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Optimal Placement of Substations Based on Economic and Technical Risk Management

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Abstract

Design and expansion of distribution systems seems inevitable in view of the need to satisfy the rise in energy consumption in a technical and economical way. Optimal location, sizing and determining the service area of substations is one of the principle problems in expansion of distribution systems. Also uncertainty is one of the important factors that increase risk of exact decision makings. This paper presents a fuzzy multi-objective model for HV/MV substations planning so that uncertainties are modeled using fuzzy numbers (trapezoidal form). The proposed fuzzy model is based on the risk of economic and technical objectives as well as fuzzy values of investment, operation and loss cost of the substations and primary feeders. This model determines the optimal time, location and size of substations using a multi-objective genetic algorithm (NSGA-II). The proposed model is applied on a typical distribution system to assess the efficiency of the approach.

Keywords: Optimal locating, substation, Risk Management, Non-Dominated sort genetic algorithm.

1. Introduction

Distribution substation planning is considered the most important step in the power system planning process. This is because it represents the main link between transmission and distribution system. By increasing the customer demands, distribution system needs to be expanding in case of lost adequacy of supply the loads[1]. Substation placement analysis could have a substantial effect on system total cost index, distribution system topology and network lost cost, so it is vitally important in distribution system planning. The final aim of substation expansion planning is to determine the required expansion capacity of the existing substations as well as the allocation and size of new substations to meet the future demand such that loads are served as inexpensively as possible, while ensuring a reliable supply of power.

A large amount of optimization tools and decision making strategies have been presented in the field of substation placement so far.[2] Used an integer programming while [3] applied dynamic planning algorithm.[4] presented a new dynamic branch and bound method which final solution obtained considering lost cost minimization. In [5], optimization procedure is based on the distance between loads and substations. In [6] the problem is divided into two consecutive stages. In the first stage optimal capacity of substations determined, in the second stage primary feeders specified using a linear programing. [7] Used a combinatorial linear integer programming while in [8] and [9] linear programming is applied. In [10] optimal final solution obtained using an integer programming while network power loss is bounded by the allowable limits. Genetic algorithm applied in [11] as optimization tool and uncertain data modelled with fuzzy based theory. Objective function includes; equipment and area cost and feeder lost cost. Pseudo dynamic methodology is presented for long term planning. [12] Presented a new modified genetic algorithm for static expansion of substations. Although Modified operator of proposed GA decrease the possibility of getting stuck in local minima, the consume time of calculation rise significantly. [13] Presented a distribution network planning while the optimal placement and service areas of substations are studied using an optimization methodology based on loss cost minimization. [14] Introduced a new methodology for long term planning of substations using integer programming. In addition to these, particle swarm algorithm [15-16], ant colony algorithm [18] and some other heuristic algorithms [19-20] are studied in substation placement problem. In [21] substation expansion planning is considered as a non-linear problem and in [22] simulated annealing is used for optimization. In [3], [5] and [11] optimal solution are selected from the candidate list of substations while [7] and [10] are able to find, initially, a list of feasible candidates by observing the limitations, but it is not easy to apply them in extensive real networks. [23] Introduced a new heuristic algorithm which finds optimal capacity of substation at the first. Next optimal placement of substations determined, by minimizing the linear model of power network losses.

This paper presented a new methodology for substation placement problem based on risk management. Uncertain network data are modelled using fuzzy numbers. Static method is applied for long term expansion planning and NSGAII algorithm is used as an optimization tool. The model and the algorithm have been intensively tested in a distribution network, which proves their efficiency and practical application.

2. Modeling of uncertainty

Several types of uncertainty should be considered in planning a power system expansion. Uncertainty could be existed in technical or economic parameters. In this paper, modeling of uncertainties is presented using concept of fuzzy set theory. LR fuzzy numbers are a very useful and convenient framework to integrate vague information in the model. In this context, uncertain parameters are modeled using trapezoidal fuzzy numbers (TFNs).

2.1. Uncertain Load Modelling

Since load variation with time is an inherent characteristic of the distribution networks and also less than 10% of nodes in the distribution networks are just monitored due to economic and technical reasons, the prediction of an exact value for the peak load of a certain year is far from sufficient to obtain reliable and accurate results[24]. Therefore, power demand at each node of the distribution network is represented by the theory of fuzzy numbers as illustrated in Fig.1.

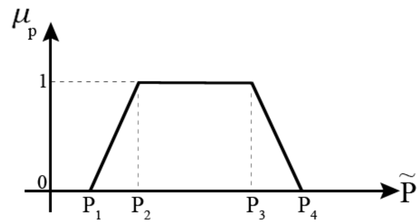

Fig.1. Fuzzy load model

2.2. Uncertain modeling of electricity price and land cost

Uncertainties in the electricity price exist because of various reasons like government policies and other criteria in distribution network management. Land cost is also another parameter which has unusual changes and accurate prediction of that during planning period is impossible. In this paper electricity price and land cost are modeled using TFNs.

3. Risk Function modeling (Constraints modeling)

Because of fuzzy modelling of some parameters and applying mathematical operators to fuzzy numbers, results are obtained in the fuzzy domain. For example, In Fig.2, voltage at node k is presented as TFN ($\tilde{V}$) whereas the upper voltage limit in this node are represented as the deterministic crisp value (V_{max}). So voltage constraint does not have a simple ‘true’ or ‘false’ value. It is violated only with a certain degree of possibility.

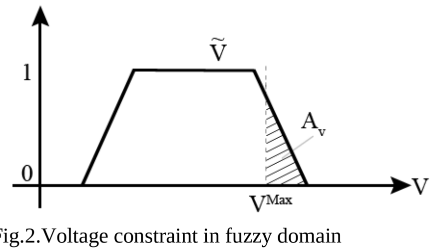

Fig.2.Voltage constraint in fuzzy domain

Risk index is defined as the ratios between violation area (A_V) and the total area under the membership function (A_{Tot}) which is shown in Fig.2 and mathematically defined as follows [24], [25]:

$$V_k \leq V^{max} \quad (1)$$

$$S_{volt} = risk\{(V_k \geq V^{max}\} \quad (2)$$

$$S_{volt} = \frac{A_v}{A_{tot}} \quad (3)$$

Hence, by changing the parameters of TFN $\tilde{V}$, the ratio between areas A_{Tot} and A_V also changes, affecting the possibility S_{Volt} As well.

4. Problem Formulation

The total cost of the system is composed of the following:
1-Substation investment cost including land cost; construction cost; transformer cost and other substation equipment cost
2-Subtransmission line installation cost
3-Primary feeder installation cost
4-Primary feeder loss cost
5-Transformer loss cost (no-load and load loss)

4.1. Monetary Objective Function

The aggregation of the above-mentioned cost items in a single function can be performed, since all of them represent monetary expenses, only differing in which time the money is spent. With interest and inflation rates, any future cash flow can be transferred to a 'present value', and therefore these different time monetary expenses can be joined. Thus, monetary objective function of substation placement can be formulated as:

$$\tilde{f}_m = \sum_{i=1}^{nsb} Cost_{sb,i} \quad (4)$$

$$+\sum_{i=1}^{nsb}\sum_{j=1}^{nl} Cost_{df} \times d_{i,j} + \sum_{k=1}^{ntr} Cost_{uf} \times d_k \times n_k$$

$$+\sum_{m=1}^{ny} \beta^m \sum_{i=1}^{nsb}\sum_{j=1}^{nl} \frac{8760 \times r_{df}}{V^2} \times S_j^{\,2} \times Cost_{ls} \times d_{i,j}$$

$$+\sum_{m=1}^{ny} \beta^m \sum_{i=1}^{nsb}\sum_{r=1}^{ntf} P_{no-load,r} \times 8760 \times cost_{ls}$$

$$+\sum_{m=1}^{ny} \beta^m \sum_{i=1}^{nsb}\sum_{r=1}^{ntf} P_{cu,r} \times 8760 \times \left(\frac{S_r}{S_r^{max}}\right)^2 \times cost_{ls}$$

$$\beta = \frac{1+inf}{1+int} \quad (5)$$

Where $\tilde{f}_m$ is the monetary objective function (10^6 R); $Cost_{sb,i}$ is the ith substation investment cost including area, transformer, equipment and construction cost (10^6 R); $cost_{ls}$ is the energy loss cost (10^6 R/MW h); $d_{i,j}$ distance between ith substation and jth load point (Km); inf the inflation rate; int the interest rate; $P_{cu,r}$ the rth transformer load loss (MW); $P_{no-load,r}$ the rth transformer no-load loss (MW); $Cost_{df}$ the primary feeder installation cost (10^6 R/Km); $Cost_{uf}$ the sub-transmission line installation cost; d_k the length of k^{th} corridor; n_k the total number of sub-transmission lines in kth corridor; S_j the demand of jth load point (MVA); r_{df} the line resistance of primary feeder (Ohm/Km); V the nominal system voltage; S_r the output power of rth transformer (MVA); S_r^{max} the maximum capacity of rth transformer (MVA); nsb the total number of all existing and candidate substations; nl the total number of load points; $nsbc$ the number of candidate substations; ntr the total number of all existing and candidate sub-transmission corridors; ny the planning period (Year); ntf the total number of transformers in a substation.

4.2. Technical Risk Function

According to section 3, Technical risk objective function is mathematically defined as:

$$f_t = max\{S_{volt\_max}, S_{sb\_cap\_max}, S_{\ln\_cap\_max}\} \quad (6)$$

$$S_{volt\_max} = max\{S_{volt,k} | k \in nf\} \quad (7)$$

$$S_{sb\_cap\_max} = max\{S_{sb\_cap,k} | k \in nsb\} \quad (8)$$

$$S_{\ln\_cap\_max} = max\{S_{\ln\_cap,k} | k \in ntr\} \quad (9)$$

Where f_t is the technical risk objective function; $S_{volt,k}$ is the possibility degree of over voltage occurrence in the kth load node; $S_{sb\_cap,k}$ the possibility degree of overloading occurrence in the kth substation; $S_{\ln\_cap,k}$ the possibility degree of overloading occurrence in the kth subtransmission line segment; nf the total number of primary feeders.

4.3. Economic Risk function

As mentioned in section 4.1, the total planning cost is a fuzzy number due to fuzzy values in monetary objective function. In order to perform optimization and comparison among different solutions, a defuzzified or crisp value of total planning cost is needed. For this purpose total fuzzy cost value is converted to a crisp number using defuzzification methods. Obtained crisp number is an approximation of total cost value and it is possible to be increased during network implementation since the total planning cost is a fuzzy number in nature.

According to Fig.3, with assuming the defuzzifed value of total cost as a final expected cost, the increase of the network implementation cost from final expected cost could be defined as economic risk; which means, the final planning cost would be increased from final expected cost in respect to possibility degree of economic risk. Thus by giving different solutions together with associated economic risk, planner would able to decide which solution is more appropriate.

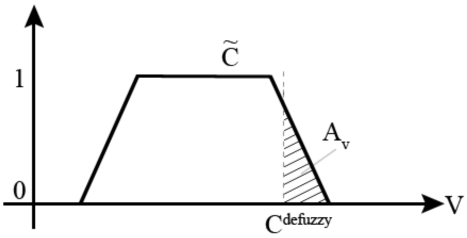

Fig.3.Fuzzy cost and defuzzified cost value

According to above description, economic risk function defines as:

$$f_e = Risk\left(\tilde{f}_m > cost_{exp}\right) \quad (10)$$

Where $\tilde{f}_m$ is the total planning cost (fuzzy); $cost_{exp}$ is the final expected planning cost and f_e is the economic risk function.

5. Constraints of Problem

5.1. Radial flow constraint

It is assumed that each load point is supplied from one substation only to satisfy the radial flow constraints. These constraints can be expressed as follows:

$$\sum_{i=1}^{nsb} \delta_{ij} = 1\,, \qquad j = 1, \dots, nl \quad (11)$$

δ_{ij} is the variable indicating the possibility that load point j issupplied from substation i, it has a value of one or zero.

5.2. Number of sub-transmission lines constraint

The number of sub-transmission lines in a corridor should be less than the maximum allowed number and defined as:

$$0 \le n_k + n_k^0 \le n_k^{max} \qquad k = 1,2, \dots, ntr \quad (12)$$

Where n_k^0 is the number of existing lines in kth corridor; n_k is the number of new lines in kth corridor and n_k^{max} is the maximum allowable number of lines in k^{th} corridor.

5.3. Load flow constraint

To calculate power flow on sub-transmission network, load flow is required. To estimate the behaviour of network, fuzzy dc load flow model is applied. To do this, first in respect to existing substations and corridors, the B matrix of the network is composed. Then, according to substations loading, a fuzzy dc power flow is performed to the network in a normal situation. HV/MV substations are modelled as load bus and transmission transformers are modelled as slack bus.

Sub-transmission lines resistance assumes to be zero, so the aggregate network power which received from transmission lines should be equal to the aggregate power delivered to substations.

$$PG_i - PD_i - \sum_{j=1}^{nsb} P_{ij} = 0 \quad (13)$$

$$P_{ij} = \frac{\theta_i - \theta_j}{X_{ij}} \quad (14)$$

Where PG_i is the power generated in i^{th} bus; PD_i is the consume power in ith bus;P_{ij} is the power transferred from ith bus to jth bus;θ_i is the phase angle of ith bus which determine from load flow and X_{ij} is the line reactance between i^{th} bus and j^{th} bus.

5.4. Substation loading constraint

To consider reliability constraint, Substation loading must be in acceptable margins.

$$0 \le P_{sb,i} \le (1 - rfs_i)S_{sb,i} \quad i = 1, \dots, nsb \quad S_{sb,i} \epsilon \partial_i$$
(15)

Where rfs_i is the reserve capacity factor of ith substation;∂_i is the available capacities for the ith substation; $P_{sb,i}$ is the ith substation loading and $S_{sb\,,i}$ is the capacity of i^{th} substation.

5.5. Sub-transmission line loading constraint

Reliability is considered as reserve factor for sub-transmission lines and expressed as follows:

$$|P_k| \le (1 - rfl)|P_k^{max}| \qquad k = 1,2, \dots, ntr \quad (16)$$

Where rfl is the reserve factor to ensure that a line in a corridor would not be overloaded in case of other lines are out of service; P_k is the k^{th} sub-transmission line loading and P_k^{max} is the maximum capacity of k^{th} sub-transmission line.

6. Solution algorithm

In this paper substation placement is modelled as a multi-objective problem with the three objective functions mentioned above. The problem considered here is a combinatorial problem and the objective functions are nonlinear with fuzzy numbers. Thus, classical optimization methods cannot be implemented easily in this case. In this paper, the NSGA-II, which incorporates the concept of Pareto optimality into its search algorithms and can find optimal trade-offs among the multiple conflicting objectives simultaneously, has been developed and implemented. This algorithm is similar to conventional genetic algorithm which consists of several steps like initialize population, fitness evaluation, reproduction (parent selection), crossover, and mutation. The main difference between these two algorithms is two added blocks in gray color in Fig.4, which has been described as follows. Briefly, the responsibility of non-dominated sort block is to classify individuals into some fronts (layers) according to the fitness of objective functions and crowding distance block is responsible to determine a value for individuals in each front to prioritize them.

To choose the final solution among the obtained non-dominated (Pareto optimal) solutions as the multi-objective optimization results, planner scan select the final substation placement solution, considering the most satisfactory values of the three objectives and according to their experience and professional point of view.

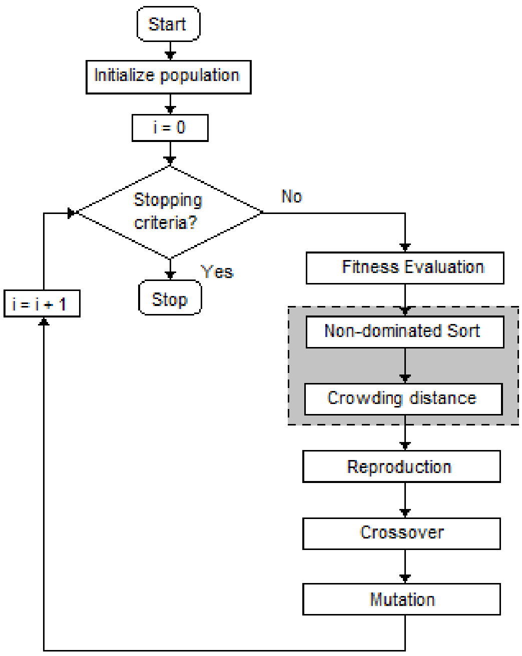

Fig.4.NSGA-II flowchart [24]

In this paper, a max–min approach is used to select the best (final) multi-objective substation placement solution. Each solution in the set of Pareto-optimal solutions has an associated vector of values $\{f_{mk}, f_{tk}, f_{ek}\}$ that can be normalized using the following expressions [24]:

$$f_{mnk} = \frac{f_{m,max} - f_{mk}}{f_{m,max} - f_{m,min}} \quad (17)$$

$$f_{tnk} = \frac{f_{t,max} - f_{tk}}{f_{t,max} - f_{t,min}} \quad (18)$$

$$f_{enk} = \frac{f_{e,max} - f_{ek}}{f_{e,max} - f_{e,min}} \quad (19)$$

Where $f_{m,max}$, $f_{t,max}$ and $f_{e,max}$ are the maximum values obtained for the monetary objective function [defuzzified value], technical risk objective function and the economic risk objective function, respectively, and $f_{m,min}$, $f_{t,min}$ and $f_{e,min}$ the minimum values obtained.

Genetic algorithm use binary coding as a standard form which chromosomes are represented by the string or binary number. In this problem DCGA (decimal genetic algorithm) is used which the chromosome are represented by real decimal numbers [26]. Fig.5 shows the chromosome structure for the substation placement problem.

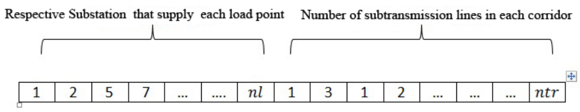

Fig.5. Chromosome structure

7. Numerical results

The proposed methodology for substation placement has been implemented in the MATLAB 7.0 environment and tested on a distribution network considering uncertainty in the real network data.

With respect to operational limitations the maximum number of allowable sub-transmission lines in each corridor is assumed to be five. Reserve capacity factor of every substations and sub-transmission lines is 30%. Data of the Future load, substation and sub-transmission line are listed in Table 1 to 3 in appendix 1. During time period, the rate of inflation and interest is assumed to be 5.5% and 12% respectively. The peak load of each area is the loads aggregation into the area and is considered in the center of gravity of that. Sub-transmission line capacity is assumed to be 50 MVA. Planning period is 9 years and static methodology is used to solve the problem in the planning horizon. Maximum acceptable voltage drop from supply to demand

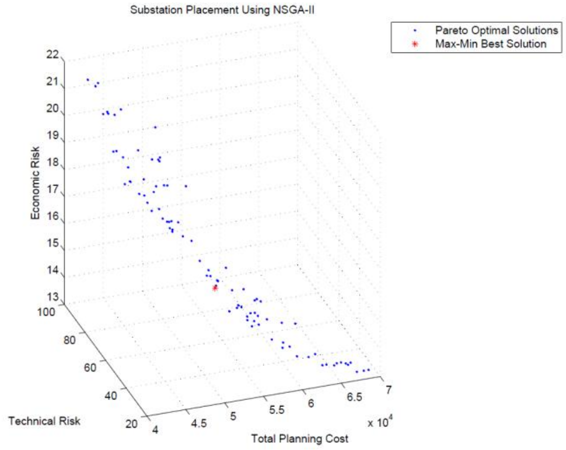

Fig.6.Obtained pareto optimal solutions

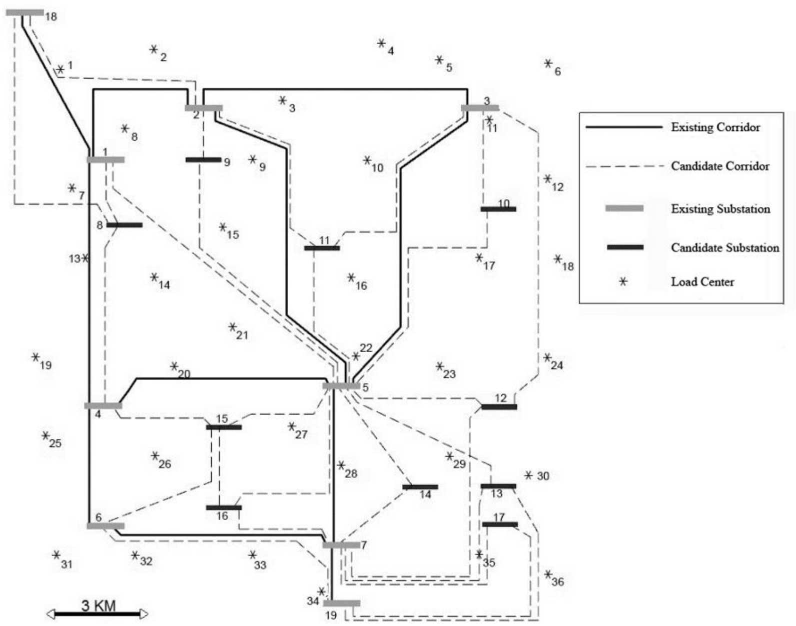

Fig.7. System under study

sector is assumed as 5% of the network nominal voltage. The proposed NSGA-II has been executed with the following parameters: population size=100; generation=300; crossover probability= 0.9; mutation probability=0.1. Tournament selection and two-point cross over with inversion is used for algorithm. Defuzzification is based on COA methodology.

With respect to above mentioned data the problem solved in two case

1- With considering technical and economic Risk management
2- Without considering technical and economic risk management and compare with case 1

Application of the proposed NSGA-II determines the Pareto-optimal solutions for the planning horizon. Fig.4 illustrates the obtained Pareto-optimal solutions against the defuzzified value of the substation placement cost index, the technical risk and economic risk. Final best solution achieved by using a max-min approach and presented in Table 1-3.

According to Table.1 by entering new loads to network and also growing the old ones, network is not capable enough to supply the network and need to expand. So substations 1-7 are expanded and four candidate substations 8,12,13,17 are added to network. Some substations are faced with technical risk.

Table.1
Substation capacity and loading at the end of planning horizon

Substation #	State	New Capacity	Substations Fuzzy loading				Tech Risk %	Feeding Loads
1	Exist	60	21.24	22.42	24.78	25.96	0	7-1
2	Exist	60	36.34	38.36	42.39	44.41	23.3	2-3-4-9-15
3	Exist	60	37.26	39.34	43.48	45.55	40.5	5-6-10-11-12-17-18
4	Exist	90	51.3	54.15	59.85	62.7	0	19-20-25
5	Exist	60	35.24	37.2	41.11	43.07	5.03	16-21-22-23-27-28
6	Exist	75	45.27	47.78	52.81	55.33	20.8	26-31-32
7	Exist	75	42.48	44.84	49.56	51.92	0	33-34
8	New	45	23.36	24.66	27.25	28.55	0	8-13-14
12	New	60	34.2	36.1	39.9	41.8	0	24-29
13	New	30	17.1	18.05	19.95	20.9	0	30
17	New	60	34.2	36.1	39.9	41.8	0	35-36

Since every load points are connected to nearest substation, voltage constraint violation risk is eliminated that can be observed from Table.2.

To compare and observe the effect of economic and technical risk on the total substation placement cost index, the final solution obtained from previous section is calculated again without considering risk management. Comparison results are presented in Table 6-8.

Table.3
Sub-transmission line capacity and loading

Corridor Number	Line loading				State	Number of lines in corridor	Tech risk %
1	49.57	52.33	57.84	60.59	Exist	3	0
2	26.21	27.66	30.58	32.03	Exist	1	0
3	2.13	2.24	2.48	2.60	Exist	1	0
4	29.83	31.48	34.80	36.46	Exist	1	12.871
5	25.91	27.35	30.23	31.66	Exist	1	0
6	7.44	7.85	8.68	9.09	Exist	1	0
7	0.74	0.78	0.86	0.90	Exist	1	0
8	24.36	25.71	28.42	29.77	Exist	1	0
9	17.51	18.49	20.43	21.40	Exist	1	0
10	18.84	19.89	21.98	23.03	Exist	1	0
11	39.77	41.98	46.40	48.61	Exist	2	0
13	89.95	94.95	104.94	109.94	New	3	16.283
14	88.47	93.38	103.21	108.13	New	3	6.7434
17	23.36	24.66	27.26	28.56	New	1	0
28	34.20	36.10	39.90	41.80	New	2	0
31	17.10	18.05	19.95	20.90	New	1	0
41	35.58	37.55	41.51	43.48	New	2	0
42	69.78	73.65	81.41	85.28	New	3	0

Table.2
Primary feeders voltage drop at the end of planning horizon

Load #	Fuzzy Voltage Drop				Tech Risk%	Load #	Fuzzy Voltage Drop				Tech Risk %
1	283.60	299.39	330.90	346.66	0	19	402.9	425.3	470.12	492.51	0
2	229.40	242.15	267.64	280.38	0	20	369.3	389.9	430.94	451.47	0
3	187.70	198.12	218.98	229.41	0	21	32.75	34.57	38.21	40.03	0
4	334.80	353.37	390.57	409.17	0	22	65.32	68.95	76.21	79.84	0
5	122.50	129.28	142.89	149.70	0	23	153.7	162.3	179.39	187.93	0
6	163.30	172.38	190.52	199.60	0	24	335.8	354.4	391.77	410.42	0
7	133.50	140.89	155.72	163.13	0	25	302.2	319.0	352.59	369.38	0
8	122.60	129.44	143.07	149.88	0	26	402.9	425.3	470.12	492.51	0
9	125.10	132.08	145.99	152.94	0	27	115.3	121.7	134.54	140.95	0
10	28.98	30.60	33.82	35.43	0	28	102.5	108.2	119.59	125.29	0
11	27.22	28.73	31.75	33.27	0	29	335.8	354.4	391.77	410.42	0
12	190.50	201.11	222.28	232.86	0	30	134.3	141.7	156.71	164.17	0
13	150.20	158.50	175.18	183.52	0	31	108.8	114.9	127.02	133.06	0
14	102.60	108.31	119.71	125.41	0	32	250.2	264.1	291.97	305.87	0
15	49.49	52.24	57.73	60.48	0	33	250.2	264.1	291.97	305.87	0
16	150.20	158.50	175.18	183.52	0	34	291.9	308.1	340.63	356.85	0
17	62.57	66.04	72.99	76.47	0	35	100.7	106.3	117.53	123.13	0
18	294.70	311.08	343.83	360.20	0	36	335.8	354.4	391.77	410.42	0

Table.4
Planning cost details

	Fuzzy Cost (10^6 R)			
Primary feeders installation cost	1590.413	1590.413	1590.413	1590.413
SubtransmissionLinesinstallation Cost	10090.43	10090.43	10090.43	10090.43
Primary feeders loss cost	7643.21	9245.993	12855.45	14353.6
New substation installation cost	15590.59	15942.42	16880.61	17232.44
Existing substation expansion cost	4676.054	4676.054	4676.054	4676.054
Transformer loss cost	3907.679	4249.553	4853.716	4947.21
Total fuzzy cost	43498.38	45794.86	50946.68	52890.14

Table.5
Defuzzified final solution

Solution cost (10^6 R)	Tech Risk %	Eco Risk %
50946.6801	40.5	13.36

Table.6
Effect of considering risk management on total cost at the end of planning horizon

	With consideringRisk	Without Risk
Total Cost	50946.68	59235.21

Table.7
Effect of considering risk management on substation capacity at the end of planning horizon

		With considering Risk	Without consideringRisk
Substation #	State	substation Capacity	substation Capacity
1	Exist	60	60
2	Exist	60	75
3	Exist	60	75
4	Exist	90	90
5	Exist	60	75
6	Exist	75	90
7	Exist	75	75
8	New	45	45
12	New	60	60
13	New	30	30
17	New	60	60

8. Conclusion

Applying Risk management methodology in distribution networks, has introduced new alternatives in planning that acquire significant economic benefits for DisCo. Uncertainty in distribution network data is always inevitable so the model considers a fuzzy explicit representation of the uncertainties. In this paper the effect of different source of technical risk on distribution network studied. The results showed that it is possible to achieve more desirable solutions with managing various technical and economic risks. In the proposed model in addition to substation and network corridors placement, optimal capacity and service area of the substation are determined. A specialized NSGA-II has been proposed as a solution algorithm. A max–min approach has been proposed to select the best Pareto-optimal solution. The new substation placement algorithm has been tested in a typical distribution network. The obtained results show that the suggested substation placement model is a powerful decision-making tool for risk management in distribution networks planning.

Table.8
Effect of considering risk management on corridor capacity at the end of planning horizon

		With considering Risk	Without considering Risk
Corridor Number	State	number of Lines in corridor	number of Lines in corridor
1	Exist	3	2
2	Exist	1	1
3	Exist	1	1
4	Exist	1	1
5	Exist	1	1
6	Exist	1	1
7	Exist	1	1
8	Exist	1	1
9	Exist	1	1
10	Exist	1	1
11	Exist	2	1
12	New	_	1
13	New	3	3
14	New	3	3
16	New	_	1
17	New	1	2
27	New	_	1
28	New	2	1
29	New	_	1
30	New	_	1
31	New	1	3
41	New	2	1
42	New	3	3

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