METROLOGY AND MEASUREMENT SYSTEMS
VOL. XV, NUMBER 3 (2008)

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METHODS OF QUALITY CHARACTERIZATION OF FOIL-BASED CAPACITORS

The quality of aluminium foil-based capacitors is sensitive to various technological parameters within the production process. There are a few methods of their quality assessment that can identify defects inside the wound foil structures, poor metal contacts or bad packing. These methods are often applied at the end of production to monitor the quality of the final products. Only a small fraction of the produced capacitors is checked by a long-lasting procedure of extensive and repeatable charging and discharging. This procedure makes it plausible that some capacitors can fulfil the assumed quality requirements but will deteriorate soon and can cause serious economic losses when used in equipment. Therefore, it is recommended to identify the most informative methods of capacitor quality assessment. This paper investigates the problem by presenting measurement results of the third harmonic index, dielectric loss and acoustic emission in type WXPC capacitors which are widely applied to reduce electromagnetic interference caused by domestic electric equipment.

Keywords: capacitors, nonlinearity, dielectric loss, acoustic emission, partial discharges

1. INTRODUCTION

Foil-based capacitors are extensively used in domestic electric equipment. The main reason for this is a reduction of electromagnetic interference emitted by the electric equipment. The popularity of these elements means a continuous need of their quality improvement when costs of the applied materials and of the assembly process decrease. Both requirements are contradictory and lead to the necessity of continuous quality monitoring that is often more severe than that required by the obligatory industrial standards.

The presently-applied tests of capacitors are expensive and time-consuming. Moreover, there is no clear answer which of the tests is more informative than the others. The decisive test of capacitor durability takes even 1000 hours and is destructive for poor samples. Additionally, only a small fraction of the produced capacitors is tested in this way after assembling and cannot be used for running quality check-ups. Therefore, there is a need of a thorough research of various testing methods to establish their informative value and a more precise correlation between the measured parameters and the possible defects of the capacitor structure.

The paper presents stages of capacitor production and points at various defects that can be formed then. The measurement techniques that are used for capacitors quality assessment are introduced as well. In the final stage, we present measurement results of a few capacitors of the same type selected at random, by applying measurements of the third harmonic index, dielectric loss and acoustic emission of the samples under stress. The same measurements were repeated after a long-lasting procedure of their continuous charging and discharging by applying a harmonic voltage signal at elevated temperature. The results of this exploratory study give us a base for further and more thorough investigations of a larger number of capacitors by focusing on measurements that can reveal major defects existing in these structures.

2. PROCESSES OF CAPACITOR FABRICATION

The baked-foil capacitors are produced in five separate stages (Fig. 1) [1-2]. At the beginning the foils are wound to get the main structure which is comprised of two one-sided metalized foils (Fig. 1a). Each foil has a margin without metallization on one edge and a reinforced metallization on the second. Additionally, a shift between the foils makes the further process of contact preparation much easier.

In the next stage, the structures of wound foils are heated up and shaped by stressing between two parallel planes (Fig. 1b). Further, the metal contacts are sprayed on both heads of the wound foil (Fig. 1c). Finally, the terminals are welded (Fig. 1d) and the foil wad is packed together with a self-extinguishing paste to reach its final shape (Fig. 1e). The foil wad prepared during production and the ready capacitor is shown in Fig. 2.

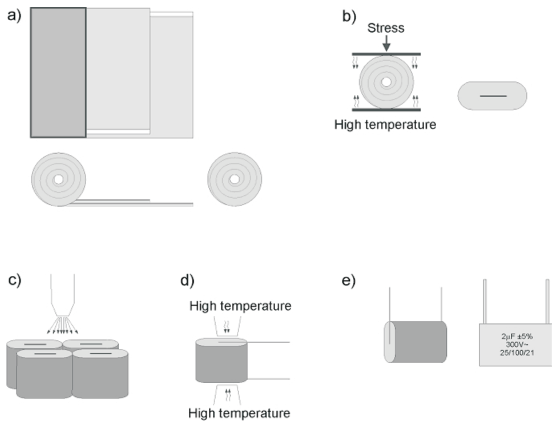

Fig. 1. Stages of the capacitor production: (a) winding two one-side metalized foils, (b) baking and shaping, (c) spraying metallized contacts, (d) terminal welding, (e) final packing.

The indicated production stages can introduce various imperfections within the capacitor structure which limit their use and durability. Thus, it is valuable to consider in detail what kinds of fault are possible within the consecutive production phases. Then, we can reconsider what kind of measurements would be the most informative and economically efficient.

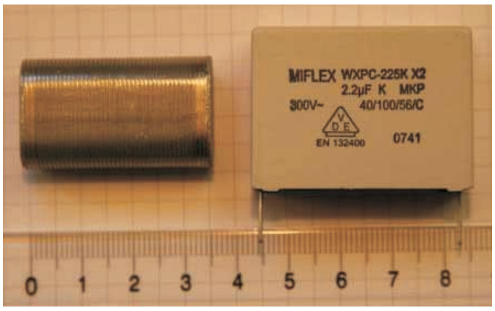

Fig. 2. Capacitors: the wound foil (left), after final package (right).

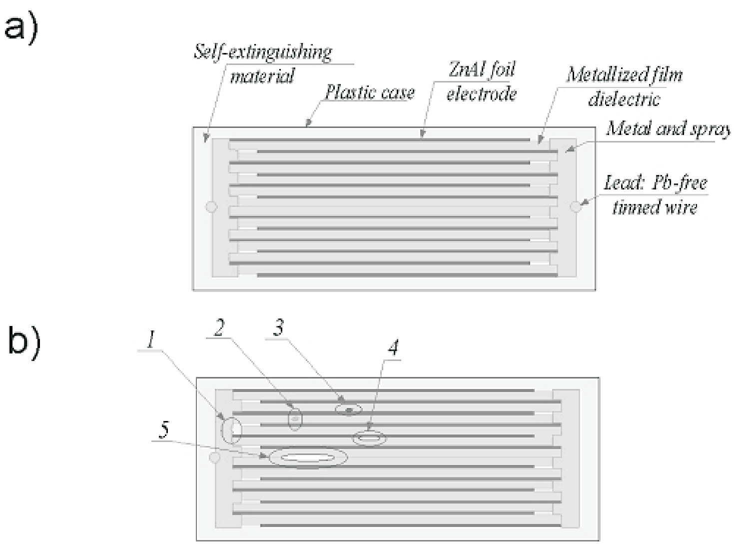

Fig. 3. Capacitor cross-section: (a) across the wound foil, (b) with the distinguished imperfections; 1 – faulty connection between the metallized head and dielectric, 2 – intrusion inside the dielectric structure, 3 – intrusion at the metal surface, 4 – air void at the metal surface, 5 – air void between the dielectric layers.

The typical defects within the capacitor structure are presented in Fig. 3. These defects can appear due to poor quality of the applied materials (various intrusions in the dielectric or metal structure), incorrect production parameters – especially during foil winding (creation of air voids with various degrees of humidity), terminals welding or final packing.

The presence of these faults can manifest itself in various ways, e.g.: high leakage current, increased dissipation factor tg, more nonlinear current-voltage characteristic or capacitance lower than expected. Some of these defects can finally lead to capacitor failure.

3. CAPACITOR QUALITY TESTING

There are various tests of capacitor quality assessment. These tests determine how the capacitors behave at various electric shocks (short-time intensive current and voltage pulses) or evaluate selected capacitors parameters (dissipation factor, leakage current, insulation resistance, dielectric absorption) [2-3]. Additionally, investigation of a partial discharge phenomenon in dielectric structure (inside voids characterized by a higher voltage gradient than the rest of the dielectric) is also very informative. This phenomenon causes a partial breakdown of the dielectric by sparking across the existing air voids. It does not result immediately in a complete insulation breakdown but can cause rapid deterioration of the dielectric film and/or its metallization due to the hot spot temperature resulting from the heat concentrations during the sparking [4-6]. This effect can destroy the capacitor case and can lead to further serious damages of the adjacent elements. The sparking intensity is characterized by ignition voltage and/or charge amount that takes part in the event. It can be also characterized by sounds emitted during the events. This effect is similar to the sounds of thunder after lighting [7].

We suppose that another method worth of being considered for detection of voids inside the dielectric structure is acoustic emission induced by a restricted pressure of the sample under test. Acoustic signals are widely used for various materials characterization when the sample is gently stressed without causing its destruction [8]. We can expect that voids contained inside the capacitor structure would emit sounds when the foil wad is squeezed. This means that the proposed method could characterize the quality of the dielectric inside the capacitor without its destruction.

The decisive and obligatory test of quality of the prepared capacitor series is performed after their final package. A small fraction of the produced capacitors is tested in a long interval, even up to a few thousands of hours, by applying a harmonic voltage to their terminals. Capacitors are considered as properly prepared when this extensive test does not destruct any of the tested capacitors. This procedure means that within the accepted capacitor series some but not numerous items can be present which can lead to serious damage when the capacitors are applied in electric equipment.

4. EXPERIMENT AND RESULTS

In this experimental study, the foil wads were investigated. These structures are used for production of 2.2 μF capacitors, type WXPC (factory label for the reinforced polypropylene foil-based capacitors). The wads were prepared nominally in the same way. Their preparation ended after spraying metallized contacts (Fig. 1c). We omitted the phase of terminal welding and packing to provide access to the flat surfaces on both sides of the foil wad to apply stress during acoustic emission measurements.

Initially, the third harmonic index was measured within the set of 30 foil wads which were randomly chosen from the production line. The stimulating harmonic signal with a frequency of f = 10 kHz was applied. The non-linearity of the tested capacitor is determined by measurement of the third harmonic component at 30 kHz. The meter consists of a generator, together with low-pass and high-pass filters that separate the excitation signal and the third harmonic component. It was found that only the third harmonic has a non-negligible level in the tested capacitors and all higher harmonics have not to be taken into account. The meter was controlled by a computer through the GPIB interface. A virtual instrument, prepared in LabVIEW software, controlled the serial measurements in the established voltage range. A more detailed description of the determination of the third harmonic component is presented elsewhere [9].

The sample was placed between the springing golden contact electrodes to assure electric contacts to the sprayed metalized heads. The measurement results were repeatable even by changing the position of the electrode which contacted the sample heads. Thus, we can exclude the influence of the contacts on variations of the value of the third harmonic component values between the samples. Therefore, we can conclude that there exist serious differences between the wads. The three wads that exhibited significant differences were preselected for further testing (Fig. 4).

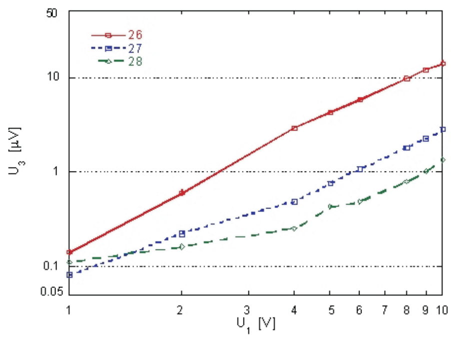

Fig. 4. Third harmonic component U_3 observed for the selected foil wads, no. 26, 27 and 28 of 2,2 μF capacity and excited by harmonic of amplitude U_1.

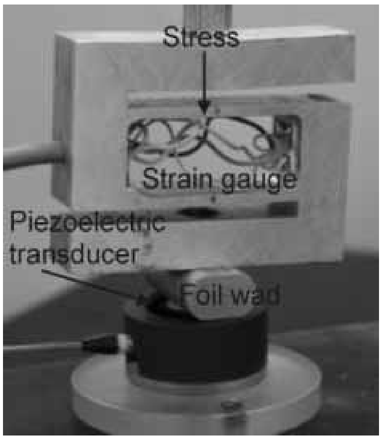

Fig. 5. Acoustic emission measurements in foil wads.

The experiment was continued by observing acoustic emission within these selected three wads only. The standard system MISTRAS 2001 for registering and analysing the emission of an acoustic signal was applied [10]. The acoustic signal was registered by a piezoelectric transducer at a sampling frequency of 8 MHz. The stress was monitored by registering a signal from a strain gauge at the same time as the acoustic emission signal. The foil wad was placed between the strain gauge and cylindrical-shaped prop (Fig. 5). The piezoelectric transducer was placed inside the prop and adjoined to the foil wad. The stress changed in the measurement from 0 up to 25 kG within a long period of 20 min., to assure precisely linear stress change in time. The applied stress was adjusted to be enough strong to induce acoustic emission signal and not too strong to crush the wad. The transducer was in contact with the wad thanks to a small spring which pressed the transducer to the wad. The registered acoustic emission signals were analyzed by using their relative probability distribution only. Thus the coupling between the transducer and the applied wad did not influence the observed results and calibration of the measurement system was not necessary.

The registered signal contained numerous intervals with visible oscillations that are characteristic for acoustic emission (Fig. 6). The power spectra of the registered signals were similar in the investigated sample set and no clear division between them could be made. More valuable information is revealed when the probability distribution $p(x)$ of the registered $x(t)$ signal is considered. There is a noteworthy variation of $p(x)$ between the sample at relatively high $x(t)$ values (Fig. 7). The sample no. 26 had a much lower $p(x)$ when compared with results obtained for other samples. Variations between the samples under test are also visible when the sum of acoustic signal energy is considered as a function of stress that changed linearly with time. The foil wad no. 26 emits almost no acoustic signals at low stress (Fig. 8) when the other sample emits a signal evenly distributed during the stress growth (Fig. 9, Fig. 10). Therefore we can assume that sample no. 26 was more rigid and had the foil wound in a better way without numerous air voids in its structure. The other structures (no. 27 and no. 28) were more plastic due to voids that could be easily squeezed.

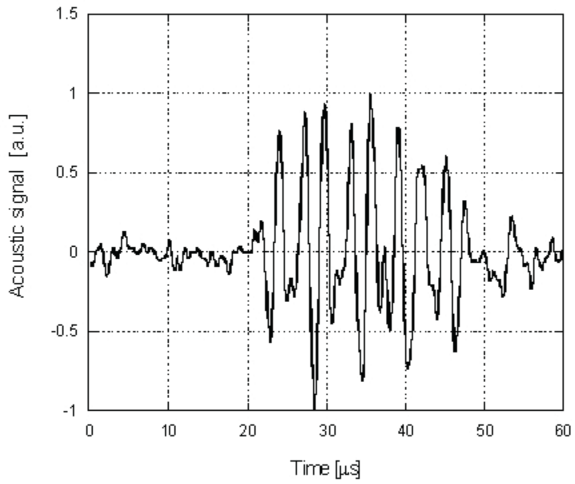

Fig. 6. Registered acoustic signal

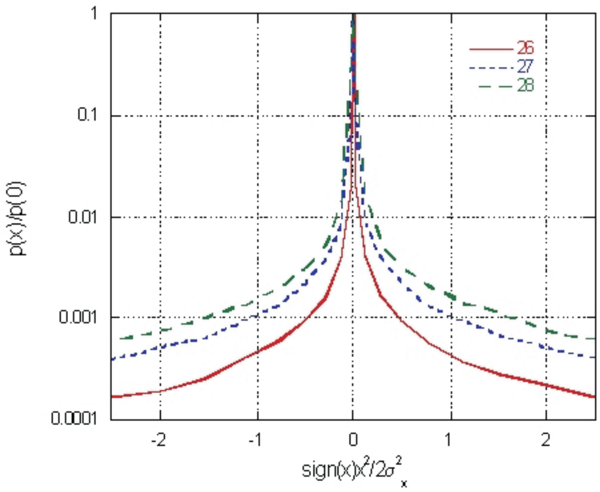

Fig. 7. Normalized probability density $p(x)/\ p(0)$ of acoustic signal $x(t)$ having variation σ_x^2 observed for the foil wad samples no. 26, 27 and 28 when stressed up to 25 kG.

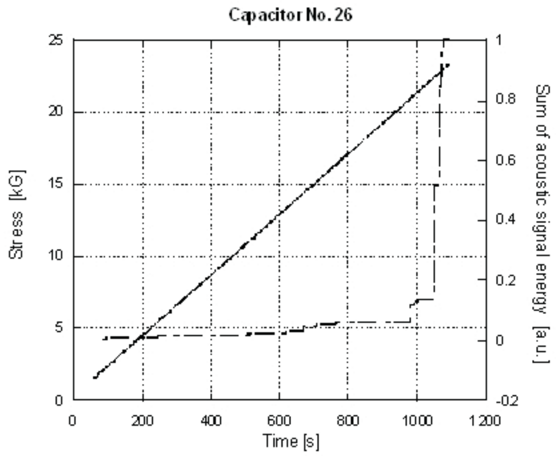

Fig. 8. Sum of the registered acoustic signal energy at stress linearly increasing in time for the investigated foil wad no. 26.

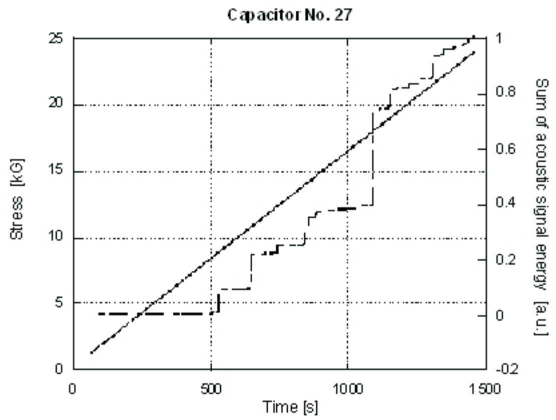

Fig. 9. Sum of the registered acoustic signal energy at stress linearly increasing in time for the investigated foil wad no. 27.

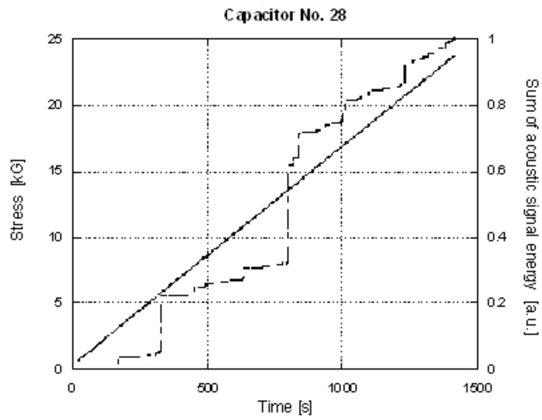

Fig. 10. Sum of the registered acoustic signal energy at stress linearly increasing in time for the investigated foil wad no. 28.

The suggested explanation is confirmed by additional measurements of tgδ at various voltages (Fig. 11). Dielectric loss in the sample no. 26 was a little bit higher and has changed in a different way than in other samples. At higher voltages the dielectric loss started to increase faster for samples no. 28. This effect can be explained by partial discharges in the air voids that were present in these structures. When the voltage increased, the dielectric within the voids area was locally destroyed by discharging processes and slightly changed the equivalent capacitance of the foil wad. This assumption was confirmed by audible sounds at voltage U $\approx$ 550 V when the sample no. 28 was measured. It is plausible that partial discharging took place even at lower voltages but was not heard by the authors due to their too high frequency or too low intensity.

The same measurements (Fig. 11) were performed after a procedure of applying at temperature 100 C a harmonic voltage signal of rms value 375 V to the terminals of the tested capacitor through a 47 Ω resistor during a 1000 h interval. Deterioration of the samples during the test caused a stronger increase of tgδ for the wads no. 27 and no. 28 than for the sample no. 26 (Fig. 12). These measurements were performed up to 400 V only because the deteriorated dielectric within the investigated samples was more prone to partial discharges at higher voltages which could damage completely the investigated wad. The tested samples exhibited decrease of their capacitance which did not exceed 7% and was acceptable by binding industry standards.

Similar conclusions can be drawn from measurements of insulation resistance R_I (Tab. 1) that declined stronger for the samples no. 27 and no. 28. This suggests that partial discharges were more abundant and extensive in these two samples when compared with sample no. 26.

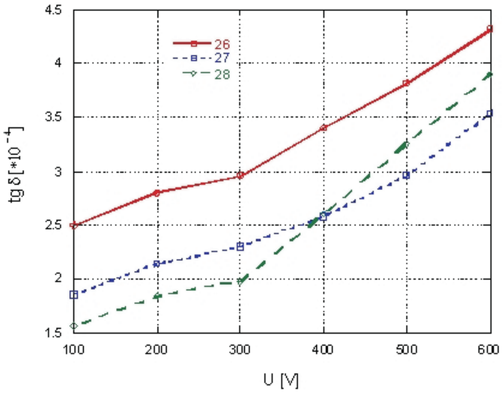

Fig. 11. Dielectric loss of the as-prepared foil wads measured at various voltages, at the excitation signal frequency of 50 Hz, measured by a Tettex 2805 bridge.

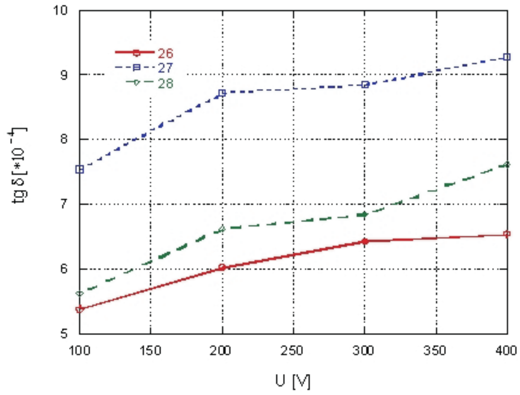

Fig. 12. Dielectric loss of the foil wads measured at various voltages, at the excitation signal frequency of 50 Hz by a Tettex 2805 bridge; the wads before measurements were subject to a 1000 h-long continuous charging and discharging procedure, as presented in the paper

Table 1. Insulation resistance R_I of the tested foil wads measured at room temperature and at DC 100V applied within 60s to: as-prepared samples at relative humidity 36% (second column) and after a 1000 h-long continuous charging and discharging procedure at relative humidity 46% (third column); a megaohmmeter, type IM6, was used.

Sample No.	R_I [10^5 MΩ] (as-prepared)	R_I [10^4 MΩ] (after deterioration)
26	2.0	6.0
27	2.0	0.8
28	2.2	2.0

5. CONCLUSIONS

In this exploratory study we present results of various tests of foil wads that make capacitors. This study was done to establish informative values of the performed tests. We conclude that the third harmonic index differentiates the quality of the tested samples but there is no clear physical explanation of the observed result. This parameter was previously combined mainly with the quality of the welded terminals that were not fabricated in the investigated foil wads. It is believed that improper welding of the capacitor terminals leads to an increase in the measured nonlinearity component [3]. In the presented experimental results we can only suppose that air voids, which have a lower dielectric constant than the applied film dielectric, decrease the nonlinear component generated in the tested foil wads.

When the results of acoustic emission under stress and dielectric loss are considered, we can draw almost the same conclusions from both types of measurements but acoustic emission data (e.g. Fig. 8–10) differentiate the samples in a more evident way. Additionally, the existence of air voids was confirmed by audible noise emitted by the foil wad during the measurements of tg . These results were obtained for the limited number of samples only and a more thorough investigation would be valuable. The suggested in-depth investigation, together with other and presently not applied methods, is planned in the future.

To sum up, we suppose that acoustic emission induced by partial discharge phenomena is useful in the same way as acoustic emission induced by stress. Therefore, we will consider applying in the future ultrasound measurements of the partial discharge phenomenon at a low voltage as a more convenient tool in industrial applications than acoustic emission induced by stress.

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