A Discrete Bat Algorithm Based Optimal Location and Sizing of Power Distribution Substation

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ABSTRACT

Distribution substation planning is considered one of the most important steps in the power system planning process. A planning model seeks to determine a strategy that will minimize losses and total costs associated with configuring and operating an electric power distribution system over a given planning horizon. Metaheuristic methods are usually deployed in solving the distribution planning problem but face complexity and constraint limitation in some cases. Discrete Bat Algorithm (DBA) is a combinatorial technique that is a robust algorithm that will be suitable for solving a distribution substation location and sizing problem. The approached comprises two stages which include: Optimal Distribution Substation Location (ODSL) using a Modified Load Gravity (MLG) based method; and Optimum Sizing of Distribution Substation (OSDS) using DBA. Zaria distribution substation network is used as the case study. The results obtained has been compared with other similar literatures and validated. The results obtained using DBA achieved an expansion cost of $2,634,410.08 representing 59.7% cost reduction. While the particle swarm optimization (PSO) which amounted to $6,541,000.00, represent 40.28% cost reduction. By comparing the results of PSO and DBA, it is clear that both methods have the ability to find proper solutions to substation expansion planning, but DBA is more able than PSO to find an optimal solution to substation expansion planning.

1. INTRODUCTION

Distribution Network planning can reduce the probability of blackouts, reduce transmission loss, and improve power quality, so it is an important part of power distribution network automation system (Sun & Chang, 2015). The main task of distribution network planning is to optimize network structure and find the optimal expansion scheme of power distribution network. The distribution network planning problem consists of minimizing the investments and operational cost as the objective function within technical constraints, such as overload, voltage drop and radial network (Sun et al., 2015). Distribution network expansion planning is a complex and large-scale combinatorial optimization problem; the classical mathematical methods cannot solve problem satisfactorily. Modern metaheuristic methods, such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Bat Algorithm, and Ant Colony System (ACS), are used recently to solve the distribution network planning problem and have achieved some results. In Substation Expansion Planning (SEP), the problem is to determine the required expansion capacities of the existing substations as well as the locations and the sizes of new substations together with the required availability times, so that the loads can be adequately supplied (Seifi et al., 2011). The loads to be supplied are widely geographically distributed. For substation planning, the normal procedure is to initially determine the distribution substation requirements and moving upward, to finally determine the transmission substation requirements (Sedghi et al., 2013). This approach, although accurate and practical for short and midterm planning may prove impractical for long-term studies for transmission and distribution network planning (Fletcher et.al, 2007a). One way to overcome this problem is to propose an algorithm in which the geographically distributed loads are somehow assigned to transmission substations. Although this does not happen in practice, the final transmission substations allocations and capacities can prove appropriate, provided various constraints are properly observed. The assigning procedure is, however, crucial as an unsuitable procedure can result in improper solutions. Substation (Capacity) Expansion Planning (SEP) of distribution networks is accomplished in practice by planning engineers. The network planners take into consideration the existing network and forecasted load, together with the technical and economic considerations with aims to optimize the routing (layout), location, re-conductor size of the distribution feeders (Ravadanegh et al., 2014).

Distribution network expansion planning is therefore a complex multi-objective optimization problem (Falaghi et al., 2011). Moreover, the intricacy of the problem is increased critically as the system size becomes large. There exist numerous studies into distribution network expansion problem but the problem modeling is still far from being standardized (M Sedghi et al., 2013b). Every network operator has a different policy regarding the operation constraints of their power systems and different repositories of electrical facilities (Luong et al., 2014). Most studies evaluate the reliability of distribution networks based on the average failure rates and restoration times of components, in which reserve cables are considered as options to enhance the network reliability, (Falaghi, *et. al.,* 2011). The result of such reliability analysis can then be capitalized into customer outage cost to include in the overall cost to be optimized or can be treated as a separate objective function, (Carrano, *et. al.,* 2006). However, it has been shown that reliability in practice is a relative index as its calculation involves many intricate problems with high uncertainty, (Slootweg et al., 2005). The research work had combined the model parameters used in different literatures in order to come up with a highly flexible, realistic and robust method used to simulate various scenarios of network expansion. Distribution expansion planning was a complex and large-scale combinatorial optimization problem; classical mathematical method cannot perform satisfactorily for solving it. Modern meta-heuristic methods, such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony System (ACS) were used recently to solve the distribution network planning problem and have achieved some results, but effectiveness of the solution cannot be guaranteed.

In this study, DBA is used to compliment the deficiency of other algorithm like reducing the complexity of turning parameters and also to solve the problem of distribution system planning to find the optimum number of substations, location and sizing to be effectively, reliably and more efficient, for optimal substation placement.

2. LITERATURE REVIEW

In the literature, a large number of researches have been made on various aspects related to electric power distribution network expansion. And quite number of such works have been consulted. Haghifam et al., (2002) presented an approach for optimal location, sizing and determining the service area for range of planning period using psedodynamic methodology. Costs of equipment, area of cables for MV and power loss are considered in cost function. Uncertainty in loads is modeled using left and right fuzzy (LR fuzzy) numbers in load points for optimization genetic algorithm with a new coding is used. Load points splitting in each area between substations and infeasibility solutions are considered in such procedure. (Albadi et al., 2008) in the work, an approach optimization for the determination of the optimum location and capacity of DG sources in the deregulated electric market through net-present-value analysis was presented. The model aims to minimize the investment cost, utility cost and the losses cost of a distribution network considering uncertainty of peak demand. Improved genetic algorithm and a fuzzy model were employed to solve the network expansion problem. The efficiency of the proposed approach was demonstrated using a sample 24-node network. The major setback of the work was that: the objective function developed in the work is not robust enough to tackle expansion problems involving large number of nodes subjected to more than one constraint. (Carrano et al., 2007)**:** In this work, the authors addressed the problem of electric distribution substation capacity expansion under condition of uncertainty in the evolution of node loads (both load growth rates and node positions) and within a given time horizon. An immune- based evolutionary Algorithm was employed to find the optimal and suboptimal network topology, for a given set of network expansion scenarios. A Monte-Carlo simulation and a multi-objective analysis of solutions are employed to test the performance of solutions over a set of other possible scenarios. Two case studies of electric distribution network design were presented: a 23-bus system network (benchmark system) and a 21-bus system network. The mathematical model developed is quite complex and will be too difficult to apply as the network size increases. Therefore, further simplification can be made, and the model can be extended to enhance its flexibility. (Carrano et al., 2008): In the work, a dynamic programming genetic algorithm was developed for electric distribution system expansion planning was presented. A set of network expansion scenarios were simulated, and the numerical test results shows that the proposed algorithm outperforms other non-dynamic programming methods. The developed model is less flexible and therefore, may not support simulations with higher number of constraints. A number of other model parameters could be introduced into it to improve its flexibility.

(Khan et al., 2010): In the work, a Genetic Algorithm (GA) based method for distribution network capacity expansion including Distributed Generation (DG) was presented. A combinatorial optimization method that determines the location and capacity of feeders and substations while minimizing the network loss and installation cost was developed. DGs were considered in the network expansion planning as to regulate the distribution network. The work also proposes a new objective function considering the installation cost of equipment (feeders, substations and DGs), cost of losses and cost of DGs operation. The capability of the proposed model can be enhanced by incorporating realistic assumption such as the dynamic nature of load. Other parameters could also be introduced to improve its flexibility.

(Sedghi et al., 2013): In the work, Medium-voltage/High-voltage substations, main and reserve Medium-voltage feeders, dispatch-able DG sources and storage units were considered as possible solutions for multistage distribution expansion planning. A three-load level was used for variable load and some strategies were proposed for DG and storage units' operation. A modified PSO algorithm was applied to solve the complex optimization problem. Numerical results of the case studies were used to demonstrate the effectiveness of the developed model. The major setback of the work is that the developed objective function is less flexible; too complex and its complexity might further increase, with increase in the number of nodes to be considers.

(Javadi et al., 2011): In the work, optimal DG expansion decision was made based on annual load pattern of a given system and its load duration curve. An economical evaluation was then presented on expansion choices using sensitivity analysis and value of investment. The presented approach considers both concerns of Independent System Operator (ISO) and Generation Companies (GenCos). A short-term Security Constraint Unit Commitment (SCUC) for each of the selected scenario was considered from ISO's point of view. The proposed algorithm was finally applied to IEEE-24 Bus test system. Even though the technique was shown to converge for a 24-bus network, it will not be suitable for solving multi objective optimization problems; therefore, other parameters can be introduced to enhance its flexibility.(Heidari et al., 2013)**:** In the work, a novel profit-based model for multistage distribution network capacity expansion planning considering distribution automation was presented. An objective function was developed with the aim of maximizing the net present value of a given distribution company's profit. Genetic algorithm was proposed for solving the optimal distribution network expansion problems. The proposed method effectiveness was finally evaluated on an illustrative 24-node test network and the obtained results and discussions were then presented. The develop models were strictly based on profit maximization and failed to consider the balance between profit and reliability.

(Zhang, 2013)**:** In the work, a novel approach for electrical distribution substation expansion planning using multi-objective particle swarm optimization (PSO) was presented. The optimization objectives were investment and operation cost, energy losses cost, and power congestion cost. A two-phase multi-objective PSO algorithm was employed to solve the optimization problem. The feasibility and effectiveness of both the proposed multi-objective planning approach and the improved multi-objective PSO were demonstrated using an 18-node typical system. The setback of the proposed modes is the fact that, complex mathematical formulations were adopted. The complexity will deteriorate as the number of nodes gets higher which may lead to a non-converging solution. (Chuang et al., 2014): The work presented a methodology of solving an optimal substation location and capacity expansion problem for distribution system by using the genetic algorithm (GA). S-curve with different time constant was used to represent load growth of each customer class for a load forecasting of each fenced area. Load flow analysis was performed to estimate power demand of each fenced area for annual system operation over the study period. The overall costs of power loss and substation investments were included in the developed objective function. Each feasible solution was expressed as a chromosome in the GA simulation process. The fitness is then enhanced by considering the diversity of chromosomes so that the global optimization during the solution process can be obtained. The developed models were then tested on Taipei Distribution System through the utility data. Test results demonstrated the feasibility and effectiveness of the method for the applications. The major setback of the work is that the developed objective function considered investment cost as a single parameter. Therefore, the flexibility of the developed model can be improved by representing the investment with multiple parameters. (Huang, 2014)**:** In the work, regulation impact on network planning methods and network tariff designs in unbundled electricity network was firstly analyzed in order to formulate a long-term network expansion planning model considering distributed generation (DG). Photovoltaic (PV) power and wind power plants were used as the DG. Secondly, a deterministic model for low-voltage (LV) networks mainly considering PV connections based on the worst-case scenario was developed. Thirdly, a distribution medium-voltage (MV) network planning model considering wind power plant connections was developed. The developed models were then extended to consider the uncertainties from DG production and load. The developed models mainly focused on DG placement and therefore, a number of other parameters need to be introduced to improve its flexibility and aid simulation of various scenarios of network expansion. (Kumar et al., 2014): The work developed a technique for optimizing the total annual cost of a distribution network. The cost was represented as a sum of the investment cost (fixed cost) for feeder line as well as substation and operational costs (energy loss costs). The developed method was then used to find the optimal route for each load point in a given distribution system and to obtain the optimal radial network. An algorithm was also developed for simplified case study of a feeder network. A set of network expansion scenarios were simulated, and the results were discussed. The results of the simulation showed that the method was effective for small scale distribution network having not more than 50 nodes. The major setback of the proposed method is that the cost functions used only a few parameters which limit its flexibility and its ability to accommodate wide variety of scenarios.

Therefore, the flexibility and robustness of the proposed technique can be improved.

It can be observed from the literatures reviewed so far, that most of the research works are on distribution substation capacity expansion problem and with less emphasis to the optimum location of substations and the network/feeder expansion. As such there should be work that look at getting optimal location and sizing of distribution network system when expending. In this research Discrete bat algorithm (DBA) has been applied for the optimal locating and sizing of substation on distribution networks to minimizing expansion cost while considering power loss reduction and enhancing the voltage profile.

3. METHODOLOGY

One of the objectives of power distribution system expansion planning is to minimize the total cost of feeders in the future expansion of distribution system. The network expansion problem is usually subjected to a number of constraints.

3.1 Mathematical Models of Network Expansion Problem

In the general case, solving this problem is not an easy task. Therefore, different mathematical approaches have been proposed in the literature for simplifying the problem in order to achieve the desired aim and objectives.

The main cost function included set of decision variables such as location, sizing and, number of required substations, associated service area and, determining type of medium voltage (MV) feeder that it should be minimized under different technical constraints (Chuang et al., 2014). This objective function is presented as follows:

$$min\, C = \sum_{y=1}^{y}\left(\sum_{i=1}^{m} X_{yi} C_{inv,i} + C_{loss,y}\right) \quad (1)$$

$$C_{loss,i} = (\sum_{k=1}^{m} X_{yk} \sum_{j=1}^{nm} \left(\frac{X_{yi}}{V_{yi}}\right)^2 * r * \sqrt{\left[\left(u_k - u_j\right)^2 + \left(v_k - v_j\right)^2\right]} * W * 8760) \quad (2)$$

$$C_{inv,i} = \frac{i}{T} * j \quad (3)$$

Equation (1) represents the objective function with m substation candidates having total cost of power loading loss and the possible substation investment cost as its functions. Equation (2) is the cost of power loading loss for the substations to serve the load and (3) is the capital investment cost of state with j units of substation transformers for year i.

The following constraints are considered in the optimization problem.

- The maximum and minimum installation capacities
  $S_j \leq S_{capj}^{S} \leq (1 - res_j)S_j \quad (4)$
- Voltage Constraints
  $|V_i|^{MIN} \leq |V_i| \leq |V_i|^{MAX},$
  $i \in \{1,2, \ldots, m\} \quad (5)$
- Line flow constraints
  $|S_i| \leq |S_i|^{MAX}, \quad i \in \{1,2, \ldots, m\}$ 6)

3.2 Bat Algorithm

The bat algorithm (BA) is a bio-inspired meta-heuristic base on echolocation characteristics of bats. It is derived from the principle of echolocation of bats with varying pulse rates of loudness and emission during prey capture and avoidance of obstacles (Chen, 2021). BA developed in 2010 by Chen was inspired by the echolocation characteristics of bats with varying pulse rates of loudness and emission (Meng, 2015). BA was developed based on the nature that bats emit ultrasonic pulses to the surrounding environment with hunting and navigating purposes (Osaba et al., 2016). This ability aids the bats in finding prey in darkness.

Furthermore, all the variants further mimic the behavior of bats and successfully enhance the performance of BA (Meng et al., 2015). BA has some advantages of simple structure, easy to understand and realize together with few adjustable parameter (Zhou et al., 2018). The discrete bat algorithm used in this study, overcome the imperfection of BA by further mimicking the living environment the bats inhabit to make it available for solving dynamic community detection problem. From the original BA, the main equation of updating bat location based on velocity and frequency are given by

$$f_i = (f_{max} + f_{min})\beta \qquad (7)$$
$$v_i^t = v_i^{t-1} + \left(x_i^{t-1} - x_*\right) f_i \qquad (8)$$
$$x_i^t = x_i^{t-1} + v_i^t \qquad (9)$$

4. Numerical results

In this section, a typical network is assumed, and the results of sub-station expansion planning using DBA are obtained. This test network is a 33/11-kV distribution system that is supplied by 2 x 15MVA existing substations and consists of 170 loads located in the town of Zaria city of Kaduna state, Nigeria.

The original network which consists of two number power transformers taken as substations located as 1 & 2, and the distribution transformers are considered as load and these make the total loads connected to the network as shown in figure 1. Table 1 provides the details of the total loads connected its capacities and that of the existing two number substations.

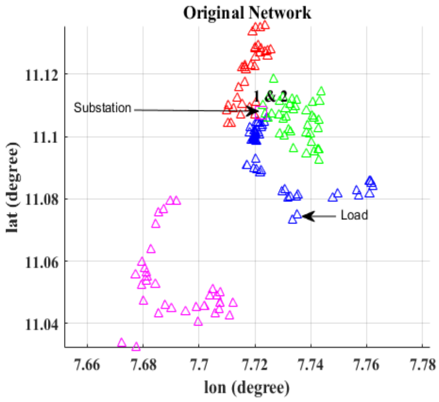

Fig. 1: Original network model of 33/11kV K/Doka Injection Substation

Table 1: Details of original network of 33/11kV Kofan Doka Injection Substation of Zaria Distribution Network

Number of the existing substation	Sum of loads	Sum of old substation capacity rating
2	37.65 MVA	30 MVA

The possible substations' locations are obtained by dividing the area under study into a number of small squares, and the center of each square was considered as the candidate point as depicted in figure 2.

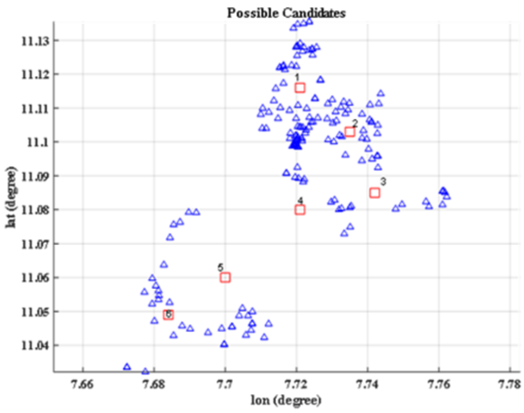

Fig. 2: Possible substations' locations

Figure 3 depicts the results of applying DBA on the original network and after 5 iterations was performed, it is grouped the loads into six different clusters and assigned sizes to the six substations in each of the cluster group. The loads are to be fed by substations located on those location positions as in figure 3 and the details are provided in Table 2.

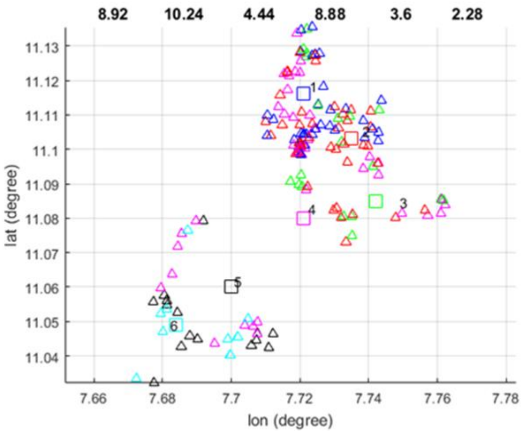

Fig. 3: Applying DBA on test network after 5 iterations

Table 2: Details of the test network after applying DBA for 5 iterations were performed

Number of new installed substation	Sum of loads	substation capacity	Expanded substation	Total expansion cost
6	37.65MVA	90 MVA	4	$ 15,840,000.4634

Figure 4 depicts the solution after 40 iterations were performed and the number of the substations reduced to 4. The optimal location (in latitude "lat" and longitude "lon") and size (in MVA) for the four substations are as follows: (Substation-1: lat-11.12, lon-7.721;

11.35MVA), (Substation-2: lat-11.08, lon-7.721; 14.4MVA), (Substation-3: lat-11.1, lon-7.735; 9.5MVA) and (Substation-4: lat-11.09, lon-7.742; 12.7MVA) and table 3 give the summary of the simulation after 40 iterations.

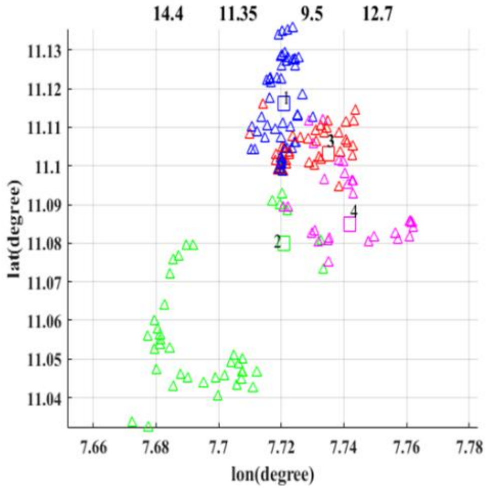

Fig. 4: Applying DBA on the test network after 40 iterations

Table 3: Details of the test network after applying DBA for 40 iterations were performed

Number of new installed substation	Sum of loads	substation capacity	Expanded substation	Total expansion cost
4	37.65 MVA	60 MVA	2	$ 2,661,930.4634

Figure 5 depicts the final solution after 120 - 200 iterations were performed and reduces the number of the substations reduced to 3. The optimal location and size for the four substations are as follows: (Substation-1: lat-11.12, lon-7.721; 13.28MWA), (Substation-2: lat-11.08, lon-7.721; 12.64MVA) and (Substation-3: lat-11.1, lon-7.735; 12.44MVA) and table 4 give the summary of the simulation after 120 - 200 iterations.

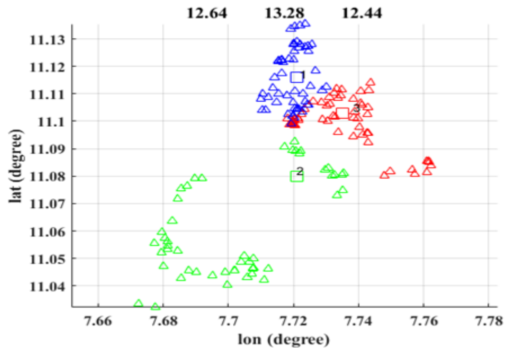

Fig. 5: Applying DBA on the test network after 120 - 200 iterations

Table 4: Details of the test network after applying DBA for 120 - 200 iterations were performed

Number of new installed substation	Sum of loads	substation capacity	Expanded substation	Total expansion cost
3	37.65 MVA	45 MVA	1	$ 2,634,410.03

Particle swam Optimization (PSO) is applied to the same test network in order to compare it with the results of DBA as shown in figure 6. The two methods show good sub-optimal solution to the expansion problem. The result obtained by DBA achieved reduction on the expansion cost to $2,634,410.08 representing 59.7% while the PSO which amounted to $6,541,000.00 representing 40.28%. The result show that both PSO and DBA have the ability to find proper solutions to substation expansion planning, but DBA performs better than PSO to find an optimal solution to substation expansion planning.

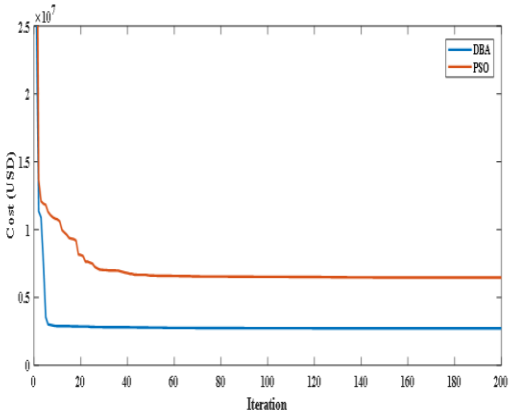

Fig. 6: Comparison of DBA and PSO result for the test network

5. Conclusion

Sub-station expansion planning is one of the important parts of the power system expansion planning studies. The diversity of decision variables in the SEP problem has made the solution process more difficult. This paper used meta-heuristic method for solving SEP as an optimization problem. The optimization method was based on DBA. To demonstrate the capabilities of DBA, PSO was used as the benchmark method to validate the result of DBA. A typical and real network was assumed, and the results of SEP by the use of PSO and DBA were obtained. The results obtained showed that DBA was more capable than PSO, and more efficient in finding the solutions. The results of applying DBA to a real network showed the functional capabilities of the presented method.

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