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Stress corrosion cracking and brittle failure in a fiber-reinforced plastic (FRP) insulator from a 400 kV transmission line in humid environment

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ABSTRACT

A fiber-reinforced plastic (FRP) suspension insulator belonging to the Israel Electric Corporation (IECo) failed catastrophically on a 400 kV transmission line during service at the humid south Israeli coastline. The failure occurred during the summer of 2016 after 15 years of service. The suspension had a declared life expectancy of 30 years. The failure resulted in a local outage at a high cost. An investigation was commissioned. The insulator includes a FRP rod with a housing and weather-sheds made of silicon rubber (SiR); the FRP rod is fitted into a metal connector at its end. The fracture occurred 30–40 mm above the metal fitting/grading ring area near the first weather-shed. Macroscopically, the fracture surface was partially characterized by the features of brittle fracture mode in FRP, while the rest of the fracture surface featured severe fiber pullout and debonding. It was also possible to observe that a large crack in the SiR housing led directly to the fracture surface area that included stained and crushed fibers. EDS analysis revealed that the housing around the crack and the stained fibers themselves were polluted with a significant amount of nitrogen, in addition to other foreign pollutants. After surveying similar cases, it was strongly suggested that the source of nitrogen was nitric acid formed as a result of corona discharges on the insulator's surface. The acid caused the housing, fiber and resin to undergo corrosion. SEM imaging revealed fiber fracture surfaces with a morphology typical of stress corrosion cracking, showing that stress was part of the failure mechanism. The fracture of fibers and loss of resin led to a decrease in FRP rod strength and to failure.

1. Introduction

In the power industry, many types of failures are common whether they occur at the generation [1,2], transmission [3–5] or transmission to-distribution [6,7] stages. Transmission infrastructures in particular are constantly exposed to damaging environmental factors such as wind, natural and artificial pollutants, heat, humidity, UV radiation and other factors. In recent decades, the use of composite non-ceramic insulators has increased amongst electric transmission companies worldwide due to their advantages such as low weight and cost, high mechanical strength-to-weight ratio, high damage tolerance, flexibility, excellent impact resistance, and ease of installation [3–5]. Insulators of this type have been successfully applied on transmission lines ranging from 69 to 735 kV [3]. However, over time it has become apparent that insulators of this type have unique weaknesses that have made them prone to certain failures over time. Common failure mechanisms include brittle fracture mode, and over-crimping [4].

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Fig. 1. 400 kV composite insulators (Reliable corp.)

Composite insulator failures and their mechanisms in brittle mode have been widely studied for the last two and half decades. In a number of notable studies [5,8], it was established via FTIR that nitric acid was the main corrosive medium that formed on insulators as a result of corona discharges, and eventually caused the FRP rod to corrode and fail in brittle fracture mode (stress corrosion process); A formation process of nitric acid was suggested, and in certain cases it was possible to pinpoint insulator areas where acid was at its highest concentration during and after failure. In other studies, the stress corrosion fracture process in nitric acid was investigated [9], and the performance of a number of FRP types was studied in a series of experiments [4], including a comparison of their mechanical performance in nitric acid.

A clear presentation of the most important brittle-fracture process characteristics has been presentenced in the literature [3], including fractographic guidelines for indentifying the stress corrosion fracture mechanism. Such characteristics were also presented when the stress corrosion process itself was investigated [10].

Other studies have investigated the process mechanism involving the deterioration of the silicon rubber material which protects the FRP rod in the insulator; Such deterioration included changes in mechanical properties and filler-related weight loss [11]. Silicon rubber deterioration was also investigated in the context of hydrophobicity loss [12], important in assessing the decrease in insulator resistance.

The following work presents the failure analysis of a composite fiber-reinforced plastic (FRP) suspension insulator. The insulator was vertically installed on a 400 kV transmission line along the humid south Israeli coastline (average: ~70% RH) Fig. 1. The insulator had a declared life expectancy of 30 years and failed after 15 years in service. The failure caused a temporary local outage at a high cost. An investigation was commissioned to find the root cause of the failure (RCA). The insulator has a length of 4 m, includes 75 weather-sheds with alternating diameters of 169 and 137 mm, two grading rings with diameters of 210 and 310 mm and two metal connectors/fittings at each side of the insulator, Fig. 2. The rod core of the insulator is composed of FRP, and is housed with a silicon rubber (SiR) protection layer which is also the material composing the weather-sheds. The rod diameter including housing is 30.3 mm. The metal fitting is connected to the FRP rod via crimping, Fig. 2.

Initially, visual examination of the FRP and housing fracture surface revealed that the FRP fracture had distinct zones, indicating a multistage failure involving brittle fracture and fiber pullout. It was also revealed that the SiR housing had undergone chemical deterioration at a point just above the area where it was suggested that the FRP had also deteriorated chemically.

Stereoscopic examination revealed that the degraded area in the SiR housing included a deep crack along the whole width of the SiR housing from the external to the internal surface, enabling the passage of polluted mediums from the surface into the FRP rod. SEM imaging revealed the physical damage that had occurred to the FRP material, and chemical analysis via EDS together with cross-referencing of the literature revealed the nature of the acidic pollutant that had infiltrated the SiR housing and had caused corrosion. EDS analysis also revealed the presence of nitrogen-based species on the external housing surface and the chemical deterioration of the SiR housing, partly responsible for creating the conditions enabling crack development along the width of the housing.

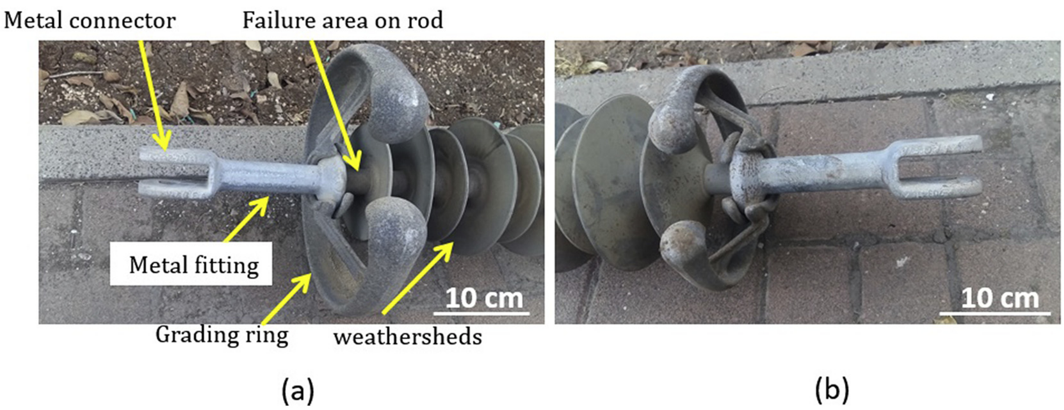

Fig. 2. (a) insulator end with long-diameter grading ring (b) insulator end with short-diameter grading ring.