Research on Construction Methods of Transient Security Region of AC/DC Hybrid Power Grid

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Abstract: In order to study the AC/DC hybrid system transient stability assessment methods, this article is based on the New England 10 machine 39 node communication system after modification of AC/DC mixed system, the use of PSD-BPA software, to pure AC system and AC/DC hybrid system of AC busbar three-phase short-circuit fault transient stability of the numerical simulation analysis, and uses Matlab to solve its active power injection space transient security region.

1. Introduction

The distribution of energy resources and power demand in China is extremely unbalanced, showing obvious "reverse distribution" characteristics. Therefore, "west to East power transmission" and "north to South power supply" have become the important characteristics of China's power grid planning. The development of long-distance transmission promotes the application of DC transmission technology. In the future, AC / DC hybrid power grid will be popularized in a large area, which also brings new challenges to the stable operation of power grid. Therefore, it is of great significance to study the stability of large power grid under complex conditions.

At present, scholars at home and abroad have done a lot of research on AC power grid transient stability. Literature [1-4] explores the analysis of influencing factors of system transient stability. Reference [5-6] studies the dynamic process of system instability caused by different faults. Reference [7] studies the influence of different measures on power grid stability after fault. Literature [8-9] explores the relevant measures to improve the transient stability of the system. In reference [10], the small signal dynamic model was built by MATLAB, and the system stability was simulated and analyzed. Literature [11] introduces the research status of three kinds of transient stability assessment methods in China. Several large disturbance stability analysis methods are introduced in reference [12], and their advantages and disadvantages are compared. Based on the practical dynamic security region in the power injection space, the paper [13-16] studies the relationship and application between the practical dynamic security region and the transient stability after fault. However, there are few researches on the transient stability of AC / DC hybrid power grid, and there is no suitable evaluation method to describe and quantify the transient stability.

In order to promote the engineering application of transient security region, from the perspective of security region, this paper puts forward the mathematical model of dynamic security region, then uses psd-bpa to simulate the fault transient stability, then uses MATLAB software to solve the simulation data of transient security region, and finally calculates the relationship between DC transmission capacity and transient security region boundary quantitatively.
2. Mathematical Model

The research of power system transient stability aims at the given injection before the accident and the determination of the accident, and judges the stability through dynamic simulation. After a fault occurs in the power system, it is detected and operated by the relay protection device, and the system reaches a new equilibrium state, which will go through the following three stages: (1) before the accident: the original stable state of the system. (2) During the accident: the big disturbance attack starts until the relay protection device acts. (3) After the accident: the process of gradually restoring the stability of the system after the fault is cleared.

This stage can be described mathematically by a system of equations with three differential equations

\[
\begin{align*}
\dot{x}_1 &= f_i(x_i(t), y) & -\infty < t < 0 \\
\dot{x}_2 &= f_e(x_2(t), y) & 0 \leq t < \tau \\
\dot{x}_3 &= f_j(x_3(t), y) & \tau \leq t < +\infty
\end{align*}
\]

(1)

Where \(i, F\) and \(j\) represent the system before, during and after the accident respectively, \(x(t)\) is the state vector of the system at time \(t\), and \(Y\) is the power injected into the system before the accident, \(\tau\) It's the fault clearing time. The critical clearing time \(t_{cr}\) can also be used to judge whether the system is stable \(\tau > t_{cr}\), the system is unstable. Figure 1 is the dynamic security domain labeling diagram.

![Fig.1 Dynamic security region labeling diagram](image)

Dynamic security domain \(\Omega_d(i, j, \tau)\) It is a set in the system injection power space. If the system is transient stable under a certain injected power \(y\), then the injected power \(y\) is dynamic safe. Therefore, the transient stability of the post fault system \(J\) can be used to reflect the dynamic security of the pre fault system \(I\), that is, to define the dynamic security region in the injected power space \(\Omega_d(i, j, \tau)\):

\[
\Omega_d(i, j, \tau) = \{ y \mid x_d(y) \in A(y) \}
\]

(2)

Where, \(x_d(y)\) represents the system state when the fault is cleared, and \(A(y)\) represents the stability region bounded by the post fault stable equilibrium point determined by \(y\) in the injected power space. A specific injection \(y\) corresponds to a specific stability region \(A(y)\). The relationship between the two is shown in Figure 2:

![Fig.2 Mapping relationship between dynamic security region and stable region](image)
Dynamic security domain boundary $\partial \Omega_d(i, j, \tau)$ can be expressed as:

$$\partial \Omega_d(i, j, \tau) \triangleq \{ y \mid x_d(y) \in \partial A(y) \}$$

(3)

Formula (2) is defined in infinite space, but in real life, the injected power of our power system is limited, such as the maximum output limit of generator, maximum load, minimum load, etc. Therefore, the injection power constraint set can be defined as:

$$W_i \triangleq \{ y \in \mathbb{R}^n \mid y_{\min} < y < y_{\max} \}$$

(4)

In formula (4), $y_{\max}$ and $y_{\min}$ represent the upper and lower limits of injection power $y$ respectively. Therefore, the definition of dynamic security domain in formula (2) can be modified to:

$$\Omega_d(i, j, \tau) \triangleq \{ y \mid x_d(y) \in A(y) \} \bigcap W_i$$

$$\triangleq \{ y \mid x_d(y) \in A(y), y_{\min} < y < y_{\max} \}$$

(5)

In practice, the power system has the characteristics of dense security region, compact security region boundary and no knot, so it only needs to judge whether the injected power $y$ is in the security region $\Omega_d$, that is, compare the injection $y$ with the security domain boundary $\partial \Omega_d$ position can be obtained whether it has transient stability. Therefore, we focus on the security domain boundary defined by formula (3) and define formula (4) as a restrictive condition.

3. Transient Stability Simulation

In this paper, the New England 10 machine 39 bus AC system is used. The system topology is shown in Figure 3.

In this paper, PSD-BPA software is used for numerical simulation. Firstly, the power flow program is run to observe whether the output converges and whether the output of each generator exceeds the maximum active power output. When the power flow results converge, the transient stability program is run. By setting the relevant fault type and fault clearing time, the power angle of each generator is observed to see whether it is continuously open and whether it is unstable. In case of instability, check the result output file, analyze the cause of instability, and adjust the active power output of key generators.

3.1. Pure AC System Simulation

In Figure 3, the fault is set as three-phase short circuit at the outlet of AC bus 18, and the fault line 18-17 is removed with the help of BPA software. When the fault removal time is 6 cycles, the system maintains transient stability (Figure 4); When the fault clearing time is adjusted to 7 cycles, the stability of the system is destroyed (Fig. 5).
It can be concluded that the critical clearing time is between 6 and 7 cycles. Therefore, given that the fault clearing time is 7 cycles, the power angle changes of all generators are plotted in a graph for comparative analysis, as shown in Figure 6. Among them, the reference generator is new30, that is, the power angle of the generator in the figure is the power angle difference between the current generator (new31-new38) and the reference generator (new30).
Fig.6 Change chart of power angle of generator in faulty pure AC system

As can be seen from the above figure, the power angle of generator new34 is the fastest, followed by generator new33, and then generator new38. Therefore, 33, 34 and 38 generators are selected as the key generators.

3.2. Simulation of AC / DC Hybrid System

In the last section of New England system, a DC transmission line is paralleled with AC transmission line 19-16, the rectifier side is node 19, its DC bus name is NEW19, the inverter side is node 16, its DC bus name is NEW16, the transmission direction of the line is from rectifier side to inverter side, and the DC transmission capacity is 5000MW

Except for Parallel DC lines, other system parameters and AC faults remain unchanged. Running the simulation program, it can be found that the critical fault clearing time is between 4 and 5 cycles. Obviously, compared with pure AC system, the critical fault clearing time is reduced, and the transient stability of the system is reduced. Given that the AC fault clearing time is 4.1 cycles, the waveform of generator power angle change is shown in Figure 7 below.

Fig.7 Change chart of power angle of generator in faulty AC / DC system

As can be seen from the above figure, the most critical generator nodes are still new33 and new34. But the third key generator here has changed from new38 to new36. It can be seen that when the HVDC transmission lines are connected, not only the critical fault clearing time of the system will be affected, but also the local power flow transfer of the whole system will be affected, resulting in the change of
4. Construction of Transient Security Region

In this paper, the transient security region boundary is solved as follows:

(1) Set specific fault and fault clearing time $\tau$.

(2) The injected active power $y$ is determined in the range of the maximum and minimum active power. The dichotomy principle is used to determine whether the injected active power $y$ is a critical safety point through numerical simulation analysis.

(3) If the injection $y$ is not the critical injection point, change the injection $y$ and return to step (2) to search again; If the injection $y$ is the critical injection point, record the point, continue to change the injection $y$, repeat step (2) until the end of the search, and enter step (4);

(4) The data of all critical injection points are read, and the transient security region plane is fitted by the least square method.

MATLAB is used to solve the three-phase short-circuit fault dynamic security region of the two systems. The flow chart is shown in Figure 8. Because three key generator nodes are selected to form the injection power space, the corresponding transient security region will be displayed in three-dimensional graphics.

![Flowchart of solving transient security region boundary](image)

Fig.8 Flowchart of solving transient security region boundary
The program can be used to solve the three-dimensional transient security region of AC / DC hybrid system, as shown in Figure 9 below.

![Fig.9 Transient security region of AC / DC hybrid system](image)

In the AC / DC hybrid system, when the DC transmission power is too high, the system will present the mode of "weak AC and strong dc". If the AC three-phase outlet short circuit occurs near the DC receiving bus, the bus voltage at the DC inverter side will drop sharply, and even the DC commutation failure will occur, and then the DC blocking will occur. After that, all the DC transmission power will be transferred to the AC network, and the AC network can not bear all the power flow transferred after DC blocking, so the system is prone to instability.

The DC transmission capacity is changed to 4500MW and 4000MW in turn, and the other parameters remain unchanged. Run the program again to get the security domain boundary. The three-dimensional rotation diagrams of the three DC transmission capacities are presented below (see Figure 10, Figure 11 and Figure 12).

![Fig.10 Hybrid system transient security region boundary of 5000MW](image)
5. Quantitative Calculation of DC Transmission Capacity and Transient Safety Zone Boundary

The analysis of the three-dimensional transient safety domain rotation diagram in the previous section shows that the whole plane where the critical point is located is basically projected on a line of the plane composed of new33-new34. Therefore, we do not consider the influence of the third key generator new36 for a while, and use MATLAB program to solve the transient safety boundary of two-dimensional injected power space composed of new33 and new34, and quantitatively calculate and study the law between the boundary curves corresponding to different DC transmission capacity.

First, the DC transmission capacity is 4000-4600MW and 5000MW, and the step is 100. Then, eight series points shown in Figure 13 are solved by MATLAB. The same color point is the critical point of transient stability under the same DC transmission power, and almost all the points of each color are in the same line. Therefore, these critical points are fitted by linear regression, forming 8 sets of fitting lines, and the transmission power corresponding to the downward to the upper lines increases in turn.
Fig. 13 Critical point of transient security region under different DC transmission power

It can be seen from the above figure that the lines fitted by these critical points seem to be parallel to each other. Therefore, according to the fitting line, the intersection points of these critical points and the horizontal (new34) and vertical (new33) coordinates are respectively $x_i$, $y_i$. And the absolute value of the slope of the line is obtained. Absolute value of slope $|k_i| = \frac{y_i-5.3}{x_i-3.5}$, Table 1 can be drawn as follows.

| DC Transmission Power /MW | Inter-section of Ordinates $y_i$ | Inter-section of Abscissa $x_i$ | Absolute Value of Slope $|k_i|$ | Inclination Angle of Straight Line /rad | Inclination Angle of Straight Line /° |
|---------------------------|---------------------------------|-------------------------------|-------------------------------|----------------------------------------|----------------------------------------|
| 4000                      | 5.800                           | 4.050                         | 0.909                         | 0.738                                  | 42.271                                 |
| 4100                      | 5.885                           | 4.134                         | 0.923                         | 0.745                                  | 42.707                                 |
| 4200                      | 5.970                           | 4.218                         | 0.933                         | 0.751                                  | 43.015                                 |
| 4300                      | 6.045                           | 4.290                         | 0.943                         | 0.756                                  | 43.320                                 |
| 4400                      | 6.100                           | 4.339                         | 0.954                         | 0.762                                  | 43.651                                 |
| 4500                      | 6.150                           | 4.384                         | 0.962                         | 0.766                                  | 43.890                                 |
| 4600                      | 6.280                           | 4.500                         | 0.970                         | 0.770                                  | 44.128                                 |
| 5000                      | 6.347                           | 4.550                         | 0.997                         | 0.784                                  | 44.914                                 |

It can be seen from the first three columns of the above table that with the increase of DC transmission power, the intersection value of fitting line and abscissa and ordinate increases, indicating that the range of its security region increases. Then, by observing the first and fourth columns of the above table, it can be found that the absolute value of the slope of these lines increases with the increase of DC transmission capacity. According to the absolute value of the slope of the straight line, the corresponding inclination angle of the straight line is obtained, which is reflected in radian system and angle system.

Since the inclination angle of the straight line increases with the increase of the DC transmission capacity, can we find the mapping relationship between the two, so that the remaining required boundary lines can be obtained according to a known boundary line in the engineering application. Taking the DC transmission capacity (1000) as the independent variable $x$ and the linear inclination angle (rad) as the dependent variable $y$, we draw the line diagram of the scattered points with the help of MATLAB, and find that it is approximately a linear relationship (as shown in Figure 14). Therefore, the linear regression can be used to fit, and the linear function can be obtained $y = 0.0457x + 0.5584$. 


Fig.14 The relationship between DC transmission capacity and the inclination angle of the boundary line

With the increase of transmission power, the slope of the boundary line increases. The reason is that the key generator new34 plays a major role in the transient instability process of the hybrid system. Therefore, with the increase of transmission capacity, the larger the transmission scale of the power grid, the more important the influence of the key generator new34. That is, when the abscissa new34 increases (or decreases) the same unit, the ordinate new33 needs to decrease (or increase) more units to adapt to it. When the transmission power is greater than 4400MW, the increase speed of the slope of the transient security region boundary is delayed. It should be because the larger the transmission scale is, the stronger the power system is, and the better the self-regulation ability between AC and DC hybrid systems is.

6. Conclusion
Through the above research, we can draw the following conclusions.

(1) Through the BPA simulation of the critical fault clearing time and generator power angle swing speed, it is found that the hybrid system is more serious than the AC system under the AC bus three-phase short circuit fault.

(2) In complex network topology, two key generator nodes can always be found to form a two-dimensional power injection space. The other nodes have little influence and can be ignored in large power grid operation. In the two-dimensional transient security region, when the DC transmission power increases in a certain range, the boundary line of the transient security region moves upward and the inclination angle of the line increases. The relationship between the inclination angle of the straight line and the DC transmission capacity can be expressed quantitatively by a linear function.

The above conclusions simplify the solution process of large power grid transient security region under complex conditions, and can guide the stable operation of power grid more quickly and easily.

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