Analysis of High-Energy Electron Distribution and Insulation Aging Effect of Air Ionization in Ultra-High Voltage AC / DC Lines

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Abstract: Focusing on the high-energy electrons generated by air ionization in ultra-high voltage AC and DC transmission lines, the coupling of space charge and aging in typical insulation systems such as cross-linked polyethylene (XLPE) and oil-paper is analyzed. The mutual constraints of space charge capture-release kinetics, trap energy level structure and electrical tree initiation-expansion process under strong electric field / heating conditions are focused, and the remodeling of electric field distortion and degradation path is discussed accordingly. Under DC condition, the charge injection and migration are more sensitive to aging, and the space charge accumulation caused by the increase of trap depth and density enlarges the local field strength more significantly, thus compressing the insulation redundancy and breakdown threshold.

Keywords: High voltage cable; Insulation aging; Space charge; Electrical treeing; Electric field characteristics

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1. Introduction

In ultra-high voltage AC (HVAC) and DC (HVDC) systems, with the expansion of voltage level and operating environment, the insulation reliability is dominated by electric field-thermal field coupling and environmental stress superposition. The expansion of trap spectrum and the change of space charge steady-state distribution lead to the enhancement of electric field non-uniformity, and the partial discharge and breakdown mechanism are reconstructed accordingly. In DC cables, the aging-induced capture-release imbalance increases the difficulty of detrapping, and the polarization and conduction channel rearrangement deepen the electric field distortion. The alternating current system is more likely to form the opposite accumulation of heteropolar charges. The periodic electric field and the current-carrying temperature rise change the injection and recombination criteria together. The electrical tree becomes a key degradation channel under the combined action of high electric field pulsation, defect tip enhancement and thermo-mechanical relaxation. The sensitivity of XLPE requires that the space charge effect, partial discharge threshold and thermal steady-state edge should be simultaneously constrained in insulation design and operation strategy. In terms of DC external insulation and sheathing, pollution, acid rain and ultraviolet have a stronger impact on surface charge and hydrophobicity degradation, which is transformed into a dominant risk in specific scenarios.

2. Characteristics of Ultra-High Voltage Cable Insulation Materials

(1) Structure and material of extra-high voltage cable

Ultra-high voltage cable is composed of conductor, semi-conductive shielding layer, insulation layer, metal

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shielding and outer sheath, in which the insulation layer determines the electrical and thermal stability of operation. XLPE has become the mainstream because of its high dielectric strength, low loss and moderate thermal-mechanical properties. However, the stability under strong stress and long-term load depends on the distribution of crosslinking degree, crystal morphology and by-product residues. The experimental results of 160 kV DC cable show that the homopolar injection is enhanced under the driving of electrical aging. However, in the given period, some chain segments and crystal regions still maintain high integrity, which inhibits the accumulation of macroscopic charge. In electrical treeing, the initial threshold and propagation rate are jointly restricted by voltage and temperature, and the interaction between partial discharge and micro-defects constitutes the dominant channel. Under the premise of increasing sensitivity after aging, structural design and temperature rise control need to tighten the limit. The process optimization needs to take into account the comprehensive influence of crystallinity-crosslinking degree-impurity content on trap distribution and migration length.

(2) Electrical characteristics of insulating materials

Space charge and trap spectrum are the core quantitative dimensions to characterize the electrical state, and the evolution paths corresponding to DC and AC conditions are different. Under DC load, thermal and electrical (and electrothermal) aging causes the increase of deep level traps and the increase of average energy depth, the capture-detrapping balance is broken, the charge migration is slowed down and the accumulation layer is formed, and the peak and position of local field strength change accordingly. The characterization of isothermal relaxation current shows that the energy storage and polarization hysteresis of the unaged medium are weak, the heteropolar charge of the sample after running for many years increases step by step, and the electric field distortion and relaxation time constant are amplified simultaneously. Under AC stress, the polarity alternation resets the injection / depolarization period, but the deepening of the trap spectrum leads to the stable existence of heteropolar charges at the interface or in a specific area inside, and the frequency-dependent distortion coupling occurs. The threshold and path of electrical treeing are highly sensitive to the above charge behavior. The enhancement of the local field at the tip and the extension of the charge residence promote the branch expansion, and the temperature regulates the expansion rate through the chain motion and the trap state lifetime.

3. The Influence of Insulation Aging on Cable Performance

(1) Main manifestations of insulation aging

The microstructure evolution is first reflected in the systematic shift of space charge behavior. The chain fracture and oxidation products cause the trap spectrum to expand to the high energy side. The delayed polarization and retention dominated by deep traps lift the space charge density and significantly aggravate the electric field non-uniformity, and the partial discharge threshold decreases accordingly. In the HVDC cable, the homopolar injection threshold is superimposed with the channel expansion, the trap deepening and increment make the detrapping rare, the steady-state charge transfers to the bulk phase, and the potential distribution deviates from the linearity. Although there is a stage inhibition ability in some material systems, abnormal distribution and safety margin decline may still occur in long-term operation. In high-voltage AC cables, heteropolar charges are more likely to accumulate near the interface and defects, and the distortion rate increases significantly, which is positively correlated with the aging factor. As a process from penetrating micro-defects to macroscopic breakdown, the electrical tree is dually modulated by voltage and temperature. The tip field enhancement and thermal softening jointly promote the branch extension. Repeated discharge increases the channel conductance and further strengthens the distortion.

(2) The change of space charge distribution

PEA measurement shows that the homopolar charge near the aluminum electrode is dominant in unaged XLPE. After aging, the heteropolar charge forms a stable accumulation layer at the relative position, and the polarity and interface barrier change jointly determine the distribution. The early deterioration of accelerated aging samples is mostly promoted from the inside to the outside, while the long-term operating cables are more likely to be triggered by the external environmental stress, and the distribution difference is generated accordingly. Under the direct current condition, the thermal, electrical and electrothermal aging lifts the trap depth and density, the space charge density increases significantly, the homopolar injection is more significant, and the ' slow diffusion ' under the deep trap constraint and the difficulty of decollement form a persistent non-uniform electric field pattern. The subsequent steady-state reconstruction rearranges the local maximum field strength position and affects the energy release and expansion direction of the electrical tree tip.

(3) Influence of aging on breakdown characteristics of cables

Breakdown is highly sensitive to space charge. The increase of deep traps and charge accumulation enlarge the local field strength peak, and the field enhancement near the defect is more prominent. In the 160 kV DC cable, the electrical aging strengthens the same polarity injection and bulk phase migration, and the breakdown risk increases. After the aging of AC XLPE cable, the accumulation of heteropolarity is formed near the aluminum electrode, the distortion rate increases and the breakdown threshold decreases. PEA observed that the deepening of aging corresponded to the increase of shallow trap density, the obstruction of detrapping and the uneven distribution of field, and the breakdown voltage showed a downward trend. At the same time, in some materials and loading paths, the homopolar pre-injection can smooth the local field distribution in a short time scale, and the breakdown voltage of the oil-paper sample increases after the homopolar pre-compression, suggesting that the space charge can exhibit a ' shielding ' effect under certain conditions. Its sustainability and boundary are constrained by trap spectrum and loading history.

4. Strategies to Improve the Aging Resistance of Insulating Materials

(1) Material modification and development of new insulation materials

Material modification is carried out for space charge suppression, trap spectrum stability and electrical tree threshold enhancement. XLPE exhibits certain charge inhibition and aging resistance under DC field. Through the synergy of crosslinking process and antioxidant system, it can reduce polar by-products and polarizable groups while maintaining crystal / amorphous phase synergy, and weaken the formation of injection channels and deep traps. The aging factor and trap-byproduct correlation revealed by IRC suggested that the hysteresis and retention were reduced by removing cross-linking by-products and inhibiting deep trap formation. Facing the dendritic and interface defect sensitivity, the filler modification, blending and gradient structure increase the charge dissipation channel and homogenize the trap without sacrificing the dielectric strength. In DC engineering, the hydrophobicity of silicone rubber sheath declines rapidly under the action of acid rain and ultraviolet. It is necessary to improve the anti-degradation ability of weathering components and cross-linked network, or introduce multi-scale barrier layer to slow down the change of surface energy and charge retention.

(2) Aging monitoring and evaluation technology

The isothermal relaxation current method (IRC) can quantify the correlation between the aging factor, trap spectrum and space charge behavior of XLPE AC cables. The aging factor of unaged samples is low and

the accumulation of heteropolarity is weak. The aging factor of samples running for many years increases and the space charge is significant, which is suitable for life assessment and preventive maintenance. The electro-acoustic pulse method (PEA) can distinguish the total amount, position and polarity evolution of charges in DC cables. The increase of total amount and the deepening of traps caused by electrical aging can be visually presented, and the material differences that still have inhibition ability during aging can be identified. The complementarity of the two methods can provide comparable aging indicators under AC and DC stress paths, which are used to screen modification schemes and check operating thresholds, and combine multi-physics data fusion to achieve enhanced recognition of early deviations.

(3) Optimization of operation and maintenance strategy

The operation strategy needs to be dynamically adjusted with the environment and stress spectrum. In the DC project of pollution, acid rain and ultraviolet superposition environment, the hydrophobicity of silicone rubber external insulation degrades rapidly, shortens the hydrophobicity test cycle and increases the frequency of surface charge measurement, which can identify the surface energy and adhesion anomalies early and avoid the failure caused by surface charge-wet pollution coupling. In AC XLPE cables, the threshold maintenance criterion can be established by using the aging factor and trap spectrum obtained by IRC and the space charge distribution of PEA : when the heteropolar accumulation or the growth rate of deep trap density exceeds the limit, the load reduction, local replacement or environmental improvement will be triggered. The three-dimensional linkage analysis of temperature rise-current-environment is introduced, and the material modification, structural optimization and maintenance cycle are coupled to form an integrated aging resistance scheme of ' material-structure-operation and maintenance '.

5. Conclusion

Based on the action path of high-energy electrons in ultra-high voltage AC / DC transmission lines, the space charge, trap distribution and electric field distortion of XLPE and oil paper under different aging conditions are analyzed, and the remodeling of charge accumulation, trap depth and field distribution by aging is confirmed. The role of electrical treeing, electrical aging and thermal aging in degradation is clear. The systematic description of partial discharge characteristics and growth rules provides a basis for threshold setting and structural optimization. In the DC system, the sensitivity of environment and stress superposition is stronger, and the insulation aging may be accelerated. The maintenance cycle and detection strategy of external insulation and sheath need to be adjusted accordingly. The subsequent work can refine the injection-scattering-capture-compound chain of high-energy electrons under complex field thermal conditions and its influence on the trap spectrum at the mechanism level, and develop a material system with stable trap topology and controllable interface around anti-aging and space charge suppression at the engineering level. The fusion of IRC, PEA and operating data is used for life prediction and strategy closed-loop.

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