

Evaluation Of Metal Oxide Surge Arresters And Their Polymeric Housing Under Moisture Conditions

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Abstract — When conditions are favorable, moisture will diffuse through the metal oxide surge arrester (MOSA) polymeric housing which will accelerate the device degradation. This can be noted, for example, as an increase on the power loss dissipated along the device. However, one question that should be answered is whether this increase occurred because moisture reached the MOSA inner part or if the insulation provided by the polymeric housing was affected in such a way that allowed the formation of conductive path, due to moisture in the polymer material. The results indicated that silicone housing presented a higher diffusion coefficient, higher water vapor permeation rate and higher dielectric dissipation factor than the Ethylene Vinyl Acetate (EVA) housing. The complete surge arresters with silicone housing, also presented higher power loss than the arresters with EVA housing when submitted to an immersion test. However, the housing conductivities remained very low throughout the test, what leads to the hypothesis that the increase in conduction measured for certain full arresters are not due to increased conduction inside polymer housing, instead it must be due to increased conduction in the interfacial areas.

Keywords — *metal oxide surge arrester; polymeric housing; average power loss; diffusion coefficient; moisture performance.*

I. INTRODUCTION

In Brazil, some studies indicate that lightning is responsible for over 30% of all non-programmed interruptions that occur in distribution systems [1]. This situation demands a better understanding of the energy system and its equipment's, as well as, the failures mechanisms associated with important devices, such as surge arresters.

Some studies involving SiC arrester [2,3], metal oxide surge arrester (MOSA) with porcelain housing [4] and MOSA with polymeric housing [5, 6] have showed that moisture ingress was the most significant cause of arrester failures. The mechanisms of arrester failures related to moisture ingress are quite complicated and each mechanism could lead the surge arrester to a different level of degradation, which could mislead about the real responsible for the failure.

On the past decade, an effort has been made to understand the different causes of arrester's failure, on which they have demonstrated that water can be formed in the internal part of the

surge arrester due to partial discharge and resulting as chemical reactions or can penetrate in the arrester by capillary effect through imperfections in the housing, sealing structures, cracks, etc. or even by diffusion through polymeric housing [3]. In this way, the arrester design (void free, good sealing) is deemed a very important feature in the arrester behavior what can contribute to minimize the moisture generation by chemical reactions and ingress by capillary effect.

Previously, all surge arresters were constructed using porcelain or glass housing, but with the development of technology, polymeric housing have been gaining space. Polymers present a relevant ability to withstand high electric fields with negligible conduction layer which has allowed its extensively use for insulating applications, especially as surge arresters housing. However, the knowledge related to diffusion process through polymeric material used in energy network system is not yet fully explored. The available literature is related with packaging used in the industry (especially food industry) or applied to transformers [7, 8].

Due to the lack of data, the present paper is aimed to investigate by means of experimental tests whether surge arresters degraded by moisture present expressive values of current also on the housing material. As measuring the surge arrester internal current without the housing is not a simple task, in this work the total leakage current will be measured on the full surge arrester and used later to calculate the average power loss, while the analysis on the housing conduction will be carried out using bulk material removed from the surge arrester sheds.

The performance of silicone and Ethylene Vinyl Acetate (EVA) used on the MOSAs housing is evaluated throughout theoretical calculation of the diffusion coefficient for each material extracted from MOSAs lower sheds and by experimental tests carried out during an immersion test, which involves electrical measurements (dielectric dissipation factor and DC current). The water vapor transmission rate of the silicone and EVA was also determined, according to specific test with controlled humidity and temperature. Additionally, the dissipated power for four complete surge arresters (two with silicone housing and two with EVA housing) was also verified under the same immersion condition that the housing material.

II. PERMEATION PROCESS THROUGH POLYMERIC MEMBRANE

Gases permeate through polymers when a pressure difference is established between opposite interfaces. This process is dependent on numerous polymer properties (crystallinity degree, additives, filler type and amount of it in polymer), the nature of penetrant (chemical affinity between the vapor and barrier, vapor concentration) and environmental conditions (temperature, pressure, humidity) [9], consisting of a sequence event [10]:

- (1) Vapor absorption into the polymeric material;
- (2) Diffusion of vapor in and through the polymer;
- (3) Desorption of vapor at the opposite interface.

In most of applications, diffusion is the slowest and, hence, the rate-determining step in the permeation process. It can in many cases of practical interest be described by Fick's two laws [10]. It is generally measured using flat films, which is easier to model than complex geometries, such as the surge arrester housing. This approach may bring a divergence between the calculated and the measured diffusion coefficient, however it is broadly accepted as an indicative for quantifying the moisture that will diffuse through the polymer.

It is also expressed by Henry's law, that even though is applied for gases that become liquid at far from standard temperature and pressure (0 °C and 1 atm) [9], a special assumption can be made in cases where the concentration of the penetrant is very low [10] and the material involved in moisture absorption/transport is a hydrophobic polymer [15]. For this case, Henry's law is obeyed over the complete range of relative pressures and a general relationship between the three main permeation properties permeability (P), solubility (S) and diffusivity (D) is almost exactly valid [11].

The diffusion coefficient, D, depends on temperature and the nature of the penetrant/polymer system and can be constant or a function of penetrant concentration [10].

$$D(T) = D_0 \cdot \exp\left(\frac{-E_d}{R \cdot T}\right) \quad (1)$$

Where:

- D: diffusion coefficient;
- D₀: pre-exponential factors;
- E_d: activation energy of diffusion;
- R: universal gas constant;
- T: absolute temperature.

III. MOISTURE DIFFUSION COEFFICIENT CALCULATION

As previously stated, in most applications, diffusion is the slowest and, hence, the rate-determining step in the permeation process.

The activation energy of diffusion (E_d) has a connection with the diameter of the gas molecule; this characteristic allows the estimation of E_d/R on (1) using a relation described by the glass transition temperature of the polymer and the second power of a ratio between the molecular diameter of the penetrant molecule and the molecular diameter of a standard gas (Oxygen) [11].

$$\frac{E_d}{R} = \left(\frac{\sigma_{H_2O}}{\sigma_{O_2}}\right)^2 \left[6,4 \times 10^3 - 0,16(298 - T_g)^2 \pm 1,5 \times 10^3\right] \quad (2)$$

Where:

- σ_{H_2O} : diameter of water molecule;
- σ_{O_2} : diameter of a chosen standard gas (Oxygen);
- T_g: glass transition temperature of the polymer.

Once $\frac{E_d}{R}$ is calculated for the gas-polymer system, it is possible to use the correlation demonstrated by [10], in order to estimate the pre-factor D₀ and later determine the diffusion coefficient.

$$\log(D_0 / m^2 s^{-1}) = 0,001 \times \frac{E_d}{R} - 8,0 \pm 0,4 \quad (3)$$

By applying (3) and (2) on (1) it is shown that the diffusion coefficient varies between a lower and upper value. This variation can be understood as a consequence of the differences in the material composition, e.g. use of additional fillers applied to improve some of its characteristics.

The smallest penetrant (H₂O) possesses the highest solubility and thus can diffuse even in a hydrophobic polymer [12]. As observed in Fig. 1 for silicone rubber, the diffusivity of water through this material increase with temperature.

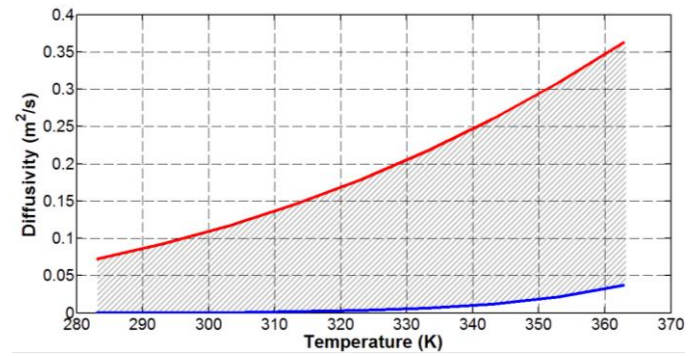


Fig. 1. Theoretical diffusion coefficient for water vapor – silicone rubber.

Depending on the polymer molecular organization, the glass transition temperature varies, which will affect the diffusion. For a simple gas-polymer system, the polymers with lower T_g presents higher diffusion coefficient. In the case of EVA, the glass transition temperature can be found between 256 K and 261 K [13]. The diffusivity of EVA has been described in Fig. 2, for T_g equal to 256 K, which brings the worst case.

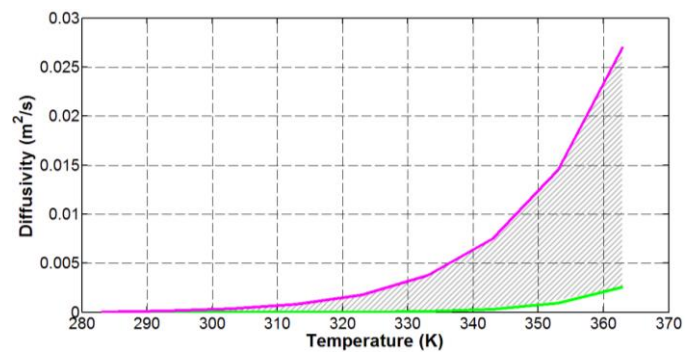


Fig. 2. Theoretical diffusion coefficient for the water vapor – EVA.

Although the theoretical calculation gives an indication of the diffusion coefficient values, the polymers' molecular

structure, its composition and the way it is processed, form a very complex system for moisture permeation.

IV. EXPERIMENTAL SETUP

The test involves evaluating four distribution class ($U_{cov} = 20$ kV) metal oxide surge arresters with polymeric housing (two silicone – Manufacturer A and Two ethylene vinyl acetate – Manufacturer B) and the bulk material samples (Fig. 3) extracted from the surge arresters lower sheds in water immersion with salt concentration of 1 kg/m^3 at 80°C for 1 month or until the leakage current amplitude measured on the full arrester was very high.

Prior to electrical measurements the complete surge arresters and bulk materials were removed from the hot water and kept cooling in water at ambient temperature for two hours, followed by one hour of cooling/drying at ambient conditions (see [14] for more details).

Apart of the immersion, the housing materials were also inserted into an environmental chamber, to verify their water vapor transmission rate.

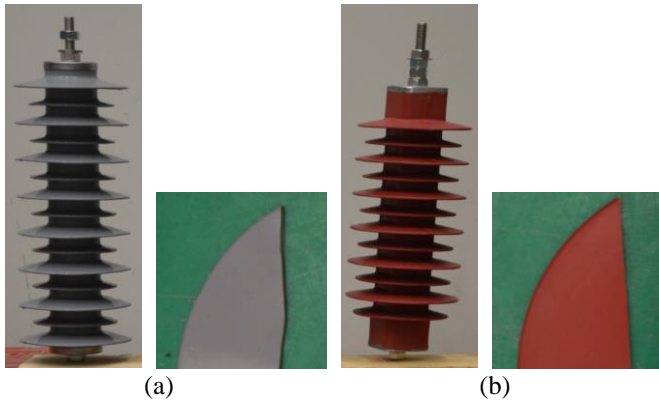


Fig. 3. (a) Manufacturer A MOSA and part of its silicone housing. (b) Manufacturer B MOSA and part of its EVA housing.

A. Average Power Loss

Through the data of applied voltage and the total leakage current, the power loss in the complete surge arresters was determined considering the leakage current resistive component, calculated by the point-on-wave technique [15]. As the power loss dissipation is directly related to the resistive current, any increase of this component will also be described by an increase at the average power dissipated by the surge arrester, what in a long term will reduce its useful life. This evaluation, is well known in the literature and offers a practical way to analyze the surge arrester degradation.

$$p(t) = I_r(t) \times V(t) \quad (4)$$

Where:

- $p(t)$: Instantaneous power.
- $I_r(t)$: Resistive leakage;
- $V(t)$: Applied voltage.

If the instantaneous power is multiplied by an infinitesimal time interval (dt) and integrated for each cycle, the energy absorbed by each surge arrester is specified and the average

power dissipated in one cycle can be calculated integrating the absorbed energy during this cycle, according to:

$$P_m = \frac{1}{T} \int_0^T p(t) dt \quad (5)$$

Where:

- P_m : Average dissipated power;
- T : Duration of the signal in seconds.

According to (5) the average power will be calculated from instantaneous values, which allows its use for any waveform and encompasses the losses due to the polarization of the dielectric material that constitutes the arresters, and the losses due to conduction.

B. Dielectric dissipation factor

The permittivity of an insulating material is, in a measurement system, the product of its relative permittivity (ϵ_r) and the dielectric constant (ϵ_0). The relative permittivity represents how easily a dielectric material can become polarized when submitted to an electric field. It can be influenced by several factors, such as, frequency, temperature, humidity and field strength [16]. In case some energy of the applied field is lost due to the polarization of the material, dielectric dissipation occurs. This loss can be represented by a dielectric dissipation factor, which is function of frequency, temperature and material properties.

In the current research, the dielectric dissipation factor of silicone and EVA used on surge arrester housing (Fig. 3) were analyzed throughout the immersion test.

The electrical measurements were carried out before the immersion and thereafter every 6 days, including a measurement 6 days after the samples were removed from the immersion tank, using an Insulation Dielectric Analyzer (IDA 200). This equipment calculates the complex impedance of a specimen at a specific frequency (in this case, at 50 Hz) and AC voltage applied on the sample (15 V/mm), by the measurement of the test voltage and current through the bulk material. The thickness of silicone housing was equal to 1.66 mm and the EVA 2.32 mm. The measured values are used later to calculate the dielectric dissipation factor based on (6), described by the international Standard IEC 60250 [16].

$$Tg \delta = \frac{1}{R_p \cdot C_p \cdot \omega} \quad (6)$$

Where:

- R_p : Measured resistance of the insulating material;
- C_p : Measured capacitance of the insulating material;
- ω : Angular frequency.

The characteristics of the climate room during the electrical measurements are described in Table I.

The series resistance of cables and connections used on the measurement system can lead to an extra loss peak at high frequency [17]. However, when considering low frequency, the effects of the series resistance can be neglected. As the network system frequency is 50 Hz, the resistance of cables and connections were not considerate on the calculation of the

dielectric dissipation shown on Fig. 6, which lead to an easier discussion of the results.

TABLE I – CLIMATE ROOM DATA.

Measurement	Temperature (°C)	Humidity (%)
Pre immersion	20.3	37.4
First	20.6	34.1
Second	20.3	31.1
Third	20.8	39.8
Fourth	21.1	33.8
Fifth	20.2	34.2
Pos immersion	20.7	32.9

C. DC measurement

The same bulk materials evaluated under AC measurements were analyzed using DC, with a time interval of 6 days between measurement (before, during and after the immersion test). By applying DC on the polymers, the dielectric loss resulting from the polarization is eliminated. The applied voltage was set according to the samples thickness (15 V/mm) and respective current measured by a picoanmeter.

D. Water Vapor Transmission Rate

A permeation process comprises a sequence of three events, in which sorption, diffusion and finally desorption takes place [10]. The smallest penetrant (H_2O) possesses the highest solubility and thus can diffuse even in a hydrophobic polymer [12].

In order to understand the permeation process throughout polymeric materials used on surge arresters housing the water vapor transmission rate is used to quantify the passage of water vapor through a substrate. It can be done using a wide variety of methods and for the purpose of this work it was carried out using gravimetric dish technique according to ISO 2528 [18].

On each polymer (Silicone and EVA) three parallel samples were extracted from the lower shed of the arresters housings, with a testing area of 2.5cm^2 , 2 mm thick, which were attached to adhesive aluminum foil masks and to special test cups for the measurements. These cups were placed into an environmental chamber (Espeq PR-1KPH) with controlled temperature of 38°C and 90 % RH, where the weight of each sample cup was daily measured (Precisa XT 620M) and the water vapor transmission rate of each test piece was then calculated from steady state weight increase data ($\text{g/m}^2\text{d}$) according to the standard ISO 2528 [18]. A detailed description on how the measurement was conducted, can be found in [14].

V. RESULTS AND DISCUSSIONS

A. Average Power Loss

The average power loss for both samples of Manufacturer A and Manufacturer B are shown on Fig. 4 and Fig. 5, respectively.

As stated by [5], when the surge arrester presents a power dissipation in the range of 6 W, its original characteristics will not be recovered even if the stress that originated its degradation had ceased. As it was clear that moisture had reached the inner part of arresters A-1 and A-2, the immersion of the full surge arrester with silicone housing, stopped after 19 days.

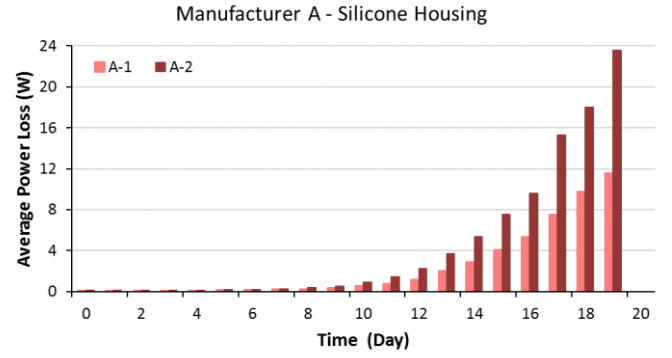


Fig. 4. Average power dissipation of surge arresters with silicone housing during immersion test.

During the first 5 days of immersion, no changes in the power dissipated by sample A-1 was observed. During this period, the power loss remained around $0.11\text{ W} \pm 5\%$ and after this period it started to increase 0.1 W per day, until the 11st day. After this initial phase, the power loss increased consistently until it had reached 11.5 W after 19 days of immersion, which clearly indicates that moisture took place.

The initial performance of A-2 was pretty much similar to A-1, with power loss in the range of $0.13\text{ W} \pm 5\%$, during the initial 5 days of immersion. On the following days, the losses increase about 50% for each measurement, when comparing to its previous value, reaching 1.44 W on the 11st day of immersion. The power dissipated on B-2 increased day-by-day, with his maximum value of 23.54 W , recorded after 19 days of immersion.

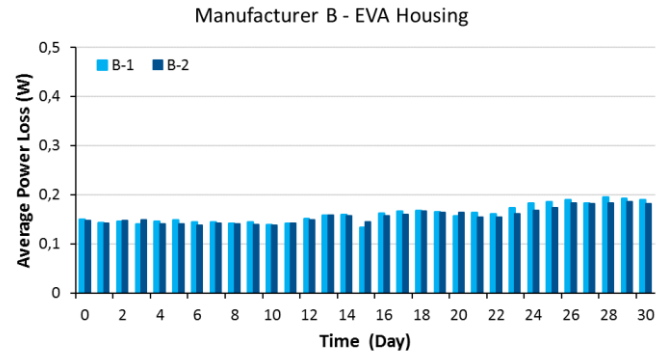


Fig. 5. Average power dissipation of surge arresters with EVA housing during immersion test.

As shown in Fig. 5 both samples from Manufacturer B demonstrated a stable behavior regarding dissipated power. The initial power loss calculate before the immersion was 0.14 W for both samples and even after 30 days of immersion, it increased only to 0.19 on B-1 and to 0.18 on B-2, demonstrating a very good withstand to moisture.

B. Dielectric dissipation factor

The dielectric dissipation loss calculated according to (6), is described in Fig. 6.

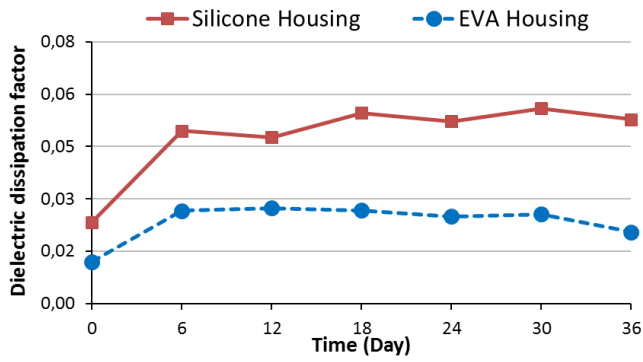


Fig. 6. Dielectric dissipation loss factor of MOSA with polymeric housing Adapted [14].

When verifying the dielectric dissipation factor for the EVA housing, it is possible to see that it kept practically the same value for the whole immersion test (0.0128 prior to the immersion test and 0.0274 on the last day of immersion). After 6 days outside the water tank, the dielectric dissipation loss factor was measured again, and its value decreased to 0.0218.

On the other hand, the silicone housing presented an increasing dissipation factor, during the test. Its original value was 0.0249 (in the beginning of the tests) and increased to 0.0597 on the last immersion day. Once the immersion was interrupted, the sample was kept for 6 days in laboratory conditions and the dissipation loss factor was measured again, indicating 0.563.

The results showed that dielectric dissipation factor of both materials, increased during the immersion test, what indicates that some moisture was absorbed. However, the variation of the dielectric dissipation factor was higher to the silicone housing than to EVA material. Once the immersion test was interrupted, both silicone and EVA could recover partially their dielectric characteristics, what probably happened because part of the moisture presented in the material disappeared. This is in accordance with the calculations shown in Fig. 1 and Fig. 2.

C. DC measurement

The values presented in Fig. 7 are the average value of approximately three thousand points corresponding to the stable period of each DC measurement. For these cases, the standardized measure of dispersion calculated according to the coefficient of variation (CV) is detailed on Table II.

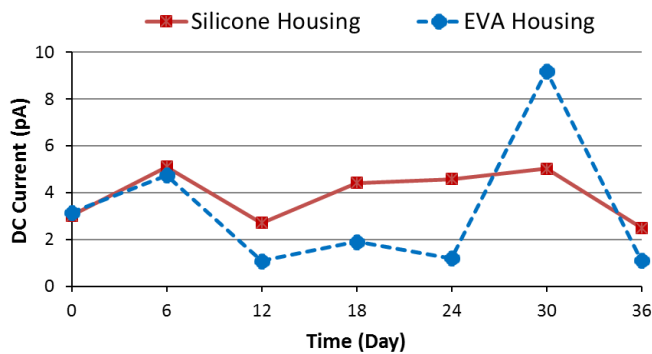


Fig. 7. DC average current on MOSA with Silicone and EVA housing.

TABLE II – COEFFICIENT OF VARIATION APPLIED TO THE DC CURRENT.

Days of Immersion	Polymer A	Polymer B
0	2.55	4.31
6	2	2.81
12	6.69	8.91
18	2.16	3.63
24	1.25	7.08
30	6.18	7.37

Dispersion of the data shown in Table I, is in an acceptable level. The DC current illustrated by Fig. 7 for both materials is extremely low which most probably is in the sensitivity level of the measurement system. As opposed to the average power loss from the full surge arrester and the dielectric dissipation factor loss, the DC current measured only on the polymer housing did not show a specific trend and or correlation with the other tests results.

D. Water Vapor Transmission Rate

For the silicone housing, the gain in mass followed basically the same trend for all samples which rose approximately 0.28 g in 820 h of test. For the same period of analysis, the EVA samples absorbed less than 0.03 g, demonstrating extremely low water absorption. These results were synthesized on Table III, where the inclination of each sample determined in the graphic, according to the rate of increase in mass, in milligrams per hour and also the values of water vapor permeation rate are detailed.

TABLE III – WATER VAPOR PERMEATION RATE.

Sample	Area (m ²)	Inclination	WVTR (g/m ² /d)
1-A	0.000254	3.47×10^{-4}	32.70666
2-A		3.30×10^{-4}	31.15537
3-A		3.41×10^{-4}	32.19859
1-B	0.000254	3.41×10^{-5}	3.22145
2-B		1.48×10^{-5}	1.39637
3-B		3.05×10^{-5}	2.87477

VI. CONCLUSION

Even though the surge arresters with silicone housing presented higher power losses than those with EVA housing, it is not possible to address this result on the device's performance, only to the difference on the material housing. These surge arresters have different manufacturers and different concepts, which may be stressed at distinct levels by moisture, especially if the interface between the external part of the active column and the housing internal face are not well bounded.

The dielectric dissipation factor for both materials increased during the immersion test (30 days). As the test frequency and temperature were the same all along the tests, the explanation for this difference is a change in the material properties, possible due to moisture absorption.

The DC conductivities remained very low throughout the test, what leads to the hypothesis that the increase in conduction measured for the full arresters and detailed in this paper using the average power losses were not due to increased conduction inside polymer housing, instead it must be due to increased conduction in the interfacial areas.

Although silicone material is widely used for outdoor insulation because its hydrophobic behavior, this characteristic is related to its behavior when considering liquid water, not vapor. This fact was verified by the data acquired during water vapor permeation test, which demonstrated that silicone housing material were more prone to moisture diffusion than EVA.

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