Journal of Power and Energy Engineering, 2021, 9, 63-75
https://www.scirp.org/journal/jpee
ISSN Online: 2327-5901
ISSN Print: 2327-588X

Optimal Placement of Reclosers to Minimize Power Losses during Non-Load Bearing Disturbances in a Power Distribution Using Firefly Algorithm

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How to cite this paper: Amolo, W.O., Musau, P. and Nyete, A. (2021) Optimal Placement of Reclosers to Minimize Power Losses during Non-Load Bearing Disturbances in a Power Distribution Using Firefly Algorithm. *Journal of Power and Energy Engineering*, **9**, 63-75.
https://doi.org/10.4236/jpee.2021.95004

Received: December 17, 2020
Accepted: May 19, 2021
Published: May 22, 2021

Abstract

The research reported in this paper focuses on non-technical power loss reduction for power distribution systems. Such reduction of costs of energy not served (ENS.COST), is intelligently evaluated and optimized using a firefly algorithm, from where savings of 43.3% on energy not served are achieved.

Keywords

Loss Minimization, Non-Load Bearing Power Losses, Optimum Location, Reclosers, Transient Power Balance

1. Introduction

Apparently, power distribution undergoes recurrent power outage due to transients and needless to say, consumers decry economic losses as a result. Notably, the situation is pegged on lack of metering facilities, unlawful tapping of power and fraudulence in the industry among others. The fact still remains that keeping quality and stability in power system needs among other things a huge amount of capital investment for its protection. Lack of proper protection amasses to power losses and the credibility of investments fails to prove its worth. The semi-conductor energy controlling mechanism (SCECM) replaced common electromagnetic circuit-breakers in distribution of energy against the effect of various loading [1] [2] [3]. This practice had the resulting rewards: Advanced stable variables; the application of the recovery plan was more innovative than before; low number of mathematical calculations and internetworked enactment was possible. To restore stability in distribution of power system, where data on transients has deficiency, reclosing technique with adaptive formulation is applicable [4] [5] [6] [7]. Microchip-based electrical relay and reclosers for data keeping are utilized in the energy distributing section on overload currents and disturbances. A multi-objective approach combining "energy amounts" and "reliabilities in communicating channels" was used in another invention to position reclosing device by means of the genetic-algorithm code (GAc) [8]. The first objective-function comprised of recloser cost outlays and the latter was for reliability status of the system. In general, a flowchart with optimization, numerical integration, with randomness to solve problems was modelled to handle random errors. This model was able to provide line (KVA * t) power with momentary failure. It has been shown that rigorous measures can be used to develop four placement methods of reclosers for optimal operation [2] [3] [9] [10].

Among the reviewed works in this research include [5], who developed a detection of theft of electricity (TOE) at various check points. Fraudulent behaviour among the consumers could then be put under check and non-technical power loss monitored. This was possible through a software applying database analysis and deciding on fraudulent cases. [11] described a proposed programmable recloser logic that when programmed would reduce protection time, detect upstream conductor slap and provided timely lockout. More still could detect fault location in a non-communication loop. [12] proposed analytical hierarchy process method (AHP) to analyze the system losses in distribution systems. This technique could minimize non-technical power losses through alteration of network topological arrangement. [11] employed probability based or Monte Carlo method of setting reclosers along power system distribution. The method exclusively provided a means to optimally place reclosers at intervals, making them operate at various optimal timings at various protection zones. More importantly the proposed method had the ability to determine an optimal reclosing cost benefit analysis for power quality and protection efficacy. [13] designed an intelligent fault location and detection technique along the power transmission lines. Electromagnetic induction effect was the principle applied to detect faulted point along the transmission line. GSM was used to remotely relay real-time information. [14] [15] came up with a piloted scheme that used smart switches combined with sectorized distribution feeder recloser technology. This method managed to lower the affected number of end users during power outages resulting from transient faults. This method applied current-time-curve to determine reaction time of reclosers.

Regardless of the various developments in this topic, non-technical power losses still are dragged on reliability concept as though it as a solution. More if not all energy production managers might choose to shut down just because electricity theft and its damage is alarming. Transformers are short circuited and high currents endanger those who are culprits. The most affected areas such as slum dwellings may begin to go without power.

This work improved the reclosers' response period capability, providing its finest placement within the system distributing energy during transients. The study achieved an untroubled power distribution system and balance in the midst of transient conditions. Thus, 43.3 percent utility savings during operation of reclosers is achieved. Increased financial savings would increase investment and boost long-term productivity. Power producers would ultimately reduce the cost of power charged to consumers. Some of the consumers who will benefit are those who steal electricity because now they will pay for what is affordable. Meanwhile, more alarming state that's addressed in this work is outages caused by interruptions from those who steal by using illegal connections. This work is shedding light on how the menace can be technically controlled even though it is outright non-technical. Reliability improvement of power distribution system has been addressed sufficiently if not completely. The Kenyan utility company shut down their power transformer owing to unlawful connection in Kibera, a slum area in Nairobi City. This happened on 24th August 2019, according to Kenya News Agency (KNA). Optimal reclosing that focuses on minimizing illegal power connections losses requires an intelligent approach which is applicable to transients. Reclosing cycle model (RCM) formulated using firefly algorithm is planned for this work. The problem formulation is based on ideal reclosers' location, in electrical energy distributing network.

2. Formulation of the Problem

2.1. Problem Definition

A number of considerations were made for problem formulation featured separately hereafter, targeting the following operational issues:

1) Brief shut down improved in several ways, including the following:

a) Reduce faults—such as power tapings, tree lowering, tree fall, creatures' movements, arresters, tour duties, and so on;

b) Reclosing quickly;

c) Reduce the number of consumers' disturbance by using downstream recloser.

2) Distribution Line Reclosers

In this kind of recloser arrangement, the strategy is to minimize recloser time because it is based on the time delay required to extinguish the fault. Table 1 provides an overview of how recloser types and set-up work together with reclosing schemes. These standard ratings were important to guide all sectors of power systems.

The reclosing technique design was meant to have at most three delays. For all types of reclosers the power fault condition completely would have subsequent opening and closing the affected area three times to check whether the fault was able to clear itself. It is only the permanent faults, which normally open or cut off after the third delay to safe guard the power system apparatus. The time values provided are considered to be within the minimum accepted range for the purpose of setting a recloser depending on criteria applicable to the designer.

Table 1. Recloser schemes (IEEE Practices).

Recloser Setting	Recloser Schemes	Period Interruption A	Period Interruption B	Period Interruption C
1	Instantaneous	2 s	15 s	30 s
2	Fast	2 s	15 s	30 s
3	Delayed	5 s	30 s	60 s
4	Hydraulic	2 s	2 s	2 s

Firefly MATLAB coding for this work uses instantaneous values of 15 sec for period B and 30 sec for period C. These are time delays meant to safeguard especially transformers from stressing currents which are abnormally very high during transients.

2.2. Non-Technical Loss Reduction

Considering the costs incurred in an event that transient and permanent faults or "non-technical power occurs". The objective cost function of transient faults were calculated as (1)

$$w_{\text{ENS}} = \min \sum_{r=1}^{n} P_r T_r C_r \tag{1}$$

where C_r, P_r and T_r are load based cost of energy, consumed power and recovery period in seconds during short-lived failures. C_r is subject to recloser settings and brief power cut off caused by the operation:

2.3. Electricity Consumption

This model aims to reduce the cost and increase the system reliability with recloser' optimization model given by Equation (2). This equation describes amount of power transferred during a blackout in a distribution network.

$$E_h = \sum_{0}^{9} \text{kVA}_I * t_r = P * t \tag{2}$$

In which, t_r is operation time of the recloser, P is transferred power and E_h, kW sec of the lost supply. $\text{kVA} * t_r$ is the thermal energy required to melt a specific fuse element; taken as recloser dead-time. Using reclosing philosophy as shown in (3)

$$\text{ENS} = \text{kVA} * t_1 + 0.01 * \text{kVA} * t_2 + 0.06 * \text{kVA} * t_3 \tag{3}$$

where ENS is Energy not served during reclosing operation.

kVA = Transformer rating or size, t_1, t_2 and t_3 time interval for reclosing period. The work aimed at optimizing savings in cost of energy, according to formulation in Equation (4)

$$\min f(x) = ENS = d_i t_1 + 0.11 d_i t_2 + 0.06 d_i t_3 \tag{4}$$

where,

$$d_i = D_j F_k L_m R(t) CC_r \tag{5}$$

subject to;

$$0.5 \le t_r \le 45.9;$$

$$75 \le D_j \le 400;$$

$$0 \le F_k \le 1;$$

$$R(t) \ge R_0$$

In which D_i is upstream supply for the model nine zones, F_k is rate of failure over the length of line, L_m is downstream length of line, t_r fault clearance time based on recloser operation in 3 shots, C is accumulated recloser cost of operation and maintenance, C_r is cost of blackout per Kilowatt while $R(t)$ is the rate of failure.

2.4. Operation and Maintenance Cost

Considering single recloser device, the total everyday device operation and maintenance cost is given by:

$$C_{rom} = \xi * \text{CENS} \tag{6}$$

$$\xi * \text{CENS} = \min\left(f\left(C_{rom}\right)\right) \tag{7}$$

$$R(t) \ge R_0 \tag{8}$$

$$\text{ENS}_{\max} \ge \text{ENS} \ge \text{ENS}_{\min} \tag{9}$$

In which CENS is unserved energy cost resukting from reclosing operation as a protective measure for feeders. Thus $R(t)$ is the probability of success (reliability) index of a distribution system, under a given recloser constraints. $R_0(t)$ is the occurrence or reliability index projection compels, hence the location based energy savings realized according to the formualtion for the radial network.

2.5. Vector Parameters

Parameters in the vector settings included power, current, distance and time. These parameters are equated such that: x_1 is per kilometer detection period, based on standard setting of the recloser x_2 is downstream length of line in kilometer. And x_3 is upstream length of line in kilometer. The per kilometer detection period along feeders is approximated as two second per kilometer. Parameters in the vector *i.e.* power, current and time are set and equated as;

$$x_2 = \sum_{i=1}^{9} L_i \tag{10}$$

$$x_3 = \sum_{i=1}^{9} L_j \tag{11}$$

$$L_i = 5.6, 7.4, 10.4, 13.2, 16.7, 19.9, 22.5, 24.5, 26.1 \tag{12}$$

$$L_j = 26.1, 25.4.22.5, 19.9.16.7, 13.2, 10.4, 7.4, 5.6 \tag{13}$$

$$g_1 = x_2 / \left(x_2 + x_3\right) x_1 \tag{14}$$

where g_1 is time taken to locate fault, while x_1 is standard setting for detection period, *i.e.* two seconds per kilometer. Equation (14) shows feeder's switching time. Post fault switching period for individual feeder is given as per Equation (15) while Equation (16) illustrates period taken to clear faults. Demand based un-served energy during the blackout is shown in Equation (17) and the Per kVA, per zone rate of failure is given by Equation (18), In which D is downstream demand. Protective equipment cost of maintenance and operation is formulated in Equation (19) and the cost savings for unserved demand modeled as shown in Equation (20)

$$g_2 = g_1 + 15\text{ s} \tag{15}$$

$$g_3 = g_2 + 30\text{ s} \tag{16}$$

$$C_r = \$\,1/\text{kVA} \tag{17}$$

$$g_4 = g_1 D + 0.11 D g_2 + 0.06 D g_3 \tag{18}$$

$$g_5 = 0.008D \tag{19}$$

$$g_6 = \$\,0.008/\text{kVA} \tag{20}$$

$$\text{CENS} = \min\left(C_r * \sum\left(g_1 g_2 g_3 g_4 g_5 g_6\right)\right) \tag{21}$$

The limits for these vector parameters include:

$$0.5 \le x_1 \le 45;\ \ 80 \le D \le 1800;\ \ 0 \le g_5 \le 1 \ \text{ and }\ 1 \le x_3 \le 26$$

$\text{ENS}_{\max}$ is the highest outage and expressed by considering the recloser operation in terms of fault location time, which is given by;

$$\text{“Fault location time”} = x_1 / \lfloor x_1 + x_2 \rfloor * \text{“Recloser set time”}$$

where, x_1 and x_2 are downstream and upstream distances to the faulted area. Fault location is the place where a short circuit current occur. The distance is measured from the sub-station recloser position. Fault location time for faulted area was calculated using Equation (13).

3. Methodology

Intended reclose operation is optimized via FA, minimizing un-served-energy, according to formulated problem in Section 2. Process of mitigating Recloser for reduction of outage costs (9), is considered. Types of fault and faulty area are defined by setting parameters. Numerical results are achieved through applicable irregular testing based on computation, solved by FA, factoring in vulnerabilities of reclosing operation (13).

3.1. FA's Classical Pseudo Code

Step 1: Initialization of algorithm parameters.

Step 2: Creation of first population using: $X_{j,i} = X_{j.i}^{L} + \text{rand}\left(X_{j,i}^{U} + X_{j,i}^{L}\right)$

(In which *j* and *i* are integers ranging from 1 to *n* and *N* respectively *i.e.* count of decision variables).

Step 3: Objective Function Computation using: $f(X), X = \left(x_1, \cdots, x_N\right)^{\mathrm{T}}$.

Step 4: Iterative FA parameter definition for attractiveness (β), randomization

(α) and coefficient of light absorption (γ).

Step 5: Firefly attraction, in which attractiveness depends on distance, such that: $d_{a,b} \exp\left[-\gamma d_{a,b}^2\right]$.

Step 6: Light Intensity Update as per the created and computed solution.

Step 7: Limiting violation to both inequality and equality constraints.

Step 8: finding current best out of rated fireflies.

Step 9: Report result.

Step 10: Screen printout optimum solution based on firefly with highest light intensity.

Step 11: time plotting of iterations/time vs., light intensity.

Step 12: Stop.

Application of this pseudo code to the formulated problem is illustrated in the diagram of Figure 1.

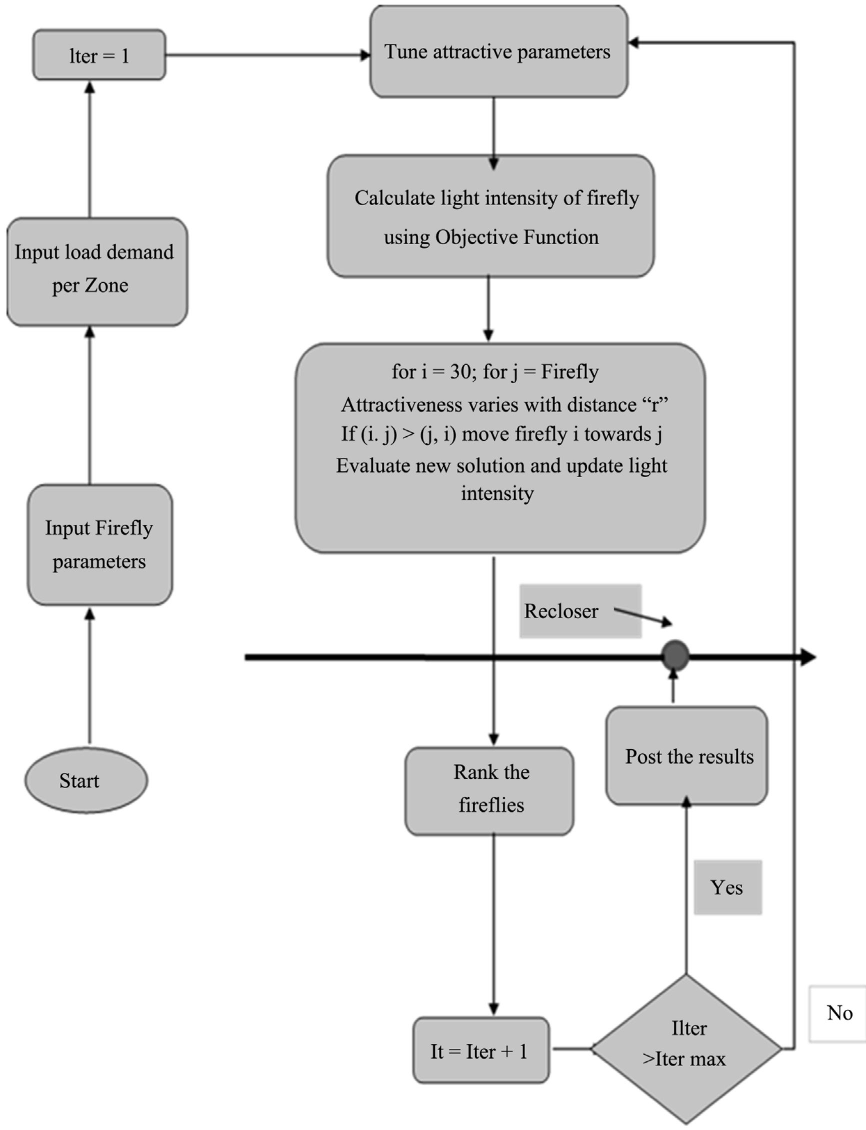

Figure 1. Application of firefly algorithm to the formulated problem.

3.2. Data for the Formulation Model Simulation

The data for the firefly algorithm coding utilized a radial network. This network has values including: downstream load power demands symbolized as d, distances where transformers are placed and their kVA values, the reliability ratings of each line and is based on power demand of the section.

1) Network Zones and Parameters

For each of the nine zones, three parameters are considered for data inputs, as tabulated in **Table 2**. These include maximum kVA, downstream network length (km) and line failure rates.

2) Fault Location Time for 9 Zones

Once a faulty occurs on the downstream network, it takes time for the system to detect and locate. The data in **Table 3** shows the time taken by system, to locate the faults.

Table 3 and **Table 4** values were used to develop matrices for reclosing coefficient. Reclosing coefficient values were useful for optimization technique developed in firefly algorithm. Basically, all the zones' distances are stretched for different kilometers along the network. Fault location and clearing time are solved using Equations (11) and (13) respectively. At first, fault location and clearing times are shorter and increases downstream. As long as the recloser is closer to the upstream distribution system, it is made to have a shorter time to locate and clear the fault once it occurs along the proposed radial line.

Table 2. Proposed network parameters.

Zone	1	2	3	4	5	6	7	8	9
Demand (KVA)	100	300	315	400	230	110	160	75	90
Feeder Length (Km)	5.6	7.4	10.4	13.2	16.7	19.9	22.5	24.5	26.1
Failure Rate	0.7143	0.54	0.384	0.303	0.239	0.201	0.177	0.163	0.153
Maintenance & Operation Cost	25.0	75.0	78.75	100.0	57.0	27.0	40.0	18.7	22.5

Table 3. Fault location time along the radial line.

Zone	1	2	3	4	5	6	7	8	9
Location 1	0.1767	0.1918	0.2652	0.8132	0.3203	0.3645	0.3733	0.4746	0.6087
Location II	0.2209	0.2387	0.3366	0.8595	0.3985	0.4464	0.4405	0.5441	0.6727
Location III	0.2849	0.3587	0.3917	0.8859	0.4567	0.5057	0.5841	0.6265	0.7429

Table 4. Fault clearing time along the radial line.

Zone	1	2	3	4	5	6	7	8	9
Trip Setting I	45.1767	45.1918	45.2652	45.8132	45.3203	45.3645	45.3733	45.4746	45.6087
Trip Setting II	45.2209	45.2387	45.3366	45.8595	45.3985	45.4464	45.4405	45.5441	45.6727
Trip Setting III	45.2849	45.3587	45.3917	45.8859	45.4567	45.5057	45.5841	45.6265	45.7429

4. Simulated Results and Discussions

4.1. Summary of Results

Tabulated results (**Table 5**), have each column's input variables, as per the model system of radial network. Levels of reliability are inversely proportional to zonal span. Distance depended detection-period, for faults establish the clearance times in which distance is referenced to location of upstream recloser. This criterion implies longer clearing periods for furthest zone 9. Zone 9 has higher CENS, as compared to zone 8 that possesses less operation, maintenance and kVA * t costs, hence lowering the cost savings. A methodology to evaluate the economic advantages of using reclosers in power distribution system permitting. Self-operative procedures were discussed in [9].

The economic advantage contradicted the capital and the operational consumptions against the investment funds because of the decrease with the expense of energy not served. The use of a single recloser was obviously expensive compared to using two. The cost of capital investment for several reclosers became much beneficial to an extent that 40% of power was saved in a techno-economic assessment. Simulated result in this work realized a higher benefit of 43.3%.

4.2. Unserved Energy Cost-Savings

During power outages, derivation of equations based on un-served energy gives sufficient problem formulation for non-technical losses. Animal based power interruptions and illegal tapings contribute to transients causing blackouts. The plotted results of unserved energy cost savings is illustrated in **Figure 2**. These results indicate downstream CENS, with automatic optimization of upstream reclosing, as per the scheme of protection modeled in Equation (2). The plots imply that power transfer for upstream loads is higher in each zone.

Table 5. Summary of results.

Zone	1	2	3	4	5	6	7	8	9	
KVA	100	300	315	400	230	110	160	75	90	
Distance Downstream	5.6	7.4	10.4	13.2	16.7	19.9	22.5	24.5	26.1	
Failure Rate (Reliability Level)	0.7143	0.54	0.384	0.303	0.239	0.201	0.177	0.163	0.153	
Maintenance and Operation Cost ($)	25.0	75.0	78.75	100.0	57.0	27.0	40.0	18.7	22.5	
Fault Location Time	0.1767	0.2209	0.2849	0.3359	0.3902	0.4326	0.4630	0.4842	0.5000	
Fault Clearing Time	45.1767	45.2209	45.2849	45.2849	45.3902	45.4326	45.4630	45.4842	45.5000	
Min CENS ($)	234,137	189,518	125,643	104,778	81,795	71,376	59,705	52,307	54,746	822,339
Min (Cost) ($)	1,451,400									
Savings ($)	629,061 = 43.3%									

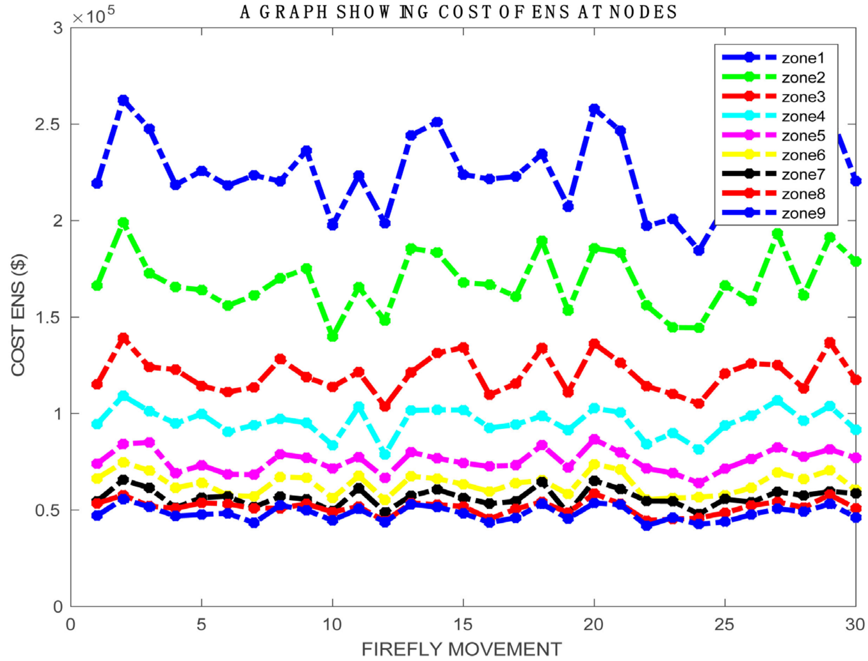

Figure 2. Unserved energy costs.

4.3. Recloser Optimization, Distributed in 3D

Difference in cost of un-served energy varies from zone 1 to zone 9, based on simulated models, with significant variations. Figure 3 illustrates 3D distribution of cost of energy not served and demand distribution, in same plot. Both maximum and minimum values are illustrated for reclosed feeder zones, according to the simulation, as opposed to generation of un-served energy costs.

4.4. Validation of Results

To attest on results generated in this work, the reviewed publication [11] had a 40% savings for recloser placement. This previous work demonstrated recloser placement in a rural distribution network with a radial setting. Tradition formulation, recloser placement developed was on two levels. The problem was to optimize recloser placement. The first level, recloser allocation was reliability estimation of SAIFI and CAIDI in smaller areas within the feeder network. Estimation of reliability indices was on assumption that customers were evenly distributed. To some extent, second level placement was exact location employing simulation technique based on Roy Billiton Test System (RBTS).

In [15], optimal recloser placement in fault condition was based on design to cost methodology. The formulation was based on matrix tables available which could be used to determine maximum number of reclosers in the network. Cost benefit analysis was done and payback was possible within a yearly period. The results were that cost benefit factor was greater than 1 (one). This translated to benefit greater than cost when reclosers were distributed in a radial system.

Having analyzed these two techniques, the proposed technique appears to be an improvement in comparison. 43.3% savings which could be calculated in

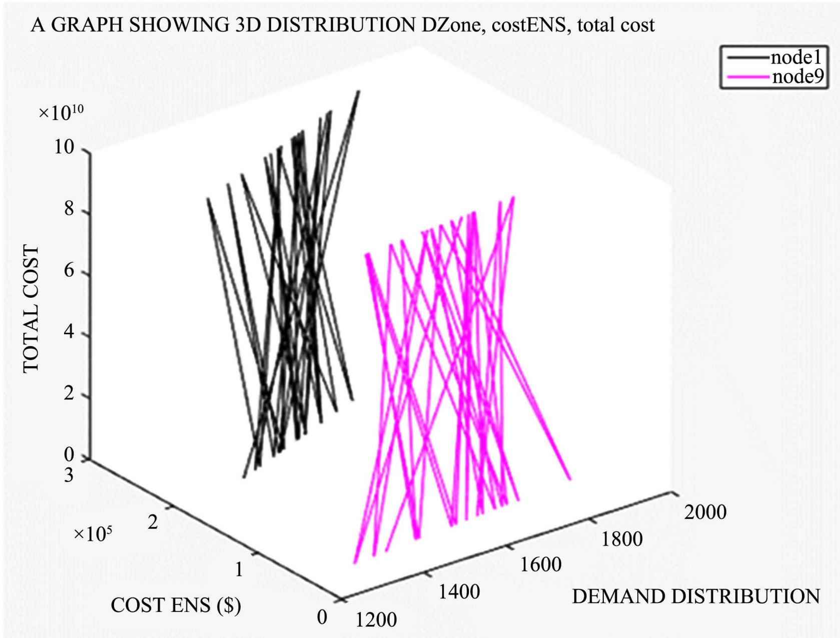

Figure 3. Reclosers' distribution along the Line (1 and 9 only).

every interruption is a better idea. The cost benefit analysis which runs for a year could be tedious work compared to the proposed method so far. This cost benefit factor kept the real unknown.

5. Conclusions

Cost of outages reduced as reclosers location moved away from substation, as per the analysis of realized results. Cost-Savings *i.e.* CENS were attained with minimization of zones, due to avoidance of multiple-outages. Reclosures were useful instead of either fuse or switch, which lead to prolonged outages, and the increased allocation and placement of CENS Reclosing can be achieved satisfactorily with the firefly algorithm simulation with optimum reclosing technique. CENS savings were achieved as predicted. Measure of success of the deployed technique is judged on basis of difference between minimum values of CENS and total cost.

In the future, it is possible to continue optimizing the recloser utilizing FA on harsh limitations, and inclusion of topologies for network. The mathematical technique used to optimize the reclosure placement was based on the CENS value. It has been found that the firefly algorithm has an effect on the reclosing ability of the feeder according to the cost of the process. The firefly algorithm has been effective in placing reclosers according to the regional energy cost not served.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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