An Alternative Method for GIS Insulation Performance Evaluation

Song Lin Wu¹, Bo Xiao¹, Min Hu²,³, Yong Yao¹, Wei Fu¹ and Haiyan Zhang²

¹State Grid Chongqing Electric Power Company Urban Power Supply Branch, Chongqing, China
²Chongqing University of Science & Technology, China
174661848@qq.com

Abstract. The continuous improvement of system capacity and voltage level is somewhat accompanied by insulation fault as one of the main faults of GIS device. In this paper, an alternative method for identifying the GIS insulation performance based on fuzzy evidence theory is proposed by way of judging the four main features of GIS insulation level. Firstly, the fuzzy statistic test was used to obtain the normalized values of the four feature quantities of GIS insulation level. Four methods were used to calculate their respective expectations and deviations. The membership degree value was determined by the membership function, and the difference between the membership degrees was also considered. The degree of fusion was used to determine the weight of each feature quantity, so that the membership degree of the same kind of feature information fusion was obtained. Finally, the merged membership degree was transformed into the basic trust distribution function. The evidence theory then took the job to realize the pairwise fusion of the trust distribution functions between different feature quantities. The experimental results showed that this alternative way was proven to make effective judgment on the GIS insulation performance.

1. Introduction
The development of computer technology is accompanied by the improvement of artificial intelligence and testing technology. In GIS device, the condition monitoring circuit breaker is oriented by the large-scale expert system based on intelligent theory and neural network. At present, there are some results on the research of equipment state assessment at home and abroad, but it remains difficult to perform the study on the state assessment of GIS. As we all know, the research work on GIS device status assessment is not only of important academic significance and social benefits, but also has shown impressive values in economic and engineering applications. More investments in GIS state assessment is therefore encouraged so as to continuously improve the related technologies, which would then be beneficially promoted in the power system.

GIS device failures can be roughly divided into two categories: discharge faults and mechanical faults. Specifically, major faults include insulation faults, mechanical faults, casing leaks, and secondary loop faults. Looking to the previous investigation and statistics, there are five main reasons that are responsible for the occurrence of GIS insulation faults (as shown in figure 1). Among them, SF6, which is an indispensable insulating gas for GIS device, will decompose under the action of arc, electric spark and corona discharge, resulting in insulation degradation. This situation may be complicated by SF6 gas leakage, increase of water content, decomposition of the gas composition, etc. As a result of the impact
on the insulation strength of GIS device, the probability of insulation accidents accounted for 38.1% of GIS accidents. Obviously, it does make sense to evaluate the insulation state of GIS.

![Figure 1](image.png)

**Figure 1.** Failure Rate on Common Fault Types of GIS Device.

Huang Yucheng et al. in Jiangsu Tianfang Power Technology Co., Ltd. introduced DR detection technology to achieve visual diagnosis of the internal structure of GIS device, being able to effectively diagnosing the internal defects of GIS [1]. Lu Fangcheng et al., who worked in the key laboratory for safety and defense of power transmission and transformation equipment in North China Electric Power University, used ultrasonic sensors to collect waveforms under three discharge models. The collected data were identified by way of BP neural network. The recognition rate was app. 80% [2]. Wang Taoyun et al., from the School of Energy and Electric Engineering, Hohai University, combined the Petri net theory with fuzzy inference rules. With reference to a large number of statistical fault cases, the correctness of the methodology was verified by establishing a diagnostic model to find out the cause of the fault in the process of reverse fuzzy reasoning. Liu Yongye et al. took the feature gas as the input library of the fuzzy Petri net, and established a diagnosis model for GIS insulation fault. This made it possible for the Petri net to analyze the credibility of the GIS defect type [3-4]; Yan Xianglian from China National Electric Power Research Institute tested the decomposition products of SF6 and obtained the decomposition product features of equipment, thereby judging the operating conditions of SF6 equipment in different types [5]. Wang Taoyun, who worked with State Grid Shanghai Electric Power Company Jinshan Power Supply Company, introduced the extension analysis theory and solved the weight problem of each index in GIS state assessment with the aid of entropy method theory, which accurately evaluated the gas chamber status of GIS [6].

2. Membership

Monitoring the GIS evaluation parameter is mainly to check the state of SF6 gas, including (1) SF6 gas detection, (2) resistance parameter, (3) accessory parameter analysis, (4) working environment and other factors parameter analysis, wherein the SF6 gas detection is directed to the trace water content of the SF6 gas; the pressure of the SF6 gas; the density of the SF6 gas; the composition of the SF6 gas. The GIS insulation state is mainly related to the SF6 gas state, so the gas trace water content, the arc extinguishing chamber including other gas chambers, the gas leakage rate and the partial discharge product were used in this work as the four feature quantities for evaluating the GIS insulation performance.

The four feature quantities of GIS insulation performance were determined by means of fuzzy statistical test.

As for these four feature quantities of GIS, the smaller the better, so choose formula (1) as the normalization function.

\[ f(x) = \exp \left( \frac{(x - b)}{b} \right) \]

Where: \( f(x) \) is the membership function argument, \( x \) is the parameter raw data, and \( b \) is the threshold specified in the procedure.

According to the State Grid Corporation's substation testing and management regulations, in the State Grid (Yunjian/3) 829-2017, the standard for SF6 gas testing items stipulates that trace water content in the operation of the compartment with arc decomposition is required not exceed 300μL/L, the
compartment free of arc decomposition shall not exceed 500 μL/L; the gas leakage rate shall not exceed 1%; the partial discharge (PD) product shall not exceed 10 μL/L; thus, the threshold values of all feature quantities are known. A total of 28 experts were invited to fill out the questionnaire to determine the degree of trace water membership in the arc chamber, as shown in table 1.

**Table 1.** State Evaluated by Experts Corresponding to the Trace Water Content of the GIS Arc Extinguishing Chamber.

| Insulation state | Good | Average | Note | Danger |
|------------------|------|---------|------|--------|
| 1                | 70   | 150     | 230  | 265    |
| 2                | 120  | 200     | 220  | 240    |
| ...              |      |         |      |        |
| 28               | 100  | 120     | 160  | 245    |
| Range            | 0-170| 120-224 | 155-268 | 192-300 |

The corresponding normalized values of Table 1 were obtained from Equation 1, and the other gas chamber had the similar trace water content, gas leakage rate and PD products.

The GIS insulation state boundary is not particularly obvious, so the different insulation states of GIS can be described by information entropy. Information entropy describes the degree of chaos in the system. The more chaotic the system is, the higher the entropy is. Different entropies can be described in terms of the order of different aspects. The system information entropy is defined as: Let W be an algebra generated by the measurable set class v and a Lebes space with p measure, p(W)=1, and W can be expressed in its finite partition C = \{Ci \} as the form of mutually incompatible collections, i.e.:

\[ W = \bigcup_{i=1}^{n} C_i \bigcap C_i \cap C_j = \emptyset, \forall i \neq j \]  \hspace{1cm} (2)

Then the information entropy for this partition C:

\[ H(C) = - \sum_{i=1}^{n} p(C_i) \log(C_i) \] \hspace{1cm} (3)

In this work, four entropy features including wavelet energy spectrum entropy, power spectral entropy, singular spectral entropy and wavelet spatial state feature entropy were used to describe the GIS insulation state. The same entropy feature of GIS various insulation cases also obeys Gaussian distribution. Hence, the membership function was chosen as Gaussian type, i.e.

\[ \mu(x) = \exp \left( - \frac{(x-a)^2}{b^2} \right) \] \hspace{1cm} (4)

Where, \( a, b \) are the mathematical expectation and the mean square error, so that the membership function matrix is a goal within reach. The following table 2-5 present the corresponding a and b values among various entropy values of the GIS feature quantity.

**Table 2.** Mathematical Expectation and Mean Square Error of Wavelet Energy Spectral Entropy in Different Cases.

| Feature quantity                      | Good     | Average  | Note     | Danger |
|---------------------------------------|----------|----------|----------|--------|
| Trace water content in arc chamber    | a        | 0.8447   | 0.8453   | 0.8447 | 0.8450 |
|                                       | b        | 0.0009   | 0.0004   | 0.0006 | 0.0002 |
| Trace water content in other air chambers | a        | 0.8446   | 0.8449   | 0.8452 | 0.8449 |
|                                       | b        | 0.0005   | 0.0004   | 0.0002 | 0.0003 |
| Gas leakage rate                      | a        | 0.8315   | 0.8446   | 0.8437 | 0.8446 |
|                                       | b        | 0.0120   | 0.0039   | 0.0029 | 0.0004 |
| PD product                            | a        | 0.8451   | 0.8452   | 0.8450 | 0.8451 |
|                                       | b        | 0.0001   | 0.0002   | 0.0003 | 0.0001 |
| Feature quantity                   | Good   | Average | Note   | Danger |
|-----------------------------------|--------|---------|--------|--------|
| Trace water content in arc chamber| 0.4247 | 0.4213  | 0.4332 | 0.4217 |
|                                  | 0.0572 | 0.0520  | 0.0408 | 0.0024 |
| Trace water content in other air chamber | 0.3823 | 0.4194  | 0.4235 | 0.4395 |
|                                  | 0.0296 | 0.0059  | 0.0318 | 0.0014 |
| Gas leakage rate                 | 0.3696 | 0.3894  | 0.3958 | 0.4139 |
|                                  | 0.0358 | 0.0221  | 0.0830 | 0.0079 |
| PD product                       | 0.4272 | 0.4167  | 0.4373 | 0.4289 |
|                                  | 0.0100 | 0.0281  | 0.0096 | 0.0092 |

| Feature quantity                   | Good   | Average | Note   | Danger |
|-----------------------------------|--------|---------|--------|--------|
| Trace water content in arc chamber | 0.1140 | 0.1038  | 0.0991 | 0.0869 |
|                                  | 0.0022 | 0.0001  | 0.0205 | 0.0311 |
| Trace water content in other air chamber | 0.1089 | 0.0755  | 0.0705 | 0.0621 |
|                                  | 0.0152 | 0.0131  | 0.0352 | 0.0052 |
| Gas leakage rate                 | 0.2443 | 0.2092  | 0.1690 | 0.1204 |
|                                  | 0.0433 | 0.0020  | 0.0085 | 0.0368 |
| PD product                       | 0.0519 | 0.1136  | 0.0507 | 0.0555 |
|                                  | 0.0163 | 0.0060  | 0.0054 | 0.0085 |

| Feature quantity                   | Good   | Average | Note   | Danger |
|-----------------------------------|--------|---------|--------|--------|
| Trace water content in arc chamber | 0.0939 | 0.0711  | 0.0578 | 0.1033 |
|                                  | 0.0743 | 0.0536  | 0.0177 | 0.0415 |
| Trace water content in other air chamber | 0.0661 | 0.0504  | 0.0503 | 0.0519 |
|                                  | 0.0334 | 0.0157  | 0.0240 | 0.0064 |
| Gas leakage rate                 | 0.2242 | 0.1964  | 0.0999 | 0.0718 |
|                                  | 0.0472 | 0.0573  | 0.0543 | 0.0793 |
| PD product                       | 0.0559 | 0.1264  | 0.0600 | 0.0430 |
|                                  | 0.0494 | 0.0216  | 0.0181 | 0.0267 |

3. Discrimination of insulation state
After extracting four kinds of entropy features from the sample data of four feature quantities, the parameters of the membership function were determined to perform data fusion of different feature quantities. For example, extract the sample value of the trace water content of the arc extinguishing chamber for a certain period of time, and obtain the wavelet energy spectrum values corresponding to the sample, power spectrum, singular spectrum, and wavelet spatial spectrum. They were substituted into the formula (4) to get the values of insulation state memberships:

\[
\mu = \begin{bmatrix}
0.9960 \\
0.5283 \\
0.9863 \\
0.7108 \\
0.7175 \\
0.5744 \\
0.8122 \\
0.3950 \\
0.2522 \\
0.6987 \\
0.1624 \\
0.3109 \\
0.0868 \\
0.5650
\end{bmatrix}
\]

The degree of mutual support between the degrees of entropy was used to measure the degree of mutual support between the entropy values. The definition:
the greater $d_{ij}$, the lower the support between the two different entropy values, and the smaller the value, the higher the support. Therefore, the fusion function of different algorithms with the same feature quantity is defined:

$$r_{ij} = 1 - \frac{\sum_{k=1}^{K}(\mu_{ik}(x_i) - \mu_{jk}(x_j))^2}{\theta} \quad (6)$$

Get the maturity matrix:

$$r = \begin{bmatrix} 1.0000 & 0.7900 & 0.2354 & 0.5732 \\ 0.7900 & 1.0000 & 0.0026 & 0.0674 \\ 0.2354 & 0.0026 & 1.0000 & 0.4066 \\ 0.5732 & 0.0674 & 0.4066 & 1.0000 \end{bmatrix}$$

To ensure the maximum credibility, when determining the fusion degree of the i-th entropy value with other entropy values, the smallest of the other entropy values and the i-th entropy value may be obtained, that is,

$$s = [0.2354 \quad 0.0026 \quad 0.0026 \quad 0.0674]^T$$

Let the weight coefficient of the i-th feature quantity be determined by $s_i$ in the proportion of the total phase fusion, i.e.:

$$q_i = \frac{s_i}{\sum_{i=1}^{N}s_i} \quad (7)$$

The resulting weight coefficient vector:

$$q = [0.7641 \quad 0.0085 \quad 0.0085 \quad 0.2188]^T$$

After fusion, the degree of membership of the arc extinguishing chamber trace water content corresponding to each insulation state:

$$\beta = [0.7615 \quad 0.0045 \quad 0.0084 \quad 0.1555]$$

From the above, the fusion of the insulation performance evaluation of a certain feature quantity is completed, and the result of discriminating the insulation state of the other three feature quantities can be obtained by analogy. Then it's the turn of the evidence theory to do its part on insulation discrimination. The evidence theory works well with uncertain information, and it has been widely used in fault diagnosis detection, multi-objective recognition, information fusion, and uncertainty multi-attribute decision-making. Specifically, the acquisition of the mass function is the key to the application of evidence theory [7].Han Feng [8] et al. introduced a method of credibility distance; Xu Yanke et al. [12] explored the methods for fuzzy sets; Xu Jiali [9] counted on the information amount of evidence to determine the credibility, thus obtaining the mass function. All have achieved certain results that matter.

Since the GIS insulation performance extracted the M-class features, the corresponding basic trust distribution functions were $m_1, m_2, \ldots, m_4$, and each type of feature corresponded to the same K-class insulation state. In this way, the focal point of the basic trust distribution function was the same.

The value of the basic trust assignment function was transformed from the merged membership value. To satisfy $\sum m(A_i) = 1$, it was determined by the following formula:

$$m_i(A_i) = \frac{\beta_i^{(r)}}{\sum_{i=1}^{K}\beta_i^{(r)}} \quad (8)$$

The converted basic trust assignment function value from above:

$$m_1 = [0.8189 \quad 0.0049 \quad 0.0091 \quad 0.1672]$$

Similarly, the basic trust assignment function values of other features were obtained:

$$m_2 = [0.2412 \quad 0.3015 \quad 0.1573 \quad 0.3000]$$

$$m_3 = [0.2691 \quad 0.0629 \quad 0.6426 \quad 0.0254]$$

$$m_4 = [0.2463 \quad 0.2275 \quad 0.3808 \quad 0.1454]$$

In the presence of the many types of features, the evidence theory worked to combine the pairwise features, that is, the pairwise fusion of $m_1, m_2, m_3,$ and $m_4$:

$$m = [0.9615 \quad 0.0016 \quad 0.0257 \quad 0.0136]$$
Judging from this, the GIS insulation type was good, which was consistent with the actual situation. The same method was applicable for identification of other sample data. They are not listed here in details.

### 4. Conclusion

Four feature quantities of continuous sampling GIS were analyzed for judgment with the corresponding evaluation models obtained with the aid of a large number of test data. The GIS parameters to be tested were targeted to determine the insulation capability in reference to the evaluation model. In this paper, the proposed recognition method based on fuzzy evidence theory performed well on the relationship among various features, aiming to avoid the subjectivity in the fusion process. Experiments showed the effectiveness of the proposed method in merging the GIS features in various situations.

### Acknowledgments

This work was supported by State Grid Chongqing Electric Power Company Urban Power Supply (Project no. SGTYHT/18-JS-206, Contract no. SGCQSQ00BDJS1900987). The project name is State Grid Chongqing Electric Power Company Urban Power Supply 2019 Research Service of Health Assessment Model for GIS.

### References

[1] Xuancheng H, Tao H and Quanyi H. 2018 J Detection of internal insulation defects of GIS devices by DR technology. Thermal Power Generation. 47 140-146.

[2] Fangcheng L and Bo Z. 2014 J Identification of GIS Insulation Defect Type Based on Ultrasonic Method. Electrical Measurement and Instrumentation. 51 22-26.

[3] Taoyun W, Hongzhong M, Yangliu C, Ning J, Kai L and Honghua X. 2016 J Fault Diagnosis and Reliability Analysis of GIS Based on Fuzzy Petri Nets. New Technology of Electrical Engineering and Energy. 35 (5) 67-73.

[4] Yongye L, Hongzhong M, Yong L and Honghua X. 2018 J GIS Fault Diagnosis Method Based on Gas Detection and Fuzzy Petri Net. Journal of Electric Power Science and Technology. 33 141-146.

[5] Xianglian Y, Gao S and Chengyu W. 2014 J Gas Insulated Switchgear State Monitoring Based on SF6 Decomposition Products Detection. Electric Power Automation Equipment. 34 83-88, 95.

[6] Taoyun W, Hongzhong M and Yangliu C. 2016 J Condition Evaluation of Gas Insulated Switchgear Based on Extension Analysis and Entropy Method. Power System Protection and Control. 44 115-120.

[7] Jouesselme A L, Chunsheng L and Grenier D. 2006 J Measuring Ambiguity in the Evidence Theory[J]. IEEE Transactions on Systems, Man and Cybernetics, Part A. 36 890-903.

[8] Feng H, Wanhai Y and Xiaoguang Y. 2010 J Evidence Theory Information Fusion Method Based on Fuzzy Set. Control and Decision. 25 449-452.

[9] Yanke X, Xiaogeng L and Xiaohong J. 2012 J Information Fusion Based on Fuzzy Evidence Theory and its Application in Target Recognition. JOURNAL OF HARBIN INSTITUTE OF TECHNOLOGY. 44 107-111.