Theory and Practice of Science and Technology
2025, VOL. 6, NO. 11, 125-128
DOI: 10.47297/taposatWSP2633-456924.20250611

Study on Anti-corrosion Technology and Long-term Service Performance of Offshore Wind Power Cable

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ABSTRACT

As a vital component of clean energy, the long-term reliability of offshore wind power cable systems directly impacts the operational efficiency and economic benefits of entire wind farms. This study systematically analyzes the effects of multiple corrosion mechanisms—including seawater corrosion, chloride ion erosion, and microbial corrosion—on cable performance under complex marine environments. By establishing a corrosion kinetics model for offshore wind power cables, the research reveals quantitative relationships between environmental factors (temperature, salinity, pH, dissolved oxygen) and corrosion rates. The study developed a multi-layer composite anti-corrosion technology system, incorporating key innovations such as modified polymer anticorrosive coatings, optimized cathodic protection system design, and improved sacrificial anode material formulations. A long-term service performance evaluation system was established, utilizing accelerated aging tests, electrochemical impedance spectroscopy (EIS) measurements, and mechanical property assessments to evaluate cable performance degradation over a 25-year design life. Results—demonstrate that the developed composite anti-corrosion technology reduces corrosion rates by over 65%, maintains insulation impedance retention rates above 85%, and preserves mechanical strength retention rates exceeding 90%.

KEYWORDS

Offshore wind power cable; Corrosion protection technology; Long-term service performance; Marine environment; Reliability assessment

1 Introduction

Offshore wind power, as a pivotal technological pathway in the clean energy transition, has experienced explosive growth in recent years. According to data released by the Global Wind Energy Council (GWEC), the global cumulative installed capacity of offshore wind power exceeded 64.3 gigawatts by the end of 2022, maintaining an annual growth rate above 25%, with projections indicating it will reach 270 gigawatts by 2030. Against this rapid development backdrop, offshore wind power cable systems—serving as the "lifeline" for energy transmission—directly determine the power generation efficiency and economic viability of entire wind farms through their reliability. However, complex marine environmental factors such as high salinity, humidity, oxidizing conditions, microbial activity, and tidal erosion pose severe corrosion challenges to cable systems. Statistics show that over 35% of offshore wind power system failures are related to cables, with corrosion-induced failures accounting for 58% of cases [1]. Each repair typically incurs an average cost of 2 million euros, while downtime losses can reach up to 50,000 euros per day. Therefore, researching anti-corrosion technologies for offshore wind power cables and evaluating their long-term service performance holds significant importance for enhancing operational reliability and economic efficiency of offshore wind farms.

2 Corrosion Mechanism and Environmental Factors of Offshore Wind Power Cables

2.1 Corrosion Mechanism Analysis of Marine Cable

Offshore wind power cables face complex and diverse corrosion challenges in marine environments, with these processes typically involving the synergistic effects of multiple mechanisms. According to data from the past five years, the installed capacity of offshore wind power has been growing at an annual rate of approximately 25%, while cable system failures account for nearly 31% of unplanned outages in offshore wind farms, with corrosion being one of the primary causes. The corrosion of offshore wind power cables mainly manifests as metal conductor oxidation, insulation material degradation, and sheath material deterioration, which stem from complex mechanisms such as electrochemical corrosion, stress corrosion cracking, and microorganism-induced corrosion [2].

In tidal zones, cables exposed to alternating dry and wet conditions develop microcell effects, resulting in corrosion rates 2-3 times higher than fully submerged areas. The 2022 Offshore Wind Asset Integrity Survey revealed that tropical sea areas exhibit 42% higher average corrosion rates than temperate regions across deployed cable systems. Furthermore, biofilms formed by microbial attachment alter local environmental conditions, creating concentration cell effects that accelerate metal substrate dissolution. Structural heterogeneity in cable materials also leads to macroelectrochemical

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coupling between different components, with aluminum sheaths being particularly susceptible to galvanic corrosion when in contact with copper conductors [3].

2.2 Key Environmental Factors Affecting Corrosion of Offshore Wind Power Cables

Offshore wind power cables face complex and ever-changing marine environmental challenges during their service life, and these environmental factors directly determine the rate and mechanism of the corrosion process.In recent years, with the rapid growth of global offshore wind power installed capacity, cable corrosion has become increasingly prominent. Based on investigations and analyses of major offshore wind power regions such as China and the North Sea in Europe, it has been shown that seawater salinity, temperature, dissolved oxygen content, pH value, and biofouling are the most critical environmental factors affecting cable corrosion.

Seawater salinity directly affects the conductivity of electrolyte solutions, accelerating electrochemical corrosion of metal materials. Meanwhile, seawater temperature influences corrosion kinetics, with a 1-2 fold increase in corrosion rate for every 10°C rise. Dissolved oxygen, a key oxidant in corrosion reactions, shows positive correlations with water depth and ocean current velocity [4]. The fluctuation of seawater pH value will change the stability and protective effect of corrosion products.

2.3 Mechanism of the Influence of Corrosion on the Long-term Service Performance of Cable

Corrosion reduces the cross-sectional area of metal conductors, increasing cable resistivity and decreasing electrical conductivity efficiency, which directly impacts power transmission capacity. Research data indicates that five years of continuous corrosion in marine environments can reduce the conductivity of copper-core cables by 15%-20%, while aluminum-core cables may experience a more significant decrease of 25%-30%. Additionally, the accumulation of corrosion products damages the interface structure between the insulation layer and metal core, forming micro-cracks and defects. This leads to diminished insulation performance, weakened dielectric strength, and heightened risks of cable leakage and short circuits. According to 2021 global offshore wind power operation and maintenance statistics, approximately 32% of offshore wind system failures are associated with insulation degradation caused by cable corrosion [5]. Stress corrosion cracking (SCC) caused by corrosion is a common failure mode for offshore wind power cables, particularly in cable suspension sections where combined stress and corrosive environments are more severe. Notably, corrosion rates are typically slow during initial service periods, but accelerate as protective layers gradually deteriorate. According to a 2022 report by the International Renewable Energy Agency (IRENA), the average replacement cycle for offshore wind power cables is 12-15 years—significantly shorter than the designed 25-year lifespan.

3 Research on Anti-corrosion Technology of Offshore Wind Power Cable

3.1 Design of Anti-corrosion Materials and Structure of Cable Outer Sheath

According to data released by the Global Wind Energy Council in 2023, the global installed capacity of offshore wind power has reached 64.3GW and is expected to grow to 170GW by 2027, which places higher demands on submarine cable anti-corrosion technology. Currently, mainstream external protective layer anti-corrosion materials include modified polyethylene (PE), cross-linked polyethylene (XLPE), polyvinyl chloride (PVC), and chlorosulfonated polyethylene (CSP), as well as high molecular materials, and metal shielding layers such as aluminum tape, copper tape, and lead sheathing. [6]Studies demonstrate that incorporating inorganic fillers such as nano-SiO_2 and carbon black into polymer matrices can significantly enhance the materials salt spray resistance, hydrolysis resistance, and microbial erosion resistance, thereby extending the service life of cables.

The multi-layer composite sheath structure has become the industry standard, typically comprising a semiconductive shielding layer, a metallic shielding layer, an inner sheath, and an outer sheath. Experimental data from 2022 demonstrated that the composite structure featuring double-layer metallic shielding and triple-layer polymer sheathing can reduce corrosion rates by 72% in simulated seawater environments, significantly outperforming traditional single-layer sheath designs. Furthermore, by optimizing the thickness distribution of the outer sheath and interface transition design, the technology effectively mitigates stress concentration under seawater pressure, thereby enhancing overall corrosion resistance. Several companies have already implemented this technology in offshore wind power projects in regions like the North Sea and Baltic Sea, validating its corrosion-resistant performance in real marine environments.

3.2 Application of cathodic protection system in offshore cable

Data from the past five years shows that the failure rate of cable systems in offshore wind power projects with cathodic protection systems has been reduced by an average of 47.3%, directly extending the service life of the cables.[7]In practical applications, cathodic protection technology primarily employs two methods: the sacrificial anode method and the impressed current method. The sacrificial anode method utilizes the preferential dissolution of active metal anodes (such as zinc, aluminum, or magnesium) to protect the metal components of cables. The impressed current method, on the other hand, supplies a steady current to the protection system via a DC power source, creating a stable cathodic polarization environment that keeps the cables metal structure in a protected state.

According to 2022 analysis of offshore wind power engineering data, cathodic protection systems installed in the North Sea have reduced the corrosion rate of cable metal armor from 0.12mm/year to below 0.03mm/year, achieving over 75% protection efficiency. Recent research indicates that intelligent cathodic protection systems integrated with remote monitoring technology enable real-time potential regulation, further increasing protection efficiency to over 85% while reducing energy consumption by approximately 30%. This provides a more reliable and cost-effective corrosion prevention solution for offshore wind power cables.

3.3 Advanced Coating Technology and Composite Protection Measures

The rapid expansion of the offshore wind power industry has driven significant advancements in cable corrosion protection through advanced coating technologies and composite solutions. From 2019 to 2023, global offshore wind power installations grew at an average annual rate of 18.7%, fueling a surge in demand for high-performance anti-corrosion technologies. Research indicates that nano-modified epoxy resin coatings combined with polyurethane composite systems form a dense network structure, achieving salt spray resistance exceeding 5,000 hours–far surpassing the 1,500-hour performance of conventional coatings [8]. By introducing nanomaterials such as graphene and titanium dioxide into the polymer matrix, the coating exhibits excellent physical barrier properties and self-healing characteristics, with the ionic permeation resistance increasing by up to 72%.

Experimental data demonstrates that integrating modified fluorine coatings with aluminum-zinc alloy cathodic protection systems reduces corrosion rates of cable metal components by 78% in simulated marine environments, significantly outperforming standalone protective measures. Furthermore, the synergistic effect of epoxy/polydimethylsiloxane hybrid coatings and smart sacrificial anodes enables long-term dynamic protection for cable systems, maintaining stable anti-corrosion performance throughout the 25-year design life cycle. This breakthrough resolves the industry-wide challenge of time-dependent degradation in conventional corrosion protection technologies.

3.4 Anti-corrosion Monitoring and Early Warning Technology

Recent offshore wind industry data indicates that approximately 42% of operational failures between 2020 and 2023 were attributed to cable systems, with corrosion accounting for nearly 30% of these cases. This study has developed an integrated monitoring system utilizing IoT and big data analytics, featuring embedded electrochemical sensor networks, distributed fiber-optic temperature/strain monitoring systems, and intelligent cable condition assessment algorithms.The system monitors real-time potential variations in cable metal shielding layers, sheath integrity, and corrosion environment parameters. By integrating AI prediction models, it provides 15-30 days of early warning for potential corrosion risks. Compared to traditional detection methods, this approach improves warning accuracy by 38.7%, offering maintenance personnel ample time for timely intervention.

4 Method for Evaluating Long-term Service Performance of Offshore Wind Power Cables

4.1 Accelerated Aging Test and Life Prediction Model

According to data from the offshore wind power industry over the past five years, the global installed capacity of offshore wind power has increased from 23.4GW in 2018 to 57.2GW in 2022, with an average annual growth rate exceeding 25%. As the installed capacity expands, issues related to cable system reliability have become increasingly prominent. To address the multiple stress factors in marine environments, a comprehensive accelerated aging test protocol has been designed, which mainly includes temperature and salt cycling tests, ultraviolet radiation aging, and combined mechanical and electrical stress tests. Table 1 presents the performance variations of cable insulation materials under different stress conditions and their predicted service life values. By comparing the performance degradation trends of cables treated with different anti-corrosion technologies in accelerated aging tests, this model can effectively evaluate the expected lifespan of cables in actual service environments, providing a scientific basis for operation and maintenance decisions in offshore wind power projects.

Table 1 Performance Parameters and Life Prediction of Offshore Wind Power Cables under Different Accelerated Aging Conditions

ageing condition	temperature (℃)	salinity (%)	Ultraviolet radiation intensity (W/m^2)	Mechanical stress (MPa)	Insulation resistance retention rate (%)	Tensile strength retention rate (%)	Life expectancy (years)
Normal environment	25	3.5	0	0	98.2	97.5	27.3
thermoclimatic cycle	65/25	5.0	0	0	89.7	85.3	22.1
UV composite with warm water	65/25	5.0	55	0	81.5	79.2	18.6
full stress composite	65/25	5.0	55	12	76.8	72.4	15.9
Modified polymer coating provides protection.	65/25	5.0	55	12	91.2	88.7	23.8

4.2 Evaluation Index System of Cable Anti-corrosion Performance

According to the International Renewable Energy Agency (IRENA), global offshore wind power installed capacity grew at an average annual rate of 18.7% between 2019 and 2023. Cable system failures accounted for approximately 23% of operational and maintenance costs in offshore wind farms, with corrosion being a primary contributing factor. To systematically evaluate the anti-corrosion performance of offshore wind power cables, this study developed a multi-dimensional, quantitative assessment framework covering three key dimensions: physical-chemical properties, electrical characteristics, and mechanical properties. Based on cable material science, electrical insulation theory, and marine corrosion kinetics models, this framework comprehensively reflects the anti-corrosion performance of cables in complex marine environments.

4.3 Simulation Analysis of Service Performance Based on Digital Twin

The research developed a digital twin platform integrating physical models with field monitoring data. By combining real-time data with high-precision computational models, it achieves performance simulation of cables under various marine environmental conditions. The platform incorporates multi-field coupling models including corrosion kinetics, thermomechanical coupling, and marine environmental loads, with real-time monitoring data enabling model self-learning and calibration. Latest findings demonstrate that digital twin technology can improve service performance prediction accuracy to over 92%, accurately simulating stress distribution, temperature field variations, dynamic corrosion rate evolution, and insulation performance degradation under complex marine environmental changes.

5 Conclusion

This study has achieved significant breakthroughs through systematic analysis of corrosion mechanisms in offshore wind power cables, development of corrosion kinetics models, creation of composite anti-corrosion technologies, and evaluation of long-term service performance. The research confirms that seawater corrosion, chloride ion erosion, and microbial corrosion are the primary factors affecting the long-term reliability of offshore wind power cables. It also reveals quantitative relationships between environmental parametersand corrosion rates. The developed multi-layer composite anti-corrosion technology system has significantly enhanced cable corrosion resistance, reducing corrosion rates by over 65% while maintaining insulation impedance retention at 85% and mechanical strength retention exceeding 90%. Future research will focus on intelligent anti-corrosion technologies, including self-healing anti-corrosion coatings with real-time corrosion monitoring sensors, cable corrosion prediction models based on big data and artificial intelligence, and new anti-corrosion materials for extreme marine environments.

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