

Research on Distribution Network Reconfiguration Method Considering Switching Operations

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Abstract. The traditional distribution network reconfiguration method does not consider the impact of switching operations, resulting network equipments voltage instability and user blackouts in actual implementations. In this paper, the loop operation security constraints have been fully taken into account as establishing distribution network reconfiguration model by introducing constraints into the traditional model. The greedy random adaptive search procedures (GRASP) is adopted to obtain optimal solution and detailed steps of reconfiguration scheme and switching operation for distribution network, which ensures the solution is realized without network equipments voltage instability and user blackouts. After IEEE 14-bus system verification, this method shows its better adaptability and practical value, which fully combines actual work statues to improve distribution network reliability.

1. Introduction

Distribution network reconfiguration plays a crucial role in grid optimization, which refers to changing segment switches and contact switches status to adjust distribution network structure, aiming network loss decrease, balance and other purposes[1]. Link and unlink operations are commonly used in grid dispatching department to achieve network structure adjustment, as closing a contact switch to form a ring and then open the ring by switching off a certain segment breaker to restore its radial wiring, without user power loss during load transfer process. With the increasing complexity of distribution grids and demanding power supply reliability, the link and unlink operations have become a routine for network dispatchers to adjust grid structure to realize power flow redistribution[2].

However, in items of security constraints, the current distribution network reconfiguration methods basically only verify the final network structure after the model is solved, which lacks detailed analysis for each switch operation process and its relevant network security constraint. In particular, the node voltage and line power flow constraints required to meet switching operation during reconfiguration process are generally not taken into consideration.

Therefore, although the final network structure can meet security constraints, problems like network equipments voltage instability and user blackouts may still occur during the reconfiguration implementation causing infeasibility in areas where the demand for power supply reliability is high.

In summary, this paper researches the distribution network reconfiguration method considering switching operations in order to ensure its rationality and feasibility. First, it establishes distribution network reconfiguration model by introducing constraints into the traditional model. Then, the greedy random adaptive search procedures (GRASP) are used to solve the model based on the Thevenin equivalence theorem. Finally, an example of a 14-node system is given to verify the correctness and validity of the proposed method.



2. Distribution network reconfiguration method considering switching operations

After link and unlink operations, the system security constraints of distribution network reconfiguration model include both radiation and ring connection. To ensure system security during the whole reconfiguration procedures, corresponding constraints have to be included after each switch operation in the model. According to the daily actual operation of distribution network, only single link or unlink operation is commenced at the same time. Based on the considerations above, the distribution network reconfiguration method considering switching operations is shown as follows:

$$\min P_{loss} = \sum_{ij=1}^{N_l} r_{ij} \left(\frac{p_{ij(2g)}^2 + q_{ij(2g)}^2}{v_{k(2g)}^2} \right) \quad (1)$$

s.t.

$$\left\{ \begin{array}{l} \sum_{i=1}^k (p_{ij(2t-1)} + jq_{ij(2t-1)}) = p_{dj} + jq_{dj} \\ v_{i(2t-1)} - v_{j(2t-1)} = z_{ij} i_{ij(2t-1)} \\ \sqrt{p_{ij(2t-1)}^2 + q_{ij(2t-1)}^2} \leq s_{ij \max} \\ v_{i, \min} \leq v_{i(2t-1)} \leq v_{i, \max} \\ N_b = N_l \end{array} \right. \quad (2)$$

$$\left\{ \begin{array}{l} \sum_{i=1}^k (p_{ij(2t)} + jq_{ij(2t)}) = p_{dj} + jq_{dj} \\ v_{i(2t)} - v_{j(2t)} = z_{ij} i_{ij(2t)} \\ \sqrt{p_{ij(2t)}^2 + q_{ij(2t)}^2} \leq s_{ij \max} \\ v_{i, \min} \leq v_{i(2t)} \leq v_{i, \max} \\ N_b = N_l - 1 \end{array} \right. \quad (3)$$

$$t = 1, 2, \dots, g \quad (4)$$

Among them, P_{loss} for system actual loss, N_l for number of lines, N_b for number of nodes, r_{ij} , p_{ij} , q_{ij} , i_{ij} , z_{ij} , $s_{ij \max}$ for resistance, active power, reactive power, current, impedance, maximum apparent power of line ij respectively, v_i , v_j for voltage value of node i and node j . $v_{i, \max}$, $v_{i, \min}$ for upper and lower voltage limits of node i . p_{dj} , q_{dj} for active load and reactive load value of node j . g for total number of link and unlink operations, one operation represents one step, t for t_{th} step.

In the model, equation (1) is the objective function which aims to minimize line loss in this chapter. The variable with a subscript of $2g$ in the objective function represents all the operational variables of the final reconstructed radial grid after all link and unlink operations have been commenced.

Equation (2) is the set of network constraints for the single-loop network after link operations, where all the variables with the subscript $2t-1$ represent the operational variables after link operations. This constraint set includes the power balance constraint, Kirchhoff's voltage law constraint, line current limit constraint, voltage limit constraint and ring topology constraint for the single-loop network after link operations.

Equation (3) is the set of network constraints for the single-loop network after unlink operations, where all the variables with the subscript $2t$ represent the operational variables after unlink operations.

This constraint set includes the power balance constraint, Kirchhoff's voltage law constraint, line current limit constraint, voltage limit constraint and ring topology constraint for the single-loop network after unlink operations.

Equation (4) for the step of link and unlink operations, t for t_{th} step.

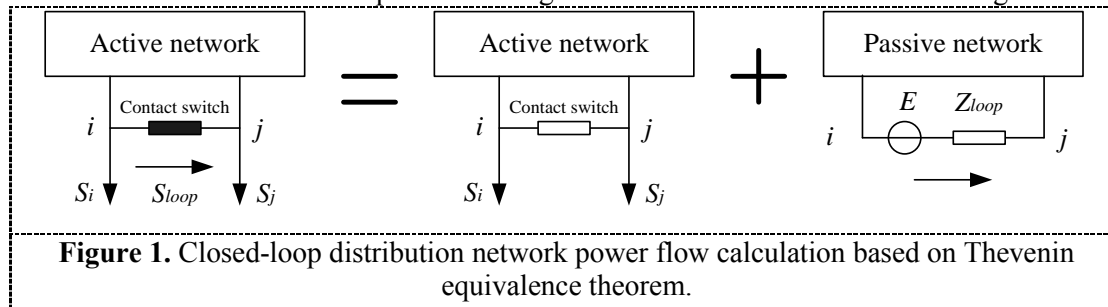
Comparing equation (2) and (3), we can see that except variable subscript, the only difference between two equations is the relationship between the number of nodes N_b and the number of branches N_l . As a single ring network in the distribution grid is generated after link operation, the number of nodes N_b and the number of branches N_l are exactly the same.

The model designed in this paper includes more variables and constraints comparing traditional distribution network reconfiguration model, which satisfies voltage, power and load balance limit constraints in each link and unlink operation during reconfiguration process. Therefore, it is practicable to solve the safety constraints in link and unlink operation by adopting the distribution network reconfiguration method presented in this chapter.

3. Closed-loop distribution network power flow calculation

Closed-loop distribution network power flow calculation is an important way to verify the operation safety of distribution network when the loop is closed.

This chapter uses the Thevenin equivalence theorem for the distribution network closed-loop power flow calculation considering its advantage of fast calculation speed and no need to modify the original forward and backward substitution power flow algorithm. The illustration is shown in figure 1:



The calculation steps of Closed-loop distribution network power flow calculation based on Thevenin equivalence theorem are shown as follow:

- (1) Obtaining voltage values v_i , v_j of the nodes on both sides of loop by using forward and backward substitution method to calculate power flow of initial distribution grid;
- (2) Calculating Thevenin equivalent impedance $Z_{loop} = \sum_{i=1}^{loopb} Z_i$, as $loopb$ for the number of branches and Z_i for the impedance of the i_{th} branch in the loop;
- (3) Calculating closed-loop current: $I_{loop} = \frac{v_i - v_j}{Z_{loop}}$. Obtaining equivalent injection power of node i,j in

the closed-loop branch according to closed-loop current value. Adding equivalent injection power values to node i,j, generating radiation equivalent circuit as shown in figure 2:

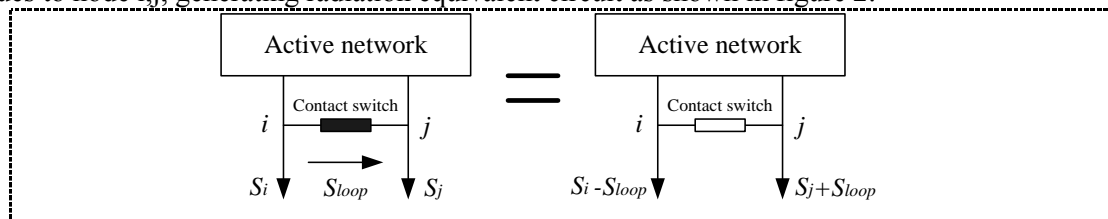


Figure 2. Equivalent closed-loop circuit.

(4) Calculating power flow of radial network shown in figure 2 by forward and backward substitution method;

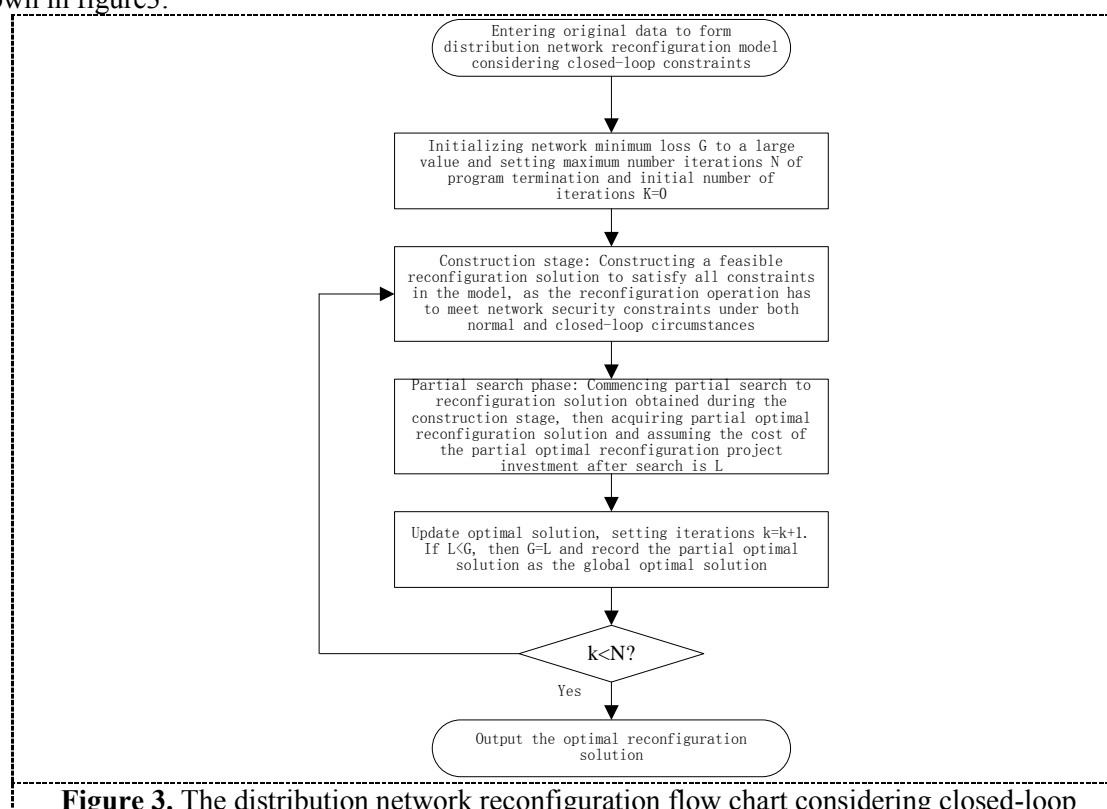
(5) Verifying the network voltage and line power constraints according to power flow calculation results after equivalent process.

As can be seen from the closed-loop power flow calculation method mentioned above, the closed-loop branches finally become equivalent to the nodes on both sides the branch in actual calculation, which can be directly calculated by using forward and backward substitution method. The safety of link operation can be verified by closed-loop power flow calculation and it will be not feasible if the safety constraints are not satisfied.

4. Model solving

At present, there are three kinds of algorithms to solve distribution network reconfiguration model. The first one is the heuristic algorithm, which is easy to achieve but difficult to get optimal solution. The second one is the classical mathematical algorithm, which can get the global optimal solution but the solution speed will become slow when system gets huge. The third one is the modern optimization algorithm, which is more suitable for solving large-scale combinatorial optimization problems and it has been widely used in power system optimization problems[3]. The greedy random adaptive search procedures (GRASP) presented in this paper is such an algorithm.

Compared with other modern optimization algorithms such as genetic algorithm and simulated annealing algorithm, the GRASP has advantages with less parameter to be set and easy to make configurations[4]. In addition, since the GRASP is based on line-by-line construction to generate initial feasible solution, the specific operation process of reconfiguration switch can be reflected and achieve security verification at construction stage[5]. The other types of modern optimization algorithms generally provide final reconfiguration solution directly without detailed reconfiguration process. The distribution network reconfiguration flow chart considering closed-loop constraints is shown in figure 3:

**Figure 3.** The distribution network reconfiguration flow chart considering closed-loop

constraints.

The main steps of using GRASP to solve distribution network reconfiguration model considering closed-loop constraints are shown as follows:

- (1) Entering original data to form distribution network reconfiguration model considering closed-loop constraints as equation (1)-(4);
- (2) Initializing network minimum loss G to a large value and setting maximum number iterations N of program termination and initial number of iterations $K=0$;
- (3) Construction stage: constructing a feasible reconfiguration solution to satisfy all constraints in the model, in other words, the reconfiguration operation has to meet network security constraints under both normal and closed-loop circumstances;
- (4) Partial search phase: Commencing partial search to reconfiguration solution obtained during the construction stage, then acquiring partial optimal reconfiguration solution and assuming the cost of the partial optimal reconfiguration project investment after search is L ;
- (5) Update optimal solution, setting iterations $k=k+1$. If $L < G$, then $G=L$ and record the partial optimal solution as the global optimal solution;
- (6) If the current number of iterations k is less than the maximum number of iterations N set before, then goes to step (3). Otherwise, the program will terminate and output the optimal reconfiguration solution with its investment cost G .

As can be seen from the above calculation steps of the GRASP algorithm, the construction phase and the partial search phase are two crucial components of the algorithm. The detailed steps of two stages are explained in the next part.

4.1. Construction phase

- (1) Using forward and backward substitution method to calculate current radial connection distribution network power flow;
- (2) Calculating the voltage difference between two sides of all contact switches and sort them in descending order, selecting pre-sequence CL switches to form an alternative ring switch set;
- (3) Randomly selecting a contact switch from the set of alternative closed-loop switches and closing it;
- (4) Calculating power flow in closed-loop distribution network and check safety constraints. If the constraints are met, turn to (5). Otherwise, turn to (3);
- (5) Selecting the segment switch that minimizes network loss in the ring formed by contact switch, and then turning it on. Among them, the degree of loss reduce enabled by different sections of switches can be immediately obtained by equation (5);

$$\Delta P = \operatorname{Re} \left\{ 2 \left(\sum_{i \in D} I_i \right) (E_m - E_n)^* \right\} + R_{loop} \sum_{i \in D} |I_i|^2 \quad (5)$$

- (6) Calculating the power flow in open-loop distribution network by forward and backward substitution method, if the safety constraint is satisfied, keep the operation and turn to (7). Otherwise, mark the segment switch not for open in this loop and turn to (5);
- (7) If the loss changing indicators $\Delta P > 0$ turn to (1). Otherwise, terminating the program and output the candidate reconfiguration solution.

An initially feasible distribution network reconfiguration solution will be generated through construction phase.

4.2. Partial phase

- (1) Selecting the reconfiguration solution generated in construction phase as the initial solution in partial search phase;
- (2) Select one of the link and unlink operations in the reconfiguration solution and temporarily cancelling it to restore grid connection before any operation;
- (3) Calculating the power flow of distribution network and solving the change of network loss;

(4) If $\Delta P > 0$, the network loss will increase, then the link or unlink operation is retained in the reconfiguration solution, marking it as a non-cancellable operation and turning to (2). Otherwise, if the network loss is unchanged or reduced, the link or unlink operation will be permanently cancelled in the reconfiguration solution and turning to (5);

(5) If all the link and unlink operations have completed temporary cancellation and verification, the final reconfiguration solution will be presented. Otherwise, turn to (2).

Based on the N times iterations, the global optimal solution with the least loss is obtained and the model solving process is completed.

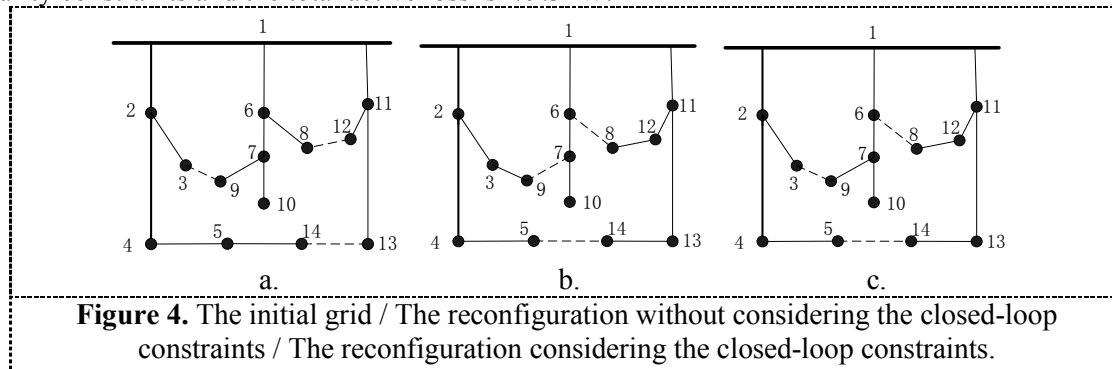
5. Example analysis

This chapter uses 14 nodes system as an example to verify the method in this paper. The example assumes that the lower voltage limit for all nodes is 0.95 pu. The power limits for lines 1-2, 2-4, 4-5, 5-14, 2-3, 3-9 are 10 mW. The revised load data is shown in table 1:

Table 1. 14 nodes system load data.

Node number	Active power (mW)	Reactive power (mVar)	Node number	Active power (mW)	Reactive power (mVar)
1	0.21	0.10	8	0.95	0.87
2	2.13	1.41	9	0.46	-0.55
3	2.94	0.16	10	4.73	-1.76
4	2.01	-0.33	11	1.16	0.82
5	1.67	0.99	12	0.80	-1.15
6	3.77	2.92	13	0.97	0.78
7	4.98	2.00	14	1.06	-2.73

The initial grid topology of a 14 nodes power distribution system is shown in figure 4-a, where the solid lines represent segmented lines and dashed lines for contact lines. The initial grid satisfies security constraints and the total active loss is 479.3 kW.



First of all, the reconstruction results of the initial grid are obtained by using the traditional distribution network reconfiguration method to get the optimal reconfiguration grid connection without considering the constraints of closed-loop is shown in figure 4-b. The final grid without considering the constraints of closed-loop can satisfy the safety requirements under regular radial grid connection. The total active loss is 431.0 kW.

It can be seen from figure 4-b that regardless of the closed-loop constraints, the states of six switches in reconfiguration solution have changed in total. However, according to the conventional calculation method, it is impossible to obtain the detailed operation steps of six switches. In order to avoid power cut, according to the location of the ring where the switch is located, the final reconfiguration solution can be achieved by the following operations: close the contact switch of lines 3-9 and open the segment switch of lines 7-9; close the contact switch of lines 8-12 and open the

segment switch of lines 6-8; close the contact switch of lines 13-14 and open the segment switch of lines 5-14.

However, the flow current of line 1-2 is 11.7 mW, when the link operation is commenced based on closed-loop power flow calculation method, which is higher than the line limit of 10mW. The optimal network frame shown in figure 4-b cannot be achieved by link or unlink operation. To avoid line overrun, the segment switch of line 7-9 must open and the contact switch of lines 3-9 must close, but it will lead to power cut in node 9. Therefore, it is not possible to realize the optimal reconfiguration solutions shown in figure 4-b through link and unlink operations without power cut.

The optimal reconfiguration solution is obtained as shown in figure 4-c using the method proposed in this paper considering closed-loop constraints. Four switching states have changed based on the optimal reconfiguration solution in this chapter. The specific steps use of switch operations during the reconfiguration process can be obtained by improved GRASP algorithm. The optimal reconfiguration solution is shown as following process: close the contact switch of lines 8-12 and open the segment switch of lines 6-8; close the contact switch of lines 13-14 and open the segment switch of lines 5-14.

The link and unlink operations mentioned above have been verified by closed-loop power flow which meets the requirements of the closed-loop safety constraints. The network loss of the optimal reconfiguration solution is 458.2 kW. The improved GRASP algorithm proposed in this chapter has faster calculation speed when solving the model. When the population number N is set to 10, the calculation can be completed in only 0.53 second to obtain optimal reconfiguration solution. The calculation results of 14 nodes system in all cases are summarized in table 2:

Table 2. 14 nodes system calculation results comparison.

Grid Type	Active power loss (kW)	Network contact switch	Closed-loop constraints status
Initial network	479.3	3-9, 8-12, 13-14	/
Without considering closed-loop constraints	431.0	6-8, 7-9, 5-14	Line 1-2 will overrun as the contact switch of line 3-9 is closed
Considering closed-loop constraints	458.2	3-9, 6-8, 5-14,	No line will overrun

6. Conclusion

From the reconfiguration solution given in table 2, it can be seen that the optimal reconfiguration solution obtained by the method in this paper can meet the requirements of the closed-loop safety constraints. Compared with the solution without considering the constraints, it has higher loss, but it can achieve uninterrupted power supply during the whole reconfiguration process, which has good operation feasibility in areas with high requirements on power supply reliability.

Reference

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