**ABSTRACT** Field grading within the dry-type bushing insulation presents a major challenge for DC applications due to the highly temperature-dependent conductivity of the epoxy resin insulation. An electric field regulation method based on the epoxy/graphene oxide (EP/GO) nanocomposites with the reduced temperature coefficient of conductivity is proposed and investigated in this paper. DC conductivity of EP/GO nanocomposites with different loadings of 0, 0.05, 0.1 and 0.5 wt% at various temperature are investigated. Trap level distributions are characterized by the isothermal discharge current (IDC) method to clarify the conduction mechanism. Obtained results show that more shallower traps are introduced and the thermal activation energies of the nanocomposites are reduced by the GO nanoparticles, indicating that the temperature coefficient of conductivity of the nanocomposites is reduced. The improvement of electric field distribution within the bushing insulation under operating voltage is verified when the EP/GO nanocomposite with an appropriate content is employed, based on an established ±800 kV valve-side bushing for a converter transformer. However, more defects will be introduced by the GO fillers with excessive content (0.5 wt%), resulting in an obvious reduction of the DC breakdown strength.

**INDEX TERMS** Valve-side bushing, electric field regulation, temperature coefficient of conductivity, graphene oxide, epoxy-based nanocomposites.

**I. INTRODUCTION**

The valve-side bushing for a converter transformer is one of the key HV equipment in the high voltage direct current (HVDC) system, and the performance of which is closely associated with the safe and stable operation of the HVDC system [1], [2]. A series of surveys conducted by the International Council on Large Electric Systems (CIGRE) Study Committee (SC) showed that the bushing failures were classified as one of the most frequent causes of transformer failure. What is worse is that bushing failures cause 56% of failures accompanied by fire and which would cause huge collateral and ecological damages at the switchyard [3], [4]. Root cause analysis pointed out that the electric field distortion was responsible for a significant proportion of the bushing failures [5], [6]. Therefore, the regulation of the electric field distribution within the bushing insulation is of great significance for the development of the HVDC system.

In the case of DC voltage, the electric field distribution is mainly determined by the insulation conductivity, while the conductivity is highly dependent on temperature. However, there is a large temperature gradient inside the bushing insulation especially under HV and UHV due to the higher insulation thickness, which may lead to a conductivity gradient and a field migration [7]. It was pointed out in [8], that when considering the temperature effects, the electric field distribution...
within the bushing insulation became more complicated, and the electric field could be reversed so that the highest stress transferred from the inner insulation to the outer insulation. Same problems also can be found in HVDC cable, which greatly limit the current-carrying capacity and the structure design [9].

Researches show that the reduction of the temperature coefficient of conductivity could reduce the dependence of conductivity on temperature and hence is beneficial to the improvement of electric field distribution [10], [11]. Two materials with different thermal activation energy of 0.98 and 0.56 eV respectively were selected in [12], for a 150 kV DC solid dielectric cable, to calculate the electric field distribution under a temperature gradient of 40 °C. Obtained results showed that the electric field distribution using the material with lower thermal activation energy (0.56 eV) was more uniform than that with higher activation energy (0.98 eV). BaTiO$_3$-based compound (BT60) with positive temperature coefficient (PTC) of resistivity was employed in [13] to modify the DC resistivity of epoxy resin at elevated temperature. Experimental results showed that the DC resistivity of the composite doped with 2 wt% fillers was nearly equal to that of pure resin at room temperature, while the DC resistivity of the composite was increased by 55 % at high temperature (90 °C), indicating that the introduction of this PTC material could weaken the changing of the resistivity of epoxy resin caused by temperature and was capable to apply in the insulation of bushings.

Recently, GO-based nanocomposites have found various applications in many fields due to its active surface functional groups and unique two-dimensional structure [14]–[16]. Of particular note is that there is a growing interest in the tuning of the material conductivity by GO filler [17], [18]. It was reported in [19], that the temperature coefficient of conductivity of the GO was closely related to the amount of surface groups, and one can transform the temperature-resistance behaviors by adjusting the functional groups of the GO since the latter often acts as the traps. It was found in [20] that the graphene and GO hybrid films had a small temperature coefficient of resistivity, and the electrical response to the temperature variation of this kind material could be tuned by the interaction between GO and graphene. GO nanoparticles have shown a great potential to modify the temperature dependence of conductivity of the epoxy resin. However, few studies have been done to investigate the conductivity response to the temperature variation of the EP/GO nanocomposites.

In this paper, the EP/GO nanocomposites with the filler content of 0, 0.05, 0.01 and 0.5 wt% were prepared firstly. The SEM images of the fractured areas of various samples were measured to characterize the micromorphology of these nanocomposites. DC conductivity of various nanocomposites, at a range of temperature from 20 to 100 °C, were investigated and fitted. Trap distributions were carried out to clarify the effects of the GO on conductivity modification. Meanwhile, DC breakdown tests were performed to assess the insulation performance of the prepared nanocomposites. Based on the above results, the conduction mechanism of the reduced temperature coefficient of conductivity of the EP/GO nanocomposites is discussed. Finally, the improvement of the electric field distribution of a ± 800 kV valve-side bushing for a converter transformer is verified by the electro-thermal simulation.

II. EXPERIMENTAL

A. SAMPLE PREPARATION

The materials used are a bisphenol A type epoxy resin and an anhydride-based hardener of methylethahydrophthalic anhydride (MTHPA). The graphene oxide (GO) with a thickness of < 3 nm and a lamellar diameter of < 10 μm is purchased from Suzhou Tanfeng Graphene Technology Co., Ltd.

Two main procedures were employed to prepare the epoxy-based nanocomposites, i.e. filler dispersion and curing. The two-phase (liquid-liquid) extraction method was used to distribute the filler into the resin. The GO particles were dissolved into the ethanol (C$_2$H$_5$OH) with a ratio of 0.1 wt%. Then, the mixture of filler and ethanol was ultrasonicated for 1 h to get a homogenous dispersion. Next, the epoxy component was weighed and added into the suspension, where the filler concentration was 0.05, 0.1 and 0.5 wt% to the weight of the epoxy component respectively. The obtained mixture was ultrasonicated for 1 h and stirred with a magnetic stirrer at 90 °C for 6 h to remove the ethanol due to the boiling point of ethanol is about 78 °C. After the evaporation of ethanol, the mixture of epoxy component and the GO was obtained, and then used to synthesize the epoxy-based nanocomposites. The as-prepared mixture and the hardener was weighed with the ratio of 100:85 and mixed by the magnetic stirrer for 30 min. The obtained mixture was degassed in the vacuum oven at 50 °C for 1 h to remove the bubbles. The degassed mixture was poured into the mold with an inner dimension of 10 mm × 10 mm × 0.5 mm and 10 mm × 10 mm × 0.2 mm, and cured at 100 °C for 15 h and then 145 °C for 20 h. Here the samples with a thickness of 0.2 mm were prepared for the DC breakdown strength tests and that with a thickness of 0.5 mm were employed for other tests (Conductivity, scanning electron microscopy (SEM) and isothermal discharge current (IDC) tests). The composites of EP/GO with the loading of 0.05, 0.1 and 0.5 wt% were named as EP/GO-0.05, EP/GO-0.1 and EP/GO-0.5, respectively.

B. SEM

The cross sections of specimens with different filler contents are observed by the scanning electron microscopy (SEM, Hitachi S4800). The specimens for SEM observing are previously fractured in liquid nitrogen and sputtered with a thin gold layer.

C. ELECTRICAL EXPERIMENTS

DC conductivity of the neat epoxy and the various nanocomposites are measured by a three-electrode system as shown
FIGURE 1. Three-electrode system for DC conductivity measurement.

in Figure 1. This system is installed in a thermostatic chamber, where the high-voltage electrode is a stainless-steel cylindrical electrode with a diameter of 80 mm and the grounding electrode is 50 mm. The current is measured by the electrometer Keithley 6514 with <1 fA noise. Every kind of sample is tested 5 times and the average value is chosen as the final conductivity. The conductivities under different temperature and electric field are calculated by (1) [21]:

\[
\gamma = \frac{I}{V} \frac{4d_2}{\pi (d_1 + g)^2}
\]

where \(\gamma\) is the conductivity (S/m), \(I\) is the mean value of the charging current during the final 2100-2400 s (A), \(V\) is the applied voltage (V), \(d_2\) is the thickness of the sample (m), \(d_1\) is the diameter of the measuring electrode (m), and the \(g\) is the gap between the measuring electrode and the guard ring (m).

DC breakdown tests are performed using a sphere-plate electrode system. The electrode system was immersed in an oil bath to prevent the unexpected flashover during the tests. The specimens are tested at a voltage rising rate of 500 V/s until the specimens are broken down. Two samples are tested for 10 breakdown sites and the two-parameter Weibull distribution is employed to characterize the DC breakdown strength.

IDC tests are employed to obtain the trap level distribution of nanocomposites with different filler contents. The tested specimen is first polarized under 30 kV/mm for 30 min, and then short-circuited for 40 min to release the polarization charges. Every kind of sample is tested 3 times to reduce the measurement error, and the density and level of traps are calculated by [22]:

\[
N_t(E) = \frac{I}{eS} \frac{e^{\frac{E_t}{k_BT}} - 1}{k_BT \ln(vt)}
\]

where \(N_t(E)\) is the density of traps (eV\(^{-1}\)m\(^{-3}\)), \(E_t\) is the level of traps (eV), \(I\) is the isothermal discharge current (A), \(e\) is the electronic charge (C), \(S\) is the sample thickness (m), \(e\) is the electronic charge (C), \(L\) is the sample thickness (m), \(S\) is the electrode area (m\(^2\)), \(k_B\) is the Boltzmann constant, \(T\) is temperature (K), \(v\) is the ‘attempt to escape’ frequency (s\(^{-1}\)) and \(t\) is the time (s).

III. EXPERIMENTAL RESULTS

A. SAMPLE MORPHOLOGY

Figure 2 shows the SEM images of the fractured surface of the EP/GO nanocomposites with various loadings. It is evident that the surface of the neat epoxy is very smooth and typical characteristic stripes are observed as shown in Figure 2a [23]. The fractured surface starts to become rough with the introduction of the GO particle. When the concentration is low, few GO fillers could be found and the surface is relative smooth. However, more fillers appear on the surface with the increase of the concentration. When the concentration is increased to 0.5 wt%, many river-shape stripes could be observed and which often starts from the particle as shown in Figure 2d. Furthermore, it is obvious that the GO fillers are homogeneously dispersed in the resin, and the sizes are about 5 µm in diameter and consistent with the parameters provided by the supplier.

B. DC CONDUCTIVITY

Figure 3 shows the relationship between the applied electric field \(E\) and the electrical conductivity \(\gamma\) at room temperature (RT). The difference is insignificant when the electric field is lower than 8 kV/mm, yet an apparent increase of the conductivity is observed when the field increases up to 16 kV/mm due to the Poole-Frenkel effect. It should be noted that the maximum field strength is often designed below 8 kV/mm under DC voltage for dry-type bushings [24], and the influence of electric field on conductivity is ignored in this paper.

Figure 4 shows the DC conductivity characteristics of the neat epoxy and various EP/GO nanocomposites under 8 kV/mm with respect to the inverse of temperature (1000/T). It is found that the conductivity is highly dependent on temperature. In the case of the neat epoxy, the conductivity is...
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FIGURE 3. DC conductivity behaviors of EP/GO nanocomposites under various electric field strength at RT.

FIGURE 4. DC conductivity behaviors of EP/GO nanocomposites under various temperature and 8 kV/mm.

7.70 \times 10^{-17} \text{ and } 4.55 \times 10^{-13} \text{ S/m at RT and 100 °C, respectively, and the difference between them is up to several orders of magnitude. It is because the probability of the de-trapping of the carriers is increased by the elevated temperature, and the carriers could get more energy to finish the hopping conduction. The conductivities of the EP/GO nanocomposites with the concentration of 0.05, 0.1 and 0.5 wt% are 4.81 \times 10^{-16}, 1.73 \times 10^{-15} \text{ and } 4.25 \times 10^{-15} \text{ S/m, respectively, at RT. The conductivity increases with the increase of the GO loading, and the maximum enhancement is by 290 % for the EP/GO-0.5. However, the conductivities of these composites at 100 °C are 3.89 \times 10^{-13}, 2.68 \times 10^{-13} \text{ and } 5.86 \times 10^{-13}, \text{ respectively. As can be seen in Figure. 4, the absolute value of the slope of the temperature-dependent conductivity is reduced. The difference of the conductivity between the neat epoxy and the EP/GO-0.05 is insignificant, yet that between the neat epoxy and the EP/GO-0.1 as well as the EP/GO-0.5 is obvious. It is indicated that the temperature coefficient of conductivity is decreased due to the introduction of the GO filler.}

In order to further investigate the doped fillers on the temperature coefficient of conductivity, the temperature-dependent conductivity is fitted based on the so-called Arrhenius equation [11]:

\[
\gamma(T) = \gamma_0 e^{\frac{-E_a}{k_B T}} = \gamma_0 e^{\frac{-E_a}{kT}} \quad (3)
\]

where \(\gamma(T)\) is the conductivity of the material at the temperature \(T\) in K, \(\gamma_0\) is a constant relating to the nature of the material (S/m), \(E_a\) is the thermal activation energy (eV). The conductivities \(\gamma\) of the EP/GO samples conductivity as a function of the temperature \(T\) is fitted by (3). The expressions of the fitted curves are listed in the bottom left part of the Figure. 4.

\begin{table}[h]
\centering
\caption{Calculated activation energy of EP/GO nanocomposites under 8 kV/mm.}
\begin{tabular}{llll}
\hline
Sample & The neat epoxy & EP/GO-0.05 & EP/GO-0.1 & EP/GO-0.5 \\
\hline
Activation energy (eV) & 1.05 & 0.80 & 0.59 & 0.58 \\
\hline
\end{tabular}
\end{table}

The thermal activation energy is calculated as shown in Table 1. It is found that the activation energy decreases with the increasing of the GO loading. The activation of the neat epoxy is 1.05 eV, while that of the EP/GO nanocomposites is 0.8, 0.59 and 0.58 eV at the loading of 0.05, 0.1 and 0.5 wt%, respectively. The reduction of these samples could reach 23.8 %, 43.8 % and 44.8 %, respectively. It is evident that the temperature coefficient of conductivity is reduced. Detailed explanation will be presented in following section.

C. DC BREAKDOWN STRENGTH

Figure. 5 demonstrates the Weibull distribution of the DC breakdown strength of the EP/GO nanocomposites at RT. It can be seen that the DC breakdown strengths at the cumulative failure probability of 63.2 % of the neat epoxy is 188.3 kV/mm, while that of the EP/GO-0.05, 0.1 and 0.5 are

FIGURE 5. Weibull distribution of DC breakdown strength of EP/GO nanocomposites at RT.
184.9, 180.5 and 171.0 kV/mm, respectively. The reduction of these samples could reach 1.8%, 4.1% and 9.2%. It is noted that an obvious reduction of the DC breakdown strength of the EP/GO-0.5 is found while that of the EP/GO-0.05 and 0.1 is insignificant. It may be attributed to the introduction of more ionic impurities by the GO filler. It is pointed out in [25], that the GO filler has the large number of functional groups on the GO surface. These groups will become unstable and be dissociated into ions under high electric field, which may result in more heterocharges accumulation leading to the enhancement of local electric filed strength [26]. On the other hand, the higher DC conductivity as shown in Figure 4 may lead to enhanced electrical power causing “thermal breakdown” at least part of the insulation.

D. IDC TEST AND TRAP DISTRIBUTION
The principle of IDC method is that analyzing the depolarization current varying with the time at constant temperature after poling for a long time [22]. The applied electric field is high enough and the time is long enough so that charges could be injected into the material and trapped charges could be built up. Here, 50 °C was selected according to the suggestions given in [21]. Figure 6 shows the IDC current of the EP/GO nanocomposites with different loadings as a function of depolarization time at constant temperature of 50 °C. It is found that all the EP/GO nanocomposites have larger decay speed than that of the neat epoxy, and the current decreases gradually with the depolarization time and tends to be zero. The initial current decreases with filler content of 0.05 wt%, and then increases with a further increase of filler content to 0.5 wt%. It is because that there are different trap distribution inside various nanocomposites.

![Figure 6. Isothermal discharge current (IDC) of EP/GO nanocomposites as a function of depolarization time.](image)

Figure 7 shows the trap distribution characteristics of the neat epoxy and various EP/GO nanocomposites based on the IDC. It is found that more shallower traps are introduced by the GO filler, while the depth of the deeper traps are lowered with the introduction of the GO concentration. The related trap level and the density are listed in Table 2. The centers of the shallower and deeper trap level are about 0.79-0.81 eV and 0.85-0.88 eV, respectively. Both the shallower and deeper trap level center have a shift, though not significantly, with the introduction of GO filler. However, the density of the traps differs a lot. It is found that, compared with the neat epoxy, the density of the shallower traps of the EP/GO nanocomposites increases with the increase of the filler content. The densities of the shallower traps are \(1.0 \times 10^{21}, 2.4 \times 10^{21}\), and \(2.8 \times 10^{21}\) eV\(^{-1}\)m\(^{-3}\) of the neat epoxy, the EP/GO-0.05, 0.1 and 0.5, respectively.

![Figure 7. Trap level distributions of EP/GO nanocomposites at 50 °C.](image)

It is assumed that there is no recombination of charges and the current is generated by the de-trapping of the trapped charges. More charges would be captured as trapped charges due to the higher trap density and the deeper trap level. In the initial stage of the depolarization process, the trapped charges are easier to overcome the energy barrier and drift to the electrodes resulting a higher current. In the later stage, the de-trapping of the charges in shallower traps is thought to be completed and the charges in deeper trap levels are hard to overcome the energy barrier, thus the current tends to be zero and the decay speed of all the nanocomposites is enhanced as shown in Figure 6. The density of deeper trap for EP/GO-0.05 is reduced obviously resulting in the integral area is reduced. This is the reason why the EP/GO-0.05 has the minimum initial current. However, compared with the neat epoxy, more shallower traps are introduced with the introduction of GO filler. The shallower traps start to play roles and the integral area of traps increases with the increase of GO filler content, resulting in the increase of the initial current.

There are abundant surface groups in the GO particle such as many hydroxyl groups on the basal plane. It is suggested by Meunier et al [27], that the chemical defects originating from hydroxyl groups present shallower traps. This is the reason why the EP/GO nanocomposites have a bigger density of shallower traps than that of the neat epoxy. With the increase of the GO filler, the density of the deeper traps increases, but the density of the EP/GO nanocomposites are lower than the neat epoxy. The density of the deeper traps is...
that of the trapped charges. The effective mobility of the shallower traps and in deeper traps is.

Characteristics of trap distribution of various EP/GO samples.

| Sample       | Shallower trap level (×10^{11} eV·m^{-3}) | Density (×10^{13} eV·m^{-3}) | Deeper trap level (×10^{11} eV·m^{-3}) | Density (×10^{13} eV·m^{-3}) |
|--------------|--------------------------------------------|-------------------------------|----------------------------------------|-------------------------------|
| Neat epoxy   | 0.79                                       | 1.0                           | 0.87                                   | 2.6                           |
| EP/GO-0.05   | 0.81                                       | 2.4                           | 0.88                                   | 1.5                           |
| EP/GO-0.1    | 0.80                                       | 2.4                           | 0.86                                   | 2.2                           |
| EP/GO-0.5    | 0.79                                       | 2.8                           | 0.85                                   | 2.6                           |

reduced for the EP/GO-0.05 and 0.1, with 1.5 × 10^{21} and 2.2 × 10^{21} eV·m^{-3}, respectively, while that of the neat epoxy is 2.6 × 10^{21} eV·m^{-3}. The epoxide groups of the GO will react with the hardener resulting in the reduction of the crosslinking degree as well as the decrease of the deeper traps [28]. Therefore, both level and density of deeper trap of the EP/GO nanocomposites are reduced. However, the deeper trap density of the EP/GO-0.5 is nearly equal to that of the neat epoxy, and which may be attributed by the more interfacial regions produced by the GO particle since the GO has a large specific surface area with a high aspect ratio as evidenced by Figure 2d.

IV. DISCUSSIONS

The conduction mechanism for the EP/GO nano-composites is complicated. Both the interfacial regions and the introduced defects caused by the GO particle may change the trap distribution inside the material [29], which limits the carrier mobility \( \mu \) and further influences the conductivity \( \gamma \).

As shown in the Figure, 7, two obvious trap level centers are observed and roughly divided as the shallower trap center and the deeper trap center. Therefore, the discrete energy levels model was employed here to analyze the influence of traps in different energy level on the effective mobility \( \mu_{\text{eff}} \). When the processes of trapping and de-trapping of the carriers reach the steady state, the density of the trapped charges could be calculated by [30]:

\[
q_{\text{trap}} = \frac{q_{\text{free}}eN_t}{q_{\text{free}} + \frac{4\pi\kappa_0e_T}{\mu_0} \exp(-\frac{E_{\text{trap}}}{k_B T})} \quad i = 1, 2
\]  

(4)

where \( i = 1 \) represents the shallower trap level and \( i = 2 \) represents the deeper trap level. \( q_{\text{free}} \) is the density of the free charges, \( e \) is the elementary charge, \( N_t \) is the density of the trap level, \( \epsilon_T \) is the permittivity of vacuum, \( \kappa_T \) is the relative permittivity, \( \nu \) is the ‘attempt to escape’ frequency \( (s^{-1}) \), \( \mu_0 \) is the mobility for no trap inside the insulation, \( E_{\text{trap}} \) is the carrier that is activated from the energy level of \( E_n \) to the conduction band, and \( T \) is the temperature. The ratio of charges in shallower traps and in deeper traps is

\[
\frac{q_{\text{trap}1}}{q_{\text{trap}2}} = \frac{N_{t1}q_{\text{free}}\mu_0 + 4\pi\kappa_0e_T\nu \exp(-\frac{E_{\text{trap}}}{k_B T})}{N_{t2}q_{\text{free}}\mu_0 + 4\pi\kappa_0e_T\nu \exp(-\frac{E_{\text{trap}}}{k_B T})}
\]  

(5)

The amount of the free charges \( q_{\text{free}} \) is far smaller than that of the trapped charges. The effective mobility \( \mu_{\text{eff}} \) can be represented by:

\[
\mu_{\text{eff}} = \frac{q_{\text{free}}\mu_0}{q_{\text{trap}1} + q_{\text{trap}2}}
\]

It is indicated that the \( \mu_{\text{eff}} \) of the material is determined by both the shallower traps and the deeper traps. Based on the (6), it is found that the \( \mu_{\text{eff}} \) is inversely proportional to the trapped charges density.

When at lower temperature, the injected charges keep small and then the de-trapping probability maintains low. The \( \mu_{\text{eff}} \) is dominated by the deeper traps, since more charges will be first captured by the deeper traps. Reduced density of the deeper traps \( q_{\text{trap}2} \) causes the increased effective mobility of the carrier \( \mu_{\text{eff}} \), which results in an increase of the conductivity. On the other hand, the intrinsic conductivity of GO is higher than that of the neat epoxy. When the concentration of GO is up to 0.5 wt%, the contribution of the high conductivity of GO cannot be ignored, and it is the main reason why the EP/GO nanocomposite has the maximum value at RT.

As the temperature increases, more injected charges are captured and fill the deeper traps. The shallower traps start to play roles in the conduction. Increased density of the shallower traps causes the increased ratio of \( N_{t1}/N_{t2} \), which leads to the reduction of the \( \mu_{\text{eff}} \) where the energy difference between the shallower traps and the deeper traps is considered as constant. This is the main reason for the reduced conductivity. In addition, the intrinsic conductivity of GO decreases with the increase of temperature due to the enhanced lattice vibrations and phonon scattering. Therefore, the differences of conductivity between the EP/GO nanocomposites and the neat epoxy, as well as the growth rate of conductivity with the temperature, tend to be lowered with the increase of temperature. The temperature coefficient of conductivity of the EP/GO nanocomposites is reduced and the apparent activation energy is lowered by the GO filler.

V. SIMULATION ANALYSIS

The temperature coefficient of conductivity and the activation energy for the EP/GO nanocomposites decrease with the increase of the GO content. Under the same temperature gradient, the EP/GO nanocomposites could effectively reduce the conductivity gradient and then make electric field well-distributed. In order to verify the field grading effect of the prepared composites, a ± 800 kV valve-side bushing of the converter transformer is taken as the research object based on our previous work [31], where the geometry, material parameters and electro-thermal characteristics of the bushing were investigated in detail. The conductivity of the condenser core is set as a function of the temperature \( T \) according to Figure 4. The ambient temperature and transformer oil temperature are set as 50 and 90°C, respectively, according to IEC 62199 [32]. The simulations are performed under loading current RMS of 4500 A and operating voltage 800 kV.
Figure 8 shows the effects of the conductivity of the neat epoxy, EP/GO-0.05, 0.1 and 0.5 on the electric field distribution inside the condenser core. The electric field distribution with the constant conductivity without temperature coupling was also shown for the sake of comparison. Of particular note is that there is little difference of the electric field distribution between the EP/GO-0.1 and EP/GO-0.5 because their activation energies are almost equal. It is found that the maximum field strength is reduced and the field distribution becomes well-distributed, due to the introduction of the GO filler.

![Figure 8. Electric field distribution of the condenser core for a) constant conductivity, b) neat epoxy, c) EP/GO-0.05 and d) EP/GO-0.1 and EP/GO-0.5.](image)

The specific radial and axial electric field distributions of the condenser core using different materials as insulation are shown in Figure 9 and 10, respectively. It is found that the maximum radial field strength is 6.2, 9.3, 7.7 and 6.4 kV/mm when conductivity function is used by the constant conductivity, neat epoxy, EP/GO-0.05 and EP/GO-0.1 & 0.5, respectively. The maximum axial field strength in the upper part of bushing is 0.28, 0.65, 0.55 and 0.46 kV/mm, respectively, while that in the lower part is 0.55, 1.30, 1.09 and 0.93 kV/mm, respectively. Compared with the neat epoxy, the EP/GO nanocomposite with the content of 0.1 wt% has the best performance on the improvement of electric field distribution with an approximately 30% reduction of maximum field strength inside the bushing insulation and only a 4.1% reduction of DC breakdown strength.

![Figure 9. Radial electric field distribution when using different insulation materials (Measurement points for radial electric field are shown in Figure. 8a).](image)

![Figure 10. Axial electric field distribution when using different insulation materials. (Measurement points for axial electric field are shown in Figure. 8a).](image)

VI. CONCLUSION

The EP/GO nanocomposites with reduced temperature coefficient of conductivity have been prepared. SEM, DC conductivity behaviors under different electric field and temperature, DC breakdown strength, and trap distributions are investigated. The mechanism of the GO filler on the reduced temperature coefficient of conductivity based on the dual discrete energy levels model is discussed. Finally, the effects of the modified insulating materials on the improvement of electric field distribution are verified, based on a ± 800 kV valve-side bushing model. The conclusions are as follows:

1) Thermal activation energy of epoxy resin could be reduced by the introduction of the GO filler with appropriate content. The EP/GO nanocomposites show a smaller temperature coefficient of conductivity than that of the neat epoxy.

2) The inclusion of the GO filler could introduce more shallower traps inside the composites and reduce the density of the deeper traps due to the abundant surface groups. The reduced deeper trap density and high intrinsic conductivity of GO are responsible for the increase of the conductivity of EP/GO nanocomposites at lower temperature. The increased shallower trap density and improved phonon scattering may...
be the reasons why the growth rate of the conductivity, as the temperature increases, of EP/GO nanocomposites is lowered.

3) Both the radial and axial electric field distributions, coupled with temperature, within bushing insulation are improved when using the EP/GO nanocomposites. The EP/GO-0.1 has the best performance on the improvement of the electric field distribution with acceptable reduction of breakdown strength.

EP/GO nanocomposites show a great potential for applications in HV bushing insulation system, and the field grading based on the material modification has been proven to be a promising route to regulate the electric field distribution.

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