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Pattern Recognition of Growth Characteristics Based on UHF PD Signals of Electrical Tree

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ABSTRACT In insulation system of power equipment, electrical tree grown under the effect of partial discharges (PD) is one of the main degradation processes leading to failure of high voltage polymeric insulation. PD signals are measured and analyzed for condition monitoring of electrical insulation. In this paper, the combine detection system of Ultra-High Frequency (UHF) PD and electrical tree was used to test PE samples. Based on the energy amplitude variation, the average energy and the average energy distribution of PD signals to identify the growth process of electrical tree, twenty-eight PD characteristic parameters were used as input parameters, such as the energy percentage of 16-layer wavelet decomposition, the wavelet coefficient parameter and the time-frequency domain parameter, which entered the three-layer Back Propagation Neural Network (BPNN) of forty-five hidden neurons, and then the accuracy of pattern recognition during the growth process of electrical tree can reach 99.93% after 5000 steps of training cycle. The consistency of calculation results and experimental results presents that the calculation method can reveal the relationship between PD signals and the growth of electrical tree, which lays the foundation for the process analysis of electrical tree and insulation state monitoring.

INDEX TERMS Partial discharge, ultra-high frequency signal, electrical tree, pattern recognition.

I. INTRODUCTION

Polyethylene (PE) is widely used in power and electronics industry because of its excellent electrical, mechanical and process properties [1]–[3]. In the long-term working environment, polymer insulation often breaks down caused by the interaction of mechanical, thermal and electric field [4]–[5]. Although there are many factors caused insulation failure, partial discharge (PD) and electrical tree are one of the main factors [6]–[7]. Du et al fabricated the typical void defect model, and studied its PD characteristics at different DC voltages. It is found that with the increase of applied voltage, the discharge magnitude and the discharge repetition rate increase and the *Q-t* pattern shows the shape of hilly, and then that the skewness and kurtosis of density histogram of discharge time interval increased gradually. It provides the theoretical basis for PD research of cable insulation [8]–[9]. Zheng et al analyzed the growing characteristics of electrical tree in crosslinked polyethylene. It is found that the growth of electrical tree is due to the existence of congregating states, crystalline structures, and residual stresses in the semi-crystalline polymer, and that there are three stages of tree propagation including initiation, stagnation, and rapid propagating. And then the growth rate L, the fractal dimension d_f, and expansion coefficient D/L are used to express the growth feature of electrical trees [10]–[12]. Iddrissu et al studied the effects of voltage polarity and initial defect size on DC tree propagation. It is found that space charges from the needle electrode can form the homocharge zone, which can modify the local electrical field distribution and change the growth characteristics of electrical trees. The growth of electrical trees is strongly dependent on the voltage polarity. And that the minimum size of critical defects is about 45μm when the needle is negative polarity [13].

In recent years, lots of researchers consider that there is an obvious correlation between PD signals and electrical tree states, and then PD is one of the important parameters to characterize electrical aging properties of polymers [14]–[15]. Therefore, characteristic parameters which can characterize electrical tree discharge are found in the process of detecting

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PD signals of insulation, and then the relationship between the characteristic parameters of the PD and the growth process of electrical tree is established. Zhang et al studied the relationship between PD and electrical tree. It is found that with the growth of electrical trees, the pulse height and number of partial discharges continually increased, and then that the pulse height of partial discharges decreases gradually, even almost none of discharge signal [16]–[18]. At the moment, the state diagnosis and the faulty pre-warning of electrical insulation can be realized so as to effectively avoid the occurrence of power accidents.

Montanari et al presented models suitable for aging investigation of insulation and systems based on the quantity associated with PD measurements and electrical tree. In the model, the run time was related to PD activity and tree growth, and experimental results derived from PD measurements and electrical tree observations performed on insulation systems were used to verify the proposed models [19]–[22]. Iddrissu et al found that different electrical tree structures and stages of development generate different magnitude of PD, with thick and dark tree branches associated with magnitudes of 1pC to about 1nC, whereas fine tree channels growth is linked with PD magnitudes of 0.4pC or less [23]. Gao et al studied the relationship between electrical tree and PDs with 20.2kV and 63.5kV based on the slice materials of 35 kV and 110 kV XLPE cables. It is found that there were three significant statistical characteristics of PDs in the process of electrical tree growth. The first feature was that PD magnitudes were small when the initial electrical trees grew out. Subsequently, PD magnitudes maintained the high and stable level. The third feature was that PD magnitudes became weakened when electrical trees increased rapidly until the breakdown of cable insulation [24]. Madariaga et al used classification techniques of PDs to determine the growth stage of electrical trees in alternating electric fields of different frequencies. It is found that the waveforms of PDs varied with the growth of electrical tree and that the proportion of energy in the low frequency band was increasing with tree propagation [25]. However, the energy characteristics of Ultra-High Frequency (UHF) PD signals during the growth of electrical tree, and the relationship between electrical tree growth processes and PD energy distributions have rarely been investigated.

In the paper, the relationship between PD signals and tree aging processes is established based on characteristics of PD signals during the growth of electrical tree, and then the state diagnosis and fault warning of electrical insulation are realized. The electro-acoustic nondestructive testing method is used. Based on the energy amplitude, the energy percentage and the time-frequency domain characteristics of UHF PD signals, the process of electrical tree growth in polyethylene samples is accurately identified by Multiscale Analysis (MA) and multi-layer Back-Propagation Neural Network (BPNN). And then the availability of the recognition method is verified by experiments, which lays the foundation for the process analysis of insulation during electrical tree and insulation condition monitoring.

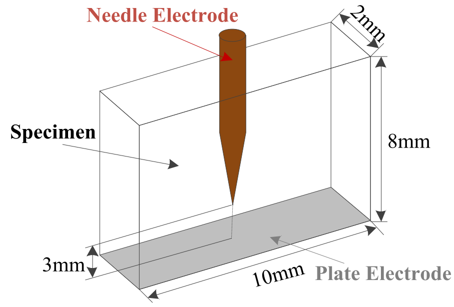

FIGURE 1. Schematic diagram used in the electrical tree experiment.

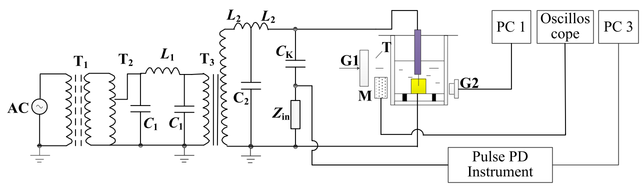

FIGURE 2. Schematic graph of combining detection system of electrical tree and PD. T_1-Isolation transformer; T_2-Voltage regulator; C_1, L_1-The π type filter of low pressure low pass; T_3-High voltage experimental transformer; C_2, L_2-The filter of high voltage low pass; C_k-Coupling capacitor; Z_{in}-Detecting impedance; G1-The cold light source; M-UHF antenna; T-The oil box; G2-The DSZ-1 image acquisition system of ultra-high definition of electrical tree.

II. EXPERIMENTAL

A. SAMPLE PREPARATION

Pure polyethylene samples (PE) are prepared by mixing polyethylene with 0.3% antioxidant used torque rheometer at 150°C, and then PE samples are hot-pressed into (10 × 8 × 2)mm sheet at 150°C. In the process of electrical tree initiation, the tungsten wire with diameter of 6μm and curvature radius of 3±0.1μm is used as the high voltage needle electrode, and while the bottom surface coated with conductive gel is used as the grounding electrode. In order to make sure the uniformity of experimental results of electrical tree, it is necessary to ensure that the distance between the needle electrode and the grounding electrode is always 3mm, as shown in Fig. 1.

1) MEASUREMENT SYSTEMS OF PARTIAL DISCHARGE AND ELECTRICAL TREE

The measurement system of PD and electrical tree is shown in Fig. 2. The applied voltage is 11kV, and M is UHF antenna that the maximum frequency of the detection antenna is up to 4GHz. Furthermore, the oscilloscope is the Tektronk DPO7254 digital oscilloscope, with the highest sampling rate of the single channel up to 40GS/s, the maximum bandwidth of 2.5GHz, and the maximum storage depth of 500M.

It is worth noting that the tests of electrical tree and PD are all completed in the shielding room, in order to effectively shield the external electromagnetic and noise interference. The entire experimental setup of combining detection system of electrical tree and PD is shown in Fig. 3.

FIGURE 3. **The entire experimental setup of combining detection system of electrical tree and PD.**

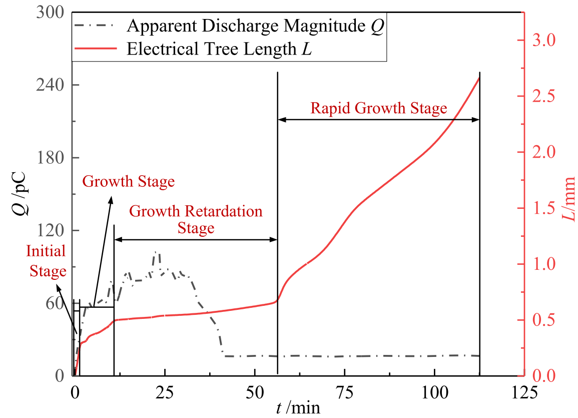

FIGURE 4. **Complete growth morphology of electrical tree in PE corresponding PD diagram.**

III. TEST RESULTS OF PARTIAL DISCHARGE AND ELECTRICAL TREE

There are obvious PD in the process of electrical tree. The corresponding relation between the growth process of electrical tree and PD in PE is shown in Fig. 4.

The growth process of electrical tree can be divided into four stages, which are initial stage, growth stage, growth retardation stage and rapid growth stage, respectively. And the UHF PD of different degrees is accompanied in each stage of electrical tree. Typical UHF PD signals of each stages are shown in Fig. 5.

In the process of electrical tree discharge in PE, the apparent discharge magnitude of initial stage increased rapidly from 20pC to 60.4pC, and the length of dendritic electrical tree grew rapidly to 0.35mm at the growth rate of 98.81μm/min. Then, growth of electrical tree gradually entered into the growth stage. At this time, the apparent discharge magnitude is gradually stable, up to 83.8pC, and on the basis of the longitudinal growth of electrical tree, there also appeared transverse extension. After that PD gradually decreased or even extinguished in the next of 44.8min, and the main channel of electrical tree almost stopped growing, thus entering the growth retardation stage. At this time, the color of main channels gradually deepened and tips of twigs gradually

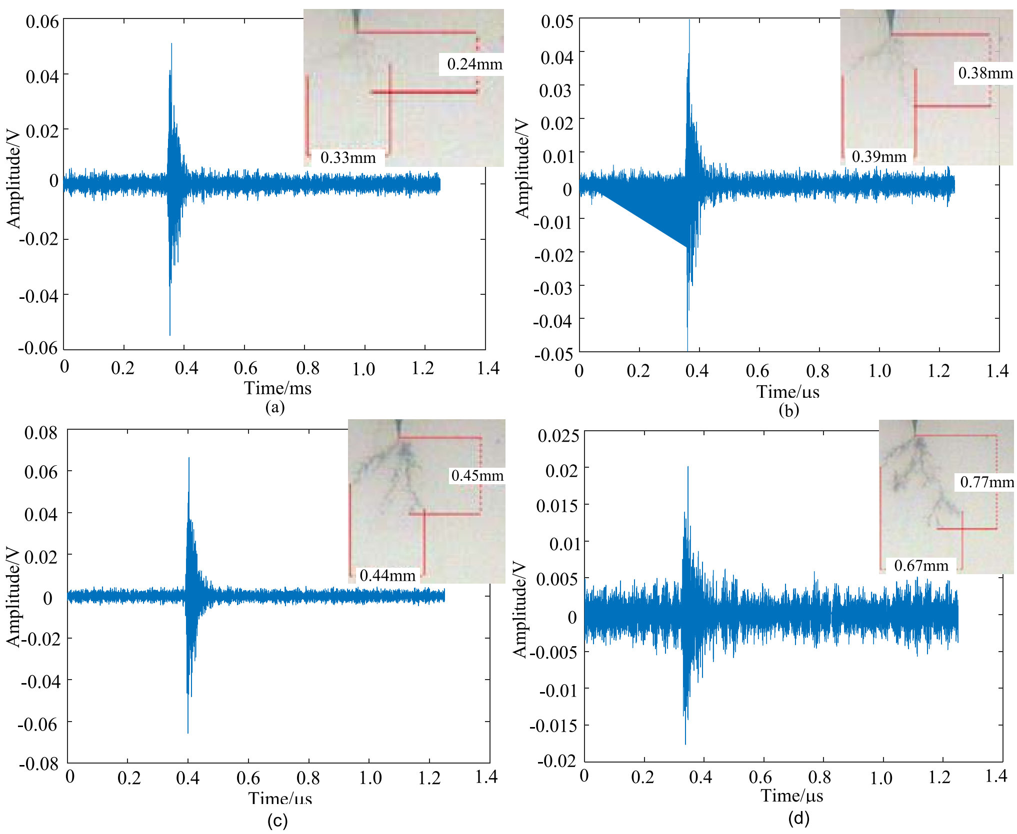

FIGURE 5. **Typical UHF PD signals and electrical tree morphologies during (a) initial stage, (b) growth stage, (c) growth retardation stage and (d) rapid growth stage.**

blackened, where the clumped black areas appeared near tips. Finally, during PD extinguishment, the average growth rate of electrical tree suddenly increased dramatically, and then the secondary growth occurred during the growth of electrical tree until the critical breakdown of PE sample.

In order to more clearly identify the relationship between PD signals and the growth process of electrical tree, the PD signals corresponding to the electrical tree length of 0.24mm, 0.38mm, 0.45mm and 0.77mm in PE were taken as examples. By comparison, it was found that with the increase of electrical tree length, the color of electrical tree gradually deepened, and the amplitude of PD signals firstly increased and then decreased. Time domain spectra of discharge signals showed exponential oscillation attenuation, but due to the superposition of multiple signals, discharge waveforms were relatively compact and had some distortion. This is mainly because molecules near needle electrode are always subjected to the combined action of electro-mechanical stress and PD under the action of alternating electric field [26]–[29].

First of all, molecular chains at the needle tip are the first to break due to stress fatigue caused by electro-mechanical stress, thus forming a series of micro-holes and cracks. And then, under the action of high electric field strength, these micro-holes or cracks produce strong PD. At the moment, although the electrical tree length is very small (about 300μm), the growth rate of electrical tree is fast, and the PD magnitude is gradually increased, namely to enter the initial stage of electrical tree.

Secondly, PDs in electrical tree channels cause the surrounding molecular chains to break quickly, and then decompose and gasify, which form an expansion stress pushing in all directions. At this point, the combined action of expansion stress and particle collision process leads to the rapid expansion of branch channels along amorphous regions with weak mechanical strength, which virtually increases the branch channel width, decreases the gas pressure drop. As a result, the impact effect of charged particles is weakened, the discharge phenomenon is gradually stable, and then the growth rate of electrical tree slows down, namely to enter the growth stage of electrical tree.

Thirdly, when the electrical tree grows to a certain length, there are more small branches crossing each other at the end of trees, which can result in smaller distances between branches. Therefore, the field strength at the tips of adjacent branches appears to shield each other, and then there are the shielding effect and the homogenized electric field effect. At the moment, the main channels of branches almost stopped growing, and magnitude of PD gradually weakened and even extinguished. Namely to enter the growth retardation stage of electrical tree.

Finally, molecular chains of branch tip are subjected to the long-term effect of alternating Maxwell stress, so that molecular chains are broken and new branch channels are formed, which effectively weakens the shielding effect and the homogenized electric field effect of branch tips. At this point, the average growth rate of electrical tree suddenly increases sharply, and the phenomenon of secondary growth appears in the process of branching growth until the critical breakdown of the sample occurs, namely to enter the rapid growth stage of electrical tree.

TABLE 1. The correspondence between decomposition layers and frequency bands.

Levels	A15 /MHz	D1 /GHz	D2 /GHz	D3 /GHz
Frequency Bands	<0.61	20.00-10.00	10.00-5.00	5.00-2.50
Levels	D4 /GHz	D5 /GHz	D6 /MHz	D7 /MHz
Frequency Bands	2.50-1.25	1.25-0.62	625.00-312.50	312.50-156.25
Levels	D8 /MHz	D9 /MHz	D10 /MHz	D11 /MHz
Frequency Bands	156.25-78.12	78.12-39.06	39.06-19.53	19.53-9.76
Levels	D12 /MHz	D13 /MHz	D14 /MHz	D15 /MHz
Frequency Bands	9.76-4.88	4.88-2.44	2.44-1.22	1.22-0.61

To sum up, there are different degrees of PDs during the growth process of PE electrical tree. Therefore, the typical characteristics of PD can be obtained by counting discharge characteristics of the frequency domain spectrum and energy distribution, and then the corresponding relationship between the growth stage of electrical tree and the characteristics of PD can be obtained.

IV. DISCUSSION OF TEST RESULTS

A. ANALYSIS OF ENERGY DISTRIBUTION BASED ON MULTISCALE ANALYSIS IN THE PROCESS OF PARTIAL DISCHARGE AND ELECTRICAL TREE

In the process of Multiscale Analysis (MA), the wavelet function db10 is selected as the parent wavelet function and the 16 layers is selected as the number of wavelet decomposition layer by selection methods of wavelet function and decomposition layer. The correspondence between decomposition layers and frequency bands in the discharge energy is shown in Table 1.

Based on the energy characteristics of the background noise decomposition layer and the adaptive multi-threshold denoising algorithm, the low-frequency energy interference is eliminated. Taking a certain electrical tree discharge signal in each stage as an example, after denoising UHF PD signals, the energy distribution of discharge signals are shown in Fig. 6.

As can be seen from Fig. 6, for the energy distribution of UHF PD signals in the growth process of PE electrical tree, with the increase of branch length, there are the maximum value at D4 decomposition layer in the initial stage, growth stage and growth retardation stage, which is 34.94%, 39.78% and 45.19%, respectively. And there are the second-peak at D3, which is 19.41%, 19.93% and 26.06%, respectively. But when the branch length continues to increase, the growth of electrical tree enters the rapid growth stage, and the first-peak and the second-peak of UHF PD signals are found at D11 and D4 decomposition layer, which are 31.68% and 21.17%, respectively.

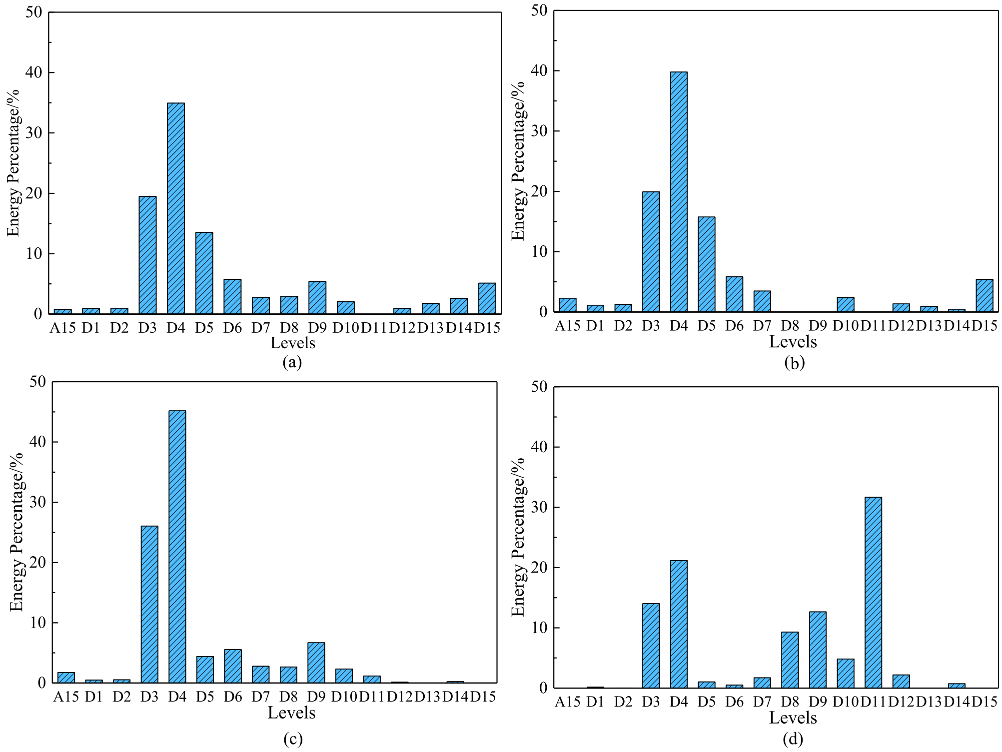

FIGURE 6. Energy distribution characteristics during (a) initial stage, (b) growth stage, (c) growth retardation stage and (d) rapid growth stage of electrical tree in PE.

However, it is not reliable to just use characteristics of one signal as the basis for pattern recognition, so the variation trend of PD amplitude at each stage is compared and analyzed, as shown in Fig. 7. During the initiation of electrical tree, with the increase of the branch length, amplitudes of PD signals show the trend of upward oscillating, of which the maximum amplitude can reach 0.078V. At the end of the initial stage, the amplitude of PD signals increased by 200% compared with the beginning of that. And in the growth stage of electrical tree, the signal amplitudes always fluctuate around (0.054±0.025)V. Then the branch length continues to increase and the growth process of electrical tree gradually enters the growth retardation stage. At the moment, amplitudes of PD signals show the trend of downward oscillating, which the decrease of signal amplitude can reach 55.56%. Finally, the growth process of electrical tree enters the rapid growth stage, the signal amplitude always fluctuated around (0.015±0.006)V, and amplitudes of PD signals and oscillation are significantly weakened compared to the first three stages.

Through the above analysis, it can be seen that during the growth process of PE electrical tree, the energy distribution and the amplitude fluctuation of UHF PD signals have certain regularity and fluctuation in initial stage, growth stage, growth retardation stage and rapid growth stage. Therefore, in order to avoid the wrong pattern recognition caused by fluctuation of UHF PD signal, the characteristic parameters, such as average discharge energy and average energy distribution of UHF PD signals, can be used to recognize the growth process of polymer electrical tree.

The average discharge energy and the average energy distribution at each stage in the development process of PE electrical tree are shown in Fig. 8, in which the average energy of discharge signal can be calculated by formula (1):

$$E_i = \frac{\Delta t}{R} \sum_{N} D_i^2 \tag{1}$$

where Δt is the time of sampling interval, R is the matching impedance (50Ω), and N is the total number of waveform samples. It is calculated that the time of sampling interval is 25ps when the sampling frequency is 40GSa/s.

After wavelet decomposing and threshold filtering, the average energy and its distribution of each stage are different to some extent, that is, the energy state of decomposition layers and the mean energy value are also different.

First of all, in every stage, the maximum energy percentage of decomposition layer all appears in D4 layer, which are 28.59% and 32.85%, 44.04% and 32.34%, respectively. And then the variation trend of energy percentage during initial stage and growth stage is very similar, and the energy is concentrated in D3, D4, D5 and D11 layers. At this time, it is not easy to distinguish the growth processes of electrical tree using energy distribution only, and the average energy of discharge signals needs to be used.

Secondly, the average discharge energy of rapid growth stage is the smallest (about 0.11pJ), while the average discharge energy of growth stage is the largest (about 4.31pJ), which is more than 30 times that in other stages. This lays a foundation for explaining the growth process of electrical tree by PD energy. The reason may be that, in the growth

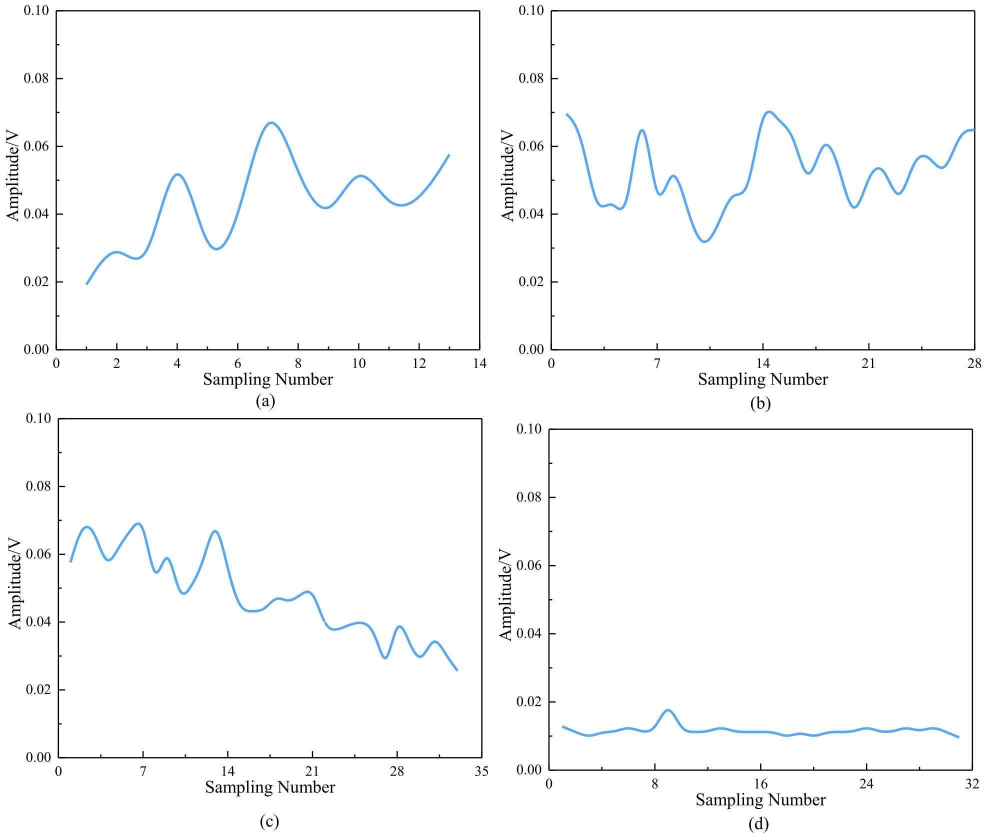

FIGURE 7. **The amplitude variation of UHF PD signals during (a) initial stage, (b) growth stage, (c) growth retardation stage and (d) rapid growth stage of electrical tree in PE.**

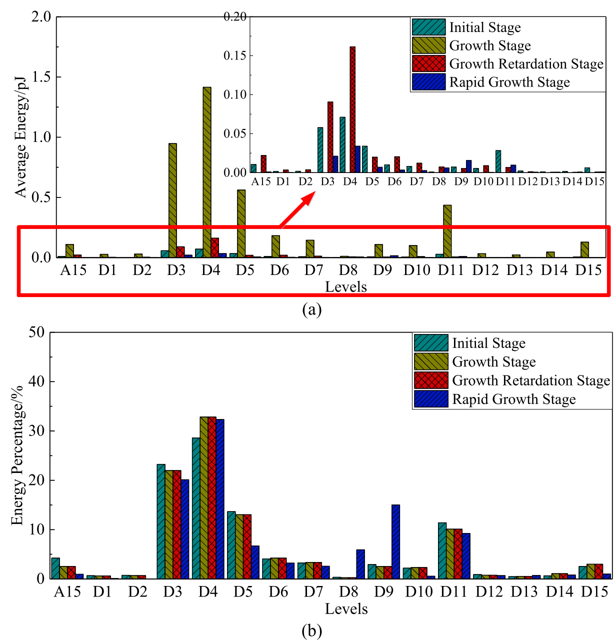

FIGURE 8. **(a) average energy and (b) energy distribution of PD signals during four stages in PE.**

stage of electrical tree, the larger PD energy is easy to form heat accumulation in polymer, which is conducive to speed increasing of electrical tree growth. Subsequently, under the corrosive effect of PD for a long time, polymers in the trunk channel of electrical tree are carbonized, so that the local short circuit phenomena appear in channels, and the PD energy decreases obviously.

Thirdly, in the growth retardation stage, the energy distribution is more concentrated in D3 and D4 layers, and the total energy percentage of rest decomposition layers is less than 7%. But in the rapid growth stage, the distribution of energy is the most dispersed, and energy percentages in D3, D4, D5, D8, D9 and D11 layers are all higher than 6%. Significantly, the D9 decomposition layer exists in the maximum energy percentage for the first time.

It can be seen from the above analysis that there is little difference between the characteristic and the magnitude of the average energy distribution in the initial stage, the growth stage and the growth retardation stage, and then in this case, the pattern recognition results of only using the average discharge energy and the energy average distribution as the characteristic parameters are still fuzzy. So far, the four stages of branch growth in PE can be roughly distinguished by characteristic parameters of discharge energy——the average discharge energy and the average energy distribution. Therefore, to realize more reasonable and accurate identification of branch growth discharge stage, the Back Propagation Neural Network (BPNN) is specially used after training learning and weight adjustment.

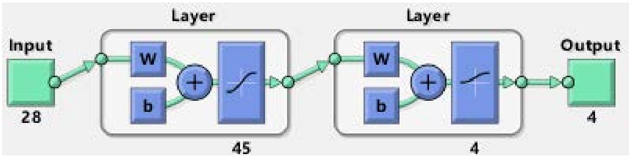

FIGURE 9. Schematic diagram of BPNN.

B. ANALYSIS OF PATTERN RECOGNITION BASED ON BACK PROPAGATION NEURAL NETWORK IN THE PROCESS OF PARTIAL DISCHARGE AND ELECTRICAL TREE

Continuous function approximating arbitrary precision and Boolean function can be expressed by the two-layer BPNN, while the three-layer BPNN structure can approximate any function with arbitrary precision.

Key information in the growth process of electrical tree is often hidden in PD signals. To realize the pattern recognition of PD signal in the branch growth stage, the three-layer BPNN structure was used, in which the number of the given input characteristic parameters is twenty-eight and the number of hidden neurons is forty-five, as shown in Fig. 9.

In the process of recognizing electrical tree growth by BPNN, there are five characteristic parameters selected to describe the discharge signals, such as a, b, c, d and e. The calculation formula is shown in formula (2) [30]:

$$\begin{cases} a = \dfrac{1}{N}\displaystyle\sum_{n=1}^{N} x[n] \\ b = (\dfrac{1}{N}\displaystyle\sum_{n=1}^{N} (x[n]-a)^2)^{1/2} \\ c = \dfrac{1}{ba^3}\displaystyle\sum_{n=1}^{N} (x[n]-a)^4 \\ d = \dfrac{1}{Na^4}\displaystyle\sum_{n=1}^{N} (x[n]-a)^4 \\ e = \dfrac{a}{b} \end{cases} \tag{2}$$

where N is the number of wavelet decomposition layers, and $x[n]$ is the wavelet coefficient of wavelet decomposition of the nth layer. After calculation and comparison, it is found that the five characteristic parameters are intertwined with each other and that their variation trend and regularity are not enough to realize pattern recognition. Therefore, it is necessary to use the energy distribution of decomposition layers (16 layers) of discharge signals, and then the time-frequency domain spectra is statistically analyzed, so as to realize the judgment and classification of detected PD signals. In this paper, characteristic parameters of time domain signals are usually statistical parameter of signals, and the common characteristic parameters are shown in Table 2 [31]–[38].

According to the characteristics of each parameter, the dimensional parameters and the dimensionless parameters are selected as characteristic parameters of branch discharge signals, including the Mean Value μ_x, Mean-Square Error σ_x^2, the Effective Value x_{rms}, the Peak-to-Peak Value X_{p-p},

TABLE 2. Statistical indicators of commonly used characteristic parameters.

Dimensional parameters	
Parameter Name	Calculation Formula
Mean Value	$\mu_x = \frac{1}{N}\sum_{n=0}^{N-1} x(n)$
Impulsion Index	$X_{if} = \frac{x_{max}}{\lvert\bar{x}\rvert}$
Mean-Square Value	$\Psi_x^2 = \frac{1}{N}\sum_{n=0}^{N-1} x^2(n)$
Waveform Indicator	$X_{wf} = \frac{x_{rms}}{\lvert\bar{x}\rvert}$
Mean-Square Error	$\sigma_x^2 = \frac{1}{N}\sum_{n=0}^{N-1} [x(n) - \hat{\mu}_x]^2$
Peak Index	$X_{pf} = \frac{x_{max}}{x_{rms}}$
Effective Value	$x_{rms} = \Psi_x = \sqrt{\lim_{T\to\infty} \frac{1}{T}\int_0^T x^2(t)dt}$
Skewness Indicator	$X_{sf} = \frac{\frac{1}{N}\sum_{i=1}^{N} x_i^3}{x_{rms}^3}$
Peak Value	$x_{max} = \max\lvert x(t)\rvert$
Kurtosis Index	$X_{kf} = \frac{\frac{1}{N}\sum_{i=1}^{N} x_i^4}{x_{rms}^4}$
Peak-to-Peak Value	$X_{p-p} = x_{max} - x_{min}$
Clearance Factor	$X_{cf} = \frac{x_{max}}{\left(\frac{1}{N}\sum_{i=1}^{N}\sqrt{\lvert x_i\rvert}\right)^2}$
Mean Absolute Value	$\lvert\bar{x}\rvert = \frac{1}{N}\sum_{i=1}^{N}\lvert x_i\rvert$

the Skewness Indicator X_{sf}, the Kurtosis Index X_{kf}, and the Clearance Factor X_{cf}.

At this time, the characteristic parameters of 28 are passed through the three-layer BPNN with hidden neurons of 45, and then the PD characteristics in the process of PE growth are accurately identified and classified after training cycle of 5000 steps. Fig. 10 is the training results of PE. After training of BPNN, the identification accuracy of branch stage can reach 99.93%. Subsequently, 500 groups of discharge characteristic parameters in the process of electrical tree growth are input into BPNN for pattern recognition, and the recognition results are shown in Fig. 11.

As can be seen from Fig. 11, the four stages in the growth process of PE electrical tree can all be identified accurately, including the initial stage, the growth stage, the growth retardation stage and the rapid growth stage. So far, the pattern

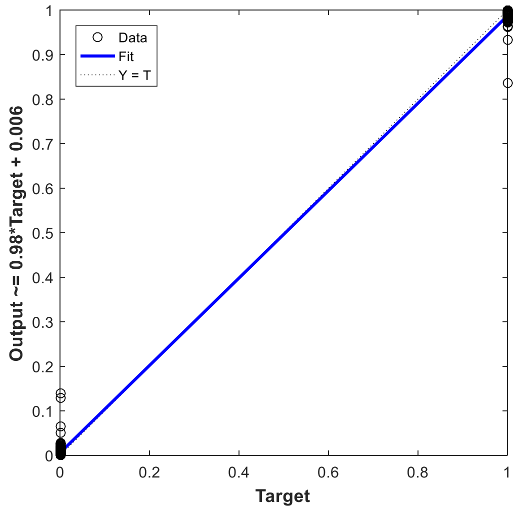

FIGURE 10. Training curve of PE.

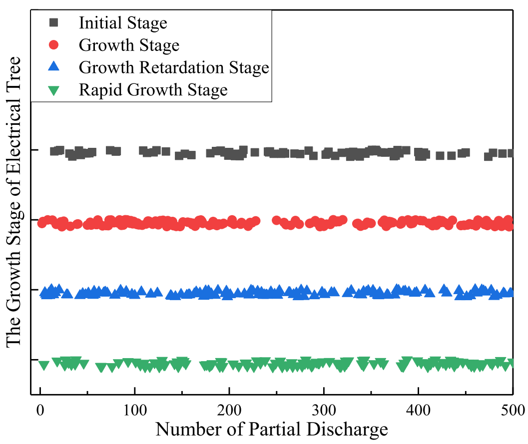

FIGURE 11. Discharge pattern recognition results of BPNN for the growth of electrical tree.

recognition of the discharge process is well realized, which lays the foundation for the subsequent insulation condition monitoring.

V. CONCLUSION

In this paper, the effective method of pattern recognition of electrical tree growth in PE samples is studied. Aiming at the main characteristics of PD signals during electrical tree, the twenty-eight parameter of UHF PD signals is selected as the characteristic parameter, and then the pattern recognition of electrical tree growth stages is carried out by the three-layer BPNN, such as initial stage, growth stage, growth retardation stage and rapid growth stage. The conclusions are as following:

(1) The energy amplitude varies at different stages. Amplitudes of UHF PD signals oscillate upward in the initial stage, which can reach up to 0.078V. In the growth retardation stage, the signal amplitude shows a trend of oscillating decline, with the decrease of 55.56%. In the growth stage and the rapid growth stage, the signal amplitude fluctuates in a certain range, and the discharge amplitude in the growth stage is much larger than that in the rapid growth stage.

(2) The average energy varies at different stages. The average discharge energy is the highest in the growth stage, which is as high as 4.31pJ, while the average discharge energy is the lowest in the rapid growth stage, which is as low as 0.11pJ.

(3) The average energy percentage varies at different stages. For the four stages of electrical tree growth, the concentration of average energy percentage is slightly different. The energy distribution is concentrated in the initial stage, the growth stage, and the growth retardation stage, while the energy distribution is scattered in the rapid growth stage. In addition, maximum energy percentage of four stages exists in D4 wavelet decomposition layer, which is 28.59%, 32.85%, 44.04% and 32.34%, respectively.

(4) Twenty-eight PD characteristic parameters were used as input parameters, such as the energy percentage of 16-layer wavelet decomposition, the wavelet coefficient parameter and the time-frequency domain parameter, which entered the three-layer Back Propagation Neural Network (BPNN) of forty-five hidden neurons, and then in the process of electrical tree growth, the accuracy of pattern recognition of any PD signals can reach 99.93% after 5000 steps of training cycle. The method can realize the accurate pattern recognition of PD signals during the growth stage of electrical tree.

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