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DC-bias-voltage dependence of degradation of aluminum electrolytic capacitors

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Abstract

Attention has been paid to reliability-related issues for dc-link capacitors such as monitoring methods, power-loss estimation, and ageing test. The degradation of the capacitors depends on their operating condition including temperature, ripple current, and dc-bias voltage, which has a strong influence on failures as well. In design stages of power converters, it is desirable to know the relation between the degradation and electrolytic parameters. This paper makes an intensive discussion on the voltage dependence of the degradation of a small aluminum electrolytic capacitor with an ageing test and a leakage-current measurement. The ageing test reveals that a higher dc-bias voltage brings a faster increase in ESR but results in a slower drop in capacitance in a range within the rated voltage. This result implies that either capacitance or ESR cannot be a unique indicator of the lifetime. Attention should be paid both to the ESR and to the capacitance when one monitors the capacitor condition. On the other hand, more than the rated voltage leads a rapid degradation of the capacitor, which can be confirmed by a leakage-current measurement instead of the ageing test.

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1. Introduction

DC-link capacitors are a major factor in degrading the reliability of power electric converters because they usually have a shorter lifetime and higher failure rate than those of semiconductor or magnetic devices [1]. Many researchers have been addressed reliability-related issues for the capacitors such as monitoring methods of capacitance and equivalent-series resistance (ESR) [2], power-loss estimation [3-5], and ageing test [6-9]. Ageing test of capacitors is often carried out both inside and outside their supported range because it intends for endurance test with acceleration and for ensuring reliability in the range.

The degradation of the capacitors depends on their operating condition such as temperature, ripple current, and dc-bias voltage, which has a strong influence on failures as well. In design stages of power converters, it is desirable to know the relation between the degradation and electrolytic parameters. In addition, the minimum design margin of capacitors is also required for cost reduction without undue risk [1].

Reference [10] presents the service life of large aluminum electrolytic capacitors, which confirms that the degradation of the large capacitors gets faster and faster as the dc-bias voltage becomes higher and higher. On the other hand, some technical notes describe that small size electrolytic capacitors do not have a dc-bias-voltage dependence on the service life [12].

This paper presents an experimental verification of the relation between dc-bias voltage and degradation of a small aluminum electrolytic capacitor, comparing with an existing ageing law. In addition, this paper investigates the relation between the degradation and leakage current of the capacitor.

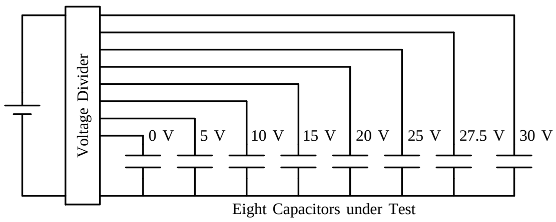

Fig. 1 Circuit configuration providing different voltages to eight capacitors under test for the ageing test.

2. Existing ageing laws for capacitors

2.1 Dependence of operating temperature

It is well known that the lifetime of the capacitor is estimated by the so-called Arrhenius equation that is a general formula for the temperature dependence of chemical reaction. The equation for the capacitors is given by

$$L_{\mathrm{T}} = L_{\mathrm{T0}} \times 2^{\frac{T_0 - T}{10}} \tag{1}$$

where L_{T} is the life time at the operating temperature of T, L_0 is that at a testing temperature of T_0. Equation (1) suggests that a decrease in the operating temperature by 10 K doubles the life time of the capacitor. This results from drying of the electrolyte in aluminum electrolytic capacitors. This Arrhenius equation indicates that an intentionally provided high temperature achieves an accelerated ageing test.

2.2 Dependence of dc-bias voltage

References [11, 13] describe that the lifetime of capacitors depends on the dc-bias voltage as follows:

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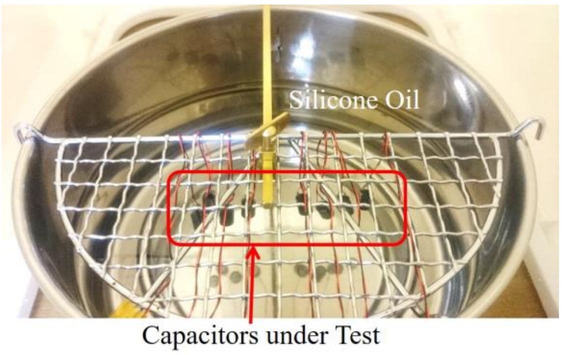


Fig.2 Experimental setup of accelerated ageing test with an oil bus.

$$L_V = L_{V0} \times \left(\frac{V}{V_0}\right)^{-n} \tag{2}$$

where V and V_0 are voltages at the operating condition and testing one, respectively. L_{VO} is the life time under the testing condition. For aluminum electrolytic capacitors, the parameter n typically takes 3-5 [9, 10]. On the other hand, reference [12] describes that L_V takes unity for a small electrolytic capacitor. Equation (2) is empirical and does not fully take physical meaning into account, unlike the dependence of the operating temperature.

3. Ageing test with different dc-bias voltages

3.1. Circuit configuration

Fig. 1 shows circuit configuration for the ageing test, where a dc-voltage supply with a voltage divider provides different voltages of 0-30 V to eight capacitors under test. The voltage divider consists of a resistor network. Specifications of the capacitors are 25 V, 470 μF, and 85 degrees Celsius. The nominal lifetime of the capacitors is 2000 hours. Note that two of the capacitors are forced into voltages more than the rated voltage (27.5 V and 30 V) because this paper also intends an endurance test.

Eight sets of capacitors under test with different voltages are introduced for the ageing test with the rated temperature of 85 degrees Celsius, where each of the sets consists of four capacitors in parallel. Ageing test with a room temperature of 20 degrees Celsius is also conducted.

3.2. Accelerated by rated temperature

Fig. 2 is a photo of the ageing test using an oil bus filled with silicone oil in which the capacitors under

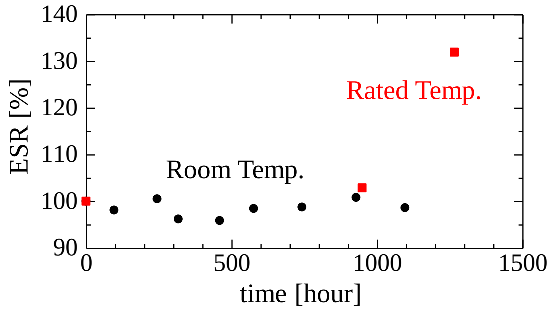


Fig.3 Comparison between rated- and room-temperature for ESR.

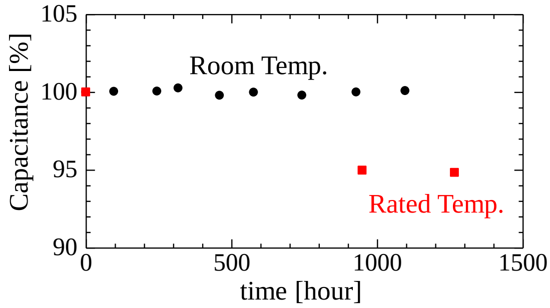


Fig.4 Comparison between rated- and room-temperature for capacitance.

test was immersed. The oil bus kept the temperature of the silicone oil to be 85 degrees Celsius.

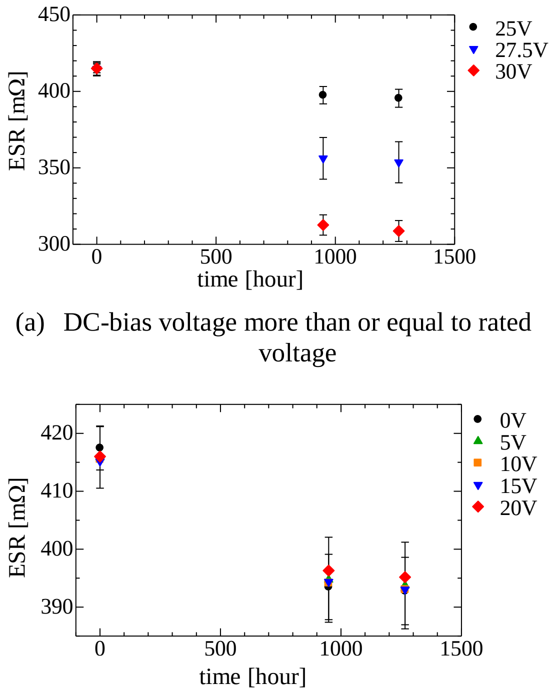
Note that the capacitors were pulled up so as to make their temperature the room temperature when they were measured. This eliminates the influence of temperature because the ESR and capacitance of the aluminum electrolytic capacitor is a function of its operating temperature [5].

4. Results and discussion

4.1 Comparison between rated- and room-temperature conditions

An LCR meter (ZM2371, NF corp.) was used for ESR and capacitance measurement. Fig. 3 shows ESR measurement results with the rated temperature and the room temperature with a dc-bias voltage of 0 V, the result with the room temperature was almost constant in more than 1000 hours, whereas that with the rated temperature was monotonically increasing.

Fig. 4 shows capacitance measurement results with the same condition as that in Fig. 3. The result with room temperature was almost constant, while that with the rated temperature was decreasing.



(a) DC-bias voltage more than or equal to rated voltage

(b) DC-bias voltage less than rated voltage

Fig. 5 ESR change with different dc-bias voltages.

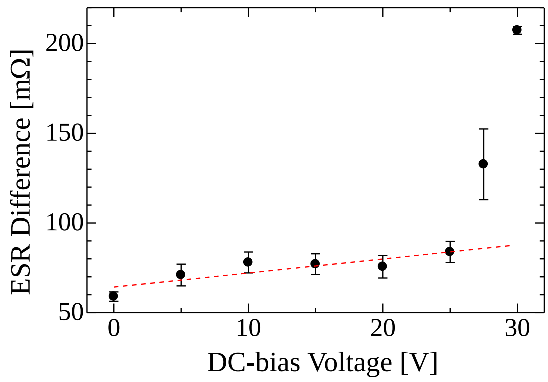


Fig. 6 ESR deference between initial and last values of 1250 hours.

These results in Figs. 3 and 4 have confirmed that the higher temperature accelerated the ageing of the capacitors under test. The following subsections show experimental results with the rated temperature.

4.2 ESR change with different dc-bias voltages

Fig. 5 shows ESR changes with a different dc-bias voltage of 0-30V, where each plot shows the mean value of four capacitors with an error bar indicating the standard deviation. ESR was measured under the room temperature. Fig. 6 shows differences between initial ESR values and last ones at 1250 hours. The ESR difference within the rated voltage was almost a monotonically increasing function, whereas that more than the rated voltage brought a rapid increase. Thus, a higher dc-bias voltage resulted in a faster degradation in terms of ESR change even though less than the rated voltage is applied to the capacitor.

Fig. 7 shows capacitance change with the same condition as that shown in Fig. 5. Fig. 8 shows differences between initial capacitances and last ones. The capacitance difference was a monotonically increasing function in a range less than the rated voltage, which implies that a higher dc-bias voltage makes the degradation slower. This result differs from the ESR change. On the other hand, voltages more than the rated voltage also brought a rapid drop in capacitance.

Fig. 9 shows the lifetime of the capacitor under test. The lifetime is estimated by linear functions obtained from the capacitance and ESR differences shown in Figs. 6 and 8, respectively, where the lifetime is defined as the time that the capacitance decreases by 20% or the time that the ESR doubles. This result implies that either capacitance or ESR cannot be a unique indicator of the lifetime. As a consequence, attention should be paid both to the ESR and to the capacitance when one monitors the capacitor condition. On the other hand, voltages more than the rated voltage brought a rapid degradation.

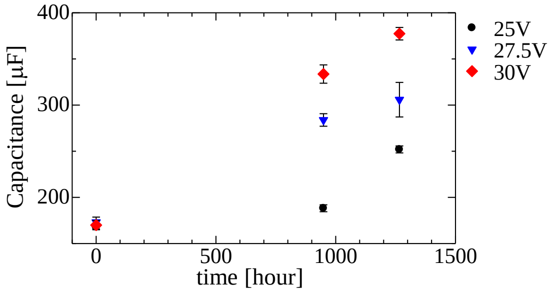
4.3 Weight of Capacitors under Test

Fig. 10 shows measured weights of the eight capacitors under test after an ageing test accelerated by a high temperature of 90 degrees Celsius, which is severer than the ageing test described in the subsection 4.2.

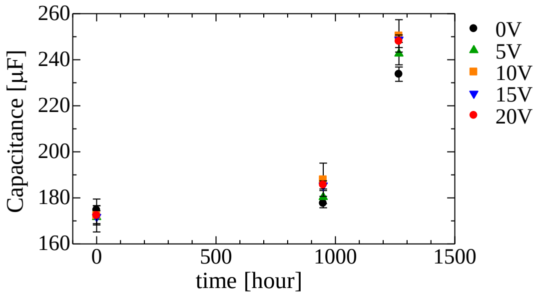
The weights were almost uniform, which indicates that the weight did not change according to the degradation. Thus, the degradation would not result from consumption of the electrolyte of the capacitor but be caused by degradation of the electrode.

5. Leakage-current measurement indicating the degradation

Fig. 11 illustrates the leakage-current measurement



(a)DC-bias voltage more than or equal to rated voltage



(b) DC-bias voltage less than rated voltage

Fig. 7 Capacitance change with different dc-bias voltages.

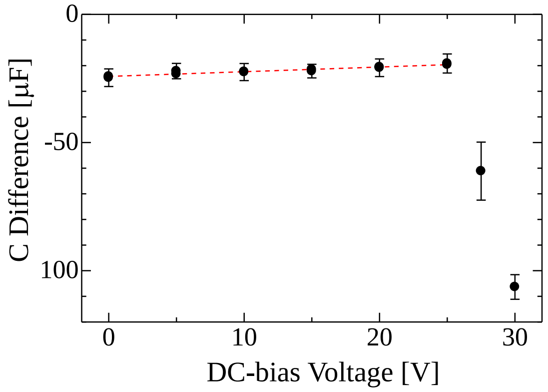


Fig. 8 Capacitance difference between initial and last values of 1250 hours.

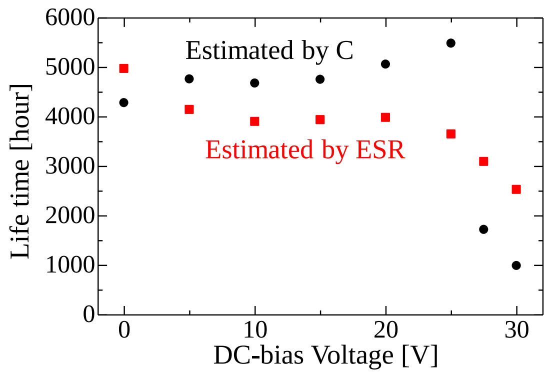


Fig. 9 Estimated lifetime of the capacitor under test.

circuit consisting of a current-to-voltage converter, where an operational amplifier of LMC6001 is used. The operational amplifier has a greatly small input current of 25 fA.

Fig. 12 shows measured results of the leakage current of the capacitor against the dc-bias voltage. Note that the capacitor under test used in this measurement was new, i.e., it was not the same capacitor used in the ageing test. In voltages less than the rated voltage of 25 V, the leakage current was almost in proportion to the voltage, which indicates that the capacitor act as a constant resistance. On the other hand, the dc-bias voltages more than the rated voltage resulted in a rapid increase in the leakage current, so that the capacitor behaved as a smaller resistance than that less than the rated voltage. This relation is similar to that between the degradation and the dc-bias voltage, so that the leakage current is a good indicator of the degradation.

6. Conclusion

This paper presents an experimental discussion on the dc-bias-voltage dependence of the degradation of small-size aluminum electrolytic capacitors with an ageing test. The ageing test has revealed that a higher dc-bias voltage brings a faster increase in ESR but results in a slower drop in capacitance in a range within the rated voltage. Thus, attention should be paid both to the ESR and to the capacitance when one monitors the capacitor condition. On the other hand, more than the rated voltage leads a rapid degradation of the capacitor, which can be confirmed by a leakage current measurement.

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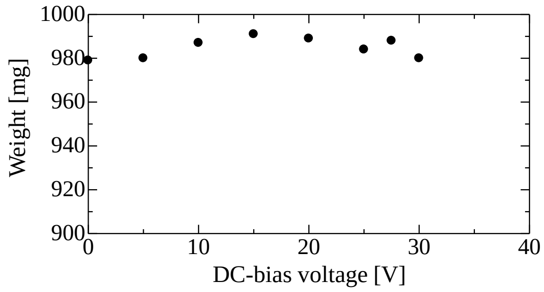

Fig. 10 Weights of the capacitors under test with different dc-bias voltages after the ageing test accelerated by a high temperature.

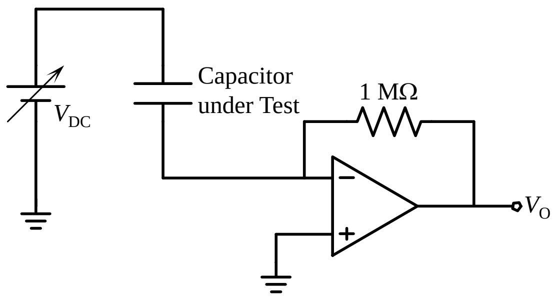

Fig. 11 Leakage-current measurement circuit

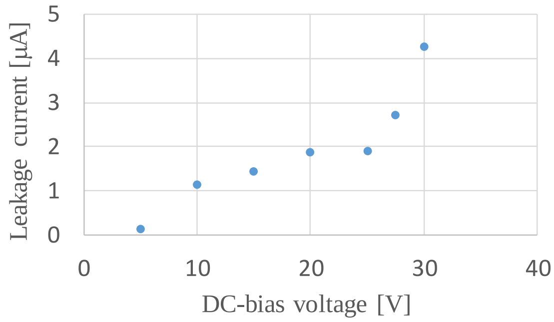

Fig. 12 Experimental result of the leakage current of the capacitor against dc-bias voltage.

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