A reactive tabu search for service restoration in distribution systems

Ahmed El-Habachi
Electrical Eng. Dept., Faculty of Eng., Alexandria University, Alexandria, Egypt

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 through typical service restoration cases. 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.

في هذا البحث نقدم طريقة البحث المُحرّم المعدل لاسترجاع الخدمه لشبكات التوزيع الكهربي، إذ تعتبر عملية إسترجاع الخدمة هي خدمة طوارئ في مراكز التحكم للموزعات والتي من شأنها إعادة الخدمة للمناطق بأسرع مايمكن، لذلك فهذه العملية تحتاج إلى سرعة ودقة إتخاذ القرار لإسترجاع التيار الكهربي للمشتركين. ومعالجة هذه المشكلة تحتاج إلى دراسة العديد من الحلول المحتملة لإتخاذ القرار الأمثل، وفي هذا البحث نتخذ إحدى طرق الذكاء الاصطناعي لحل مثل هذه المشكلات المعقدة، كما تم تطبيق هذه الطريقة على أمثلة عديدة ومقارنة النتائج مع التي استنبطت من قبل باستخدام كلا من البحث المُحَرم التقليدي والخوارزمات الجينية وكذلك محاكي التخمير المتوازي ، هذا وقد أثبتت النتائج سرعة ودقة وتميزهذه الطريقة عن مثيلاتها.

Keywords: Distribution system, Service restoration, Reactive tabu search, Genetic algorithms, Simulated annealing

1. Introduction

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 non Polynomial (NP)complete problem.

In the past, considerable efforts have been devoted to the subject of service restoration in electric power distribution systems [1-7]. The problem has been addressed with methods such as heuristic algorithms [1], [3], and [5], expert systems [2], database [4], genetic algorithms [6] and simulated annealing [7]. However, these methods have produced solutions, which may not even be sub-optimal.

Tabu Search (TS) is one of the modern heuristic methods for combinatorial optimization problems and is recognized as one of the effective approaches [8]. 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 [8]. 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 illustrates 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). Section 6 summarizes the conclusion of the paper.

2. Problem formulation of service restoration

2.1. Distribution system model

The following assumptions are usually used for practical application of service restoration.

- Power source can be formulated as current injection source.
- Voltage at the power source is assumed to be known.
- Each load can be formulated as constant current.
- The line impedance *Z(n)* of each section can be calculated as an equivalent resistance using load power factor and line constants.

2.2. Circuit calculation method

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 [7].

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),CUR(n) are total and contracted load currents at node *n*, respectively.

n-1 is the 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, *Z(n)* is the 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, *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 is the number of power source,
SP_i is the spare capacity of source *i* in pu,
SP_{ave} is the average of spare capacity of all sources in pu,
V_{min} is the Minimum voltage of the target network in pu, and
w_1, w_2 are the weighting coefficients for each term.

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

i. Radial network constraint: Distribution network is composed of radial structure. Therefore, each section has only one upstream section.

ii. Power source limit constraint: The total loads of each partial network cannot exceed the capacity limit of the corresponding power source.

$$CAP_i \geq \sum_{k=1}^{J_i} LOAD_{ik} \ , \qquad (5)$$

where,

J_i is the number of load for power source i,

CAP_i is the capacity of power source i,

$LOAD_{ik}$ is the capacity of LOAD k energized by power source i.

iii. Voltage constraint: Voltage magnitude at each node must lie within its permissible ranges.

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

where, V_{min} , V_{max}: permissible minimum and maximum load section voltage respectively.

iv. Current constraint: Current magnitude of each branch (switch and line) must lie within their permissible ranges.

$$I_i \leq I_{\max} \, , \qquad (7)$$

where, I_{max} is the allowable maximum load section current.

Constraints (i) can be checked using a search method. The objective function value and constraints (ii)-(iv) can be checked using the above circuit calculation method.

3. Reactive tabu search

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 adjusting search parameters for efficient search. However, in general, the appropriate parameter values depend on each problem. Therefore, parameter tuning is 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 [8]. Research Tabu Search (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 cannot avoid long search cycles. Therefore, RTS introduces the escape procedure. It consists of 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 crossover 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

3.1. Tabu list

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

- 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.

ii. 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

iii. 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, CAP_G are the spare capacity and capacity of source *G* respectively,

P_{max}, P_{min} are the maximum and minimum probability of $P_{connect}$ respectively.

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

Changing the power source direction of one load in the current network configuration can generate neighboring states in the solution space. 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.

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. 1 shows the flow chart of the proposed method.

5. Numerical example

5.1. Simulation conditions

Fig. 2 shows a part of test distribution substation [5] with three distribution transformers and each transformer has six feeders. A fault at No. 2 transformer is assumed to occur. The fault is very severe practically and these feeders shown in fig. 2 should be re-energized from the neighboring transformer feeders through tie-line switches.

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

Results of RTS, TS, GA, and PSA are compared for the above fault. Tabu length

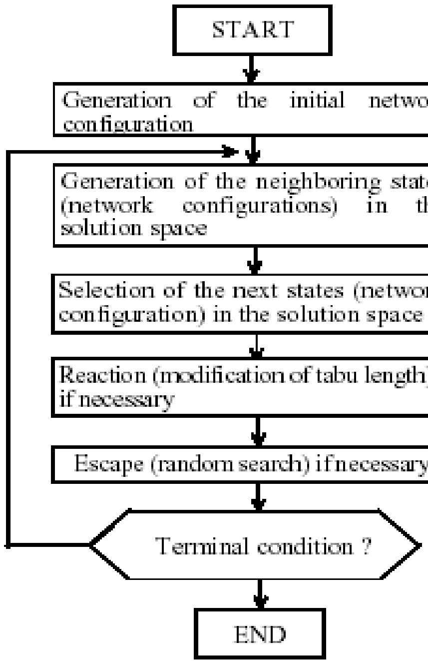

Fig. 1. Flow chart of the proposed method.

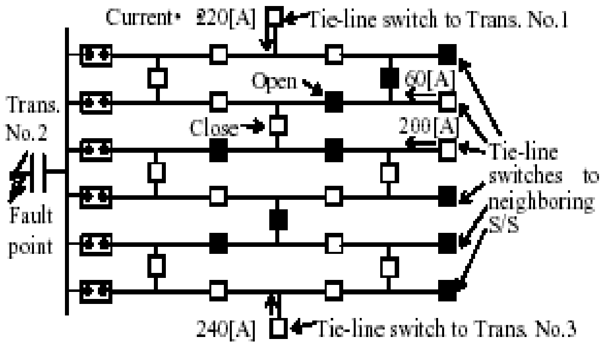

Fig. 2. A network configuration for the distribution network by RTS.

modification is 0.02. Namely, new TL will be 1.02x(original TL) or 0.98x(original TL) when performing reaction. GA and 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. 2 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 (0.97-1.03 pu). Table 1 shows maximum and average of maximum objective function values through 100 trials when the objective value of fig. 2 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. 3 shows the average execution times for 100 search iterations using the above fault by RTS, GA, and PSA on IBM 600 MHz 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. Using GA, the execution time in 30 [s] is required for even the severer fault. The results indicate the 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.

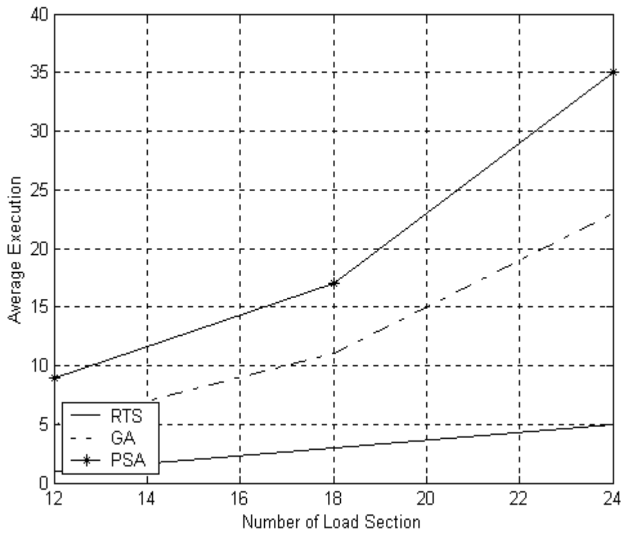

Fig. 3. Comparison of average execution time.

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

Method	PSA	GA	RTS
Max. value	1.0	0.6725	1.0
Min. value	0.9586	0.6284	0.9931

* The objective function of Fig. 3 is assumed to be 1.0

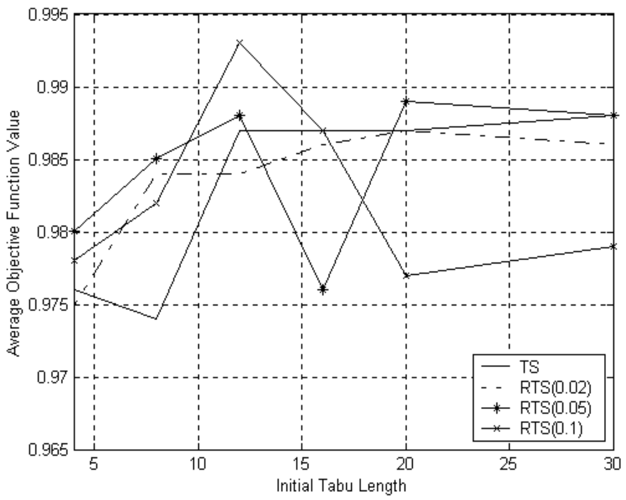

Fig. 4. Comparison between TS and RTS

Fig. 4 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. Assuming that the number of load sections has been extended to 24 in this simulation. In the fig. 4, 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. According to the result, 12 for initial tabu length and 0.1 for TL modification rate are the most appropriate parameters for the system.

6. Conclusions

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 cannot 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.

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 (4), pp. 1177-1185 (1987).

[2] Y.Y. Hsu and M. Huang et al. “Distribution System Service Restoration Using A Heuristic Search Approach,” IEEE Trans. on Power Delivery, Vol. 7, pp. 734-740 (1992).

[3] K.N. Miu, H.D. Chiang, B. Yuan, and G. Darling, “Fast Service Restoration for Large-Scale Distribution Systems with Priority Customers and Constraints,” IEEE Trans. on Power Systems, Vol. 13 (3), pp. 789-795 (1998).

[4] C. Vcak and A. Pahwa, “An Analytical Approach for Step-by-Step Restoration of Distribution System Following Extended Outages,” IEEE Trans. on Power Delivery, Vol. 9 (3), pp. 1717-1723 (1994).

[5] K. Aoki, et al. "A New Algorithm for Service Restoration in Distribution Systems," IEEE Trans. on Power Delivery, Vol. 4 (3) (1989).

[6] R. Abdelaziz and A. El-Habachi, “Hierarchical Genetic algorithm-Based Switching Device Placement in Distribution System,” Proceedings of the 11th IEEE Mediterranean Electrotechnical Conference, MELECON’2002, pp. 585-589 (2002).

[7] El-Habachi and A.R. Abdelaziz, “Simulated Annealing-Based Restoration of Distribution Systems,” Proceedings of the 9th IEEE Middle East Power Conference, MEPCON’2003, pp. 47-51 (2003).

[8] R. Battiti, "The Reactive Tabu Search," ORSA Journal on Computing, Vol. 6 (2), pp.126-140 (1994).

Received January 10, 2004
Accepted Marh 31, 2005