Design of adaptive bushing based on field grading materials

Xiaolei Zhao | Jun Hu | Zhikang Yuan | Jinliang He

Correspondence
Jun Hu, Tsinghua University Beijing, China.
Email: hjun@tsinghua.edu.cn

Funding information
National Natural Science Foundation of China under, Grant/Award Number: U1766221; National Key R & D Program of China under, Grant/Award Number: 2018YFE0200100; State Grid Corporation of China under, Grant/Award Number: SGTYHT/17-JS-199

Abstract
Electrical bushings, as important power system components, are critical to the reliability of power systems. The capacitance-graded bushing is a type of high voltage bushing that is most commonly used in current power systems. However, the limitations of and problems with capacitance-graded bushings are exposed when the operating voltage level increases. A new direct current wall bushing with adaptive field grading materials is proposed, based on the core features of the problem that the bushing is intended to solve. The main insulation structure of the proposed DC wall bushing with adaptive field grading materials comprises three parts: a field grading layer, a current limiting layer and an electrode extension layer. The proposed bushing has characteristics that include a simple structure, small size and environmental friendliness, and it also meets the requirements of existing power systems. The proposed bushing also conforms to the intended development direction for future power equipment and will aid in the development of power systems for operation at higher voltages.

1 | INTRODUCTION

In power systems, high-voltage bushings are required when high voltage current conductors pass through metal bushings or through walls at different electrical potentials. A high-voltage bushing electrode typically has a ‘plug-in’ structure, where the high-voltage conductor pole is inserted into the centre of the ground electrode flange, which produces a very inhomogeneous electric field with a strong radial component. The local electric field at the flange is very high and tends to cause ageing and even breakdown of the insulating material, thus affecting the insulation performance. At the same time, the axial electric field distribution over the bushing surface is uneven and this causes the electric field to be largely concentrated on the side closest to the flange, which can easily lead to flashover occurring along the surface [1, 2]. High-voltage bushings are important equipment for electrical power systems and their safety and reliability are critical for reliable operation of the entire power system.

Further, to meet increasing demand for electricity, the operating voltage levels of power system must be improved continuously and the equipment required must thus be improved accordingly. Therefore, to meet the resulting requirements for higher operating voltage level and higher operational reliability, the electrical bushings are usually developed step-by-step. First, the design is optimised based on the existing bushing [3–5].

Second, online monitoring is performed during bushing operation to prevent failures in advance [6–8]. Finally, the reasons for bushing failures are subsequently analysed and the bushing design is then re-optimised following this failure analysis. [9–11] These three steps form a closed loop process that improves the bushing reliability continuously.

2 | PRESENT STATE OF TRADITIONAL BUSHINGS

The capacitance-graded bushing is the most commonly used type of high-voltage bushing in current power systems. The inner insulation structure of the capacitance-graded bushing or the main insulation is composed of a conical condenser core. This condenser core is composed of multiple alternately wound metal plates and oil-impregnated or resin-impregnated paper layers to regulate the radial and axial electric field distributions [12]. Depending on the internal insulation materials used, capacitance-graded bushings can be divided into oil-impregnated paper bushings and resin-impregnated paper bushings. The insulation inside oil-impregnated paper bushings is formed using vacuum oil immersion technology, which reduces the number of internal defects present in the condenser core. This means that good insulation is maintained at
high voltage levels with low partial discharges and low dielectric dissipation. After winding, the condenser core of the resin-impregnated paper bushing is immersed in epoxy resin and is then layered and solidified to form a condenser core with high electrical insulation properties and high mechanical strength.

While capacitance-graded bushings are optimised continuously using the three steps described above, bushing failures still occur frequently at high voltage levels. The main disadvantages of the most widely used capacitance-graded bushings are detailed as follows:

1. The long-term operating electric field of the condenser core design is low; that is, the average electric field within the main insulation of a capacitance-graded bushing is low and generally does not exceed 4 MV/m. This value is largely determined by the long-term operating electric field of the oil-impregnated paper or resin-impregnated paper used in the condenser core, which must withstand the highest possible electric field to enable long-term operation. As shown in Figure 1, the relationship between the breakdown electric field of the condenser core insulation material and the voltage action time must be considered as it has become an important factor [13]. Therefore, as the operational voltage level increases, the capacitance-graded bushing diameter must be designed to be larger to meet the basic electric field requirements of the device.

2. Long-running bushings are subject to a serious heating phenomenon, particularly in DC systems, which will affect the long-term reliability of the bushing. At higher voltage levels, the capacitance-graded bushing is too large, which affects its heat dissipation capability; this then leads to an increase in the temperature gradient in the radial direction of the main insulation, thus affecting the electrical conductivity of the insulating material. Here, the ageing of the insulating material is accelerated; additionally, the electric field inside the main insulation component is distorted severely, which then causes the local electric field to be too high and may even cause insulation breakdown, thus affecting bushing reliability during long-term operation.

3. The electric field in the condenser core is graded by the capacitor plate; therefore, when the metal plate is thin, electric field concentration is likely to occur at the end of metal plate. To increase the partial discharge voltage, semiconductor paper is commonly mounted on the end of the metal plate. However, when the voltage level increases, the electric field at the end of the metal plate will be concentrated, thus causing partial discharges and affecting the reliability of bushings.

4. Because of the complex manufacturing process required, capacitance-graded bushings are prone to a variety of problems during the manufacturing process, including insufficient insulation in the insulating paper and bubbles in the condenser core. Additionally, the volumes and weights of these bushings are also increasing along with the increasing operating voltage levels, which can easily cause problems during both transportation and installation. Many accidents have been caused by disconnection of the grounding wire from the last layer of the condenser core, which then leads to breakdown of condenser core. Disconnection of the grounding wire is likely to be caused by motion between the condenser core and the outer insulation during installation and transportation. Many problems are thus still caused by the fabrication process complexity and the increased bulk and weight of the bushing, which then affect its reliability.

5. When oil-impregnated paper bushings fail, they may explode, causing the scope of the initial accident to aggravate further. In addition, the use of bushings filled with SF₆ is environmentally unfavourable because SF₆ is a greenhouse gas [14].

3 | DC WALL BUSHING BASED ON ADAPTIVE FIELD GRADING MATERIALS

The problems discussed above hamper the use of capacitance-graded bushings at high voltage levels in DC power systems. In light of these problems, and based on the core factors of the problems, it is found that high voltage DC (HVDC) bushings are required to solve these problems while also meeting their power requirements simultaneously, and hence a DC wall bushing based on electric field-adaptive composite materials is proposed. Here, simulation models of a traditional capacitance-graded bushing and a new type of bushing based on a material with nonlinear conductivity at a DC voltage of 800 kV are established using COMSOL Multiphysics software. The electric field distributions in these bushings are analysed under various temperature fields and overvoltage conditions. The proposed new bushings using the new proposed material with
nonlinear conductivity avoids the use of greenhouse gases such as SF₆ and also uses polyethylene, which has higher electrical strength and reduces the bushing size significantly. Therefore, the proposed bushing offers the advantages in terms of both environmental friendliness and small size.

### 3.1 Structure

The simulation model used here is based on an 800 kV DC system. The capacitance-graded bushing is a resin-impregnated paper bushing. The structural diagram of the bushing is shown in Figure 2. The condenser core contains 60 layers of plates. These plates are arranged according to the principle of equal steps. The innermost plates are connected with conductive rods to act as high-voltage electrodes. The length of the plate is $L_n = 9300$ mm and the plate radius is $R_n = 65$ mm. The outermost plate is connected to the flange to act as a low-voltage electrode, and the length of this plate is $L_0 = 3400$ mm, while its radius $R_0 = 305$ mm.

The DC wall bushing based on the adaptive field grading material does not use the conventional condenser core structure; instead, it adopts a three-layer structural design between the conductive rod and the flange. This three-layer structure includes the field grading layer, the current limiting layer and the electrode extension layer in order from the interior to the exterior [15]. A schematic diagram of the proposed 800 kV DC nonlinear bushing is shown in Figure 3. The field grading layer uses a nonlinear composite material with a low nonlinear coefficient and a high switching field, while the electrode extension layer is a nonlinear composite material with a high nonlinear coefficient and a low switching field, and the current limiting layer is composed of the insulating material cross-linked polyethylene (XLPE). The field grading layer and the electrode extension layer use adaptive matching of the electrical parameters of the nonlinear composite material and the electric field to improve the electric field distribution intelligently. The designed electric field for the traditional capacitance-graded bushings is 4 MV/m, while the XLPE layer can operate for long periods under an electric field of 15 MV/m, and can withstand an electric field of 45 MV/m under transient overvoltage conditions. Moreover, to make best use of the insulation properties of XLPE, two sizes are used in the nonlinear bushing design. The first size has the same insulation thickness as that of the traditional capacitance-graded bushing, while the second size reduced main insulation layer thickness of the nonlinear bushing by 50% when compared with that of the conventional capacitance-graded bushing.

#### 3.1.1 Main insulation design

The main insulation of nonlinear bushing consists of field grading layer and leakage current limiting layer, as shown in Figure 3. To design the appropriate thickness ratio for the field grading layer and the current limiting layer in the main insulation structure of the nonlinear bushing, it is necessary to characterise the uniformity of the bushing’s electric field distribution in the radial direction first and then define the uneven distribution coefficient $\xi$ of the electric field, as shown in Equation (1).

$$\xi = \frac{\sum_{x=1}^{1000} |E_x - U/R|}{1000U/R}$$

where $U$ is the voltage applied to the bushing; $E_x$ is the electric field at each position; and $R$ is the main insulation thickness of the bushing.

In a bushing without the field grading structure in main insulation, the electric field distribution in the main insulation is very uneven in the radial direction, such as gas-filled bushing. Therefore, the use of field grading structure in the main insulation is essential. In capacitance-graded bushing, the structure of condenser is used, and in the adaptive bushing, the

---

**FIGURE 2** Structural diagram of capacitance-graded bushing

**FIGURE 3** Structural diagram of nonlinear bushing [16]
field grading layer in main insulation is used. When the main insulation of adaptive bushing consists of only field grading layer, the value of $\xi$ approaches 0 in the DC steady state and the electric field distribution will be most uniform. However, when the bushing’s main insulation structure is subjected to an overvoltage, the average electric field is greater than the switching field of the nonlinear material; this means that the leakage current in the nonlinear material increases and the insulation thus fails. Therefore, the field grading layer cannot be used as the main insulation alone and it must be used together with an insulating dielectric material, which can be used to limit the leakage current. However, a higher proportion of leakage current layer would lead a higher $\xi$. According to the uneven distribution coefficient of the traditional capacitive bushing, the upper limit for the inhomogeneity coefficient is set at 15% \[17\].

Under the condition that the inhomogeneity coefficient is ensured to be less than 15%, the proportion of the current limiting layer in the insulating material of the main insulation structure is then increased as much as possible to improve the bushing’s ability to withstand overvoltage. Simulation results show that the thickness ratio of the field grading layer to the current limiting layer is designed to be 1:1. At this ratio, the inhomogeneity coefficient in the bushing is guaranteed to be less than 15% under any actual temperature field, and the maximum electric field of the current limiting layer will also lie within the allowable range for the material under overvoltage conditions.

3.1.2 Electrode extension layer design

The distortion of the local electric field is most serious at the flange, and a nonlinear composite material with a low switching field and a high nonlinear coefficient is used to improve the electric field distribution at the flange. For DC wall bushings based on field grading materials, the structural and material parameters of the electrode extension layer should be designed according to the application of voltage level. The main structural parameter is the length of the electrode extension layer and the main material parameter is the switching field of the field grading material. The structural parameters and material parameters of this electrode extension layer interact with each other \[16\].

When the electrode extension layer length increases, the switching field of the nonlinear material decreases. Conversely, when the electrode extension layer length decreases, the switching field of the nonlinear material increases. Because of the limitations of the surface creepage distance and the field grading effect at the flange, the structural and material parameters of the electrode extension layer must be selected appropriately. An excessively long electrode extension layer will reduce the surface insulation distance, while an electrode extension layer is too short, it will cause the field grading effect at the flange to be negligible. Therefore, under the condition that the local maximum electric field must be less than the highest operating electric field of the insulating material, the electrode extension layer length is reduced as far as possible to ensure that the bushing length is minimised under a sufficient creepage distance condition.

4 MATERIALS

The field grading layer and the electrode extension layer are both made from nonlinear electrically conductive composite materials and the characteristics of these nonlinear electrically conductive composites also differ because it is necessary to implement different functions using these layers. Using the different mechanisms of their nonlinear characteristics, these nonlinear composite materials can be divided into two types. The first is a nonlinear composite composed of doped varistor powders, for example, ZnO varistor microspheres \[18\]. These nonlinear composites have lower switching fields and higher nonlinear coefficients, and their leakage currents are relatively high; they are suitable for use in locations where the local electric field distortion is severe, and they also provide a good field grading effect. The second is a semiconducting nanoparticle-doped nonlinear composite that uses dopants such as SiC and ZnO nanoparticles \[19\]; these nonlinear composites have higher switching fields, lower nonlinear coefficients and relatively low leakage currents, are suitable for use in locations where the electric field distortion is low, and can be used as the main insulation layer. The nonlinear electrically conductive composite material that is used in the field grading layer is also regarded as an insulating material because it functions as a main insulation layer. Therefore, the polymer must be doped using a specific number of nanoparticles to have a higher switching field, and its conductivity can vary within an order of magnitude within the operating electric field range. In the nonlinear conductive composite used in the electrode extension layer as the extension of the ground electrode flange, the conductivity varies over several orders of magnitude under the operating electric field. Therefore, it is necessary to dope this polymer layer with a specific number of ZnO varistor microspheres to ensure that the material has a lower switching field \[20–22\]. The electrical properties of ZnO varistor microspheres composites and semiconducting nanoparticle-doped nonlinear composites are much different; therefore, two kinds of nonlinear composites have different definition of switching field and nonlinearity coefficient. The electrical conductivity of the insulating dielectric materials is affected by both the temperature and the electric field, and the conductivity of the nonlinear materials is also affected by the temperature. The $\sigma(E, T)$ curve is fitted to the different materials used in the three layers of the nonlinear bushing \[23\].

The formula used for the fitting curve for the insulating material is as shown in Equation (2):

$$
\sigma(E, T) = \sigma_0 + \sigma_1 \cdot ge^{B_1 \cdot (T - 273.15)} \cdot E^2
$$

where $\sigma_0$ and $\sigma_1$ are the conductivity constants related to the insulating material, $B_1$ is the temperature constant, $E$ is the electric field and $T$ is the temperature.
The formula used for the low switching field nonlinear composite fitting curve is shown in Equation (3):

$$\sigma(E, T) = \sigma_2 \cdot e^{A_2 \cdot E + B_2 \cdot (T - 273.15)} \quad (3)$$

where $\sigma_2$ is the conductivity constant related to the low switching field nonlinear composites, $A_2$ is the electric field coefficient and $B_2$ is the temperature coefficient. The switching field $E_0$ and the nonlinear coefficient $\beta$ of low switching field nonlinear composites are defined by Equation (4) [20]:

$$\beta = \frac{\log (J_2/J_1)}{\log (E_2/E_b)} \quad (4)$$

where $J$ is the current density and $J_2 = 30 \mu A/cm^2$, $J_1 = 3 \mu A/cm^2$, $E_2$ and $E_b$ are electric fields of $J_2$ and $J_1$, respectively, which were determined from the $fE$ curve.

The formula used for the high switching field nonlinear composite fitting curve is shown in Equation (5):

$$\sigma(E, T) = \sigma_3 \cdot \left(\frac{E}{E_0}\right)^{\alpha} \cdot e^{B_3 \cdot (T - 273.15)} \quad (5)$$

where $\sigma_3$ is the conductivity constant related to the high switching field nonlinear composites, $B_3$ is the temperature coefficient, $E_0$ is the switching field of high switching field nonlinear composite and $\alpha$ is the non-linear coefficients [24].

### 4.1 Simulation model

As a result of the development of flexible HVDC transmission technology, inversion of the system voltage polarity can now be avoided [25]. Under DC steady-state conditions, a coaxial double-layer dielectric structure model is established. According to Maxwell's theory, the polarity and quantity of the charge at the interface are determined by the polarity of the applied voltage, the material conductivity and the dielectric constant. In the coaxial structure model, the electric field distributions of the two insulating dielectrics are inversely proportional to their radii, and the electric field increases as the radius decreases. Because the space charge that is formed at the interface between the two insulating dielectrics has a radial electric field of zero on the inner side of the interface, it has no effect on the radial electric field on the inner side of the interface. The electric field outside the interface is low and the effect of the space charge on the electric field is far lower than the effect of the material's own conductivity on the electric field distribution. The electric field simulation software available at present does not support simultaneous consideration of both the full current law and the space charge calculation method. (According to full current law, there are $n$ equations in $n$ finite element nodes. However, according to Poisson equation, the $n$ finite element nodes also have $n$ equations. Now there are $n$ unknowns with $2n$ equation, and the solution matrix would be a full rank matrix.) In addition, the space charge accumulation is affected by numerous factors and no theory is available to date that can calculate the space charge completely. Therefore, under DC steady-state conditions, the influence of the space charge under the conditions considered in the current simulation is small and hence its effects can be ignored in the simulations without affecting the results [26].

In the analysis proposed above, the model is established under the condition of coupling of the electric field and the temperature field [27].

**Electric field setting:** Under application of a DC electric field (when transients are not considered), the electric field distribution method uses a resistance sharing voltage and follows the current continuity law, which means that all simulation areas follow the relationship shown in Equation (6):

$$\nabla \cdot \vec{j} = 0, \quad \vec{j} = \sigma \cdot \vec{E} \quad (6)$$

where $\vec{j}$ is the current density, $E$ is the electric field and $\sigma$ is the electrical conductivity of the material.

In addition to reliable long-term operation under normal operating conditions, DC transmission systems must also withstand some specific conditions, such as lightning impulse voltages and switching impulse voltages, so the modelling method is used to analyse the behaviour of the structure under two overvoltage conditions. When an impulse voltage such as a lightning or switching impulse voltage occurs, the dielectric constants of each part of the insulating dielectric material share the voltage and the simulation region must then satisfy the relationship shown in Equation (7):

$$\nabla \cdot \vec{j} = 0, \quad \vec{j} = \sigma \cdot \vec{E} + \frac{\partial (\varepsilon \vec{E})}{\partial t} \quad (7)$$

When a lightning overvoltage is applied to the DC system, the standard lightning overvoltage model of 2.6/50 $\mu$s is used as the supply voltage in this case. The other case occurs when a switching impulse voltage is applied to the DC system; the input in this case uses the standard switching impulse voltage model of 250/2500 $\mu$s as the power supply voltage, while the standard lightning overvoltage and the switching impulse voltage are represented by the double exponential Equation (8):

$$V(t) = V_0 \left(e^{k_1 t} - e^{k_2 t}\right) \quad (8)$$

For the $\pm 800$ kV DC transmission system, the lightning overvoltage parameters are $V_0 = 2500$ kV, $k_1 = 0.015$ $\mu$s$^{-1}$ and $k_2 = 1.86$ $\mu$s$^{-1}$; the corresponding parameters for the operational overvoltage case are $V_0 = 1800$ kV, $k_1 = 317$ $\mu$s$^{-1}$ and $k_2 = 16,000$ $\mu$s$^{-1}$. When the voltage reaches its peak value, the results are used as the output.
According to the heat transfer equation shown in Equation (9), the temperature distribution in the dielectric under steady state is calculated.

\[
\rho c_p \nabla T = \nabla \cdot (k \nabla T) + Q
\]

where \( \rho \) (kg/m\(^3\)) is material density, \( c_p \) (J/(kg K)) is specific heat capacity, \( k \) (W/(m K)) is the coefficient of thermal conductivity, \( T \) is the temperature, \( \nabla \) is the direction vector and \( Q \) (J/m\(^3\)) is the heat generation.

The heat source for the bushing is mainly ohmic heating, which is produced by the central conductive rod, and the heat generated is determined using the load current of the conductive rod. When the load is increased, the heating also increases, and when the load is reduced, the heating is also reduced. During actual operation, the load current in the conductive rod varies in real time. Therefore, the temperature inside the bushing also shows real-time variations with great volatility [28, 29]. In order to reduce calculation, the heat generation is replaced by different temperature gradients. Therefore, four different temperature condition simulation models were established by the authors to satisfy the different working conditions. First, a simulation model was established without a temperature field. Three more models with different temperature fields were then established. When the temperature outside the bushing was fixed at 37°C, the inner conductive rod temperatures were fixed at 47, 57 and 67°C, respectively. This means that the values of the temperature difference \( \Delta T \) between the innermost conductor of the bushing and the outermost layer of the bushing in the cases above are 10°C, 20°C and 30°C, respectively [30]. Under the four temperature conditions described above, the electric field distribution in the capacitance-graded bushing and that in the nonlinear bushing based on the adaptive field grading materials were then compared.

5 | SIMULATION RESULTS AND ANALYSIS

5.1 | Electric field distribution under DC steady state conditions

According to Equations (2), (3) and (5), the conductivity of current limiting layer is \( \sigma (E, T) = 1 \times 10^{-16} + 1 \times 10^{-15} \times e^{0.06x(T - 273.15)} \times E^2 \) S/m, the conductivity of electrode extension layer is \( \sigma (E, T) = 1.6 \times 10^{-15} \times e^{0.000022 \times E + 0.055 \times (T - 273.15)} \) S/m and the conductivity of field grading layer is \( \sigma (E, T) = 1 \times 10^{-15} \times (E/ (3.75 \times 10^6))^2 \times e^{0.06x(T - 273.15)} \) S/m. The dielectric constants of the current limiting layer, the electrode extension layer and the field grading layer are 3.2, 5.5 and 4.3, respectively.

The radial electric field distributions of the capacitance-graded bushing and the nonlinear bushing under the operating voltages without consideration of the temperature field are as shown in Figure 4. For a single insulating dielectric with a cylindrical structure, the radial electric field distribution satisfies the relationship shown in Equation (10), and the electric field is inversely proportional to the structure's radius as shown here:

\[
E(r) = \frac{U}{r \ln \left( \frac{R_2}{R_1} \right)} \quad (R_1 \leq r \leq R_2)
\]

where \( R_1 \) is the inside radius and \( R_2 \) is the outside radius.

In the absence of a temperature field, the capacitance-graded bushing provides a good field grading effect that compensates completely for the effects of the cylindrical structure on the electric field distribution in the radial direction of the bushing. The radial electric field distribution becomes slightly higher than that in the middle on both sides; the electric field inhomogeneity coefficient in the radial direction of the capacitance-graded bushing is 14.2%. In the nonlinear bushing, a double-layer structure is used in the main insulation layer, the inner layer is the field grading layer, and the outer layer is the current limiting layer. Therefore, the results show that the electric field distribution changes significantly. In the field grading layer, the electric field distribution is highly uniform and in that it remains almost equal throughout the layer, and the material's electrical conductivity varies with changes in the electric field to compensate fully for the effects of the cylindrical structure on the electric field. Because of the effects of the cylindrical structure, the electric field distribution in the current limiting layer is characterised by a high internal field and a low external field. The electric field inhomogeneity coefficient in the radial direction of the nonlinear bushing containing the nonlinear conductivity material is 8.6%, which is smaller than that of the capacitance-graded bushing.

The radial electric field distributions of both the capacitance-graded bushing and the nonlinear bushing within the normal operating voltage range and under various temperature differences are shown in Figure 5. For the capacitance-graded bushing, in the model where the temperature is considered, the electric field distribution in the radial direction is reversed, and low inner and high outer fields are observed. This behaviour is attributed to the existence of the temperature field, which causes the conductivity of the insulating material in the condenser core to change, and the inner side's conductivity
is higher than the outer side’s conductivity. Simultaneously, because the condenser core compensates for the effects of the cylindrical structure on the electric field distribution, the effects of the temperature on the electric field distribution are manifested completely, which means that the electric field distribution is more uneven than in the model where the effect of the cylindrical structure on the electric field distribution is considered. For the nonlinear bushing, the main insulation structure is composed of two layers. In the field grading layer, the electric field distribution is uniform. In the current limiting layer, the electric field distribution is reversed because of the effects of the temperature, as compared with the results obtained without consideration of the temperature. Because of the effects of the cylindrical structure on the electric field distribution, the effect of the temperature on the electric field distribution is suppressed, which means that the inhomogeneity coefficient of the electric field in the current limiting layer is reduced. According to Equation (1), the inhomogeneity coefficient values of the radial electric field for the conventional capacitance-graded bushing are given in Table 1, while the inhomogeneity coefficient values of the radial electric field for the nonlinear bushing are given in Table 2.

Tables 1 and 2 show that as the temperature difference increases, the value of inhomogeneity coefficient of electric field in the radial direction of the capacitance-graded bushing also increases. This is mainly because of the increased temperature difference within the bushing, which leads to an increase in the conductivity difference in the main insulation structure and results in a more uneven electric field distribution. The presence of the condenser core compensates for the effects of the cylindrical structure on the electric field distribution, which means that the temperature effects on the electric field distribution are more obvious. In the nonlinear bushing, the main insulation component has a two-layer structure, which means that the electric field distribution in the radial direction shows a two-stage distribution. The results show that the electric field distribution in the field grading layer is uniform and the inner and outer electric fields are almost equal, but the effects of the temperature on the electric field distribution of the field grading layer can still be observed. Under lower temperature difference conditions, the inner electric field is slightly higher than the outer electric field; in contrast, under higher temperature difference conditions, the inner electric field is slightly lower than the outer electric field. In the current limiting layer, the electric field changes are observed very clearly. As the temperature difference increases, the outer electric field becomes significantly higher than the inner electric field. However, because of the effects of the cylindrical structure on the electric field distribution, the uneven electric field distribution that is caused by the temperature difference is partially suppressed. Therefore, the results show that the unevenness of the electric field distribution in the current limiting layer of nonlinear bushing is lower than the unevenness of the corresponding electric field distribution in the capacitance-graded bushing. In general, when the temperature factor is considered, the field grading effect of the nonlinear bushing in the radial direction is better than the field grading effect of the capacitance-graded bushing.

In addition to consideration of the uniformity of the electric field distribution within the bushing, the problem of the excessive local electric fields must also be considered. This paper therefore analyses the electric field distributions at critical positions in both the capacitance-graded bushing and the nonlinear bushing at a temperature difference of $\Delta T = 20^\circ$C. The electric field distribution at the end of the condenser core plate is illustrated in Figure 6. The electric field distribution at the flange in the nonlinear bushing is illustrated in Figure 7, while the electric field distribution at the end of the electrode extension layer in the nonlinear bushing is illustrated in Figure 8.

Figure 6 shows that the electric field concentration in the capacitance-graded bushing occurs at the end of the condenser core plate. Under the condition where $\Delta T = 20^\circ$C, the maximum electric field at the end of the condenser core plate is 9.29 MV/m; this is higher than the material’s designed working electric field which means that the material will be prone to partial discharges that can seriously affect the bushing’s long-term reliability. In the nonlinear bushing, as shown in Figure 7, the part of the structure that is in contact with the flange is the electrode extension layer, and the adaptive field grading composite materials used in this electrode extension layer have a relatively low switching field and a high nonlinear coefficient.

### Table 1 Values of $\xi$ under various temperature conditions for the conditional capacitance-graded bushing

| $\Delta T (^\circ$C) | 0   | 10  | 20  | 30  |
|----------------------|-----|-----|-----|-----|
| $\xi (%)$            | 14  | 11.0| 22.2| 37.9|

### Table 2 Values of $\xi$ under various temperature conditions for the nonlinear bushing

| $\Delta T (^\circ$C) | 0   | 10  | 20  | 30  |
|----------------------|-----|-----|-----|-----|
| $\xi (%)$            | 8.6 | 4.5 | 2.8 | 5.4 |
long-term operating electric field for XLPE of 15 MV/m. This design can thus ensure the long-term operational reliability of the bushing. Figure 8 shows that the electric field at the end of the electrode extension layer is slightly higher than the surrounding electric field and the maximum electric field is 3.24 MV/m, which is also much lower than the long-term operating electric field of the material. The maximum electric field distributions in the capacitance-graded bushing under various temperature difference conditions are given in Table 3. The corresponding maximum electric field distributions in the nonlinear bushing are given in Table 4.

Tables 3 and 4 show that in a capacitance-graded bushing, the electric field at the end of the condenser core plate increases gradually as the temperature difference increases. In the high-voltage capacitance-graded bushings, the temperature difference can be expanded further and the electric field at the end of the plate will also continue to increase. However, the local electric field will be too high, which will lead to partial discharges and will thus affect the bushing's long-term reliability. In the nonlinear bushings, even if the temperature difference changes, the electric field within the field grading layer can always be limited to the designed range because of the use of the adaptive field grading composite materials. This design can ensure that the field grading layer has a sufficiently large sharing voltage and that the maximum electric field can thus be limited to remain within the designed range. Changes in the temperature difference do have significant effects on the conductivity of the current limiting material. However, while the maximum electric field in the current limiting layer increases along with increases in the temperature difference, yet because the field grading layer ensures that the sharing voltage is sufficient, and the electric field then remains within the designed range, which is much smaller than the long-term operating electric field of the material.

5.2 | Electric field distribution under overvoltage conditions

In DC power systems, bushings must be safe and reliable during operation under normal conditions. If necessary, bushings must also withstand various overvoltages, including lightning overvoltages and switching overvoltages. Therefore, simulations were performed under both lightning overvoltage and switching overvoltage conditions to analyse the resulting electric field distributions in both the capacitance-graded bushing and the nonlinear bushing.

The electric field distributions in the radial direction for both the capacitance-graded bushing and the nonlinear bushing are shown under lightning overvoltage conditions in Figure 9 and under switching overvoltage conditions in Figure 10. The lightning overvoltage and the switching overvoltage are both transient voltages. During these transient processes, the electric field distribution in the bushing is largely determined by the dielectric properties of the main insulation layer. From the results in Figure 9, which were obtained under lightning overvoltage conditions, the electric field distribution
for the capacitance-graded bushing shows that the electric fields on both sides are slightly higher than the intermediate electric field because of the presence of the condenser core. The radial electric field inhomogeneity coefficient is 15.5% and the overall electric field distribution is fairly uniform. In the nonlinear bushing, however, the dielectric constants of the field grading layer and the current limiting layer material are different, so the electric field distribution in this case is shown to be segmented. In each layer, the dielectric constant has a constant value. The effect of the cylindrical structure leads to an electric field distribution phenomenon in each layer, where the inner electric field is high and the outer electric field is low in each case. The nonlinear bushing has a radial electric field inhomogeneity coefficient of 20.6%, which is slightly higher than that of the capacitance-graded bushing.

The peak switching overvoltage value is 1800 kV and the peak lightning overvoltage value is 2500 kV. Therefore, apart from the maximum electric field value, the radial electric field distribution obtained under the switching overvoltage is similar to that obtained under the lightning overvoltage. From the results in Figure 10, the electric field distribution inhomogeneity coefficient for the capacitance-graded bushing is 17.3%. The corresponding electric field distribution inhomogeneity coefficient for the nonlinear bushing is 22.3%, which is slightly higher than that of the capacitance-graded bushing.

In general, under a transient overvoltage impulse, the radial electric field distribution of the nonlinear bushing is distributed more unevenly than that of the capacitance-graded bushing, and the maximum electric field in the nonlinear bushing is also slightly higher than the maximum electric field in the capacitance-graded bushing. However, as the main insulating material of the nonlinear bushing is XLPE, its dielectric strength is much higher than that of the main insulation layer of the capacitance-graded bushing, and the electric field under the overvoltage conditions is entirely within its tolerable range. This means that the nonlinear bushing meets the operating condition requirements under impulse transient conditions.

### 5.3 Electric field distribution of small-sized nonlinear bushing

The analysis above indicates that when capacitance-graded bushings and nonlinear bushings with the same main insulation thickness are considered, the nonlinear bushing shows a better field grading effect on the electric field in the radial direction under normal operating conditions. In addition, when the effects of temperature difference changes are considered, the nonlinear bushing based on the adaptive field grading composite materials can provide better suppression of the
FIGURE 11 Electric field distributions of small-sized nonlinear bushing

TABLE 5 Values of $\xi$ under various temperature conditions for the small-sized nonlinear bushing

| $\Delta T$ (°C) |  10  |  20  |  30  |
|---------------|------|------|------|
| $\xi$ (%)     |  4.5 |  2.9 |  5.3 |

Temperature effects that cannot be matched by the conventional capacitance-graded bushing. Because the main insulation material in the nonlinear bushing is XLPE, its operating electric field is 15 MV/m, which is much higher than the designed electric field of traditional capacitance-graded bushings. Therefore, to make full use of XLPE’s insulating properties, it was proposed that the nonlinear bushing insulation thickness should be halved in this work. The internal electric field was then analysed using simulations to determine whether the bushing’s operational requirements could be meted out. The electric field distributions in the radial direction for the small-sized nonlinear bushing at various temperature differences are shown in Figure 11.

The results in Figure 11 show that changes in the temperature difference have insignificant effect on the electric field distribution of the small-sized nonlinear bushing composed of the composite with nonlinear conductivity. The changes in the temperature difference do cause changes in the material conductance, but the conductance is more sensitive to changes in the electric field. These results show that the electric field distribution in the field grading layer remains highly uniform under any temperature difference condition. However, the temperature difference changes affect the electric field distribution in the current limiting layer. The results show that when the temperature difference increases, the unevenness of the electric field distribution in the current limiting layer also increases. Because the field grading layer shares a sufficient voltage, the maximum electric field in the current limiting layer is always limited to remain within a specified range and a sufficient electric field margin is thus reserved for the XLPE. The uneven electric field distribution results for the small-sized nonlinear bushing obtained under the various temperature differences are shown in Table 5. The corresponding simulation results for the small-sized nonlinear bushing are shown in Table 6.

Comparison of Table 1 with Table 5 shows that under various temperature differences, the unevenness of the electric field distribution in the radial direction for the small-sized nonlinear bushing is less severe than that for the conventional capacitance-graded bushing. In addition, the maximum electric field in the small-sized nonlinear bushing is lower than the long-term operating electric field of XLPE of 15 MV/m.

The electric field distribution inside the small-sized nonlinear bushing has also been studied in the overvoltage case. The radial electric field distributions obtained under lightning overvoltage conditions and switching overvoltage conditions are shown in Figure 12.

Figure 12 shows that the electric field distributions of the nonlinear bushing under the lightning overvoltage conditions and the switching overvoltage conditions are similar. In the instantaneous impulse voltage case, the electric field distribution is mainly determined by the dielectric constant of the insulating material. In the small-sized nonlinear bushing, the dielectric constants of the field grading layer and the current limiting layer material are different, so the electric field distributions are shown to be segmented. In each layer, the dielectric constant has a constant value, and because of the effect of the cylindrical structure, the inner electric field is high while the outer electric field is low. While the instantaneous maximum

| $\Delta T$ (°C) | 10 | 20 | 30 |
|----------------|----|----|----|
| Maximum electric field (MV•m$^{-1}$) | 8.67 | 8.69 | 9.60 |
| Position      | Field grading layer | Field grading layer | Current limiting layer |
electric field reaches as high as 30 MV/m under the over-voltage conditions, this electric field is still within the insulation level conditions for XLPE, which can withstand an instantaneous electric field of 45 MV/m.

A comprehensive analysis of the internal electric field distribution of the small-sized nonlinear bushing under the various temperature difference and over-voltage conditions shows that while the nonlinear bushing insulation is reduced in size by half, it still meets the insulation requirements and can be used as a bushing at a DC voltage of 800 kV.

6 CONCLUSION

Future power systems equipment will be developed to enable miniaturization, environmental friendliness and intelligent operation. In AC low-voltage power systems, the traditional capacitance-graded bushing has a good insulation effect, but with increasing system voltages and the development of DC transmission systems, conventional capacitance-graded bushings will not be able to meet the needs of contemporary power systems. The three-layer structure of the nonlinear bushing proposed here, which is based on the use of nonlinear electrically conductive composite materials, can meet the requirements of these power systems.

The three-layer structure replaces the original condenser core structure and thus greatly simplifies the bushing production process. In addition, there is no limit to the designed electric field for the insulating material, as there would be in the condenser core; XLPE and its composites are used as the main insulation materials. The designed electric field of the bushing can be improved significantly, thus allowing the bushing size to be reduced, which will then have a positive impact on heat dissipation, production and transportation. At the same time, use of greenhouse gases such as SF₆ is avoided and the proposed bushing is thus more environmentally friendly.

The use of nonlinear electrically conductive composite materials, use of the characteristics of the material performance parameters and use of electric field adaptive matching can produce a very good field grading effect. In particular, under the condition where the temperature difference changes in real time, the electric field inside the bushing can always be maintained with a uniform distribution, which helps to prevent both flashover at the flange and partial discharge from the main insulating material.

In addition to consideration of the electric field distribution effects under the various working conditions, it is also essential to evaluate whether the thermal, mechanical and other material properties will meet the actual device requirements. Here, XLPE alone is used as the matrix material for the calculations in the electric field distribution simulations, and the other properties will require further evaluation. In addition to XLPE, epoxy, polypropylene, ethylene propylene rubber and other organic insulating materials that are commonly used in a variety of power systems can also be used as the matrix for the nonlinear composite materials and may possibly provide a more comprehensive performance.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China under Grant No. U1766221, the National Key R & D Programme of China under Grant No. 2018YFE0200100 and the Research Project of State Grid Corporation of China under Grant No. SGTYHT/17-JS-199.

ORCID
Xiaolei Zhao https://orcid.org/0000-0003-1263-3326

REFERENCES

1. Monga, S., et al.: Design optimization of high voltage bushing using electric field computations. IEEE Trans. Dielectr. Electr. Insul. 13(6), 1217-1224 (2006)
2. Li, C.Y., et al.: Charge cluster triggers unpredictable insulation surface flashover in pressurized SF₆. J. Phys. D. Appl. Phys. 54(1), 015308 (2020)
3. Zhang, S., Peng, Z., Liu, P.: Inner insulation structure optimization of UHV RIP oil-SF₆ bushing using electro-thermal simulation and advanced equal margin design method. IEEE Trans. Dielectr. Electr. Insul. 21(4), 1768-1777 (2014)
4. Wang, Q., et al.: A novel dissipating heat structure of transformer RIP bushings based on 3-D electromagnetic-fluid-thermal analysis. IEEE Trans. Dielectr. Electr. Insul. 24(3), 1938-1946 (2017)
5. Haque, N., et al.: Studies on the effects of moisture and ageing on charge de-trapping properties of oil-impregnated pressboard based on IRC measurement. High. Volt. 4(2), 151-157 (2019)
6. Nikjoo, R., et al.: Dielectric response of oil-impregnated paper by utilising lightning and switching transients. IEEE Trans. Dielectr. Electr. Insul. 22(1), 335-344 (2015)
7. Nikjoo, R., Taylor, N., Edin, H.: Dielectric response measurement by impulse stimulus on AC: measurement considerations, and laboratory testing on a bushing. IEEE Trans. Dielectr. Electr. Insul. 24(1), 511-518 (2017)
8. Li, S., Li, J.: Condition monitoring and diagnosis of power equipment: review and prospective. High. Volt. 2(2), 82-91 (2017)
9. Mc Dermid, W., Black, T.: External flashovers, related insulation failures and corrective measures in converter stations of Nelson River bipole 1 and bipole 2. IEEE Trans. Dielectr. Electr. Insul. 21(6), 2406-2414 (2014)
10. Lang, F., Zhang, H.: Fault analysis and structure optimization of 40.5kV wall bushing In: 2015 5th International Conference on Electrical Utility Deregulation Restructure Power Technology, 1628-1631. IEEE, Changsha, China (2015)
11. Luo, X., et al.: Fault diagnosis and insulation structure improvement on 550 kV resin-impregnated paper oil-SF₆ bushings. In: 2017 IEEE 7th International Conference on Power Energy System, 1-6. IEEE, Toronto, Canada (2017)
12. Liu, Z., et al.: Research on key technologies in ±1100 kV ultra-high voltage DC transmission. High. Volt. 3(4), 279-288 (2018)
13. Xie, H.: Electrical Insulation Design Principles. Mechanical Industry Press Beijing, China (1992)
14. Ravi shankara, A.R., et al.: Atmospheric lifetimes of long-lived halogenated species. Science. 259(5092), 194-199. American Association for the Advancement of Science, Budapest, Hungary (1993)
15. Zhao, X.L., et al.: Design and electric field calculation of a wall bushing made from nonlinear materials. In: 21st International symposium on high voltage engineering, pp. 52-60. Springer, Cham (2019)
16. Zhao, X.L., et al.: Electrode extension layer design of DC wall bushing based on field grading material. In: IEEE International conference on high voltage. IEEE, Beijing, China (2020)
17. Huang, Z.W., et al.: Main insulation optimization of DC wall bushing based on field grading material. IEEE international conference on high voltage. (2020)
18. Clarke, D.R.: Varistor ceramics. J. Am. Ceram. Soc. 82(3), 485-502 (1999)
19. Wang, X., et al.: Mechanisms leading to nonlinear electrical response of a nano p-SiC/silicone rubber composite. IEEE Trans. Dielectr. Electr. Insul. 17(6), 1687-1696 (2010)

20. Yang, X., He, J., Hu, J.: Tailoring the nonlinear conducting behaviour of silicone composites by ZnO microvaristor fillers. J. Appl. Polym. Sci. 132(40), 1-6 (2015)

21. Gao, L., et al.: ZnO microvaristors doped polymer composites with electrical field dependent nonlinear conductive and dielectric characteristics. Mater. Lett. 171, 1-4 (2016)

22. Zhao, X., et al.: Tuning the potential distribution of AC cable terminals by stress cone of nonlinear conductivity material. IEEE Trans. Dielectr. Electr. Insul. 24(5), 2686-2693 (2017)

23. Zhao, X., et al.: Synergistic effect of ZnO microspherical varistors and carbon fibres on nonlinear conductivity and mechanical properties of the silicone rubber-based material. Compos. Sci. Technol. 150:187-193 (2017)

24. Christen, T., Donzel, L., Greuter, F: Nonlinear resistive electric field grading part 1: theory and simulation. IEEE Electr. Insul. Mag. 26(6), 47-59 (2010)

25. Flourentzou, N., Agelidis, V.G., Demetriades, G.D.: VSC-based HVDC power transmission systems: an overview. IEEE Trans. Power Electron. 24(3), 592-602 (2008)

26. Zhao, X., et al.: Simulation and design of 500 kV DC cable terminal accessory based on ZnO varistor microsphere composites. IEEE Trans. Dielectr. Electr. Insul. 27(1), 10-16 (2020)

27. Zhang, S.: Evaluation of thermal transient and overload capability of high-voltage bushings with ATP. IEEE Trans. Power Deliv. 24(3), 1295-1301 (2009)

28. Reddy, C.C., Rama, T.S.: On the computation of electric field and temperature distribution in HVDC cable insulation. IEEE Trans. Dielectr. Electr. Insul. 13(6), 1236-1244 (2006)

29. Wei, D., et al.: Electro-quasistatic high voltage field simulation of large scale 3D insulator structures including 2D models for conductive pollution layers. Stud. Appl. Electromagn. Mech. 30(3), 431-437 (2008)

30. Wang, Q.Y., et al.: 3-D coupled electromagnetic-fluid-thermal analysis of epoxy impregnated paper converter transformer bushings. IEEE Trans. Dielectr. Electr. Insul. 24(1), 1768-1777 (2017)

How to cite this article: Zhao X, Hu J, Yuan Z, He J. Design of adaptive bushing based on field grading materials. High Voltage. 2021;1–12. https://doi.org/10.1049/hve2.12090