A Review on Optimal Network Reconfiguration in the Radial Distribution System using Optimization Techniques

Juma S A, Ngoo L M and Muriithi C M

Abstract**—**Distribution network systems face many problems, mostly of enormous power losses compared to the rest of the network, which lead to poor performance and degradation of the system and components. For maximum benefit of distributed generation (DG), optimal placement and sizing integrated in the radial distribution system has to be performed to obtain minimum power losses and improve the voltage profile of the system. The contribution of optimum network reconfiguration has greatly benefited in effective power loss reduction. The changes in network topology alters the current flowing through the line and the resistive losses. To solve network reconfiguration problems in radial distribution systems, strategic optimal network reconfiguration which can minimize power losses while maintaining the operating constraints is used to review various optimization techniques.

Keywords**—**Network reconfiguration, Power loss reduction, Radial distribution system, Optimization techniques.

I. INTRODUCTION

The electric utility restructuring has become a major concern on the overall system reliability as the industry expands in size, becoming increasingly complex. The complexity of the electric power systems has contributed to some of the technical and economic problems, which power system engineers solve by engaging in effective planning activities. The distribution lines are normally forced to operate at low voltages to enable smooth transition of power to the consumer loads. Due to the low voltages and high currents in the distribution system, high power losses in the form of heat (I^2R) are experienced, making the distribution system less efficient. The distribution networks normally have radial feeders, which are rigid and vulnerable to outages with over-loading experienced in many parts of the system. It is essential to look at the methods of reduction in distribution network losses when planning to lower energy consumption, cost and balancing load-generation power. Reduced power losses will increase the life span of equipment due to enhanced power quality and reliability of the network. Feeder reconfiguration is not only limited to reducing power losses, but also benefit in system security, improving the voltage profile, load balancing of the system and improve in efficient use of DG systems.

S. A. Juma, Department of Electrical Engineering, PAUISTI (JKUAT) (phone: +2540797034602; e-mail: shaibu900@gmail.com).

The topological arrangement of the distribution feeders is manipulated by varying the tie and sectionalizing switches while maintaining the constraints levels known as Distribution Network Reconfiguration (DNR) [1][2][3][4]. The reliability of a distribution system is of great importance as electric power has to be supplied to the consumer in an elastic manner in case of any contingencies while maintaining protection of equipment and feeders. The reconfiguration of the network system ensures that all network operations are carried out in lucid and most favorable conditions while maintaining adequate levels that are reliable and secure for quality power supply [5][6].

From the recent studies on network reconfiguration, numerous proposed techniques were applied to find an optimum solution to power loss reduction. This paper will review some of the strengths and limitations of the recent optimization techniques used in solving network reconfiguration problems in radial distribution systems.

II. DISTRIBUTION SYSTEMS

The electrical power distribution system provides power at very low voltages to the consumer loads. The two common types of distribution networks are radial distribution system, which has separate feeders that radiate from a single substation and ring main distribution system, which has feeders in a ring fashion that terminates back to the substation.

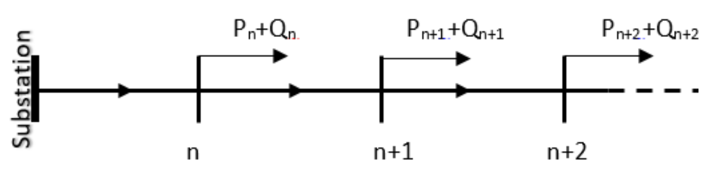

Fig. 1: A single line diagram of distribution system

The ring main system is generally expensive compared to the radial system as it has more switches and conductors required in the construction and for the power generation at such low voltages, thus a radial system is a more preferred choice [7][8].

L. M. Ngoo, Department of Electrical Engineering, MMU (e-mail: livingngoo@gmail.com).
C. M. Muriithi, School of Engineering and Technology, MUT (e-mail: cmainamuriithi@gmail.com).

However, the radial distribution system is less reliable due to its structure that has each bus connected to the source via a single path.

III. PROBLEM FORMULATION AND CONSTRAINTS

Switch state changes will manipulate the distribution network's topography and allow for the distribution of loads to be balanced accordingly and avert the system from overloading. Power loss of any line between buses in a distribution system can be evaluated by [9][10][11]:

$$P_{loss} = \sum_{n=1}^{NL} r_n \left| I_n \right|^2 \tag{1}$$

P_{loss}: the total power loss in the network distribution.
NL: Set of branches.
r_n: the resistance in the branch n.
I_n: the current in the branch n.

The most common constraints taken into account during optimization of network reconfiguration are [12]:

$$V_{n,\min} \le V_n \le V_{n,\max} \tag{2}$$

The voltage limits must be retained within the range at the buses and V_n is the voltage magnitude at *nth* bus.

Feeder's capability must have power limits in n branch:

$$k_n / P_n / P_{n\max} \quad n \in NL \tag{3}$$

$$k_n / Q_n / Q_{n\max} \quad n \in NL \tag{4}$$

$$\varphi(k) = 0 \tag{5}$$

Q_n ,P_n : reactive power and real power in the *nth* branch.
K_n : status topology of the branches (if branch n is closed k_n =1 and if it is open it is 0).

The topological radial structure constraints for each candidate is represented in (5). There will be no isolated nodes and the final configuration must be radial with all loads connected.

IV. METHODS OF NETWORK RECONFIGURATION WITH OPTIMIZATION TECHNIQUES

Different methods have been developed for the reconfiguration of the distribution network with some of the works including a multi-objective function for capacitor placement and DG (sizing and placement) and FACTS devices playing a role in solving network problems. This paper will summarize some of the optimization methods used in network reconfiguration of the distribution system.

Computer Intelligence (CI) is a branch of Artificial Intelligence (AI) that came up in the early 90s based on nature inspired computational paradigms and collection of numerical information [13]. Fuzzy logic (FL), Artificial Neural Network (ANN) and bio-inspired algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Tabu Search (TS), Ant Lion Optimization (ALO) and Ant Colony Optimization (ACO) are some of the AIs primarily focused on computer-based intelligence. According to Abedinia *et al.*, [14] metaheuristic optimization techniques solve real-world problems which are too complex to solve using numerical optimization methods. Some of the advantages of AI are high flexibility, simple and efficient to model. Heuristic algorithms are inspired by nature and observes the special ability of animals' superiority over other animals. They have a greedy approach that makes them easy to implement for high searching efficiency but have a drawback on convergence to a global solution when applied in a large-scale distribution system. A correct problem function must be formulated for the technique to be very effective in finding the global optimal solution. A direct search to global optimal can easily be processed in AI algorithms [1][15]. When an optimization procedure is constrained, it will mathematically determine optimal allocation of scarce resources subject to a set of constraints. Fig. 2 shows the flow chart for reconfiguration process. The optimization techniques are used to identify the best possible switching sequence of the distributed system.

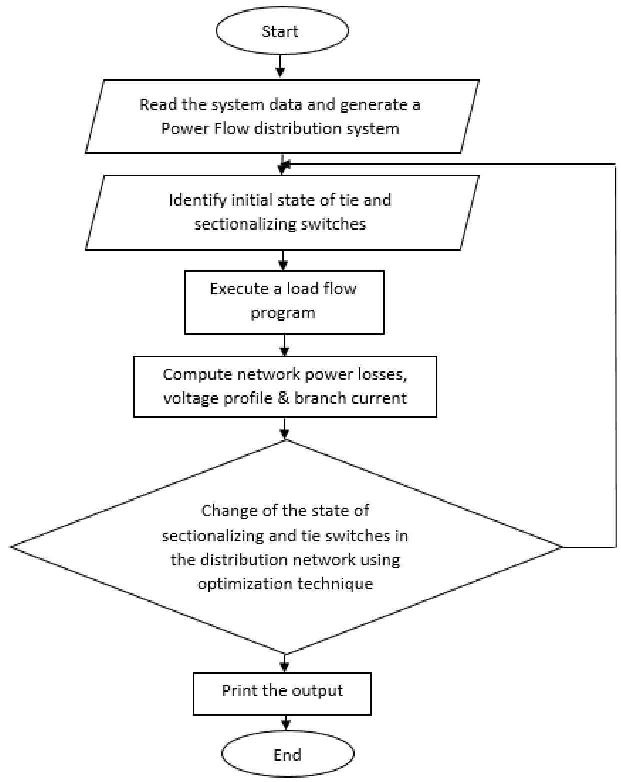

Fig. 2: Flow chart for reconfiguration process

In a Cuckoo Search Algorithm (CSA) the cuckoo birds produce and deposits their eggs in the nests of other host birds of different species and benefit by tricking the birds into brooding their eggs. CSA is an efficient population-based heuristic Evolutionary Algorithm (EA) for solving optimization problems with the advantages of simple implementation procedure and a few control parameters [1]. It is proposed to optimize the Radial Distribution Network (RDN) problem concerning power transmission losses and improving voltage profiles. The net power loss is calculated by equation (6).

$$\Delta P_{loss}^{R} = \frac{P_{loss}^{rec}}{P_{loss}^{0}} \tag{6}$$

where P_{loss}^{R} is the net power loss; P_{loss}^{rec} and P_{loss}^{0} is system's total active power loss after and before reconfiguration, respectively.

The initialized population of the nests will determine the nests to be checked by the algorithm in the radial topology and the load flow to be run. The fitness of each nest is calculated by the objective function. The quality of the every new cuckoo eggs produced by Levy flights will replace the bad nests from their position. The CSA was implemented for RDN by considering process of each radial structure of the network as a host nest and each egg was a solution randomly generated during initialization. The algorithm was performed on three different IEEE test systems (33-node, 69-node and 119-node) and it can be noticed how CSA is more applicable on large scale RDN due to its more noticeable effect on the 119 node test systems. CSA obtained the global optimum faster than Continuous Genetic Algorithm (CGA) and PSO.

Bradan *et al.*, [16] proposed a technique which determines the optimal sequence path of switching operations given an optimal RDN and DG output with variable load using the Firefly Algorithm (FA) for daily basis power loss reduction while improving the voltage profile. FA is a metaheuristic optimization method based on the behavior of fireflies characterized by each individual in a colony having its own activity plan though the group as a whole appears to be highly organized. The optimal switching sequence path will obtain a large number of possible sequences. The first step was to determine the DGs real power output and network reconfiguration with variable load simultaneously while second step looked at determining the optimal switching sequence path to change the network configuration from the original form to the optimal form at any hour, from the obtained results in step 1. FA was applied on both the steps with the objective function of total fitness described below:

$$Min \rightarrow F = \sum_{h}^{T}\left(w_1 \times P_{loss}^{R} + w_2 \times si\right) \tag{7}$$

where h is the taken current time taken; T is the total hours (in the time frame); w_1 and w_2 are the weighting factors (w_1=w_2=0.5) and si is the voltage stability index.

Application of the firefly algorithm to achieve the distribution minimum main fitness gave an approach that had high quality and capable of realizing the optimal switching sequence path, optimal network configuration, and DG output. The proposed method indicated a possibility of being implemented in real systems with DGs.

In [17] a Hybrid Genetic Algorithm Particle Swarm Optimization (HGAPSO) was proposed, a combination of two algorithms to effectively minimize power losses and improve the voltage profile. The combined algorithm had an added advantage and combined merits for both algorithms breaking through the limitations of PSO and having an ability to control convergence and algorithmic simplicity. The GA updated positioning for the global best updates in order to avoid premature convergence experienced in PSO. Local maximum is avoided by introducing mutation by GA to PSO. The number of iterations were equal for both the algorithms with first half run by GA. The obtained solution became the initial population of the PSO and ran the remaining iterations in PSO to find the appropriate topology of the network. This paper vehemently looked at the gain of network configuration with and without DG units presence further assisting to obtain further optimum power loss reduction of the network. Despite the considerable decrease in power losses when DG units are placed, it was noted that some nodes violated voltage constraints, thus network reconfiguration also amended voltage violations to remain within acceptable limits.

Rao and Reddy [18], proposed a method which used a GA optimization approach to get optimal switching scheme for the reconfiguration of the feeder distribution network. The GA involves an initial population, selection, from the population, crossover and then mutation in the form of binary strings which represent the switch sequences in a given configuration topology. The feasible solutions should ensure that they are within the set constraints limits known as legal points. The fitness assignment to a chromosome should be chosen appropriately so that incase of any infeasible strings in the obtained solutions such a fitness function will be declined by using equation (8) if a low fitness value is experienced.

$$Fitness = 1/(1+P_c) \tag{8}$$

P_c is a high value penalty term

A roulette wheel method is used when selecting a mating population. A solution point with a bigger fitness value has a higher chance of being selected to be in the mating population. Mutation will keep the local optimum value from premature convergence. The chromosome with the highest fitness in the new generation is then decoded to give the required solution in network reconfiguration. Since the lines connected between the substations to the loads experience major losses in the copper losses, GA solved the configuration that gave minimum losses and a best voltage profile in the solution. The proposed method was tested on a 3-feeder and an IEEE 33 bus distribution system. From the results obtained it showed that the efficiency levels and voltage regulations operated better above 0.9 p.u and had reduced power line losses in the distribution network. The GA method was able to yield a global optimum solution. Proper selection of the parameters and fitness assignment must be observed carefully since they play a major role in ensuring that an optimal solution is obtained when using GA. However, an improvement can be made when performing the fitness function process during the load flow analysis. An ANN should be trained to have data for all feasible network configurations to avoid running the load flow for each configuration obtained before achieving the global optimum. GA takes quite a number of iterations to achieve an optimum solution and a high computational time which can be improved by using PSO.

In [19], the researchers proposed a modified PSO (MPSO) which accelerates the algorithm to reach optimum solution faster in network reconfiguration problem. It has a filtered random selective search space for initial positions. This improves the search capability of the particles since unfeasible particle will be neglected, reducing on computational time and increasing on the convergence rate. PSO techniques are based on the animal behavior of swarming into a group to achieve a certain task such as movement of fish, birds flying in a flock and ants in a colony [20]. The behavior of such a biological system can be interpreted through mathematical equations to show the particle movement as it adjusts its position and velocity based on its experience and neighboring particles through a search space in order to obtain an optimal solution. IEEE 33-bus system was used to test the proposed algorithm in Interactive Power System Analysis (IPSA) software tool and the algorithm was created in python programming language. The results were compared to other versions of PSO algorithms such as Binary PSO (BPSO) and Selective PSO (SPSO).

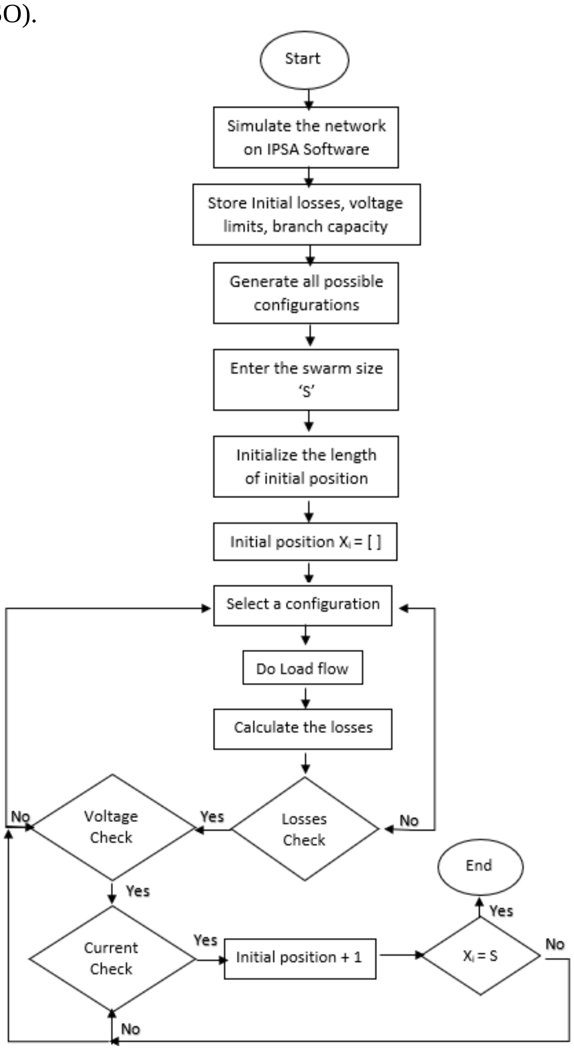

Fig. 3: MPSO Procedure in network reconfiguration [19]

Fig. 3 shows the filtered random selection adopted in controlling the initial positions of the particles. A position control algorithm will ensure that a feasible search space is maintained. For accuracy in the algorithm, the software has to be initialized after each and every loss calculation for each position. The proposed MPSO performed better in both power losses and computational time thus the modifications made achieved some improvements. The challenge faced in the algorithm was in duplication of some switches in the same position due to retaining of particles in the search space, which would violate the condition of the tie switch numbers. This might lead to the network topology to not remain radial. Lengthy computational time due to inaccuracy in results was noted when the algorithm changes the position without a reference configuration. Thus, a known configuration has to be chosen in the first attempt before each trial.

In [21], a hybridized Evolutionary PSO (EPSO) was introduced into solving the network reconfiguration problem. It is a combination of Evolutionary Programming (EP) and PSO, which will enable the algorithm to find the optimal solution with less computational time. PSO alone had less optimal solutions for the computational time in obtaining power loss reduction thus EP assisted with combination and selection method that made it faster to reach the global optimal solution. The proposed algorithm was evaluated on the IEEE 33-bus distribution system and compared to EP and PSO. The computational time was 12.2s faster than the other two methods and obtained minimum power losses achieved by final switch sequence (11, 28, 32, 33, and 34) for the open switches. The total losses were computed using Newton-Raphson load flow program in Matlab.

Rajam *et al.*, discussed how network reconfiguration problem has been solved for load balancing, power loss reduction, improving operational conditions, etc. by using various EAs such as BPSO and neuro-fuzzy techniques [22]. Network reconfiguration is a complex combinatorial constrained non-linear optimization problem that is solved in a heuristic manner to achieve a given objective. In this paper the researcher proposes an EA, Modified Plant Growth Simulation Algorithm (MPGSA) in network reconfiguration with and without DG. The constraints and the objective function are dealt with separately. PGSA can handle problems with load and generation variation with time since it is based on growth process of plants, the root is the initial growth taken as the initialization and the branches and tree trunk growth at the nodes will be taken as the search for an optimal solution. With the modification made it will converge faster. The sum of power loss after reconfiguration with DG connected is taken as the objective function to maximize on the total loss reduction subject to current, power flow and voltage constraints given below:

$$Maxf = \max.(\Delta P_{Loss}^{R} + \Delta P_{Loss}^{DG}) \quad (9)$$

Subjected to $V_{\min} \le |V_K| \le V_{\max}$ and $|I_{k,k+1}| \le |I_{k,k+1,\max}|$

$$\sum_{k=1}^{n} P_{GK} \le \sum_{k=1}^{n} \left(P_K + P_{Loss,k}\right) \quad (10)$$

Where

ΔP_{Loss}^{R} -Total power loss reduction due to reconfiguration.

ΔP_{Loss}^{DG} - Total power loss reduction due to DG connection.

$V_{\min}$ -minimum bus voltage; $V_{\max}$ -maximum bus voltage.

$I_{k,k+1}$ -current through the branch between k and $k+1$ bus.

$I_{k,k+1,\max}$ - maximum current through the branch between k and $(k+1)$ bus.

Since the main contribution is in fixing a value for β as 0.5 (a selected random number, which enable prioritization in the growth process), thus the algorithm is called modified PGSA. It is based on number of trial and error combination values tried between 0 to 1 disabling any random search for β value making the algorithm faster and more suitable for real-time applications. The proposed method was implemented using Matlab program on an IEEE 33-bus radial distribution system with simultaneous reconfiguration and DG placement using the modified PGSA, which gave better results and faster convergence compared to ordinary PGSA. MPGSA also performed better than other EAs such as GA, refinery GA, ACO in hypercube framework and Harmony Search Algorithm (HAS), making it more suitable for practical applications on a real distribution system.

Bradan *et al.*, [23] proposed different metaheuristic algorithms in solving a multi-objective network reconfiguration problem with optimal DG output. The main objective in this paper is to simultaneously maximize the DG output, minimize the real power losses and voltage profile improvement. The objective function given in the equation (11) below represents the total fitness:

$$F = w1 \times \left(P_{loss}^{R} + IVD\right) + w2 \times \left(\frac{1}{DG_{output}}\right) \quad (11)$$

Where

P_{loss}^{R} -net power loss to be minimized,

IVD - voltage profile index to be minimized,

DG_{output} -distributed generation output to be maximized.

The multi-objective problem was solved using different optimization techniques for validation purposes. Some of the methods used were PSO, EP, (Firefly Algorithm) FA and Gravitational Search Algorithm (GSA). However, only the GSA technique implementation is described since the other techniques have already been discussed. GSA is based on the law of gravity interaction with mass of objects. The force of gravity pulls all objects towards a heavier mass. The masses will represent the population of individuals, measured by the masses' position to find their performances. A solution represented by each position while the fitness function is given by the gravitational and inertia masses. According to the law of attraction, the object with the heavier mass will attract all other objects and, in this case, heavy masses are a sign of good solutions and move slower towards lighter masses (bad solutions).

The proposed method was tested on an IEEE 33-bus distribution system in Matlab program. The optimal solutions were obtained for the tie switches and the real power loss out of the DG, which were determined simultaneously. Three cases were analyzed to evaluate on the validity of the proposed strategy. The first case aimed to minimize the power losses by simultaneous network configuration with optimal DG output. FA produced better results compared to the other techniques with losses as minimum as 72.436kW which is about 64.25% power loss reduction. The second case looked at minimizing the power losses and improving the voltage profile index by simultaneous network reconfiguration with optimal DG output and FA still out-performed the other techniques. The third case minimized power losses, improved voltage profile index and maximized the DG output by simultaneous network reconfiguration with optimal DG output. FA still emerged superior over EP, PSO and GSA. Case 2 had lesser power losses compared to case 3 hence optimizing the DG output lead to more power losses than maximizing it. A high quality and robustness in realizing an optimal network reconfiguration and DG output was presented in the proposed approach. The results also showed that the voltage profile index performed better when improved with minimizing power losses than in other cases.

In [24], Nayak discusses on how loss sensitivity analysis is used to identify optimal location for DG units in feeder reconfiguration problem solved by an EA called Hyper-Cube framework Ant Colony Optimization (HC-ACO) algorithm. The main characteristics of the proposed algorithm are as follows:

- Positive feedback - rapid search for a global solution.
- Distributed computation – to avoid premature convergence.
- Constructive greedy – heuristics assist in finding quicker acceptable solutions.

ACO algorithm is based on the colony of ants in communication when solving a problem and adapting to a situation with heuristic information and acquiring search experience in the process. The model of selection of a proper algorithm depends on the application. The HC framework will provide the automatic scaling of the auxiliary fitness function in the search process based on changing the pheromone update rules used in ACO algorithm. This will enable a robust and easier implementation of an ACO procedure.

The load flow analysis is performed using the backward-forward sweep method due to its computational efficiency and robustness in convergence making it suitable for distribution load flow analysis. The objective function is to minimize the real power losses and improve the voltage profile with given constraints. Artificial ants' movement through the buses will also help in selecting sectionalizing switches to minimize total power losses in the system. The proposed algorithm is validated in the IEEE 33 bus radial distribution system implemented using Matlab program. The presence of DG units in network reconfiguration problem had effective performance of the overall system. Some of the merits of the algorithm are fewer iterations to reach optimum solution and fast optimum convergence.

In [25], the application of GA with variable population size (GAVAPS) is proposed in solving reconfiguration problem. If the population is allowed to adapt in size according to the status of the GA search, a more efficient solution can be obtained compared to the standard GA (SGA). A population that evolves through successive generations will be used in the reconfiguration problem with the help of the proposed algorithm in searching for a solution. A possible solution is represented in the population by each individual (chromosome). Locations of open switches in the power distribution network will be contained as a string coded by each chromosome with a lifetime parameter assigned at its creation. Each generation, creates an offspring population from the current population using the GA operators. If the chromosome exceeds the lifetime parameter, they will die and leave the genetic pool. The proposed algorithm was tested on the IEEE 33 bus radial distribution system and the performance was compared to the SGA. Significant decrease in computational cost and better exploration of the solution space was noticed with the GAVAPS algorithm.

V. DISCUSSION

In this review, it has been seen that network reconfiguration in the distribution system plays a major role in network planning and operational management in order to come up with an efficient, reliable and cost-effective system. Normally, the researchers had the same basic objective to minimize power losses despite different approaches in methodology and implementation. Other additional objectives, which have been used include cost minimization of power generated, improving on switch time, power quality improvement, improving the bus voltage deviation, minimizing cost of DG integration and balancing the load at the feeder as well as doing away with overload conditions.

Table I: Simulation results for different algorithms for IEEE 33-bus distribution system

Method	Tie-switches	Power Losses (kW)	Min. Voltage (pu)
GA [18]	7, 9, 14, 32, 37	139.54	0.9378
MCPSO[11]	7, 9, 14, 32, 37	138.93	0.9423
HC-ACO[24]	7, 14, 9, 32, 37	136.30	0.9385
MPSO [19]	7, 9, 14, 32, 37	136.36	0.9400
EPSO[21]	11, 28, 32, 33,34	120.7	0.9980
HGAPSO[17]	10, 7, 14, 32, 27	140	0.9423
GAVAPS[25]	7, 12, 31, 35,37	114.27	-
CSA [1]	7, 9, 14, 32, 37	139.51	0.9378
PSO[19]	33, 28, 34, 8, 17	149.8	0.9310

At the end of reconfiguration, power supply must be ensured to reach all the loads and the radial structure must be maintained. Optimal sizing of the DG in the distribution network also gave a high reduction in power losses. When performing reconfiguration, DG placement and sizing should not be neglected because it is also a major factor in reducing the system losses. The combination of the two techniques gave a tremendous improvement in loss reduction especially when the two are performed simultaneously together. When DG units are connected, there will be a significant improvement in voltage profile. The opening of tie and sectionalizing switches during reconfiguration lead to voltage transfer from one feeder to another and balancing it with the reduction in real power losses leading to a voltage profile improvement.

The methods applied in reconfiguring the network utilized various objectives and limited constants based on the algorithm. Heuristic methods tend to be very fast, but do not reach global solutions while meta-heuristic algorithms could reach a global solution but they have a greater computational time due to the random selections and probabilistic nature. Some of the methods require a minimum number of iterations. Table I shows the effectiveness in optimal reconfiguration of the network with the different algorithms. Table II shows some of the merits and drawbacks of some of the algorithms discussed in this work.

VI. RECOMMENDATIONS

Most research has been focused on network reconfiguration with DG integration. There is still more research to be looked at with network operations in the distribution system such as VAR compensation, restructuring of transformer, conduction size and type of feeder which should be taken into consideration when performing network reconfiguration. Some recommendations are as follows:

- Taking into account dynamic loads and DG operation modes.
- Enhancement in stability of microgrid operations.
- Taking into account the transformer life loss cost.
- Improvement of algorithm suitable for real-time network reconfiguration.

Table II: Merits and drawbacks of some of the algorithms

Algorithm	Merits	Drawbacks
GA [18][9]	Easy, simple to implement, efficient to search large solution space without getting trapped in local minimum, reasonable computational time and robust method for seeking global minimum	Slow and could not find the optimal solution easily
ACO[24]	Efficient and easy to understand and code, fewer iterations to reach optimum solution and fast optimum convergence.	High iteration is needed to find the optimum solution and takes longer computational time
EP[21]	Simple and direct,	It takes time to converge, very little literature on this algorithm
CSA [1]	Simple implementation procedure and few control parameters, finds the global optimum solution fast, can deal with multi-criteria optimization problems, can be hybridized with other algorithms	Long computational time
PSO[19]	Simple and easy to implement, powerful algorithm to aid and speed up decision making, able to escape local optimal solution and can often find good solutions for complicated problems	Not designed for discrete functions optimization, and has less optimal solutions making it difficult to obtain the global optimum solution, slow convergence

- Enhance voltage stability and maximize the use of DG.
- Applying smart systems and reducing on overall pollution.
- Minimizing on generation cost by incorporating different renewable energy sources.

VII. CONCLUSION

Different optimization techniques were studied for network reconfiguration problem, mostly to reduce the power losses and improve the profile of the voltage. The results show that reduction in power losses also lead to an improved system voltage profile. Furthermore, DG integration to the network gave significant power losses especially when a simultaneous approach is applied with network reconfiguration making it more efficient in solving the distribution system problems. Each algorithm used demonstrated the optimization problem in its own unique manner in solving the network reconfiguration problem. However, some algorithms proved to be more superior when solving the same optimization problem.

APPENDIX

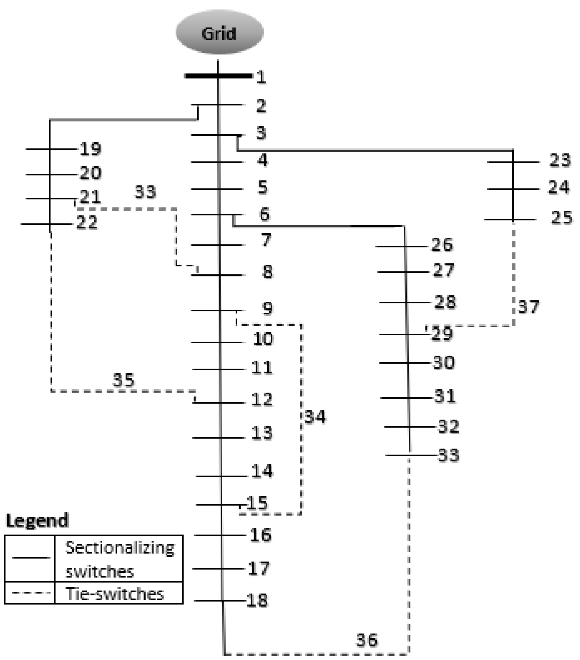

Fig. 4: IEEE 33-bus radial distribution system

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