Effects of ZnO magnetron sputtering on surface charge and flashover voltage of oil-impregnated paper

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Abstract: With the aim of exploring an alternative method of nano-doping in cellulose paper and improving flashover strength of oil-impregnated paper, radio frequency (RF) magnetron sputtering method is introduced into the structural modification of insulating paper for converter transformers. In this experiment, insulating paper was treated with ZnO sputtering for 0, 7.5, 15 and 30 min, respectively. The surface morphology of dry paper was observed with a scanning electron microscope. The bonding mode of sputtered ZnO particles with cellulose matrix was investigated via attenuated total reflection infrared (ATR-IR) spectroscopy and mechanical property of the sputtered samples were studied. Surface and volume conductivities of the oil-impregnated sputtered paper were measured. Moreover, the charge dissipation characteristics of sputtered insulating paper was investigated by means of surface potential decay. In addition, trap distribution and carrier mobility of specimen were further obtained. Finally, the DC flashover strength were tested. The results showed that ZnO magnetron sputtering had a distinct influence on the structure of the insulating paper, resulting in the formation of hydrogen bond and chemical bond and an increase of the surface and volume conductivities. ZnO sputtering was found to decrease the initial potential and accelerate charge decay. Moreover, appropriate sputtering enhanced the surface flashover strength.

1 Introduction

High-voltage direct current (HVDC) system is becoming a major trend in the field of power transmission with the steady promotion of global energy internet and the growth of power transmission capability and voltage grade. The converter transformer, as the core equipment of HVDC system, is the junction of AC and DC systems. The oil-impregnated paper is an important part main insulation dielectric of converter transformer [1]. Therefore, the high dielectric properties of oil-impregnated paper is of great significance to the safe and stable operation of the converter transformer.

The interface between the oil and oil-impregnated paper is a discontinuous medium, where electrical field concentration and abnormality exist [2]. When the DC component is applied, charge accumulation occur both on the surface and in the bulk of oil-impregnated paper [3]. There will be more charge accumulation at the oil-paper interface, which will lead to serious electric field distortion. [4]. Electric field distortion caused by charge accumulation at oil-paper interface is an important cause of flashover failure [5]. The insulation faults are most likely to occur in the overlapping area of the surrounding barrier, spacer and stay sides in the insulation structure of the valve side [6].

Researchers have been paying attention to the characteristics of space or interface charges in oil-paper insulation under different conditions such as the applied voltage, temperature, moisture, and aging [7–10]. Meanwhile more attention was given to the suppression method of space charge or interface charge in oil-paper insulation. The insulating paper was immersed in the insulating oil dispersed with TiO2 nanoparticles, which diffused into the insulating paper during the swelling process of cellulose. Partial discharge and the creeping flashover properties of the nanofluid/pressboard interface under both AC and impulse voltage were studied in [11]. Obtained results showed that the shallow trap density of nanofluid/pressboard increased with the TiO2 nanoparticles introduced, which cause the acceleration of charge dissipation, resulting in the improvement of creeping flashover strength. Al2O3 and ZnO nanoparticles were doped into cellulose pulp during papermaking. The injection and accumulation of space charge in this nanocomposite under DC voltage can be suppressed effectively [12]. Our previous work focused on the effects of molecular structure modification method on the surface charge properties of insulating paper. The results show that paper treated for 5 min showed excellent charge decay properties in virtue of the trap balance related to physical and chemical defects [13].

The radio frequency (RF) magnetron sputtering method has been widely used in the field of film preparation benefiting from its high deposition rate, ease of scaling and high quality of films [14]. The technique makes a significant impact in application areas including wear-resistant coatings, low friction coatings, corrosion-resistant coatings and coatings with specific optical or electrical properties [15].

The purpose of this paper is to introduce a novel method to modify the structure properties of the insulating paper used in converter transformer. The modified insulating papers were obtained by means of ZnO magnetron sputtering at different times.

The surface morphology of the insulating paper before and after sputtering was investigated with scanning electron microscopy. Effects of ZnO sputtering on the dielectric property of insulating paper was studied by surface potential decay experiment and surface flashover measurement. It was observed that sputtering can significantly influence the surface charge property and the surface dielectric strength. Obtained results presented changes in trap distribution and carrier mobility in the charge decay process as the consequence of the sputtering varying with time.

2 Experimental setup

2.1 Test sample

The oil-impregnated paper comprised 25# mineral oil (produced by Kunlun Energy) and insulating paper with 0.14 mm thickness (produced by Nantong Zhongli Co. Ltd.), the insulation paper was cut into 60 mm square sheets. The main ingredient of insulation paper was cellulose.

The insulating oil and insulating paper samples obtained after the procedure in Section 2.2 were dehydrated and degassed for 48 h at 80°C/5 Pa in a vacuum dryer. Then, the insulating paper was treated with ZnO sputtering for 0, 7.5, 15 and 30 min, respectively. The surface morphology of dry paper was observed with a scanning electron microscope. The bonding mode of sputtered ZnO particles with cellulose matrix was investigated via attenuated total reflection infrared (ATR-IR) spectroscopy and mechanical property of the sputtered samples were studied. Surface and volume conductivities of the oil-impregnated sputtered paper were measured. Moreover, the charge dissipation characteristics of sputtered insulating paper was investigated by means of surface potential decay. In addition, trap distribution and carrier mobility of specimen were further obtained. Finally, the DC flashover strength were tested. The results showed that ZnO magnetron sputtering had a distinct influence on the structure of the insulating paper, resulting in the formation of hydrogen bond and chemical bond and an increase of the surface and volume conductivities. ZnO sputtering was found to decrease the initial potential and accelerate charge decay. Moreover, appropriate sputtering enhanced the surface flashover strength.
specimens were impregnated into the insulating oil at 80°C/5 Pa for 48 h to ensure the adequate immersion of insulating paper. Finally, the samples were stored in a vacuum environment.

2.2 Sputtering process

RF magnetron sputtering device is used for the ZnO sputtering of insulating paper. The target, with 60 mm diameter and 3 mm thickness; was made of dense ZnO (CHINO New Material Technology Co. Ltd.), which was 70 mm from the substrate. The insulation paper was placed on a water-cooled substrate table directly beneath the sputtering target, and insulation paper withstanded a temperature of ~40°C in the sputtering process, under which the insulation paper was intact. Before starting sputtering, the chamber was vacuumed to a pressure <5 × 10⁻³ Pa by mechanical pumps and molecular pumps in sequence. After reaching the required conditions of sputtering, a RF voltage with a power of 90 W was applied in Ar with a pressure of 2 Pa and a flow rate of 35 SCCM.

The schematic diagram of the RF magnetron sputtering is shown in Fig. 1. When the voltage between electrodes reaches the RF, stabilised RF glow discharge will occur. Electrons accelerating in motion collide with argon atoms under electric field, accompanied by energy transfer. The energetic argon ions come into being after collision and bombard the ZnO target under the action of electric field. The sputtered target atoms produced in the bombardment process then deposited on the substrate [15]. The sputtering of the target atoms can be attributed to the cascade collision of atoms on the crystal lattice, which is exhibited in the microstructures of the oil-impregnated paper, the flashover voltages of the samples were measured at 20°C in an ambient environment. In this experiment, the needle electrode was served as a high voltage electrode, which was connected to a HVDC power supply through a 2-MΩ resister that could limit over-current caused by breakdown. The grounded electrode was a plate electrode, and the separation distance was 5 mm. An oscilloscope was used for monitoring the voltage between the two electrodes through a voltage divider.

During the surface flashover tests, the voltage boosting process was conducted as follows. In order to highlight the effect of charge accumulation on the surface flashover process. First, a DC voltage of 5 kV was applied for 2 min, then 1 kV DC voltage was added every 1 min until flashover occurred. After each flashover, the impregnated paper was replaced to avoid the influence of the structural damage of specimens. The interval between two tests was 5 min. There are no ~20 valid data for samples of each sputtering time.

3 Results and analysis

3.1 Sample characteristics

The microstructures of the insulating papers with different sputtering times are illustrated in Fig. 3. It can be observed that
there exist many ridges and valleys in the surface of the untreated paper, which are associated with the crisscross array of the cellulose fibre. For paper with sputtering time of 7.5 min, there still exist many valleys and holes on the surface. The surface tends to become more flat for paper with sputtering time of 15 min, and the ZnO aggregates distribute evenly. However, the excess ZnO particles gather, lump and even overlap when the paper is subject to continuous sputtering. It is worth mentioning that traces of carbonisation are found on the 30 min sputtered specimens, which indicate that the cellulose structure may be destroyed. A clearer distribution of ZnO particles in cellulose paper is shown in Fig. 4.

3.2 ATR-IR spectroscopy and tensile strength

Fig. 5 reports the ATR-IR spectra of the sputtered paper in the region 4000–600 cm⁻¹. The strong bands at ∼3333 and ∼1035 cm⁻¹ are ascribed to OH-stretching vibration and OH-bending vibration of the insulating paper, respectively. The transmittance at ∼3333 cm⁻¹ of the specimen with 7.5 min sputtering increases compared with the untreated specimen, indicating the reduction of hydrogen bonds in cellulose. When the sputtering increases to 15 min, the transmittance displays a decreasing trend which implies the hydrogen bond formation between ZnO particles and cellulose. However, with the further prolongation of sputtering time, the transmittance increases again obviously, which can be attributed to the destruction of cellulose structure by excessive sputtering. The decrease in quantity of the hydroxyl groups may be due to the consumption in the reaction with ZnO particles. Moreover, in the region 1276–1270 cm⁻¹, there appears a small peak after the specimen being sputtered. With the increase of treating time, the transmittance value of the peak decreases first and then increases, which is likely that the Zn-O-C bond was formed. Presumably, the hydrogen bond between ZnO particles and cellulose and the Zn-O-C bond together constitute the bonded layer mentioned above [17].

3.3 Surface and volume conductivity

The surface and volume conductivity of the oil-impregnated paper with different sputtering times are shown in Fig. 7. The blue bar represents the surface conductivity corresponding to the left y-axis, and the volume conductivity represented by the white bar is
measured by the right y-axis with logarithmic coordinates. It is obvious that both the surface and volume conductivity increase with the extension of sputtering time. Compared with the untreated paper, the surface conductivity of the sputtered paper at 7.5, 15 and 30 min increases by 3.48, 9.90 and 34.68, respectively, and the volume conductivity is enhanced by 2.03, 19.50 and 3049, respectively. For the specimens with sputtering time of 7.5 and 15 min, the conductivities increase due to the large number of carriers and carrier transport channels provided by ZnO particles. For the 30 min sputtered sample, the sharp increase of volume conductivity can be explained by the following two reasons. First, it is probable that the specimen exhibits non-linear conduction behaviour. The content of nanoparticles in insulating paper may exceed the percolation threshold, many local conduction channels are formed in the sample body due to the overlap of the interaction region around the adjacent particles. Under the action of electric field, carrier migration is less hindered, resulting in the drastic increase of material conductivity [19]. Second, traces of carbonisation are found on the 30 min sputtered specimens, the cellulose structure may become looser due to the cellulose chains being destroyed with the prolongation of the impact time of target atoms, the polar or conductive by-products increases. The barrier of ion conductivity inside the oil-paper reduces simultaneously. More collision ionisation may occur in the loose areas of cellulose fibre, resulting in the surge of carrier concentration. Consequently, the conductivity will rise sharply.

3.4 Surface charge

Fig. 8 shows the relationship between the surface potential and the sputtering time under different charging polarities. The possible routes for the surface charge dissipation can be divided into the following three main patterns: lateral diffusion, recombination with the ions in the air and transfer through the bulk. Charge passing through the bulk of sample in a way of trapping and de-trapping is regarded as the dominant path of charge dissipation considering that the vertical electrical field built by the surface charges is much larger than the horizontal electrical field because of the thin thickness of the sample [20].

According to the decay curves of the surface potential, the decay process of the surface potential could be roughly divided into two stages. The surface potential declines quickly initially and then slows down, which could be attributed to the different states of trapped charges, and the different time charges need to escape. In addition, regardless of the charging polarity, the specimens treated by sputtering exhibits faster surface potential decay rate compared with the ordinary sample. Moreover, the initial surface potential reduces with prolonging the sputtering time. If contrasting these initial surface potentials under two charging polarities, the higher initial surface potentials are shown for the negative charging condition, indicating an accumulation of more negative charges. Owing to the polarity effect of the corona discharge, the field strength near the negative tip would be enhanced, and the initial voltage of negative corona was lower than that of the positive. Therefore, under the same conditions, as negative corona discharge is more likely to occur, more negative polar charges will accumulate on the surface of the sample. With regard to the decay
The destructive effect on cellulose paper results in the formation of excessive sputtering destroyed the structure of the cellulose paper. Physical defects show a strong ability to capture charges and charges are not easy to collapse, which will slow down the surface charge decay. However, the decay ratio of 30 min sputtered sample is still larger than that of the untreated one, which can be attributed to chemical defects formed by ZnO particles and cellulose. Moreover, for all the different sputtering times, the decay ratio of the positive charging is higher than the negative charge.

The time of carrier passing through the sample bulk can be obtained by the relationship between surface potential differential and time. The relationship between carrier mobility and sputtering time under different polarities of corona charging is shown in Fig. 10. It was exhibited that the carrier mobility heights with increasing the sputtering time from 0 to 15 min and goes down with prolonging the sputtering time more. The specimens with 15 min of sputtering show the fastest carrier migration speed.

The interaction zone between the ZnO particles and the polymer matrix are helpful to form conductive paths because of the introduction of a shallower band, which speeds up the mobility of charge carriers [21]; therefore, all the sputtered samples exhibit higher carrier mobility than the untreated samples. However, as the content of ZnO particle further increased, because of the high surface conductivity, part of the injected charges may dissipate along the surface of the sample rather than through the sample to the ground electrode, resulting in the decrease of the measured mobility. Furthermore, for the reasons motioned in Section 3.1, the significant increase of the carrier concentration results in a conductivity surge of papers with 30 min sputtering, as shown in Fig. 7, in spite of the reduction of carrier mobility.

3.5 Trap distribution

The migration process of surface charge is considered to be related to the trapping and de-trapping processes of carrier, which is dependent on the depth and density of traps distributed in the sample. With the increasing of time, the trapped charges excited into the conduction levels escape from shallow traps first, and charges in deeper traps will escape later. The traps energy level $E_i$ and density $N(E_i)$ of dielectrics can be expressed as:

$$E_i = kT \ln(\nu i),$$

$$N(E_i) = \frac{\nu e d}{e d} e^{-\frac{d}{d}}.$$  

where $k$ is the Boltzmann constant, $T$ is the environment temperature, $\nu$ is the attempt frequency of order $10^{12} - 10^{14}$ s$^{-1}$, $i$ is the surface potential decay time, $\nu i$ is the permittivity of vacuum, $e$ is the charge quantity, $d$ is the thickness of the sample and $F$ is the surface potential [22, 23].

Relationships between the trap distribution and the sputtering time of specimens under voltages of 5 and −5 kV are shown in Fig. 11. For positive corona charging, it can be seen from Fig. 11a that for the ordinary sample, the energy level of its main trap peak is 0.8110 eV, which is deeper than these sputtered specimens with 0.8017, 0.7654 and 0.7899 eV corresponding to sputtering times of 7.5, 15 and 30 min, respectively. The energy level of the main trap peak decreases with an increased sputtering time from 0 to 15 min, but increases slightly with further sputtering. The energy level of the main trap peak for paper with 15 min sputtering has the lowest trap depth among the four samples. Moreover, less trap densities for the sputtered specimens compared with the ordinary specimens. Both variations of trap level and density of the main peaks imply that the introduction of ZnO particles causes the decrease of the trap level and density of oil-impregnated paper. For the negative corona charging in Fig. 11b, the energy levels of the main peaks corresponding to the four specimens with 0, 7.5, 15 and 30 min are 0.8650, 0.8269, 0.8269 and 0.8372 eV, respectively. The characteristics of the trap distribution for the four types of specimens are parallel to the positive ones.

The deep and shallow trap distribution of various sputtering times after positive and negative charging, shown in Fig. 12, are obtained through peak separation of the data in Fig. 11. The two
kinds of peaks are consistent with the assumption of deep trap and shallow trap. The solid lines represent deep traps, and the dashed lines signify shallow traps. For both charging polarities, there are distinct differences for the curves that represent the deep traps, where the trap densities of the sputtered samples decline evidently. When the sputtering time varies from 0 to 30 min, the trap density first decreases and then increases; the density then reaches the minimum for the sample with 15 min sputtering time. As shown in Fig. 10, the carrier mobility increases first and then decreases with the variation of the density of deep trap. Compared with deep trap, the changes of curves on behalf of the shallow trap are not so obvious. It can be inferred that the shallow trap density of the sputtered sample with 15 min is highest for positive charging and in a relatively high region among the four samples for negative charging. For both treated and untreated samples, higher density of the shallow level traps occurs for positive voltage, and higher density of deep level traps occurs for negative voltage, which could explain why the decay ratio of positive charging is higher than for negative charging in the initial phase of potential decay, as depicted from Fig. 9. The higher density of the shallow level hole traps indicates that ZnO particle can introduce many hole traps.

Based on the above results, ZnO sputtering introduces impurity levels with relatively low potential barrier, many deep traps within the polymer matrix are shielded due to the electric field built by charges trapped in the shallow traps. The density of deep traps decreases obviously, and appropriate sputtering increases the shallow trap density.

### 3.6 Flashover voltage

To investigate effect of ZnO sputtering on the flashover strength, the flashover voltages of the sputtered and untreated samples were measured. As shown in Fig. 13, the surface flashover behaviour of both oil-impregnated sputtered paper and oil-impregnated paper was described by two-parameter Weibull distribution, and the mean value and standard deviation of the testing results are shown in the small size graph. It can be observed that samples with sputtering of 15 min shows enhanced surface dielectric strength that is increased by 25.57%. However, the flashover strength declines slightly when sputtered at 7.5 or 30 min comparing with the untreated one. The scale parameter $\alpha$, the shape parameter $\beta$ and the estimated 5% probability breakdown voltage (P5%) obtained by two-parameter Weibull distribution fitting are listed in Table 1.

It can be observed from Table 1 that the 63.2 and 5% probability flashover voltages of the sputtered sample with 15 min are 22.56 and 47.27% higher than those of the untreated sample. However, the 63.2 and 5% probability flashover voltages of oil-
impregnated paper with sputtering of 7.5 and 30 min show minor reduction. The above results indicate that the sputtering time applied on paper has a considerable impact on the flashover property, and only papers with appropriate sputtering time have improved surface dielectric strength. A decline occurs in the flashover strength whether the sputtering time is too short or too long. The change of the flashover voltage with different sputtering times can be interpreted considering the carrier transportation and the trap distribution properties process according to Figs. 7 and 12, respectively.

The flashover voltage of sputtered paper with 7.5 and 30 min is slightly less than that of the untreated paper. This phenomenon can be explained as follows:

There are both advantages and disadvantages for the existence of deep traps and the improvement of the conductivity. More deep traps reduce the energy and mean free path and inhibit the formation of electron avalanche [24]. While charges trapped in the deep trap are difficult to de-trap and generate a local strong field which promotes the development of electron avalanches and cause the formation of breakdown channel can be suppressed by the decrease of the carrier density and energy. In addition, good bonding strength may resist the influence of local temperature rise caused by high conductivity. Therefore, The sputtered paper with 15 min and exhibits a higher flashover voltage.

4 Conclusions

In order to explore an alternative method of nano-doping in cellulose paper which belongs to a kind of porous polymer. This paper proposed a novel method to modify the structure properties of insulating paper through ZnO sputtering. The surface and volume conductivities of the samples were measured. Properties of the surface charge decay and trap distribution were analysed. DC surface flashover voltages were obtained and compared based on sputtering time. The results can be summarised as follows:

i. ZnO sputtered papers were obtained by means of a ratio frequency magnetron sputtering method. ZnO particles not only adhere to the cellulose fibres on the surface of the insulating paper but also enter deeper positions through the pores between cellulose fibres.

ii. The hydrogen bond formation between ZnO particles and cellulose and the Zn-O-C bond constitute the bonded layer between ZnO particle and cellulose matrix. Excessive sputtering decreases the number of hydrogen bond obviously and degrade the mechanical properties of the specimen.

iii. The surface and volume conductivity increased with the increase of sputtering time. Thereinto, the volume conductivity increased by an order of magnitude when sample was sputtered for 30 min.

iv. The surface potential decay process first increases with sputtering time and then decelerated with prolonging time further for both two charging polarities. Paper sputtered with 15 min was observed to have the fastest carrier mobility among the sputtered samples, which could be due to the lowest deep trap density and the greatest shallow trap quantities.

v. The average flashover voltage was improved by 25.57% for sputtered paper with an appropriate sputtering time of 15 min compared with the untreated paper, which could be attributed to the inhibition of the shallow traps on the distortion of the electric field and the formation of the breakdown channel.

vi. The acceleration of surface charge decay and improvement of flashover voltage are of great importance to the stable operation of the convertor transformer. It is also meaningful to study the effects of ZnO sputtering on the space charge properties of oil-impregnated paper in future studies.

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6 References

[1] Wang, S.Q., Zhang, G.J., Mu, H.B., et al.: ‘Effects of paper-aged state on space charge characteristics in oil-impregnated paper insulation’, IEEE Trans. Dielectr. Electr. Insul., 2012, 19, pp. 1871–1878
[2] Taylor, R.J.: ‘Effect of permittivity matching on the flashover of solid/liquid interfaces’, Proc. Inst. Electr. Eng., 1977, 124, pp. 899–904
[3] Huang, M., Zhou, Y., Chen, W., et al.: ‘Space charge dynamics at the physical interface in oil-paper insulation under DC voltage’, IEEE Trans. Dielectr. Electr. Insul., 2015, 22, pp. 1739–1746
[4] Du, B.X., Zhang, J.G., Liu, D.S.: ‘Interface charge behavior of multi-layer oil-paper insulation under DC voltage’, IEEE Trans. Dielectr. Electr. Insul., 2015, 22, pp. 2628–2638
[5] Wu, K., Zhu, Q., Wang, H., et al.: ‘Space charge behavior in the sample with two layers of oil-immersed paper and oil’, IEEE Trans. Dielectr. Electr. Insul., 2014, 21, pp. 1857–1865
[6] Qi, B., Chen, Y., Li, C., et al.: ‘Oil-pressboard interface charges under combined AC/DC electric field: their characteristics and influence on surface flashover voltage’, IEEE Electr. Insul. Conf. (EIC), Seattle, WA, USA, 2015, pp. 65–68
[7] Du, B.X., Jiang, J.P., Zhang, J.G., et al.: ‘Dynamic behavior of surface charge on double-layer oil-paper insulation under pulse voltage’, IEEE Trans. Dielectr. Electr. Insul., 2016, 23, pp. 2712–2719
[8] Tang, C., Chen, G., Fu, M., et al.: ‘Space charge behavior in multi-layer oil-paper insulation under different DC voltages and temperatures’, IEEE Trans. Dielectr. Electr. Insul., 2010, 17, pp. 757–784.

[9] Zhou, Y.X., Huang, M., Chen, W.J., et al.: ‘Space charge behavior of oil-paper insulation thermally aged under different temperatures and moistures’, J. Electr. Eng. Technol., 2015, 10, pp. 1124–1130.

[10] Ciobanu, R., Priseanu, I., Schreiner, C.: ‘Space charge evolution in thermally aged cellulose materials’, IEEE Int. Conf. Solid Dielectr., (ICSD), Toulouse, France, 2004, pp. 221–224.

[11] Lv, Y., Zhou, Y., Li, C., et al.: ‘Nanoparticle effects on creeping flashover characteristics of oil/pressboard interface’, IEEE Trans. Dielectr. Electr. Insul., 2014, 21, pp. 556–562.

[12] Liao, R.J., Liu, T., Yang, L.J., et al.: ‘Surface charge characteristics of cellulose insulation paper with nano-modified under DC field’, High Volt. Eng., 2015, 41, pp. 3006–3013. (In Chinese)

[13] Du, B.X., Li, X.L., Jiang, J.P.: ‘Surface charge coupling behavior of fluorinated polyimide film under DC and pulse voltage’, IEEE Trans. Dielectr. Electr. Insul., 2017, 24, pp. 567–573.

[14] Montanari, G.C., Fabiani, D., Palmieri, F., et al.: ‘Modification of electrical properties and performance of EVA and PP insulation through nanostructure by organophilic silicates’, IEEE Trans. Dielectr. Electr. Insul., 2004, 11, pp. 754–762.

[15] Roy, M., Nelson, J.K., MacCrone, R.K., et al.: ‘Polymer nanocomposite dielectrics—the role of the interface’, IEEE Trans. Dielectr. Electr. Insul., 2005, 12, pp. 629–643.

[16] Wang, W.W., Li, S.T., Liu, W.F.: ‘Dielectric breakdown of polymer nanocomposites’, Trans. China Electrotech. Soc., 2017, 32, pp. 25–36. (In Chinese)

[17] Du, B.X., Li, J., Du, W.: ‘Dynamic behavior of surface charge on direct-fluorinated polyimide films’, IEEE Trans. Dielectr. Electr. Insul., 2013, 20, pp. 947–954.

[18] Rossnagel, S.M., Hopwood, J.: ‘Magnetron sputter deposition with high levels of metal ionization’, Appl. Phys. Lett., 1994, 63, pp. 3285–3287.

[19] Watson, P.K.: ‘The transport and trapping of electrons in polymers’, IEEE Trans. Dielectr. Electr. Insul., 1995, 2, pp. 915–924.

[20] Tanaka, T.: ‘Dielectric nanocomposites with insulating properties’, IEEE Trans. Dielectr. Electr. Insul., 2005, 12, pp. 914–928.

[21] Zhou, Y.X., Zhang, L., Sha, Y.C., et al.: ‘Numerical analysis of space charge characteristics in low-density polyethylene nanocomposite under external DC electric field’, High Volt. Eng., 2013, 39, pp. 1813–1820. (In Chinese)