IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 24, 2020, accepted September 4, 2020, date of publication September 21, 2020,
date of current version September 29, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3024768

Effect of Moistures on Space Charge and Trap Level Characteristics of Oil-Impregnated Pressboards

YI GUAN[1], MINGHE CHI[1], JINFENG ZHANG[2], QIAN WANG[1], XINLAO WEI[1], AND QINGGUO CHEN[1]
[1]Key Laboratory of Engineering Dielectrics and Its Application, Ministry of Education, School of Electrical and Electronics Engineering, Harbin University of Science and Technology, Harbin 150080, China
[2]School of Electrical Engineering and Automation, Qilu University of Technology (Shandong Academy of Sciences), Jinan 250353, China

Corresponding authors: Minghe Chi (chiminghe1985@hrbust.edu.cn) and Qingguo Chen (qgchen@263.net)

This work was supported in part by the National Key Research and Development Program of China under Grant 2017YFB0902704, in part by the National Natural Science Foundation of China under Grant 51677046 and Grant 51877056, and in part by the University Nursing Program for Young Scholars with Creative Talents in Heilongjiang Province under Grant LGYC2018JC021.

ABSTRACT Oil-paper insulation as an irreplaceable insulation system in the electrical power transformer is inevitably suffering the water intrusion on working condition, which will make dielectric performance degraded and insulation aging accelerated. In high interest of explaining the deterioration effect of absorbing moisture on the dielectric properties of oil-paper insulation system and corresponding mechanism, the space charge and trap level characteristics are investigated for the specially prepared oil-impregnated pressboards with different moisture contents. The Pulsed Electro Acoustic and Isothermal Surface Potential Decay experiments are performed to test the space charge distributions and evaluate the trap level depths, respectively. It is indicated that the polarity of injected space charges is alternated with the decaying rate being raised when the absorbing moisture is aggravated in oil-impregnated pressboards. The charge carriers are more prone to be captured by the shallow-level traps that have been introduced by water permeation near pressboard surface than the intrinsic deep-level traps inside pressboard. The captured charge carries accounts for the significantly exacerbated space charge accumulation as manifested by the surface charges of oil-impregnated pressboards.

INDEX TERMS Oil-paper insulation, space charge accumulation, charge trap, moisture.

I. INTRODUCTION

Converter transformer, as a key equipment of high voltage direct current power transmission, works under the combined voltages of alternating and direct current (AC and DC) electrical fields, where space charges are apt to accumulate inside insulator so as to distort internal electric field and accelerate dielectric aging [1]. The space charge characteristics is always a hot spot pertaining to the electrical insulation performances of converter transformers [2]. Space charge accumulations are essentially determined by charge mobility and trap level distribution [3], [4]. The micro-porous structures of the insulating paper materials in electrical transformer are filled with transformer oil after being specially treated by oil-impregnation, which is so called as oil-impregnated pressboards and bearing the deterioration of space charge characteristics caused by the environmental moisture, dielectric aging, and operating temperature elevation [5]–[7]. It has been reported that the temperature elevation will significantly increase charge mobility and cause considerable homocharge and heterocharge accumulations inside the oil-impregnated pressboards when DC voltage is applied or polarity reversal of electric field occurs [8]. Nanofluid/pressboard composite insulation filled by Al2O3 NRs has acquired a significant improvement in dissipation rate of space charges due to the lower trap level depth in them [9], [10]. Based on the bipolar charge transport model, the numerical simulations were carried out to estimate space charge distributions in oil-impregnated pressboards at various temperatures [11]. The hydrophilic hydroxyl groups in cellulose fibers of pressboards are apt to adsorb moisture from air environment,

The associate editor coordinating the review of this manuscript and approving it for publication was Jenny Mahoney.

which will possible lead to the electrical insulation damaged and finally cause electrical breakdown of oil-impregnated pressboards [12], [13].

Although the humidity in oil-paper insulation system has been strictly controlled during the manufacture process of converter transformers before leaving the factory, the external water vapor in air from humid operating circumstance is inevitably introduced into oil-impregnated pressboards to promote substantial space charge accumulations in voltage converting processes, leading to insulation deterioration and accelerated aging of converter transformers. The Piezoelectric Induced Pressure Wave Propagation tests indicated that the moisture absorption can expedite the space charge injection to reach equilibrium and extend the charge accumulation area in oil-impregnated pressboards [14]. The Pulsed Electro Acoustic (PEA) experiments have also demonstrated that absorbing moisture will increase electrical conductance and space charge decaying rate [15]. Introduced by the corroding water impurity, fewer negative charges rather than positive charges are accumulated inside oil-impregnated pressboards in the early stage of electrical breakdown, and the density and level of charge traps have a great effect on the injection and decay of space charges [16].

Most reported studies on the space charge characteristics of oil-impregnated pressboards with different water contents focused on the summary of experimental phenomena. The work covering the charge trapping mechanism related to the moisture effects on insulation performances is rare. In this article, the PEA method is used to measure the space charge characteristics of oil-impregnated pressboards with various water impurity (moisture) contents, and the Isothermal Surface Potential Decay (ISPD) is employed to test the surface potential which can be exploited to accurately evaluate the trap level distributions for revealing the intrinsic attributes that how absorbing moisture affects the dielectric properties of oil-paper insulation.

II. EXPERIMENTAL SETUP

A. SAMPLE PREPARATION

The samples of oil-impregnated pressboards are prepared in thickness of 0.25mm and diameter of 6cm. The transformer oil used for test is the model of Karamay 45#. Before tests, the transformer oil needs to be treated by oil filter to remove moisture and other impurities and saved in a vacuum tank. The insulating pressboards are firstly dried by heating for 48h in vacuum, and then impregnated into the transformer oil under vacuum. The obtained oil-impregnated pressboards are eventually stored in a vacuum container. Through natural moisture absorption and regular measurements of water content, the pressboards with the moisture contents of 0.34%, 1.47%, 2.54%, 3.74% in weight were obtained. The pressboard moisture content was measured as IEC733—82.

B. SPACE CHARGE MEASUREMENT

PEA measurements of space charge distribution are implemented under 10kV/mm and 20kV/mm respectively at the ambient temperature of 20°C, utilizing the facility as schematically shown in Fig.1. The width of pulse source is set as 10ns and the amplitude of DC power source is set in ±30kV. The testing period of applying voltage and short-circuit is 1 hour with the tested data being recorded per 10s.

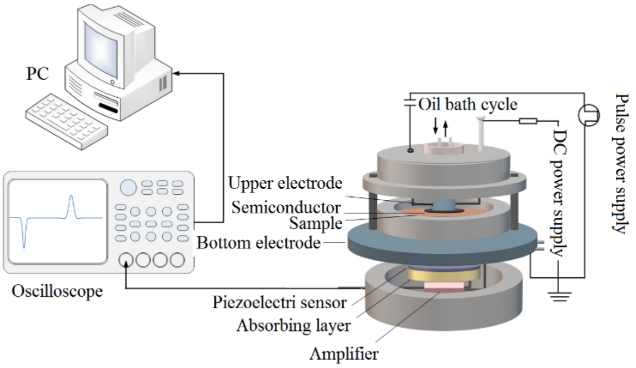


FIGURE 1. Schematic facility of measuring space charge distribution.

C. ISOTHERMAL SURFACE POTENTIAL DECAY TEST

ISPD method is used to measure the surface potential decaying curves as the testing schematics shown in Fig.2. The charges are generated through corona discharging by a needle electrode migrating across the sample surface, which are captured by the surface traps to form an electrostatic potential on sample surface. The attenuation patterns of surface charge mainly include: migration to ground electrode along the thickness direction, neutralization with charged particles in the air, and migration to the ground electrode along the surface of the sample [19]. In order to reduce the neutralization of surface charges and charged particles in the air, the ambient relative humidity is controlled to be <30%. By setting the voltage of gate electrode, the potentials at individual points in the central region of sample are controlled to be identical, which reduces the migration of surface charges along sample surface. The voltages of needle and gate electrodes are set to be −6kV and −3kV respectively. The charging process persists for 3min and the potential decay is prolonged to 2 hours.

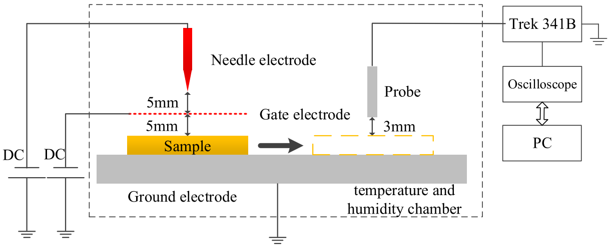


FIGURE 2. Schematic diagram of ISPD test.

III. MATH

The double exponential function can be used to simulate the surface potential decay curve with time [20], which can be expressed as following:

$$V_s(t) = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} \tag{1}$$

where $V_s(t)$ represents surface potential decaying with time t, and A_1, A_2, τ_1 and τ_2 denote the fitting parameters. To further analyze the effect of moisture on surface charge dissipation rate, the average speed (U_{as}) of surface potential decay is defined as following:

$$w_{as} = [(U_0 - U_t)/tU_0] \times 100\% \tag{2}$$

where w_{as} is average speed of surface potential decay, U_0 and U_t identify the initial surface potential and the surface potential at time t respectively.

According to the theory proposed by Simmons and Tam, it is assumed that the detrapping charges will not be captured by traps again during the surface potential decay process with the electron-hole recombination being ignored [21], [22]. The trap distribution in sample can be calculated from the surface potential decaying curves [20], as the trap level density be presented by:

$$N_t(E_t) = \frac{4\varepsilon_0\varepsilon_r}{eL^2kT}\left|t\frac{dV_S(t)}{dt}\right| \tag{3}$$

where L is the sample thickness, e denotes the fundamental unit charge, $N_t(E_t)$ indicates the density of trap energy level E_t varying with time t, k and T are Boltzmann constant and temperature respectively, ε_0 and ε_r are the vacuum and relative dielectric permittivity respectively. Trap level E_t is derived as following:

$$E_t = kT\ln(\nu_e t) \tag{4}$$

in which ν_e denotes the escaping frequency factor (distributed in the range of $10^{12} \sim 10^{14}$ Hz) of the charges captured by traps In this article, the escape frequency factor is set to the representative value of 10^{12} Hz according to recently reported experiments [23].

IV. RESULTS AND ANALYSES

A. SPACE CHARGE CHARACTERISTICS

The mean volume density of injected space charges is calculated to further analyze the accumulation and decaying characteristics of space charges, being formularized as:

$$Q(t) = \frac{1}{L}\int_0^L |\rho(x,t)|dx \tag{5}$$

where $Q(t)$ indicates the mean volume density averaged from the total quantity of injected space charges at time t, $\rho(x, t)$ identifies space charge density, and L is sample thickness. The mean volume densities of space charges accumulating inside the oil-impregnated pressboards with different moisture contents being polarized under a relatively lower DC electric field of 10kV/mm and dissipating with time under short-circuit are shown in the upper and bottom panels of Fig.3, respectively. The mean volume densities in all samples rise sharply with the polarizing time at early stage to reach a constant maximum value, and shows a higher increasing rate as the moisture content is increased. The oil-impregnated pressboard with a moisture content of 2.54% represents the highest saturated value of 2.75C/m^3 after polarizing for 600s. During the short-circuit tests, the mean volume densities of the space charges in all samples decrease rapidly in the early stage (0-600s) and then reduce continuously to an unchanged residual value, as shown in the bottom panels of Fig.3. Higher decaying rate and amplitude of space charges have been acquired by the oil-impregnated pressboard with a higher moisture content.

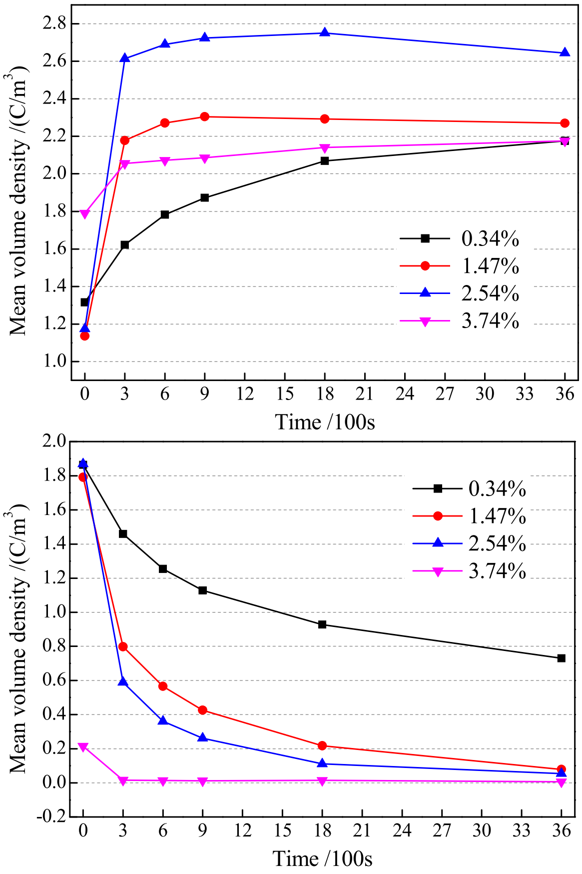
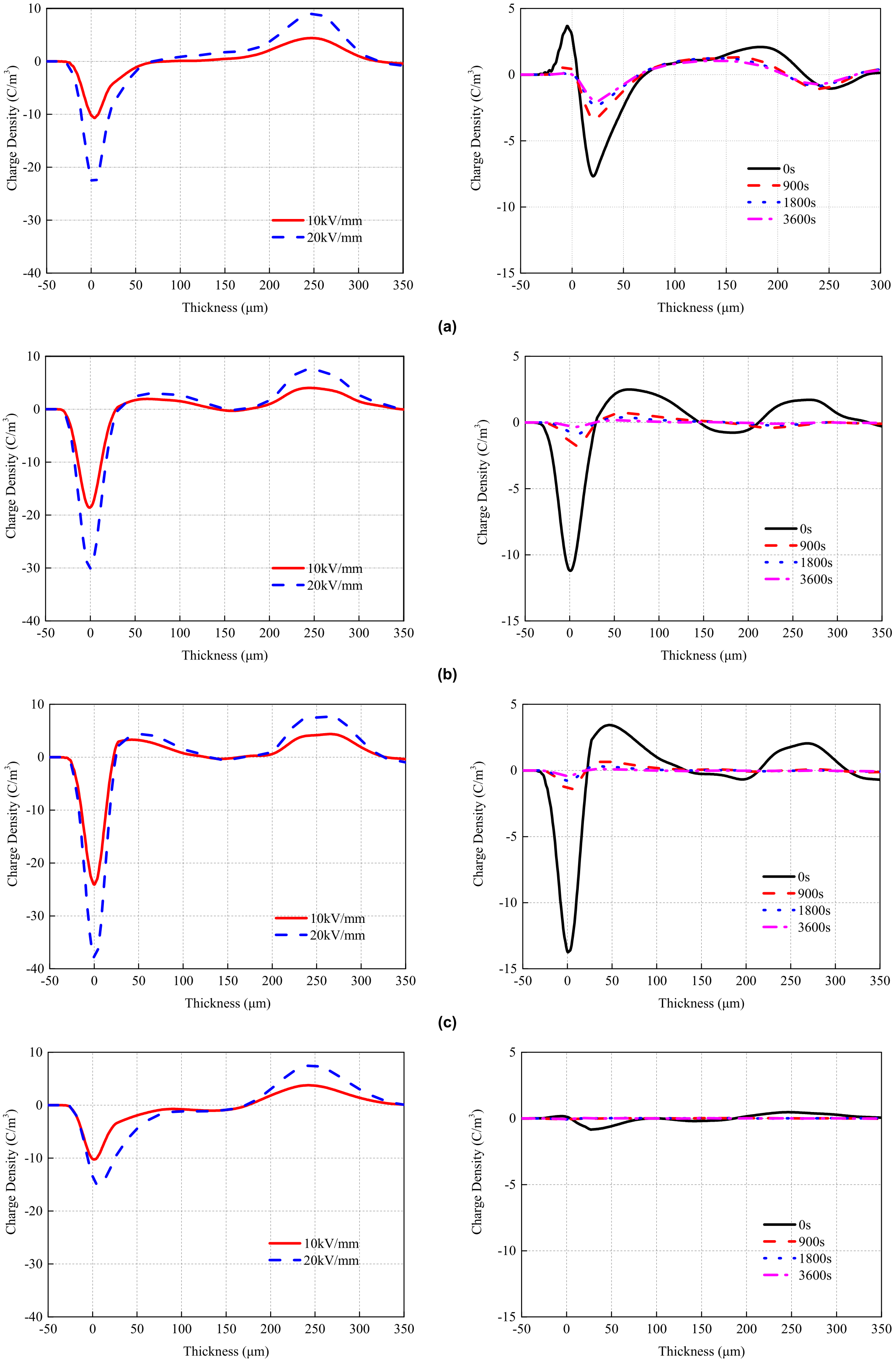


FIGURE 3. **Mean volume density of space charges accumulated in oil-impregnated pressboards with different moisture contents under 10kV/mm electric field (upper panel) and short-circuit (bottom panel).**

The space charge distributions in the oil-impregnated pressboards with different moisture contents being polarized for 1h under DC electric field (10kV/mm and 20kV/mm) and then dissipating with time under short-circuit are shown by the left and right panels in Fig.4, respectively. The space charges with an explicitly higher density are accumulated inside samples under higher electric field. Heterocharge accumulates near the upper electrode (cathode) in the oil-impregnated pressboards with the moisture content of 1.47% and 2.54%, while only homocharge are injected from cathode for the moisture contents of 0.34% and 3.74%. Moreover, higher density of space charge accumulations has been observed for higher moisture contents. Compared to the sample with the moisture content of 1.47%, the heterocharge



(a)

(b)

(c)

(d)

FIGURE 4. Space charge distributions of oil-impregnated pressboards with moisture contents of (a) 0.34%, (b) 1.47%, (c) 2.54% and (d) 3.74%, being polarized under DC electric field for 1h (left panels) and decaying with time under short-circuit (right panels).

distribution in the sample with the moisture content of 2.54% is closer to electrode, which confirms the smaller injection depth of space charge in the sample with the moisture content of 2.54%. It is noted from Figure 4(d) that some negative charge has transported across the dielectric material and accumulate near anode.

The space charge accumulations for all the moisture contents during short-circuit process show identical polarity as those in polarizing process such that heterocharge accumulate near cathode. During the short-circuit process, the surface charges accumulation near cathode derives from the space charges dissipating out off inside sample, retaining the heterocharge near cathode. Furthermore, the decay rate and amplitude of the accumulated space charges rise as moisture content is raised.

B. SURFACE POTENTIAL DECAY

Moisture has a great effect on the surface potential decay, as the ISPD curves shown in Fig.5. The surface potentials are decaying faster initially and slowing down to a most unchanged residual potential even after 7200s for the moisture samples of 0.34% and 1.47%. In comparison, the decaying speed and amplitude are significantly increased by raising moisture content, as indicated by the 2.54% and 3.74% curves rapidly restoring to zero potential only after approximate 100s and 300s respectively. These results imply that the trap level distributions have been remarkably altered towards smaller trapping depth by introducing water impurity into oil-impregnated pressboards, which accounts for the acceleration of surface charge dissipation caused by increasing moisture content as illustrated by the averaged decaying rates at 5min for various moisture contents in Fig.6.

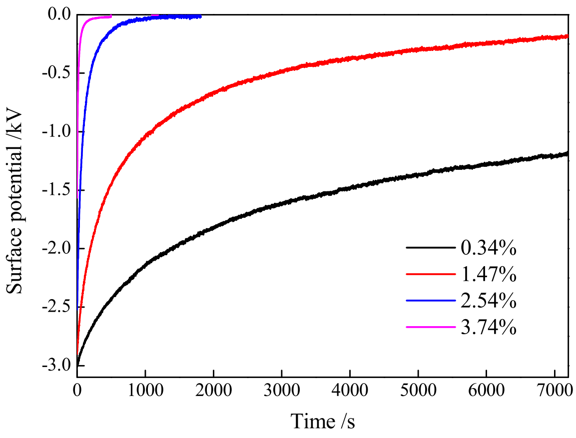


FIGURE 5. Surface potential decaying curves of oil-impregnated pressboards with different moisture contents.

V. DISCUSSION

In order to elucidate the effect of moisture on the trap level distributions of oil-impregnated pressboards, the trap level density as a function of energetic depth is calculated by equations (3) and (4), as shown in Fig.7. Two characteristic peaks arising in the trap energetic spectrum of oil-impregnated pressboards with the lowest moisture content indicate the intrinsic traps and water-introduced shallow traps respectively. The charges being captured by shallow traps are more easily to escape from trapping states (detrapping) with a higher dissipating rate so that the surface potential decays with a faster rate in the early stage. In contrast, the probability that charges captured by the deep traps are detrapping is low, which results in a longer period of charge dissipation and a lower decaying of surface potential. The moisture absorption of the insulating pressboards is mainly attributed to the hydrophilic groups (such as hydroxyl) on cellulose molecules, which will remarkably change the intrinsic trap level distributions. Traps level depth is appreciably decreased due to the polar molecular group introduced by absorbing moisture, as the results shown in Figure 7. Thus, space charges accumulated inside the oil-impregnated pressboards with high moisture content dissipate faster under short-circuit. Furthermore, the shallow traps introduced by water impurity can scatter charge carrier to accelerate relaxation in electrical transport process so that the space charge distribution reaches equilibrium faster under DC electric field, which is consistent with the previously reported conclusions from IRC measurements [24].

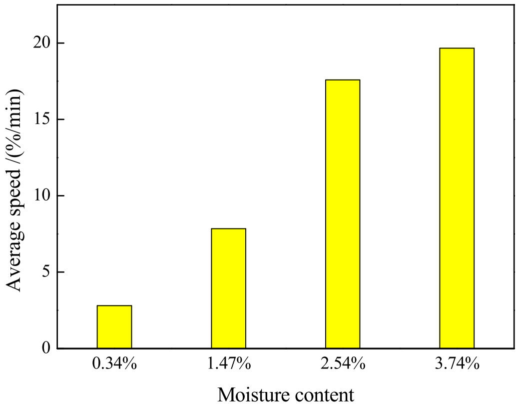


FIGURE 6. Average speed of surface potential at 5 min for the oil-impregnated pressboards with different moisture contents.

As shown in Figure 8, the electrical conductivity of oil-impregnated pressboards increase with the increase of moisture content. The opposite trend is observed in the dielectric breakdown strength result. The shallow traps facilitate charge transport as indicated by the increased conductivity. The higher charge mobility of oil-impregnated pressboard with a higher moisture content implies that energy accumulation is more likely to happen and lead to a lower breakdown field strength. Moreover, the high conductivity can also increases dissipating rate of surface charges.

Moisture absorption will also affect the polarity of space charges accumulated inside oil-impregnated pressboards. Homocharge accumulate inside the oil-impregnated pressboards with the moisture content of 0.34% and 3.74%, while heterocharge accumulate inside the oil-impregnated

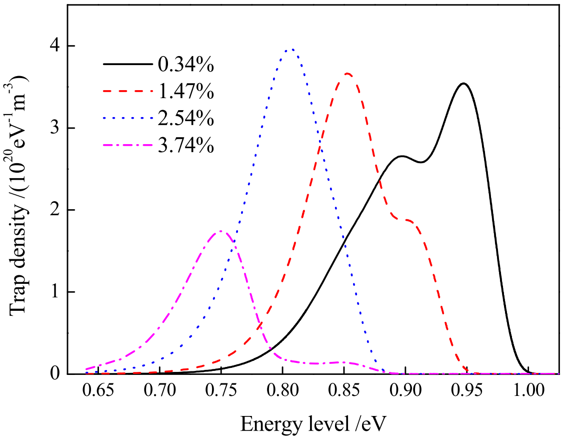


FIGURE 7. Trap level distributions of oil-impregnated pressboards with different moisture contents.

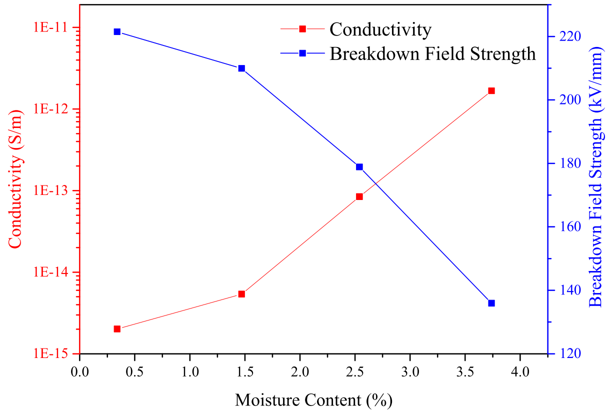


FIGURE 8. Electrical conductivity and dielectric breakdown strength of oil-impregnated pressboards with different moisture contents.

paper with the moisture content of 1.47% and 2.54%. The homocharge accumulation originates primarily from electrode injections which comply to the mechanisms of Schottky and tunneling effects under low and high electric field respectively. The thermal dissociation of impurities inside the sample under electric field can generate the positive or negative ions which will move to electrodes to form heterocharge. Water will promote impurities to dissociate, as shown in Fig.4, the space charge dissipating more rapidly in higher moisture.

Accordingly, the highest electric field in space charge tests is set to 20kV/mm so that electrode injection is dominated by Schottky effect, as the current density of electrode injection being expressed by:

$$j = AT^2 \exp[\frac{-\left(eW - \sqrt{e^3E/\left(4\pi\varepsilon_0\varepsilon_r\right)}\right)}{k_bT}] \tag{6}$$

where j denotes the current density of electrode injection, A is Richardson constant, W characterizes the energy barrier of charge injection, k_b is the Boltzmann constant, T is the absolute temperature, e is fundamental unit charge of electron. In equation (6), W can be expressed by:

$$W(x) = \phi_m - \chi - \frac{e^2}{16\pi\varepsilon x} - eEx \tag{7}$$

where $W(x)$ denotes the barrier height from metal Fermi level, ϕ_m is the work function of the metal electrode, χ is the electron affinity of dielectric. The injected current density increases with the increasing electric filed and the decreasing energy barrier of charge injection W, which means amount of charges injected into sample will increase accordingly.

The relative dielectric permittivity is the real part of the complex dielectric spectrum which is measured by frequency-dependent dielectric spectroscopy. It is indicated from Fig.9 that the relative dielectric permittivity of oil-impregnated pressboards is evidently promoted by increasing moisture content especially at the low frequency range. The real dielectric permittivity of all samples reduce gradually with the increasing frequency. According to equation (6), the increment of relative dielectric permittivity can reduce the injection current density which will lead to a larger amount of homocharge, which is contradictory to the common sense and the results of other researchers that water increases the injection current of dielectrics [25]. It means that the electron affinity of dielectric χ is enhanced with water increment.

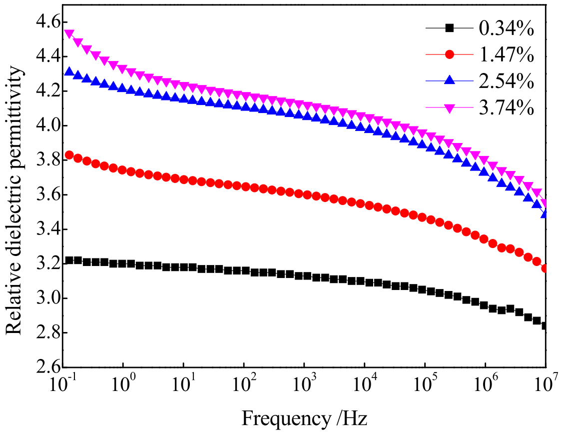


FIGURE 9. Relative dielectric permittivity of oil-impregnated pressboards with different moisture contents.

The dissociation rate of molecules per unit volume and unit time is expressed as follows:

$$N = N_0 v_0 \exp[-\Delta U_\mathrm{dis}/(k_\mathrm{b}\mathrm{T})] \tag{8}$$

where N_0 symbolizes impurity concentration, v_0 denotes thermal vibration frequencyof atomic groups, and ΔU_dis signifies the barrier to be overcome when the molecules are dissociated from equilibrium state. The moisture content always implies the water impurity concentration, so heterocharge accumulations deriving from molecular dissociation also increases as the moisture content being raised.

In the oil-impregnated pressboard with a moisture content of 0.34%, the low concentration of water impurity is consistent with the result that only the homocharge can substantially accumulates inside sample. It should be noted that both the homocharge and heterocharge will simultaneously accumulate when moisture absorption being intensified to a higher value, as verified by the considerable heterocharge arising inside sample for the higher moisture contents of 1.47% and 2.54%. The smaller injection depth of heterocharge for the moisture content of 2.54% is attributed to the higher charge mobility deriving from the lower scattering probability of the charge carriers and the shallower level traps, as shown in Fig.7. The shallowest charge traps level for the moisture content of 3.74% leads to highest charge mobility, so that the heterocharge are mainly distributed very near electrodes, which has been concealed by the higher density of homocharge. The electric field inside pressboard samples is smaller than that near electrodes, and the charge mobility of the samples with the moisture contents of 0.34%, 1.47% and 2.54% is not high enough to allow the charge carriers to transport through traps near the middle area, as illustrated by that no charge accumulation arises in the middle of pressboard materials. In comparison, the higher charge mobility and more shallower traps are achieved for the moisture content of 3.74%. Some negative charges injected from cathode can migrate to anode, so that the negative charges accumulate in an larger area from middle position to anode as shown in Fig 4(d). All these results can be essentially comprehended by significant reduction in trap level depth of oil-impregnated pressboards caused by absorbing moisture. A series of processes for charge inside sample that contains generation, migration, trapping, detrapping, and recombination are aggravated by moisture so that the space charge accumulations are accelerated to reach equilibrium.

VI. CONCLUSION

The space charge distribution and surface potential decay of oil-impregnated pressboards are systematically investigated in this article. The effect of absorbing moisture on the trap energy level distribution is analyzed to make some conclusions being highlighted as follows:

(1) The homocharge and heterocharge increase with the increase of moisture content. Homocharge accumulate inside the oil-impregnated pressboards with the moisture content of 0.34% and 3.74%, while the heterocharge accumulates at the moisture contents of 1.47% and 2.54%.

(2) With the increase in the moisture content, the rate and amplitude of surface potential decay are raised to exacerbate the accumulation and decaying of space charges.

(3) The trap energy levels are reduced by absorbing moisture, which accounts for the acceleration of space charge accumulation and dissipation.

REFERENCES

[1] E. I. Amoiralis, M. A. Tsili, and A. G. Kladas, "Power transformer economic evaluation in decentralized electricity markets," *IEEE Trans. Ind. Electron.*, vol. 59, no. 5, pp. 2329–2341, May 2012, doi: 10.1109/TIE.2011.2157291.

[2] G. Montanari, "Bringing an insulation to failure: The role of space charge," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no. 2, pp. 339–364, Apr. 2011, doi: 10.1109/TDEI.2011.5739438.

[3] R. Men, Z. Lei, T. Han, D. Fabiani, C. Li, S. V. Suraci, and J. Wang, "Effect of long-term fluorination on surface electrical performance of ethylene propylene rubber," *High Voltage*, vol. 4, no. 4, pp. 339–344, Dec. 2019, doi: 10.1049/hve.2019.0005.

[4] Z. Lei, C. Li, R. Men, and J. He, "Mechanism of bulk charging behavior of ethylene propylene rubber subjected to surface charge accumulation," *J. Appl. Phys.*, vol. 124, no. 24, Dec. 2018, Art. no. 244103, doi: 10.1063/1.5054702.

[5] L. E. Lundgaard, W. Hansen, D. Linhjell, and T. J. Painter, "Aging of oil-impregnated paper in power transformers," *IEEE Trans. Power Del.*, vol. 19, no. 1, pp. 230–239, Jan. 2004, doi: 10.1109/TPWRD.2003.820175.

[6] Q. Zhu, X. Wang, K. Wu, Y. Cheng, Z. Lv, and H. Wang, "Space charge distribution in oil impregnated papers under temperature gradient," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 1, pp. 142–151, Feb. 2015, doi: 10.1109/TDEI.2014.004481.

[7] K. Wu, Q. Zhu, X. Chen, X. Wang, and Y. Cheng, "Effect of temperature gradient on space charge distribution in oil impregnated papers," *High Voltage Eng.*, vol. 37, no. 4, pp. 823–827, 2011, doi: 10.13336/j.1003-6520.hve.2011.04.008.

[8] C. Tang, G. Chen, M. Fu, and R.-J. Liao, "Space charge behavior in multi-layer oil-paper insulation under different DC voltages and temperatures," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 3, pp. 775–784, Jun. 2010, doi: 10.1109/TDEI.2010.5492250.

[9] M. Rafiq, Y. Lv, C. Li, and Q. Sun, "Effect of Al_2O_3 nanorods on the performance of oil-impregnated pressboard insulation," *Electr. Eng.*, vol. 102, no. 2, pp. 715–724, Jun. 2020, doi: 10.1007/s00202-019-00907-5.

[10] M. Rafiq, L. Chengrong, and Y. Lv, "Effect of Al_2O_3 nanorods on dielectric strength of aged transformer oil/paper insulation system," *J. Mol. Liquids*, vol. 284, pp. 700–708, Jun. 2019, doi: 10.1016/j.molliq.2019.04.041.

[11] J. Zhang, Q. Chen, M. Chi, P. Tan, W. Sun, and J. Cao, "Effect of temperature on space charge characteristics of oil-paper insulation and its numerical simulation," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 26, no. 4, pp. 1334–1342, Aug. 2019, doi: 10.1109/TDEI.2019.008046.

[12] Pahlavanpour, M. Martins, and Eklund, "Study of moisture equilibrium in oil-paper system with temperature variation," in *Proc. 7th Int. Conf. Properties Appl. Dielectr. Mater.*, Nagoya, Japan, 2003, pp. 1124–1129, doi: 10.1109/ICPADM.2003.1218621.

[13] A. Betie, F. Meghnefi, I. Fofana, Z. Yeo, and H. Ezzaidi, "Neural network approach to separate aging and moisture from the dielectric response of oil impregnated paper insulation," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 4, pp. 2176–2184, Aug. 2015, doi: 10.1109/TDEI.2015.004731.

[14] R. Liu, A. Jaksts, C. Tornkvist, and M. Bergkvist, "Moisture and space charge in oil-impregnated pressboard under HVDC," in *Proc. IEEE 6th Int. Conf. Conduction Breakdown Solid Dielectr. (ICSD)*, Stockholm, Sweden, Jun. 1998, pp. 17–22, doi: 10.1109/ICSD.1998.709217.

[15] J. Hao, G. Chen, R. Liao, L. Yang, and C. Tang, "Influence of moisture on space charge dynamics in multilayer oil-paper insulation," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 19, no. 4, pp. 1456–1464, Aug. 2012, doi: 10.1109/TDEI.2012.6260023.

[16] R. Liao, Z. Zhou, J. Hao, and L. Yang, "Space charge characteristics of oil-immersed paper under moisture," *High Voltage*, vol. 38, no. 10, pp. 2647–2654, 2012.

[17] T. Takada and T. Sakai, "Measurement of electric fields at a Dielectric/Electrode interface using an acoustic transducer technique," *IEEE Trans. Electr. Insul.*, vol. EI-18, no. 6, pp. 619–628, Dec. 1983, doi: 10.1109/TEI.1983.298700.

[18] P. Morshuis and M. Jeroense, "Space charge measurements on impregnated paper: A review of the PEA method and a discussion of results," *IEEE Elect. Insul. Mag.*, vol. 13, no. 3, pp. 26–35, May 1997, doi: 10.1109/57.591529.

[19] J. Li, F. Zhou, D. Min, S. Li, and R. Xia, "The energy distribution of trapped charges in polymers based on isothermal surface potential decay model," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 3, pp. 1723–1732, Jun. 2015, doi: 10.1109/TDEI.2015.7116370.

[20] Z. L. Li, B. X. Du, Z. R. Yang, and C. L. Han, "Temperature dependent trap level characteristics of graphene/LDPE nanocomposites," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 25, no. 1, pp. 137–144, Feb. 2018, doi: 10.1109/TDEI.2017.006850.

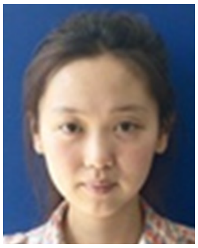
[21] J. G. Simmons and M. C. Tam, "Theory of isothermal currents and the direct determination of trap parameters in semiconductors and insulators containing arbitrary trap distributions," *Phys. Rev. B, Condens. Matter*, vol. 7, no. 8, pp. 3706–3713, Apr. 1973, doi: 10.1103/PhysRevB.7.3706.

[22] P. K. Watson, “The energy distribution of localized states in polystyrene, based on isothermal discharge measurements,” *J. Phys. D, Appl. Phys.*, vol. 23, no. 12, pp. 1479–1484, Dec. 1990, doi: 10.1088/0022-3727/23/12/002.

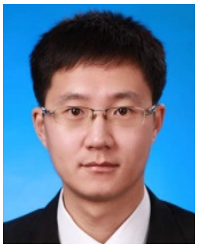
[23] B. X. Du, X. L. Li, and J. P. Jiang, “Surface charge accumulation and decay on directfluorinated oil-impregnated paper,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 23, no. 5, pp. 3094–3101, Oct. 2016.

[24] N. Haque, S. Dalai, B. Chatterjee, and S. Chakravorti, “Studies on the effects of moisture and ageing on charge de-trapping properties of oil-impregnated pressboard based on IRC measurement,” *High Voltage*, vol. 2019, pp. 151–157, Jan. 2019, doi: 10.1049/hve.2018.5095.

[25] C. Minghe, C. Qingguo, W. Xinyu, W. Yonghong, and W. E. I. Xinlao, “Influence of temperature on electric field distribution of oil-paper insulation under compound voltage,” *Proc. CSEE*, vol. 35, no. 6, pp. 1524–1532, 2015, doi: 10.13334/j.0258-8013.pcsee.2015.06.029.



YI GUAN was born in Heilongjiang, China, in 1987. She received the B.S. and M.Sc. degrees in electrical engineering from the Harbin University of Science and Technology, Harbin, China, in 2009 and 2012, respectively, where she is currently pursuing the Ph.D. degree in high voltage and insulation. Her major research interest includes electrical insulation of converter transformer.



MINGHE CHI was born in Heilongjiang, China, in 1985. He received the B.Sc., M.Sc., and Ph.D. degrees in high voltage engineering from the Harbin University of Science and Technology, Harbin, China, in 2008, 2011, and 2015, respectively. He is currently an Associate Professor with the Department of High Voltage Engineering, Harbin University of Science and Technology. His research interests include electrical insulation materials and insulation structure optimization in transformer.

JINFENG ZHANG was born in Heilongjiang, China, in 1991. He received the B.S. and Ph.D. degrees in electrical engineering from the Harbin University of Science and Technology, Harbin, China, in 2015 and 2019, respectively. He is currently a Lecturer with the School of Electrical Engineering and Automation, Qilu University of Technology (Shandong Academy of Sciences). His major research interests include electrical insulation of converter transformer and insulation detection and diagnosis technology for power equipment.

QIAN WANG was born in Hebei, China, in 1996. She received the B.S. degree in electrical engineering from the Anhui University of Technology, Ma’anshan, China, in 2018. She is currently pursuing the M.S. degree in high voltage and insulation with the Harbin University of Science and Technology. Her major research interest includes insulation characteristics of oil-paper in converter transformer.

XINLAO WEI was born in Shanxi, China, in 1960. He received the B.S. degree in high voltage technology and equipment from Xi’an Jiaotong University, Xi’an, China, in 1982, the M.S. degree in high voltage technology from the China Electric Power Research Institute, Beijing, China, in 1988, and the Ph.D. degree in electric machines and electric apparatus from the Harbin Institute of Technology, Harbin, China, in 2003. His research interests include high voltage and insulation testing technology and equipment for test and fault location used for electric power cable, and test technology and equipment used for air-core electric power reactor.

QINGGUO CHEN was born in Heilongjiang, China, in 1970. He received the B.S. and M.S. degrees in electrical engineering from the Harbin University of Science and Technology, Harbin, China, in 1992 and 1995, respectively, and the Ph.D. degree in high voltage and electrical engineering from Xi’an Jiaotong University, Xi’an, China, in 2001. He is currently a Professor with the High Voltage Division, School of Electrical and Electronics Engineering, and the Key Laboratory of Engineering Dielectrics and Its Application, Ministry of Education, Harbin University of Science and Technology. His major research interests include high-voltage insulation, insulation detection and diagnosis technology for power equipment, and the new technology of high-voltage application.

• • •