

1/f NOISE OF ELECTROLYTIC CAPACITORS AS A RELIABILITY INDICATOR

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SUMMARY

The electrical noise of capacitors and the relationship between typical imperfections in capacitors and their excess noise are described. It was assumed that a noisy capacitor is a poor-quality one. Investigations were aimed at the determination of a correlation between the inherent noise of capacitors and their reliability (time to failure) and also at the determination of an indicator to predict reliability.

Investigations (noise measurements and reliability tests) were carried out on two samples of aluminium electrolytic capacitors. The method of reliability prediction for electrolytic capacitors based on their low-frequency noise is described. For reliability prediction the noise intensity G at a frequency of 2 Hz was used as a reliability indicator.

It was found that the evaluated correlation coefficients between the noise parameter G and the time to failure, t , are statistically significant. It is concluded that it is possible to predict the lifetime of aluminium electrolytic capacitors on the basis of their 1/f noise. ©1998 John Wiley & Sons, Ltd.

KEY WORDS: electrolytic capacitors; 1/f noise; reliability indicators

INTRODUCTION

Capacitors have the reputation of being noise-free electronic components. In practice there are several loss mechanisms, so that an excess of low-frequency noise can be generated especially when the capacitors are biased. The inaccuracy of the capacitor manufacturing process and defects in the materials are the sources of capacitor failures, and simultaneously in many cases these are also the reasons for 1/f noise (excess noise) generation.

To date, only a few papers have been published on capacitor noise measurements [1–6].

It is proposed to classify electrolytic capacitors into different groups according to their expected quality. This means that the quality of a capacitor can be predicted individually.

By the individual prediction of the quality of a capacitor one may understand that capacitors are classified into different groups according to their expected quality (high, good, low, poor) immediately after manufacture. The reliability of a capacitor may be classified on the basis of a physical quantity—it is proposed here that this is the intensity of inherent low-frequency noise.

NOISE OF CAPACITORS

Capacitors produce thermal noise, which depends on the parallel loss resistance R_C of the capacitor, and 1/f noise, which depends on the manufacturing process and the bias conditions of the operating point.

The power spectral density function of thermal noise,

G_{uT} , is given by

$$G_{uT} = 4kTR_C \quad (1)$$

where k is Boltzmann's constant, T is the temperature and R_C is the loss resistance of the capacitor.

The power spectral density function of thermal noise, $G_{uc}(f)$, of an $R_C C_T$ circuit can be expressed by [7]

$$G_{uc}(f) = \frac{4kTR_C}{1 + (2\pi f R_C C_T)^2} \quad (2)$$

where f is the frequency and C_T is the capacitance of the capacitor.

From relation (2) one can consider that the power spectral density function of thermal noise of an $R_C C_T$ circuit is constant in the frequency range $f \ll f_0 = 1/(2\pi R_C C_T)$ and is proportional to $1/f^2$ for $f \gg f_0$.

Another source of noise in the low- and very-low-frequency range is 1/f noise. Based on theoretical relations reported in the literature, [1,3,7,8] one can conclude that the power spectral density function of 1/f noise, $G(f)$, is proportional to U^2 and $1/f$:

$$G(f) = A \frac{U^2}{f} \quad (3)$$

where A is a constant and U is the bias voltage of the capacitor.

This inherent noise of capacitors is caused by imperfections of materials or/and of technology. It is therefore due to defects which are produced during manufacturing.

CAPACITOR DEFECTS AND THEIR NOISE

The defects in the dielectric layer and in the capacitor electrodes and the inaccuracy of the bonding operation

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Table 1. Reasons for failure of capacitors and their effects

Reason for failure (type(s) of capacitor)	Effect
Heterogeneity, microcracks of electrodes (mica, ceramic, metallized)	Flicker of capacity
Improper adhesion of silver to dielectric (mica, ceramic)	Flicker of capacity
Narrowing of dielectric, inclusions of conducting particles in dielectric (metallized foil, thin film)	Emission of random self-restoring impulses
Regions with strains (polystyrene, quartz)	Impulse noise
Polymerization process (dielectric film)	Impulse noise
Radioactive particles, X-radiation (mica, quartz, dielectric foil)	Rise of low-frequency noise
Ionization, improper assembly (mica, ceramic)	Discharges inside capacitors

are the main reasons for failures of capacitors. The relations between imperfections of capacitors and their excess noise are presented in Table 1 [3].

From Table 1 one can conclude that there are links between the failure of capacitors and their excess noise. Taking into account these relations, it was assumed that the level of noise generated by capacitors is a useful parameter (indicator) for prediction of their lifetime.

RESULTS OF NOISE MEASUREMENTS

The experiments were performed on samples of aluminium electrolytic capacitors (sample I, 57 capacitors type II 04/U 10 $\mu\text{F}/16\text{ V}$; sample II, 56 capacitors type II 04/U 22 $\mu\text{F}/16\text{ V}$).

The noise of the capacitors from samples I and II was measured by means of a spectrum analyser (B&K 2033). The experiments comprised the following steps:

- measurements of C (capacitance), $\tan \delta$ and I (leakage current);
- measurements of noise (power spectral density in the frequency range from 2 Hz to 10 kHz);
- classification of capacitors into reliability groups based on their noise intensities $G_j (f = f_m)$, $j = 1, 2, \dots, N$, where $f_m = 2\text{ Hz}$;
- aging of capacitors during the reliability test with constant bias U_n (capacitor rated voltage), temperature $T = 373\text{ K}$ and time $t_1 = 125\text{ h}$; next, after every 250 h the measurements of typical parameters ($C, \tan \delta, I$) were repeated (the reliability test was applied in order to verify the rules of classification of capacitors by means of their noise).

The results of noise measurements are presented in Figure 1 [3].

For the capacitors from samples I and II the noise measurements were done at bias voltages U of 16 and 36 V respectively. A similar noise measurement circuit is presented in Reference [6].

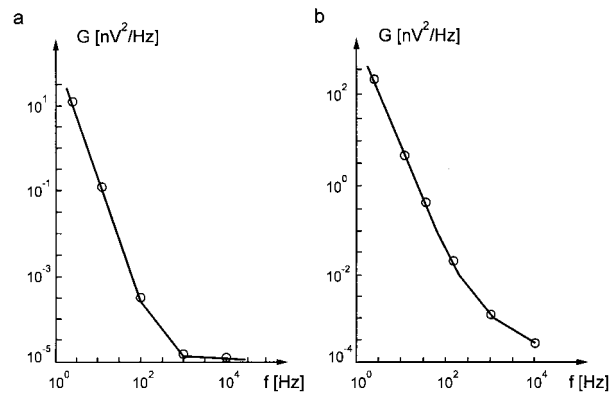


Figure 1. Average power spectral density functions of noise of (a) sample I and (b) sample II

Table 2. Statistical parameters

Sample	G ($\text{nV Hz}^{-1/2}$)	S ($\text{nV Hz}^{-1/2}$)	$n\omega^2$
I	3.4	2.0	0.120
II	12.8	6.7	0.094

The statistical parameters of the random variable G of the samples are collected in Table 2 together with the values of $n\omega^2$ (the hypothesis of normal distribution of G at the test significance level $\alpha = 0.05$ is true for $n\omega^2 \leq n\omega_{kr}^2 = 0.126$).

The capacitors from samples I and II were classified into four groups (reliability groups) according to the following relation for the border values of groups, G_{bm} [3]:

$$G_{bm} = \bar{G} + Sz_{\alpha m}, \quad m = 1, 2, 3 \quad (4)$$

where \bar{G} and S are the mean value and standard deviation of the intensity of noise in the sample respectively and the $Z_{\alpha m}$ are standardized random variables with normal distribution. In our case the standardized random variables are given by

$$Z_{\alpha 1} = -0.67, \quad Z_{\alpha 2} = 0.00, \quad Z_{\alpha 3} = 0.67$$

The rules of the individual classification of capacitors into four groups are as follows [8,10]:

- $G_j < G_{b1}$, first group, high quality expected;
- $G_{b1} \leq G_j < G_{b2}$, second group, good quality expected;
- $G_{b2} \leq G_j < G_{b3}$, third group, low quality expected;
- $G_j \geq G_{b3}$, fourth group, poor quality expected.

Here G_j is the noise intensity for the j th capacitor, $j = 1, 2, \dots, N$.

For example, for sample II the values of G_{bm} are

$$\begin{aligned} G_{b1} &= 5.4 \text{ nV Hz}^{-1/2} \\ G_{b2} &= 12.8 \text{ nV Hz}^{-1/2} \\ G_{b3} &= 20.2 \text{ nV Hz}^{-1/2} \end{aligned}$$

During the test it was found that the high-noise capacitors (from the third and fourth groups) failed first, whilst all capacitors from the first and second groups did not fail during the test.

A non-parametric method of statistical inference, Spearman's method of rank correlation, was applied to evaluate the link between the noise parameter G of the capacitors (measured before a reliability test) and the time to failure, t [3].

The rank correlation factor r has been evaluated as [9]

$$r = \frac{n^3 - n - 6 \sum_{j=1}^n (\text{rank } G_j - \text{rank } t_j)^2 - \frac{L+M}{2}}{\sqrt{(n^3 - n - L)(n^3 - n - M)}} \quad (5)$$

with

$$L = \sum_{i=1}^S k_i^3 - k_i, \quad M = \sum_{i=1}^T m_i^3 - m_i$$

where n is the number of failed capacitors in the sample, rank G_j is the j th capacitor noise parameter rank, rank t_j is the j th capacitor failure time rank, L and M are corrections for ties and for noise and time ranking respectively, S is the number of groups in L -correction, T is the number of groups in M -correction, k_i is the number of capacitors in the i th group (ranks of noise parameter) and m_i is the number of capacitors in the i th group (ranks of time).

Rank of noise parameter. The capacitors which failed during a reliability test are arranged (ranked) in increasing order according to their values of noise intensity G_j —measured before the reliability test—and every capacitor has its initial number in a noise parameter data sequence.

Rank of failure time. The capacitors which failed during a reliability test are arranged (ranked) in increasing order according to their times to failure, and every capacitor has its serial number in a failure time data sequence.

Capacitors which have the same value of noise intensity or the same time to failure have to be marked by the same ranks. For example, if five capacitors failed at the same time (in the same step of a test) and they are arranged in rank positions 1, 2, 3, 4, 5, then the rank of time for each capacitor is the same and is equal to

$$(1/m_i) \sum_j t_j = (1/5)15 = 3$$

To evaluate the statistical significance of the rank correlation factor, the Student test was applied [9]. The value of the statistic was determined from the relation

$$t^* = \frac{r_s}{\sqrt{1-r_s^2}} \sqrt{n-2} \quad (6)$$

The values of the correlation coefficient are collected in Table 3.

Table 3. Values of correlation coefficient r

Sample	r	t	t_{kr}	Test
I	-0.519	-2.50	-2.10	H1
II	-0.468	-2.24	-2.10	H1

It was found that the evaluated correlation coefficients are statistically significant. The hypothesis (H1) about the correlation between noise G and time t is significant at the level $\alpha = 0.05$ (proved by Student's test), $|t| \geq |t_{kr}|$.

CONCLUDING REMARKS

The reported experiments indicate that the correlation between the noise parameter and time to failure of capacitors is statistically significant. The value of the noise intensity at $f = 2$ Hz can be used as an indicator to predict the individual lifetime of an aluminium electrolytic capacitor.

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Author's biography:

Alicja Konczakowska received her MSc in 1966 from the Faculty of Electronics, Technical University of Gdańsk. In 1966–1977 she took part in solving problems concerned with the evaluation of the noise behaviour of semiconductor devices and the construction of systems for measuring noise in semiconductor devices. She was also involved in the problem of the analysis of surface roughness. The last topic was summarized in her doctoral thesis; she received the PhD in 1977 (Technical University of Gdańsk). For many years she has worked on relations between the low-frequency noise of electronic components and their reliability. She has been involved in several research projects on this topic. In 1992 she received her Dr Hab in electronics and since 1996 she has been a professor at the Technical University of Gdańsk. She is the author or co-author of 73 papers, 64 research works and two patents, mainly concerned with the low-frequency (1/f noise) problems of electronic components.