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A GENETIC ALGORITHM FOR NETWORK RECONFIGURATION USING THREE PHASE UNBALANCED LOAD FLOW

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***Abstract*:** This paper presents a genetic algorithm for solving network reconfiguration using three phase unbalanced load flow in distribution systems. A proper string representation for the problem is devised and a method to yield a good problem-dependent initial string population is presented. An appropriate selection method for strings is used for fast convergence and improving quality of solutions. Three phase unbalanced load flow is used for taking constant power and unbalance loads in the practical distribution network into account. The feasibility of the developed algorithm for network reconfiguration is demonstrated on distribution networks with promising results.

Key word: Genetic algorithm, Network reconfiguration,
Three phase unbalanced load flow

INTRODUCTION

Distribution automation is one of the hot issues in power systems and power utilities have been making efforts to automate many functions in distribution control center recently. Power utilities are especially concentrating on a loss minimization problem using network reconfiguration because it does not require new equipment and can reduce electric power generation only by changing switch status.

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.

Distribution systems have huge number of single phase loads and large unbalanced voltage at the end of the feeders. Moreover, increase of constant power loads requires three phase unbalanced load flow rather than conventional simple single phase circuit calculation to consider the above practical characteristics of the distribution systems.

Network Reconfiguration 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. However, three phase unbalanced load flow has not been used for the sake of simplicity.

This paper presents a genetic algorithm for solving network reconfiguration in distribution systems using three phase unbalanced load flow. A proper string representation for loads and power supplies is devised and a method to yield a good problem-dependent initial string population is presented. The meaning of the operations of cross-over and mutation in the context of network reconfiguration is explained. A repair operator which modifies the string so as to improve the objective function of the network reconfiguration problem and to satisfy the radial network constraints is presented. A modification to the fitness function evaluation is made to reinforce the satisfaction of the power source limits and voltage as well as current constraints. The feasibility of the developed algorithm for network reconfiguration is demonstrated on distribution networks with promising results.

PROBLEM FORMULATION

Network reconfiguration for loss minimization can be formulated as follows :

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

where, n : number of branch,
$Loss_i$: loss at branch i

subject to

(1) Radial network constraint
Distribution network should be composed of radial structure considering operational point of view.

(2) Power source limit constraint
The total loads of a certain partial network can not exceed the capacity limit of the corresponding power source.

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

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

OVERVIEW OF APPLIED METHODS

Genetic Algorithm (GA)

GA is one of the stochastic search algorithms based on the mechanics of natural genetics. 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 search point in the solution space. GA uses a set (population) of strings (i.e. multiple search points). Therefore, it can be a parallel search method. 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 details could be found in [10].

Three phase unbalanced load flow

(1) Distribution system model

Each device in distribution systems can be modeled as follows:

a) Power Source:

Voltage at the secondary side of the distribution transformer is assumed to be balanced for the power source of the distribution systems.

b) feeder and laterals

Impedance of the feeders and laterals can be represented by series impedance matrix Z_k.

c) Load

A load is modeled as constant impedance, constant current, and constant complex power, and its combination.

(2) Solution Algorithm

Zbus Gauss iterative algorithm [11] is used as the solution algorithm. The method is known as a proper method for load flow calculation for distribution systems [11].

DETAILS OF GA FOR THE PROBLEM

String representation

Short and robust string representation is necessary for formulation of a problem using GA. The following representation method and decimal coding are used here.

(Representation method)

* The length of a string equals to the number of sections.

* Each string position represents the upstream section or power source of the section of each position.

Fig. 1 shows a simple radial network. In the figure, (1)-(8) are load sections and (9)-(11) are power sources. Parentheses <> represent power sources for each partial system. Namely, power source (9) supplies power to sections (1) and (2); power source (10) to (3), (4), (5) and (6); power source (11) to (7) and (8). Sections (2) and (3), and (6) and (7) are disconnected by open switches. Using the above representation method, the radial network shown in Fig. 1 can be represented by the following string:

(9)(1)(4)(5)(10)(3)(8)(11)

Namely, the upstream of section (1) is source (9) and that of section (2) is section (1). The upstream of load (8) is source (11) in the same way.

Since the number of each string position shows the neighboring section or power source number, available numbers for each position are restricted and the restriction affects the string operation efficiently.

Generation method of initial string population

Using sub-optimal strings for initial population based on the problem-dependent method leads to a fast convergence. However, it may suffer from lack of variety and convergence to a local minimum. To avoid the problem, the following heuristic procedure is repeatedly applied to each power source concentrating on power source capacity constraint.

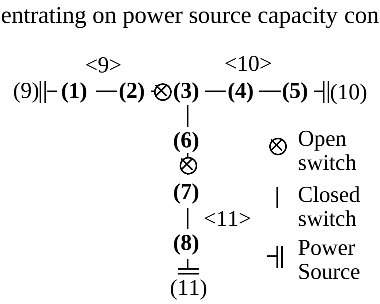


Fig. 1 Example No. 1 of radial networks.

Step 1. Open all of switches in target systems.

Step 2. Statistically select a section S, that is next to the section sets supplied by the current power source P and it has not determined power source yet.

Step 3. Determine statistically whether the power source P supplies power to the section L using the following probability, $P_{connect}$. It should be noted that if SCM_P equals 0, $P_{connect}$ is 0.5. Moreover, the larger the SCM of source P is, the larger $P_{connect}$ can be. Here, minimum value of $P_{connect}$ is set to P_{min}.

$$P_{connect} = \frac{SCM_P + CAP_P}{2 \times CAP_P} \times (P_{\max} - P_{\min}) + P_{\min} \qquad (2)$$

where, SCM_P : Supply capacity margin of source P
CAP_P : Capacity of source P
P_{max} : Maximum probability
P_{min} : Minimum probability

Step 4. If every section has its power source, exit. Otherwise, go to step 2.

Step 5. Convert the obtained radial network to a string.

The concept of the above procedure is shown in Fig. 2. Since the method determines target sections supplied by each power source stochastically and radially, sub-optimal and various initial string populations, can be obtained.

String evaluation and selection

(1) String evaluation

String evaluation can be obtained using the fitness described by the following equation:

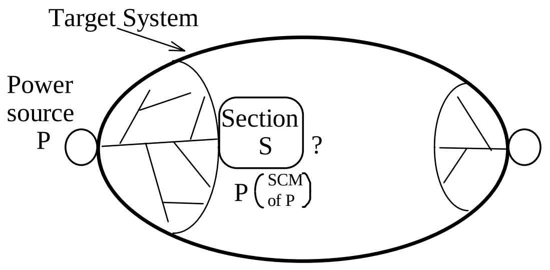
$$f = \frac{1}{f_c} \qquad (3)$$

According to the above equation, the less loss the distribution system has, the higher the fitness value is.

A certain string may be dominant in the initial stage of the optimization. In such a case, the whole population may converge to a string quickly (premature convergence). In order to avoid this difficulty, a linear scaling technique [10] is used in the proposed method. The scaling technique is used for maintaining appropriate conflict conditions among strings because large variation of the strings is one of the most important characteristics in GA. Maximum fitness value can be bounded using the scaling technique for maintaining variety of strings. Linear scaling modifies each fitness value using the following equation.

$$f' = \alpha f + \beta \qquad (4)$$

where, f' : modified fitness value α : coefficient
f : original fitness value β : coefficient



SCM = Supply Capability Margin

Fig. 2 Concept of generation for initial population.

Here, coefficients can be calculated using the maximum and minimum fitness values at each generation to keep the rate of the maximum and minimum fitness values at a certain value.

(2) String selection

The simple GA utilizes the roulette wheel selection (RWS) [10] as a string selection strategy, while the proposed method uses the remainder stochastic sampling with replacement [10] for improvement of convergence characteristics. The procedure can be summarized as follows:

* Sum up the fitness values of each string (f_i).

* Calculate the following probability.

$$pselect_i = f_i \,/ \sum f_i \qquad (5)$$

* The expected number of strings (e_i) can be calculated using the following equation.

$$e_i = pselect_i \cdot n_s \qquad (6)$$

where, n_s: the number of strings

* Each string is reproduced using the integer part of e_i.

* Each string is reproduced more by using the fraction part of e_i as the weight for the roulette wheel selection. Namely, the method uses RWS only for the fraction part of e_i. The procedure is repeated until the number of strings reaches n_s.

For example, if e_i equals 2.5, two strings are reproduced according to the integer part. The more reproduction rate for RWS should be 0.5 for the string.

String operation

(1) Cross-over

Cross-over operation exchanges partial radial networks at the boundary of the section of the cross-over point. For example, string shown in Fig. 3 can be represented as follows:

(9)(1)(2)(5)(10)(3)(6)(11)

Suppose cross-over of strings in Fig. 1 and Fig. 3 at the third position, the following strings can be obtained.

(9)(1)(4)|(5)(10)(3)(8)(11) (9)(1)(4)|(5)(10)(3)(6)(11)
→
(9)(1)(2)|(5)(10)(3)(6)(11) (9)(1)(2)|(5)(10)(3)(8)(11)

According to the result, a radial networks shown in Fig. 4 can be obtained. It is clear from the figure that the upstream of the section (3), that is the position of cross-over, were changed by the operation.

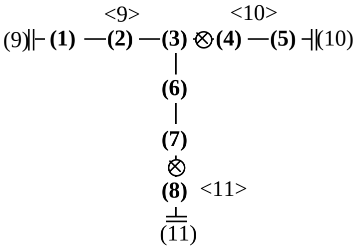
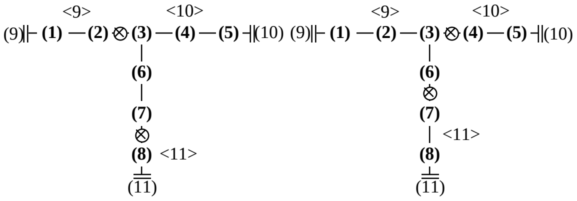


Fig. 3 Example No. 2 of radial networks.



(a) Example No. 1. (b) Example No. 2.

Fig. 4 Examples of radial networks after cross-over.

Generally, representing the upstream of each neighboring sections as →, status of neighboring sections before cross-over can be categorized as follows:

(a)←→ (b)→→ (c)←←

Here, (a) indicates power sources of each section are different; that means the switch must be opened between these sections. (b) indicates the upstream of the right section leads to the power source and (c) indicates the upstream of the left section leads to the power source. Neighboring loads after the cross-over can be represented as follows:

(a)←→ (b)→→ (c) ←← (d)→←

The added (d) indicates that neighboring sections represent the upstream node each other and all of downstream sections of these loads lose their power source (violation of radial network constraint). Namely, even if the above restricted string representation method is used, strings that violate the constraints (d) may generate. For example, Fig. 5 (a) and (b) show other radial network examples. Here, the upstream of each section is represented as →. Suppose cross-over at the third position, network configurations shown in Fig. 6 (a) and (b) can be obtained.

(9)(1)(2)|(3)(10)(3)(8)(11) (9)(1)(2)|(5)(10)(3)(6)(11)
→
(9)(1)(4)|(5)(10)(3)(6)(11) (9)(1)(4)|(3)(10)(3)(8)(11)

In Fig. 6 (b), sections (3) and (4) correspond to their upstream each other and section (3), (4), and (6) lose their power source. When a string that violates the constraints is generated, there are three ways to modify the string.

(i) Change the cross-over point until a string which does not violate the constraints is generated [9].
(ii) Modify string after the string operation [12].
(iii) Consider a problem-dependent operator [13].

Here, (ii) is utilized as the modification of the string. Moreover, the fitness values of strings that violate power source limit, voltage, and current constraints are modified.

(2)Repair operator

A repair operator which modifies the string so as to improve the objective function and to satisfy the radial network constraint is developed. The operator modifies the string according to the following rules:

(i) If there are power sources that can supply power to the isolated area without power source, connect the area to the sub-system whose connected node voltage is the highest; otherwise,
(ii) Connect the area to the sub-system with the largest SCM.

For example, for the radial network shown in Fig. 6 (b), sections (3), (4), and (6) must be connected to the subsystem whose power source is (9), (10), or (11), that satisfies the above strategy. Fig. 7 shows an example supposing that the power source (9) is selected.

(3) Mutation

Mutation is a bit exchange at a string position. This indicates an exchange of the direction of power source at a certain section. Therefore, the only section, that is next to a section connected to a different power source, can perform mutation. For example, in Fig. 7, only sections (4), (5), (6), and (7) can mutate.

NUMERICAL EXAMPLES

A simple distribution model system

(1) System condition

Fig. 8 shows a simple 6.6 [kV] model system with 27 switches, 20 sections, and 64 loads. All of switches are remotely controllable. The voltage at the secondary side of the distribution transformer which can be a source of the network is fixed at 6.9 [kV]. Distribution line is modeled using characteristics of actual hard drawn copper wires. Line length is assumed to be 1 [km/section] and load values are determined by the average actual feeder currents. Calculation parameters for GA are shown below.

Cross-over probability: 0.5 Mutation probability: 0.01
Number of strings: 20

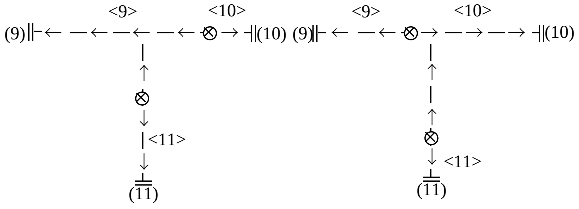
(2) Case conditions and calculation results

Increase of loss at unbalanced condition can be verified in case 1. Network reconfiguration using GA is performed in case 2 and 3.

a) Case 1

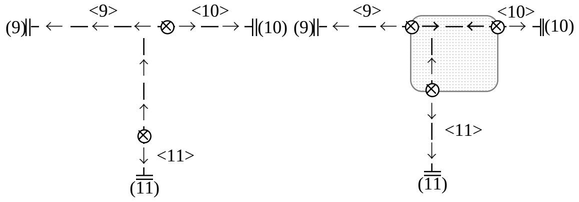
Loads are equally allocated in each section in the model system and the following conditions are compared.

* Loads are equally allocated to each phase
(allocated rate is 1:1:1 for each phase: load condition 1)
* Loads are allocated to each phase at unbalanced condition
(allocated rate is 4:3:3 for each phase: load condition 2)



(a) Example No. 3. (b) Example No. 4.

Fig. 5 Examples of radial networks.



(a) Example No. 3. (b) Example No. 4.

Fig. 6 Examples of radial networks after cross-over.

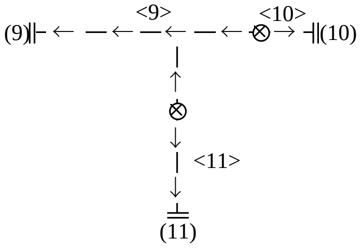


Fig. 7 A radial network after repair for example No. 4.

Here, note that the total loads at each node is the same and the load at each phase is different. The large value (allocated rate is 4) is allocated at the same phase at each feeder in load condition 2. This unbalanced condition leads approximately 1 [%] unbalanced voltage at the end of the feeder.

The results show that load condition 2 increases 2.54 [%] loss compared with load condition 1 even though the total loads at each node is the same. It indicates that unbalanced conditions increase losses and the loss can be reduced by compensating unbalanced conditions.

b) Case 2

Network reconfiguration is performed for load condition 1 of Case 1.

In the case, since line impedance and loads are totally balanced, the optimal network can be symmetric regarding switch status. Therefore, switch No. 7 and 28 should be close and No. 8 and 16 should be open. The proposed method generates the optimal solution in 5 [min] (C language, EWS [SPECint:52.6]).

c) Case 3

Case 3 gives more imbalance to each feeder considering practical distribution systems. Loads at feeder of FCB No. 9 and 17 is set to be approximately double those at feeder of FCB 1 and 24. Moreover, loads at each phase is also set to be unbalanced (load condition 3). Switch No. 7 and 28 should be close and No. 15 and 23 should be open for the optimal solution for the load condition 3.

The solution averages total load amounts for each feeder and compensates unbalanced conditions. Fig. 9 shows the convergence characteristics of GA for the case. The figure indicates that the optimal solution is obtained at generation 12 and strings can be converged rapidly to the optimal solution.

In simulation, most of the execution time is spent by three phase unbalanced load flow. Therefore, in order to reduce the execution time, it is necessary to reduce the number of executing the load flow. The conventional string representation method [9] requires recalculation (other cross-over and mutation) when strings that violate the radial network constraint are generated. This causes increase of number of load flow calculation. On the contrary, the proposed method does not require such recalculation and it indicates effectiveness of the proposed problem-dependent string representation method for fast computation. Moreover, strings violating current and voltage constraints are generated

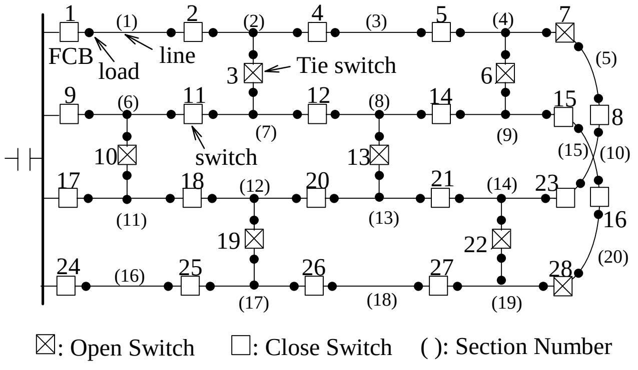


Fig. 8 A radial distribution model system.

at the early generations. However, the strings are converged to the optimal solution without constraint violation. For example, minimum voltage in the optimal solution in load condition 1 is 6564.35 [V]. This means that the proposed method can use infeasible regions in the solution space efficiently. This is another advantage of the proposed method.

Table 1 shows current values of each load condition.

Practical system

The proposed method is applied to a practical distribution system with 219 switches and 525 loads. A result can be obtained in approximately 30 [min]. Although optimality is not assured, the result averages loads among feeders and loss reduction is observed.

CONCLUSIONS

This paper has developed a genetic algorithm for network reconfiguration using three phase unbalanced load flow. The conclusion can be summarized as follows:

- The proposed method can reduce transmission power loss considering unbalanced condition and various load characteristics.
- The method can be applied to practical distribution systems and obtain appropriate solutions.

An advanced network reconfiguration method which can consider both loss reduction and various contingency will be investigated as future works.

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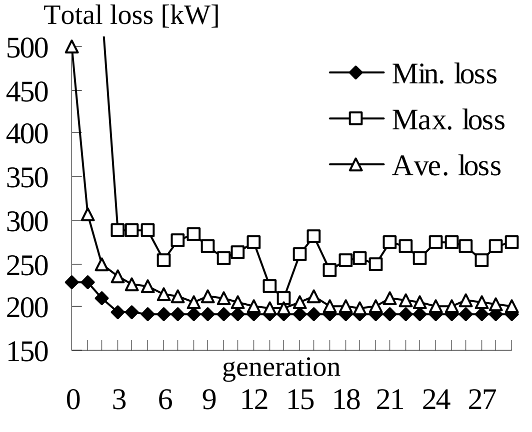

Fig. 9 Convergence characteristics for load condition 3.

Table 1 Load current at each section.

Load Condition	Section Number	Section Load Current [A]		
		Phase A	Phase B	Phase C
No. 1	(1)～(20)	13.33	13.33	13.33
No. 2	(1)～(4)	16.00	12.00	12.00
	(6)～(10)(20)	12.00	16.00	12.00
	(5)(11)～(15)	12.00	12.00	16.00
	(16)～(19)	16.00	12.00	12.00
No. 3	(1)(4)(16)(19)	11.43	8.57	8.57
	(2)(5)(17)(20)	8.57	11.43	8.57
	(3)(10)(15)(18)	8.57	8.57	11.43
	(6)～(8)(11)～(13)	22.22	22.22	22.22
	(9)(14)	9.52	9.52	9.52