Research on Optimal Operation Mode for Large-scale Urban Distribution Network Considering Safety Constraints

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Abstract. As an important measure for structure optimization, the network reconfiguration has been drawing attention of scholars at home and abroad. At present, the general goal for network reconfiguration is to reduce network line loss achieving load balance. In this paper, the reconstruction methods for distribution network considering closed loop constraints is proposed from the perspective of load transfer between different loops to improve closed system reliability. After Dongjing Town distribution network verification, this method has shown important theoretical significance and high practical value.

1. Introduction

Optimizing the operation mode for distribution network will create revenue by the network loss reduction. However, when the operation is implemented, the effects of load balancing, voltage quality and network reliability must be considered, as certain constraints need to be met. Therefore, the objective function of the optimal operation mode for distribution network is not just for loss reduction, but a multi-objective decision problem. The early reconstruction of distribution network was mainly to achieve minimal total cost providing certain power supply path to users, in short, the distribution network reconstruction in planning stage.

Research on distribution network reconfiguration has been carried out earlier abroad, initially focusing on urban power grids \cite{1}. The urban power grid is characterized by the extensive use of underground cables, which have a ring structure and are usually operated in a radial shape. As the problem for optimal power supply pattern for distribution transformers in underground cable system is presented.

Distribution network reconfiguration is a multi-objective nonlinear hybrid optimization problem. Most existing algorithms use a single objective function or a dimensionality reduction method to select one main target and to set other targets as constraints. At present, most structural optimization for power grid reconfiguration is in theoretical research stage and mainly uses single objective function by selecting a main target and setting other targets as constraints.

In this paper, the optimization strategy for inter-ring transition is proposed from the perspective of load transfer between different loops to improve closed loop system reliability. It also analyzes the constraints of the inter-ring power transfer operations and proposes the principle of engineering
application, making the network operational indicators, such as line loss, load balancing or voltage quality, the best way to operate.

2. Constraints on inter-ring operations

2.1. Basic concept of distribution network closed loop operation

The distribution network is capable of closed loop operation when two feeder lines are respectively carried by the lower voltage side bus bars from the two substations and a tie switch is arranged between the feeder lines. In normal operation mode, the lower voltage bus bars of the two substations each have a corresponding feeder line and the contact switch is disconnected [2].

As the moment one of the feeders has a power outage on the whole or parts it, the contact switch is closed at first, then the forehead switch or the segment switch is disconnected. The whole or part of the electrical load is carried by the other feeder line. Distribution network is capable of closed loop operation in urban area is usually equivalent to the ring network structure as figure 1.

![Figure 1. Closed loop operation in distribution network.](image)

Closed loop operation means when bus bar I requires maintenance due to power failure, it is necessary to close the contact switch at connection point in distribution network and transfer part of the load from maintenance areas, ensuring uninterrupted power supply.

2.2. The cause of closed loop operation problems

At the moment when closed loop operation is commenced in distribution network, a transient change will occur in power flow instantaneously and the transient process will be experienced due to the voltage difference between two ends of the loop (contact switch), as \( \Delta U \neq 0 \).

When the contact switch is closed, the voltage difference between the two sides will get equal abruptly, as \( \Delta U \neq 0 \). At the same time, it causes corresponding changes in voltage amplitude and angle of each node in the whole ring, together with the node generator. However, considering the moment of generator rotor inertia, the power angle cannot be instantaneously changed so that an oscillation process is required for the generator to become a new steady state. When closed loop operation is commenced, due to different phase angle and frequency of the outlet voltage, a transient process will undergo after the feeder is looped, including steady and transient (impulse) current. In summary, the reasons for closed loop operation current of the distribution network are as follows: the amplitude and phase difference between two feeder lines ready to close will cause loop current when commencing closed loop operation.

In simplified calculation, if the short-circuit impedances of the substation's lower voltage bus bars related to these two feeder lines are approximately equal, the closed loop current is generally equal to the voltage difference of two end divided by the total impedance of closed loop. When the calculation result of this method is checked with the actual value, the error is usually within 20%.

2.3. Potential Risks
(1) When two feeders require parallel operation, in normal circumstances, as long as the voltage difference between the two lines is within allowable range, the closed loop current generated during the operation process will be acceptable. However, if the system has a temporary fault or the load is unbalanced, such as a lightning strike or a short-circuit condition, the contact switch between two feeder lines may pass through large power flow transmitted from the higher voltage side of transformer, which will inevitably cause relay protection action. It may expand the scale and range of power outages, resulting serious impact on user's daily production and life.

(2) When two feeders require parallel operation, if the system short-circuit impedance of the bus bars on both sides is different, the closed loop operation will also tend to cause large steady and impulse current, enabling tripping action for feeder relay protection. That is the reason why in higher voltage transmission network, it usually operates in a closed loop. While in lower voltage distribution network like 110 kV and below, the radiation operation is dominant.

(3) Insufficient experience of operating personnel may also lead to misjudgement of closed loop conditions of feeder lines, resulting loop closing failure and power outage.

2.4. Influencing factors
Circulation current occurs when the distribution network loop is closed, mainly because of voltage amplitude and phase difference on both sides of the loops, together with asymmetrical system parameters of feeder lines. Therefore, when the distribution network loop is closed, the amplitude of circulating current should be kept as low as possible to prevent relay protection malfunction from feeder line current exceeding limit and power failure of closed loop. Before commencing closed loop operation, the operator must first understand the overall operation mode of system, including voltage, power allocation and relay protection settings. At the same time, the operator also needs to fully estimate and analysis the possible change of power flow change after closed loop operation to ensure that the operation meets following conditions:

(1) Before the loop is closed, the phase and its sequence are guaranteed to be the same. Phase measurement is required before the operation of closed loop, and follow-up work should not proceed if the phase is not consistent;

(2) After the loop is closed, the load and voltage of each component of feeder line should be monitored in real time to ensure that operational parameters will not exceed limit;

(3) The malfunction of relay protection should be avoided. The integrated impedance of the two feeders at the joint point should be kept in acceptable range and corresponding measures can be taken to adjust impedance of loop line if necessary;

(4) The sum load of closed loop should not exceed any original switch before operation. According to theoretical calculation analysis, the line with the larger circulation current should exit the recloser;

(5) When performing a closed loop operation on a heavily loaded line, the operator should wait until maintenance team arrives at the scene.

The conditions above are all ideal. In the daily dispatching operation practice, the influencing factors of closed loop need to be calculated before operation, and whether the closed loop condition meets the requirements should be examined and determined by calculation result.

3. Reconstruction methods for distribution network considering closed loop constraints

3.1. Operation steps
After switch close and open operations, the system security constraints include both radiation and loop connection. To make sure that the system is safe during the whole reconfiguration procedure, certain corresponding constraints have to be met with every switch operations in the model [3].
According to the daily operation practice, it is crucial that only one switch close and open operation is commenced at the same point. In terms of the considerations mentioned above, the distribution network reconfiguration method considering closed loop operations is shown as follows:

\[
\min P_{\text{loss}} = \sum_{g=1}^{N_g} P_g \left( \frac{P_{ij}^2 + q_{ij}^2}{v_{kij}^2} \right)
\]  

(1)

In this model, formula (1) for objective function, this paper sets as minimal line loss as target. The variable with a subscript of 2g in this function represents all the operational variables of the final radial network reconstructed after all operations accomplished.

In this form, \(P_{\text{loss}}\) is system overall active power loss, \(N_f\) is the count of lines, \(N_b\) is the count of nodes, \(r_j, p_{ij}, q_{ij}, l_{ij}, z_{ij}, s_{ij}^{\text{max}}\) stands for resistance, active power, reactive power, current, impedance, maximum apparent power of line \(ij\) accordingly, \(v_i, v_j\) are the voltage of node \(i\) and node \(j\). \(v_{i,\text{max}}, v_{i,\text{min}}\) are the upper and lower voltage limits for node \(i\). \(p_{dj}, q_{dj}\) are active load and reactive load values of node \(j\). \(g\) is the total count of loop close and open operation steps, regarding one operation as one step, \(t\) is the t-times step.

\[
\begin{align*}
\sum_{i=1}^{g} (p_{ij(2t-1)} + jq_{ij(2t-1)}) &= p_{dj} + jq_{dj} \\
v_{i(2t-1)} - v_{j(2t-1)} &= z_{ij}^{\text{r}} l_{ij(2t-1)} \\
\sqrt{p_{ij(2t-1)}^2 + q_{ij(2t-1)}^2} &\leq s_{ij}^{\text{max}} \\
v_{i,\text{min}} &\leq v_{i(2t-1)} \leq v_{i,\text{max}} \\
N_b &= N_f
\end{align*}
\]  

(2)

Formula (2) presents for the collection of safety constraints for network after close loop operations, where all the variables with a subscript 2t-1 stand for the operational parameter variables after close loop operation. This constraint collection provides active power balance, Kirchhoff’s voltage law, line current upper limit, voltage limit and loop topology constraints for single-loop network after close loop operations.

\[
\begin{align*}
\sum_{i=1}^{g} (p_{ij(2t)} + jq_{ij(2t)}) &= p_{dj} + jq_{dj} \\
v_{i(2t)} - v_{j(2t)} &= z_{ij}^{\text{r}} l_{ij(2t)} \\
\sqrt{p_{ij(2t)}^2 + q_{ij(2t)}^2} &\leq s_{ij}^{\text{max}} \\
v_{i,\text{min}} &\leq v_{i(2t)} \leq v_{i,\text{max}} \\
N_b &= N_f - 1
\end{align*}
\]  

(3)

Formula (3) presents for the collection of safety constraints for network after open loop operations, where all the variables with a subscript 2t stand for the operational parameter variables after open loop operation. This constraint collection provides active power balance, Kirchhoff’s voltage law, line current upper limit, voltage limit and loop topology constraints for single-loop network after open loop operations.

\[
t = 1, 2, \cdots, g
\]  

(4)

Formula (4) is the step of switch open and close operations, \(t\) is the t-times step.

When comparing Formula (2) and (3), it is apparent that except the variable subscript, the only difference between two equations or two states is the equality relationship between the count of nodes.
$N_b$ and branches $N_t$. Regarding single loop network will be generated after close loop operation, the count of nodes $N_b$ and branches $N_t$ are exactly the same number.

3.2. Model Solving

In order to improve the rapidity and practicability of reconstruction solution, it is advised that switches obviously not feasible or with high operation cost can be screened out according to actual situation of switch candidates and field operation practice of the feeder lines before establishing reconstruction model. It is also possible to add the total number of switching operations as an optimization target in objective function, forming a multi-objective distribution network reconstruction model considering closed loop constraints. The closed loop reconstruction model with multi-objective can refer to the processing method of the model presented in this paper, combining with the multi-objective optimization theory.

The Greedy Random Adaptive Search Procedure (GRASP) algorithm [4] used in this paper is algorithm of this kind. Compared with other modern optimization algorithms such as genetic algorithm and simulated annealing algorithm, the GRASP algorithm has the advantage that it requires less parameter information with easy accession. The vital steps of using GRASP to solve distribution network reconfiguration model considering closed-loop constraints can be found in corresponding paper [5].

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 shown in figure 2:

**Figure 2.** The construction phase and the partial search phase flow chart considering closed-loop constraints.
4. Reconstruction methods for distribution network considering closed loop constraints

In this paper, we take the distribution network of typical distribution grids in Dongjing Town, Songjiang District in Shanghai as an example. The distribution network is powered by 35 kV Dongjing Substation and 110 kV Xuejiabang Substation. The relative distance between the two substations is about 2.3 km.

There are 3 transformers each with a capacity of 20MVA in Dongjing Station. The whole station peak load rate in summer is 74.14%. The overall load rate of Dongjing station is relatively high, so it is necessary to adjust the operation mode to reduce the load rate of Dongjing station. There are 22 10 kV output lines in 35 kV Dongjing station and the lines with higher load rate are shown in table 1, reserved line positions not included.

| Table 1. 10 kV output lines with higher load rate of 35 kV Dongjing station. |
|-----------------|-----------------|----------|--------|------------------------|
| Line Name       | Line Type       | Current  | Current | Load Rate              |
|                 | (Overhead/Underground/Mixed) | Limit(A) | (A)     |                        |
| Dong 26 Gongye  | Mixed           | 315      | 288.86  | 91.70%                 |
| Dong 32 Caijiabang II | Mixed        | 375      | 306.68  | 81.78%                 |
| Dong 35 Dhua     | Mixed           | 375      | 301.06  | 80.28%                 |
| Dong 11 Zhenye   | Mixed           | 375      | 242.2   | 64.59%                 |
| Dong 22 Zhuanxing| Mixed           | 375      | 200.7   | 53.52%                 |
| Dong 12 Anquan   | Mixed           | 375      | 181.71  | 48.46%                 |
| Dong 16 Xufu     | Mixed           | 400      | 185.23  | 46.31%                 |
| Dong 33 Kaifa    | Mixed           | 375      | 153.34  | 40.89%                 |
| Dong 37 Zhangjing| Mixed           | 375      | 151.47  | 40.39%                 |
| Dong 25 Wantou   | Mixed           | 375      | 141.62  | 37.76%                 |
| Dong 15 Dongye   | Mixed           | 315      | 105.74  | 33.57%                 |
| Dong 31 Donggong | Mixed           | 315      | 94.02   | 29.85%                 |
| Dong 23 Dongshui | Mixed           | 375      | 80.89   | 21.57%                 |
| Dong 34 Huaxing  | Mixed           | 375      | 70.34   | 18.76%                 |
| Dong 38 Huaqiao  | Mixed           | 375      | 60.49   | 16.13%                 |
| Dong 18 Bianqiao | Mixed           | 375      | 53.22   | 14.19%                 |
| Dong 27 Laidun   | Mixed           | 375      | 30.95   | 8.25%                  |

As can be seen from the table data above, the load rate of 10 kV output lines in 35 kV Dongjing station is considerably uneven, with both heavy and light loaded lines. There are 2 transformers each with a capacity of 80MVA in Xuejiabang Station. The whole station peak load rate in summer is only 28.70%. It can be seen that the overall load rate of Xuejiabang station is relatively low, it is also necessary to adjust the operation mode to increase load rate to a reasonable interval.

There are 18 10 kV output lines in 110 kV Xuejiabang station and the lines with higher load rate are shown in table 2, reserved line positions not included:
Table 2. 10 kV output lines with higher load rate of 110 kV Xuejiangbang station.

| Line Name    | Line Type (Overhead/Underground/Mixed) | Current Limit(A) | Current(A) | Load Rate  |
|--------------|----------------------------------------|------------------|------------|------------|
| Xue 35 Dongshe | Mixed                                  | 375              | 316        | 84.27%     |
| Xue 23 Lianggao | Mixed                                  | 375              | 213.6      | 56.96%     |
| Xue 36 Dongzhou | Mixed                                  | 375              | 188        | 50.13%     |
| Xue 15 Jiju   | Mixed                                  | 375              | 177.6      | 47.36%     |
| Xue 16 Zhanye | Mixed                                  | 375              | 87.2       | 23.25%     |
| Xue 34 Nanzhe III | Underground                          | 400              | 81.6       | 20.40%     |
| Xue 14 Nanzhe II | Underground                          | 400              | 80         | 20.00%     |
| Xue 31 Haiqiao II | Underground                         | 400              | 70.4       | 17.60%     |
| Xue 11 Haiqiao I | Underground                         | 400              | 55.2       | 13.80%     |
| Xue 24 Yinchuang | Mixed                                | 400              | 52.8       | 13.20%     |
| Xue 33 Yuekun  | Mixed                                  | 375              | 32         | 8.53%      |
| Xue 21 Kechuang I | Underground                         | 400              | 24         | 6.00%      |
| Xue 41 Kechuang II | Underground                        | 400              | 17.6       | 4.40%      |
| Xue 13 Yuanzhi | Mixed                                  | 375              | 12         | 3.20%      |

As can be seen from the table data above, the load rate of 10 kV output lines in 110 kV Xuejiangbang station is apparently low, with poor equipment utilization level. Two substations above have 40 10kV output lines in total. According to the circuit diagram, it can be seen that the number of 10 kV output lines with contact switches within 110 kV Xuejiabang station supplying area is 21, and the number in 35 kV Dongjing station is 29. The number of 110 kV output lines with contact switches between 110 kV Xuejia Station and 35 kV Dongjing Station is 7. The result is acquired by adopting the reconstruction methods for distribution network considering closed loop constraints in this paper.

Table 3. 10 kV output lines with higher load rate of 110 kV Xuejiangbang station.

| Network Type                              | Active Power Loss/MW | Close/Open Operation Counts | Constraint Satisfaction |
|-------------------------------------------|----------------------|----------------------------|-------------------------|
| Initial network                           | 3.74                 | /                          | /                       |
| Reconstructed network without considering loop constraints | 2.86                 | 33                         | 3 operations not satisfied |
| Reconstructed network considering loop constraints | 3.12                 | 27                         | No violation occurred |

It can be seen from the reconstruction results given in table 3 that the conventional optimal solution may cause lines to be out of operational limits during the implementation process of open or close loop operation, violating system security requirements. Although the optimal reconstruction scheme proposed in this paper has increased network loss, the safety of open or close loop operation featuring practical feasibility can be realized.

5. Conclusion
Research on optimization and adjustment method of distribution network operation mode in this paper fully identifies and calculates the distribution network topology and line power flow information, analyzing the current operational status. Topology adjustments are made by changing the state of contact and segment switch on the premise of ensuring radial network, feeder heat capacity, voltage drop requirements and transformer capacity.
The load is transferred between feeder lines and substations, so that the operating parameters of the network including line loss, load balancing and voltage quality, etc. are presented in an optimal status. The result has important theoretical significance and high practical value. Especially in summer load peak period, the optimization calculation of distribution network operation mode can provide dispatcher with the recommendations for contact and segment switches of feeder lines, optimizing the operation status of the whole network.

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