Some Problems With RIP-Insulated Bushings

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Abstract—**In this paper the possible reasons RIP-insulated high voltage bushing failures are investigated and discussed: first, factory technology defects, bushing test tap contact defects, mechanical strengthes in main insulation body, and a few another. With this in view, the authors have recommended on-site PD measurement and FRA technology as mandatory diagnostic methods; to revise construction contact last foil layer with a test tap; HV protect elements (capasitor, surge arrester) installation.**

Keywords—RIP insulation; failure; bushing; partial discharge; diagnosis

I. INTRODUCTION

In design of internal insulation high-voltage bushings with RIP-insulation refer to capacitor type leakproof bushings and have main insulation in the form of insulation body with conductive electrodes (plates). Location equalizing plates ensures optimum electric field distribution in both the radial (insulation thickness) and axial (from bushing ends relative to the grounded flange) directions. Basic RIP insulation of high-voltage bushings (RIP - Resin Impregnated Paper) is insulating crepe paper which were impregnated with epoxy resin. As a material of the plates preferably used metal foil superposed directly on the paper surface.

Recently many factories have industrial manufacturing of 110 - 550kV bushings [1]. The main RIP-insulated bushings advantages are:

- Any installation angle - from horizontal to vertical;
- The low dielectric loss - less than 0.5%;
- Low intensity of partial discharge (less than 5 pC);
- High mechanical and thermal resistance;
- Explosion and environmental safety.

Main disadvantages are:

- The lack of "self-healing" effect of minor defects; High demands to the technology, since workmanship leads to the appearance of cavities, mechanical stresses and cracks in the insulation bulk;
- Low C_2 value with long wires from test tap to the relay protection box increases damage insulation risk [2].

The high voltage RIP-insulated bushing consists of the following structural elements:

- Solid insulation body made wound onto the body tube insulating paper followed by impregnation with epoxy resin (RIP-insulation);
- Coupling sleeve rigidly fixed on the insulating body;
- Test tap;
- Supporting flange for bushing installing;
- Contact terminal;
- Porcelain or plastic top cover;
- Spring system to compensate temperature changes (bushings with porcelain cover).

Despite improvements in manufacturing technology RIP-insulated bushings reliability leaves much to be desired. Typically in operation the bushing body is damaged and one layer breakdown precedes breakdown of the layers of insulation between the equalizing plates. Breakdown reasons of the insulation layer occurs at some distance from the bushing central part are most incomprehensible. It can be assumed that this damage may be initiated by defects in the form of air pores or cracks, flaws or other types of resonance of high frequency overvoltages. Defects can be caused by disorders of the technology process and should be identified in the factory tests.

Resonance overvoltages occur when switching processes. As in any object with reactive elements, the resonances have a right to be. Obviously, the more dangerous for the insulation are voltage resonances. It is important, however, to understand the frequencies at which they can occur, and what voltage source can be resonance exciter, i.e. contains in its spectrum of resonant frequency harmonics. Ultimately, it is necessary to understand how the voltage distribution across (in layers) and along (height) may be occur in bushing insulation. According [3] resonance frequency is 8 MHz for 220 kV bushings. Such high frequencies can be generated by SF6 switchgears, where probably we should expect effect of these processes onto the bushing reliability.

Insulation damage in the bushing central part reasons look clearer, especially in the area of test-tap contact to last plate (Fig. 1a). According to available statistics in Russia they occur in 70% of all failures. The main causes damage of this part are mostly of poor grounding quality, inefficient insulation protected against overvoltage and high transition resistance of contact connection test tap to last electrode. In case of bad grounding insulation test tap is damaged first (Fig. 1b).


a) b)

Fig. 1. Examples of bushing damages: a) internal breakedown over 7 layers; b) ungrounding test tape - breakedown insulation.

Switching overvoltages on test output can occur when insufficient effectiveness of protective devices (capacitors, varistors, surge) or remote from the test tap location [2]. High transition resistivity is observed mainly in the bushings with spring design pin connection and is not seen at the last plate soldering wire connects guide her to the test tap.

II. STUDIES OF RIP INSULATION BY CAPILLARY METHODS

The basis of porosity structure studies are behavior wetting and non-wetting liquids in capillaries. Liquid wetting the material which has a capillary it will rise. Conversely, liquid not wetting capillaries it will be omitted. In addition, the liquid height (lowering) depends on tube thickness: the thinner the capillary, the more lift height (lowering of) liquid. The studies were provided on RIP-insulation samples thickness of 10 ± 1 mm, cut by diamond blades from bodies 110 kV bushings of Russian production with great caution (Fig. 2).

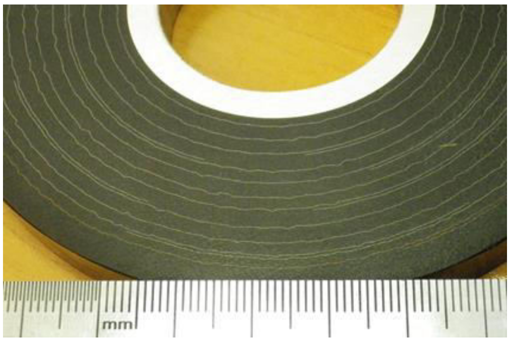

Fig. 2. Cutting example of RIP insulation.

A. *Penetrating of the Painted Liquid*

The purpose of this experiment was to establish the presence of through capillaries. The experiment was performed according to the method of 9.4.1 IEC 62217 [4]. Typically, each sample had one through the capillary (Fig. 3) and sometimes there were several. High painting liquid penetration rate (about 1 mm/sec) evidence of small capillaries diameters.

Mercury porosimetry is based on mercury discharge into the sample from which the prevented. As soon as filled with the biggest, then the smaller capillaries and pores, it requires more and more pressure to push the mercury in them. Quantitatively the connection aspect ratio channels in the sample is expressed in changing amounts of mercury entering the sample at successively increasing pressures.

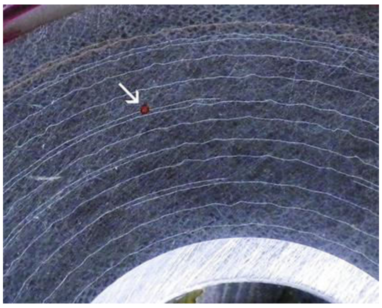

Fig. 3. Painted liquid penetration through capillary (arrow).

Thus, the mercury porosimetry method is direct measurement of the sample pore volume and indirect method of determining the equivalent pore radius, as it is based on cylindrical capillaries model. So the results obtained are valid only within a cylindrical models applicability for the description of the porous structure.

The method is based on the equation of Washbourne, who first applied for the determination of mercury intrusion pore size:

$$D = \frac{-4\sigma \cdot \cos\theta}{\Delta P}, \tag{1}$$

where σ – mercury surface tension (485 din/cm), θ – angle of the tube with respect to horizontal axis (130-145^0), ΔP – gauge pressure (Pa).

This method allows to estimate complete specific surface area:

$$Syy = \frac{1}{\sigma \cdot \cos\theta} \sum_{i=1}^{n} P_i \cdot \Delta V_p, \tag{2}$$

where $_{\Delta}V_{\mathrm{p}}$ –gain of dent mercury volume at raise of pressure from P_{i} to $P_{\mathrm{i+1}}$.

In accordance with the principle mercury porosimetry has another drawback. Pore volume filling with mercury takes place from the sample surface, so the pores are in the central part of the sample, filled with delay even at higher pressure, resulting in distortion on the actual distribution of pore diameters. To avoid this, it is desirable that the individual pieces of the sample were probably smaller (3 - 5) mm in section.

Measurements on the "Avtopor 9420" by «Micromeritics» (USA) was done. Two test samples by 12×10×6 mm were prepared. Before the experiment they were washed with spirit and placed in vacuum for 3-4 hours at 100°C. Typical results are shown in Fig. 4 - differential distribution capillaries on diameters.

According to the studies results the following conclusions are possible to draw:

1. Left part of the curve can be explained not only by the presence of capillaries with diameters of tens and even hundreds of microns, but also be consequence of the uneven sample surfaces. Delamination of epoxy resin foil linings may

also be perceived as the equipment of large diameter capillaries.

2. Similarity central and right parts of the curves obtained on different samples indicates the stability properties of the internal structure. Thus small pore sizes are likely to belong to the crepe paper. Probably, during the manufacture of insulation they are not impregnated with epoxy resin due to counteract the surface tension forces. It should be noted that a large number of tiny capillaries leads to a large hygroscopic properties of conventional materials.

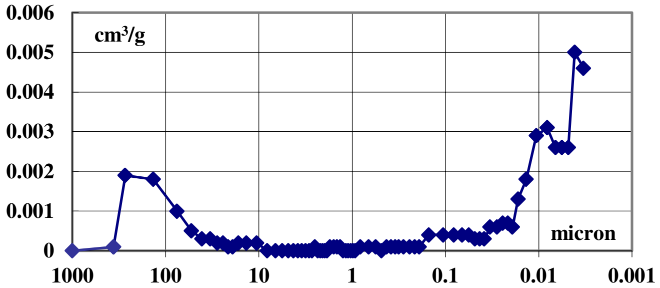

Fig. 4. Incremental volume (left axis) *vs* capillary diameter (lower) – graf (differential distribution).

Main authors' doubts in the test results associated with the preparation of samples: large diameter capillaries could appear not only in the process of impregnating the poor but also for cutting samples.

B. *Effect of Electrode Irregularities on Electric Field Strength*

Irregularities plates arise due to irregularities in crepe paper and clearly seen in Fig. 2. Electric field calculations were carried out in model of two insulated layers separated by irregulating plate. Example electric field pattern in the model shown in Fig. 5.

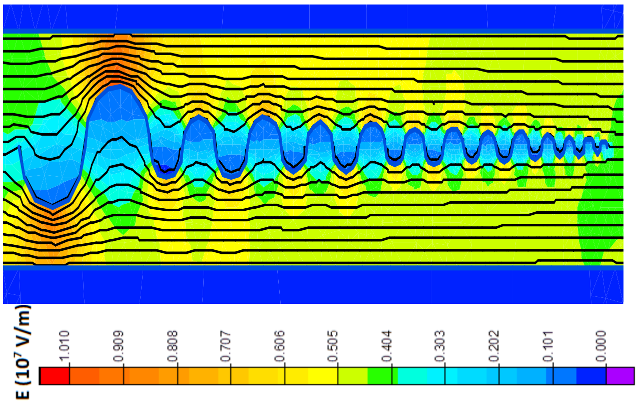

Fig. 5. Field pattern in two insulation layers with “hilly” middle electrode (plate).

The model parameters were: voltage electrodes from bottom to top 17.2 kV, 8.6 kV, 0 kV, distance between the plates - 2 mm, ε = 4, tubercles radius varied in length sheath average from 1 to 0.1 mm. It can be seen local increase in strength caused by the irregularities are not so great to cause insulation breakdown directly subject to its quality. RIP insulation electric strength is estimated over 30 kV/mm. With average field strength in insulation layers about 4 kV/mm, even doubling the local field enhancement caused by the roughness of the plates should not have been so radically (up to a few months) to reduce the bushing life.

C. *Effect of Mechanical Sresses*

In the bushing body insulation local mechanical stresses may arise in the manufacturing process or during the operation. They can lead to cracks, which can initiate PD. Time to occurrence of cracks can be defined by the formula:

$$\tau(\sigma,T)=\tau_0\cdot\exp\left(\frac{w_{act}-\gamma\sigma}{kT}\right), \qquad (3)$$

where k - Boltzmann constant; $\tau_0 \approx$ 10-13 s - time close to period of atoms oscillation in solids; w_{act} - activation energy of fracture process;
$\gamma = qVa$, where Va - activation volume in elementary act dissociation, q - coefficient of local stresses.

III. DIAGNOSING RIP-INSULATED BUSHINGS

Manufacturer's recommended range of preventive field testing involves measuring the resistance test tap voltage by megger with 2.5 kV and tangent delta and capacitance measurement of main insulation ($\mathrm{tg}\delta_1$ and C_1) at 10 kV. Our opinion on that diagnosis is different. If we talk about the dielectric characteristics it is preferable to measure ones under operating voltage and in automatic monitoring mode, since insulation degradation after first layer breakdown can quickly complete a full body breakdown. Thus it is necessary to take into account the specific behavior of tangent delta in time. Tgδ magnitude may increase in the development breakdown stage and return to the previous value at the breakdown completion. In addition, large temperature gradient along the bushing length creates uncertainty in interpretation of measurement results. So more reliable indicator could be changing in capacitance C_1 [5].

At early stage of defect development main indicator may be partial discharge intensity [6], measured under operating voltage by electrical or electromagnetic method. Another fundamentally possible diagnosing methods, for example, IR and UV inspection may considered as helper methods. They may detect the defect but can not in some cases, particularly when it is formed in the lower bushing part covering by transformer tank.

Let’s back to the question about PD impact on the insulation. Solid insulation pecificity is that it has not “self-healing” effect. The process of insulation destruction, once arisen, will never stop. Initial potentially dangerous defect in the form of air void has a volume of less than 1 mm^3. If it has PD yet, they may cause to insulation breakdown without significant changes in the discussed above integral dielectric characteristics.

We ask the question: "In what fields and in pores of what size PD can ignite?" We assume the pores and capillaries in insulation filled with air and the air pressure equals outside one. Then we can determine strength on the right side of the Paschen curve. Thus it is necessary to consider the form of void impact on size and distribution of electric field in its entirety.

In the flat cavities (for example, foil plate delamination which is likely due to insufficient adhesion of resin with aluminum foil) field strength in ε times the average. With average operating strength 4 kV/mm PD burn in air voids of all sizes (it means size across field vector) with thickness exceeding 20 microns.

In spherical shape pores electric field has a peak on the axis and approximately 1.33 times greater than the average, i.e. about 5.2 kV/mm. In accordance with Paschen curve for air pressure PD should burn in pores having diameters greater than 400 microns. We assume that the void of this size in insulation does not occure. But when you consider the field enhancement due to irregularities plates the possibility of PD in the pores smaller increases. This is especially cocerned in electrodes area where the field intensity is high and the probability of occurrence of spherical air voids than in other places.

Studies ratio of apparent and true PD charge in spherical shape pores have shown that PD apparent charge becomes close to the true only when void size becomes comparable with electrode gap dimensions. Taking into consideration thickness of insulation layer and real void's size even in (10-100) microns PD apparent charge is 100-1000 times less than true one.

True charge estimating pores with diameter of 100 microns is 500 pC. Hence the apparent charge being measured in a single layer is (5 - 0.5) pC. Furthermore, due to effect of layers it will have N times less where N - number of insulation layers [7]. For this reason, we "do not feel" spherical voids at all although PD danger in them is very high!

In flat voids it is more sophisticated because field strength is sufficient to PD ignite in all delamination thickness over 20 microns. PD apparent charge according to [8] is strongly dependent on the thickness of the cavity d, b and the thickness of the relative dielectric constant or rather lack of education or the discharge spot along the surface of the deposited charge:

$$d_{crit} \geq -2.8\left(\frac{\text{b}}{\varepsilon}\right)^2 + 3.3\left(\frac{\text{b}}{\varepsilon}\right) - 0.05. \qquad (4)$$

When layer thickness b = (2 - 4) mm and ε = 4, we obtain d_{crit} = (0.9 - 0.45) mm. We assume this size delamination does not allow by manufacturer. In delamination with $d < d_{crit}$ size voids PD are formed as microdischarge series and discharged from 1 to 10% of the cavity. The rest of cavity "is not involved in PD". Something more definite is hard to say but in any case the apparent charge is N times less when PD are measured in whole bushing.

If we take N = 10 (110 kV bushing) the 10 pC apparent charge corresponds to true 100 pC one, and this is already much. In bushings over 110 kV with large number of plates situation with sensitivity PD registration by electrical method becomes worse. Therefore, it seems necessary to verify PD absence other methods such as electromagnetic or acoustic.

CONCLUSIONS

1. The main cause of RIP insulation damage are most likely defects in form pinholes, which in turn, are impaired or technology or from an interaction with the filling material and hardening. Why factory tests do not detect these shortcomings can be explain by the inability measurements true charge of PD and "masking" effect equalization plates with respect to PD signals.
2. A number in test tap damage unit can be initiated not only the absence of grounding but the poor quality and high resistance contact connection test output from the last electrode.
3. On breakdown stage of individual insulation layers to prevent the complete bushing destruction most expedient leakage currents monitoring.
4. For early defect detection PD measurements by electromagnetic or acoustic methods suitable.

REFERENCES

[1] IEC 60137 (2008). Insulated bushings for alternating voltages above 1000 V.

[2] S. Botov, V. Rusov, "Effect protective relay KIV-500 with TPS on technical state of high-voltage RIP-insulated bushings", Energoexpert, vol.1, 2013. – p. 18-21.

[3] K. Johansson, "Modeling and Measurements of VFT Properties of a Transformer to GIS Bushing", Proceedings of the 43rd CIGRE Session, Paris, 2010. – Paper A2 – 302.

[4] IEC 62217 (2012). Polymeric HV insulators for indoor and outdoor use – General definitions, test methods and acceptance criteria.

[5] T. McGrail, K. Elkinson, "Asset Management: Power Transformer Fleet Condition Assessment and Risk Management", Proc. 18th ISH, Seoul, 2013. – Paper OG1-02.

[6] M. Koch, S. Raetzke, M. Krueger, "Interpretation of the Dielectric Response of Instrument Transformers, Bushings, Cables, Rotating Machines and Power Transformers", Proc. 17th ISH, Hannover, 2011. – Paper F-083.

[7] A.Ovsyannikov, "Estimation Problems in Insulation Condition at PD Intensity Measurement", Proceedings CIGRE SC 33 Conference. – Prague, September 7th – 8th, 2000. – Paper S4 – 4.

[8] A. Ovsyannikov, "The Space-Time and Energy Characteristics of Partial Discharges in Air Void of Solid Dielectric", Proc. 14th ISH, Beijing, 2005. – Paper G-54.