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APPLICATION OF WHALE OPTIMIZATION ALGORITHM (WOA) FOR DISTRIBUTION NETWORK RECONFIGURATION SCHEME FOR POWER QUALITY IMPROVEMENT

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ABSTRACT

Electrical power distribution networks (DN) are usually designed and operated in a radial configuration, but their topology, especially when highly loaded, is often meshed in order to improve system reliability and quality of the supply. This makes it feasible to alter the network topology after an outage to restore the service to affected areas. In addition, various power quality indicators can be improved by modifying the topology of the DNs, achieved by changing the close/open status of sectionalizing and ties switches on the feeders. However, Distribution Network reconfiguration (DNR) is a non-linear, multi-objective, constrained and combinatorial optimization problem hence, Whale Optimization Algorithm (WOA) technique is employed for optimal Distribution Network Reconfiguration of primary Distribution Network with the aim of minimizing the real power loss (PL) and voltage deviation (VD), as well as improving feeder load balancing (FLB). The developed method is applied on IEEE 33 and 69 test systems. To ascertain its applicability to real-life system, the developed DNR technique is also applied on 11kV RIGASA feeder in Kaduna State, Nigeria. The problems this research is trying to address are power losses and voltage deviation and feeder load balancing experienced in Kaduna electricity distribution network subject to some operational constraints. From the simulation results, substantial reduction in power loss was achieved, the voltage profile has improved and the feeder load balancing was achieved when compared with the original network before reconfiguration as well as when compared to using Runner Root Algorithm based DNR.

1. INTRODUCTION

Distribution Network (DN) is that part of power system which connects the distribution substations to the customers' service-entrance equipment (Abdelaziz, 2017; Jafar-Nowdeh, *et al*., 2020). It is therefore, the last stage in delivery of electric power. DNs are designed as overhead and underground cable (Saadat, 1999), and characterized majorly by two voltage levels; primary or feeder voltage level mostly in the range of tens of kV like typical 13.2kV systems and secondary or customer voltage level in the range of hundreds of volts. Typical example of secondary DN serves customers at levels of 415/240V, single-phase, three-wire system. DS at this level is always radial in nature. It is the final stage of conveying power to customers. Being the last stage of the of power delivery, DN contributes at least 40% of the total power loss occurring in the entire system (Abdelaziz, 2017). DNs are generally designed in loop configuration however; they are operated in radial configuration, for effective coordination of their protection systems. To change the topology of the network from mesh to radial configuration or vice versa, DN reconfiguration technique is applied (Salau, et al., 2016).

Distribution Network Reconfiguration (DNR) is the technique of changing the topological structure of DN by changing the open/close status of the network sectionalizing and tie switches. Sectionalizing switches are Normally Closed (NC) switches placed within each feeder of the DN while tie switches are Normally Open (NO) switches that connect sections of different feeders (Ghasemi, 2016). DNR is one of the complex activities in electric power systems planning as poor configuration leads to increased power losses, poor voltage profile, and low power factor. As such, optimal DNR is an effective way of improving the performance of power DNs such as reducing power losses (Raju & Bijwe, 2008; Thanh & Viet, 2015), voltage profile improvement (Moshtagh & Ghasemi, 2013; Abdelaziz, 2017), balancing load demand (Thanh & Viet, 2015; Zhai, *et al*., 2018), increasing distributed generation (DG) penetration (kianmehr, et al., 2018; Capitanescu, *et al*., 2015), mitigating operational constraint violations (Zhai, et al., 2018), service restoration (P, *et al*., 2009; D & LIiuwhe, 1997), improving system security (Zu, et al., 2018) and relieving primary feeders either due to overload or allow maintenance activities on that feeder (Nguyen, *et al*., 2017). There are other services applied to DNs to improve its conditions such as optimal placement of distributed generation (DG) and use of Flexible AC Transmission System (FACTS), however, DNR is the most cost effective (Salau, *et al.*, 2016). The change of the configuration alters the power flow path in the network resulting in altered line currents, node voltages, and degree of unbalances and also level of distortion of the node voltages in presence of harmonics. Since the impedance of the power flow path also changes due to reconfiguration, the voltage available at a node during a voltage sag condition is also liable to be changed. DNR is carried out either offline better known static DNR or online called dynamic DNR. In static DNR, all the system load demands, generations (both from conventional and DG sources) are assumed constant throughout the reconfiguration process. However, in practice, the load demand and DG output change continuously. In some cases, varying load demand and DG output may cause the system condition outside of permitted operating conditions (Zhai, et al., 2018), hence necessitating the dynamic reconfiguration. In dynamic DNR, the distribution system operators can change the topological structure of DNs in real time by changing the status of remotely controlled switches (Zu, et al., 2018). For instance, (Capitanescu, et al., 2015) applied the dynamic reconfiguration method to improve the DG hosting capacity of active DNs by efficiently countering the effects of time-varying demand and DG output. Due to the quite large number of sectionalizing switches (tie switches are not as that many) in typical DN, choosing the right switch to be turned ON or OFF in order to find the optimal configuration is a challenging problem (Kunya, et al., 2019). This is as a result of many candidate-switching combinations in the system. For this reason coupled with nonlinear characteristics of the DN constraints, DNR is a complex, nonlinear, combinatorial and non-differentiable constrained mixed-integer optimization problem. The complex nature of the DNR problem makes it prohibitive to adopt most of the exact optimization methods to solve it. On the other hand, heuristic techniques have been shown to be particularly suitable to handle the complex optimization problem of DNR. Merlin and Back (Merlin & Back, 1959) were the first to propose the network reconfiguration technique for loss minimization of the system. Later on many researches have been reported in the literature among which are hybrid evolutionary algorithm (EA) (Niknam, 2009), non-dominated sorting genetic algorithm-II (NSGAII) (Moshtagh & Ghasemi, 2013), plant growth simulation algorithm (PGSA) (PV, et al., 2010), ant colony algorithm (Saffar, et al., 2011), multi objective honey bee mating optimization (MHBMO) (Niknam, 2011) and binary particle swarm optimization (B-PSO) (Kunya, et al., 2019). Moreover, due to the impact of network reconfiguration for reduction of network power losses, in most of research works reviewed, this objective is considered along with other objectives formulated multi-objective optimization problem using different evolutionary, heuristic and meta heuristic techniques. In (Ahuja, et al., 2017), a nature-inspired algorithm is adopted to solve the expanded multi-objective DNR model. The hybrid artificial immune systems-ant colony optimization approach is selected in the work due to its ability to handle the multi-objective formulations and to provide restoration solution during contingencies.

2.0 METHODS

2.1 Model of the Network Reconfiguration

The developed optimal DNR of primary DN is aimed at minimizing the real power loss (PL) and voltage deviation (VD), as well as improving feeder load balancing (FLB). These power quality indicators are chosen to improve the system efficiency and equipment (for both customer and utility) reliability.

2.2 Aggregate Objective Function

The objectives of the proposed technique are to minimize the active PL, improve VP and enhance feeder LB. Thus, the objective function has three terms as formulated in (1).

Where;

$$F = \psi f_1 + \beta f_2 + \xi f_3 \quad (1)$$

The first part of the objective function depicts the power loss component obtained by normalizing the PL with its original value as expressed in (2),

$$f_1 = \frac{P_{loss}}{P_{loss}^{initial}} \quad (2)$$

where P_{loss} is the power loss experienced in the optimized DN, while $P_{loss}^{initial}$ is its inherent power loss calculated as;

$$P_{loss}^{initial} = \sum_{i=1}^{n_l} R_i \left\{\frac{P_i^2 + Q_i^2}{V_i^2}\right\} for\ i = 1,2, \dots, n_l \quad (3)$$

The second part of the objective function, f_2 is reflects the component of the total voltage deviation, which when minimized, the VP improves. It is similarly obtained by normalizing its minimized value, V_{dev} with its initial value, $V_{dev.}^{initial}$

$$f_2 = \frac{V_{dev}}{V_{dev}^{initial}} \quad (4)$$

The total inherent voltage deviation is computed as;

$$\Delta V_{total}^{initial} = \sum_{j=1}^{n_b} \left|V_{ref,j} - V_j\right|\ for\ j = 1,2, \dots n_b \quad (5)$$

$V_{ref,j}$ is the nominal voltage magnitude of load bus j.

The third term of the objective function denotes for the LB component of the lines in the feeders, which is shown in (6) (Georgilakis & Hatziargyriou, 2013).

$$LB = \sum_{j=1}^{n_f} \sum_{i=1}^{n_l} \left(\frac{n_f I_i}{\sum_{i=1}^{n_f} I_i}\right)^2 \quad (6)$$

Where n_l and n_f are the total number of lines (branches) and feeders in the DN respectively. ψ, β and ξ are the weighing coefficients of the power loss, voltage deviation and LB components of the objective function respectively. Since there are different objectives to be satisfied simultaneously, after normalizing all the terms of the objectives, the weighing coefficients are chosen thoughtfully to avoid convergence problem.

3.0 POWER FLOW ANALYSIS

The DNR technique requires the bus voltages, line currents, active and reactive power demands at each bus and inherent power loss of the system while determining the optimal reconfiguration. These information of the network are primarily obtained using load flow analysis (LFA). However, due to the low R/X ratio of typical DNs and their tri-diagonal admittance matrices, the commonly used Newton Raphson and fast decoupled load flow methods are ineffective in analyzing such networks as they present lot of convergence problem. Hence, in this study, backward-forward sweeping technique for solving PF recursively, proposed in (Das, 1995) is employed.

Load flow is one of the three major problems encountered in symmetrical steady state of power system (PS) operation. The other two are *optimal load scheduling* and *systems control* problems. Load Flow Analysis (LFA) in PS is the steady state solution of the system network.

3.1 APPLICATION OF WHALE OPTIMIZATION ALGORITH FOR DISTRIBUTION NETWORK RECONFIGURATION

Whale Optimization Algorithm (WOA) is one of the biologically inspired optimization techniques mimicking the hunting behavior of humpback whales. It is the simulated hunting behavior with random or the best search agent to chase the prey and the use of a spiral to simulate bubble-net attacking mechanism of humpback whales. The efficiency of the WOA algorithm developed in this research is evaluated by solving 29 mathematical optimization problems and six structural optimization problems. Optimization results demonstrate that WOA is very competitive compared to the state-of-the-art optimization methods (Mirjalili & Lewis, 2016).

The distribution systems can be described as a matrix with dimensions *MxL*. Where *M* is number of branches and *L* is number of buses. It can be assumed that whales move between branches and select which one is to be open.

The following steps are used to implement the WOA algorithm on distribution network reconfiguration.

Step (1): Initializing the position of search agents Initial random positions for each search agent are set and selecting random switches to be opened (tie switches). Then the initial configuration is checked whether it is a radial system or not. If the system is radial, we can run a power flow analysis on it to calculate total power loss in the system and minimum bus voltage. Now, we can assume that the best configuration is the initial configuration and then start the next step to change the reconfiguration of the system.

Step (2): Updating positions of search agents

In each iteration (i), a new configuration is produced using (WOA) by selecting some switches to be open. The configuration must be evaluated by 3 important actions:

1. Check system radiality:

By forming incidence matrix (A), the system is checked if it is radial or not if the system is not radial, the configuration is discarded and the fitness function (power loss) is set to equal infinity.

2. Run power flow analysis:

"Forward Sweep Backward Sweep" is the method used for load flow of the system and check the bus voltage limit. $V_{min} > 0.91$ and $V_{max} < 1$. If the system does not satisfy voltage limit condition, the configuration is discarded also, and the fitness function is set to equal infinity.

3. Evaluate fitness function (P_{loss})

Step (3): Determination of best configuration to get minimum power loss. The process continues until reaching the maximum number of iterations. At each iteration, if fitness function is less than initial fitness function, then the current configuration is set to be the best configuration.

4.0 RESULTS AND DISCUSSION

4.1 Validation Using IEEE 33-bus System

The first DN used in this work is 33-bus, single feeder radial DN with a total active and reactive load demand of 3.72MW and 2.30MVAr on 12.66*kV* respectively (Mahboubi-Moghaddam, et al., 2016). It has 37 branches, 32 sectionalizing switches and 5 tie switches as shown in Figure 1.

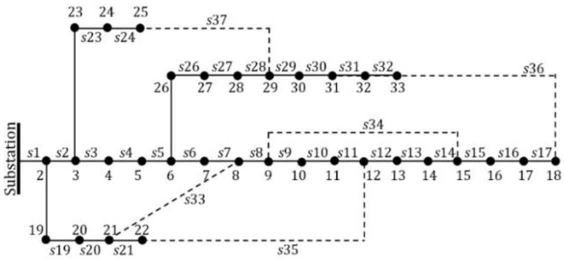

FIG 1. SINGLE LINE DIAGRAM OF IEE 33-BUS SYSTEM

The comparison of results obtained using base case (before reconfiguration) as well as runner root algorithm (RRA) optimization presented (Nguyen *et al*., 2017) is summarized in table1, fig 2 discusses the voltage profile improvement obtained using WOA when compared to the original case (before reconfiguration) and when using Runner Root Algorithm (RRA). Also, fig 3 and fig 4 describes the reduction in active and reactive power loses when compared to the case before optimization and after optimization.

Table 1: Summary of WOA performance on IEEE 33-bus system

Scenario	Tie-switches	Voltage Deviation (*pu*)	Power Loss (*kW*)	Feeder Load Balancing (%)
Base case (original)	*s*33, *s*34, *s*35, *s*36, *s*37	1.772	210.98	67.71
RRA-optimized	*s*7, *s*9, *s*14, *s*32, *s*37	1.342	188.43	52.88
WOA-optimized	*s*7, *s*11, *s*14, *s*28, *s*32	1.124	175.94	46.72
% reduction of WOA over base case		57.65%	44.56 %	48.09%
% reduction of WOA over RRA		19.39%	22.26 %	15.66%

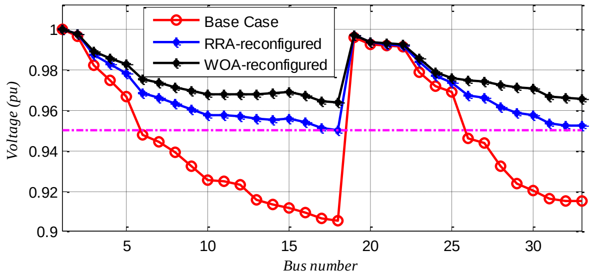

Fig 2. Voltage Profile of Original, RRA-reconfigured and WOA-reconfigured IEEE 33-bus System

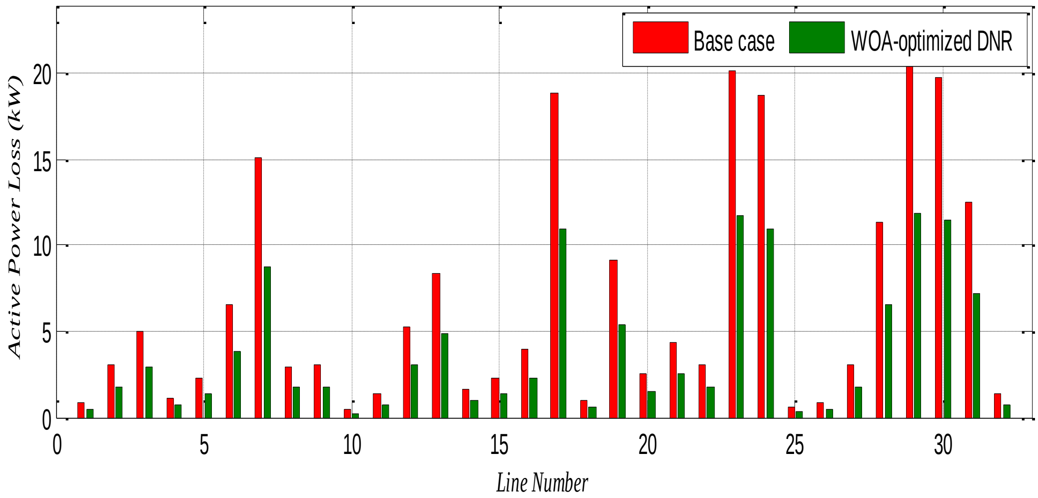

Fig 3. Active power loss of IEEE 33-bus system with and without WOA-based DNR

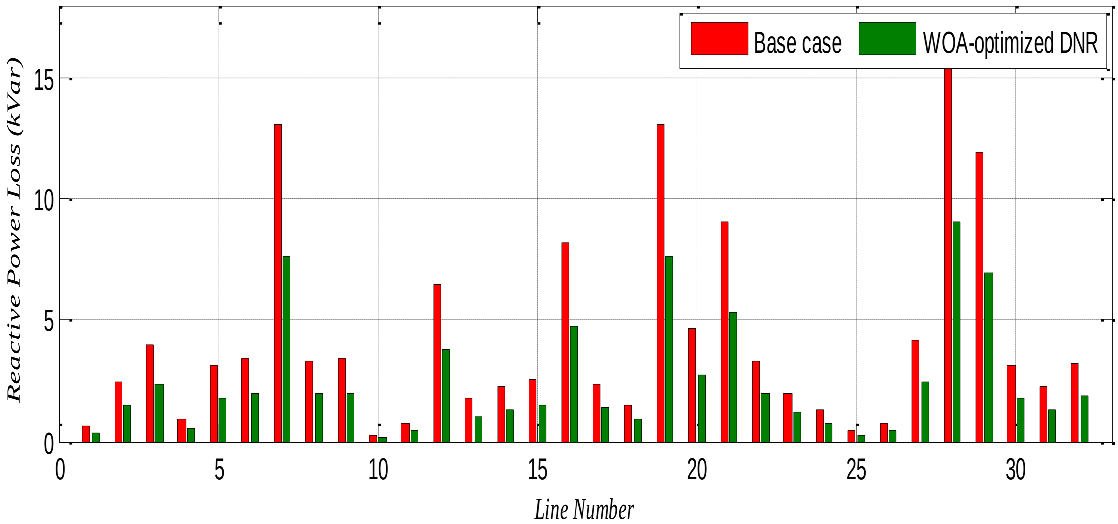

Fig 4. Reactive power loss of IEEE 33-bus system with and without WOA-based DNR

4.2 Validation Using IEEE 69-Bus System

The 69-bus system is also one of the standard test systems. The developed reconfiguration model is validated using the standard 69-Bus distribution network. This system consists of 69 buses, 1 main feeder, 7 laterals, 73 branches of 68 sectionalizing switches and 5 tie switches. The substation voltage is 12.66kV and the base power is 10MVA (Savier & Das, 2007).This is represented by the single line diagram as shown in Figure 5 (Fathy *et al.*, 2017).

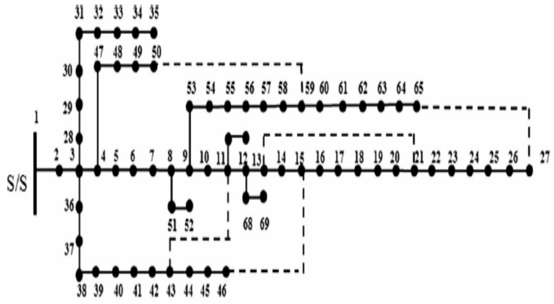

Fig 5. single line diagram of IEEE 69-bus test feeder system

the performances of WOA on the IEEE 69-bus system is elaborated in table 2 where the comparison was made with results obtained before and after reconfiguration as well as those obtained using Runner Root algorithm (RRA).

Table 2. Summary of WOA performance on IEEE 69-bus system

Scenario	**Tie-switches**	**Voltage Deviation (*pu*)**	**Power Loss (*kW*)**	**Feeder Load Balancing (%)**
Base case	*s*69, *s*70, *s*71, *s*72, *s*73	0.2140	224.98	82.25
RRA-optimized	*s*14, *s*58, *s*61, *s*68, *s*69	0.1982	192.62	74.48
WOA-optimized	*s*15, *s*58, *s*62, *s*69, *s*70	0.1744	167.22	61.33
% reduction of WOA over base case		22.70%	34.54 %	34.11%
% reduction of WOA over RRA		13.64%	15.18 %	21.44%

Figures 6 below describes the voltage profile improvement before and after reconfiguration as well as the comparison made using Runner Root Algorithm (RRA). The voltage profile has Improved by 22.7% after using WOA while 13.64% voltage profile improvement was achieved when compared with the result obtained using Runner Root Algorithm.

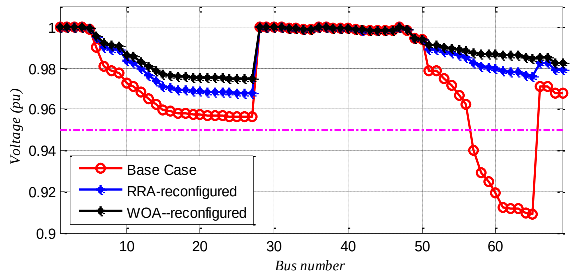

Fig 6. Voltage profile of original, RRA-reconfigured and WOA-reconfigured IEEE 69-bus System

The reduction in active and reactive power losses are elaborated in figure 7 and 8. 34.54% reduction in power loss was achieved after optimization using WOA and 15.18% reduction in power loss was achieved when compared with the optimization using Runner Root algorithm (RRA).

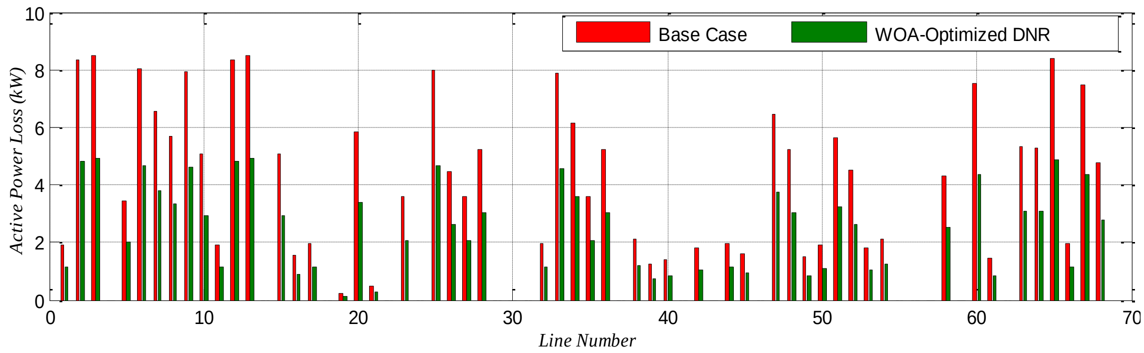

Fig 7. Active power of IEEE 69-bus system with and without WOA-based DNR

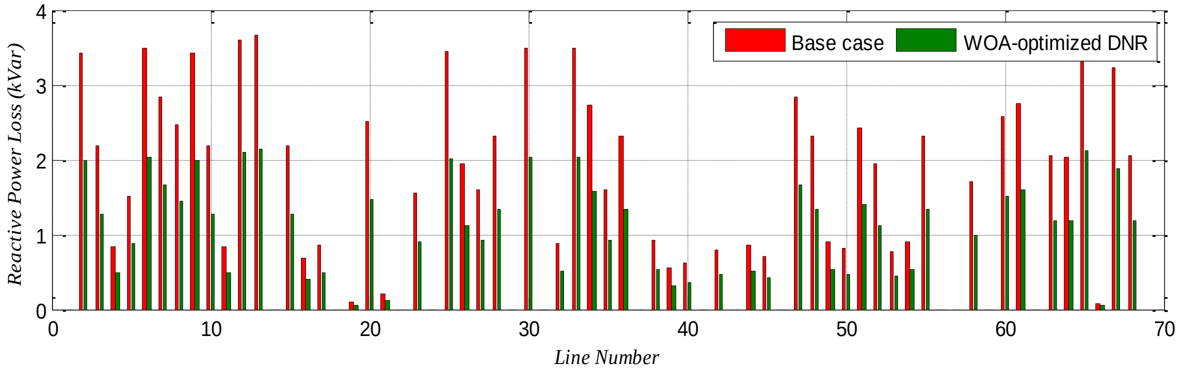

Fig 8. Reactive power of IEEE 69-bus system with and without WOA-based DNR

4.3 11kV RIGASA FEEDERS

Rigasa injection substation is a 4-feeder, radial DN supplied through twin 15MVA, 33/11kV transformers. The network is owned and operated by Kaduna Electric Distribution Company (KAEDCO). For the purpose of this study, two feeders of the network are considered. The first feeder has 46 substations (buses) interconnected with 42 distribution lines (branches). The feederhas a radial topology as shown in its single line diagram in Figure 9. The second feeder has 31 buses and 30 branches. Each of the branches has a sectionalizing switch as shown in figure 10, while between buses 35 – 50 (*s*72), 44 – 56 (*s*73), 33 – 58 (*s*74) and 41 – 65 (*s*75), there are normally-open tie switches, though not indicated on the line diagrams for brevity's sake.

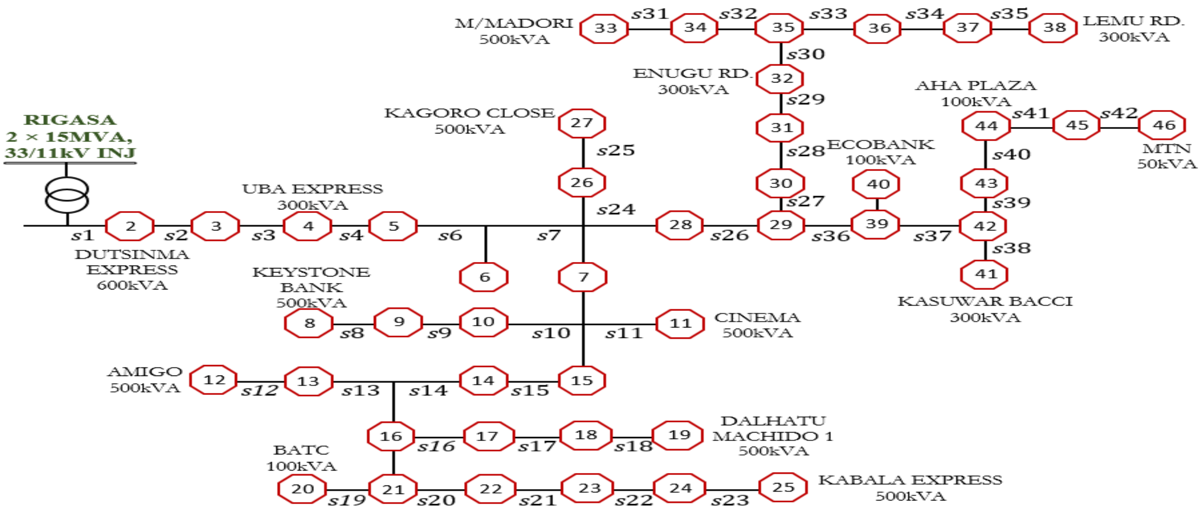

FIG 9. Feeder 1 of RIGASA 2×15MVA, 33/11kV Injection Substation

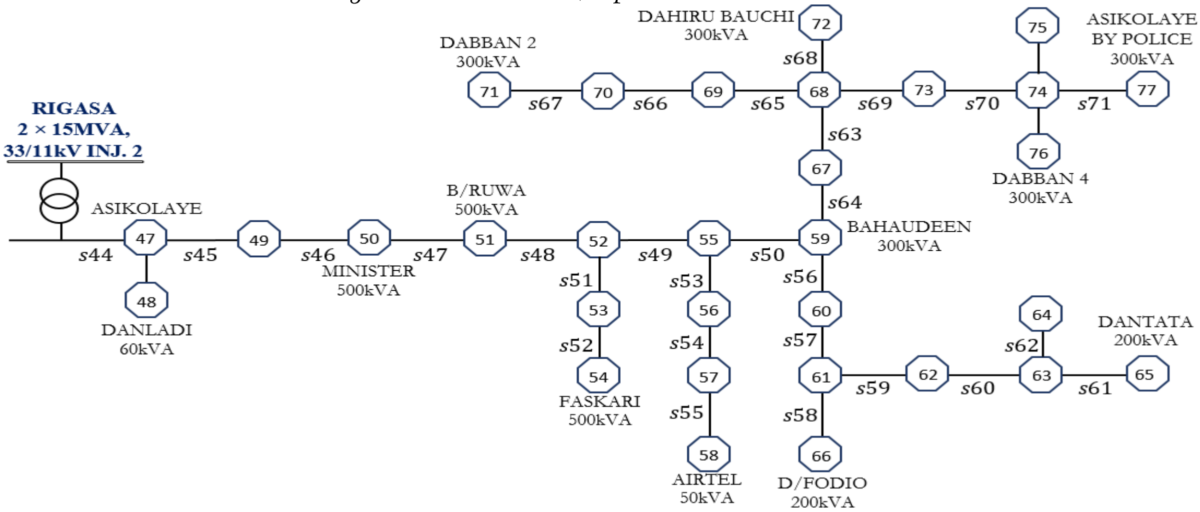

FIG 10. Feeder 2 of RIGASA 2×15MVA, 33/11kV Injection Substation

The network is analyzed with a total active and reactive load demands of 5.6MW and 4.3MVar.

By optimally reconfiguring the network using the WOA algorithm, the topology of the network changes. The normally-closed sectionalizing switch *s*30 is opened there by separating buses 32 and 35. The normally - opened tie switch between buses 35 – 50 is closed. This transferred the loads on buses 33, 34, 35, 36, 37 and 38 from Feeder 1 to Feeder 2. Similarly, the loads on buses44, 45 and 46 are also transferred to Feeder 2 by opening *s*40 and closing *s*73.

The voltage profiles of the reconfigured are shown in Figure 11. It can be observed that the voltages of buses on Feeder 1 have significantly improved, even though it is at the detriment of those on Feeder2.

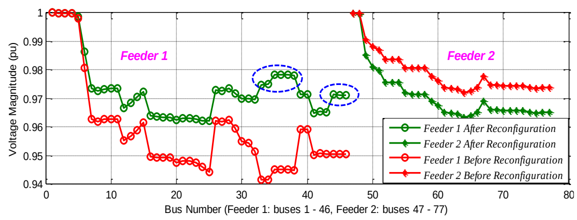

Fig 11. Voltage profile of Rigasa Feeder system before and after the WOA-based DNR

It not only the voltage profiles that improve, but also the remaining components of the objective function; power loss and feeder load balancing. Table 3. summarizes the improvement observed on the voltage profile and the reduction in the power loss.

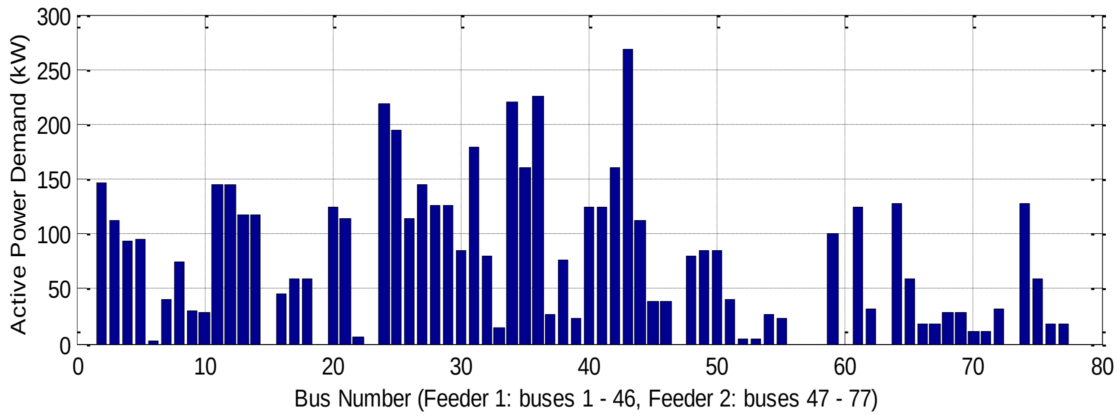

Fig 12. Active power of Rigasa Feeder system before and after the WOA-based DNR

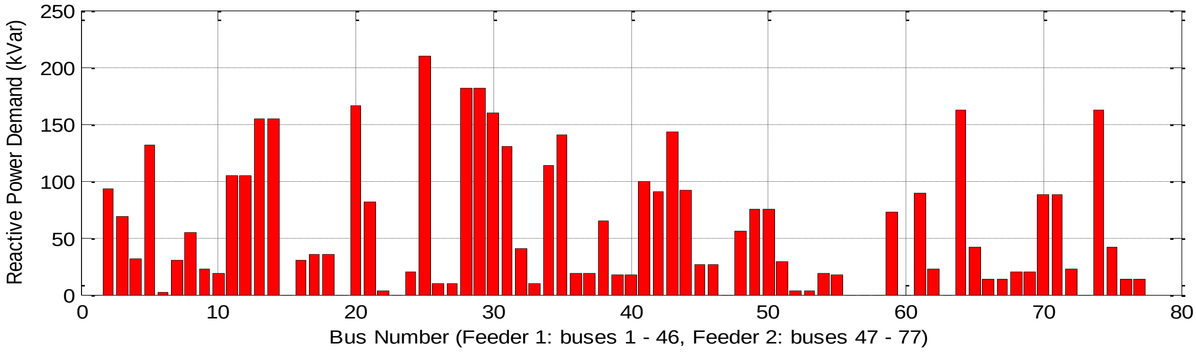

Fig 13. Reactive power of Rigasa Feeder system before and after the WOA-based DNR

Table 3. Summary of WOA performance on Rigasa feeder

Parameters	Before Reconfiguration	After Reconfiguration	%Improvement /Reduction
Tie switches	*s*72, *s*73, *s*74, *s*75	*s*30, *s*40, *s*74, *s*75	- - - - -
Voltage Deviation (*pu*)	2.5484	2.1153	20.47%
Power Loss (*kW*)	427.28	294.67	44.90%
Feeder Load Balancing (%)	43.72%	58.01%	32.68%
Min voltage magnitude (*pu*)	0.9415	0.9622	- - - - -

It is observed that through the optimal reconfiguration of the network, the voltage deviation (VD) has been reduced by 20.47%, implying that the voltage profile has been improved by that percentage. Similarly, the power loss has been reduced by 44.90%, while the feeder load balancing(FLB) index is found to have improved from 43.72% to 58.01%.

5.0 CONCLUTION

An optimal network reconfiguration scheme for the 33kV RIGASA FEEDER was established using Whale Optimization Algorithm (WOA) for the purpose of minimizing the real power loss (PL) and voltage deviation (VD), as well as for improving feeder load balancing (FLB).

i. It is observed that through the optimal reconfiguration of the network, the voltage deviation (VD)has been reduced by 20.47%, implying that the voltage profile has been improved by that percentage.
ii. Similarly, the power loss has been reduced by 44.90%.
iii. The feeder load balancing (FLB) index is found to have improved from 43.72% to 58.01%.

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