

COMPARATIVE STUDY OF MODERN HEURISTIC ALGORITHMS TO SERVICE RESTORATION IN DISTRIBUTION SYSTEMS

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Abstract: This paper presents a comparative study for four modern heuristic algorithms (MHAs) to service restoration in distribution systems: reactive tabu search, tabu search, parallel simulated annealing, and genetic algorithm. Since service restoration is an emergency control in distribution control centers to restore out-of-service areas as soon as possible, it requires fast computation and high quality solutions for customers' satisfaction. The problem can be formulated as a combinatorial optimization problem to divide the out-of-service area to each power source. The effectiveness of the MHAs is compared against each other on typical service restoration problems.

Keywords: Service Restoration, Distribution Systems, Combinatorial Optimization, Modern Heuristic Algorithms, Reactive Tabu Search, Tabu Search, Parallel Simulated Annealing, Genetic Algorithm

I. INTRODUCTION

Customer satisfaction and service reliability are of primary concerns in the power industry. Several studies on power utilities' experience suggest that customer satisfaction is closely correlated with service interruption frequency and interruption duration. The main objective of service restoration is to restore as many loads as possible (i.e. minimize loads in out-of-service areas) by transferring de-energized loads in the out-of-service areas to other supporting distribution feeders without violating operating and engineering constraints via network reconfigurations. Developing effective service restoration procedures is a cost-effective approach to improve service reliability and consequently, enhance customer satisfaction. Therefore, fast service restoration has a multi-fold benefit. In actual use, distribution operators are required to restore service of out-of-service areas as soon as possible.

The service restoration problem is a combinatorial, non-

linear, and constrained optimization problem. The complexity of such a problem calls into doubts the effectiveness of the restoration procedures based on pre-established guidelines. In fact, the service restoration problem belongs to the so-called NP-complete problems. There are no known methods to solve NP-complete problems exactly in a reasonable time.

In the past, considerable efforts have been devoted to the subject of service restoration in distribution systems [1-7]. The problem has been addressed with methods such as heuristic algorithms [1,3,5], expert systems [2], data base [4], and fuzzy reasoning [7]. However, these methods produce solutions, which may not even be sub-optimal. In [6], the Hopfield type neural network was applied. However, they devoted their efforts to analyzing the neural network itself and the method itself is not practical.

Recently, modern heuristic algorithms (MHAs) [8] such as genetic algorithm [9], parallel simulated annealing [10], tabu search [11][12], and reactive tabu search [13][14] have been used for various combinatorial optimization problems including service restoration in power systems. The authors have developed a parallel genetic algorithm for service restoration and showed promising results on several distribution networks [15]. However, it requires parallel processors and, unfortunately, conventional engineering workstation (EWS) or personal computer (PC) is still utilized for the main computer in practical distribution control centers. Therefore, an EWS-based or PC-based efficient method is eagerly awaited for practical implementation of service restoration.

This paper investigates the applicability of the following four different MHAs in the service restoration problem: genetic algorithm (GA), parallel simulated annealing (PSA), tabu search (TS), and reactive tabu search (RTS). A problem-dependent heuristic method is presented for representing the state variable and generating initial sub-optimal states in a solution space. The feasibility of the algorithms for service restoration is compared and demonstrated on typical distribution networks with promising results.

II. MODERN HEURISTIC ALGORITHMS

Genetic Algorithm [9]

GA is one of the stochastic search algorithms based on the mechanics of natural genes. A solution variable for the problem is first represented using artificial chromosomes (strings). In other words, the problem is encoded to strings that GA can

handle. A string represents one state (searching point) in the solution space. Since GA utilizes a set (population) of strings (i.e. multiple searching points), it belongs to a kind of the parallel search methods. It modifies strings (searching points) using natural selection and genetic operators such as cross-over and mutation. After convergence, strings are decoded to the original solution variables and the solutions are obtained. The procedure of GA can be expressed as follows:

Step.1 Representation of the problem using strings

The parameters of the original problem are represented using a series of binary, decimal, and floating point number, namely string.

Step.2 Generation of an initial set of states (string population)

Strings are generally generated randomly. However, it is sometimes effective to produce initial strings using the problem-dependent methods. These methods produce sub-optimal initial searching points in the solution space. Using the sub-optimal initial searching points sometimes realizes fast convergence to the optimal solution.

Step.3 Evaluation and selection of each string

Strings are evaluated using the fitness function, which represents the tendency of fitness of each string to the target problem. A good candidate for the fitness function is the objective function of the problem. Basically, the strings that have higher fitness values are selected for the next generation with high probability. In other words, better searching points are selected according to their objective function values. The original GA utilizes roulette wheel selection [9]. However, improved methods such as stochastic sampling with and without replacement [9] and elite strategy have been proposed.

Step.4 String operations (generation of neighboring states)

GA performs string operations such as cross-over and mutation. The operations produce new searching points using the current searching points. Crossover generates two new searching points from the two current searching points. Mutation generates one new searching point from one current searching point. Natural selection and string operations are repeated until the strings are converged to the optimal or sub-optimal solution.

The details on GA could be found in [9].

Parallel Simulated Annealing [10]

Parallel Simulated Annealing (PSA) is an extension of simulated annealing (SA). Although SA is an attractive optimization technique, small state transition often makes SA gets stuck in local minima in cases where the solution space of the target problem is large or constraints of the target problem are strict. In order to overcome the problems, PSA parallelizes the routines of state transition in the original SA to obtain better searching points efficiently. PSA basically utilizes one searching point like SA. However, it generates multiple

neighboring states rather than a single state like SA. It allows to find out a solution near a global minimum over a wide range due to handling a set of solution candidates. The characteristics of PSA are summarized as follows:

- a) PSA has a distinct possibility of reaching a optimal solution due to multiple searching points.
- b) PSA has better convergence characteristics because of selecting the best state among solution candidates.

The PSA algorithm can be written as follows:

Step.1 Initialization

Give the initial state, searching point x_0 and temperature T_0 and evaluate the energy function $E(x)$, which is generated by the objective function of the original problem.

Step.2 Generation and evaluation of neighboring states

Generate several perturbation states Δx_i (Δx of the searching point) of the current state (x) and evaluate the energy function $E(x + \Delta x_i)$ at each neighboring states. Calculate the energy ΔE using the following equation:

$$\Delta E = \min_i \{ E(x + \Delta x_i) \} - E(x) \quad (1)$$

Step.3 Generation of the next state

if the following condition is satisfied

$$\Delta E < 0 \quad (2),$$

or

$$\exp(-\Delta E / T_k) > R \quad (3),$$

then the current state is changed to

$$x = x + \Delta x_i \quad (4).$$

Update the temperature and repeat step 2 and 3 until the convergence criterion is satisfied.

Tabu Search [11][12]

TS is based on the use of prohibition-based techniques and basic heuristic algorithms like local search. Therefore, the main advantage of TS with respect to conventional GA and SA lies in the intelligent use of the past history of the search to affect its future search procedures. Since the method utilizes a tabu list for storing the past history of the search, the efficient structure of the tabu list is important for fast computation. The procedure of TS can be expressed as follows:

Step.1 Initialization

Give the initial state, searching point x_0 and put the current state into the tabu list.

Step.2 Generation and evaluation of neighboring states

Generate all of possible neighboring states and check whether the states are tabu or not.

Step.3 Generation of the next state

Move the current state to the next state that is not tabu and have the lowest objective function value.

repeat step 2 and 3 until the convergence criterion is satisfied. The details of the method can be found in [11][12].

Reactive Tabu Search [13][14]

The conventional modern heuristic methods like GA, SA, and TS require adjusting search parameters for efficient search.

However, in general, the appropriate parameter values depend on each problem. Therefore, a parameter tuning problem is known as one of the disadvantages of the MHAs. The Reactive Search (RS) framework proposes the introduction of feedback (reactive) schemes in heuristics for discrete optimization problems [13]. RTS is one of the RS methods and it has feedback-based tuning mechanism of tabu length (TL) and automated balance mechanism of diversification and intensification. RTS stores all searched states. After one move is performed, the algorithm checks whether the current searching point has already been found. TL increases if a searching point is repeated, while TL decreases if no repetitions occur during a sufficient long period. This adjusting mechanism allows us to escape from the local valley. Moreover, since the basic TS mechanism cannot avoid long search cycles, RTS introduces the escape procedure. It consists of a number of random steps starting from the current searching point.

Effective search in the solution space requires balance of diversification and intensification. GA realizes the balance by the string operations and the selection mechanism, and sometimes requires more effective local search procedure. PSA realizes parallel search by several conventional SA search procedures. However, it requires parallel processors for practical speedup. TS realizes the balance between diversification and intensification using a tabu list. RTS, moreover, strengthens the mechanism using reaction and escape mechanism.

III. PROBLEM FORMULATION OF SERVICE RESTORATION

Distribution system model

The following assumptions for distribution systems are usually made for practical application of service restoration.

- Power source can be formulated as current injection source.
- Voltage at the power source is known.
- An area surrounded by switches is called a section. Each section has a concentrated load and each load can be formulated as constant contracted current.
- Each section line impedance $Z(n)$ can be calculated as an equivalent scalar impedance using load power factor and line constants.

According to the above assumption, distribution system can be expressed as shown in Fig. 1.

Circuit calculation method

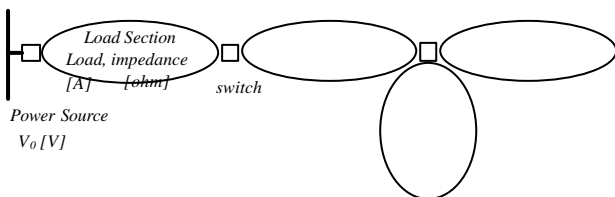


Fig. 1 A distribution system model.

In order to calculate voltages and currents in the target distribution system correctly, load flow calculation is necessary. However, the following backward and forward sweep circuit calculation is usually performed for the sake of fast service restoration [15].

Step.1 Sum up total load currents (backward calculation)

Sum up total load currents from the end of the branches to the power source according to the following equation.

$$SCUR(n) = CUR(n) + SCUR(n-1) \quad (5)$$

where,

$SCUR(n)$: Total load currents at section n,

$CUR(n)$: Contracted load currents at section n,

n-1 : Node that is next to section n at the downstream side.

If the node n is the end of feeder, $SCUR(n-1)$ is 0 (A).

Step.2 Calculate voltage drops

Calculate voltage drop at each node according to the following equation:

$$\Delta V(n) = SCUR(n) \times Z(n) \quad (6)$$

where,

$\Delta V(n)$: Voltage drop at node n,

$Z(n)$: Equivalent impedance at node n.

Step.3 Calculate voltage (forward calculation)

Voltage at each node can be calculated from the power source using the following equation:

$$V(n) = V(n+1) - \Delta V(n) \quad (7)$$

where,

$V(n)$: Voltage at node n,

n+1 : Node that is next to node n at the upstream side.

The voltage and current calculation method is appropriate when the target distribution system is always operated in radial network structures, like in Japan. However, if it is required to consider a network with loops, we have to utilize backward forward power flow calculation methods which can handle loops [16].

Objective function and constraints

The most important objective of the service restoration is to restore as many customers as possible. In many fault cases, it is enough to energize the out-of-service area from the only one neighboring power source. However, it is necessary to utilize several power sources next to the large out-of-service area. In such a case, service restoration can be formulated as one of the graph partitioning problems to divide the out-of-service area to corresponding power sources. The objective function is to counterbalance spare capacity of each power source considering next faults and maximize the minimum voltage of the network considering customers' satisfaction in the large out-of-service area. The function can be expressed as follows:

$$f_c = \min \left\{ w_1 \sum_{i=1}^m (SP_i - SP_{ave})^2 + w_2 \frac{1}{V_{\min}} \right\} \quad (8)$$

where,

m : number of power source,

- Sp_i : Spare capacity of source i ,
- SP_{ave} : Average of spare capacity of all sources,
- V_{min} : Minimum voltage of the target network,
- w_i : coefficients for each term.

The followings are constraints, which should be considered for practical service restoration.

(a) Radial network constraint

Distribution network should be composed of radial structure from an operational point of view. Therefore, each section has only one up-stream section.

(b) Power source limit constraint

The total load capacity of each partial network cannot exceed the capacity limit of the corresponding power source.

$$\sum_{k=1}^{l_i} LOAD_{ik} \leq CAP_i \quad (9)$$

where,

- l_i : number of load for power source i ,
- CAP_i : Capacity of power source i ,
- $LOAD_{ik}$: Capacity of load k energized by power source i .

(c) Voltage constraint

Voltage magnitude at each section must lie with their permissible ranges.

$$V_{min} \leq V_i \leq V_{max} \quad (10)$$

where,

- V_{min} : Allowable minimum section voltage,
- V_{max} : Allowable maximum section voltage,
- V_i : Voltage at load section i .

(d) Current constraint

Current magnitude of each branch (switch and line) must lie with their permissible ranges.

$$I_i \leq I_{max} \quad (11)$$

where,

- I_{max} : Allowable maximum load section current,
- I_i : Current at load section i .

Constraints (a) can be checked using a search method. The objective function value and constraints (b) - (d) can be checked using the above-mentioned circuit calculation method.

IV. PROBLEM FORMULATION USING MODERN HEURISTIC ALGORITHMS

Problem formulation using MHAs includes the following items:

- (1) Representation of state variable
- (2) Generation of initial states
- (3) Generation of neighboring states

The above formulation should be made clear explicitly because the efficiency of each method depends on the formulation. In other words, the comparison of each method is only based on the formulation as mentioned below.

Representation of the state variable

Each MHS requires to store state variable (searched points) for various purposes. Therefore, the representation method for the state variable is one of the key issues for applying MHS to a certain problem. The above-mentioned methods generate neighboring states of the current searching point by various methods. Therefore, it is necessary to consider whether the neighboring states can be generated easily and effectively or not, using the representation of the state variable. Conventionally, a network has been represented by the switch states [17]. However, this paper proposes the following method to represent the state variable considering the whole searching procedures of each method.

(Representation method)

- The length of an array equals to the number of loads in the out-of-service area.
- Numbering all of nodes including power sources and loads.
- Each array position represents the upstream load or power source section number of each position.

Fig. 2 shows an example of radial distribution system and its expression using the above method. For example, load No. 1 and 2 are energized from power source No. 9 in the figure. The upstream of load No.1 is source No.9 and that of load No.2 is load No.1. Therefore, the first two contents of the array is 9 and 1.

Generation of initial searching point

Initial states, namely initial network configurations in the service restoration problem, can be generated by various methods such as random and problem-dependent methods. This paper proposes the following problem-dependent procedure considering efficiency of fast convergence to the global optimal state.

- Step.1 Select a certain load L , statistically. The load L should be next to the load sets energized from the current power source G and it has not determined its power source yet.
- Step 2 Determine statistically whether the power source G supplies power to the load L or not using the following probability, $P_{connect}$. The larger the spare capacity (SC) of source G is, the larger $P_{connect}$ can be. Here, minimum

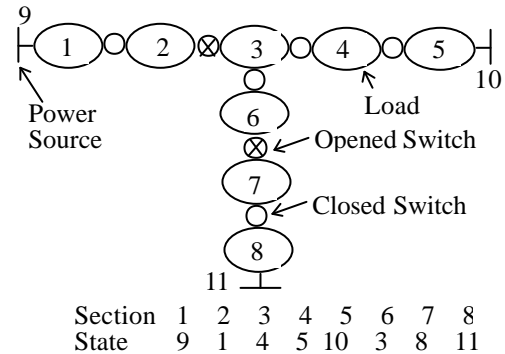


Fig. 2 An example of radial distribution system and its representation using the proposed state representation method.

value of $P_{connect}$ is set to P_{min} and maximum value of $P_{connect}$ is set to P_{max} .

$$P_{connect} = \frac{SC_G + CAP_G}{2CAP_G} \times (P_{max} - P_{min}) + P_{min} \quad (12)$$

where,

- SC_G : Spare capacity of source G,
- CAP_G : Capacity of source G,
- P_{max} : Maximum probability of $P_{connect}$
- P_{min} : Minimum probability of $P_{connect}$

Step 3 If every load has its power source, exit. Otherwise, go to step 1.

Step 4 Convert the obtained network configuration to an array. The above method can generate sub-optimal solution of the problem and it can be an efficient initial point in the solution space.

In other words, each power source determines energizing loads by tracing connection of the target network and using $P_{connect}$. $P_{connect}$ is gradually decreasing when the number of loads connected to the target power source is increasing.

Modification of the current searching point (network configuration)

Modification of the current searching point means modification of the network configuration in the service restoration problem. The modification method of the network configuration is different among the MHAs. Each method generates the candidates for the next states, evaluates the candidates, and selects the next state among the candidates.

A. Genetic Algorithm [15]

GA utilizes string operations such as cross-over and mutation for generation of the candidates for the next state. Cross-over performs partial exchange of two strings and it means partial exchange of network configurations of two different configurations in the service restoration problem. Mutation can be realized as a bit exchange at a certain string (array) position. This indicates an exchange of the direction of power source at a certain load. Therefore, the only load, which is next to a load connected to a different power source, can perform mutation operation. In other words, only restricted loads can mutate and the constraints can be satisfied if the mutation is performed at the allowed load. For example, power source direction of load 2, 3, 6, and 7 can be changed in the network configuration of Fig. 2. States of at least two switches have to be changed by changing the direction of power source of one load section.

Using the mutation procedure, generated neighboring states can be divided into the following two kinds of states.

- (a) Changing a source of a partial sub-network (e.g. changing power source direction of load No.3 in fig. 2)
- (b) Changing a source direction of one terminal load (e.g. changing power source direction of load 7 in fig.2)

Namely, using the above representation method of the searching point and generation method of neighboring states,

one can generate various kinds of neighboring states. Conventionally, as mentioned above, a network has been represented by the switch states [17]. Using the method, one should close one switch to make a loop and open another switch for generating a radial network. Therefore, one should trace the network to determine the newly opened switches and it is time-consuming. On the contrary, using the proposed methods, the only information utilized for generating neighboring states is linked sections of each load and there is no need for tracing the network for generating neighboring states. It should be noted that GA performs the string operation such as cross-over and mutation with a certain probability. Therefore, GA may not perform the string operation at every iteration. The next state (string) can be selected using various methods such as the roulette wheel selection as mentioned above.

B. Parallel Simulated Annealing

The neighboring states, the candidates for the next state, can be generated using the same method of the mutation of GA. The next state (network configuration) can be selected using equations (1) - (4).

C. Tabu search and Reactive tabu search

The neighboring states, the candidates for the next state, can be generated using the same method of the mutation of GA. The next state (network configuration) can be selected among the candidates. The procedure of generating neighboring states and selection of the next state can be expressed as follows:

- Step 1 Select loads, which can change the direction of power source in the current network configuration.
- Step 2 Generate the neighboring states by changing the power source direction of each load selected at step 1. These states are candidates for the next states.
- Step 3 Choose one candidate, which is not tabu and has a minimum objective function value.

TS and RTS utilizes the search list and the following items are stored in the search list:

- Network configuration (state variable)
- Iteration number at which the current configuration was found.
- Objective function value

The current configuration is added into the tabu list and the configuration searched before the current tabu length is removed from the tabu list. The fixed tabu length by TS and the variable tabu length by RTS, and the escape function of RTS cause difference of search procedure between TS and RTS. Since TS and RTS stores and retrieves searched points when searching, efficient storing and retrieving method is required for fast computation. Therefore, a hashing function is utilized using network configurations as a key to the hash function. Fig. 3 shows a flow chart for service restoration by RTS as an example.

V. QUALITATIVE COMPARISON OF MHAs

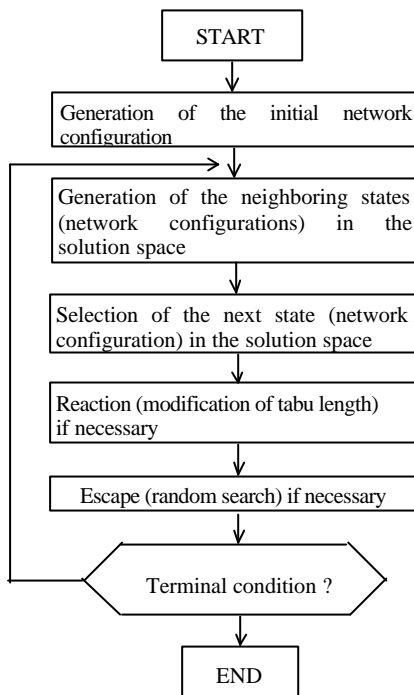


Fig. 3 A flow chart for service restoration by RTS.

This section presents qualitative comparison of MHAs using the above problem formulation for each method.

The same method is utilized for generation of initial state among all of compared methods in this paper. Although the probabilistic method is utilized for the generation of initial states, the search procedure can be started using the same kind of initial states. The probabilistic characteristics have been investigated in the simulation. Consequently, the target for comparison is how to change the searched states in the search procedure.

The same procedure is utilized for the mutation by GA and generation of neighboring states by PSA, TS, and RTS. The procedure performs exchange of source direction of one terminal load in most cases, and it is corresponding to a local search procedure. On the contrary, cross-over by GA performs exchange of a source of partial sub-network and it is corresponding to a global search procedure. The problem formulated for service restoration should perform circuit calculation for modified search points and check whether the constraints are violated or not. Therefore, it is time-consuming to evaluate the modified search points. The following observations can be found:

(a) GA can utilize cross-over, a kind of a global search procedure. Therefore, GA can change the current states more drastically compared with other methods. GA performs the global and local search procedure with a certain probability. On the contrary, PSA, TS, and RTS perform only the local search procedure to move the next states every time. It is not clear which strategies are more effective

especially for services restoration.

(b) GA utilizes many search points and it takes long time to evaluate the modified search points. The number of evaluation for searching points only depends on the number of strings and probability for cross-over and mutation. On the contrary, PSA, TS, and RTS utilize only one search point. However, they have to evaluate several neighboring states for moving to the next states. Therefore, if the number of neighboring states is small, PSA, TS, and RTS may have less computation time compared with GA to move to the next state. According to the problem formulation mentioned above, the generated neighboring states are restricted and the number of states is not large even if the problem size increases.

(c) GA and PSA may revisit the already searched states many times essentially. On the contrary, TS and RTS prohibit to revisit the already searched states and they may realize more effective search procedure. When TS generates search cycles, RTS can generate higher quality solution than TS. Otherwise, TS and RTS may trace different search trajectory according to modification of TL and it is not clear which method can generate higher quality solution.

The following quantitative studies are required for more detailed comparison.

VI. QUANTATIVE COMPARISON OF MHAs

Distribution system models

(1) Simulation conditions

The four MHAs are applied to ordinary practical distribution system models, which are constructed referring the number of feeders, sections, and other items of practical distribution systems. Fig. 4 shows the concept of the 6.6kV model systems. The followings are parameters of the model systems:

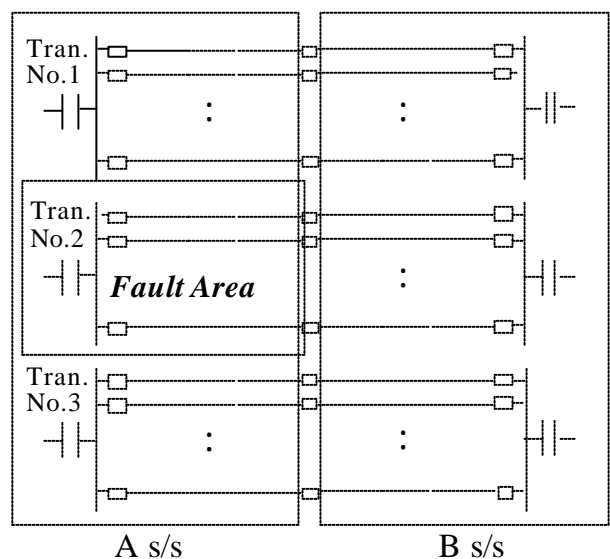


Fig.4 Concept of 6.6kV model distribution systems.

- (a) 18 section system: 6 lines/Tr., 3 sections/line
- (b) 24 section system: 8 lines/Tr., 3 sections/line
- (c) 30 section system: 10 lines/Tr., 3 sections/line
.
- (d) 36 section system: 6 lines/Tr., 6 sections/line
- (e) 48 section system: 8 lines/Tr., 6 sections/line
- (f) 60 section system: 10 lines/Tr., 6 sections/line

The ends of lines are assumed to be connected to the neighboring substation (s/s) using tie-line switches. Equivalent resistance of the lines are assumed to be 0.6649 (ohm/km) and total length of each line is assumed to be 3.0 (km) considering practical urban areas. Load current value of each load section is assumed 20,40,60 (A) for 3 section model systems and 10, 10, 20, 20, 30, 30 (A) for 6 section model systems from the power source. Source voltages are assumed to be 6.9 (kV). All section switches installed between sections are assumed to be remotely controllable. A transformer fault is assumed to be occurred at Trans. No.2 of A s/s. The system reconfigurations after the fault generated by RTS, TS, GA [15], and PSA [19] are compared in the simulation. Simulation parameters determined by the pre-simulation are as follows:

RTS	Modification rate of tabu length	0.1	
	Initial tabu length	12	
TS	Tabu length	12	
GA	Cross-over rate	0.5	
	Mutation rate	0.01	
	Number of strings	16	
PSA	Cooling schedule		
	$T^{k+1} = bT^k, T^0 = 100000, b = 0.99$	(13)	
	where, T^k : temperature at iteration k		
	Number of searching points	16	

$w_1=10.0, w_2=1.0$ in (8) so that the two terms of the objective function has approximately the same order of values.

Representation of state variables and generation of initial state condition method of all of compared MHAs are the same. The maximum evaluation values within 100 iterations through 100 trials are compared. All calculation are performed on EWS (SPECint95 7.72, gcc ver.2.7.2.2).

(2) Simulation results

Fig. 5 shows the service restoration result for the 18 section model system with the maximum objective function

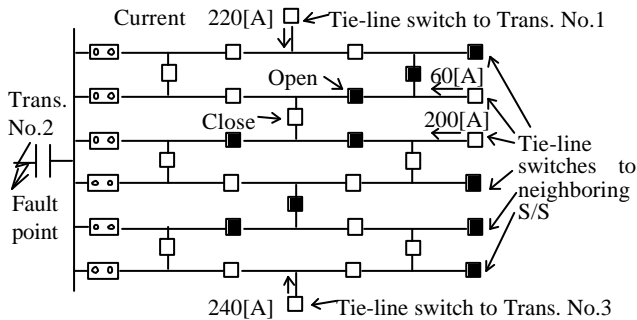


Fig. 5 A network configuration for the 18 section distribution network by RTS.

value generated by RTS. The results counterbalance the spare capacity of neighboring transformers. All of section voltages are within allowable ranges. Table 1 shows the following results through 100 trials:

- (a) maximum value: maximum evaluated value through 100 trials.
- (b) average value: average value of maximum evaluated value at each trial
- (c) variance: maximum variance value at each trial

Maximum and average value is normalized using the maximum values by RTS at each case. Variance values are also normalized using the variance values by RTS at each case.

Variance values of RTS increase as the system becomes larger. However, RTS generates the best result in almost all cases compared by TS, GA, and PSA.

Fig. 6 shows the average execution times in 100 search iterations by RTS, TS, GA, and PSA for the above model systems through 100 trials. The execution time of TS is almost the same as that of RTS. The results indicate efficiency of RTS even if the number of load sections increases. Consequently,

Table 1 Comparison of objective function values by RTS, TS, GA, and PSA.

18 section system	RTS	TS	GA	PSA
maximum	1.0000	1.0000	0.8463	1.0000
average	0.9644	0.9609	0.6669	0.9875
dispersion	1.0000	1.8497	33.1934	1.4480
24 section system	RTS	TS	GA	PSA
maximum	1.0000	0.9920	0.7674	0.9674
average	0.9930	0.9867	0.6102	0.9272
dispersion	1.0000	1.4030	1.3247	1.1042
30 section system	RTS	TS	GA	PSA
maximum	1.0000	1.0000	0.8211	1.0951
average	0.8588	0.8586	0.6925	0.9681
dispersion	1.0000	1.0001	13.1101	1.8118
36 section system	RTS	TS	GA	PSA
maximum	1.0000	1.0000	0.8468	0.9951
average	0.9788	0.9780	0.8341	0.9721
dispersion	1.0000	1.0602	0.0983	0.4468
48 section system	RTS	TS	GA	PSA
maximum	1.0000	1.0000	0.6725	1.0
average	0.9586	0.9583	0.6284	0.9931
dispersion	1.0000	0.9089	3.7252	0.8382
60 section system	RTS	TS	GA	PSA
maximum	1.0000	0.9745	0.7173	0.9663
average	0.9586	0.9242	0.6722	0.8967
dispersion	1.0000	0.8267	1.5926	0.5898

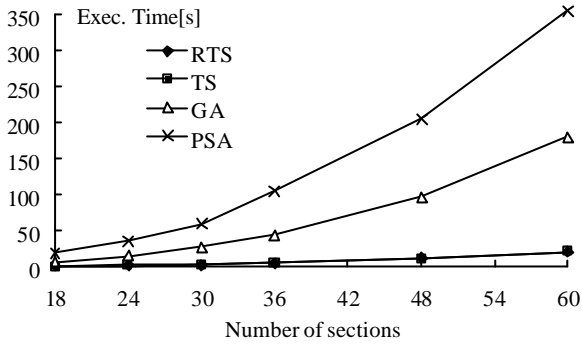


Fig. 6 Comparison of average execution time.

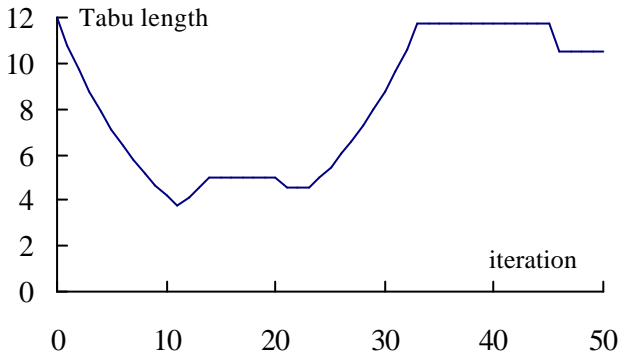


Fig. 7 An example of transition of tabu length.

RTS can generate the highly qualified results and realize fast computation. GA can be improved using parallel computation [15]. However, for the practical application, an EWS-based or PC-based control system is utilized in distribution control centers and the results indicate the potential of RTS for practical application.

Fig. 7 shows an example of automatic tuning of TL through search procedures. In the example, the initial TL is set to 12 and TL is decreasing at the beginning of search procedure because there are no cycles in the search procedure. Then, the already searched point is found and TL is tuning by the reaction mechanism.

Fig. 8 shows comparison of average of maximum objective function values between TS and RTS using various initial tabu lengths and tabu length modification through 100 trials. The number of load sections is set to 24 in this simulation. In the figure, for example, RTS (0.02) means TL modification rate is 0.02. The result indicates the suitable TL modification rate for all of initial tabu length does not exist. However, RTS is always better than TS for various initial tabu lengths. Fig. 5 is a practical model distribution system. According to the results, 12 for initial tabu length and 0.1 for TL modification rate are the most appropriate parameters for the practical model system.

A practical distribution system

The RTS-based method is applied to practical distribution systems in Wakayama distribution control center located in the south of Kansai area. The total number of switches in the

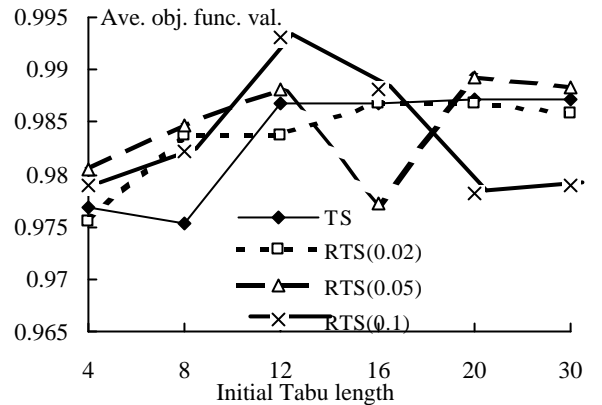


Fig. 8 Comparison of TS and RTS.

system fed by the target transformer is 66. The method is applied to various faults including distribution transformer faults and compared with the conventional method, which is now utilized in the actual operation. The RTS-based method restored about 20 % larger area than the conventional system for the transformer fault. It can restore 97% of the de-energized area even in the transformer fault which can be considered as one of the severe faults. The results indicate the efficiency of the RTS-based method in practical operation.

VII. CONCLUSIONS

This paper has compared modern heuristic algorithms: genetic algorithm, parallel simulated annealing, tabu search, and reactive tabu search, for service restoration in distribution systems. The results can be summarized as follows:

- RTS can generate only local neighboring states at moving to the next states. However, the simulation results for typical distribution systems and a practical distribution system indicate that RTS can generate the most highly qualified results.
- The computation time by RTS depends on the number of evaluated neighboring states at each iteration. According to the results, RTS can realize the fastest computation especially for practical service restoration. Therefore, RTS is the best method for service restoration.

If the out-of-service area can not be restored only using the power sources next to the area, multistage switching is required to increase spare capacity of the neighboring power sources [18]. Multistage switching is a large combinatorial problem and we have much knowledge on the problem. Therefore, expert system (ES) is suitable for the problem. On the contrary, decomposition of out-of-service area can be formulated as a combinatorial optimization problem and it is suitable for RTS as shown in this paper. We plan to develop a practical service restoration using ES and RTS as one of the future works. In such a case, the role of ES is to move the initial configuration inside the feasible region in the solution space [18]. Application of the proposed method with the function of

multistage switching to larger service restoration problems is one of the future works.

It is important to consider load priority and reliability and switching complexity in the service restoration. For example, one of the ways to handle the load priority and reliability is to utilize weighted penalty terms in the objective function. It is also important to consider switching complexity. One simple way is to minimize the difference of switching states between the post-fault network and the target restored network. Another way is to generate switching procedures and check each switching sequences precisely. It is time-consuming and it may not be suitable considering the current computer speed. The consideration of these constraints are also one of the future works.

Our final goal is to develop a network reconfiguration method considering loss minimization and service restoration. We have already developed a GA-based network reconfiguration method considering loss minimization using three phase unbalanced load flow [20]. We plan to integrate the proposed method for service restoration and the loss minimization method using RTS in the near future in order to realize efficient and reliable operation of distribution systems.

REFERENCES

- [1] K. Aoki, et al., "Outage State Optimal Load Allocation by Automatic Sectionalizing Switches Operation in Distribution Systems", *IEEE Trans. on Power Delivery*, Vol. PWRD-2, No. 4, pp. 1177-1185, October 1987.
- [2] C. C. Liu, et al., "An Expert System Operational Aid for Restoration and Loss Reduction of Distribution Systems", *IEEE Trans. on Power Systems*, Vol. 3, No. 2, pp. 619-626, May 1988.
- [3] K. Aoki, et al., "Voltage Drop Constrained Restoration of Supply by Switch Operation in Distribution Systems", *IEEE Trans. on Power Delivery*, Vol. 3, No., 3, pp. 1267-1274, July 1988.
- [4] C. E. Lin, et al., "A Distribution System Outage Dispatch by Data Base Method with Real-Time Revision", *IEEE Trans. on Power Delivery*, Vol. 4, No. 1, January 1989.
- [5] K. Aoki, et al., "A New Algorithm for Service Restoration in Distribution Systems", *IEEE Trans. on Power Delivery*, Vol. 4, No. 3, July 1989.
- [6] C. Fukui, et al., "Switch Pattern Planning in Electric Power Distribution Systems by Hopfield-type Neural Network", *Proc. of IJCNN* Wash. DC. Vol. II-591, 1990.
- [7] Imamura, et al., "An Application of Fuzzy Reasoning for Service Restoration", *Trans. of IEE of Japan*, Vol.113C, No.5, May 1993 (in Japanese).
- [8] C. R. Reeves, *Modern Heuristic Techniques for Combinatorial Problems*, Blackwell Scientific Publications, 1993.
- [9] D. E. Goldberg, *Genetic Algorithms in Search, Optimization, and Machine Learning*, Addison-Wesley, 1989.
- [10] H. Mori, et al., "Parallel Simulated Annealing for Power System Decomposition", *IEEE Trans. on Power Systems*, Vol.9, No.2, May 1994.
- [11] F. Glover, "Tabu Search Part I", *ORSA(Operations Research Society of America) Journal of Computing*, Vol. 1, No. 3, Summer 1989.
- [12] F. Glover, "Tabu Search Part II", *ORSA Journal of Computing*, Vol. 2, No. 1, Winter 1990.
- [13] R. Battiti, "The Reactive Tabu Search", *ORSA Journal on Computing*, Vol. 6, No. 2, pp.126-140, 1994.
- [14] R. Battiti, "Reactive Search: Toward Self-tuning Heuristics", *keynote talk at Applied Decision Technologies*, April 1995, Brunel, UK.
- [15] Y. Fukuyama and H. D. Chiang, "A Parallel Genetic Algorithm for Service Restoration in Electric Power Distribution Systems", *Proc. of IEEE FUZZ/IFES conference*, Yokohama, March 1995.
- [16] D. Shiomohammadi, et al., "A Compensation-based Power Flow Method for Weakly Meshed Distribution and Transmission Networks", *IEEE Trans. on Power Systems*, Vol. 3, No. 2, pp. 753-762, 1988.
- [17] K. Nara, et al., "Implementation of Genetic Algorithm for Distribution Systems Loss Minimum Re-configuration", *IEEE Trans. on Power Systems*, Vol.7, No.3, pp.1044-1051, August 1992.
- [18] Y. Fukuyama et al., "A Hybrid System for Service Restoration Using Expert System and Genetic Algorithm", *Proc. of ISAP '96*, January 1996.
- [19] Y. Fukuyama, et al., "Application of Meta-heuristic techniques to Service Restoration in power Distribution Systems", *Proc. of 6th Intelligent System Symposium*, Oct. 1996 (in Japanese).
- [20] Fudo, et al., "A Genetic Algorithm for Network Reconfiguration Using Three Phase Unbalanced Load Flow", *Proc. of ISAP'97*, July 1997.

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