7th WSEAS Int. Conf. on MATHEMATICAL METHODS and COMPUTATIONAL TECHNIQUES IN ELECTRICAL ENGINEERING, Sofia, 27-29/10/05 (pp315-319)

An Improved Single Loop Algorithm in Network Reconfiguration

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Abstract: -Network reconfiguration is an important tool in achieving economical and high quality operation in the distribution systems. But network reconfiguration belongs to a kind of complicated combinatorial optimization problem, it is hard to get an optimal network configuration at a feasible computer time when network scale is very large. As a result, network reconfiguration is usually used at the planning stage and not suitable for the real-time operational stage. This paper presents an improved single loop algorithm for quickly solving the distribution network reconfiguration problem. The problem formula is simplified, the complexity of the problem is decreased greatly and huge computation time is saved. Furthermore, an optimal transfer load algorithm is developed to easily determine the branch exchange with the maximum power loss reduction in the loop without calculating power loss reductions of all relevant branch exchanges. Two test systems are studied with the proposed approach. Test results not only have proved the validity and high efficiency of the proposed method but also indicate that the proposed method is suitable for real time control in large-scale real distribution systems.

Key-Words: -Distribution systems, network reconfiguration, optimal transfer load algorithm, heuristic algorithm, single loop algorithm

1 Introduction

Network reconfiguration is an important tool for reducing power loss, balancing systems loads, improving bus voltage profiles and others in distribution systems. Nowadays, with the increasing demand on power supply and the increasing concern of system efficiency and power quality, arising from proliferation of computer systems and remote control systems, network reconfiguration has played a more and more important role in the automation of distribution system. Network reconfiguration is a complicated nonlinear combinational optimization problem. It requires a significant amount of computational requirements and effort. To make it available for real-time control in a distribution system, it would be necessary to develop a quick solution algorithm.

Reconfiguration of distribution systems has a significant economic impact. It has received a lot of attention in the past decades. Civanlar [1] presented a switch exchange method, in which a simple formula for the estimation of the loss reduction by a particular switching option is developed. Baran [2] proposed the *simplified DistFlow equations* to simplify the calculation of power flow and heuristic methods to find a branch exchange resulting in maximum power loss reduction. J.Y. Fan [3] formulated the network reconfiguration problem as a LP (linear programming) problem and used a single-loop algorithm to search for the optimal network structure. M.A. Kashem [4] presented a geometrical approach for network power loss minimization, which searched every branch exchange in the largest zero loss-change circle to find the maximum loss-reduction branch exchange. V.N.Gohokar [5] used a network topology approach to formulate the network reconfiguration problem, and combined with the single-loop optimization approach to reconfigure the network structure efficiently. Shirmohammdi [6] proposed closing all tie switches first, then opening the these switches one after another according to the optimum flow pattern. H.D.Chiang [7] proposed a solution method for the network reconfiguration problem using the simulated annealing algorithm which was extended later by D.Jiang [8] and Y.J.Jeon [9]. In Y.H.Ying [10] and Y.C.Huang [11], B.Venkatesh[12] proposed a fuzzy adaptation of the evolutionary programming algorithm to solve the network reconfiguration problem.

The solution methods proposed by previous works are generally classified into two main categories: that is, (1) heuristic algorithms and (2) intelligent methods. The iteration process of a heuristic algorithm usually contains the following two steps: (1) finding the network loop in a distribution system, which gives the maximum power loss reduction, (2) determining a branch exchange in that loop to obtain the maximum power loss reduction. To simplify the computation, the heuristic rules are used in these two steps. However, the heuristic rules, which are derived from voltage differences across tie-switches, require a power flow study for the system at each iterative stages. The heuristic rule of starting the search from the lower bus voltage side of a tie-switch is not always right according to a counter-example given by Baran [2]. Intelligent methods, such as the tabu search, simulated annealing algorithm and genetic algorithm all inevitably require a large number of power flow and branch-exchange combinational tests. They are hard to be used for real-time application in distribution systems.

In this paper, an improved single loop algorithm for network reconfiguration in distribution systems is presented. It is aimed at speeding up the reconfiguration process and obtaining a feasible optimal network structure.

2 Problem Formulation

The primary goal of network reconfiguration in a distribution system is to reduce power loss at the operational stage. The total power loss of the system is the sum of power loss of all branches, and is expressed by:

$$P_{loss} = \sum_{i=1}^{n} \frac{P_i^2 + Q_i^2}{U_i^2} \cdot r_i \qquad (1)$$

where P_{loss} is the total power loss of the distribution system; P_i and Q_i are the powers flow of branch i; r_i is the resistance of branch i ; U_i is the voltage corresponding to P_i and Q_i ; n is the total number of branches in distribution system.

Fig.1 shows a simple radial distribution system. When tie switch s is closed, a loop network is formed, which is comprised of branches $\{j,\ldots, n, k,\ldots, m\}$.

The loop network can be replaced by an equivalent power load attached to bus N_i, as shown in Fig 2. The equivalent load is given by:

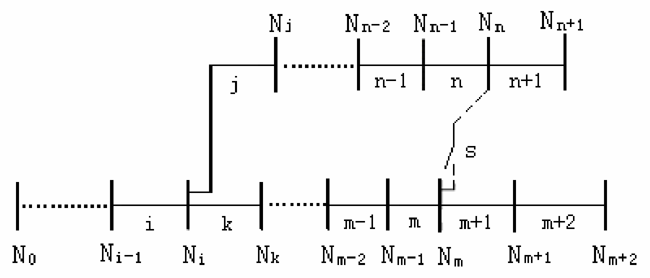

Fig.1 A simple distribution system

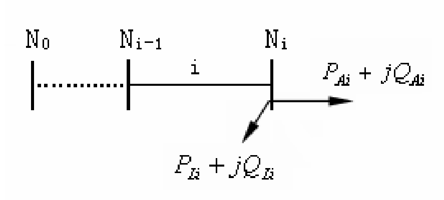

Fig.2 Equivalent network

$$\begin{aligned} P_{Ai} + jQ_{Ai} &= \sum_{t\in Loop}(P_{Lt} + jQ_{Lt}) + \sum_{j\in Loop}(\Delta P_j + j\Delta Q_j) \\ &= \sum_{t\in Loop}(P_{Lt} + jQ_{Lt}) + (\Delta P_{loss} + j\Delta Q_{loss}) \end{aligned} \qquad (2)$$

where P_{Ai}+jQ_{Ai} is the equivalent load; P_{Lt}+jQ_{Lt} is the power load in bus t in the loop; $\triangle P_j$+j$\triangle Q_j$ is the power loss of branch j in the loop; $\triangle P_{loss}$+j$\triangle Q_{loss}$ is the power loss of the loop.

It is noted that the bigger is the second term of Eq.2, the bigger is the equivalent load, as well as the total power loss of the system. The first term of Eq.2 is a constant. As a result, the objective function of network reconfiguration can be equivalently replaced by Eq.3, as follows:

$$Min(\Delta P_{loss\_i}) \mid i \in (1 \ldots m) \qquad (3)$$

where ΔP_{loss_I} is the total power loss of the loop associated with tie switch i; m is the total number of tie switches.

It is clear that the network reconfiguration problem is changed into each tie switch associated loop network reconfiguration sub-problems. It is the single loop algorithm.

Here, introducing the same assumptions, *simplified DistFlow equations*, constant power loads (P_{Li}+jQ_{Li}) and $U_i \approx 1$p.u., used in [2], the total power loss of a loop can be approximately expressed by:

$$\Delta P_{loss\_i} = \sum_{i=1}^{ni} (P_i^2 + Q_i^2) \cdot r_i \qquad (4)$$

ni is the branch number in the loop network.

Branch power flow P_j+jQ_j can be simply calculated using Eq.(5):

$$\begin{cases} P_i = \sum_{t\in i} P_{Lt} \\ Q_i = \sum_{t\in i} Q_{Lt} \end{cases} \qquad (5)$$

3 Optimal transfer load algorithm

To determine the branch exchange with the maximum power loss reduction in a loop simply and quickly,an optimal transfer load algorithm is developed.

Let the branches $\{j,\ldots,n\}$ in the loop , as shown in

Figure 1, be denoted by Set L and the others in the loop $\{k,\ldots,m\}$ by Set R. The resistance of tie switch s is assumed to be r_s. When the tie switch s closed and a sectionalizing switch in the loop is opened, there is a load P_s+jQ_s transferred between two sets. Assume that the transferred power load P_s+jQ_s is a continuous variable, and is transferred from set L to set R.

The power loss, P_{al}, of the loop after branch exchange are given, as follows:

$$\begin{aligned} P_{al} &= \sum_{i\in L}[(P_i - P_s)^2 + (Q_i - Q_s)^2]\cdot r_i \\ &+ \sum_{i\in R}[(P_i + P_s)^2 + (Q_i + Q_s)^2]\cdot r_i \\ &+ (P_s^2 + Q_s^2)\cdot r_s \end{aligned} \tag{6}$$

To seek an optimal transfer load P_s+jQ_s that makes P_{al} a minimum, the partial differentials of P_{al} with respect to P_s and Q_s respectively, are set to be zero, as follows:

$$\begin{cases} \dfrac{\partial P_{al}}{\partial P_s} = 0 \\ \dfrac{\partial P_{al}}{\partial Q_s} = 0 \end{cases} \tag{7}$$

Solving Eqs (6) yields a solution of the optimal transfer load

$$\begin{cases} P_s = \dfrac{\sum_{i\in L} P_i r_i - \sum_{i\in R} P_i r_i}{\sum_{i\in L\cup R} r_i + r_s} \\ Q_s = \dfrac{\sum_{i\in L} Q_i r_i - \sum_{i\in R} Q_i r_i}{\sum_{i\in L\cup R} r_i + r_s} \end{cases} \tag{8}$$

The optimal transfer load P_s+jQ_s is a continuous variable. It cannot match any branch power flow in the loop exactly. Thus the rule for finding the matching branch is derived according to the magnitude and sign of optimal transfer power load, as follows:

(1) If $(P_s^2+Q_s^2)<(P_n^2+Q_n^2)/2$, or $(P_s^2+Q_s^2)<(P_m^2+Q_m^2)/2$, the power loss in the loop is already a minimum. The tie switch should be kept opened.

(2) If P_s+jQ_s >0, the optimal transfer power flow P_s+jQ_s is really transferred from set L to set R. The branch in set L with power flow being closest to P_s+jQ_s is to be exchanged.

(3) If P_s+jQ_s <0, the optimal transfer power flow P_s+jQ_s is really transferred from set R to set L. The branch in set R, with power flow being closest to P_s+jQ_s is to be exchanged.

4 Improved single loop algorithm

The branch exchange for network reconfiguration means closing a tie switch and open a sectionalizing switch at the same time to maintain a radial configuration. In previous works, the tie-switch with the maximum voltage difference is selected for branch exchange at each iterative stage. Obviously, it is a greedy searching algorithm, and usually converges to local optima.

In this paper, the loop associated with tie switch in the system is reconstructed one by one at an original order rather than following the maximum power loss reduction order. Each iteration stage corresponding to a tie switch associated loop network optimization. This method not only reduces the computation resources for determining a branch exchange, but also conducts a wider search over the solution space. If a loop does not have common branches with other loops, the loop will be reconstructed only once.

On the other hand, according to the *simplified DistFlow equations*, the loop reconstruction will not affect the power flow of the branches outside the loop. After loop reconstruction, the only thing needed is to simply adjust the branch power flow within the loop by adding or subtracting the actual transfer load corresponding to the optimal transfer power load. As a result, the power flow at each iterative stage is not necessary within this method.

The procedure of the proposed algorithm is described, as follows:

1. Inputting network data and forming an original radial network structure.
2. Selecting a tie switch, and forming the branch sets L and R of the loop.
3. Computing the optimal transfer power load P_s+jQ_s of the loop, determining the exchange branch, in the corresponding branch set, with the power flow being the closest to it, then performing the corresponding branch-exchange.
4. Stopping further loop reconfiguration if all loops have minimal power loss, and outputting the optimization results. Otherwise, go to 2.

5 Test results

The proposed improved single loop algorithm has been implemented by using Microsoft VC++. Test system I is a 12.66 kV system with 69 buses and 5 tie branches. The detailed data of the test system were found in [13]. The total system load of the original configuration is 3802.19kW and 2694.6kvar. Test system II is a 33-bus system with 5 tie branches, and the detailed data of this system was provided in [2].

Table 1 shows the summary of the simulation results for testing system I using the proposed method. As seen in the table 1, there are eight branch exchanges in searching to obtain the optimum structure. Both optimal transfer power OTPL and actual transfer power ATPL resulting from each branch exchange are presented in the table. Figure 3 shows the optimal configuration of the testing system.

Table 2 gives the computation time required using a Pentium 3/500MHz computer. It is noted that network reconfiguration is speeded up greatly compared with the previous works. The results comparison for two testing systems including the optimal configuration, total power loss, the lowest bus voltage, etc, are given in Tables 3 and 4, respectively..

As shown in Table 3, the total power loss in testing system 1 after reconfiguration is reduced greatly down to 44.27% of the total power loss of the original network. The minimum bus voltage profile rises from 0.9091 to 0.9428. The system voltage quality is improved greatly.

Table1 69-Bus test system running course

Search level	Closed switch	OTPL (kVA)	Opened switch	ATPL (kVA)
1	70-10	832.01+j 586	8-9	767.8+j529.1
2	12-20	261.45+j174.20	16-17	236.3+j160.1
3	90-14	250.95+j167.38	11-12	357.8+j236.1
4	38-48	1064.4+j760.55	47-48	1662+j1187
5	26-54	300.39+j220.13	50-51	318+j227
6	8-9	407.61+j282.65	70-10	410+j293
7	16-17	364.14+j253.78	12-20	554.3+j387.1
8	11-12	78.21+j49.09	14-13	16+j11

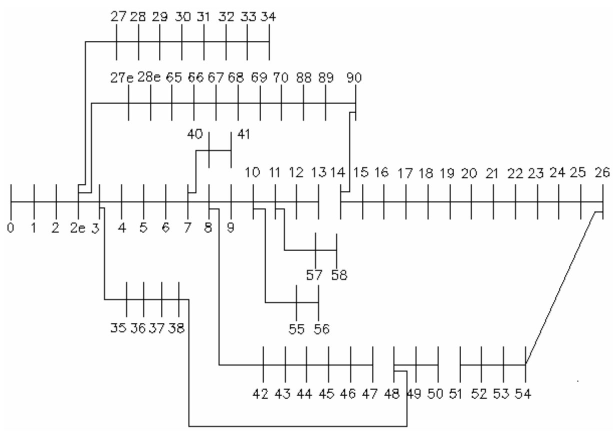

Fig.3 The optimal configuration of 69-bus test system

Table 2 run-time comparison between different methods

	Test system I	Test system II	Programming language	Computer system
Proposed Method	0.0004[s]	0.0002[s]	VC++	PIII500MHz
Method in [8]	2.57[s]	0.34[s]	C	PII350MHz
Method in [9]	N/A	25[s]	N/A	PIV
Method in [10]	13[s]	N/A	Turbo C	PIII600MHz

Talbe 3 Results comparison of different methods(69-bus system)

	Original Network	Method in [4]	Method in [8]	Method in [11]	Proposed Method
Open Switches	(10-70) (12-20) (14-90) (26-54) (38-48)	(10-70) (12-20) (13-14) (47-48) (50-51)	(10-70) (16-17) (89-90) (52-53) (46-47)	(10-70) (12-20) (11-12) (26-54) (47-48)	(10-70) (12-20) (13-14) (47-48) (50-51)
Power Loss(kW)	225.02	99.62	119.92	123.03	99.62
Lowest V. (p.u.)	0.9092	0.9427	0.9413	0.9263	0.9427
Lowest V. Bus	54	50	52	54	50

Table 4 Results comparison of different methods(33-bus system)

	Original Network	Method in [2]	Method in [10]	Method in [12]	Proposed Method
Open Switches	(7-20) (8-14) (11-21) (24-28) (17-32)	(6-7) (9-10) (13-14) (26-27) (29-30)	(7-20) (8-9) (8-14) (27-28) (17-32)	(5-6), (8-9), (13-14) (24-28) (31-32)	(6-7) (8-9) (13-14) (24-28) (31-32)
Power Loss(kW)	202.68	161.01	146.37	142.83	139.55
Lowest V. (p.u.)	0.9131	0.9043	0.9367	0.9390	0.9378
Lowest V. Bus	17	30	32	32	31

6 Conclusion

An improved single loop algorithm is proposed in this paper. To make an amount of computation required linearly proportional to the total number of tie switches and the total number of sectionalizing switches, the network reconfiguration problem is reformulated into tie switch associated loop network reconfiguration sub-problems. To efficiently and accurately determine the branch exchange with the maximum power loss reduction in a loop, an optimal transfer load algorithm is developed. Furthermore, the searching manner is improved from the complicated greedy search to the simplified single loop optimization, i.e. each loop is reconfigured one by one iteratively. The proposed method has been applied successfully to two test systems. The high efficiency in finding the global optimal configuration is demonstrated. Test results show that the proposed improved single loop algorithm is suitable for the real-time application in the large scale distribution systems.

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