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Power Distribution System Planning with Demand Uncertainty Consideration

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Abstract – This paper proposes a method for solving distribution system planning problems taking into account demand uncertainty and geographical information. The proposed method can automatically select appropriate location and size of a substation, routing of feeders, and appropriate sizes of conductors while satisfying constraints, e.g. voltage drop and thermal limit. The demand uncertainty representing load growth is modeled by fuzzy numbers. Feeder routing is determined with consideration of existing infrastructure, e.g. streets and canals. The method integrates planner's experience and process optimization to achieve an appropriate practical solution. The proposed method has been tested with an actual distribution system, from which the results indicate that it can provide satisfactory plans.

Keywords: demand uncertainty, fuzzy model, heuristic rule, power distribution system planning

1. Introduction

Distribution system planning basically involves the optimization of both locations and sizes of a new substation and feeders to meet expected demand while satisfying specified constraints, e.g. substation capacity, feeder thermal capacity and voltage drop. The optimal distribution system planning is recognized as a complex problem due to the number of variables and candidates for a network configuration which is, in practice, related to geographical characteristics. The planning time horizon normally ranges from 5 to 20 years. However, intrinsic uncertainty on the future demand, in general, is not explicitly considered in solving distribution system planning problems [1-15].

Generally, there are several proposed solving methods based on mathematical programming techniques, e.g. linear programming [1, 2], mixed-integer programming [3], non-linear programming [4], dynamic programming [5, 6], quadratic programming [7], and branch and bound algorithm [8, 9]. In addition, other techniques can also be applied, e.g. genetic algorithm [10-12] and tabu search algorithm [16]. Most of the approaches take all considering issues, i.e. substation locations, substation sizes, feeder routing and feeder sizes, as constraints of an optimization problem. However, to solve the problem, we need to assume that the candidates of feeders routing and substation locations are known in advance.

In this paper, the proposed method can automatically select the optimal substation location and feeder configuration without the need to know candidates for the substation location and feeder configuration in advance. The method also takes into account demand uncertainty and available geographical constraints, e.g. existing or future routes of streets and roads and canals. To cope with the demand uncertainty, the future demand will be represented by a fuzzy number. Then, heuristic rules by experienced planners will be incorporated to determine feeder path according to geographical conditions. Based on the proposed algorithm, the developed program selects location and size of a substation and the path and size of conductors, which provide a minimum or close to minimum total cost for the system.

2. Distribution System Planning

2.1 Objective Function

In general, the objective of distribution system planning is to determine size and location of a substation and feeders, which provides minimum total cost. The objective function usually includes costs of a substation, feeders, and power losses, which can be formulated as (1).

$$\text{Min Cost}_{\text{total}} = \text{Min}\,[\text{Cost}_{\text{sub}} + \text{Cost}_{\text{feeder}} + \text{Cost}_{\text{losses}}] \quad (1)$$

$\text{Cost}_{\text{total}}$ is the total cost over the planning period,
Cost_{sub} is the cost of the substation to be built,
$\text{Cost}_{\text{feeder}}$ is the cost of the conductor to be installed,

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and

$\text{Cost}_{\text{losses}}$ is the cost of expected power loss.

2.2 Load Growth Model

All the cost components in (1) are concerned with the future demand at each load point in the system, of which its value is uncertain in nature. In this paper, a triangular fuzzy model [17 - 18] as shown in Fig. 1 is used to represent the predicted load growth uncertainty.

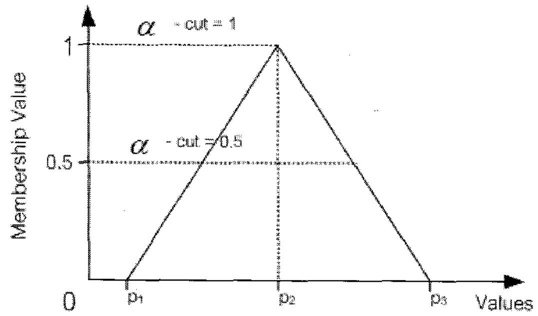

Fig. 1. A triangular fuzzy number, $\tilde{p} = (p_1, p_2, p_3)$

p_1 - represents the minimum plausible load growth value

p_2 - represents the highest plausible load growth value

p_3 - represents the maximum plausible load growth value

Based on planner's experiences, the future load growth can be defined. For example, the planner expects the future load growth to be about 4% but not over 5% and not less than 3%. Therefore the expected future load growth can be defined by (3%, 4%, and 5%).

With the objective function and defined load growth model, the developed methodology will search for an appropriated plan for the system being considered. The detailed solving procedure is presented in the next section.

3. The Proposed Methodology

The proposed method comprises four calculation steps, i.e. 1) define appropriated substation locations, 2) determine optimal routing, 3) select optimal size of feeders, and 4) select optimal substation capacity. Each step can be summarized below.

Step 1: A simplex method [19] is used to find possible locations of the substation which provides fairly low or minimum loss of the network. Moreover, expert opinion is applied to preliminarily decide candidates for practical locations.

Step 2: The optimal feeder routing of the system is determined by a minimum path algorithm, of which its capacity limits, voltage drop, and radiality are considered as constraints. In addition, geographical information will be taken into account.

Steps 3 and 4: The optimal capacities of conductor and substation are determined respectively. The fixed and variable costs of all equipment are assumed to be known. The minimum cost is used as selection criteria.

The details of each step will be described below.

3.1 Substation Location

The substation location will be firstly determined to effectively serve all system load points at low cost. In general, the substation location has impacts on the system power loss. Therefore, the objective of this section is to determine the optimal substation location by minimizing feeder losses while the geographical constraints will be considered according to a set of defined heuristic rules.

The planning process begins with the predefined future demand at each load point. Then the connection from the substation to all load nodes will be determined according to the function shown in (2).

$$\min P_{Loss} = \sum_{i=1}^{n}\left(\sum_{j=1}^{m} Loss_{i,j}\right) = \sum_{i=1}^{n}\left(\sum_{j=1}^{m} R\cdot d_{sj}\cdot L_d\cdot\left(\frac{L_j}{V_j}\right)^2\cdot(1+\tilde{\tau}_j)^{2i}\right) \tag{2}$$

n = planning time horizon (years),
m = number of load points,
R = feeder resistance per unit length,
d_{sj} = distance between substation and load point j,
L_d = load factor,
L_j = peak demand of load point j (MVA),
V_j = expected voltage at each load point, and
$\tilde{\tau}_j$ = fuzzy load growth of load point j.

The objective function in (2) can be simplified by assuming that all feeders of the substation are of the same conductor size and neglecting voltage drop at each load point. Then, we can rewrite the objective function as shown in (3).

$$\min P_{Loss} = \sum_{i=1}^{n}\left(\sum_{j=1}^{m} d_{sj}L_j^2\cdot(1+\tilde{\tau}_j)^{2i}\right) \tag{3}$$

d_{sj} = $\sqrt{(x_s - x_j)^2 + (y_s - y_j)^2}$
(x_s, y_s) = the coordinate of substation location
(x_j, y_j) = the coordinate of load point j

A simplex method can be applied to solve an unconstrained non-linear problem of (3) to find an appropriate substation location. Since the load growth at each load point is represented by a fuzzy number, (3) can be used to solve for each α-cut.

In search for the optimal coordinate (x_s, y_s) at each α-cut, (3) will be solved and the solutions starting from the predefined initial to the converged optimum coordinates will be added to the solution set. The converged optimum coordinate is selected, and then verified through a set of heuristic rules. If the coordinates of the location being considered do not comply with the rules, then the next location that is the previously stored coordinate in the solution set will be selected until it is satisfied with the rules, which are listed below.

Rule 1. The location must comply with geographical constraints, e.g. river or school.
Rule 2. The acquirement of the land for the substation is not too costly.
Rule 3. The location does not have a right of way problem.
Rule 4. The location must not cause serious social and political problems.

Finally, we obtain a set of locations with certain membership values. Then an appropriate location will be obtained by defuzzification, using the center of area method in this paper. If an appropriate location does not satisfy the rules, the location at the highest membership value will be selected instead.

Fig. 2 indicates an appropriately selected substation location for the system with 130 load points. The demand capacity and the coordinates of all load points are listed in the Appendix.

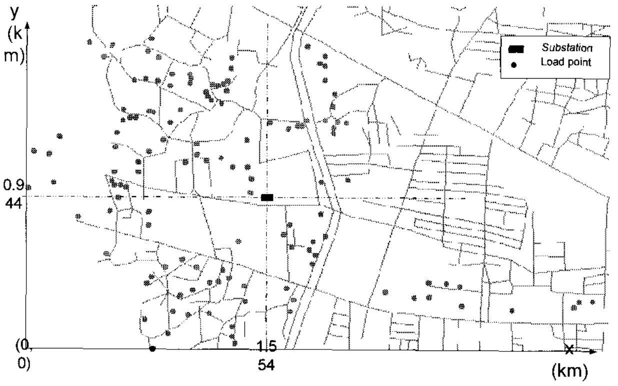

Fig. 2. The optimal substation location

3.2 Optimal Feeder Routing

Appropriate selection of feeder routing can save both investment and operation cost, e.g. loss and length of conductors. While length of the feeders and cost are normally related to each other, the appropriate route of feeders may be simply considered as the shortest path.

In this process, a minimum path algorithm described below will be used to determine the feeder routing with practical consideration taking into account expert judgment and existing infrastructure.

The minimum path algorithm [15]:

To simplify for sake of comprehension, an example having 9 load points whose coordinates are known is considered, and shown in Fig. 3.

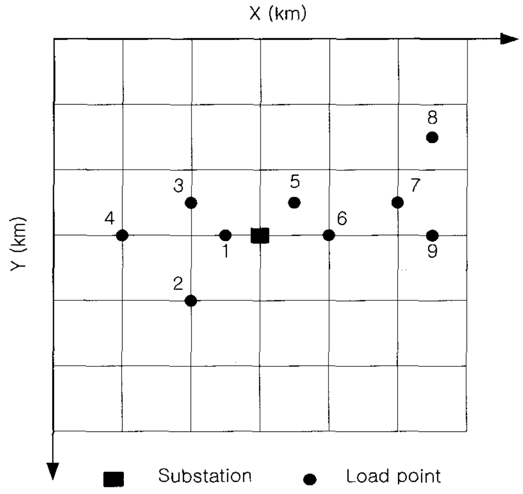

Fig. 3. A sample system

The planner initially assigns the required number of feeders from the substation location defined from the previous steps, e.g. 2 feeders. Then, two sets of nodes are created.

The set of connected nodes = {substation, substation} or A = {F1, F2}

The set of unconnected nodes (A′) = {1, 2, 3, 4, 5, 6, 7, 8, 9}

The distance from any node in A′ to the node in A is computed and the number of nodes (equal to number of feeders), the nearest to the substation, is removed from set A′ to set A. In this example, node 1 and node 5 are close to the substation respectively. Therefore,

$$A = \{(F1, 1), (F2, 5)\}, \quad A' = \{2, 3, 4, 6, 7, 8, 9\}$$

The distances from any node in A′ are then compared with any node in A. The shortest distance node in A′ is then sought out and moved to A. Let load point 3 be the nearest node to node 1. Then, connect node 1 to 3. The set A and A’ will be

$$A = \{(F1, 1, 3), (F2, 5)\}, \quad A' = \{2, 4, 6, 7, 8, 9\}$$

Again compare the distance from any nodes in A′ to any nodes in A and find the minimum distance. The shortest distance exists between nodes 5 and 6. Therefore, connect node 5 to 6. At this stage we obtain the following sets A and A' as follows:

$$A = \{(F1, 1, 3), (F2, 5, 6)\}, \quad A' = \{2, 4, 7, 8, 9\}$$

This procedure is repeated until all load points are connected, i.e. all the nodes are in A, and $A' \in \phi$ (null). After the procedure is completed, the minimal path of the feeder can be shown in Fig. 4, and set A and A' will be

$$A = \{(F1, 1, 3, 2, 4), (F2, 5, 6, 7, 9, 8)\}, \quad A' = \{\}$$

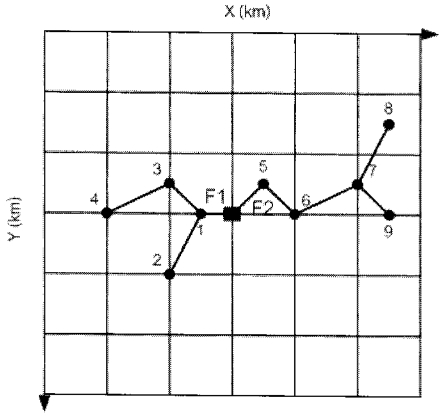

Fig. 4. The minimum feeder routing

In case of ignoring existing infrastructure, the optimal feeder routing will be obtained by using the minimum path algorithm and feeders will be directly connected from one load point to another. If existing infrastructure is considered, and with the assumption that the main feeders should be lined along the existing roads, the point on the road which is the nearest to the defined load point will be considered and used as a candidate for determining the optimal feeder path.

The procedure for considering the existing road can be described below.

1) Firstly, the planner defines a maximum allowable length from a load point to an existing road, e.g. 50 meters.

2) The distance between each load node and the closest point on the road, manually defined in this paper, is considered. If the distance is within the defined value, a lateral line will be connected from that load point to the existing point on the road, which will then be used as a candidate for determining the main feeder routing. However, if the load points having distance to the road are longer than the defined value, it will be used to determine the main feeder routing, which may pass through concerned areas.

3) In case that some load points are connected to very close points on the same road, e.g. within 5 meters, they will be set into the same group. In Fig. 5, there are three load groups.

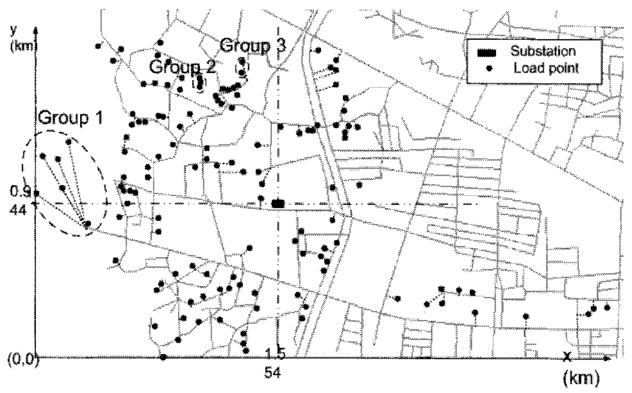

Fig. 5. Distance from node to the nearest road is determined

4) In each group, all load points are connected to each other before being connected to the main feeder using the minimum path algorithm. For example, group 1 consists of 6 load points, which are connected to each other using the minimum path algorithm. The result is depicted in Fig. 6. The node that is closest to the specified road is defined as the connecting point of the group to the road.

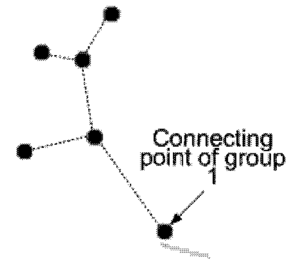

Fig. 6. Minimal path in group 1

In addition each candidate has to strictly comply with the heuristic rules defined below.

Rule 5. If the line has a right of way problem then it is not acceptable.

Rule 6. If the line has high cost passage then it is not acceptable.

Rule 7. If the line passes through an obstacle, i.e. forest, lake, etc., then it is not acceptable.

After running the above process, the optimal feeder routing is determined by the minimal path algorithm. Then the optimal conductor sizes of feeder in each branch are selected and all of the constraints are considered in the next process.

3.3 Selecting Optimal Conductor

In this paper, the cost function is composed of two parts, i.e. *fixed cost* representing capital cost and maintenance and operation (O&M) cost, and *variable cost* representing cost of energy and demand loss. The total cost is obtained by the following expression.

$$\tilde{C}_{Total} = C_{fixed} + \tilde{C}_{\text{var}} \cdot L^2 \tag{4}$$

where $$C_{fixed} = \left[\frac{A \cdot i}{[1-(1+i)^{-N}]} + B \right] \times \frac{1}{i} \left[1-(1+i)^{-n} \right] \tag{5}$$

$$\tilde{C}_{\text{var}} = \left(\frac{8760 \times 10^3 \cdot E \cdot R \cdot L_f}{V^2} \right) \sum_{m=1}^{n} \frac{(1+\tilde{\tau})^{2m}}{(1+i)^m} \tag{6}$$

L = peak demand flow in conductor (MVA)
A = investment cost (Baht)
B = maintenance & operation cost (Baht)
E = energy cost of losses (Baht/kWh)
i = interest rate (%)
L_f = loss factor, $\left(L_f = 0.3L_d + 0.7L_d^2\right)$
N = expected life time (years)

An appropriate size of conductors should be selected in order that the total cost is minimal and all the constraints are not violated. Based on equation (4), the total cost of each conductor which supports the defined load is determined and the most suitable size providing the lowest cost will be selected. Four 22 kV conductor sizes, the details of which are shown in Table 1, are considered in this paper.

Table 1. The details of each feeder size

Type (mm^2)	Investment Cost (Baht/km)	O & M Cost (Baht/km)	R (Ω/km)	X (Ω/km)
50	102740	1541	0.6895	0.7888
95	131670	1975	0.4005	0.7548
120	168320	2525	0.3158	0.7576
185	241587	3624	0.2250	0.7434

From the cost information in Table 1, we can obtain the cost of each conductor by assuming that the loss value of 2 Baht/kWh, 20 years planning period, 30 years life-time, 6% annual interest, and load growth is (4%, 6%, 8%). The fuzzy costs of each conductor, with the assumed 2 MW load flow in the line of 22 kV, are shown in Fig. 7.

The optimal conductor size will be selected after we obtain the substation location and feeder configuration. The fuzzy cost of each conductor size will be compared to find the best option using the center of areas method to convert the fuzzy costs into a crisp cost value. In Fig. 7, the 185 sqmm conductor size is selected, accordingly.

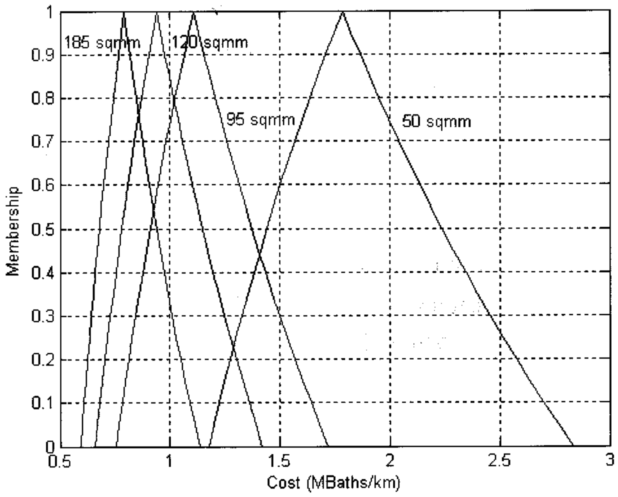

Fig. 7. The fuzzy cost of each conductor size at load 2 MW

Voltage drop is then considered after the above process has been completed. If the voltage drop is within an acceptable limit (5%), the process will be terminated. However, if it violates the limit, one of the following steps must be performed.

- *Adjusting the conductor size*: size of the conductor in each branch will be adjusted until it does not violate the constraint.
- *Balancing load in each feeder*: review the load balance in the case of having more than one feeder. If the difference of the aggregated load on each feeder is more than the capacity of lowest load point, the feeder which supplies loads less than other feeders will be forced to connect with more loads, i.e. the nearest load.
- *Increasing the number of feeders*: if 1) and 2) still violate constraints, the number of feeders should be increased by one at a time.

This procedure is repeated until the voltage drop is with in the limit, and then substation capacity will be determined.

3.4 Selecting Optimal Substation Capacity

In the final step, the optimal substation capacity will be determined in the same way as the optimal conductor size. The substation which provides minimum cost capacity will be selected. This cost consists of two parts as shown in Equations (4), (5), and (6). In this paper, there are three substation sizes to be considered. Details of the cost of each substation size are presented in Table 2.

Table 2. The details of a MV substation

Size (MVA)	Structure & Construction Cost (Million Baht)	Operation & Maintenance Cost (Million Baht)
25	58.448	1.169
50	60.276	1.206
2*50	85.740	1.715

4. Case Study

An actual distribution system as shown in Fig. 2 has been used for testing the proposed methodology. It is a 22-kV network comprising 130 nodes, and is divided into two groups. In each group, the fuzzy future load growth is assumed to be different, i.e. (2, 4, 6) % and (1, 3, 5) % respectively. Group I is composed of nodes 1 – 69, whereas others are put in group II. The data of each load point is given in the Appendix.

The solutions of the proposed method are revealed below. Initially, the coordinates of the appropriated substation location (1.554, 0.944) are obtained. The results of location, capacity, and cost of the substation are indicated in Table 3. Then the optimal routing considering and ignoring existing infrastructure is determined with optimal conductor size, of which the results are shown in Table 4. Finally, a substation with 50 MVA capacity is selected and presented in Table 3.

Table 3. The results of substation

Capacity (MVA)	Coordinate X–Y (km)	Cost of substation (MBaht)	
		Fuzzy	Defuzzy
50	1.554, 0.944	(76.657, 76.858, 77.195)	76.869

Table 4. Comparative results of two cases

Case Optimal Routing	Cost of conductor (MBaht)	
	Fuzzy values	Defuzzy
Case I	(5.268, 6.857, 9.527)	6.946
Case II (with maximum allowable length to the road)		
- 50 m	(5.625, 7.231, 9.931)	7.322
- 60 m	(5.706, 7.330, 10.059)	7.421
- 70 m	(5.951, 7.660, 10.533)	7.757
- 80 m	(5.880, 7.522, 10.283)	7.615
- 90 m	(5.870, 7.504, 10.251)	7.596
- 100 m	(5.878, 7.511, 10.256)	7.603

In Table 4, the results of optimum routing in each case are shown. In case I, in which the existing roads are ignored, the highest plausible cost of the conductors is at 6.857 MBaht, with the defuzzied value of 6.946 MBaht. In case II, where the existing roads are taken into account, we can see that the value of maximum allowable length, 50 – 100 meters, from a load point to the road affects the total conductor cost. It can be found that the maximum allowable distance of 50 meters provides the lowest cost while the highest cost is at the allowable length of 70 meters. The results show that the defined distance does not dictate the conductor cost; however, the geographical characteristics play an important role in such case. The network configurations for cases I and II at the allowable length of 50 meters are shown in Figs. 8 and 9, respectively.

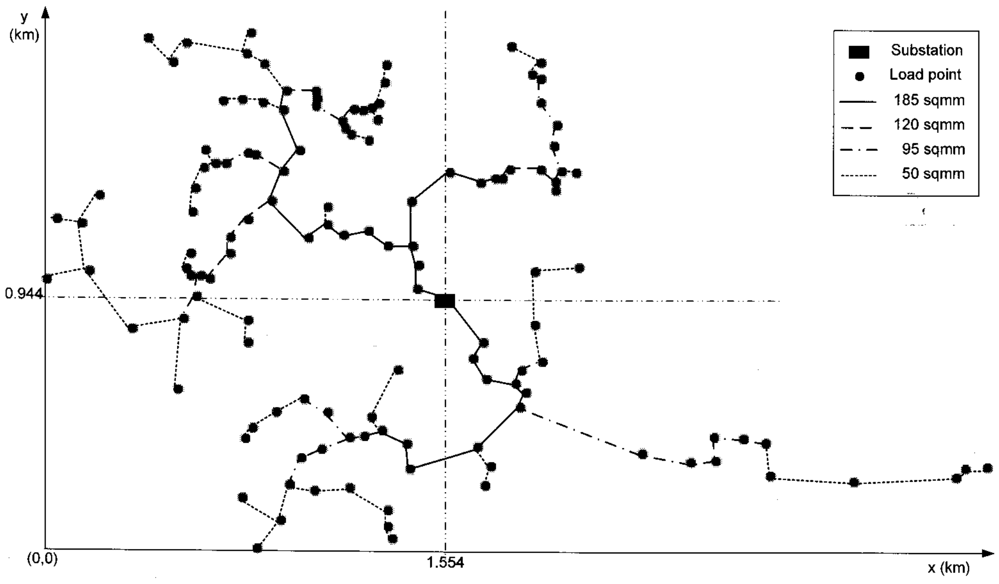

Fig. 8. The minimum feeder routing ignoring existing roads

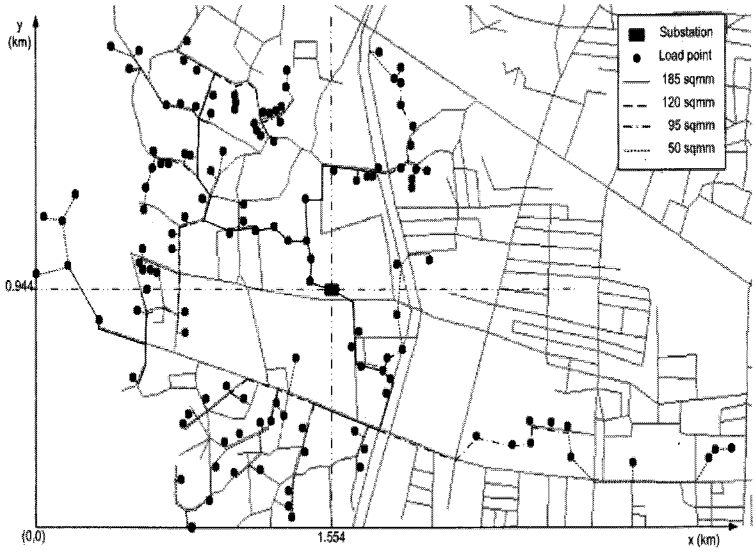

Fig. 9. The optimal feeder routing considering existing road with allowable length of 50 m

5. Conclusion

A distribution system planning method has been addressed. It takes into account demand uncertainty and existing infrastructure. It has advantages over other general methods that the obtained plan's total cost is close to optimum, the uncertainty of future load through a fuzzy model is considered, and all technical (voltage drop, thermal limits) and physical (existing way) constraints are taken into account. This method can be effectively applied in an actual system, where all the above mentioned factors exist.

Appendix

Table A. Load point data

No.	Coordinate (km)		Load
	X	Y	(MVA)
1	1.83	1.04	0.033
2	1.833	0.843	0.083
3	1.641	0.774	0.105
4	1.606	0.715	0.167
5	1.857	0.706	0.167
6	1.782	0.671	0.417
7	1.756	0.62	0.417
8	1.653	0.637	0.167
9	1.797	0.585	0.083
10	1.774	0.533	0.083
11	0.814	1.662	0.105
12	0.664	1.667	0.017
13	0.738	1.672	0.083
14	0.891	1.632	0.083
15	1.011	1.704	0.017
16	1.016	1.676	0.083
17	1.014	1.649	0.133
18	1.373	1.293	0.033
19	0.893	1.409	0.017
20	0.788	1.468	0.105
21	0.756	1.472	0.105
22	0.599	1.482	0.033
23	0.548	1.254	0.083
24	0.557	1.343	0.167
25	0.59	1.417	0.133
26	0.638	1.447	0.167
27	0.677	1.432	0.267
28	0.847	1.295	0.033
29	0.691	1.155	0.083
30	0.691	1.099	0.017
31	0.755	1.224	0.033
32	0.984	1.156	0.033
33	1.055	1.276	0.083
34	1.057	1.209	0.017
35	1.117	1.166	0.105
36	1.212	1.188	0.105
37	1.285	1.131	0.105
38	0.542	1.098	0.033
39	0.527	1.047	0.083
40	0.541	1.02	0.105
41	0.581	1.021	0.017
42	0.564	0.94	0.083
43	0.612	1.009	0.083
44	0.513	0.858	0.033
45	0.758	0.851	0.083

No.	Coordinate (km)		Load
	X	Y	(MVA)
46	0.757	0.769	0.083
47	1.392	0.972	0.083
48	1.397	1.056	0.033
49	1.377	1.131	0.083
50	0.902	1.705	0.053
51	1.32	0.673	0.083
52	0.954	1.483	0.083
53	1.12	1.566	0.083
54	1.143	1.543	0.017
55	1.156	1.638	0.083
56	1.187	1.634	0.083
57	1.221	1.645	0.067
58	1.11	1.595	0.083
59	1.248	1.661	0.033
60	1.246	1.602	0.083
61	1.27	1.736	0.167
62	1.214	1.525	0.167
63	0.474	1.812	0.033
64	0.751	1.844	0.033
65	0.821	1.806	0.105
66	0.769	1.922	0.017
67	0.381	1.899	0.083
68	0.524	1.88	0.053
69	1.279	1.805	0.167
70	1.619	0.381	0.053
71	1.663	0.309	0.105
72	1.646	0.237	0.053
73	1.996	1.052	0.333
74	1.907	1.34	0.105
75	1.819	1.774	0.105
76	1.851	1.753	0.417
77	1.853	1.666	0.417
78	1.912	1.581	0.053
79	1.903	1.505	0.017
80	1.983	1.405	0.083
81	1.932	1.414	0.017
82	1.854	1.417	0.083
83	1.91	1.373	0.083
84	1.736	1.419	0.053
85	1.71	1.382	0.167
86	1.681	1.384	0.053
87	1.634	1.369	0.083
88	1.517	1.408	0.167
89	1.221	0.493	0.053
90	0.776	0.451	0.083
91	0.747	0.413	0.167
92	0.957	0.338	0.033
93	1.032	0.372	0.105
94	1.142	0.414	0.053
95	1.197	0.424	0.167
96	1.262	0.443	0.053
97	1.354	0.393	0.167
98	1.366	0.302	0.21
99	1.137	0.231	0.033
100	1.008	0.22	0.105
101	0.915	0.237	0.033
102	0.877	0.105	0.017
103	0.738	0.188	0.033
104	0.792	0	0.033
105	1.285	0.148	0.083
106	1.283	0.087	0.053
107	1.301	0.037	0.21
108	0.201	1.311	0.033
109	0.135	1.209	0.033
110	0.038	1.222	0.033
111	0	1.005	0.033
112	0.16	1.037	0.083
113	0.321	0.823	0.053
114	0.965	0.562	0.167
115	1.059	0.512	0.083
116	0.864	0.512	0.267
117	0.494	0.591	0.267
118	1.851	1.816	0.083
119	1.742	1.877	0.033
120	2.234	0.36	0.21
121	2.701	0.402	0.133
122	2.616	0.415	0.133
123	2.716	0.277	0.083
124	3.029	0.255	0.083
125	2.506	0.423	0.083
126	2.511	0.335	0.017
127	2.417	0.328	0.083
128	3.419	0.273	0.083
129	3.449	0.303	0.067
130	3.534	0.309	0.167

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