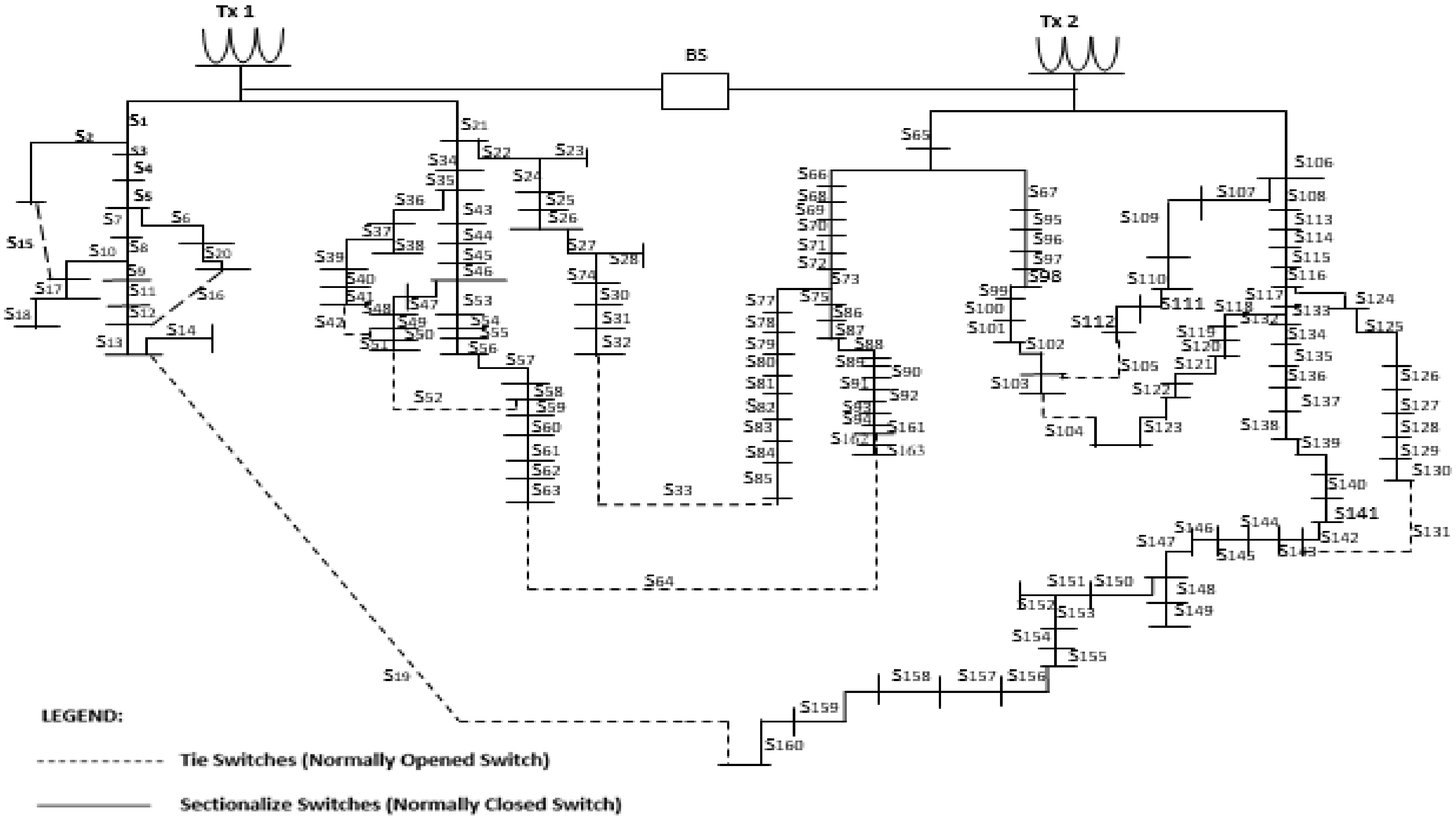

Figure 3: The Existing Configuration of the Ugbowo 2 x 15 MVA, 33/11 kV Distribution Network

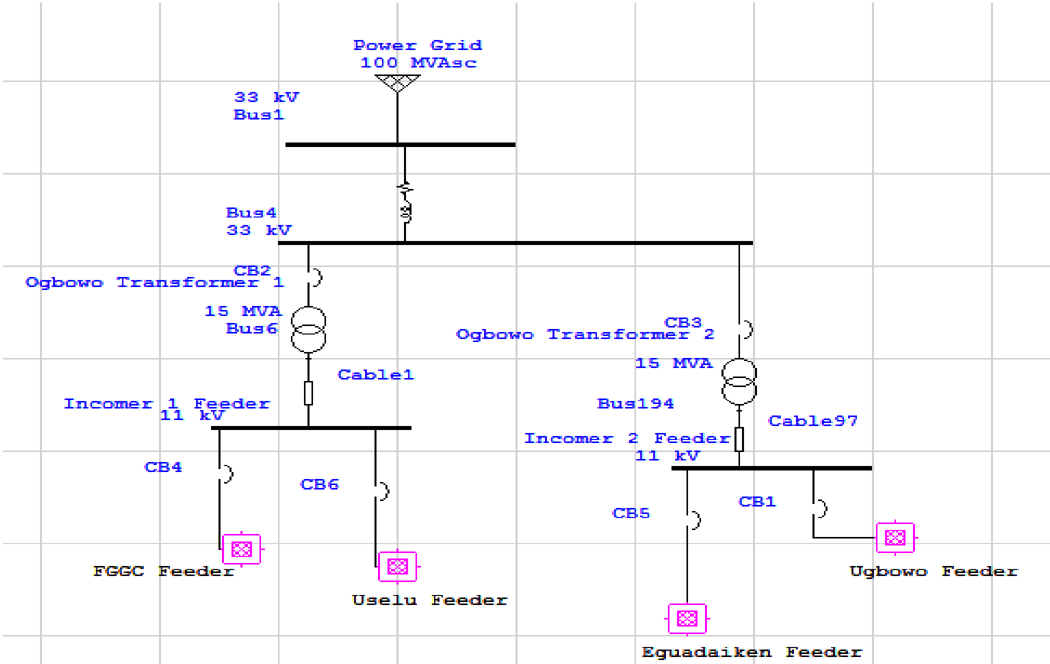

Figure 4: Single Line Diagram of Ugbowo 2 x 15 MVA, 33/11 kV Distribution Network in ETAP Environment

3 RESULTS AND DISCUSSION

This section will present the simulation results and the extensive discussion.

3.1 RESULTS

The simulation results are presented as follows:

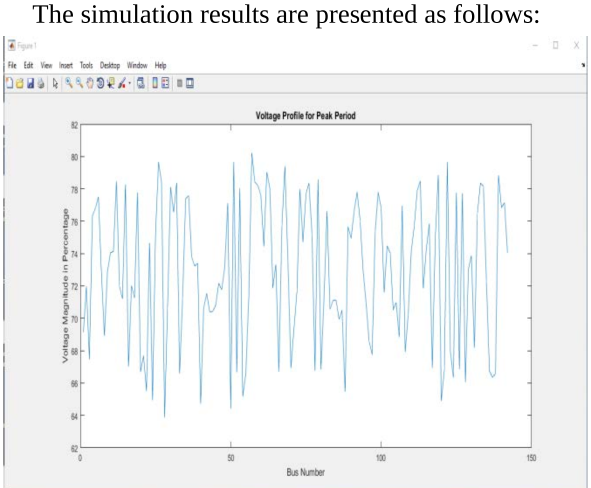

Figure 5: Voltage Profile of Existing or Base Configuration for Peak Period with 100mm^2 and 150mm^2 Conductor Sizes

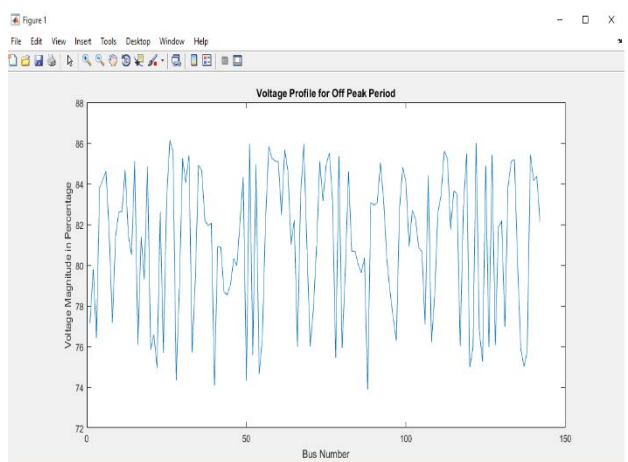

Figure 6: Voltage Profile of Existing or Base Configuration for Off Peak Period with 100mm^2 and 150mm^2 Conductor Sizes

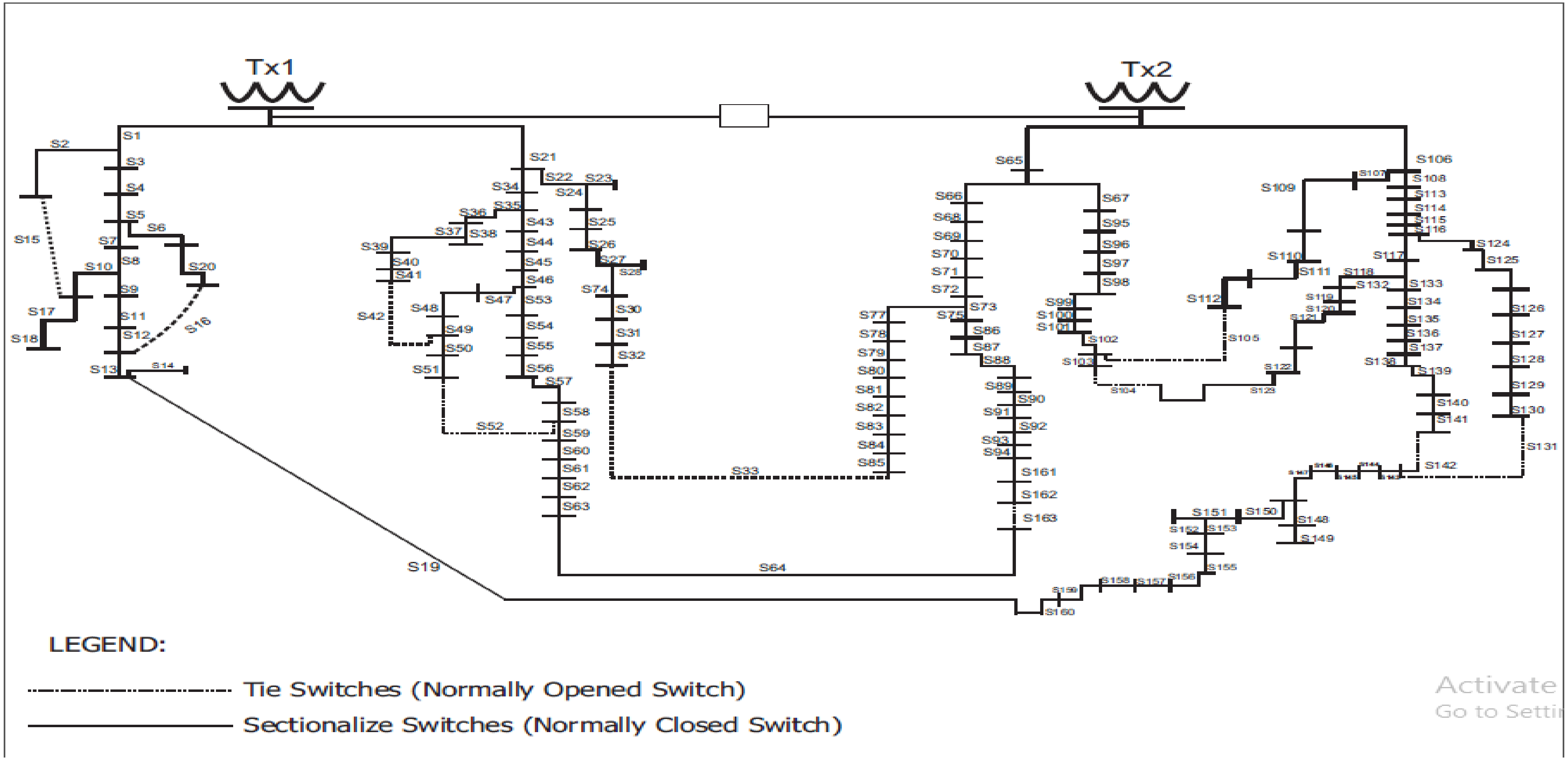

Figure 7: The Proposed Configuration of the Ugbowo 2 x 15 MVA, 33/11 kV Distribution System after Optimal Network Reconfiguration

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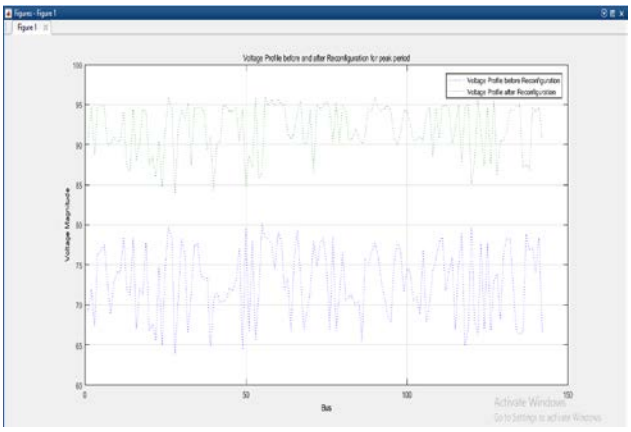

Figure 8: Voltage Profile of the Existing and the Proposed Configuration with 100mm^2 and 150mm^2 Feeder Conductor Sizes for Peak Period

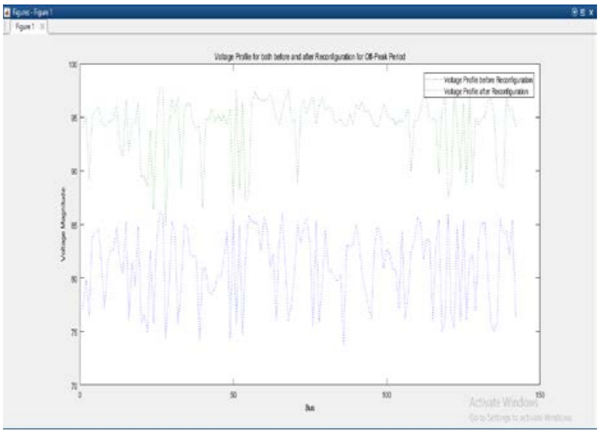

Figure 9: Voltage Profile of the Existing and the Proposed Configuration with 100mm^2 and 150mm^2 Feeder Conductor Sizes for Off Peak Period

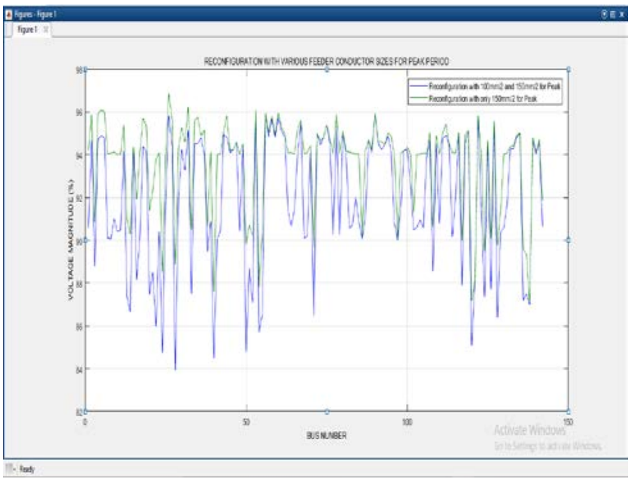

Figure 10: Voltage Profile of the Proposed Configuration with 100mm^2&150mm^2 and with only 150mm^2 Feeder Conductor Sizes for Peak Period

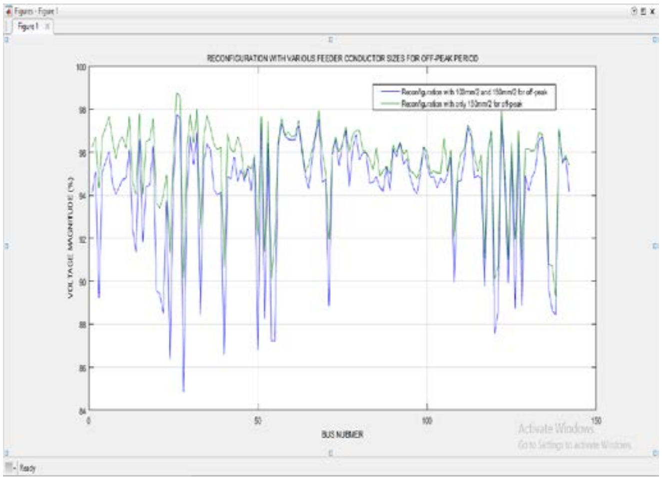

Figure 11: Voltage Profile of the Proposed Configuration with 100mm^2&150mm^2 and with only 150mm^2 Feeder Conductor Sizes for Off Peak Period

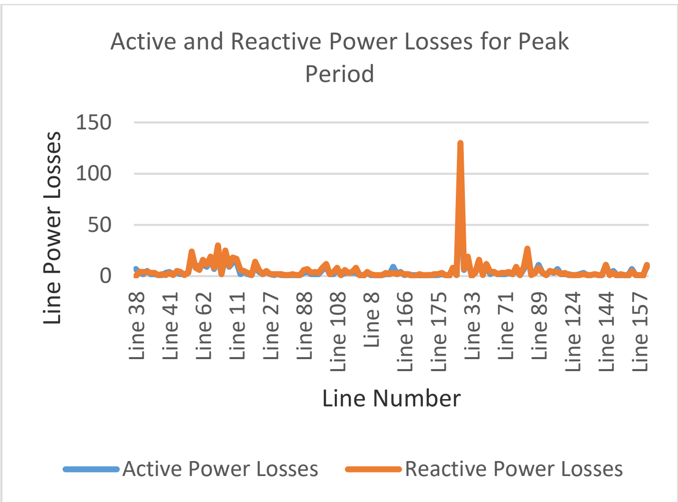

Figure 12: Active and Reactive Line Losses for Base Configuration of each Connected Bus for Peak Period.

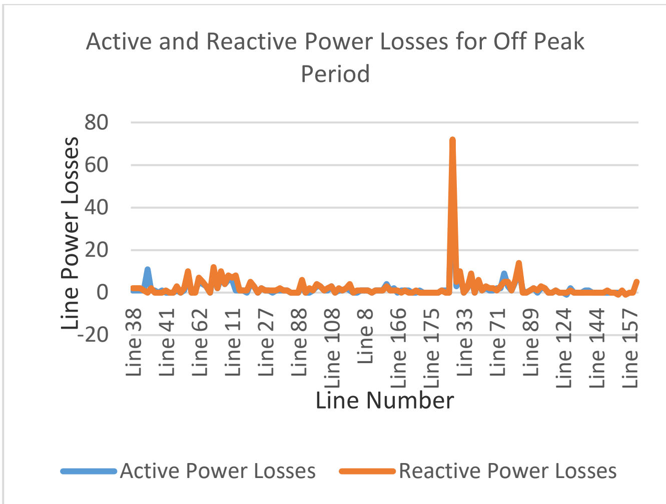

Figure 13: Active and Reactive Line Losses for Base Configuration of each Connected Bus for Off Peak Period.

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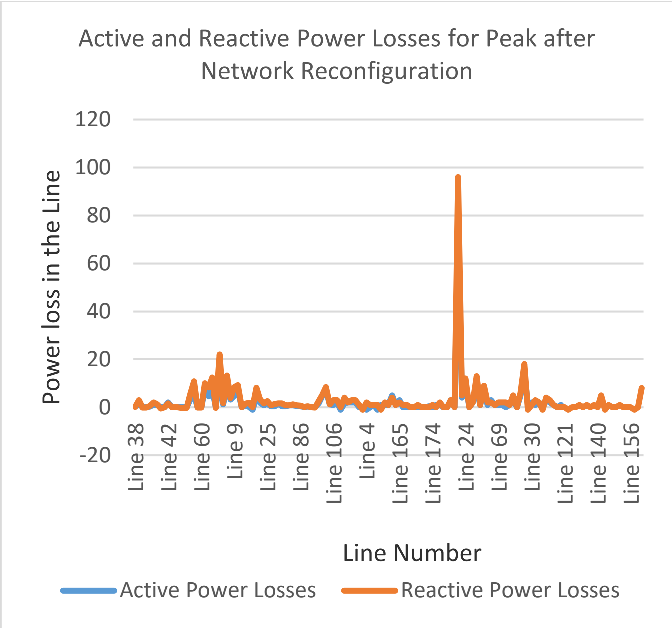

Figure 14: Active and Reactive Line Losses for each Connected Bus for Peak Period after Optimal Network Reconfiguration.

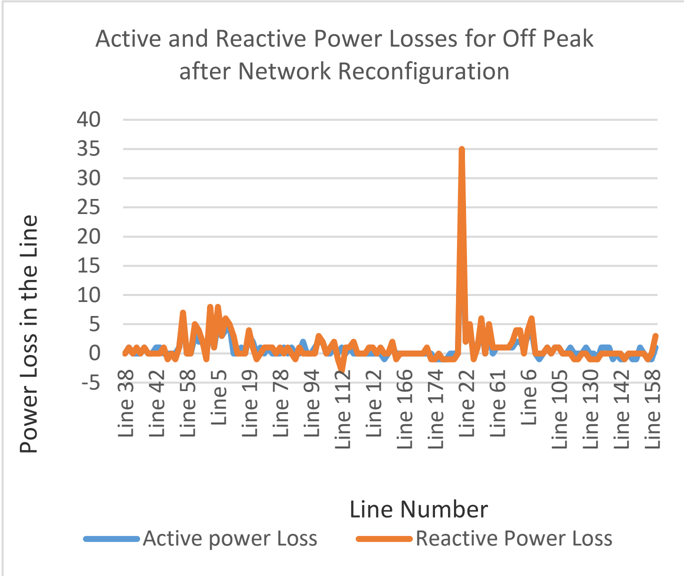

Figure 15: Active and Reactive Line Losses for each Connected Bus for Off Peak Period after Optimal Network Reconfiguration.

Table 1: Summary of Optimal Results of the Ugbowo One Hundred and Forty-Two (142) Bus Distribution Network

Description of Items	Before Optimal Network Reconfiguration		After Optimal Network Reconfiguration without Contingency		After Optimal Network Reconfiguration with Contingency	
	Peak Period	Off Peak Period	Peak Period	Off Peak Period	Peak Period	Off Peak Period
Power Losses (kW)	3606	1723	1527	791	867	517
Power Losses (kVAr)	2137	1012	985	456	564	314
% of Power loss reduction (kW)	-----------	-----------	57.654	54.09	75.96	69.99
% of Power loss reduction (kVAr)	-----------	------------	53.91	54.94	73.61	68.97
Power loss reduction Index (kW)	-----------	------------	0.4235	0.4591	0.2404	0.3001
Power loss reduction Index (kVAr)	-----------	-----------	0.4609	0.4506	02639	0.3103
Maximum Voltage (PU)	0.8023	0.8614	0.9596	0.9776	0.9685	0.9877
Minimum Voltage (PU)	0.6387	0.7390	0.8391	0.8486	0.8712	0.901
Total Load Demand (MW)	18.843	11.734	19.629	12.645	20.13	13.424
Total Load Demand (MVAr)	11.306	7.040	11.119	6.123	10.287	5.918
System Load Balancing Index (LBI_{Syst})	0.9564		0.5294		0.4851	
Percentage Reduction of LBI_{Syst}	--------------		44.6466		49.2785	
Tie Switches	15 16 19 33 42 52 64 104 105 131		15 16 33 42 52 104 105 131 142 163			

3.2 DISCUSSION OF RESULTS

Figure 5 and 6 showed the results of the voltage profiles of the base configuration, while Figure 12 and 13 showed the power losses for both peak and off peak periods respectively. Figure 7 showed the proposed optimal configuration of the network under investigation after the binary version of particle swarm optimization (BPSO) algorithm was optimally used to select the switches to be opened and closed respectively to produce the best configuration in the distribution network at time, t. Also, Figure 8 and 9 showed the voltage profile improvement of the proposed network with 100mm^2 and 150mm^2 feeder conductor sizes; while Figure 14 and 15 showed the power losses of the improved network with 100mm^2 and 150mm^2 feeder conductor sizes for both peak and off peak periods respectively. Figure 10 and 11 showed further the voltage profile improvement when line contingency analysis was done in the network. That is the voltage profile improvement in Figure 10 and 11 showed the optimal voltage curve with 100mm^2 & 150mm^2 and 150mm^2 only feeder conductor sizes for both peak and off peak periods respectively and Table 1 showed the summary of the results for the existing configuration with 100mm^2 & 150mm^2 feeder conductor sizes, proposed configuration with 100mm^2 & 150mm^2 feeder conductor sizes and proposed configuration with 150mm^2 only feeder conductor sizes for both peak and off peak periods.

4. CONCLUSION

The capability of the optimization tool deployed in this research for optimal power loss reduction, feeder load balancing and voltage profile improvement has been shown in the robustness of the methods applied in minimizing the power losses, load balancing and voltage profile improvement of the Ugbowo 2 x 15 MVA, 33/11 kV distribution network which consists of one hundred and forty-two (142) buses.

The validity of the BPSO algorithm suggested was achieved by altering the parameters that stimulated the system power loss reduction and voltage profile improvement [22]. The parameters that were controlled were the particles velocities and positions whereby the resultant effect showed that the BPSO capacity in reducing power losses, optimal feeders' load balancing and voltage profile improvement was optimal. The proposed algorithm results demonstrated higher capacity of power loss reduction, feeders' load balancing and a better voltage profile improvement when the line contingency analysis was done as compared to other heuristic family in the literatures surveyed.

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