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Critical design, testing and manufacturing features for the selection of high quality composite insulators for transmission overhead lines

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Abstract

The large variety of designs, materials and composite insulator manufacturing processes available today has created the perception that polymer insulators have become a commodity. The accumulations of severe failures in service which have occurred in the last decade (and still continue) tend however to demonstrate that utilities might need to reconsider some major criteria described in their specifications to reduce such risks. This paper will cover specific design and material selection criteria, testing and critical manufacturing details, taking into consideration current knowledge as well as field experience for the determination of ultimate performance of polymer insulators.

Introduction

At various occasions, experts had mentioned the need for reinforcing existing standard testing requirements, recognizing the limits of their screening and selection capacity. These same experts admitted that current standards are insufficient to weed out marginally acceptable products (1). Today, benchmarking of polymer insulators would show an almost unlimited diversity in designs and materials, all, of course, used under a large variety of processes. The reason for this to exist is the complexity in the nature of composite materials, typically organic materials which require from utilities to enter quite deeply into chemistry for achieving a better understanding of the possible risks and potentials of these products.

Very often, we see specifications describing in very generic terms the rubber housing, with a basic definition of the insulator very often limited to rubber covering a fiberglass rod having metal end fittings at each end, the final product being in compliance with IEC 61109 (with the more recent related IEC 62217). Little (if any) attention is given to the manufacturing process itself, keeping the door wide open to any new supplier with no field experience. As a result, we can see good materials used with inadequate processes, and vice versa, bad materials going through well designed processes. In both cases, when failures occur, there is a chance to see the root cause of the problem reported to the wrong parameter, since process, design and materials are intimately linked together.

- Among many other aspects of design, the fiberglass rod and the rod crimping process is one example of interaction which requires a more detailed approach in technical specifications. The mechanical integrity of a composite insulator depends entirely on the quality of the strength of this connection.
- The choice of the rubber housing and the associated process form a couple with numerous interactions where three critical properties are at stake:

    - Interface between rod and housing, very critical since it is a longitudinal interface between line end and ground end.
    - Sealing of the rubber housing to the end fitting, essential for preventing moisture penetration recognized to be the worse threat for polymers. (with risks of brittle fractures mainly) (3).
    - Ageing of the rubber housing under various environmental stresses over time.

1. Rod and rod crimping

a) Fiberglass rod

- Chemical aspect

The materials used for the fiberglass rods have evolved over time, and today, most major manufacturers agree on the following key descriptive parameters:

Glass fiber weight in the rod: > 70%, but normally should stay below 80%
Resin : epoxy

The type of glass has evolved since the beginning with today a possible selection between E glass and acid resistant glass. While acid resistant glass can delay the time to failure in brittle fracture, it would be wrong to consider that such rods are totally immune to this phenomenon. Figure 1 show a brittle fracture obtained in the laboratory, (which occurs faster as ambient temperature increases). The only way to prevent such failures is to keep moisture penetration from happening.

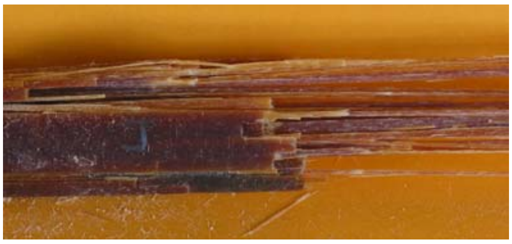
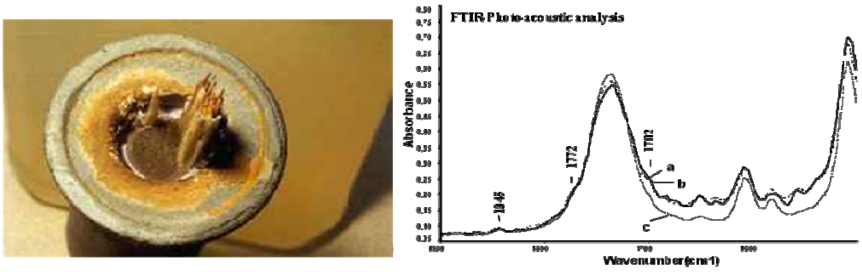


Figure 1: brittle fracture of acid resistant rod

In the particular case of brittle fractures, a lot of research work was done and is still being done to identify possible scenario of failures. While in the past only nitric acid (resulting from corona) was identified as a possible source of problem, it has also been pointed out that under some conditions (mainly unfinished reticulation of the resin during the pultrusion process, or excess of hardener in the mixing of the chemicals), moisture with no initial acid could generate acid from the resin system itself. (figure 2 below)



Curve "a" shows the IR spectrum of an area selected on the fracture surface,
Curve "b" the IR spectrum of a different part of the fracture surface
Curve "c" the IR spectrum of a zone inside the rod.
All three curves show a small peak at 1845 cm^{-1} and a smaller peak at 1772 cm^{-1}.
These two peaks belong to hardener B and indicate that small amounts of unreacted hardener B are present in the FRP rod. Curve "a" and curve "b" show a small peak at 1702 cm^{-1}. This peak indicates the presence of the acid that is obtained by the hydrolysis of hardener B.
Curve "c" does not show this peak.

Figure 2: Determination of the presence of carboxylic acid in brittle fractures.

This was clearly demonstrated in the laboratory as well as from insulators returned from the field (4). Carboxylic acid formed from such chemical reaction appear to be an extremely strong acid under the circumstances, and it shows that a composite insulator does not necessarily need corona activity with nitric acid generation to fail, but only humidity in contact with rods having this possible acidic reaction. This also implies that any damage to the housing during installation is a major threat, and care in handling of polymer insulators is paramount.

- Mechanical aspect

Precise definition of the rod diameter is the result of mechanical studies and testing using acoustic emission for the determination of the damage limit of the core. Under a specified tensile load, a given rod diameter will generate noises corresponding to the first fibers breaking in the rod. (figure 3). This point corresponds to the damage limit of the rod. The choice of the most suitable diameter is deducted from this determination, with a criterion that the elastic limit of the end fitting should be below the damage limit of the rod (the concept of damage limit can be assimilated to an equivalent elastic limit).

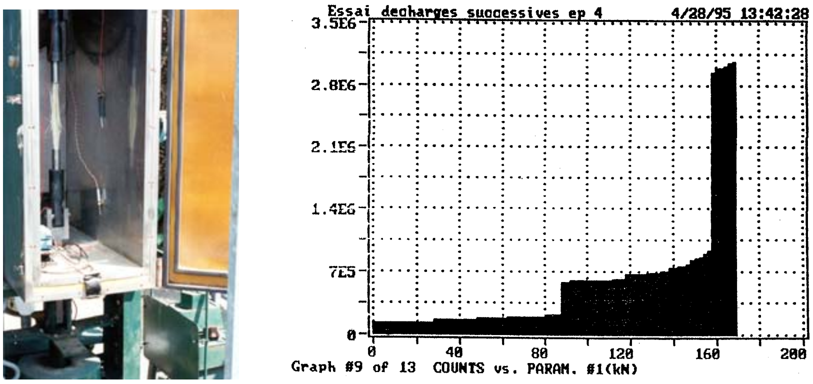


Figure 3: acoustic emission for the definition of the damage limit of fiberglass rods.

b) Crimping

The connection of the end fittings to the rod is one of the most critical operations since it implies direct consequences to the mechanical integrity of the rod. For quite many years, since the introduction of compression crimping, there was almost a consensus for using a crimping process where the crimping blades are moving towards the rod as a result of friction onto a master tool being pushed by a hydraulic ram.

This process, based on friction, will transfer to the rod the pressure resulting from the applied force with quite substantial differences from one blade to the other. Furthermore, this type of equipment will suffer of mechanical ageing typical of a friction process. To cope with such fluctuations and inherent lack of consistency, some manufacturers will use a rod of a larger diameter than what is required from pure mechanical strength considerations. The risk of damage to the rod remains however high, and small cracks might exist which are not necessarily critical enough at this stage to be caught in mechanical routine tests. Additionally, more important cracks (figure 4) might exist in the rod length inside the fitting leaving a crimped surface with sufficient strength for a routine test. Dynamic loads or thermal cycles over the course of time might make this a critical issue in the long run.

Figure 4 : crack in the rod after excessive or uneven crimping operation. The crack is far enough inside the end fitting to go through the mechanical routine test without being detected.

Crimping experience has led to new designs of crimping machines, progressively used by major manufacturers in the recent past. Instead of moving blades by friction, each crimping blade is controlled separately in such manner that the rod will receive a more balanced compression force, strictly perpendicular to the center line of the rod (figure 5). In this case, there is a lower risk of damaging the rod, and a higher consistency in the applied force to the rod.

A second advantage of such a process is the reduced noise emission which allows a better monitoring of the crimping operation. Various acoustic methods have been developed to help monitor and detect damaged rods during crimping. While it appears today that such control device should be specifically required from manufacturers, it is obvious that the performance of such detection device is a function of the background noise. Sophisticated digital techniques are now available and used by major suppliers.

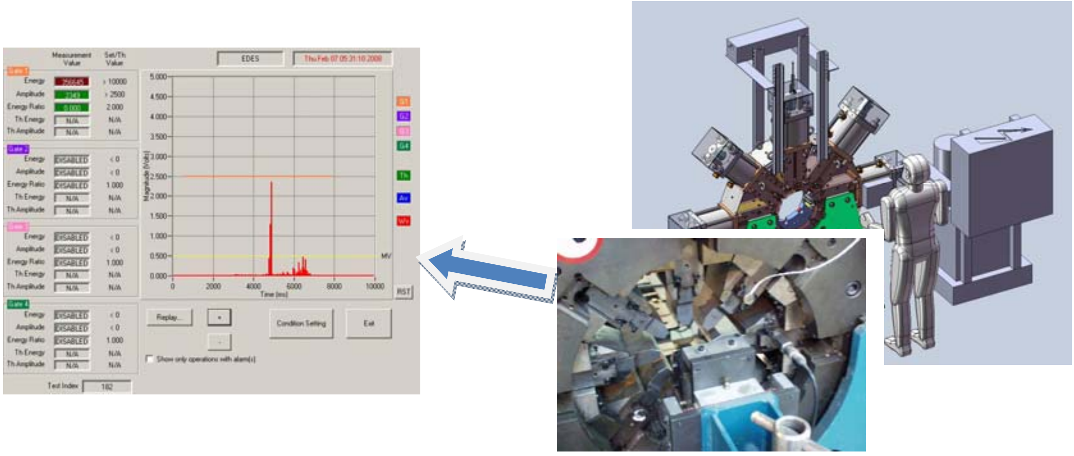


Figure 5: Optimum crimping process with separate crimping blade controls and digital monitoring of acoustic sensors for detection of rod damage.

A few years ago, utilities started to consider high temperature conductors as a standard. The question of thermal stability of the rod and the crimp itself became an interesting topic of research and development. A correlation between rod crimping parameters and performance at high temperature was established. Beyond intrinsic properties of the chemistry of the rod itself, (epoxy resin being a preferred choice), it appears that the crimping itself should sustain heat related relaxation. In the case of molded housing technology (involving heat) some manufacturers would either attach the end fitting after molding (with all the risks of artificial sealing technique to implement between rubber housing and end fitting) or proceed to a last crimping operation after molding the rubber to ensure optimum strength. Unfortunately, a repeated second crimping over an already initial crimp will induce a risk of rod damage since the first crimp will have locked the rod already against the metal of the end fitting. It is therefore strongly recommended to achieve the necessary strength without any damage to the rod prior to molding. This can be achieved through the selection of a proper combination between material and process. Extensive tests have shown that compliance to this criterion can be verified from mechanical tests at high temperature.

The test procedure is as follow:

- The insulator is submitted to a permanent load of 50% of the rating for 24 hours under a temperature of 100°C
- After the 24h temperature-load preconditioning, the insulator is pulled up to failure in a mechanical test itself performed on the insulator still hot. The ultimate mechanical failing load should be higher than the SML.

2. Rubber housing

a) Material considerations

Rubber housing selection is very often reduced to the simple wording of “silicone rubber”, ignoring the necessary details of chemistry involved, as well as other options such as EPDM. The diversity of silicone chemistries and the difficulty of control of the rubber itself makes that most utilities do not go further in the description of the properties of this material, other than making a reference to IEC 61109 (2).

Field experience is showing that for silicone rubber, the loss of hydrophobicity can be a major problem under severe continuous pollution conditions. Increasingly strong activity on the surface might damage the housing and end up with sufficiently deep erosion that the rod would be exposed. Chemical parameters such as silicone structure and filler content (mainly Alumina Tri Hydrate, also called ATH) are key in the mitigation of such aspects.

a) Inclined plan test : this erosion resistance test should be a first criteria, used next to the usual 1000h and 5000h ageing tests. The criteria to use should be the classification 1A4,5 under the 6 hour procedure described in IEC 60587.

b) Recent work has shown the influence of acids on silicone housing. Under corona activity, with the generation of ozone, nitric acid will be present on the surface of the housing. Also, some reports of acid related degradation in specific chemical industrialized area (sulphuric acids…) are showing that silicone rubber can be degraded under such environments (figure 6), unlike EPDM. Acid tests are not yet described by standards, and while work is still needed, there is a clear indication that this represents a major threat for composite insulators. Figure 7 gives a comparison between two silicone rubber formulations slightly different in the selection of fillers tested in the laboratory in an acidic environment. It seems obvious that specifying optimum silicone rubbers requires far more detailed description than a generic wording.

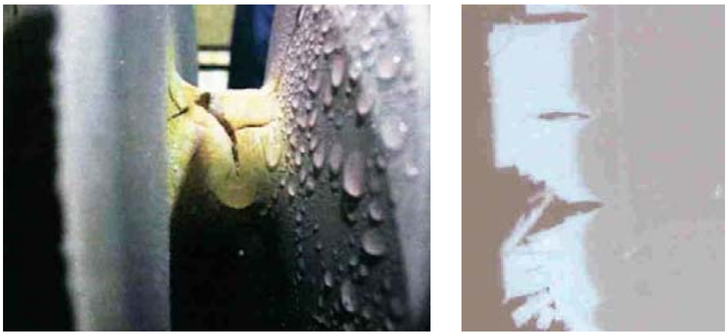


Figure 6 : silicone rubber degradation related to acid and detailed cross section.

a) silicone degraded by acid test

b) silicone with optimum protection against acids

Figure 7: Test samples of two different silicone rubbers and electronic microscopic detail of silicone compound structure after acid related degradation. (laboratory test)

c) Many laboratories are studying new evolutions in multistress long term tests to accelerate the possible degradations expected in service. Major work is being done in this field, and there is a good indication that the simulation of the ageing of polymer housing would require long term testing time far beyond 5000h and under specific testing conditions (5). The fact is that very severe testing conditions are often unrealistic, and could hide fundamental behavior changes. For instance, high salt content in fog chambers can be seriously misleading, and IEC has reduced in its most recent version the salt content of the fog in the 1000h test from 10g/l to 8g/l.

More so, it has been established that long term clean fog test could help identify the expected risks of degradation and erosion with much more discrimination than traditional 1000h fog tests. Figure 8 show the difference in erosion between two main families of silicone: on one hand (sample a) the insulator housing is a liquid silicone rubber (LSR) with little ATH filler. While LSR is promoted for a higher hydrophobicity and faster recovery, it appears in this test that the level of erosion is far beyond any acceptance criteria. Sample b) corresponds to a HTV silicone compound with a relatively high level of ATH, which will prevent deep erosion from happening. With only clean fog, this test procedure will maintain the arcing activity closer to the rubber instead of having a crust of salt protecting the housing from thermo chemical degradation. In this regard, such a test could be a much better indicator for erosion classification. It also demonstrate the fundamental difference between two materials both covered by the generic designation of "silicone rubber".

Sample (a)

Sample (b)

LSR (liquid silicone rubber)

min 45% ATH filler silicone rubber

Figure 8 : erosion after 2000h in clean fog chamber. (same leakage distance)

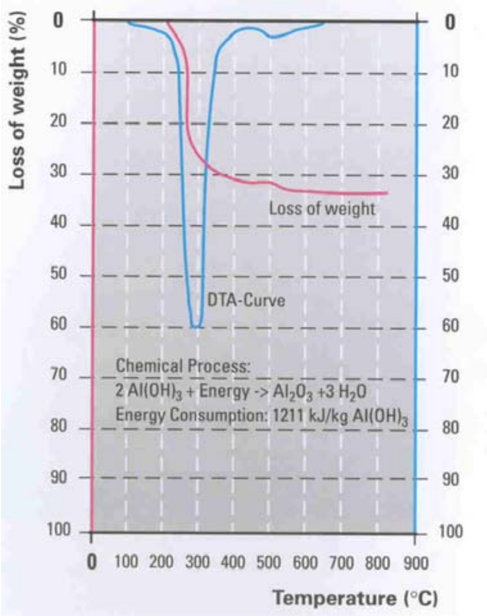


Figure 9: Typical thermo gravimetric curve

In order to be capable to sort out between a large spectrum of silicone rubbers, one might consider the level of ATH filler as a preliminary condition. ATH levels can be estimated by thermo gravimetric analyzes (figure 9). Under such requirements, silicone rubber should be capable to comply with very stringent acceptance criteria based on inclined plan (1A4.5) test results, tracking wheel test, and combined clean and/or salt fog tests. Such curves can be required on the bases of comparing material used during qualification and sample testing.

b) Process considerations

The choice for ATH filled silicone rubber has deep consequences on the process to be used for the housing material. While molding is today considered as the preferred technology, there is a broad diversity in processing. Depending upon the viscosity of the rubber, more or less pressure is needed. With LSR, lower pressure will be possible to use since the rubber flows easily. For highly filled rubbers, higher pressures are required. One of the consequences is that good adherence, especially on the end fittings is easier to achieve consistently. One of the main reasons for direct injection molding to rise above any other technology is the unique ability, while using high consistency rubbers, to eliminate the need of seals. All other techniques carry the inherent weakness of single or multiples seals which are for most part largely hidden under the fitting and therefore impossible to control.

Besides the end fitting seal, there is a critical need to ensure the good adherence between rod and rubber, along the longitudinal line separating the end fittings. Advanced technology for non destructive controls (7) is possible thanks to ultrasounds which will assist the control of the molding or any rod covering process. (figure10)

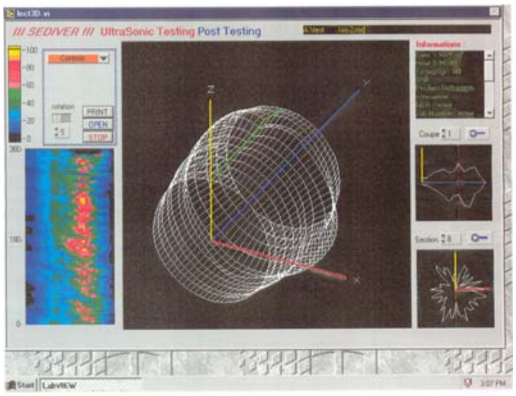


Figure 10: Ultrasound control of the longitudinal interface

Summary

More precise description of product and process is needed in procurement specifications to enhance the level of confidence and performance over time of polymer insulators. Among others, criteria such as crimping process details, resin characteristics and rod performance can be evaluated through specific thermo mechanical test conditions. As far as rubber performance, utilities will need to enter the organic chemistry environment and specify rubber in much more precise terms than the generic terminology. Minimum levels of ATH, minimum acceptance criteria of 1A4.5 in inclined plan test should be added to any specification. Chemical attack of silicone rubber being relatively harmful, specific tests should be implemented to verify the ability of silicone to sustain acidic conditions. Clean fog long duration test can provide additional information in the ageing and erosion characteristics of rubbers. Thermo gravimetric Analyses will provide an additional fingerprint helpful when comparing silicone used for qualification with rubbers supplied over the course of time. Such technical requirements are necessary to complete the test protocols from existing international standards recognized to be too loose for high performance expectations. A more stringent overall attitude towards qualification and performance evaluation is more and more necessary given the broad diversity of products on the market.

References

[1]. Claude de Tourreil. “Longevity issues for line insulators”. INMR 12. Issue 2004.
[2]. IEC 61109 : composite insulators for AC lines with a nominal voltage greated than 1000V.
[3]. Polymer insulator survey. EPRI 2003.
[4]. C. de Tourreil, L. Pargamin, G. Thévenet. S. Prat and N. Siampiringue, “Brittle Fracture of Composite Insulators: The New Explanation and a Field Case Study", ISH 2001, Paper 5-25, Bangalore, India, Aug. 2001.
[5]. P. Andrews, D.J. Childs, H. Schneider –EPRI- “Water drop corona effects on full scale 500kV non ceramic insulators” IEEE transactions on power delivery. Vol 14, N°1,1999
[6]: JM George: Internatioanl Symposium on modern insulators technologies. Florida USA 1997. “Non destructive technique for the evaluation of the integrity of composite insulators”.