Risk Assessment of Wind Swing Flashover of Transmission Lines Based on Matter-Element Extension Model

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Abstract: In extreme weather, the line trip-out events caused by the wind swing of the transmission line occur frequently, severely affecting the normal operation of the power system. Since the structure of the operating transmission line is difficult to be improved, wind swing flashover risk assessment is of great significance for the operating transmission lines. In this paper, a transmission line wind swing flashover risk assessment model based on the matter-element extension model is proposed. The analytic hierarchy process (AHP) and entropy weight method are applied to comprehensively calculate the weight value of the selected assessment index. This model can assess the early warning level of a certain tower unit in the transmission line. Finally, the feasibility and effectiveness of the proposed assessment model are verified by practical examples.

1. Introduction
In strong convective weather, the transmission lines often trip-out due to wind swing flashover, resulting in seriously influencing the power supply reliability of the power system.

At present, the research on the wind swing of transmission lines around the world mainly focuses on the calculation of the maximum wind swing angle and the minimum air gap. Most of the wind swing assessment methods, which are used for certain types of towers, cannot be fully applicable to all types of towers. Xiong et al. [1] proposed a method for calculating the minimum air gap of a straining tower based on a two-dimensional Descartes coordinate system. Hou et al. [2] used the Monte Carlo method to sample wind speed and wind direction, calculated the wind swing angle based on the design value of the line, corrected the wind swing angle under rainfall conditions based on fuzzy mathematics, and conducted wind swing trip risk assessment. Wang et al. [3] calculated the wind swing angle according to the predicted value of wind speed and wind direction, so as to perform a wind swing warning. Clapp A L [4] employed a drawing method to calculate the gap between the conductor and the building. Zhao [5] established a wind swing flashover risk assessment model based on BP neural network.

Most assessment methods do not apply to all types of towers, and cannot fully consider the influencing factors of wind swing. When calculating the wind swing angle and the minimum air gap, it is only combined with the design data but not fully integrated with the field data. Therefore, this study aims to combine real-time data and establish a wind swing assessment model for transmission lines based on multiple factors. Specifically, a transmission line wind swing flashover risk assessment method based on the matter-element extension model is proposed. Besides, the real-time data of some 500KV transmission line towers in the Shandong area is used to verify the validity of the assessment model.
2. Wind swing flashover mechanism analysis and assessment process

2.1. Analysis of Wind Swing Flashover Mechanism
Under the action of wind load, the conductor inclines to the tower body or surrounding objects, wind swing flashover will occur when the gap between them is insufficient. In case of rainfall, the insulation strength of the gap will be reduced, resulting in wind swing flashover when the minimum air gap is not less than limit. The system may have switching overvoltage during autoreclosing acts, and secondary flashover occurs when the gap is large, which leads to low reclosing success rate [6].

Transmission line wind swing flashover mainly occurs on the jumper wind swing on the strain tower and the insulator string wind swing on the straight tower, and the occurrence probability of phase to phase wind swing on the AC transmission line is very small [7]. Therefore, the risk assessment of this paper mainly considers the wind swing of jumper and insulator string.

2.2. Risk Assessment Process
The assessment model proposed in this paper can not only get the early warning level under a single index, but also comprehensively assess it as a whole. The assessment process is mainly composed of two parts: (1) Calculating the weight value of the selected risk assessment index. (2) Constructing an assessment model. The overall idea is as follows: Firstly, select the assessment index according to the influencing factors of the wind swing; Then, the AHP and entropy weight method is used to comprehensively calculate the weight value of the assessment index; Finally, according to the assessment model and the real-time meteorological data around the tower, the wind swing is assessed and the warning level of the tower is determined. In the case of sufficient data, all towers on the entire transmission line can be assessed for risk according to the wind swing flashover risk assessment flow diagram shown in figure 1.

![Flow diagram of risk assessment for wind swing flashover](#)
3. Determination of evaluation index weight

3.1 Selection of risk assessment index of wind swing flashover of transmission line

The influencing factors of wind swing are analyzed from three aspects: weather, line parameters, and topography.

- Meteorological factors. Wind speed and wind direction will affect the air gap between the line and the tower; rainfall and humidity will reduce the air breakdown voltage of the gap. 
- Line parameters. The transmission line parameters will affect the maximum wind swing angle and the minimum air gap. 
- Topography factors. Altitude will reduce the air breakdown voltage of the gap; The surface roughness will change the wind speed to indirectly affect the wind swing angle.

Now it is necessary to conduct wind swing flashover risk assessment based on real-time data for actual operating transmission lines. The influence factors of height difference, span, conduct parameters, altitude, and sag have been fully considered when designing transmission lines. Therefore, wind speed, wind direction, rainfall intensity and humidity are selected as assessment indexes.

3.2 Calculation of index weight value

Due to the selected assessment index, there are both qualitative and quantitative. Firstly, the analytic hierarchy process is used to combine qualitative analysis with quantitative analysis to calculate the weight value of assessment index. Then, using the entropy method to modify the index weight, which can make up for the lack of human subjective factors in the analytic hierarchy process. The calculation of the weight value is not the main part and will not be analyzed in detail.

4. Wind-swing flashover risk assessment model based on matter-element extension model

4.1 Matter-element extension model

4.1.1 Concept of classic domain.

The name of a certain thing is $N$, the characteristic is $C$, and its characteristic value $V$ constitutes the matter-element [8], which is expressed as $R = (N, C, V)$. Dividing things into $j$ levels.

$$R_j = (N_j, C_i, v_{ji}) = \begin{bmatrix} N_j & C_1 & v_{j1} \\ ... & ... & ... \\ C_n & v_{jn} \end{bmatrix} = \begin{bmatrix} N_j & C_1 & \begin{pmatrix} a_{j1}, b_{j1} \end{pmatrix} \\ ... & ... & ... \\ C_n & \begin{pmatrix} a_{jn}, b_{jn} \end{pmatrix} \end{bmatrix}$$ (1)

In the formula, $N_j$ represents the $j$ level, $v_{ji}$ represents the value range of the feature $C_i$ at this $j$ level, that is, the classic domain. Among them $(i = 1, 2, ..., n; j = 1, 2, ..., m)$

4.1.2 Concept of section domain

$$R_p = (P, C, v_p) = \begin{bmatrix} P & C_1 & v_{p1} \\ ... & ... & ... \\ C_n & v_{pn} \end{bmatrix} = \begin{bmatrix} P & C_1 & \begin{pmatrix} a_{p1}, b_{p2} \end{pmatrix} \\ ... & ... & ... \\ C_n & \begin{pmatrix} a_{pn}, b_{pm} \end{pmatrix} \end{bmatrix}$$ (2)

In the formula, $P$ represents the set of all levels, which is the set of classical domains of the feature $C_i$, that is, the section domain.
4.1.3 Matter-element to be assessed

\[ R_0 = \begin{bmatrix}
  N_0 & C_1 & v_{01} \\
  \ldots & \ldots & \ldots \\
  C_n & \ldots & v_{0n}
\end{bmatrix} \tag{3} \]

In the formula, \( N_0 \) represents the object to be assessed, namely the tower unit to be assessed, and \( v_{0i} \) is the value of \( N_0 \) with respect to \( C_i \).

4.1.4 Correlation function.

The correlation function is used to quantitatively describe the extent of correlation between each assessment index and each level, as shown below:

\[
k_j(v_i) = \begin{cases} 
  -\frac{p(v_{0i}, v_{ji})}{v_{ji}}, & v_{0i} \in v_{ji} \\
  \frac{p(v_{0i}, v_{ji}) - p(v_{0i}, v_{pi})}{v_{0i} \notin v_{ji}} 
\end{cases} \tag{4}
\]

Among them, \( p(v_{0i}, v_{ji}) \) represents the distance between \( v_{0i} \) in the assessment index and the classic domain \( v_{ji} \), and \( p(v_{0i}, v_{pi}) \) represents the distance between \( v_{0i} \) and the section domain \( v_{pi} \).

\[
p(v_{0i}, v_{ji}) = \sqrt{\left( a_{ji} + b_{ji} \right) - \frac{1}{2} \left( b_{ji} - a_{ji} \right)} \\
p(v_{0i}, v_{pi}) = \sqrt{\left( a_{pi} + b_{pi} \right) - \frac{1}{2} \left( b_{pi} - a_{pi} \right)} \\
v_{ji} = \left| b_{ji} - a_{ji} \right| (i = 1, 2, \ldots, n; j = 1, 2, \ldots, m) \tag{5}
\]

4.1.5 Comprehensive correlation extent.

The comprehensive correlation extent of the objects to be assessed with respect to each assessment level is as follows.

\[
k_j(N_0) = \sum_{i=1}^{n} \omega_i k_j(v_i) \tag{6}
\]

In the formula, \( N_0 \) is the weight value of each assessment index.

If the comprehensive correlation extent of the objects to be assessed is as follows:

\[
k_j(N_0) = \max k_j(N_0) (j = 1, 2, \ldots, m) \tag{7}
\]

The object to be assessed is at assessment level \( j \).

4.2 Establishment of risk assessment model

4.2.1 Thresholds of risk assessment index

In this paper, the risk of wind swing flashover is divided into four levels: safe, low, medium and high, and the warning levels are first, second, third and fourth respectively. According to engineering experience, under the four warning levels, the selected transmission line wind swing flashover risk assessment index thresholds are shown in table 1.
Table 1. Thresholds of risk assessment index for wind swing flashover of transmission lines

| Assessment index | Warning level |
|------------------|---------------|
|                  | First level   | Second level | Third level | Fourth level |
| Wind speed (m/s) | 0~10          | 10~20        | 20~30       | 30~40        |
| Wind direction (°)| 0~22.5        | 22.5~45      | 45~67.5     | 67.5~90      |
| Rainfall intensity| 0~2           | 2~4          | 4~6         | 6~8          |
| Humidity (%)     | 0~25          | 25~50        | 50~75       | 75~100       |

4.2.2 Constructing classic domain and section domain.

According to table 1, the classic domains $R_i (i = 1, 2, 3, 4)$ for determining each risk level in the risk assessment model and section domain $R_p$ are as follows. Among them, $N_1, N_2, N_3$ and $N_4$ respectively correspond to the wind flashover risk levels of the tower unit: safe, low, medium and high. The section domain of the risk assessment index is a collection of its classic domains, and the section domain $R_p$ is as follows.

$$
R_i = \begin{bmatrix}
N_1 & c_1 & (0, 10) \\
N_2 & c_2 & (0.225) \\
N_3 & c_3 & (0.2) \\
N_4 & c_4 & (0.25)
\end{bmatrix}
$$

$$
R_p = \begin{bmatrix}
N_1 & c_1 & (0, 40) \\
N_2 & c_2 & (0.90) \\
N_3 & c_3 & (0.8) \\
N_4 & c_4 & (0.100)
\end{bmatrix}
$$

4.2.3 Determining the matter element to be evaluated.

The real-time meteorological data around the tower unit is used as the value of each assessment index.

5. Field data analysis

The phase A line in the towers of #015, #016, #017 of the MengZhao I line of the 500KV transmission line in the Linyi City, Shandong Province and the phase B line in tower of #168 of HeShen II line of the 500KV transmission line in the Yantai City, Shandong Province are selected. The #168 tower of the HeShen II line is a corner tower, used to verify the jumper wind swing of the corner tower; The #015, #016, #017 towers of the MengZhao I line are all straight towers, used to verify the suspension insulators of the straight tower wind swing. The real-time meteorological data near the selected tower unit are shown in table 2.

Table 2. Meteorological data near the selected tower unit

| Transmission line tower | Assessment index |
|-------------------------|------------------|
|                         | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
| MengZhao I line (#015 tower) | 29.3m/s  | 38 degree | 3 | 95% |
| MengZhao I line (#016 tower) | 29.3m/s  | 73 degree | 3 | 95% |
| MengZhao I line (#017 tower) | 29.3m/s  | 66 degree | 3 | 95% |
| HeShen II line (#168 tower) | 35m/s  | 85 degree | 3 | 96% |

$C_1, C_2, C_3, C_4$ represents wind speed, wind direction, rainfall intensity and humidity respectively.
As the #015, #016, and #017 towers of the MengZhao I line are relatively close, the wind speed, rainfall intensity, and humidity data are consistent, but the change in the line direction changes the angle between the wind direction and the line. According to the meteorological data in table 2, combining formula (4) and formula (5) to calculate the correlation table of the risk level of the tower unit to be evaluated is shown in table 3 and table 4.

Table 3. Correlation table of assessment indexes of #015, #016 and #017 towers of MengZhao I line

| Assessment index | Correlation extent | Weight value |
|------------------|--------------------|--------------|
|                  | \( k_i( v_j) \)    |              |
| \( C_1 \)        | -0.643             | 0.4591       |
| \( C_2(#015) \)  | -0.290             | 0.2748       |
| \( C_3(#016) \)  | -0.748             | 0.2748       |
| \( C_4(#017) \)  | -0.644             | 0.2748       |
| \( C_5 \)        | -0.25              | 0.1653       |
| \( C_6 \)        | -0.933             | 0.1009       |

\( a \) Represents the wind direction assessment index in the #015 tower to be assessed of the Meng Zhao I line

\( b \) Represents the wind direction assessment index in the #016 tower to be assessed of the Meng Zhao I line

\( c \) Represents the wind direction assessment index in the #017 tower to be assessed of the Meng Zhao I line

Table 4. Correlation table of assessment indexes of #168 tower of HeShen II line

| Assessment index | Correlation extent | Weight value |
|------------------|--------------------|--------------|
|                  | \( k_i( v_j) \)    |              |
| \( C_1 \)        | -0.833             | 0.4591       |
| \( C_2 \)        | -0.926             | 0.2748       |
| \( C_3 \)        | -0.25              | 0.1653       |
| \( C_4 \)        | -0.947             | 0.1009       |

According to the correlation extent of each assessment index in table 3 and table 4, combining formula (6) and formula (7) to calculate the comprehensive correlation extent of each risk level of the #015, #016 and #017 towers of the MengZhao I line and the #168 tower of the HeShen II line, as shown in table 5.

Table 5. Comprehensive correlation extent of each risk level and its early warning level

| Transmission line tower | Comprehensive correlation extent | Warning level |
|-------------------------|----------------------------------|---------------|
|                         | \( k_1(N_0) \)                  | \( k_2(N_0) \) | \( k_3(N_0) \) | \( k_4(N_0) \) | \( \max k_i(N_0) \) |
| MengZhao I line (#015 tower) | -0.5103 | -0.1362 | -0.1328 | -0.2101 | -0.1328 | Third |
| MengZhao I line (#016 tower) | -0.6362 | -0.3926 | -0.1570 | -0.0230 | -0.0230 | Fourth |
| MengZhao I line (#017 tower) | -0.6076 | -0.4780 | -0.0714 | -0.1062 | -0.0714 | Third |
| HeShen II line (#168 tower)  | -0.7738 | -0.5988 | -0.5694 | 0.2240 | 0.2240 | Fourth |

According to the results of early warning levels in table 5, due to the difference in the angle between the wind direction and the line direction, the results of the wind swing flashover risk assessment and early warning levels of the towers of #015, #016 and #017 of Mengzhao I Line are different. The warning level of #016 tower of MengZhao I line and #168 tower of HeShen II line is level IV, and they are in a high-risk situation. In fact, the A-phase conductor of the #016 tower of MengZhao I Line and the B-phase jumper of the #168 tower of HeShen II line both had a wind swing flashover phenomenon, and the line autoreclosing was unsuccessful. The warning level of the phase A line in the #015 and #017
towers of the Mengzhao I line is third level and is at a medium risk. Actually, there is no wind swing flashover phenomenon. It can be seen that these two towers are in a risk-controllable state. Therefore, the assessment results are consistent with the actual tower situation, which can verify the effectiveness of the assessment model.

6. Conclusion
In this paper, the risk assessment index is selected according to the influencing factors of transmission line wind swing flashover. Using analytic hierarchy process and entropy method to calculate indicator weights can quantify the results of subjective analysis, enhance the accuracy of index weights, and eliminate the interference of subjective factors.

The risk assessment model of wind swing flashover based on matter-element extension model is constructed, which can comprehensively assess the wind swing risk of tower by combining qualitative and quantitative analysis, and the assessment results are objective and accurate. Combining with the field data analysis of some 500kV transmission line towers in the Shandong area, the level of risk assessment index is analyzed, and the risk warning level of wind swing flashover of transmission line towers can be identified. The risk assessment results are conducive to the scientific decision-making and later treatment of operation and maintenance personnel.

Acknowledgments
Thank you for the relevant data provided by Shandong Electric Power Company, and also thank the people who helped me in the process of writing the paper.

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