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Electrical Performance Evaluation of HDPE Developed for Surge Arresters Housings

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***Abstract* — This paper aims at investigating the application of high density polyethylene (HDPE) for manufacturing distribution surge arresters housings. For this purpose, it was developed prototypes of HDPE surge arresters with rated voltages of 10 kV, 15 kV and 24 kV. Two types of polymeric materials were used to manufacture the prototypes: unplasticized and plasticized HDPE. The HDPE surge arresters were submitted to electrical performance tests, according to Brazilian NBR 16050 standard. The main tests carried out were: short-circuit, weather aging, water immersion and operation duty. The results obtained have demonstrated that unplasticized HDPE surge arresters shown low performance under short-circuit and weather aging tests. On the other hand, plasticized formulation has demonstrated good stability under electrical tests and it seems to be suitable for manufacturing surge arresters housings.**

Keywords – Electrical performance, surge arresters housings, high density polyethylene.

I. Introduction

Polymeric insulation is normally constituted of Silicon Rubber (SiR), Etilene Propilene Monomerer (EPM), Etilene Propilene Diene Monomerer (EPDM) or blends of EPDM and SiR (EPDM/SiR). This group of materials is largely used in distribution surge arresters housings, because of their very simple design, reduced size and weight, easiness to shape, and other advantages compared to porcelain-housed.

Failures due to acid corrosion have been reported on literature in these categories of materials [1-4]. Two types of chemistry agents that cause deterioration on current polymer-housed surge arresters are nitric acid (HNO_3), formed due to corona activity in presence of moisture, and sulfuric acid (H_2SO_4), present on acid rain. In recent experiment performed on High Voltage Laboratory (LAT-EFEI), a total of four different types of commercially available distribution surge arresters, comprising EPDM and SiR housings, were submitted to nitric and sulfuric acid immersion, 0.1 normal, at 60 °C, during 840 h (5 weeks).

Acid deterioration was quantified by measuring the samples' weight each 120 h. Because the samples had different dimensions, percentage weight (W(%)) was adopted, according to (1), where W_s and W_i are the weights of a sample during the measurements and sample's initial weight, respectively.

$$W(\%) = \frac{W_s}{W_i} \cdot 100. \tag{1}$$

Fig. 1 shows the behavior of percentage weight over 840 h of experiment. All samples immersed in sulfuric acid presented degradation. At the end of the experiment, the total weight loss was 17%. Otherwise, the samples immersed in nitric acid presented variation of weight due to water absorption. Fig. 2 shows some examples of EPDM and SiR samples after immersion in nitric acid, indicating cracking, erosion and deterioration of the specimens.

In distribution networks, the surge arresters are commonly installed to protect transformers, capacitor banks, voltage regulators, reclosers, vacuum switches, end others equipments against overvoltages [5]. Considering the large number of surge arresters used on medium voltage networks and their mass-productions volume, the economical analysis plays an important role. Therefore, the design of new formulations for applications on surge arresters housings could be economically attractive. Aiming this issue, this paper proposes the utilization of high density polyethylene (HDPE), in substitution to silicon rubber, considering material properties and costs.

Comparing the prices practiced in São Paulo, Brazil, of HDPE and SiR, over the period comprising April to August 2015, the SiR costs reach up to nine times the HDPE costs, as shown in Fig. 3. Thus, the HDPE seems to be interesting to application in surge arresters housings.

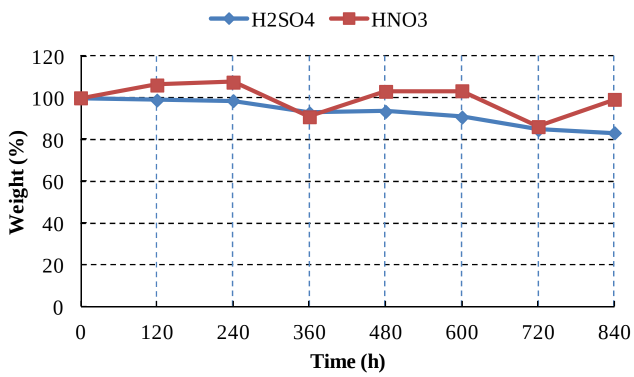

Figure 1. Percentage weight over 840 hours of experiment.

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Figure 2. Examples of EPDM samples ((A) and (B)) and SiR (C) after immersion test in nitric acid, at 60 °C.

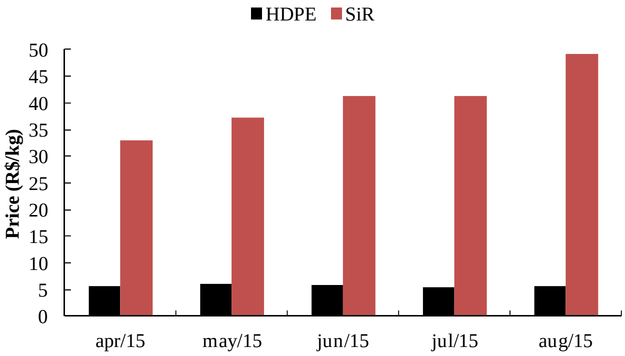


Figure 3. Price of HDPE and SiR practiced in São Paulo, Brazil, in April 2015 to August 2015 [6].

Beyond the economical advantages, some attractive properties of HDPE are listed as:

- The semi crystalline nature of HDPE allowed it to become one of the most worldwide used polymers in the manufacturing of medium and high voltage insulated power cables [7-8];
- HDPE exhibits good ability to resist nitric and sulfuric acid, excellent resistance to weathering, adequate hydrophobicity surface and high thermal and oxidative stability [9-11];
- Additional useful properties of HDPE can be listed as excellent mechanical strength, ease of shaping, low energy consumption in material processing, high production rates, possibility of reprocessing and recycling, long service life and possibility of improving the dielectric properties through the nanotechnologies [12-14].

Although HDPE presents interesting properties to application on surge arresters housings, some questions could be asked, as:

- What would be the long-term performance of HDPE housed surge arresters? Could the dielectric material withstand the accelerated aging tests provided on standard?
- What would be the behavior of HDPE surge arresters during a failure condition? Are the dispositive able to withstand the short-circuit tests? Would the surge arresters failure in a safe way?
- Would the energy capability of the HDPE surge arresters be adequate to provide thermal stability? Are the HDPE surge arresters able to withstand the operating duty test without cause thermal runaway?
- Would the HDPE adequate to provide correct sealing performance against moisture or water ingress?

Therefore, this paper aims to evaluate the behavior of HDPE surge arresters under short-circuit, weather aging, water immersion and operating duty tests.

II. Electrical Testing

A. *Materials*

The HDPE surge arresters were produced by one-shot injection molding process, where the housing was injected directly around the core in one piece. Unplasticized and plasticized HDPE resins were used. The differences between them consist basically in crystallinity degrees and mechanical properties (tensile strength, elongation, Young's modulus). Further information can be obtained in [15].

To evaluate their performance, these arresters were submitted to short-circuit, aging, water immersion and duty cycle tests, according to current version of NBR 16050 [16] that is based on IEC 60099-4 (2009) recommendations [17].

B. *Short-Circuit Test*

In order to develop HDPE surge arrester with safety performance, the metal-oxide surge arrester prototypes were subjected to short-circuit tests in specific conditions. The unplasticized HDPE surge arresters were tested at High Power Laboratory of Electrical Energy Research Center (CEPEL), Rio de Janeiro, Brazil. The surge suppressors were installed in the center of a circular enclosure, with 1,8 m of diameter and 0,4 m in height. The surge arresters were connected to the non-metallic pole using a mounting bracket. The main test arrangement is shown in Fig. 4.

The plasticized HDPE surge arresters were tested at VEIKI-VNL Laboratories, Budapest, Hungary. The support structure was installed in the center of a square enclosure with dimensions of 1.80 m x 1.80 m and 0.4 m in height. The surge arrester was connected to a fixed wood post. The height at the bottom terminal of the arrester was 0.9 m, and the main test arrangement is shown in Fig 5.

For each type of HDPE surge arrester (unplasticized and plasticized), a sample was submitted to rated short-circuit current, with amplitude of 16 kA and duration of 200 ms. Another two samples were submitted to reduced short-circuit currents of 6 kA and 3 kA during 200 ms. A fourth sample was submitted to a low short-circuit current, with an amplitude of 600 A, applied during 1 s.

Figure 4. Short-circuit test arrangement according to NBR 16050 [16]. Unplasticized HDPE surge arresters of 24 kV.

Figure 5. Short-circuit test arrangement according to NBR 16050 [16]. Plasticized HDPE surge arresters of 15 kV.

C. Weather Aging Test

The weather aging test was designed to verify the HDPE surge arrester resistance to tracking and erosion. The setup of the salt fog chamber used in the present study is shown in Fig. 6. The chamber's dimension is 3.5 m x 2.5 m and 2.5 m in height. Six fine full cone fogging nozzles, distributed along both sides of the wall's chamber, were used to generate the salt fog conditions.

The salt water solution was prepared having a concentration of 5 kg/m^3 of NaCl in deionized water. The solution conductivity was verified and remained around 8,700 µS/cm. The reservoir was filled up every 24 h and its conductivity adjusted to the, previously mentioned, standard value.

Three samples of HDPE surge arresters, brackets and fault indicators were fixed to a wooden post and submitted to salt fog conditions during 1,000 h. The continuous operating voltage (U_c), which corresponded to 12.7 kV, was applied to the samples and at every 100 h, visual and thermal inspections were conducted in order to find potential failures. It is worth to note that each of these interruptions did not exceed 10 min.

D. Water Immersion Test

The water immersion test was performed to verify the resistance of HDPE surge arresters to water penetration. Two HDPE-housed surge arresters were immersed in a vessel, with boiling salt water solution, during 42 h. The salt water solution was prepared with 1 kg/m^3 of NaCl in deionized water. After the 42 hours of test, the HDPE surge arresters were kept in the vessel until the water cools to 50 °C. Finally, the verification tests were performed on samples cooled to ambient temperature.

The verification tests carried out consisted in visual inspection on surge arresters housings; watt losses measurements at U_c; internal partial discharge (PD) and residual voltage (U_{res}) measurements at nominal discharge current (I_n) of 5 kA, 8/20 µs. The last three tests procedures are described in item "*F. Complementary Tests*".

E. Operating Duty Test

The operating duty test was carried out to verify the performance of the HDPE surge arresters under service conditions. Fig. 7 shows the setup circuit used to carry out the operating duty test on HDPE surge arresters. First, the U_{res} of three identical samples were measured at I_n. Following, the samples were submitted to the conditioning test, that consists of 20 impulses at I_n superimposed on 1.2 times U_c, that correspond to 9 kV. The I_n impulses were applied in four groups of five impulses. The interval between the impulses was 60 s and between the groups was 30 min.

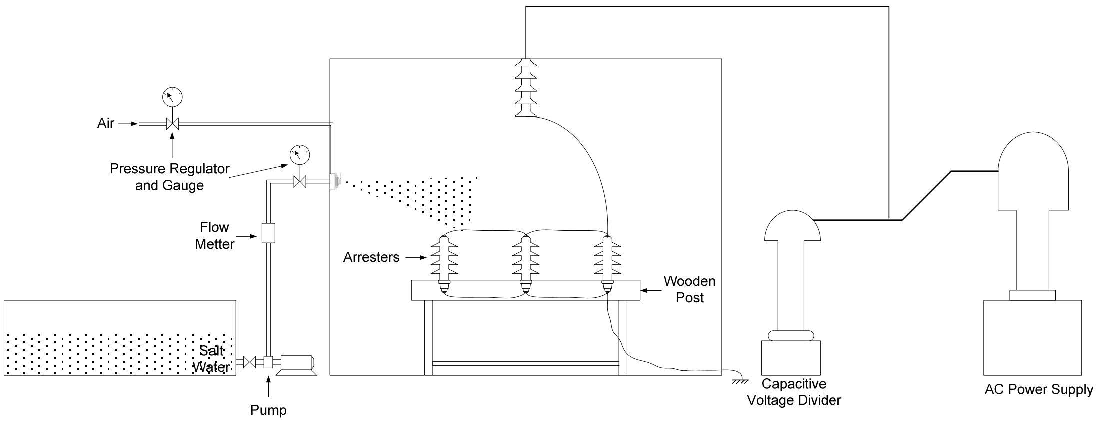


Figure 6. Weather aging test set up. Three HDPE surge arresters were positioned in the middle of the chamber. Six fogging nozzles distributed on the walls were fed by saline water and pressured air. The high voltage was supplied by the test transformer (20 kVA, 150 kV).

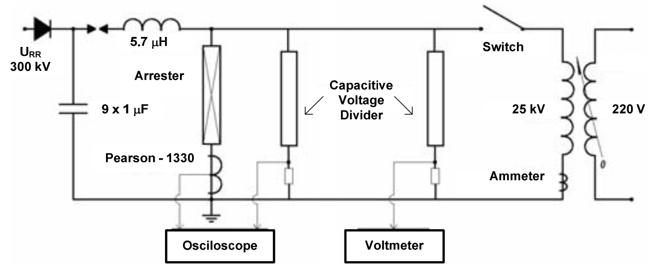


Figure 7. Operating duty test setup. High current impulse generator formed by 12 stages, maximum voltage charge of 90 kV, nominal current of 100 kA, 4/10 µs. AC voltage supplied by a test transformer of 10 kVA, 220 V – 25 kV.

After the conditioning test, the samples were submitted to two high current impulses of 65 kA, 4/10 µs. The first high current impulse was applied in ambient temperature and the second impulse was applied after the samples were preheated to 60 °C in an electrical oven.

Afterwards the second high current impulse application, the samples were submitted to the rated voltage (U_r) of 10 kV during 10 s subsequently to U_c of 7.5 kV during 30 min. Finally, U_{res} was measured and compared to the values obtained before the operating duty test.

The main condition to pass this test is that the surge arrester is able to cool down during the U_r and U_c applications. It is noteworthy that operating duty test was performed in three samples with a rated voltage of 10 kV, according to the tests facilities. However, both samples of U_r of 10 kV and 15 kV have the same thermal behavior. Therefore, the results obtained for U_r of 10 kV can be extended to 15 kV, according to NBR recommendations [16].

F. Complementary Tests

The complementary tests were performed before and after the main tests, with the objective to verify critical changes in the performance of surge arresters.

1) PD Measurements

The circuit for PD measurements consists in one voltage regulator connected to the primary side of a power transformer. To avoid harmonic interference, it is installed a filter of high frequencies in the secondary side of power transformer. PD is undirected measured by comparing to a reference signal, using a Hipotronics equipment, model CDO68C.

2) Watt Losses and Reference Voltage Measurements

The circuit for watt losses and reference voltage measurements is composed by a power transformer supplied through a signal booster, generating sinusoidal waveforms with very low voltage harmonic distortion. The high voltage is measured by an oscilloscope connected to the low voltage branch of resistive divider. The leakage current is measured through the voltage drop across a 1 kΩ shunt resistor. The reference voltage is the peak value of power-frequency voltage divided by $\sqrt{2}$ applied to the arrester to obtain 1,0 mA (peak value) of resistive component of a power-frequency current.

3) U_{res} Measurements

U_{res} measurements are carried out during the passage of I_n. Basically, the same circuit employed in operating duty test (Fig. 7) is also used in U_r measurement, however without the AC voltage supplied by a test transformer of 10 kVA.

III. RESULTS AND DISCUSSION

A. Short-Circuit Test

The surge arresters are considered approved in short-circuit tests since no violent shattering is observed; no parts of the test sample shall be found outside the enclosure (except soft parts or fragments less than 60 g each) and the open flames, if existing, must be self-extinguish within 2 min.

The performance of unplasticized HDPE surge arresters under short-circuit tests was considered unsatisfactory. The high crystallinity of the unplasticized HDPE constitutes the major disadvantages for the manufacture of surge arresters housings. The huge mechanical strength of the housing results in heavy shattering during the short circuit test, as shown in Fig. 8. On field, this is very dangerous for bystanders, and in some way a performance similar to the porcelain.

On the other hand, during the short-circuit tests on plasticized HDPE surge arresters, it was not observed any violent shattering of the housing, resistor block, fitting or surge arresters connections. After short-circuit current application, the surge arrester was able to self-extinguish incandescent particles. Following all test procedures, the surge arresters remained connected to the power circuit. Therefore, the results are considered satisfactory, according to NBR 16050 standard [16]. The Fig. 9 (A) proves that the power arc was developed outside the surge arrester structure, and the Fig. 9 (B) shows the polymer housing cracked, indicating the slid from where the arc was expelled.

B. Weather Aging Test

During the weather aging tests, it was observed surface discharges due to dry-band arcing, as shown in Fig. 10. For unplasticized HDPE surge arresters, the frequency of surface discharges was kept below 10 discharges per minute until 300 hours of test. Between 500 to 700 h, the discharges level rose above 20 discharges per minute, until the failure of surge arresters samples.

Fig. 11 (A) shows the initial formation of cracking on unplasticized HDPE housing, normally observed after 400 h of weather aging tests. Fig. 11 (B) shows the completely failure of unplasticized HDPE surge arresters due to cracking, erosion and puncturing of housing.

The developed of dry-band arcing creates a non-uniform temperature distribution along the housing. The thermal gradient produces expansions and/or contractions, stressing the polymeric material. The high crystallinity of unplasticized HDPE does not permit to accommodate the volumetric variation of the polymer, resulting in small surface cracks. The salt and moisture accumulation in small cracks allow increasing the leakage current, generating a cycle process until the complete failure of unplasticized HDPE surge arresters.

(A) (B)

Figure 8. Unplasticized HDPE surge arresters after short-circuit tests (3 kA, 200 ms). (A) Polymer-housed failure resulting in violent shattering. (B) Polymer-housed ejected out the enclosure.

(A) (B)

Figure 9. (A) External power arc commuted to the outside through the plasticized HDPE housing; (B) polymer housing cracked, indicating the slid from where the arc was expelled.

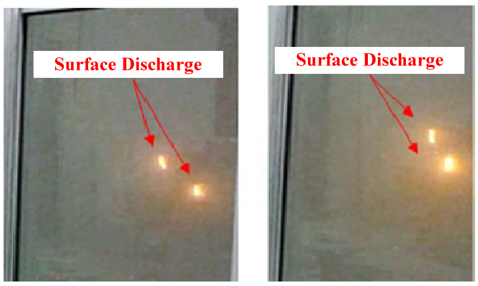
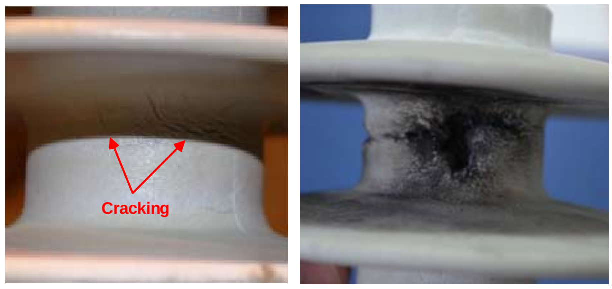


Figure 10. Surface discharges normally observed during the weather aging tests.

On the other hand, for plasticized HDPE, it was observed an increasing in the superficial housing roughness, especially between the sheds. After finishing the weather aging test, there was an accumulation of NaCl particles, mainly in the roughest parts on the housing. Fig. 12 (A) and (B) show, respectively, samples before and after testing. Nevertheless, no evident erosion, cracking, tracking, punctured or another serious degradation in either surge arrester sample was observed. The reference voltage measured before and after the weather aging test indicated a difference of about 1%. In the same way, partial discharge measurements carried out before and after the weather aging test indicated values below 10 pC for both cases.



(A) (B)

Figure 11. Unplasticized HDPE surge arresters during weather aging test. (A) Cracking normally observed after 400 h of test; (B) polymer-housed failure due to cracking, erosion and punching the unplasticized HDPE.

(A) (B)

Figure 12. Surge arrester housing before (A) and after (B) the weather aging test.

Due to failures identified on unplasticized HDPE surge arresters during short-circuit and weather aging tests, water immersion and operating duty tests were not performed on these prototypes.

C. *Water Immersion Test*

At the end of water immersion test, any mechanical change was observed on plasticized HDPE surge arresters by visual inspection. The results of watt losses measurements carried out before and after the immersion tests are shown in Table I. For the first surge arresters sample, it was observed a decrease of the watt losses around 13% after the tests. Otherwise, the second HDPE sample submitted to the test showed an increase of the watt losses around 17%. However, the NBR 16050 standard [16] allows an increase from the initial measurement less than 20%.

The maximum difference between the U_{res} measured before and after the water immersion test was less than 1%, as indicated in Table II. The values obtained during PD measurements were less than 1 pC. Therefore, plasticized HDPE surge arresters are considered approved in water immersion tests, according to the NBR standard [16].

TABLE I. DIFFERENCE IN WATT LOSSES MEASUREMENTS.

	Initial Values	**Final Values**	**Difference**
Sample	**P (W)**	**P (W)**	**P (%)**
1	5.32	4,61	-13,3
2	5.68	6,67	17,4

TABLE II. PERCENTAGE DIFFERENCE IN U_{RES} FOR I_N DURIGN WATER IMMERSION TEST.

	Initial Values		Final Values		Difference	
Sample	**I_n (kA)**	**U_{res} (kV)**	**I_n (kA)**	**U_{res} (kV)**	**I_n (%)**	**U_{res} (%)**
1	5.1	28.8	5.3	29.0	3.9	**0.6**
2	5.3	28.8	5.3	28.8	0.0	**0.0**

D. *Operating Duty Test*

No puncture, cracking or degradation were observed on surge arresters samples. During the operating duty test, all the surge arresters samples were able to maintain the thermal stability. The maximum difference between the U_{res} measured before and after the test was 4%, as indicated by Table III. The results are considered satisfactory according to the NBR standard [16].

TABLE III. PERCENTAGE DIFFERENCE IN U_{RES} FOR I_N DURING OPERATING DUTY TEST.

	Initial Values		Final Values		Difference	
Sample	**I_n (kA)**	**U_{res} (kV)**	**I_n (kA)**	**U_{res} (kV)**	**I_n (%)**	**U_{res} (%)**
1	5.3	28.2	5.4	29.0	1.9	**2.8**
2	4.8	27.9	4.7	28.7	-2.1	**2.8**
3	5.1	27.7	5.2	28.8	2.0	**4.0**

IV. CONCLUSIONS

The present studies have demonstrated that the developed plasticized HDPE surge arresters housings seem to exhibits suitable performance for applications on power distribution systems. The performance of these prototypes of surge arresters under weather aging, short-circuit, water immersion and operating duty tests was considered satisfactory according to the tests results and the evaluation criteria established by the technical NBR 16050 standard.

Additionally, the unplasticized HDPE surge arresters have not been approved in electrical tests performed. It seems that the high crystallinity index of unplasticized HDPE resin plays an import role in surge arresters housings' applications. The short-circuit tests carried out on unplasticized HDPE surge arresters have demonstrated that housings formed by a more rigid material may take the surge arresters to fail in an unsafe manner. Likewise, weather aging test performed on unplasticized housing has confirmed that a stiffer resin can induce a premature failure on surge arresters during the accelerating aging tests.

Therefore, the results seem to indicate that the plasticized HDPE is technically and economically feasible to substitute silicon rubber for application on distribution arrester housings. However, a complete test based on current version of IEC 60099-4 (2014) and ANSI/IEEE C62.11 (2012) must be carried on to verify the performance of plasticized HDPE surge arresters according these international standards.

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