

Simulation Study on Transient Processes of Space Charge Polarization and Depolarization in Non-linear Dielectrics with Coaxial Electrode Structures (Postprint)

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Abstract

Nonlinear dielectrics are defined as dielectric materials whose conductivity and/or permittivity vary with electric field strength. In non-uniform electric fields, nonlinear dielectrics undergo space charge polarization due to the spatial gradient variation of dielectric parameters, and the space charges formed by polarization subsequently influence the electric field distribution. Investigating this dynamic process of space charge polarization facilitates the design and fault analysis of high-voltage DC insulation structures. To this end, the polarization and depolarization processes under step voltage were simulated and studied for nonlinear dielectrics exhibiting field-enhanced and temperature-enhanced conductivity in a coaxial electrode configuration, utilizing the transient solver in COMSOL Multiphysics finite element software. The research findings demonstrate that: during the polarization establishment process, the space charge density near the inner electrode exhibits a temporal “overshoot” phenomenon; during the depolarization process, space charges near the inner electrode exhibit a “reverse-polarity overshoot” phenomenon; the “overshoot” and “reverse-polarity overshoot” phenomena are interrelated, both originating from the spatiotemporal distribution of dynamic relaxation time; temperature gradient and electric field strength exert different influence patterns on the space charge “overshoot” behavior.

Full Text

2 Space Charge in Nonlinear Dielectric under Coaxial Electrode Structure

With the development of flexible power transmission technology, polymer-extruded insulated high-voltage DC cables have broad application prospects

[1-6]. As is well known, the DC steady-state electric field distribution depends on the conductivity of the insulating material. Therefore, under temperature gradient conditions where the inner side is hotter than the outer side, the nonlinear conductivity characteristics of polymer insulating materials in HVDC cables can cause an “electric field distribution reversal” phenomenon, where the electric field strength at the cable conductor surface becomes lower than that at the outer insulation surface [7-8]. Since the maximum electric field is the primary basis for insulation structural design, the engineering community typically focuses only on electric field distribution issues. However, the essence of “electric field distribution reversal” is the space charge formed by slow polarization under DC electric field.

For a long time, research on the generation, accumulation, and dissipation mechanisms of space charge, as well as space charge measurement and suppression, has been a hot topic in the field of electrical insulation [9-12]. Space charge in insulating media often originates from thermal ionization of impurities, polarization of polar molecules, charge injection from electrodes, traps, and the influence of interfaces due to non-uniform distribution of permittivity or conductivity [13-14]. Space charge can be divided into two categories: one is space charge generated in high electric fields that depends on microscopic material properties (such as traps); the other is space charge caused by slow polarization due to spatial variation of macroscopic dielectric parameters. The former has been extensively studied [15-20], but it is the latter type of space charge that causes electric field distribution reversal in HVDC cables under high temperature gradients. This phenomenon is related to the nonlinear conductivity properties of insulating materials, structural parameters, temperature gradients, and applied voltage, and occurs at any electric field level. Since space charge measurement techniques cannot distinguish between these two types, the latter is generally considered relatively small in magnitude [21-22] and is often overlooked by researchers, with few related studies reported to date.

Following the insulation structure of HVDC cables, this paper establishes a two-dimensional axisymmetric coaxial electrode structure model. Based on COMSOL finite element analysis software, the spatial and temporal distribution of the electric field in the insulating medium is solved numerically, and then the variation 规律 of space charge spatial and temporal distribution during polarization and depolarization processes is obtained. The research results contribute to understanding the space charge polarization characteristics of nonlinear insulating media in complex insulation structures.

2.1 Simulation Model

Referring to the typical structure of a 320 kV, 500 MW DC cable [23], a simplified two-dimensional axisymmetric coaxial electrode structure model was established as shown in [Figure 1: see original paper]. The inner electrode radius is 26 mm, the nonlinear insulating medium thickness is 24 mm, and the outer electrode radius is 52 mm.

2.2 Material Properties, Boundary Conditions, and Loading Method

2.2.1 Material Properties The material properties of each component used in model solving are shown in .

** Material properties in the model**

Component	Conductivity γ /(S · m ⁻¹)	Relative Permittivity
Inner/Outer Electrode (Copper)	5.998×10	-
Nonlinear Dielectric	(E, T)	2.3

The conductivity expression $\gamma(E, T)$ in is given by reference [24] as:

$$\gamma(E, T) = A \exp\left(-\frac{\phi_e}{k_b T}\right) \sinh(B|E|)$$

where γ is conductivity (S · m⁻¹), A is a material constant (V · (Ω · m²)⁻¹), ϕ_e is activation energy (eV), q is elementary charge, k_b is Boltzmann constant (J · K⁻¹), T is absolute temperature (K), B is the electric field dependence coefficient of conductivity (m · V⁻¹), and E is electric field strength (V · m⁻¹). Based on measured conductivity data fitted according to equation (6), the parameters are A = 3.59×10⁻¹ V · (Ω · m²)⁻¹, ϕ_e = 0.96 eV, and B = 1.14×10⁻¹ m · V⁻¹.

2.2.2 Temperature Field Determination The temperature boundary conditions set in the model are shown in .

** Boundary conditions of temperature**

Boundary	Temperature/K
Inner electrode boundary T _{in}	T _{out} + ΔT
Outer electrode boundary T _{out}	-

Different temperature gradient distributions in the medium are achieved by changing ΔT in . The temperature at radius r in the medium is:

$$T(r) = T_{in} - \frac{\ln r - \ln R_{in}}{\ln R_{out} - \ln R_{in}}$$

where R_{in} and R_{out} are the inner and outer electrode radii, respectively, and r is the radius at any point in the medium.

2.2.3 Electric Field Boundary Conditions The outer electrode is grounded, and the inner electrode is excited by the voltage determined by equation (3):

$$U(t) = \begin{cases} 0 \text{ s} \leq t < 50,000 \text{ s} & \text{Polarization} \\ 50,000 \text{ s} \leq t < 150,000 \text{ s} & \text{Depolarization} \end{cases}$$

2.4 Numerical Solution Results

The COMSOL Multiphysics finite element software's transient solver was used to solve the model, which essentially involves numerical solution of Poisson's equation. During the numerical solution process, the spatial mesh element size and time step are critical factors affecting solution accuracy. For triangular meshing of the computational domain, the maximum element size was set to 0.2 mm. To ensure that both polarization and depolarization processes reach steady state, the total calculation time was 150,000 s, with the first 50,000 s for polarization and the subsequent 100,000 s for depolarization.

To ensure calculation accuracy while reducing computation time, time steps were set in segments as shown in .

** Simulation time step**

Time Period /s	Step Size /s
0-1 (50,000-50,001)	1×10^{-4}
1-10 (50,001-50,010)	1×10^{-3}
10-100 (50,010-50,100)	1×10^{-2}
100-1,000 (50,100-51,000)	0.1
1,000-10,000 (51,000-60,000)	1
10,000-50,000 (60,000-150,000)	10

COMSOL Multiphysics can directly provide spatial and temporal distributions of electric potential ϕ , electric field intensity E , electric displacement D , and charge density ρ . However, the directly extracted space charge density ρ contains model errors (determined by mesh refinement) that are inconsistent with physical reality at electrode boundaries. Therefore, this study calculates the electric displacement D near electrodes (where model errors occur) from the overall spatial and temporal distribution of D , and then further calculates the space charge density ρ distribution using:

$$\rho_i = \frac{D_{i+1}r_{i+1} - D_i r_i}{r_{i+1}^2 - r_i^2}$$

where D_i and D_{i+1} are the electric displacements at radii r_i and r_{i+1} , respectively.

3 Space Charge Polarization Establishment Process

To study the effect of voltage amplitude on space charge polarization in nonlinear dielectrics, U was set to positive polarity values of 100 kV, 200 kV, 300 kV, 400 kV, and 500 kV.

3.1 Temperature Gradient Effect on Space Charge Polarization Process

To investigate the influence of temperature gradient on space charge during polarization establishment, a positive step voltage with amplitude $U = 300$ kV was applied to the inner electrode. Numerical simulations were conducted under temperature gradients of $\Delta T = 0$ K, 10 K, 20 K, 30 K, 40 K, and 50 K. The resulting spatial and temporal distribution cloud maps of electric field intensity are shown in [Figure 2: see original paper].

From [Figure 2: see original paper], it can be observed that as the temperature gradient increases, the steady-state electric field distribution gradually reverses. Since the boundary conditions remain unchanged, the essence of electric field reversal within the dielectric must be space charge accumulation.

By calculating the space charge density distribution corresponding to the electric field distributions under various temperature gradients in [Figure 2: see original paper], the spatial and temporal distribution cloud maps are obtained as shown in [Figure 3: see original paper].

[Figure 3: see original paper] reveals that under positive step voltage, the accumulated space charge in the dielectric during polarization is all positive polarity. For the inner electrode (anode), this is homocharge that weakens the electric field near the inner electrode; for the outer electrode (cathode), it is heterocharge that enhances the electric field near the outer electrode, causing the electric field to gradually reverse as shown in [Figure 2: see original paper]. Under the studied voltage amplitudes, the steady-state radial space charge density distribution gradually transitions from higher-near-inner-electrode to higher-near-outer-electrode as the temperature gradient increases. Under similar temperature and field conditions, the space charge density values are on the same order of magnitude as measured values reported in references [13], [22], [25], and [26].

The steady-state average space charge density in the dielectric reflects the total accumulated space charge at steady state. The relationship between steady-state average space charge density and temperature gradient is shown in [Figure 4: see original paper]. It indicates that at a given voltage, the average space charge density increases with temperature gradient.

In [Figure 3: see original paper], when $\Delta T = 0$ K, the radial charge density increases monotonically with time. However, when a temperature gradient exists, the charge density near the inner electrode exhibits an “overshoot” phenomenon—non-monotonic behavior where space charge density first increases,

then decreases, and finally stabilizes.

To more clearly demonstrate the dynamic process of space charge density “overshoot” during polarization under different temperature gradients, space charge density was extracted at positions $r = 26$ mm (inner electrode), $r = 38$ mm, and $r = 50$ mm (outer electrode) in the dielectric. The resulting curves of space charge density versus polarization time are shown in [Figure 5: see original paper].

[Figure 5: see original paper] shows that the space charge polarization “overshoot” phenomenon is not obvious when $\Delta T = 0$ K. As the temperature gradient increases, the “overshoot” becomes more pronounced, the time to reach steady state at any position shortens, and the transient space charge peak near the inner electrode increases. At the middle of the dielectric, the transient overshoot gradually disappears, while no overshoot occurs near the outer electrode during polarization, though the steady-state charge density increases monotonically.

Space charge polarization results from the spatial gradient distribution of dielectric conductivity. The time variation of charge density at different positions is governed by equation (5) [27]:

$$\frac{\partial \rho(t, r)}{\partial t} + \frac{\rho(t, r)}{\tau(t, r)} = \nabla \cdot \mathbf{J}$$

where $\tau(t, r)$ is the dynamic relaxation (response) time of charge carriers in the dielectric, expressed as:

$$\tau(t, r) = \frac{\varepsilon}{\gamma(t, r)}$$

where ε is permittivity (independent of temperature and electric field) and $\gamma(t, r)$ is the spatial and temporal distribution of dielectric conductivity.

The dynamic behavior of space charge largely depends on the spatial and temporal distribution of relaxation time. The calculated spatial and temporal distribution of relaxation time $\tau(t, r)$ under different temperature gradients is shown in [Figure 6: see original paper].

[Figure 6: see original paper] reveals that the dynamic relaxation time of the dielectric shows a lower-near-inner-electrode and higher-near-outer-electrode distribution at any moment. At the initial voltage application, the spatial gradient of dynamic relaxation time is higher than that at steady state. When positive voltage is applied to the inner electrode, positively charged carriers migrate from the inner to outer electrode. Since the relaxation time at position r near the inner conductor is smaller than at $r + \Delta r$, the charge migration rate at r is greater than at $r + \Delta r$, resulting in accumulation of positive space charge. Simultaneously, this positive charge accumulation reduces the electric field at

r, causing conductivity to decrease and carrier migration rate to slow down—a negative feedback process that ultimately reaches steady state.

[Figure 6: see original paper] also shows that as the temperature gradient increases, the spatial and temporal gradient of dynamic relaxation time increases. This causes excessive charge accumulation rate near the inner electrode at the initial voltage application, leading to the “overshoot” phenomenon during space charge polarization near the inner electrode. Larger temperature gradients produce more pronounced “overshoot.” Since dielectric relaxation time increases gradually from inner to outer regions, the corresponding charge accumulation rate decreases gradually, producing the pattern shown in [Figure 5: see original paper].

To characterize the “overshoot” behavior during space charge polarization, the transient maximum charge density and steady-state charge density distributions during polarization were extracted for the case of $\Delta T = 30$ K and $U = 300$ kV, as shown in [Figure 7: see original paper].

Due to model errors in simulation results, the exact coincidence point of the two curves in [Figure 7: see original paper] is difficult to determine. Therefore, the critical point is defined where the difference between transient maximum and steady-state values is less than 3% of the steady-state value. This point is marked as point A (the determination standard for point A does not affect subsequent analysis). The region between point A and the inner electrode is defined as the “overshoot” region. The maximum “overshoot” degree k is defined as the ratio of the difference between the transient maximum and steady-state values at the inner electrode edge to the steady-state value.

Based on this definition, the degree and region of space charge “overshoot” during polarization under different temperature gradients at a fixed voltage amplitude are shown in [Figure 8: see original paper]. It demonstrates that at a given voltage amplitude, increasing temperature gradient enlarges both the degree and region of space charge “overshoot.”

3.2 Voltage Amplitude Effect on Space Charge Polarization Process

To study the effect of voltage amplitude on space charge polarization, the polarization process under positive step voltages of 100 kV, 200 kV, 300 kV, 400 kV, and 500 kV was simulated at a fixed temperature gradient of $\Delta T = 50$ K. The resulting typical spatial and temporal distribution cloud maps of electric field during polarization are shown in [Figure 9: see original paper].

Combined with [Figure 9: see original paper] and previous [Figure 2: see original paper] ($\Delta T = 50$ K, $U = 300$ kV), it can be observed that larger voltage amplitudes accelerate the electric field reversal process.

Similarly, the corresponding spatial and temporal distribution cloud maps of space charge density under different voltage amplitudes were calculated, as shown in [Figure 10: see original paper].

The relationship between steady-state average space charge density and polarization voltage is shown in [Figure 11: see original paper]. It indicates that the total space charge in the dielectric increases with polarization voltage, but the rate of increase decreases with higher polarization voltage.

To more clearly compare the dynamic space charge polarization processes under different voltage amplitudes, the space charge density versus polarization time curves at radii $r = 26$ mm (inner electrode), $r = 38$ mm, and $r = 50$ mm (outer electrode) are shown in [Figure 12: see original paper].

[Figure 12: see original paper] shows that as voltage amplitude increases, the time for space charge at any position to reach steady state shortens, the transient space charge peak near the inner electrode increases, the transient overshoot phenomenon gradually disappears in the middle of the dielectric, and no overshoot occurs near the outer electrode, though the steady-state charge density increases with polarization voltage.

The influence of voltage amplitude on the degree and region of space charge “overshoot” during polarization at a fixed temperature gradient is shown in [Figure 13: see original paper].

[Figure 13: see original paper]b shows that when $\Delta T = 0$ K, obvious “overshoot” only appears at voltages ≥ 300 kV, with both degree and region increasing with voltage amplitude. When $\Delta T \geq 10$ K, increasing voltage amplitude reduces the degree and region of “overshoot.” Thus, voltage amplitude has opposite effects on polarization “overshoot” compared to temperature gradient. From the conductivity formula (1), higher temperature gradient increases the spatial gradient of conductivity distribution, while increased voltage amplitude makes the field-enhanced nonlinear insulating medium in the coaxial structure tend toward more uniform electric field distribution [8], thereby reducing the spatial distribution gradient of conductivity.

4 Space Charge Depolarization Dissipation Process

4.1 Temperature Gradient Effect on Space Charge Depolarization Process

To study the effect of temperature gradient on space charge during depolarization, the depolarization process was simulated under polarization voltage $U = 300$ kV with temperature gradients of $\Delta T = 0$ K, 10 K, 20 K, 30 K, 40 K, and 50 K. The resulting spatial and temporal distribution of electric field during depolarization is shown in [Figure 14: see original paper].

[Figure 14: see original paper] shows that during depolarization, the electric field near the inner electrode is opposite to that during polarization, while near the outer electrode it is in the same direction. A zero-field point exists in the middle region, whose position changes during depolarization and eventually becomes zero everywhere at steady state.

The corresponding spatial and temporal distribution of space charge density during depolarization under different temperature gradients was calculated, as shown in [Figure 15: see original paper].

[Figure 15: see original paper] indicates that when $\Delta T = 0$ K, space charge density in the dielectric decreases monotonically with time, consistent with the absence of “overshoot” during polarization at this temperature gradient. When $\Delta T = 10$ K, as temperature gradient increases, “opposite-polarity overshoot” appears near the inner electrode—space charge does not decrease monotonically to zero but shows a peak of opposite polarity before decaying to zero. The “opposite-polarity overshoot” during depolarization echoes the “overshoot” during polarization, both determined by the spatial and temporal distribution of dynamic relaxation time. The “opposite-polarity overshoot” occurs because a reverse electric field appears near the inner electrode during depolarization.

To characterize the degree of “opposite-polarity overshoot” during depolarization, the initial charge density and transient maximum charge density distributions were extracted, as shown in [Figure 16: see original paper].

In [Figure 16: see original paper], point A is the critical point where “opposite-polarity overshoot” appears. The region between point A and the inner electrode is defined as the “opposite-polarity overshoot” region. The maximum “opposite-polarity overshoot” degree k is defined as the ratio of the absolute value of the negative charge density peak at the inner electrode edge to the initial value at that position. The influence of temperature gradient on the degree and region of space charge “opposite-polarity overshoot” during depolarization at fixed voltage amplitude is shown in [Figure 17: see original paper].

[Figure 17: see original paper] demonstrates that during depolarization, temperature gradient affects the degree and region of space charge “opposite-polarity overshoot” in the same way as during polarization—both increase with temperature gradient.

4.2 Polarization Voltage Amplitude Effect on Space Charge Depolarization Process

At a fixed temperature gradient of $\Delta T = 50$ K, typical electric field distribution cloud maps and corresponding space charge density distribution cloud maps during depolarization were simulated for polarization voltage amplitudes of 100 kV and 500 kV, as shown in [Figure 18: see original paper] and [Figure 19: see original paper].

[Figure 18: see original paper] and [Figure 19: see original paper] show that increasing polarization voltage increases the initial depolarization charge density and the electric field during depolarization.

The influence of polarization voltage amplitude on space charge “opposite-polarity overshoot” during depolarization is shown in [Figure 20: see original paper].

[Figure 20: see original paper]a indicates that during space charge depolarization, the degree of “opposite-polarity overshoot” decreases with increasing polarization voltage amplitude, consistent with the polarization process pattern. However, changes in polarization voltage amplitude have basically no effect on the “overshoot” region, which differs from the polarization process.

5 Conclusions

When temperature gradient exists in coaxial structure nonlinear dielectrics, space charge polarization caused by conductivity gradient occurs under applied electric field. This paper investigated the effects of temperature gradient and polarization voltage amplitude on this space charge polarization and depolarization behavior, reaching the following conclusions:

1. At fixed polarization voltage, as temperature gradient increases, the steady-state space charge density distribution transitions from higher-near-inner-electrode to higher-near-outer-electrode. Larger temperature gradients result in greater average space charge density in the dielectric and shorter time to reach polarization steady state.
2. During space charge polarization, “overshoot” appears near the inner electrode; during depolarization, “opposite-polarity overshoot” appears. These two phenomena echo each other, both originating from the spatial and temporal gradient distribution of dynamic relaxation time.
3. Temperature gradient and electric field have opposite effects on space charge “overshoot” and “opposite-polarity overshoot” behavior.

Note: Figure translations are in progress. See original paper for figures.

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