Study on Comprehensive Evaluation System and Method of AC-DC Hybrid System

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Abstract. With the rapid development of renewable energy worldwide, the electricity from large-scale renewable energy bases is transmitted to load-intensive area by DC transmission lines, forming an AC-DC hybrid system with AC and DC coupling obviously and tightly. Measuring the development level of the AC-DC hybrid system is of great significance for grid construction and power transmission. This paper first establishes a kind of comprehensive evaluation system that reflects both the interaction of AC-DC and the overall system capability. Then the evaluation method combining the three methods of AHP-Entropy-TOPSIS is carried out relatively. Finally the evaluation system and method is applied in the actual grid example. The comprehensive evaluation system and method of AC-DC hybrid system constructed in this paper is of reference significance to power grid planning and operation management.

1. Introduction

With the widespread application of DC technology in long-distance transmission scenarios, the traditional AC grid has developed into an AC-DC hybrid system with multiple DC feed-in. DC converter stations are tightly coupled via the AC grid, while AC and DC interacting with each other signally. Considering the millisecond-level fast dynamic characteristics of DC control systems, commutation failures, and the mutual coupling effects of multiple DCs, AC-DC hybrid systems are facing the risk of failure with a narrower time scale, greater impact, and multiple complex components.

The "Code on security and stability for power system" make clear the basic requirements for ensuring the safe and stable operation of power systems. On the other hand, in the process of developing the power grid of China from traditional AC grid to UHV AC-DC hybrid system and the application of VSC-HVDC technology, the evaluation index for DC operating characteristics have been widely studied[1-4].

This paper extracts evaluation index from two aspects: reflecting the interaction of AC-DC and reflecting the overall capability of AC-DC hybrid system, establishing the comprehensive evaluation system and method, and objectively measuring the development level of AC-DC hybrid system.

2. Evaluation index of AC-DC hybrid system

2.1. Key index reflecting the interaction of AC-DC

The key index reflecting the interaction of AC-DC can be divided into these aspects: the impact of AC/DC fault on AC-DC hybrid system, the structural characteristics of AC-DC hybrid system.
2.1.1. Index reflecting the impact of AC fault on AC-DC hybrid system. Commutation failure is one of the high-frequency faults in the DC system. In addition to the fault of DC system itself, the voltage drop caused by the failure of the AC system, especially the bus near the converter station, is an important reason for commutation failure. After the commutation failure is recovered, the DC system usually can resume normal operation in a short time. Continuous commutation failure for a long time may lead to DC blocking, transient instability of the power grid, and even chain failures of the AC-DC hybrid system. This paper extracts the N-1 continuous commutation failure passing rate and N-1 multi-circuit continuous commutation failure passing rate as the key index to reflect the impact of AC fault on AC-DC hybrid system.

1) N-1 continuous commutation failure passing rate, CCFP

With checking the N-1 fault of AC lines near the DC converter station buses, the index is defined as the number of times that no continuous commutation failure occurs / total number of times, when verifying the N-1 fault of AC lines near the DC converter station bus. Continuous commutation failure is determined as that the interval between two commutation failures is less than or equal to 250ms. The equation of the index is as follow:

$$CCFP \; N = \frac{N_{n1} - \sum_{i=1}^{N_{n1}} D_{ji}}{N_{n1}}$$

Where $N_{n1}$ is the total number of times verifying the N-1 fault of AC lines near the DC converter station buses. And $D_{ji} = 1$ when continuous commutation failure occurs at time $i$, otherwise $D_{ji} = 0$.

2) N-1 multi-circuit continuous commutation failure passing rate, MCCFP

With checking the N-1 fault of AC lines near the DC converter station buses, the index is defined as the number of times that no continuous commutation failure occurs / total number of times, when verifying the N-1 fault of AC lines near the DC converter station bus. The equation of the index is as follow:

$$MCCFP \; N = \frac{N_{n1} - \sum_{i=1}^{N_{n1}} D'_{ji}}{N_{n1}}$$

Where $N_{n1}$ is the total number of times verifying the N-1 fault of AC lines near the DC converter station buses. The $D'_{ji} = 1$ when continuous commutation failure occurs on more than one AC lines at time $i$, otherwise $D'_{ji} = 0$.

2.1.2. Index reflecting the impact of DC fault on AC-DC hybrid system. The impact of DC fault on the AC system is mainly the voltage stability and power angle stability of the AC system. For the power grid at power-sending end, the situation that DC fault causes the voltage rise in the near area of the converter station and the generation units off grid are the focus of attention. Therefore, it is necessary to investigate the power frequency overvoltage level and fault ride-through capability. For the power grid at power-receiving end, since the recovery of DC near-field voltage after fault has a direct impact on whether the fault will happen again, it is necessary to investigate the voltage recovery qualified rate.

1) Power frequency overvoltage level, OV

With checking the single pole blocking failure of DC lines, the index is defined as the total number of nodes whose maximum instantaneous voltage exceeds 1.3 times of the normal operation state / the total number of AC nodes within the system. This index is used to reflect the response of system to the change of instantaneous power, and reflects the ability of safe operation of the system. The larger the value is, the weaker the ability of system facing DC faults. The equation of the index is as follow:
\[ OV = \frac{\sum_{i=1}^{N_d} D_{DVi}}{N_{in}} \]  

(3)

Where \( N_{in} \) is the total number of nodes within the system. And \( D_{DVi} = 1 \) when continuous commutation failure occurs at time \( i \), otherwise \( D_{DVi} = 0 \).

2) Fault ride-through capability, FRTC

With checking the single pole blocking failure of DC lines, the index is defined as the sum of power capacity of wind turbine and PV unit which can ride through grid faults / the sum of power capacity of wind turbine and PV unit within the system. This index is used to measure the impact of DC faults on wind turbine and PV unit within the system. The larger the value is, the weaker the ability of system facing DC faults. The equation of the index is as follow:

\[ FRTC = \frac{\sum_{i=1}^{N_m} P_{FRTC_i}}{P_{in}} \]  

(4)

Where \( P_{in} \) is the sum of power capacity of wind turbine and PV unit within the system. And \( P_{FRTC_i} \) is the power capacity of wind turbine and PV unit which can ride through grid faults.

3) Voltage recovery qualified rate, VRQ

With checking the single pole blocking failure of DC lines and the N-1 fault of AC lines near the DC converter station buses, the index is defined as the number of times that voltage can be restored to 0.8p.u within 10s after fault occurred / total number of times. The larger the value is, the stronger the voltage recovery capability of the system. The equation of the index is as follow:

\[ VRQ = \frac{N_{n1} - \sum_{i=1}^{N_{VRQ}} D_{VRQi}}{N_{n1}} \]  

(5)

Where \( N_{n1} \) is the total number of times verifying the single pole blocking failure of DC lines and the N-1 fault of AC lines near the DC converter station buses. And \( D_{VRQi} = 1 \) when continuous commutation failure occurs at time \( i \), otherwise \( D_{VRQi} = 0 \).

2.1.3. Index reflecting the structural characteristics of AC-DC hybrid system

Reasonable power grid structure is the basis of ensuring the safe and stable operation of power system. The multi-infeed short current ratio and the multi-infeed interaction factor can reflect the structural characteristic of AC-DC hybrid system. The multi-infeed short current ratio is used to evaluate the voltage support ability of AC power grid to DC lines; The multi-infeed interaction factor reflects the interaction between DC and DC by reflecting the closeness of electrical coupling between two DC converter buses through AC system. It is suitable to extract multi-infeed short current ratio and multi-infeed interaction factor to reflect the structural characteristic of AC-DC hybrid system.

1) multi-infeed short current ratio, MSCR

CIGRE established the WG B4 in 2007 and proposed the definition of multi-infeed short circuit ratio [5], the equation is as follow:

\[ MISCR_i = \frac{S_{ac_i}}{P_{dn_j} + \sum_{j=k+1}^{a} \Delta U_j P_{dn_j}} \]  

(6)
$U_i$ is the amount of voltage change caused by switching a small-capacity capacitor on the \(i\) commutation bus; $U_j$ is the amount of voltage change of the \(j\) bus caused by switching a small-capacity capacitor on the \(i\) commutation bus; \(P_{dNi}\) and \(P_{dNj}\) is the transmission capacity for the \(i\) and \(j\) DC line.

The calculated value of the index is the average value of the calculated values of the multi-infeed short circuit ratio of each DC line.

2) multi-infeed interaction factor, MIIF

The CIGRE WG B4 also proposed the definition of multi-infeed interaction factor [6], the equation is as follow:

$$MIIF_{ji} = \frac{\Delta U_j}{\Delta U_i}$$

\(\Delta U_i\) is the voltage change of the AC bus voltage of the converter station where the disturbance is applied. When a DC system is operating in the rated state, a parallel reactive power compensation is switched on and off at the converter bus line of the converter station to make the converter bus voltage step change. The change amount (expressed as a percentage) is usually 1%; \(\Delta U_j\) is the change amount of the AC bus voltage of the disturbed converter station.

The calculated value of the index is the average value of the maximum calculated values of the multi-infeed interaction factor of each DC line with other DC lines.

2.2. Key index reflecting the overall system capability of AC-DC hybrid system

The research of the evaluation system on the safe and stable operation of the traditional AC system have been rich, mainly from two aspects of static security and transient stability.

Power system planning usually only adopts the N-1 principle, but with the increasing complexity of power system and the improvement of users' requirements for power supply reliability, it is necessary to consider the situation of the double circuit part of important transmission lines, the N-1 fault of important substation during transformer maintenance, DC double pole blocking and so on. The requirement of the "Code on security and stability for power system" is to meet the N-1 principle. Therefore, we use "qualified" to determine the verification results of N-1 principle, such as static N-1 qualified rate and transient N-1 qualified rate. We use "passing" to determine the verification results of N-2 principle, such as static N-2 passing rate and transient N-2 passing rate. The grid frame that can meet the N-2 principle verification reflects the ability of the system to face serious faults.

Voltage deviation qualified rate, Line current qualified rate and Short current qualified rate reflect the overall system capability of the system under normal operation mode.

2.2.1. Index reflecting the static security of AC-DC hybrid system.

1) Static N-1 qualified rate, SQ

With checking the single pole blocking failure of DC lines and the N-1 fault of AC lines near the DC converter station buses, the index is defined as the number of times that no overload of lines and transformers occurs / total number of times. The equation of the index is as follow:

$$SQ = \frac{N_{n1} - \sum_{i=1}^{N_{sqi}} D_{sqi}}{N_{n1}}$$

Where \(N_{n1}\) is the total number of times verifying the N-1 fault of AC lines near the DC converter station buses and the single pole blocking failure of DC lines. And \(D_{sqi} = 1\) when overload of lines or transformers occurs at time \(i\), otherwise \(D_{sqi} = 0\).

2) Static N-2 passing rate, SP
With checking the double pole blocking failure of DC lines and the N-2 fault of double circuit AC lines near the DC converter station buses, the index is defined as the number of times that no overload of lines and transformers occurs / total number of times. The equation of the index is as follow:

$$SP = \frac{N_{n1} - \sum_{i=1}^{N_{n1}} D_{spi}}{N_{n1}}$$  \hspace{1cm} (9)

Where $N_{n1}$ is the total number of times verifying the N-2 fault of double circuit AC lines near the DC converter station buses and the double pole blocking failure of DC lines. And $D_{spi} = 1$ when overload of lines or transformers occurs at time $i$, otherwise $D_{spi} = 0$.

3) Voltage deviation qualified rate, $VDQ$

The index is defined as the number of nodes whose voltage deviation is 1.1 times of rated voltage / total number of nodes in AC power grid under normal operation mode.

4) Line current qualified rate, $LCQ$

The index is defined as the number of lines that do not exceed the thermal stability limit power of the line transmission / the total number of AC lines under normal operation mode.

5) Short current qualified rate, $SCQ$

The index is defined as the number of buses with short-circuit current not exceeding the short-circuit interrupting current / total number of AC grid buses under normal operation mode.

2.2.2. Index reflecting the transient stability of AC-DC hybrid system.

1) Transient N-1 qualified rate, $TQ$

With checking the single pole blocking failure of DC lines and the N-1 fault of AC lines near the DC converter station buses, the index is defined as the number of times that power angle, voltage and frequency is qualified during the transient process / total number of times. The equation of the index is as follow:

$$TQ = \frac{\sum_{i=1}^{N_{n1}} D_{qi}}{N_{n1}}$$  \hspace{1cm} (10)

Where $N_{n1}$ is the total number of times verifying the N-1 fault of AC lines near the DC converter station buses and the single pole blocking failure of DC lines. And $D_{qi} = 1$ when power angle, voltage and frequency is qualified during the transient process at time $i$, otherwise $D_{qi} = 0$.

2) Transient N-2 passing rate, $TP$

With checking the double pole blocking failure of DC lines and the N-2 fault of double circuit AC lines near the DC converter station buses, the index is defined as the number of times that power angle, voltage and frequency is qualified during the transient process / total number of times. The equation of the index is as follow:

$$TP = \frac{\sum_{i=1}^{N_{n1}} D_{spi}}{N_{n1}}$$  \hspace{1cm} (11)

Where $N_{n1}$ is the total number of times verifying the N-2 fault of double circuit AC lines near the DC converter station buses and the double pole blocking failure of DC lines. And $D_{spi} = 1$ when power angle, voltage and frequency is qualified during the transient process at time $i$, otherwise $D_{spi} = 0$. 

3. Comprehensive evaluation technology of AC-DC hybrid system

3.1. Evaluation system of AC-DC hybrid system

This paper establishes the comprehensive evaluation system of AC-DC hybrid system, from the top to the bottom as the target layer, criterion layer and index layer. The above index reflecting the interaction of AC-DC and the overall system capability of the AC-DC hybrid system belong to the index layer. Index considering the transient process after the fault belong to the "Transient stability" of the criterion layer, and the index without considering the transient process after the fault belong to the "Static security" of the criterion layer. The evaluation results of the two are finally attributed to the target layer "Comprehensive evaluation of AC-DC hybrid system".

3.2. Comprehensive evaluation method of AC-DC hybrid system

The comprehensive evaluation method of AC-DC hybrid system is a combination of AHP (Analytic Hierarchy Process) [7], entropy [8] and TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [9]. AHP and entropy method respectively realize the subjective and objective comprehensive weight of each index. TOPSIS is a common method for multi-objective fusion decision-making, which is used to rank according to the proximity of limited evaluation objects and idealized ones, and the results of relative advantages and disadvantages of evaluation objects are obtained.

3.2.1. Comprehensive weighting method of AHP and entropy.

Among the subjective weighting methods, AHP is widely used in various models due to its theoretical background and strong reliability. The decision-maker constructs the judgment matrix through the relative evaluation of the importance of the index, and the final calculation result is the subjective weight vector of the index, \( W = (W_1, W_2, ..., W_M)^T \) is set.

In the objective weighting method, entropy value can be used to judge the dispersion degree of the index. The greater the index, the greater the influence (weight) of the index on the comprehensive evaluation, and the smaller the entropy value. The final result is the objective weight vector of the index, \( V = (V_1, V_2, ..., V_M)^T \) is set.

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Further, the comprehensive weight vector of the index, \( U = (U_1, U_2, ..., U_M)^T \) is determined.

\[
u_i = w_i v_i / \sum_{i=1}^{M} w_i v_i \tag{12}\]
3.2.2. **TOPSIS**

The steps to obtain the optimal solution of multi-objective fusion decision by TOPSIS are as follows:

1) Construct a weighted normalized decision matrix $A$

$$
A = \begin{bmatrix}
    w_1 v_1(x_1) & w_2 v_2(x_1) & \ldots & w_n v_n(x_1) \\
    w_1 v_1(x_2) & w_2 v_2(x_2) & \ldots & w_n v_n(x_2) \\
    \vdots & \vdots & \ddots & \vdots \\
    w_1 v_1(x_n) & w_2 v_2(x_n) & \ldots & w_n v_n(x_n)
\end{bmatrix}
$$

(13)

In the formula, each scheme has $M$ indicators $X_m$ (the No.m index), and there are $N$ schemes in total, $V_j(X_m)$ is the normalized value of the $X_m$ index of the No.i scheme and $W_m$ is the weight of each indicator, among which \( \sum_{i=1}^{M} w_i = 1 \); 

2) Calculate positive and negative ideal solutions:

$$
V_j^+ = \max_{i \in \mathcal{I}} v_i(x_j), \quad (i = 1, 2, \ldots, n)
$$

$$
V_j^- = \min_{i \in \mathcal{I}} v_i(x_j), \quad (i = 1, 2, \ldots, n)
$$

(14)

Formula: $V_j^+$ is the best positive ideal solution for every virtual index, $V_j^-$ is the worst negative ideal solution for every index of virtual.

3) Calculate normalized value of index $v_j(x_i)$: Euclidean distance from positive and negative ideal solutions:

$$
S^+(v_j) = \left( \sum_{j=1}^{n} (v_j^+ - v_j(x_i))^2 \right)^{\frac{1}{2}}
$$

$$
S^-(v_j) = \left( \sum_{j=1}^{n} (v_j(x_i))^2 - v_j^- \right)^{\frac{1}{2}}
$$

(15)

In the formula, $S^+(v_j), S^-(v_j)$ separately express $v_i$ Euclidean distance from positive and negative ideal solutions;

4) Calculate the comprehensive evaluation according to the following formula $C(v_j)$:

$$
C(v_j) = \frac{S^-(v_j)}{S^+(v_j) + S^-(v_j)}, \quad (i = 1, 2, \ldots, n)
$$

(16)

In the formula, the larger the value $C(v_j)$ is, the closer the scheme is to the positive ideal solution, and the further away from the negative ideal solution, the scheme is the best one among the alternatives.

3.2.3. **Evaluation steps**

The steps of comprehensive evaluation method for AC-DC hybrid system are as follows:

1) Through the simulation calculations, the values of all kinds of index in the index layer of each scheme are obtained, and the numerical normalization processing is carried out.

2) The subjective weight and objective weight are calculated for the indexes which belong to static security and transient stability respectively, and finally the comprehensive weight vector of each index, $U=(U_1, U_2, \ldots, U_M)^T$ is obtained.

3) The evaluation index of static security and transient stability in the index layer are evaluated by the method of TOPSIS. The calculated evaluation values are used as the calculation values of "static security" and "transient stability" in the criterion layer.

4) Repeat steps 2) and 3), and the calculated evaluation value is the final evaluation value of the comprehensive evaluation of AC-DC hybrid system in the target layer.

4. **Example analysis**
4.1. Example setting

Jiangsu power grid is a typical AC-DC hybrid system, which is an important receiving-end power grid in the eastern region of China. Jiangsu power grid connects with the outside system through 1000kV and 500kV AC channel, as while as DC channel. By 2020, Jiangsu 500kV power grid will form a six vertical and seven horizontal backbone network, and realize the closed-loop operation of East China UHV ring network. Four UHV DC lines, namely Inner Mongolia Ximeng to Jiangsu Taizhou (±800kV, LCC-HVDC), Shanxi Jinbei to Jiangsu Nanjing (±800kV, LCC-HVDC), Jinping to Sunan (±800kV, LCC-HVDC) and Baihetan to Jiangsu (±800kV, Hybrid DC). This paper applies Jiangsu power grid as the typical example to verify the rationality and correctness of the comprehensive evaluation system and corresponding evaluation method.

Considering a new UHV DC project in voltage level of ±800kV and a transmission capacity of 8000MW in Jiangsu power grid, it can be divided into two schemes according to the different drop points, the north and the south of Jiangsu Province. The two schemes shut down the same local generation unit.

![Example schemes](image)

(a) North scheme
(b) South scheme

Figure 2 Example schemes

The original scheme without new DC is also included in the example analysis.

4.2. Example calculation

Based on the BPA software, the power flow calculation, short-circuit current calculation and transient stability calculation are carried out for the three schemes, and the calculation results of each key index are shown in the table below.

| Table 1 calculation results of key index |
|------------------------------------------|
| **Index name** | **North scheme** | **South scheme** | **Original scheme** |
| Static N-1 qualified rate, SQ | 100% | 100% | 100% |
| Static N-2 passing rate, SP | 100% | 100% | 100% |
| Voltage deviation qualified rate, VDQ | 100% | 100% | 100% |
| Line current qualified rate, LCQ | 100% | 100% | 100% |
| Short current qualified rate, SCQ | 100% | 100% | 100% |
| multi-infeed short current ratio, MSCR | 3.293 | 3.704 | 3.764 |
| multi-infeed interaction factor, MIIF | 0.246 | 0.288 | 0.212 |
Transient stability

|                      | Transient N-1 qualified rate, TQ | Transient N-2 passing rate, TP | N-1 continuous commutation failure passing rate, CCFP | N-1 multi-circuit continuous commutation failure passing rate, MCCFP | Voltage recovery qualified rate, VRQ |
|----------------------|----------------------------------|--------------------------------|-----------------------------------------------------|---------------------------------------------------------------|-----------------------------------|
|                      | 100%                             | 100%                           | 68.80%                                              | 98.3%                                                         | 100%                             |
|                      |                                  |                                | 75%                                                 | 93.7%                                                         | 100%                             |
|                      |                                  |                                | 68.3%                                               | 97.9%                                                         | 100%                             |

The comprehensive evaluation results of the three schemes are shown in the table below.

**Table 2 calculation results of comprehensive evaluation**

|                      | Comprehensive evaluation of AC-DC hybrid system | Static security | Transient stability |
|----------------------|-----------------------------------------------|-----------------|---------------------|
| North scheme         | 0.5799                                        | 0.3123          | 0.9773              |
| South scheme         | 0.3951                                        | 0.3152          | 0.4395              |
| Original scheme      | 0.6847                                        | 0.8245          | 0.5962              |

4.3. Conclusion

According to the above calculation of the three schemes, the following conclusions are obtained:

1) The scheme of DC drop point in north scheme and south scheme is reasonable.

According to the results, both north scheme and south scheme have passed the electrical calculation verification. And the static N-1 qualified rate, the short current qualified rate and the transient N-1 qualified rate are all 100%. The static N-2 passing rate, voltage deviation qualified rate and line current qualified rate of the two schemes are all 100%; In terms of transient stability, the voltage recovery qualified rate of the two schemes are all 100%, the transient N-2 passing rate is higher than the original scheme.

2) The north scheme is better than the south scheme.

Jiangsu power grid is a typical AC-DC hybrid power grid. The power flow of Jiangsu grid presents a pattern of "north power transmitted to south". The existing UHVDC projects are all located in southern Jiangsu, so Southern Jiangsu presents a situation of centralized DC feed-in. The centralized feeding of DC will bring challenges to the stability of power grid, and a single fault may lead to cascading faults. According to the calculation results of multi-infeed interaction factor, the value of south scheme is greater than that of north scheme, which means the coupling between DC lines in south scheme is closer than north scheme. According to the values of N-1 continuous commutation failure passing rate and N-1 multi-circuit continuous commutation failure passing rate, the north scheme is higher than south scheme. This reflects the fact that the south scheme has added a new DC line to the southern Jiangsu grid, which has aggravated the situation of close coupling between DC and AC. The static security, transient stability and comprehensive evaluation of the two schemes show that the north scheme is better than the south scheme as a whole.

3) The reason why the south scheme is weaker than the original scheme for some key index.

Comparing the results of multi-infeed short current ratio and multi-infeed interaction factor, the north scheme is weaker than original scheme. It is because that both the north scheme and south scheme added a new DC line to Jiangsu grid and shut down local thermal power plants, so the local power capacity which can support the strength of Jiangsu grid is limited, and the dependence on the external power in the region is increased, resulting in the power supply balance pressure increases and the supporting capacity of AC power grid to DC decreases. It is reasonable that the calculation results of two index of north scheme are weaker than that of the original scheme, which further verifies the rationality and correctness of the evaluation system and corresponding method of AC-DC hybrid system.
5. Conclusion
In this paper, the key index reflecting the interaction of AC-DC and the overall system capability of AC-DC hybrid system are combed, and the evaluation system and corresponding method is established. Taking Jiangsu power grid as an example, the advantages and disadvantages of the new DC drop points in different regions are compared. The comprehensive evaluation system and corresponding method of AC-DC hybrid system constructed in this paper can provide reference for power grid planning and operation management. The next step is to study the changes of each index during the dynamic operation of power grid and establish a more accurate evaluation system.

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