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Review on Corrosion Development and Studies on Overhead Line Conductors

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ABSTRACT

Overhead line conductors play a critical role in the transmission of electrical power, ensuring the efficient flow of electricity across long distances. However, these conductors are vulnerable to environmental factors, which can lead to corrosion—a major issue that compromises their structural integrity and operational efficiency. This paper provides a comprehensive review of the corrosion phenomenon affecting overhead line conductors, exploring how corrosion develops over time and identifying the key factors that influence its progression, including environmental exposure and material composition. The chemical reactions involved in the corrosion process and the subsequent impacts on conductor performance are analysed in detail. The review also examines various mitigation strategies designed to protect overhead line conductors from corrosion, including protective coatings, cathodic protection, and design improvements. In addition, the paper addresses the importance of continuous monitoring to detect early signs of corrosion, emphasizing the role of advanced sensor technologies and inspection methods. The modelling approaches and key findings from relevant studies are discussed to highlight their significance in corrosion research.

Keywords: *Conductors; corrosion; mitigation; modelling*

1. Introduction

Overhead conductors are crucial components of power transmission systems, responsible for transferring electrical energy over long distances from power generation facilities to end consumers. These conductors, typically made of aluminum, copper, or steel, are exposed to harsh environmental conditions, which can lead to deterioration over time [1]. One of the main concerns related to the longevity and reliability of overhead line conductors is corrosion, a phenomenon that affects metallic surfaces when they react with environmental elements such as oxygen, water, and pollutants. Corrosion not only compromises the mechanical strength of conductors but also increases electrical resistance, leading to energy losses and potential failures in power distribution systems requiring costly replacements or repairs [2].

The development of corrosion on overhead conductors is influenced by various factors including atmospheric conditions (e.g., humidity, temperature, and pollution), and material properties. Studies have shown that coastal areas with high salt content in the air, as well as industrial regions with high levels of pollutants, are particularly prone to accelerate corrosion rates on exposed metallic surfaces

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[3]. The chemical reactions responsible for corrosion involve the interaction of metals with electrolytes in the environment, leading to the formation of oxides, hydroxides, or salts on the conductor surface [4].

In recent years, researchers have focused on developing mitigation strategies to prevent or slow down the corrosion of overhead line conductors. These strategies include the use of protective coatings, corrosion-resistant materials, and cathodic protection systems, all of which have proven to be effective in reducing the rate of corrosion [5]. Additionally, advancements in corrosion monitoring technologies, such as remote sensing and real-time data analytics, have enabled better detection of early corrosion signs, allowing for timely maintenance interventions [6].

To better understand the corrosion behaviour of overhead line conductors, numerical modelling has become an essential tool in simulating the long-term effects of environmental factors on conductors. The use of COMSOL Multiphysics, for instance, allows researchers to create detailed models that simulate the corrosion process under varying conditions, providing valuable insights into how to improve the design and maintenance of transmission lines [7]. Experimental studies are also crucial in validating these models and offering real-world data on corrosion rates, the ability of protective measures, and the durability of materials used in power transmission systems.

1.1 Overhead Line Conductor Types

Overhead line conductors are categorized based on their material composition and mechanical properties, which directly influence their susceptibility to corrosion. The two main categories of conductors are conventional conductors and High-Temperature Low-Sag (HTLS) conductors, each with distinct characteristics that affect their performance in corrosive environments.

1.1.1 Conventional conductors

Conventional conductors have been the standard in overhead transmission lines for decades. These conductors are typically made of aluminum or copper and have been reliable for low to medium temperature operations. Conventional overhead conductors, such as Aluminum Conductor Steel Reinforced (ACSR), Aluminum Conductor Aluminum Reinforced (ACAR), and All Aluminum Alloy Conductor (AAAC), have been widely used due to their availability, cost-effectiveness, and established performance characteristics. ACSR is one of the most popular conventional conductors, consists of layers of aluminum strands wound around a steel core. The steel core provides strength, while the aluminum strands ensure high conductivity. However, conventional conductors have limitations, especially in high-temperature environments where sagging becomes a significant issue. When the temperature rises, conductors tend to sag due to thermal expansion, which could lower ground clearance, pose safety risks, and affect the transmission capacity [8]. This has led to the development of advanced conductor designs, such as High-Temperature Low-Sag (HTLS) conductors, which offer better thermal performance and reliability in demanding environments.

1.1.2 High-temperature low-sag (HTLS) conductors

HTLS conductors represent a significant advancement in overhead line conductor technology. These conductors are designed to operate at higher temperatures (up to 210°C) without sagging excessively, making them ideal for increasing transmission capacity on existing lines without the need for major infrastructure changes. HTLS conductors include variants like Aluminum Conductor Composite Reinforced (ACCR), Aluminum Conductor Composite Core (ACCC), and Invar Steel Core conductors. The primary advantage of HTLS conductors is their ability to maintain lower sag even under high thermal stress. This is achieved using materials with superior mechanical and electrical properties, such as composite cores that are lighter and stronger than traditional steel cores. The increased strength and thermal resistance of HTLS conductors ensure enhanced performance, especially in regions where high temperatures and heavy electrical loads are common [9].

1.2 Corrosion and Its Development on Overhead Conductors

Corrosion is an inevitable process for metal structures exposed to the environment, including overhead conductors. Two primary types of corrosion affecting these conductors are galvanic corrosion and atmospheric corrosion. Each develops under specific conditions, driven by electrochemical reactions, and both can significantly damage the performance and longevity of conductors, leading to costly failures.

1.2.1 Galvanic corrosion

Galvanic corrosion occurs when two dissimilar metals are in contact in the presence of an electrolyte, which causes one metal (the anode) to corrode while the other (the cathode) is protected. This type of corrosion is particularly problematic in overhead conductors that combine different materials, such as in ACSR conductors, where aluminum (the cathode) is in contact with a steel core (the anode). In this setup, aluminum, being the more anodic metal, tends to corrode preferentially, while steel acts as the cathode [10].

1.2.1.1 Chemical reactions in galvanic corrosion

In the galvanic corrosion of Aluminum, which is more anodic than steel, acts as the sacrificial anode and oxidizes (loses electrons). The key reaction for aluminum oxidation is:

$$Al \rightarrow Al^{3+} + 3e^{-} \tag{1}$$

This process releases aluminum ions into the environment. At the cathode (steel), the oxygen reduction reaction occurs. This reduction typically involves dissolved oxygen in the electrolyte (water) and occurs as:

$$O_2 + 4e^{-} + 2H_2O \rightarrow 4OH^{-} \tag{2}$$

The hydroxide ions produced at the steel cathode combine with aluminum ions to form aluminum hydroxide which appears as a white or gray powdery residue on the surface of the aluminum strands. This material is non-protective, meaning it does not form a barrier against further corrosion. As a result, the corrosion process continues as long as moisture and oxygen are present.

1.2.2 Atmospheric corrosion

Atmospheric corrosion is the result of exposure to the environment, where moisture, oxygen, and pollutants such as sulfur dioxide or chlorides initiate and accelerate the corrosion process. For overhead conductors, aluminum strands are particularly susceptible to this form of corrosion in areas with high humidity, industrial pollution, and coastal environments. Unlike galvanic corrosion, which requires two dissimilar metals, atmospheric corrosion can affect both the aluminium and steel components of the conductor, though the rate and form of degradation depend heavily on environmental conditions [11].

1.2.2.1 Chemical reactions in atmospheric corrosion

Atmospheric corrosion involves both physical and chemical interactions between the conductor's surface and its surroundings. In the presence of oxygen and moisture, aluminum forms a thin, stable oxide layer (aluminum oxide, (Al_2O_3) which generally protects the underlying metal. However, in aggressive environments, such as coastal regions with high chloride concentrations, this oxide layer can be compromised [12]. The chemical reaction of aluminum in the presence of water and oxygen proceeds as follows:

$$4Al + 3O_2 \rightarrow 2Al_2O_3 \quad (3)$$

This reaction forms a protective aluminum oxide layer, but when exposed to chloride in coastal areas, this passive layer can break down, leading to pitting corrosion. The chloride ions interfere with the passivation layer, allowing the underlying aluminum to corrode:

$$Al_2O_3 + 6Cl^- + \ 6H_2O \ \ \rightarrow 2AlCl_3 + 6OH^- \quad (4)$$

This reaction produces soluble aluminum chloride (Al_2O_3) which washes away, exposing more aluminum to corrosion.

1.2.3 Forms of corrosion

The corrosion that affects overhead line conductors can take in several forms, each with distinct characteristics and implications for conductor performance.

1.2.3.1 Pitting corrosion

Pitting corrosion is a localized form of corrosion that leads to the formation of small, deep pits on the metal surface. For overhead conductors, pitting often occurs due to the presence of chloride ions (Cl^-) from marine environments or industrial pollutants, which break down the naturally protective aluminum oxide layer. This corrosion type is especially harmful as it creates deep, narrow pits that can quickly reduce the conductor's cross-sectional area and weaken its structure. The pits form when the aluminum oxide layer is compromised, exposing the underlying metal to an aggressive environment [13]. The initiation of pitting often occurs at microscopic defects or scratches on the conductor's surface, where chlorides or other corrosive agents concentrate, leading to rapid metal dissolution.

1.2.3.2 Crevice corrosion

Crevice corrosion is a localized form of corrosion that occurs in areas where water or other electrolytes can become trapped, creating an environment that is depleted of oxygen but rich in ions. In overhead conductors, crevice corrosion typically develops in areas with narrow gaps, such as between conductor strands or between the conductor and fittings. In these confined spaces, moisture and ions get trapped, and as oxygen levels decrease, a differential aeration cell is created, where the oxygen-deprived area becomes anodic and corrodes faster than the rest of the surface. This form of corrosion can be particularly aggressive and difficult to detect until significant damage has occurred [13].

1.2.4 Impacts of corrosion on overhead line conductors

One of the most well-documented cases of corrosion affecting overhead conductors occurred in the regions of Australia, where high-voltage power lines experienced premature failure due to severe atmospheric corrosion [3]. The power lines, composed of ACSR conductors, were installed in a coastal environment rich in chlorides from sea spray. The combination of high humidity and salt-laden air created ideal conditions for atmospheric corrosion. The ACSR conductors suffered both uniform and pitting corrosion, primarily due to the breakdown of the protective aluminum oxide layer. Over time, the steel core inside the conductor also began to corrode through galvanic processes. This combination of atmospheric and galvanic corrosion caused significant degradation of the conductors' mechanical strength.

The investigation revealed that the presence of chlorides from the coastal and industrial environment had penetrated the aluminium surface, leading to extensive pitting corrosion. As the corrosion progressed, the weakened steel core could no longer support the mechanical loads imposed on the conductor. In response, the utility company had to replace the damaged conductors with corrosion-resistant alternatives, incurring significant costs [14]. This case highlighted the need for better corrosion monitoring systems and more robust conductor materials for installations in highly corrosive environments.

2. Methodology

2.1 Mitigation and Monitoring Strategy for Overhead Line Conductors

Material selection is a fundamental mitigation strategy for preventing corrosion in overhead conductors. Choosing materials with higher resistance to environmental factors, such as humidity, pollutants, and temperature fluctuations, can enhance conductor longevity. Material selection for overhead conductors is closely aligned with the specific environmental challenges of the installation location, as different settings expose conductors to various corrosive elements. In coastal areas, high humidity and salt spray can rapidly accelerate corrosion. To prevent this, conductors such as All Aluminum Alloy Conductor (AAAC), which is more resilient to chloride-induced corrosion due to its aluminum-magnesium-silicon alloy composition. Alternatively, HTLS conductors Aluminum Conductor Composite Core (ACCC) conductors, which feature a carbon or glass fibre composite core, are also well-suited to coastal regions. These materials eliminate the risk of galvanic corrosion by having a layer of fiberglass and maintain high flexibility, reducing thermal stress [15]. Applying protective coatings such as galvanization, anodization, or polymer-based layers creates an additional barrier against moisture, salt, and pollutants, protecting both aluminum and steel components from direct environmental exposure [13].

Monitoring strategies enable early detection of corrosion, allowing for timely maintenance and minimizing the risk of unexpected failures. Regular visual inspections are commonly performed to identify visible signs of degradation, such as rust, pitting, or discoloration. Robots and drones equipped with high-resolution cameras are often used for large-scale inspection, especially in difficult-to-access areas, enabling a widespread overview without manual checks [16]. Infrared thermography is another useful monitoring tool, detecting temperature variations that may indicate increased resistance and potential corrosion-related hotspots along the conductor [17]. Ultrasonic testing allows for precise measurement of conductor thickness, detecting internal degradation due to pitting or crevice corrosion. For more sensitive detection of early-stage material damage, acoustic emission monitoring is applied; this technique captures high-frequency sound waves emitted as the conductor material undergoes stress and minor fractures due to corrosion [18]. These combined approaches help ensure the integrity of overhead conductors by both preventing corrosion and monitoring their development, leading to safer and more cost-effective power transmission systems.

3. Result

3.1 Modelling and Experimental Analysis of Overhead Conductors

3.1.1 Deformation mechanisms in aluminium strands

The deformation of aluminum strands caused by galvanic corrosion on overhead conductor is studied using COMSOL Multi-physics, and the results are presented in Figure 2. The simulation data input includes the material and the cross-section area of the conductors and the environmental conditions. Figure 1 illustrates the cross-sectional model of ACSR/TW conductor. The conductor consists of 7 outer aluminum strands arranged around steel wire core. The modelling area is focused on the localized region at the interface of aluminum and steel.

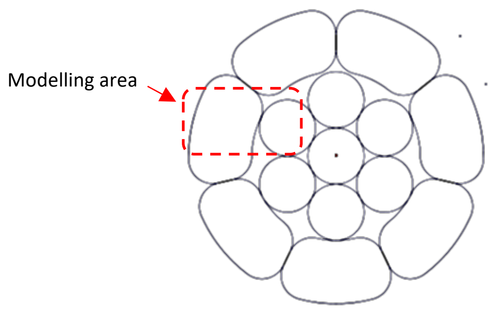

Fig. 1. ACSR/TW conductor

The trapezoidal wire ACSR/TW is modelled to study the deformation of aluminium strands. Then the materials and electrolyte properties are set accordingly. Once the model is found appropriate, the deformation and the loss of aluminium area is recorded to find the corrosion rate of the modelled conductors.

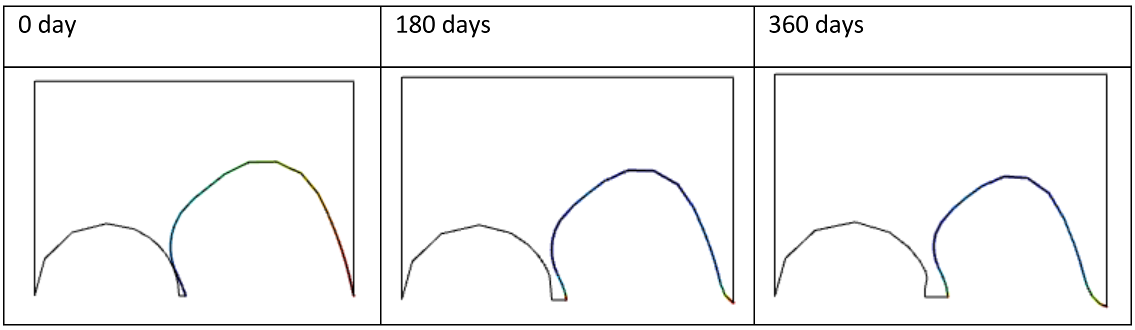

Fig. 2. Progress of ACSR/TW deformation

The trapezoidal design in ACSR/TW conductors experiences corrosion but generally at a slower rate due to the reduced surface exposure when compared to round wire type ACSR. The compact structure limits the aluminum-steel interaction surface and makes it harder for moisture to permeate through, thereby reducing the rate of galvanic corrosion. This slower corrosion rate shows a more gradual loss in the aluminum cross-sectional area over time. As a result, ACSR/TW conductors typically retain their conductive and mechanical properties longer under corrosive conditions compared to ACSR/RW, leading to a more extended operational lifespan.

3.1.2 Experimental works on overhead line conductors

For overhead conductor corrosion studies, experiments often involve exposing aluminium conductors or aluminium alloys to simulate environmental conditions that mimic the factors impacting actual conductors in service. One common experimental setup for testing conductor corrosion involves Salt Spray Chambers or Fog Testing. In these tests, aluminium conductor samples are placed in a controlled chamber where they are exposed to a mist containing saline solution, replicating the salt-laden atmosphere of coastal areas [19]. Over time, samples are observed for signs of pitting corrosion and surface degradation, providing data on how quickly and intensely corrosion progresses under these specific conditions.

Another experimental approach uses Electrochemical Impedance Spectroscopy (EIS) to measure the corrosion rate of conductor materials. In this method, an aluminium sample is submerged in an electrolyte solution with controlled levels of chloride and sulfate ions, simulating exposure to coastal and industrial environments. Finally, High-Resolution Microscopy, such as Scanning Electron Microscopy (SEM), is used to examine the microstructure of corroded conductor samples [20]. Comparing these observations to COMSOL's models allows researchers to assess how accurately the software simulates deformation and corrosion patterns. These experimental works are invaluable in validating the results from COMSOL simulations. Such validation ensures that the COMSOL model can reliably predict conductor lifespan and performance, guiding improvements in materials selection, design, and maintenance strategies for overhead line conductors.

4. Conclusion

This review underscores the significant impact of corrosion on overhead line conductors, showing how environmental factors and material choices influence corrosion progression. While protective measures such as coatings and HTLS conductors provide better defense, their effectiveness was compromised if these protections are damaged, leading to accelerated degradation. Comparative analysis reveals that HTLS conductors better preserve structural integrity and ampacity under corrosive conditions compared to conventional ACSR conductors. However, further analysis is required to refine these findings and explore additional protective strategies. Enhanced monitoring and predictive maintenance remain critical to extending conductor lifespan and ensuring reliable power transmission.

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