Overview of insulator state intelligent assessment in smart grid through fuzzy logic method

Simin Luo*, Le Luan, Yiping Cui, Shuo Xu, Quinten Guo and Tian Liu
Guangzhou Power Supply Bureau of Guangdong Power Grid Corporation

*Corresponding author e-mail: luosimin@gd.sgcc.com.cn

Abstract. In the transmission system, the operating state of the line insulator is always a state quantity with both fuzziness and randomness. Fuzzy logic theory has certain advantages for evaluating such a system with both fuzziness and randomness. According to the theory of fuzzy logic in the field of insulator state evaluation development situation, this paper introduces four methods - weights fuzzy logic method, the multistage fuzzy logic judgment, variable weight fuzzy logic judgment and cloud theory. The paper also analyses the characteristics and advantages of four methods, the results show that the cloud theory and variable weight fuzzy logic method more engineering significance.

Keywords: Fuzzy logic theory, Insulator, Cloud theory, Ambiguity, randomness.

1. Introduction

Insulator is an indispensable part of transmission line, and its on-line detection is always a difficult point in power system. Existing studies mostly try to use one-dimensional parameters such as voltage distribution, leakage current and corona current to characterize and analyze the operating state of insulators, but all of them are one-sided [1]. Although the leakage current method can accurately measure the change of the leakage current at the low voltage end, it cannot accurately reflect the deterioration degree of insulators due to the influence of multiple factors, and can only reflect the major fault of insulators to a certain extent [2-3]. Therefore, it is unlikely to be widely used in practice alone. As a method to judge insulator deterioration, pulse current method also has some defects to some extent. It is greatly disturbed by external humidity conditions. In addition, when insulator deterioration is serious, this detection method will be greatly limited and its accuracy will be reduced.

In view of the fuzziness of insulator state evaluation and the diversity of factors affecting insulator state, Nie Yixiong from Huazhong University of Science and Technology proposed the multidimensional parametric fuzzy logic method for insulator state comprehensive evaluation for the first time in China in 2003.

The application of fuzzy logic method includes the establishment of fuzzy set, fuzzy relation set and fuzzy data input set. The application of fuzzy logic method includes the establishment of fuzzy set (fuzzy output set, fuzzy relation set and fuzzy data input set, etc.); The determination of fuzzy operation rules (the operation between fuzzy quantities and the establishment of fuzzy criteria) which includes the fuzzy relation of input data, the determination of fuzzy output quantity, etc. This paper summarizes the
evolution and development of fuzzy logic method in insulator state evaluation, and the development trend of fuzzy logic method in insulator state evaluation is prospected.

2. Constant weight fuzzy logic method

2.1. Single level fuzzy logic evaluation

2.1.1. Output and input sets. Nie Yixiong [4] from Huazhong University of Science and Technology pointed out that the deterioration of insulators refers to the deterioration of insulator string insulation performance, so he adopted the status parameters reflecting insulator insulation performance under high voltage, such as leakage current, corona current pulse, as the maximum fuzzy characteristic quantity. According to the characteristics of the insulator studied, the fuzzy signals detected online are processed into four grades: normal (NL), common (CM), more serious (MS) and serious (SR), that is, the fuzzy output set Y is

\[ Y = \{NL, CM, MS, SR\} \]

At the same time, in view of the diversity of factors affecting insulator state, Nie Yixiong proposed the main electrical parameters that can be detected to reflect the insulation performance judgment of insulators, Corona current probability \( (F_c) \), leakage current effective value \( (F_l) \), leakage current peak \( (F_p) \) and leakage current pulse frequency \( (F_f) \).

Therefore, the fuzzy input set X is

\[ X = \{F_c, F_l, F_p, F_f\} \]

2.1.2. Fuzzy relation matrix and fuzzy membership function. According to the one-to-one correspondence between output set and input set, the fuzzy relation matrix R can be determined according to the influence of various factors on the output of each line.

\[
\begin{bmatrix}
0.8 & 0.15 & 0.05 & 0 \\
0.3 & 0.5 & 0.15 & 0.05 \\
0.05 & 0.35 & 0.35 & 0.25 \\
0 & 0.3 & 0.35 & 0.35 \\
\end{bmatrix}
\] (3)

Each element in the first line of the Relation matrix represents the importance of various electrical signals relative to the "normal" insulation fault state. Each element in the second line of the Relation matrix represents the importance of various electrical signals relative to the "common" insulation fault state. Each element in the third line of the Relation matrix represents the importance of various electrical signals relative to the "more serious" insulation fault state. Each element in the fourth line of the Relation matrix represents the importance of various electrical signals relative to the "more serious" insulation fault state.

The key point of fuzzy logic method is not only the fuzzy relation matrix, but also the establishment of fuzzy membership function. The determination of fuzzy membership function and fuzzy relation matrix directly affects the reliability of the fuzzy logic method.

(1) The fuzzy transformation function with flat top model is selected to realize the fuzzy processing of corona current.

\[
F_c = \begin{cases} 
1 & \beta \leq 0.95 \\
 f(\beta) & 0.95 \leq \beta \leq 1.3 \\
0 & \beta \geq 1.3 
\end{cases}
\] (4)
Among them,

$$\beta = \frac{\text{the highest affordale voltage value } V}{\text{Maximum standard voltage } V_{N_{\text{max}}}}$$  \hspace{1cm} (5)$$

Considering that the deterioration of insulator increases sharply when $\beta$ value is greater than 1 in practice, the fuzzy normal distribution of $F(\beta)$ is selected as unilateral cut-off.

$$f(\beta) = e^{-2\pi(\frac{\beta-0.95}{1.3-0.95})^2}$$  \hspace{1cm} (6)$$

(2) Leakage current fuzzy processing, due to the change of leakage current range is bigger, its value can be in a few microamps to dozens of milliampere. The greater the current value is, the more serious the insulation deterioration of the insulator is. Therefore, the normalization process of selecting the corrected leakage current value is expressed by fuzzy function in exponential form of the logarithm of leakage current.

$$F_I = \begin{cases} 0 & I_l < b \\ 1 - e^{-a\log_\beta(I_l b)} & I_l \geq b \end{cases}$$  \hspace{1cm} (7)$$

Where $a$ is a constant, representing the convergence degree of the fuzzy function, $b$ is the threshold current, and $I_l$ is the effective value of the leakage current.

(3) Due to the randomness of pulse current peak value, the fuzzy membership function of leakage current peak value adopts discrete random function.

$$F_p = \begin{cases} 0 & I_p < 50mA \\ 0.2 & 50mA \leq I_p < 150mA \\ 0.4 & 150mA \leq I_p < 250mA \\ 0.6 & 250mA \leq I_p < 350mA \\ 0.8 & 350mA \leq I_p < 450mA \\ 1.0 & I_p \geq 450mA \end{cases}$$  \hspace{1cm} (8)$$

Where $I_p$ is the peak leakage current.

(4) Fuzzification of leakage current pulse frequency. For the peak leakage current with different amplitude, different fuzzy values are assigned by calculating the occurrence frequency $n_i$ in a certain period of time, and the final fuzzy membership is determined by fuzzy operation. The fuzzy membership function defined is,

$$F_{f_i} = \begin{cases} \frac{3}{10} \log n_i & 50mA \leq I_p < 150mA \\ \frac{1}{3} \log n_2 & 150mA \leq I_p < 250mA \\ \frac{1}{2} \log n_3 & 250mA \leq I_p < 350mA \\ \log n_4 & 350mA \leq I_p < 450mA \\ 0 & n_5 = 0 \\ 1 & n_5 \geq 1 \end{cases}$$  \hspace{1cm} (9)$$
In the meantime,

\[
F = F_{f1} \cup F_{f2} \cup F_{f3} \cup F_{f4} \cup F_{f5} = \max(F_{f1}, F_{f2}, F_{f3}, F_{f4}, F_{f5})
\]

(10)

2.1.3. Fuzzy operation and decision making. Considering the effect of various factors, the results must be reflected in the output results, so the design adopts the operation rules based on algebraic matrix to fully reflect the influence of various factors on the analysis results. The fuzzy operation is:

\[
Y = R \times X
\]

(11)

That is

\[
y_i = \sum_{j=1}^{n} r_{ij} x_j
\]

(12)

The fuzzy decision is chosen according to the state characteristics of insulator operation: in general, when the output value of a certain insulation operation condition is greater than 0.5, the insulator can be considered to be operating under this insulation condition. For multiple output values greater than 0.5, the insulation state of the insulator is determined according to the principle of SR>MS>CM>NL.

In order to verify the correctness of this detection method, the author verified it through laboratory experiment and field test. The experimental results are shown in Table 1:

| Table 1. The result of insulator state evaluation by single - stage fuzzy logic method. |
|-----------------------------------------------|-------------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Condition                                    | Insulator                                      | 1               | 2\(^a\)          | 3               | 4               | 5\(^b\)          | 6\(^d\)          |
| Filthy conditions\(^c\)                      | 0.05mg/cm\(^2\)                                | 0.2mg/cm\(^2\)  | 0.3mg/cm\(^2\)  | More serious    | More serious    | Clean            |
| Relative humidity/%                         | 70                                             | 100\(^d\)       | 100\(^d\)       | 75              | 75              | 70              |
| Voltage classes/kV                          | 35                                             | 15.6            | 35              | 110             | 110             | 110             |
| Corona probability/%                        | 0                                              | 100\(^d\)       | 100\(^d\)       | 5               | 18              | 0.5             |
| Leakage current/mA                          | 0.1                                            | 3.6             | 12.4            | 0.25            | 1               | 0.2             |
| Current peak/mA                             | <1                                             | <50             | 210             | <1              | <50             | <1              |
| Number of leakage current pulses\(^e\)      | 0/0/0/0/0/0/0                                 | 658/105/0/0/0/0 | 0/0/0/0/0/0     | 0/0/0/0/0/0     | 0/0/0/0/0/0     |
| Experiment environment                      | Library                                        | Library         | Library         | Library         | Library         | Library         |
| Fuzzy operation result\(^f\)                 | 0.95/0.30/0.0                                 | 0.9/0.70/0.3/0.3 | 0.17/0.59/0.70/0.7 | 0.85/0.465/0.166/0.1 | 0.89/0.62/0.27/0.19 | 0.84/0.43/0.09/0.08 |
| Fuzzy detection conclusion                   | Normal                                         | General failure | Serious         | Normal          | General failure | Normal          |
| Reality                                      | Artificial pollution                           | Artificial pollution | Artificial pollution | Normal          | Pollution caused | Normal          |
| Result                                       | Coincide                                      | Coincide        | Coincide        | Coincide        | Coincide        | Coincide        |

2.2. Single level fuzzy logic evaluation

On the basis of the model proposed by Yixiong Nie [5], Li Bo of Sichuan University introduced a multi-level evaluation method, which took into account two factors: the odd-harmonic characteristics of the
leakage current and the pulse current peak value. Through the second-level fuzzy comprehensive evaluation, more intuitive maintenance suggestions can be given, as shown in Fig. 1.

**Figure 1.** Multistage judgment flow chart.

### 2.2.1. First level judgment
The detection amount of insulator (such as peak value, effective value, etc.) is taken as the fuzzy input set $A$, the insulation performance of insulator as the output set $B$, and the fuzzy relational matrix of the first level is $R$,

$$ B = A \cdot R $$

Where $A = (A_{PL}, A_{I}, A_{H}, A_{F}, A_{PP})$, $A_{PL}$ is the peak of the leakage current, $A_{I}$ is the effective value of the leakage current, $A_{H}$ is the odd harmonics of the leakage current, $A_{F}$ is the pulse current frequency, $A_{PP}$ is the peak of the pulse current. $B = (E, S, C, N)$, $E$ means insulation damage is extremely serious, $S$ means insulation damage is serious, $C$ means insulation damage is general, $N$ means insulator insulation condition is normal.

### 2.2.2. Second level judgment
After the first-level evaluation of insulator state, the first-level evaluation results are used as the new input set, the maintenance suggestions are used as the fuzzy output set $C$, and $T$ is the second-level fuzzy relation matrix.

$$ C = B \cdot T $$

In the formula, $C$ is the fuzzy output set of maintenance suggestions, $C = (M, D, W)$, $M$ means immediate maintenance, $D$ means to be repaired, and $W$ means no maintenance.

Compared with single-level evaluation, multi-level fuzzy logic evaluation can directly give maintenance suggestions, and the results are clearer and more practical.

### 3. Comprehensive evaluation of variable weight fuzzy logic

#### 3.1. Basic variable weight method evaluation
Xiong Lan et al. [6] from Chongqing University introduced variable weight theory on the basis of the constant weight fuzzy logic method proposed by Nie Yixiong. The variable weight theory is one of the important modeling principles of factor space theory. The difference between variable weight synthesis and constant weight synthesis lies in that variable weight synthesis not only considers the importance of the basic factors, but also considers the level state of the target value on the decision variable. The roles of these two aspects are in the variable weight.

**3.1.1. Weighting processing**
Considering the complexity of insulator condition evaluation system, the index contains both quantitative data and qualitative judgment, and the index system is hierarchical structure, so the analytic hierarchy process is used to determine the weight coefficient. At the same time,
in order to avoid the impact on the evaluation results when some parameters deviate from the normal value seriously, the fixed weight obtained is corrected by variable weight formula,

$$\omega_i(x_1, x_2, \cdots, x_m) = \omega_i^0 x_i^{\alpha - 1} / \sum_{k=1}^{m} \omega_k^0 x_k^{\alpha - 1}$$  \hspace{1cm} (15)

Where: $x_i$ is the value of the evaluation factor $i$; $m$ is the number of evaluation factors; $\omega_i$ is the weight of the $i$ factor; $\omega_i^0$ is the constant weight of the $i$ factor. In general, when the equilibrium of various factors is not considered much, $\alpha > 0.5$ is taken. When serious defects of some factors cannot be tolerated, $\alpha < 0.5$; When $\alpha = 1$, it equals the constant weight model. In this paper, the index layer of inherent factor and environmental factor is set as $\alpha = 0.2$ and $\alpha = 0.5$ respectively when applying constant weight to calculate variation weight.

3.1.2. Fuzzy operation and decision making. The choice of fuzzy operator is related to the analysis characteristics of the result of the whole fuzzy decision model. After comparing the characteristics of four different fuzzy synthesis operators, the $M(\circ, \oplus)$ model with weighted mean co-type is adopted. This kind of calculation is the boundary sum operation, which considers the influence of both main factors and non-main factors, and is suitable for the evaluation of the comprehensive index of the system. This operator not only considers the influence of all factors on the insulator, but also preserves all the information of a single factor.

The same batch of insulator samples were evaluated by both constant weight and variable weight, and the results were assigned (attention =1, general =2, good =3, very good =4).

The constant weight calculation result is 2.9812. The state level is the attention level, and the result is close to 3. It can be considered that the state is developing from the general level to the attention level, but it has not reached the attention level yet.

The result of variable weight calculation is 3.1602. The state level is attention level, and the result is close to 3. It can be considered that the state is developing from general level to attention level, and there are signs of attention.

If this value is maintained, the insulator needs to be treated, which is more consistent with the actual situation. It can be seen that the variable weight can reflect the insulator's state more objectively than the constant weight.

3.2. Cloud theory

Cloud theory is a mathematical tool to study uncertain problems. Based on the traditional fuzzy theory and probability statistics, it can realize the exchange of qualitative and quantitative, and has the unique advantage of dealing with the fuzziness and randomness of things at the same time.

3.2.1. Evaluation Matrix Modification. Based on the common method of variable weight, Fan Li [7] improved the judging matrix which core is expert system. She set the insulator filthy state comprehensive evaluation level boundaries as a double constraints space $[c_{\min}, c_{\max}]$, giving full consideration to the uncertainty of constraint space boundary value and moderate extension, reusing the interval number and cloud model transformation relationship to calculate the expected value of the $E_x$, entropy $E_n$ and super entropy value $H_e$. Combined with the corresponding index of fuzziness and randomness to realize soften the classification interval. Finally, the normal cloud model of insulator pollution state is obtained. Among them, the expected value $E_x$ is the point value that best represents the fuzzy qualitative concept C on the domain U, which is the distribution centre of the cloud. The superentropy $H_e$ and entropy $E_n$ together determine the fuzziness and randomness of the concept C. Finally, the correlation degree $k$ between the value $x$ and the normal cloud is obtained by calculating the above parameters. The specific formula is as follows:
\[ k = \exp\left( -\frac{x - E_n}{2(E_n^2)} \right) \]  

(16)

\( E_n \) is a normally distributed random number with expected value of \( E_n \) and standard deviation of \( H_r \).

### 3.2.2. Calculation and decision making

By calculated for correlation between evaluation of each index weight and evaluation grade standard normal cloud, it is concluded that comprehensive evaluation matrix \( A \), combined with weight coefficient \( W' \), the comprehensive evaluation results vector \( B = W'A \) can be get. The weighted average method can be used to obtain the evaluation result \( R \).

\[
R = \frac{\sum_{i=1}^{m} b_i f_i}{\sum_{i=1}^{m} b_i}
\]

(17)

Where: \( b_i \) represents the corresponding component of vector \( B \); \( f_i \) represents the score value of different pollution levels. The mean value \( E_r \) and variance \( E_{RN} \) were taken as the final parameters of \( r \). At the same time, confidence \( \theta \) can be introduced,

\[
\theta = \frac{E_{rn}}{E_{rx}}
\]

(18)

The higher \( \theta \) value is, the greater the dispersion of the judgment result expressed by \( E_{RX} \) is, the smaller the situativeness of the judgment result is; otherwise, the greater the situativeness of the judgment result is. Therefore, the comprehensive evaluation model of insulator pollution state based on cloud theory can not only obtain the evaluation results, but also obtain the placement degree information of the evaluation results.

### 4. Conclusion

Compared with the single variable method, the fuzzy logic calculation method is more comprehensive and representative for the evaluation of composite insulator pollution and operating state with fuzziness and randomness. The fuzzy calculation method can not only divide the influence degree of different characteristic quantities, but also evaluate the comprehensive state by integrating different characteristic quantities.

The constant weight fuzzy logic method is the first fuzzy logic method used to evaluate composite insulators. Compared with the single variable evaluation at that time, this method is more comprehensive, and a fuzzy calculation method of characteristic quantity in multiple composite insulator evaluation is proposed.

The multi-level fuzzy evaluation method adopts the model of constant weight fuzzy logic method, but introduces the element of "overhaul" results into the evaluation mechanism, which makes the fuzzy logic method more engineering in the evaluation of composite insulator state.

The variable weight fuzzy logic method is improved on the calculation of constant weight, and the variable weight formula is used to modify the fixed weight, which reduces the subjectivity of the evaluation results and improves the objective credibility of the evaluation results.
The cloud theory improves the fuzzy judgment matrix in the fuzzy logic algorithm. By combining the cloud theory and fuzzy logic calculation, the randomness in the evaluation calculation is improved, so as to improve the accuracy of insulator evaluation results.

Acknowledgments
This work was financially supported by the key technology research and application practice of big data situation awareness on digital urban distribution networks.(Item number: GZHKJXM20180068).

References
[1] Liu Yunpeng, Ji Xinxin, Pei Shaotong, Wang Shenghui. High Voltage Technology, 2018, 44 (10): 3352 - 3358.
[2] Zhao Chuan, Yu Suihua, Chu Jianjie, Li Wenhuai. Improved fuzzy logic based rapid upper limb assessment method (RULA) [J]. Journal of Harbin Institute of Technology, 2018, 50 (07): 87 - 93.
[3] Xiong Weihong, Zhang Hongzhi, Xie Zhicheng, Han Xionghui, Li Zhengtian, Lin Xiangning. Transformer Potential Fault Risk Assessment Method Based on Cloud Theory and Entropy Weight Method [J]. Electric Power Automation Equipment, 2018, 38 (08): 125 - 130+146.
[4] Yixiong Nie, Xianguen Yin, Chun Liu, Yuanfang Wen. Evaluation of On-line Inspection Results for Insulator Strings Using Fuzzy Logic Method [J]. Proceedings of the Csee, 2003 (03): 131 - 136.
[5] Li Bo, Liu Nian, Wang Xiujie. Multi-level Fuzzy Comprehensive Evaluation of On-line Insulation Performance of Insulators in High Voltage Power Networks [J]. Power System Technology, 2007 (15): 75 - 79.
[6] Xiong Lan, Liu Yu, Lin Yinyu, Yao Shuyou, He Wei, Wang Jingang. Application of Fuzzy Variable Weight Method in Comprehensive Evaluation of Insulator State [J]. Journal of Electric Power Systems and Automation, 2010, 22 (01): 96 - 100.
[7] Fan Li, Xia Fei, Su Haoyi, Li Ruqi. Risk assessment of high voltage insulator pollution state based on cloud theory [J]. Power System Protection and Control, 2012, 40 (15): 57 - 62.
[8] Jiao Shangbin, Liu Ding, Zheng Gang, Zhang Qing. Evaluation of pollution degree of high voltage insulator based on fuzzy logic method [J]. Automation of Electric Power Systems, 2005 (07): 84 - 87+107.
[9] Li Heming, Wang Shenghui, Lv Fangcheng, Liu Yunpeng, Chen Lei, Wei Jinxiang. Evaluation of Insulator Contamination Condition Based on Discharge Ultraviolet Imaging Parameters [J]. Transactions of China Electrotechnical Society, 2010, 25 (12): 22 - 29.
[10] Zhou Quan, Wang Shizheng, rui-jin liao, founder, XieHuiLi, RaoJunXing. Transformer Fault Diagnosis Method Based on AdaBoost Optimization Cloud Theory [J]. High Voltage Technology, 2015, 41 (11): 3804 - 3811.