

A Reactive Tabu Search for Service Restoration in Electric Power Distribution Systems

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Abstract

This paper presents a reactive tabu search for service restoration in electric power distribution systems. Service restoration is an emergency control in distribution control centers to restore out-of-service area as soon as possible when a fault occurs in distribution systems. Therefore, it requires fast computation time 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 proposed method is demonstrated on typical service restoration problems. It is compared favorably with conventional tabu search, genetic algorithm, and parallel simulated annealing. The results reveal the speed and effectiveness of the proposed method for solving the problem.

1. 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 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 (i.e. minimize loads in out-of-service areas) 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. Fast service restoration has a multi-fold benefit. In actual use, distribution operators need to restore service to out-of-service areas as quickly as possible. Currently, the restoration is performed step-by-step and mostly

manually, based on pre-established guidelines and operating procedures.

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 problem. 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 electric power distribution systems [1-9]. 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 produced 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. The authors have developed a parallel genetic algorithm for service restoration and showed promising results on several distribution networks[8][9]. 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 (TS) is one of the modern heuristic methods for combinatorial optimization problems and is recognized as one of the effective approaches for the problems [10][11]. However, the method requires advanced parameter tuning for efficient search in a solution space. Reactive tabu search (RTS) is one of the improved methods for the conventional tabu search and it can adjust solution parameters during the search procedure [12]. Therefore, it can avoid disadvantages of the conventional tabu search.

This paper develops a reactive tabu search for service restoration in distribution systems. A

problem-dependent heuristic method is presented to generate an initial sub-optimal state in a solution space. The method generates neighboring states in a solution space by exchange of the direction of power source at a certain load. The searched states are stored in a tabu list using a hash function. Therefore, fast storing and retrieving data are realized. Tabu length is modified using reaction mechanism. If a great number of states which are already searched appear, random search is performed using escape mechanism. The feasibility of the developed algorithm for service restoration is demonstrated on typical distribution networks with promising results.

The paper is organized as follows. Section 2 describes the problem formulation of service restoration. Section 3 reviews a reactive tabu search. Section 4 describes the problem formulation of service restoration using a reactive tabu search. Section 5 shows numerical examples and comparison with conventional tabu search (TS), genetic algorithm (GA), and parallel simulated annealing (PSA).

2. Problem formulation of service restoration

2.1 Distribution system model

The following assumption is usually used for practical application of service restoration.

- (i) Power source can be formulated as current injection source.
- (ii) Voltage at the power source is assumed to be known.
- (iii) Each load can be formulated as constant contracted current.
- (iv) Each section line impedance $Z(n)$ can be calculated as an equivalent resistance using load power factor and line constants.

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

2.2 Circuit calculation method

In order to calculate voltages and currents in the target distribution system correctly, loadflow calculation

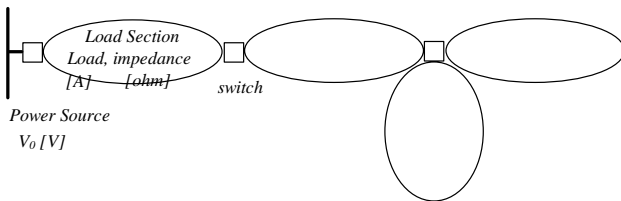


Fig. 1 A distribution system model.

is necessary. However, the following backward and forward sweep circuit calculation is usually performed for the sake of fast service restoration [8].

- 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.

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

where,

- $SCUR(n)$: Total load currents at node n.
 $CUR(n)$: Contracted load currents at node n.
 $n-1$: Node that is neighboring to node n at the end of the branch side.

Here, 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.

$$\Delta V(n) = SCUR(n) \times Z(n) \quad (2)$$

where,

- $V(n)$: 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.

$$V(n) = V(n+1) - \Delta V(n) \quad (3)$$

Where,

- $V(n)$: Voltage at node n.
 $n+1$: Node that is neighboring to node n at the power source side.

2.3 Objective function and constraints

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:

$$f_c = \min \left\{ w_1 \sum_{i=1}^m (SP_i - SP_{ave})^2 + w_2 \frac{1}{V_{min}} \right\} \quad (4)$$

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.

- (1) 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.

(2) Power source limit constraint

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

$$CAP_i \geq \sum_{k=1}^{l_i} LOAD_{ik} \quad (5)$$

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.

(3) Voltage constraint

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

$$V_{min} \leq V_i \leq V_{max} \quad (6)$$

where,

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

(4) Current constraint

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

$$I_i \leq I_{max} \quad (7)$$

where,

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

Constraints (1) can be checked using a search method. The objective function value and constraints (2) - (4) can be checked using the above circuit calculation method.

3. Reactive Tabu Search (RTS)

3.1 Tabu Search

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. Since the method uses a tabu list for storing the past history of the search, the efficient structure of the tabu list is important for fast computation.

3.2 Reactive Tabu Search

The conventional modern heuristic methods like GA, SA, and TS require to adjust search parameters for

efficient search. However, in general, the appropriate parameter values depends on each problem. Therefore, parameter tuning is known as one of the disadvantages of the modern heuristic methods. 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 of tabu length and automated balance of diversification and intensification. In the method, all searched states are stored. After a move is executed, the algorithm checks whether the current searching point has already been found. Tabu length (TL) increases if a searching point is repeated, TL decreases if no repetitions occurred 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. TS realizes balanced mechanism using a tabu list. RTS, moreover, strengthens the mechanism using reaction and escape mechanism. 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.

4. Problem Formulation using RTS

4.1 Tabu list

(1) Representation of state variable

RTS requires to store state variable (searched points) in the solution space as a tabu list. Therefore, the representation method for the state variable should be suitable to store and retrieve. Here, the following method is used to represent state variable.

(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 number of the load of each position.

Using the above method, the array can represents how loads in the out-of-service area are divided for each power source. Fig. 2 shows an example of radial distribution system and its expression using the above method. For example, load No. 1 and 2 are allocated to

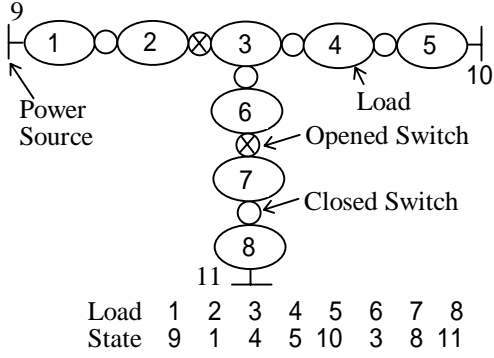


Fig. 2 An example of radial distribution system and its expression using the state representation method.

Configuration	Iter. num. for tabu		Obj. Func. Val.
	1	2	
9 1 2 ...	11	10	5.76
9 1 4 ...	11	15	3.65
9 1 2 ...	11	10	5.76

Fig. 3 An example of tabu list.

power source No. 9 in the figure.

(2) Representation of tabu list

The following items are stored in the tabu list:

- Network configuration (state variable)
- Iteration number at which the current configuration became tabu
- Objective function value

Fig. 3 shows an example of tabu list.

(3) Storing method of tabu list

RTS stores and retrieves searched points when searching. Therefore, efficient storing and retrieving method is required for fast computation. Here, a hashing function is utilized using network configuration as a key.

4.2 Generation of initial network configuration

Initial network configuration can be determined using the following problem-dependent procedure.

- Step 1 Select a certain load L, statistically, a load 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, $P_{connect}$. It should be noted that if SC_G equals 0, $P_{connect}$ is 0.5. Moreover, the larger the SC of source G is, the larger $P_{connect}$ can

be. Here, minimum value of $P_{connect}$ is set to P_{min} and maximum value of $P_{connect}$ is set to P_{max} .

$$P_{connect} = \frac{SC_G + CAP_G}{2CAP_G} \times (P_{max} - P_{min}) + P_{min} \quad (8)$$

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 is an efficient initial point in the solution space.

4.3 Generation of neighboring states and selection of the next state

Neighboring states in the solution space can be generated by changing the power source direction of one load in the current network configuration. Distribution network has to be radial by the operational constraint. Therefore, the load, at which the direction of power source can be changed, is limited. Such a load is the load neighboring to the load which is connected to different power source. For example, power source direction of load 2, 3, 6, and 7 can be changed in the network configuration of Fig. 2. It should be noted that states of at least two switches have to be changed by changing the direction of power source of one load.

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.

Fig. 4 shows a flow chart of the proposed method.

5. Numerical Examples

5.1 Simulation conditions

Fig. 5 shows a part of test distribution substation with three distribution transformers and each transformer has six feeders. A fault at No.2 transformer is assumed to be occurred. The fault is very severe practically and these

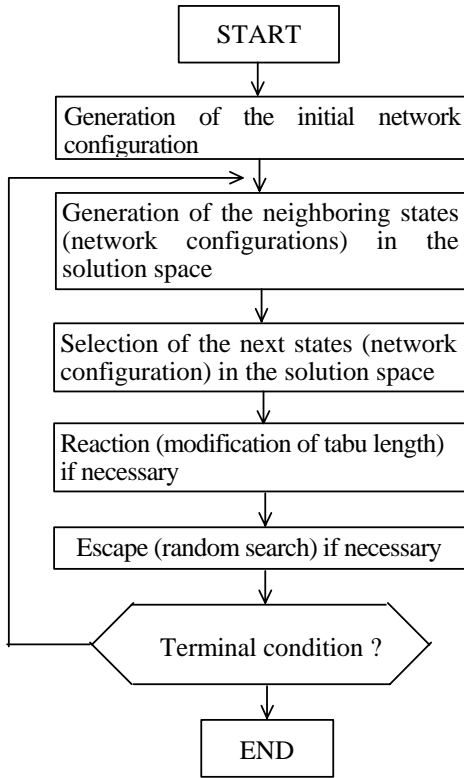


Fig. 4 A flow chart of the proposed method.

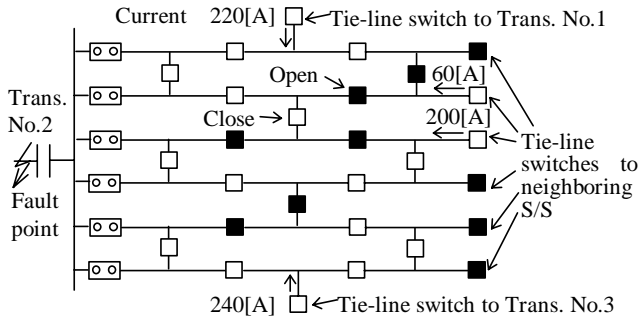


Fig. 5 A network configuration for the distribution network by RTS.

feeders shown in fig. 5 should be re-energized from the neighboring transformer feeders through tie-line switches.

Considering the practical distribution systems, the length of each load section is assumed 1 [km] and equivalent impedance of each load section is assumed to be 0.6649 [ohm]. Load current value of each load section is assumed 20,40,60 [A] from the power source. Source voltages are assumed to be 6.9 [kV].

Results of RTS, TS, GA[8], and PSA[12] are compared for the above fault. Tabu length modification is 0.02. Namely, new TL will be $1.02 \times (\text{original TL})$ or $0.98 \times (\text{original TL})$ when performing reaction. GA and

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

	R T S	G A	P S A
Max. Val.	1.0	0.6725	1.0
Ave. Val.	0.9586	0.6284	0.9931

* The obj. function values of Fig. 6 is assumed to be 1.0.

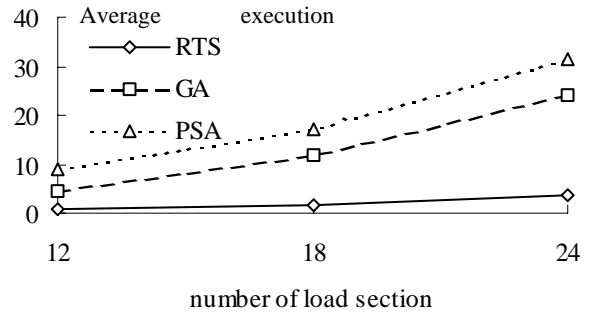


Fig. 6 Comparison of average execution time.

PSA utilize 16 searching points, the same state representation, and the same initial configuration generation method. Crossover rate is 0.5 and mutation rate is 0.01. The maximum objective function values within 100 search iterations are compared through 100 trials.

5.2 Simulation results

The service restoration results in Fig. 5 show the case with the maximum objective function value by RTS. The results counterbalance the spare capacity of neighboring transformers. All of section voltages are within allowable ranges. Table 1 shows maximum and average of maximum objective function values through 100 trials when the objective value of Fig. 5 is assumed to be 1.0. According to the results, the outputs of both RTS and PSA are highly qualified. PSA also generates the highly qualified average results.

Fig. 6 shows the average execution times for 100 search iterations using the above fault by RTS, GA, and PSA on EWS [SPECInt92: 52.6] through 100 trials. The execution time of TS is almost the same as that of RTS. Here, various numbers of load sections for the transformer No. 2 are utilized for simulation. The execution time in 30 [s] is required for even the severer fault. 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 improve using parallel computation [8]. However, for the practical application, EWS-based control system is utilized in distribution control centers and the results indicate the potential of

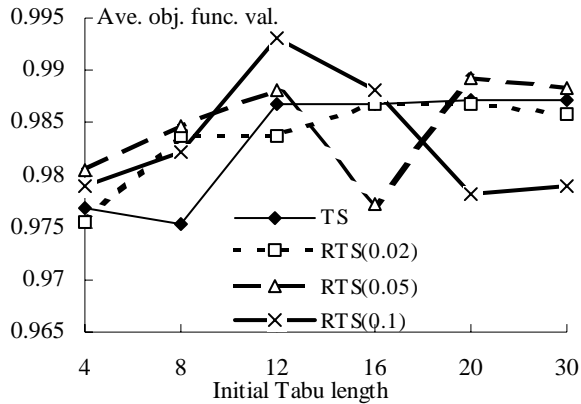


Fig. 7 Comparison of TS and RTS.

RTS for practical application.

Fig. 7 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. Number of load sections is 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 result, 12 for initial tabu length and 0.1 for TL modification rate are the most appropriate parameters for the practical model system.

6. Conclusions and future works

This paper has developed a reactive tabu search for service restoration in electric power distribution systems. The method has been compared favorably with conventional tabu search, genetic algorithm, and parallel simulated annealing with promising results.

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. 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 here. We plan to develop a practical service restoration using ES and RTS as one of the future works. The role of ES is to move the initial configuration inside the feasible region in the solution space [9].

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 mini-mization using three phase unbalanced loadflow [15]. 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 the electric power distribution systems.

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