Determination of the Brittle Fracture Process of Field Failed HV Insulators

by

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Abstract : The brittle fracture of composite insulators is caused by the simultaneous action of an acid and a tensile mechanical stress on the FRP (Fiber Reinforced Plastic) core. Two diagnostic techniques are described that can be used to determine what type of acid is present on the fracture surface of field failed insulators. The analysis of 18 field failed insulators reveals, for most of them, the presence on the fracture surface of a type of acid that is produced by the hydrolysis of the resin of the FRP core.

Key words : insulators, brittle fracture, nitric acid analysis, carboxylic acid analysis

1- Introduction

The first brittle fracture failures of composite insulators occurred in the early 1970's [1], [2]. This type of failure is still affecting composite insulators. However the total number of insulators that have failed in that way is very small. Worldwide, that number has been estimated to be at most of few hundred units [3]. This number is very small compared to the several millions of composite insulators installed on transmission lines. Nevertheless, the brittle fracture of an insulator is a serious event since it likely leads to a conductor drop to the ground.

The brittle fracture phenomenon has been reproduced in the laboratory shortly after the first events in service [4]. It was found that the simultaneous application of a tensile stress and of nitric acid to the FRP (Fiber Reinforced Plastic) core would quickly lead to the failure of the core by brittle fracture. This first experiment influenced all the work done subsequently to explain the brittle fracture phenomenon [5]. However, a different scenario recently showed that an acid generated by the hydrolysis of the resin of the FRP core could also lead to the failure of the core. The present state of knowledge on the brittle fracture phenomenon has been summarized in a recent papers [6].

In the laboratory, many different acidic as well as alkaline solutions can produce the brittle fracture of FRP cores. Therefore, to establish the correct cause of a brittle fracture that occurred in service, it is necessary to find some analytical methods that can be used to establish the presence of a given type of acid on the fracture surface of the insulators. This only can decide which one of a number of scenarios is responsible for the failures that occurred in the field. In the study presented here, 18 brittle fracture surfaces of insulators that had failed in the field have been analyzed to establish the type of acid that caused the fractures.

2- Brittle Fracture Processes

Two stress factors are required to obtain the brittle fracture of the core of a composite insulator. The first, a mechanical tension, is always present because of the service load applied to suspension/tension composite insulators. The second necessary component is the presence of an acid that comes in contact with the FRP rod.

The uncertainty regarding the exact type and the source of the acid that causes brittle fractures in the field is the probable reason why the problem is still affecting composite insulators.

It is unlikely that acids, such as nitric or sulfuric, found in acid rain would be of sufficient potency to lead to insulator failures. In addition, to be the cause of failure, such an external source of acid would have to have direct access to the FRP rod. This means that somewhere along the length of the insulator, its housing has been damaged and no longer protects the FRP core.

It has also been proposed that an acid, possibly oxalic acid, created by electrical discharges occurring on the surface (usually epoxy) of very small voids possibly present inside the FRP rod, would explain field failures [7]. Tests, performed by CIGRE WG 22-03 (now B2-03) have indicated that this scenario is unlikely and is no longer considered.

Two other failure processes are described in this report, the first involves nitric acid and the second one an acid generated by the hydrolysis of the resin used for the impregnation of the glass fibers of the FRP core.

2.1 The nitric acid scenario

When corona or dry band discharges occur in moist air, nitric acid can be produced. Some chemical reactions that explains the phenomenon are :

Primary reactions :
$N_2 + O_2$ and corona $\rightarrow$ oxides of nitrogen
$3O_2$ and corona $\rightarrow 2O_3$

Some examples of secondary reactions to create Acids :
$NO + O_3 \rightarrow NO_2 + O_2$
$2NO_2 + H_2O \rightarrow HNO_3\,(aq) + HNO_2\,(aq)$
$N_2O_5 + H_2O \rightarrow 2HNO_3$
$HNO_2 + O_3 \rightarrow HNO_3 + O_2$

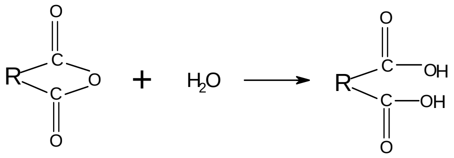
If the core of a composite insulator is exposed to the atmosphere because of a damaged housing in an area where the electrical field is such that electrical discharges can occur, nitric acid may be generated. Provided that the nitric acid is of sufficient concentration and is not washed off by the rain, a brittle fracture can occur because, in service, the insulators is also under a mechanical tension load.

2.2 The carboxylic acid scenario

Three families of resins are presently used for the manufacture of the FRP core of composite insulators. They are epoxy, vinylester and polyester resins.

It can be shown that all three families can, under certain circumstances specific to each family, be affected by water and generate, because of hydrolysis, carboxylic acid.

In the case of a specific epoxy resin commonly used to make FRP cores, the hydrolysis of the hardener leads to the creation of carboxylic acid according to the following reaction :



For this to happen electrical discharges are not required. However, water or moisture must be in contact with the core and some hardener must still be present in the cured resin. This could be the case if too much hardener has been used in the formulation or, more likely, if the polymerization is not complete because of insufficient curing time or temperature. This can be checked by IR analysis of the FRP core.

The presence of water can be explained by the migration of water vapor through the housing in an area where there is a lack of bonding to the core where it then accumulates. More likely water can reach the FRP core because of a damaged housing or a faulty seal between the housing and the end fitting.

The simultaneous presence of carboxylic acid and of the mechanical tension load is sufficient to lead to the brittle fracture of the insulator core.

3- Field Brittle Fractures

Laboratory simulations show that both the nitric acid and the carboxylic acid scenarios can produce the brittle fracture of FRP cores. It is therefore necessary to use special diagnostic techniques that permit to decide which scenario is responsible for a given failure that occurred in service. The diagnostic technique must be capable of detecting the presence of the relevant type of acid on the fracture surface of the insulator.

Infrared spectroscopy is commonly used both as qualitative tool for identifying the molecular structure of organic compounds and as a quantitative technique for determining component concentrations. The position of wavelength of the infrared absorption band depends only of the molecular arrangement of the various atoms. This technique involves the study of molecular vibrations. A continuous beam is passed through or reflected off the surface of the sample, individual molecular bonds and bond groupings vibrate at characteristic frequencies. The resulting curve is known as an infrared (IR) spectrum. FTIR-PAS (Photo-Acoustic Spectroscopy) is a variant of the technique that can be used on any sample that absorbs infrared radiation and is independent of the sample morphology and requires no special sample preparation.

FTIR-PAS analysis has been used in this study for the detection of both nitric and carboxylic acids.

3.1 Detection of the presence of nitric acid

The presence of nitric acid on the fracture surface of an FRP core is detected using the reaction of potassium bromide (KBr) with nitric acid (HNO_3). This reaction produces a potassium nitrate salt (KNO_3). This nitrate ion has a specific IR absorption at 1384 cm-1. Figure 1 compares the IR spectrum obtained by FTIR of a standard sample of KNO_3 salt with that obtain from the reaction of HNO_3 and KBr. FTIR microspectroscopy was also carried out.

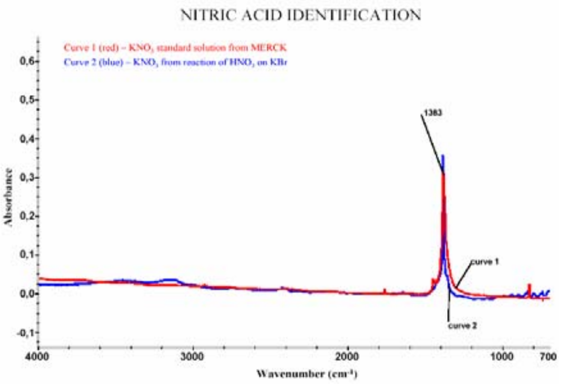


Fig. 1 : Identification of nitric acid

This technique can be used to analyze the fracture surface of field failed insulators. Fig 2 shows the spectrum associated with the fracture surface of a composite insulator and that of a sample taken from inside its core.

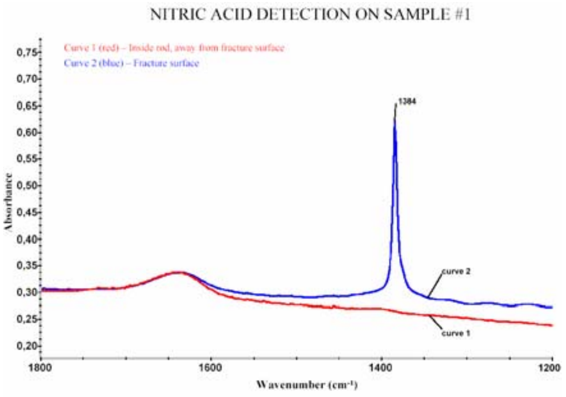


Fig. 2 : Identification of nitric acid on the fracture surface of sample 1

3.2 Detection of the presence of carboxylic acid

Comparing the FTIR spectra of the fracture surface with that of a sample taken within an epoxy resin core, i.e. that has never been exposed to moisture can show the presence of carboxylic acid and its source. The carboxyl function has a peak around 1710 cm^{-1} and 1700 cm^{-1} and the hydroxyl function a peak around 3437 cm^{-1}. When such peaks are present in the spectrum associated with the fracture surface, the spectrum of a sample taken inside the core shows peaks at 1845 cm^{-1} and 1770 cm^{-1} indicating the presence of residual anhydride (unreacted hardener). These peaks being absent on the fracture surface show that the unreacted hardener has been transformed into carboxylic acid. This is shown on Figure 3 and Figure 4.

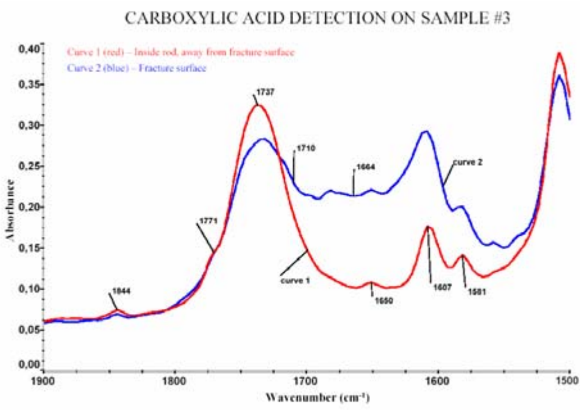


Fig. 3 : Identification of carboxylic acid on the fracture surface of sample 3

Similarly, with vinylester resins cores, the comparison of the FTIR spectra of the fracture surface and of samples taken inside the core shows modifications around 3650-3000cm^{-1} (hydrolysed products), and the appearance of a peak at 1700 cm^{-1}, corresponding to the absorption from carboxylic acid. In addition there is a global absorption increasing between 1600 and 1850 cm^{-1}. This shows that the hydrolysis of vinylester can also generate carboxylic acid.

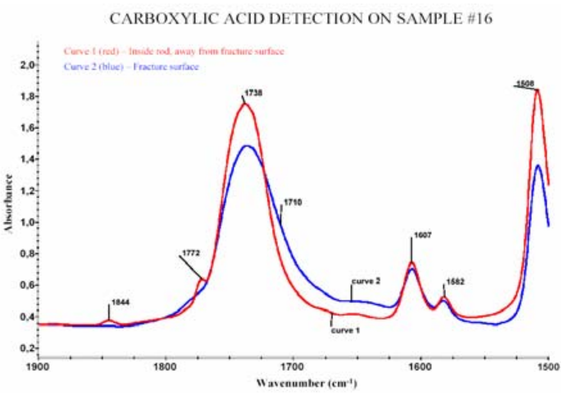


Fig. 4 : Identificationof carboxyklic acid on the fracture surface of sample 16

The same comparison between the spectra of the fracture surface and of a resin sample taken within a core made with polyester resin shows a large absorption band appearing between 3650 cm^{-1} and 3000 cm^{-1} (hydrolysed products). It also shows an absorption band of lower magnitude between 1600 cm^{-1} and 1710 cm^{-1} (carbonyl function), with, in particular, a peak around 1700 cm^{-1}. A global absorption between 1600 and 1850 cm^{-1} (carbonyl function) can also be observed. As previously, these modifications indicate the presence of carboxylic acid.

4- Analysis of Field Failed Insulators

The FTIR diagnostic technique has been used to establish what kind of acid was responsible for the brittle fracture of field failed composite insulators.

The fracture surfaces of 18 insulators have been analyzed to look for evidence of both nitric acid and carboxylic acid. All these insulators failed after a few years in service on transmission lines. They had FRP cores made of epoxy, vinylester or polyester. Table 1 presents the results of this analysis.

Table 1

Results of Spectra Analysis

Sample No :	Loca-tion	Core Type *	**N**** acid	**C**** acid	Probable scenario
1	USA	**P**	Very high	High	**N** and/or **C**
2	USA	**P**	Traces	High	**C**
3	USA	**E**	Traces	Very high	**C**
4	USA	**V**	Traces	High	**C**
5	USA	**P**	Low	High	**N** and/or **C**
6	USA	**E**	Very high	Low	**N**
7	USA	**P**	Traces	High	**C**
8	USA	**V**	Traces	High	**C**
9	USA	**P**	Traces	Low	**N** and/or **C**
10	USA	**E**	Very high	Very high	**N** and/or **C**
11	USA	**V**	Low	Very high	**C**
12	USA	**P**	Traces	High	**C**
13	USA	**P**	Traces	High	**C**
14	USA	**V**	Very high	Very high	**N** and/or **C**
15	ZA	**E**	Traces	High	**C**
16	ZA	**E**	Traces	High	**C**
17	Israel	**V**	No	Very high	**C**
18	USA	**V**	Very high	Traces	**N**

* : E is Epoxy
P is Polyester
V is Vinylester

** : N is nitric acid
C is carboxylic acid

5- Discussion

The type of resin used for the manufacture of the cores is fairly well divided between the 18 insulator samples, one third is vinylester with one more polyester resin and one fewer epoxy resin.

Eleven samples failed because of carboxylic acid; this is clearly more than the two samples that failed because of nitric acid. For 5 samples it is not possible to clearly attribute the failure to one or the other acid type.

It is important to note that the presence of carboxylic acid indicates that the particular core was susceptible to hydrolysis. In the five samples where both types of acids were found it is possible that the failure was initiated by the carboxylic acid in an area of high electrical field and that the process took long enough for electrical discharges to produce nitric acid and consequently compound the problem.

In addition, other observations do not favor the nitric acid scenario [8]. Several composite insulators that have been in service for many years with some defects have not failed. For example there are many more insulators that have operated for several years with an exposed rod and evidence of electrical discharges on the core. These insulators have not failed by brittle fractures although all the necessary factors were present : a tensile mechanical load and electrical discharges in moist air that could have lead to the production of nitric acid.

6- Conclusion

This study has shown that diagnostic techniques are available to examine the fracture surface of composite insulators that have failed by brittle fracture in the field. It is therefore possible to determine what type of acid is responsible for each failure.

The examination of 18 composite insulators that have failed in service by brittle fracture has shown that it is at least 5 times, or even close to 10 times more likely that these service occurring brittle fractures had been caused by carboxylic acid than by nitric acid. This means that particular care should be taken for the manufacture of FRP cores. In addition it would be useful to investigate if there exist other types of resin that are not sensitive to hydrolysis and still have the characteristics required for the manufacture of high quality FRP core for composite insulators.

It should be noted that the use of glass fibers that are more resistant to acid attack, such as E-CR fibers, can delay the failure of the core by brittle fracture for a practically sufficiently long period to avoid failures in service.

7- Acknowledgement

The authors are grateful to Dr. A. Phillips for his help in the procurement of several of the samples and to CIGRE WG B2-03 for both supplying some samples and the results of their analysis.

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