Journal of Electrotechnology, Electrical Engineering and Management (2026)
Clausius Scientific Press, Canada

DOI: 10.23977/jeeem.2026.090109
ISSN 2560-6697 Vol. 9 Num. 1

Structural Design and Practice for Condensation Prevention in Outdoor Power Distribution Equipment in Hot, Humid Regions

Zhong Jinhan

Suzhou Clou-MGE Electric Co.,Ltd. Shanghai Branch, Shanghai, China

Keywords: High temperature and wet heat; Outdoor power distribution equipment; Anti-condensation design; Hot pressure ventilation; Hydrophobic coating; Temperature and humidity warnings

Abstract: Outdoor distribution equipment in the hot and humid climate zone is exposed to insulation failure and corrosive damage caused by condensation for a long time. Traditional box designs have systemic deficiencies in sealing continuity, ventilation drive capacity, and protection of key components, and cannot adapt to the double superimposed conditions of high negative pressure difference and high absolute humidity throughout the year in this climate zone. Starting from the thermodynamic formation mechanism of dew point temperature difference, this paper analyzes the intrinsic connection among the sealing leakage path of the box, the dead zone of the ventilation duct, and the hydrophilic failure on the surface of the insulating parts, and proposes structural optimization schemes for systems such as labyrinth composite sealing, hot-pressure-driven vertical duct, nano-hydrophobic coating treatment, and active temperature and humidity early warning linkage. The optimization effect is verified and analyzed through engineering practice cases.

1. Introduction

The operating conditions of distribution equipment in the coastal areas of South China, the inland basins of Central China and the low-altitude river valleys of Southwest China are among the most demanding in the global climate adaptability classification of distribution network equipment. The annual average wet-bulb temperature has been consistently high, and the repeated disturbances of diurnal and seasonal temperature differences to the gas saturation inside the box have caused the occurrence frequency of condensation to be much higher than that in temperate and arid climate zones. A large number of operation and maintenance records of outdoor ring main units and switch boxes show that the trigger time of insulation faults is concentrated in the first large temperature difference cooling period after the change of seasons, indicating that condensation is the real trigger factor of faults, rather than accidental operation interference. However, anti-condensation has been regarded as an auxiliary maintenance measure rather than a design program. Passive measures such as installing heaters and regular manual drainage have been widely adopted, and there has been almost no systematic development of the condensation suppression potential of the box structure itself. The lag in engineering cognition is the institutional cause of the persistently high condensation faults.

2. The formation mechanism of the condensation problem

2.1 Characteristics of high-temperature and humid environments

Thermodynamically, the environmental characteristics of the hot and humid climate zone are a superposition of high absolute moisture content and relative humidity that periodically approach saturation values. In meteorological terms, when the relative humidity of the atmosphere remains at an extremely high level for a long time and there is a non-negligible range of differences between the daily maximum temperature and the daily minimum temperature throughout the year, The closed metal box placed outdoors is bound to undergo periodic thermal expansion and cold contraction. This process prompts the outside hot and humid air to continuously permeate into the box under the effect of pressure difference. When the temperature drops at night, a liquid water film precipitates on the cold side, and the poorly sealed inlet and outlet holes, the four corners of the door frame and other stress concentration areas become low-resistance channels[1] for gas exchange between the inside and outside of the box.

2.2 Physical processes of condensation formation

The thermodynamic criterion for the occurrence of condensation is whether the temperature of the local wall inside the box is lower than the dew point temperature of the gas inside the box at that time. The dew point temperature itself is a monotonic function of absolute humidity. In a wet heat environment with extremely high absolute humidity, the difference between the dew point temperature and the dry bulb temperature is significantly narrowed. Even a slight temperature drop on the box wall can cause condensation. Contrary to the experience in temperate climates where a large temperature difference is required for condensation, the positive feedback effect of phase change heat further amplifies the amount of condensation. After the water film adheres to the metal cold surface, its thermal conductivity is much lower than that of the metal substrate, forming a local insulation layer that depresses the temperature of the cold surface and instead accelerates the migration and precipitation of water vapor to that point, if the ventilation path is not smooth, The high humidity inside the box cannot be replaced, and the above positive feedback will continue to accumulate until the insulation of the equipment fails.

2.3 Design correlations of the equipment structure

From the perspective of structural design, the condensation problem is essentially caused by the coupling out of control of seal integrity, gas migration path, and heat exchange interface. Seal integrity determines the upper bound of the rate of infiltration of outside wet air into the box, and the geometry of the gas migration path determines the retention time and spatial distribution of wet hot air inside the box. The material properties and geometric configuration of the heat exchange interface determine the spatial distribution of the cold surface temperature. Design flaws in any one dimension can cause condensation faults alone on the basis of good design in the other two dimensions. Therefore, anti-condensation design must be a three-dimensional synchronous optimization system engineering, rather than a point-to-point improvement[2] of a single module.

3. Main problems with anti-condensation design

3.1 Inadequate sealing performance of the box

At present, the sealing of outdoor distribution box bodies mostly adopts single rectangular cross-section rubber sealing strips. This scheme has a very uneven distribution of sealing compression at the four corners of the door frame, especially at the corners. After long-term opening and closing vibration, the sealing strips at the corners undergo permanent compression deformation, forming a continuous gap at the micrometer level at the sealing interface. Under the drive of the pressure difference inside and outside the box, a distinct moisture penetration channel is formed The sealing treatment of the incoming and outgoing line holes is more serious. After the cable is inserted, the remaining gap is generally filled with rough packing, and the interface sealing between the packing and the cable and the hole body relies on construction experience, with a large consistency difference. After repeated thermal expansion and contraction, the packing cracks, resulting in the loss of sealing continuity. These two types of leakage pathways have been repeatedly proven to be the main source of continuous dehumidification inside the box during actual operation in hot and humid areas.

3.2 Poor ventilation and dehumidification pathways

There is an inherent contradiction and tension in the physical mechanism between ventilation and heat dissipation and anti-condensation. To meet the heat dissipation requirements of the heat-generating elements, the traditional design tends to open multiple ventilation holes on the side walls of the box and install rainproof louvers. However, the presence of the louvers makes the air intake direction almost perpendicular to the direction of natural convection induced by vertical thermal buoyancy, resulting in obvious flow conflict. A large area of hot and humid air retention dead zone is formed in the corners of the bottom of the box and in and out of the line area. The relative humidity of the gas in the retention zone is close to saturation for a long time. When the temperature drops at night, this area is the first to trigger condensation. Because the gas cannot be displaced, the condensation water accumulates continuously and is difficult to evaporate, causing the bottom of the structure to remain in a moist state for a long time, accelerating the process[3] of metal rusting and insulation degradation.

3.3 Lack of isolation of critical components

The condensation failure mechanism of insulators is different from that of metal components. The condensation on metal walls is mainly corrosion, and the water film on the surface of insulators directly constitutes the surface conduction path, causing a sharp drop in insulation resistance and, in severe cases, interphase short circuit. In high-voltage distribution equipment, although there is some space left in the conventional design for the dielectric safety margin of insulators, in the case of surface water film coverage, The rate of degradation of its surface withstand voltage capacity is much greater than the design expectation. Most of the existing designs lack independent micro-environmental protection for high-voltage insulating parts, have no targeted hydrophobic treatment, and have no local micro-heating insulation measures. As a result, once the outer box seal fails locally, the condensation water can directly contact the insulating parts and rapidly approach the breakdown condition under the action of the electric field.

3.4 Absence of monitoring of condensation conditions

A large number of outdoor distribution devices are not designed with active perception of condensation status, no temperature and humidity sensing intervention, and no dew point calculation logic. Condensation occurs in an invisible passive state for operation and maintenance personnel. Only after the equipment has an insulation alarm or trip fault can the traces of condensation and water accumulation inside be discovered by unpacking and inspecting. The passive perception mode makes the fault completely unknown when it is in the stage of hidden danger accumulation, and no preventive maintenance strategy based on historical data can be established. The contrast between the fine monitoring of electrical quantities in the distribution network automation system and the monitoring blind spot of the microenvironment inside the box is a systemic shortcoming that has been overlooked in the current construction of intelligent distribution networks.

Table 1 Comparison of key Parameters for anti-condensation Design between traditional and optimized schemes

Design parameters	Typical flaws of traditional schemes	Optimize the improvement direction of the plan	Validation methods
Box seal structure	Multiple leakage paths coexist, and the sealing compression is uneven	Labyrinth composite seal, uniform pre-compression control	IP protection class test
Cross-section of the ventilation duct	Insufficient thermal buoyancy driving force, significant dead zone of wet air retention	Thermal pressure drives the vertical air ducts, eliminating the transverse retention zones	CFD flow field simulation verification
Surface condition of the insulator	Hydrophilic substrates adsorb water films, and the insulation resistance decreases along the surface	Nano-hydrophobic coating treatment significantly increases the contact Angle	Surface withstand voltage and creepage tests
Temperature and humidity monitoring nodes	No sensor intervention, passive perception lag of condensation status	Multi-point temperature and humidity sensing array, active early warning linkage control	Dew warning response delay test

Table 1 systematically summarizes the typical flaws of the traditional scheme and the improvement directions of the improved scheme in terms of four main parameters: sealing structure, ventilation duct, surface condition of insulating parts, and temperature and humidity monitoring. Among them, the ventilation duct problem deserves particular attention. In CFD simulation for a standard cabinet, the stagnant region with trapped hot and humid air resulting from the conventional side air intake design occupies a large portion of the cabinet’s bottom. This proportion indicates that a large number of high-value insulating components have been in the high-humidity retention area for a long time, and the degradation rate of surface insulation performance under repeated condensation conditions is much greater than the expected design life, which is a systematic design defect rather than an individual deviation.

4. Optimization measures for anti-condensation structures

4.1 Enhance the sealing structure of the box

The door frame sealing system upgrade should start with a redesign of the cross-sectional shape, replacing the traditional single rectangular cross-section strip with a three-lip composite sealing strip. The three-lip structure can provide two separate sealing interfaces under the same compression stroke, and the inner lip can still maintain effective sealing even if the outer lip undergoes slight deformation due to aging. The corner connection uses injection-molded corner pieces instead of cutting and splicing to fundamentally solve the problem of the discontinuity of the corner seal. The sealing scheme of the incoming and outgoing line holes uses labyrinth threading kits, with multiple ring-shaped sealing lips preset on the inner wall of the kit to form a stepwise seal with the outer sheath of the cable, and the remaining gap is filled with high elastic mold expansion type sealant. The intumescent compound expands in volume after absorbing water to actively fill the micro-cracks and has a certain self-healing ability. The integrity of the above seal improvement can be quantified and verified by the water vapor transfer rate test with enhanced IP protection level.

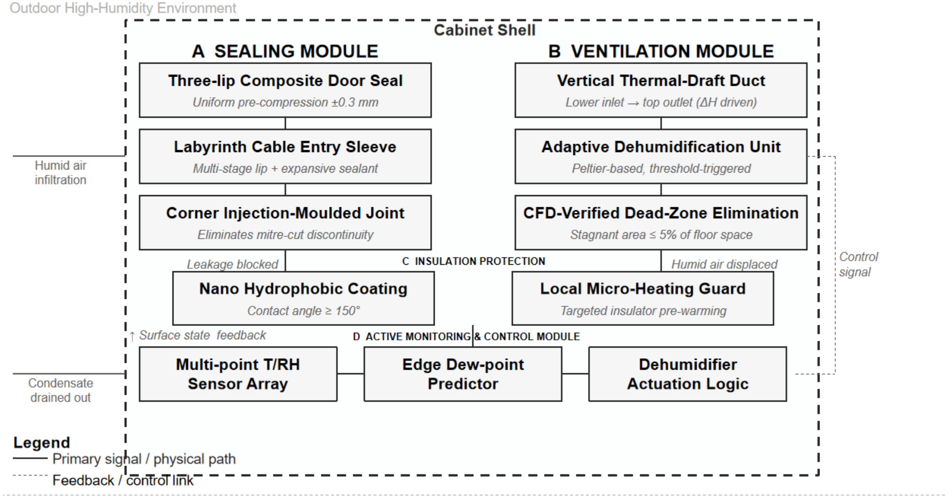

Figure 1 Topological diagram of the anti-condensation optimized box sealing and ventilation system structure

Figure 1 shows the coupling relationship between the two modules of seal upgrade and ventilation improvement. The pre-compression amount of the three-lip seal section is constrained by the geometric tolerance chain of the door hinge locking mechanism and is represented by bidirectional dimensioning in the figure to ensure that the seal compression amount is within the effective range. The constraint relationship between the axial dimension of the inlet and outlet labyrinth kit and the cable bending radius is also illustrated in a geometrically coordinated manner in the figure. The air inlet of the vertical air duct is located on the lower side plate of the box, and the air outlet is located on the top cover of the box. There is a certain height difference between the two, forming a stable hot press head that drives the wet hot air inside the box to move upward. The CFD calculation results show that when the heat inside the box reaches the typical working condition level, this hot press head can maintain an effective convective air change rate and completely eliminate the dead zone of moisture retention at the bottom.

4.2 Improve the ventilation and dehumidification system

The core of the hot-pressure-driven air duct design is to rely on the natural thermal buoyancy generated by the heat-generating elements inside the box to ensure continuous and effective air displacement inside the box with minimal additional energy consumption. The determination of the vertical air duct cross-sectional area should balance the heat dissipation requirements and the resistance of the insect-proof and dust-proof filtration. The equivalent flow resistance of the filter screen and the air duct cross-sectional area jointly determine the number of air changes in the natural convection state. In extremely hot and humid weather and when the heat output is low, the thermal buoyancy driving force is insufficient and an adaptive dehumidification module is needed as an active supplement. This module cools the local air inside the box to below the dew point based on the Pelteret cooling effect, forces the moisture to be released out of the box through the drain pipe, and the start-stop logic is controlled by the comparison result of the measured values of the temperature and humidity sensor nodes inside the box and the preset dew point threshold. Flexibly adjust threshold parameters in accordance with local climatic features to avoid component fatigue induced by excessive frequent startup operations[4].

4.3 Strengthen the protection of critical components

Hydrophobic treatment of the surface of high-voltage insulators is an important line of defense against water film forming conductive channels along the surface. The contact Angle of the nano-superhydrophobic coating is more than twice the intrinsic value of the insulating substrate, causing water to form bead-like rather than continuous water films on the surface of the insulators, physically cutting off the conditions for the formation of conductive paths along the surface. The coefficient of thermal expansion matching of the coating with the insulating substrate is a constraint for long-term adhesion and should be verified through thermal shock cycling tests during the material selection stage. The protection of metal conductive parts and metal structural parts should be treated separately. Insulating coatings should not be used on the surface of conductive parts; instead, methods such as corrosion-resistant alloying or hot-dip galvanizing should be adopted, and organic anti-rust coatings can be superimposed on structural parts. The integrity of the coating is a prerequisite for providing continuous barrier protection in a wet and hot environment over a long period of time. Scratches and indentations that occur during installation need to be repaired through the recoating process; otherwise, the defect points will become the preferred starting point[5] of corrosion.

4.4 Add a condition monitoring device

The layout strategy of the temperature and humidity sensing nodes should not be to place just one sensing point at the center of the box. Instead, multiple sensing points should be placed in the high humidity retention area identified by CFD analysis, near the critical insulation, and around the heat dissipation element to form multi-point arrays. The array data is processed by the edge computing unit for real-time inference of the dew point approximation trend. When the difference between the measured humidity at any node and the saturation humidity corresponding to the current temperature inside the box narrates to within the warning threshold, the system automatically triggers the dehumidification module to start and reports the condensation warning event to the distribution network automation master station. The master station system then dynamically adjusts the maintenance cycle of the equipment, achieving a shift from passive fault handling to active state management. In actual engineering deployment, The setting of the early warning threshold should be adaptively configured in combination with local climate statistics, and the general default value should not be applied. This is the key to ensuring the accuracy of the early warning in engineering practice.

The data trends in Figure 2 show several characteristics worthy of further study. Near the seasonal cooling node, the pre-optimization scatter sequence shows a significant inflection point of sudden humidity increase, and the rate of sudden increase is much faster than that of the post-optimization sequence. This is because the rate of infiltration of external moisture into the box is effectively controlled after the box sealing integrity is improved, and the time constant of humidity increase is longer. There are also significant differences in the convergence behavior of the curves in the area close to saturation humidity. The pre-optimized sequence would remain near the saturation line for a longer time during the high humidity season, corresponding to the physical state of continuous condensation, while the optimized sequence would quickly fall back after multiple triggers of dehumidification linkage, demonstrating the effective truncation ability of active intervention for humidity peaks. The above trends are mechanistically corroborated by CFD predictions and material test data, indicating a good consistency between the actual performance of the systematic optimization scheme and the theoretical expectations.

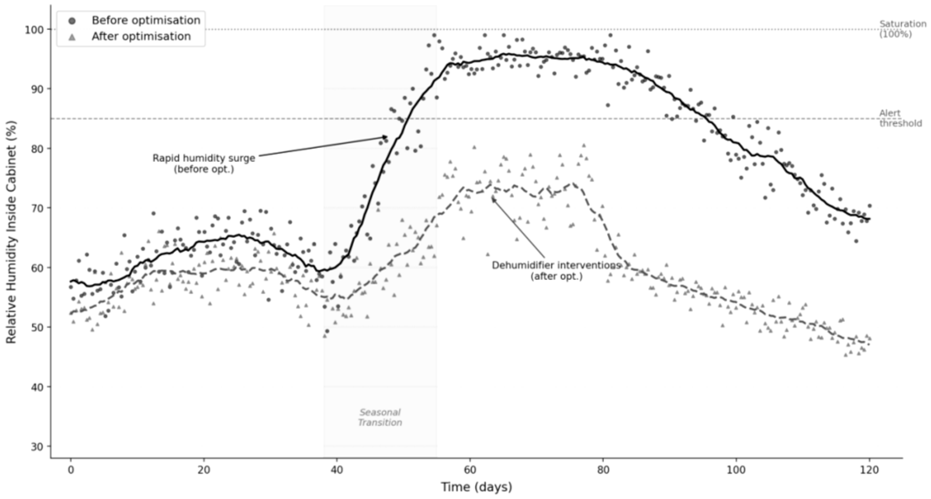

Figure 2 Scatter plot comparison of the trend of relative humidity inside the box over time before and after the implementation of the optimization scheme

5. Conclusion

The prevention and control of condensation in outdoor power distribution equipment in high-temperature and humid regions is not an isolated issue of waterproof sealing engineering, but a systematic integration challenge in three design dimensions: sealing integrity, optimization of heat and moisture migration paths, and active regulation of micro-environments. When there are deficiencies in other dimensions, improvements in a single dimension can only delay but not prevent the occurrence of condensation faults. The systematic optimization framework proposed in this paper has been engineered to show significant improvement in condensation control at key seasonal transition points, demonstrating the engineering superiority of the systematic design perspective over the single-point repair strategy. Given that the current intelligent transformation of distribution networks provides a technical basis for the embedding of state perception capabilities, The deep integration of active temperature and humidity warning linkage modules with traditional passive structural protection schemes is the main trend for the next stage of design evolution of distribution equipment in high-temperature and humid climate zones. Subsequent studies can explore dynamic threshold setting strategies relying on adaptive learning algorithms based on climate characteristics, as well as the long-term reliability decay law of hydrophobic coatings under actual wet and hot aging conditions.

References

[1] Tian Shuxin, Xiao Wenyuan, Fu Yang, Zhou Jian, Li Zhenkun, Mi Yang. Research on Resilience Enhancement Strategies for cable-type distribution networks under extreme heat disasters [J]. Proceedings of the CSEE, 2020,45(9):3408-3419+I0011.

[2] Shi Kejian, Zhu Yidong, Hu Dawei, Tian Ye, Gu Taiyu. Research on Non-destructive Testing Method for high-temperature Fault Early Warning in Distribution Networks Based on YOLOv8n [J]. Power Grids and Clean Energy, 25,41(7):19-26.

[3] Shi Cheng, Gao Hongjun, Luo Longbo, Chen Minghui, Zhu Jiankun, Liu Junyong. Dynamic reconfiguration of distribution networks considering demand response in extreme high-temperature scenarios [J]. Power Grid Technology, 2020,49(1):136-145.

[4] Liang Zhenfeng, Zhang Jiahao, Yan Junjie, Zhang Jiankang, Wang Xiaowei. Risk assessment methods for distribution networks under extreme heat conditions [J]. High Voltage Technology, 2020,51(10):5042-5052.

[5] Yin Guozhan, Song Liwei, Liu Xuhui. Research on Operation and Maintenance Testing, Protection Level Adjustment Optimization for High and Low Voltage Distribution Equipment [J]. China Science and Technology Journal Database Industry A, 2025(12):130-133.