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Distribution Network Reconfiguration Considering Feeder Length as a Reliability Index

Kwabena Amoako Kyeremeh[a], Isaac Kofi Otchere*[b], Nana Twum Duah[c], Joseph Owusu[d]

Department of Computer and Electrical Engineering, University of Energy and Natural Resources, Sunyani, Ghana

[a]kwabena.kyeremeh@uenr.edu.gh; *[b]Isaac.otchere@uenr.edu.gh; [c]nana.duah@uenr.edu.gh, [d]joseph.owusu@uenr.edu.gh

ABSTRACT

Power distribution network reconfiguration is achieved by opening or closing sectionalizes and tie switches to optimize a set of objectives. Active loss reduction is the objective in the reconfiguration of distribution networks since distribution networks usually record high levels of power losses. Reliability of the network is also an important objective. In this work, the objective function of the optimization is the reduction of power loss, improvement of line loading index and improvement of reliability. This paper seeks to shift the focus from the traditional objectives of passive (without distributed generations) networks to the security and reliability objectives. Since network reconfiguration is a planning problem, the work was performed to solve the problem for multi – period scenarios which spanned 24hrs. Genetic Algorithm was employed in this study and the simulation was performed in MATLAB software environment using a modified IEEE 69 Bus test system.

Keywords: Distributed Generation, Distribution Network, Genetic Algorithm, Multi – Period Scenarios, Optimization, Power Loss, Reconfiguration and Reliability.

1. INTRODUCTION

Distribution networks (DN) are a pivotal element of the power system. Generally, distribution networks have much more complex structure [1]. The complexity of the distribution network keeps increasing and therefore require automating tasks that hitherto were performed manually. The DN is built as mesh circuits but operated as radial and connected by tie switches [2]. The distribution network reconfiguration (DNR) identifies, through an optimization technique, the best radial structure of the distribution network from a set of radial network topologies [3]. Approaches used by researchers to solve the DNR problem can be clustered into four major categories: heuristic, metaheuristic, and mathematical programming [4]. Heuristic techniques adapt a set of different heuristic rules or estimate expressions which are unfavourable for large networks as they produce local optimum solutions in a slow processing time [4]. The metaheuristic approach on the other hand produces global optimum solutions which uses an iterative approach to improve an initial population of solutions based on evolution theory concepts, social interactions, and simulation of animal behaviour [2, 4]. Mathematical approaches such as mixed integer linear programming (MILP) and mixed integer quadratic programming, show a slow rate of convergence for large distribution networks [4-21].

Authors in [5, 7] used genetic algorithm (GA), a metaheuristic method, to solve the DNR problem. In [8, 9], the particle swarm optimization (PSO) technique was used. A hybrid GA and PSO algorithm was developed in [10, 11].

The objectives considered by many researchers in the DNR optimization is the active power loss reduction, minimization of line loading, voltage stability and improvement of the reliability of the network [1, 5]. The DNR can either be a single or a multi – objective optimization problem. In [1, 3], the authors optimized the DNR problem to improve on voltage stability index. The loss minimization and voltage stability objectives were combined as a single optimization problem in [13]. However, in [2] considered reduction of active power loss and line loading.

In a deregulated power sector, the distribution networks' reliability has become increasingly important. The ability of the power networks to supply consumers with quality power without interruptions is referred to as a reliable distribution network [14]. Authors in [15] performed a multi – objective optimization of the DNR problem and considered objective functions which included active loss reduction, voltage stability, balancing of load and a reliability index which was based on consumer interruption cost. In [17], the reliability index was based on the outage rate per annum and annual outage duration as the objective of the optimization along with minimization of active losses. Literature has revealed that the typical quantities to evaluate distribution network reliability are the system average interruption frequency index, the system average interruption duration index, the system average service unavailability index and the expected energy not supplied [18]. The need for a reliable network is of essence as recorded in [22]. The length of a feeder, as reported in [15], has a direct significant effect on failure rate and thereby reducing the reliability of a network.

This paper proposes a reliability index which relates to the length of the feeder. The paper also demonstrates, with the use of genetic algorithm, that optimizing this reliability index as an objective function also optimizes the well-known objective functions of active power loss minimization and line loading. The structure of the paper is; Section 2 gives the optimization model, section 3 explains the genetic algorithm, section 4 presents the tests and results, and the last section concludes the paper.

2. OPTIMIZATION MODEL

2.1. Objective Function

2.1.1. Minimization of Active Power Loss

It is the aim of the Distribution Network Operators to reduce the active losses of the network to the minimum value possible. This reduces operational costs and increases the life span of the equipment. The objective function is modelled as:

$$OF\_PL = \frac{PL_K}{PL_{init}} \tag{1}$$

$$PL = \sum_{n=1}^{P} (PG_n - PD_n) \tag{2}$$

where PL_K is the *kth* network configuration, n to P is the range of the period and PL_{init} is the initial configuration of the network. PL_k and PL_{inint} is obtained with equation (2).

2.1.2. Minimization of Line Loading

The relevance of this objective function is in the context of distributed generators. The minimization of the line loading ensures that the network avoids staying close to the maximum ampacity of the lines. The margins to the thermal limits of the lines are in effect optimized, thus, indirectly the hosting capacity of the network is optimized. Equation (3) is a ration of the current through branch b, to the current carrying capacity of that same branch.

$$I_{b_{ratio}} = \frac{I_b}{I_{b\max}} \tag{3}$$

For each configuration, the branch that gives the highest value of this ration is determined, i.e. max (I_{b_ratio}), for the entire period under consideration. A sum of the values for the whole period is computed as shown in equation (4). The desired solution of the optimization problem is the minimization of equation (4).

$$OF\_I = \left(\sum_{n=1}^{P} \max\left(\frac{I_b}{I_{b\max}} \right) \right) \tag{4}$$

2.1.3. Increasing Feeder Length Reliability

In an electric supply line, a fault can occur anywhere along the line. The longer the line, the higher the probability of occurrence of a fault. Since a feeder is made up of many lines, it can be said that the probability of a fault on a feeder (and hence the probability of interrupting customers / generators) is dependent on the length of the line. Moreover, the more customers you supply, and the more generators are connected to the feeder, the higher customers are exposed to disconnection in the event of a fault. Therefore, an objective function to quantity this is proposed in equation (5).

$$OF\_R = \sum_{n=1}^{P} RI_n \tag{5}$$

$$RI = \left(\sum_{f=1}^{F} l_f \right) * \left(\sum_{f=1}^{F} PD_f + \sum_{f=1}^{F} PG_f \right) \tag{6}$$

where RI = Reliability Index; l_f = length of feeder, f; PD_f = total demand on feeder, f and PG_f = total generation on feeder, f.

2.2. Constraints

The objective functions previously defined are subject to a set of constraints that defines the feasible operating point of the network. Equations (7) and (8) represent the Power

Flow constraints at bus *i* while (9) is the constraint on the current loading of the branch, *b.* The voltage at bus, *i,* is constrained by (10). Finally, the radial topology is realized by constraining the network with (11) as depicted with the graph theory in [19].

$$P_{Gi} - P_{Di} = |V_i| \sum_{k=1}^{n} |V_k| \cdot |Y_{ik}| \cos\left(\theta_{ik} + \delta_k - \delta_i\right) \tag{7}$$

$$Q_{Gi} - P_{Di} = -|V_i| \sum_{k=1}^{n} |V_k| \cdot |Y_{ik}| \sin\left(\theta_{ik} + \delta_k - \delta_i\right) \tag{8}$$

$$|I_b| \le I_{b\max} \tag{9}$$

$$V_{i\min} \le V_i \le V_{i\max} \tag{10}$$

$$\varphi(k) = 0 \tag{11}$$

3. GENETIC ALGORITHM

The genetic algorithm requires that an initial population is randomly generated, based on which the other operators of the algorithm will be applied. In this work the individual configurations are randomly generated to keep the radial characteristics of the network. The technique uses the CoArcs of the initial network as a base. The chromosome coding or the structure of the individual is the CoArcs which represent opened branches of the network. Therefore, the Tree i.e. the closed branches do not appear in the structure of the individual. The genetic algorithm flow chart is shown in Figure 1 below.

A fitness function is formulated based on the objectives and constraints of the optimization problem. This function is individually applied to each of the individual configuration, I, of the initial population and to the population at generation k, to ascertain their fitness to the desired objectives and violation or otherwise of the constraints. In this work, the fitness is defined by:

$$F = OF + PI + PV \tag{12}$$

where

$$PV_{\min} = \frac{V_{\min} - V}{V_{norm} - V_{\min}} \tag{13}$$

$$PV_{\max} = \frac{V - V_{\max}}{V_{\max} - V_{norm}} \tag{14}$$

$$PV = PV_{\min} + PV_{\max} \tag{15}$$

$$PI = \frac{I_b}{I_{\max}} \tag{16}$$

The parameter $PV_{\min}$ and $PV_{\max}$ are the penalties for the violation of the minimum and maximum respectively and the PV in equation (13) is the sum of $PV_{\min}$ and $PV_{\max}$. $V_{\min}$ and $V_{\max}$ is the respective minimum and maximum allowed voltage at the nth bus while V_{norm} is the nominal bus voltage and V is the measured voltage at bus n. PI on the other hand is the penalty for the violation of the current carrying capacity of the branch, b.

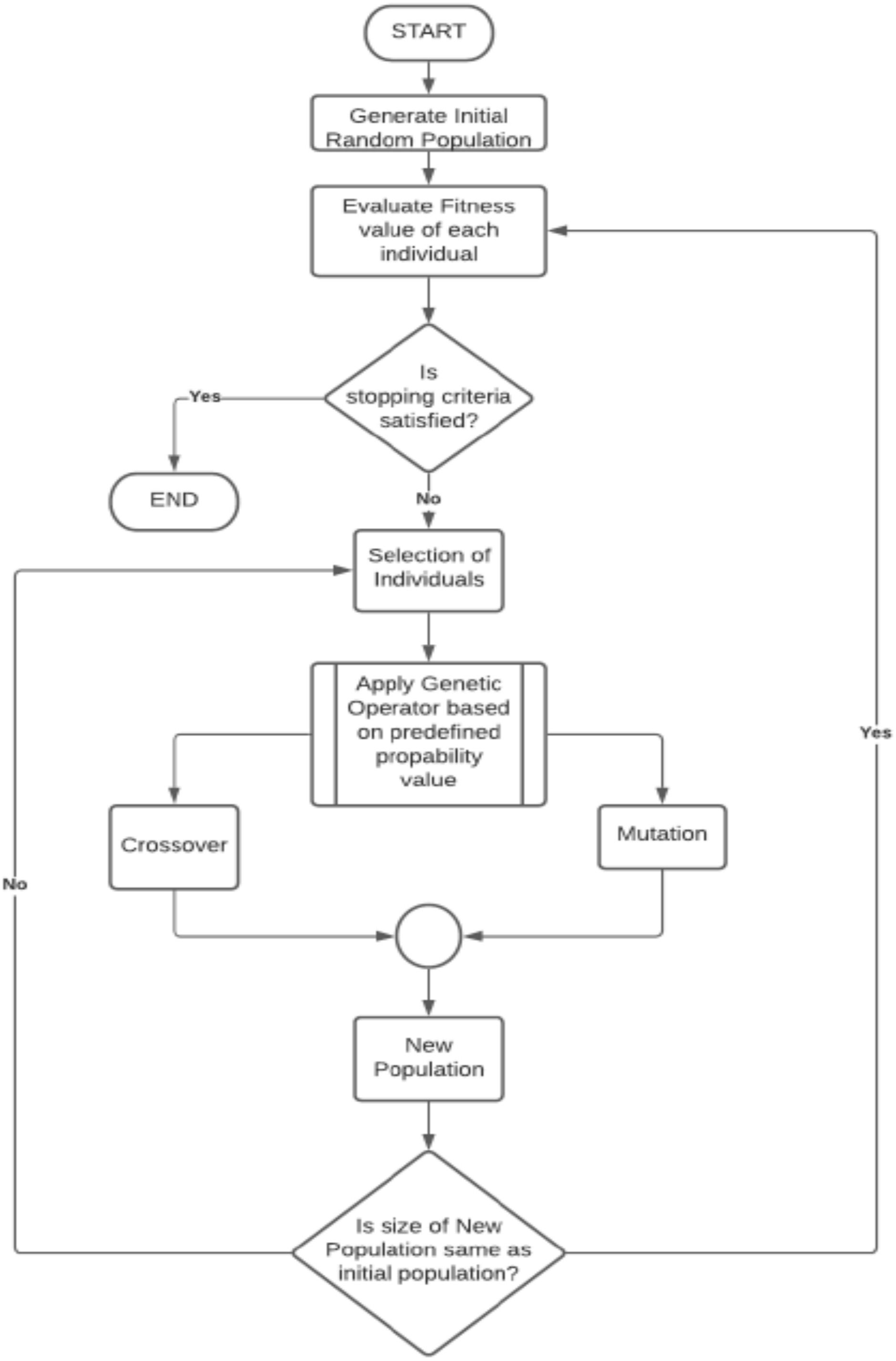


Figure 1. A Flow Chart of Genetic Algorithm

4. TEST AND RESULTS

The algorithm was implemented in MATLAB R2016b software environment. The genetic algorithm set up to have a population size of 150, generations of 200, a probability of crossover of 0.9 and a probability of crossover of 0.05. The best selection technique determined in [20] was the tournament technique with 4 competitors. The algorithm was tested on a 136 – bus distribution network in Figure 2 with three (3) feeders which was built starting from an IEEE 69 – bus network.

The network has 19 generators (shown as a rectangle in Figure 2) with a total nominal power of 8.0852MW and a total (nominal power) of 7.8826 MW. The multi – period used here was a percentage (normalized to 1) of the connected load and installed generation capacity (assumed as PV in this work) for a 24 – hour period as shown in Figures 3 and 4 respectively. Having established the best setup for the algorithm, each of the objective functions explained in the earlier section was run separately with a stopping criterion to stop the algorithm when the value of the best fitness does not improve more than 1% over 10 consecutive generations. The algorithm was run for a multi – period scenario and an optimum configuration of the network for the entire period was obtained for each objective function. The result from each simulation is presented in the subsection that follow.

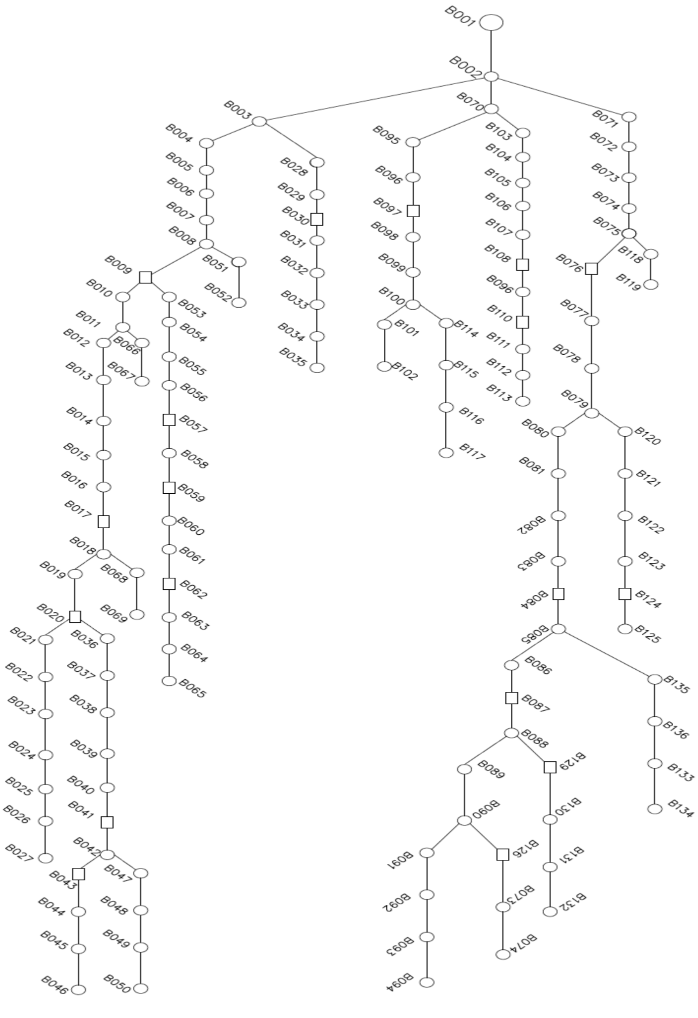


Figure 2. Initial Network Topology of 136 – Bus Network

4.1. Case 1: Minimization of Power Loss (OF 1)

To determine this OF for the multi – period scenario, the initial losses over all scenarios was determined and summed. Then the sum of the losses over all periods in each configuration of the initial population is determined. These values of the losses of the individual configurations are scaled to that of the initial losses. The same is valid for the OF evaluation during the convergence process. The fitness started at 0.7656 and reached a steady value of 0.45. This means a reduction of the energy loss of about 50% of the initial topology. Applying the stopping criteria explained in the earlier section, the algorithm ended at the twenty – third generation. The final configuration which corresponds to this fitness value is: (10 41 48 57 84 87 88 98 99 110 118 136 138 146) with a topology shown in Figure 5a.

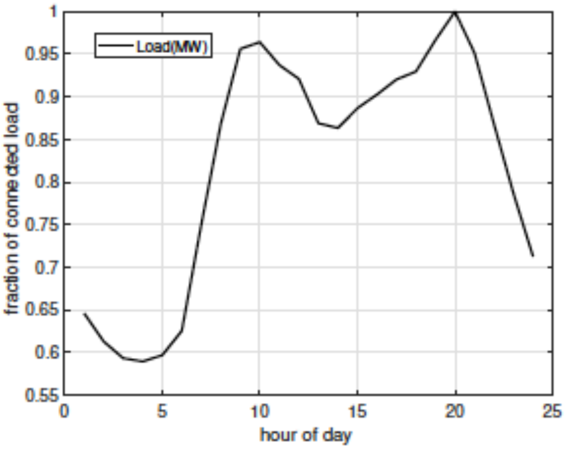


Figure 3. 24-hour connected load curve

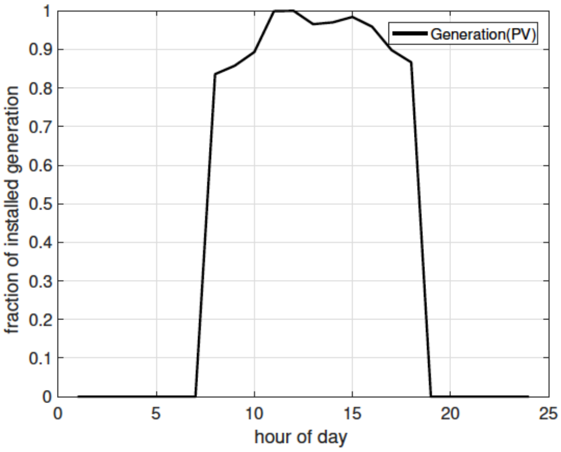


Figure 4. 24-hour generation (PV) curve

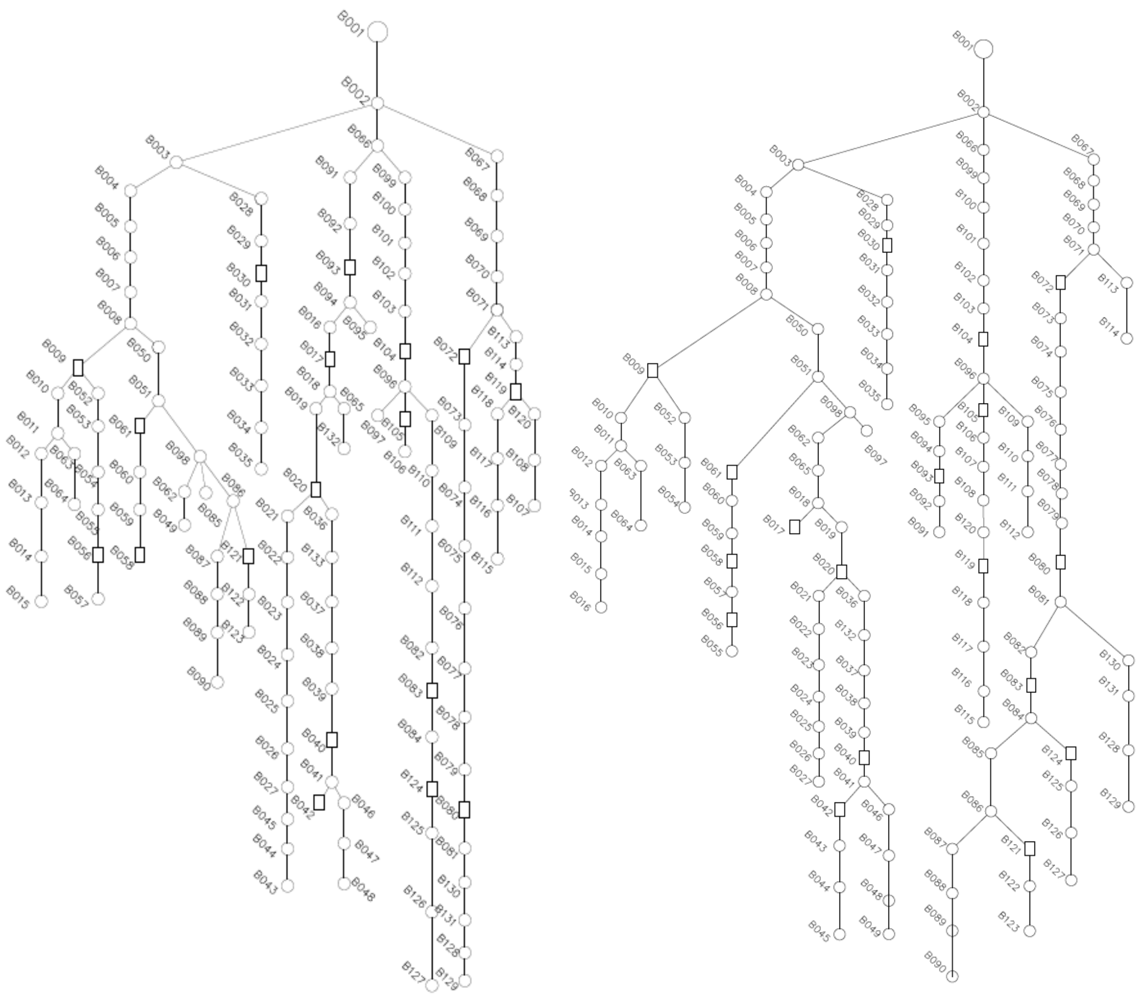
4.2. Case 2: Minimization of Line Loading (OF 2)

In this objective function, the algorithm searched for the maximum fitness value for the line loading index over all considered periods for the corresponding network configuration. The minimum of these fitness values was selected, and its corresponding configuration was selected as the optimum for the OF.

The optimal value of OF 2 is 0.2541 which corresponds to about 25% improvement of the loading capacity of the network. The final configuration to achieve this improvement is: (15 54 93 99 118 135 136 139 140 142 145 146 147 148) in twelve generations. This configuration gives 132 Buses as shown in Figure 5b. With this configuration, the other objective functions have the following fitness values; OF 1: 0.9034 and OF 3: 1.6177e+04.

4.3. Case 3: Feeder Length Reliability Index (OF 3)

The algorithm finds the length of the feeder and the generation and load connected to it such that the maximum amount of load and generation is connected to the shortest feeder. This operation is applied to the multi – period scenario by finding the initial fitness value of the initial network and scaling the corresponding configurations for all the considered periods to it. The optimal value of the OF 3 is 1.1728e4. The final configuration of the network for this OF is: (39 47 55 66 106 114 122 135 136 137 144 146 147 148) which was achieved in 20 generations. The network obtained when this configuration is applied is shown in Figure 6 which is a 133 – Bus network. The fitness values for the other OFs with respect to this network are; OF 1: 1.3461 and OF 2: 0.2571.



(a) (b)

Figure 5. (a) Network when Power loss reduction is optimized, (b) Network Topology when Line Loading is optimized.

4.4. Comparison of the Results Obtained for the Three Objective Functions

First of all, it is clear that the three (3) objective functions are in conflict as the minimum value of each of them gives high values in the remaining two, i.e. the ones that were not optimized. Therefore, it is not possible to achieve more than one goal at a time. Secondly, it is interesting to analyse the results from the perspective of the introduction of DGs in the distribution network. As shown in Table 1, achieving the "traditional" goal of DN reconfiguration, i.e. loss minimization, gives high non-optimal values for the other objectives. This means that the loss minimization may not be a goal capable of assessing an optimal hosting capacity of DG on the DN (the line loading OF is the worst over all cases) and an improvement of the reliability of the network.

Optimizing the reliability of the network (OF 3) gives the best balance between feeder length and load/generation connected to it without sacrificing the capacity of the network to host DGs (the value of OF 2 is very close to the optimal value).

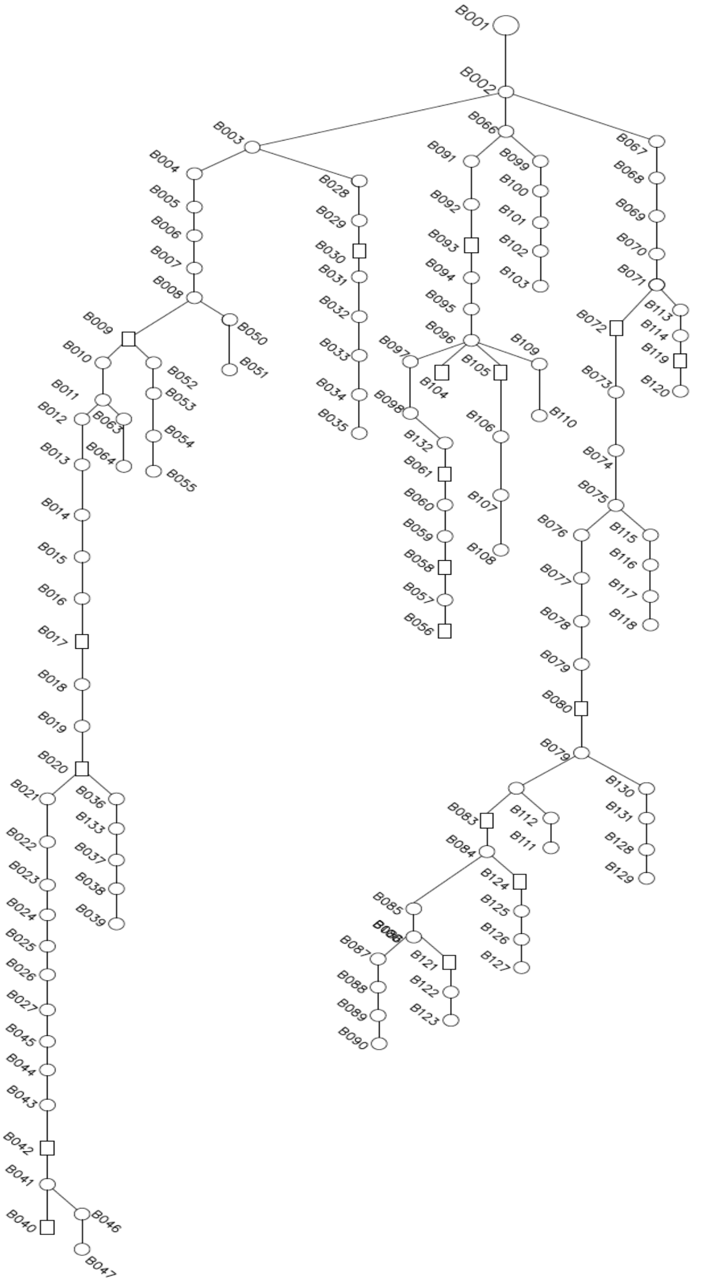


Figure 6. Network Topology when Feeder Length Reliability is optimized.

Table 1. Comparison of the Three Objective Functions

Case	Power (OF 1)	Loss	Line Loading (OF 2)	Reliability (OF 3)
min OF 1	0.45		0.41	1.59e4
min OF 2	0.90		0.25	1.61e4
min OF 3	1.34		0.26	1.39e4

The optimization of these objectives (OF 2 and OF 3) highly deteriorate the energy losses in the network. However, the DGs can be optimized during real time operation of the Distribution Network to minimize the energy losses. The preliminary results reported in this work show that in the presence of DG, the feeder length reliability of the networks may be the goal for the planning of the network in the future.

5. CONCLUSION

A distribution network reconfiguration is presented where an objective function is proposed in addition to the power loss and line loading objective function. The new objective function is a reliability and a security index which uses the length of a feeder. The line loading is particularly important to distributed generators as it prevents staying close to the maximum ampacity of the lines and the margins to the limits are in effect being optimized, thus indirectly, the hosting capacity of the network. Moreover, the optimization model was designed to consider multi – period scenarios which is a crucial aspect in the network configuration problem as it is a planning problem, and the optimal configuration needs to be optimized not only for one operating scenario but for a large range of possible operating scenarios.

A Genetic Algorithm is proposed where the bi – partite graph theory is employed to ensure that the individuals of the population are feasible regarding the radiality constraint of the Distribution Network. Finally, the tests were performed on a 136 – Bus Network. In conclusion, the proposed algorithm proved its efficiency in evaluating a real Distribution Network in the case of multi – period scenarios. Further improvements should focus on the reduction of the computation time.

The computation time is mainly made up of the evaluation of the fitness function hence by the calculation of the PF which delays the time to find the optimal solution. Techniques based on 1st and 2nd order sensitivities should be investigated to obtain, in a shorter duration, a good approximation of the exact nonlinear power flow solution.

CONFLICT OF INTERESTS

The authors would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

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