Long-term Distribution Network Expansion Planning Considering Multiple Construction Plans

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Abstract: Distribution network expansion planning is one of the important activities at distribution control centers. Many approaches have been proposed for automatic expansion planning in distribution systems using computer systems. However, most of them have been developed for allocation of substation and feeders. The method for generating combination of several construction plans, namely multiple construction plans, considering yearly increase of network loads and newly installed loads for each year is eagerly awaited. This paper proposes a distribution network expansion planning method considering multiple construction plans. The proposed method is verified by comparing construction plans generated by the proposed method with the actual plan composed by experienced planning persons in practical distribution systems. The proposed method can generate the same plan generated by the experienced persons. Moreover, the method can generate various alternative construction plan candidates. The results indicate the practical applicability of the proposed distribution expansion planning method.

Keywords: Distribution Network Expansion Planning, Multiple Construction Plans, Modern Heuristic Method, Search Method, Three-phase Unbalanced Load Flow Calculation

I. INTRODUCTION

Distribution network expansion planning is one of the important activities in distribution control centers [1]. Several objective functions, including new equipment installation cost, equipment utilization rate, reliability of the target distribution system, and loss minimization should be evaluated considering increase of network loads and newly installed loads for each year at the planning. Experienced persons have been performed the planning conventionally. However, only a few cases have been evaluated practically because of limited planning time and it is difficult to evaluate optimality of the generated plans in many points of above mentioned view.

In recent years, energy-saving and reduction of costs restraining investment are of primary concerns in distribution systems. In this situation, more efficient planning in distribution network is required. Many approaches have been proposed in the automatic expansion planning using computer systems [2-6]. Most of them have been developed for allocation of substations and feeders. The authors also have presented the optimal network configuration, service restoration, and network expansion methods for the planning tools [7,8,9]. However, the practical network expansion planning systems including exchange of distribution lines to thicker lines, installation of new switches, lines and so on which applied practical network expansion in Japan, and considering long term equipment costs are not existed.

The proposed distribution network expansion planning method [10,11] evaluates multiple factors including new equipment installation cost, equipment utilization rate, reliability of the target distribution system, and loss minimization. The proposed method generates various construction plans using expert system, reactive tabu search, and three phases unbalanced load flow calculation. The proposed method is performed as follows. Firstly, loss minimization and service restoration for various contingencies are performed considering load increase and new load installation plans for the target year, and necessity of additional construction plans is checked. If the method determines to generate new construction plans, the construction plan candidates are generated. The procedure is repeated until the target year reaches the final decision year. Finally, the optimal plan is determined using evaluation of construction cost, loss minimization, service reliability, and equipment utilization rate.

The proposed method is verified by comparing construction plans generated by the proposed method with the actual plan composed by experienced planning persons in practical distribution systems. The proposed method can generate the same plan generated by the experienced persons. Moreover, the method can generate various alternative construction plan candidates. The results indicate the practical applicability of the proposed distribution expansion planning method.

II. OUTLINE OF THE PROPOSED METHODS

Fig.1 shows a general flow chart of the proposed method. Firstly, distribution network data, including load current, switch status whether the switch is open or close, connection status between sections is set at the current year. Then, the proposed method checks the existence of an optimal network configuration without construction. It utilizes a loss minimization function using reactive tabu search (RTS), three phases unbalanced load flow calculation, and a service restoration function for various contingencies using RTS and expert system (ES) are performed. Namely, it is checked whether the operation constraints including voltage, current, and power source constraints are violated or not. If these constraints are violated, the method generates several construction plans. The procedure is repeated considering load growth and new load installation until the target year reaches the final decision year. It is assumed the section load growth ratio a year is constant in the target distribution system. Finally, each generated construction plan using the proposed method is evaluated with respect to construction costs, loss minimization, service restoration for various contingencies, and equipment utilization rate. Then, the optimal construction plan, and the optimal network configuration after applying the optimal construction plans are decided.

III. PROCEDURES OF NETWORK EXPANSION PLANNING

Concept of network expansion planning [11,12]

The proposed method generates construction plans under the following constraints:

(1)Power source constraint
The total loads of a certain partial network cannot exceed the capacity limit of the corresponding power source.
(2)Current constraint
Current magnitude of each branch (feeder, line, and switch) must lie with their permissible ranges.
(3)Voltage constraint
Voltage magnitude at each node must lie with their permissible ranges to guarantee maintaining the predetermined power quality level.

In actual expansion planning, various construction plans are applied. Therefore, actual construction plans are categorized, and evaluated the effect of cancellation of each constraint violation. As a result, following construction plans will apply to cancel each constraint violation in Table. 1.

Construction plans with power source constraint

The power source constraint means power source current is over the permissible power source capacity. Namely, this means the target distribution network has overload feeders. In such a case, it is necessary to reduce total load currents by transferring several loads to neighboring feeders. In actual expansion planning, experienced planning persons install new tie-lines, tie-switches, section switches, and feeders in order to reduce the load currents. Installation of new tie-lines or tie-switches means generation of a new connection between two sections through the distribution lines or switches. Installation of new section switches means division of one large section into two sections. If there are some margins of substation transformer bank capacity, new feeders can be installed.

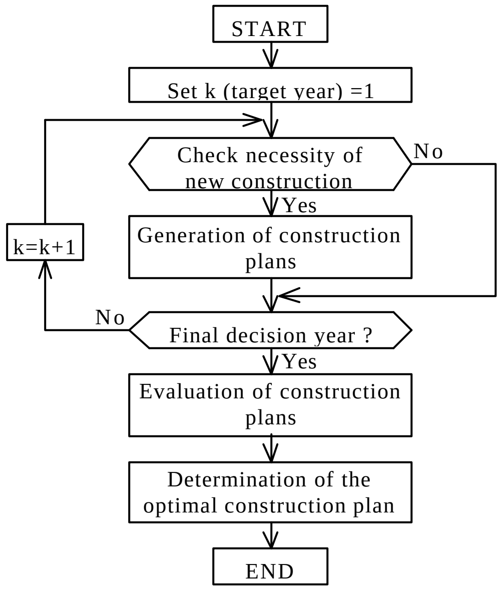


Fig. 1 A general flow chart of proposed the method.

Table. 1 Considering construction plans.

Constraint violation	Considering construction plans
Power source	•Installation of new tie-lines •Installation of new tie-switches •Installation of new section switches •Installation of new feeders
Current	•Exchange of lines to thicker lines •Installation of new tie-lines •Installation of new tie-switches •Installation of new section switches
Voltage	•Exchange of lines to thicker lines •Installation of new tie-lines •Installation of new tie-switches •Installation of new section switches •Installation of voltage regulators

Construction plans with current constraint

The current constraint means section current is over the permissible section current capacity. In such a case, thin lines are often exchanged to thicker lines in order to increase the permissible current capacity. Other methods to cancel the current constraint are installation of new tie-lines, tie-switches, and section switches. The experienced planning persons utilize the methods because these methods can reduce the section current by transferring loads to neighboring feeders.

Construction plans with voltage constraint

The voltage constraint means voltage magnitude deviates from the permissible ranges. In such a case, thin lines are often exchanged to thicker lines in the same way to the current constraint in order to decrease the line impedance. The decrease of line impedance can lead to decrease of voltage drop. Other methods to cancel the voltage constraint are installation of new tie-lines, tie-switches, and section switches in actual expansion planning. The decrease of load current can lead to decrease of voltage drop. Moreover, voltage regulators (Step Voltage Regulator: SVR) are sometimes installed in the actual expansion planning.

Combination of construction plans

Since installation of new tie-lines, tie-switches, section switches, and feeders include load transformation, these four construction plans can affect to other feeders. These four construction plans may lead to constraint violations to other feeders. On the other hand, exchange of lines to thicker lines and installation of SVR do not affect to other feeders because of no load transformation. These two construction plans may not be able to cancel constraint violations by itself. Namely, only one construction plan may not be enough to cancel constraint violations. In such a case, the second construction plan has to be applied to the network configuration to which the first construction plan is applied. Moreover, the third construction plan should be considered if constraint violations could not be canceled. Thus, multiple construction plans are considered until constraint violations are canceled. Namely, expansion planning is usually composed of combinations of several construction plans. Fig. 2 shows a concept of combinations of construction plans. These combinations of construction plans are described as follows.

(Step 1) The First construction plan is applied in order to cancel the constraint violations. If the constraint violations are canceled, the procedure comes to an end. Otherwise, go to step 2.
(Step 2) If constraint violations are not canceled, or new constraints are violated in neighboring feeders, the second construction plan is applied.
(Step 3) Step 2 is repeated until all constraint violations are canceled or the total number of combinations of construction plans reaches the predetermined maximum number.

IV. TOTAL EVALUATION METHOD OF EACH CONSTRUCTION PLAN

Outline of total evaluation method

The proposed method requires deciding the optimal construction plans and the optimal network configurations. Therefore, the proposed method must maintain the network configurations reflected to its construction plans of each year. Namely, the proposed method must make relations among the network configuration candidates of each year clear. Fig. 3 shows an example of the network transition until 4th year. The proposed method checks an existence of an optimal network configuration without construction for initial network (No.1 circle in Fig. 3). Since the optimal network configuration dose not exist, the proposed method generates three construction plans (No.2, 3 and 4 circle in Fig. 3). Namely, the network configurations reflected each construction plan become

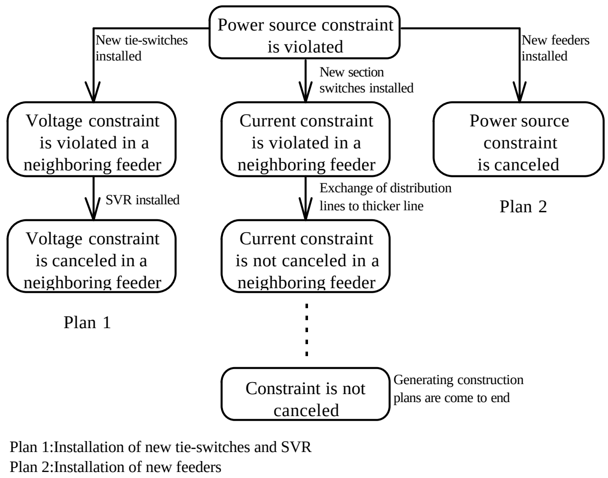


Fig. 2 A concept of combinations of construction plans.

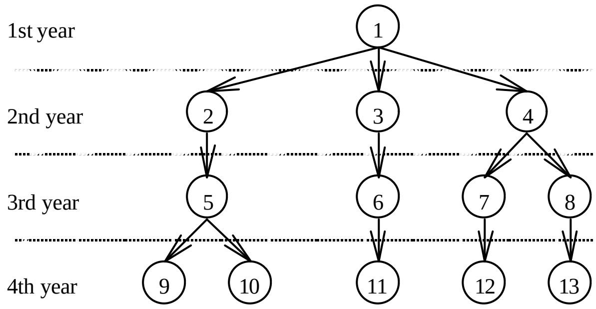


Fig. 3 A concept of network transition.

Table. 2 Network transitions of each year.

Network transition candidates No.	Network configuration No. of each network transition			
	1st	2nd	3rd	4th
1	1	2	5	9
2	1	2	5	10
3	1	3	6	11
4	1	4	7	12
5	1	4	8	13

network candidates 2, 3, and 4, respectively in Fig. 3. In Fig. 3, the procedure is repeated until the final decision year (4th year). As a result, the proposed method generates 5 network transition candidates as shown in Table. 2. The proposed method calculates total costs of each network transition candidate including construction costs and conversion costs of network losses. The network transition minimizing the total costs becomes the optimal network transition. Then, the optimal construction plans and the network configurations included in the network transition become the optimal construction plans and the optimal network configurations. For example, if the network transition candidate 3 in Table. 2 produces the minimum costs, the network configuration 3 in 2nd year, 6 in 3rd year and 11 in 4th year become optimal network configurations of each year.

Formulation of total evaluation method

The proposed method evaluates the total costs generated for each network transition. It calculates construction costs and conversion costs of network losses. As a result, the proposed method decides the network transition minimizing total costs as an optimal solution. The proposed method calculates the total costs as yearly costs. Long-term evaluation can realize by comparison of the yearly costs of each generated network transition.

The yearly costs of generated construction plans calculate as follows. First, the actual construction plan costs are calculated by the following equation:

$$C_i = A_i \times B_i \qquad (1)$$

where,

C_i : The costs of generated construction plan i
A_i : Unit cost of plan i
B_i : The total amount of plan i

For example, in case of exchange of lines to thicker lines, A_i is the unit costs of exchange lines, B_i is the total length of exchanged lines. In case of installation of new switches, A_i is the unit cost of newly installed switches, B_i is the total number of newly installed switches.

The equally divided yearly costs are calculated by the following equation:

$$F_i = C_i \times (1+E)^k \times D_i \qquad (2)$$

where,

F_i : The equally divided yearly costs of generated construction plan i
E : Inflation ratio of installed equipment
D_i : Unit weighting factor of plan i
k : The construction year of plan i

The total yearly costs of each network transition are calculated by the following equation:

$$F = \sum_{i=1}^{n} F_i \qquad (3)$$

where,

F : The total yearly costs of each network transition
n : The total number of construction plans included each network transition

The conversion costs of network losses are calculated by the following equation:

$$G_k = L_k \times H_k \qquad (4)$$

where,

G_k : The conversion costs of network losses of year k
L_k : The network losses of year k
H_k : The network unit cost of year k

The total conversion costs of network losses of each network transition are calculated by the following equation:

$$G = \sum_{k=1}^{m} G_k \qquad (5)$$

where,

G : The total conversion costs of network losses of each network transition
m : The final planning year

Finally, the total yearly costs are calculated by the following equation:

$$J = F + G \qquad (6)$$

where,

J : The total yearly costs

Then, the proposed method calculates each J with respect to all network transitions. The proposed method decides a minimum J and the network transition with the minimum J as an optimal solution. The other network transition candidates are decided as the sub-optimal solutions.

V. SIMULATION RESULTS

Simulation conditions

The proposed method is applied to some practical distribution network models in order to demonstrate functions including generation algorithm of construction plans, combination of construction plans, and determination of the optimal construction plan. Fig. 4 shows a practical distribution network model with 3 feeders and 21 sections. The maximum allowable current for power source and each section are assumed to be 300[A]. Power source voltage is assumed to be 6.9[kV] considering a heavy loading condition. The maximum allowable voltage drop from power source is assumed to be 300[V]. The load growth ratio of each year is assumed to be 2.5%. The maximum total planning year is assumed to be 10. The maximum number of combinations of construction plans is assumed to be 2.

Simulation results

(1) Results of generation of construction plans in the initial year

Firstly, the proposed method checks the existence of the optimal network configuration without construction. However, the distribution network model shown in Fig. 4 does not have the optimal network configuration without construction because the network reconfiguration cannot cancel the power source constraint violations. In Fig. 4, power source current in feeder 3 is 312.9[A]. Therefore, the proposed method generates some construction plans in order to cancel the power source constraint violations. Since the network configuration shown in Fig. 4 becomes minimum network losses, Fig. 4 becomes initial network configuration in the proposed method. The proposed method generate construction plans by applying the generation algorithm of construction plans. As a result, the proposed method generates 3 construction plans. Each network configuration and generated construction plan is shown in Fig. 5 and in

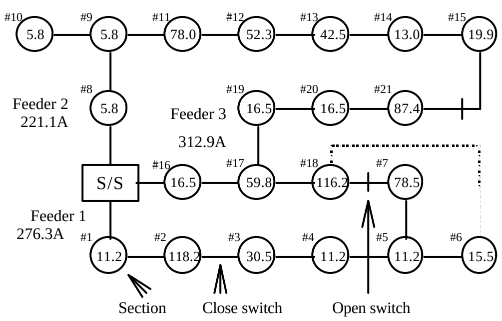
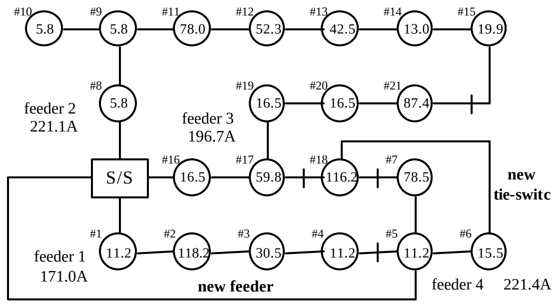
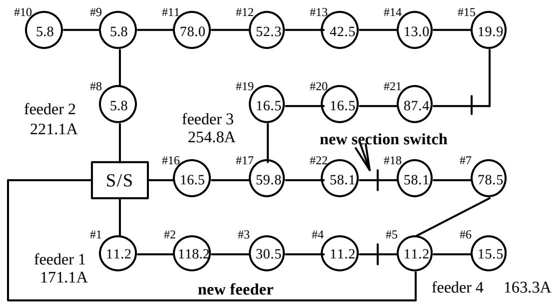


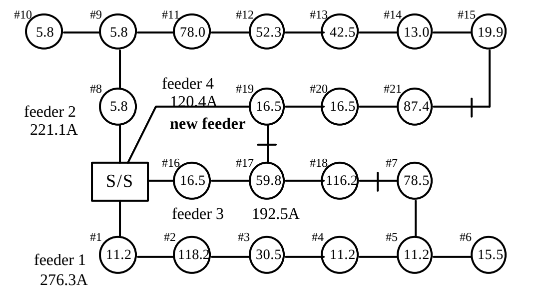
Fig. 4 A practical distribution network model.



(a) Installation of a new tie-switch and feeder



(b) Installation of a new section switch and feeder



(c) Installation of a new feeder

Fig. 5 Results of expansion planning for the initial year

Table. 3 Generated construction plans for the initial year.

No	Generated construction plans
(a)	Installation of a new tie-switch and feeder
(b)	Installation of a new section switch and feeder
(c)	Installation of a new feeder

Table. 3, respectively. All generated construction plans can cancel the constraint violations. On the other hand, the construction plan generated by the experienced planning persons is to divide the feeder 3 into two feeders. The construction plan is the same as (c) shown in Fig. 5. Namely, the proposed method can generate the same construction plan generated by the experienced planning persons. Moreover, since the proposed method considers the combinations of construction plans, it can generate other 2 practical construction plans (a), (b) shown in Fig. 5.

(2) Results of generation of construction plans after initial year

Fig. 6 shows the network transition results until the planning year reaches the 10th year. The network configuration candidate No. 0 shown in Fig. 6 shows the initial network configuration shown in Fig. 4. The network configuration candidates No. 1, 2 and 3 shown in Fig. 6 correspond (a), (b) and (c) shown in Fig. 5, respectively. The network transition with thick lines requires the construction. On the other hand, the network transition with thin lines does not require the construction. After initial year, the network configuration candidate No. 12 at 4th year requires the construction. As a result, the proposed method generates 3 construction plans. Finally, the proposed method generates 5 network transitions.

(3) Results of total evaluation

The proposed method evaluates the total yearly costs generated 5 network transitions. Table. 4 shows the results of total evaluation including the construction plans, the construction year, the total yearly costs, and a rank order based on the total yearly costs. The total yearly costs show relative values when the network transition No. 4 is a reference value (100.0). According to the result, the network transition No. 4 is found to be the optimal network transition. Namely, the optimal network transition has two construction plans. It has the installation of a new feeder at 1st year and the installation of a new section switch at 4th year. Table. 4 shows that the network transition No. 5 is the most expensive network transition because it includes the installation of new feeders at 1st and 4th year. The network transitions No. 1 and 3 include the same construction plans installing a new tie-switch and a new feeder. However, the network transition No. 1 is more expensive than No. 3 about 1.73 times. On the other hand, the network transitions No. 2 and 4 include the same construction plans installing a new section switch and a new feeder. However, the network transition No. 2 is more expensive than No. 4 about 1.73 times. The results indicate that delay of the partial construction plans (4th year) are cheaper then all construction plans performed at a same year (1st year). In this way, the proposed method can easily compare the total yearly costs.

Table. 5 shows the execution time in 6 practical distribution network models. All calculation are performed using EWS (SPECint95 16.1). The maximum execute time is about 830 seconds (about 15 minutes) in case No. 2 with 4 feeders and 27 sections. The results indicate the practical applicability of long-term distribution network expansion planning.

VI. CONCLUSIONS AND FUTURE WORKS

This paper proposes a long-term distribution network expansion planning method considering multiple construction plans. The proposed method can generate the same construction plan generated by the experienced planning persons. Moreover, the proposed method can generate construction plans, which the experienced planning persons do not generate. The proposed method can easily compare the total yearly costs using total evaluation. The maximum execute time is about 830 seconds for a model system with 4 feeders and 27 sections. The results indicate the practical applicability of the proposed distribution expansion planning method.

As a future work, the proposed method will apply to

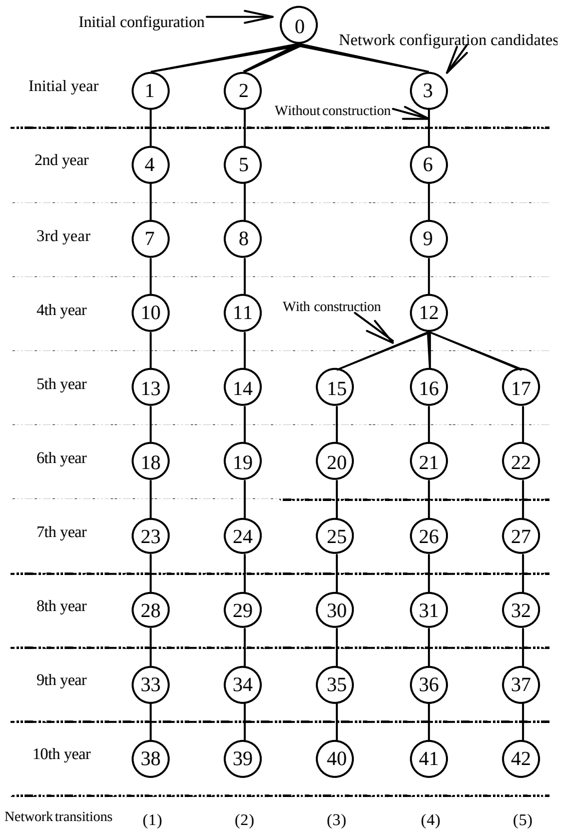


Fig. 6 Results of network transition.

Table. 4 Results of total evaluation.

Network transitions	Planning year	Construction plans	Object sections	Yearly costs	Rank order
(1)	1	New tie-switch	6,18	175.2	**4**
		New feeder	5		
(2)	1	New section switch	18	173.6	**3**
		New feeder	5		
(3)	1	New feeder	19	101.7	**2**
	4	New tie-switch	6,18		
(4)	1	New feeder	19	100.0	**1**
	4	New section switch	7		
(5)	1	New feeder	19	206.2	**5**
	4	New feeder	3		

Table.5 The execution time of each case.

Case	Network configuration	Total network configuration	Total network transitions	Execution time (s)
1	3 feeders 21 sections	42	5	248.235
2	4 feeders 27 sections	62	16	830.113
3	2 feeders 7 sections	41	4	77.383
4	2 feeders 15 sections	19	6	99.810
5	3 feeders 14 sections	41	8	239.476
6	2 feeders 16 sections	41	8	127.856

various distribution network models and improve the generation algorithm of the construction plans. Moreover, the proposed method will be considered as one of the additional functions for the existing distribution network expansion planning system.

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BIOGRAPHY

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