Risk Assessment for Alternating Current / Direct Current (AC/DC) Hybrid Systems with Renewables Penetration

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Abstract. In this paper, a risk assessment method is proposed for AC/DC hybrid systems with renewables penetration, considering the effect of renewables penetration and the application of DC transmission. The sequential Monte Carlo method is introduced to simulate the output of renewables generators, and the unified iterative method is used to solve the problem of AC/DC hybrid system power flow calculation. By establishing the quantized risk assessment indices, the risk of AC/DC hybrid systems with renewables penetration can be analysed. The results of EPRI of China 6-machine-22-bus Test case show that the proposed method can effectively evaluate the risk level of AC/DC hybrid systems with renewable energy penetration and provide reference for power grid planning and the actual operation in advance.

1. Introduction
The utilization of renewables is of great importance for sustainable development all over the world [1]. On the one hand, renewables penetration optimizes the structure of power supply, which alleviates the shortage of traditional fossil energy and improves the environment; on the other hand, it brings challenges to the stability of power system. Furthermore, because of the imbalanced energy distribution in China, HVDC and AC/DC hybrid systems are commonly used in the power transmission of large scale and long distance, which may result in extremely serious problems when accidents happen [2]. Therefore, it is necessary to carry out risk assessment for systems with renewables penetration, thus evaluating the reliability and security of the power system, then some preventive measures can be taken [3].

In recent years, research on risk assessment of power system mainly focuses on the following four aspects: static risk assessment, voltage stability risk assessment, transient stability risk assessment and decision optimization based on risk assessment. A random power flow simulation method based on LMIL algorithm considering the randomness and volatility of renewables output was proposed in [4]. A quantitative framework for voltage risk assessment was proposed in [5], indicating that replacing conventional generation with wind power will probably lead to voltage stability risk. An effective risk assessment algorithm was put forward in [6], where a quantitative method was used to obtain the weighted joint probability distribution of random variables. An information extraction process based on principal component analysis was designed in [7], reducing the complexity of the optimal power flow problem, so as to obtain a more efficient solution. As for risk assessment with renewables penetration, a dispatching method based on risk assessment model was proposed in [8], analysing the real cases with renewables through combination sampling method, but AC/DC hybrid system was not mentioned. An index system of static security and transient stability for AC/DC hybrid system is
presented to evaluate the proportion of UHV in [9], however, the impact of renewables on risk index was not considered.

The existing problems are concluded as follows: 1) Risk index system needs to be improved; 2) Renewables are not considered; 3) Consideration of AC/DC hybrid system is insufficient. Based on the existing problems, an improved risk assessment method for AC/DC hybrid system with renewables penetration is proposed in this paper, and the correctness and effectiveness are testified by the test case.

2. AC/DC power flow calculation modeling

2.1. Renewables output

The non-sequential Monte Carlo simulation method is adopted to simulate the renewables (in this paper, taking wind power as an example) output, which determines the system state. Two-parameter Weibull distribution is used for wind velocity probability distribution, which can be expressed as

\[ f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \]

where \( k \) and \( c \) are the shape parameter and scale parameter of the distribution, respectively.

According to the usual curve of wind power, its output can be written as

\[ P_{\text{wind}} = \begin{cases} 0 & 0 \leq v_i \leq v_{ci} \\ P_r(A + B \times v_i + C \times v_i^2) & v_{ci} < v_i \leq v_{ct} \\ P_r & v_{ct} < v_i \leq v_{ce} \\ 0 & v_i > v_{ce} \end{cases} \]

where \( P_{\text{wind}} \) and \( P_r \) are the actual output and the rated power, respectively; \( v_i \), \( v_{ci} \), \( v_{ct} \) and \( v_{ce} \) are the actual velocity, cut-in velocity, rated velocity and cut-off velocity, respectively; \( A \), \( B \) and \( C \) are the characteristic parameters.

2.2. Power flow calculation

When it changes from AC power system to AC/DC hybrid system, the traditional power flow calculation method is no longer applicable. Hence DC related variables and equations should be added into the model. Unified iterative method is one of the effective ways with good convergence to solve the power flow calculation problem of AC/DC hybrid system.

For an AC node, the equation is the same as the traditional one, which is written as

\[ \begin{align*}
\Delta P_i &= P_{\text{in}} - V_i \sum_{j=1}^{n} \left( V_{j} \left( G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right) \right) = 0 \\
\Delta Q_i &= Q_{\text{in}} - V_i \sum_{j=1}^{n} \left( V_{j} \left( G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right) \right) = 0
\end{align*} \]

where \( i \) is the index of AC nodes and \( j \) is the index of either AC or DC nodes.

Different from traditional power flow calculation equations, for a DC node, there is an additional DC term in the equation, which can be written as

\[ \begin{align*}
\Delta P_i &= P_{\text{in}} - V_i \sum_{j=1}^{n} \left( V_{j} \left( G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right) \pm V_{ik} I_{ik} \right) = 0 \\
\Delta Q_i &= Q_{\text{in}} - V_i \sum_{j=1}^{n} \left( V_{j} \left( G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right) \pm V_{ik} I_{ik} \tan \varphi_k \right) = 0
\end{align*} \]

where \( i \) is the index of either AC or DC nodes and \( k \) is the index of DC nodes; the plus-minus sign indicates if it is an inverter or a rectifier; the reference direction of the DC voltage of the inverter is from the cathode to the anode, while the rectifier comes the opposite; the reference direction of the DC current is always from the anode to the cathode of the valve.

The converter control mode of AC/DC hybrid system will affect the operation of the system, so the control mode of the converter must be specified. There are five ways shown as
1) Constant voltage control
\[ V_d - V_{d_0} = 0 \]  
(5-a)

2) Constant current control
\[ I_d - I_{d_0} = 0 \]  
(5-b)

3) Constant power control
\[ P_d - P_{d_0} = 0 \]  
(5-c)

4) Constant ratio control
\[ k_r - k_{r_0} = 0 \]  
(5-d)

5) Constant controlling angle control
\[ \cos \theta_d - \cos \theta_{d_0} = 0 \]  
(5-e)

where the index \( s \) indicates a specified constant.

Apart from (3) and (4), there are some additional equations needed when solving the problem.

1) For the \( k \)th converter, the basic equations of converters are
\[ \Delta d_{ik} = V_{ik} - k_{Tk} V_{n,i,k} \cos \theta_{ik} + X_{ik} I_{ik} = 0 \quad k = 1, 2, ..., n_c \]  
(6-a)

\[ \Delta d_{ik} = V_{ik} - k_i k_{Tk} V_{n,i,k} \cos \varphi_k = 0 \quad k = 1, 2, ..., n_c \]  
(6-b)

2) DC network equation
\[ \Delta d_{ik} = \pm I_{ik} - \sum_{j=1}^{n_c} g_{ik} V_{ik} = 0 \]  
(7)

3) For the \( k \)th converter, \( k_{Tk} \) and \( \cos \theta_{dik} \) are the ratio and the cosine of the controlling angle respectively, the control equations are
\[ \Delta d_{ik} = d_{ik} (I_{ik}, V_{ik}, \cos \theta_{dik}, k_{Tk}) = 0 \]  
(8-a)

\[ \Delta d_{ik} = d_{ik} (I_{ik}, V_{ik}, \cos \theta_{dik}, k_{Tk}) = 0 \]  
(8-b)

where \( n_c \) is the number of DC nodes.

2.3. Optimal load curtailment
Load curtailment refers to the reduction of load from the grid in order to maintain the stability of the whole system. Based on the DC power flow model, the optimal load curtailment problem can be transformed into a linear programming problem. The objective function is
\[ \min \sum_{i=1}^{NG} c_i P_{G_i} \]  
(9)

where \( NG \) is the number of bus nodes, \( P_{G_i} \) is the output of the generator \( i \), \( c_i \) is the ratio of load curtailment to the output.

The constraints of the problem can be written as
\[ P_G - P_D = B\theta \]  
(10-a)

\[ F \leq X\theta \leq \bar{F} \]  
(10-b)
where \( \mathbf{P}_c \) and \( \mathbf{P}_d \) are the active power vector and active load vector, respectively.

3. Risk assessment modeling
In this section, three indices are used to measure the risk of AC/DC hybrid system.

1) Voltage risk

\[
R_v = \sum_{i=1}^{n} \alpha_i R(U_i)
\]

where \( n \) is the total number of bus nodes, \( \alpha_i \) is the importance degree of the \( i \)th node, \( R(U_i) \) is the \( i \)th result of voltage state sampling, and it can be expressed as

\[
R(U_i) = \begin{cases}
100 & 0 \leq U_i < 0.9 \\
451.7e^{1-U_i} - 451.7 & 0.9 \leq U_i < 1 \\
0 & 1 \leq U_i < 1.05 \\
200U_i - 200 & 1.05 \leq U_i < 1.5 \\
100 & U_i \geq 1.5
\end{cases}
\]

2) Power risk

\[
R_p = \sum_{j=1}^{m} \alpha_j R(S_j)
\]

where \( m \) is the total number of transmission lines, \( \alpha_j \) is the importance degree of the \( j \)th line, \( R(S_j) \) is the \( j \)th power flow calculation result of state sampling, and it can be expressed as

\[
R(S_j) = \begin{cases}
0 & 0 \leq S_j < 0.9 \\
100e^{S_j-0.9} - 100 & 0.9 \leq S_j < 1.2 \\
100 & S_j \geq 1.2
\end{cases}
\]

3) Load curtailment risk

\[
R_L = \sum_{k=1}^{v} R(L_k)
\]

where \( v \) is the total number of loads, \( R(L_k) \) is the load curtailment ratio of the \( k \)th node, and it can be expressed as

\[
R(L_k) = 100\alpha_k L_k / L_{total}
\]

where \( \alpha_k \) is the importance degree of the load, \( L_k \) is the load curtailment, and \( L_{total} \) is the total load of the hybrid system.

4) Composite risk

\[
R = \sum_{k=1}^{n} \phi_k R_k(x)
\]

where \( R_k(x) \) is the risk result of the \( k \)th index, \( \phi_k \) is the weight of the \( k \)th index.
4. Case study
In this section, a modified 22-bus AC/DC hybrid system of China Electric Power Research Institute is used to verify the effectiveness of the proposed method. For detailed information of system structure, network parameters and operation modes, please refer to [10]. The AC transmission line between bus No.11 and No.12 is replaced with a DC transmission line, and the parallel reactance on them is removed, meanwhile, the parallel capacitor with an admittance of 2.1 (per-unit value) is installed on bus No.11. The converter connected to bus No.11 is a rectifier, and the converter connected to bus No.12 is an inverter. The controlling modes of rectifier side are constant power and constant controlling angle, and the controlling modes of inverter side are constant voltage and constant controlling angle. Comparisons of risk values with different proportions of renewables penetration, at different penetration locations and different amount of DC transmission lines are analysed respectively.

4.1. Comparison of different proportions of renewables penetration
There is a rated power of 50MW wind penetration added to bus No.4. Assume that each wind turbines in the wind farm is undifferentiated, the cut-in velocity is 3m/s, the rated velocity is 13m/s and the cut-off velocity is 25m/s. The composite risk value consists of 25% of voltage risk, 25% of power risk and 50% of load curtailment risk. All the nodes and lines are of the same importance. The results of this case are shown in Table 1.

| Penetration (MW) | Voltage Risk | Power Risk | Load Curtailment Risk | Composite Risk |
|-----------------|--------------|------------|-----------------------|---------------|
| 0               | 94.0215      | 109.9549   | 0                     | 50.9941       |
| 20              | 94.8724      | 111.6632   | 0                     | 51.6339       |
| 40              | 97.3978      | 115.3677   | 0                     | 53.1914       |
| 60              | 101.9609     | 120.2176   | 0                     | 55.5446       |
| 80              | 126.0730     | 135.1516   | 0.7208                | 65.6665       |

As can be seen from Table 1, with the continuous increase of the wind penetration, all the risk values keep rising. The penetration within a certain range will not cause load curtailment, however, if it exceeds a certain range, the randomness and volatility of wind will lead to load curtailment, and further leading to a rapid increase of risk value.

4.2. Comparison of different locations of renewables penetration
The conventional generators at bus No.3, No.4 and No.5 are replaced by wind turbines with the same rated capacity of 50MW respectively. The results of this case are shown in Table 2.

| Bus Number | Voltage Risk | Power Risk | Load Curtailment Risk | Composite Risk |
|------------|--------------|------------|-----------------------|---------------|
| 3          | 98.9056      | 113.8775   | 0                     | 53.1958       |
| 4          | 99.2552      | 117.7585   | 0                     | 54.2534       |
| 5          | 99.4229      | 137.1579   | 0                     | 59.1452       |

As can be seen from Table 2, the results are markedly different at different locations. Bus No.5 has the highest risk value and bus No.3 has the lowest risk value. The reason is that there is only one transmission line connected with bus No.5, which is easy for it to reach the upper limit of transmission capacity, but there are four transmission lines connected with bus No.3, and it would be much better for it to share the transmission pressure. Therefore, the locations of renewables penetration should be considered when planning and operating.
4.3. Comparison of different amount of DC transmission lines
The location of wind penetration remains unchanged (Bus No.4), and the comparison of different amount of DC transmission lines is shown in Table 3.

| Transmission Lines | Voltage Risk | Power Risk | Load Curtailment Risk | Composite Risk |
|--------------------|--------------|------------|-----------------------|----------------|
| 1                  | 99.2552      | 117.7585   | 0                     | 54.2534        |
| 2                  | 130.3120     | 241.1182   | 3.4429                | 94.5790        |
| 3                  | 240.7317     | 284.6291   | 11.3522               | 137.0163       |

As can be seen from Table 3, with the increase of the number of DC transmission lines, the composite risk increases significantly. By analysing the results of the AC/DC power flow calculation, it is found that the power flow of the line connected to the DC nodes increases obviously, and the voltage of the nearby nodes also shows a tendency of voltage off-normal. Therefore, the adverse effects of the DC transmission lines on a large scale should be considered for power system planning and management.

5. Conclusion
An improved risk assessment method is proposed for AC/DC hybrid system with renewables penetration, and a composite risk value can be obtained. The proposed method takes renewables into account, which is closer to the real conditions. Moreover, both AC and DC power transmission are analysed, which makes the risk assessment results more comprehensive. According to the result of the assessment, a reasonable generation plan with renewables penetration can be made, which is safer and more reliable for the hybrid power system.

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