J Electr Eng Technol Vol. 9, No. 2: 635-642, 2014
http://dx.doi.org/10.5370/JEET.2014.9.2.635

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Space Charge Behavior of Oil-Impregnated Paper Insulation Aging at AC-DC Combined Voltages

Jian Li†, Yan Wang* and Lianwei Bao*

Abstract – The space charge behaviors of oil-paper insulation affect the stability and security of oil-filled converter transformers of traditional and new energies. This paper presents the results of the electrical aging of oil-impregnated paper under AC-DC combined voltages by the pulsed electro-acoustic technique. Data mining and feature extractions were performed on the influence of electrical aging on charge dynamics based on the experiment results in the first stage. Characteristic parameters such as total charge injection and apparent charge mobility were calculated. The influences of electrical aging on the trap energy distribution of an oil-paper insulation system were analyzed and discussed. Longer electrical aging time would increase the depth and energy density of charge trap, which decelerates the apparent charge mobility and increases the probability of hot electron formation. This mechanism would accelerate damage to the cellulose and the formation of discharge channels, enhance the acceleration of the electric field distortion, and shorten insulation lifetime under AC-DC combined voltages.

Keywords: Oil-paper insulation, Electrical aging, Space charge, PEA, Trap, Apparent charge mobility

1. Introduction

Oil-impregnated paper is a major type of insulation material used in oil-filled converter transformers for traditional and new energies [1]. Oil-impregnated paper degrades during routine operations under combined thermal, chemical, mechanical, and electrical stresses, especially winding-to-ground insulation, which affects the lifetime of converter transformers. Insulation failures of valve-connected windings account for about 50% of the total faults of converter transformers [2]. The formation and transportation of space charge can enhance the distortion of the electrical field distribution, which could lead to insulation failure [3]. Therefore, research on space charge behaviors of oil-paper insulation is significant for improving the physical, chemical, and electrical properties of oil-paper insulation.

The electrical aging of oil-paper insulation under AC-DC combined voltages has been studied for about two decades. Previous studies investigated the breakdown properties of oil-impregnated paper under AC-DC combined voltages with different magnitude ratios of DC to AC voltages [4]. The pulsed electro-acoustic (PEA) method allows the observation of space charges during poling and provides thorough information on space charge dynamics [5]. Chen [6] researched the effects of charge injection and extraction in polyethylene. Montanari [7] and Mazzanti [8] focused on the space charge properties and the space charge-derived quantities of dielectric materials in studying threshold voltage and apparent charge mobility. Liu and Jaksts showed that higher moisture concentration results in the faster establishment of space charge and deeper charge penetration in oil-paper insulation [9]. R. Ciobanu, I. Prisecaru, and S. Aradoaei focused on the influence of gamma radiation aging influence on space charge and field evolution [10]. J.Hao [11], C. Tang [12] and G. Chen [13] performed space charge behaviors in multi-layer oil-paper insulation system were analyzed and the influence of temperature on charge dynamics was discussed. The electrical tree occurs when the local field is greater than the breakdown strength of the material. Space charge is also closely connected to insulation breakdown [14]. S. Q. Wang and G. J. Zhang [15, 16] performed paper aged states affect the space charge characteristics of oil-paper insulation. The fundamental breakdown or degradation theories that involve space charge have been discussed, showing space charge can influence directly or indirectly processes bringing accelerated degradation and failure. The role of space charge can be fundamentally to alter, magnifying or lowering, the local electric field, to increase the aging rate and to bring degradation processes to a highly energetic state that causes premature failure [17].

In this paper, data mining and feature extractions were performed on the influence of electrical aging on space charge dynamics based on a large number of previous results obtained by PEA methods. Characteristic parameters such as total charge injection and apparent charge mobility

† Corresponding Author: State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, China. (jianli@cqu.edu.cn)
* State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, China. (wangyanhv@cqu.edu.cn)
Received: July 9, 2013; Accepted: October 14, 2013

were calculated and discussed. Based on the mechanism of the isothermal decay current, the trapping level and trap depth distribution inside the oil-paper were calculated using characteristics parameters of charge decay. The influences of electrical aging on the trap energy distribution in the oil-paper insulation system were analyzed. Longer electrical aging time will increase the depth and energy density of charge trap, which decelerates apparent charge mobility. This mechanism would enhance electric field distortion, facilitate partial discharge, deteriorate chemical and physical performances of oil paper insulation and shorten insulation lifetime under AC-DC combined voltages.

2. Theory

2.1 Total charge

Total space charge is related to electrical performance and the physical, chemical, and microcosmic characteristics of insulation. Total space charge reveals the property of space charge transport in the bulk of insulation. The total charge accumulated in the samples can be calculated based on charge density distribution using the following Eqs. [12, 18]:

$$Q(t)=\int_0^x \left|\rho(x,t)\right| Sdx, 0\le x\le d \tag{1}$$

where $Q(t)$ is the volt-on total absolute amount of charge; $\rho(x, t)$ is the charge density, S is the electrode area, and d is the thickness of the sample. The volt-on total absolute amount of charge includes contributions from both fast and slow moving charges.

2.2 Apparent charge mobility

Trap-controlled mobility, which is a depolarization characteristic, could be estimated by the apparent charge mobility and obtained by the mobility of space charge in decay condition. The de-trapping information could be significant to research on dielectric insulation performance. Space charge mobility $\mu(t)$ can be obtained by

$$\mu(t)=\frac{2\varepsilon}{q(t)^2}\frac{dq(t)}{dt} \tag{2}$$

where $q(t)$ is the charge density, ε is the relative dielectric constant, and t is the depolarization time. The variation of apparent charge mobility with decay time reflects the de-trapping process of space charge captured by traps with different trap energies [12]. The charge density information acquired through PEA only reflects the charge carrier information of shallow traps. Therefore, the charge trap discussed in this paper is the shallow trap with different trap levels.

2.3 Trap energy distribution

The trap energy density distribution could reflect the trap information of space discharge, aging condition of oil-paper insulation, and the dielectric performance from a microscopic view. The isothermal charge equation suggests that trap energy information could be obtained by the PEA method under decay condition. The energy distribution of the surface trap was then obtained through formula derivation and calculation [19]. Charge density is related to the current. Charge condition in the bulk of dielectrics material could be represented by the results of surface potential measurement. The average charge centroid after corona charging locates on the thin layer traps near the surface. The equivalent surface charge density σ increases with increasing surface potential V_s .Thus, the surface potential can be calculated by

$$\sigma=\frac{\varepsilon_0\varepsilon_r V_s}{r'} \tag{3}$$

where σ is the equivalent surface charge density; ε_0 is the dielectric constant under vacuum ε_0 = 8.854*10^{-12} F/m; ε_r is the relative dielectric constant of test sample; V_S is the surface potential V; r' is the average charge centroid, 120 pm.

Trapped charges are de-trapped after removing the applied voltage. The specimen is under a short-circuited condition if the electron charge is not trapped [19, 20]. Charge density is then given by

$$n_t=f_0(E_t)N_t(E_t)e^{-e_n t} \tag{4}$$

where n_t is the density of trapped charge; $f_0(E_t)$ is the original occupation rate of traps inside the dielectrics 1/2; $N_t(E_t)$ is the trap energy density distribution function (meV)$^{-1}$; E_t is the trap energy level eV; t is the time, and e_n is the thermal emission rate of electron trap. The variation of charge density in the trap (potential decay) is approximate to an exponential decay, which is

$$\sigma=n_t=0.5\times N_t e^{-\varepsilon_n t}=B\times e^{-1/\tau} \tag{5}$$

where B is a constant, B=0.5N_t and τ is the constant of decay time, which is shown in Table 1, τ =1/e$_n$. The relationship between the attenuation of surface potential and the current is shown in Eq. (6).

$$i(t)=C\frac{dV_S(t)}{dt} \tag{6}$$

Based on Eq. (6), the current density can be obtained by

$$C=\varepsilon_0\varepsilon_r\frac{A}{d} \tag{7}$$

$$j(t)=\frac{i(t)}{A} \tag{8}$$

$$j(t)=\frac{\varepsilon_0\varepsilon_r}{d}\frac{dV_s(t)}{dt}=\frac{r'}{d}\frac{d\sigma(t)}{dt} \tag{9}$$

where $i(t)$ is the current; C is the electric capacity of test sample F; A is the surface area; d is the thickness of test sample, and $j(t)$ is the current density. Eq. (9) shows that the current density is proportional to the reciprocals of the surface potential and surface-charge density.

Based on Eqs. (5) and (9), the variation of the current density, including the constant of decay time, can be obtained by

$$|j(t)|=\frac{r'}{d}\frac{B}{\tau}e^{-t/\tau} \tag{10}$$

The carriers bounded in the shallow traps are released earlier than the carriers bounded in the deep traps for oil-paper insulation material when the applied voltage is removed. The relationship among trap energy level E_t, the current density j, and trap energy density N_t can be calculated by the following equation if the carriers are not trapped again [21]:

$$E_t = kT\ln vt \tag{11}$$

$$j(t)=\frac{qdkT}{2t}f_0(E_t)N(E_t)=\frac{r'}{d}\frac{B}{\tau}e^{-t/\tau} \tag{12}$$

where q is the electron charge 1.6×10^{-19} C; k is the Boltzmann's constant 8.568×10^{-5} eV/K; T is the absolute temperature K; v is the frequency of electron vibration $3\times10^{12}\text{s}^{-1}$, and d is the thickness of the test sample. The trap energy of the hole is calculated from the peak of the valence band, and the trap energy of the electron is calculated from the bottom of the conduction band.

If $\eta_1=\frac{qLkT}{2t}f_0(E)$, $\eta_2=\frac{r'B}{d}$, η_1 and η_2 are constant, the trap energy density can be calculated by

$$N(E_t)=\frac{\eta_2}{\eta_1}\frac{t}{\tau}e^{-t/\tau} \tag{13}$$

Eq. (13) indicates that the density of trap energy level $N_t(E_t)$ is related with the decay constant of charge density and decay time.

3. Apparatus and Experimental Setup

3.1. Electrical aging experiment

In high voltage direct current transmission system, Voltages across winding-to-ground insulation of converter transformer that contain components of DC and AC voltages were determined. And the voltages are composed of AC, DC, and strong harmonic voltages. Windings of delta-connected single-phase transformers withstand AC-DC combined voltages with a magnitude ratio of DC to AC peak values equal to 1:1. The AC-DC combined voltages across the windings in wye-connected single-phase transformers are composed of AC and DC components with a magnitude ratio of DC to AC peak values equal to 3:1 [22].

Fig. 1 shows the experimental setup for the electrical aging of oil-impregnated paper. Testing voltages consist of AC and DC voltage sources for constant stress tests. Both voltages were supplied at the same time, which form the pulsating voltages. Both voltages were increased from zero until breakdown to ensure that the cause of breakdown was always a voltage that was increasing at a constant rate. Fig. 2 and Eq. (14) define the ripple factor RF of the pulsating voltages. U_{ac} is the maximum value of AC voltage and U_{dc} is the maximum value of DC voltage. The rising rates of the peak values of testing voltages were controlled at 1000 V/s. The rising rates of the peak value of AC and DC voltages are similar at 500 V/s when RF is equal to 100%. DC voltages with positive polarities were used for constant stress tests.

$$RF=\frac{U_{ac}}{U_{dc}} \tag{14}$$

The insulation paper used for the constant-stress test was provided by China Hunan No. 1 Paperboard Co., Ltd. The insulation paper had a diameter and a thickness of 80 and 0.2 mm, respectively. The insulation paper was dried in a

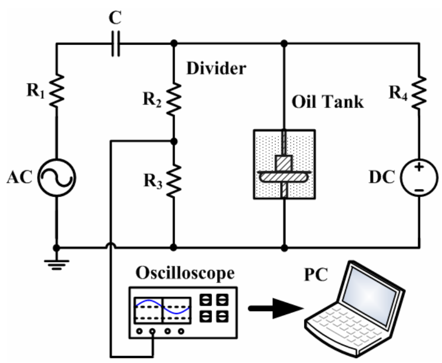


Fig. 1. Experimental system on site

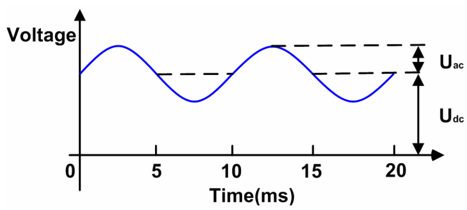


Fig. 2. Definition of ripple factor *RF*

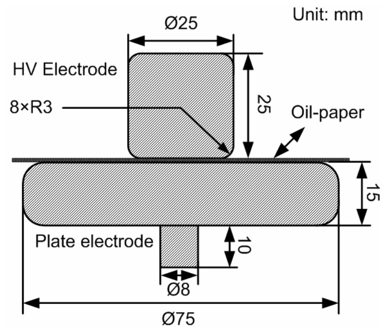


Fig. 3. Electrode system on site

50 Pa vacuum at 90 °C for 48 h and then impregnated with Karamay 25# transformer oils in a 50 Pa vacuum at 40 °C for 48 h. The transformer oils were first degassed in vacuum at 40 °C. The drying process reduced the water content in the paper to 0.4% weight. The water content in the oil was reduced to 9 mg/kg, which was considered acceptable for the proposed test program. Oil-impregnated paper insulation specimens were placed in a sealed glass vessel prior to the electrical breakdown experiments.

The experimental system consisted of an oil tank and a rod-plate electrode system. The dimension of the oil tank is Φ220×250 mm. Fig. 3 shows that the electrode system was designed according to IEC 60243-1[23]. The electrode system and oil-paper insulation specimens were completely immersed in transformer oils at room temperature. Both electrodes are made of brass. The testing voltage of the sample was 7.6 kV ±500V during the electrical aging process. The aging times were set at 6, 12, 24, 72, and 144 hours.

3.2 PEA measurement

In the PEA technique, acoustic pressure waves are generated as a result of the interaction of the pulsed electric field and the charge layer. Acoustic pressure wave is detected and determine charge distribution across the sample. Details of the PEA technique are documented in literatures [6, 24].

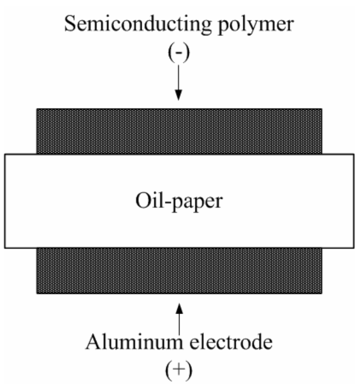


Fig. 4. Schematic diagram of sample arrangement

The space charge measurements were taken using the PEA system, which has an applied pulse voltage of 400 V, a width of 5 ns, and a minimum resolution for sample is less than 10 μm. Silicone oil was used as the acoustic coupling agent. The space charge distribution in vertical and lateral directions of the applied pulsed electric field can be observed by using an electro-acoustic sensor. The test temperature was set at 20°C ±2°C. All samples were stressed under 30 kV/mm and a negative DC electric field. Therefore, the applied voltage is 6 kV ±500V. Space charge measurement was taken at various times during the volt-on (DC voltage being applied) and decay (DC voltage being removed) periods using the PEA technique. During volt-on and decay the charge density inside the aging sample could be acquired. The top electrode is a semi-conducting polymer, whereas the bottom electrode is an aluminum plate. Both electrodes have a diameter of 15 mm. Fig. 4 shows that the experiments on space charge measurement were performed on a single layer oil-impregnated paper insulation sample (~190 μm after oil immersion and after being pressed by electrodes).

4. Results and discussions

4.1 Total charge

Fig. 5 shows the evolution of total space charges during the volt-on experiments. The total charge in the bulk oil-paper sample increased with increasing stress and aging time. Therefore, with a longer aging time, more charges are injected into the bulk sample under a similar testing time.

Fig. 6 shows that the total charges decrease rapidly before 50 s before slowing down. The total charges arrive at the ultimate state after 100 s. The charges decayed more slowly with increasing aging time. Space charge inside the oil-paper was de-trapped and neutralized rapidly at the beginning of the decay process because of the high residual electrical field. This mechanism decreased the total charge quickly. The effect of residual electrical field weakened

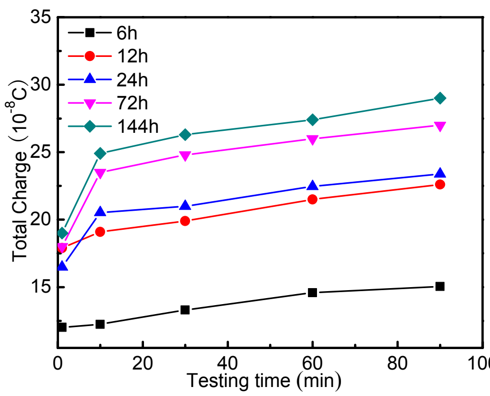


Fig. 5. Total charge of different aged samples during the volt-on

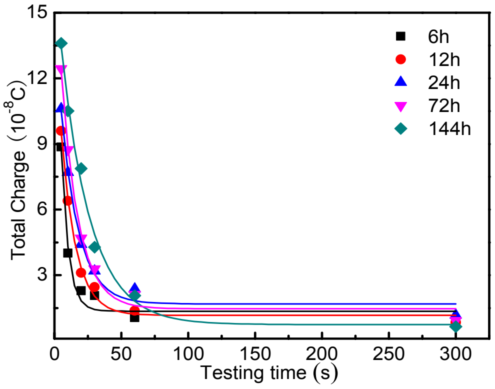


Fig. 6. Total charge of different aged samples during decay

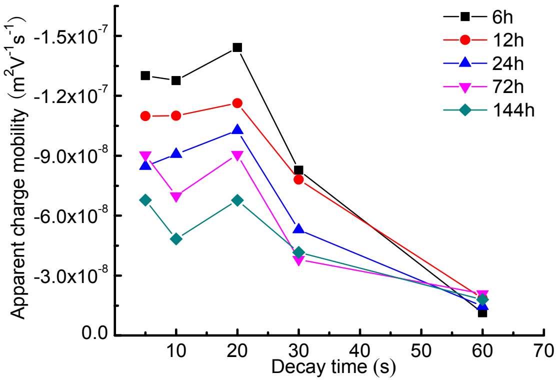


Fig. 7. Apparent charge mobilities under different aging times vs. decay time

Table 1. Parameters of the total charge model of different aged samples during decay

Aging Time (h)	Parameters			
	T_0	B	Decay time τ	R^2
6h	1.13	9.92	9.02	0.975
12h	1.17	13.13	11.09	0.994
24h	1.69	12.85	13.36	0.991
72h	1.46	15.99	12.97	0.993
144h	0.79	17.64	20.44	0.995

with the increase of decay time. Space charges in slow decay stage that remained in the bulk of the oil-paper samples were mainly trapped in relatively deep traps, thereby requiring more energy to de-trap. Therefore, the decay rate of total charge decreased continuously. With a longer aging time, the disappearance of the total charge of trapped charges became slower. The total charge model of different aged samples during decay is shown in Eq. (15).

$$y = T_0 + B \times e^{(-x/\tau)} \tag{15}$$

x is the testing time during decay; y is the total charge of different aged samples during decay; B is the slope of fitting line; τ is the decay time. The dissipation of the total charge represents an exponential decay curve. The fitting lines of different aged samples during decay are shown in Fig. 6. And the parameters of model are shown in Table 1. A larger slope B means that the apparent charge mobility is larger with increased of the aging time. And decay time τ increases with the increasing aging time of the oil-paper sample. With increased decay time τ, the total charge of trapped charges disappears slower.

4.2 Apparent charge mobility

Fig. 7 shows that longer decay and aging times result in smaller apparent charge mobility. This indicates that the apparent charge mobility initially decreased rapidly and then tended to stabilize. The de-trapping of space charge inside the oil-paper is restrained by the shallow traps, which resulted in the initial rapid decrease. A slow decline with longer decay time reflects the de-trapping of space charge bounded in the relatively deep traps, which requires more energy to de-trap. The maximum value of the apparent charge mobility was reduced at 144 h. This finding indicates that the trap energy density is larger in the shallow traps, which are in a relatively low trap level. The amount of relatively deep trap increased with increasing aging time. Thus, the capability to restrain the charge increased, and the apparent charge mobility decreased.

The total charges of fast and slow moving charges increased with increasing aging time. A longer aging time means that more charges were trapped in the sample and that the number of relatively deep traps increases. The decay curve of the total charge indicates that longer aging time results in the slower disappearance of the total charge of trapped charges. The residual amounts of space charge are related to trap depth and density. The charge needs more energy to de-trap when trapped in deeper traps or higher density of oil-paper insulation. This mechanism could lead to more trapped and accumulated charges. The slope of the decay curve and decay time τ also reflects charge mobility. A larger slope means that the apparent charge mobility is larger. And the decay time τ means that the disappearance of apparent charge mobility is slower.

Therefore, longer aging time could increase the density of relatively deep traps, which decreases apparent charge mobility. The curve of apparent charge mobility tends to move downward, which indicates that the apparent charge mobility became smaller because of longer electrical aging excitation. Considering the mechanism of charge trap formation inside the dielectrics, electrical aging effects the trap excitation and formation of new traps, which could increase trap density. Longer aging time will strengthen the capability of bounding charge carrier, increase the depth of the charge trap, and decelerate the apparent charge mobility.

4.3 Trap energy distribution

Fig. 8 shows the trap energy distribution of oil-paper at different aging times.A shallow trap is less than 1.10 eV, whereas a deep trap is more than 1.10 eV because of the

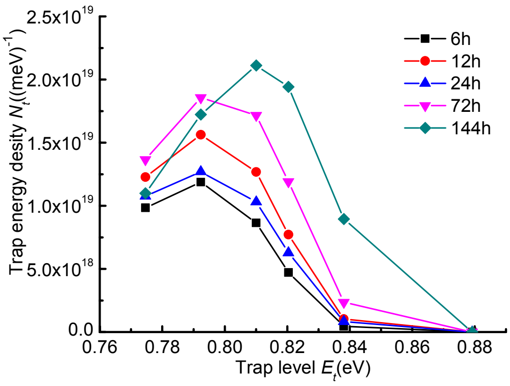


Fig. 8. Trap energy distributions of samples at different aging times

limit of test sensitivity of the PEA method. Fig. 8 shows that the trap energy of the oil-paper was in the range of 0.77 to 0.88 eV. Trap density increased initially and then decreased. Very few trap levels were larger than 0.88 eV. Therefore, the trap energy density of the space charge discussed in this paper is mainly the shallow trap with different trap levels. This shallow trap shows that the trap energy density at different trap levels increased with increasing aging time, especially at 144 h. This finding proves the accuracy of previous analysis on trap energy density. This finding also indicates that the trap density increases because of longer electrical aging excitation. The energy densities of the shallow and deep traps increase with increasing aging time. Increased aging time facilitated the formation of deep traps and increased the shallow trap density inside the oil-paper.

The electrons from the cathode were injected into the conduction band under high voltage pressure. The electrons were then bounded quickly by the trap after a few times of scattering because of short mean free path of the electrons. The electrons transmitted from high to low energy state during charge trapping and recombination. The redundant energy was then passed to another electron in a non-thermal radiation process for hot electron formation [25]. The energy released by the hole trap after hole injection is passed to another electron in a non-thermal radiation process to form a hot electron.

During the dissociation process, the hot electrons bombarded cellulose, which is dissociated into radicals and leads to more trapped charges and released energy. The energy release caused by dissociation and trapping will be transferred to another electron, which will be transformed into a hot electron. This process will continue as a chain action to produce more radicals. The trap theory of polymer aging trap indicates that the deep traps reduce the number of free carriers in conduction band. The deep traps have strong binding capacity and lead to short effective mean free path of the electrons in the conduction band. As a result, the formation of hot electrons is difficult in the electric field inside insulation. Therefore, the increasing deep trap energy density would decrease the number of hot electrons that form more trapped charges and energy release. On the contrary, the increased shallow trap energy density will increase the number of these electrons. This mechanism will increase the bombardment of the cellulose and accelerate the formation of discharge channels in the bulk of oil-paper insulation. The amount of trapped charges is proportional to the distortion factor of the electric field in the bulk of sample.

Combined with the results and analysis of previous parts, more traps are formed with increased aging time. The trap depth of the oil-paper and the density of relatively deep traps increased with longer aging time. Shallow trap density increased with the increased probability and energy of hot electron formation inside the oil-paper caused by electron movement. Therefore, longer aging time increased the shallow trap density inside the oil-paper and accelerated cellulose damage, which led to electric field distortion. This finding indicates that electrical aging could enhance electric field distortion in the bulk of oil-paper insulation, which will deteriorate chemical and physical performances and shorten insulation lifetime. The growth and formation of electrical trees are initiated when the distortion factor of electrical field is above the critical value. The increased distortion factor of the electric field will result in partial discharge, which could accelerate the growth of electrical trees.

5. Conclusion

Electrical aging experiments of oil-paper insulation under AC-DC combined voltages were presented in this paper. Based on the results obtained by the PEA method, feature extractions were performed on the influence of electrical aging on charge dynamics. The conclusions are as follows.

(1) Longer aging time of the oil-paper sample means that more charges are injected into the bulk of the sample and that trapped charges disappear in samples more slowly. Longer aging time also means that the total charge of the trapped charges becomes larger. The residual electrical field effect weakened with increased decay time. Space charges in slow decay stage that remained in the bulk of the oil-paper samples were mainly trapped in relatively deep traps, which require more energy to de-trap. This causes longer aging time, which slows the disappearance of the total charge of trapped charges. The dissipation of total charge represents an exponential decay curve. With increased electrical aging time, a larger decay curve slope *B* indicates that the apparent charge mobility is larger; a larger decay time τ indicates that the total charge of trapped charges disappears slower.

(2) The decreased apparent charge mobility was caused by the increased capability to restrain charge when the aging time is increased because the number of

relatively deeper traps increased. Electrical aging effects trap excitation and the formation of new traps, which could increase trap density. The apparent charge mobility decreased because of longer electrical aging excitation. Longer electrical aging time would strengthen the capability of the bounding charge carrier, decelerate the mobility of the trapped charges, and increase the depth and energy density of charge trap, which lead to the deceleration of the apparent charge mobility.

(3) Trap energy density increased with increased aging time. Increased aging time facilitated the formation of deeper traps inside the oil-paper and increased shallow trap energy density. The increased shallow trap energy density increased the probability and energy of hot electron formation inside the oil-paper because of the electron movement. The hot electrons bombarded cellulose, which are dissociated into radicals and caused more charges to become trapped. As a result, the electric field distortion was enhanced, and the formation of discharge channels was accelerated. The trapped charges also induced partial discharge, which accelerated the growth of electrical trees. This indicates that electrical aging could enhance electric field distortion inside the oil-paper insulation, accelerate cellulose damage, and deteriorate chemical and physical performances, which shorten insulation lifetime under AC-DC combined voltages.

Acknowledgements

The authors acknowledge National Basic Research Program of China (973 Program, No. 2012CB215200), Natural Science Foundation of China (No. 51177180) and for supporting this study. We also thank the support and funding of the 111 Project from the Ministry of Education, China (B08036), Innovative Research groups of China (No. 51021005) and Specialized Research Fund for the Doctoral Program of Higher Education (No. 20110191130004).

References

[1] W. X. Lu and B.T. Ooi, "Optimal Acquisition and Aggregation of Offshore Wind Power by Multi-terminal Voltage-Source HVDC", *IEEE Trans. Power Delivery*, vol. 18, no. 1, pp.201-206, Jan. 2003.

[2] CIGRE Joint Task Force B4.04/A2-1, "Analysis of HVDC Thyristor Converter Transformer Performance," *in Proceedings of Council on Large Electric Systems*, Canada, Feb. 2004.

[3] W. Choo, G. Chen and S. G. Swingler, "Electric Field in Polymeric Cable Due to Space Charge Accumulation under DC and Temperature Gradient," *IEEE Trans. Dielectr. Electr. Insul.*, vol.18, no.2, pp.596-606, April 2011.

[4] Y. Wang, J. Li, Y. Y. Wang, S. Grzybowski, "Electrical breakdown properties of oil-paper insulation under AC-DC combined voltages," *in Proceedings of IEEE Conf. Power Modulator and High Voltage*, Atlanta, America, May 2010.

[5] G. Mazzanti, G. C. Montanari and J. M. Alison, "A space-charge based method for the estimation of apparent mobility and trap depth as markers for insulation degradation-theoretical basis and experimental validation," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 10, no.2,pp.187-197, April 2003.

[6] G. Chen, Y. Tanaka, T. Takada and L. Zhong, "Effect of polyethylene interface on space charge formation," *IEEE Trans. Dielectr. Electr. Insul.,* vol.11, no.1, pp. 113-121, Feb. 2004.

[7] Montanari G. C., "Dielectric material properties investigated through space charge measurement," *IEEE Trans. Dielectr. Electr. Insul.*, vol.11, no.1, pp. 56-64, Feb. 2004.

[8] Mazzanti G, Montanari G C. "Quantities extracted from space-charge measurements as markers for insulation aging," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 10, no.2, pp.198-203, April 2003.

[9] R. S. Liu, Jaksts A., Tornkvist C., Bergkvist M., "Moisture and space charge in oil-impregnated pressboard under HVDC," *in Proceedings of the 6th IEEE Conference on Conduction and Breakdown in Solid Dielectrics*, Vasteras, Sweden, June 1998.

[10] R. Ciobanu, I. Prisecaru, and S. Aradoaei, "PEA measurements upon cellulose materials submitted to gamma radiation," *in Proceedings of the 8th International Conference on Solid Dielectrics*, Toulouse, France, July 2004.

[11] Jian Hao, George Chen, Ruijin Liao, Lijun Yang and Chao 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, Mar. 2012.

[12] C. Tang, R.J. Liao, G. Chen, L.J.Yang, "Research on the feature extraction of DC space charge behavior of oil-paper insulation," *SCIENCE CHINA-Technological Sciences*, vol.54 no.5, pp.1315-1324, May 2011.

[13] Chao Tang, George Chen, Ming Fu, RuiJin 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, Aug. 2010.

[14] Mahmoud Abou Dakka, Alexander Bulinski and Soli Bamji, "Space Charge Development and Breakdown in XLPE under DC Field," *IEEE Trans. Dielectr. Electr. Insul.*, vol.11,no.1,pp.41-49, Feb. 2004.

[15] S. Q. Wang, G. J. Zhang, H. B. Mu, D. Wang, M. Lei, Y. Tanaka, et al., "Effects of paper-aged state on space charge characteristics in oil-impregnated paper insulation," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 19, no.6, pp.1871-1878, Dec. 2012.

[16] S. Q. Wang, G. J. Zhang, J. L. Wei, S. S. Yang, M.

Dong, and X. B. Huang, "Investigation on dielectric response characteristics of thermally aged insulating pressboard in vacuum and oil-impregnated ambient," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 17, no. 6, pp. 1853-1862, Dec. 2010.

[17] G. C. Montanari, "Bringing an insulation to failure: the role of space charge," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no.2, pp.339-364, April 2011.

[18] Xu Zhi Qiang. Space charge measurement and analysis in low density polyethylene film [D] Southampton: University of Southampton, 2009.

[19] X. Wang, S. Q. Chen, X. Cheng, D. M. Tu, "Measuring energy distribution of surface trap in polymer insulation by PEA method," *Proceedings of the CSEE*, vol.29, no.1, pp.127-132, Jan. 2009.

[20] B. T. Yang, T. Demin, and Y. N. Liu "Theory of isothermal charge and direct determination of trap distributions in solid dielectrics," *Journal of Applied Sciences*, vol. 10, no.3, pp. 233-240, Mar. 1992. (in Chinese)

[21] Y. Yin, D. M. Tu, M. Li, and Z. H. Li, "Study on the action mechanism of the free redical scavenger with isothermal current-decay method: an experimental verification of trap theory for electrica aging in polymer," *Proceedings of the CSEE*, vol. 20, no.3, pp. 13-15, Mar. 2000.

[22] W.J. Zao, *High* Voltage *Direct Current Transmission Engineering Technology*, 2nd ed., Peking: China Electric Power Press, 2011, pp.308-309. (in Chinese)

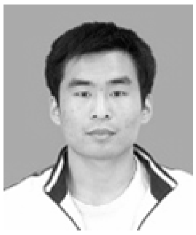
[23] IEC 60243-1, "Electrical Strength of Insulating Materials - Test Methods - Part 1: Tests at Power Frequencies," IEC Publication, 1998.

[24] G. Chen, M. Fu, X. Z. Liu and L. S. Zhong, "Ac aging and space-charge characteristics in low-density polyethylene polymeric insulation," *Journal of Applied Physics*, vol.97, no.8, pp.083713-0-83713-7, April 2005.

[25] K. C. Kao, "New theory of electrical discharge and breakdown in low - mobility condensed insulators," *Journal of applied physics*, vol. 55, no.3, pp. 752-755, Sept. 1984.

Jian Li He received the M.S. and Ph.D degree in electrical engineering in 1997 and 2001, from Chongqing University, Chongqing, China. He is currently a professor and the head of High Voltage and Insulation Technology Department at Chongqing University. His major research interests include online detection of insulation condition in electrical devices, partial discharges, and insulation fault diagnosis for high voltage equipment. He is an author and coauthor of more than 40 journal papers and 30 papers published in proceedings of international conferences.

Yan Wang She was born in China in 1984.She is a Ph.D. student in school of Electrical Engineering at Chongqing University, China. She was invited to Technical Graz of University, Austria as a visiting student from 2010 to 2011. Her research interests include the aging and life evaluation of insulation for converter transformer in HVDC transmission system.



Lianwei Bao He received his Bachelor degree in electrical engineering in 2010, from Southwest Jiaotong University, Chengdu, China. He is currently a Ph.D. degree student in school of Electrical Engineering at Chongqing University. His major research interests include online detection of insulation condition in electrical devices, insulation fault diagnosis for high voltage equipment.