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Influence of thermal ageing on dielectric response of oil-paper insulation

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Results of dielectric response measurements in frequency domain at various temperatures have been presented for oil impregnated paper samples unaged and thermally aged containing various amounts of moisture. The obtained results were used for defining respective master curves and activation energies. Discrepancies of the results for similar samples are also discussed. Finally, statistical spread of the data was presented and the influence of moisture content on the dielectric response of paper samples has been discussed.

Key words: *dielectric response; oil-paper insulation; thermal ageing; moisture content in oil-paper insulation*

1. Introduction

Increase of moisture content in paper results in appreciable decrease of its electrical strength. Similarly, electrical strength of oil depends on relative moisture content as well. Increase of moistening in transformer insulation system results in decrease of bubble effect initial temperature, a very dangerous phenomenon in transformers [1]. Moreover, the paper ageing rate almost linearly depends on its moistening [2–5].

Moisture can penetrate into transformer paper insulation not only from outside. It is a product of cellulose degradation at high temperatures. Unfortunately, presence of water additionally increases the ageing rate.

Paper insulation directly contacts with transformer winding, and is endangered to the influence of hot spots. Paper thermal ageing near hot spots can destroy its electrical strength and leads to transformer failure.

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2. Experimental

Objects of investigation. Transformer paper samples impregnated with transformer oil were investigated. Their preparation included the following operations: drying, moisturising, and impregnation with oil. Firstly, samples were dried at 80 °C in a vacuum-thermal chamber for 2–3 days. Their weights were continuously monitored. After drying, the samples were kept in open atmosphere for absorbing moisture from air. Weight changes of the samples were again monitored to obtain predefined levels of moisture intakes. Then the samples were put into containers filled with unused mineral transformer oil, NYNAS Nytro 10 GBN for impregnation. Measured moisture content in the oil was 12 ppm. Three groups of samples were prepared with moisture intake equal to 0.6%, 2.0%, and 4.0%.

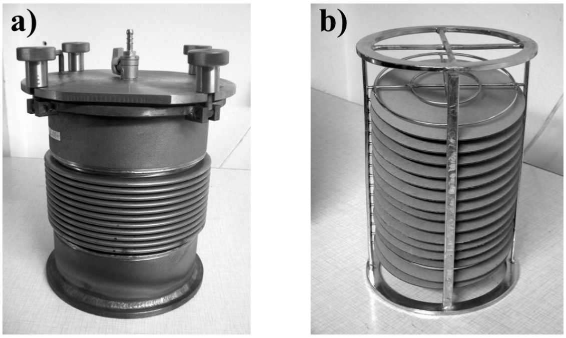

Fig. 1. Container (a) and the stand (b) used to store the samples

Special steel containers (Fig. 1a) were designed for sample storage. The containers were hermetically sealed and prepared to provide possibility for performing temperature treatment. Flexible bellows on the container body reduced inside pressure during ageing at high temperatures. Also a metal stand was designed for holding the samples inside the container. Fifteen samples with the same moisture intake were placed into one container (Fig. 1b).

Paper and pressboard samples with moisture intake of 0.6%, 2.0% and 4.0% were artificially aged. The ageing was carried out in a closed system at 130 °C. Total time of ageing was about 800 h. A temperature distribution in the oven and along the container was regularly observed using a thermal image from an infrared camera. Furthermore, in order to maintain the same ageing conditions, container positions in the oven were regularly changed. From each container (with unaged and aged samples), three samples with similar moisture content were selected and investigated.

Measurement set-up. For the measurements, a paper sample was placed into a test cell filled with oil. Similar oil was earlier used for impregnation of the paper. The test cell was placed in a conditioned chamber. The test cell was designed for three-electrode measurements as shown in Fig. 2. Object of investigation was connected to

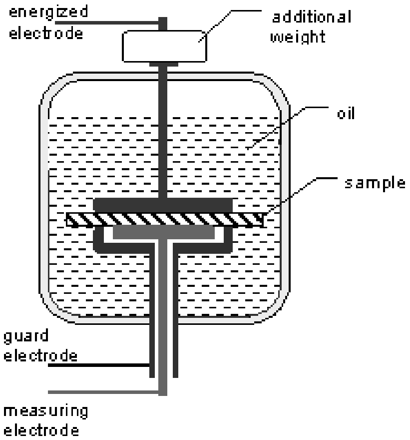

Fig. 2. Scheme of the test cell

Fig. 3. IDA 200 instrument

IDA 200 instrument (Fig. 3). Dielectric response in frequency domain (FDS) was investigated in the frequency range from 0.1 mHz to 1 kHz.

3. Results of investigations

3.1. Dielectric response of unaged and thermally aged paper

Figure 4 presents dielectric responses of chosen new and thermally aged paper-oil samples. Unaged paper was prepared on 4.0% moisture intake, but in the Karl–Fischer (K-F) measurement paper with 4.8% moisture intake was used. After ageing, paper samples were again investigated by the K-F titration, and 3.8% of moisture was determined.

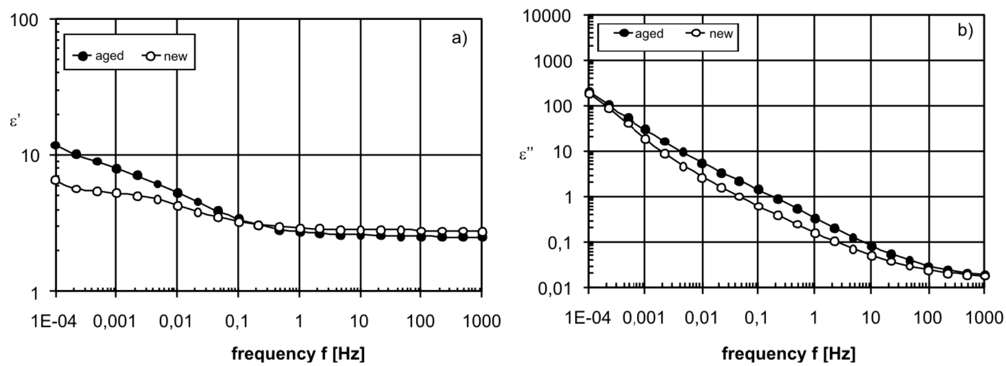

Fig. 4. Dielectric response of paper samples in frequency domain
at 20 °C; permittivity: a) real part, b) imaginary part

The shift of dielectric response curves is probably connected with the increase of moisture content in paper samples during ageing. Unfortunately measurements by the K-F method showed decreasing amount of water in aged paper.

The dielectric responses of aged and new samples differ significantly. It clearly shows that dielectric response of paper depends not only on moisture content and temperature but also on ageing state or the substances formed during ageing such as low molecular acids. However, further careful analysis is essential for better clarification of the problem. Table 1 presents average moisture content for investigated paper samples.

Table 1. Average moisture content in paper samples before and after thermal ageing [%]

Moisture content before ageing [%]	Moisture content after ageing [%]
0.6	1.7
2.0	1.7
4.0	2.5

Unfortunately, very dry aged samples (with 0.6% moisture intake) were probably additionally moistened during transport, what manifests in the K-F titration results. The remaining data in Table 1, however, show possible problems with accuracy of the K-F titration method used for measurements.

3.2. Master curves and activation energy

Measured responses of the paper samples with various moisture intake at three temperatures were utilised for obtaining their master curves. Figure 5 presents chosen master curves of permittivity and losses of aged paper at 20 °C. All presented master curves are derived from mean response of three similar samples.

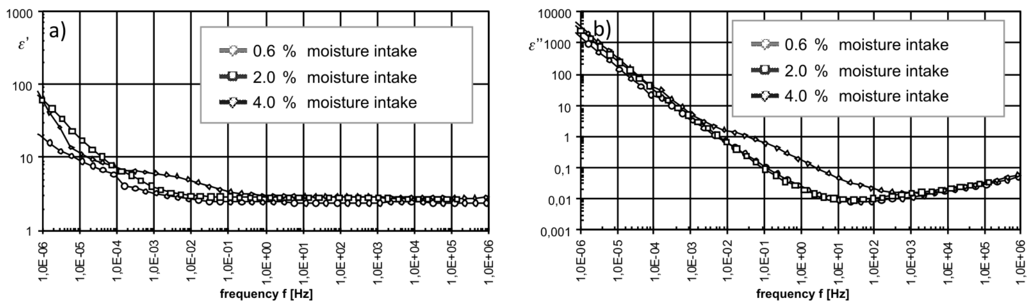

Fig. 5. Master curves at 20 °C for aged paper samples with various moisture content; permittivity: a) real part, b) imaginary part

At first it results from the figures that a real part of permittivity for aged paper is not a good criterion for evaluating the moisture content. Initial moistening of the paper has an immense influence on the ageing process. That is why two samples of the paper with identical moisture content (1.7%) have different ε' values. The moisture content in aged paper should be rather determined based on the analysis of the imaginary part of permittivity.

Table 2. Values of activation energy in aged paper samples

Average moisture intake [%]	Activation energy [eV]
0.6	0.9665
2.0	0.9116
4.0	1.0908

The activation energies with different moisture contents are given in Table 2. No clear dependence of the activation energy for aged paper samples on the moisture intake is visible.

3.3. Discrepancies of the results for similar samples

In Figure 6, the results of measurements of dielectric response for two groups of aged paper samples are presented, with moisture intake of 0.6% and 4.0% at 20 °C. The differences in the results are not significant. They are small enough to distinguish moisture degree of aged paper.

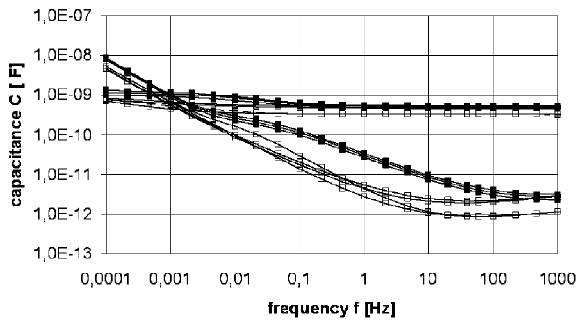

Fig. 6. Complex capacitance in the frequency domain of thermally aged paper samples with moisture intake 0.6% and 4.0% at 20 °C

Figures 7–9 show dispersion bars of dielectric responses for aged samples with 0.6%, 2.0% and 4.0% moisture intake. It is visible that dispersion bars decrease with increasing of moisture intake in paper.

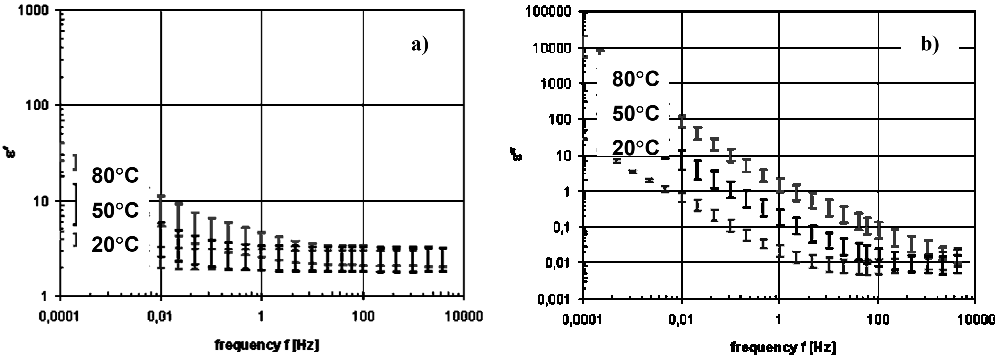

Fig. 7. Dispersion of permittivity error bars of three aged paper samples with moisture intake of 0.6%; permittivity: a) real part, b) imaginary part

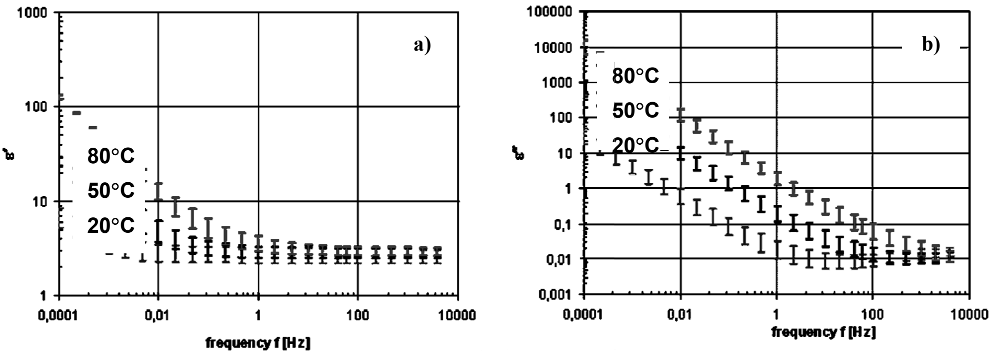

Fig. 8. Dispersion of permittivity error bars of three aged paper samples with moisture intake of 2.0%; permittivity: a) real part, b) imaginary part

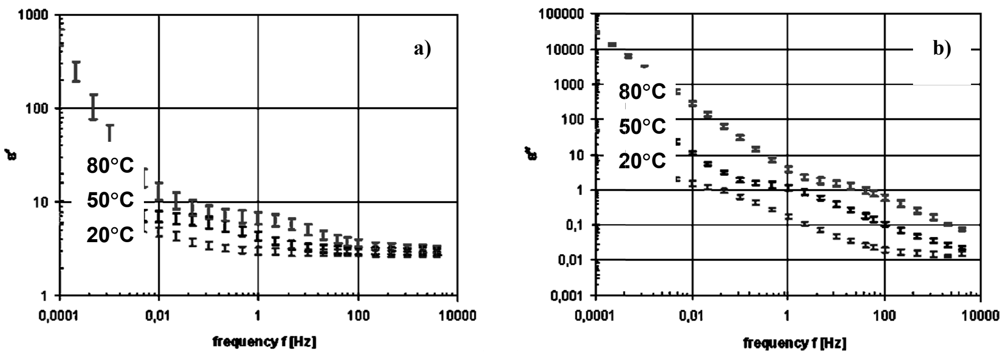

Fig. 9. Dispersion of permittivity error bars of three aged paper samples with moisture intake 4.0%; permittivity: a) real part, b) imaginary part

Presence of the discrepancies in the results of measurements is probably connected with slight differences in moisture content in samples due to various rates of ageing of samples connected with the location of the sample in the container during ageing. These discrepancies in results of measurements diminish with increase of paper moistening.

4. Conclusions

- Measurements of moisture content in thermally aged paper by the Karl–Fischer titration underrates the values of water content.
- Paper dielectric response depends not only on moisture content and temperature but also on ageing state or presence of substances formed during ageing.
- A real part of permittivity for thermally aged paper is not a good criterion for evaluation moisture content,
- Initial moistening of the paper has a great influence on its thermal ageing.

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