FRACTAL CHARACTERISTIC RESEARCH OF LEAHAGE CURRENT FOR INSULATORS CONTAMINATION DEGREE PREDICTION

WEI-GEN CHEN [1], QING XIA [1], BING LUO [2], LI-CHENG LI [2]
1.State Key Laboratory of Power Transmission Equipment and System Security and New Technology(Chongqing University), Shapingba District, Chongqing 400044, China
2. China South Grid Technology Research Center, Guangzhou 510623, Guangdong Province, China
Email: weigench@cqu.edu.cn, taozi-qing@163.com

Abstract： The extreme result of insulators contamination discharge is contamination flashover, in order to obtain effective characteristics of contamination discharge, the fractal theory had been used to extract fractal dimension and multi-fractal characteristics of leakage current waveform by taking a number of experiments in the laboratory. The change features of fractal dimension and multi-fractal spectrum were analyzed of leakage current under four kinds of contamination degrees. It is found that variation characteristics of fractal dimension during contamination discharge are obvious, besides, along with increased contamination degrees fractal dimension values decrease integrally and spectrum width of multi-fractal spectrum is increased. The result shows that fractal characteristics of leakage current can estimate insulator contamination degrees effectively. It has provided new methods and valid characteristic volume to contamination flashover pre-warning.

1 INTRODUCTION

The insulator surfaces attach to a large number of pollutants for long-term working in the outdoor of high field strength and strong polluted areas. When in a humid environment, surface contamination of insulators are moist, followed by soluble salts ionization and leakage current increase, and in severe flashover will occur [1]. This affects the safety and reliability of electricity supply and cause a huge loss to the power system. There are many researches on contamination degree of insulators and have achieved some results in contamination flashover prevention, but have not fundamentally solve the problem [2]. It is hoped to find a characteristic quantity which can fully reflect insulator contamination degree, and the detection method is simple. It has been verified that the leakage current affected by the operating voltage, temperature and humidity can provide a more comprehensive description about the state of the contaminated insulators than the other methods [3]. Therefore, the leakage current is called as one of the most effective dynamic parameters.

Recently the leakage current research has focused on the time domain and frequency domain analysis [4-5], new methods tried less. Contamination degrees forecast by a single characteristic quantity is not reliable, unless to synthesize a variety of leakage current characteristics. As the leakage current having the fractal-body characteristics of nonlinear, irregular, and self-similarity, the fractal theory can be used to research leakage current. According to the analysis of the nonlinear characteristics of the leakage current, it is hope to obtain valuable results, and provide new methods for contamination prediction.

In this paper, the leakage current signal characteristics are described by fractal ideology based on fractal theory, and fractal dimensions and multi-fractal spectrum of the leakage current waveform are obtained through the transformation method of fractal theory. Through the leakage current fractal dimensions analysis of different contamination degrees, the leakage current fractal dimensions in contamination discharge development process present a prominent law, fractal dimensions of different contamination degrees have different values, moreover, the multi-fractal spectrum width increases with the contamination levels increase. Test result indicates that the fractal dimensions and multi-fractal spectrum of the leakage current can be effective characteristic quantities to predict the insulator contamination discharge development stages and the severity of contaminations.

2 THEFUNDAMENTAL OF FRACTAL THEORY

Fractal has a certain similarity between a part and the whole. The fractal geometry takes the prevalent and irregular complex phenomena in nature and nonlinear systems as research objects, describes the general structure of a large class of non-smooth or irregular functions and collections which can not be described by the traditional Euclidean geometry and calculus methods [6].

2.1 Calculation of the fractal dimension by conversion method

The box width conversion method used in this paper [7] and the box counting method are the same in essence, all using the box with changed size to cover graphics. But the box width conversion method is more accurate than the box counting method, because of 1) it allows the box number to be a non-integer; 2) the box number is obtained by throughout all data points without sampling.

The steps of fractal dimension calculated with the conversion method are as follows:

1) The fractal curve *L* to be disposed is obtained.

2) The rectangular box with the width r is set to cover on the fractal curve. The height of the rectangle is equal to the difference between the value max (*L*) of the highest point and the value min (*L*) of the lowest point of the fractal curve in the box. The rectangle is moved over all the data points step by step, the height and width of each rectangle is multiplied and then added together to get the total area of *S(r)*. i.e.:

$$S(r) = \sum_{i=1}^{M} (\max(L) - \min(L)) * r \tag{1}$$

Where *M* is the matrix number that all over the entire data points.

3) Changing the size of *r* in series and repeating above operation to get a series of *S(r)*. The fractal curve range should be much larger than the rectangle width *r* in the above operation process. The *S(r)* divided by r^2 gets $N(r) = S(r)/r^2$, where *N(r)* actually is the box number of area of r^2 needed to cover part of the rough curve. Merely it is generally not an integer, this is one of the reasons of more accurate than the box counting method.

4) Plotting the curve of $\ln N(r) \sim \ln(1/r)$ and taking the linear part as scale-less zone to be fitted with the least squares. The slope of the line obtained is the fractal dimension D. So there is:

$$D = \lim_{r \to 0} \frac{\ln N(r)}{\ln(1/r)} \tag{2}$$

The fractal dimension D is obtained.

2.2 The calculation of generalized dimension

For many fractal sets, fractal dimension reflects the set irregularity as a whole, can not fully reflect the probability distribution characteristics of the local region, so people put forward the concept of multi-fractal. Multi-fractal are infinite sets defined on fractal structure, and constituted by bizarre scale of many scale exponential [8]. First, a partition function $\chi_q(r)$ is defined, and the probability *P*(*r*) is weighted sum with the *q* power, the mathematical expression is:

$$\chi_q(r) = \sum_i P_i^q(r) = r^{\tau(q)} \tag{3}$$

There is a power function between the partition function and *r*, so it can be obtained from the slope of $\ln \chi_q \sim \ln r$ curve:

$$\tau(q) = \lim_{r \to 0} \frac{\ln \chi_q(r)}{\ln r} \tag{4}$$

The generalized fractal dimensions *Dq* can be obtained from $\tau(q)$:

$$D_q = \begin{cases} \dfrac{1}{q-1} \lim\limits_{r \to 0} \dfrac{\ln \chi_q(r)}{\ln r}, & q \neq 1 \\ \lim\limits_{r \to 0} \dfrac{\sum P_i(r) \ln P_i(r)}{\ln r}, & q = 1 \end{cases} \tag{5}$$

The multi-fractal spectrum *f(a)* can be obtained from the relationship between $\tau(q)$ and *q*, namely:

$$\tau(q) = aq - f(a) \tag{6}$$

The singularity index *a* can be obtained from the following formula, namely:

$$a = \frac{d\tau(q)}{dq} \tag{7}$$

The above two equations are actually Legendre transform of $\tau(q)$ and q to obtain multi-fractal spectrum *f(a)*.

3 TEST EQUIPMENT AND PROGRAM

3.1 Test devices and test samples

A large number of simulation tests were performed using an artificial fog chamber (volume 4.0 m×3.7 m×4.0 m) in the High Voltage Laboratory of Chongqing University. The test system is shown in Figure 1. The power supply meets the requirements for power sources of artificial pollution tests of IEC60507 and GB/T4584-2004 [9]. The high voltage (HV) supply is connected to the fog chamber through a 110kV wall bushing. The HV end is connected to an AC capacitance voltage divider (SGB-200A) with the divider ratio of 1:1000. The leakage currents can be monitored by the detecting system and recorded by a computer continuously [10].

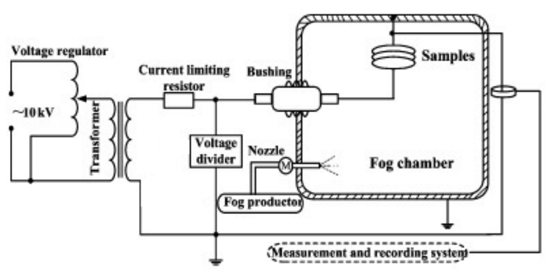

Figure 1: Connecting diagram of the measuring system

The suspension porcelain insulators of XP-70 were selected as the test samples. Three insulators were used for each sample suspension insulator string. The energizing voltage was 20.2 kV of the phase to ground voltage, applied to simulate the 35 kV power line voltage. The solid layer method was used to produce uniform pollution layers on the surface of the insulators. Based on the IEC-60507 standard, four kinds of ESDD levels were applied to simulate four contamination levels, as shown in Table 1.

Table 1: Contamination sorts of samples XP-70

Serial number	1	2	3	4
ESDD(mg/cm^2)	0.06	0.12	0.2	0.25
NSDD(mg/cm^2)	1.0	1.0	2.0	2.0

3.2 Test method

Based on the IEC standard, clean steam fog was released into the fog room slowly and continuously. A thermo-hygrograph was used to measure air humidity conditions in the fog chamber for controlling the air relative humidity steady at 60%~80% during the test process. The insulator samples were brushed according to the above 4 contamination levels. The pre-contaminated samples were completely dried for 24 hours before entering the fog room. Then they were suspended vertically in the fog chamber. After the insulator surface was moist, the operation voltage was applied, at the same time, the leakage current sampling values of the samples were recorded continuously until flashover occurrence.

4 ANALYSIS OF TEST RESULTS

4.1 The fractal dimension calculation of leakage current waveform

The leakage current waveform data measured was imported into the matlab software to carry out wavelet noise canceling. For noise canceling of leakage current with low signal to noise ratio and large signal to noise ratio, the adaptive threshold is the relatively most effective method in wavelet noise canceling methods. It can not only smooth the waveform, and the details are best reserved.

Fractal dimensions of the leakage current data of non-interference signal after the wavelet noise canceling can be calculated by the above calculation steps of fractal dimension. The $\ln N(r) \sim \ln(1/r)$ curve obtained is shown in Figure 2, in a certain scale range, the relationship of $\ln N(r)$ changed with $\ln(1/r)$ has good linear relation. This indicates that the leakage current waveform curves meet the scale invariance, are fractal curves, so fractal dimension characteristic quantity can be extracted, and the slope of the line in the graph is the fractal dimension D.

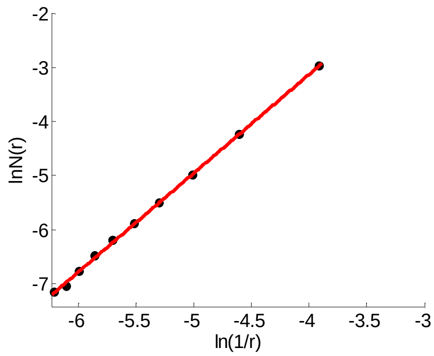

Figure 2: Fractal dimension of leakage current waveform

4.2 Change analysis of the leakage current fractal dimensions

To compare the relationship between the fractal dimensions and the contamination degrees during the insulator discharge development process, insulators under 4 different contamination degrees of ESDD=0.06, 0.12, 0.20 and 0.25mg/cm^2 in the experiment program were tested for measuring the leakage current sampling values under constant voltage until flashover, in which the two insulator groups with ESDD of 0.2 and 0.25mg/cm^2 had flashover occurrence. The subsection fractal dimension calculation results of leakage current sampling values measured under different contamination levels were shown in Figure 3. Data of the leakage current measured in the entire discharge process under every contamination level divided into 30 or 36 segments equally in chronological sequence and data length is the data segment in the figure.

Seeing from the figure 3, when the salt density ESDD=0.06mg/cm^2, for the less contamination on the insulator surface, the discharge was not strong, so the leakage current was very small and relatively uniform, there were no large number of pulses, its fractal dimensions were higher with less variation range, had no sharp decrease and increase process. The contamination of insulators is heavy when ESDD= 0.12, 0.2 and 0.25mg/cm^2. In the initial discharge, contamination layer was in the wet stage for low humidity, this moment the leakage current fluctuation is very small, with only sporadic sparks and glow discharge, and the corresponding fractal dimensions present more homogeneous slow upward trend. With the surface fouling fully wetted, arcs begin to emerge, the arc discharge causes a greater impact on leakage current, and pulses increase, the non-uniform level of leakage current is very high, so the fractal dimensions decline rapidly. As the test conduct, a large arc discharge begins to form and gradually develops into the main arc, and the fractal dimensions present a shock rise trend. When the main arc running through the insulator that flashover occurs, the fractal dimension suddenly increases to a very high value, that the fractal dimensions of the data segment after 30 points are high, greater than 1.95. Throughout the discharge process, the fractal dimensions have significant features, which are increasing slowly at first, with the increasing clamping time rapidly declining and shock rising, when flashover suddenly increasing to a high value. Therefore, the insulators have light contaminations when their leakage current fractal dimensions are higher and have no obvious decrease and increase process, or have heavy contaminations when their fractal dimensions have significant stage change characteristics.

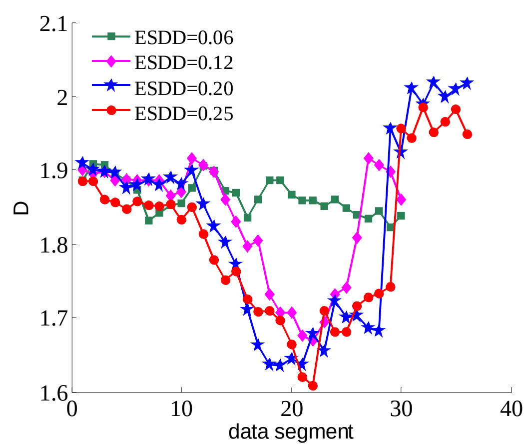

Figure 3: Fractal dimensions of the leakage current under different contamination degrees

Figure 3 also shows that the leakage current fractal dimension sizes of different contamination degrees are not the same. With the contamination degree increase the fractal dimension values present the entirety downward trend, which is due to the more serious the contamination is, the more intense the insulator discharge is, and the more and very dense the number of pulses is, resulting in the partial uneven degree of the leakage current waveform is greater. The more non-uniform the leakage current waveform is, the smaller the fractal dimension reflecting its local details is. Therefore, in the discharge process, insulator with its leakage current fractal dimensions changing significantly and being the least has the most serious surface contamination. This allows by analyzing the variation and value of the fractal dimension D to predict the insulator contamination levels and the contamination discharge development trend, clean insulators in advance and prevent the flashover occurrence.

4.3 The relationship between multi-fractal spectrum and contamination degree

For further study of fractal characteristics of leakage current under different contamination degrees, and finding new contamination forecast characteristic quantity, the generalized dimension of leakage current measured under different contamination degrees were calculated by 1.2 methods, and the multi-fractal spectrum were obtained, as shown in Figure 4 and Figure 5 below. Figure 4 is the relationship between the generalized dimensions *Dq* and the *q* corresponds to insulators of ESDD=0.2. It can be proved that $\lim_{q\to+\infty} D_q = a_{\min}$, $\lim_{q\to-\infty} D_q = a_{\max}$, where $a_{\max}$ and $a_{\min}$ are the largest and smallest strangeness index respectively, and the leakage current generalized dimensions of the remaining 3 contamination degrees are similar to the results in Figure 4. Figure 5 is the multi-fractal spectrum *f*(*a*)-*a* of the leakage current measured under 4 contamination levels, while the spectral width Δa of multi-fractal spectrums were calculated as below:

$$\Delta a_{0.06} = (a_{0.06})_{\max} - (a_{0.06})_{\min} = 1.0716 - 0.9698 = 0.1018$$

$$\Delta a_{0.12} = (a_{0.12})_{\max} - (a_{0.12})_{\min} = 1.1716 - 0.9628 = 0.2088$$

$$\Delta a_{0.2} = (a_{0.2})_{\max} - (a_{0.2})_{\min} = 1.1389 - 0.9251 = 0.2138$$

$$\Delta a_{0.25} = (a_{0.25})_{\max} - (a_{0.25})_{\min} = 1.1409 - 0.8338 = 0.3071$$

According to the multi-fractal theory, the spectral width Δa of multi-fractal spectrum can reflect uneven distribution degree of probability measure on the fractal structure, which describes the physical features of different local or different levels of the fractal structures. The multi-fractal spectrum width Δa can quantitatively characterize the curve undulate degree, in theory, the greater the spectral width Δa is, the rougher the curve is, and the smaller the spectral width is, the smoother the curve is.

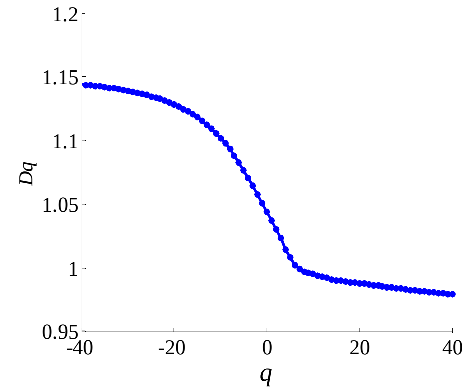

Figure 4: Generalized dimension of leakage current on insulators with ESDD=0.2

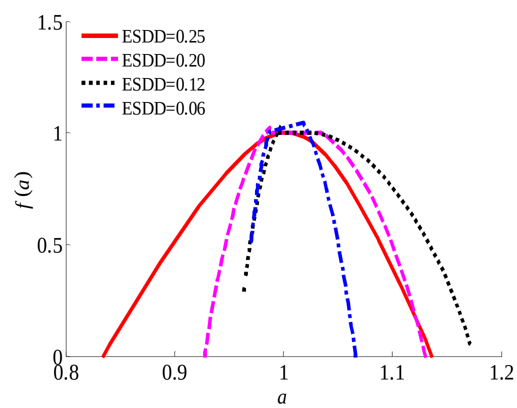

Figure 5: Multi-fractal spectrum *f(a)-a* of four kinds of contamination degrees

The above multi-fractal spectrums and comparison of the calculation data show that the multi-fractal spectrums of leakage current under different contamination degrees are clearly different, and the more serious the contamination is, the greater the spectral width is. This is because the insulator surface discharges lesser when the contamination is light, the leakage current waveform is relatively uniform, so its spectral width Δa of multi-fractal spectrum is small; on the contrary, the surface discharge more intense and more leakage current pulse when the contamination is more serious, and the waveform uneven degree is also higher. The more uneven the waveform is, the greater its spectral width Δa is, which is consistent to the theoretical results above.

Therefore, the insulator surface contamination is heavier when its multi-fractal spectrum width of leakage current is larger, and the insulator surface has very serious pollution when Δa is greater than 0.3, at this time, timely insulator clean is needed for preventing flashover occurrence. But to determine an accurate estimate value of the severe contamination still needs a lot of field tests and analysis, this will be the focus of the future work.

5 CONCLUSION

By the study of leakage current fractal characteristics under 4 contamination levels obtaining:

1) Throughout the insulator discharge process, the leakage current fractal dimensions of different contamination degrees have different variation trend, with a significant feature, and the fractal dimension values present entirety downward trend with increased contamination.

2) Multi-fractal spectrum width Δa increases with the contamination degree increase, the more serious contamination is, the greater Δa value is.

3) According to the fractal dimensions and multi-fractal characteristic quantities of leakage current, the insulator surface contamination condition can be predicted, and providing new ideas and new features to prevent the flashover occurrence.

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