POLYMER MATRIX COMPOSITES IN HIGH VOLTAGE TRANSMISSION LINE APPLICATIONS

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1 Background Information

Polymer matrix composites (PMC) can be highly desirable materials for various types of electrical and mechanical applications because of their excellent specific properties. However, these properties can be seriously compromised if the composites are subjected to extreme environments. Many extreme environments can be envisioned, including high voltage (HV) transmission line applications (Fig. 1).

Fig.1. High voltage transmission lines.

In HV applications, Glass Reinforced Polymer (GRP) composites have been widely used in the designs of composite transmission line insulators (Fig. 2), transmission and distribution towers, and in substation applications [1-19]. However, it was been shown by Kumosa et al. [1-12] that the in-service conditions can be especially damaging to the structural integrity of transmission line insulators based on PMC if they are improperly designed.

Composite suspension insulators (also referred to as either non-ceramic, polymer or polymeric insulators) are used worldwide in overhead transmission line applications with line voltages in the range of 69 kV to 735 kV. The first composite insulator was developed in the US by General Electric in the 50s. Then, over the years, the technology has been developed predominantly in Europe and in the US into the second and third generation of insulators supporting, in some cases, the most critical transmission lines in many places of the world. Despite the fact that this technology has been dramatically improved, the insulators have been sporadically failing in service, dropping energized transmission lines and causing line outages at various utilities.

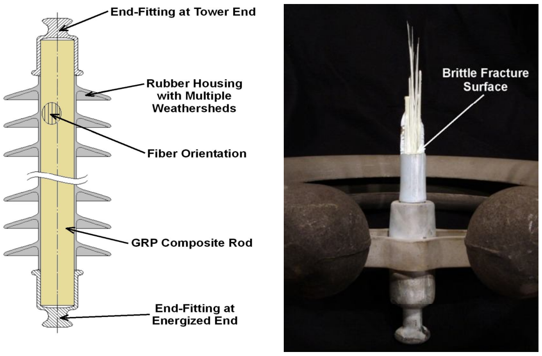

Fig. 2. Non-Ceramic Insulators; (left) design and (right) in-service failure by brittle fracture of a 500kV insulator.

The design of composite suspension insulators is rather straightforward. The insulators rely on unidirectional GRP composite rods as the principle load-bearing component (Fig. 2). The rods, usually 15 mm in diameter, are manufactured by pultrusion and the constituents are either polyester, vinyl ester, or epoxy resins reinforced with either E-glass or Electric Corrosion Resistant (ECR)-glass (also called boron-free E-glass) fibers. The surface of the GRP rod is covered with a rubber housing material with multiple weathersheds. The purpose of the housing is to protect the GRP rods against outside environments (predominantly moisture, pollution and corona discharges).

The primary purpose of the weathersheds is to increase the leakage distance between the energized and ground ends of the insulators and to protect the GRP rod against the outside environment. Today, common housing materials are ethylene-propylene rubbers, different types of silicon rubbers and ethylene vinyl acetate-based elastomers. Other composite insulators such as substation or line post insulators are based on the same design. However, they usually rely on large GRP rods, up to 50 mm in diameter. There are two metal end fittings attached to the GRP rods at both ends of the insulators (Fig. 2). In modern composite insulators the fittings are usually attached to the rod by crimping [2].

In spite of many benefits, which the insulators can offer in comparison with their porcelain counterparts (high mechanical strength-to-weight ratio, improved damage tolerance, flexibility, good impact resistance, and ease of installation), they can fail mechanically in service by rod fracture, and electrically by flashover [1-12].

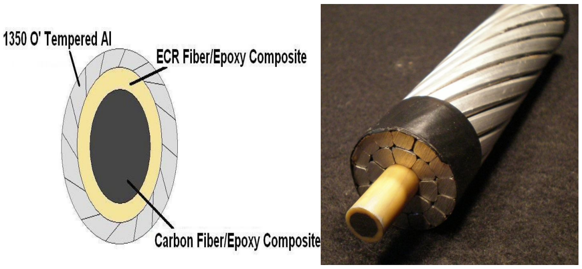

Fig. 3. High Voltage PMC conductor; (left) schematic and (right) design of ACCC.

PMCs are also beginning to be used in the next generation HV high temperature (HT) electric conductors (Fig. 3) [13-19]. Present overhead electrical conductors are based on either the Aluminum Conductor Steel Reinforced (ACSR) or Aluminum Conductor Steel Supported (ACSS) design. These lines are subject to significant amounts of sag during HT operation. Thus, new designs of HV overhead conductors have been considered for potential applications [13], which could reduce the "sag problem," and allow more power to be transmitted using the existing structures. One of the new designs, known as the Aluminum Conducting Composite Core (ACCC^{TM}) conductor [13], is based upon hybrid PMC core rods with two different reinforcing fibers (Fig. 3). The inner high strength core is based on continuous carbon fibers embedded in a high temperature epoxy. The carbon core is surrounded by a thin sheath of unidirectional dielectric ECR-glass fiber/high temperature epoxy composite. The glass/epoxy layer is incorporated into the design in order to prevent a direct electrical path between the conducting aluminum wires and the conductive carbon fibers, preventing a potential galvanic reaction.

To mitigate stress corrosion cracking of the glass fiber composite portion of the conductor [4], corrosion resistant ECR (boron free) glass fibers are used. The current expectation is that the PMC conductors, especially the ACCC design, should be able to transport, in theory, up to 3 times more electric current at much higher temperatures (up to 180°C) and significantly reduce sagging. These advantages could revolutionize power transmission world-wide.

In this review paper the most important accomplishments from the composite insulator research performed between 1993 and 2007 [1-6,8-12] in our laboratory and its impact on the global transmission line systems and the global economy are described. Then, our current on-going HT PMC conductor research [14-17, 19], its' most important findings thus far, and its' international importance is presented.

2 In-Service Stresses on PMC HV Insulators and Conductors

In-service, PMC insulators and conductors are subjected to the combined action of severe mechanical, electrical and environmental (chemical) stresses [1-19]. The mechanical stresses consist of multi-axial loads caused by the weight of the lines, manufacturing residual stresses, dynamic stresses caused by Aeolian vibrations (high cycle fatigue) and line galloping (low cycle fatigue), complex multi-axial stresses dominated by transverse compression near the mechanical connections (suspension clamps). In addition, the lines can be affected by the manufacturing/installation stresses created by excessive bending of the conductors around mandrels, travelers and tensioners, and mishandling of the insulators mostly during either manufacturing or installation. The electrical and environmental stresses imposed on the PMC insulators and conductors in-service are equally complex and consist of high voltage fields (up to 735kV), corona, partial discharges and extreme leakage currents. In addition, internal galvanic reactions between the aluminum strands and carbon fibers in the PMC conductor design can occur if the dielectric barrier (see Fig. 3) is compromised either by mechanical loads, mishandling, or aging.

The chemical stresses can also be damaging to PMC insulators and conductors. In the case of the conductors, prolonged exposure to elevated temperatures up to 180°C in air may lead to physical and chemical aging of the composite core in the presence of ozone and atomic oxygen. Other pollutants such as nitric acid, sulfur, alkalis, chlorine, etc. can also concentrate on the insulator and conductor surfaces in highly contaminated areas. Vandalism can be a major problem, as well. In certain areas gunshot damage to transmission lines is a common phenomenon.

3 PMC Insulator and Conductor Research

3.1 Composite HV Insulators

The combined effect of complex mechanical and environmental stresses, in some cases, has led to the catastrophic and unpredictable mechanical and electrical failures of the insulators in-service resulting in the drop of energized transmission lines [1-12]. The most important mechanical failure modes of the insulators are electro-mechanical failures by a process termed, by the electric community, as “brittle fracture”, as shown in Fig. 2. Regarding purely electrical in-service failures, they include contamination flashovers, the failures of the rods due to internal discharges and others [7, 12].

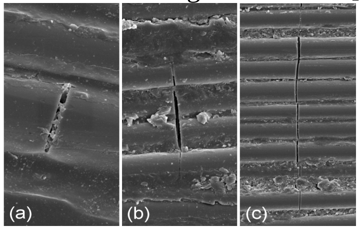

Fig. 4. Stages of stress corrosion cracking on the surface of GRP rods used in PMC insulators.

In brittle fracture, stress corrosion cracks are formed inside the GRP rods of the insulators due to either corona or partial discharges in the presence of moisture, creating nitric acid solutions of a considerable strength [1, 6, 9, 10, 12]. The cracks are initiated on the surface of the GRP rods very close to their energized end fittings (Fig. 2).

The corrosion process starts from a single fiber crack which subsequently propagates across the composite in the transverse directions to the fibers (Fig. 4). The process is highly dependent on the supply of nitric acid, insulator design, the external mechanical and electrical loads, and other variables. This process has been simulated under laboratory conditions with and without the presence of corona discharges [1, 6, 9, 10, 12]. In addition, a brittle fracture failure model of GRP insulators has been proposed (Fig. 5), which is now widely accepted by the transmission line community [6, 10].

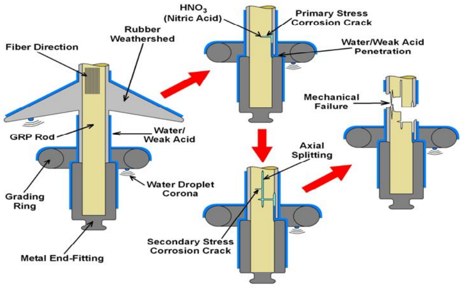

Fig. 5. Brittle fracture model.

Several stress corrosion tests with and without high voltage have been designed [9]. However, it turned out that the most successful test was a four point bend test shown in Fig. 6. In that test, composite specimens are subjected to bending in the presence of an acidic solution. At the same time acoustic emission was monitored to identify the fracture of individual glass fibers by stress corrosion. Using the set-up all most important glass fiber/polymer insulator composites were ranked for their resistance to stress corrosion cracking, and thus brittle fracture (see Table 1) [4, 6, 11, 12].

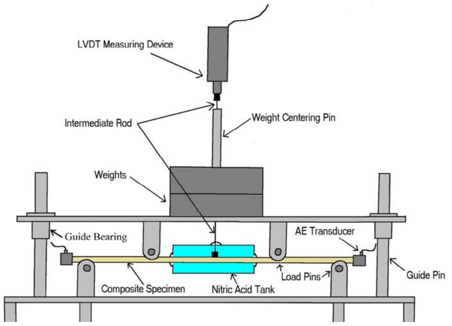

Fig. 6. Four point bend stress corrosion set-up.

Table 1. Average AE Events after 72 hours for as-supplied glass/polymer materials subjected to1N nitric acid in the four point bend fixture.

Material	Average AE Events
E-glass/Modified Polyester	44,000 out of (6) tests
E-glass/Epoxy	1500 (5)
E-glass/Vinyl Ester	35 (5)
ECR (high seed)-glass/Modified Polyester	325 (3)
ECR (high seed)-glass/Epoxy	140 (3)
ECR (high seed)-glass/Vinyl Ester	175 (3)
ECR (low seed)-glass/Epoxy	3.5 (3)
ECR (low seed)-glass/Vinyl Ester	15 (3)

Evaluating several different GRP composite systems for HV insulation applications for their resistance to stress corrosion (Table 1), moisture absorption, leakage currents and others, it has been established that E-glass/modified polyester exhibits by far the lowest resistance to brittle fracture with the ECR (low seed)- glass/vinyl ester being the best [4, 6, 11, 12]. At present almost all composite transmission insulators are manufactured based on the ECR-low seed/epoxy system, which was not the case when the project was initiated fifteen years ago. At that time, E-glass/polyester was commonly used in the insulators.

Seeds are small trapped air bubbles inside ECR-glass fibers left from glass fiber manufacturing (Fig. 7) [5]. It can be seen in Table 1 that the seeds affect the resistance of this type of glass fiber to corrosion. In addition, they have a dramatic effect on the electrical properties of ECR-glass/polymer composites (Fig. 7) [5, 8].

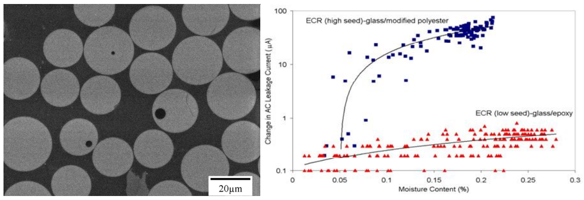

Fig. 7. Effect of seeds on leakage currents; (left) seeds in ECR-glass/polymer insulator composite and (right) leakage currents vs. moisture for low and high seed ECR/polymer composites.

The effect shown in Fig. 7 [5, 8] was one of the reasons why some insulator manufacturers were, in the past, understandably reluctant to replace E-glass fibers with their boron free counterparts to prevent brittle fracture. The low seed fibers tested in our research contained on average approximately 0.5 seeds/gram, whereas the high seed fibers exhibited a wide range between 10 and 60 seeds/g. Therefore, the seed counts in the high seed ECR fibers were 20-120 times higher than in the low seed fibers. The high content of seeds resulted in much higher leakage currents (approximately 100 times higher) in the high seed composite, in comparison with the low seed composite, especially for large amounts of absorbed moisture. At present, almost all new PMC composite insulators and conductors are based on low-seed ECR-glass fibers.

3.2 PMC Conductors

Several critical issues regarding the structural integrity of the next generation HV HT conductors based on PMC have been recently investigated in our laboratory [14-17, 19]. First of all, the effect of excessive bending loads generated either during manufacturing, transportation and/or installation on ACCC conductors was examined both numerically and experimentally [14-17].

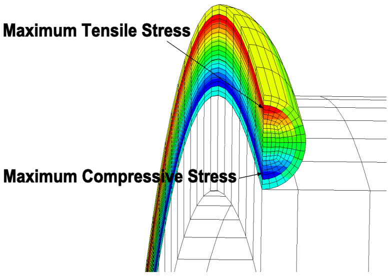

Fig. 8. Stresses in ACCC core under large bending.

As an example, internal stresses in the conductor core are shown in Fig. 8. This was accomplished by performing a non-linear bending/contact analysis. The most internally overstressed region of the rod under bending was found inside the carbon/epoxy section of the rod just near the carbon/glass fiber interface, on the compressive side of the rod. A clearly defined critical bend radius for the onset of damage of the current designs of the ACCC conductors has been found [16]. Bending ACCC rods over small mandrels, travelers, pins, etc. below the critical bend radius will generate compressive stresses in the rods high enough to cause fiber kinking and splitting affecting the structural integrity of the conductors in-service.

Fig. 9. In service failures of ACCC conductors [18].

Using the critical bend radius determined numerically and verified experimentally through our research, three catastrophic failures of the conductors which occurred in Poland in 2008 [18] (Fig. 9) and an additional failure in the US were explained. Our explanations were reported to the transmission line community in 2010 (IEEE PES, Minnesota July 2010) [17].

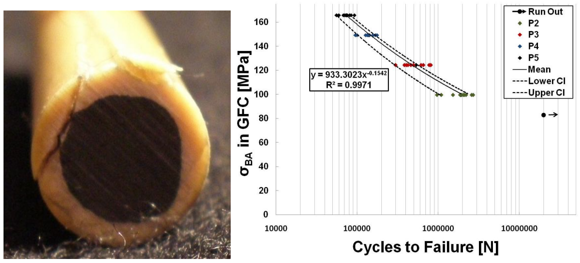

Fig. 10. HCF of ACCC conductors; (left) damage to the core and (right).

The effect of high cycle fatigue (HCF) on the conductor PMC composites has also been evaluated [19]. This was done to determine life of the conductors as a function of the degradation rate of their PMC. HCF failures of the conductors occur in-service most commonly at mechanical connections, under relatively low frequency, and low magnitude vibrations called aeolian vibrations. The vibrations will generate cracks of various shapes and orientations in the glass/epoxy part of the composite (Fig. 10) depending on the magnitude of bending, and transverse compressive stresses caused by the sleeves.

The influence of HT and HV fields on the long term performance of the PMC conductors is a significant concern at present among potential users of the conductors. Therefore, the individual and combined effects of HT, ozone and atomic oxygen on HT epoxies and glass fiber/carbon fiber/HT epoxy composites is being investigated in our present research, both experimentally and numerically. As an example, the oxidation layer in a HT epoxy subjected to 1% ozone at 140°C and the three point bending strengths after aging in different aging condition are shown in Fig. 11.

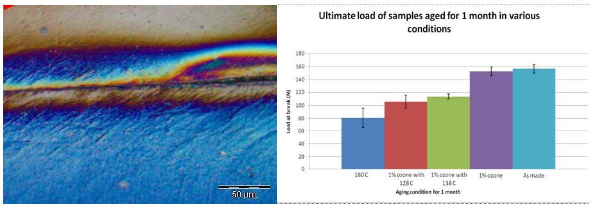

Fig. 11. Aging of high temperature epoxy; (left) oxidation layer in 1% ozone at 140°C and (right) three point bend strengths as a function of various aging conditions.

It is hypothesized that a computational chemistry approaches, such as Gaussian or Molecular Dynamics, could be used to model the interaction between a cured HT epoxy resin and the presence of elevated temperature, atomic oxygen, and/or ozone to determine their resistance to oxidation under in-service conditions. For example, Gaussian 09 was used to find the most favorable bonding sites for atomic oxygen in DGEBA cured with EDA. The very reactive atomic oxygen atom can attach in many places. However, as expected, the most energetically favorable sites were where a lone pair was available to complete the valence shell on the atomic oxygen. These sites were either on the nitrogen site of EDA or on the aromatic carbon ring of the DGEBA (Fig. 12).

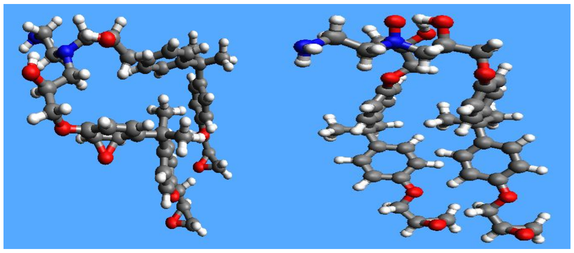

Fig. 12. An epoxy model with atomic oxygen bonded to the aromatic ring (left) and to nitrogen (right).

4 Conclusions

This research has been supported by the National Science Foundation, Electric Power Research Institute and a large consortium of major federal and private electric utilities and manufacturers in the US, namely, the Bonneville Power Administration, Western Area Power Administration, Alabama Power Company, Pacific Gas &Electric, the Tri-State Generation and Transmission Association, the National Rural Electric Cooperative Association,

Glasforms, Inc., NGK-Locke, the Composite Technology Corporation and others. Thanks to the generous support of the above sponsors, significant impacts on the entire transmission line technology have been made. Our accomplishments include:

-Explanation of two sets of major insulator failures by brittle fracture in the US in 1992/93 and 1995/96;

-Identification of the type of acid responsible for brittle fracture of composite non-ceramic insulators;

-Identification of critical conditions leading to brittle fracture and other failure modes;

-Providing a ranking of the commonly used GRP rod materials for their resistance to brittle fracture and other failure modes (electrical, over-crimping);

-Establishing that the most damaging mechanical loading case for ACCC conductors occurs if the conductors are subjected to large bending moments over mandrels with relatively small diameters;

-Determining that ACCC rods are very sensitive to transverse loading under aeolian vibrations at mechanical connections;

-Preliminary establishing the most damaging aging conditions on ACCC rods.

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