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Investigation on Oil-paper Degradation Subjected to Partial Discharge Using Chaos Theory

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Abstract – In this paper, oil-paper samples composed of transformer windings were used to investigate the insulation degradation process subjected to partial discharge (PD), with artificial defects inside to simulate the PD induced insulation degradation. To determine appropriate test voltages, the breakdown time obtained through a group of accelerated electrical degradation tests under high voltages was firstly fitted by two-parameter Weibull model to acquire the average breakdown time, which was then applied to establish the inverse power law life model to choose advisable test voltages. During the electrical degradation process, PD signals were synchronously detected by an ultra-high frequency (UHF) sensor from inception to breakdown. For PD analysis, the whole degradation process was divided into ten stages, and chaos theory was introduced to analyze the variation of three chaotic parameters with the development of electrical degradation, namely the largest Lyapunov exponent, correlation dimension and Komogorov entropy of PD amplitude time series. It is shown that deterministic chaos of PD is confirmed during the oil-paper degradation process, and the obtained results provide a new effective tool for the diagnosis of degradation of oil-paper insulation subjected to PD.

Keywords: Partial discharge, Electrical degradation, Chaos theory, Oil-Paper insulation, Transformer

Nomenclature

p_n	PD amplitude series after normalization
p	PD amplitude series before normalization
$p_{\max}$	maximum value of PD amplitude series
$p_{\min}$	minimum value of PD amplitude series
$x(t_i)$	time series of PD
m	dimension of reconstructed phase space
n	number of delay vectors
τ	delay time
N	length of PD amplitude series
d_A	fractal dimension of original attractors
$h(t)$	electron emission probability
$N_{SC}(t)$	number of detrapped electrons
v_0	fundamental phonon frequency
ψ	detrapping work function
e	elementary charge
$E(t)$	electric field intensity
ε_0	vacuum permittivity
K	Boltzmann constant
T	temperature
$N_S(t)$	decayed surface charge
σ_S	surface conductivity
$E(2h)$	instantaneous potential drop
τ_{stat}	Statistical time delay
E_i	minimum discharge inception strength
E_e	discharge extinction strength
p	gas pressure inside the insulation defect
a	equivalent radius of the insulation defect
M	constant related to gas properties

1. Introduction

Oil-impregnated transformer is one of the most critical equipment in the electric power system, and the operational state of which directly determine the security of the power grid [1]. Partial discharge (PD) has been proved to be one of the principal reasons leading to insulation failure, and as a nondestructive test method, it has a wide range of applications in insulation condition evaluation of power equipment.

PD often appears inside transformers due to multifarious and inevitable defects, which will inevitably accelerate the degradation process and finally give rise to insulation breakdown. Therefore, as a complement of overall aging condition evaluation based on traditionally physicochemical parameters, PD analysis with the development of electrical degradation is of great significance, especially for risk assessment and fault diagnosis. So far a lot of researches focus on the analysis of PD properties and

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corresponding degradation products, mainly applied for epoxy and XLPE, in which prominent achievements have been made [2-6]. However, there are few reports in regard to the degradation process of oil-paper insulation in power transformers.

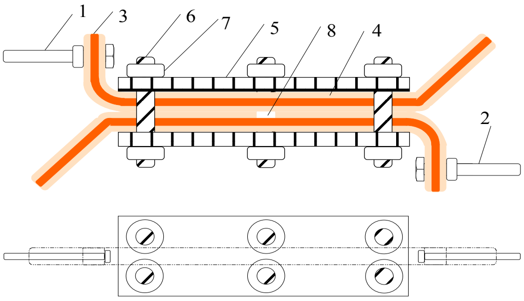
It has been proved by a large number of studies that PD is a relatively complex chaotic process rather than an entirely random phenomenon [7, 8]. With the application of chaos theory, a chaotic and mathematic method was proposed by Nelson [9], to analyze PD signals effectively. Moreover, a further detailed research applying chaos theory to PD analysis was presented in article [10]. However, the differences of chaotic parameters among PD signals from various sources attract much more attentions, while much less attention has been paid to PD variation during the development of insulation degradation. Article [11] introduced correlation dimension and Komogorov entropy to represent the electrical aging condition of XLPE, and pointed out that the chaotic parameters extracted from PD pulses of different aging stages differ from each other. Furthermore, in the previous studies, the insulation pressboards model were usually utilized to simulate the PD process of a new oil-paper insulation defects according to the famous CIGRE II electrode model [12-15], which is too simple and makes it difficult to closely simulate real situation of transformer insulation.

In this paper, oil-paper samples were first manufactured to simulate the winding insulation defects of oil-impregnated transformers in the laboratory. During the degradation process, test samples were stressed by three different voltages for continuous electrical degradation, and PD signals were synchronously collected by an ultra-high frequency (UHF) detector. After that, the variation of three extracted chaotic parameters, namely the largest Lyapunov exponent, correlation dimension and Komogorov entropy, was mainly analyzed with the development of electrical degradation, aiming to provide useful reference for the application of chaos theory to condition assessment of oil-paper insulation of transformers.

2. Experimental Procedures

2.1 Sample pre-treatment

In order to more closely simulate winding degradation induced by PD in transformers, oil-paper samples were prepared according to reference [16] by real transformer windings, as shown in Fig. 1. The dimension of each sample is 200mm long, 11.2mm wide and 2.5mm thick, with a 45° angle on one end and a 90° angle on the other end. The internal copper is wrapped by four sheets of 0.07 mm thick insulation paper, and a cylinder defect with a diameter of 1mm is made on the surface of one wire. All the test samples were impregnated in mineral oil to prevent surface discharge happening in the electrode terminals.



1-high voltage electrode; 2-low voltage electrode; 3-winding copper; 4-insulation paper; 5-epoxy splint; 6-PTFE insulating bolt; 7-PTFE nut; 8-artificial defect

Fig .1. Winding defect model of oil-paper insulation

Before the PD induced degradation experiment, a two-step pretreatment must be implemented first. The first step was to dry and degas the test samples in a thermal-vacuum chamber under the condition of 120ºC/50Pa for 2h. The next step was impregnating the dried samples with 25# naphthenic mineral oil under a vacuum environment at the temperature of 60ºC for 48h. After these processes, the test samples could be more similar to the real oil-paper insulation systems in power transformers.

2.2 Determination of test voltage

As an important parameter for the electrical degradation experiment of oil-paper insulation, if the applied voltage is too low, the breakdown time of test samples will be excessively long or be even without breakdown. On the contrary, if the voltage is too high, the samples will break down in a very short time, which will make it impossible to accurately and adequately study the variation of PD signals. In this research, the Weibull distribution was introduced to determine the average breakdown time of test samples at different voltages. Fig. 2 depicts the Weibull distribution of test samples under four different high voltages ranging from 12kV to 15kV, and the inception voltage of PD is about 5.5kV. The breakdown time corresponding to a

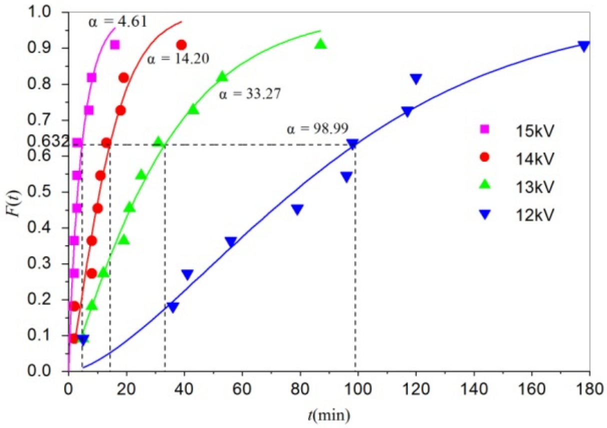
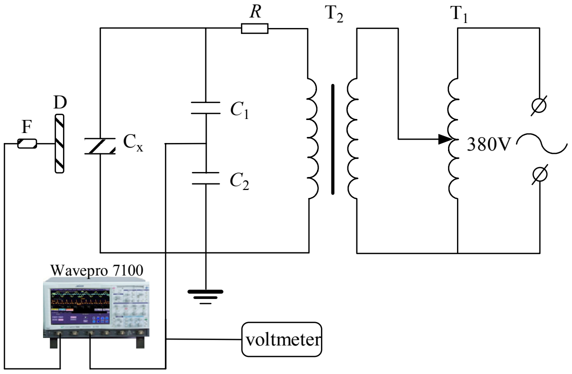


Fig. 2. Weibull distribution of test samples under different applied voltages



T_1-autotransformer, T_2-testing transformer, R-protective resistance; C_1, C_2-capacitive divider, C_x-testing sample, D-UHF antenna, F-filter

Fig. 3. Schematic of PD induced degradation experiment

cumulative failure probability of 63.2% is commonly regarded as the average life expectancy of samples under the critical voltage. Afterwards, the acquired average breakdown time is fitted by the inverse power law life model of $L = bU^{-n}$, where the fitted values of parameters b and n are 2.18×10^{16} and 13.29, respectively.

After the inverse power law life model was established, the breakdown time of test samples under different voltages can be deduced optionally. Therefore, the applied voltage for PD degradation experiment can be well determined. In this work, three different voltages were finally chosen, namely 9.5kV, 10kV and 12.5kV, with a predicted average breakdown time of 36.8h, 18.6h and 0.96h, respectively. While the final experimental results indicated that the actual breakdown time were respectively 27h, 20h and 0.8h.

2.3 PD measurement

PD measurements were executed by constantly applying test voltages which were determined in the preceding section to the oil-paper samples at ambient temperature. The experimental schematic is shown in Fig. 3. The AC high voltage applied to test samples was generated by a voltage regulator and a discharge-free testing transformer.

The PD signals were collected by a logarithmic-periodic UHF antenna and a filter, then displayed and stored in a Lecroy Wavepro 7100 digital oscilloscope. The UHF antenna can achieve a gain of 2.5~6dB in its operating frequency band from 300MHz to 3GHz. Comparatively, the filter owns a bandwidth of 300MHz~1GHz, making it possible to eliminate interference effectively.

3. Chaotic Analysis of PD

3.1 Time series construction of PD

At present, observations utilized to construct PD time series normally include applied voltages when PD activities occurred, amplitudes of PD events, as well as the time intervals between two consecutive PD pulses [7]. In this paper, the amplitudes of PD pulses within 100 power-frequency cycles collected by the UHF antenna were adopted to construct the PD time series, which were recorded as p and should be normalized before chaos analysis, as shown in Eq. (1).

$$p_n = \frac{p - p_{\min}}{p_{\max} - p_{\min}} \quad n = 1, 2, \ldots, N \tag{1}$$

where p_n – PD amplitude series after normalization, $p_{\max}$ – the maximum value of PD amplitude series, $p_{\min}$ – the minimum value of PD amplitude series.

The delay coordinate method was brought into the reconstruction of the phase space, whose basic principle is to select an appropriate delay time τ in the M-dimensional space to form a new state vector, as shown in Eq. (2).

$$X(t_i) = \{x(t_i), x(t_i+\tau), \ldots, x[t_i+\tau(m-2)], x[t_i+\tau(m-1)]\},\ i = 1, 2, \ldots, n \tag{2}$$

where $x(t_i)$ – time series of PD, m – the dimension of reconstructed phase space, n – the number of delay vectors, which is equal to $N\text{-}\tau(m\text{-}1)$.

It is suggested that the topological characteristics of attractors could be recovered from embedded dimension space if inequality $m \geq 2d_A+1$ is satisfied, where d_A represents the fractal dimension of original attractors [17].

The delay time and embedding dimension are quite important for the trajectory recovery of attractors. This paper employed C-C algorithm [18] to determine the delay time τ, and then calculated the embedding dimension m by Cao's method [19]. C-C algorithm has many outstanding advantages, such as easy operation, lower computation loads, higher anti-interference ability and reliability to smaller data sets. As for Cao's method, its merit is mainly embodied in the elimination of influence resulting from subjective factors, compared with the pseudo k-nearest-neighbor method.

The most common parameters to depict chaotic attractors are the largest Lyapunov exponent, correlation dimension and Komogorov entropy, which are discussed in details as follows.

3.2 The largest LYAPUNOV exponent

Lyapunov exponent can reflect the sensitivity of chaotic motion to initial values. Particularly, the largest Lyapunov exponent connected with the most widely practical applications is an important parameter to judge whether the system is chaotic or not. By far, lots of methods have been proposed to calculate the largest Lyapunov exponent, among which the small-data method [20] is selected in this study. The small-data method costs a relatively short computation time, has a greater reliability for smaller time series data, and can be used for the data mixed with noise interference effectively. Hence, it is quite suitable for the calculation of the largest Lyapunov exponent of PD time series.

3.3 Correlation dimension

Correlation dimension is a complete characterization of geometric structural complexity of strange attractors, which describes the static nature of strange attractors (i.e., invariant measure). The dominant method to calculate correlation dimension is the G-P algorithm [21], which acquires the results through reconstructing the relationship between correlation integral $C_m(r)$ and distance r in phase space, as shown in Eq. (3).

$$D_2 = \lim_{r \to 0} \frac{\ln C_m(r)}{\ln r} \tag{3}$$

3.4 Komogorov entropy

Komogorov entropy is defined according to the concept of thermodynamic entropy, which is a measure for loss rate of initial information in chaotic system and can effectively reflect the disordered degree of the system. Considering the difficulty to directly calculate Komogorov entropy from one-dimensional time series, Grassberger and Procaccia proposed a practical approach by using the second-order Renyi entropy K_2 to replace traditional Komogorov entropy K [22]. K_2 is an approximation of K and theoretically equals to K when m approaches infinity. In fact, when m increases to a certain value, K_2 tends towards stability. This relatively stable value could be regarded as the estimate value of K.

4. Experimental Results

First of all, the collected PD signals at each voltage level were divided into ten stages equally according to the breakdown time t_a of relevant samples. The delay time τ and embedding dimension m calculated by C-C algorithm and Cao's method are exhibited in Table 1.

The variation of the largest Lyapunov exponent, correlation dimension and Komogorov entropy of PD time series during electrical degradation process are shown in Fig. 4 to Fig. 6, respectively. It is demonstrated that the largest Lyapunov exponent and Komogorov entropy are both greater than zero in all stages. Furthermore, the correlation dimension presents fraction values which ranged from 1.7 to 2.9, which means the trajectory is located on strange attractors with fractal dimensions. As a result, it is confirmed that PD of oil-paper insulation is a chaotic process, and it is feasible to realize PD analysis by the use of chaos theory.

Table 1. Calculation results of delay time and embedding dimension

Aging stages	Parameters					
	delay time			embedding dimension		
	9.5kV	10kV	12.5 kV	9.5 kV	10kV	12.5 kV
$0.1t_a$	3	1	2	9	10	9
$0.2t_a$	1	2	2	10	10	10
$0.3t_a$	1	1	2	10	8	10
$0.4t_a$	1	3	1	10	10	10
$0.5t_a$	1	3	3	11	10	10
$0.6t_a$	2	2	2	10	12	11
$0.7t_a$	2	1	1	10	10	10
$0.8t_a$	2	2	1	8	11	10
$0.9t_a$	1	1	2	10	10	12
t_a	4	4	3	4	9	9

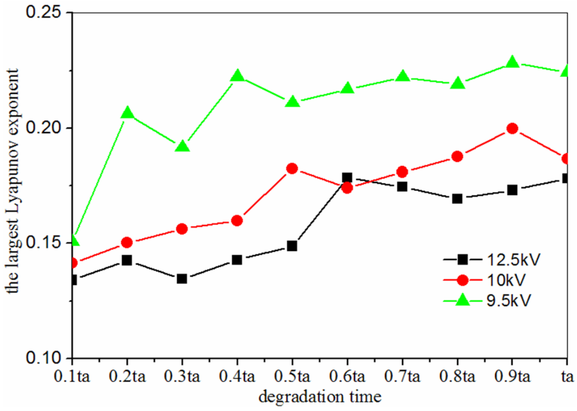


Fig. 4. Variation of the largest Lyapunov exponent with degradation time

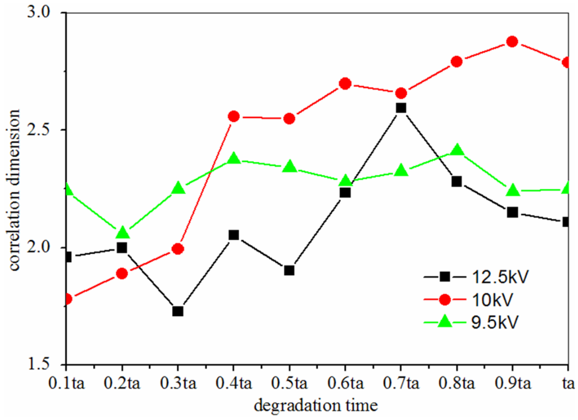


Fig. 5. Variation of correlation dimension with degradation time

More useful information can be acquired by further comparative analysis of variation of the three chaotic parameters. Firstly, the largest Lyapunov exponent decreases gradually with the increasing applied voltages, indicating that the sensitivity of PD amplitudes to system's initial condition becomes weak while the chaotic orbit region of PD becomes more and more stable. Secondly, the

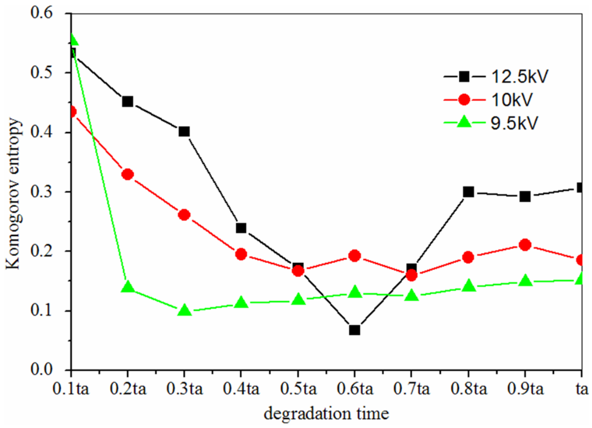


Fig. 6. Variation of Komogorov entropy with degradation time

correlation dimension under each test voltage presents a kind of behavior of fluctuation. Specifically, the fluctuation is relatively smooth under 9.5kV and 10kV, while turns into much choppy under 12.5kV. Finally, the data range of Komogorov entropy becomes larger when applied voltages increase, that is to say, the unpredictability and chaotic property of PD time series enhance gradually. However, the fluctuation of Komogorov entropy under 12.5kV is the highest among the three conditions.

In addition, with the development of electrical degradation of oil-paper insulation, the chaotic parameters of PD time series also provide some significant information. Firstly, the largest Lyapunov exponent shows a consistently increasing trend during the electrical degradation process. Hence, it can reflect the degradation state of oil-paper insulation to some extent. Secondly, with the extension of degradation time, the correlation dimension under 10kV increases obviously, indicating an evidently increasing complexity of PD. However, the data under 9.5kV and 12.5kV both have a moderate increase with strong fluctuation. In particular, the correlation dimension under all test voltages has a distinct decrease in the end of electrical degradation progress, which demonstrates the complexity of PD in pre-breakdown stage reduces greatly. Thirdly, the Komogorov entropy drops rapidly from a large initial value at the beginning, and then increases slowly with the development of electrical degradation. Therefore, similar conclusions can be drawn that the chaotic property of PD is most remarkably reflected in the initial degradation stages, then falls to the bottom, and finally keeps a flat increase in the mid-to late stages. This phenomenon may be attributed to the reason that the PD activities have not yet reached a relatively stable state in the early stages.

5. Discussion

The occurrence of PD due to inside insulation defects should simultaneously meet two conditions: (1) There exists at least one availably initial free electron; (2) Internal electric field intensity achieves the minimum discharge inception strength.

The initial free electrons mainly derive from field emission [23], and the emission probability $h(t)$ complies with Richardson-Schottky's law [24, 25], as shown in Eq. (4).

$$h(t)=N_{SC}(t)v_0\exp\left(-\frac{\psi-\sqrt{e\left|E(t)\right|/\left(4\pi\varepsilon_0\right)}}{KT}\right) \tag{4}$$

where N_{SC} (t) – the total number of electrons detrapped from insulation surface at time t, v_0 – fundamental phonon frequency, ψ – detrapping work function, e – elementary charge, $E(t)$ – electric field intensity inside insulation defects at time t, ε_0 – vacuum permittivity, K – Boltzmann constant, T – temperature.

The detrapping work function ψ is related to the electron scattering properties of defect surfaces such as material, roughness and chemical state. $N_{SC}(t)$ is largely dependent on the balance of electrons' production and decay during the time intervals between two PD events. The decay of electrons on the surface of insulation defects, which would lead to a lessened emission probability $h(t)$, is mainly caused by surface conduction, hetero-charge recombination and capture by deep traps. Furthermore, the decay velocity of electrons can be approximately described by Ohm's law [26], as shown in Eq. (5).

$$-\frac{dN_S(t)}{dt}=\left(\frac{\pi}{2}\right)\sigma_S E(2h) \tag{5}$$

where $N_S(t)$ – charge decayed on the surface of insulation defects, σ_S – surface conductivity of insulation defects, $E(2h)$ – instantaneous potential drop inside insulation defects.

When there is no free electron inside insulation defects, the PD phenomenon will not occur even if the applied voltage is higher than the discharge inception voltage. Statistical time delay τ_{stat} is defined as the time interval from the moment that the applied voltage exceeds the discharge inception voltage to the moment that initial free electrons appear, which will reduce gradually with the rising of applied voltages due to the increase of electron emission probability $h(t)$. For sinusoidal voltages with power frequency, the influences of τ_{stat} are mainly reflected in phase drift and the increase of discharge quantity.

The other necessary condition to determine the occurrance of PD is the minimum discharge inception strength, which presents a relationship [27] with the discharge gas medium shown in Eq. (6).

$$\frac{E_i}{p} = \left[1 + \frac{M}{\sqrt{2ap}}\right]\frac{E_e}{p} \tag{6}$$

where E_i – the minimum discharge inception strength, E_e – discharge extinction strength, p – gas pressure inside the insulation defect, a – equivalent radius of the insulation defect, M –constant related to gas properties [28].

Article [29, 30] launched the microscopic damage mechanism analysis of oil-impregnated insulation paper caused by PD, and found that PD activities during the damage process are principally affected by two aspects. On the one hand, the surface roughness increases firstly and then decreases, while the surface conductivity shows a consistently rising trend as well as the number of shallow traps on the insulation surface. The change of surface roughness brings about electric field distortion around the insulation surface. The increase of surface conductivity leads to the reduction of detrapping work function and affects the decay velocity of electrons, while the increase of shallow traps gives rise to a less statistical time delay, these two factors result in the changes of discharge quantities and discharge phases. On the other hand, during the whole damage process, gas consumption and generation inside insulation defects sustain all the time, causing alternative changes of the minimum discharge inception strength of internal defects. Therefore, the changes of material characteristics and discharge media are the major factors that lead to the variation of PD signals in oil-paper insulation during electrical degradation process, which engenders some obvious changes of both PD quantities and PD phases, and results in continuous variation of chaotic parameters of PD amplitude time series.

6. Conclusion

In this paper, three chaotic parameters of PD amplitude time series, namely the largest Lyapunov exponent, correlation dimension and Komogorov entropy, were introduced to deeply investigate the PD induced degradation process of oil-paper insulation. As a result, several instructive conclusions are drawn below:

(1) During the whole degradation process, the largest Lyapunov exponent shows an ever-increasing tendency and presents a distinct correlation with the electrical degradation state of oil-paper insulation.
(2) With the extension of degradation time, the correlation dimension increases apparently under 10kV while presents a slow increase with obvious fluctuation under 9.5kV and 12.5kV. However, the correlation dimension under all three conditions has a significant decrease in the pre-breakdown stage, indicating the complexity of PD reduces rapidly at that period.
(3) Based on the analysis of Komogorov entropy, it is found that the chaotic property of PD is most remarkable at the beginning, and then dramatically decreases to the minimum. Finally, it maintains a slight increase in the mid- to late stages.
(4) The principal reasons leading to the variation of chaotic parameters of PD amplitude time series in oil-paper insulation during the electrical degradation process are the changes of material characteristics and discharge media.

The obtained results will provide a new effective tool for the diagnosis of PD induced degradation of oil-paper insulation. Future research will focus on the establishment of the relationship between the variation of PD chaotic parameters and the microscopic mechanism of PD induced degradation. Meanwhile, the influences of temperature on the test model also need a further in-depth investigation and more valuable information will be presented in the future.

Acknowledgements

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