SALINITY EFFECT ON THE CORONA ONSET FOR A 765 KV AC SUBSTATION CONNECTOR

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SUMMARY

Outdoor substations placed in coastal areas are affected by saline environments. In the technical literature it is found extensive information regarding insulations problems in presence of saline environments [1]. The accumulation of salts and other contaminants promotes the onset of partial discharges on the devices subjected to very high voltages. Insulators are also affected by this phenomenon. While rainfall has a cleaning effect on the insulator surface, humidity enhances the corrosion effect and degrades the performance of insulation [2], favouring onset conditions for partial discharge.

Corrosion due to saline environments or dirt increases the roughness of the insulator surface, thus facilitating the appearance of partial discharges [3]. It is well known that the air pollution has a great impact on metals corrosion. Chloride ions are common in coastal environments, because seawater acts as a source of air mineralization. Deposition of chloride ions on metal surfaces intensifies metallic corrosion, thus degrading the conductor surface [4].

In this work the behaviour of a 765 kVRMS AC (line-to-line voltage) outdoor substation connector is analyzed when operating under both dry conditions and under wet saline environments by means of three-dimensional finite elements simulations (3D-FEM).

FEM simulations show that the electric field strength in the connector surroundings does not exceed the electric breakdown strength for air under clean and dry atmospheric conditions when energized at its rated voltage, 765 kVRMS AC (line-to-line). These results are corroborated by means of experimental measurements carried out in a high-voltage laboratory. Both, the laboratory tests and the 3D-FEM simulations performed in this study concluded that the corona onset voltage is approximately 980 kVRMS AC (line-to-line voltage). Additionally, 3D-FEM simulations allow detecting the connector weakest points regarding to electrical stress. Hence, this software allows redesigning the connector geometry to optimize its performance, thus minimizing the corona occurrence risk and their associated unwanted effects. Additionally, FEM simulations performed under a saline atmosphere were carried out by including a thin conductive saline moisture layer acting as a wetting film on the connector surface. Results revealed that saline environments worsen the connector behaviour, thus favouring corona onset conditions and their related effects.

KEYWORDS
Corona, partial discharge, environmental pollution, moisture, salinity.
1.- INTRODUCTION

The harmful effect of atmospheric salinity on high voltage equipment is well known. It is recognized that the atmospheric air may contain an important amount of sodium chloride, especially in coastal areas. This harmful effect decreases rapidly to a few hundred meters from the coast, reducing the atmospheric salinity and metallic corrosion. According to [5] the wind transports and stirs up the sea water, thus being in part responsible for the elevated salinity contained in marine atmospheres. The aerosols formed in oceanic air by the evaporation of sea water drops are transported by the wind to coastal areas. Consequently, the concentration of marine aerosol in the coastal atmosphere depends on diverse factors including distance from the sea, land topography and orography, and wind direction among others.

It is well known that metallic corrosion phenomenon is accelerated by saline particles already present in marine atmospheres owing to the soluble corrosion products generated due to the presence of marine chlorides in the atmosphere. These chlorides may be dissolved by the moisture layer deposited on the metallic connector surface, raising its electrical conductivity and accelerating metallic corrosion [4,5].

In absence of humidity, the salts and other contaminants accumulated on the exposed surface of high voltage apparatus cannot form ions which promote the development of partial discharges. It has been reported that in coastal areas, due to the presence of salinity and moisture, the withstand voltage of air gaps is much lower than in case of dry air conditions [1]. Consequently, the presence of saline moisture affects the behavior of high voltage apparatus, especially for outdoor equipment near coastal areas. In [1] is reported a breakdown voltage reduction up to 22 % in case of short rod-rod air gaps with fixed separation when conductivity of saline solutions increased from 370 to 1000 pS/m.

From experimental data, several authors have proposed mathematical models for calculating ignition points and critical voltages for different high voltage apparatus. The effect of rainfall and salinity on flashover and aging in insulators is reported in [2, 6-8] but the effect of atmospheric conditions on substation connectors has been seldom modeled.

In this work the behaviour of a 765 kV AC outdoor substation connector is analyzed by means of 3D-FEM simulations as far as the electrical field distribution is concerned. Firstly the simulations are performed assuming clean and dry air conditions, and the critical points of the connector geometry regarding the electrical stress are identified. Results from simulations are validated through experimental tests carried out in a high voltage laboratory. Next, simulations are performed when the same connector operates under a saline humid environment. The results presented show that in this case the electrical stress increases notably thus favouring corona onset conditions.

The analysis method presented in this work allows optimizing the performance of substation connectors from the analysis of the critical points of the initial connector design. Hence, it permits obtaining a more reliable and safe product while minimizing the number of experimental tests required, thus reducing the time-to-market and the economic cost of the connector.

2.- FINITE ELEMENTS METHOD SIMULATIONS

Nowadays, numerical methods are widely used due to their capabilities to perform different types of simulations, while assisting the design of different kind of devices. They let lessening overall costs for manufacturing prototypes, while shortening the time-to-market.

Numerical electric field analyses can be broadly classified into domain-based and boundary-based methods. Domain-based methods include finite element method (FEM) and finite difference methods.
(FDM), while boundary-based methods include charge simulation and boundary element methods (BEM).

Domain methods divide the domain into regular volume elements for calculation purposes, based on solving differential equations. The electric potential is calculated over the region that satisfies some particular boundary conditions.

Boundary Elements Methods (BEM) use integral equations instead of differential ones. Volume integrals are transformed into surface integrals using the Green’s theorem. Therefore, elements are considered only along the boundary of different materials. The simulation accuracy depends on the number, shape and distribution of the boundary elements dealt with.

In this work we deal with 3D-FEM simulations and for minimizing the computational cost of the simulations carried out, the internal volume of the connector is not meshed. Thus we made the assumption of isotropy and homogeneity of properties in the internal part of the connector. This assumption is justified since the connector is made of aluminum, a good electrical conductor and also because the purpose of the simulation is to calculate the electrical stress at the outer surface of the connector. Hence, by this way, the weakest points of the connector surface regarding corona onset conditions are identified.

The first step when conducting a FEM analysis is the calibration of such a method to ensure accurate enough results. This step has been performed by means of an image-based algorithm whose results are recognized to be very accurate when simulating overhead power lines with bundle conductors [9]. To validate the FEM results a four-bundle conductor was simulated by means of both 3D-FEM and the images method and the boundary conditions of the first one were adjusted to obtain the same results as with the second method. Fig. 1 shows the geometry analyzed, where a meshed air box of different sizes with zero voltage and infinite elements boundary condition were imposed.

Fig. 1. Four-bundle geometry and 3D meshed domain simulated by mean of 3D-FEM. The conductors (39 mm diameter) are equally spaced 150 mm, and the applied voltage is 508 kV AC (line-to-line).

In case of the four-bundle geometry analyzed, simulations performed by means of the images method provide a maximum value of the electric field strength on the conductor surface of 21.5 kV/cm. It was found that in order to obtain results accurate enough (relative error below 5%) in accordance with measurements, the dimensions of the 3D meshed domain should be at least one order magnitude larger than the specific length of the two dimensional length, as detailed in Table 1.

Calculations are performed into the three-dimensional domain by applying the quasi-static approximation, which is justified since the power frequency is 50 Hz [10]. This assumption is valid because the size of HV substation connectors is much lower than the characteristic wavelength of the electromagnetic field produced by the system (approximately 6000 km). For a detailed analysis of the mathematical background related to the quasi-static approximation, the reader is addressed to [11-12].
Table 1 Comparison between the results of the two dimensional images method and the 3D-FEM parametric simulations.

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<th>Box length/Main length*</th>
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*Main length refers to quad bundle spacing (150 mm).

The analyzed substation connector connects a substation bus bar to a four-bundle transmission system in which the spacing between wires is 450 mm and the wires diameter is 39 mm. According to the results presented in Table 1, the meshed domain should be of the order of at least 4.5 m side.

3.- MATERIALS

In order to perform the 3D-FEM simulations, the air conductivity has been taken as 1 fS·m⁻¹ according to the results presented in [13] for atmospheric air in coastal areas. Additionally, the saline water layer conductivity was selected to 0.4 S·m⁻¹ and the dielectric constant has been assumed $\varepsilon_r = 80$ [1,14].

The studied substation connector is made of aluminium and is designed to operate continuously at a voltage level of 765 V_RMS AC (line-lo line).

4.- RESULTS

In this section the behavior of the selected substation connector is analyzed by means of 3D-FEM simulations. For this purpose a set of parametric simulations from 600 to 1200 kV_RMS AC (line-to-line) are conducted when two type of atmospheric conditions namely dry and wet are considered. For the dry case, experimental results obtained through simulations are compared with corona tests performed in a high voltage laboratory. This procedure allows validating the results obtained by means of 3D-FEM simulations.

4.1 Experimental and simulation results under dry air conditions

In this section the electrical stress around substation connectors is simulated and verified by means of experiments when the connector operates under dry atmospheric conditions. Tests performed in the HV test hall where performed to evaluate corona inception and corona extinction voltages, which according to the NEMA 107-1987 standard [15] are expressed as $V_{peak}/1.4142$. The experimental tests showed that corona total extinction voltage was about 980 kV (line-to-line). Ignition corona points were recorded using an analogical camera and added to the report as detailed in Fig. 2.

Fig. 2. Corona test performed in the high voltage hall.
The behavior of the same substation connector was analyzed by means of a set of parametric simulations, studying a voltage range from 600 to 1200 kV_{RMS} (line-to-line). These simulations allow detecting and analyzing the most stressed parts of the connector surface. Fig. 3 shows both the geometry of the three-dimensional mesh dealt with and the electric field strength at the connector surface. As expected, the most stressed parts are placed at the outer connector surface, particularly in the most curved areas [16]. The red arrows in Fig. 3 show the electric field strength direction whereas their length is proportional to the electric field strength.

![Fig. 3. Meshed connector outer surface and electric field strength obtained by means of 3D-FEM simulations when the connector is energized at 700 kV_{RMS} (line-to-line) under dry air conditions. Electric field in kV/cm.](image)

As shown in Fig. 3, the most stressed parts of the substation connector are colored from yellow to white at its surface. Fig. 3 shows clearly that the most stressed areas are on the bottom part of the connector and on the four sides of the farthest rounded connector parts.

According to both experimental and simulation results, the most stressed area of the connector has a geometric radius of about 19 mm. From references [17-18] the corona onset threshold value corresponding to this radius is comprised between 40 and 60 kV/cm. Simulation results show that the electric field strength in the most stressed surface reach the threshold values when energized at about 1000 kV_{RMS} AC (line-to-line). Consequently, simulation results are in close agreement with the laboratory tests.
4.2 Simulation results under saline moisture conditions

In this section the connector is simulated when a 1 mm thick saline moisture layer completely wets the connector surface. During foul weather, most of the connector surface may become wet because of dew, fog or rain. Under these circumstances it is known that streamers may initiate between 4.5 and 11 kV\text{rms}/cm [19]. Hence, the 8 kV\text{rms}/cm mean value is considered as the threshold stress value for corona initiation.

Fig. 4. Electric field strength through the most stressed path. Results from the set of parametric FEM simulations from 600 to 1200 kV\text{RMS} (line-to-line) under dry atmospheric conditions.

Fig. 5. Meshed connector outer surface and electric field strength obtained by means of 3D-FEM simulations when the connector is energized at 700 kV\text{RMS} (line-to-line). The simulation has into account a 1 mm thick moisture saline layer of 0.4 S m\textsuperscript{-1} conductivity that surrounds the connector. Electric field in kV/cm.
Results from Figs. 4 and 6 shown that under a saline moisture environment, the electric stress at the connector surface is enhanced by an average value of 30%, which is in agreement to the results presented in [19]. According to simulation results, the partially conductive water film greatly increases the average electric field at the connector surface, thus lowering the corona inception threshold and promoting the initiation of electrical discharges.

5.- CONCLUSIONS

Substation connectors are vulnerable to flashover, especially when operating in outdoor coastal areas under wet atmospheric conditions. In this work the behavior of a 765 kV AC outdoor substation connector has been analyzed by means of 3D-FEM simulations when operating under both dry air and saline wet conditions.

Firstly, the boundary conditions imposed to the 3D-FEM analysis have been checked by comparing the results from the 3D-FEM with the ones arising from a validated charge simulation algorithm when analyzing a simple geometry. Next, results obtained from 3D-FEM simulations of the analyzed substation connector operating under clean and dry atmospheric conditions were compared with experimental tests conducted in an indoor high voltage laboratory. Experimental results allowed validating the simulations, since both results were in close agreement. Finally, simulation tests conducted under saline moisture conditions, shown that these conditions promote the initiation of electrical discharges.

Corona tests conducted in high-voltage laboratories to check whether a connector meets the standards currently in force, are usually performed under dry conditions since most of the test halls are located in indoor laboratories. However, in this work it has been shown that wet conditions have a great impact on the electrical stress at the connector surface. Consequently, the performance of outdoor substation connectors regarding the corona inception threshold may be greatly affected when exposed to adverse atmospheric conditions, thus favoring the propagation of electrical discharges.

Hence, the method proposed in this work allows product engineers to design safer and more reliable connectors which are in compliance with the standards currently in force while ensuring an adequate behavior under adverse atmospheric conditions.
BIBLIOGRAPHY


