OPEN LOOP DISTRIBUTION SYSTEM DESIGN

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ABSTRACT

The ability to supply consumers of an urban area, without any longer interruption during a feeder segment or substation transformer outage, is assured by a uniform cable size of the feeder segments along the entire loop. Based on the criterion of the uniform cable size, a loop configuration is obtained first (by minimizing the installation costs), and then an open loop solution is find (by minimizing the power losses). Heuristic rules are proposed and used to obtain an initial solution, as well as to improve current solutions.

Key words: power distribution planning, urban areas, open loop configuration, power distribution serviceability, power distribution economics, load management.

INTRODUCTION

Distribution system planning is aimed at increasing the distribution system ability to meet the forecasted load, subject to expected level of service, and minimizing the cost of service. The cost of service includes capital investment, annual operating cost and capitalized annual cost of power losses. The level of service is defined by:

1) the quality of service, which is required for both radial (see Fig.1) and open loop (see Fig.3) distribution systems, and

2) the increased availability on demand by the planned alternative feeding point for most of the load points, which is required for loop distribution system.

The alternative feeding point is ensured by a planned tie-line as a connection to other feeder or substation. Without serviceability requirement 2), for an urban distribution system, cost-saving can always be achieved by degrading the continuity of power delivery.

Although many algorithms for optimal planning of distribution systems exist [1-13], to the authors' knowledge few have been considered for dealing with the open loop distribution systems. Most of the existing algorithms [1-9] can be applied only on the radial distribution systems. The radial solution, where each load point is fed only by one feeder, is obtained using either a load splitting technique [5] or a radiality constraint [3]. As a result, these algorithms are not able to find an optimal plan of tie-lines that will ensure a required level of serviceability for an urban distribution system.

However, past and present research efforts [10-15] face the problem of planning an open loop distribution system. For example, the power supply area of each substation of a loop distribution system has been solved using the criterion of power loss reduction [10]. The authors of the paper [11] have developed an algorithm for primary feeder planning, which is done for each substation. Based on the branch-and-bound formulation, the authors of the paper [12] have developed a heuristic circuit-exchange algorithm combined with fast network analysis to check circuit overloads for a range of outage conditions. The paper [13] presents an effective method to relieve the heavily loaded feeders and substation transformers.

How to improve and to maintain a given level of serviceability for an existing urban distribution system is the main objective of the algorithm developed in this paper. The algorithm is based on heuristic rules that determine the routing and sizing procedures. The problem of minimal cost network configuration is defined as a problem of minimal total investment cost of new feeders. The total number of new feeders is optimized by considering different ratings of the used cable during an iterative application of the minimal loop network algorithm. The minimal substation siting and sizing solution is obtained by using an iterative application of the minimal loop network algorithm for various substation locations. The system variable costs are optimized by applying the algorithm for minimal losses network configuration [14] to the obtained loop network solutions.

DATA REQUIREMENTS

The data required for open loop distribution design consist of load data and description of existing and planned equipment. The possible substation locations and the existence of potential right-of-way are known in advance.

To supply the consumers without interruption for any feeder segment outage condition (known as a serviceabilty requirement), each feeder has to be connected with another feeder by a tie-line. Two feeders connected by a tie-line form a loop, which appears at one substation, and it is closed at the same or another substation (see Fig.2). To afford a higher level of serviceabilty the distribution system planners tend to close each loop to another substation, wherever it is possible. The cable size of the feeder segments forming a loop is uniform along the entire loop. This will satisfy the voltage and capacity limits during an outage of any feeder segment along the loop. Also, a ca-

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outage of any feeder segment along the loop. Also, a cable with a uniform size will be used to build all new feeder segments of each loop. Namely, most utilities have developed standards for substation configurations, switching schemes, loading patterns and substation transformer and cable ratings, which should help the planners in this decision-making process. The chosen cable will have a standardized rating within the range of cable ratings depending on the load-density of the planned urban distribution area. The uniform cable size used for each new feeder segment implies that the feeder length is a favorable unit to be optimized in order to find the optimal network configuration.

The size and the number of substation(s) transformers depend on the forecast load growth of the planned urban area. The estimated number of loops associated with the new substation(s) is evaluated in order:

1) to pick up all loads of the planned distribution area, and to satisfy voltage or capacity limits during a normal state operating condition,and

2) to satisfy voltage or capacity limits during an outage condition.

Requirement 1) is a common task for both radial and loop distribution networks, but requirement 2) is set only for loop networks. To allow load transfer during an outage condition, a reserve margin is instaled in the new equipment. This planning reserve margin is specified by the known load that could be transferred by a tie-line to another feeder or transformer. However, in this paper the reserve margin is not defined by the specified percentage of the thermal rating of the equipment [4,8,9] but is a result of the planning process for a possible transfer of a known load.

DISTRIBUTION SERVICEABILITY LEVELS

This paper will focus the attention to the problem of sizing and locating of a new substation and its associated feeders, satisfying the serviceability requirements of an urban distribution system. There are several levels of serviceability the planner has to choose from:

The radial network level

This level is the objective of the algorithms for planning a strictly radial distribution system, which is a typical configuration of a rural area. From this perspective the size of the substation transformer has to meet only the loads of its associated feeders. Also, the size of each feeder has to meet the loads of its associated customers and the voltage drop requirement at each load point. The voltage and capacity limits in conjunction with the objective function, for a radial network, will cause different cable size along the entire feeder[4].

Feeder serviceability level

To supply the consumers without interruption during a feeder segment outage, the size of the substation transformer obtained by the radial network level criterion should be increased. The new substation transformer should be able to supply its feeders customers, including the highest load among its associated loops. To maintain a feeder serviceability level, a cable of larger size should be used.

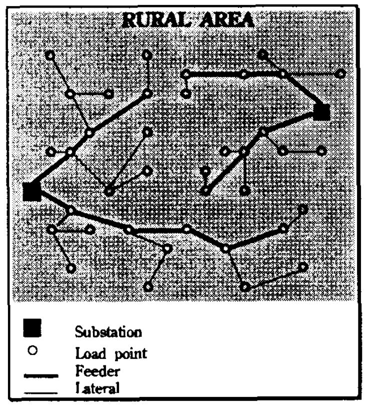

Fig.1 Radial network level

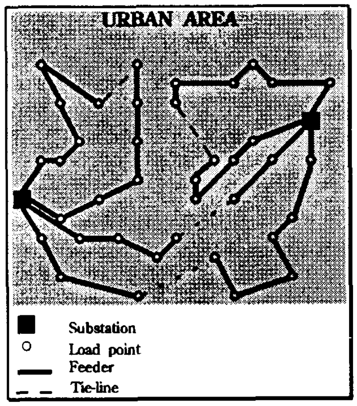

Fig. 2 Feeder serviceability level

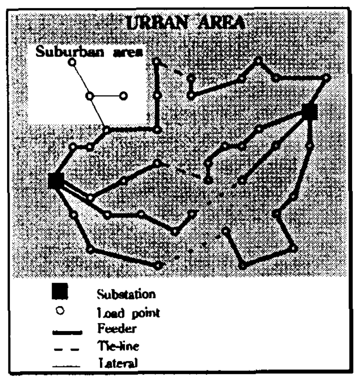

Fig. 3 Transformer serviceability level

Transformer serviceability level

To maintain serviceability during transformer outage conditions, load transfer should be backed up by the sizes of its neighboring substations. As a result, the new substation transformer should be able to supply simultaneously its loops customers, as shown in Fig. 3. To maintain a transformer serviceability level a cable, as well as transformers of larger size should be used.

FORMULATION OF HEURISTIC RULES

The following rules help the decision-making process to be controlled by the distribution operating and planning practice. Also, they enable the user to direct the course of action. The conclusion that a cable of a uniform size will be used to build the new feeder segments, helps in formulating the basic heuristic rule for finding an optimal solution:

Rule 1: The sum of lengths of the feeders associated with a new substation, and also lengths of the tie-lines should be minimum. This rule defines the objective function for a problem of minimal cost network design, which is a combinatorial optimization problem.

Rule 2: Each lateral type of load point should be excluded from the finite set of configurations as a trivial case. If the attempt to ensure each load point to be supplied by at least two feeding points fails (typical for suburban areas), then these loads will be supplied by lateral lines (see Fig.3). In that case, load of entire lateral line will be located at its feeding point.

Rule 3: The load current of each feeder consists of the loads that are supplied in a normal state. The load current of each loop consists of the loads that should be supplied during an emergency state, such as a feeder segment or transformer outage.

Rule 4: The load current of each feeder, during an outage condition along the loop, is limited to be less than the current capacity of the used cable.

Rule 5: The load of each substation transformer is limited to be less than the thermal rating of the transformer. The transformer load consists of:

- the loads of its associated feeders, including the highest load of its associated loops (for the feeder serviceability level), or
- the loads of its associated loops (for the transformer serviceability level).

Rule 6: The voltage profile along each feeder, during an outage condition along the loop, must be within the permitted percent voltage drop ΔU_{max}.

Rule 7: Two feeder sections must be connected to each load point, except for load points defined by Rule 2.

Rule 8: To include the existing feeder segments into the final solution, the length of each existing feeder segment is assumed as zero. If the current of a loop (defined by Rule 3) exceeds the ampacity of the existing feeder segment, then reconductoring should be made to improve the current capacity of the used cable. Then, the procedure is repeated with the original length of the existing feeder segment, which becomes a new feeder segment.

Rule 9: While obtaining an open loop network with minimal power losses (by applying procedure [14]), the existing feeders are handled with their original lengths.

OPTIMAL SUBSTATION SERVICE AREA

The service area of the new substation covers, besides the new load points, also some loads usually served by existing substations. Probably some of these loads will be served by the same existing substations, but the new substation should be able to serve them in the case of a possible feeder or transformer outage condition.

The basic Rule 1, outlined in the previous section, allows to obtain the initial configuration and to improve the current solution until the optimal solution is reached. The problem could be defined as a problem of minimal sum of loops lengths as an equivalent of the investment costs.

Algorithm for finding a loop network configuration

For a known location of each substation (including the location of new one), the problem of the optimal service area will be solved by finding an optimal loop network configuration. The algorithm for finding an open loop network configuration is based on the procedure that adds nodes (one at a time) to the network subtree, until all nodes are connected in the final network. The algorithm begins with an initial subtree of the network that consists of all substation nodes.

The algorithm that produces the open loop network configuration for a given location of each substation could be described as follows:

Step 1: Input data for:

- substations: location and size (possible sizes of new substation),
- feeders: unified cable size and estimated number of feeders for each transformer.

Step 2: An initial set of feeder endings **FE** and an initial set of feeders length **FL** should be generated. The feeder ending of a new feeder initially coincides with node index of the new substation transformer. The feeder ending of an existing feeder is the index of node at the end of the feeder supplied by an existing substation. The feeder length consists of the lengths of feeder segments from the feeding substation to the feeder ending. The length of each feeder is initially set to be zero. Load points along the feeder could be easily found by a set of preceding (feeding) nodes **PN**. Each feeder is defined by sets **FE**, **FL** and **PN**. An initial set of active nodes **AN** should be generated also. Set **AN** consists of service area nodes of a new substation (new load points) that are not picked up by the existing feeders.

Step 3: The minimal distance from each active node, e.g. $M \in AN$, to nodes of **FE** is:

$$L'_M = \min_{G \in FE} \{ L_G + f_{G-M} \} \ , \ M \in AN \ , \ f_{G-M} \neq \infty \qquad (1)$$

Where:

L_G - present length of feeder with node G as a feeder ending, $L_G \in$ **FL**.

L'_M - possible new length of feeder with node M as a possible new feeder ending.

$f_{G\text{-}M}$ - length of feeder segment G-M.

Step 4: If the node M could be connected to any node of **AN**, go to Step 6.

Otherwise, go to Step 5.

Step 5: Node M should be checked for a possible connection to a node, e.g. Q, which is a feeder ending. Then, if node Q is fed by a feeder associated with the same substation (as the feeder that supplies node G, see Step 3), the feeder serviceability level is met. Otherwise, if node Q is fed by a feeder associated with another substation, then both feeder and substation serviceability level are met. Go to Step 7.

If node M cannot be connected to any node of **AN**, or to any feeder ending, then go to Step 3 (by discarding a possible connection of node M to node G).

Step 6: Among the feeders with new endings find the one with minimal length:

$$L_{K^*} = \min_{K \in \mathbf{AN}} \{ L'_K \} \tag{2}$$

Step 7:The radial power flow method should be run only for feeder found by (2). Rules 3-5 should be checked for a possible connection of node K^* load.

For rules violation, possible new ending K^* will be regarded as unfeasible. Go to Step 3.

Otherwise, go to step 8.

Step 8: Rule 6 should be checked for a possible connection of new ending K^*.

For Rule 6 violation, new possible ending K^* will be regarded as unfeasible. Go to Step 3.

Otherwise, go to step 9.

Step 9: Node K^* should be connected to the network subtree. Accordingly update sets **FE**, **PN** and **FL**.

Step 10: Use the procedure for improvement of current solution (see the following section).

If the result of any change of current solution is better, then update sets **FE**, **PN** and **FL**.

Step 11: If set **AN** is empty, the obtained network subtree represents a loop network configuration. Go to Step 12.

Otherwise, go to Step 3.

Step 12: End of the algorithm.

Procedure for improvement of current solution

For optimization purposes it seems unreasonable to rely solely on the solution obtained by the above algorithm. Probably the obtained solution could be a local minimum. It should be noted that the simple branch exchange mechanism based on a highest cost saving rule could not be the right course to obtain a minimal solution. To afford a multiplicative perturbation mechanism and to overcome numerous transitions among the network configurations, the removal of a feeder segment is accompanied by the following procedures.

Routine 1: decrease of current network subtree (some load points of the current feeders become temporary active nodes),

Routine 2: straightforward procedure of returning to the previous size of network subtree.

The steps of the procedure are as follows:

Step 1A: For each node of feeder (with length L_{K^*}), found by (2), do following Steps 2A-4A.

Routine 1

Step 2A: Find all possible connections from current node, e.g. M, to nodes of neighboring feeders. The neighboring feeder of feeder defined in Step 1A may originate from the same or from another transformer or substation.

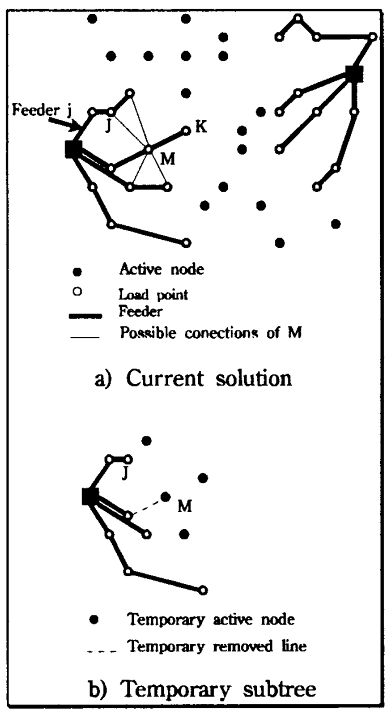

Fig.4 Improvement of current solution

The preceding node of node M should be set as a temporary feeder ending of feeder defined by Step

1A. All nodes that succeed node M (along the feeder), including node M, are set as temporary active nodes (see Fig.4).

Any node of a neighboring feeder (e.g. j), with a possible connection to node M, can be set as an ending of feeder j. Among these nodes, as a temporary feeder ending is set node, e.g. J, which is closest to its transformer. Other feeder nodes, from node J to the current ending of feeder j, temporarily become active nodes.

Temporary sets FE', FL' and AN', for feeder defined by Step 1A and its neighboring feeders, should be generated .

Routine 2

Step 3A: Steps 3-10 of the algorithm for finding a loop network configuration (presented in the previous section) should be run for temporary sets FE',FL' and AN'.

Step 4A: To check the improvement of the current solution, sum of feeder lengths of sets FL and FL' should be compared. If the result of removing a feeder segment is better, then update sets FE ,FL and PN.

OPTIMAL LOOP NETWORK CONFIGURATION

The feeders, defined by the previous procedure, establish the load location plan or the service area of each substation. As a result of Step 5, each feeder ending can be connected to other feeder ending to obtain the network loop. To obtain an optimal network configuration of the transformer serviceability type, the presented algorithm should be run again. This time the algorithm will be applied only on the load points of the service area defined by <u>loops that are routed between two substations</u>. The algorithm will be applied on each pair of substations, until further improvement cannot be obtained. The obtained new solution may differ from the initial solution. Then the new load location plan is reached.

Substation location and sizing

The need for new substation (or substations) and its associated feeders, creates the problem of optimal substation location and sizing and the problem of network configuration to meet the expected serviceability level. To find the optimal substation location and sizing, the previously described network building algorithm should be iterated for:

1) different sizes of standardized cable ratings,

2) different sizes of standardized transformer ratings,

2) different number of new feeders, and

3) each new substation location.

Variable cost optimization

In the previous sections the object of the network optimization is limited to the investment cost of feeders and transformers. The distribution system variable costs will be minimized by applying the algorithm for reduction of power losses [14] to the previously obtained loop distribution system. Using the criteria presented in paper [14] each loop of the obtained loop network solution will be traced. Starting from both ends (substations) of a loop, two feeders are formed until a joint tie-line is obtained. Because of the power losses optimization, <u>the radial operating configuration</u> of each substation will be defined and the tie-line will be selected among the feeder segments of each loop.

NUMERICAL EXAMPLE

The computer program written in FORTRAN 77 to carry out the procedures described above was developed on an IBM 4331 computer. The program is designed to be run interactively, so that the user can quickly change the program parameters. For this purpose, once the optimal planning of loop distribution system has been realized for the feeder serviceability level, the planning procedure is chosen to be directed towards a transformer serviceability level.

Tab.I Load and location data

Node	x km	y km	P MW	Node	x km	y km	P MW
SUB1	16	10	0.00	37	12	12	0.25
SUB2	1	6	0.00	38	9	12	0.10
SUB3	6	21	0.00	39	7	1	0.40
4	14	4	0.60	40	7	7	0.30
5	12	8	0.30	41	6	4	0.35
6	8	3	0.45	42	4	4	0.45
7	3	2	0.25	43	2	23	0.10
8	7	11	0.50	44	11	24	0.10
9	11	8	0.60	45	7	9	0.20
10	13	13	0.20	46	7	13	0.25
11	17	12	0.10	47	4	24	0.10
12	16	8	0.30	48	14	21	0.10
13	4	9	0.50	49	15	15	0.30
14	2	13	0.10	50	12	6	0.15
15	10	6	0.25	51	6	18	0.10
16	9	16	0.20	52	9	4	0.20
17	9	20	0.30	53	12	15	0.25
18	8	23	0.20	54	15	2	0.20
19	5	22	0.10	55	15	5	0.25
20	2	21	0.20	56	13	9	0.45
21	4	17	0.15	57	5	6	0.80
22	7	15	0.10	58	15	17	0.20
23	13	18	0.15	59	6	16	0.20
24	12	22	0.15	60	3	19	0.30
25	13	23	0.25	61	5	11	0.20
26	16	19	0.70	62	11	20	0.10
27	16	16	0.60	63	12	17	0.35
28	12	1	0.20	64	13	20	0.15
29	11	3	0.30	65	14	12	0.30
30	2	8	0.70	66	10	23	0.15
31	3	11	0.20	67	2	4	0.15
32	1	17	0.10	68	9	11	0.40
33	3	16	0.25	69	10	7	0.10
34	2	15	0.30	70	3	8	0.50
35	8	22	0.10	71	14	8	0.70
36	8	14	0.55	72	3	5	0.10

To illustrate the performance of the proposed open loop network design program, the hypothetical distribution system shown in Fig. 5 was studied. The system consists of three substations and 69 load points.

The locations of substations (given by x,y coordinates) and location and load of each load point are shown in Tab.I. To simulate a real distribution system, maximum length of 3 km is allowed for each possible feeder segment. Using these requirements 375 possible feeder segments are obtained. The standardized cable with series impedance (0.206+j0.092) Ω/km per phase. The voltage limit is defined by $\Delta U_{max}=8\%$. The power capacity limit of the used cable is $P_{max}=2.9$MW. The power factor of the network is $\cos\varphi = 0.9$. For a transformer serviceability level the available substation capacities are set: $P_{SUB1}=12$MW, $P_{SUB2}=12$MW and $P_{SUB3}=8$MW. Iterating the number of feeders of each substation the following feeders are obtained: 5 feeders for SUB_1, 5 feeders for SUB_2, and 4 feeders for SUB_3.

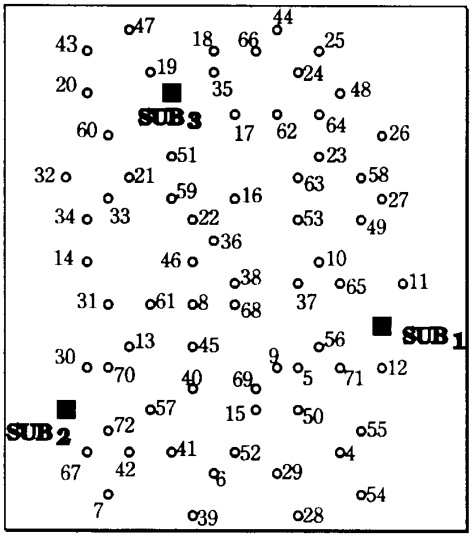

Fig.5 Simple distribution system

Some of the applied procedures are shown in the following figures. The improvement obtained by simple branch exchange is shown in Fig.6a. In the next Fig.6b, an improvement is obtained by multiple branch exchange procedures.

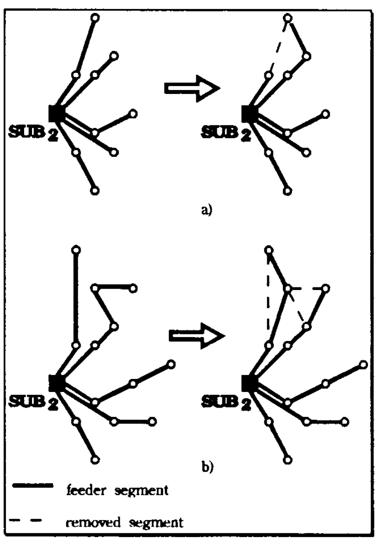

Fig.6 Types of feeder segment removal

For a transformer serviceability level, as a higher level of serviceability, the procedure for finding the substation service area forms loops of the solution shown in Fig.7.

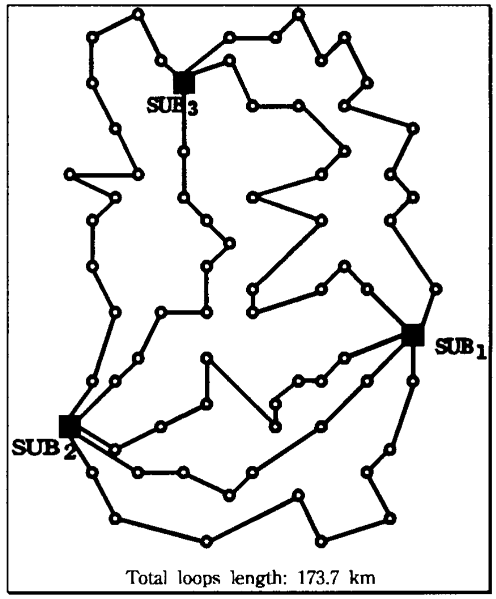

Fig.7 Transformer serviceability level

The optimal solution, shown in Fig.8, is obtained by applying the procedure for finding optimal loop network configuration on each pair of substations. The final choice of tie-lines is obtained using the algorithm for power losses reduction [14].

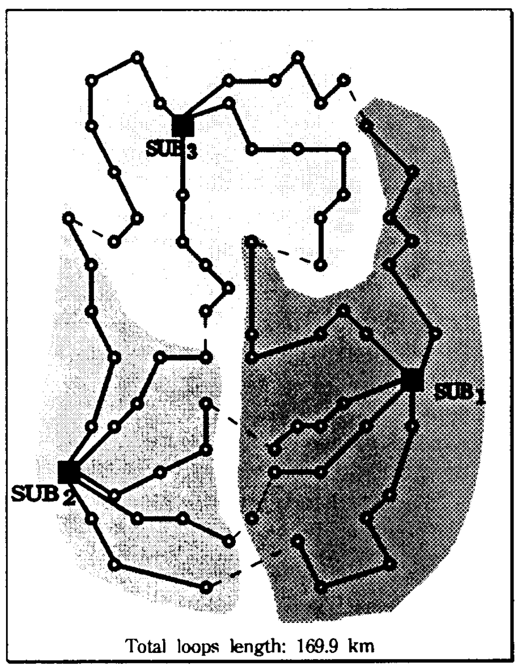

Fig.8 Optimal solution

CONCLUSIONS

The problem of optimal location and sizing of the substations and network routing for an urban distribution system that would improve and maintain a given level of serviceability has been considered. The algorithm developed in this paper is based on a requirement that each load point should be supplied by at least two feeding points, either from the same substation or from the other substation. The suggested algorithm solves the problem of minimal sum of lengths of paths, where each load point of the new substation area is picked up only by one path. The requirements to be satisfied during any outage (feeder segment or transformer outage depending on the level of serviceability) are: cable and transformer capacity limits and voltage drop constraints. Although the solution of the planning process is a loop network, a radial operating solution is specified by applying the optimal loss reduction algorithm to the obtained loop network. Power losses optimization leads to minimal distribution system variable costs. The problem of optimal substation location and sizing is solved applying the algorithm for each standardized feeder and transformer ratings, also for each possible location of new substations.

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