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RESEARCH ARTICLE

The Partial Discharge Evolution Characteristics of 10kV XLPE Cable Joint

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ABSTRACT The evolution of partial discharge (PD) with time can provide a deep understanding on the insulation status of power cables. It is of great significance for intelligent operation and maintenance of power cables. In this paper, the PD pulse signal in the 10kV cable joint during accelerated electrical aging under 20kV AC voltage was acquired in the real-time for about 160h. The characteristic parameters of partial discharge–pulse number, average voltage, maximum voltage and energy per second were extracted. The results show that the phase of partial discharge is mainly concentrated at 30°-90° and 200°-270°, which can be characterized as internal discharge. PD characteristic parameters gradually increased after 50h. The pulse number, energy per second and the average voltage of PD pulse reached a peak between 60-80h. Then these parameters reached a steady state between 80-130h and showed a steep rise after 130h. The maximum voltage of PD pulse shows a steep rise at about 70h from 0.1V to 0.3V. It rises sharply from 0.3V to 0.5V after about 120h and then enters a relatively stable oscillation stage. The evolution rules of the PD characteristic parameters comply well with the electrical tree growth states-initiation period, lag period and rapid growth period. Furthermore, model for predicting and evaluating the insulation state based on BP neural network are established and the prediction accuracy is verified. The proposed models can provide early warning for the cable joint before the insulation failure, so as to ensure timely maintenance or replacement.

INDEX TERMS XLPE cable, partial discharge, accelerated electrical aging, BP neural network, state prediction.

I. INTRODUCTION

As the core equipment for high-voltage power grid energy transmission, XLPE (Cross-linked Poly-ethylene) cables have a significant impact on the reliability of power grid operation [1], [2], [3]. Compared with the cable body, cable joints are prone to insulation degradation and breakdown due to their complex structure and on-site production. PD signal is an important parameter to investigate the insulation aging mechanism of cable [4], [5]. The evolution rule of PD parameters is helpful for evaluating the degradation status and revealing aging mechanism of cable insulation [6]. It is of great significance for intelligent operation and maintenance of power cables.

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In recent years, the partial discharge characteristics with typical defects in cable and the partial discharge characteristics during the growth of electrical tree are mainly concerned. Yang et al. [7], Chang et al. [8], Zhou et al. [9], Chang et al. [10] and Zhao et al. [11] revealed the characteristics and evolution process of partial discharge under different defects by designing discharge models of cable joint defects. The results indicated that the PD evolution rules of cables is varied under different defects. They can provide experimental basis for further research on the discharge mechanism of cable joint and pattern recognition of discharge types. However, the above researches is insufficient to investigate the specific relationship between cable insulation degradation status and partial discharge.

Electrical treeing is a type of cable aging phenomenon [12]. It is of great significance to investigate the partial discharge characteristics during the electrical treeing process for evaluating the insulation degradation status of cables. Zhu et al. [13] investigated the effect of space charge on PD under AC voltage. Simulation results suggested that the characteristics of PD and tree growth may be associated with the accumulated charge around the needle tip. Peng et al. [14] and Han et al. [15] investigated the effects of voltage and temperature on the morphology of electrical trees. The results showed that the partial discharge intensity increases with the increase of voltage and temperature. Liu et al. [16], Liu et al. [17] and Zhu et al. [18] investigated the growth characteristics of electrical trees in cables under DC and AC voltages, and the results showed that under the same conditions, DC trees grow quite slowly compared with AC trees. Liao et al. [19] and Liu et al. [20] revealed that the growth rate of electrical tree is highly consistent with the severity of partial discharge. The main concern of above researches is the growth of electrical tree and evolution rules of PD characteristics in cables under different conditions. It can contribute to reveal the mechanism of cable insulation degradation and evaluating the status of cable insulation degradation. However, there is insufficient research on the long-term evolution of partial discharge in cable joints. Besides, there are few studies about the relationship between the evolution trend of partial discharge characteristic parameters and the growth of electrical tree during the whole process of cable insulation deterioration. So the present researches are insufficient for evaluating and predicting the cable insulation state based on the partial discharge characteristics.

This paper investigated the evolution characteristics of PD in 10kV XLPE cable joint. The characteristic parameters of partial discharge-pulse number, average voltage, maximum voltage and energy per second are extracted. The results show that these PD characteristic parameters appeared after 50h and the evolution rules of them can divide into three stages. The rules of PD characteristic parameters in this three stages comply well with the electrical tree growth states-initial period, lag period and rapid growth period. So these parameters can be used to judge the insulation aging degree of cable. In order to further evaluate and predict the insulation condition of the cable by these parameters, the prediction model of cable insulation aging based on BP neural network is established. The results show that the accuracy of prediction model is high. So this prediction model are of great significance to the condition-based maintenance of the cable.

II. EXPERIMENTAL DESIGN OF PARTIAL DISCHARGE IN XLPE CABLE JOINT

A. CONSTRUCTION OF EXPERIMENTAL PLATFORM

In this paper, a PD detection system based on high-frequency current detection is set up as shown in Fig.1. It used to collect the PD parameters of the cable joint. The system mainly includes a testing transformer, voltage regulator, signal acquisition and storage module.

In the detection system, a set of PD acquisition and storage device based on Labview is built. It is composed of HFCT, ultrasonic sensor(type PVDF, PVDF piezoelectric sensor has the advantages of high sensitivity of electro-mechanical conversion, wide frequency band, low acoustic impedance and good mechanical properties, so the ultrasonic sensor is used in the experiment.), oscilloscope (type DPO7054) and upper computer software(the software system for collecting and storing the PD pulse signal). Among them, HFCT is used to collect PD signals and ultrasonic sensor is used to collect power frequency signals (In order to extract phase information). Coaxial cable shielding lines are used as the output lines of the sensor to avoid electromagnetic interference. Sampling rate of the oscilloscope is set to 20M/s, the storage depth is set to 400K and the sampling duration is set to 1s.

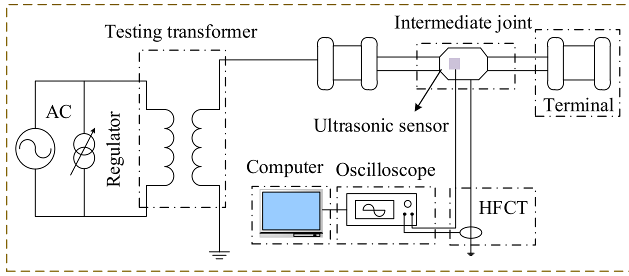

FIGURE 1. Experimental circuit of PD detection for cable joint.

Experimental cable is composed of cable body, cable joint and cable terminal. Two cables (type YJV-8.7/15kV-3 × 70) are connected by cable joint (type JLS-8.7/15kV-1 × 70). The outer shield and semiconducting layer of cable terminal are stripped for a length. Then, it is inserted into oil cup that filled with pure transformer oil. The cable core passes through the metal base of the high voltage end of the oil cup, and is connected to testing transformer by halo free line. The type of the testing transformer is TDM (G) -5/100. It is indoor testing transformer with 50Hz.

B. ACCELERATED AGING AND PD DETECTION EXPERIMENT

In this paper, the aging cycle of cable is shortened through accelerated aging experiments, which can used to investigate the evolution characteristics and achieve accurate evaluation and prediction of cable insulation aging status within limited time. The cumulative time that used to accelerate aging is more than 160 hours under the AC 20kV voltage with 50Hz. The specific process of the experiment is shown in Fig.2. The main experimental steps are as follows.

(1) Connecting the experimental cable as shown in Fig.1. Continuous AC voltage of 20 kV is applied to the cable circuit by controlling the voltage regulator. The PD detection system is used to collect PD signals from accelerated aging cables.

(2) When the PD signals occur, the time is needed to record. In order to further confirm whether the PD signal only comes from the cable joint, it is necessary to conduct PD detection on the cable terminal and the cable body. The specific methods are as follows.

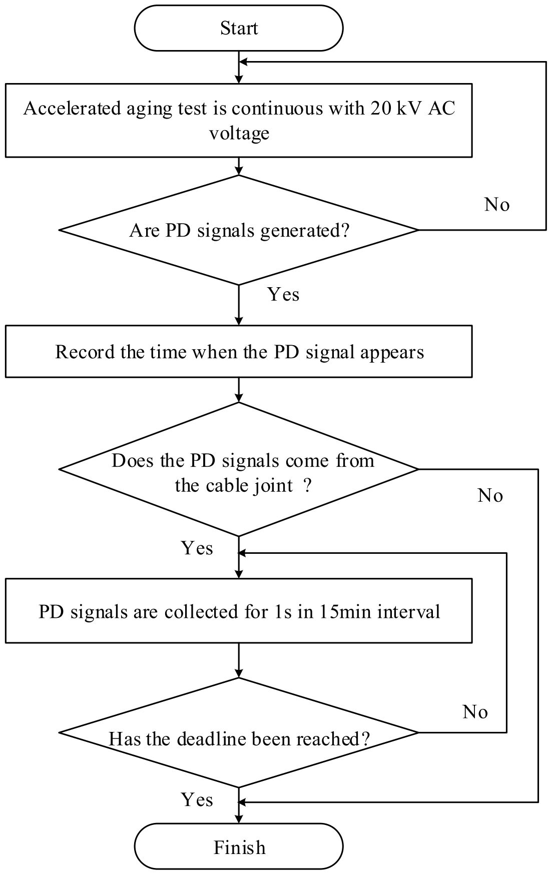

FIGURE 2. PD signals detection process for cable joint.

An ultrasonic sensor is attached to the cable joint, and the other one is attached to the cable body or the cable terminal. The ultrasonic sensor attached to the cable body is connected to the first channel of the oscilloscope, and the other one is connected to the second channel of the oscilloscope. Through the experiment, it is found that the PD signal from the second channel of scilloscope is more obvious and there is almost no PD signals from the first channel of scilloscope, which can accurately judged that the PD signal only comes from the cable joint. At this time, the PD signal of the cable joint is continuously collected.

(3) The time interval for recording data is set to 15min and the duration of collecting PD signals is set to 1s. The data collection is completed in the aging cycle.

III. SIGNAL PROCESSING OF PARTIAL DISCHARGE

A. PD SIGNALS DENOISING

PD signals measured in the laboratory contain white noise. In order to effectively extract the PD signals and accurately analyze the evolution process of the PD signals under accelerated aging conditions, it is necessary to conduct noise reduction processing on the original PD signals.

In this paper, the denoising function named wden is used to suppress white noise in PD signals based on wavelet analysis [21]. The obtained PD signal waveforms before and after noise reduction are shown in Fig.3 and Fig.4. As can be seen from Fig.3 and Fig.4, the wavelet denoising effect is obvious. The amplitude and the corresponding time of partial discharge do not change before and after denoising, so it can be seen that the signal is real after denoising.

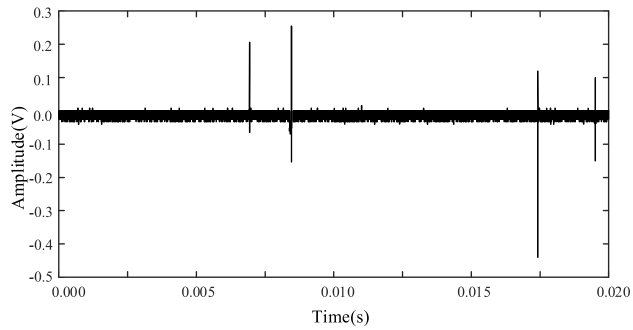

FIGURE 3. Original PD signals of cable joint.

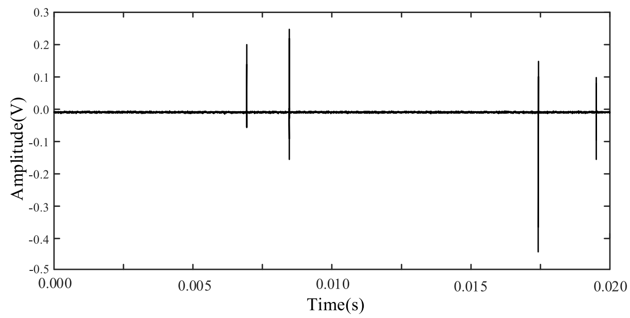

FIGURE 4. Denoising effect of original PD signals.

B. SELECTION OF CHARACTERISTIC PARAMETERS

PD signals are related to cable insulation aging status. Therefore, the four characteristic parameters of PD signals-pulse number, average voltage, maximum voltage and energy per second are extracted based on matlab. They are used to analyze the evolution rules of cable aging. The specific extraction method is as follows.

1) PULSE NUMBER(N)

In this paper, a method named sliding window with adaptive threshold is used to extract pulses from the denoised PD signals in order to construct the PRPD spectrum of a partial discharge signal [22].

After denoising the output signal of the HFCT sensor, the amplitude of the PD voltage is extracted. If the amplitude is greater than the set threshold value, it indicates that there is partial discharge. Then the number of times that the PD appears is recorded.

2) MAXIMUM VOLTAGE(V_{max})

The partial discharge voltage within 1s is collected. So the maximum partial discharge voltage within 1s can be extracted.

3) AVERAGE VOLTAGE(V_{av})

The ratio of the accumulated partial discharge voltage amplitude within 1s to the pulse number is the average value of the partial discharge voltage.

4) ENERGY PER SECOND(E)

During the experimental time of T, it is assumed that the number of partial discharge occurs is n and the energy of each partial discharge is W_i. W_i is as shown in Equation 1.

$$W_i = 0.5 \times q_i \times U \tag{1}$$

where U represents the effective value of the applied voltage. q_i represents the apparent charge of the i-th partial discharge. It can be calculated by the pulse current calibration method based on IEC stipulation.

When calculating the total partial discharge energy, the partial discharge energy for each time is accumulated. The unit is μJ. Calculation of the total partial discharge energy within T is shown in equation (2).

$$W = W_1 + W_2 + \cdots + W_n \tag{2}$$

C. JUDGMENT OF THE PARTIAL DISCHARGE TYPE IN CABLE JOINT

In this paper, the phase information is collected from ultrasonic sensors. Initial phase is obtained by Fourier decomposition. Sampling depth is 400K. Angular spacing between each two points can be calculated using equation (3).

$$\Delta\varphi = \frac{360°}{400\text{K}} \tag{3}$$

Phase angle corresponding to each partial discharge can be calculated using equation (4).

$$\varphi = \varphi_0 + n \times \Delta\varphi \tag{4}$$

where φ_0 is the initial phase. n is the location of the data point where partial discharge occurs. When φ is outside 0° to 360°, it should adjust to be within the phase range.

After extracting the characteristic parameters of PD signal, the two-dimensional spectrogram of the PD signal are drawn as shown in Fig.5.

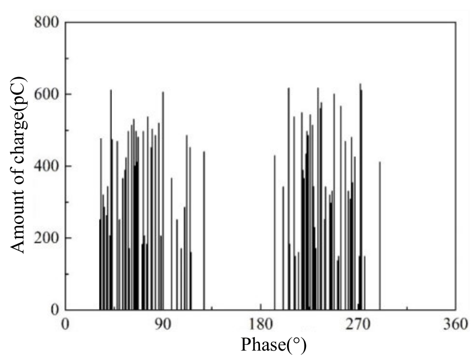

FIGURE 5. Spectrogram of partial discharge in the cable joint.

It can be seen from Fig.5 that the phase of partial discharge is mainly concentrated at 30°-90° and 200°-270°, which can be characterized as internal discharge.

D. EVOLUTION RULES AND ANALYSIS OF THE PD PARAMETERS

Curves of PD parameters are shown in Fig.6 to Fig.10. It can be seen from the figures that the characteristic parameters of partial discharge gradually increase after 50 hours.

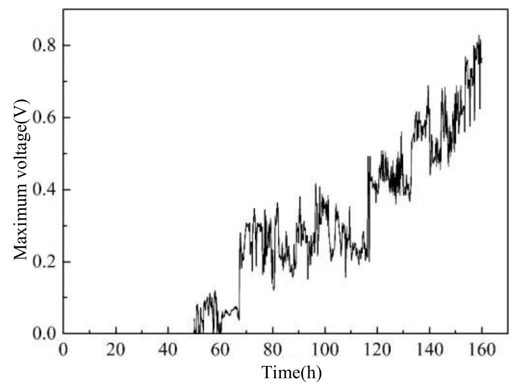

FIGURE 6. Curve of maximum voltage with time.

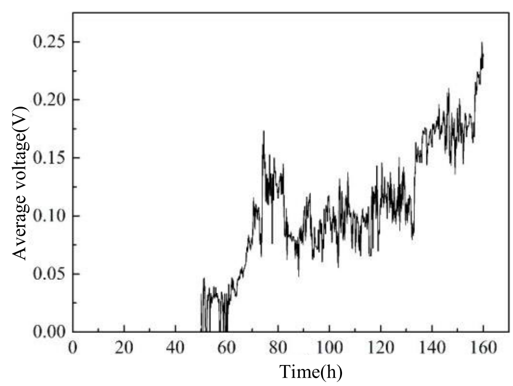

FIGURE 7. Curve of average voltage with time.

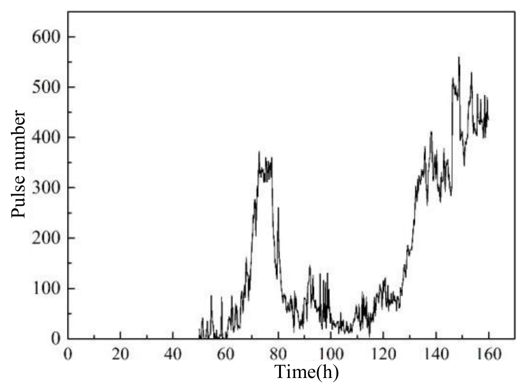

FIGURE 8. Curve of pulse number with time.

It can be seen from Fig.6 that V_{max} rises sharply from 0.1V to 0.3V in about 70 hours. It remains stable for a period of

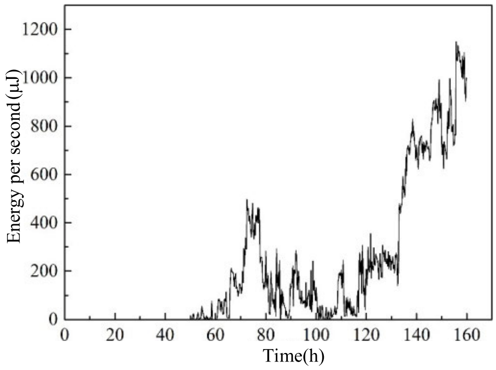

FIGURE 9. Curve of energy per second with time.

time after 70 hours. In about 120 hours, it rises sharply from 0.3V to 0.5V. It enters a relatively stable oscillation stage after 120 hours. The amplitude of partial discharge pulse increases with the increase of aging time. It indicates that the insulation damage of cable joint is becoming more and more serious under accelerated electrical aging.

It can be seen from Fig.7 to Fig.9 that V_{av}, N and E reach the peak value between 60 hours to 80 hours. Then they reach a stable state between 80 hours to 130 hours. During this period, the changes of every characteristic parameters with time are relatively stable. After the stable period, they began to rise sharply in about 130 hours. The curves of PD parameters have strong volatility because of the large randomness of partial discharge. So in the following work, the PD parameters are filtered that used the sliding window filtering method and then their evolutionary characteristics are analyzed.

In order to describe the rules of cable insulation aging more clearly and guide to estimate its insulation aging status. E and V_{av} are selected for filtering. Then comparing the filtered E and V_{av} with the growth process of the electrical tree. The result is shown in Fig.10.

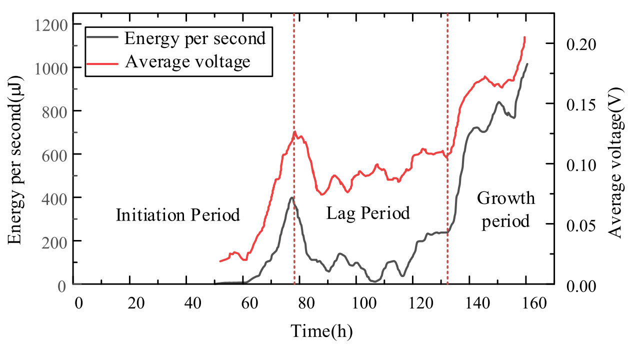

FIGURE 10. Evolution rules of energy per second and average voltage with time.

It can be seen from Fig.10 that partial discharge does not appear until about 50 hours after accelerated electrical aging. This is because there is an initiation time in the first stage of electrical tree growth. After 50 hours, the average value of E and V_{av} slowly increase to 414.09 μJ and 131.36 mV. It means that they enter the second stage.

The second stage lasted nearly 56 hours. E and V_{av} were in a fluctuating status in this stage. Their amplitudes ranged from 16.82 μJ to 414.09 μJ and 77.32 mV to 131.36 mV respectively. At the end of this stage, there is a platform period that accounts for nearly one fifth of the total duration of the stage. There is no significant fluctuation in E and V_{av} within the platform. The average value of E and V_{av} at the end stage is 243.73 μJ and 108.28 mV respectively.

In the third stage, E and V_{av} have significantly increased compared to the previous two stages. This indicates that the aging rate of insulation is accelerated. The amplitude eventually increased to 1022.81 μJ and 207.14 mV respectively.

From the above analysis, it can be seen that the evolution rules of E and V_{av} comply well with the electrical tree growth states-initiation period, lag period and rapid growth period. At the same time, the breakdown of cable joints caused by partial discharge can be regarded as the effect of energy accumulation. When the discharge energy accumulates to a certain extent, it can lead to the insulation failure of the cable joint. Therefore, the insulation aging status of cable joints can be evaluated by predicting the E and V_{av} of the cable joints.

IV. PREDICTION MODEL OF XLPE CABLE INSULATION STATUS

A. ESTABLISHMENT OF THE PREDICTION MODEL

From the above analysis, E and V_{av} can effectively reflect the insulation aging status of the cable. Therefore, the insulation aging status of the cable can be estimated by predicting these values. In this paper, a prediction model based on BP neural network is established. The network structure is shown in Fig.11.

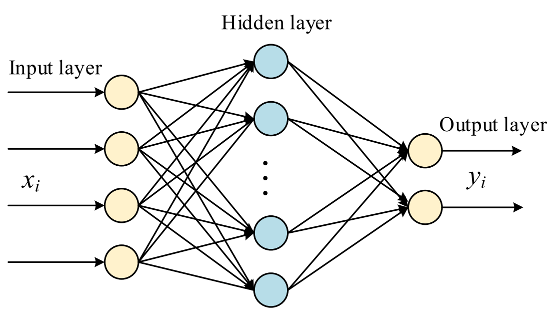

FIGURE 11. Three-layer structure of neural network.

1) INPUT LAYER

The current pulse number (N), the maximum voltage (V_{max}), the average voltage (V_{av}) and the energy per second(E) are used as input variables.

2) OUTPUT LAYER

The future average voltage (V_{av}) and the energy per second(E) are used as the output variable.

TABLE 1. Prediction results I.

Sample	True Value(μJ)	Prediction(μJ)	Relative Error(%)	True Value(V)	Prediction(V)	Relative Error(%)
75	249.65	240.49	3.67	0.0904	0.0871	3.69
76	264.54	253.52	4.17	0.0910	0.0867	4.72
77	278.13	266.98	4.01	0.0951	0.0914	3.93
78	289.57	278.42	3.85	0.0991	0.0947	4.41
79	302.60	289.66	4.28	0.1039	0.1001	3.71
80	319.36	305.17	4.44	0.1069	0.1021	4.55
81	331.62	319.85	3.55	0.1105	0.1048	5.19
82	342.85	327.29	4.54	0.1115	0.1064	4.59
83	356.76	339.52	4.83	0.1126	0.1065	5.35
84	364.25	348.05	4.45	0.1131	0.1073	5.05

3) HIDDEN LAYER

The number of neurons in the hidden layer is calculated according to formula (5).

$$l = \sqrt{n+m} + c \tag{5}$$

In the above formula, l is the number of hidden layers. n is the number of neurons in the input layer. m is the number of neurons in the output layer. c is a variable constant which value ranges from 1 to 10. During network training, the number of hidden layers is only a range value. Therefore, the method of successive analysis is used to obtain.

4) FUNCTION SELECTION

The prediction of V_{av} and E in this paper are nonlinear problems. Therefore, an S-type tangent function is selected as the activation function. As shown in Formula (6).

$$f(u) = \frac{1-e^{-2u}}{1+e^{-2u}} \tag{6}$$

The average value of V_{av} and E in the output layer is greater than 0. Therefore, an S-type logarithmic function is selected as the output layer function, whose formula is shown in Equation (7).

$$f(u) = \frac{1}{1+e^{-u}} \tag{7}$$

B. DETERMINE SAMPLE DATA

In this paper, the curves of PD parameters are divided into three stages-initiation period, lag period and rapid growth period corresponding to electrical tree aging. The determination process of samples at different aging stages are as follows referring to Figure 10.

(1) Firstly, it is necessary to extract the first peak point in E. The time point corresponding to the peak point is the end time of the initiation period.

(2) It needs to calculate the difference of energy at adjacent time points after the peak point. Then it needs to set a threshold value for the difference. When the energy difference is less than the set threshold value, the platform period is found. The end time point of the platform period is the end time of the lag period.

(3) The stage after the lag period is the growth period of the electrical tree.

Using the above method, the sample data is divided into three different aging stages. When training a model, the model should be trained in different stages during prediction because the growth rules of electrical tree branches are different at different stages, so that the prediction results are more accurate at different stages.

C. DATA HANDLING

The sample data used in this paper are PD data about accelerated aging of cables. It needs to normalize them because the different units of recorded sample data, as shown in Equation (8).

$$X_p' = \frac{X_p - X_{p\,\mathrm{min}}}{X_{p\,\mathrm{max}} - X_{p\,\mathrm{min}}} \tag{8}$$

In the formula, the sample data are X_p, where $p = 1,2,\ldots, n$. The maximum and minimum values of X_p are $X_{p\,\mathrm{max}}$ and $X_{p\,\mathrm{min}}$ respectively.

In this paper, there are 420 sets of data in the sample data, which are divided into three stages. When training the network model for each stage, the first 80% of the normalized data are chosen to train the network and the last 20% of the data as the network error test.

D. PREDICTION RESULTS OF THE MODEL

Taking 80 percent of the sample data in each stage as the training set and the remaining data as the test set. So as to obtain the prediction results in initiation period, lag period and rapid growth period as shown in Tab.1 to Tab.3 represently.

As can be seen from Tab.1, the prediction error of V_{av} and E during the initiation period is about 4%. During this stage, V_{av} and E have the strongest regularity.

As can be seen from Tab.2, the relative error of the predicted values named V_{av} and E within the lag period is less than 7%. In this stage, V_{av} and E decrease significantly compared to the previous stage, but their fluctuation intensity is large and their regularity is weak. Therefore, the relative error of the prediction results at this stage tends to increase

TABLE 2. Prediction results II.

Sample	True Value(μJ)	Prediction(μJ)	Relative Error(%)	True Value(V)	Prediction(V)	Relative Error(%)
309	243.00	232.68	4.25	0.1148	0.1206	5.05
310	242.92	229.49	5.53	0.1145	0.1193	4.19
311	242.26	227.42	6.13	0.1110	0.1168	5.23
312	234.99	221.63	5.69	0.1113	0.1182	6.20
313	232.82	217.26	6.68	0.1091	0.1161	6.42
314	243.73	231.12	5.17	0.1083	0.1149	6.09
315	255.11	238.87	6.37	0.1091	0.1157	6.05
316	265.96	249.89	6.04	0.1092	0.1162	6.41
317	275.04	260.64	5.24	0.1118	0.1183	5.81
318	288.03	271.41	5.77	0.1121	0.1191	6.24

TABLE 3. Prediction results III.

Sample	True Value(μJ)	Prediction(μJ)	Relative Error(%)	True Value(V)	Prediction(V)	Relative Error(%)
416	860.55	904.57	5.12	0.1773	0.1870	5.44
417	881.11	912.24	3.53	0.1780	0.1861	4.53
418	903.33	955.08	5.73	0.1763	0.1850	4.93
419	917.14	972.96	6.09	0.1750	0.1853	5.89
420	927.67	957.50	3.22	0.1755	0.1811	3.22
421	940.86	974.59	3.58	0.1757	0.1827	3.96
422	950.94	997.32	4.88	0.1769	0.1866	5.48
423	955.66	1010.21	5.71	0.1791	0.1886	5.31
424	958.37	1009.70	5.36	0.1821	0.1939	6.46
425	965.01	1029.97	6.73	0.1838	0.1934	5.27

compared to the previous stage. As the insulation at this stage is slightly damaged, so the insulation strength can also ensure stable operation of the cable for a long time. Even if the relative error of the prediction results at this stage is too large, it will not cause serious impact.

As can be seen from Tab.3, the prediction error of V_{av} and E during the growth period is about 6%. During this stage, V_{av} and E have strong regularity.

To sum up, the error between the predicted value and the actual value in the above three stages is within 7%. Therefore, the validity of the prediction model about cable insulation status is verified, which has important reference value for the preventive maintenance and overhaul of the cable in the later stage.

V. CONCLUSION

This paper experimentally investigated the evolution of PD characteristic parameters with time in 10kV cable joint during accelerated electrical aging. A novel method for estimating the insulation state of XLPE cable joint is proposed by establishing a BP neural network prediction model. The main conclusions are as follows:

1) The discharge pulse phase of the cable joint through accelerated electrical aging is mainly concentrated in 30°-90° and 200°-270°, which can be characterized as internal discharge.

2) After 50h of 20kV accelerated electrical aging, the partial discharge signal occurs at the cable joint. Moreover, the evolution rules of PD characteristic parameters can be divided into three stages. They are comply well with the electrical tree growth states-initial period, lag period and rapid growth period, which can be used as the characteristic parameters to judge the insulation aging degree of cable.

3) The prediction and evaluation model of cable insulation status based on BP neural network is established. The prediction errors are all within 7%. The proposed model can provide early warning to cable before insulation failure, which is of great significance to the later condition-based maintenance of the cable.

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