

Measurement and analysis of low-frequency noise in large capacity high voltage aluminum electrolytic capacitors

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Abstract—The testing technique of low-frequency noise in electrolytic capacitors was presented. Using this method the time series and power spectra of low-frequency noise under room temperature and the dependences of power spectra on both terminal voltages and temperatures were measured. The results showed that the low-frequency noise in aluminum electrolytic capacitors was $1/f$ noise in the frequency range from 0.1Hz to 30Hz. The variation curves of extracted noise power spectra densities at 1Hz with biases and temperatures agree well with theoretical analyses. The low-frequency noise characterization method presented in this paper will render a solid basis for both the investigation of low-frequency noise and the establishment of low-frequency based nondestructive inspection schemes for electrolytic capacitors.

Keywords—Aluminum electrolytic capacitors; Low-frequency noise; Testing method; Reliability

I. INTRODUCTION

Because of the low price and large capacitance, electrolytic capacitors were widely used in a variety of electronic systems^{[1][2]}. In ideal state, capacitors are lossless components, and as a result, are noiseless elements. But there are many loss mechanisms in a actual electrolytic capacitor, which results in an ever existing non-equilibrium state and gives rise to a certain level of electronic noise^{[2][3]}. Leakage current is induced by the internal charges

leakage between the two plates of the capacitors, which can be described by $I_L = KCU$, in which K is the coefficient of leakage current, C is the capacitance, U is the nominal voltage. When the voltage between the two terminals of the electrolytic capacitors is not zero, low-frequency noise will be generated in the leakage current. The magnitude of low-frequency noise in an electrolytic capacitor is dominantly determined by the density of defects in the oxide of anode foil and the extent of damnnification during riveting process. Electrolytic capacitor bearing large amplitude of low-frequency noise not only means that it will increase the noise level of the circuits, but also indicates a deterioration of the reliability of the capacitor^[2]. An investigation on the relation between low-frequency noise and the mean time to failure of the aluminum electrolytic capacitors claims that there is a close relation between these two qualities. Low-frequency noise can be taken as a sensitive indicator for the screening and classification of aluminum electrolytic capacitors in the perspective of reliability^[3].

The prerequisite for investigation of the low-frequency noise in aluminum electrolytic capacitors is the correct testing technology of the low-frequency noise in this type of high voltage and large capacitance components. Because the leakage only exists between the anode and cathode foils of

the aluminum electrolytic capacitors, as a result, it does flow through the external circuit when there is no external power supply^{[4] [5]}. In order to lead the leakage current out of the capacitor, high voltage dry battery pack was needed. However, the internal resistance of the battery pack will pose large impact on the measurement of low-frequency noise if the pack was not properly designed and prepared. Till now, there were just a few papers published focused on this issue, and most of them were dealing with the problems of tantalum electrolytic capacitors with lower nominal voltage. For example, in the paper published by Smith et al. a low-frequency noise testing circuit for tantalum electrolytic capacitors was presented. Because was powered by dry batteries, the testing circuit was impressionable to deficient current supply that would deteriorate the accuracy of the noise measurement procedure^[4]. In the paper written by Wang Dong, there was no detailed testing circuit illustrated^[6]. Because the low-frequency noise is a rather weak signal even compared with leakage current, the correct technique measurement is of great difficulties, and deserves a systematic investigation.

In this paper, the measurement technique for low-frequency noise in high nominal voltage and large capacitance aluminum capacitors was brought forward, in which detailed circuit and procedure were rendered. Based on the testing technique provided, the time series and power spectra of the low-frequency noise in aluminum electrolytic

capacitors were measured. The dependences of power spectra of low-frequency on both terminal voltages and environment temperatures were investigated. The results show that the testing technique presented in this paper is capable of measurement the low-frequency noise in large capacitance components even under high terminal voltage conditions. The noise power spectra densities obtained can more eloquently reflect the unstable changing processes of the internal defects in the capacitors with both terminal voltages and temperatures^[3].

II. LOW-FREQUENCY NOISE MEASUREMENT

Illustrated in Fig.1 is the ac-coupling testing circuit for low-frequency noise in aluminum electrolytic capacitors employed in this work. Because the DUT in this work is the high voltage and large capacitance capacitor, two groups of power supply were used, with one being rapid charging source and the other being low-noise source. During low-frequency noise measurement, this two power sources is used alternatively. In Fig.1, V1 is a generally used output-voltage adjustable power source with ac-input, which is used to quickly charge the capacitor under test to a given terminal voltage. BT1 is a dry battery pack made up of small volume Ni-MH batteries, which is used to sustain the terminal voltage of the capacitor during low-frequency noise measurement because of its preferable noise standards compared with V1.

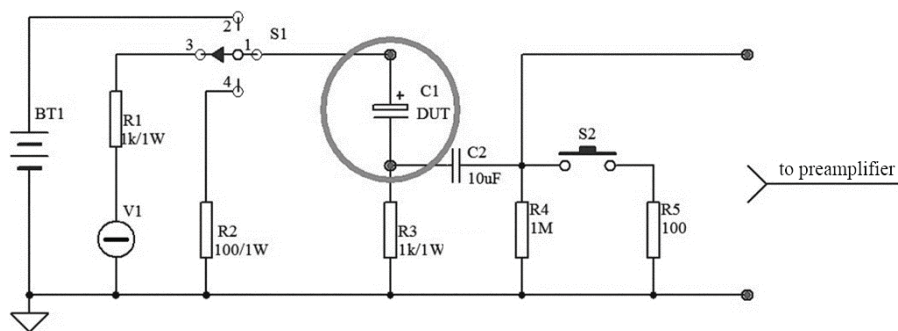


Fig.1 AC-coupled low-frequency noise testing circuit for large capacity high voltage electrolytic capacitors.

When start to test, s1 is switched to channel 3. Then C1 is charged by V1 to a given terminal voltage through R1 and R3. When the voltage across C1 is stale, s1 is switched to channel 2, and BT1 is used to

maintain the voltage over C1. A noise sampling loop comprised of BT1, the capacitor under test C1 and the sampling resistor R3 is established. The leakage current of C1 flowing from the anode to the cathode

of C1 is led out of the capacitor by BT1, and will go back to BT1 through R3. As a result, the voltage across R3 is proportional to the leakage current. During the noise testing, the time for the stabilization of the leakage current is determined by the terminal voltage and capacitance of C1 and the resistance of R3. A rapid discharging circuit of coupling capacitor C2 is made up by S2 and R5 to ensure the quickly voltage reset of the sampling point. After noise acquisition, S1 must be switched to channel 4 to discharge the sample capacitor C1 before the replacement of it. The voltage signal sampled from R3 is firstly amplified by a low-noise pre-amplifier, and then fed into an A/D data acquisition card. The time series and power spectra of the low-frequency noise are saved in a computer for further analysis. To electrolytic capacitors, the power spectra of the low-frequency noise in the frequency range from 0.1 to 30Hz contain the most useful information relating to reliability. So the accurate measurement of this part of the spectra should be guaranteed firstly.

The capacitors characterized in the experiments is the Aishi 100 μ F/400V aluminum electrolytic

capacitors produced by Hunan Yiyang Aihua Corporation. In the experiment, not only the time series and power spectra of the low-frequency noise were measured, but also the dependences of the power spectra density on both terminal voltages and environment temperatures were characterized. The highest voltage applied in the test is 390V. Of course, voltages such as 400V or even higher can be applied if the highest output voltages of V1 and BT1 have the capacity. Shown in Fig.2 is an obtained time series and power spectrum of the low-frequency noise in the aluminum electrolytic capacitor. From the left panel of Fig.2 one can see that the time series of the low-frequency noise in the aluminum electrolytic capacitor is very much similar to that of a MOSFET [7]. The power spectrum given in the right panel of Fig.2 is a ten-times average result, from which one can find that the power spectrum approximately abide by a $1/f$ one at the frequency range lower than 30Hz, while the spectrum above 30Hz being thermal noise. The results shown in Fig.2 agree with the predications of the models for aluminum electrolytic capacitors [8][9].

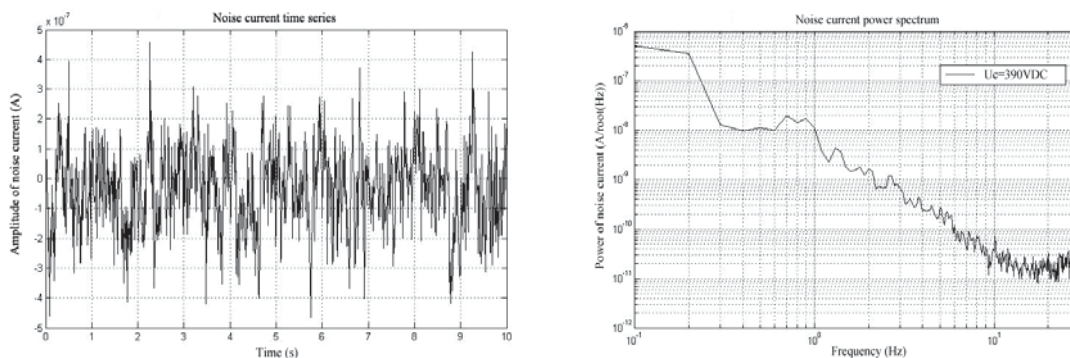


Fig.2 Time series and power spectrum of low-frequency noise measured at room temperature.

III. RESULTS AND ANALYSIS

Only when the leakage current was lead out of the aluminum electrolytic capacitors by the dry battery pack, low-frequency noise of the leakage current can be measured in the external circuit. The choice of coupling approaches is of great importance in the measurement. In the ac-coupling circuit, the dc blocking effect of the large capacitor was utilized, only the ac signal can go through the capacitor and enter the next stage for pre-amplification. However,

in a dc-coupling circuit, the dc component of the signal was reserved, and the mixed dc and ac signal was feed into the next stage. According to their advantages, the ac-coupling was usually used in the amplification, reshaping, and transmitting circuits, while the dc-coupling was frequently applied to low-frequency circumstances such as switching signal transmission and charge detection and comparison. When dc-coupling was adopted, the floating of the bias should be considered carefully.

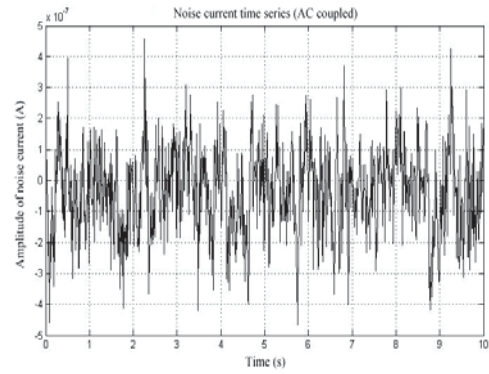
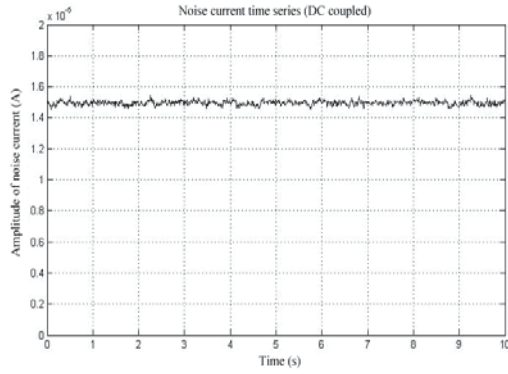


Fig.3 Time series of low-frequency noise measured by DC and AC coupling methods.

In order to seek a preferred coupling method, both dc- and ac-coupling were employed during the low-frequency noise measurement. Fig.3 presented the time series measured by dc- and ac-coupling methods. From Fig.3 one can see that the time series of the low-frequency noise measured by dc-coupling approach has a dc component with very much larger amplitude than that of the noise. When ac-coupling method was employed, the low-frequency noise signal is rather obvious. Fig.4 provided the power spectra of the low-frequency noise measured by the two coupling methods. Similarly, the spectrum obtained by dc-coupling has a larger value compared with that acquired by ac-coupling because of the influence of the dc component in the measured signal. At very low frequencies, the power spectrum densities obtained by dc-coupling converge to those of the dc component. From these results we can conclude that ac-coupling method other than dc-coupling should be adopted in the characterization of low-frequency noise in aluminum electrolytic capacitors, because the dc component will impose grave impact on the time series and power spectrum of low-frequency noise once dc-coupling approach was employed.

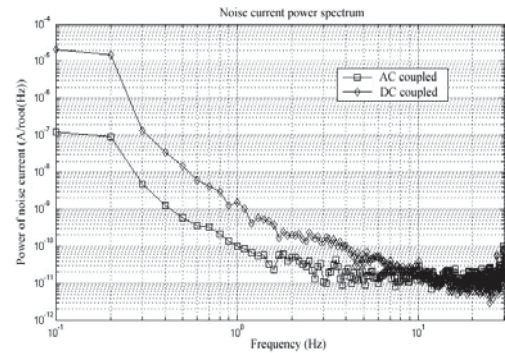


Fig.4 Power spectra of low-frequency noise measured by DC and AC coupling methods.

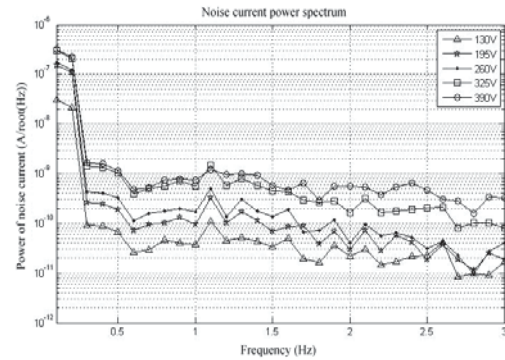


Fig.5 The power spectra of low-frequency noise of electrolytic capacitors under different biases.

Shown in Fig.5 are the power spectra of the low-frequency noise of an aluminum electrolytic capacitor under different terminal biases. It is obvious that the power spectrum densities of the low-frequency noise in a 100 μF /400V aluminum electrolytic capacitor increase with the terminal biases. The low-frequency noise voltage of the aluminum electrolytic capacitors can be described by Equa.(1) [2] [3]

$$S_V = \frac{4kTR_C}{1 + (2\pi f R_C C)^2} + A \frac{U^2}{f} \quad (1),$$

in which, k is the Boltzmann constant, T is the temperature in Kelvin, R_C is the equivalent parallel resistance, f is frequency, C is the capacitance of the capacitor, A is a constant, U is the voltage across the capacitor. In the right hand side of Equa.(1), the first term is the power spectrum of thermal noise generated in the equivalent RC network of the capacitor, the

second term is the contribution of the low-frequency noise in the leakage current. The measured power spectrum in the experiment is the sum of these two terms. From Equa.(1) we can derived that the power spectrum of low-frequency noise can be approximated as when frequency $f > 1/(2\pi R_c C)$ [2]

$$S_V = A \frac{U^2}{f} + B(T) \frac{1}{f^2} \quad (2),$$

where $B(T) = 4kT / 4\pi^2 R_c C^2$. A positive relation between the power spectrum densities of low frequency noise and terminal voltages can be easily found from Equa.(2), which is in consistent with the experiment result show in Fig.5 [2].

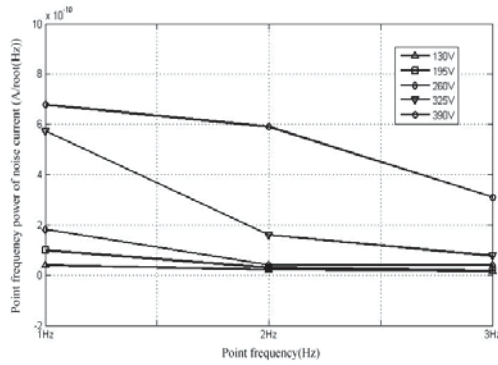


Fig.6 The extracted noise power spectra densities for three frequencies under different bias.

The power spectrum densities at certain frequencies of the low-frequency noise were ever used as an indicator for the reliability of aluminum electrolytic capacitors [2] [3]. Given in Fig.6 are the variations of the power spectrum densities of low-frequency noise at 1Hz, 2Hz and 3Hz with the voltages across the aluminum capacitor. It is clear that the power spectrum densities of low-frequency noise at all frequencies are increasing with the voltage. This is also in agreement with Equa.(2). Because the DUT in this work are large capacitors, the power spectra of the low-frequency noise decrease quickly with frequency. If low-frequency noise was chosen as an indicator for reliability, power densities at lower frequencies measured under high bias conditions should be adopted in order to depressing the influences of thermal noise and dc component.

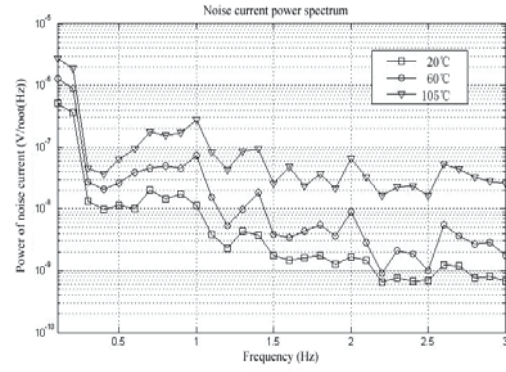


Fig.7 The power spectra of low-frequency noise of electrolytic capacitors under different temperature.

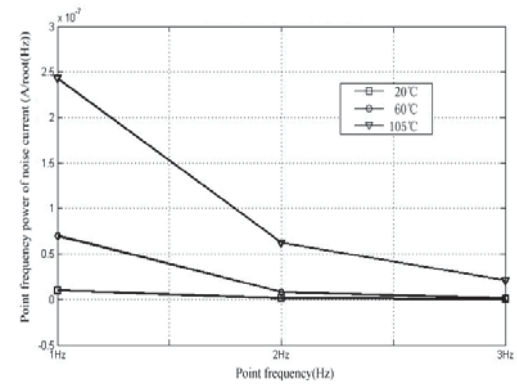


Fig.8 The extracted noise power spectra densities for three frequencies under different temperature.

Shown in Fig.7 are the power spectra of the low-frequency noise in the electrolytic capacitor under different temperatures. One can see that the power spectra densities of low-frequency noise at nearly all frequencies increase with temperature. This is mainly because of the enlargement of leakage current with temperature, which induced the increase of power spectra densities of low-frequency noise with temperature. From Fig.7 we also can perceive that the power spectrum densities under 105°C is about two orders of magnitude larger than those under 20°C and 60°C. This indicates that when the temperature is elevated to 105°C, the core of the aluminum electrolytic capacitor is in an unstable state, and the leakage points in the anode foil are rather active, which will lead to a sudden increase of the low-frequency noise. The power spectra densities at three frequencies are given in Fig.8, from which one can see that the power spectrum densities at all frequencies show an increase dependence with temperature, and the only

differences are their rates of rise. The large increase in power spectrum densities at lower frequencies can more clearly reflect the unstable state inside the capacitor^{[2][8]}.

IV. CONCLUSION

The characterization of low-frequency noise in aluminum electrolytic capacitors is not only helpful to improve the precision of the circuit, but also of great significance to the development of low-frequency noise based reliability evaluation and screening technologies^{[2][3][9]}. In the measurement of low-frequency noise in high nominal voltage and large capacitance aluminum electrolytic capacitors, a dry battery pack that can supply the leakage current must be employed in order to lead the leakage current out of the capacitors. And at the same time, ac-coupling method that can block the dc component of the leakage current should be adopted to guarantee the accuracy of the measurement for both the time series and power spectra of the low-frequency noise. The dependences of power spectra and their densities at different frequencies on both terminal voltages and temperatures acquired in the experiment are in accordance with theoretical analyses^{[2][8]}. It is discovered that the power spectrum densities at lower

frequencies measured under higher terminal voltages can better reflect the internal unstable state of the capacitor, as a result, should be exploited in the assessment of reliability of the aluminum electrolytic capacitors.

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