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Reliability optimization on power systems network using genetic algorithm

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ABSTRACT

In this study, reliability optimization of a non-linear transmission network using Genetic Algorithm (GA) based optimization approach is presented and proposed. A GA based algorithm was developed for Koko, Guinness, Nekpenekpen, Ikpoba-Dam, Switch station, Etete and GRA 33kV tertiary transmission feeders within Benin Metropolis, Nigeria and was used to determine the optimal performance of the feeders' reliability and availability through the minimization of downtime and the Mean Time between Failure (MTBF) by the appropriate selection of the objective functions and constraints. The equality and inequality constraints for each feeder on the network were defined, thereafter, codes were written on the Matlab 2016a environment to optimize the selected parameters. The results from the study showed a reduction in downtime of 5.63%, 26.87%, 34.20%, 5.42% 8.37%, 5.18% and 10.97% and an increment increased in MTBF by 4.95%, 19.87%, 4.58%, 3.85%, 4.88%, 5.77% and 13.56% for Guinness, Etete, Nekpenekpen, GRA, Switch station and Ikpoba-Dam feeders respectively. The obtained results, therefore, yielded an average corresponding improvement on the network's reliability and availability by 1.85% and 2.83% respectively. Conclusively, the desired result reached in this paper validates the robustness of the GA tool in reliability studies. However, conscious effort must be geared concerning the ways and manners the system is operated in order to achieve desired results.

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1. Introduction

The Transmission Company of Nigeria, Benin City, Edo State is fed directly by a 330kV circuit transmission lines emanating from Delta, Egbin and Sapele generating stations respectively. The Benin 330kV main bus feeds the following regions: Ajaokuta, Onitsha, Ikeja-west, Oshogbo and Ihovobor; via a double circuit, and a single circuit transmission line respectively. There are two 132kV buses (main and reserve) present in the station. From the 132kV main bus, other regions (Effurun, Oghara, Irrua, Amukpe and Delta) are fed, while the reserve 132kV bus is kept as a redundant unit. Present in the station also are 4×60MVA transformers, which step down the 132kV voltage to 33kV that

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eventually feeds the 33kV feeders of interest for this study (namely: Etete, GRA, Switch station, Koko, Ikpoba-dam, Nekpenekpen and Guinness feeders respectively).

The station also has a spare feeder that is to be called into action should there be an emergency. However, this network has been characterized by failures, which are systematic, random or intermittent and this can lead to partial or total change in the same properties of a device or system in a manner that the functioning is seriously impeded or completely stopped thereby leading to suppressed demand from the operators to the customers. Since the reliability of equipment or the system cannot be up to 100%, it then implies that failure usually occur during the normal operation of the system. The contributive factors of failure could be as a result of incompatible tolerance excursions of the component parts, human errors in system assembly or undue exposure of various electronic components to vibration, shock and extreme temperature. Hence, failure rate could increase, decrease or remain constant and that depends on the context of operation. There is therefore a need for the optimization of the indices leading to failure in this network for the purpose of reliability improvement.

2. Related Review on Genetic Algorithm Applications

Genetic Algorithm (GA) based optimization is a stochastic search technique, which involves the generation of random prospective design solutions [1] and eventually refines and evaluates the solutions in a systematic order until a stopping criterion is met [2]. The three common operators involved in the search algorithm of the GA tool are: selection, crossover, and mutation. GA is now widely used in the academics and engineering industry because of its merit in solving non-linear problems, and ease of implementation, although its computational cost may be high [3]. Genetic Algorithm (GA) is an optimization technique used to provide solution to problems that are non-linear in nature. The name GA comes about, because it imitates the concept of evolutionary biology to solve optimization problem by searching for a convergence point within the global minimum. It works by initially generating individuals with unique characteristics. If an individual performs well, common similarities are selected between them taking cognizance of those that are similar to generate a new set of individuals. Finally, mutation takes place and this gives rise to the new individual [4]. Due to its uniqueness, GA has found many applications in solving problems in engineering: in the optimization of design in reinforced concrete beam [5], in the optimization of mining process [6], as well as in expert systems and geology [7]. It has also found applications in distributed renewable generation systems [8] and in the optimization of machines.

The identification and remedial actions on the weak link(s) in a system/component/equipment was identified by [9] as one of the ways forward to improving its reliability. The authors further assert that such actions could help in saving the cost of operating the systems or otherwise. The paper utilizes the Particle Swam Optimization technique to achieve their aim. However, the paper only dwell on ways of mitigating cost while the technical areas like downtime, ageing etc. are not considered. Similarly, in [10], the authors were able to estimate the monetary cost of reliable power to an asset considering the unreliable power supply from utility.

The authors in [11] carried out a research on the reliability analysis in Ekpoma, South-South Nigeria using reliability indices as a metrics. It was revealed from the study that the epileptic power experienced within Ekpoma was as a result of poor reliability within which the network was operated. The authors concluded by stating that reliability optimization is necessary for an improved system to be attained.

In [12], a study on reliability assessment in six locations in Nigeria (Oyo, Lagos, Ondo, Ogun, Osun and Ekiti) was carried out to determine the reliability worth of the selected states using the indices of reliability. It was observed from the study that system's reliability and is seasonally dependent. In other to improve on the system's performance, optimization is required in order to balance the reliability across the months of the year.

The assertion of [13] was that, for an improvement in system's reliability, the same attention that is given to generating and transmitting station should also be given to the distributing station because the effect of poor reliability is mostly felt in the former than in the later. Consequently, [14] affirmed that if operation of the system is optimized periodically, then, the chances of the system to age on time and become obsolete are on the high side.

A study on the investigation into reliability assessment was carried out by [15] using Fault Tree Analysis (FTA). The FTA showed an improvement of 51% along the network of interest. However, other study (Ahmed IEEE) have shown that the FTA as a method has so many drawbacks; time consuming, no function representing domain, low accuracy of results, etc.

In [16] the authors carried out a study to identify the feeders more prone to failure in Benin metropolis using the Vital Few and Trivial Many (VFTM) technique. The paper identified the vital feeders as well as the trivial ones. The paper however recommends that the optimization of the vital as well as the trivial feeders is necessary for an improved reliability within the metropolis.

A procedure, which establishes the maximal reliability of a complex system was introduced in proposed [17]. The developed system links are maximized in accordance with their criticalities. A criticality-based GA was developed and utilized to assess the optimum reliability of a complex system. However, the paper only considers cost reduction while other vital areas like minimization of downtime were not considered.

According to [18], GA can be used to illustrate models; series-parallel, parallel-series, non-linear network etc. taking the lower and the upper limits of the interval valued reliabilities of component. It can also be used to investigate the stability of the recommended network with respect to several GA parameters (such as, population size, mutation and crossover rates).

The goal of reliability optimization is to obtain the best way possible to minimize failure while improving reliability. According to [19] reliability optimization can be achieved through the various means; improving on the component's reliability that forms the system, applying the redundancy technique particularly for the less reliable components and also for the purpose of buffer or reserve, applying corrective maintenance to replace faulty components. However, the authors in [20] asserted that the new era of technology has naturally brought changes in the ways and manners engineering challenges are managed. Furthermore, since the research community is presently in the era of mathematical programming using available software, then, such insights should also be welcomed within all levels in the field of reliability engineering particularly in the field of active reliability improvement.

A study on the improvement on network reliability for the community in Afam, Rivers State Nigeria was carried out by [21]. The paper utilized the Electrical Transient Analyzer Program (ETAP) software to determine the reliability of the network. The addition of static VAR to the network was said to increase the network performance. The authors further assert that more static VAR compensator should be added to the network for an overall improvement. The work however did not consider if the improvement noted is a function of the available reliable indices.

A study to apply GA to secure power system network was carried out by [22] using the power system network in Libya. In the study, GA was used to determine the amount of load to be subjected to load shedding as a means of defending the network, and the obtained results showed that the defense mechanism by GA offers a great improvement when compared to the existing defense mechanism of the network. Furthermore, [23] carried out a work on economic load dispatch using GA in the power network of Algeria. The results showed that there was a considerable improvement in the reduction of losses along the line, as well as the determination of the best method of power generation at a low cost. A study to determine the optimal position to site a transformer in a distribution network was carried out by [24] in Osun State Nigeria using GA and the results obtained proved satisfactory. Further results showed that GA can also be used to plan for system expansion. GA has proven itself to be a reliable optimization technique in power system network, although more work is still needed to be done especially in the application of GA in reliability study. From the review carried out, it is obvious that only little work has been done when it comes to applying GA on the distribution network in Nigeria. Additionally, majority of the studies on reliability of power systems network that was reviewed recommended the need for optimization of the system network. This paper, therefore, is aimed at optimizing the distribution network in Benin metropolis, Nigeria using GA.

3. Methodology

In order to achieve the aim of this study, historical failure data, which comprise outages and downtime of each feeder were collected from [25]. The data sample for GRA feeder is presented in Appendix A. Thereafter, the following indices of reliability: MTBF, availability and reliability were calculated using equations (1) – (3). The feeders' downtime was gotten directly from the data sample. The goal of optimization process, therefore, is to adjust the global minimal (downtime) and (MTBF) in order to get the optimal results for reliability and availability respectively.

3.1. Reliability Function R(t)

The probability of the system not failing prior to some time: The feeders reliability were calculated using (1)

$$R(t) = e^{-\lambda t} \tag{1}$$

λ is the Failure rate and t is the time of outage.

3.2. Mean Time Between Failures (MTBF)

When a failure is observed in a system and such failure is cleared or repaired, then, the interval between these periods is known as MTBF. Thus, it is an index that relates to repairable item or components. The MTBFs of the feeders were calculated using (2)

$$\text{MTBF} = \frac{number\ of\ unit\text{-}hour\ of\ operation}{number\ of\ failures} \tag{2}$$

3.3. Availability (A)

This is the probability that the feeder would continue to carry out its required function at a given period of time in order to meet the set objectives of the system's operator and it was calculated using (3)

$$\text{Availability} = \frac{up\ time}{uptime + downtime} \tag{3}$$

The optimization of the feeder's reliability and availability were achieved using Genetic Algorithm. The fitness function, linear and non-linear constraints, the upper and lower bounds and the test files are coded in the Matlab 2016a environment. The fitness function, constraints imposed on the feeders for the optimization of the availability and reliability of GRA feeder are given by (4) – (6) and (7) – (9)

respectively. From (4) and (7), the global minimal were chosen, which represents the indices to be altered in order to achieve the optimization. The data on network reliability used for this study was collected from literature [25]. The flow chart for the GA implementation is presented in Fig. 1.

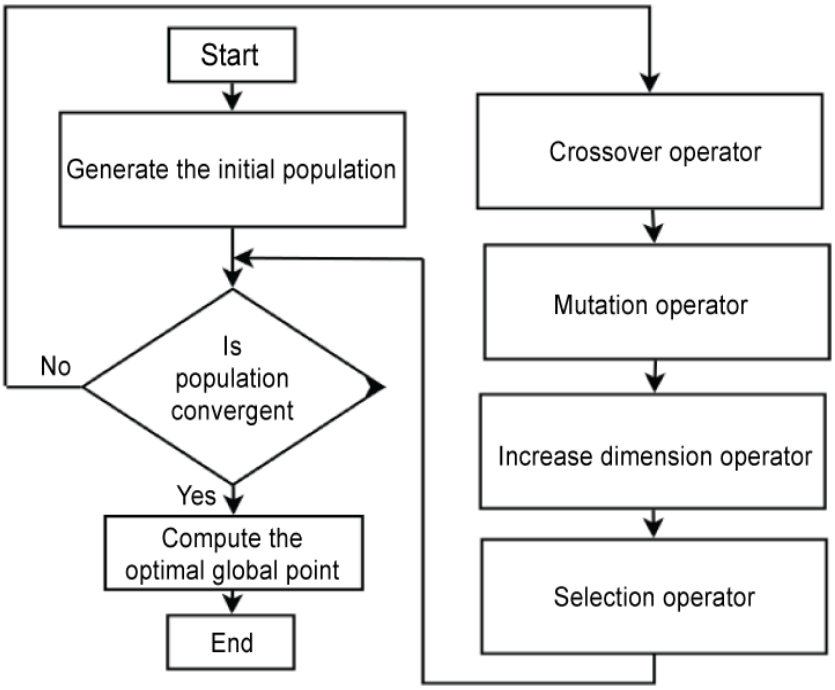

Fig. 1 GA Implementation Flow Chart

The algorithm in Fig. 1 starts by generating an initial population of the input data i.e., MTBF, MTTR and downtime which serves as the dependent variables (global minimal) to be used to get the optimal availability and reliability respectively. Thereafter, the Fitness Function (FF) as presented in (4) and (7) was used in scoring each member of the current population through the computation of their fitness value. The algorithm scales down this fitness value to convert them to a more usable range of values as presented in (5) - (6), (8) - (9). The global optimal point is then computed from the algorithm if the stopping criterion, which is a function of the lower bound (LB) and upper bound (UB) is reached. If this condition is not satisfied, the algorithm initiates the crossover, mutates the best performing event and passes through an operator. This process is repeated until a desired stopping criterion is reached.

The fitness function can be expressed as (4) subject to constraints given by (5) and (6), bounded by the LB and UB; *y* is the availability and *x(1)* is the global minimal.

$$y = x(1) - \frac{\sum_{i=1}^{n} DT_i / \sum_{i=1}^{n} Fo_i}{x(1)} \tag{4}$$

$$\text{Linear Constraints: } \frac{\sum_{i=1}^{n} DT_i}{\sum_{i=1}^{n} Fo_i} - 12.483 = 0 \tag{5}$$

$$\text{Non-Linear Constraints: } \left[\frac{\sum_{i=1}^{N} T_{DTi}}{F_{Oi}} + \frac{\sum_{i=1}^{N} T_{UTi}}{F_{Oi}}\right] - 2929.9 > 0 \tag{6}$$

LB = [3000] and UB = [3400]. Also, *DT* is the downtime, *FO* is the feeder outage, T_{DT} is the total downtime, and T_{UT} is the total uptime.

Conversely, the fitness function can be expressed as (7) subject to constraints given by (8) and (9), bounded by the LB and UB; where *y* is the reliability and *x(1)* is the global minimal.

$$y = \frac{\sum_{i=1}^{N} T_{OHi} - x(1)}{\sum_{i=1}^{N} T_{OHi}} \tag{7}$$

Linear Constraints: $T_{OHi} - 7296 = 0$ (8)

Non-Linear Constraints: $x(1) - 63.7 < 0$ (9)

where

$$x(1) = T_{OH} - e^{t[-\sum_{i=1}^{N} \lambda_i \times T_{OH}]} \tag{10}$$

LB = [20] and UB = [50]; T_{OH} is the total operating hour, λ_i is the failure rate and t is the time.

4. Results and Discussion

The results obtained through the running of the codes for the various feeders using the Genetic Algorithm (GA) are presented in Table 1. Similarly, the percentage improvement for the various feeders were also calculated with respect to their reliability, availability and downtime using (11) – (16) and the results obtained are presented in Table 2. The results obtained for the optimization of the reliability indices: Reliability (R), Availability (A) and Downtime (DT) presented graphically in Figs. 2 – 8.

$$R_{GRA_{optimized}} = \frac{1}{5}\left[\frac{\sum_{i=1}^{N} T_{OHi} - T_{DTi}}{\sum_{i=1}^{N} T_{OHi}} + \frac{\sum_{i=1}^{N} T_{OHi} - T_{DTi}}{\sum_{i=1}^{N} T_{OHi}} + \frac{\sum_{i=1}^{N} T_{OHi} - T_{DTi}}{\sum_{i=1}^{N} T_{OHi}} + \frac{\sum_{i=1}^{N} T_{OHi} - T_{DTi}}{\sum_{i=1}^{N} T_{OHi}} + \frac{\sum_{i=1}^{N} T_{OHi} - T_{DTi}}{\sum_{i=1}^{N} T_{OHi}}\right] \tag{11}$$

$$A_{GRA_{optimized}} = \frac{1}{5}\left(\frac{\sum_{i=1}^{N} T_{UTi}}{\sum_{i=1}^{N} T_{UTi} + \sum_{i=1}^{N} T_{DTi}} + \frac{\sum_{i=1}^{N} T_{UTi}}{\sum_{i=1}^{N} T_{UTi} + \sum_{i=1}^{N} T_{DTi}} + \frac{\sum_{i=1}^{N} T_{UTi}}{\sum_{i=1}^{N} T_{UTi} + \sum_{i=1}^{N} T_{DTi}} + \frac{\sum_{i=1}^{N} T_{UTi}}{\sum_{i=1}^{N} T_{UTi} + \sum_{i=1}^{N} T_{DTi}} + \frac{\sum_{i=1}^{N} T_{UTi}}{\sum_{i=1}^{N} T_{UTi} + \sum_{i=1}^{N} T_{DTi}}\right) \tag{12}$$

$$DT_{GRA} = \frac{1}{5}\left[DT_{GRA_{2011}} + DT_{GRA_{2012}} + DT_{GRA_{2013}} + DT_{GRA_{2014}} + DT_{GRA_{2015}}\right] \tag{13}$$

$$\%R_{Koko_{Improvement}} = \frac{R_{AFTER_{Optimization}} - R_{BEFORE_{Optimization}}}{R_{AFTER_{Optimization}}} \tag{14}$$

$$\%DT_{Koko_{Improvement}} = \frac{DT_{AFTER_{Optimization}} - DT_{BEFORE_{Optimization}}}{DT_{AFTER_{Optimization}}} \tag{15}$$

$$\%A_{Koko_{Improvement}} = \frac{A_{AFTER_{Optimization}} - A_{BEFORE_{Optimization}}}{A_{AFTER_{Optimization}}} \tag{16}$$

T_{UT} is the total uptime of the feeder; T_{DT} is the total downtime of the feeder; T_{OH} is the total operational hour; F_0 is the number of feeder outage; DT is the downtime; MTTR is the mean time to repair; MTTF is the mean time to failure; λ is the failure rate of the feeder; A is the availability; R is the reliability and A is the Availability.

Table 1 Summary of results before optimization

Feeders	Reliability	DT	MTBF	Availability
GRA	0.9785	182.36	1810	0.9806
Guinness	0.8052	1653.3	316	0.7707
Koko	0.7890	1795.1	347.1	0.7378
Switching Station	0.9467	445.36	1395.1	0.9648
Nekpenekpen	0.9741	218.92	908.5	0.9763
Ikpoba-Dam	0.8679	1118.96	884.9	0.8685
Etete	0.9656	294.28	908.1	0.9667

Table 2 Summary of optimization results

Feeders	Reliability	DT	MTBF	Availability
GRA	0.9799	172.1	1899.6	0.9819
Guinness	0.8153	1209	979.2	0.8328
Koko	0.8673	1181.2	363	0.7675
Switching Station	0.9494	421.2	1448.8	0.9692
Nekpenekpen	0.9761	200.6	952.8	0.9772
Ikpoba-Dam	0.8746	1061	936	0.8795
Etete	0.9692	262	1031.2	0.9687

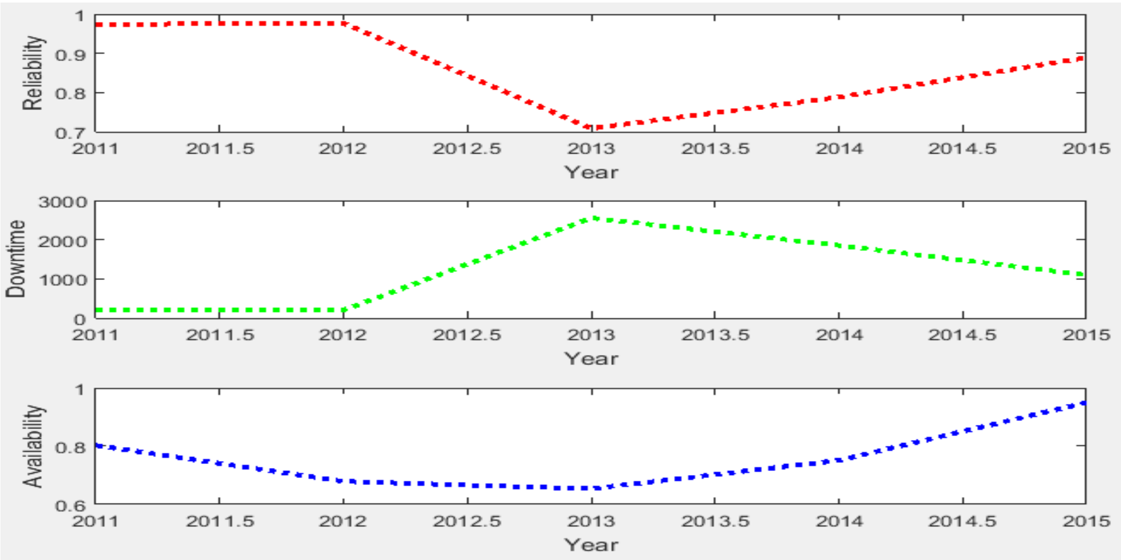

Fig. 2 Optimized load point indices (LPI) for Koko

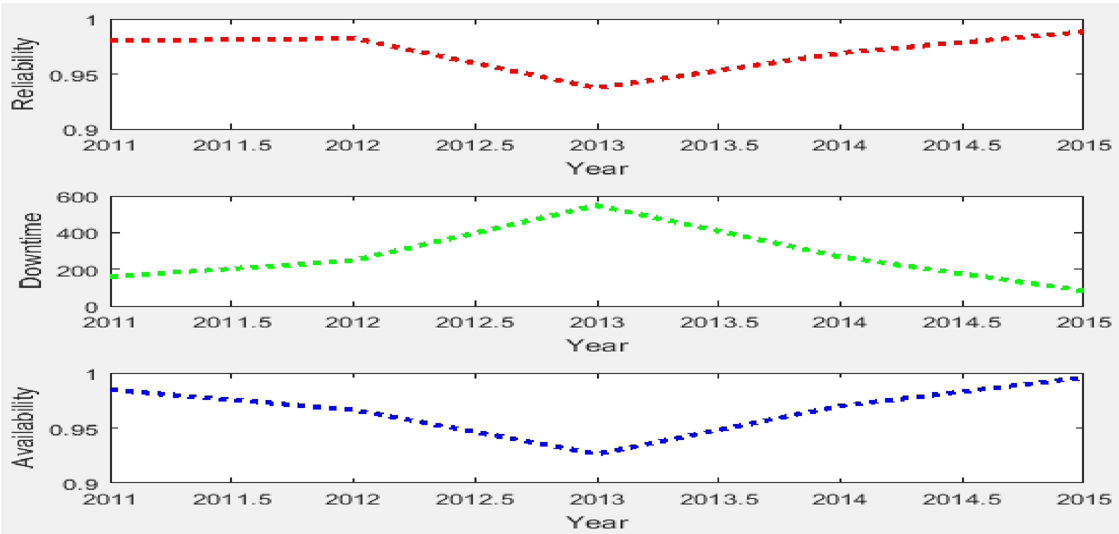

Fig. 3 Optimized load point indices (LPI) for Etete

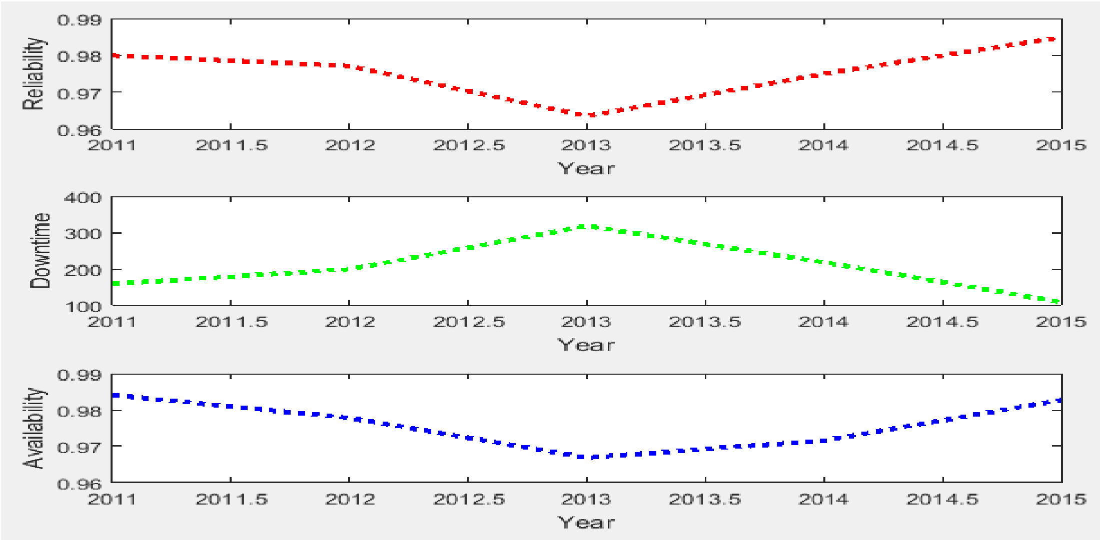

Fig. 4 Optimized load point indices (LPI) for Nekpenekpen

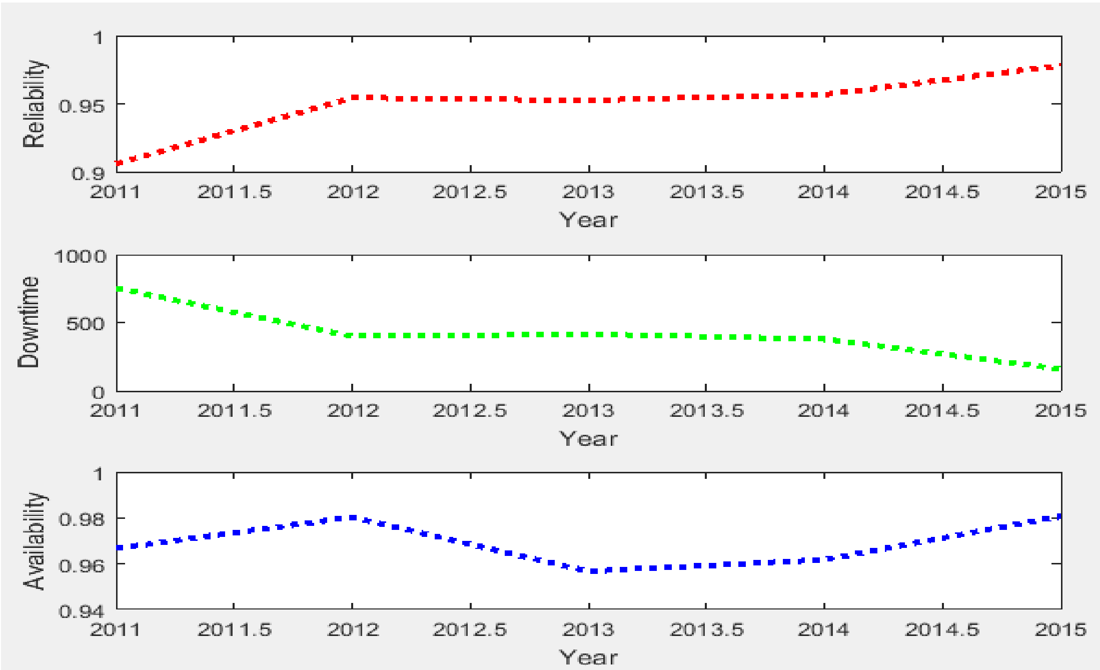

Fig. 5 Optimized load point indices (LPI) for Switch station

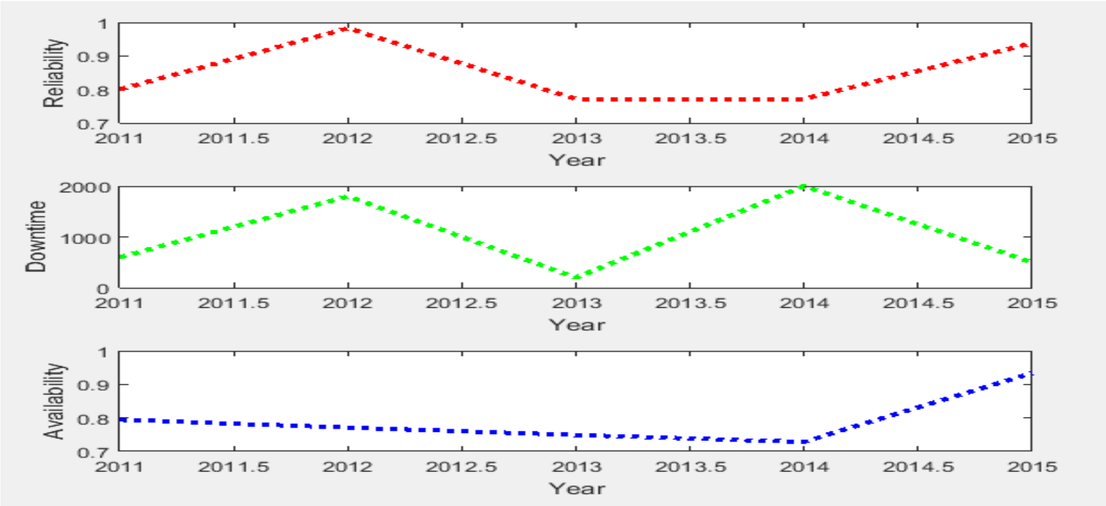

Fig. 6 Optimized load point indices (LPI) for Guinness

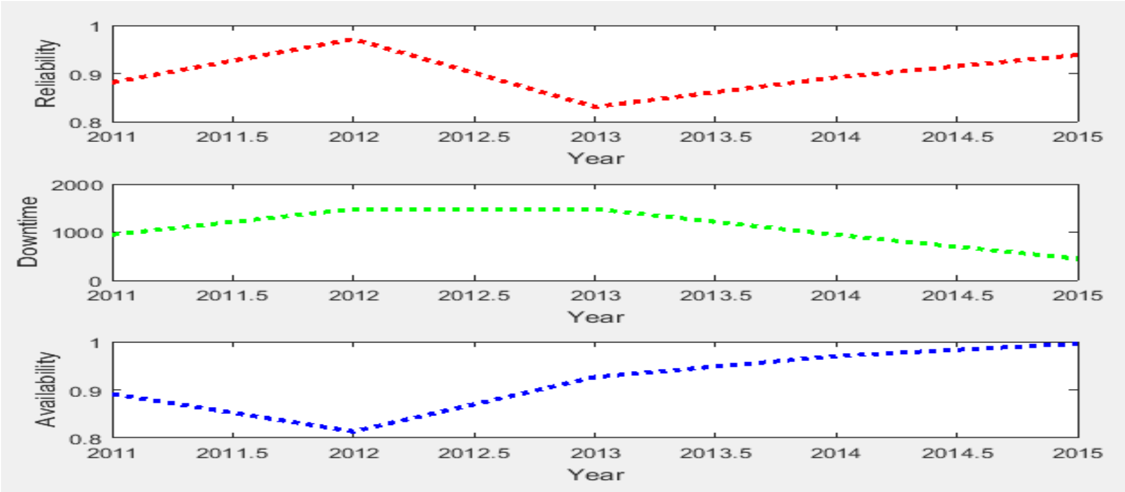

Fig. 7 Optimized load point indices (LPI) for Ikpoba-Dam

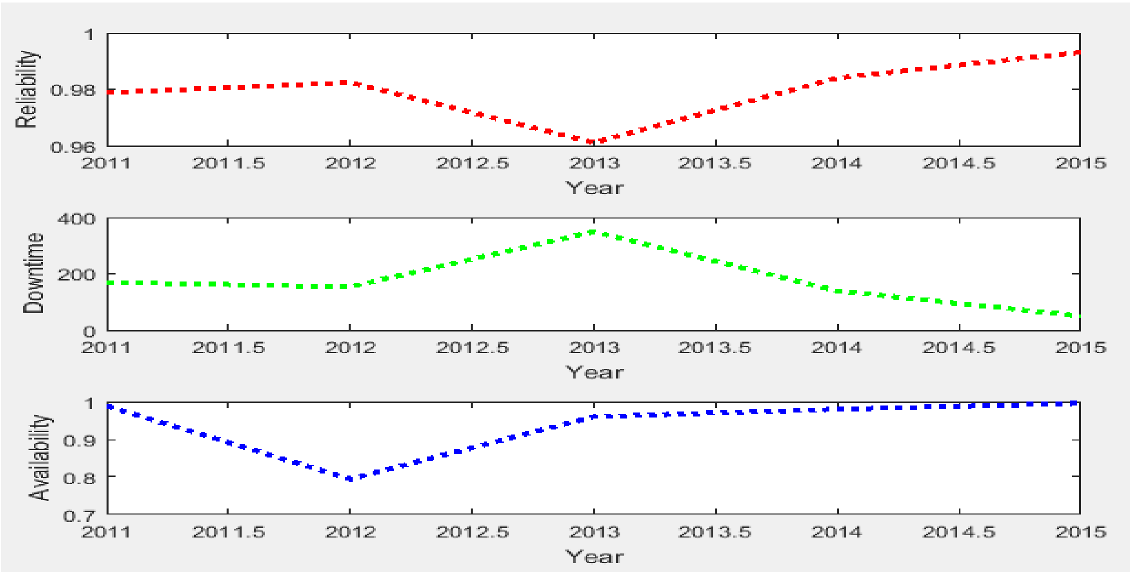

Fig. 8 Optimized load point indices (LPI) for GRA

Table 3 Percentage Improvement

Feeders	Reliability (%)	DT (%)	MTBF (%)	Availability (%)
GRA	0.14	5.63	4.95	0.13
Guinness	1.25	26.87	19.87	8.05
Koko	9.93	34.20	4.58	4.02
Switch Station	0.29	5.42	3.85	0.46
Nekpenekpen	0.21	8.37	4.88	0.09
Ikpoba-Dam	0.78	5.18	5.77	1.27
Etete	0.37	10.97	13.56	0.21

Unlike other optimization technique, a function that affects the system's performance was identified based on the available mathematical equations (4) – (10). The goal of using the GA is to minimize these functions thereby improving the overall system. The results from the study therefore, show a 5.63%, 26.87%, 34.20%, 5.42% 8.37%, 5.18% and 10.97% reduction in down time of GRA, Guinness, Koko, Switch Station, Nekpenekpen, Ikpoba-Dam and Etete feeders' respectively. These values correspondingly led to an increase in the feeders' reliability by 0.14%, 1.25%, 9.93%, 0.29%, 0.21%, 0.78% and 0.37% for the feeders' respectively. The optimal results gotten for the reliability was able to indicate that downtime is a major contributing factor that could lead to poor system reliability. Hence, remedial and optimal actions are necessary across the clock in order to guard against unnecessary downtime that could plunge the system into failure. Additionally, as presented in Table 3, the GA technique was able to increase the MTBF by 4.95%, 19.87%, 4.58%, 3.85%, 4.88%, 5.77% and 13.56% for GRA, Guinness, Koko, Switch Station, Nekpenekpen, Ikpoba-Dam and Etete feeders thereby improving the feeders' availability by 0.13%, 8.05%, 4.02%, 0.46%, 0.09%, 1.27% and 0.21% in that order.

From the above results (Table 3), Koko was identified as the feeder with the highest reduction in downtime. This implies that, the reliability of the feeder could be improved by as much as 9.93% if conscious efforts are taken to reduce the downtime. On the flip side, an increase in MTBF of Guinness feeder by 19.87% yielded an improvement on the feeders' availability by 8.05%. Based on these results, the most reliable feeder might not always be available while the feeders with an improved availability might not always be reliable. Hence, all effort must be put in place to ensure that these parameters are within the standards of international best practices.

Additionally, other research [26] on reliability improvement concentrated on using the Particle Swam Optimization (PSO) in improving the power loss along a network, while others [27]-[28] utilizes the principle Pareto to increasing the significant value "9" in a reliability index. This paper, however, carried out reliability optimization by using the reliability indices itself to actualize the goal of the paper.

5. Conclusion

This study concentrated on optimization of reliability indices of feeders within Benin metropolis, Nigeria using GA as an Artificial Intelligence tool in achieving the purpose. The results from the study identified that if adequate concentration are placed on systems' downtime and MTBF, then, there can be a corresponding improvement on the reliability and availability of the network. The study also recommends that other AI tools like the hybrid GA etc. can be used for similar studies in order to ascertain their effectiveness in the field of reliability

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Appendix A Data sample for GRA feeder

S/N	Feeder	Month	Year	No. of Outages	Downtime (h)
1	GRA	January	2011		
2	GRA	February	2011	16	15.1
3	GRA	March	2011	24	15.8
4	GRA	April	2011	27	24.8
5	GRA	May	2011	53	30
6	GRA	June	2011	9	26.5
7	GRA	July	2011	4	12.8
8	GRA	August	2011	11	18.6
9	GRA	September	2011	3	10.3
10	GRA	October	2011	3	9.6
11	GRA	November	2011	1	2
12	GRA	December	2011	3	9.3
13	GRA	January	2012	0	0
14	GRA	February	2012	1	2.6
15	GRA	March	2012	5	10.5
16	GRA	April	2012	5	9.7
17	GRA	May	2012	5	8.9
18	GRA	June	2012	2	17.6
19	GRA	July	2012	2	13.1
20	GRA	August	2012	4	29.1
21	GRA	September	2012	6	3.4
22	GRA	October	2012	7	15.5

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