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Reactive Tabu Search for Distribution Load Transfer Operation

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Abstract: This paper presents a reactive tabu search for distribution load transfer operation. The load transfer operation at steady-state operation and planning aims at reconfiguring the target network for various purposes including loss minimization. On the contrary, the operation at restoration is called service restoration and aims at minimizing out-of-service area as quickly as possible. Both operations can be formulated as combinatorial optimization problems to divide the target network into several sub-networks, where each one having only one power source. The effectiveness of the proposed reactive tabu search is compared with other modern heuristic approaches (MHAs) on typical distribution systems with promising results.

Keywords: Load Transfer Operation, Loss minimization, Service Restoration, Combinatorial Optimization, Reactive Tabu Search

1. INTRODUCTION

Power utilities have been making efforts to automate many functions in distribution control center. Power utilities are especially concentrating on a loss minimization problem using network reconfiguration because it does not require new equipment. Namely, it can reduce electric power generation only by changing switch states. Average power transmission loss in ten Japanese power utilities is around 5.7 - 5.8 [%] of total power demand [1] and 60 - 70 [%] of the loss is considered to be lost in distribution systems. Therefore, loss reduction in distribution systems can be efficient to reduce transmission loss in the whole power systems. The problem can be formulated as a large combinatorial optimization problem. Various kinds of methods such as heuristics [2,3,4] and expert systems [5,6] have been applied for the problem. Recently it is found that modern heuristic methods such as genetic algorithm (GA), simulated annealing (SA), and tabu search (TS) can be efficient tools for large combinatorial optimization problem [7]. There are some papers which have applied SA [8] and GA [9] for network reconfiguration.

Customer satisfaction and service reliability are of primary concerns in the power industry. Several studies on power utilities' experience suggest that customer satisfaction is more closely correlated with service interruption frequency and interruption duration. The main objective in service restoration procedures is to restore as many loads as possible by transferring de-energized loads in the out-of-service areas via network reconfigurations to other supporting distribution feeders without violating operating and engineering constraints. 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 need to restore service to out-of-service areas as soon as possible. The service restoration problem is a combinatorial, non-linear, and constrained optimization problem. In the past, considerable efforts have been devoted to the subject of service restoration in distribution systems [10-16]. The problem has been addressed with methods such as heuristic algorithms [10,12,14], expert systems [11], data base [13], and fuzzy reasoning [16]. However, these methods produce solutions, which may not even be sub-optimal. In [15], 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) 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 [17]. However, it requires parallel processors and, unfortunately, conventional EWS is still utilized for the main computer in practical distribution control centers. Therefore, an EWS-based efficient method is eagerly awaited for practical implementation of service restoration. Tabu search [18][19] is one of the efficient methods for large combinatorial optimization problems and it can realize fast convergence with high quality solutions. However, one of the disadvantage of TS is that tabu length should be tuned properly for each target problem. Reactive tabu search (RTS) realizes adaptive modification of the tabu length in search procedures to solve the problem [20][21].

This paper presents RTSs for load transfer operations of network reconfiguration and service restoration in distribution systems. The effectiveness of the proposed reactive tabu search is compared with other modern heuristic approaches (MHAs) on typical distribution systems with promising results.

2. REACTIVE TABU SEARCH

2.1 Tabu Search[18][19]

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 influence its future search procedures. 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 of evaluation of neighboring states

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

Step.3 Move to the next state

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

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

2.2 Reactive Tabu Search [20][21]

The conventional MHAs like GA, SA, and TS require to adjust search parameters in advance for efficient search. However, in general, the appropriate parameter values depends on each problem. Therefore, a parameter tuning problem is known as one of the disadvantages of the conventional MHAs. The Reactive Search (RS) framework proposes the introduction of feedback (reactive) schemes in heuristics for discrete optimization problems [20]. 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. After one move is executed, 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. The basic TS mechanism can not avoid long search cycles. Therefore, RTS introduces the escape procedure. It consists on a number of random steps executed starting from the current searching point.

Effective search in the solution space requires balance of diversification and intensification. GA realizes diversification by cross-over and intensification by mutation generally. It 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 balanced mechanism between diversification and intensification using a tabu list. RTS, moreover, strengthens the mechanism using reaction and escape mechanism.

3. SERVICE RESTORATION BY RTS

3.1 Problem formulation of service restoration

Service restoration can be formulated as one of the graph partitioning problems to divide the out-of-service area to each power source. The objective function is to counterbalance spare capacity of each power source and maximize the minimum voltage of the network. The function can be expressed as follows:

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

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 considering operational point of view. Therefore, each section has only one up-stream section.

(b) Power source limit constraint

The total loads of each partial network can not exceed the capacity limit of the corresponding power source.

(c) Voltage constraint

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

(d) Current constraint

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

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

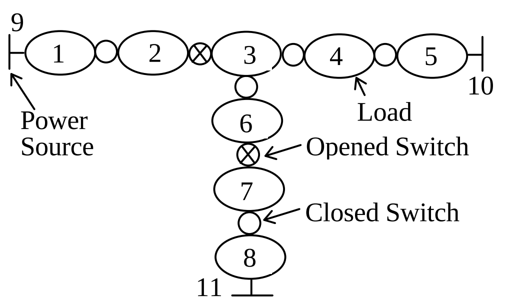
3.2 Problem formulation using RTS

(1) Representation of the state variable

It is necessary to consider whether the neighboring states can be generated easily and effectively or not, using the representation of the state variable. The following method is utilized to represent the state variable considering the whole searching procedures of RTS.

(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.



Section	1	2	3	4	5	6	7	8
State	9	1	4	5	10	3	8	11

Fig. 1 An example of radial distribution system and its representation using the proposed state representation method.

* Each array position represents the upstream load or power source section number of each position.

Fig. 1 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.

(2) 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. The problem-dependent procedure is utilized considering efficiency of fast convergence to the global optimal state.

(3) Modification of the current searching point

The neighboring states, the candidates for the next state can be generated by an exchange of the direction of power source at a certain load. The exchange can be performed at the only load, that is next to a load connected to a different power source. For example, power source direction of load 2, 3, 6, and 7 can be changed in the network configuration of Fig. 1. Status of at least two switches have to be changed by changing the direction of power source of one load section.

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

(a) Changing a source of a partial sub-network (e.g. changing power source direction of load No.3 in fig. 1)

(b) Changing a source direction of one terminal load (e.g. changing power source direction of load 7 in fig.1)

Namely, using the above representation method of the searching point and generation method of neighboring states, one can generate various kind of neighboring states.

Fig. 2 shows a flow chart for service restoration by RTS.

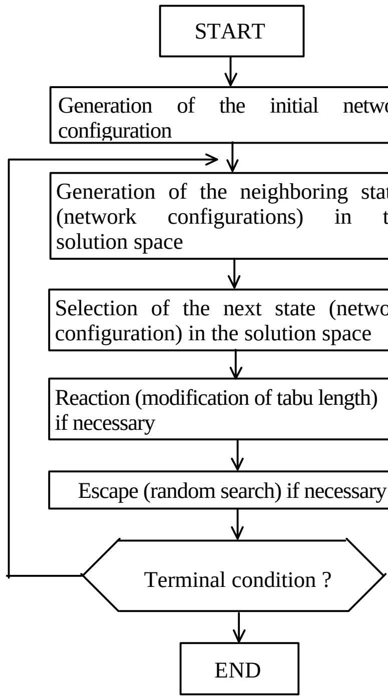


Fig. 2 A flow chart for service restoration by RTS.

3.3 Numerical Examples

3.3.1 Distribution Models

(1) Simulation conditions

The four MHAs (GA, Parallel Simulated Annealing (PSA), TS, RTS) are applied to ordinary practical distribution system models which are constructed referring number of feeders, sections, and other items of practical distribution systems. The followings are parameters of the model 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 end of lines are assumed to be connected to the neighboring substation (s/s) using tie-line switches. 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, and PSA are compared in the simulation. Simulation parameters determined by the pre-simulation are as follows:

RTS	Modification rate of tabu length α	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	

$$T^{k+1} = bT^k, T^0 = 10000.0, b = 0.99 \quad (2)$$

where, T^k: temperature at iteration k

	Number of searching points	16

w_1=10.0, w_2=1.0 in (1).

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 iteration through 100 trials are compared. All calculation are performed using EWS (SPECint95 7.72, gcc ver.2.7.2.2).

(2) Simulation results

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) dispersion: maximum dispersion at each trial

Maximum and average value is normalized using the

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

maximum values by RTS at each case. Dispersion values are also normalized using the dispersion values by RTS at each case.

Dispersion 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. 3 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, RTS can generate the highly qualified results and realize fast computation. GA can be improved using parallel computation [17]. However, for the practical application, EWS-based control system is utilized in distribution control centers and the results indicate the potential of RTS for practical application.

Fig. 4 shows an example of automatic tuning of TL through search procedures. In the example, the initial TL is 12 and TL is decreasing at the beginning of search procedure because there are no cycles in the search procedure. Then,

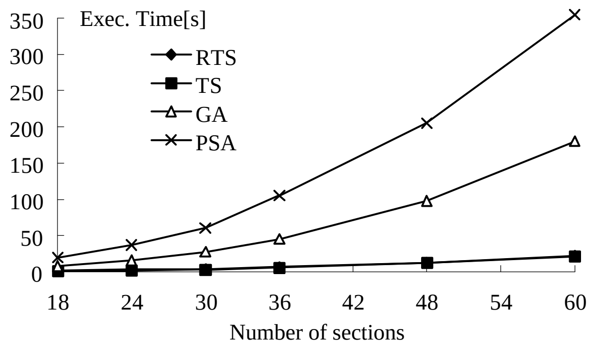


Fig. 3 Comparison of average execution time.

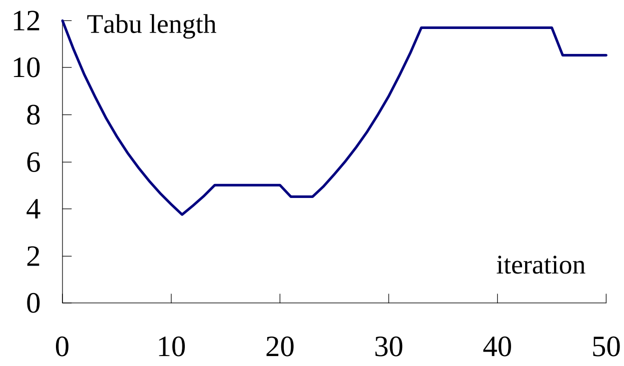


Fig. 4 An example of transition of tabu length.

the already searched point is found and TL is tuning by the reaction mechanism.

3.3.2 A practical distribution system

The proposed system 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 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 proposed 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 proposed method in practical operation.

If the out-of-service area can not be restored only using the power source neighboring the area, multistage switching is required to increase spare capacity of the neighboring power sources [22]. 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 developed a practical service restoration using ES and RTS as another work [22].

4. NETWORK RECONFIGURATION BY RTS

4.1 Problem formulation of network reconfiguration

Network reconfiguration for planning and steady state can be formulated as follows :

minimize $f_c = \sum_{i=1}^{n} Loss_i$ (3)

where, n : number of branch,

$Loss_i$: loss at branch i

subject to

(a) Radial network constraint

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

(b) Power source limit constraint

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

(c) Voltage constraint

Voltage magnitude at each node must lie with their permissible ranges to maintain power quality.

(d) Current constraint

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

Constraints (a) can be checked using a search method. The objective function value and constraints (b) - (d) can be checked using a three phase unbalanced load flow calculation.

4.2 Problem formulation using RTS

(1) Representation of the state variable

The same representation method for service restoration can be used in the network reconfiguration problem.

(2) Generation of initial searching point

The original network configuration is used as the initial searching point in network reconfiguration.

(3) Modification of the current searching point

The same method for service restoration can be used in the network reconfiguration problem.

Namely, Only the objective function and the calculation method for each constraint is different for both problems and the main functions for RTS is common in both problems.

4.3 Numerical Examples

(1) Simulation conditions

Table 2 Comparison of loss minimization by RTS and GA.

	Execution time per search (iteration) [sec]	Average number of 3 phase load flow calculation per search	Minimum number of search for obtaining optimal solution
GA	20	86.6	12
RTS	4	14.6	4

RTS and GA is applied to a simple distribution system with 1 S/S transformer and 4 feeders and compared. Each feeder has 5 sections and sending feeder current is 300 [A]. All switches are remotely controllable and source Voltage is 6.9 [kV].

(2) Simulation results

Table 2 shows the comparison results of loss minimization by RTS and GA for an unbalanced load case. According to the results, RTS is 5 times faster than GA for one search and RTS is 15 times ((20*12)/(4*4)) faster than GA to obtain the optimal solution.

The proposed RTS is also applied to a practical distribution model with 6 transformer banks, 36 feeders, and 108 sections. The results indicate that the RTS can generate the optimal solution.

5. CONCLUSIONS

This paper proposes reactive tabu searches for load transfer operation in distribution systems. The proposed methods has compared modern heuristic algorithms: genetic algorithm, parallel simulated annealing, tabu search, and reactive tabu search, for loss minimization and service restoration in distribution systems. The results can be summarized as follows:

(a) 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 for both loss minimization and service restoration.

(b) 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 and loss minimization. Therefore, RTS is the best method for load transfer operation.

The proposed RTS methods were combined as a practical planning tool for generating an optimal network configuration considering loss minimization and various contingencies [23].

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REFERENCES

[1] *Electric Power business handbook*, The Federation of Electric Power Companies statistics committee 1994 (in Japanese).

[2] S. Civanlar, et al., “Distribution Feeder Reconfiguration for Loss Reduction”, *IEEE Trans. on Power Delivery*, Vol.3, No.3, pp.1217-1223, July 1988.

[3] C. C. Liu, K. Vu, et al., “Loss Minimization of Distribution Feeders: Optimality and Algorithms”, *IEEE Trans. on Power Delivery*, Vol.4, No.2, pp.1281-1289, April 1989.

[4] I. Roytelman, et al., "Multi-objective Feeder Reconfiguration

by Distribution Management System", *IEEE Trans. On Power Systems*, Vol.11, No.2 May 1996.
[5] T. Taylor and D. Lubkeman, "Implementation of Heuristic Search Strategies for Distribution Feeder Reconfiguration", *IEEE Trans. on Power Delivery*, Vol.5, No.1, pp.239-246, January 1990.
[6] K. L. Tomsovic, et al., "A Heuristic Search Approach to Feeder Switching Operations for Overload, Faults, Unbalanced Flow and Maintenance", *IEEE Trans. on Power Delivery*, Vol.6, No.4, pp.1579-1585, October 1991.
[7] C. R. Reeves (eds.), *Modern Heuristic Techniques for Combinatorial Problem*, Blackwell Scientific Publications, 1993.
[8] H. D. Chiang and R. Jean-Jumeau, "Optimal Network Reconfigurations in Distribution Systems: Part 1: A New Formulation and A Solution Methodology", *IEEE Trans. on Power Delivery*, Vol. 5, No. 4, pp.1902-1909, November 1990.
[9] 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.
[10] 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.
[11] 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.
[12] 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.
[13] 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.
[14] K. Aoki, et al., "A New Algorithm for Service Restoration in Distribution Systems", *IEEE Trans. on Power Delivery,* Vol. 4, No. 3, July 1989.
[15] 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.
[16] Imamura, et al., "An Application of Fuzzy Reasoning for Service Restoration", *Trans. of IEE of Japan*, Vol.113C, No.5, May 1993 (in Japanese).
[17] 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.
[18] F. Glover, "Tabu Search Part I", *ORSA(Operations Research Society of America) Journal of Computing*, Vol. 1, No. 3, Summer 1989.
[19] F. Glover, "Tabu Search Part II", *ORSA Journal of Computing*, Vol. 2, No. 1, Winter 1990.
[20] R. Battiti, "The Reactive Tabu Search", *ORSA Journal on Computing*, Vol. 6, No. 2, pp.126-140, 1994.
[21] R. Battiti, "Reactive Search: Toward Self-tuning Heuristics", *keynote talk at Applied Decision Technologies*, April 1995, Brunel, UK.
[22] 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)*, 1998.
[23] Y. Fukuyama, et al., "Optimal Network Reconfiguration Considering Customer Reliability", Proc. of IEEE ISAP Conference, April 1999.

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