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A GENETIC ALGORITHM APPROACH TO OPTIMAL PLACEMENT OF SWITCHING AND PROTECTIVE EQUIPMENT ON A DISTRIBUTION NETWORK

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ABSTRACT

This paper proposes a genetic algorithm-based method for determining the optimal number and location of switching and protective equipment such as sectionalizers, cut-out fuses and reclosers in distribution network. The presence of a wide range of transient faults in the distribution network means that each switching and protective devices has a different impact on the reliability indices. Installation of switching and protective equipment on the distribution network reduces the duration of outages and improves network reliability, but the high price of some of these devices encourages any attempt to optimize their numbers and location. In this paper, objective function has incorporated the cost of protective equipment and profit gained from reducing unsupplied energy costs, and then a number of constraints have been added to improve the reliability indices. In the end, the Performance of the proposed method has been evaluated by implementing it on a 15-bus network model.

Keywords: switching, protective equipment, optimal placement, genetic algorithm, fault detection and isolation.

INTRODUCTION

The increasing importance of electrical energy and growing energy demand has led to increasing attention to adequate reliability and efficient protection of electrical systems, and layout and equipment used in distribution networks play an important role in this regard. A significant share of faults and undesirable events occurs in this section of power system so the majority of blackouts and resulting customer dissatisfaction is concerned to this part of power grid. Improving the reliability can increase customer satisfaction, prevents additional costs caused by power outages and therefore improve the economic performance distribution companies. Installation of switching and protective equipment such as sectionalizers, cut-out fuses and reclosers is a tested and efficient method to improve the reliability of distribution networks. The success of any recovery operation in the distribution network depends on the number and location of these devises; therefore, determining the optimal position of the equipment on a network can improve the efficiency of recovery operations and increase the reliability of that distribution network [1, 8].

So far, there have been few researches on the manner of determining the location of switching and protective devices in distribution networks. In [1], authors have determined the optimal number, location and type of switching and protective equipment network based on Energy Not Supplied (*ENS*) index; objective function proposed in that article consists of Constant and variable costs which has been optimized by Genetic Algorithm. In [3], the importance of optimal location of recloser on distribution network has been emphasized and the ant colony algorithm has been used to optimize the objective function on that basis. In [2], authors have proposed a method to achieve the optimal placement of sectionalizers on a distribution network in the presence of distributed power plants. In that article, first a multi-objective function has been designed to improve functionality and minimize the costs of sectionalizers by defining each as a fuzzy membership function, and then it has been optimized by an ant colony optimization algorithm. In [9] authors have proposed a multi-objective optimization method to determine the optimal type and location of switches and protective equipment over a distribution network. In that article, Ant colony optimization algorithm has been used to optimize a multi-objective function that minimizes the total cost along with two reliability indices of System Average Interruption Frequency Index (*SAIFI*) and System Average Interruption Duration Index (*SAIDI*). In [6], optimal placement of reclosers and distributed power plant has been studied to improve the network safety (voltage profile and power losses) and reliability. In that article, authors have performed a sensitivity analysis on load distribution equations to locate the optimal position of distributed power plants, and then have used genetic algorithm to find the optimal placement of reclosers. In [10], the effect of protective equipment on facilitation of power recovery in the event of faults and interruptions has been demonstrated, and then tabu search algorithm has been used to find the optimal position of protection and control equipment for radial distribution feeders. In [4], ABB engineers have studied the effects of adding reclosers and sectionalizers to radial distribution network, and have achieved significant results regarding

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installing reclosers based on fault location or with respect to sensitive loads.

In this paper, the genetic algorithm has been used to determine the optimal number and location of switching and protection equipment. The objective function used in this paper incorporates the cost of protective equipment and profit gained from reducing unsupplied energy costs, but also minimizes the number of Transient power interruptions.

THE EFFECT OF SWITCHING AND PROTECTIVE EQUIPMENT ON RELIABILITY INDICES

Various solutions and equipment can be used to improve the reliability of the distribution network, and objective of all of these approaches is to somehow reduce the number and duration of outages on distribution feeders.

When a fault occurs in a feeder, necessary steps must be taken to return the network to its normal state, because any such fault cause the feeder circuit breaker to cut out the entire feeder as well as all distribution substations powered through this feeder. So it becomes necessary to Fault Detection and Isolation (FDI), use appropriate switching equipment to isolate the faulty section from the healthy sections of feeder, and then use maximum capacity of backup resources and super grid supporting this feeder to supply the healthy sections until repairs are done. This ensures that only the faulty section and the parts that cannot be isolated get affected by the fault. The sum of all these steps is generally called the maneuvering operation.

It is clear that performance of any maneuver in the distribution network is highly dependent on the number and location of switching and protective devices, thus proper placement of the equipment can improve the performance of recovery operations as well as the reliability of the distribution network. Proper isolation of faulty section and performing necessary maneuvers to supply the healthy sections requires a suitable and well-designed layout for equipment positions over the distribution network. Another important concept which must be considered in this regard is the "network zoning". A zone refers to a set of busbars and lines which in the event of any fault at one of them the rest must also remain unsupplied until the end of repairs [10]. This concept is illustrated in Figure-1.

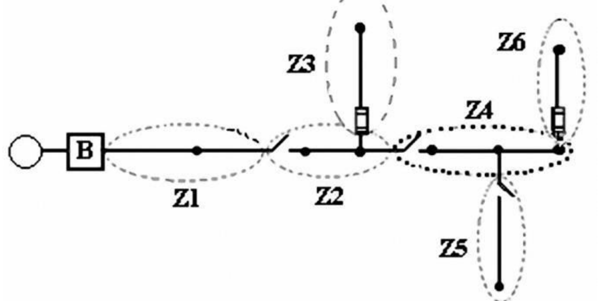

Figure-1. Zoning distribution network for example.

Reclosers are among protective equipment that are installed on overhead lines and can reduce the number or duration of power outages in the distribution network. Any fault that occurs in the distribution networks is either Transient or permanent. Statistics gathered on power outages show that more than 70 percent of interruptions in overhead lines are caused by Transient faults. In the event of any Transient fault on the main or subsidiary lines, a recloser cut out the power of its downstream line and isolates the faulty section and therefore prevents any interruption in the power supply of customers using its upstream line. In addition, the switching mechanism of recloser reconnects the network as soon as line status becomes normal which is very soon in the case of Transient faults.

It should be noted that advantages of using reclosers are not limited to just controlling Transient faults, and also affect the impact of permanent faults on consumers. When the fault occurred at the line downstream the recloser has a permanent nature, after a number of switchings, recloser keeps its switch in the open position, and again prevents any interruption in the power supply of customers using its upstream line. This obviously increases the reliability of service provided to this group of customers by reducing the number and duration of outages in the section of network where it is installed [9] [10].

The performance of cut-out fuses and their impact on network reliability are similar to those of reclosers when they are handling permanent faults. Their difference is that in the event of a permanent fault, recloser isolates the line after a few (quick) switchings, but cut-out fuse must isolate the line immediately after the fault occurrence provided that it functions properly according to time-current curve. Sectionalizers cannot cut off faulty undercurrent and in the event of such fault equipment such as primary circuit breaker, recloser, or cut-out fuse must be used to isolate the faulty section.

PROBLEM FORMULATION

To optimize the number and location of switching and protective equipment in a distribution network, we first need to define a suitable objective function. So an objective function composed of equipment purchase and installation cost and undistributed energy cost is used for this purpose. To ensure a more realistic approach to the subject, the current expenditures (such as annual undistributed energy cost) during the study period are converted to their corresponding first year values by using a present value factor.

Reliability indices

Equipment such as sectionalizers, cut-out fuses, and reclosers are the main focus of this paper, so indices such as Momentary Average Interruption Frequency Index (*MAIFI*), System Average Interruption Frequency Index (*SAIFI*), System Average Interruption Duration Index

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(*SAIDI*) and the Energy Not Supplied (*ENS*) index are discussed in this section [4] [7] [9] [10].

$$MAIFI=\frac{\sum_{i=1}^{n}\gamma_i N_i}{\sum_{i=1}^{n}N_i} \quad \text{[mom.inter./cust/yr]} \quad (1)$$

$$SAIFI=\frac{\sum_{i=1}^{n}\lambda_i N_i}{\sum_{i=1}^{n}N_i} \quad \text{[per.inter./cust/yr]} \quad (2)$$

$$SAIDI=\frac{\sum_{i=1}^{n}U_i N_i}{\sum_{i=1}^{n}N_i} \quad \text{[hour/cust/yr]} \quad (3)$$

In the above equations, n is the number of load points, γ_i is the average rate of momentary interruptions in the load point i, λ_i is the annual rate of faults per kilometer in the *i-th* branch of feeder, U_i is the average annual interruption time of *i-th* section in hours per year, and N_i is the number of customers connected to the load point i. The average energy not supplied (*ENS*) in KWH per year is calculated as below [1].

$$ENS=\sum_{i=1}^{nb}\lambda_i \,.\, L_i \,.\, \left(\sum_{j\in S_i}P_j \,.\, TS_i+\sum_{j\in R_i}P_j \,.\, TR_i\right) \quad (4)$$

Where nb is the number of feeder branches, L_i is the length of *i-th* branch, S_i is the set of load points that are supplied through switching and maneuver operations after a fault in *i-th* branch, P_j is the average load of *j-th* point, R_i is the set of load points that are supplied after the repairs when there is a fault in *i-th* branch, TS_i is the time required for maneuver and switching operation when there is a fault in *i-th* branch (in hours) and TR_i is the time required for repairing the damaged section of the feeder when there is a fault in *i-th* branch (in hours). Any change in the condition and number of reclosers lead to a change in S_i and R_i in equation (4) which consequently lead to a different *ENS*.

Objective function

In this problem, the number and location of reclosers must be determined in a way that minimizes installation and *ENS* cost while satisfying the minimum momentary average interruption frequency index (*MAIFI*) in the system.

With this explained, objective function subject to constraint can be represented as follows (Jahromi *et al.*, 2012):

$$Min\ F=\sum_{t=1}^{ny}PW^t \,.\, CENS+\sum_{i=1}^{N_s}S_i \,.\, CS_i \quad (5)$$

$$Where \quad PW=\frac{1+InfR}{1+IntR}$$

$$And \quad MAIFI\le 0.5 \quad \text{mom.inter./cust/year}$$

Where F is the total value of the objective function, *CENS* is the cost of *ENS* (is a functions of *ENS*), PW is a factor for converting the current expenditures to their corresponding presents value, *InfR* is the inflation rate, ny is the study period in years, S_i is the decision variable representing the installation of equipment i (1= equipment is installed, 0 = equipment is not installed), CS_i is the cost of purchase and installation of equipment i, and N_s is the total number of switching and protective equipment to be installed. The maximum value of *MAIFI* is 0.5. In the provided model, the economic evaluation is conducted via comparing the present value of schemes.

SOLUTION ALGORITHM

Mathematical (analytical) algorithms used for solving non-linear optimization problems usually stuck in local optimums because they use only one direction at a time to move toward the absolute optimum. But unlike analytic methods, intelligent optimization algorithms move from several directions toward absolute optimum and are more likely to converge to the absolute optimum. Therefore in this paper, a genetic algorithm is used to solve the optimization problem.

Basic definitions

In genetic algorithms, each point in the search space is called a chromosome or genetic string. Chromosomes themselves are made of a fixed number of genes (problem variables) and group of chromosomes are called population.

Representation of problem variables

In genetic algorithm, each chromosome is a solution. Chromosomes are coded in form of binary or real strings. For example, Figure-2 shows the candidate positions for the installation of switching equipment. As can be seen, both sides of each section can be considered as a candidate position for the installation of this equipment (if there is no other restriction in terms of geographic location or practical considerations).

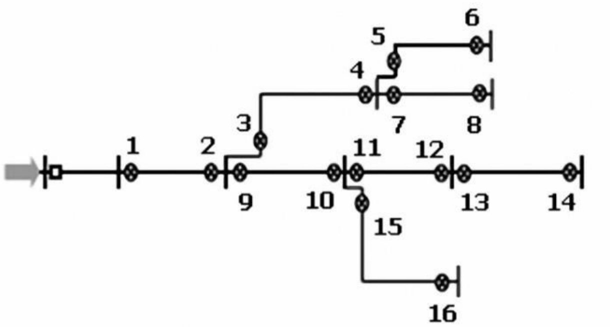

Figure-2. Candidate places for recloser installation in the sample distribution network.

As can be seen in Figure-2, 16 candidate locations have been considered for the installation of this equipment; in other words, all possible locations in the network have been determined as candidates. Therefore the chromosome for this network is defined as a 16-cell string as shown in Figure-3.

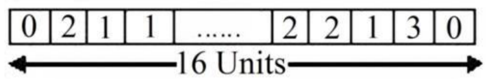

Figure-3. An example of chromosome coding for sample distribution network.

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Each cell can take an exact value in the range [0,3]. "Zero" indicates that no equipment will be installed in that cell; "one" indicates that a sectionalizer will be installed; "two" indicates that a cut-out fuse will be installed and "three" indicates that a recloser will be installed in that cell.

Decoding the chromosomes information determines the location and type of protective equipment. For example, the decoding the chromosome shown in Figure-3 indicates that none of the switching and protective equipment should be installed in the first and sixteenth candidate locations; cut-out fuses must be installed In the second, twelfth and Thirteenth locations; sectionalizers must be installed in the third, fourth and fourteenth locations, and a recloser must be installed in fifteenth location. The other cells will also be decoded similarly.

Genetic algorithm flowchart

Figure-4 shows the proposed flowchart algorithm

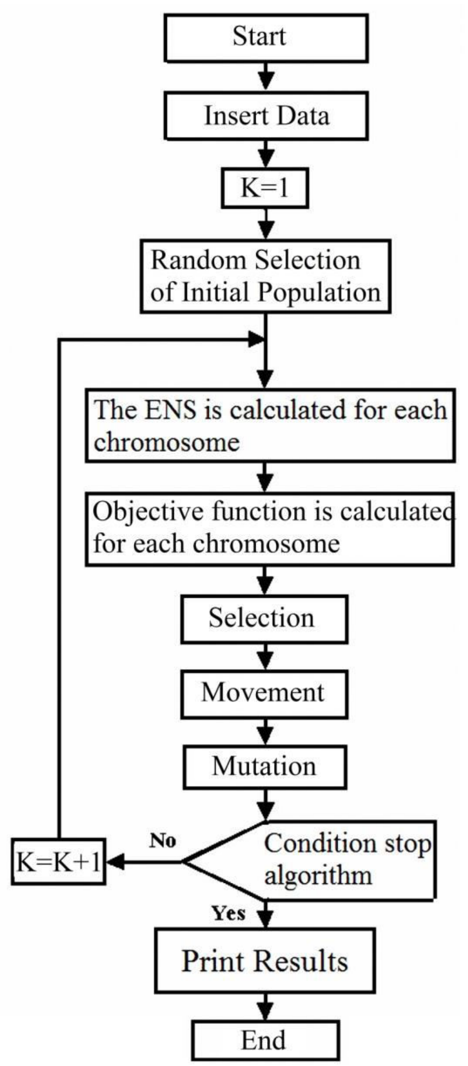

Figure-4. The proposed algorithm flowchart.

In the flowchart algorithm (Figure-4), first the input data regarding the fault rate and fault period and the costs arising from purchase and installation of protective and switching equipment are inserted, and then the iteration process of the genetic algorithm begins. The initial population that consists of various combinations of protective equipment over the network is determined randomly at the start of algorithm. Then the energy not supplied (*ENS*) is calculated for each chromosome, which is a combination of protective equipment; after that the objective function and fitness of that chromosome are calculated. Then genetic operators including selection, crossover and mutation are applied to these chromosomes to generate the next population. This process repeats until it meets the algorithm's stop condition. Algorithm's stop condition in this problem is the number of iterations. In the end, the results including the number of protective and switching equipment, their location, equipment type and the value objective function value are obtained.

NUMERICAL RESULTS

Figure-5 shows the 15-busbar distribution network model studied in this paper. In this model, average permanent and momentary failure rates are 0.2 and 3 times per year per kilometer and the average time required to repair a permanent fault is considered 5 hours. To assess the effects of switching equipment on reliability indices, numerical studies were conducted in the form of following two scenarios.

Scenario 1: The effect of presence of switching and protective equipment

This scenario is designed to assess the impact of switching and protective equipment on the line 6-8 (Section S7) on the reliability indices. This scenario consists of following sub-scenarios:

1.1. Without any equipment (initial condition)

1.2. Only sectionalizers

1.3. Only Cut-out fuses

1.4. Only Reclosers

The results achieved by implementing scenario 1 are presented in Table-1. the results of sun-scenarios presented in Table-1 show that the presence of each switching and protective equipment has improved the steady state indices (*SAIFI, ENS* and *SAIDI*) compared to their initial state, but installing the sectionalizer has had no effect on *SAIFI*. Also the results obtained for *ENS*, *SAIFI* and *SAIDI* indices show that installing cut-out fuse and recloser has had the same effect, which shows the identical impact of cut-out fuse and recloser on steady state faults (but only when cut-out fuse operates properly). According to Table-2, *MAIFI* has improved only when a recloser has been installed on the network.

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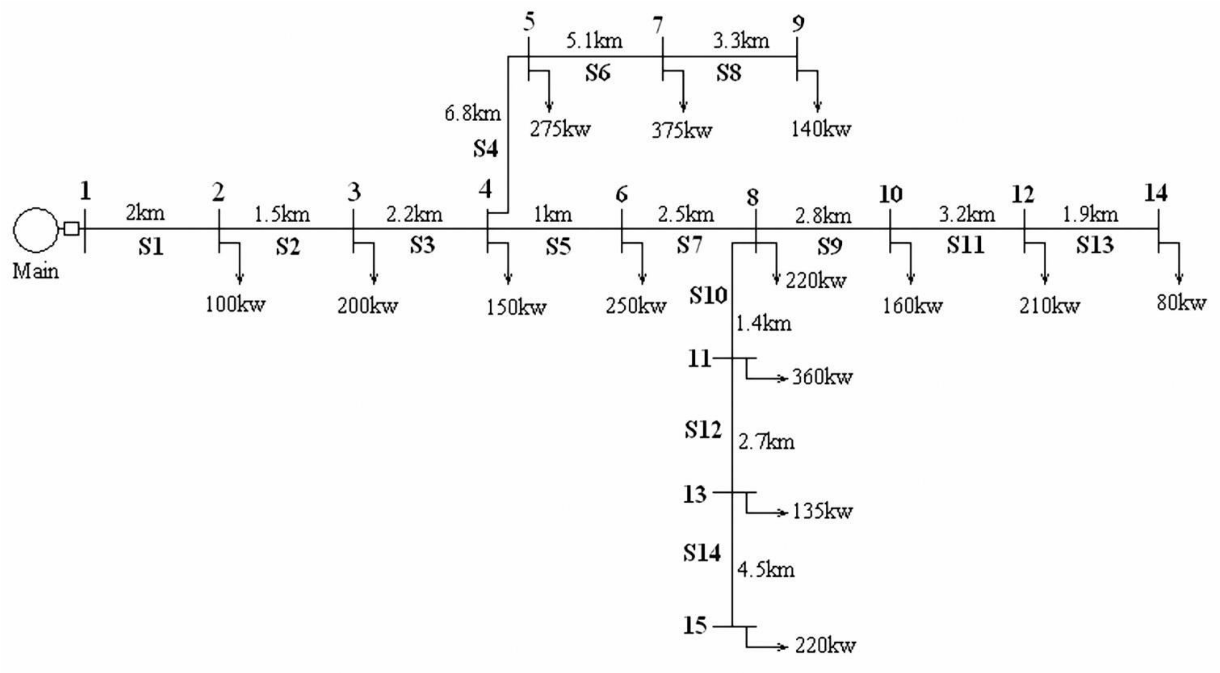

Figure-5. Real 15-busbar distribution network model.

Table-1. Shows the results of a scenario 1.

Scenario 1	*ENS* (kwh /yr)	*SAIFI* (inter/cust/yr)	*SAIDI* (hour/cust/yr)	*MAIFI* (mint/cust/yr)
1.1	117.59	8.18	40.9	1.227
1.2	94.94	8.18	33.24	1.227
1.3	89.278	6.26	31.32	1.227
1.4	89.278	6.26	31.32	0.94

Scenario 2: The effect of optimal placement of switching and protective equipment

In this scenario, the effect of optimum placement of sectionalizers, cut-out fuses and reclosers are assessed by genetic algorithm are discussed in the following sub-scenarios. The candidate locations for equipment placement are at the start and end of each busbar:

2.1. Without any equipment (initial condition)

2.2. Sectionalizer placement only

2.3. Cut-out fuse placement only

2.4. Recloser placement only

2.5. Simultaneous placement of all three equipment

In this problem, the cost of purchase and installation is 25 million rials for recloser, 15 million rials for sectionalizer, and 0.5 million rials for cut-out fuse, and the energy not supplied (*ENS*) cost is 700 rials, the interest rate is 17%, the inflation rate is 15% and the study period is considered 5 years.

The results achieved by implementing scenario 2 are presented in Table-2.

According to Table-2, the comparison of the results of sub-scenarios 2 and 3 shows that the low cost of cut-out fuses, compared to sectionalizers, has caused a higher number of this equipment to be installed which has led to a greater reduction in the reliability indices. While installing cut-out fuses, the protection coordination issue, which limits the use of this equipment in the network, must also be considered; but in this paper the protection coordination issue is not taken into consideration. *MAIFI* has only improved with the installation of reclosers. In sub-scenario 5 where simultaneous placement of all three equipment has been performed, the genetic algorithm has not recommended any sectionalizer and this is because of low cost of cut-out fuses compared to sectionalizers and the relative advantage of cut-out fuse and reclosers to sectionalizers (shown in Table-1). The results of sub-scenario 5 have achieved the lowest values of reliability indices and objective function compared to other sub-scenarios. *SAIFI* is also minimal in sub-scenario 5. The reason behind this issue is the high number of cut-out fuses and reclosers in this sub-scenario. Meanwhile *SAIDI* has reached its best value in this sub-scenario which is because of optimum placement of reclosers and cut-out fuses in this design. The interesting point is that the achieved *MAIFI* value is 0.485 which is lower than the objective value (*MAIFI*$\leq$ 0.5)

Table-2. Shows the results of a scenario 2

Scenario 2	**Objectiv function** (milion rials)	***MAIFI*** (mom/Inter/ cust/yr)	***SAIDI*** (hour/ cust/yr)	***SAIFI*** (inter/ cust/yr)	***ENS*** (MWH /YR)	**Recloser** (section number)	**Cut-out fuse** (section number)	**Sectionalizer** (section number)
2.1	390.93	1.227	40.9	8.18	117.59	--	--	--
2.2	251.27	1.227	19.99	8.18	57.532	--	--	4,5,9,12
2.3	158.67	1.227	13.87	2.77	40.208	--	4,5,6,9,12	--
2.4	235.12	0.485	16.18	3.24	48.162	4,9,10	--	--
2.5	221.15	0.485	13.61	2.72	39.450	4,9,10	5,8,14	--

CONCLUSIONS

The presence of equipment such as sectionalizers, cut-out fuses and reclosers in distribution network greatly affects the system reliability and any change in the number and location of switching and protective equipment significantly changes the level of feeder reliability. In this paper, the effects of switching and protective equipment on interruptions cause by various momentary and permanent faults were assessed. The genetic algorithm was used to optimize the number and location of these devices separately and simultaneously and the performance of the proposed method was evaluated by implementing different scenarios on a 15-busbar network model.

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