

Long-term Distribution Network Expansion Planning by Network Reconfiguration and Generation of Construction Plans

Takanobu Asakura, Takamu Genji, Toshiki Yura,
Naoki Hayashi, and Yoshikazu Fukuyama, *member, IEEE*

Abstract-- This paper proposes a distribution network expansion planning method by network reconfiguration and generation of construction plans. Considering natural growth of electric loads and installation of new large customers, the method first tries to reconfigure the target network by changing switch status for loss minimization and analyzing security of the target network by contingency analysis. If operational constraints are violated even in the reconfigured network, the method tries to generate construction plan candidates, which can eliminate the operational constraint violations. The proposed method handles long-term yearly load increase and generates the best network expansion plans, namely, the best network reconfiguration and construction plans for each year of the target term. The proposed method is verified by comparing construction plans generated by the proposed method with the actual plan composed by experienced planning persons in distribution control centers. It is found that the proposed method can generate the same plans 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 network expansion planning method.

Index Terms-- Construction Plans, Distribution Network Expansion Planning, Modern Heuristic Technique, Network Reconfiguration, 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 evaluation items such as 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 large customer loads when planning. Experienced persons have performed the planning conventionally. However, only a few cases have been evaluated practically because of limited planning time. Therefore, it is difficult to evaluate optimality of the generated plans from the above-mentioned points of view.

Takanobu Asakura, Takamu Genji, and Toshiki Yura are with technical research center, Kansai Electric Power Co., Inc., 3-11-20, Nakoji, Amagasaki, Hyogo 661-0974, Japan.

Naoki Hayashi and Yoshikazu Fukuyama are with Corporate Technology Development Office, Fuji Electric Corporate Ltd., No.1, Fuji-machi, Hino, Tokyo 191-8502, Japan. Email: {hayashi-naoki, fukuyama-yoshikazu}@fujielectric.co.jp.

Recently, reduction of maintenance costs, restraining investment for equipment and energy-saving are of primary concerns in power utilities. Therefore, more efficient distribution network expansion planning is required. Many approaches have been proposed in the expansion planning [2-6]. Most of them have been developed for allocation of substations and feeders. The authors have also presented the optimal network configuration, service restoration, and network expansion methods for the planning tools [7-10]. However, a practical network expansion planning system for generating construction plans such as exchange of distribution lines to thicker lines, installation of new switches considering long-term equipment costs has not been developed yet.

This paper proposes a distribution network expansion planning method by network reconfiguration and generation of construction plans. The method evaluates various items including new equipment installation cost, equipment utilization rate, reliability of the target distribution system by contingency analysis, and loss minimization. It also copes with yearly load growth during the target term. It generates various construction plans using expert system (ES) [9,10], reactive tabu search (RTS) [8-10], and three phases unbalanced load flow calculation [7,10]. The load flow calculation utilizes backward-forward sweep (BFS) type fast distribution power flow calculation method [11]. The proposed method is verified by comparing construction plans generated by the proposed method with the actual plan composed by experienced planning persons in distribution control centers. It is found that the proposed method can generate the same plans 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 network expansion planning method.

II. OUTLINE OF THE PROPOSED METHOD

Fig.1 shows a general flow chart of the proposed method. Firstly, distribution network data such as load increase rates, switch status (open/close), and connection status between sections are set at the current year (Step.1), and loads of the current year are calculated. Then, the proposed method tries to reconfigure the target network by evaluating loss minimization, correction of imbalance, and equalization of utilization rate of the target networks using RTS [7][10] (Step.2). If operational constraints such as voltage and current constraints, and power source capacity constraints are violated even in an optimal

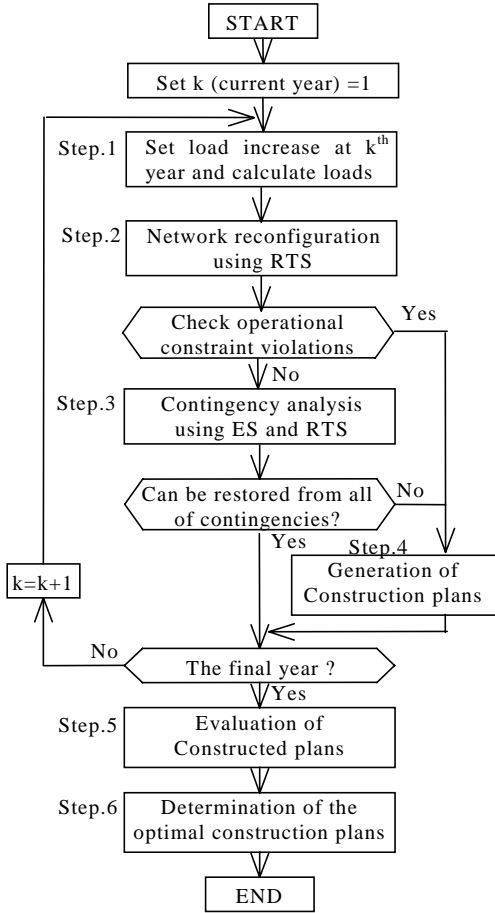


Fig. 1 A general flow chart of the proposed method.

network configuration, the method determines to generate construction plans (Step. 4). Otherwise, the method performs contingency analysis using ES and RTS [9] (Step.3). Namely, the method automatically generates various faults in the target network and checks whether the network can be restored for all of the contingencies. If the network cannot be restored for all of the contingencies, the method also determines to generate construction plans (Step.4). If the method determines to generate construction plans, it generates several construction plan candidates and performs network reconfiguration and contingency analysis again for each network configuration with each construction plan. The method repeats to generate construction plans until a certain network configuration, without operational constraint violations and which can be restored for all of the contingencies, can be generated. Considering load growth and new large customer load installation, the procedure is repeated until the current year reaches the predetermined final year. Finally, each generated construction plan using the proposed method is evaluated with respect to construction costs, loss minimization, capability of service restoration for various contingencies, and equipment utilization rate (Step.5). Then, the optimal construction plans are determined (Step.6) and the network configuration of each year is also determined.

In the proposed method, three phase unbalanced load flow calculation is used for calculating values of the objective function and checking whether the constraints are satisfied or

not. Generally, distribution systems have huge number of single-phase loads and it may cause unbalanced voltage at a long feeder. Therefore, three phases unbalanced load flow calculation is more suitable than the conventional simple single-phase calculation [11][12].

Reactive Tabu Search (RTS) [13] is utilized to search the optimal solutions in step.2 and 3. RTS is a kind of modern heuristic methods. The other methods like Genetic Algorithm (GA), Simulated Annealing (SA), and Tabu Search (TS) require adjusting search parameters for efficient search in advance. However, in general, the appropriate parameter values depend on the target problem. On the other hand, RTS can adjust search parameters during search procedure automatically. Therefore, RTS can avoid disadvantages of conventional modern heuristic methods [13].

III. PROBLEM FORMULATION OF NETWORK RECONFIGURATION (STEP. 2) [10]

The optimal network configuration is generated by changing switch on/off status using RTS. This problem is formulated as follows:

[Objective function]

The following objectives are considered:

(1) Loss minimization

Minimize total active power loss at all branches in the network.

(2) Correction of voltage imbalance

Minimize summation of means of voltage standard deviations at nodes in each end-section of the network because imbalance is usually maximized at the end sections and the violation of the voltage constraints may be occurred at the sections.

(3) Voltage regulation

Maximize summation of differences from the voltage limits at nodes in each end-section of the network. As a result, voltages are regulated at appropriate values within its permissible range. The following equations express the objective function mentioned above:

Minimize

$$f = w_1 \sum_{i=1}^l Loss_i + w_2 \sum_{k=1}^m \left\{ \frac{\sum_{j=1}^{n_k} Std_{kj}}{n_k} \right\} + w_3 \frac{1}{\sum_{k=1}^m \sum_{j=1}^{n_k} \sum_{j=A}^C \Delta V_{kji}^2} \quad (1)$$

$$Std_{kj} = \sqrt{\frac{\sum_{i=A}^C (V_{kji} - \bar{V}_{kj})^2}{3}} \quad (2)$$

where, l : number of branches,

$Loss_i$: loss at branch i ,

m : number of end-sections,

n_k : number of nodes in end-section k

Std_{kj} : voltage standard deviation at node j
in end-section k

V_{kji} : voltage of phase i at node j in
end-section k

\bar{V}_{kj} : mean voltage of phase A, B, and C at node
 j in end-section k

w_i : weighting factor for each term,

ΔV_{kji} : difference of voltage of phase i from its limit at node j in end-section k

ΔV_{kji} is calculated by the following equations.

$$\text{If } V_{kji} > V_{\max} \text{ or } V_{kji} < V_{\min}, \quad \Delta V_{kji} = \varepsilon \quad (3)$$

$$\text{If } \frac{V_{\max} + V_{\min}}{2} < V_{kji} < V_{\max}, \quad \Delta V_{kji} = (V_{\max} - V_{kji}) \quad (4)$$

$$\text{If } V_{\min} < V_{kji} < \frac{V_{\max} + V_{\min}}{2}, \quad \Delta V_{kji} = (V_{kji} - V_{\min}) \quad (5)$$

where, V_{\max} : upper limit of voltage

V_{\min} : lower limit of voltage

ε : a small number

[Constraints]

(1) Radial network constraint

Distribution network should be composed of radial structure considering operational point of view.

(2) Power source limit constraint

The total loads of a certain partial network cannot exceed the capacity limit of the corresponding power source.

(3) Voltage constraint

Voltage magnitude at each node must lie with their permissible range in order to maintain power quality.

(4) Current constraint

Current magnitude of each branch (feeder, laterals, and switches) must lie with their permissible range.

IV. CONTINGENCY ANALYSIS [8][9]

The method performs contingency analysis using ES and RTS. Namely, the method automatically generates various faults in the target network and checks whether the network can be restored for all of the faults. The types of fault must be specified by human operators in advance. Human operators can specify any combination of the following types of faults:

(1) Substation fault

Specify a substation where a fault occurs. All sections in the substation become an out-of-service area.

(2) Transformer fault

Specify a transformer where a fault occurs. All sections connecting to the transformer become an out-of-service area.

(3) Feeder fault

Specify a feeder where a fault occurs. All sections in the feeder become an out-of-service area.

(4) Section fault by direct specification

Specify a section where a fault occurs. All downstream sections of the section become an out-of-service area.

(5) Section fault by specified feeder and distance from power source

Specify a feeder and distance from power source. All downstream sections of the section, which has specified distance from power source in the specified feeder, become an out-of-service area.

(6) Direct specification of an out-of-service-area

Specify sections, which become an out-of-service area directly.

After specifying the target contingencies, the proposed method is checked whether it can restore the target distribution system for the contingencies. The service restoration method tries to utilize as many neighboring power sources of an out-of-service area as possible. The method has the following features:

(1) This method is a hybrid method with Expert System (ES) and Reactive Tabu Search (RTS).

(2) ES performs multistage switching operation to increase the total spare capacity of the neighboring power sources of the out-of-service area.

(3) RTS decomposes the loads in the out-of-service area to the neighboring power sources.

In the service restoration method, ES performs multistage switching operation when the total spare capacity of the neighboring power sources of the out-of-service area is less than the total loads of the out-of-service area. Multistage switching operation is to determine switch on/off status so that a part of the loads of a power source is transferred to a neighboring power source of the power source. As a result, spare capacity of the neighboring power sources of the out-of-service area can be increased. Multistage switching is a large-scale combinatorial optimization problem and we have a lot of knowledge on the problem. Therefore, Expert System is suitable for this problem [9].

After the procedure of ES, RTS determines switching operation for decomposing the out-of-service area into several partial areas for each neighboring power source. This problem can be also formulated as a combinatorial optimization problem like the problem shown in chapter III. Therefore, this problem can be solved using RTS as a combinatorial optimization method. The advantages of RTS are already shown in chapter III [8].

Namely, in a solution space, ES can move the initial solution for RTS into a feasible region when the initial solution is outside the feasible solution. Then, RTS can search the optimal network configuration for service restoration inside the feasible region. The concept of the role of ES and RTS in service restoration is shown in Fig. 2.

V. PROCEDURES OF NETWORK EXPANSION PLANNING

A. Concept of network expansion planning

Even in the optimal network configuration generated by the above-mentioned method, the operational constraints may be violated. In such a case, the proposed method generates construction plans under the following constraints:

(1) Power source constraint

The total loads of a certain partial network cannot exceed

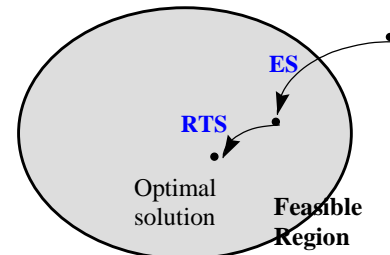


Fig.2 Roles of ES and RTS in solution space for service restoration.

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 generated. The effect of elimination of each constraint violation by the construction plans is evaluated. The following construction plans will apply to eliminate each constraint violation as shown in Table 1.

B. Construction plans for power source constraint violations

The power source constraint violation means that at least one of power source currents is larger than the permissible power source capacity because of heavy loads. Namely, this means the target distribution network has overloaded 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 on the feeder. 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 decomposition of one section into two sections. If there are some margins of substation transformer capacity, new feeders can be installed.

C. Construction plans for current constraint violations

The current constraint violation means that at least one of section currents is larger than 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 handle the current constraint violation 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.

D. Construction plans for voltage constraint violations

The voltage constraint violation means that at least one of node voltages 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 handle the voltage constraint violation are installation of new tie-lines, tie-switches, section switches, and voltage regulators (Step Voltage Regulator: SVR) in actual expansion planning. The decrease of load current can lead to decrease of voltage drop.

E. 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 other feeders. Therefore, the construction plans may lead to constraint violations of other feeders. On the other hand, exchange of lines to thicker lines and installation of SVR do not affect other feeders because of no load transformation. The two construction plans may not be able to handle constraint violations by themselves. Namely, only one construction plan may not be enough to handle 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 already applied. Moreover, the third construction plan should be considered if constraint violations could not be eliminated even after the second construction is applied. Thus, multiple construction plans are considered until constraint violations are eliminated. Namely, expansion planning is usually composed of combinations of several construction plans. Fig. 3 shows a concept of combinations of construction plans. The combinations of construction plans are described as follows:

- (Step 1) The First construction plan is applied in order to handle the constraint violations. If the constraint violations are eliminated, exit. Otherwise, go to step 2.
- (Step 2) If constraint violations are not eliminated, 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 eliminated or the total number of combinations of construction plans reaches the predetermined maximum number.

TABLE I
CONSTRUCTION PLANS FOR CONSTRAINT VIOLATIONS.

Constraint violation	Construction plans
Power source	<ul style="list-style-type: none"> • Installation of new tie-lines • Installation of new tie-switches • Installation of new section switches • Installation of new feeders
Current	<ul style="list-style-type: none"> • Exchange of lines to thicker lines • Installation of new tie-lines • Installation of new tie-switches • Installation of new section switches
Voltage	<ul style="list-style-type: none"> • 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

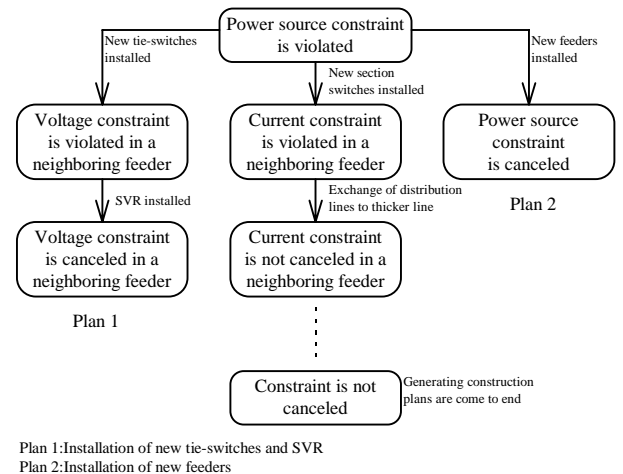


Fig. 3 A concept of combinations of construction plans.

VI. TOTAL EVALUATION METHOD OF EACH CONSTRUCTION PLAN

A. Outline of total evaluation method

The proposed method determines the optimal construction plans and the optimal network configurations. Therefore, the proposed method must store the network configuration of each year in which construction plans of each year are reflected. Namely, the proposed method must store transitions among the network configuration candidates. Fig. 4 shows an example of the network configuration transition until 4th year. The proposed method generates an optimal network configuration without construction for initial network (No.1 circle in Fig. 4). Since the optimal network configuration does not exist, the proposed method generates three construction plans (No.2, 3 and 4 circle in Fig. 4) for the 2nd year. Namely, the network configurations with construction plans become network configuration candidates 2, 3, and 4, respectively in Fig. 4. In Fig. 4, the procedure is repeated until the final decision year (4th year). As a result, the proposed method generates 5 network configuration transition candidate scenarios as shown in Table 2. The proposed method calculates total costs of each network configuration transition candidate including construction costs and conversion costs of network losses. The network configuration transition with the minimum total cost becomes the optimal network configuration transition. Then, the construction plans and the network configurations included in the network configuration transition become the optimal construction plans and the optimal network configurations. For example, if the network transition candidate 3 in Table 2 has 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.

B. Formulation of total evaluation method

The proposed method evaluates the total costs generated

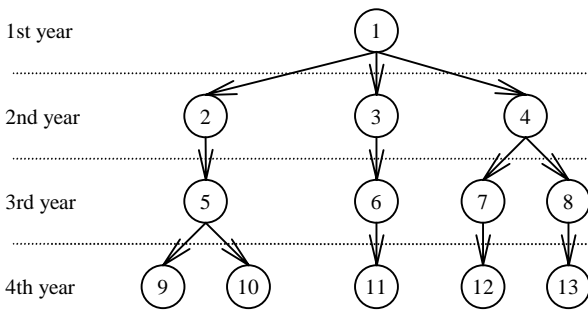


Fig. 4 A concept of network configuration transition.

TABLE II
NETWORK CONFIGURATION TRANSITIONS OF EACH YEAR.

Network configuration 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

for each network configuration transition. It calculates construction costs and conversion costs of network losses. As a result, the proposed method determines the network configuration 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 sum of the yearly costs of each generated network configuration transition.

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

$$C_i = A_i \times B_i \quad (6)$$

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:

$$F_i = C_i \times (1 + E)^k \times D_i \quad (7)$$

where,

F_i : The equally divided yearly costs of generated construction plan i,

E : Discount rate of installed equipment,

D_i : Unit weighting factor of plan i,

k : The construction year of plan i.

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

$$TCC_j = \sum_{i=1}^n F_i \quad (8)$$

where,

TCC_j : The total yearly construction costs of each network transition j,

n : The total number of construction plans in network transition j.

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

$$G_k = L_k \times H_k \quad (9)$$

where,

G_k : The conversion costs of network losses of year k,

L_k : The network losses of year k,

H_k : A unit generator installation cost corresponding to the losses at year k.

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

$$TNL_j = \sum_{k=1}^m G_k \quad (10)$$

where,

TNL_j : The total conversion costs of network losses of network transition j,

m : The final planning year.

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

$$TYC_j = TCC_j + TNL_j \quad (11)$$

where,

TYC_j : The total yearly cost of network transition j .

The proposed method calculates TYCs of all network configuration transitions. Then, the proposed method determines a minimum TYC as an optimal solution. The other network transition candidates are decided as the sub-optimal solutions.

VII. NUMERICAL SIMULATIONS

A. Simulation conditions

The proposed method has been 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. 5 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 heavy loading conditions. 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.

B. Simulation results

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

Firstly, the proposed method generates the optimal network configuration without operational constraint violations. The distribution network model shown in Fig. 5 does not have the optimal network configuration without the violation because the network reconfiguration cannot eliminate the power source constraint violations. In Fig. 5, power source current in feeder 3 is 312.9[A]. Therefore, the proposed method generates some construction plans in order to handle the power source constraint violations. Since the network configuration shown in Fig. 5 becomes minimum objective function, Fig. 5 becomes initial network configuration in the proposed method. The proposed method generates construction plans by applying the generation algorithm of construction plans. As a result, the proposed method generates 3 construction plans. The network

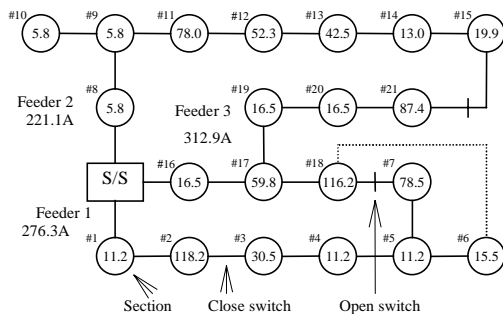


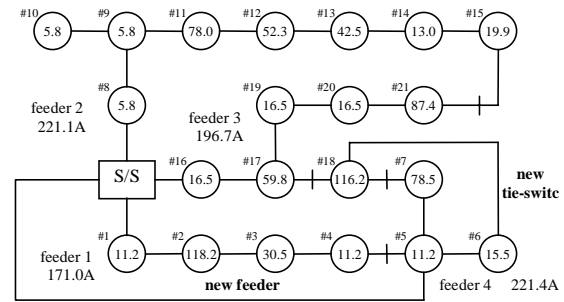
Fig. 5 A practical distribution network model.

configuration and generated construction plan are shown in Fig. 6 and in Table 3, respectively. All generated construction plans can eliminate the constraint violations. 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. 6. 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 plan alternatives (a), (b) shown in Fig. 6.

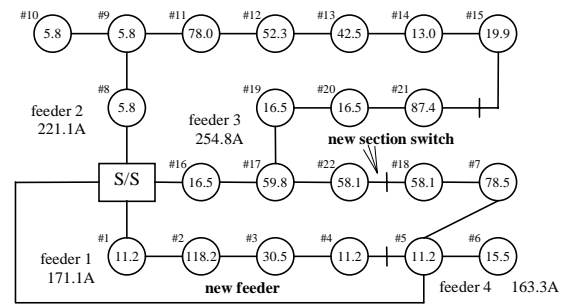
(2) Results of generation of construction plans after initial year

Fig. 7 shows the network configuration transition results until the planning year reaches the 10th year. The network configuration candidate No. 0 shown in Fig. 7 shows the initial

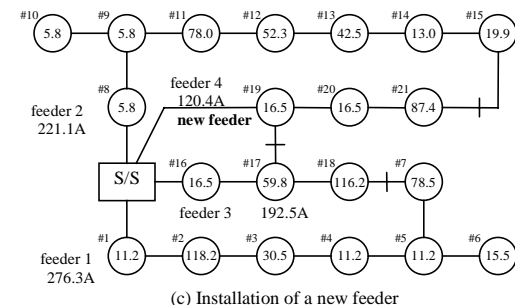
No	Generated construction plans
(a)	Installation of a new tie-switch and feeder
(b)	Installation of a new section switch and feeder
(c)	Installation of a new feeder



(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. 6 Results of expansion planning for the initial year.

network configuration shown in Fig. 5. The network configuration candidates No. 1, 2 and 3 shown in Fig. 7 correspond (a), (b) and (c) shown in Fig. 6, respectively. The network transition with broken lines in Fig. 7 requires the construction. On the other hand, the network transition with full 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 configuration transitions.

(3) Results of total evaluation

The proposed method evaluates the total yearly costs of 5 generated network configuration 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 value of the network transition No. 4 is set to a reference value (100.0). According to the result, the network transition No. 4 is found to be the optimal network configuration transition. Namely, the optimal network configuration transition has two construction plans during the target 10 years. 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 configuration transition No. 5 is the most expensive network transition because it includes the installation of new feeders at 1st and 4th year. The network configuration transitions No. 1 and 3 include the same construction plans, which install a new tie-switch and a new feeder. However, the network transition No. 1 is more expensive than No. 3 (about 1.73 times). The network configuration transitions No. 2 and 4 include the same construction plans, which install 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 than all construction plans are performed at a same year (1st year). As indicated in the example, the proposed method can easily compare the total yearly costs.

Table 5 shows the execution time in 6 practical distribution network models. All calculations 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.

Fig.8 (a)(b) shows an example of display for showing the planning results on a proto type system. All of the characters in Fig.8 are Japanese. The upper figure shows the original network and the lower figure shows one of the construction plans. Fig. 8 (b) shows a network configuration transition with construction plans from 2000 (current year) to 2007. Fig. 8 (a) will be appeared when a network configuration candidate number is pushed in Fig. 8 (b).

VIII. CONCLUSIONS AND FUTURE WORKS

This paper proposes a long-term distribution network expansion planning method by network reconfiguration and generation of construction plans. The proposed method can generate the same construction plan generated by the

experienced planning persons. Moreover, the proposed method can generate other two practical construction plans, which the experienced planning persons do not generate. The proposed method can easily compare the total yearly costs using the total

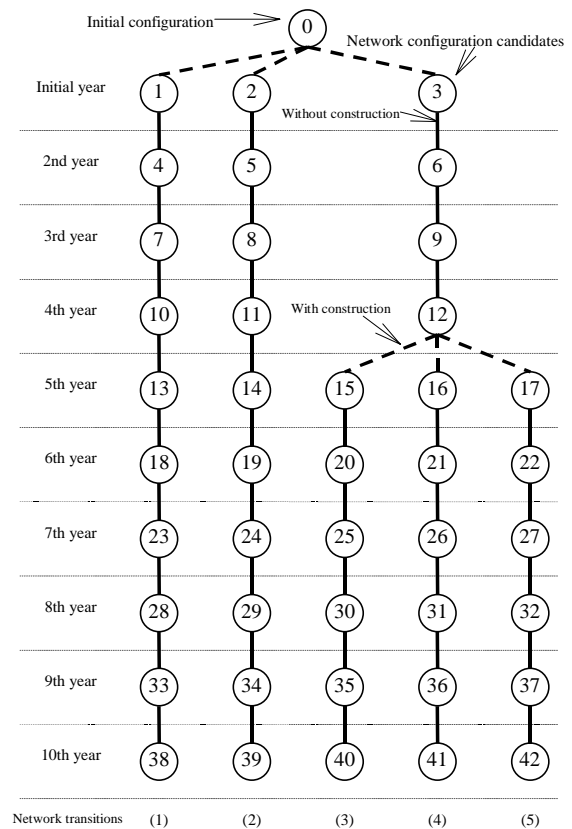


Fig. 7 Results of network configuration transition.

TABLE IV
RESULTS OF TOTAL EVALUATION.

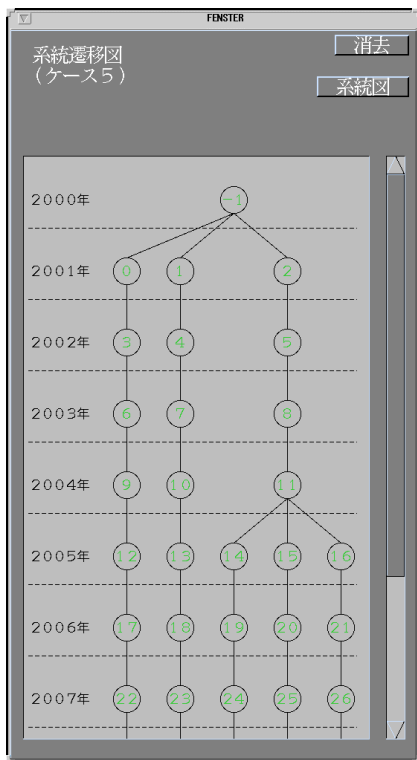
Network transitions	Planning year	Construction plans	Target sections	Yearly costs	Rank order
(1)	1	New tie-switch	6,18	175.2	4
		New feeder	5		
(2)	1	New section switch	18	173.6	3
		New feeder	5		
(3)	1	New feeder	19	101.7	2
	4	New tie-switch	6,18		
(4)	1	New feeder	19	100.0	1
	4	New section switch	7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

TABLE V
THE EXECUTION TIME OF EACH CASE.

Case	Network configuration	Total network configuration	Total network transitions	Exec. 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



(a) The original network and the network with a construction plan.



(b) A network transition from 2000 to 2007.

Fig.8 An example of display on EWS.

evaluation method. 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.

Introduction of distributed generators is one of the current primary concerns in distribution planning. Introduction of distributed generators is easily considered in the proposed method at step.1 in fig.1. Various simulation models for distributed generators have been already developed in [11] and expanded to three phase unbalanced models [12]. Therefore, introduction of distributed generators can be easily considered in the proposed method.

The execution time is increasing as the number of the network configuration candidates increases. Therefore, if

speed-up of the whole execution time has to be realized, parallel computation methods based on distributed memory tools such as PVM [14] and MPI [15] or shared memory tools such as OpenMP [16] can be utilized for the network reconfiguration and contingency analysis parts. Moreover, if three phase unbalanced data cannot be obtained or three phase unbalance does not have to be considered, single-phase load flow calculation can be utilized instead of three phases unbalanced load flow calculation and speed-up of the whole execution time can be realized.

IX. REFERENCES

- [1] Y. Y. Hsu, J. L. Chen, "Distribution Planning Using A Knowledge-based Expert System", *IEEE Trans. on Power Delivery*, Vol.5, No.3, 1990.
- [2] K. Aoki, K. Nara, et al., "New Approximate Optimization Method for Distribution Systems Planning", *IEEE Trans. on Power Systems*, Vol.5, No.1, 1990.
- [3] P. P. S. Carvalho, L. M. F. Barruncho, et al., "Optimal Distribution Network Expansion Planning under Uncertainty by Evolutionary Decision Convergence", *Proc. of 12th PSCC*, Dresden, August 1996.
- [4] K. Nara, Y. Hayashi, et al., "A New Feeder Route Determination Algorithm by Dijkstra Method and Tabu Search", *Proc. of ISAP97*, July 1997.
- [5] I. J. Ramirez-Rosado, et al., "Genetic Algorithm Applied to the Design of Large Power Distribution Systems", *IEEE Trans. on Power Systems*, Vol.13, No.2, May 1998.
- [6] L. M. Ferreira, et al., "Distribution Planning Tool Optimizes Design", *Transmission and Distribution World*, October 1998.
- [7] H. Fudou, T. Genji, Y. Fukuyama, et al., "A Genetic Algorithm for Network Reconfiguration Using Three Phase Unbalanced Load Flow", *Proc. of ISAP*, July 1997.
- [8] S. Toune, T. Genji, Y. Fukuyama, et al., "Comparative Study of Modern Heuristic Algorithms to Service Restoration in Distribution Systems", *IEEE Trans. on Power Delivery*, Vol.17, No.1, January 2002.
- [9] S. Toune, T. Genji, Y. Fukuyama, et al., "Hybrid System for Service Restoration in Distribution Systems Using Expert System and Reactive Tabu Search", *Proc. of International Conference on Electrical Engineering (ICEE)*, July 1998.
- [10] T. Genji, Y. Fukuyama, et al., "Optimal Network Reconfiguration Considering Customer Reliability", *Proc. of IEEE ISAP Conference*, 1999.
- [11] T. Genji and Y. Fukuyama, "Practical Equipment Models for Fast Distribution Power Flow Considering Interconnection of Distributed Generators", *Proc. of IEEE PES Summer Meeting*, July 2001.
- [12] T. Genji, Y. Fukuyama, et al., "Development of Equipment Models for Fast Distribution Three Phase Unbalanced Load Flow Calculation", *Trans. on IEE of Japan*, Vol.122B, No.2, February 2002 (in Japanese)
- [13] R. Battiti, "The Reactive Tabu Search", *ORSA Journal on Computing*, Vol. 6, No. 2, pp.126-140, 1994.
- [14] J. Dongarra, et al., *PMV 3 User's Guide and Reference Manual*, Oak Ridge National Laboratory, May 1993.
- [15] W. Gropp, et al., *Using MPI*, The MIT Press, 1994.
- [16] *OpenMP C and C++ Application Program Interface Version 1.0*, OpenMP Architecture Review Board, October 1998.

X. BIOGRAPHIES



Takanobu Asakura received B.S. and M.S. degrees in electrical engineering in 1986 and 1988, respectively, from Kyoto University, Japan. He has been working at Kansai Electric Power Co. Japan from 1988. His research interests include distribution system equipment failure and distribution system.



Takamu Genji received B.S. and M.S. degrees in electrical engineering in 1973 and 1975, respectively, from Okayama University, Okayama, Japan. He joined Kansai Electric Power Co. in 1975 and has been working at Technical Research Center from 1985. His research interests include lightning countermeasures in distribution systems and distribution automation. He is a member of IEE of Japan.



Naoki Hayashi received B.S. and M.S. degrees in electrical engineering in 1988 and 1990, respectively, from Niigata University, Niigata, Japan. He has been working at Fuji Electric Co. R&D Japan from 1990. His research interests include application of distribution systems. He is a member of IEE of Japan.



Toshiki Yura received B.S. and M.S. degrees in electrical engineering in 1975 and 1977, respectively, from Kyoto University, Kyoto, Japan. He joined Kansai Electric Power Co. in 1977 and has been working at Technical Research Center from 1999. His research interests include distribution systems. He is a member of IEE of Japan.



Yoshikazu Fukuyama (M'90) received B.S., M.S., and PhD degrees in electrical engineering in 1985, 1987, and 1997, respectively, from Waseda University, Tokyo, Japan. He has been working at Fuji Electric Co. R&D Japan from 1987. He was a visiting scientist at Cornell University from 1993 to 1994. His research interests include application of intelligent systems such as expert system, neural network, and modern heuristic techniques to power and energy systems, and power system analysis including voltage stability and load flow. He is also interested in applications of modern heuristic techniques to practical and general optimization problems. He is a member of IEEE and IEE of Japan.