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Multi-Objective Optimal Planning and Operation of Distribution System Using Genetic Algorithm

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Abstract – *This paper proposes optimal planning and operation procedures for radial distribution systems (RDS). The proposed optimal RDS procedures aim to obtain the best selection of cross-section size of distribution branches that leads to the optimal desired performances. The genetic algorithm (GA) is used to obtain the optimal cross-section size of RDS through minimizing the total operating costs and the feeder energy costs, while keeping the voltage regulation within a prescribed value and satisfying the growth factor. After the selection of the optimal branches size, an optimal procedure of RDS is proposed using a distribution system software programming (DSSP). This program is applied to define the optimal radial reconfiguration system with minimum energy loss costs and to satisfy the RDS constraints such as: branch voltage drop, thermal current carrying capacity and balance generation-load demand equation. The DSSP is very useful to find the optimal operation of RDS in the normal and abnormal operating conditions. Different studies are presented to illustrate the capability of the proposed procedures using two real life power distribution systems in Egypt.*

Keywords – Distribution systems, genetic algorithm, minimum energy loss, multi-objective technique, optimal planning and operation.

1. INTRODUCTION

Planning and operation of distribution systems involve a long list of optimization problems, like expansion at minimum cost or network reconfiguration keeping in mind a certain objective function (*e.g.*, feeder and/or substation balancing, loss reduction, voltage profile etc.).

A key factor when practically implementing those optimization problems refers to the fact that, while distribution networks are structurally meshed, they are radically operated. The optimal planning and operation of distribution networks are obtained when the networks present minimum losses, minimum voltage deviations at the customer loading points, and maximum reliability. Network reconfiguration is the process of altering the topological structures of distribution feeders by changing the open/closed states of the sectionalizing and tie switches under both normal and abnormal operating conditions. During normal operating conditions, networks are reconfigured to reduce the system real power losses, relieve loads in the network and to increase network reliability. When a fault occurs on a feeder, the faulted section has to be identified and isolated. The isolated sections will have to be fed from alternative feeders until the faulty branch is repaired.

Several categories of network reconfiguration techniques for power loss reduction can be distinguished [1]. On the one hand, the safest way to solve the reconfiguration problem consists of trying all possible trees for the system has done in [2]. On the other hand, the combinatorial nature of the problem has held researchers to explore purely heuristic solution techniques [3]-[5]. Finally, a third category comprises those contributions using artificial intelligence, like simulated annealing [6], fuzzy logic [7], genetic algorithms [8], or artificial neural networks [9] (which requires substantial amount of accurate data for training). Reference [10] presented an optimization methodology for distribution networks expansion using an evolutionary algorithm. This methodology deals with only planning distribution problems.

Reference [11] presented a systematic procedure to study the effect of temperature change to the power system load demand (load profiles and feeder losses). Recently, the reconfiguration of distribution system considering loss minimization was presented in [12]-[13]. This paper presents two proposed procedure. The first procedure is presented to obtain the optimal cross-section branches to be suitable for existing and extending distribution network, while the second procedure deals with the operation of RDS for normal and abnormal operating conditions.

2. PROBLEM FORMULATION

Planning and operation of distribution systems involve multi-objective functions must be achieved while necessary system constraints have to be satisfied.

Objective Functions

a. Minimization of Energy Loss Cost

This paper aims to minimize the system power loss which can be expressed as:

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$$Min \quad F_1 = Min\sum_{i=1}^{n} 3T\,10^{(-3)} I_i^2 R_i\,(LLF) \qquad (1)$$

Where, n is the total number of branches, I_i is the load current flow in branch i, R_i is the resistance of branch i, T is the number of operating hours per year and LLF is the loss of load factor which is a function of load factor (LF) and was defined as [14]:

$$LLF = A\,(LF)^2 + B\,(LF) \quad where,\ A+B=1 \qquad (2)$$

The total energy loss is to be calculated on the basis of present worth cost for the period of conductor, assumed life time (D years) for a discount rate of annual percentage r. Therefore, the energy loss costs can be expressed as:

$$Min \quad F_1 = \sum_{i=1}^{n} 3T10^{-3} I_i R_i (LLF) h \sum_{d=1}^{D} (1/(1+r)^d) \qquad (3)$$

Where, h is the cost of energy per kWh.

b. Minimization of Feeder Cost

The actual cost of the distribution feeder involves a fixed cost as well as a variable cost. The fixed cost component involves cost for conductor's pole, accessories, labor and erection. The variable cost component reflects the cost of conductor material and is a function in cross-section area. Then, the minimization of total costs over the life period of the feeders in the distribution system can be expressed as:

$$Min \quad F_2 = \sum_{k=1}^{D}\sum_{i=1}^{n} (w_{1i} a_i + w_{2i}) l_i \qquad (4)$$

Where, W_{1i} and W_{2i} are the cost constants of feeder i per unit length (1 km).

c. Minimization of Voltage Deviation

The voltage deviation with respect to the flat voltage (1.0 p.u.) must be minimized, so that the regulation factor at load bus in the distribution system can be modified. This objective function can be expressed as:

$$Min \ F_3 = \sum_{j=1}^{N} (V_j - V^{sp}) \qquad (5)$$

Where, V_j is the voltage magnitude at bus j, V^{sp} is specified voltage (1.0p.u) and N is the total number of load buses.

Constraints of Distribution System

The minimization of the objective functions shown in Equations 3 to 5 may result to cross-section areas that may lead to either high or low service quality.

a. Voltage Level Constraints

The voltage level at the consumer in the distribution system is the main constraint. The voltage drop in the distribution feeder depends on the choice of its cross-section area, loading level, power factor and circuit operating voltage. However, the small value of feeder voltage drop leads to high conductor size and consequently more investment and less system losses. The voltage magnitude at each bus must be maintained within its limits as:

$$V_j^{\min} \le V_j \le V_j^{\max} \qquad j=1,\ldots,N \qquad (6)$$

Where, V_j^{min} and Vj^{max} are the minimum and maximum voltage magnitude at bus j.

b. Current Flow Constraint

This current has to lie within its capacity rating of branch j as follow:

$$\left|I_j\right| \le I_j^{\max} \qquad (7)$$

Where,$|I_j|$, I_j^{max} are the current magnitude and maximum current limit of branch j.

c. Thermal-limit Constraint

The maximum allowable conductor temperature, at which the conductor can be operated, is called the thermal limit or thermal rating of that conductor. This constraint can be expressed as:

$$A_j \ge A_j^{\min} \qquad (8)$$

Where, A_j and A_j^{min} are cross-section area and its minimum limit of branch j. However, the minimum cross-section area in the first branch must carry the total current of ring distribution before transfer it to RDS.

The total current flow must be equal to the total nodal loading current as the following equation:

$$\sum_{i=1}^{n} I_i = \sum_{j=1}^{N} IL_j \qquad (9)$$

Where, IL_j is the loading current at node j.

3. GENETIC ALGORITHM FOR OPTIMAL CROSS-SECTION AREA OF BRANCHES

Genetic algorithm (GA) is based on the mechanisms of natural selection. GA produces high quality solutions because they are independent of the choice of initial configurations. Initial population is generated randomly. Population consists of individuals, each representing a particular selection of the values of the variables coded in binary form. Each individual is evaluated to obtain a measure of its fitness in terms of objective function to be optimized.

In this paper, GA is used to find the optimal cross-section area of branches to achieve multi objective functions shown in Equations 3 to 5. After this start, successive population is generated using the following three basic operators namely, reproduction, crossover and mutation.

The reproduction operator is a process in which individual strings are copied according to their fitness value. In this process, strings with higher value have a higher probability of contributing one or more off-springs to the next generation. After reproduction, the crossover operator is used to create new individuals and takes place according to a given probability value as shown in Figure 1. Finally, the mutation operator creates a new individual by changing a randomly selected bit in its coding as shown in Figure 2.

0	1	1	1	0
1	1	0	1	1

(a)Before crossover

0	1	0	1	1
1	1	1	1	0

(b) after crossover

Fig.1 Crossover operator

0	1	0	1	0

(a)Before crossover

0	1	1	1	0

(b) after crossover

Fig. 2. Mutation operator

4. MULTI-OBJECTIVE OPTIMIZATION PROBLEM

Many real-world problems involve simulation optimization of several objective functions. Generally, these functions are often competing and conflicting objectives. Multi-objective optimization with such conflicting objective functions gives rise to sets of optimal solutions, instead of one optimal solution. The reason for the optimality of many solutions is that no one can be considered to be better than any other with respect to all objective functions. A general multi-objective optimization problem consists of one or more objectives to be optimized simultaneously and is associated with a number of constraints. It can be formulated as follows:

$$Min\, f_i(x) \qquad i = 1,....,N_\circ \tag{10}$$

Subject to:

$$\begin{cases} g_j(x) \geq 0 & j = 1,...., \quad M \\ h_k(x) \leq 0 & k = 1,...., \quad k_c \end{cases}$$

(11)

Where, f_i is the ith objective functions, x is a decision vector that represents a solution, N_0 is the number of objective functions and $g_j(x)$ and $h_k(x)$ are the inequality constraints of power system.

The genetic algorithm (GA) is used to achieve the fitness function as shown as in:

$$Min\ f = w_1.F_1 + w_2.F_2 + w_3.F_3 \tag{12}$$

Since, there is no feasible solution when these objectives are minimized simultaneously; the priority goal programming (PGP) is used to achieve the simultaneous the priority goal programming (PGP) optimization of several objective functions. In Equation 12 the weighting factor w_1 takes 1.0 while the other weighting factors w_2 and w_3 take zeros in order to minimize F_1. In order to achieve the two objective functions (F_1 and F_2), the weighting factors w_1 and w_2 take 1.0 while w_3 takes zero. Which, the weighting factors w_1-w_3 take 1 to achieve the three objective functions (F_1 - F_3) and so on.

5. DISTRIBUTION SYSTEM SOFTWARE PROGRAMMING (DSSP)

Power and Energy Loss Computation in Medium Voltage (MV) Network

The DSSP starts with closing all tie switches to create a meshed network. This meshed network will contain many closed loops, and each loop should have an optimal opening point for minimum losses. Therefore, our goal in normal operation is to find the optimal opening switch for each loop according to the following steps:

1. Input Data:
   a) Feeder parameters (resistance and reactance), type of conductor, length and number of circuits.
   b) Voltage, current, power factor, load factor and loss factor at the sending end of feeder.
   c) Peak adjustment factor (PAF=Last Year Annual Peak Load /Last Year Peak Load in the month corresponding to the month of measurements).
   d) Node connection for each branch, cross-section area of each branch and percentage loading at each node.
2. Compute feeder input apparent power (S=√3*VI*, where *V* and *I* are measured values).
3. Compute voltage profile, active power flow and reactive power flow in each section using Z-bus (based on measured transformers loading).
4. Compare feeder sending end calculated power with measured power within a certain tolerance (ε ≤ 0.0001 for Gauss-Seidel method).
5. If (the measured power minus the calculated power) ≤ ε then stop calculations. Otherwise, modify the calculated power for each node according to the following relations:

$$P_{modified} = \frac{S}{KVA_{calculated}} \times input\ KVA\ loading \times \cos\varphi,$$

and,

$$Q_{modified} = \frac{S}{KVA_{calculated}} \times input\ KVA\ loading \times \sin\varphi$$

6. Go to step 4.

Reconfiguration of Medium Voltage Loops Operation Schemes

The medium voltage distribution system is designed as loops. These loops are normally opened in the normal operation conditions. The points of opening the loops are determined by the operation and control groups in the electricity distribution company.

The optimal operation scheme (the best point of opening) for the MV loops, in order to minimize the power losses, is determined using the following steps:

1. Input Data:

a) Feeder sections data: type of conductor, length, number of circuits.
b) Actual voltage at the sending end.
c) Kiosks (transformer points) data (Active power, reactive load and capacity).

2. Computations:

Based on the Medium Voltage cables and load data input, the program solves the load flow in the closed loop, and determines the optimal location of opening the loop to minimize the power losses. This location is the node at which the load flow reverses its direction. The program calculates the load flow and power losses in the new operation system. The reduction in power losses may be calculated by comparing the losses in the original operation condition with that in the optimal operation condition.

6. OPTIMAL PROPOSED PROCEDURES

The first optimal proposed procedure (OPP) concerns with the planning problem of finding the optimal cross-section areas of branches. The first branches in both sides of meshed system must has the capability to carry the total current in the both distributors. In this procedure the MOGA was used to minimize Equation 12 and satisfy the distribution system planning constraints, as shown in Equations 6 to 9. After the determination of the optimal cross-section areas of branches, the second OPP was applied using the DSSP in order to find the best radial reconfiguration system in order to minimize the total system losses. However, a tie switch and some sectionalizing switches with the feeders form a loop. A certain switch of each loop is then selected to open to make the loop become radial, and the selected switch naturally becomes a tie switch. In the second OPP, the network reconfiguration problem was identical to the problem of selection of an appropriate tie switch for each loop so that the power loss (F_1) is minimized and the RDS operation and planning constraints shown in Equations 6 to 9 are satisfied.

Table 1. Input data for the first case study

Node No.	kVA rating	Percentage Loading, %	Section No.	Length m.
2	100	45	1	435
3	500	50	2	75
4	500	75	3	1000
5	500	65	4	720
6	500	75	5	300
7	300	72	6	380
8	500	64	7	120
9	500	71	8	230
10	250	48	9	540
11	500	74	10	400
12	200	52	11	140

Voltage level is 11KV, total current is 205 A., feeder loss factor is 0.4013, power factor is 0.85, and load Factor is 0.6046.

Table 2. Input data for the second case study

Node No.	kVA rating	Percentage Loading, %	Section No.	Length, m.
2	500	50	1	240
3	300	64	2	270
4	300	35	3	100
5	1000	55	4	40
6	500	51	5	350
7	500	52	6	100
8	500	44	7	100
9	500	44	8	320
10	500	56	9	200
11	300	53	10	250
12	1000	20	11	750
13	100	60	12	100
14	300	73	13	650
15	160	39	14	30
16	300	28	15	650
17	300	47	16	50
18	500	75	17	420
19	500	71	18	150
20	500	61	19	170
21	250	75	20	380
22	250	85	21	80
23	250	65	22	400
24	500	70	23	210

25	300	37	24	70

Voltage level is 11KV, total current is 160 A., feeder loss factor is 0.4580, power factor is 0.93, and load Factor is 0.6220.

7. APPLICATIONS

Cases Study

Two real cases distribution study were used to find the optimal planning and operation of these systems. These cases study are real parts of Tanta city in Egypt. Figures 3 and 4 show the configuration of these distribution systems and the input data were shown in Tables 1 and 2, respectively. These systems contain three normally open switch closed only when a fault occurs. The cost of kWh is equal to 0.14 Egyptian Pounds (LE). While, the cost of three-phase 240 mm^2 and 150 mm^2 cross-section areas are equal to 115 and 87.5 LE/meter, respectively.

Four cases were considered to choose the optimal cross-section area of the feeders which are:

Case 1: the cross-section areas of all branches are equal to 150 mm^2.

Case 2: the cross-section areas of all branches are equal to 150mm^2 except the first branches in both sides of meshed network for both distribution systems (1-2 , 11-12 in the first system and 1-2 , 24-25 in the second system) are equal to 240 mm^2.

Case 3: the cross-section areas of all branches are equal to 150 mm^2 except the two first branches in both sides of meshed network for both systems (1-3 , 10-12 in the first system and 1-3 , 23-25 in the second system) are equal to 240 mm^2.

Case 4: the cross-section areas of all branches are equal to 150 mm^2 except the three first branches in both sides of meshed network for both systems (1-4 , 9-12 in the first system and 1-4 , 22-25 in the second system) are equal to 240 mm^2. However, the current capacities of cross-section area for 150 mm2 and 240 mm2 are equal to 219 and 289 Amperes, respectively.

Tables 3 and 4 show the percentage increasing in load demand from year 2003 to year 2006 and the transformer rating as a KVA at each loading point for two cases study, respectively. From these tables, the increasing in load demand were varied from 35% to 77% and from 0% to 85% for two cases study, respectively. These tables were used to obtain the optimal planning of the distribution systems for the different cases (1-4).

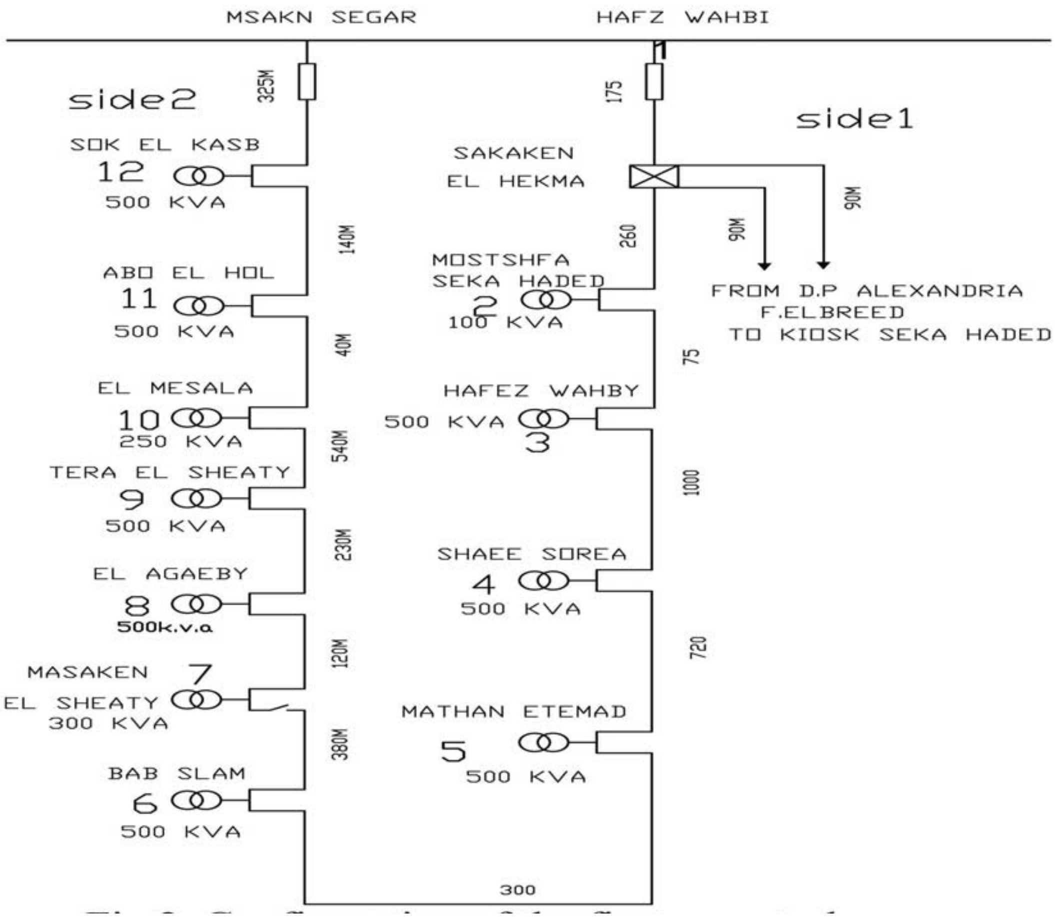


Fig. 3. Configuration of the first case study

Table 3. Percentage increase in load demand for the first case study

Node No.	KVA Rating of Transformers	Year			
		2003	2004	2005	2006
2	100	35	51	51	45
3	500	51	44	50	50
4	500	59	65	66	75
5	500	69	70	65	65
6	500	76	77	75	75
7	300	45	49	72	72
8	500	61	63	64	64
9	500	62	68	70	71
10	250	40	43	48	48
11	500	36	66	71	74
12	500	51	52	54	52

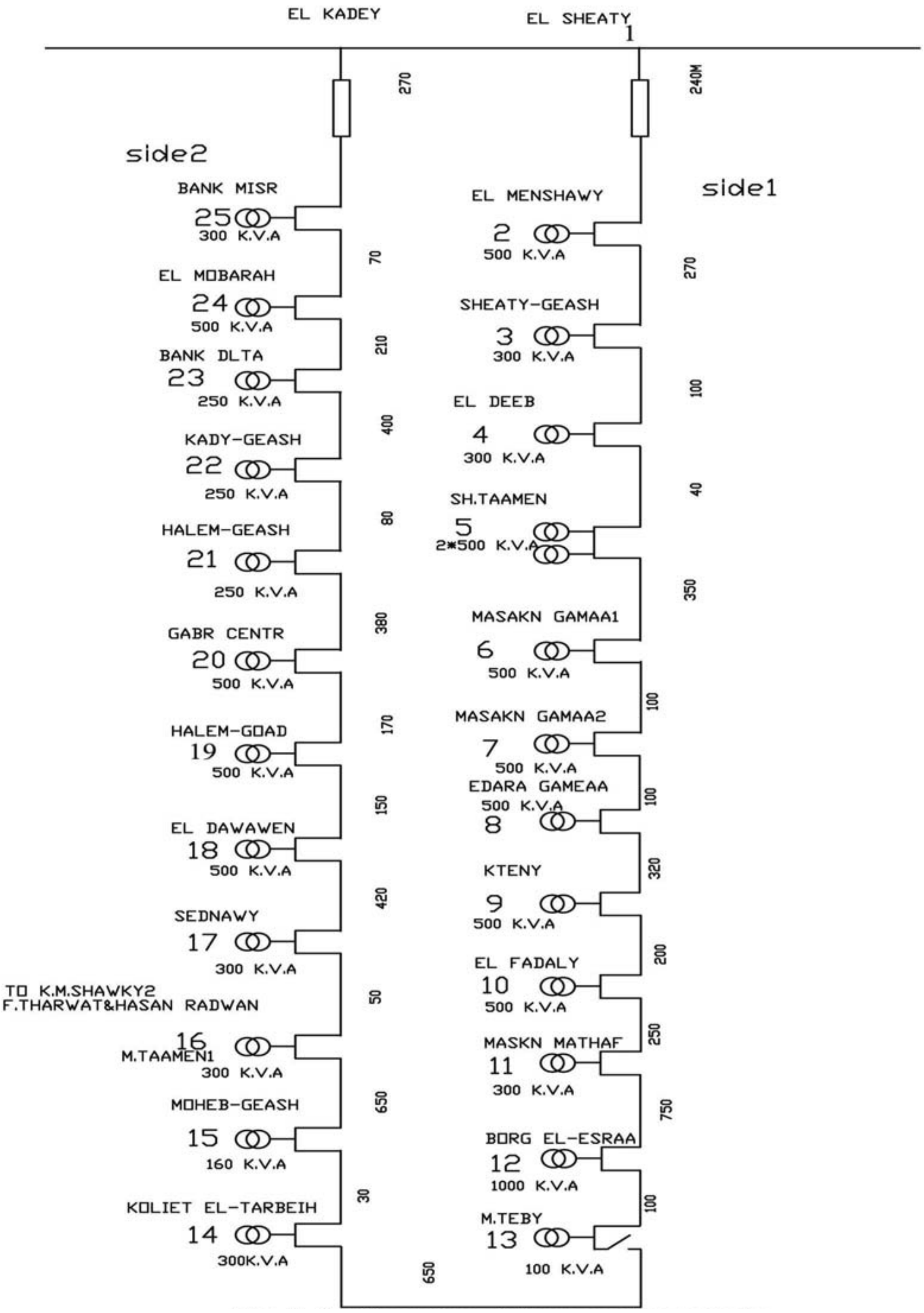


Fig. 4. Configuration of the second case study

Table 4. Percentage increase in load demand for the second case study

Node No.	KVA Rating of Transformers	Year			
		2003	2004	2005	2006
2	500	48	48	50	50
3	300	67	57	71	64
4	300	0	0	0	35
5	1000	55	55	55	55
6	500	44	44	51	51
7	500	52	52	52	52
8	500	39	43	41	44
9	500	53	55	50	44
10	500	53	53	56	56
11	300	56	55	53	53
12	1000	53	51	23	20
13	100	56	56	60	60
14	300	20	19	25	73
15	160	62	62	66	39
16	300	53	40	63	28
17	300	68	64	85	48
18	500	59	82	69	75
19	500	51	54	55	71
20	500	69	65	73	61
21	250	68	63	73	75
22	250	10	33	43	75
23	250	5	10	21	65
24	500	32	42	65	70
25	300	73	73	73	73

Results and Comments

Figures 5 to 8 show the optimal cross-section areas of the branches using the first OPP (case 1) compared with other cases (2-4). The optimal cross-section area is 150 mm^2 which is suitable for increasing in load demand in future (up to year 2009). While, Case 4 is more suitable for increasing in load demand up to year 2013. Figures 5 and 6 show the total costs (F1 and F2) of Equations 3 and 4 of cases (1 to 4) for each side of the distribution system using the first OPP applied on the two case studies, respectively.

Figures 7 and 8 show the power losses (F_1) in each side of branches using the first OPP for the two studied cases, respectively. In Figures 5 to 8, the MOGA was applied to achieve one or more objective functions in the same time. The minimization of total costs F_1 and F_2 were obtained in case 1 (when the cross-section areas of all branches are equal to 150mm^2), while this case has a maximum power losses (F_1) for both cases study. However, the minimization of power loss costs F_1 were very small compared with the feeder costs (F_2) as shown in Figure 9. Case 2 can be standing to face increasing in load demand in future up to 100% for the two cases study.

Figures 10 and 11 show the voltage regulation factors for different cases of cross-section areas (cases 1-4) applied on the first side for the RDS of the two cases study, respectively. From these Figures, the voltage regulation factors were improved in the case 4, but the total costs of power loss and feeder costs were increased compared with case1, as shown in Figures 5 to 9.

The second OPP starts with closing all tie switches to create a meshed network. The tie switches are connected between (4-5), (5-6) and (6-7) in the first case study, and between (12-13), (13-14) and (14-15) in the second case study. This meshed network will contain one closed loop, this loop should have an optimal opening point to minimize the power loss. However, our goal was to find the optimal opening switch for each loop. Tables 5 and 6 show the optimal opening switch to minimize the power loss and maintain the voltage profile within the permissible limits using the first OPP for the two cases study, respectively. From these tables, the minimum loss values were obtained using the second OPP compared with the other original open switches. However, the optimal open switches were between 5-6 and 13-14 for the two cases study, which have minimum power loss equal to 16.3839 kW and 8.85491 kW, respectively.

Comprehensive studies were carried using the first OPP to find the optimal opening switch for the different cases (1-4). However, the optimal opening switches are independent on the changing of cross-section from cases 1-4. From these studies, the optimal opening switches are independent on the changing of cross-section areas from case to another.

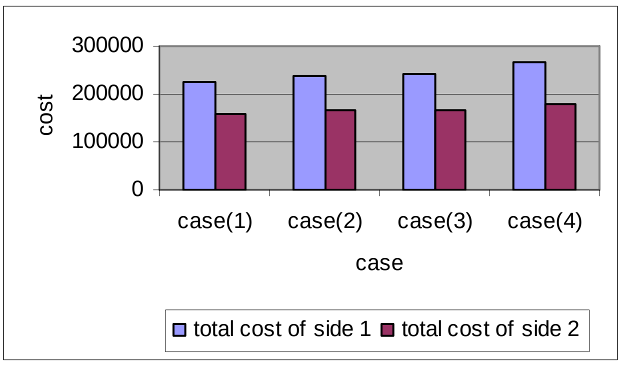


Fig. 5. Total costs of each side of the feeder for different cases 1-4 using the first OPP for the first case study

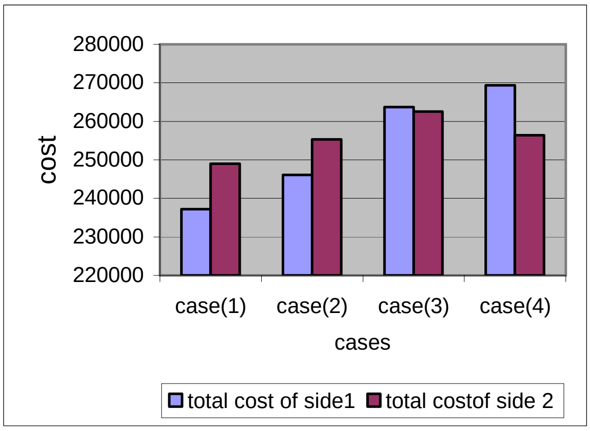


Fig. 6. Total costs of each side of the feeder for different cases 1-4 using the first OPP for the second case study

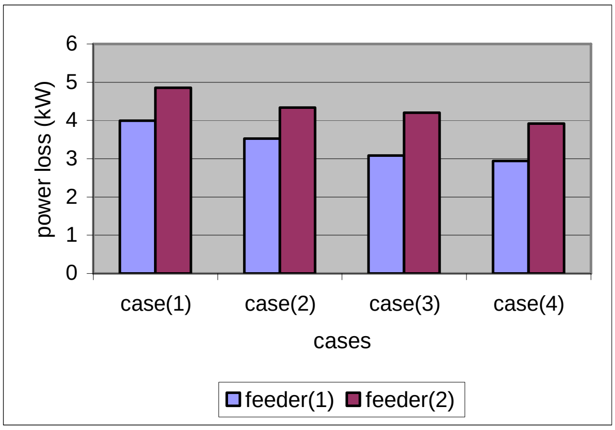


Fig. 7. Power losses in each side using the first OPP for the first case study

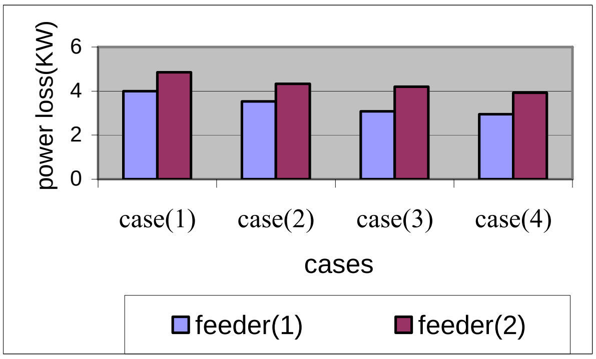
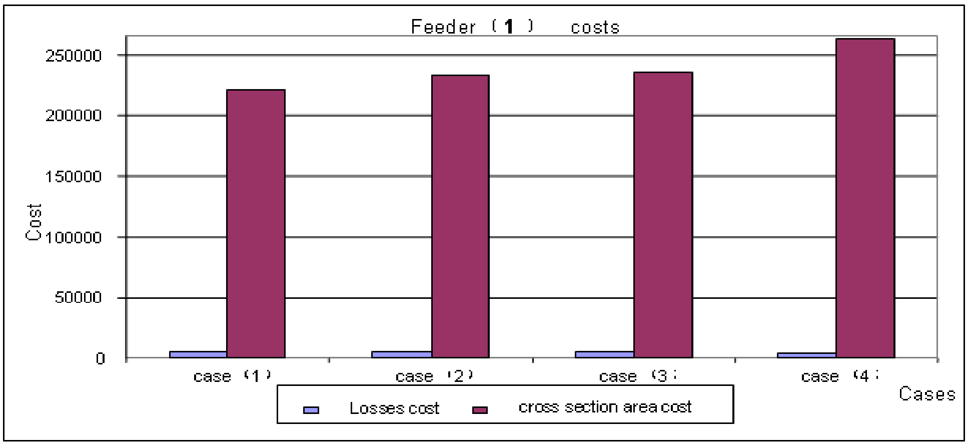
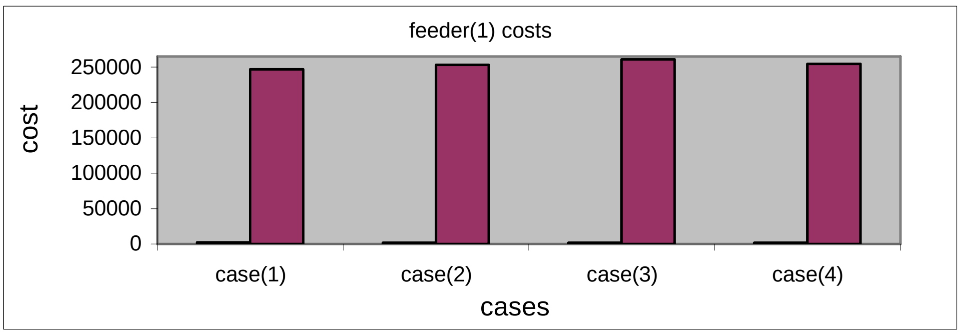


Fig. 8. Power losses in each side using the first OPP for the second case study



(a) First case study



(b) Second case study

Fig. 9. The costs of power losses and feeder costs for different cases 1-4

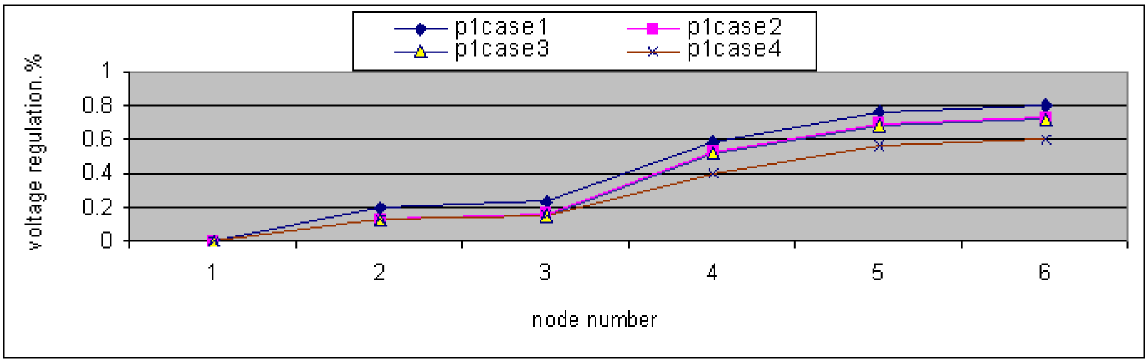


Fig. 10. Voltage regulation factors for the first side of the first case study

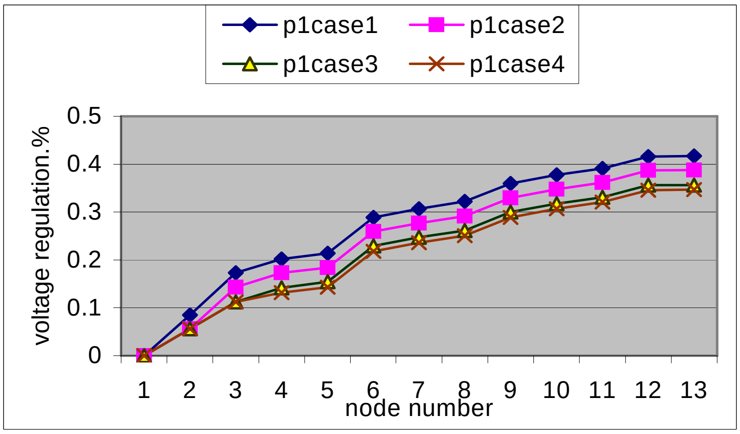


Fig. 11. Voltage regulation factors for the first side of the second case study

Table 5. A comparison between the three original tie switches for the first case study

Variables	Original open switches		
Tie switches	4-5	5-6	6-7
Power loss (kW)	17.61657	16.3839	18.82705
Voltage Magnitude (KV)	V_{max}=11.00 at bus bar V_{min}=10.806	V_{max}=11.00 at bus bar V_{min}=10.786	V_{max}=11.00 at bus bar V_{min}=10.765

Table 6. Comparison between the three original tie switches of the second case study

Main items	Original open switches		
Tie switches	12-13	13-14	14-15
Power loss(KW)	8.96233	8.85491	8.96428
Voltage Magnitude (KV)	V_{max}=11.0 at bus bar V_{min}=10.849	V_{max}=11.0 at bus bar V_{min}=10.846	V_{max}=11.0 at bus bar V_{min}=10.821

8. CONCLUSION

This paper presents an efficient optimal proposed procedure for planning and operation of distribution systems. The first procedure has been applied to find the optimal cross-section areas of branches in order to achieve multi-objective functions which were minimizing the power loss and feeder costs as well as minimization the voltage deviations with respect to the flat voltage (1.0 p.u.). The proposed method has been successfully applied to choice the optimal cross-section areas of the branches which were suitable for existing and expansion load demand while the distribution system constraints were satisfied. The second OPP has been introduced for the distribution system reconfiguration to minimize power losses and restore service to the affected loads during the normal and abnormal operating conditions. This problem has been formulated and successfully solved using the DSSP to find the optimal opening switch in order to minimize the power losses and maintain the voltage profile within the permissible limits. Using the DSSP, it was noted that the optimal opening switch was independent of the size of branches' area and the effects of power loss costs were very small compared to the feeder costs. Thus, the optimal proposed procedures were more suitable for different sizes of practical network reconfiguration.

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