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Original Article

The Application of Whale Optimization Algorithm for Optimal Placement of Autoreclosers in Improving the Reliability of Nigeria's 330kV Electric Power System

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Abstract *- This work considers the optimal placement of autoreclosers on Nigeria's 330kV transmission network using the Whale Optimization Algorithm to enhance system reliability. The network model was developed in MATLAB, and the WOA was applied to identify optimal autorecloser locations. The reliability performance was evaluated using key indices: SAIDI, SAIFI, CAIDI, ASAI, EENS, and AENS. The results revealed that the SAIDI and SAIFI values were 0.1886 hr/customer.yr and 0.2439 f/customer.yr, respectively - indicating fewer and shorter interruptions. The ASAI gave a value of 99.99%, while the CAIDI's value was 0.7733 hr/customer interruption, reflecting enhanced supply availability and quicker restoration times. Finally, the EENS and AENS gave 3270.64MWh/yr and 74.8118MWh/customer.yr, respectively, confirming minimized energy losses and better service delivery. The outcome of the WOA-based algorithm was compared with other algorithms from existing literature and found to perform better. Therefore, the results of the study confirm that the strategic optimization of the placement of auto-reclosers is a viable and impactful technique for improving the reliability and resilience of modern power systems.*

Keywords *- AENS, ASAI, EENS, CAIDI, SAIDI, SAIFI.*

1. Introduction

Auto-reclosers are integral to the enhancement of power system reliability. These devices automatically detect transient faults and perform reclosing operations after fault clearing, thereby minimizing the frequency and duration of customer outages and improving service availability. Their primary function is to quickly obviate outages and restore service to otherwise healthy circuits, ensuring continuity and reducing the scale of interruptions [1, 2]. However, the effectiveness of auto-reclosers largely depends on their strategic placement within the network. Properly positioned auto-reclosers enhance system reliability by reducing the impact and duration of faults. The strategic allocation of the devices can amplify their benefits by targeting locations with maximum impact on fault isolation and network resilience [2, 3].

The location strategies for auto-reclosers have evolved from heuristic to algorithmic frameworks that aim to maximize network reliability gains while minimizing investment and operational costs. Genetic algorithms, particle swarm optimization, and multi-objective optimization are prominent methodologies employed to explore the combinatorial space of potential placement configurations effectively. These approaches evaluate multiple criteria, including improvements in reliability indices, cost implications of device installation and maintenance, and fault isolation efficiency to reduce the size of outage-affected populations [1, 2, 4].

This study considers the 330kV network of Nigeria, which suffers from frequent outages and reliability issues. Current reliability assessments depend on deterministic methods that overlook system uncertainties. Also, algorithmic techniques are limited in their application to improve reliability. Therefore, this work applies the Whale Optimization Algorithm (WOA) to enhance reliability indices of the Nigerian 330kV network.

1.1. Literature Review

Recent research has utilized optimization methods to identify the optimal number and locations of autoreclosers, using reliability indices and cost–benefit evaluations to achieve enhanced network reliability while ensuring cost-effective investment. The optimal placement of autoreclosers refers to determining the most effective locations within the network to install auto-reclosers so that predefined objectives, like minimizing outage duration, reducing customer interruptions, or improving reliability indices, are achieved. On the other hand, reliability indices measure the reliability performance of the system. These include Expected Energy Not Supplied (EENS), Average Service Availability Index (ASAI), System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI), Customer Average Interruption Duration Index (CAIDI), and Average Energy Not Supplied (AENS).

The study in [2] introduced a dual-phase method that combined an auto-recloser with reconfiguration of the distribution system to enhance reliability. While the study focused on estimating the EENS, additional reliability indices could also be evaluated to provide a more comprehensive assessment of auto-recloser allocation. Moreover, the proposed approach can be extended to real-world power distribution networks. In [5], a genetic algorithm was used to optimize recloser location on a standard system to improve reliability. The results showed that optimal recloser placement significantly reduced outage and investment costs. The approach proved effective in enhancing utility profit. It can be extended to real-world power networks.

Notably, studies applying genetic algorithms have optimized auto-recloser locations on radial power systems, achieving significant enhancements in outage duration and frequency indices while controlling budgetary constraints [4]. Other researchers have implemented multi-objective optimization using particle swarm techniques to balance customer outage costs with investment and equipment expenditures [6]. The continuously evolving computational capabilities and advanced metaheuristics thus provide robust tools to align protective device deployment with dynamic operational needs in renewable-rich networks [5, 6]. Heuristic algorithms like particle swarm optimization have shown substantial effectiveness in recloser siting, reducing SAIFI and SAIDI by more than 70% in real-world lines, as shown in the study conducted by [7]. Additionally, the proposed study by [8] was based on the Genetic Algorithm technique, where the input data of voltage sags and interruptions were estimated through the Monte Carlo simulation. Actual coordinated and selective adjustments were applied in a modified IEEE system to verify the impact of inserting normally closed reclosers.

The proposed methodology proved to be robust in capturing the impacts of VSs and interruptions on sensitive consumers, arising from both protective philosophies. The study suggested a more complex analysis regarding the re-closer allocation, which is one of the areas of interest of the present study. In [9], a Monte Carlo-based approach was introduced for optimizing recloser settings. The results demonstrated the effectiveness of the technique. Similarly, the study in [10] examined recloser operations within South Korea's distribution network, aiming to develop strategies that enhance both safety and operational efficiency. The findings showed that the strategies maintained a high reclosing success rate. The work can be extended to cover refining these strategies to boost overall system performance.

Some researches that cover the Nigerian power system were also reviewed. The study conducted by [11] presented the evaluation of the reliability of the Auchi and Government Residential Area (GRA) feeder in a distribution. The evaluation was calculated using SAIDI, SAIFI, and CAIDI, and the results show important information to help increase the system's reliability and overall performance of the Auchi network. Future work should be extended to cover the bigger power systems. In [12], reliability assessment for the Greater Port Harcourt 33kV feeder was conducted. From the results of the assessment, the best value of SAIDI was 65.71 hours; SAIFI was 21.24, while CAIDI was 3.08 hours. The study can be extended to consider a larger system and more reliability indices. The study presented in investigated the impact of Distributed Generation (DG) on the reliability of the Yola Electricity Distribution Company (YEDC) network. The results showed improvements in reliability indices —SAIDI improved by 69.4%, SAIFI by 40.5%, and CAIDI by 29.7%, while ASAI increased to 0.960587. The study suggests that extending this approach to the high-voltage transmission network could yield broader benefits across the entire power grid. The work by [13] analyzed the reliability indices of the Ijebu Ode 11kV feeder in Nigeria between 2016 – 2020 using the Microsoft Excel Program. The result of the study showed that the Sabo feeder was the most reliable feeder between 2016 and 2019, with a reliability ranging from 65.87 to 80.49%, while the GRA feeder was the least reliable feeder among the five feeders, with a reliability value ranging between 32.26 and 54.23% throughout the period under study. The study can be extended to cover a larger power system.

1.2. Application of WOA to Reliability / Power System Optimization

This work considered the choice of Whale Optimization Algorithm (WOA) due to the following reasons [14, 15]:

- Strong global search capability
- Fast convergence speed
- Few control parameters
- High robustness and flexibility
- Effective handling of non-linear, multi-objective problems.

In recent times, meta-heuristic techniques have been applied to improve reliability: SAIDI, SAIFI, EENS, ENS, and others. Traditional algorithms like Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Ant Colony Optimization (ACO), amongst others, have been used. Recently, the WOA has been applied in related power system optimization through direct application to autorecloser placement. In the work of [16], WOA was compared with GA and PSO; the results reveal that WOA yielded better operating cost savings and converged more reliably under different load conditions. In another study by [17], WOA was benchmarked against PSO and GA across IEEE test systems. The results show that the WOA achieved the lower losses and voltage stability, especially in larger systems, outperforming other algorithms.

Also, in [18], WOA, PSO, and GA were compared for optimizing electric vehicle charging station placement. The results indicate that WOA performed better in active and reactive power loss reduction, as well as fast convergence.

1.3. Contribution of the Paper

From the review of related works, it was observed that, in some studies, the placement of reclosers was not optimized. In others, the application was not implemented and validated on an actual power system network.

Furthermore, only basic reliability indices were considered in several of the reviewed studies. In the present study, the WOA was employed to optimally place auto-reclosers on the 330kV network of Nigeria to improve the power system reliability indices. Therefore, the following contributions are made in this work:

- Optimizing the placement of auto-reclosers on the 330kV network of Nigeria to improve the reliability indices, thus enhancing service availability.
- Consideration of multi-layer reliability indices (ASAI, SAIDI, SAIFI, CAIDI, EENS, and AENS) helped achieve a deeper analysis.
- The research applies the WOA to autorecloser placement, where the objective function enhances the reliability indices.
- Validating the proposed method by applying it to a real Nigerian 330kV electric power network.

The findings underscore the critical role of optimal auto-recloser placement in strengthening network reliability, improving customer satisfaction, and supporting utility performance objectives. This research contributes to the reliability-centered planning and offers a practical framework for utilities seeking to modernize their protection schemes in an economically viable manner.

Furthermore, the novelty of applying the WOA to the optimal placement of auto-reclosers lies in its ability to intelligently balance network reliability enhancement and economic efficiency while overcoming limitations of conventional optimization and heuristic methods. In the rest of the paper, part 2 describes the mathematical modeling of the WOA, while part 3 presents the methodology. Part 4 gives the results of the work, and the conclusion is captured in Section 5.

2. Whale Optimization Algorithm

The WOA is inspired by the bubble-net hunting strategy of humpback whales, where the best-performing agent in each iteration is considered the prey, while the remaining agents adjust their positions relative to it.

Accordingly, the algorithm simulates three primary behaviors-encircling the prey, bubble-net attacking, and searching for prey-which are mathematically represented in the following Equations [19-22]:

$$\vec{D} = \left|\vec{C}.\overrightarrow{X^*}(t) - \vec{X}(t)\right| \tag{1}$$

$$\vec{X}(t+1) = \overrightarrow{X^*}(t) - \vec{A}.\vec{D} \tag{2}$$

$$\vec{A} = 2.\vec{a}.\vec{r_1} - \vec{a} \tag{3}$$

$$\vec{C} = 2.\vec{r_2} \tag{4}$$

$$\vec{a} = 2\left(1 - \frac{t}{T}\right) \tag{5}$$

$$\vec{X}(t+1) = \begin{cases} \overrightarrow{X^*}(t) - \vec{A}.\vec{D} & if\ p < 0.5 \\ D'.e^{bl}.\cos(2\pi l) + \overrightarrow{X^*}(t) & if\ p \geq 0.5 \end{cases} \tag{6}$$

$$\vec{D} = \left|\vec{C}.\vec{X}_{rand} - \vec{X}\right| \tag{7}$$

$$\vec{X}(t+1) = \vec{X}_{rand} - \vec{A}.\vec{D} \tag{8}$$

Where, $\overrightarrow{X^*}$ and $\vec{X}$ signify the position of the best solution and position vector, the current iteration is denoted by t. The $\vec{A}$ and $\vec{C}$ are coefficient vectors, $\vec{a}$ directly diminish from 2 to 0, while $\vec{r}$ is a random vector [0, 1]. The Euclidean distance between the individuals and the prey is specified through D', b, l parameters The pseudo code used for the WOA is summarized below [23]:

2.1. Objective Function

The problem was formulated as a multi-objective problem aimed at improving reliability indices by optimally placing auto-reclosers on the 330kV network. The solution minimized the interruption duration, frequency, and energy not supplied, while maximizing service availability. Therefore, the multi-objective optimization problem can be formulated as represented in Equation (9):

$$\min_x f(x) = w_1.SAIDI(x) + w_2.SAIFI(x) + w_3.EENS(x) + w_5.AENS(x) - w_6.ASAI(x) \tag{9}$$

Where x is the decision vector representing the location of auto-reclosers, while w_i is the weight assigned to each reliability index. The optimization is subject to the operational constraints and binary decision variables:

(a) Operational Constraints
- Maximum number of auto-reclosers
- Number of auto-reclosers per branch

(b) Binary decision variables
$x_i \epsilon \{0, 1\}, \forall_i \epsilon \; candiate\ locations$

3. Materials and Methods

The study for the placement of an auto-recloser was conducted using the MATLAB R2022 model. First, the network was modelled and simulated, and then run to achieve convergence.

Thereafter, the WOA was used to obtain a solution for optimally allocating the auto-reclosers on the network. The following data were obtained from the System Operator for the work:

- Bus data
- Transmission line data
- Data from power plants
- Information on the load

The transmission lines/bus data in Table 1 show the 330kV lines and the numbering used for the simulation.

The methodology is structured into three main stages:

- Network modelling and reliability analysis were conducted using the MATLAB program
- Optimization framework development in MATLAB using WOA, and
- Integration of results and validation through comparative reliability indices.

3.1. Simulation Parameters

The parameters used for the WOA are represented in Table 2.

Table 1. Simulation parameters used for the WOA

S/N	Parameters	Values
1	Buses	49
2	Fault events	52
3	Auto-reclosers to be placed	3
4	Search agents	30
5	Maximum Iteration	100
6	Candidate branches	90

3.2. Algorithm Steps

The following steps were followed to get the results of the reliability indices based on the WOA algorithm:

- Initialization: Randomly generate initial whale population (possible recloser positions).
- Fitness Evaluation: For each whale, calculate the objective function.
- Position Update:
  - ✓ If |A|<1|A| < 1|A|<1: exploit the best solution (encircling prey).
  - ✓ If |A|≥1|A| ≥ 1|A|≥1: explore new regions (search for prey).
  - ✓ Spiral updating is performed with random values.
- Convergence: Repeat the search until MaxIter or until fitness variation < tolerance.
- Output: Optimal locations of auto-reclosers and corresponding reliability indices.

4. Results and Discussion

4.1. Optimal Auto-Recloser Placement

The strategic location of the auto-reclosers on the Nigerian National grid was achieved employing the Whale Optimization Algorithm. In this method, only combinations of auto-recloser placements on these candidate branches were evaluated.

This reduces computational complexity and focuses the search on the most promising options. The results obtained include key reliability indices that evaluate the performance improvements due to the optimal protective device placement. The representation of the optimal location of auto-reclosers is presented in Figure 1.

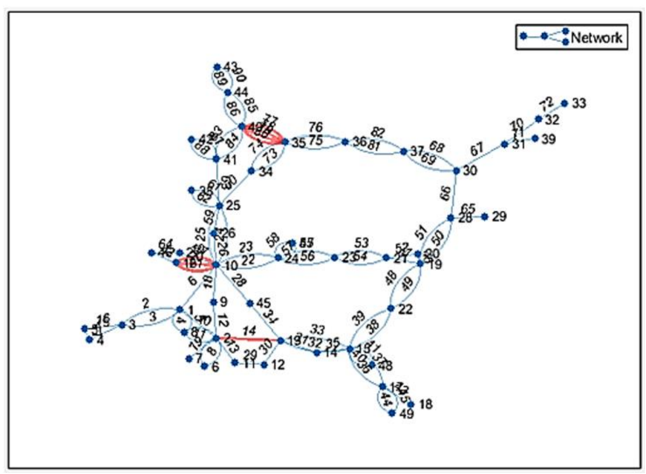

Fig. 1 Optimal placement of the auto-reclosers

From Figure 1, each numbered node represents a bus, while each line (connecting lines between nodes) represents a branch or segment of the network. The blue stars (*) mark the nodes, and the blue lines denote their connections. The red color suggests these lines or branches have been equipped with auto-recloser devices that automatically isolate and restore power after transient faults. Placement of auto-reclosers in these locations is critical for improving reliability and minimizing the impact of faults. The candidate branches that correspond to the outage branches under consideration are shown in Table 3.

Table 2. Candidate branches after application of WOA

Candidate Branches	From 330kV Bus	To 330kV Bus
4	1	8
5	1	10
6	2	6
14	3	4
19	10	16
20	10	16
21	10	24
26	10	27
32	13	15
33	13	45
34	14	15
35	15	17
36	15	17
37	15	22
40	15	48
41	16	46
43	17	49
46	19	21
50	20	21
51	21	23
68	30	37
69	31	32
75	35	36
76	35	40
77	35	40
78	35	40
79	35	40
80	36	37
81	36	37
82	40	41
83	40	41
84	40	44
85	40	44
86	41	42

From the results in Table 3 and Figure 1, the WOA identified the following lines as the optimal locations for installing auto-reclosers from a set of candidate branches:

- Line 14 (Ikeja West – Osogbo 330kV line)
- Line 19 (Benin – Sapele 330kV line)
- Line 78 (Ikot Ekpene – Ugwuaji 330kV line 3)

These lines are critical points in the network where transient faults tend to cause significant interruptions and load loss. Strategic installation of auto-reclosers at these branches allows rapid fault isolation, minimizing the extent of outages and enhancing system reliability. The placement of auto-reclosers at the lines optimally balances the trade-off between outage frequency and duration, achieving a significant reduction in load affected by faults as indicated by the low reliability cost.

4.2. Reliability Evaluation

The reliability evaluation was computed for optimally placing auto-reclosers using the WOA-based algorithm on the 330kV network of Nigeria. The results of the SAIDI, SAIFI, ASAI, CAIDI, EENS, and AENS were determined and compared with existing literature. The results are given in Figure 2.

```
| Reliability Assessment Results With Auto-Recloser Placement   |
|...............................................................|
SAIDI: 0.1886 hrs/customer/year
SAIFI: 0.2439 interruptions/customer/year
ASAI: 0.9999
CAIDI: 0.7733
EENS: 3270.6412 MWhr/yr
AENS: 74.8118 MWhr/cust.yr
```

Fig. 2 Reliability indices with auto-reclosers placement

Results of the reliability evaluation are computed in Table 4.

Table 3. Reliability indices with autoreclosers

S/N	Reliability Indices	Case Study with WOA
1	ASAI	0.9999
2	CAIDI	0.7733
3	SAIDI	0.1886
4	SAIFI	0.2439
5	AENS	74.8118
6	EENS	3,270.6412

From the results in Figure 2 and the summary in Table 4, the following applies:

- The ASAI value of 0.9999 corresponds to 99.99% network availability, confirming a highly reliable power supply with minimal downtime. The near-perfect ASAI reflects the overall robustness of the network's power availability post-optimization, emphasizing the effectiveness of heuristic optimization algorithms (such as WOA) in improving power system reliability.
- The SAIDI value of 0.1886 hours/customer/year indicates that, on average, each customer experiences approximately 11.3 minutes of outage annually. This low outage duration demonstrates prompt fault clearance and restoration due to auto-recloser operation.
- The SAIFI value of 0.2439 interruptions/customer/year means customers experience roughly one interruption every 4 years on average. This reflects a moderate frequency of outages, suggesting some interruptions remain frequent despite protection improvements.
- The CAIDI of 0.7733 hours/interruption indicates the average duration per outage is approximately 46 minutes. This relatively short duration implies practical restoration efforts when outages occur.

- The EENS value indicates the total expected quantity of energy that will not be supplied to all customers across the network annually due to interruptions. A value of 3270.64 MWh/year suggests that the system experiences significant energy losses over the course of a year due to outages or faults. The higher the EENS, the more energy is lost, which may point to frequent or prolonged outages, inadequate protection schemes, insufficient redundancy, or aging infrastructure.
- The AENS value of 74.8118 represents the average amount of energy each customer is expected not to receive annually due to power interruptions. AENS is essentially a per-customer normalization of the EENS and provides a customer-centric view of service reliability.

These results were compared with results obtained using other heuristic methods, as shown in Table 5.

Table 5. Comparative analysis of reliability analysis results

S/N	Ref.	Methodology	Results
1	[4]	PSO was applied to relocate the existing	SAIFI = 1.8221 SAIDI = 4.9114
2	[5]	GA to find optimal recloser locations	SAIFI = 1.4778 SAIDI = 5.5111 CAIDI = 3.4748 ASAI = 0.9994 AENS = 48.0800
3	[24]	GA and Prim's Algorithm (PA)	SAIFI = 9.2064 SAIDI = 17.2576 CAIDI = 1.875 ASAI = 0.9980
4	[25]	GA was implemented in JavaScript to optimize reclosers/fuses	SAIFI = 1.4492 EENS = 24,607.87
5	[26]	Application of GA	SAIFI = 3.24 SAIDI = 16.18
6	Present Study	WOA for optimizing autorecloser placement	SAIFI = 0.2439 SAIDI = 0.1886 CAIDI = 0.7733 ASAI = 0.9999 AENS =74.8118 EENS = 3,270.641

When the results were compared, it showed that the WOA technique performed better than the other techniques used in the reviewed literature, as shown in Table 5, thus leading to better service delivery to customers.

5. Conclusion

In this study, the auto-reclosers were optimally located on the 330kV network of the Nigerian grid to enhance the overall system reliability. By applying the Whale Optimization Algorithm, strategic locations for the recloser deployment were identified to minimize the frequency, duration, and impact of outages due to transient faults. The reliability performance of the network was evaluated using key reliability indices - SAIDI, SAIFI, ASAI, CAIDI, EENS, and AENS.

The results demonstrated that when compared to the existing literature, the use of optimal recloser placement significantly reduces SAIDI and SAIFI, thereby improving service continuity and customer experience. An increase in ASAI and a reduction in CAIDI further confirm improvements in supply availability and restoration time. Additionally, reductions in EENS and AENS indicate better energy delivery efficiency and reduced economic losses due to outages.

From a practical point of view, the application of WOA to autorecloser placement can help power utilities determine optimal investment strategies under a constrained budget by balancing device cost against the expected reliability improvement. Overall, the study confirms that the strategic optimization of auto-reclosers is important because it can improve the reliability of the system. Despite the demonstrated potential of WOA, its application to autorecloser placement remains in its infancy. Therefore, the following directions are recommended for future research:

- Explore hybrid WOA models to improve exploitation-exploration balance and avoid premature convergence in large power systems
- Problem formulation should be extended to a multi-objective framework covering additional reliability indices and factors affecting them.
- The comparative analysis of strategically connecting renewable energy plants and the application of an autorecloser for enhanced grid reliability can also be studied.

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Appendix

Table 4. Branch name for the 330kV lines

Line No.	From 330kV Bus	To 330kV Bus
1	Egbin	Ikeja west
2	Egbin	Aja 1
3	Egbin	Aja 2
4	Egbin	Oke Aro 1
5	Egbin	Oke Aro 2
6	Egbin	Benin
7	Ikeja West	Akangba 1
8	Ikeja West	Akangba 2
9	Ikeja West	Sakete
10	Ikeja West	Oke Aro 1
11	Ikeja West	Oke Aro 2
12	Ikeja West	Omotosho
13	Ikeja West	Olorunsogo
14	Ikeja West	Osogbo
15	Aja	Lekki
16	Aja	Alagbon 1
17	Lekki	Alagbon 2
18	Omotosho	Benin
19	Benin	Sapele 1
20	Benin	Sapele 2
21	Benin	Sapele 3
22	Benin	Ajaokuta 1
23	Benin	Ajaokuta 2
24	Benin	Onitsha 1
25	Benin	Onitsha 2
26	Benin	Asaba
27	Benin	Delta
28	Benin	Ihovbor
29	Olorunsogo	Ayede
30	Ayede	Osogbo
31	Osogbo	Ganmo
32	Osogbo	Jebba TS 1
33	Osogbo	Jebba TS 2
34	Osogbo	Ihovbor
35	Ganmo	Jebba TS
36	Jebba TS	Kainji GS 1
37	Jebba TS	Kainji GS 2
38	Jebba TS	Tripple Point 1
39	Jebba TS	Tripple Point 2
40	Jebba TS	Jebba GS 1
41	Jebba TS	Jebba GS 2
42	Sapele	Aladja
43	Kainji GS	Birnin kebbi
44	Kainji GS	Fakun 1
45	Kainji GS	Fakun 2
46	Shiroro	Katampe
47	Shiroro	Gwagwalada
48	Shiroro	Triple Point 1
49	Shiroro	Triple Point 2
50	Shiroro	Kaduna 1
51	Shiroro	Kaduna 2
52	Katampe	Gwagwalada
53	Gwagwalada	Lokoja 1
54	Gwagwalada	Lokoja 2
55	Lokoja	Ajaokuta 1
56	Lokoja	Ajaokuta 2
57	Ajaokuta	Geregu 1
58	Ajaokuta	Geregu 2
59	Onitsha	Asaba
60	Onitsha	New Haven
61	Onitsha	Okpai 1
62	Onitsha	Okpai 2
63	Onitsha	Alaoji
64	Delta	Aladja
65	Kaduna	Kano
66	Kaduna	Jos
67	Jos	Gombe
68	Jos	Lafia 1
69	Jos	Lafia 2
70	Gombe	Damaturu
71	Gombe	Yola
72	Damaturu	Maiduguri
73	New Haven	Ugwuaji 1
74	New Haven	Ugwuaji 2
75	Ugwuaji	Makurdi 1
76	Ugwuaji	Makurdi 2
77	Ugwuaji	Ikot Ekpene 1
78	Ugwuaji	Ikot Ekpene 2
79	Ugwuaji	Ikot Ekpene 3
80	Ugwuaji	Ikot Ekpene 4
81	Makurdi	Lafia 1
82	Makurdi	Lafia 2

83	Ikot Ekpene	Alaoji 1
84	Ikot Ekpene	Alaoji 2
85	Ikot Ekpene	Odukpani 1
86	Ikot Ekpene	Odukpani 2
87	Alaoji	Afam 1
88	Alaoji	Afam 2
89	Adiabor	Odukpani 1
90	Adiabor	Odukpani 2