Study of Influence of Environmental Factor on Capacitive Equipment On-line Monitoring Based on the Grey Relational Analysis

Wang Ning, Xing Lin*, Ren Yu, Wu Peng
State Grid Hebei Economic Research Institute, Shijiazhuang, Hebei, 050000, China
*Corresponding author’s e-mail: bsbbwn@163.com

Abstract. Dielectric loss factor tanδ detected by capacitive equipment online monitoring system will be affected by environmental fluctuations, thereby affecting the failure prediction of the equipment and probably causing false positives or false negatives. This paper has established a grey correlation model that detects the influences that major environmental factors (temperature, humidity, contamination) have on online tanδ monitoring value for capacitive equipment. The actual onsite online monitoring data were employed to obtain the gray correlation degree between various environmental parameters and tanδ for capacitive equipment. The results indicate that there is a strong correlation between tanδ and environmental factors, and each effect weight will show seasonal differences with changing environmental conditions. Further, it has discovered that the ambient relative humidity of 60% with ambient temperature is the critical value that influences weight change, which provides a reference for the insulation diagnostics of subsequent capacitive equipment.

1. Introduction
Online monitoring and fault diagnosis of capacitive equipment insulation is the premise and basis for realizing its state maintenance. With the implementation of state maintenance, many areas have installed online monitoring systems for capacitive devices to monitor equipment insulation levels in real time and achieved certain results. Tanδ is the main test item and diagnostic basis for capacitive equipment. Since tanδ monitoring is a high-voltage, micro-current, small-angle precision measurement, the monitoring process is susceptible to environmental factors such as ambient temperature, atmospheric relative humidity, causing large fluctuations in the tanδ monitoring value[1-2]. In actual engineering applications, its accuracy and stability are not high, and often false positives and false negatives occur[3-4].

Literature [6] uses the trend comparison method based on relative comparison to extract the evaluation of fluctuations about on-line monitoring tanδ trend, but ignores the relationship between environmental factors such as temperature and humidity and insulation parameters, and loses a lot of valuable information. In [7], the least squares support vector machine and genetic algorithm are used to correct the tanδ of the capacitive device in the presence of environmental interference factors, which restores the true tan δ of the device to some extent. However, the training model needs to perform a large number of routine tests on a single capacitive device under different environmental conditions in the field to obtain training samples, which is contrary to the actual operation and maintenance situation and does not have engineering practical value.
It can be seen that the current tanδ online monitoring technology has not yet matured, lacking the necessary fault diagnosis and analysis functions, and is still in the data processing stage. The diagnosis of the insulation level is simply judged from the threshold comparison of individual data. Therefore, the influence weight of environmental factors on tanδ online monitoring results should be deeply analyzed, which provides a reference for the development of online monitoring data processing and insulation diagnostic criteria.

2. Experimental analysis of the influence of environmental factors on capacitive equipment

2.1 Test sample selection and test device

A high-voltage tanδ measurement platform for capacitive devices was built under laboratory conditions. The test objects were three different types of 110kV capacitive devices: TYC2110/-0.007H 110kV Capacitor Voltage Transformer (CVT), LB-110 110kV current transformer (TA), CRW-110/1250 110kV Capacitive Wall Bushing. The dielectric loss measuring device is QS37 high-precision high-voltage bridge; the silicone rubber heating belt is used to change the temperature of the sample, and the infrared camera and the infrared temperature gun are used for temperature measurement; the environmental humidity simulation device is a sprayer, using a high-precision humidity sensor. The pollution simulation refers to the relevant provisions in the "Artificial Pollution Test of High Voltage Insulators for AC Systems" (GB/T 4585-2004).

Literature [2] analyzed the influence of single environmental factors on tanδ of capacitive devices, and made in-depth and meticulous research from the mechanism, summed up the following rules: Due to the different structure of the end screen, when the relative humidity of the atmosphere changes, the tanδ of the TA and the casing decreases with the increase of the humidity, and even the negative dielectric loss occurs. The tanδ of the CVT increases with the increase of the humidity; the tanδ of the casing is sensitive to the temperature change. The tanδ of CVT and TA does not change with temperature; the mechanism of contamination and the trend of tanδ change are the same as humidity. However, when a variety of environmental factors are superimposed, how the tanδ of the capacitive device changes, there are few related research reports.

2.2 The common influence of temperature and humidity

Use silicone rubber heating belt to heat the three kinds of capacitive equipment (TA, CVT, wall bushing), and use the sprayer to change the ambient humidity to simulate the humidity change, and control the sample temperature between 20°C and 65°C. The device tanδ was measured at 5°C. Plot the trend of tanδ change under the action of temperature and humidity, as shown in Figure 2.1-2.3.

It can be seen from Fig. 2.1-2.3 that for different types of capacitive devices, the influence of temperature and humidity on tanδ measurement is different: the tanδ value of the wall bushing increases with the increase of temperature, and the tanδ(%) at 25°C and 70% RH is 1.175, tanδ(%) at 65°C and 100% RH is 5.148, tanδ(%) maximum growth amplitude of 4%; tanδ of TA increases slightly with increasing temperature, tanδ(%) maximum growth amplitude of 0.4%; The tanδ of CVT increases first and then decreases with increasing temperature, but the maximum growth amplitude is only 0.006%. It can be considered that tanδ does not change with temperature.

![Figure 2.1 Tanδ variation curve of casing when temperature and humidity work together](image)
Figure 2.2  Tan δ curve of TA when temperature and humidity work together

Figure 2.3  Tanδ curve of CVT when temperature and humidity work together

At the same time, observing the change trend of tanδ when the humidity and temperature are changed separately, it can be found that the influence of humidity on tanδ is higher than that of temperature.

2.3 The common influence of temperature and pollution

Since capacitive devices are subject to outdoor pollution all year round, it is necessary to consider the surface contamination of capacitive devices when considering the influence of temperature on the tanδ measurement of capacitive devices.

The surface of the porcelain sleeve of the three test articles was sprayed with a stain solution, and after standing and drying, the silicone rubber heating belt was wound around the surface of the porcelain sleeve of the apparatus for heating, and the tanδ value was measured at a running voltage. The tanδ value of the recording device tends to change with temperature in both clean and dirty states. Figure 2.4-2.6 shows the tanδ value curve of the sample under different temperature contamination.

It can be seen from Fig. 2.4-2.6 that when the surface of the porcelain sleeve of the capacitive device is dirty, the tan δ measurement value at different temperatures is higher than the tan δ value under the clean state of the device surface. It can be seen that the contamination of the outer surface of the equipment in the case of drying of the fouling layer still has a certain influence on the tan δ value of the capacitive device, wherein the maximum growth amplitude of TA tan δ is 0.1%, and the maximum growth amplitude of CVT tan δ is 0.03%. The maximum growth rate of the tanδ of the casing is 0.04%. Compared with other factors affecting the deviation value, it can be seen that the fouling layer has less influence on the tanδ of the capacitive device in the dry state.

Figure 2.4  Curve of tan δ with temperature under CVT surface dirty
2.4 The common influence of humidity and pollution

Three different contamination conditions were chosen to simulate humidity changes, namely: wet, semi-wet, and dry. The initial measurement voltage was 5 kV, increased voltage step by step, and measured tan δ value every 5 kV. The tanδ curve of CVT pollution and humidity is shown in Figure 2.7.

![Figure 2.6 Curve of tan δ with temperature under the contamination of the wall bushing](image)

![Figure 2.7 Tan δ curve at different humidity levels under CVT surface contamination](image)

It can be seen from Fig. 2.7 that the tanδ measurement value of CVT under temperature and humidity is more obvious than that of single factor, and the maximum growth rate of tanδ reaches 1.109%. The closer to the operating voltage, the closer the measured value of tanδ is to the true value, but there is still a deviation of the amplitude measurement of 0.05%-0.45%. If the deviation of tanδ is too large, the measured value of tanδ exceeds the attention value specified in the “Operational Regulations for Online Condition Monitoring and Fault Diagnosis System of Substation Equipment” in Fujian Province, which may cause misjudgment and miss judgment of online monitoring system. Therefore, the tanδ measurement must be corrected in rainy weather.

3. Gray correlation analysis principle

3.1 Basic description of grey relational analysis

Grey relational analysis is a new method to study uncertainties such as less data and poor information. It extracts core information and mines known information to realize effective monitoring and revealing of system operating behavior and its evolution law by using known information[9-10]. The basic idea is to judge the close relationship of each sequence by analyzing the degree of approximation of the curve geometry between sequences. The closer the shape of the sequence curve is, the greater its
relevance, and vice versa. To determine the extent to which each component of the indicator sequence acts on the reference sequence\(^{[11-12]}\).

### 3.2 Calculation methods and steps

1) Determine the value of the evaluation index, determine the purpose of the evaluation, and collect the evaluation data.

2) Determine the reference sequence. The reference sequence is selected as the optimal value or the worst value of each indicator, and other ideal comparison standard reference values may be selected according to the purpose of the evaluation.

3) Using the associative operator to dimensionless the index series. Common methods include the mean image method and the initial value image method\(^{[13]}\).

4) Calculate the absolute difference between the indicator sequence and the reference sequence.

\[
\Delta_i(t) = |x_0(t) - x_i(t)|, t = 1, 2, \ldots, n, i = 1, 2, \ldots, m \quad (3-1)
\]

Where \(x_0(t)\) is the reference sequence, \(x_i(t)\) is the index sequence, and \(\Delta_i(t)\) is the absolute difference.

5) \(mm = \min_i \min_t |x_0(t) - x_i(t)|\) and \(MM = \max_i \max_t |x_0(t) - x_i(t)|\) \quad (3-2)

Where \(mm\) is the minimum difference of two levels; \(MM\) is the maximum difference of two levels. Calculate the correlation coefficient. The correlation coefficients of the comparison sequence and the reference sequence are calculated separately. Which is:

\[
r(x_0(t), x_i(t)) = \frac{mm + \rho \cdot MM}{\Delta_i + \rho \cdot MM}, t = 1, 2, \ldots, n \quad (3-3)
\]

Among them, \(r(x_0(t), x_i(t))\) is the correlation coefficient, \(\rho\) is the resolution coefficient, and the value is within \((0,1)\). The smaller the value is, the larger the difference between the correlation coefficients is, and the stronger the discrimination ability is.

6) Calculate the degree of association. Which is:

\[
r(X_0, X_i) = \frac{1}{n} \sum_{t=1}^{n} r_{oi}(t) \quad (3-4)
\]

7) Calculate the comprehensive evaluation result based on the degree of association.

### 4. Grey Correlation Analysis of Interference between Capacitive Equipment tanδ and Environmental Factors

In order to analyze the correlation between capacitive equipment tanδ and environmental factors, online monitoring tanδ values of TA and CVT under different environmental conditions and in a certain period of time in a 220kV substation are selected as reference sequences \(X_0\), That is:

\[
X_0 = [x_0(k)] = [x_0(1), x_0(2), \cdots, x_0(n)] \quad (4-1)
\]

The environmental unit monitoring sequence and the bus voltage monitoring sequence in the corresponding time period are taken as comparison sequences \(X_j\), environmental units include ambient temperature and atmospheric relative humidity (pollution degree has not been monitored online, so grey correlation analysis cannot be carried out for the time being). That is:

\[
X_j = [x_j(k)] = [x_j(1), x_j(2), \cdots, x_j(n)] \quad (4-2)
\]

Figure 4.1 is the daily environmental temperature curve of unit 15B on 110kV side of 2# main transformer in 220kV substation from August 25 to August 29, 2014. Figure 4.2 is the daily atmospheric relative humidity curve of unit 15B on 110kV side of 2# main transformer at the same time; Figure 4.3 is the diurnal tanδ change curve of phase b TA of unit 15B on 110kV side of 2# main transformer during this period. It can be seen that the ambient temperature, humidity and tanδ all have...
obvious diurnal periodicity. In addition, comparing Figure 4.1 with Figure 4.2, it can be seen that the ambient temperature is negatively correlated with the atmospheric relative humidity. Compared with Figure 4.1 and Figure 4.3, it is found that $\tan\delta$ of capacitive equipment increases with the increase of temperature, and the two are positively correlated. Comparing Figure 4.2 with Figure 4.3, it is found that $\tan\delta$ decreases with the increase of atmospheric relative humidity, and the two are negatively correlated. Therefore, in order to ensure the accuracy of the grey correlation analysis between $\tan\delta$ and environmental factors, the atmospheric relative humidity should be inverted into a quantity positively related to $\tan\delta$ and temperature by an inversion operator.

The specific method is as follows:

$$XD = (x(1)d, x(2)d, \cdots, x(n)d) \quad (4-3)$$

Among them, $x_i(k)d = 1 - x_i(k), k = 1, 2, \cdots, n$ ; $D$ is an inverse operator, $X_iD$ is the image of $x_i$ under the inverse operator $d$, that is, the inverse image.

At the same time, there is an order of magnitude difference between the reference sequence and the comparison sequence data, which needs to be normalized. Through linear transformation of the sequence, the result value is mapped to $[0, -1]$, making the sequence comparable. The treatment method is as follows:

$$X^* = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \quad (4-4)$$
Among them, $X^*$ is the reduced sample, $X$ is sample data, $X_{\text{max}}$ is the maximum value of the sample data, $X_{\text{min}}$ is the minimum value of sample data.

Since the grey correlation analysis algorithm does not require a large number of samples, a small amount of data can also accurately calculate the correlation degree of each factor. Only the data in the reference sequence and the comparison sequence need to be homogenized, and then calculated and processed according to the formulas (3-3) and (3-4) in the calculation step of 3.2 to obtain the correlation degree between environmental factors and $\tan\delta$ grey.

5. Case Study
On-line monitoring data of different types of 110kV capacitive equipment in three 220kV substations in a certain area are selected for grey correlation analysis.

5.1 Seasonal difference analysis
The online monitoring data of $\tan\delta$ and environmental parameters of capacitive equipment from 2013 to 2014 are extracted. The sampling interval is 1 hour and 24 points are sampled every day. A total of 7 sets of equipment are involved, namely 15B TA, 157TA and 110kV1 mother CVT of 1# substation respectively; 17B TA, 173TA, 110KV bushings of 2# transformer substation and 2# main transformer; 3# substation 181TA. Grey correlation analysis is carried out according to quarterly classification. The results show that, except for 17B TA of 2# substation, the atmospheric relative humidity is the first influencing factor of $\tan\delta$ between January and September for most capacitive equipment. However, the temperature weight rose to the first place from October to December. Table 5.1 lists the 157TA grey correlation analysis results of 1# substation. However, the humidity weight of 17bta in 2# substation from October to December 2014 is still higher than the temperature, and the specific analysis results are shown in 5.2.

Table 5.1 1# substation 157 TA $\tan\delta$(%) correlation degree of external environmental factors

| Time range | Bus voltage | Ambient temperature | Atmospheric relative humidity |
|------------|-------------|---------------------|------------------------------|
| 13.01-13.03 | 0.8800      | 0.8642               | 0.9024                       |
| 13.04-13.06 | 0.8458      | 0.8301               | 0.8667                       |
| 13.07-13.09 | 0.8827      | 0.6189               | 0.7992                       |
| 13.10-13.12 | 0.7460      | 0.8556               | 0.6580                       |
| 14.01-14.03 | 0.6852      | 0.6109               | 0.7254                       |
| 14.04-14.06 | 0.7381      | 0.6993               | 0.7631                       |
| 14.07-14.09 | 0.7304      | 0.7717               | 0.8168                       |
| 14.10-14.12 | 0.7955      | 0.8756               | 0.7380                       |

Table 5.2 TA $\tan\delta$(%) of unit 17B of 2# substation: correlation degree of external environmental factors

| Time range | Bus voltage | Ambient temperature | Atmospheric relative humidity |
|------------|-------------|---------------------|------------------------------|
| 13.01-13.03 | 0.9185      | 0.7269               | 0.7897                       |
| 13.04-13.06 | 0.7497      | 0.5844               | 0.7159                       |
| 13.07-13.09 | 0.8170      | 0.7571               | 0.7580                       |
| 13.10-13.12 | 0.7699      | 0.8946               | 0.6467                       |
| 14.01-14.03 | 0.9102      | 0.7468               | 0.7586                       |
| 14.04-14.06 | 0.8796      | 0.6177               | 0.7304                       |
| 14.07-14.09 | 0.9498      | 0.6154               | 0.9173                       |
| 14.10-14.12 | 0.8121      | 0.5145               | 0.7118                       |

The reason why the weight value of influencing factors of 17bta in 2# substation is different from that of other equipment from October to December 2014 is that the observed area belongs to subtropical marine monsoon climate, which is warm and humid throughout the year and the
temperature is relatively high from October to November 2014. In order to ensure the accuracy of analysis, the time range should be refined and the number of equipment to be tested should be increased. Therefore, the tanδ and environmental parameter data of 11 different types of capacitive equipment in August and December 2014 are taken, wherein the temperature change range in August is between 28℃ and 42℃, and the average value is 33.66℃; Humidity ranges from 44% to 92%, with an average of 73.40%. In December, the temperature varied between 8℃ and 29℃, with an average value of 18.58℃. Humidity ranges from 19% to 86%, with an average of 57.92%. The environmental factors of the online monitoring data in August and December were compared with the tanδ correlation analysis, as shown in Tables 5.3 and 5.4.

Table 5.3 Tanδ(%) correlation degree of external environmental factors for capacitive equipment in August

| Device name         | Bus voltage | Ambient temperature | Atmospheric relative humidity |
|---------------------|-------------|---------------------|-----------------------------|
| 1#-153TA            | 0.7431      | 0.7195              | 0.7737                      |
| 1#-154TA            | 0.7948      | 0.7820              | 0.8089                      |
| 1#-157TA            | 0.7386      | 0.7267              | 0.7531                      |
| 1#-158TA            | 0.8404      | 0.8152              | 0.8745                      |
| 3#-181TA            | 0.8176      | 0.8051              | 0.8313                      |
| 2#-173TA            | 0.9381      | 0.6447              | 0.8418                      |
| 2#-179TA            | 0.9257      | 0.8458              | 0.8857                      |
| 2#_17B TA           | 0.8717      | 0.7304              | 0.8168                      |
| 110kV bushing for 2# Transformer | 0.8594      | 0.7519              | 0.8354                      |
| Section 1#-110kV1   | 0.8521      | 0.8243              | 0.8747                      |
| 1#- bus CVT         |             |                     |                             |
| Section 1#-110kV2   | 0.8244      | 0.7520              | 0.8329                      |
| 1#- bus CVT         |             |                     |                             |

Table 5.4 Tanδ(%) correlation degree of external environmental factors for capacitive equipment in December

| Device name         | Bus voltage | Ambient temperature | Atmospheric relative humidity |
|---------------------|-------------|---------------------|-----------------------------|
| 1#-153TA            | 0.7927      | 0.8120              | 0.7802                      |
| 1#-154TA            | 0.8343      | 0.8804              | 0.8131                      |
| 1#-157TA            | 0.8205      | 0.8637              | 0.7968                      |
| 1#-158TA            | 0.7979      | 0.8400              | 0.7621                      |
| 3#-181TA            | 0.7484      | 0.7979              | 0.7820                      |
| 2#-173TA            | 0.8477      | 0.8532              | 0.8416                      |
| 2#-179TA            | 0.8302      | 0.8518              | 0.8027                      |
| 2#_17B TA           | 0.8658      | 0.8507              | 0.7018                      |
| 110kV bushing for 2# Transformer | 0.6357      | 0.6158              | 0.6139                      |
| Section 1#-110kV1   | 0.7313      | 0.7635              | 0.7001                      |
| 1#- bus CVT         |             |                     |                             |
| Section 1#-110kV2   | 0.7863      | 0.8199              | 0.7364                      |
| 1#- bus CVT         |             |                     |                             |

Table 5.3 shows that in August, the atmospheric relative humidity was the main factor affecting the change of tanδ. Table 5.4 shows that in December, the temperature difference between day and night became the most important factor affecting the change of tanδ, and the humidity influence weight decreased. Taking 154TA of 1# substation as an example, further analysis of field tanδ data (Figure 5.5) and ambient temperature data (Figure 5.6) during this period found that, in December, the tanδ
monitoring values of TA and CVT in 1# substation were relatively stable between 8 and 19 o'clock. After 19 o'clock, the ambient temperature decreased and the tanδ value decreased accordingly.

5.2 Analysis on weight index of temperature and humidity

In order to further analyze the index law that causes the weight change of temperature and humidity, the tanδ and environmental parameter data of 110kV TA, CVT and casing in December 2014 are further analyzed. Classify the environmental parameter data and tanδ data according to humidity index, and divide the atmospheric relative humidity into the following sections: <40%、<50%、<60%、<70%、<80%、<90%、>70%、60%-70%、50%-60% a total of 9 interval segments. According to the above interval, grey correlation analysis is carried out to obtain the correlation degree between tanδ of each ta and CVT and environmental parameter data in different humidity ranges. Table 5.7-5.9 shows the correlation analysis results of 110kV2# bus CVT of 1# substation, 181TA of 3# substation and 110kV side bushing of 2# main transformer of 2# substation respectively. The results show that when the ambient humidity is less than 60%, the main factor affecting the tanδ of capacitive equipment is the ambient temperature. when the ambient humidity exceeds 70%, the atmospheric relative humidity exceeds the ambient temperature and becomes the main factor affecting tanδ. It can be found that 60% of the atmospheric relative humidity is the demarcation point of the influence weight of temperature and humidity.

| Humidity range(%) | Bus voltage | Ambient temperature | Atmospheric relative humidity |
|-------------------|-------------|---------------------|-----------------------------|
| <40               | 0.4907      | 0.7722              | 0.7327                      |
| <50               | 0.5418      | 0.7366              | 0.7624                      |
| <60               | 0.6754      | 0.7853              | 0.7756                      |
| <70               | 0.7212      | 0.7707              | 0.8220                      |
| <80               | 0.7397      | 0.7756              | 0.8332                      |
| <90               | 0.8131      | 0.8343              | 0.8804                      |
| >70               | 0.5899      | 0.7763              | 0.8211                      |
| 60-70             | 0.6063      | 0.7000              | 0.7682                      |
| 50-60             | 0.7385      | 0.7851              | 0.7848                      |
Table 5.8 Tanδ(%) correlation degree of environmental factors under different humidity conditions in December at 181 Ta of No.3 mountain transformer

| Humidity range(%) | Bus voltage | Ambient temperature | Atmospheric relative humidity |
|-------------------|-------------|---------------------|------------------------------|
| <40               | 0.6066      | 0.7968              | 0.7556                       |
| <50               | 0.6697      | 0.7744              | 0.7108                       |
| <60               | 0.7151      | 0.7672              | 0.7100                       |
| <70               | 0.6653      | 0.6989              | 0.7284                       |
| <80               | 0.7057      | 0.7416              | 0.7629                       |
| <90               | 0.7484      | 0.7820              | 0.7979                       |
| >70               | 0.7081      | 0.7091              | 0.7186                       |
| 60-70             | 0.6819      | 0.6828              | 0.6833                       |
| 50-60             | 0.7159      | 0.7155              | 0.6874                       |

Table 5.9 Correlation degree of tanδ(%) environmental factors for 110kV side bushing of main transformer of 2# transformer under different humidity conditions in December

| Humidity range(%) | Bus voltage | Ambient temperature | Atmospheric relative humidity |
|-------------------|-------------|---------------------|------------------------------|
| <40               | 0.9316      | 0.8835              | 0.7617                       |
| <50               | 0.8937      | 0.8694              | 0.6833                       |
| <60               | 0.8376      | 0.8239              | 0.7293                       |
| <70               | 0.8140      | 0.7753              | 0.8002                       |
| <80               | 0.8572      | 0.7851              | 0.8491                       |
| <90               | 0.8718      | 0.7658              | 0.8507                       |
| >70               | 0.8558      | 0.8062              | 0.7644                       |
| 60-70             | 0.8504      | 0.7652              | 0.7933                       |
| 50-60             | 0.8307      | 0.7348              | 0.6626                       |

According to the above analysis, in the same season and the same month, the weight of the main factors affecting tanδ online monitoring value is not always uniform, but varies with the change of environmental conditions. When the atmospheric relative humidity exceeds 60%, the main environmental factor affecting tanδ online monitoring fluctuation is the atmospheric relative humidity, and when the humidity is lower than 60%, the environmental temperature is the main influencing factor. Therefore, 60% can be taken as the diagnostic basis. When the ambient humidity exceeds 60%, the influence of atmospheric relative humidity on tanδ needs to be considered.

5.3 Difference of weight indexes between new and old substations

Further analysis of tables 5.1-5.9 shows that voltage fluctuation is always the first influencing factor of tanδ change in 2# variable capacitance type equipment. It is understood that the 2# transformer has become a new station that has been put into operation in recent years. Compared with the Xiang 1# transformer and the Xiang 3# transformer, the operation time is shorter, the equipment fouling degree is lighter, and the insulation aging degree is lower. Tables 5.10 and 5.11 respectively list the tanδ fluctuation range of each capacitor type equipment of 2# transformer and 1# transformer. It can be found that the fluctuation amplitude of tanδ of 2# variable capacitance type equipment is obviously smaller than that of 1# variable capacitance type equipment. Therefore, it can be seen that the capacitive equipment of the new substation with short operation time is less affected by environmental factors, and its fluctuation is closer to voltage fluctuation.
6. Conclusion

(1) An experimental study on the influence of environmental factors on the tanδ change of capacitive equipment (TA, CVT, casing) was carried out. Combined with the actual situation on site, the superposition of various environmental factors was simulated, and the tanδ change trend under corresponding environmental conditions was obtained.

(2) The grey correlation analysis of tanδ of capacitive equipment with voltage fluctuation and environmental factors (environmental temperature and atmospheric relative humidity) is carried out by using on-line monitoring measured data. The influence weight of environmental parameters on tanδ is found out. It is found that the weight of environmental interference quantity will show obvious seasonal variation with environmental conditions.

(3) Through further screening and analysis of environmental conditions, it is concluded that 60% of atmospheric relative humidity is the weight change point of environmental impact factors. When humidity is higher than 60%, the main environmental factor affecting on-line monitoring fluctuation of tanδ is atmospheric relative humidity. When humidity is lower than 60%, environmental temperature becomes the main impact factor. Therefore, 60% atmospheric relative humidity can be used as a reference for subsequent data processing and fault diagnosis of tanδ environmental factor compensation for capacitive equipment.

(4) Analysis of grey correlation results of new and old substations shows that under the conditions of short operation time, high insulation level and light pollution degree of equipment, tanδ fluctuation of equipment is small, voltage fluctuation is the main influencing factor of tanδ, followed by environmental conditions.

(5) The climate in the observed area is warm and humid all year round. Due to the limitation of such environmental conditions, the grey correlation analysis between environmental disturbance and on-line monitoring tanδ has not been carried out in this paper for environmental temperature less than 20°C and atmospheric relative humidity less than 35%, which needs further research.

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