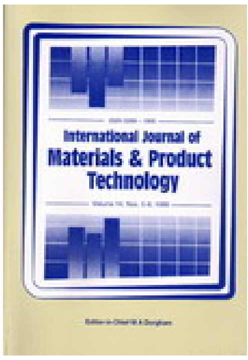

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Leakage current detection method of electrical insulation materials based on windowed-added Fourier transform

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Abstract: In order to effectively solve the disadvantages of low accuracy of leakage feature recognition and low accuracy of detection results in traditional leakage current detection methods, a leakage current detection method of electrical insulating materials based on windowed Fourier transform is proposed. Firstly, the windowed Fourier transform process is analysed to judge the related properties of leakage current signal. Then, the leakage current detection unit is designed by using the insulation equivalent model, leakage current detector, self-excited oscillator, second-order low-pass filter and windowed Fourier transform process. Finally, based on the leakage characteristics of electrical insulation materials, the leakage current detection process is designed to complete the leakage current detection of electrical insulation materials. The results show that the recognition accuracy of leakage characteristics is always above 95%.

Keywords: electrical insulation materials; leakage current; leakage detection; windowed-added Fourier transform; feature recognition.

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Biographical notes: Yulin Zhuang was a second year undergraduate major in Electrical Automation at the Guangdong University of Technology. He has tremendous interest in leakage current measurement reference, Fourier transform examples and solutions, machine vision inspection systems, and image processing. When he was a freshman, he joined the Association of Research Team and began to narrow down his interest for his future research.

1 Introduction

The essence of electrical insulation is to isolate the charged body, so as to avoid short circuit and grounding fault of the line, and also prevent the electric shock danger caused by the charged body to the external environment (Song and Cheng, 2020). Usually, electrical insulation materials are used to achieve electrical insulation. Electrical insulation materials have very high resistivity, under the action of voltage can be current through. Electrical insulation materials are often used to isolate the electric body, to promote the current to flow in the specified direction, so as to maintain electrical safety (Darwison et al., 2019). However, in some special cases, such as the line voltage is 3.5 times higher than the withstand value of the insulation material, and the continuous high voltage state is more than 1 minute, it is very likely to lead to the breakdown of the insulation material, resulting in the leakage phenomenon (Ge et al., 2019). The leakage current detection of electrical insulation materials can effectively monitor the leakage state of electrical insulation materials.

Therefore, a leakage current detection method based on harmonic extraction is designed in Kang and Zhang (2020). On the basis of analysing the causes of leakage current and the harmonic characteristics of leakage current, this method analyses the disadvantages of the existing leakage current detection hardware system. Based on this, a leakage current detection method is designed through harmonic extraction, mainly for the detection of high-frequency harmonic leakage current, continuous leakage current and sudden leakage current. However, it is found in practical application that this method has the problem of low accuracy of leakage current feature recognition. A leakage current detection method based on optimised FFT analysis is designed in Huang et al. (2019). Firstly, the ratio process of harmonic parameters is corrected, and then the frequency, amplitude and phase of harmonics are calculated by combining the window spectrum function. On this basis, windowing and correction algorithms are used to optimise the FFT process so as to reduce the influence of spectrum leakage and fence effect on the leakage current detection process. In Peng et al. (2019), a leakage current detection method based on measured spatial leakage method is designed. In the high humidity and strong electric field interference environment, the method carries out power outage test on related equipment, and finds that there is leakage current in the pressure equalising ring space at the pressure point. Therefore, the method detects the location of leakage current by analysing the leakage situation in the pressure sharing ring space. However, in practical application, the above two methods have the problem of low accuracy of detection results.

In view of the shortcomings of the above traditional methods, such as low accuracy of leakage feature recognition and low accuracy of detection results, a leakage current detection method of electrical insulating materials based on windowed Fourier transform is designed in this study. The design idea of the new method is as follows.

Firstly, the windowed Fourier transform process is analysed and applied to the sampling and conditioning module, which can analyse the change of leakage current signal and judge the related properties of leakage current signal.

Then, the leakage current detection unit is constructed by using the sampling conditioning module, insulation equivalent model, leakage current responder, self-excited oscillator, second-order low-pass filter, ad digital controller and differential detection and maintenance module. The leakage characteristics of insulating materials are determined through the establishment of these units, which lays a foundation for subsequent research.

Finally, a specific leakage current detection process is designed based on the leakage characteristics of electrical gas insulation materials.

2 Process design of windowed-added Fourier transform

Windowed-added Fourier transform is often applied in the analysis and processing of non-stationary signals to study the changes of non-stationary signals with spatial changes, so as to judge the properties of a certain position (x, y) in space (Niu et al., 2019). According to the window function of space centre point c at (x, y), the non-stationary signal s(x, y) is window-processed, and then the local characteristics of signal s(x, y) are analysed by Fourier transform.

In this process, assume that the windowed-added function is w(x, y), take any point (m, n) in the space as the local signal centre, and windowing the non-stationary signal s(x, y) as follows:

$$z(x, y) = s(x, y)w(x - m, y - n) \tag{1}$$

On this basis, the Fourier transform operation is implemented on formula (1), which can be obtained as follows:

$$\mathrm{STFT}\{z(x, y)\} = \frac{\mathrm{FFT}s(x, y)w(x - m, y - n)}{\exp(\varphi x + \omega y)} \tag{2}$$

In formula (2), exp(φx + ωy) represents the basis for the Fourier transform. Then, the windowed-added Fourier w(x – m, y – n) is used to limit its space, and the windowed-added Fourier transform basis can be obtained as follows:

$$w'(x - m, y - n) = w(x - m, y - n)\exp(\varphi x + \omega y) \tag{3}$$

Before adding the windowed-added Fourier transform, in order to avoid the interference of invalid information points in the frame, the filtering process needs to be supplemented, which is divided into the following two steps:

1. In general, the frequency of noise information is high. Therefore, the function F(m, n) is used to define the spectral value outside the stable frequency range in the windowing Fourier spectrum as 0, so as to achieve spatial local low-pass filtering (Lu et al., 2020).
2. Although the frequency of noise information is high, its power spectral density is relatively high.

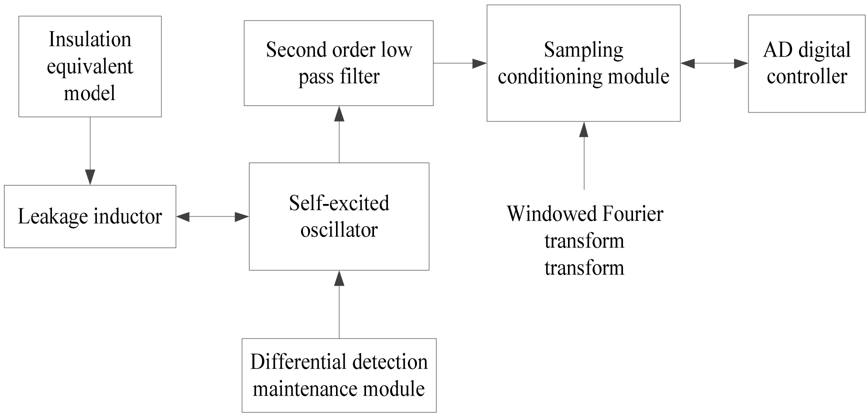
Applying the windowed-added Fourier transform process to leakage current detection of electrical insulation materials can analyse the changes of leakage current signals, so as to judge the related properties of leakage current signals, and lay a foundation for subsequent leakage current detection.

3 Design of leakage current detection method for electrical insulation materials

3.1 Leakage current detection principle of electrical insulation materials

In this study, a leakage current detection unit of electrical insulation material is designed to cooperate with the detection of leakage current. The detection unit mainly consists of insulation equivalent model, leakage current sensor, self-excited oscillator, second-order low-pass filter, sampling conditioning module, AD digital controller, differential detection and maintenance module. The simplified structure of leakage current detection unit of electrical insulation material is shown in Figure 1.

Figure 1 Simplified structure diagram of leakage current detection unit for electrical insulation materials



In the leakage current detection unit of electrical insulation material, when the leakage current occurs in the electrical insulation material, the self-excited oscillator will form a high frequency oscillation signal on the secondary winding of the leakage current sensor, and then the signal will be transmitted to the main winding of the leakage current sensor, and converted into a low frequency carrier signal. At this point, the current flows through the leakage current sensor contains a normal leakage current of high frequency signal and low frequency signal, these two kinds of signal transmission by the self-excitation oscillator to second-order low-pass filter, and then through a low-pass filter, the normal high frequency signals can also be transformed into low frequency leakage current signal, after sampling conditioning module will be transported to the AD in the digital controller. In this process, the differential detection and maintenance module can protect the leakage current with too large value, and implement windowed-added Fourier transform on the low-frequency leakage current signal in the sampling and conditioning module. Through this operation, the change of the low-frequency leakage current signal is analysed, so as to obtain the related properties of the low-frequency leakage current signal.

3.2 The equivalent insulation model of materials is constructed

Common solid state electrical insulating materials include mineral insulating oil, rubber pad, mica plate, etc. Their simplified structure is shown in Figure 2.

According to the classification of electrical insulation materials in Figure 2, it can be seen that they are mainly divided into main insulation and longitudinal insulation. Therefore, in order to further optimise the reliability and rationality of the equivalent model, this study firstly analyses the dielectric of electrical insulation before constructing the equivalent model of material insulation.

The insulation process of electrical equipment can be understood as the polarisation process between mineral insulating oil, rubber pad, mica plate and other structures (Zhang et al., 2019; Xv et al., 2019). Therefore, assuming that the external electric field of the electrical equipment is E, a certain amount of electrical displacement will be generated inside the insulating material after its contact with the insulating material. On this basis, according to Maxwell's equations, when a homogenous medium in the electrical equipment is applied to the insulating material, the current density ρ_I flowing through the electrical equipment is equal to the sum of the displacement current density and conduction current density, namely:

$$\rho_I = \sigma E + \frac{D}{t} \tag{4}$$

In formula (4), σ represents the conductivity of electrical insulation material. D represents the electric displacement vector in the vacuum state; t represents the time period of the electric displacement. It is known that in the vacuum state, there is a direct proportional relationship between the electric displacement vector D and the external electric field E of the electrical equipment, namely:

$$E = \varepsilon_0 E \tag{5}$$

In formula (5), ε_0 represents the dielectric constant in the vacuum state (Guo et al., 2020), and its value is $\varepsilon_0 = 8.8537 \times 10^{-12}$ F/m. After this formula is applied to the inside of electrical equipment, it can be found that the electric displacement also contains the polarisation intensity P of part of the dielectric, so the relationship between P and D can be expressed as:

$$D = \varepsilon_0 E + P \tag{6}$$

Formula (6) is used to analyse the dielectric and electric displacement inside the electrical equipment, and the equivalent model of material insulation is built according to the analysis results. Based on formulas (2) to (4), it can be seen that applying voltage U to both ends of electrical insulation material is equivalent to applying electric field intensity of E_1 size to both ends of an electrical equipment with a stage plate distance of l and a plate area of S. Assume that the vacuum capacitance is as follows:

$$C = \frac{sU}{l\varepsilon_0} \tag{7}$$

At this point, the electric field intensity E_1 at both ends of the electrical insulation material can be obtained:

$$E_1 = \frac{CU}{\varepsilon_0 S} \tag{8}$$

Combined with the above process, the equivalent model of material insulation can be set in the form shown in Figure 3.

According to the equivalent model of material insulation, the current I reaching the electrical insulation material can be calculated by applying voltage, and the specific process is as follows:

$$I = \frac{U}{R} + \frac{CdU}{dt} + \frac{CS(\varepsilon)U(t-\varepsilon)d\varepsilon}{dt} \tag{9}$$

In formula (9), R represents the insulation resistance of electrical equipment, and C represents the geometric capacitance of electrical equipment (Liu et al., 2019). So far, the equivalent model of material insulation has been constructed.

Figure 2 Simplified construction of solid state electrical insulation (see online version for colours)

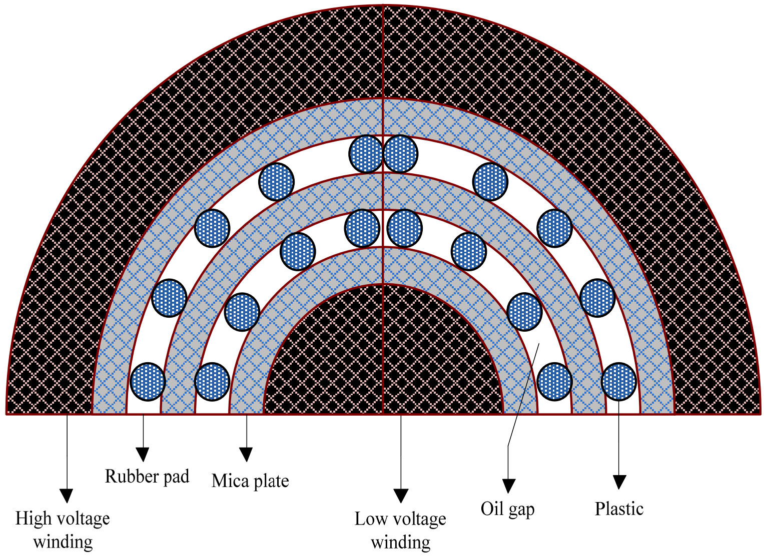
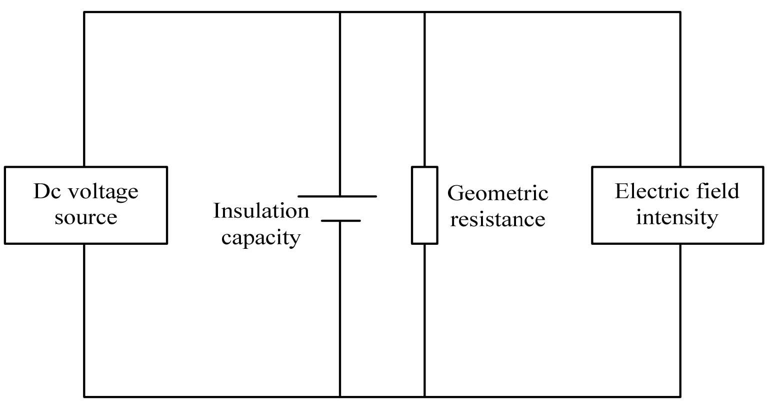


Figure 3 Structure diagram of equivalent model of material insulation



3.3 Collection of leakage characteristics of electrical insulation materials

In the material insulation equivalent model constructed above, the leakage characteristics of electrical insulation materials are collected to lay a foundation for the subsequent leakage current detection process. In the normal operation of power equipment, the value of its internal voltage and surrounding electric field is relatively large, which easily leads to cracks in electrical insulation materials (Goldshtein et al., 2019). Even if the breakdown voltage reaches more than 3.5 times of the voltage withstand value of the insulation material and lasts for a long time, the electrical insulation material is very likely to be broken down, resulting in leakage phenomenon, which also affects the electric field emission frequency to a great extent (Ahmed et al., 2020). In order to ensure the effectiveness of leakage current detection results, the leakage characteristics of electrical insulation materials are accurately identified and collected before detection in this study.

In the process of collecting the leakage characteristics of electrical insulation materials, the collected data should be combined with the optical fibre connection diagram of the whole station to implement clustering processing, so as to accurately judge the local leakage range of electrical equipment. In the process of collection, two information lights are setup within the operating range of the electrical equipment, which respectively represent the normal working state of the electrical equipment and the abnormal leakage state. If the information indicator is green, the device is working normally. When the information light is red, it indicates that there is leakage of electrical equipment. When the indicator is grey, the electrical device needs to be tested.

Based on the above process, the leakage characteristics of electrical insulation materials are collected to obtain the approximate range of gaps in electrical equipment insulation materials, so as to obtain effective leakage characteristics sample data of electrical insulation materials.

First, determine the time parameter T of crevice leakage in the electrical equipment, and the process is shown as follows:

$$T = \frac{C_2 - C_1}{2(R_1 + R_2)} \times (R_n - C_n) \tag{10}$$

In formula (10), C_1 and R_1 respectively represent the capacitance and resistance values of electrical insulation materials when cracks occur. C_2 and R_2 respectively represent the capacitance and resistance values of surrounding insulation materials when local leakage occurs in electrical equipment. The parts other than electrical insulation materials are connected in parallel. So the capacitance values and the resistance values are C_n and R_n, respectively.

On this basis, the change of internal pressure of electrical insulation material is further analysed, and the voltage at the location of local leakage of electrical equipment and the change parameters of insulation material around this area are collected. According to the rated capacity of the electrical equipment, each parameter is allocated and processed, and the electric field strength of the area with leakage and the ratio change trend of the electric field strength of the insulating material around the area are recorded, so as to judge the dielectric constant of the electrical insulating material itself (Zhou et al., 2019). When high local voltage is detected in electrical equipment, the fastest discharge rate is recorded, so as to calculate the maximum leakage charge characteristic value δ of electrical insulation material as follows:

$$\delta = \frac{\sigma(Q-1)}{2\varepsilon'(\alpha+\beta)(v-N)} \tag{11}$$

Formula (11), α and β respectively represent the presence of the leakage area electrical equipment of the change of the voltage and the surrounding insulation voltage parameters, ε' represents the dielectric constant of electrical insulation material, N represents the number of charge leakage in v represents the fastest exist when the leakage situation of electrical equipment discharge rate, Q represents the leakage of electricity charge, it meets the $Q > 1$. So far, the leakage characteristics of electrical insulation materials, especially the maximum leakage charge characteristics are collected.

3.4 Design of leakage current detection process

According to the leakage characteristics of electrical insulation materials obtained above, the area scope of leakage of electrical insulation materials is judged, and then the leakage current detection process is designed specifically.

For normal working electrical equipment, the oscillating wave of its working line will change with the variation of the line bearing voltage. Once the pulse fluctuation value in the circuit obviously decreases or increases, it indicates that there is internal conflict in the circuit. This conflict can break down electrical insulation, causing it to leak current. The oscillating pulse leakage wave characteristics of the working circuit of electrical equipment are as follows:

$$G = \sqrt{\sum_{a=1}^{b} (t_1 - t_2)^2 \times \frac{\frac{W}{3z}}{\vartheta \times A}} \tag{12}$$

Formula (12), z represents the pulse peak, t_1 represents the electrical equipment work line oscillation pulse rise time of pulse leakage process, t_2 represents the electrical equipment working line oscillation pulse discharge process of pulse time, a and b respectively represent the leakage characteristic features, the lower limit of physical integral numerical processing, W represents the total shape variable of the leakage waveform, ϑ represents the average leakage coefficient, and A represents the transmission amplitude of the oscillating wave in the working line of electrical equipment.

Each frame of vibration pulse in electrical equipment has an equivalent vibration equivalent frequency. By judging the relationship between the two, the traveling wave motion at each test point in insulation material of electrical equipment can be accurately judged. If the relative parameters match incorrectly, the calculated traveling wave vibration frequency value in the electrical insulation material is abnormal. At this point, there is leakage in the electrical insulation material, and the equivalent frequency of the pulse wave of the circuit generated here is shown as follows:

$$H = \frac{G\theta}{\sqrt{j^2 \times K \times \mu}} \tag{13}$$

In formula (10), j represents the load bearing capacity of electrical insulation material at the leakage point, θ represents the equivalent parameter, K represents the maximum oscillation fluctuation of electrical insulation material at the leakage point, and μ represents the influence parameter of local leakage position on the average load of oscillation wave. On this basis, according to the equivalent frequency of pulse wave at the leakage point of electrical insulation material, the leakage current of electrical insulation material can be obtained, which can be judged as follows:

$$I' = \frac{\partial}{2} \tau (m_1 - m_2) \times H \tag{14}$$

In formula (14), τ represents the pulse value of the leakage region of the electrical insulation material, ∂ represents the basic optimisation coefficient, m_1 and m_2 represent the oscillation wave pulse vectors at both ends of the leakage region of the electrical insulation material respectively.

For the leakage current to be detected, only the pulse characteristic quantity in the leakage area of electrical insulation material and the equivalent vibration frequency at both ends are collected, and then the collection results are put into the calculation formula (14). If the values around the equal sign of formula (14) are not equal, then there is a leakage point of electrical insulation materials; if the values around the equal sign of Formula (14) are equal, there is no leakage of electrical insulation materials.

4 Experiment and analysis

4.1 Experimental design

In order to verify the practical application performance of the above designed leakage-current detection method of electrical insulation materials based on windowed-added Fourier transform, the following experimental process is designed.

The experimental environment is as follows: taking a small power network as the research object, the AC bus voltage is 220 KV, the leading parameter of voltage controller in the line is 0.5, the active power control parameter of the line is 0.52, the harmonic frequency is 21 KHz, and the thickness of electrical insulation material is 0.8mm. The sampling interval is 0.5 s/time, and the data length is set to be consistent to ensure the effectiveness of the experimental results.

In order to avoid too single experimental results, the traditional leakage current detection method based on optimised FFT analysis [method of Huang et al. (2019)] and the leakage current detection method based on measured space leakage method [method of Peng et al. (2019)] were compared to complete performance verification together with the proposed method.

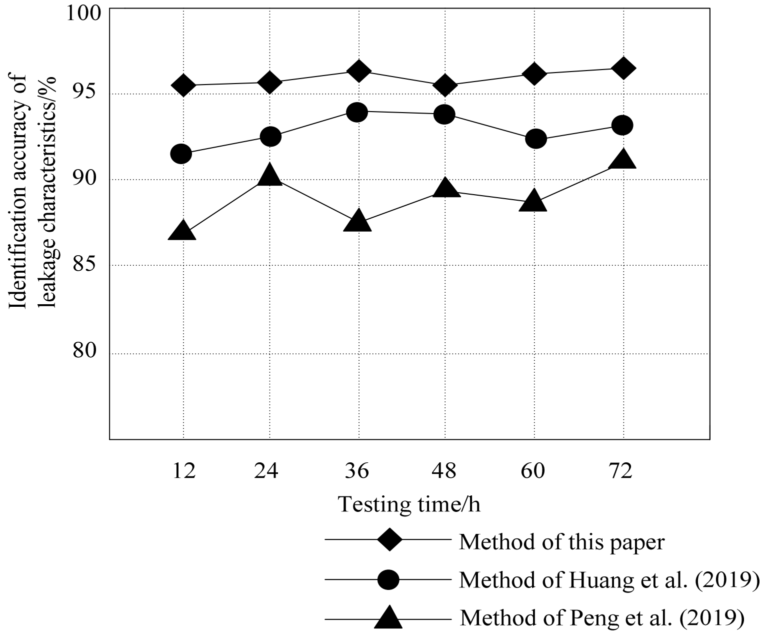
In the experiment, the accuracy of leakage feature recognition and the accuracy of detection results were taken as the test indexes. The closer the values of the two indexes were to 100%, the stronger the effectiveness of the detection method was.

4.2 Numerical analysis of results

Firstly, the identification accuracy of leakage characteristics of different methods was detected, and the results were shown in Figure 4.

The analysis of curve changes in Figure 4 shows that there is a certain gap in the accuracy of the three methods for identifying leakage characteristics. When the test time is 24 h, the identification accuracy of method of this paper is 95.5%, method of Huang et al. (2019) is 92.8%, and method of Peng et al. (2019) is 90.0%. When the test time is 48 h, the identification accuracy of method of this paper is 95.5%, method of Huang et al. (2019) is 94.0%, and method of Peng et al. (2019) is 88.6%. When the test time is 72 h, the identification accuracy of Method of this paper is 96.2%, method of Huang et al. (2019) is 93.4%, and method of Peng et al. (2019) is 91.7%. In contrast, only method of this paper has a recognition accuracy of more than 95.0% for leakage characteristics, indicating that this method is more effective.

Figure 4 Comparison of the accuracy of leakage feature recognition by different methods



On this basis, the accuracy of leakage current detection results was used as the test index to verify the application performance of different methods. The experimental results are shown in Table 1.

Table 1 Comparison of accuracy of leakage current detection results by different methods (%)

Testing time/h	*Method of this paper*	*Method of Huang et al. (2019)*	*Method of Peng et al. (2019)*
12	92.4	85.3	78.6
24	93.5	88.6	78.5
36	92.8	85.9	80.8
48	94.9	88.1	81.2
60	95.6	84.7	82.1
72	94.1	83.2	81.7

By analysing the experimental results shown in Table 1, it can be seen that there is a certain gap in the accuracy of leakage current detection results by the three methods. When the test time is 24 h, the accuracy of the test results of method of this paper is 93.5%, and that of method of Huang et al. (2019) is 88.6%. The accuracy of detection results is 78.5%; when the test time is 48 h, the accuracy of detection results of method of this paper is 94.9%, and that of method of Huang et al. (2019) is 88.1%. The accuracy of detection results is 81.2%; When the test time is 72h, the accuracy of method of this paper and method of Huang et al. (2019) is 94.1% and 83.2% respectively. The accuracy of the detection results was 81.7%. In contrast, although the accuracy of different methods is constantly changing, only Method of this paper always has an accuracy greater than 90.0%, which also indicates that this Method can more accurately detect the leakage current of electrical insulation materials.

5 Conclusions

In order to effectively improve the detection of leakage of electrical insulation materials, this study designed a method of leakage current detection of electrical insulation materials based on windowed-added Fourier transform. The method analyses the change of leakage current signal through windowed-added Fourier transform process, and then sets up leakage current detection unit, and designs a specific leakage current detection process on the basis of collecting the leakage characteristics of gas insulation materials. Through experimental verification, the identification accuracy of the leakage characteristics of this method is always above 95.0%, and its detection accuracy is always greater than 90.0%, indicating that the proposed method effectively achieves the design expectation.

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