Multi-feed System Partitioning Method Based on N-1 Preconceived Fault Set and Local Expansion Theory

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Abstract. In view of the fact that the AC system with multiple LCC-HVDC feeds is prone to simultaneous commutation failure, this paper proposes the scheme of grid division for the multiple feed system to isolate the coupling between multiple HVDC and reduce the risk of occurring simultaneous commutation failure. First, N-1 scan is performed on the multi-feed system to find the set of lines that can cause simultaneous commutation failure of multiple HVDC. The line with high line load rate is removed from the line set. Then, on the basis of local expansion theory, the nodes in the system are aggregated to form the initial partition. In this process, the calculation method of voltage/reactive sensitivity matrix considering PV node and LCC-HVDC is firstly given; moreover, the corresponding indexes were calculated by the node aggregation function and the partition fitness function. Finally, the results of the partition are modified by considering the circuit set and the partition short circuit ratio, and the flow chart of the partition scheme is given. The partitioning process is validated with an IEEE 39-node system as an example. The results show that the partitioning method is reasonable and solves the problem of the failure of commutation effectively.

1. Introduction

With the construction of large-scale power grids, the partial area power grids in China have gradually formed a pattern of receiving-end AC power grids with intensive feeding of line Commuted Converter High Voltage Direct Current(LCC-HVDC)[1]. The multi-feed system has the risk of simultaneous commutation failure. When the AC system fails, the voltage drop of the commutation bus will cause the commutation failure of the HVDC that is electrically close to the bus. If the fault cannot be cleared in time, it may cause multiple phase commutation failures, or even shutdown in severe cases. At this time, the frequency of the AC system is unstable due to a large amount of loss of active power, and system disassembly may occur[2].

Expanding the scale of the AC system is one of the ways to solve the above problems. However, the scale of the synchronous power grid is constrained by three aspects: frequency stability, low-frequency oscillation frequency and synchronization support effect. Only expanding the scale of the AC system may bring other problems.

There are few researches on partitioning methods for multi-feed systems, and mainly focus on two methods: evaluation model and N-1 verification. The reference [3] used Multi-infeed interaction factor, multi-infeed short-circuit ratio and frequency deviation factor as indicators to establish an evaluation model. Reference [4] performed N-1 fault scanning on lines to search for lines that caused multiple HVDCs to commutation failure at the same time. In these lines, select suitable lines and replace them...
with voltage source converter HVDC (VSC-HVDC) to increase the electrical distance between LCC-
HVDC. The research on power grid division mostly focuses on the control of reactive power and
voltage division to realize stable operation of power system[5]. Reference[6-7] studied the application
of community theory in power grid division. Reference [8] proposed a community discovery algorithm
based on local expansion, which can select the starting node to achieve the final partition.

Aiming at the partition problem of multiple feed-in systems, this paper proposes a method to
actively obtain partitions. First of all, the set of breakable lines is obtained by eliminating the lines
with a higher load rate of the N-1 expected accident concentration. Subsequently, according to the
voltage/reactive power sensitivity of the whole system, the partition fitness is calculated based on the
local expansion theory, and the partition process is given. Considering the set of breakable lines and
the short-circuit ratio of the districts, the partition results are revised. Finally, the IEEE 39-node model
is taken as an example to verify the feasibility of the partitioning method in PSD-BPA.

2. Models and methods

2.1. The set of partition detachable line
Perform N-1 scanning on the multi-feed system and mark the lines that can cause commutation failure
in each high-voltage direct current, forming a set of commutation failure lines. The line corresponding
to the overlapping part of the set is the set of breakable lines. The schematic diagram is shown in
Figure 1.

![Initial aggregate of interruptible lines based on N-1](image)

Figure 1. Initial aggregate of interruptible lines based on N-1

Next, remove lines with higher load rates. The high load ratio of the line indicates that the line
supplies power to the densely loaded area. Breaking the line will cause a large-scale transfer of the
power flow and affect the safe and stable operation of the AC system. Therefore, these lines need to be
excluded from the set of detachable lines.

2.2. Partition method based on voltage/reactive power sensitivity
For AC systems, the voltage/reactive sensitivity of the PQ nodes in the system can be obtained by
calculating the inverse matrix of the Jacobian matrix. Its expression is as follows:

\[
\begin{bmatrix}
\Delta \theta \\
\Delta U
\end{bmatrix} = J^{-1} \begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} = S_{PQ} \begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
\]

\[S_{PQ} = \begin{bmatrix}
S_{p0} & S_{q0} \\
S_{pu} & S_{qu}
\end{bmatrix}\]

(1)

\(S_{PQ}\) denotes the voltage/reactive power sensitivity matrix of the PQ nodes; \(S_{p0}, S_{q0}, S_{pu}\) and \(S_{qu}\)
are the block matrixes of \(S_{PQ}\), which respectively denote the sensitivity matrix of active and reactive
power injected by each node with respect to the phase angle and active and reactive power injected by
each node with respect to voltage amplitude.
For a high-voltage AC system, the reactance of each component is much greater than the resistance, then the voltage/reactive sensitivity of each PQ node can be described as:

\[ \frac{\Delta U}{\Delta Q} = S_{QU} \]  

(2)

When the traditional DC rectifier side adopts constant power control and the inverter side adopts constant arc extinguishing angle control, the external characteristics of the inverter side can be described as:

\[ Q_{LCC} = -P_{LCC} \tan \varphi + \alpha B_c U^2 \]  

(3)

In the equation (3), \( P_{LCC} \) and \( Q_{LCC} \) are the active and reactive power of the traditional DC injection AC system respectively; \( \varphi \) is the power factor of the traditional DC; \( \omega \) is the system angular frequency; \( B_c \) is the equivalent susceptance of the reactive power compensation device; \( U \) is the commutation bus voltage. The relationship between the power factor \( \varphi \) and the converter bus voltage \( U \) can be established as:

\[ \varphi(U) = \tan \left[ \arccos \left( \frac{\cos \gamma - \frac{X_{dc}}{\sqrt{2}k_f U}}{1} \right) \right] \]  

(4)

In the equation (4), \( \gamma \) is the arc extinguishing angle; \( X \) is the commutation reactance; \( I_{dc} \) is the direct current; \( k_f \) is the conversion ratio of the converter transformer. Then the following formula can be obtained by sorting:

\[ \frac{\Delta Q_{LCC}}{\Delta U} = \frac{P_{LCC}}{U^2} T(U, \xi) \]  

(5)

When the traditional DC is connected to the AC system, the \( J_{QU} \) elements in the Jacobian matrix of the system need to be corrected:

\[ J'_{QU} = J_{QU} + \frac{\Delta Q_{LCC}}{\Delta U} \]  

(6)

Because the PV nodes have a coupling relationship with other nodes, it is necessary to add the dimension of each PV nodes to the voltage/reactive sensitivity matrix \( S_{QU} \). The augmented voltage/reactive power sensitivity matrix \( S_{QU}' \) at this time is as follows:

\[ S_{QU}' = \begin{bmatrix} S_{QU,11} & \cdots & S_{QU,1m} & S_{QU,1(m+1)} \\ \vdots & \ddots & \vdots & \vdots \\ S_{QU,m1} & \cdots & S_{QU,mm} & S_{QU,m(m+1)} \\ S_{QU,(m+1)1} & \cdots & S_{QU,(m+1)m} & S_{QU,(m+1)(m+1)} \end{bmatrix} \]  

(7)

In the equation (7), the first \( m \) elements in the last row and the last column represent the voltage/reactive sensitivity of the PV node to other PQ nodes in the system after the PV node is transformed into a PQ node; \( S_{QU,(m+1)(m+1)} \) represents the voltage/reactive sensitivity of the PV node relative to itself.

After calculating the sensitivity of the PV node, reset the node to the PV node to calculate the sensitivity for the next PV node. The final sensitivity matrix \( S \) of the whole system can be expressed as:

\[ S = \begin{bmatrix} S_{PQ,m \times m} & M_{m \times (n-m)} \\ N_{(n-m) \times m} & S_{PV,(n-m-1) \times (n-m-1)} \end{bmatrix} \]  

(8)

In the equation (8), \( S_{PQ,m \times m} \) is the sensitivity matrix of \( m \) PQ nodes in the system; \( M_{m \times (n-m)} \) is the sensitivity matrix of PQ node voltage changes to PV node reactive power changes; \( N_{(n-m) \times m} \) is PV The sensitivity matrix of node voltage changes to PQ node reactive power changes; \( S_{PV,(n-m-1) \times (n-m-1)} \) is the sensitivity matrix of \( n-m-1 \) PV nodes, which is a diagonal matrix.
2.3. Partition method based on local expansion theory

The community structure can be used to aggregate and split complex network nodes. By aggregating nodes with similar voltage/reactive power characteristics into the same community, and disconnecting the tie lines with strong coupling, the AC system can be partitioned. The district leading node of the multi-feed system should be selected as the traditional DC commutation bus. In this paper, the multi-infeed system is partitioned based on the local expansion theory. The community function based on the local expansion theory can be described as:

\[ f(c) = \frac{\beta^c_{\text{in}}}{\left(\beta^c_{\text{in}} + \beta^c_{\text{out}}\right)^\alpha} \quad (9) \]

In the equation (9), \( f(c) \) represents the local fitness function of the community \( c \); \( \beta^c_{\text{in}} \) and \( \beta^c_{\text{out}} \) are the aggregation degrees of the internal and external nodes of the community \( c \); \( \alpha \) is the resolution, which is used to control the partition scale.

The above-mentioned sensitivity matrix \( S \) only reflects the voltage and reactive power change relationship between the nodes, and does not include the connection relationship between the nodes. Therefore, it is necessary to introduce an association matrix to supplement the sensitivity matrix. Set incidence matrix \( A \), its elements are:

\[ A_{ij} = \begin{cases} 1, & \text{There's a connection between } i \text{ and } j \\ 0, & \text{There's no connection between } i \text{ and } j \end{cases} \quad (10) \]

The modification to the sensitivity matrix elements can be expressed as:

\[ S'_{ij} = S_{ij} \cdot A_{ij} \quad (11) \]

\[ B_{ij} = B_{ji} = \frac{S'_{ij} + S'_{ji}}{2} \quad (12) \]

Based on the modularity function, the calculation method of the node aggregation function is given, as follows:

\[ \beta^c = \frac{1}{2m} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n-1} \left( B_{ij} - \frac{k_i k_j}{2m} \right) \cdot \delta(i,j) \quad (13) \]

Considering the above process comprehensively, the entire partitioning process is as follows: First, the corrected sensitivity matrix \( S' \) of the whole system is calculated. Subsequently, with the traditional DC commutation bus as the initial node, the node aggregation function is calculated, and then the fitness function is calculated. Add a new node, calculate the aggregation function and fitness function again, and compare the fitness before and after the addition. If the fitness increases, the node is retained to increase the community size; if the fitness decreases, the node is discarded. Search all nodes, and the last community given is the partition scheme.

3. Simulation analysis

Take the IEEE 39-node system as an example to show the entire partitioning process. The nodes 35 and 38 are set as the traditional HVDC access nodes. The traditional HVDC adopts CIGRE Benchmark model parameters; the rectifier side adopts constant power control, and the inverter side adopts constant arc-extinguishing angle control.
According to the above method, the system will be divided into two partitions. First, perform N-1 scanning on the system, and the lines that can cause commutation failure of two DC circuits are shown in Table 1.

Table 1. Transmission lines causing commutation failure

| HVDC with commutation failure | lines | The number of Voltage drop (p.u.) |
|-------------------------------|-------|----------------------------------|
| LCC₁                          | $L_7$ | 0.232                            |
|                               | $L_{26}$ | 0.264                          |
|                               | $L_{30}$ | 0.232                            |
| LCC₂                          | $L_1$  | 0.212                            |
|                               | $L_7$  | 0.208                            |
|                               | $L_{16}$ | 0.208                           |
|                               | $L_{17}$ | 0.200                           |

By analysing Table 1 we can found that breaking line $L_7$ under N-1 will cause two HVDC to occur commutation failure at the same time. And it did not cause overload of other branches. Therefore, $L_7$ is included in the set of detachable circuits. Subsequently, the system is partitioned by a local expansion community discovery algorithm. The partition result is shown in Figure 3.
According to the above division result, if all lines L7, L9, L13 and L31 are disconnected, the divisional power flow calculation cannot converge. This is because there is still a need to exchange power between partitions A and B. Then, N-1 scans were performed on partitions A and B respectively, and no lines were found that could cause two simultaneous commutation failures of traditional HVDC. In summary, the partitioning method proposed in this paper solves the problem of simultaneous commutation failure of multiple HVDC, and can basically guarantee the stable operation of each partition.

4. Conclusion
Aiming at the partition problem of the multi-feed system, this paper proposes an active partition method based on the N-1 expected accident set and the local expansion theory, and gives the partition plan, showing the sensitivity calculation process of the whole system, the partition aggregation process, and the search process of the detachable line set and the division boundary correction process. And the paper takes the IEEE 39-node model as an example to verify the partition method in PSD-BPA. The verification result indicates that the method can solve the problem of simultaneous commutation failure of multiple traditional HVDC and ensure the stable operation of the partition.

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