J Electr Eng Technol Vol. 8, No. 6: 1512-1519, 2013
http://dx.doi.org/10.5370/JEET.2013.8.6.1512

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

Influence of Electrical Aging on Space Charge Dynamics of Oil-Impregnated Paper Insulation under AC-DC Combined Voltages

Yan Wang*, Jian Li†, Sicheng Wu* and Peng Sun*

Abstract – Oil-impregnated paper is a major type of insulation used in oil-filled converter transformers for both traditional and new energy systems. This paper presents and analyzes the results of the experiment conducted on the electrical aging of oil-impregnated paper under AC-DC combined voltages using the pulsed electro-acoustic (PEA) technique. The formation and dynamics of space charge affected the performance of insulation material. The electrical aged oil-paper insulation was obtained through electrical aged experiments under the voltages. Based on the PEA technique, measurements were carried out when the oil-paper insulation system was subjected to different stressing and aging times. The space charge dynamics in the bulk of the oil-paper insulation system with different aging times were measured and analyzed. Characteristic parameters such as the total charge injection amount, the total charges of fast moving and slow moving, and the distortion factor of electric field were calculated and discussed. Results show that the longer electrical aging time, the more charges trapped in the bulk of aging sample. It leads to larger distortion factor of electric field in the bulk of aging samples and accelerate degradation of oil-paper insulation under AC-DC combined voltages.

Keywords: Converter transformer, Oil-paper insulation, Electrical aging, Space charge, PEA, Electrical field

1. Introduction

Converter transformers play important roles in high-voltage direct current (HVDC) transmission systems for both traditional and new energy systems [1]. Voltages across winding-to-ground insulation in HVDC converter transformers consist of AC, DC, and strong harmonic voltages [2]. Insulation failures in valve-connected windings account for approximately 50% of the total faults of converter transformers [3]. Oil-impregnated paper is a major type of insulation used in oil-filled converter transformers. The space charge accumulation occurs in the dielectric materials under DC conditions [4]. The formation and transportation of space charge in insulation can distort the electrical field distribution, which leads to the premature failure of the insulation [5]. The electric field distortion inside insulation materials influences the conductance, breakdown voltage, and aging process evidently [6].

Electrical aging of oil-paper insulation under AC and DC combined voltages has been studied for two decades. Previous studies investigated the breakdown properties of oil-impregnated paper under the voltages with different magnitude ratios of DC to AC voltages [7]. The pulsed electro-acoustic (PEA) method allows the observation of space charges during the poling process, and provides thorough information on space charge dynamics [8]. Tanaka, Tanada, and Chen investigated the effects of charge injection and extraction in polyethylene [9-13]. Mazzanti and Montanari focused on the space charge properties of polyethylene materials and space charge-derived quantities to study the threshold voltage and apparent charge mobility [8, 14, 15]. Publication [16] showed that space charge came from ionization at lower field intensity, and investigated the new thermo-electrical life model based on the relationship between space charge and breakdown in oil-paper insulation. Space charge behaviors in a multi-layer oil-paper insulation system were analyzed, and the influence of temperature on charge dynamics was discussed in several publications [17-19]. The electrical tree would occur when a local field is larger than the breakdown strength of the material. In addition, space charges have a close connection to the breakdown of insulation [20, 21].

In this paper, the electrical aging of oil-paper insulation was obtained through electrical aging experiments under AC-DC combined voltages. The space charge behaviors of the oil-paper insulation system with different aging times were investigated using the PEA technique. Charge dynamics in the insulation system during the volts-on and decay conditions were analyzed. The characteristic parameters such as the total amount of charge injection, the

† 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: April 11, 2013; Accepted: July 4, 2013

total charges of fast and slow moving, and the distortion factor of electric field were calculated and discussed. The electrical aging decelerates the mobility of the trapped charges. The influences of electrical aging on the charge distribution in oil-paper insulation system were studied as well.

2. Experiments

2.1 Electrical aging experiment

For converter transformers, voltages across winding-to-ground insulation containing components of DC and AC voltages were determined. Windings of delta-connected single-phase transformers could 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 consisted of AC and DC components with a magnitude ratio of DC to AC peak values equal to 3:1 [2].

Fig. 1 illustrates the experimental setup for the electrical aging of oil-impregnated paper. A 50 kV DC source and a 50 kV AC source are connected in parallel with the oil tank placed between and around the HV lead of the sources. During the tests, DC and AC voltages were changed at 500 V intervals, and synchronization was increased using the regulating transformer. Both DC and AC voltages were increased from zero until breakdown to ensure that the cause of breakdown was always a voltage increasing at a constant rate. 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.

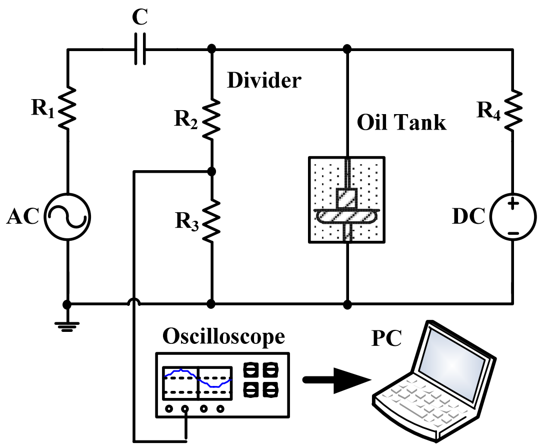


Fig. 1. Experimental system on site

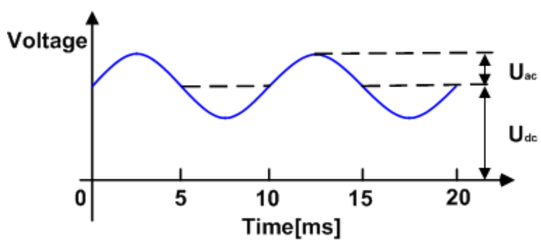


Fig. 2. Definition of ripple factor *RF*

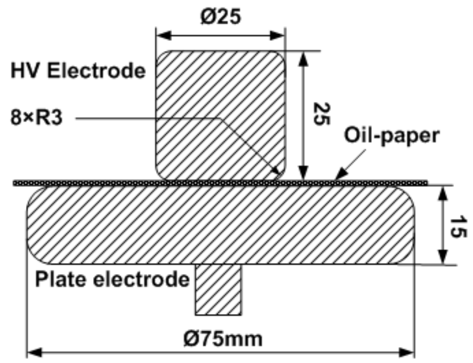


Fig. 3. Electrode system on site

Fig. 1 also shows that the testing voltages consisted of AC and DC voltage sources for constant-stress tests. Both voltages were supplied at the same time. Then, pulsating voltages were applied. Fig. 2 and Eq. (1) define the ripple factor RF of the pulsating voltages. The rising rates of peak values of testing voltages were controlled at 1000 V/s. The rising peak values of AC and DC voltages were the same and 500 V/s, respectively, when *RF* was equal to 100%. DC voltages with positive polarities were used for constant-stress tests.

$$RF = \frac{U_{ac}}{U_{dc}} \tag{1}$$

The insulation paper used for the experiment was provided by China Hunan No. 1 Paperboard Co., Ltd. The insulation paper had a diameter and thickness of 80 mm and 0.2 mm, respectively. The insulation paper was dried in vacuum of 50 Pa at 90 °C for 48 h, and then impregnated with transformer oils in vacuum of 50 Pa at 40 °C for 48 h. Karamay #25 transformer oils were used for oil impregnation insulation and first degassed in vacuum at 40 °C. The drying process used in this study reduced the water content in the paper to 0.4% weight and water content in the oil to 9 mg/kg, which were considered acceptable for the proposed test program. Oil-impregnated paper insulation specimens were placed in a sealed glass vessel prior to their usage in the electrical breakdown experiments.

The experimental system consisted of an oil tank and a rod-plate electrode system. As shown in Fig. 3, the electrode system was designed according to IEC 60243-1[22].The electrode system and oil-paper insulation specimens were completely immersed in transformer oil at room temperature. Both electrodes were made of brass. During the electrical aging process, the testing voltage of sample was 7.6 kV, and the aging times were 6, 12, 24, 72, and 144 h.

2.2 PEA measurement

The PEA method is a nondestructive testing method and popularly used to measure space charge in solid dielectric materials throughout the world. In the PEA technique, acoustic pressure waves are generated due to the interaction of pulsed electric field and charge layers. Detection of acoustic pressure waves allows the determination of charge distribution across the sample. The details of PEA technique are documented in literature [23, 24].

The space charge measurements were taken using the PEA system, which had a pulse voltage of 600 V with a width of 5 ns, and minimum resolution of less than 10 μm. Silicon oil was used as the acoustic coupling agent, and the test temperature was 20 ℃. In this study, all samples were stressed under 30 kV/mm and a negative DC electric field. Therefore, the applied voltage is 6 kV. The space charge measurements were taken at various times during the periods of both volt-on (DC voltage application) and decay (DC voltage removal) by using the PEA technique. The top electrode is a semi-conducting polymer, whereas the bottom electrode is an aluminum plate. Each electrode has a diameter of 15 mm. The electrode and tested sample were tightly compressed to avoid partial discharge. The experiments of space charge measurement were performed on single layer oil-impregnated paper insulation sample (~190 μm after oil immersion and pressed by electrodes), as shown in Fig. 4.

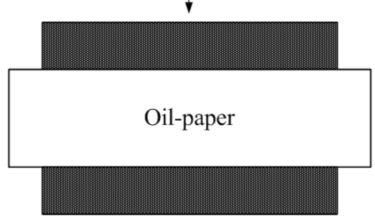


Fig. 4. Schematic diagram of sample arrangement

3. Results and discussions

3.1 Volt-on space charge dynamics of aged samples

The space charge density of oil-paper insulation is density of space charge which acquired by the PEA method. It reflects the space charge behaviors and the charge carrier information of traps in oil-paper insulation. Fig. 5 shows that the anode peak was sharp and evident because of attenuation and the scattering of acoustic waves caused by the oil-paper sample. The cathode peak was wide and flat. The positions of electrodes were confirmed and marked with black dotted lines. The approximate equilibrium of the positive charge and negative charge injection was observed after 30 min.

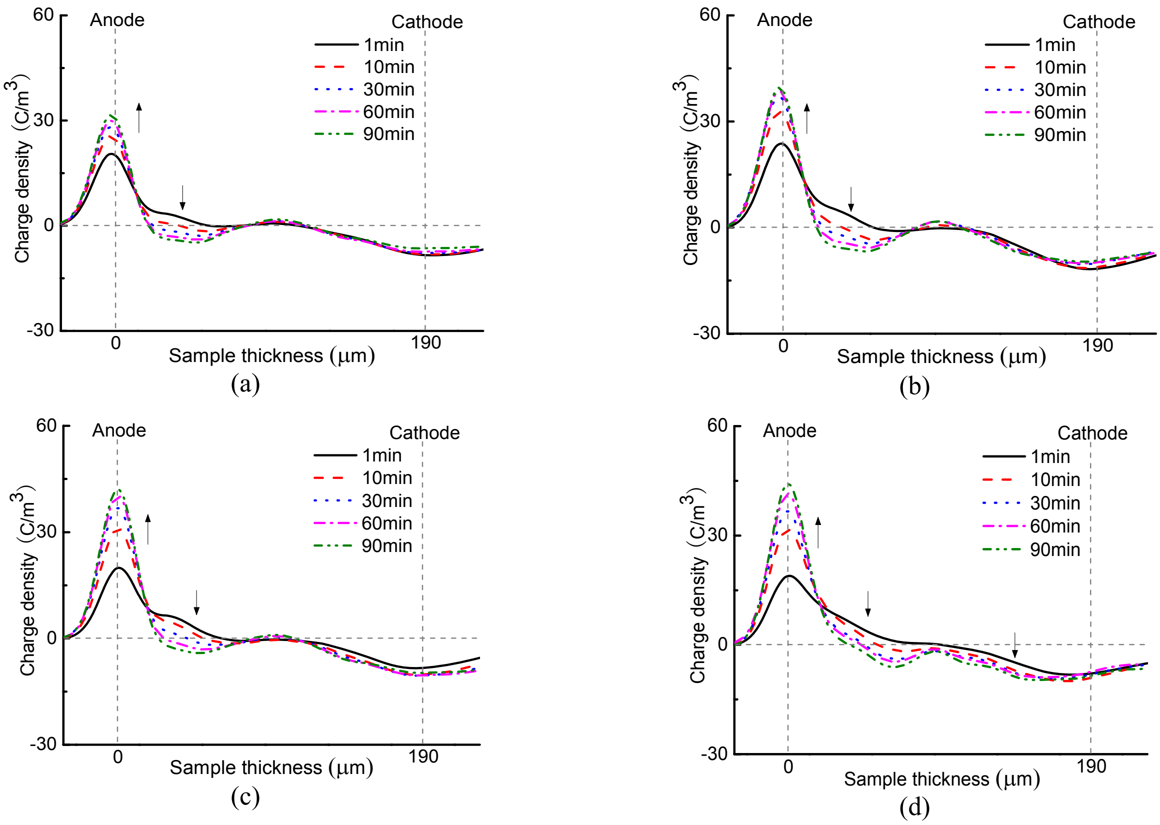
Fig. 5(a) illustrates that the charge injected quickly after voltage was switched on. The peak value of electrodes increased with increase of stressing time. Homo-charges were injected into the bulk of the sample near the anode and cathode from both electrodes after 1 min under 30 kV/mm. The quantities of electric charges on both electrodes increased when the stressing time increased. More positive charges were injected from the anode than negative charges injected from the cathode as the stressing time increases. The homo-charges from the anode and the induced charges from negative charges near to the anode resulted in the peak density of positive charges accumulating at the interface, and increasing with the increase of stressing time.

Figs. 5(a)-(d) and 5(e) show the peak density of negative charge accumulated near the anode increased when the aging time increased. Under negative DC voltage, the quantities of negative charge injection from the cathode were more than the positive charges as the stressing time increased. The peak density of negative charge appeared near the anode at the beginning of the voltage application (t = 1min). The peak density of the negative charge remained in the same region during voltage application. Then, the negative charges accumulated in the region near the anode. The charge density of the negative charge accumulated in the region near the anode increased when stressing and aging times increased. The region of negative charge that accumulated near the anode increased when the aging time increased. The result indicated that injecting more quantities of negative charges would result in the changing of the internal structure of samples by electrical aging.

Compared to the negative charge, the amount of positive charge injection did not increase as much as the negative charge with the aging time. The result indicated that the negative charge in the bulk might move faster and with fewer blockages. Some negative charges were neutralized when they moved from cathode to anode, whereas the others reached the anode quickly. More peak densities of positive charges accumulated in the interface of the anode and the samples when aging time was longer.

3.2 Space charge decay dynamics of aged samples

After applying 6 kV DC voltage for 90 min, the space charge distributions of oil-paper sample with different aging times were measured after removal from the applied voltage (see Fig. 6). In Fig. 6(a), the charge density decreased with decay time. Compared to volts-on tests in which the charges were injected into the sample, the charge movement under short-circuit condition was relatively fast. Approximately 90% of space charges disappeared in the sample after 300 s. A majority of charge in the bulk of oil-paper sample diminished through either recombination or conduction away from the sample after 300 s. The space charges diminished slower when the decay time longer.



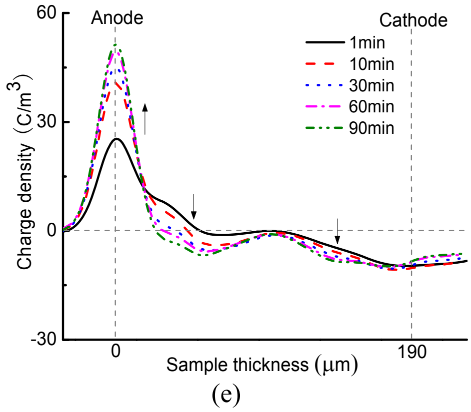


Fig. 5. Volt-on space charge dynamics of different aged samples under 30 kV/mm: (a) 6 h; (b) 12 h; (c) 24 h; (d) 72 h and (e) 144 h

Figs. 6(a)-(d) and 6(e) show that the space charges dissipated faster with longer decay time. The charge density increased with longer aging time. The result indicated that the trapped charges dissipated slower when the aging time of the oil-paper sample was longer. Therefore, electrical aging decelerated the dissipation mobility of charges in the bulk of sample, and limited the movement of the charge.

3.3 Total charge

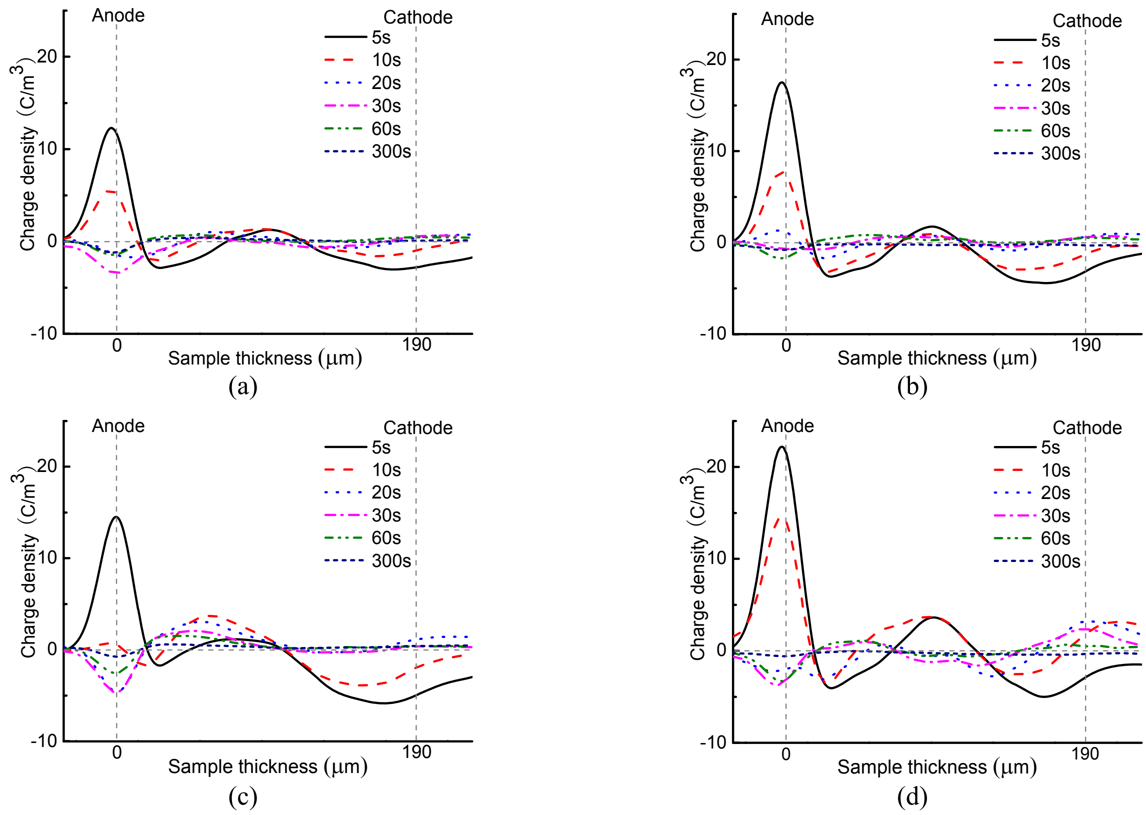
The total space charge related to the electrical performance, the physical, chemical, and microcosmic characteristics of insulation reveals the property of space charge transport in the bulk of insulation. The amount of total charge accumulated in the samples can be calculated based on the charge density distribution by the following Eq. [17, 25]:

$$Q(t) = \int_0^x \left|\rho(x,t)\right| S dx, 0 \le x \le d \qquad (2)$$

where $\rho(x, t)$ 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 $Q(t)$on includes contributions from both fast and slow moving charges.

The evolution of total space charges during the volts-on experiment is shown in Fig. 7. The amount of total charge in the bulk of oil-paper sample rose when stressing and aging times were increased. After a small fluctuation, it tended to a stable state. Therefore, more charges were injected in the bulk of sample when aging time was longer. As shown in Fig. 8, the amount of total charges decreased rapidly before 50 s, slowed down, and finally reached the ultimate state after 100 s. The charges decayed more slowly with the increase in aging time.

In the beginning of the decay process, the space charge inside oil-paper was de-trapped and neutralized rapidly because of the high residual electrical field, which made the total charge decline quickly. The effect of residual electrical field weakened when the decay time was longer.



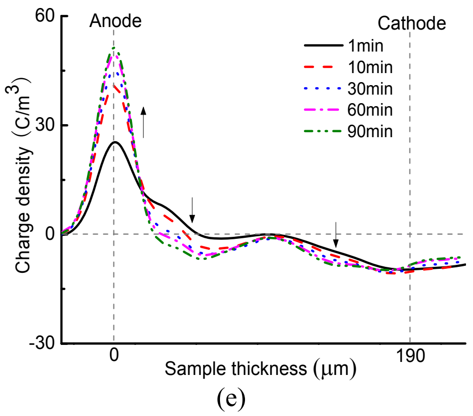


Fig. 6. Space charge decay of different aged samples: (a) 6 h; (b) 12 h; (c) 24 h; (d) 72 h and (e) 144 h

The space charges that remained in the bulk of oil-paper samples were mainly in deep traps, which required more energy to de-trap. Therefore, the decay rate of total charge decreased continuously. The dissipation of the total trapped charges was slower when the aging time was longer.

3.4 Fast and slow moving charges in the bulk of the aged samples

Total charge in volt-on condition refers to the total injection charges that include both fast and slow moving charges. Fast moving charges are charges that escape from the traps very shortly after the removal of the applied voltage, whereas slow moving charges are essentially and permanently trapped. Traps in electrical materials can be divided into two types, namely, deep and shallow. When the charges move into the deep traps, they require more energy to get out, and the velocity of the charge movement slows down. Then, they finally form slow moving charges. The volt-on total absolute amount of charge in 90 min is the total injection charge that includes both fast $Q(t)_{\text{fast}}$ and slow moving charges. The total absolute amount of charge decay in 5 s only involves slow charges. Therefore, fast moving charges can be obtained by $Q(t)_{\text{fast}} = Q(t)_{\text{on90min}} - Q(t)_{\text{decay 5s}}$.

Total fast and slow moving charges in the bulk of samples with different aging times are shown in Fig. 9. Under same stressing time, the $Q(t)_{\text{fast}}$ increased with longer aging time, and the amount of fast moving are larger than slow moving charges. More slowly moving charges were trapped in the sample when the aging time was longer. Longer aging time caused the charge to decay more slowly, and more charges were trapped with longer aging time. Based on the results and analysis in the previous section, the amount of total charges of aged sample under volt-on increased with the increase of stressing and aging times. This result indicated that electrical aging could enhance the trap ability of the slow moving charges in the bulk of sample. Longer aging time caused more charges trapped in the sample and increased the amount of deep traps. The electrical aging decelerated the mobility of the charges. Moreover, the internal structure of insulation was changed by long time aging, which could lead to the formation of a

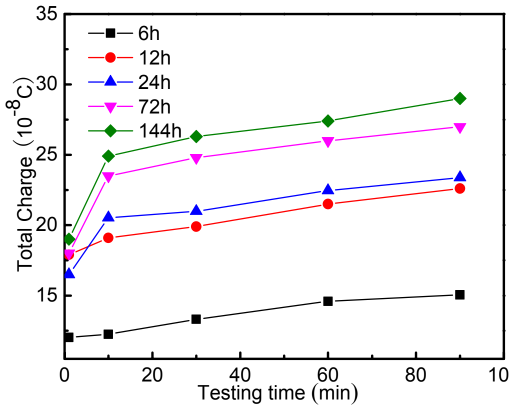


Fig. 7. Total charge of different aged samples during the volt-on

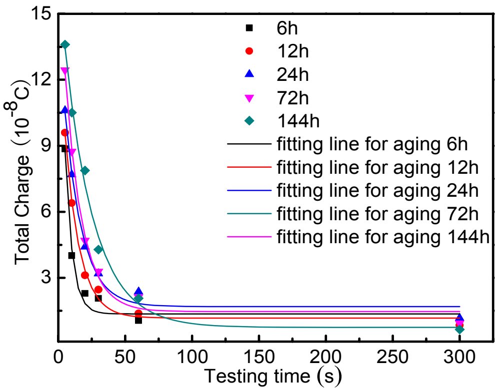


Fig. 8. Total charge of different aged samples during decay

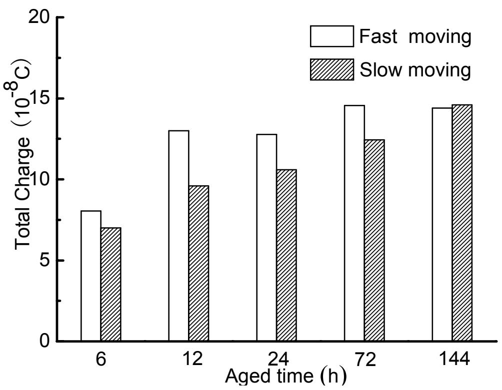


Fig. 9. Total charges of fast moving and slow moving in aging samples

large number of defects.

3.5 Electrical field at volt-on

Both positive and negative charges can be injected into the oil paper samples. The amount of charge accumulated changed the electric field inside the sample. The electric field distribution in the bulk of sample due to the trapped charge can be calculated by integrating the charge density [24]. The electric field in bulk of sample could be calculated using Eq. (3).

$$E(x)=\int_0^d \frac{\rho(x)}{\varepsilon_0\varepsilon_r}dx, 0\le x\le d \tag{3}$$

where $\rho(x)$ is the charge density of sample under volt-on for 90 min, ε_0 is the dielectric constant of vacuum, $8.852*10^{-12}$ F/m, ε_r is the relative dielectric constant of test sample, and d is the thickness of sample [9, 17, 25]. The electrical field distribution could be distorted by charge accumulation, injection, extraction, and transport. The distortion factor of electric field clearly showed the influence of space charge on oil-paper insulation. The distortion factor of electric field could be calculated by Eq. (4).

$$\Delta E=\frac{E_{\max}-E_{av}}{E_{av}} \tag{4}$$

where $E_{\max}$ is the maximum electric field of the sample under volt-on for 90 min, E_{av} is the electric field without distortion, 30 kV/mm, and ΔE is the distortion factor of electric field.

The distortion factor of aging samples during volt-on for 90 min is shown in Fig. 10. The distortion factor of electric field of aging sample increased when the aging time was longer. The distortion was more than 20% of the applied electric field after 12 h. The distortion factor of 72 h was twice that of 24 h and with more than 50% of applied electric field. The total amount of fast and slow moving charges in the aging samples increased when the aging time was longer. Then, the distortion factor of electric field increased with the increase of total charge of aged samples under volt-on for 90 min. Therefore, when the distortion factor of electric field in the bulk of aging samples was larger, more charges were trapped in the sample and more deep traps were formed. This condition caused more serious degradation of oil-paper insulation under AC-DC combined voltages. The result indicated that electrical

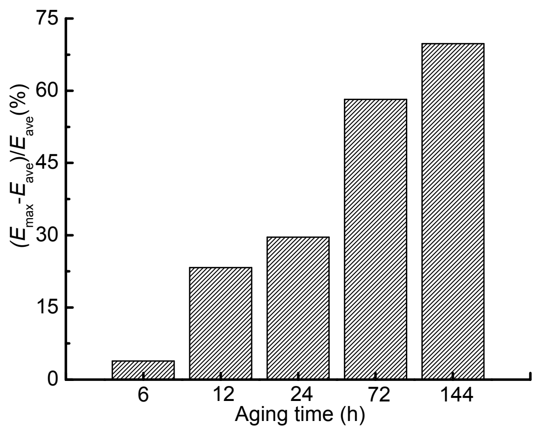


Fig. 10. Distortion factor of electric field of aging samples during volt-on

aging could enhance electric field distortion in the bulk of oil-paper insulation. When the distortion factor of electrical field was above the critical value, the electrical trees initiated and grew. The partial discharge occurred and the electrical trees accelerated their growth by partial discharges when the distortion factor of the electrical field increased. For the converter transformer, a large distortion factor of electric field could lead to fatal damage during polarity reversal operation.

4. Conclusion

This paper presented the electrical aging experiments of oil-paper insulation under AC-DC combined voltages. The space charge behavior of oil-paper insulation with different aging times during the volt-on and decay were studied using the PEA technique under negative DC 6 kV. The influence of electrical aging on charge dynamics was investigated as well. The conclusions are as follows.

(1) The homo-charges were injected into the bulk of the sample near the anode and cathode from both electrodes. The longer the aging time of the oil-paper sample resulted in more obvious the positive charge injection. The charge density of negative charge accumulated in the region near the anode which increased with the increase of stressing and the aging times. It caused hetero-charges to accumulate near the anode. This result will affect the distribution of the electrical field in oil-paper insulation.

(2) Compared to volt-on tests in which charges were injected into the insulation system, the charge movement under short-circuit condition was relatively fast. More charges were injected into the bulk of the sample when the aging time was longer, and the trapped charges dissipated at a slower rate. The electrical aging decelerated the mobility of the trapped charges and the dissipation mobility of charges. The movement of charge was limited.

(3) Both the total trapped charge and the amount of slow moving charges trapped were greater when the aging time was longer. The distortion factor of electric field increased with the increase in the total charge of aged samples under volt-on. More slow moving charges were trapped in the bulk of aging samples and more deep traps were formed when the distortion factor of the electric field was larger. Therefore, the electrical aging could enhance electric field distortion and the trap ability of slow moving charges in the bulk of oil-paper insulation, which could result in electrical trees easier to initiate and grow. Then, it would accelerate degradation of oil-paper insulation under AC-DC combined voltages.

Acknowledgements

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

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, Jan. 2003, pp. 201-206.

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

[3] 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.

[4] G. Chen, "Space Charge in Solid Dielectrics," *in Proceedings of the 14th International Symposium High Voltage Engineering*, Beijing, China, Aug. 2005.

[5] 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.

[6] Boggs S. "A rational consideration of space charge," *IEEE Elect. Insul. Mag.*, vol. 20, no. 4, pp. 22-27, July-Aug. 2004.

[7] 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.

[8] 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.

[9] 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.

[10] Li Y, Murata K and Tanaka Y,"Space charge distribution measurement in lossy dielectric materials by pulsed electroacoustic method," *In Proceedings of the 4th International Conference on Properties and Applications of Dielectric Materials*, Brisbane , Australia, July 1994.

[11] Tanaka A., Maeda, M.,Takada Tatsuo, "Observation of charge behavior in organic photoconductor using pressure wave propagation method," *IEEE Transactions on Electrical Insulation,* vol. 27, No. 3, pp. 440-444, July 1992.

[12] Tanaka R, Sunaga H, Tamura N. "The effect of accumulated charge on depth dose profile in poly (Methylmethacrylate) irradiated with fast electron beam," *Nucl. Sci.*, vol. 26, no.4, pp. 4670-4675, Aug. 1979.
[13] Tanaka T, Greenwood A. "Effects of charge injection and extraction on tree initiation in polyethylene," Power apparatus and systems. *IEEE Trans. Power Apparatus System*, vol. PAS-97, no.5, pp. 1749-1759, Sept. 1978.
[14] 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.
[15] 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.
[16] Dissado L., Mazzanti G., Montanari G. C., "A new thermo-electrical life model based on space-charge trapping," *In Proceedings of IEEE International Symposium on Electrical Insulation 1996 Conference*. Quebec, Canada, June 1996.
[17] 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.
[18] Chao Tang, RuiJin Liao, George Chen, LiJun 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.
[19] 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.
[20] D. Malec, "Contribution to Relationship between Space Charge Injection and Dielectric Breakdown of Low Density Polyethylene under a Divergent Field," *IEEE Trans. Dielectr. Electr. Insul.*, vol.14, No.2, pp. 502-507, April 2007.
[21] 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.
[22] IEC Publication 60243-1, Electrical Strength of Insulating Materials - Test Methods - Part 1: Tests at Power Frequencies, 1998
[23] 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, pp. 1-7, April 2005.
[24] G. Chen, Y. Tanaka, T. Takada and L. Zhong, "Effect of polyethylene interface on space charge formation", *IEEE Trans. Dielectr. Electr. Insul.*, vol. 11, pp.113-121, Feb. 2004.
[25] Xu Zhi qiang. Space charge measurement and analysis in low density polyethylene film [D] Southampton: University of Southampton, 2009.

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.

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.

Sicheng Wu He was born in China in 1987. He is a Master student in school of Electrical Engineering at Chongqing University, China. His major research interests include the space charge dynamics and aging breakdown of oil-paper insulation in converter transformer in HVDC transmission system.

Peng Sun He was born in China in 1989. He is a Ph.D. student in school of Electrical Engineering at Chongqing University, China. His major research interests include the Artificial intelligence application in fault diagnosis for wind turbine generators and condition assessment for wind turbines.