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Application of Fuzzy Model Identification on Insulation Detection of Insulator Strings

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Abstract: There are many uncertain factors to influence the results in the fault diagnosis of power equipment. Fuzzy set theory is an effective tool to solve these problems. By means of the fuzzy relation operation, the relevant results can be obtained from the input data or the output data. Since the fuzzy relation matrix is usually depending on experts' experience, it is deeply affected by the man-made factors. Fuzzy model identification is an approach to determine fuzzy model, which is based on the known input-output data. It can decrease the man-made influence and increase the correctness of fault diagnosis. This paper introduced the realizing process of the fuzzy logical reasoning method about the insulation detection of insulator strings, especially about the establishment of the fuzzy relation matrix. The experiments verified the correctness of this method by simulating work conditions of insulator strings on an 110kV transmission line.

Key words: Insulation detection, fuzzy model identification, insulators, diagnosis method

INTRODUCTION

When insulating property of one of the insulator strings in power transmission line degrade or faulty insulators appear, some unusual phenomena, such as the increasing of leakage current, the rising of surface temperature and the origination or change of corona current pulses etc. will happen. Various kinds of schemes have been designed to solve the on-line detection problem of faulty insulator strings[1-5]. But no method can be used to solve this problem perfectly in practice up till now.

Among various attempts, although the corona current method is a recently developed and more effective on-line detecting method, there are many factors that influence the corona current in practice. New data processing methods are needed to utilize the measured data reasonably and effectively.

The insulation property of an electric apparatus is a gradual changing process and has strong fuzzy characteristic. Fuzzy logical method is a better means to deal with this problem. In the research of the on-line detection of transmission line insulator strings, the authors attempt to use the fuzzy logical reasoning method to process the obtained data. In this paper, the establishing course of the fuzzy input and output matrix are introduced first; and then the questing principle of the fuzzy relation matrix are described and the fuzzy relation matrix are obtained then; finally, the verifying experiment results are presented.

INPUT MATRIX AND OUTPUT MATRIX

As we known, the basic condition of fuzzy logical reasoning method is the establishment of the input variable matrix, the fuzzy relation matrix and the output variable matrix.

Herein, to reflect the insulators' insulation status more accurate, the insulation statuses are divided into four degree: Normal, light, middle and serious i.e., the output matrix of the fuzzy operation is defined as $Y \{N,L,MS\}^T$.

In the resolution of fuzzy relation matrix, the values of output matrix are determined by the known experimental parameters of the insulator strings.

The parameters include the deteriorating degree and the contaminating degree of the tested insulators.

In order to detecting the insulation status of the insulator string, the probability of the corona current, the root-mean-square value, the peak value and the pulse frequency of the leakage current are chosen as the input variables in the data processing design.

And the input matrix of the fuzzy operation is defined as:

$$X = \{F_C\text{£¬}F_R\text{£¬}F_P\text{£¬}F_F\}^T$$

According to authors' previous researching results, the statistical characters of the corona pulses under different voltages in different environmental conditions can be described as follows[6]:

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a. The probability distribution function is:

$$p(V) = \int_{-\infty}^{V} f(V)dt \qquad (1)$$

where $f(V)$ = probability density function;
V = applied voltage.

b. Probability density function $f(V)$ heavily depends on the environmental factors and it conforms to the Gaussian distribution:

$$f(V) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(V-V_C)^2}{2\sigma^2}} \qquad (2)$$

where V_C = 50% corona probability voltage;
ó = standard deviation.

c. The fifty percent corona probability voltage V_C can be described as:

$$V_C = K\{e^{-0.1w}u(h) - 0.5w^{0.2}\sin^3[5\pi(h-0.7)]\cdot u(h-0.7 \\ +0.5w^{0.2}[\sin^3(5\pi(h-0.7)) - e^{h-0.8}]\cdot u(h-0.8)\} \qquad (3)$$

where h = relative humidity;
w = ESDD (mg/cm^2);
$u(h\text{-}x)$ = unit step function;

K = corona voltage coefficient (kV), it is an empirical parameter depending on the size and the manufacturer and conforms to the Gaussian distribution. For example, K is about 22.2kV for XP-7 insulator, which is the sample of the experiments.

In the application of fuzzy set theory to the modeling, it is necessary to convert non-fuzzy data into fuzzy ones. Such a conversion process is known as fuzzification. Herein, we defined the fuzzified probability of the corona current as:

$$F_C = \begin{cases} 1 & \beta \le a_1 \\ f(\beta) & a_1 < \beta \le a_2 \\ 0 & \beta < a_2 \end{cases} \qquad (4)$$

Where

$$f(\beta) = e^{-2\pi(\frac{\beta - a_1}{a_2 - a_1})^2} \qquad a_1 \le \beta \le a_2 \qquad (5)$$

Here, a_1 and a_2 are two constants and be set as 0.95 and 1.3 respective referring to reference[7].

Leakage current is another important parameter in the insulation detection of the transmission line insulator strings. In the design, the leakage current is measured and divided into three parts. Their fuzzification processes are described as follows:

THE RMS VALUE OF THE LEAKAGE CURRENT

Usually, the varying range of the RMS value of the leakage current is from tens microamperes to tens millimeters. And the greater the RMS value of the leakage current, it means that the insulation deteriorating status is more serious.

A large number of experiments show that the RMS value is influenced by humidity very much[8] and its fuzzified function can be defined as:

$$F_1 = \begin{cases} 0 & I_1 \le b \\ 1 - e^{-a\lg(\frac{kI_1}{b})} & I_1 \le b \end{cases} \qquad (6)$$

Where á is a constant and it determined the convergent rate. In the deduction of relation matrix, á is chosen as 1; b is the value of the threshold current, it depends on the type of the tested insulator. For example, b=0.1mA for XP-7 insulator.

THE PEAK VALUE OF THE LEAKAGE CURRENT

The definition of the membership degree function of the peak value of the leakage current is different from the above. According to the results of the experiments and the relative report abroad[9-10], its membership degree function is defined as the discrete function.

$$F_p = \begin{cases} 0.0 & I_p < 50mA \\ 0.2 & 50mA \le I_p < 150mA \\ 0.4 & 150mA \le I_p < 250mA \\ 0.6 & 250mA \le I_p < 350mA \\ 0.8 & 350mA \le I_p < 450mA \\ 1.0 & I_p < 450mA \end{cases} \qquad (7)$$

THE FREQUENCY OF THE LEAKAGE CURRENT PULSE

Ordinarily, the value of the leakage current pulse less than 50 m A can hardly reflect the insulation status about the insulator strings because of its randomness in occurrence. And just the appearance of the pulses above 50mA could really predicate the change of the insulation status. The fuzzified membership degree function of the frequency of the leakage current pulse is defined as:

$$F_{f1} = \frac{3}{10}\lg n_1 \qquad 50\text{mA} \le I_p < 150\text{mA} \tag{8}$$

$$F_{f2} = \frac{1}{3}\lg n_2 \qquad 150\text{mA} \le I_p < 250\text{mA} \tag{9}$$

$$F_{f3} = \frac{1}{2}\lg n_3 \qquad 250\text{mA} \le I_p < 350\text{mA} \tag{10}$$

$$F_{f4} = \lg n_4 \qquad 350\text{mA} \le I_p < 450\text{mA} \tag{11}$$

$$F_{f5} = \begin{cases} 0 & (n_5 = 0) \\ 1 & (n_5 \ge 1) \end{cases} \qquad I_p \ge 450\text{mA} \tag{12}$$

$$\begin{aligned} F_f &= F_{f1} \cup F_{f2} \cup F_{f3} \cup F_{f4} \cup F_{f5} \\ &= \max(F_{f1}, F_{f2}, F_{f3}, F_{f4}, F_{f5}) \end{aligned} \tag{13}$$

RELATION MATRIX

Ordinarily, the fuzzy operation is done in terms of the max-min relation operation rule, i.e.

$$y_i = \max\left[\min(r_{i1}, x_1), \cdots, \min(r_{im}, x_m)\right] \tag{14}$$

And the fuzzy logical reasoning operation is realized according to the fuzzy relation equation:

$$R \cdot X = Y \tag{15}$$

where R is the fuzzy relation matrix.

But in the insulation diagnosis of insulator strings, as the judgment of the insulation status depends on the comprehensive evaluation of all input parameters, the algebraic operation rule is adopted in the practical fuzzy reasoning operation here.

Least square method is the most common used method in identification technology. In the formation of the fuzzy relation matrix, this tool is also adopted.

Assume $X_{(k)}$, $Y_{(k)}$ are the known input and output parameters, R are the identifying matrix, $\text{å}_{(k)}=[e_{(1)}, e_{(2)}, \ldots, e_{(k)}]^T$ are the difference between the standard output and the calculated output, then:

$$X_{(k)} \cdot R = Y_{(k)} + \varepsilon_{(k)} \tag{16}$$

After a series of mathematical transformation, the square of the difference can be expressed as follows:

$$\begin{aligned} j &= \sum_{i=1}^{k} e^2(i) = \varepsilon^T_{(k)} \cdot \varepsilon_{(k)} \\ &= \left[X^T X R - X^T Y\right]^T (X^T X)\left[X^T X R - X^T Y\right] \\ &+ \left[Y^T Y - Y^T X (X^T X)^{-1} X^T Y\right] \end{aligned} \tag{17}$$

As the second item in the expression (17) is a constant item and independent with the parameter estimation. For obtaining the minimal value of J, there must be $X^T X R = X^T Y$, i.e.:

$$R = (X^T X)^{-1} X^T Y \tag{18}$$

The solution of equation (18) will be exclusive if the matrix $X^T X$ is in full order.

Based on the above calculation process, the relation matrix can be obtained according to the fuzzified known data of the input and output.

12 sets of data are sampled to form the input matrix and the output matrix from a large number of experiment results. They are:

$$X = \begin{bmatrix} 1 & 1 & 0.95 & 0.9 & 0.86 & 0.75 & 0.65 & 0.5 & 0.37 & 0.15 & 0 & 0 \\ 0 & 0.1 & 0.1 & 0.25 & 0.23 & 0.3 & 0.35 & 0.52 & 0.68 & 0.75 & 0.87 & 0.95 \\ 0 & 0 & 0 & 0 & 0.2 & 0.2 & 0.2 & 0.4 & 0.6 & 0.6 & 0.8 & 1 \\ 0 & 0 & 0 & 0 & 0.09 & 0.15 & 0.3 & 0.3 & 0.35 & 0.4 & 0.78 & 1 \end{bmatrix}$$

$$Y = \begin{bmatrix} 0.8 & 0.8 & 0.7 & 0.5 & 0.3 & 0.3 & 0.2 & 0.1 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.2 & 0.3 & 0.4 & 0.6 & 0.8 & 0.6 & 0.5 & 0.3 & 0.2 & 0.1 & 0.0 & 0.0 \\ 0 & 0 & 0.1 & 0.2 & 0.3 & 0.4 & 0.5 & 0.7 & 0.8 & 0.6 & 0.5 & 0.3 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.1 & 0.1 & 0.3 & 0.5 & 0.7 & 0.8 \end{bmatrix}$$

Then, the final result of the relation matrix can be deduced based on some practical modification:

$$R = \begin{pmatrix} 0.82 & 0.14 & 0.07 & 0.02 \\ 0.31 & 0.52 & 0.16 & 0.06 \\ 0.08 & 0.28 & 0.45 & 0.20 \\ 0.03 & 0.20 & 0.35 & 0.43 \end{pmatrix} \tag{19}$$

The fuzzy decision will be done in conformity to the priority principle: if two or more values of the fuzzy operation output are bigger than 0.5, the estimation of the insulation status should comply with the level sequence S>M>L>N to determine the insulation degree of the tested insulator strings and to take the corresponding protection measures. For example, if one of the results of the fuzzy operation is [0.7 0.6 0.3 0.1], then the conclusion of the fuzzy reasoning is that the insulation status is in light situation. Every value of the output of fuzzy operation figures the probability and the severity of the corresponding insulation status class, i.e. the bigger the value of the fuzzy operation result, the more severe and more probable the corresponding insulation status class is.

EXPERIMENT VERIFICATION

For verifying the correctness of this diagnosis method, some experiments are done in laboratory and the

Table 1: The verifying test result with fuzzy logic diagnosis method

	1	2	3	4
Place	Lab	Lab	Field	Field
Contamination	0.05 mg/cm^2	0.3 mg/cm^2	Moreserious	Moreserious
R. H.	70%	100%	75%	75%
Voltage	35kV	35kV	110kV	110kV
P(V)	0%	100%	5%	18%
IL(mA)	0.1	12.4	0.25	1
Number Of pulses	0/0/0/0/0	658/105/0/0/0	0/0/0/0/0	0/0/0/0/0
Fuzzy result	0.85/0.30/0.05/0	0.17/0.59/0.70/0.70	0.85/0.47/0.17/0.1	0.89/0.62/0.27/0.19
Reasoning	Normal	Serious	Normal	Light
Practice	Man-madeContamination	Man-madeContamination	Normal	Light
Conclusion	Right	Right	Right	Right

field. Table 1 shows some of the results. It can be noticed that the experiment results are coincident with the known practice.

CONCLUSION

As the deteriorating of the insulator running on the high voltage transmission line is a fuzzy process and the relation between the measured electric parameters about the insulator with the degree of the deterioration is ambiguous, it is a difficult thing to judge the insulation status of the insulator strings. By chosen the probability of the corona current, the root-mean-square value and the peak value and the pulse frequency of the leakage current as the fuzzy operating input variables and utilizing the identification method to build the fuzzy relation matrix, it has been proved that using the fuzzy reasoning method to estimate the insulation status of the on-line insulator strings is a practical approach. The results of the laboratory and the field tests verified the correctness of this approach and the validity of the identification method to build the fuzzy relation matrix.

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