Electrical Treeing Characteristics in Epoxy under Electromagnetic Coupled Field

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Abstract. Epoxy resin is a kind of material used as electrical insulation in superconducting magnetic devices. The dielectric properties of the epoxy resin directly affect the safety and stable operation of the whole magnet. While operating, the epoxy resin faces the challenges of complex electric field and strong magnetic field. Researches on the effects of harmonic superimposed dc voltage and magnetic field on the electrical treeing behaviour in epoxy resin were carried out. Experimental results show that low-order harmonics are more likely to lead to the extension of electrical tree branches, which mainly results from the higher energy generated by partial discharge under low-order harmonic voltages. Meanwhile, the addition of dc voltage can result in more severe partial discharge because of the asymmetric charge accumulation, and eventually accelerates the degradation process. Zeeman effects were taken into account while considering the effect of magnetic field. More shallow traps are generated under strong magnetic field, thus charges are more easily to migrate under the action of magnetic field and gain enough energy to break the molecular chain. Besides, Lorenz force leads charges to hit the molecular chain more frequently. The above results in the more serious damage in epoxy resin under electromagnet coupled field.

1. Introduction

Large-scale strong magnetic field devices, such as Steady High Magnetic Field Facility (SHMFF) and Experimental Advanced Superconducting Tokamak (EAST), use superconducting magnet coil to generate strong magnetic field [1]. Within the magnet system, the insulation material plays an important role in mechanical supporting and the insulating the conductors [2]. The reliability of the insulation material is the guarantee to the safety operation of the whole magnet system [3]. Epoxy resin is a kind of insulation material which is generally used in the superconducting magnet devices [4]. While operating, the epoxy resin will endure the force from the complex electric field and strong magnetic field. According to the actual operating voltage waveform in converter transformer, the 1st harmonic voltage accounts for 18.5% of the DC voltage content after the Fourier decomposition [5]. And the magnetic field generated by the superconducting Toroidal Field (TF) coil system of EAST can achieve 3.5 T [6]. The existence of harmonic voltage is proved to be a great threat to the reliability of the insulation material [7]. However, the mechanism of the insulation failure under harmonic superimposed dc voltage and the effect of strong magnetic field remain unsure. Furthermore, study on the degradation mechanism of the insulation material under complex electro-magnetic coupled field is the basis of insulation design for large-scale strong magnetic field devices.

Electrical treeing is a phenomenon of degradation during the process of dielectric breakdown [8]. The characteristics of electrical tree have close relation with the accumulation and migration of space
charge [9]. Both electric field and magnetic field have an effect on the behavior of charge carriers. The change of electric field is accompanied by the injection, extraction, accumulation and migration of space charge [10]. Different forms of applied voltage cause different effect on the charge characteristics and thus infect the electrical treeing behavior. While under dc voltage, the space charges are injected into the insulation material and accumulated around the anode, thus the electric field around the anode is weakened and the electrical tree is hard to be initiated [11]. While under ac voltage, the migration of the space charges is guided by the periodic change of the applied voltage. With the injection and extraction of the space charge and the neutralization of heteropolar charges, energy is generated and results in the initiation of the electrical tree [12]. While under pulse voltage, the instantaneous energy drives the charge to strike the molecular chain, causing the gradual degradation of the polymer. The electrical treeing process under pulse voltage is closely related to the pulse frequency and duration [13]. As for the pulse superimposed dc voltage, charges are injected and accumulated during dc voltage period. Then the charges are driven by the pulse voltage and cause the initiation of the electrical tree [14]. After the initiation of the electrical tree, the treeing process is guided by the occurrence of partial discharge (PD), which is mainly caused by the defeats such as tips, voids and impurities [15].

As for the effects of magnetic field, the moving charges are affected by the Lorentz force in the magnetic field [16]. This results in the change of paths during the migration of charges under the injection of electric field. The electrons are able to hit the molecular chain much more frequently after taking the Lorentz force into account [17]. Then the shape of electrical tree is completely changed under the effect of electric field. The migration of the space charges also has close relationship with the energy band structure of the polymer [18]. Considering the effect of a magnetic field on spintronics outside the nucleus, spin electrons are affected by the external magnetic field due to their own magnetic moment, causing electrons with different spin states on the same orbit to have different energies. The result is the split of energy level and causes the changes in the energy band structure [19].

However, there are few studies focusing on the degradation mechanism of the insulation material under harmonic superimposed dc voltage, which is a serious problem in a dc powered system. The effects of strong magnetic field on the dielectric properties of the insulation material have not been considered, although they are very important to the insulation design in superconducting magnet system. In this paper, ac voltage with the frequency of 50, 150, 250, 350 Hz were chosen as the 1st, 3rd, 5th and 7th harmonic respectively. The dc voltage was added to generate the complex harmonic superimposed dc voltage. The magnetic field whose strength was up to 1200 mT was applied to the specimens to study the electrical treeing behavior of the epoxy resin under electro-magnet coupled field. PD behavior during the treeing process was detected using the PD detector (PAP-300) [20]. In order to study the effect of magnetic field on the trap distribution of the epoxy resin, isothermal discharge current (IDC) test were carried out. This research is helpful to reveal the degradation mechanism of the epoxy resin under electro-magnet coupled field and provide reference to insulation design for superconducting magnet system in the future.

2. Experimental setup

2.1. Specimen preparation

The specimens are made of the epoxy (highly active and lowly viscous liquid bisphenol A, Yanhai-Resin, Araldite HY-511) and the hardener (low molecular weight polyamide resin, HY-651) that are commercially available. The proportion of the epoxy and the hardener is three to ensure the best cure effect. The epoxy and the hardener were mixed and stirred using a magnetic stirrer until the mixture became homogeneous. Then mixture was degassed sufficiently in a vacuum box [18]. After that, the mixture was moved into a stainless steel mold, and the metal needle (with a tip curvature radius of 3 μm and a tip angle of 30 degree) was pre-embedded for electrical tree experiment. The insulation sickness between the needle tip and the bottom of the specimen was 2 mm. The plate electrode was
well grounded by attaching copper foil to the bottom of the specimen. The specimens were manufactured into epoxy slabs with 30 mm × 40 mm × 6 mm in dimension. Finally, the specimens were cured in a drying oven at 80 °C for 2 h.

2.2. Electrical treeing measurements

The schematic diagram of the experimental device for electrical treeing measurement was shown in figure 1. The dc source output and high frequency ac source output were integrated into the harmonic superimposed dc voltage source. The frequency of ac source was set as 50, 150, 250 and 350 Hz to generate 1st, 3rd, 5th and 7th harmonic respectively. The peak amplitude of ac source was 16 kV, and the amplitude of dc source was 5 kV. During the experiments, the DC voltage was applied with a rising speed of 1 kV/s at first. Then the harmonic voltage was applied 1 min later to generate the harmonic superimposed DC voltage. The electrical treeing characteristics were observed under the digital microscope after the superimposed voltage was applied to the specimens for certain time.

The external magnetic field was generated by a pair of NdFeB permanent magnets and a constant magnetic field electromagnet. The relative positions of the magnetic poles and the specimen are as shown in figure 2. The direction of the constant magnetic field is perpendicular to the direction of the electric field. The magnetic field between the magnetic poles is a uniform magnetic field strength of 200 mT and 1200 mT respectively.

2.3. PD tests and IDC measurements

Partial discharge behavior during the treeing process was carried out through PD tests. A high frequency current transformer (HFCT) was placed around the ground wire near the bottom electrode of the sample [20]. The high frequency current signal during partial discharge was detected by HFCT and transported to the PD detector (PAP-300).

Trap distribution of the specimens was studied through observing the depolarization current during the discharging process in the IDC measurement. The specimen used in the IDC measurements the epoxy resin sheet with thickness of 2 mm. During the charging process, the specimen was charged by 5 kV dc source for 10 minutes through a pair of cylindrical brass electrodes whose diameter was 15 mm. After the charging process, the depolarization current was detected through connecting the electrodes to an electrometer (Keithley 6517B) which has a measuring range from 1 fA to 20 mA [20].

3. Experimental results

3.1. Electrical treeing under different orders of harmonic voltage

The electrical tree after the epoxy resin was applied with different orders of harmonic voltage for 15 minutes was shown in figure 3. The basic tree shape is branch structure under all kinds of harmonic voltages. There are still differences in electrical tree morphology with the varying orders of harmonic
voltage. The electrical tree initiated by low order harmonic voltage shows denser branches. Many side branches occur besides the main channel along the electric field direction. As for the electrical tree generated by high order harmonic voltage, such as 5th and 7th harmonic voltage, shows fewer side branches and the main channel tends to be shorter.

![Figure 3. Typical electrical tree under different harmonic voltage for 15 minutes.](image)

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![Figure 4. Relationship between tree length and harmonic order at 10 minutes.](image)

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![Figure 5. Relationship between accumulated damage and harmonic order at 10 minutes.](image)

Figure 5 shows the relationship between accumulated damage and harmonic order at 10 minutes.

Figure 4 shows the statistic results of the tree length after the specimens were applied with different orders of harmonic voltage and harmonic superimposed dc voltage for 10 minutes. The electrical tree length describes the furthest distance between the needle tip and tree tip. In each different condition of applied voltage, 5 specimens were used to form the final statistics. The height of the column chart represents the average value of the length of the electrical tree and the error bar shows the standard deviation of data. The tree length shows nonlinear change with the increase of harmonic order: the tree length increases first and then fall with the increase of harmonic order. The length of the electrical tree generated by 3rd harmonic voltage shows the peak value. Besides, the length of the electrical tree generated by harmonic superimposed dc voltage is longer than that without dc voltage.

Figure 5 shows the statistic results of the accumulated damage after the specimens were applied with different orders of harmonic voltage and harmonic superimposed dc voltage for 10 minutes. During the electrical treeing process, the electrical tree propagates in both vertical and horizontal direction. Accumulated damage is a parameter to assess the holistic damage degree caused by tree growth. It is calculated according to the damage region occupied by electrical tree channel in pixels [21]. With the increase of harmonic order, the accumulated damage shows a decrease trend, which means that lower orders of harmonic voltage can cause larger degradation area due to the electrical treeing process. Besides, the decrease of accumulated damage with the increase of harmonic order is alleviated under harmonic superimposed dc voltage, among which the accumulated damage caused by 7th harmonic superimposed dc voltage is larger than that caused by 7th harmonic voltage. The results reveal that the addition of dc voltage can cause more serious damage to the insulation material under the situation of high frequency harmonic voltage.
3.2. Electrical treeing under harmonic superimposed dc voltage

The electrical tree after the epoxy resin was applied with 1st and 3rd harmonic voltage and harmonic superimposed dc voltage for 10 minutes was shown in figure 6. The electrical tree under 3rd harmonic voltage tends to spread further than that under 1st harmonic voltage, which meets the former experimental results. As for the harmonic superimposed dc voltage, the electrical tree spread further than that under the condition without addition of dc voltage. However, the electrical tree tends to be denser without the addition of dc voltage. The experimental results reveal that the addition of dc voltage can drive the energy used to form side branches to cause more serious damage along the main channel.

![Figure 6. Typical electrical tree under harmonic superimposed dc voltage for 10 minutes.](image)

Figure 7 shows the statistic results of the tree length during the treeing process under harmonic voltage and harmonic superimposed dc voltage. With the increase of tree length, the speed of electrical tree growing becomes slower when the tree length reaches a certain value, then the speed rises up again with the tip of electrical tree approaching the ground side. During the treeing process, the electrical tree under harmonic superimposed dc voltage tends to spread further along the main channel comparing with that under harmonic voltage without the addition of dc voltage. The accumulated damage under harmonic voltage and harmonic superimposed dc voltage during the electrical treeing process was shown in figure 8. The accumulated damage of the electrical under harmonic voltage is larger than that with the addition of dc voltage. The experimental results reveal that the addition of dc voltage can cause more serious damage along the main channel and result in the longer tree length under harmonic superimposed dc voltage.

3.3. Electrical treeing in strong magnetic field

The electrical treeing characteristics in different magnetic field after the epoxy resin was applied with 5th harmonic superimposed dc voltage were shown in figure 9. As for the electrical treeing process in 200 mT magnetic field, the electrical tree spreads towards left and form the main discharge channel when the specimen was applied with harmonic superimposed dc voltage shorter than 10 minutes.
However, a discharge channel towards the right direction was formed during the period from 10 minutes to 15 minutes, which is marked by the blue solid circle in the figure. After the specimen was applied with harmonic superimposed dc voltage for 20 minutes, new branches were initiated from the left discharge channel and spread towards the ground side, which is marked by the blue dotted circle in the figure. As for the electrical tree in 1200 mT magnetic field, the tree was initiated in the reverse direction to the electric field, which is marked by the red solid circle in the figure. Then the electrical tree spread through very random and complex paths. The experimental results show significant different from the situation without magnetic field, which is that the electrical tree not only spreads along the electric field but also generates a lot of side branches. As a result, conclusion can be drawn to that the addition of strong magnetic field can cause much more serious damage to the insulation material under harmonic superimposed dc voltage.

Figure 9. Electrical treeing process under magnetic field after applied with 5th harmonic superimposed dc voltage.

Figure 10. Tree length and accumulated damage of the electrical tree under different magnetic field strength after applied with 5th harmonic voltage and harmonic superimposed dc voltage for 15 minutes. (The line graph represents the tree length, and the histogram represents the accumulated damage)

Figure 10 shows the tree length and accumulated damage of the electrical tree after the specimens were applied with 5th harmonic voltage and harmonic superimposed dc voltage for 15 minutes in different strengths of magnetic field. When the external magnetic field is applied, the electrical tree length in longer with the addition of dc voltage and the accumulated damage under harmonic superimposed dc voltage is also smaller. The result shows the same trend as the situation without external magnetic field. With the increase of magnetic field strength, both the tree length and accumulated damage show significant increase. The change in accumulated damage is rather serious. The accumulated damage of the electrical tree in 1200 mT magnetic field is over twice of that without external magnetic field. The experimental results reveal that the external strong magnetic field can cause serious damage to the insulation material under harmonic superimposed dc voltage, and the effect is mainly reflected in the damage area.

4. Discussion

4.1. Effect of harmonic order on electrical treeing

After an electrical tree is initiated, the spread of the electrical tree is companied with partial discharge phenomenon. The energy generated through PD process forms new discharge channels, causes the elongation of electrical tree, and eventually results in the gradual degradation of the insulation material. Figure 11 shows the Phase Resolved Partial Discharge (PRPD) images during the PD progress from
10 minutes to 15 minutes. The sinusoidal pattern in the background of the four figures represents a 50 Hz ac curve used to determine the phase corresponding to the time at which PD occurred.

Figure 11. PRPD images of the PD process during the period from 10 to 15 minutes.

As shown in the images, the occurrence of PD shows significant periodicity and phase characteristics under all four kinds of harmonic voltage. As for the PD process under 1st harmonic voltage, strong discharge signals are mainly concentrated in the first quadrant. As for the PD process under 3rd harmonic voltage, strong discharge signals mainly occur within the range between 60 and 90 degrees, which can be considered as the third quadrant under 3rd harmonic voltage. According to the experimental results, the occurrence frequency of PD is increased with the increase of harmonic order. With the increase in the frequency of applied harmonic voltage, the number of charge injections, extractions, and neutralizations increases within the certain period of time. Every injection, extraction and neutralization of charges can generate energy, and the energy has the potential to cause PDs.

However, it can also be seen that the discharge amplitude under high order harmonic voltage is weaker than that under low order harmonic voltage. Among which, the peak value of discharge amplitude under 1st and 3rd harmonic voltage achieve 600 mV, while that under 5th harmonic voltage achieve 500 mV and 400 mV under 7th harmonic voltage. With the increase in the frequency of applied voltage, there is shorter time per half cycle and causes fewer space charge accumulation during the first half cycle. When the second half cycle with opposite polarity of voltage, less neutralization occur and results in the weakness of PD. The previous results of electrical treeing show that the electrical tree under 3rd harmonic voltage shows longest tree length, and the accumulated damage shows decrease trend with the increase of harmonic order. Combining the experimental results of PD with the previous electrical treeing process, conclusions can be drawn to that both the discharge amplitude and discharge frequency determine the length of discharge channel, which results in the longest tree length under 3rd harmonic. Furthermore, lower frequency of discharge can cause more side channel during treeing process, which results in the decrease trend of accumulated damage.

4.2. Effect of superimposing dc voltage on electrical treeing

The statistic image of discharge amplitude and the amount of discharge during the PD process within the period from 5 to 10 minutes is shown in figure 12. Comparing the image of PD under 1st harmonic
voltage and that of PD under 1st harmonic superimposed dc voltage, the amount of discharge shows significant increase, especially the amount of discharge whose amplitude ranges from 450 to 500 mV. As for the PD behavior under 3rd harmonic and harmonic superimposed dc voltage, the amount of discharge whose amplitude ranges from 500 to 550 mV shows significant increase. The experimental results of PD reveal that the addition of dc voltage can cause the PD with high amplitude to occur more frequently. Considering the previous results of electrical tree that superimposing dc voltage causes increase of tree length and decrease of accumulated damage, conclusion can be drawn to that the increase in the amount of high amplitude discharge mainly cause the extension in the main discharge channel, instead of the side channels.

![Figure 12](image_url)

Figure 12. Statistic image of discharge amplitude and amount of discharge during PD process.

In order to reveal the charge behavior and the effect of superimposing dc voltage, a scheme was drawn and shown in figure 13. Three periods can be divided with in one cycle. The three periods are rising stage, falling stage and reverse stage respectively. Furthermore, the rising stage at this cycle also presents as the revers stage regarding the previous half cycle. Firstly, the amplitude of applied voltage is enhanced due to the addition of dc voltage. The increase in the amplitude of applied voltage is a main cause to the increase of discharge amplitude and amount of discharge. With the increase of applied voltage, the partial discharge inception voltage (PDIV) is more easily to be achieved. As a result, PDs occur more frequently and more serious under stronger electric field comparing to that under the situation without superimposing dc voltage.

During the rising stage, the charges are gradually injected into the specimen through needle tip with the increase of applied voltage. At this stage, the charges are motivated by the applied electric field and hit the molecular chain, which may cause the initiation of an electrical tree of degradation of the insulation material. The injected charges are then trapped in the traps around the tip of the needle electrode and form an electric field whose direction is converse to the applied electric field. During the falling stage, the applied electrical field decreases gradually with the decrease of applied voltage. When the inner electric field formed by the trapped charges, de-trapping process can occur and the potential energy of the polarons is released. At this stage, the energy can be transferred to the other
charges or polarons and cause more charges to de-trap or gain enough energy to hit and break the molecular chain. After the applied voltage crosses zero, the reverse stage is carried out. During the reverse stage, the charges with opposite polarity to the trapped charge are injected into the specimen. At this stage, the opposite polarities of charges are neutralized, generating discharges and releasing energy. After the dc voltage is added, the asymmetric applied voltage results in more charge accumulation during the positive period. When the negative period arrive, the injection of charges with opposite polarity can thus cause more neutralization and more serious discharge. As a result, PDs under harmonic superimposed dc voltage are enhanced comparing to that without the addition of dc voltage.

**Figure 13.** Schematic diagram of charge behaviour under harmonic superimposed dc voltage.

### 4.3. Effect of magnetic field on electrical treeing

As described in the previous chapters, the external strong magnetic field can cause much more serious damage to the insulation material, causing the increase of tree length and accumulated damage simultaneously. During the treeing process, the charges are motivated by the electric field and gain energy from discharge or other charges. The charges with high kinetic and potential energy are able to hit and break the molecular chain, causing the initiation and spread of an electrical tree. When the external magnetic field is applied to the specimen, the motivated charge will be subjected by Lorenz force [16]. The result is the change of migration path. The charges with high energy are able to hit and break the molecular chain more frequently and thus cause much more serious degradation to the insulation material. Besides, the change of migration path causes the electrical tree to spread in a random way. The tree branch not only doesn’t spread along the electric field but also spread along more than one main discharge channels. As a result, the random path of charge migration causes the complex formation of electrical tree, and thus causes much more serious accumulated damage to the insulation material in strong magnetic field.

In order to reveal the mechanism of insulation material degradation in strong magnetic field, the research on the effect of magnetic field on trap distribution of the epoxy resin was carried out through IDC measurements. The trap distribution of the polymer has great impact on the charge migration process in the insulation material. Considering the effect on energy band structure, Zeeman effects were taken into account. Essentially, Zeeman effects reveal the effect of magnetic field on spintronics outside the nucleus. Electrons outside the nucleus are in a spin state with a spin magnetic moment.
When the external magnetic field is applied, it interacts with the spin magnetic moment of the electron, thereby changing the spin state of electrons outside the nucleus. The result is that two electrons with opposite spin directions with the same energy in the same orbit produce different movement states under the action of a magnetic field. The difference in the effect of magnetic field on these two electrons results in the different energy levels where two electrons are in [22]. Eventually, the energy level is split in the magnetic field.

If Zeeman effects were taken account while considering the effect of magnetic field on energy structure band of the polymer, the structures of conduction band, forbidden band and trap distribution will all be changed. Figure 14 shows a schematic diagram of trap level splitting in magnetic field. Only the change in trap distribution is considered here. This schematic diagram is used to describe the general trend of trap level splitting and the charge migration process. Specific changes will be verified in the future by quantum chemical calculations and nuclear magnetic resonance experiments.

Figure 15 shows the trap distribution of the epoxy resin in different strength of magnetic field detected using IDC measurements. The trap distribution is obtained through observing the data, depolarization current, during the de-trapping process of the charges [23]. As shown in the image, the trap density rises and the central trap level decreases with the increase of magnetic field strength. Conclusions can be drawn that the external magnetic field generates more trap levels and causes higher density of shallow traps with the splitting of trap energy level. Combining the previous results of electrical tree into consideration, the formation of large amount of new shallow traps is the main cause of longer electrical tree and thus more serious damage to the insulation material. During the migration process of the charges, charges move along the conduction band. As the conduction band of the insulation is narrow, charges are easily to be trapped by the traps within the forbidden band. Then the charges need to obtain energy to jump onto the conduction band and more forward. The existence of higher density of shallow traps causes less energy that charges need to migrate within the insulation, which means that shallow traps may form conduction paths for the charges. In strong magnetic field, the charges are much more easily to migrate within the insulation material and obtain enough energy...
to hit and break the molecular chain. As a result, more serious damage to the insulation material is generated in strong magnetic field.

5. Conclusion
This paper investigates the dielectric properties of the epoxy resin under electro-magnetic coupled field. Different orders of harmonic voltage are superimposed with dc voltage to generate the complex electric field, and different strength of constant magnetic field is applied to study the effects on charge behavior and treeing process of the epoxy resin. Main conclusions can be concluded as follows:

1. With the increase of harmonic order, the tree length shows nonlinear trend and the electrical tree under 3rd harmonic voltage shows the longest discharge channel. Besides, the accumulated damage decreases with the increase of harmonic order. The electrical treeing characteristics are guided by both frequency and amplitude of partial discharge;

2. The addition of dc voltage on the one hand increases the peak value of applied voltage and causes more serious partial discharge. On the other hand, the charge behavior under harmonic superimposed dc voltage is different due to the asymmetric periodic electric field change. These two aspects result in the higher occurrence frequency of high energy partial discharge and cause longer electrical tree;

3. The external strong magnetic field not only affects the migration path of the charges, but also affects the energy band structure of the insulation material. The movement of charges is affected by Lorenz force, hits the molecular chain more frequently and causes more serious and random electrical tree branches. The trap level splits due to the Zeeman effects, thus higher density of shallow traps. The charges are more easily to gain energy through migration and eventually hit and break the molecular chain. The degradation of the insulation material under harmonic superimposed dc voltage is accelerated by the strong magnetic field.

As a result, the dielectric properties of the insulation under complex electro-magnetic coupled field are different from that under the situation without complex applied voltage and external magnetic field. Understanding the degradation mechanism of the insulation material under electro-magnetic field is important in the insulation design for large-scale strong magnetic field devices.

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References
[1] Cui C, Cheng J, Chen S, Li L and Hu X 2016 Design and test of superconducting persistent current switch for experimental Nb3Sn superconducting magnet IEEE Tran. Appl. Supercond. 26 0605704
[2] Fabian P, Haynes M, Babcock H and Hooker M 2013 Characterization and qualification of cyanate ester/epoxy insulation for NSTX-U fusion magnets IEEE Tran. Appl. Supercond. 23 7700204
[3] Bondarenko V, Egorov S, Lamzin E, Korsunsky V, Rodin I and Voronin N 2005 Components of thermal and electrical insulations for the superconducting magnet systems IEEE Tran. Appl. Supercond. 15 1435-8
[4] Yin S, Arbelaez D, Swanson J and Shen T 2019 Epoxy resins for vacuum impregnating superconducting magnets: a review and tests of key properties IEEE Tran. Appl. Supercond. 29 7800205
[5] Cheng J, Zhao L, Sun X, Yang J and Lei Y 2017 Research on electric field distribution of valve side bushing for UHV converter transformer under actual operating voltage Sou.Power Syst. Tech. 11 1-8
[6] Wei J, Chen W, Wu W, Pan Y, Gao D, Wu S and Wu Y 2010 The superconducting magnets for
EAST tokamak *IEEE Tran. Appl. Supercond.* 20 556-9

[7] Bahadoorsingh S and Rowland S 2010 Investigating the impact of harmonics on the breakdown of epoxy resin through electrical tree growth *IEEE Trans. Dielectr. Electr. Insul.* 17 1576-84

[8] Zheng H, Rowland M, Iddrissu I and Ly Z 2017 Electrical treeing and reverse tree growth in an epoxy resin *IEEE Trans. Dielectr. Electr. Insul.* 24 3966-73

[9] Wang Y, Li G, Wu J and Yin Y 2016 Effect of temperature on space charge detrapping and periodic grounded DC tree in cross-linked polyethylene *IEEE Trans. Dielectr. Electr. Insul.* 23 3704-11

[10] Tanaka T 2001 Space charge injected via interfaces and tree initiation in polymers *IEEE Trans. Dielectr. Electr. Insul.* 8 733-43

[11] Iddrissu I, Zheng H and Rowland M 2017 DC electrical tree growth in epoxy resin and the influence of the size of inceptive AC trees *IEEE Trans. Dielectr. Electr. Insul.* 24 1965-72

[12] Zhang S, Yang Y, Li Q, Hu J, Zhang B and He J 2018 Different microscopic features of AC and DC electrical trees in insulating polymer *IEEE Trans. Dielectr. Electr. Insul.* 25 2259-65

[13] Du B, Han T and Su J 2015 Electrical tree characteristics in silicone rubber under repetitive pulse voltage *IEEE Trans. Dielectr. Electr. Insul.* 22 720-7

[14] Zhu L, Du B, Su J, Han T and Danikas G 2019 Electrical treeing initiation and breakdown phenomenon in polypropylene under DC and pulse combined voltages *IEEE Trans. Dielectr. Electr. Insul.* 26 202-10

[15] Liu M, Liu Y, Li Y, Zheng P and Rui H 2017 Growth and partial discharge characteristics of electrical tree in XLPE under AC-DC composite voltage *IEEE Trans. Dielectr. Electr. Insul.* 24 2282-90

[16] Pes C, Baze M, Berriaud C, Chevalier L, Juster P, Kozanecki W and Vedrine P 2008 Lorenz forces exerted by the magnetic mirror and magnetic influence of the cryostat on the ATLAS BT coils during the test *IEEE Tran. Appl. Supercond.* 18 411-4

[17] Han T, Zhu L, Wang F, Ma T, Du B and Gao Y 2019 Magnetic-field-dependent electrical tree under impulse-superimposed DC voltage at low temperature *IEEE Tran. Appl. Supercond.* 29 8800205

[18] Du B, Wang M, Li J and Xing Y 2018 Temperature dependent surface charge and discharge behavior of epoxy/AIN nanocomposites *IEEE Trans. Dielectr. Electr. Insul.* 25 1300-7

[19] Schwartz J, Read G and Snyder V 2006 EOS MLS forward model polarized radiative transfer for Zeeman-split oxygen lines *IEEE Trans. Geosci. Remote Sens.* 44 1182-91

[20] Pan X, Du B, Wang M, Su J, Xiao M, Li J and Kong X 2019 Surface discharge property of polypropylene/BN nanocomposite for HTS apparatus application *IEEE Tran. Appl. Supercond.* 29 7700704

[21] Zheng X and Chen G 2008 Propagation mechanism of electrical tree in XLPE cable insulation by investigating a double electrical tree structure *IEEE Trans. Dielectr. Electr. Insul.* 15 800-7

[22] Lindberg M, Eijkelenborg M and Woerdman J 1997 Measuring the quantum-limited linewidth of a laser by using the Zeeman effect *IEEE J. Quantum Electron.* 33 1767-73

[23] Du B, Xing Y, Jin J, Li Jie and Li Jin 2016 Effects of direct fluorination on space charge and trap distribution of PI film in LN2 *IEEE Tran. Appl. Supercond.* 26 0607405