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UPON THE DIFFERENCE BETWEEN THE EVOLUTION VERSUS FREQUENCY OF PD AND BREAKDOWN PROCESSES, RELATED TO PAPER FOR DC CABLES INSULATION

Romeo Ciobanu [1], *Cristina Schreiner* [1], *Marinel Temneanu* [1]

[1] Technical University Iasi, Romania, rciobanu@ee.tuiasi.ro

Abstract: Significant differences between the evolution versus frequency of the PD and breakdown processes were emphasized, suggesting that the breakdown analysis, if used as unique method in quality assessment of insulating materials, proves to have limits in accuracy and may lead to errors in results interpretation.

Keywords: partial discharges, cable paper.

1. INTRODUCTION RELATED TO PD TESTS

Partial discharges (PD) usually occur, if in gas filled cavities within solid insulation or in air gaps between several layers within an insulation construction, respectively between insulating material and electrodes, the breakdown voltage of the enclosed gas (mostly air) is exceeded. For thin insulation systems (< 1 mm) and especially for safety-related applications, the verification of the non-existence of PD or the capability to permanently withstand PD should always be required.

The use of very high test voltages without measuring PDs always implies the risk of degradation of the solid insulation. Additionally, such tests can only show the important defects within the insulation system. This can be acceptable in case of type testing, but it is not appropriate for sample testing or even for routine testing. Such tests – e.g. breakdown - should never be performed for the purpose of quality control. In high-voltage engineering, the requirement of PD-testing is recognized in general, as the existence of high field stress is obvious. However, due to very small insulating distances in recent low-voltage equipment, similar or even higher fields can occur. This is usually the case if increased stresses due to overvoltages or dielectric testing are applied.

As regards the standardization of PD-testing, we need to accept PD-testing as a general recognized tool to verify the integrity of high-voltage insulation systems. By performing PD-testing, both requirements for minimum thickness through insulation and excessive amplitudes of the test voltage and duration of the test are substituted. There is no physical background for the values of minimum thickness through insulation, which are currently required, and which vary between 0,4 and 2 mm. It is difficult to understand how such different thickness values can provide the same required degree of safety.

At present, no or only few high-frequency testing procedures are performed in electric power applications. This situation involves a non-calculable risk, as no indication could be found, that from the results of power frequency tests, a reliable extrapolation to the behavior at high-frequency voltage stress might be possible. These aspects refer both to breakdown and PD tests. Some additional problems are involved, if PD-tests at higher frequency of the voltage are required, as no standard PD-measuring equipment can be used, [1-3].

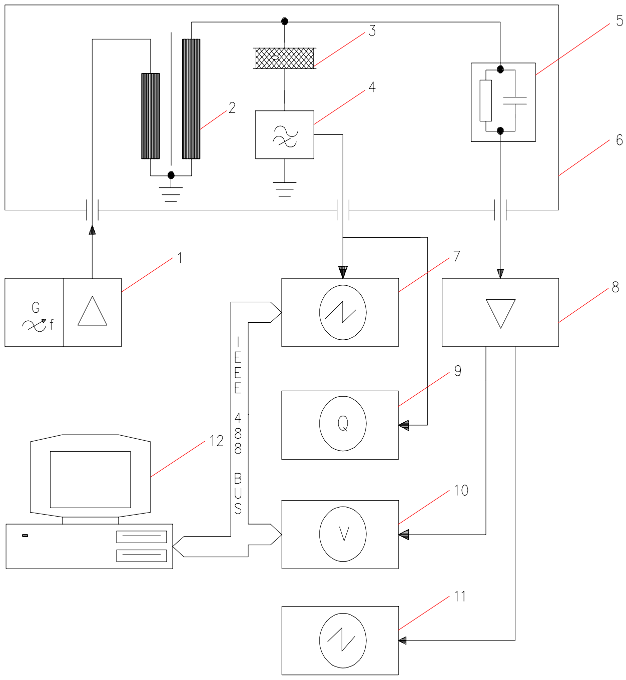

Fig. 1. PD-test circuit for broadband frequency voltage tests

1 — Power generator – up to 100 kHz
2 — Wide band high-voltage transformer
3 — Test specimen
4 — High pass filter
5 — High-voltage probe
6 — Screened cabinet
7 — High speed digital storage oscilloscope
8 — Decoupling amplifier
9 — PD-measuring instrument (narrow band)
10 — Digital voltmeter
11 — Analogue oscilloscope
12 — Control computer

The PD-measurements with broadband frequency test voltage, which are reported here, were based on the schematic test circuit shown in figure 1. In principle, for measuring the PD-intensity, a digital storage oscilloscope in combination with a rejection filter, with steep characteristic in order to suppress the high-frequency test voltage, was used. Taking into account all problems concerning higher frequency PD measurement technique, the set-up was completed towards providing advanced analytical and statistical features, and offering extra facilities, [4], such as:

- programmable shape, frequency and amplitude of test voltage;
- self-calibrating of frequency and amplitude of test voltage;
- frequency analysis, by use of an incorporated calibrator for PD pulses;
- accurate detection of periodical noises and their progressive elimination by inhibiting the measurements;
- automatic disconnecting in case of overvoltage, overload, or imposed security actions (e.g. door opening);
- complete automation of measurement process, via specialised software.

The basic measured quantities, submitted further to a statistical analysis, were:

- PD pulse peak value of Inception and Extinction Voltage
- apparent charge of individual PD pulse, via analogue integration of every PD pulse
- pulse polarity and phase
- instantaneous values of test voltage and frequency when PD pulse occurs
- q_i : charge amplitude, range-*i*
- n_i : no. of detected PD events / charge value q_i, in order to permit the calculus of the PD statistical parameters:
- N_a: average no. of events / period:

$$N_a = \frac{1}{f \cdot t_a} \cdot \sum_{i=1}^{N_c} n_i$$

- Q_M : average charge / period:

$$Q_M = \frac{1}{f \cdot t_a} \cdot \sum_{i=1}^{N_c} n_i \cdot |q_i| \quad \text{[pC/period]}$$

- q_m : average charge / individual PD pulse:

$$q_m = \frac{Q_M}{N_a} \quad \text{[pC/pulse]}$$

- $q_{\min}$: minimum value and $q_{\max}$: maximum value of charge (the limits of measured series of apparent charge).

2. ASPECTS CONCERNING FIBROUS INSULATION TESTING

In recent years, many analyses have been performed regarding PD phenomena inside or on the surface of certain dielectrics, especially films or printed circuit boards, usually taking the aim to new criteria for electrical circuits miniaturising. But only few studies were referring to thin porous materials, in spite of their large diversity and common use as part of many insulating systems. Such a relevant example is paper insulation for DC cables. As noted after analysing the scientific literature, almost all previous studies have *outlined only partially* the conditions experienced by porous and composite insulators during the cycles of in-service stresses, even if, for this kind of insulating systems, partial discharges are considered very common phenomena. Referring to the voids, having an average dimension from 0.1 up to 100μm, their shape, volume and spatial distribution lead to special behaviour under in service stress conditions and to special ageing processes. What is now considered a new and relevant aspect related to PD phenomena occurrence, is the fact that, even if initially the material may provide no internal voids (or of a negligible volume), in service, at a certain voltage and frequency, some voids may occur (and/or enlarge themselves), because of the migration of some liquid/gaseous components or by modifying the crosslinking of fibres. Here we could talk about a real dynamic process related to the shape of the voids between fibres, and the process depends on every stress parameter, i.e. voltage or frequency, but also temperature and stress duration should be distinctly considered. Hence, by analysing *the partial discharge quantities vs. frequency*, the dynamic of microstructure or ageing mechanisms may be better emphasised. Consequently, a *broadband PD analysis* may complete successfully other dielectric techniques, being also in concordance with the results obtained from other chemical, physical, thermal or microscopical procedures.

The need for such comparative studies at fundamental level and referring to a specialised application is without doubt apparent nowadays.

3. EXPERIMENTAL AND RESULTS

The investigations were performed upon laboratory papers for cable application, from demineralised - unbleached softwood sulphate - pulps, beaten industrially till a refining degree of 60° SR. The demineralisation process followed and presumed a special industrial treatment with HCL-acid (an equivalent addition of 80 kg acid / tone of absolutely dried cellulose) under controlled demineralisation duration (till a maximum admitted value of 2 hours), as described in [5]. All paper samples were finally formed and adjusted up to 80 g/m² (0.12 mm thin). The results were finally correlated directly with the mineral purity of papers, expressed as standard *mineral content* in paper, [%]. Such a procedure permitted also a direct comparison of PD characteristics and the standard breakdown, for different mineral content of papers for electrical purposes. All measurement results are presented as RMS values.

After testing the PD-characteristics, it was found that the most significant variation versus technological parameters was emphasised by the inception and extinction voltages, U_i and U_e, in the whole frequency range. That is why only the evolution of these characteristics is presented herein.

On the other hand, appreciable differences between the evolution versus frequency of breakdown and PD inception voltages were found. This observation occurred reproducible for all types of analysed samples, having different technological parameters (refining degree of pulp and type of fibres, sheet density, thickness – for both bulk and multilayer structures, surface smoothness, Gurley-porosity of papers, additives and adhesives content and type, ageing duration and type etc.), but mainly mineral content. Some examples are presented below, figures 2-4, where specific dependencies of PD inception electric field versus frequency, related to three technological parameters, were experimentally emphasised.

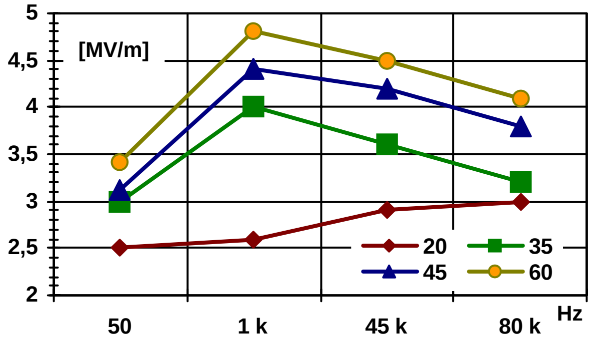

Fig. 2. Influence of refining degree, [°SR]

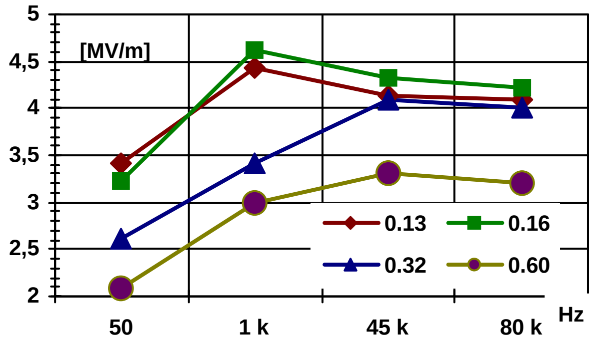

Fig. 3. Influence of paper density, [kg/10^{3}m^3]

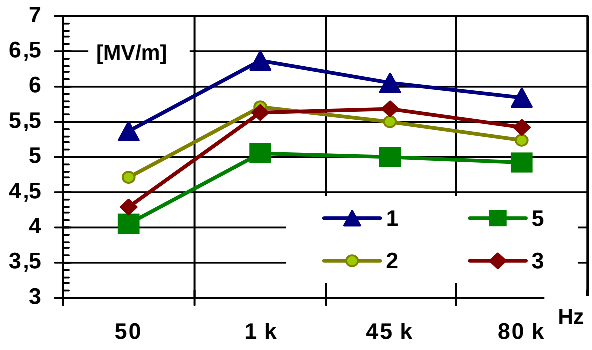

Fig. 4. Influence of number of layers, 0.08 kg/m^2 layer

It is obvious that, up to a certain value of frequency, the PD inception voltage increases, in contradiction with the evolution of braking voltage.

Another consistent example is referring to the influence of mineral content in papers for electrical purposes. Here, for a brief conclusion, only two reference values were taken into account, respectively:

- 0.42 % mineral content, considered the optimum value for the whole frequency range, and
- 1% mineral content, the standard reference content for normal papers for electrical purposes.

Figure 5 emphasises the continuous (expected) decrease of the breakdown voltage, U_d , with the increase of frequency, and **the peculiar evolution of inception voltage U_i , different from U_d** , i.e. increasing up to certain value, and than decreasing. **This phenomenon related to insulating materials is considered absolutely new - presented for the first time by the main author, being reproducible for a wide variety of porous structures and technologies.**

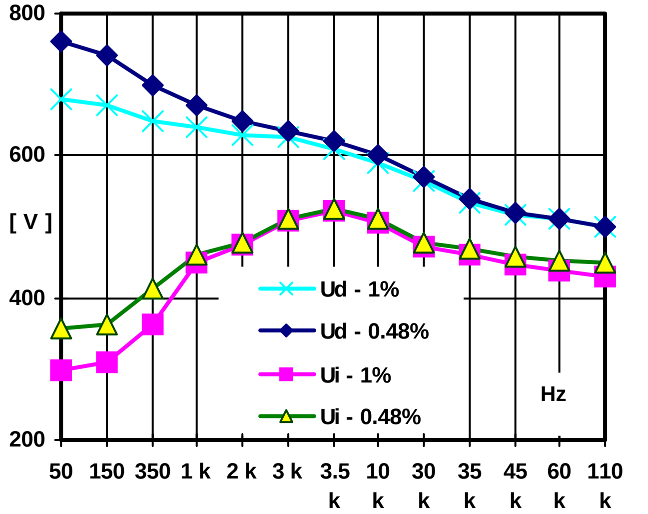

Fig. 5. Comparative evolution of breakdown and PD inception voltages versus frequency, for 1% and 0.42% mineral content of paper

List of symbols:

U_d - breakdown voltage;

U_i - PD inception voltage;

U_e - PD extinction voltage

At industrial frequencies, the PD phenomena occur clearly for lower voltages, when comparing to the homologue breakdown values, and this aspect could be a good explanation for the premature ageing of dielectric material in certain conditions at low frequencies. The decrease becomes even more important in the case of electrical insulation with higher mineral content (in principle, with higher conductivity). Basically, at over 10 kHz, the evolution versus frequency of both PD and breakdown phenomena looks concordant, i.e. decreasing, but the influence of mineral content seems to influence significantly mainly the PD inception voltage (PD phenomena).

New studies of this kind are clearly needed in future, in order to understand more accurately the intimate breakdown process and failure of dielectric structures. The possible correlation between the pulp, fibres and additives properties and both the charge transport and charge carrier density (related in fact to the specific PD phenomena) should be more precisely analysed, and related also to the physical structure of voids and on specific polarisation, considered a chemical dynamic process, as briefly described in [6,7].

On the other hand, the broadband characteristics of partial discharge may be used for the purpose of quality assessment and control, for the domains where the breakdown isn't normally recommended. Such an example is presented as follows, and refers to the demineralisation process efficiency of papers for electrical purposes. In figures 6 and 7 the evolution versus mineral content of the relative variation of the PD inception and extinction voltages (by reporting to the homologue values of the paper with 1% ash content) is presented. It was noticed that a significant variation of these characteristics occurred with a relatively small decrease in mineral content. Till 0.42 %, the increase of both PD inception and extinction voltage occurs obviously due to the diminishing of cathion content in paper, remnant from the sulphate technological process.

Demineralizing process

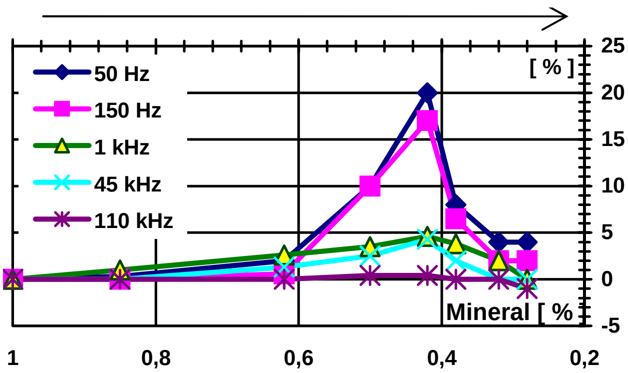

Fig. 6. PD - Inception voltage evolution versus mineral content of paper for different frequencies

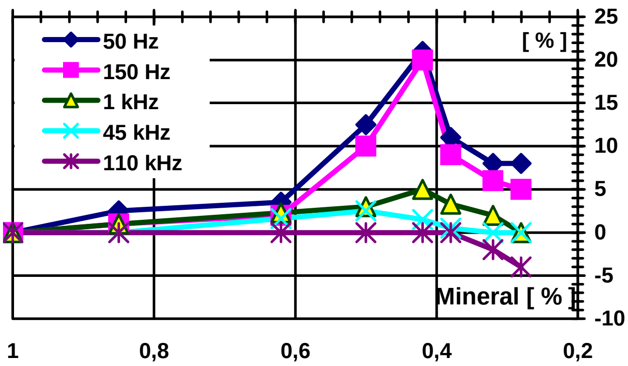

Fig. 7. PD - Extinction voltage evolution versus mineral content of paper for different frequencies

Once the mineral content becomes less than 0.4%, the positive effect of demineralisation process is progressively lost, especially at higher frequencies. This peculiar behaviour could be explained mainly by the presence of the residual Cl^- ion, but also by the specific acid attach at the cellulose fibber surface (in fact a chemical ageing process), due to the long demineralisation duration needed to reach this mineral purity limit. In addition, the increasing of mineral purity seems to influence more the extinction voltage, by improving the extinction of PD process, especially at low frequencies. Accordingly, the negative role played by the remnant ions may consist mainly in the extension of the occurrence of PD process to lower voltages.

As regards the identification of an optimum demineralisation limit, the value of 0.42 % mineral content, determined via PD analysis, seems to fulfil the technical expectations. It is lower than the previously admitted value of 0.35 %, recommended by the cable paper producers, by analysing the breakdown characteristic, [8]. Accordingly, it seems nevertheless that by applying short-term high electrical stresses - the case of breakdown strength estimation, a higher mineral purity should be needed to reach some theoretically recommended values. But exactly the chemical effects and damages related to the obtaining of the respective purity limit could favour the occurrence of PD phenomena during a long term exploitation process, leading finally to a reduced reliability of insulation. That is why we may estimate that the optimum value of 0.42 % could be considered more accurate and closer to the reality of long term in-service stresses of papers for electrical applications. This new value, if accepted, would also provide significant technological and financial advantages for paper producers, reflected in a diminished consume of reactive and/or in a reduced duration of demineralisation.

On the other hand, the appreciable differences between the evolution versus frequency of the PD and breakdown phenomena, for different types of composite insulators, suggests that the breakdown analysis (i.e. the unique electrical method accepted now in quality assessment of cellulose insulators) proves to have limits in accuracy and results interpretation.

The study is leading slowly to the conclusion that the **brodband Partial Discharge (PD) measurement technique** may be considered more accurate than a simple breakdown test and admitted as a complementary method for characterizing the quality of porous/fibrous and composite materials. It should be taken into account in the specific insulation coordination strategies too, especially at higher frequencies, when the risk of breakdown occurrence becomes greater in time, due to the local thermal aspects, and consequently, the initial instant breakdown test couldn't be considered enough accurate to characterize the insulation in-service failure.

4. CONCLUSIONS

Appreciable differences between the evolution versus frequency of the PD and breakdown processes were emphasized. This observation occurred reproducible for all types / technologies of analyzed samples, and suggests that the breakdown analysis proves to have limits in accuracy and results interpretation as regards aging phenomena.

The PD occurrence versus frequency is significantly influenced by the mineral purity of papers for DC cables application, much more than the breakdown process.

According to the aspects described in this paper and in literature, **the extended analysis versus frequency of PD phenomena could be used as a complementary method in quality control of a large variety of insulating systems**, but it may also act as a technological assessment tool, towards emphasising - at least comparatively - the **optimum structure and technology of a certain dielectric material**.

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REFERENCES

[1] DIN/VDE 0110-1/4.97 Isolationskoordination für elektrische Betriebsmittel in Niederspannungsanlagen; Teil 1: Grundsätze, Anforderungen und Prüfungen (IEC 60664-1: 1992, modifiziert); Deutsche Fassung HD 625.1 S1:1996.

[2] IEC 60270/1981: Partial discharge measurements.

[3] IEC 61180: High-voltage test techniques for low-voltage equipment — Part 1/1992: Definitions, test and procedure requirements; Part 2/1994: Test equipment.

[4] R. Ciobanu, W. Pfeiffer and S. Andrei, “Computerised system for PD phenomena evaluation and PD quantities measurement”, IMEKO TC-4, pp 328-332, Naples, Italy, September 17-18, 1998

[5] R. Ciobanu and W. Pfeiffer, “Influence of mineral content on the behavior electrical papers under high frequency partial discharges”, European Trans. on Elec. Power Eng. - ETEP, Vol. 9, No. 3, pp 193-197, 1999

[6] R. Ciobanu and W. Pfeiffer, “The influence of electrotechnical papers technology on their specific partial discharges electric field”, IEE - ICDMMA, pp 342-345, Bath, U.K., 1996

[7] R. Ciobanu, W. Pfeiffer and E.Poppel, “A theoretical approach to the P.D. phenomena in composite dielectrics”, Cellulose Chemistry and Technology, Vol. 30, No. 5, pp 624-627, 1997

[8] W. Pfeiffer, “Dielectric Testing of Solid Insulation with Respect to Insulation Coordination of Low-Voltage Equipment”, IEEE Electrical Insulation, Vol. 17, No. 3, pp 34-47, May-June 2001