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Environmental design considerations for control connector systems in outdoor distribution switchgear

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Abstract

This paper addresses the environmental design considerations required in the construction of connector systems for outdoor electronic switchgear. A general overview of these design considerations will be presented, as well as a review of the main connector technologies employed by switchgear currently available on the market. Additionally, tests performed on the various connectors to determine robustness will be reviewed. This paper concludes that there are significant performance differences between connectors used in switchgear applications, and that care should be taken when selecting a connector for use.

Introduction

Control connector problems are one of the most bothersome types of equipment failures on outdoor electrical distribution switchgear. For gear whose sole purpose is to improve distribution system reliability, failure of an auxiliary low-voltage connection hinders correct operation and is unproductive. Unfortunately, experience shows that problems do occur with control connectors on outdoor switchgear. Connectors that are misapplied, unprotected, or improperly assembled may degrade important system functions, leading to changes in sensor accuracy and potentially a complete loss of operation. Problems originating in the connector may spread to the rest of the system, affecting and possibly damaging the connected switchgear and control. In extreme cases, connector problems may even generate an outage on the very power system the switchgear was intended to protect.

Many publications have been written to address problems of connector reliability. However, most of the technical articles published are in fields such as automotive [1] or defense [3], [4], which contain valuable research but often focus on requirements that are not applicable to switchgear operations.

A primary driver in both of those industries is resistance to physical forces including vibration and shock, as in the case of an automotive engine compartment. Connectors in the defense industry often require high mating life due to frequent operation. In contrast, for switchgear products, the device is frequently mounted on a utility pole, connected at commissioning, and untouched for most of its service life. Here, the active physical resilience of the connector system is not the critical aspect; rather, its ability to withstand the effects of the environment—temperature, atmospheric pressure, moisture, ultraviolet radiation, and the like—over extended periods of time will determine the overall reliability of the system.

In a static connector system, the most likely contributor to system failure is indeed the presence of water within the connector system. Typically, water leads to such problems as galvanic corrosion that can cause shorts and opens to occur in a circuit. However, it must also be considered that most modern electronic switchgear also includes some form of high impedance analog signal, most commonly associated with a transducer for measuring the voltage on the system to which the switchgear is attached. These types of signals are much more sensitive to the presence of water than typical digital signals; it is not necessary for water ingress to reach the point of galvanic corrosion for these analog signals to be distorted outside of their specified accuracy.

Some of the most thorough investigation available on the prevention of moisture ingress in connectors can be found in Lam et al. [1]. They investigate the influence of applied temperature and humidity on a standard type of automotive connector. Two test groups were included in the study, sealed and unsealed versions of the connector, and the temperature, pressure, and humidity inside each connector were measured. Their conclusions show that even sealed connectors do not prevent the ingression of water vapor into the connector shell; rather, the pressure changes in the interior of the connector system caused by ambient temperature changes lead to a breathing action by which the connector absorbs the humidity of its surrounding atmosphere. The real design challenge, beyond simply keeping liquid water out of the connector, is to structure the connector such that the entering vapor cannot condense in such a way as to bridge pins and cause a problem in the circuitry.

The remainder of this paper will evaluate the effectiveness of each of these connector technologies in protecting against moisture ingress.

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Table 1. Environmental protection features

Connector	Coupling technology	Primary environmental seal	Interfacial seal	Wire entry seal	Cabinet–connector air seal
SAE 5015	Threaded circular	O-ring	Flat rubber	Potting	Insert-shell epoxy
M26482/I	Bayonet circular	O-ring	Flat rubber	Gasket/creepage	Insert-shell epoxy
D38999/IV	Breech circular	O-ring	Cork-in-bottle	Flourosilicone gasket	Insert-shell epoxy
DIN	Lever-lock rectangular	Rubber gasket	Creepage path	Creepage path	None

Common connector technologies

There are four primary connector technologies in use within the switchgear industry listed in **Table 1**. First, a threaded circular connector commonly containing 14, 19, or 26 conductors controlled by the SAE standard [5], series I (SAE 5015). Second, a bayonet circular connector containing 32 conductors controlled by MIL standard [6], series I (M26482/I). Third, a circular breech-coupled connector containing 37 conductors controlled by MIL standard [7], series IV (D38999/IV). Fourth, a rectangular lever lock connector containing 42 conductors controlled by DIN standards [8] through [11] (DIN).

Of these four technologies, the threaded circular connector has the longest history within the switchgear industry. Introduced to relay-operated switchgear in 1961, this connector became the standard interface at its introduction and has dominated the outdoor switchgear market for decades. This connector technology has proven to be highly reliable when properly mated, but it can be difficult to mate properly. It is also difficult to verify proper mating due to the lack of a positive stop during the mating process. The three other technologies were subsequently introduced for ease and consistency of assembly. Each accomplishes this goal by replacing the multi-turn screw tightening action with some type of short motion ending with a positive stop—whether 1/3 turn bayonet, 1/4 turn breech, or linear overtoggle lever.

Table 1 shows a summary of the environmental seals present in a connector system, and how the design of each of these four connector types addresses each seal. **Figure 1** and **Figure 2** provide visual representations of the locations of these seals in the connector system. The goal of these seals is to prevent condensation between any of the electrical surfaces within the connector system. Each of the seal types is discussed in detail.

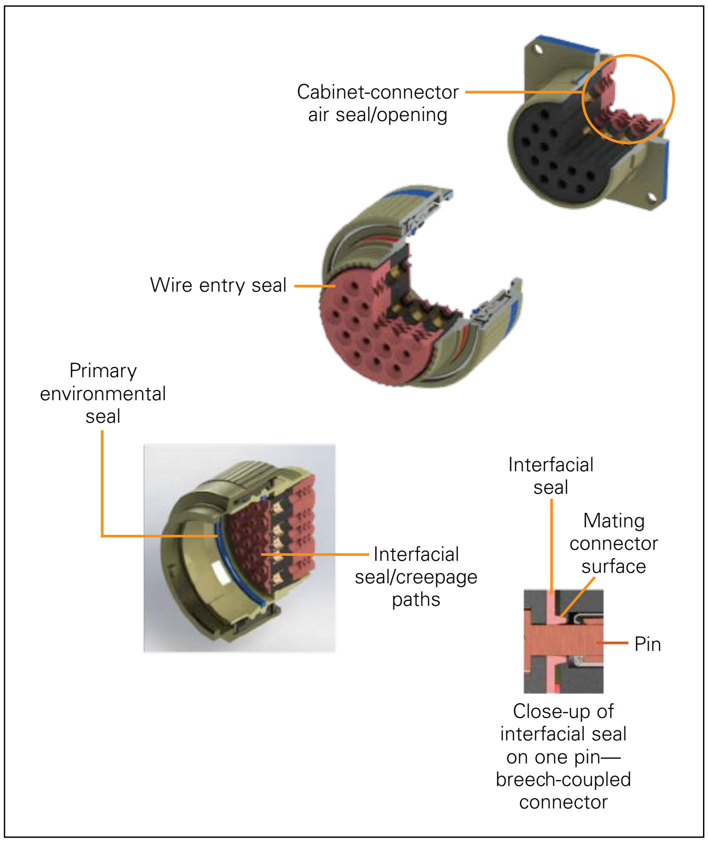

Figure 1. Location of the environmental seals on the breech-coupled circular connector. Seals on the other circular connectors are located in a similar manner.

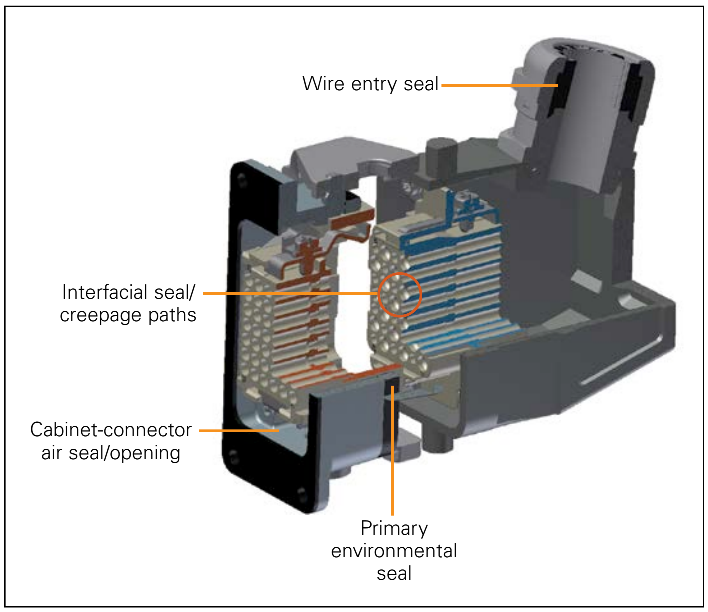

Figure 2. Location of the environmental seals on the lever-lock rectangular connector.

Primary environmental seal

All four of these connectors have a primary environmental seal of compressed rubber. This seal exists to prevent the ingress of liquid water, as a rubber seal cannot prevent the transmission of water vapor.

Interfacial seal and coupling method

The interfacial seal deals with the mitigation of condensation at the interface of the two halves of the connector system. Three types are discussed here: flat rubber, cork-in-bottle, and hard plastic creepage path. Flat rubber has the advantage of a complete seal of the entire surface of the interface, but suffers in that manufacturing variations, tolerance stackup, variability in end-user installation, and compression set of the interfacial seal can lead to gaps in the seal, compromising the system. Cork-in-bottle attempts to solve this limitation by replacing the one universal seal with individual seals around each of the connector's contacts. This system is more tolerant to manufacturing variations in the connector. Another option, the hard plastic creepage path, has long been a staple of high-voltage systems. However, because this interface type does not use a seal, water is free to condense on and around the pins. This type of interfacial protection can only protect from condensate as long as the total amount of condensate cannot bridge the entire length of the path.

The coupling method is another important factor when considering the effectiveness of the interfacial seal. Both the flat rubber and the cork-in-bottle seal types require consistent, level pressure across the entire seal face in order to protect against condensation between pins. The threaded connector coupling provides level pressure on the face, with the added benefit that the compression of the interfacial seal may be adjusted by placing additional torque on the coupling ring. Due to the screw-type threaded coupling, the faces in a threaded connector cannot be separated by applying axial or bending force to the attached cable. The bayonet connector coupling provides a controlled pressure on the interfacial seal due to its positive stop coupling ring. However, the bayonet coupling, even when fully mated, is sensitive to axial or bending loads on the attached cable. Loads on the cable can compress the springs in the coupling mechanism, leading to a gap in the interfacial seal, which exposes the pins to condensation. The breech connector coupling was designed to eliminate the force sensitivity of the bayonet coupling and tolerates bending moments of at least 650 in-lb_f, ensuring consistent pressure on the interfacial seal regardless of how the cables are trained.

Wire entry seal

Every connector system is structured as an array of pins mounted in a body to keep them aligned. The wire entry seal is designed to prevent moisture ingress along the path in which the pin/wire is installed. Covering the wire entry areas with a silastic potting compound provides robust protection, because although vapor transmission still occurs, it will prevent any condensate from forming in the areas where it is used. The disadvantage is that the potting material must be added after the connector assembly, which then requires curing time. Silicone gasketing is also a popular option, because it provides effective protection while eliminating the manufacturing time needed for potting. This seal type is an integral part of the connector design that provides an interference fit with the installed wires and doesn't require extra processing during assembly.

Cabinet-connector air seal

The cabinet-connector air seal deals with the air exchange between the interior of the connector and the enclosure to which the boxmount portion is affixed. This seal is often overlooked in switchgear design. Vented enclosures, which are common in distribution switchgear and controls, take in humidity and contamination from the ambient environment over time. The cabinet-connector air seal determines how sensitive the connector is to changes in the condition of the air inside the enclosure.

Three of the connector types (threaded circular, bayonet circular, and breech circular) are isolated from the enclosure to which they are mounted via an epoxy seal between the insert and shell housings. In contrast, the DIN style connector forgoes any attempted sealing here, relying on the interfacial creepage paths to mitigate any condensate that occurs.

Connector tests

Testing was performed on the four most common connector topologies in order to quantitatively evaluate their relative performance. As humidity was determined to be the most significant of the environmental factors discussed, testing of the connectors' resilience to water vapor was performed via measurement of the internal leakage while exposed to humidity.

Because the service life of the connector system is very long when compared to the practical duration of the test, accelerated life testing, which seeks to exceed the severity of the true application, was performed. The majority of humidity test standards provide for the application of humidity and some sort of thermal cycling, but are designed to prevent condensation from occurring on the device under test. In a connector system, however, condensation is important because it is the condensate that affects the system's insulation resistance and leads to galvanic corrosion. For this reason, the SAE humidity test of [5], paragraph 4.6.18.2 was performed. This test requires a sealed vessel containing standing water, which forces the ambient humidity as close to 100% as possible. Hourly thermal cycling is applied to the test chamber in a radiant manner that prevents the humidity level from falling during the cool-down portion of the cycle and forces condensation on the test samples.

Similar to the technique in [2], the insulation resistance was monitored during the test. Periodic monitoring allows quantification of how long the samples withstood the high humidity before moisture ingression led to a degradation of insulation resistance. Instead of being monitored weekly, however, samples in this test were monitored continuously, but the applied bias voltage was 100 V instead of 1250 V between alternating pins in each connector. This gives better resolution to the connector's performance during the 500 hours of test time, but limits the maximum resolvable insulation resistance to the order of 10 GΩ. It will be shown, however, that these limitations are not a hindrance to observing the performance differences of these connector types.

Sample preparation

The mounting and assembly configuration of a connector within its connector system is critical in determining its resilience to humidity. Sample preparation for this test was designed to match the environmental protections provided by the installations surrounding each of the connector types in their respective applications.

- The threaded circular connector had the rear wire entry areas potted with a silastic compound to protect the solder cups and was placed directly in the test chamber.
- The bayonet circular connector provides an integral grommet on the straight plug portion of the connector and utilizes a hard rubber creepage path on the boxmount portion. Wire was selected that meets the manufacturer's recommendations for overall diameter, and the grommet's compression nut was tightened after assembly to complete the seal. The boxmount portion was assembled using the same wire as the straight plug and tested in this configuration.
- The breech-coupled connector provides grommets at both wire entry areas, not requiring a compression nut after assembly. Care was taken to use wire matching the manufacturer's recommended diameter during assembly, but no other protections were added to the connectors.
- The rectangular connector was assembled according to the manufacturer's instructions. The straight plug was assembled with a length of SO jacketed cable, of an appropriate diameter for the integral sealing grip in the connector housing. The boxmount portion was assembled to an aluminum plate and was protected from falling condensate by an aluminum hood assembly above the connector. The orientation of the connector was as if it had been mounted on the bottom side of a cabinet. Illustrations of each test sample in its test configuration can be found in **Figure 3**.

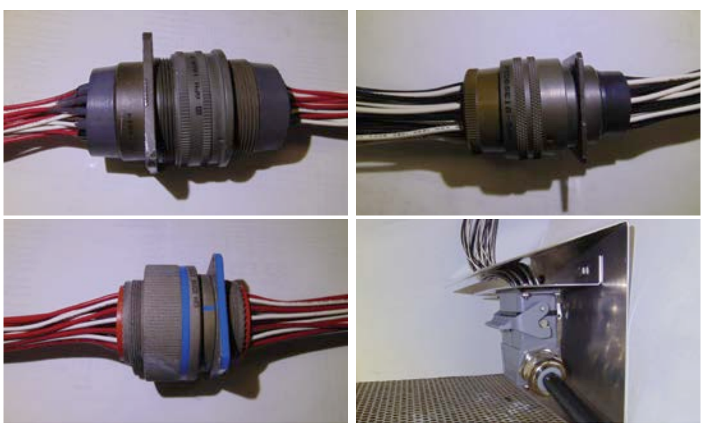

Figure 3. Preparation of test samples. Upper left: Threaded circular SAE 5015 connector. Upper right: Bayonet circular M26482/SI connector. Lower Left: Breech coupling D38999/IV connector. Lower right: Rectangular lever lock DIN connector.

Test results

The results of the testing can be seen in **Figure 4**. It is important to note that the test performed is an accelerated life test and the exact insulation resistance measurements shown here cannot be directly correlated to the connector's behavior in a real-world environment. What can be learned, however, is what the relative time constant for moisture ingression is between the connector types for a controlled set of conditions. Table II shows the time, in hours, from the start of the test to first moisture ingression for each of the tested connectors. The first moisture ingression is the point at which the measured insulation resistance drops below the maximum value that the system can measure as shown in **Figure 4**. Moisture ingress began at hour 18 of the test in the bayonet circular connector. Shortly after this, at hour 31, the rectangular lever-lock connector also began to show moisture ingress. The threaded circular connector followed at hour 390, and the test duration was not long enough to see moisture ingression in the breech-coupled circular connector.

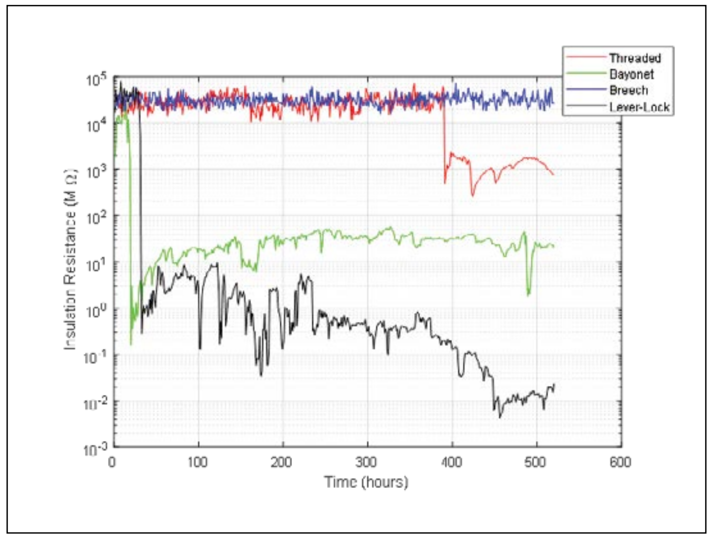

Figure 4. Insulation resistance over time during humidity testing for each of the four connector types.

Table 2. Time to first moisture ingression

Connector	Time (hours)
Threaded circular	390
Bayonet circular	18
Breech circular	>500
Lever-lock rectangular	31

The observed moisture ingression path varied for the different connector types. The threaded circular connector was found to have liquid water present in the interfacial seal. The entry path appeared to have been water vapor through the primary environmental seal, which congregated and subsequently condensed in the weakest area of compression on the rubber of the interfacial seal. The bayonet circular connector had liquid water present in several of the pin cavities, which appeared to have entered through the wire entry seal. The rectangular lever-lock connector's long creepage paths initially protected the system from the water vapor present due to the high humidity. However, the thermal cycling caused condensation to occur on the internal surfaces of the connector system and the creepage paths were eventually bridged by the volume of liquid water present.

Based on these results and observations, there are several key takeaways that should be considered in designs using each of these connector systems.

- **For the threaded circular connector:** This connector shows good performance in humid environments when properly mated. It is critical that the coupling ring is properly torqued to maintain compression of the interfacial seal and that the wire entry areas are protected via a silastic potting compound.
- **For the bayonet circular connector:** This connector system is sensitive to moisture on the cabinet side and to external loads on the attached cable. Care must be taken to protect the wire entry area of the cabinet mounted half of the connector, as its inherent protection is not as robust as the cable half. It is also critical that cables are trained so as to minimize axial and bending forces on the connection system to maintain compression on the interfacial seal.
- **For the breech-coupled circular connector:** This connector system was the least sensitive to moisture among the four types tested. It is important that wire of the manufacturer's specified diameter is selected for use in the system. Correct wire diameter is critical for the performance of the flourosilicone gasket that comprises the wire entry seal.
- **For the lever lock rectangular connector:** This connector system is sensitive to moisture on the cabinet side and may accumulate liquid water over time due to intermittent fluctuations in temperature and humidity. It is critical that the design of the cabinetry on which the connector is mounted prevents at all times the entry of condensate into the connector shell. This includes both direct condensation within the shell and condensation elsewhere in the cabinetry, which can drain into the connector shell.

Conclusion

The goals of this paper were to review the various connection system technologies currently in use within the outdoor distribution switchgear industry, understand the mechanisms by which each technology protects the circuits it carries from environmental influences, and perform testing to quantitatively evaluate the effectiveness of each system's environmental protections. It has been shown that the test performed is effective at exposing potential weaknesses in each connector's environmental protection. The test was accomplished in a highly accelerated manner that led to test results in mere weeks and provided insight into which aspects of each connection system require care when applying that system within outdoor distribution switchgear.

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