The Research on the Partitioning Optimization Strategy of 220kV Power Grid Under Accident or Maintenance Condition

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ABSTRACT

With the expansion of urban power grid, short circuit current issue becomes increasingly severe. Thus, grid partition has been applied to transmission system in many big cities. Based on a typical partitioning configuration that each 220kV partition is supplied by a single 500kV substation, a partitioning optimization strategy under accident or maintenance circumstance is proposed in this paper. To establish the optimization model, the minimum load shedding is used as an objective function. Many constraints also have been taken into consideration, including capacity limit, power flow, short circuit current, load shedding, and etc. This paper introduced an improved genetic algorithm to acquire an optimal operation solution. In order to avoid infeasible solutions and reduce computational complexity, all the possible switching combinations of each channel are listed in advance, and then each connecting channel is coded as a whole. Furthermore, two separate partitions can be connected through incidence matrix under accident or maintenance condition. Finally, the paper takes an actual urban grid as an example, which verifies the correctness and effectiveness of the theory. It contributes to a strong theoretical and technical support for grid operation and network planning in reality.

Keywords: connecting channel, genetic algorithm, grid partition, load shedding, incidence matrix, optimization model

INTRODUCTION

In recent years, with the improvement of China’s 500kV power grid and the constant increase of the load transferring, the contradiction appearing gradually between the existence of the high/low voltage electromagnetic loop networks and the increase of their short-circuit currents has become the vital problem which needs to be solved timely during the planning and operation process of the power system[1-5]. Actually, in the big cities with concentrated load, it has become an irresistible trend of the power grid development to open the 500/220kV electromagnetic loop network so as to realize the power grid partitioning, which can not only limit the short circuit current, but also contribute to the full play of the
transmission capacity of higher voltage level, the control of the power flow, and the discovery and effective isolation of the accidents to facilitate the disconnection of partitions etc[6-10].

At present, the partitioning configuration has been formed preliminarily in power grid of the big cities with developed areas in China. However, there still exist many problems in the power grid partitioning, such as the high short-circuit current, incomplete grid partitioning structure, unbalanced development of partitions, and poor reliability in part areas [11-18]. Particularly, under the accidents or maintenance conditions, it needs urgently study how to guarantee the reliability of the power supply in each partition area. Concerning the power flow distribution, security, short circuit current and ultimate supply available, the partitioning optimization method of 220kV power grid is studied in this paper, which aims at the opening of the 500/220kV electromagnetic loop network and reduction of the short circuit current of 220kV system under the accident or maintenance conditions. Also it is of practical guiding significance to such things as the mutual support of each partition under the accidents.

IDEAS OF PARTITIONING OPTIMIZATION

The grid partitioning preliminary aims at the formation of a configuration that each part of 220kV substations is powered by a single or many 500kV substations, in which the 220kV power grid of each partition operates independently. It can be known from the characteristics and formation process of the 220kV grid partition that partition has weakened the interconnectivity of the original system in practice, since the only way for the connection between each partition and external systems is 500kV main transformer. Either as the step-down transformer and the power source for partitioning power supply together with the 220kV internet power station in the partition, or as the boosting transformer, sends out the power with the residual voltage level of 220kV in the partition. In short, as the core and hub of the partition, the 500kV substation plays an important role in the reliable power supply of the partition. Thus, when the 500kV main transformer in the partition quits operation due to the accidents or maintenance, it becomes a problem needing timely research how to keep the reliability of partitioning power supply, beginning with which the study is conducted.

Partitioning Optimization Method Based on the Connecting Channels

Connecting channels are the “bridges” for partitions to connect with each other. Generally, when the 500kV power grid is strong enough and the 220kV power grid operates independently taking the 500kV substation as the center, these channels ensure few or no load shedding, and the mutual support of each 220kV partition and the security of power supply under the maintenance or accident conditions of the 500kV main transformer. During the normal operation of the system, the standby connecting channels are out of operation to realize the grid partitioning; under the maintenance or accident conditions, they are put into operation according to the requirements of power supply and realize the partition loop closing.

Beginning with the whole grid, this paper assumes that when a 500kV main transformer quits the operation due to the maintenance or accidents, one of the working main transformer (namely the 500kV main transformer N-2 or N-1-1) is also out of order because of overloading or other reasons, and assumes a partitioning method of the power grid which can not only settle the emerging problems of the short-circuit current excess, satisfying to the largest extent the requirements of the reliable operation of each partition, but also adapt to the expandable requirements of the partitions in the years to come. Based on various ways by which the connecting channels operate between the partitions, the calculation and solution of
the model are conducted using the improved genetic algorithm, and by means of the BPA software, the check analysis is carried out on the operation of each partition of this power grid and the mutual support of the partitions under the accident or maintenance conditions.

**Ideas of Partitioning Optimization**

Firstly, this paper gives explicit stipulation of the functions of the connecting channels, which is to ensure few or no load shedding and the mutual support of each 220kV partition and the security of the power supply when the 500kV power grid is strong enough, 220kV power grid operating independently taking the 500kV substation as the center, and the accident N-1-1 or N-2 of the 500kV main transformer occurs. The specific steps of the analysis are as follows.

Step one: according to the characteristics of the 220kV partition in Shanghai, the 220kV substation in Shanghai are analyzed. For example, the following aspects are analyzed: they are the terminal station in the partition, the number and distribution of the stations like the switching station and intermediate station, and the geographical distribution of the stations in each partition. And the density of the distribution of stations in the partition is studied.

Step two: the capacity of 500kV transformer in each partition and the variation of the ultimate supply available of this partition under the accidents are studied.

Step three: under the accidents or maintenance conditions of the 500kV station, the partitioning optimization model is established, which aims at the minimum load shedding after partitioning and takes into account the constraints in the power flow, node voltage, line capacity and short circuit current etc.

Step four: Effective solution of the proposed model is made with the proper algorithm, and the optimal partitioning strategy is obtained through verification with the example of the 220kV power grid in a big city in 2016, the results of which are validated by comparing various indices before and after partitioning, such as the power flow of the connecting channels and load rate of the main transformer.

Figure 1 shows the technical route of the method for realizing the partitioning of the 220kV power grid under the accidents or maintenance conditions.

![Figure 1. Technical route of the method for realizing the partition of the 220kV power grid in Shanghai under the accidents or maintenance conditions.](image)

**MATHEMATICAL MODELS OF PARTITION OPTIMIZATION**

According to the previous assumption for optimization of the grid partitioning, and under a certain load demands and system faults, this paper aims at the minimum load shedding
of the system, establishes the model of the partitioning optimization of the power grid, and seeks the optimal support program of interconnected transferring of the network.

**Objective Function**

From the perspective of the transferring supply of the load, the minimum load shedding is chosen as the objective function:

\[
\text{Min } T = \text{Min } \sum_{i=1}^{N_L} P_{ri}
\]  

(1)

Where \(N_L\) represents the total of the load shedding nodes of the system, and \(P_{ri}\) stands for the power demand of the cut-off load nodes.

**Restrictions**

(a) Flow balance restriction

\[
P_{gi} - P_{di} - P_{ri} = \sum_{j=1}^{k} B_{ij} \theta_{ij} \quad \forall i \in S_n, \ n = 1, 2...k
\]

(2)

Where \(P_{gi}\) is the output power of node \(i\); \(P_{di}\) is the load demand of node \(i\); \(P_{ri}\) is the load shedding node \(i\); \(B_{ij}\) is the node susceptance matrix; \(\theta_{ij}\) is the angle difference between node \(i\) and \(j\); \(S_n\) is the node set of \(n\)-th independent partition; \(k\) is the total number of separate partitions in the system.

(b) Channel flow restriction

\[
\underline{P}_{ij} \leq P_{ij} \leq \overline{P}_{ij} \quad \forall i \in \{1, 2,..., k\}
\]

(3)

In (b), \(P_{ij}\) is the flow in the connecting channel between node \(i\) and \(j\); \(\underline{P}_{ij}\) and \(\overline{P}_{ij}\) refer to the lower and upper limit of the flow, respectively.

(c) Short circuit capacity restriction

\[
I_i < I_c \quad \forall i \in \{1, 2,..., k\}
\]

(4)

In (c), \(I_i\) is the short circuit current in the \(i\)-th independent partition; \(I_c\) is the short circuit current limit, where the limit refers to 50kA.

(d) Reliability restriction

The reliability index mentioned here would meet the N-1 criteria, as follows.

\[
P_{gi}^{N-1} - P_{di}^{N-1} - P_{ri}^{N-1} = \sum_{j=1}^{k} B_{ij}^{N-1} \theta_{ij}^{N-1} \quad \forall i \in S_n, \ n = 1, 2,..., k
\]

(5)

\[
P_{ij}^{N-1} \leq \overline{P}_{ij}^{N-1}
\]

(6)

In (d), \(P_{gi}^{N-1}\) is the output power of node \(i\) under N-1 circumstance; \(P_{di}^{N-1}\) is the load demand of node \(i\) under N-1 circumstance; \(P_{ri}^{N-1}\) is the load shedding node \(i\) under N-1 circumstance; \(B_{ij}^{N-1}\) is the node susceptance matrix; \(\theta_{ij}^{N-1}\) is the angle difference between node \(i\) and \(j\); \(S_n\) is the node set of \(n\)-th independent partition; \(k\) is the total number of separate partitions in the system.
(e) Load Shedding restriction

\[ 0 \leq P_{R_n} \leq P_{D_n} \quad \forall n \in \{1, 2, \ldots, k\} \]  

Where \( P_{R_n} \) stands for the amount of the load shedding when the \( i \)th independent main transformer of the partition loses one main transformer, and \( P_{D_n} \) represents the limit of load shedding in this partition.

(f) Limit supply restriction

\[ D_{n,\text{max}} - D_n > 0 \quad \forall n \in \{1, 2, \ldots, k\} \]

In (f), \( D_{n,\text{max}} \) is the power supply limitation of the \( n \)-th independent partition; \( D_n \) is the load of the \( n \)-th independent partition.

(g) Connecting restriction

There cannot be an isolated island operation when using grid partition.

OPTIMIZATION STRATEGY BASED ON GENETIC ALGORITHM

The parameter mentioned in the paper refers to the switching status in and between substations on the connecting channels. Therefore, genetic algorithm is adopted here.

Genetic Algorithm

Genetic Algorithm (GA) is an adaptive heuristic search algorithm based on the evolutionary ideas of natural selection and genetics. It is commonly used to generate high-quality solutions to optimization and search problems by relying on bio-inspired operators such as mutation, crossover and selection. Genetic algorithm has the following characteristics.

- Genetic algorithm aims to optimize the code of a set of parameters, not the parameter itself, so it is more flexible to solve the problem.
- Instead of at a single point, Genetic Algorithm searches for the optimal solution from a group of points. Thus the global optimal solution can be guaranteed.
- As Genetic algorithm uses self-adaptive function, the derivative of objective function is not needed. It is simpler to solve problems.
- Genetic algorithm uses probability mechanism for iteration, with randomness. It is quicker to find the optimal solution.

Genetic algorithm is applied to the optimization strategy in grid partition. It uses the original operation mode as an initial solution and then codes it. Then the evaluation function calculates the adaptive value. Only the good ones have the opportunity to iterate to the next round, while the others would be discarded. Relying on bio-inspired operators such as mutation, crossover and selection, through re-combination, and finally a global optimal solution would be acquired.

Data Reading and Processing

Focusing on the connecting channels between each partition, this paper divides the data, considering its input, into two categories: one is the nodes, which in the project are the bus of...
each station, and the other is the circuits, which can be either determined as the circuits and stations in this partition for clarity the interior of this partition, or uncertain, namely the switches between the internal bus at the stations in the connecting channels and the line of the bus between the stations, as shown in Figure 2.

![Data reading diagram](image)

Figure 2. Data reading diagram.

Applications of Improved Genetic Algorithm in Grid Partition Optimization

The paper emphasizes on acquiring an optimal operation solution of connecting channels (the switches on buses and lines) through genetic algorithm method. However, the traditional way would arrange all the possible combinations of switches. Inevitably, the efficiency would be compromised greatly, due to huge computational complexity and non-feasible solutions.

Therefore, improved genetic algorithm is adopted in the paper. Consider a set of switching combinations of operation modes in each connecting channel as a whole, and list all the feasible ones. Then use genetic algorithm to carry out the calculation of all free combinations. Finally, it is possible to reach an optimal operating mode.

This paper firstly analyzes each connecting channel, and lists various operation modes. The arrangement principle is as follows:

(a) The main transformer N-2 principle, namely the N-1-1 principle, should be satisfied;
(b) The excess of the short circuit current after partitioning optimization should be avoided;
(c) The loop closing operation is realized between no more than two partitions;
(d) The normal overload capacity of the transformer and lines are determined as their rated capacity, and the emergency overload capability of the transformer is determined as 1.3 times the rated capacity.

Take one connecting channel of an urban grid as an example, as shown in Figure 3. Among them, A and D are two 220kV stations in independent partitions. B and C,
respectively, are the 220kV substations in the connecting channel. According to the arrangement principles mentioned above, there are three other feasible operation modes of this connecting channel, as shown in Figure 4.

Then, "1" or "0" is used to indicate which mode is adopted. For example, "1000" represents the current operation mode, "0100" represents the first operation mode in accordance with Figure 4. And so on, it is possible to have a string of "0/1" series referring to the operation modes of each connecting channel.

**OPTIMIZATION STRATEGY OF 220KV GRID BASED ON THE CONNECTING CHANNEL**

This paper assumes that when a 500kV main transformer quits the operation due to the maintenance or accidents, one of the working main transformer (namely the 500kV main transformer N-2 or N-1-1) is also out of order because of overloading or other reasons, and that if the load shedding is not needed in this partition and the power supply requirements are satisfied by means of the power flow transferring, the partitioning operation of the 220kV power grid is maintained; otherwise, if the partition can meet the power supply requirements only with the power support of neighboring partition through the connecting lines, the partition loop closing needs consideration.

**Incidence Matrix**

Since the partition loop closing is involved, in order to clarify which tow partitions will realize the loop closing under the accidents or maintenance conditions, the concept of incidence matrix is introduced in this section. Firstly, each partition is numbered, and then the incidence matrix is established according to the distribution of the connecting lines between the partitions. The specific operation procedure is shown in Figure 5. And according to the connection between each partition of the actual power grid (there are 14 partitions in this actual power grid), the incidence matrix between partitions is:

\[
A = \begin{bmatrix}
1 & 1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
1 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \\
1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1
\end{bmatrix}
\]

Figure 5. Incidence matrix of partitions.
The Flow of the Improved Genetic Algorithm

The steps of the algorithm include:

- **Step 1**: Sort the 500kV station in each partition and build the incidence matrix considering the connection between 500kV stations in each partition.
- **Step 2**: Generate randomly a set of data of operation modes and substitute them into the power grid, and then disconnect one of the 500kV stations from 2 main transformers, check whether the short circuit current is excessive and whether the circuit power flow meets the “N-1” criterion.
- **Step 3**: Without considering the merging of partitions, find out the open-close way of the switches corresponding to the minimum load shedding by means of roulette and crossover mutation with the genetic algorithm.
- **Step 4**: Conduct the partition loop closing according to the incidence matrix and check again whether the short circuit current of the power grid adjusted are excessive and whether the circuit power flow meets the “N-1” criterion.
- **Step 5**: Concerning the merging of partitions, transfer the load with the algorithm above and obtain the minimum load shedding of this partition.
- **Step 6**: If the load shedding is not needed in this partition and power supply requirements can be satisfied through the power flow transferring, maintain the partitioning operation of the 220kV power grid; otherwise, obtain the least value of the minimum load shedding of the two and choose the corresponding partitioning operation mode.

CASE STUDY

The power grid under partitioning operation in a big city during average loading in summer of 2016 is taken as an example. The city has a actual power grid with 14 500kV nodes and 126 220kV nodes, and adopt the partitioning method that each 220kV power station is powered by a single 500kV power station and that partitions operate with the loop untying. Under the accident of a 500kV main transformer N-2 or N-1-1, the least value of the minimum load shedding before and after the loop closing is analyzed through comparison by means of the improved genetic algorithm. The partitioning optimization method under the accidents of partition A will be introduced with an example below.

The capacities of four main transformers in partition A is 0.75 million kilowatts; the original ultimate supply available 2.60 million kilowatts, which drops to 1.75 million kilowatts under the accidents of the N-2 or N-1-1 of the 500kV main transformer in the partition; in 2016, partition A has a load of 2.734 million kilowatts, exceeding the stable limit by 0.984 million kilowatts. Under such circumstance, the optimization of connecting channels in normal situations cannot meet the load requirements of the partition, and the loop closing is needed. The operation and the loop closing mode of the connecting channels are shown in Figure 6 and Figure 7, respectively.

The stations g1 and g4 are transferred to G partition, during which the load transferred from the station g4 is 0.128 million kilowatts and that from the station g1 is 0.121 million kilowatts. The loop closing operation of partitions A and B are proceeding in station b, and the power that can enter the centre of partition A from the partition B via the line B-b-A is 0.321 million kilowatts; thus, the load shedding of 0.414 million kilowatts is needed in partition A.
The new partitioning optimization strategy is obtained in this paper, in which the load of each partition is listed in Table 1. Before the optimization, under the accident N-2 or N-1-1 of the 500kV main transformer, the load supply in the partition are in serious shortage, and the system requirements can be satisfied only by shedding the load to large extent. Particularly, in partitions B, C, D and E, where there are no power supply, all the ultimate supplies available under accidents drop to 0 with the largest excess of the ultimate supply available up to 1.094 million kilowatts. In partitions H and M, where the load requirements are fairly large, the largest excess of the ultimate supply available is 1.284 million kilowatts. However, there exist large margin in other partitions, indicating a seriously uneven load distribution.

After the optimization of partitions under the accidents or maintenance conditions, the capacity of the load transferring between partitions increases greatly, and the maximum load shedding drops to 0.421 million kilowatts, which shows a more uniform partition load of the city than that before optimization. Particularly, there are power supply margin in many partitions, with the maximum up to 0.866 million kilowatts.

<table>
<thead>
<tr>
<th>Partition</th>
<th>Load demand</th>
<th>Limit capacity</th>
<th>Out of limit</th>
<th>Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>273.4</td>
<td>175</td>
<td>98.4</td>
<td>41.4</td>
</tr>
<tr>
<td>B</td>
<td>51.4</td>
<td>0</td>
<td>51.4</td>
<td>0.8</td>
</tr>
<tr>
<td>C</td>
<td>109.4</td>
<td>0</td>
<td>109.4</td>
<td>0</td>
</tr>
<tr>
<td>D</td>
<td>49</td>
<td>0</td>
<td>49</td>
<td>-19.7</td>
</tr>
<tr>
<td>E</td>
<td>108.5</td>
<td>0</td>
<td>108.5</td>
<td>0</td>
</tr>
<tr>
<td>F</td>
<td>238</td>
<td>175</td>
<td>63</td>
<td>26.2</td>
</tr>
<tr>
<td>G</td>
<td>312.4</td>
<td>399</td>
<td>0</td>
<td>-86.6</td>
</tr>
<tr>
<td>H</td>
<td>418.4</td>
<td>290</td>
<td>128.4</td>
<td>6.1</td>
</tr>
<tr>
<td>I</td>
<td>340.5</td>
<td>322</td>
<td>18.5</td>
<td>0</td>
</tr>
<tr>
<td>J</td>
<td>139</td>
<td>150</td>
<td>11</td>
<td>-27.2</td>
</tr>
<tr>
<td>K</td>
<td>171.1</td>
<td>60</td>
<td>111.1</td>
<td>42.1</td>
</tr>
<tr>
<td>L</td>
<td>284.9</td>
<td>280</td>
<td>4.9</td>
<td>-43.1</td>
</tr>
<tr>
<td>M</td>
<td>383.1</td>
<td>348</td>
<td>35.1</td>
<td>-14.3</td>
</tr>
<tr>
<td>N</td>
<td>139</td>
<td>150</td>
<td>11</td>
<td>-27.2</td>
</tr>
</tbody>
</table>

Note: After optimization, positive balance means that there remains to be a certain margin in the partition; negative ones means load shedding is necessary in the partition due to capacity shortage.
CONCLUSIONS

The method for 220KV partitioning optimization of the urban power grid under the accidents or maintenance conditions was studied, and the partitioning optimization model taking the minimum load shedding as the objective function was established aiming at the typical partitioning configuration. It reduces obviously the amount of calculation by introducing the incidence matrix to consider the load transfer mode under the partition loop closing and by adopting the improved genetic algorithm to seek the optimal open-close way of the circuit in connecting channels and bus switch. Results of the example show that, under the accidents or maintenance conditions, this method promote greatly the mutual support of connecting channels of partitions, reduce the load shedding in partitions, ensure the safe and stable operation of the power grid, and provide strong theoretical and technical support for the grid operation and network planning in reality.

The connecting channels between the 220kV grid partitions can support each other basically, but some of them have single operation mode, which can neither transfer the load nor realize the mutual support of partitions as the connecting channels with the loop closing. It is recommended to be extended and renovated properly. There are a small number of partitions with few connecting channels, which is likely to cause big power shortage due to their poor mutual support ability under accidents or maintenance conditions. It is recommended to increase the number of connecting channels between each partition properly.

REFERENCES