Research Status of Experimental Characterization of Materials Electrical Properties

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Abstract. With the continuous development of the power industry, the electrical properties of materials are required to be higher. In the process of material research and development, accurate characterization of electrical insulation properties is the focus of experts and scholars. The most basic electrical performance and its characterization indexes include: electrical strength is the commonly used characterization index of electrical breakdown characteristics, resistivity is the commonly used characterization index of electrical conduction characteristics, and relative dielectric constant and dielectric dissipation factor are the commonly used characterization indexes of dielectric properties. In view of the above three kinds of indexes, this paper summarizes the principles and influencing factors involved in the experimental characterization of electrical properties of materials, traditional measurement methods, and new progress in experimental characterization.

1. Introduction
The basic principle of the characterization index of electrical properties of materials provides the basis for the characterization method of electrical properties of materials, as well as the test constraints. However, with the development of power grid and electrical equipment, the material has been used in the innovation. The traditional methods for characterizing the electrical performance test has not completely suitable for the characterization of new material needs. Experts and scholars in view of the new material design new characterization equipment to accurately characterize electrical properties. Firstly, the author discusses the relevant theories of experimental characterization of different indexes in detail and analyzes the influencing factors in the process of experimental characterization. Secondly, the author introduces the most mature and widely used test characterization methods and equipment with different test indexes, reviewed the new progress, and prospected the new research direction. The author’s research work aims to provide an experimental basis and characterization method enlightenment for material research and development.

2. Electrical strength test characterization of materials
As the most basic index of electrical equipment, electrical strength is widely used in engineering tests. According to three different states of different materials, electrical strength test characterization methods can be divided into gas, liquid, and solid test characterization. The principles of experimental characterization devices for materials are basically the same in three states. However, due to the different discharge principles of materials in different forms, the influence factors that need to be controlled in the process of characterization are also different. While grasping its core principles and influencing factors, experts and scholars put forward specific test methods for specific materials.
2.1. The influence factors of discharge theory and electrical strength test characterization

Early gas discharge theory is the Thomson theory and flow column theory [1]. In 1903, from the Angle of low-pressure breakdown, Thomas first put forward the gas breakdown theory, namely, Thomas's theory. In Thomson's theory, three coefficients are introduced to reveal the phenomenon of gas discharge, from a self-sustaining and non-self-sustaining discharge of space charge to electron avalanche, which further causes electric field distortion, thus accelerating ionization and finally forming discharge path. In 1940, h. lather and Loeb, Meek et al. proposed a flow column theory based on Thomson's theory to explain the discharge phenomenon at high pressure effectively. In recent years, Ohsawa A, Engel A V, and Hirsch M N have enriched gas discharge theory in detail from the perspective of the gas discharge model, including self-maintained discharge, glow discharge, arc discharge, corona discharge and spark discharge [2-5]. Based on the theory of gas discharge, the process of gas discharge is described in detail.

According to the above theory, the chemical properties, pressure, and purity of the gas itself are the internal reasons for the gas breakdown characteristics and are also the main aspects of the study. The external factors that affect the gas breakdown characteristics include temperature, humidity, electric field frequency, and uniformity. Among them, the factors most closely related to the electric field distortion are the frequency and uniformity of the applied electric field. Therefore, the applied electric field becomes the most important factor.

However, due to the complexity of liquid and solid, the discharge theory is less studied and immature. According to the electric breakdown theory of pure liquid and solid, the discharge process experiences the development of electron collision ionization and flow, and finally produces the breakdown phenomenon. However, as pure liquid and solid are difficult to obtain, impurities in the liquid material and bubbles in the solid material production process will inevitably affect the discharge process. Therefore, the breakdown of liquid and solid is still studied by specific tests. In the test process, the main external influencing factors are similar to gas materials, mainly including temperature, humidity, and electric field characteristics.

2.2. Material electrical strength test characterization method and equipment

![Diagram](image)

Figure 1. Schematic diagram of electrical strength test equipment

The principle of electrical strength test equipment is shown in figure 1. The earliest standard applied to the electrical strength test of gas materials is ASTM D 2477-1984. This standard provides basic test equipment and operation method for the electrical strength of gas. The electrical strength test standard applied to liquid materials is GB/T 507-2002, which is more suitable for engineering applications after two revisions. GB/T 1408.1-2006, GB/T 1408.2-2006, and GB/T 1408.3-2007 are the three standards applied to the electrical strength test of solid materials.

The further development of material electrical strength test characterization is to add temperature and humidity control devices and improve electric field generating devices to meet different test requirements. In particular, the changes of different electrodes and electric field characteristics are the
focus of domestic and foreign experts and scholars. The paper [6] for the simulation of quasi-uniform electric field, a bit uneven power plant and highly uniform electric field provides three-ball, ball, ball head rod electrode, electrode plate electrode, and needle - plate electrode respectively, and introduced the coefficient of $\eta$ to depict the electric field uniformity. Electric field uniformity coefficient $\eta$ was defined as the ratio of average field intensity and maximum field strength, and has the following relationship:

$$
\begin{align*}
\eta &= 1, \text{ Electric field is a uniform electric field} \\
1/2 < \eta < 1, \text{ Electric field is a quasi-uniform electric field} \\
1/4 < \eta < 1/2, \text{ Electric field is a slightly uneven electric field} \\
\eta < 1/4, \text{ Electric field is an extremely uneven electric field}
\end{align*}
$$

(1)

where $\eta$ is an electric field uniformity.

2.3. New progress in electrical strength test characterization of materials

In order to promote the engineering application, domestic and foreign experts and scholars begin to study the application materials of power equipment applicable to high temperature and high voltage, and their electrical strength characterization method also starts to simulate in a harsh environment. The paper [8] simulates the electrical breakdown performance test of inert gas under extremely cold conditions. The paper [9] proposed a test method to simulate transformer oil under extremely cold conditions. For solid materials, since the temperature of solid materials has little influence on the breakdown strength under the condition of electric breakdown, few scholars have studied the breakdown performance of solid materials under the condition of high cold. However, due to the extensive application of solid insulation materials in the field of power engineering, it is impossible to transfer every test to the laboratory. Therefore, the on-site electrical strength test of insulators in the process of operation requires test equipment that can be applied in engineering. The paper [10-11] designed the field test layout applicable to various elevations and designed two parallel gaps, rod, and ring, to meet the test requirements. As the test environment of the field test is difficult to control, the test results need to be modified by the weather.

In the study of the experiment itself, the electrode material has become the focus of experts and scholars. The paper [12-14] has confirmed that due to the different abilities of charge enrichment in different materials, charge injection into the sample is different in the way and amount of charge injection, resulting in different dielectric breakdown voltages in different electrode materials. The paper [15] systematically studied the influence of electrode material, electrode surface roughness, and area on the water and electrical strength. The paper [16] selected W and LB6 as electrode materials and compared the impact of breakdown voltage between different electrode materials. The paper [17] compared the effects of propylene carbonate, stainless steel, aluminum, and copper as electrode materials on breakdown characteristics. However, the above research is only in the experimental stage, and there is no detailed test of gas and solid, no scientific study on the mechanism of the test phenomenon, and no scientific demonstration on the test results. Therefore, the influence of electrode materials on the test strength of dielectric electrical appliances has become a new research direction.

3. Resistivity test characterization of materials

3.1. Influence factors of polarization and resistivity test characterization

The fundamental principle of resistivity derives from ohm's law. Ohm's law establishes the relationship between current and voltage using the concept of resistance. Further analysis shows that under the action of voltage, charged ions, or free charge inside, the material will move under the action of an electric field, forming a conductive leakage flow. A steady leakage current establishes the conductance of the material. However, the local movement of the other part of the bound charge under the action of voltage will show the electrical property on the macro level, which leads to the appearance of charge on the uneven surface and interior of the material. This phenomenon is called
polarization [18], which causes the material to produce displacement current. The displacement current is an unstable transition current.

In the process of the experiment, it is impossible to distinguish the displacement current from the leakage current, plus the polarization time of different materials is different, and the polarization time of some materials is even as long as several hours. Therefore, the polarization phenomenon has become a factor that must be considered when the material resistivity test is characterized. Standard GB/T 1410-2006 stipulates that the applied time of resistivity test voltage is 1min (the applied time of voltage of large electrical equipment is 10min), so as to facilitate the transverse comparison of resistivity at the same polarization time. This time also reduces the effect of the change in resistivity due to the heating of the material during the voltage application.

3.2. Material resistivity test characterization method and equipment

Due to the large gap between gas molecules, a stable leakage current cannot be formed. Therefore, the resistivity of gas is not studied. The surface resistivity of liquid cannot be completely defined and has no engineering application value. Therefore, the surface resistivity of liquid is not studied. In summary, the experimental characterization of resistivity focuses on the volume and surface resistivity of solids and the volume resistivity of liquids.

The standard GB/T 1410-2006 and GB/T 421-2009 respectively put forward devices and methods for measuring volume resistivity and surface resistivity of solid and liquid materials. The equipment includes dc generator, voltage, and current test equipment and test electrode. The circuit connection of voltage and current test system is mainly the Wheatstone bridge and galvanometer series connection. For different samples, the flat sample is tested with a concentric circle electrode, the tubular sample is tested with a communication sleeve electrode, and the liquid sample is tested with a standard electrode cup.

3.3. New progress in resistivity characterization of materials

With the continuous development of material technology, conductors, semiconductors, and insulating materials have been applied in all walks of life. Resistivity, as a characteristic to distinguish the electrical conduction characteristics of conductors, has been applied by experts, scholars, and engineers. The variety of material forms requires the measurement method of volume resistivity to change accordingly. In particular, the different states of solid materials require supporting test equipment.

For the test of slender materials, a method for measuring the resistivity of carbon fiber for slender materials was proposed in The paper [19]. The paper [20] has improved the double-probe method, using the four-probe fixture and electrode for testing, so that the test accuracy is higher, and the influence of temperature and the expansion rate of the silk thread is less. The paper [21] applied the method of linear volt-ampere scanning test and ac impedance test of the U.S. 5230 phase-locked amplifier to obtain the volt-ampere characteristic curve, and then calculated the resistivity, and achieved good results.

For the bulk resistivity test of conductive powder, the material is usually processed into a plate shape and then tested using the traditional method proposed by standard GB/T 1410-2006. However, powder processing is complex and may change its chemical properties. The paper [22] solved the above problems, proposed the conductive powder stacking method to test volume resistivity, and analyzed the influence of test load and filling amount on test results. The result of the precision analysis shows that the test has some error, but it is within the contact range.

For thin-layer resistivity measurement, there are two earliest methods: contactless measurement [23] and contact measurement [24]. However, contactless measuring instruments have high cost and narrow measuring range, while contactless measuring methods are easy to damage samples. Domestic and foreign experts and scholars began to improve on the basis of the above two basic methods. In reference [25], image positioning technology was used to solve the problem of difficulty in uniform measurement interval of four-probe technology, which made the measurement results more accurate,
monitored, and controlled the measurement probe and microregion, and greatly reduced the possibility of sample destruction. The paper [26-27] used LabVIEW and Matlab to draw the Mapping diagram representing thin-layer resistivity, respectively, which provided a new idea for measurement of resistivity.

4. Experimental characterization of dielectric properties of materials

4.1. Influence factors on experimental characterization of ac polarization and dielectric properties

The paper [28] discusses the polarization model of the dielectric under the alternating current field, as shown in Figure 2. In the alternating current field, the relative dielectric constant $\varepsilon_r$ is the real part of $\varepsilon_r$, consisting of $\varepsilon_0$, $\varepsilon_\infty$ and $\varepsilon_r\rho$. Dielectric dissipation factor $\tan\delta$ is the ratio of $\varepsilon_r'$ to $\varepsilon_r$. In the direct current field, the dielectric can theoretically generate slight heat, but this value is small and can be ignored in engineering. Thus, the dielectric properties of the material make sense in an alternating current field.

4.2. Experimental characterization method and equipment for dielectric properties of materials

The standard GB/T 5654-2007 proposed the experimental characterization method for dielectric properties of liquid materials, and the standard GBT 1409-2006 proposed the experimental characterization method for dielectric properties of solid materials. The principle of dielectric characterization of gases is similar to that of liquids and solids. The test electrode is only required to be placed in a closed container filled with test gas. Commonly used in the test circuit in parallel with Schering bridge, transformer bridge, T network, resonance and substation, etc., these methods put sample circuit, through the mediation of circuits of the capacitance and resistance value of the original copy of the other circuit is made to reach equilibrium, read the capacitor and resistor in the circuit components in number, and it is concluded that the relative dielectric constant and dielectric dissipation factor value. Among them, the most classic device is the Schering bridge.
Figure 3. Schematic diagram of Schering bridge

The principle of Schering bridge is shown in figure 3, where \( R_x \) and \( C_x \) represent samples and balance the bridge by mediating \( R_3 \) and \( C_4 \). At this time, there is no voltage difference between the two ends of the bridge. The dielectric properties of materials can be obtained by reading the values of \( R_3 \) and \( C_4 \) and substituting them into the formula.

4.3. New progress in the dielectric characterization of materials

With the development of industrial science and technology, many scientific applications of materials are based on their dielectric properties, which can be used to characterize the capacitance of mixtures [30], solutions [31] and other materials, so as to quickly and accurately judge their uniformity and dispersion degree of material particles. Studies on imaging rules of capacitive layer imaging systems and sensors [32-33] also require the characterization of dielectric properties. In electrical equipment, the change of the dielectric dissipation factor is often used to reflect the overall aging and defects of insulation and other operating conditions [34]. It can be said that the research involving capacitance, or the research which can reflect one of its characteristics by applying the law of material capacitance, should be based on the characterization of dielectric properties.

The permittivity is widely used, so its characterization should be focused on the accurate characterization of various materials. Limited by the influence factors of material dielectric property test characterization proposed in section 2.3.1, the most difficult to characterize are materials that are difficult to form, such as powdered solids. The paper [35] proposed the immersion method, which mixed the powder into the liquid, measured the dielectric characteristic index of the mixed liquid, and then solved the index of the powder itself through the mixing model. However, this method was difficult to recover the powder after the test, resulting in a waste of raw materials. The paper [36] proposed a replacement method, which was affected by the dispersion uniformity of powder. The paper [37] measured the relative dielectric constant of the mixture by mixing powder and air and solved the data by using the equivalent model of powder and gas proposed in The paper [38].

In engineering, the dielectric dissipation factor is mostly used to evaluate whether high-voltage power equipment has defects and aging. Therefore, the characterization of the dielectric dissipation factor is more focused on field engineering applications. Standard DL/T 474.3-2006 standard DL/T 474.3-2006 standard DL/T 474.3-2006 standard DL/T 474.3-2006 standard DL/T 474.3-2006 standard DL/T 474.3-2006 According to the standard and the field equipment, the engineers put forward the test characterization method and matters needing attention which are more suitable for engineering application according to the field experience. It was found in The paper [39] that the field test was greatly interfered with by the external electric field. In order to obtain accurate data, the interference electric field must be established. The paper [40] proposed a new test wiring method, which solved the problem of opening the SF6 air chamber in the field test process and heavy workload. In the test field, the Garton effect often occurs, which is easy to cause misjudgment of test equipment. The paper [41], combined with the field situation, details the problem of medium loss increase of paper-containing dielectric at low voltage. The paper [42] has demonstrated in detail the problem that the Garton effect is easy to produce in the dielectric loss test of equal-voltage positive connection for circuit breakers over 500kV in operation. The paper [43] details the influence of the Garton effect on the dielectric loss test of insulation bushing. In order to solve the problem of
Inaccurate measurement results caused by the Garton effect. The paper [44] proposed that a higher voltage could be used for dielectric loss test to avoid the Garton problem. The paper [46] proposed that the series resonance method could be adopted to avoid the Garton effect, and a device suitable for a work field was proposed.

In order to monitor the running state of the equipment in real-time and analyze the defects and deficiencies of the equipment, experts and scholars put forward the concept of state maintenance. The on-line monitoring technology is used to collect the equipment information in real-time and evaluate the running status of the equipment in real-time. Among them, the dielectric dissipation factor as the main state variable is widely used in the equipment online monitoring system. The online monitoring technology of the dielectric dissipation factor is mainly to analyze the waveform and phase Angle of the sampled equipment terminal voltage and current signal and extract its dielectric dissipation factor. Among them, the waveform processing method is the key. The paper [47] used the method of high-order sinusoidal wave fitting to process signals and reduced sensor and electromagnetic interference. The paper [48] has quantitatively analyzed the interference factors of signals and proposed that the partial least squares regression method can be used to filter the interference effects quickly and effectively. In reference [49], FFT transform is applied to analyze signals, and a software and hardware system that can be applied in engineering is designed. The paper [50] analyzed the interference of environmental factors on the monitoring results, and designed the relative value method to eliminate the interference of non-effective information, so as to improve the reliability of the data. As a hot research direction, online monitoring technology has been pursued by experts and scholars. Many signal processing methods have been applied in engineering, becoming more and more mature and perfect, and achieved good application results.

5. Conclusion

In this paper, the characterization indexes of electrical property test of materials are reviewed in detail, and the characterization methods of electrical property test of materials are reviewed in detail from three aspects including the principles and influencing factors involved in the experimental characterization of each index, the traditional characterization methods and the new progress of experimental characterization. The main conclusions and prospects are as follows:

Firstly, the basic theory of material electrical strength test characterization is derived from the discharge theory. It is concluded that during the test process, the main influencing factors of the gas material test are temperature, humidity, and electric field characteristics. In addition to temperature, humidity, and electric field characteristics, the purity of liquid and the pressurization time are also the main influencing factors. The main influence factors of the solid material test include temperature and humidity, electric field characteristics, and pressure time, especially the electric field uniformity in electric field characteristics. On the basis of the traditional experimental equipment, its subsequent development lies in adding temperature and humidity control devices, improving electric field generating devices, and other methods to meet different test requirements. Material electric strength test characterization of new progress is mainly two aspects, one is the engineering application, many experts and scholars put forward suitable for harsh environment test equipment and methods, the second is the electrode material itself, each scholar research results show that different electrode materials will affect electric breakdown strength, but the research only stays in the experimental stage, the lack of scientific explanation, can become a new research direction.

Secondly, the basic theory of material resistivity test characterization is derived from ohm’s law, and the inevitable polarization phenomenon during the experiment will also affect the characterization results. Traditional resistivity test characterization methods and basic equipment include dc generator equipment, voltage, and current detection equipment and test electrode. In order to meet the test requirements of different samples, the test electrode is changed to achieve the characterization purpose. The flat sample was tested with concentric circular electrodes, the tubular sample with concentric sleeve electrodes, and the liquid sample was tested with standard electrode cups. The new progress of resistivity test characterization of materials is aimed at different states. The slender material can be
tested by changing the electrode and using different probes. The conductive powder stacking method is proposed for powder solid. The thin-layer solid is usually measured by two kinds of methods, the contactless method, and the contactless method. With the development of materials, the variety of material morphology requires the change of the measurement method of volume resistivity, which is an important research direction in the future.

Finally, the basic theory of experimental characterization of dielectric properties of materials is derived from the ac polarization theory. According to the ac polarization model, the main influencing factors of experimental characterization are power frequency, temperature, and humidity, the surface flatness of the sample, and edge effect of the capacitor electrode. Traditional dielectric characteristics test circuit in parallel Schering bridge, transformer bridge, T-network, resonance, and conversion method, etc., the methods to sample as part of the balanced circuit, through the mediation of circuits of the capacitance and resistance value of the original copy of the other circuit is made to reach equilibrium, and it is concluded that the relative dielectric constant and dielectric dissipation factor value. The new progress in dielectric property test characterization of materials is firstly for powdered solids. Whether it is the immersion method or the mixed air method, the powder is evenly dispersed into other dielectrics, the dielectric constant of the mixture is measured and then solved by the equivalent model. In the engineering application, the engineers proposed the equipment and method suitable for the work field according to the field experience and paid more attention to the Garton effect in the test process. The on-line monitoring technology of the dielectric dissipation factor is widely applied in the power system. Experts and scholars adopt a multi-purpose signal processing method to collect and analyze the signal of equipment voltage and current and obtain dielectric dissipation factor of equipment in real-time.

References
[1] Kuffel, E., Zaengl, W.S., Hammond, P. (1984) High voltage engineering: fundamentals. In: Kuffel, E. (Eds), Oxford: Pergamon Press, Oxford. 311-377.
[2] Pai, S.T., Guo, X.M. (1992) Analytic approach to glowing discharge theory: result and analysis. Journal of Applied Physics, 71(12): 5826.
[3] Ohsawa, A., Ohuchi, M., Kubota, T. (1991) Improved RF-driven probe method for RF discharge plasma diagnostics[J]. Measurement Science and Technology, 2(8):801-806.
[4] Engel, A.V. (1965) Ionized Classes. In: Engel, A.V. (Eds), Oxford University Press, Oxford. 173-174.
[5] Hirsch, M.N., Oskam, H. J. (1978) Classeeous electronics. In: Hirsch, M.N. (Eds), New York: Academic, New York.145-147.
[6] Duan, Y.Y., Zhu, M.S., Han, L.Z. (1996) Experimental vapor pressure data and a vapor pressure equation for trifluoriodomethane (CF3I)[J]. Fluid Phase Equilibria, 121(1-2): 227-234.
[7] Takeda, T., Matsuoka, S., Kumada, A., et al. (2008) Insulating performance of CF3I and its by-products by spark-over discharge[C]//Proceedings of the International Conference on Electrical Engineering, Naha, The University of Tokyo, Japan.
[8] Zhang, J., Cheng, L., Zhao, K. (2017) - 50 °C under the condition of SF_6 / N_2 breakdown characteristics of mixed gas [J]. Journal of insulation materials, 50 (10): 43-47.
[9] Xu, Z.Y., Cheng, H.C., Wang, K., et al. (2015) Transformer oil breakdown characteristics test under high cold conditions [J]. High voltage technology, 41(04):1342-1348.
[10] Yang, Q., Dong, Y., Ye, X., et al. (2013) Insulation coordination between composite insulators and parallel gaps for 500kV transmission lines at high altitudes [J]. High voltage technology, 39(02):407-414.
[11] Meng, G., Zeng, X., Deng, W, et al. (2013) Impact discharge characteristics of 500kV substation equipment interphase operation at high altitude [J]. High voltage technology, 39(04):1018-1024.
[12] Song, Y., Yin, J., Bu, W., et al. (2009) Effect of Electrode Materials on Breakdown of Al2O3P1 Films[C]. Conference on Properties and Applications of Dielectric Materials, Harbin, China.
[13] Sharifpanah, H., Gholami, A., Jamali, S. (2008) Effect of Electrode Material on the Breakdown Voltage of SF6-N2 and SF6-C02 Mixtures in a Weakly Non-Uniform Electric Field[C]. 2nd IEEE International Conference on Power and Energy, Johor Baharu, Malaysia.
[14] Wang, Y., Yang, Z., Ding, B., et al. (1998) The Effect of Electrode Material and Additives on the Breakdown Strength of a Vacuum Gap[J]. IEEE Transactions on Dielectrics and Electrical Insulation, 5(2): 245-249.
[15] Wetz, D., Mankowski, J., Kristiansen, M. (2005) The Impact of Electrode Area and Surface Roughness on the Pulsed Breakdown Strength Water[C]. IEEE Conference on Pulsed Power Conference.
[16] Miron, C., Bratescu, M.A., Saito, N., et al. (2011) Effect of the electrode work function on the water plasma breakdown voltage[J]. Current Applied Physics., 11(5): S154-S158.
[17] Yang, J. (2016) Effects of electrode materials on the breakdown voltage of the liquid dielectric and its mechanism [D]. Chongqing University, Chongqing.
[18] Ren, L.Y., Yu, B. (2008) Study on dielectric polarization [J]. Journal of Xihua University (natural science edition), 27(06):95-97+125.
[19] Liu, S.M. (1999) Characteristics of carbon fiber and composite materials resistivity test method [J]. Aerospace standardization, 03:17-18.
[20] He, F.M., Li, J.P., Chen, C., et al. (2010) Evaluation and characterization of carbon fiber resistivity [J]. Aerospace materials technology, 40(02):109-111.
[21] Tian, Y.H., Hao, W.Z., Zhang, X.J. (2017) Study on volumetric resistivity measurement method of carbon fiber bundles [J]. Journal of Beijing University of Chemical Technology(Natural Science Edition),44(01):34-37.
[22] Li, X.F., Han, T.T., Zhang, Y., Hu, J., et al. (2010) The measurement method of bulk resistivity of conductive powder stacking [J]. Precious metals, 31(04):42-45.
[23] Loonian, W.R., (1980) Semiconductor measurement and instrumentation, Shanghai: Shanghai science press, 94.
[24] Sun, Y.C., Liu, X.F., Gao, Z.B., et al. (2002) Microzonal thin-layer resistance four-probe tester and its application. Advances in solid-state electronics, 1:93-99.
[25] Liu, X.F. (2003) Study on four-probe test technique for thin layer resistance in micro-region combined with image analysis [D]. Hebei University of Science and Technology, Hebei.
[26] Zhang, R.Q. (2014) Research on the four-probe thin-layer resistance test system based on LabVIEW [D]. Hebei University of Science and Technology, Hebei.
[27] Zhao, X.R. (2011) Mapping technology for characterization of thin-layer resistors [D]. Hebei University of Science and Technology, Hebei.
[28] Wang, S.L. (1993) Circuit model of dielectric alternating current polarization [J]. Journal of Huazhong University of Science and Technology, 04:154-159.
[29] Zhao, G.Z., Xu, Y.Z., Qiao, C.P, et al. (2018) Analysis of influencing factors of water content and constant dielectric model of the medium [J]. Engineering investigation, 46(07):55-61.
[30] Ehrhardt N., Montagne M., Berthiaux, H., Dalloz-Dubruecaud, B. Gatame, C. (2004) Assessing the homogeneity of powder mixtures by on-line electrical capacitance[J]. Chemical Engineering &amp; Processing: Process Intensification, 44(2).
[31] Sun, M., Liu, S., Li, Z.H., Lei, J. (2009) Measurement of gas-solid two-phase flow concentration in feed leg based on capacitance imaging [J]. Journal of instrumentation, 30(02):261-266.
[32] Tian, P., Qin, J.J., Qin, X.G. (2018) Regularized Landweber algorithm based on a two-phase flow capacitance tomography system [J]. Instrument user, 25(09):90-92.
[33] Liang, S.G. (2018) Study on capacitance tomography of gas-liquid two-phase flow [D]. University of Chinese Academy of Sciences, Beijing.
[34] Bo, W. (2016) A method for monitoring the dielectric dissipation factor of capacitive equipment [J]. Times agricultural machinery, 43(07):38+40.

[35] Robinson, D.A., Friedman, S.P. (2002) The effective permittivity of dense packings of glass beads, quartz sand, and their mixtures immersed in different dielectric backgrounds[J]. Journal of Non-Crystalline Solids, 305(1).

[36] Andeen, C., Fontanella, J. (1970) Accurate determination of the dielectric constant by the method of substitution [J]. Review of Scientific Instruments, 41(11): 1573-1576.

[37] Zou, D.J., Li, X.W., Zhang, J., et al. (2014) Measurement method and device of the relative dielectric constant of powder [J]. Chinese Journal of instrumentation, 35(02):368-373.

[38] Zou, D.J., Li, X.W, He, R.B., et al. (2013) Development of powder dielectric constant testing device based on finite element analysis [J]. Chinese Journal of instrumentation, 34(02):423-427.

[39] Lu, H.J., Yang, C.F., Yang, B.W. (2010) Field test of 220kV inverted current transformer [J]. Jilin electric power, 38(01):44-46+49.

[40] Shen, J.L., Huang, F.Y, Zhou, W.H., et al. (2009) Discussion on in-situ medium loss test method for oil/gas bushing of high-voltage transformer [J]. High-voltage electrical appliances, 45(04):71-73.

[41] Zuo, W.Q., Wang, Q., Xie, L.Y., et al. (2010) Influence of Garton effect on dielectric loss measurement of film-paper composite insulating capacitor and countermeasures [J]. Insulating materials, 43(01):71-74.

[42] Wen, J. (2012) Study on dielectric loss test of 500kV circuit breaker film insulation uniform voltage capacitance [J]. Sichuan electric power technology, 35(01):73-76.

[43] He, W.Z. (2014) Influence of Garton effect on the measurement of casing dielectric loss [J]. Electrical technology, 01:65-67.

[44] Xiao, Y.W., Ren, Q.S., Wang, S.X. (2014) Influence of Garton effect on high-pressure medium loss field tests and countermeasures [J]. Shandong electric power technology, 02:30-32.

[45] Xu, L., Feng, Y.Z., Feng, X.Y, Gu, Y. (2012) Field test method for overcoming Garton effect on high voltage dielectric loss [J]. High voltage electrical appliances, 48(02):66-70.

[46] Wang, R.M., Cao, Q.W., Dong, L.W. (2003) Design of digital dielectric loss factor tangent detector [J]. Electrical measurement and instrumentation, 02:11-14.

[47] Yang, J.F., Niu, Y.Z., Lu, A.P., et al. (2018) The measurement method of dielectric loss of power capacity equipment and analysis of influencing factors [J]. Electronic world, 09:34-35.

[48] Chen, M.W., Qiu, W.F, Zhang, K.L., et al. (2018) Application of partial least squares regression method in the error analysis of dielectric loss online monitoring [J]. Journal of power systems and automation, 30(02):138-143+150.

[49] Chen, S. (2016) Research and design of an online monitoring system for dielectric loss Angle insulation [D]. Xi An University of Science and Technology, Xi An.

[50] Ren, R.L. (2014) Study on on-line monitoring and fault analysis of transformer substation capacitive equipment [D]. Fuzhou University, Fuzhou.