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Observation of electrolytic capacitor ageing behaviour for the purpose of prognostics

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***Abstract*—Electrolytic capacitors are an important component within power electronics systems which are known to exhibit poorer reliability compared to other components within the system. In this paper, the changes in electrical parameters (capacitance and equivalent series resistance) which occur as electrolytic capacitors age are characterised at regular intervals over the life of the capacitors. Ageing is observed under three different bias conditions: no bias; constant voltage bias and square wave excitation and at two different ambient temperatures. The data captured within this work presents the changes in capacitor properties from new, reaching to a point which the capacitor parameters have changed sufficiently, such that the capacitor can be considered to have failed. Such data will prove valuable in the development of a system designed to determine the state of health of a capacitor, or could be used to predict its remaining useful lifetime.**

Keywords—Capacitors; Accelerated aging; Prognostics and health;

I. Introduction

Electrolytic capacitors form an important part of most power electronics converters and drives. As a consequence of this, the reliability of electrolytic capacitors will have a considerable influence on the overall system reliability [1]. Therefore, it would be useful to be able to predict failures within these components prior to it occurring. Over the course of an electrolytic capacitor's lifetime, changes will occur which influence the electrical properties of the capacitor. These changes will impact both its capacitance and its equivalent series resistance (ESR). By monitoring these properties it is possible to determine when a capacitor is approaching failure, allowing action to be taken. This action could take the form of dynamically adjusting the loading upon the capacitor or simply replacing it. In this paper, the criteria for a capacitor failure are defined by (1) and (2).

$$C < 0.8 \cdot C_n \text{ or } C > 1.2 \cdot C_n \tag{1}$$

$$R > 2 \cdot R_n \tag{2}$$

where C is the present capacitance; C_n was the value of capacitance when the capacitor was new; R is the present equivalent series resistance of the capacitor and R_n is the ESR of the capacitor when new.

A. Electrolytic capacitor structure

The internal structure of an electrolytic capacitor consists of two aluminium foils which are separated by a porous material (e.g. paper) which is impregnated with an electrolyte. The aluminium foil which forms the anode of the capacitor will have its surface chemically etched to increase its surface area, and therefore its capacitance. This foil is anodised to produce a layer of aluminium oxide on its surface and this forms the insulation layer between the capacitor plates and must be sufficiently thick to withstand the rated voltage of the capacitor [2]. The electrolyte is the cathode of the capacitor system; while a second aluminium foil (which is not etched) provides a means of electrically connecting to the liquid electrolyte. The use of a liquid to form the cathode of the system ensures that a good contact occurs between it and the etched anode, as the liquid can conform to the surface profile of the aluminium surface. The terminals of the capacitor are connected to the aluminium foils and the entire structure is rolled up and packaged into an aluminium can.

II. Overview of Capacitor Ageing

The variation of electrolytic capacitor electrical properties due to ageing can be attributed to two key degradation mechanisms:

1. The evaporation of electrolyte [3, 4, 5]
2. The electrolyte reacting with the insulation material within the electrolytic capacitor [6]

A. Evaporation of electrolyte

Over time the liquid electrolyte will evaporate, and therefore reduce the amount of available electrolyte within the capacitor. As this occurs, regions of the capacitor plates begin to dry out, resulting in a decrease in contact surface area within the capacitor. This reduced surface area results in a decrease to the component capacitance, while simultaneously increasing the ESR. As this wear out mechanism results in a loss of electrolyte it is possible to detect the ageing by considering the mass of the capacitor as outlined in [3]. This approach would not be practical to implement within an online prognostic system as it would require the capacitor to be weighed in isolation to a high degree of accuracy. Consequently, this approach will not be discussed any further.

B. Chemical reactions in electrolyte

Within the capacitor the electrolyte reacts chemically with the aluminium oxide insulation resulting in a thinning of the oxide layer. This manifests itself as an increase in the components capacitance. As the insulation layer is of a reduced thickness this change also results in a reduction in the capacitors maximum allowable voltage [6].

Considering the first mechanism it is apparent that the ESR of the capacitors will increase with age. Concerning the capacitance, the expected result will depend upon the conditions which the capacitor is exposed to, as these conditions will determine which of the two mechanisms is more dominant.

C. Influence of temperature on ageing

In relation to the reliability of electrolytic capacitors the Arrhenius rule (**3**) is often quoted [2]. This rule states that increasing the operating temperature of a capacitor by 10°C will halve its useful life [7]. To this end it is possible to speed up the rate at which capacitors age by performing the ageing at a higher temperature. In this work the temperatures selected for the environmental chambers are 105°C and 115°C (20°C and 30°C higher than the rated temperature of the capacitors respectively). These temperatures were selected so as to expedite the ageing of the capacitors without being so high that new failure mechanisms are introduced. The influence of temperature on ageing rates and Arrhenius' rule will be discussed in more detail when the experimental results are considered.

$$L = L_0 \cdot 2^{\frac{T_0 - T_A}{10}} \tag{3}$$

where L is the capacitor lifetime; L_0 is the capacitor lifetime under rated conditions; T_0 is the rated temperature and T_A is the operating temperature.

III. Ageing Methodology

Within this work several different ageing tests were performed to facilitate analysis into the effects that various test parameters have upon ageing. Data on the capacitors used within this work can be seen in Table I.

TABLE I PROPERTIES OF CAPACITORS UNDER TEST

Manufacturer	Forever
Nominal Capacitance	1000 µF
Tolerance	± 20 %
Rated Voltage	63 V
Can Diameter	16 mm
Can Length	26 mm
Operating temperature	-40°C – 85°C

The measurement procedure employed for each capacitor consisted of removing any biasing/drive signals from the capacitor, and ensuring that it is fully discharged through a current limiting resistor. After this, the capacitor is connected to a Hioki 3522 LCR meter (which was calibrated before use to remove the influence of the test fixtures) for the measurements to be performed. The measurements were performed at 1 kHz and the capacitors remained within the environmental chamber at the ageing temperatures during these measurements.

A. High temperature storage test

In this test the capacitors were placed into an environmental chamber which maintained the temperature at a fixed value. Two batches of capacitors were subjected to this test, one within a chamber held at 105°C and one at 115°C. Temperatures above that of the rated operating temperature were selected for this testing so as to expedite the ageing process. This test condition is representative of the case where a capacitor is installed within a system which has been stored for a prolonged period of time.

B. High temperature bias test

In this test a bias voltage of 50.4 V was applied to the capacitors within the environmental chambers (again at 105°C and 115°C). The applied voltage is equal to 80% of the capacitor's rated voltage. This test allows the effects of prolonged biasing on the capacitors to be explored. A voltage below the capacitor rating was used so as to ensure that the bias voltage was not applying electrical stress to the capacitor.

The application of a constant voltage to the capacitor inhibits damage to the oxide layer as the applied voltage aids oxide reformation. This allows separation of the ageing mechanisms, as electrolyte evaporation will be a far more significant ageing mechanism for these capacitors. At regular intervals the bias voltage was removed from the capacitors to allow the measurement of the electrical parameters at the ageing temperature.

C. High temperature driven test

In this test capacitors within the environmental chambers were driven with a square wave voltage with a frequency of 200 mHz and an amplitude of 50.4 V. To limit the charging current of the capacitors they were connected in series with a 100 Ω resistor, limiting the peak charge/discharge currents to 0.504 A. This approach allows the ageing behaviour of the capacitors when they are exposed to charge/discharge cycles to be considered. This test is representative of a capacitor which is installed within a running system.

D. Capacitors under test

In this work a total of 26 capacitors were aged using the techniques outlined previously, divided between the three operating conditions. The electrical values of each capacitor were recorded at the start of the experiment to ensure that all of the capacitors were within the manufacturers specification. All capacitors met the specification with an average capacitance of 985 µF and ESR of 29.67 mΩ. The experimental results presented in this paper show values which are normalised to the value for each capacitor when new. This is done to make the identification of capacitors which have reached their failure conditions simpler.

IV. Experimental Results

A. High temperature storage test

The changes to the electrical parameters for each of the capacitors was recorded when the capacitors were placed in environmental chambers at their test temperatures. In Fig. 1 the change in capacitance of capacitors at 105°C, with no bias are shown. From this figure, it can be observed that the capacitance exhibits a steady linear decline until a critical point is reach, at which point the capacitance exhibits a sharp increase. This sharp increase can be attributed to the electrolyte reacting chemically with the insulation layer, reducing its thickness, and therefore decreasing the spacing between the capacitor plates, resulting in an increased capacitance. The changes in ESR for the same capacitors are shown in Fig. 2. In this figure it can be observed that the ESR increases linearly until the same point, at which the ESR also increases substantially. Fig. 3 and Fig. 4 show similar results for capacitors at an ambient temperature of 115 °C with no bias. The key difference between these two sets of capacitors is the gradient at which the electrical parameters change in the linear region, prior to the rapid rise supporting the Arrhenius rule and will be considered in more detail later in this paper.

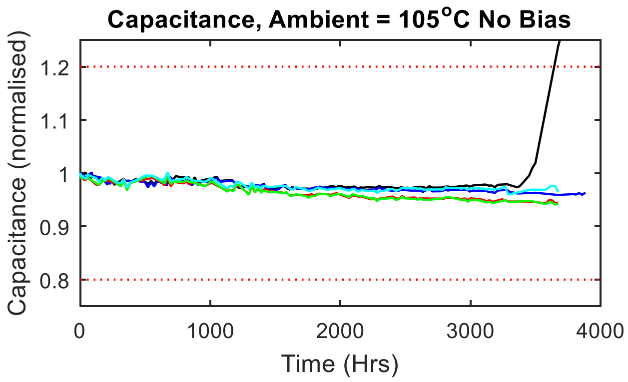

Fig. 1 Change in capacitance, 105°C, no bias, 1 kHz measurement

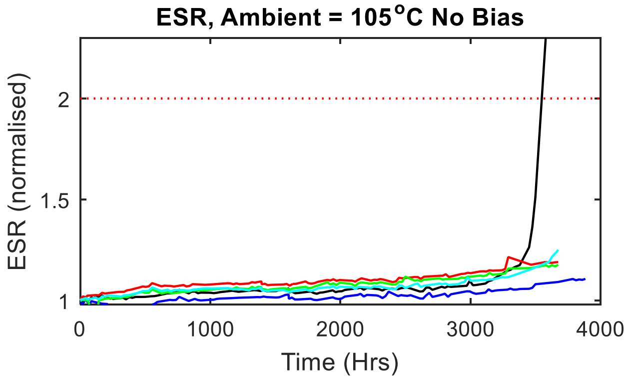

Fig. 2 Change in ESR, 105°C, no bias, 1 kHz measurement

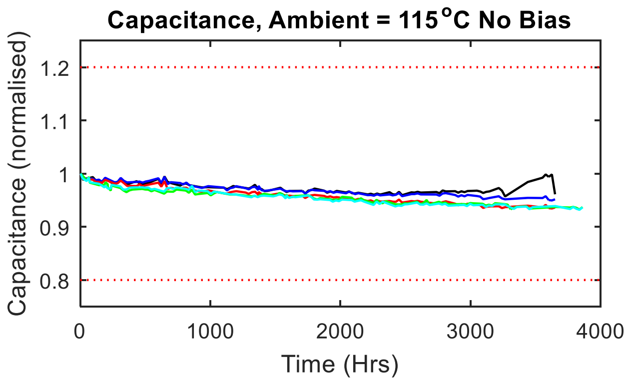

Fig. 3 Change in capacitance, 115°C, no bias, 1 kHz measurement

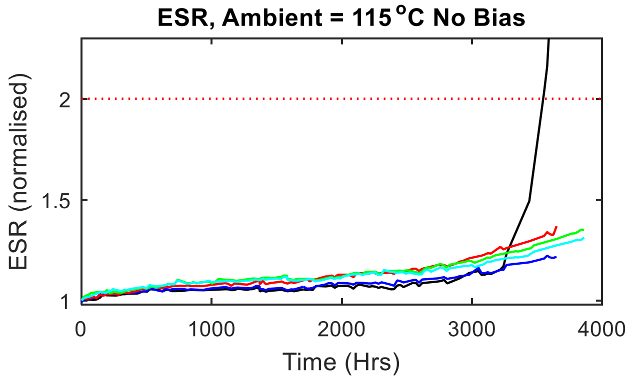

Fig. 4 Change in ESR, 115 °C, no bias, 1 kHz measurement

B. High temperature bias test

Fig. 5 and Fig. 6 show the results of ageing capacitors with an applied bias voltage of 50.4 V at 105°C. Initially, the ageing process appears to follow the same linear degradation trend which is observed for the unbiased capacitors. The key difference is that when the critical point is reached the capacitance is observed to fall rapidly and the ESR increases. The behaviour of the capacitance differs from the unbiased case. This can be attributed to the bias voltage reforming the oxide layer by re-anodising the surface using the electrolyte, inhibiting the ageing mechanism caused by insulation thinning. Therefore, ageing is caused primarily by the evaporation of electrolyte, leading to a reduction in surface area and therefore a loss in capacitance. In Fig. 7 and Fig. 8 the corresponding results for the 115°C chamber are also presented. Once more the ageing progresses in a comparable linear manner but with a steeper gradient that the 105°C chamber.

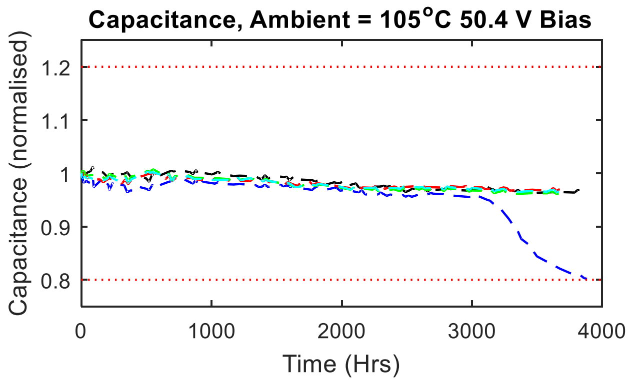

Fig. 5 Change in capacitance, 105°C, 50.4 V bias, 1 kHz measurement

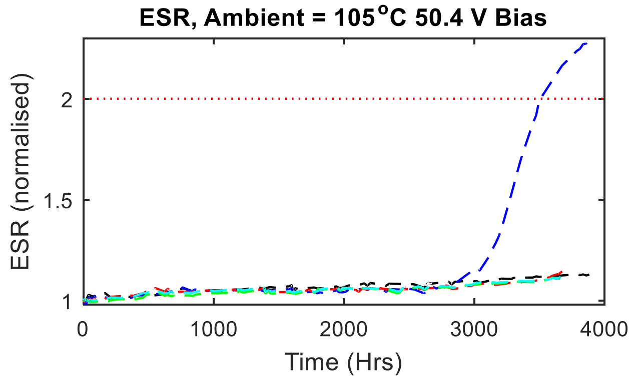

Fig. 6 Change in ESR, 105°C, 50.4 V bias, 1 kHz measurement

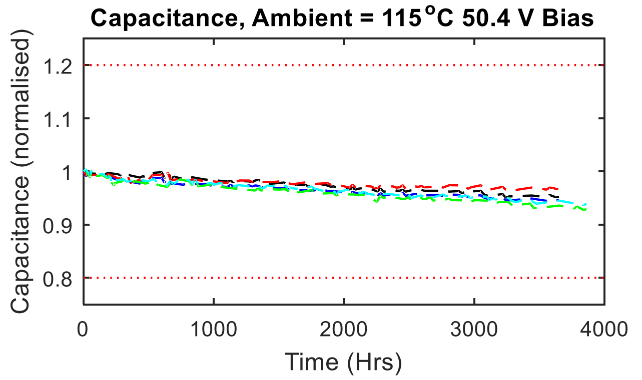

Fig. 7 Change in capacitance, 115°C, 50.4 V bias, 1 kHz measurement

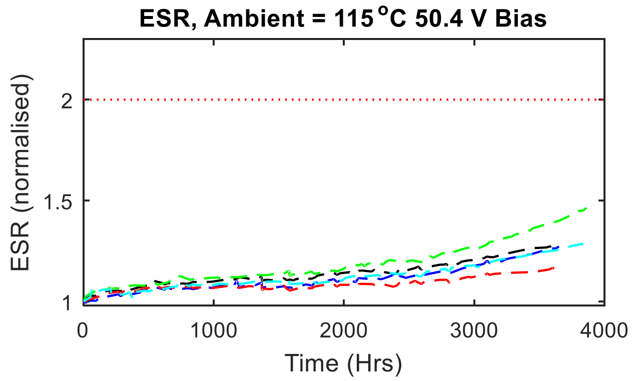

Fig. 8 Change in ESR, 115°C, 50.4 V bias, 1 kHz measurement

C. *High temperature driven test*

The capacitors within this set were driven with the square wave voltage described earlier. Driving the capacitors with this waveform allows the effect of changes in capacitor state of charge on ageing to be examined. In addition to varying the state of charge this test will also produce a small degree of internal heating due to losses within the capacitor. [8]

In Fig. 9 the change in capacitance can be observed for square-wave driven capacitors within the 105°C chamber. The changes in ESR can also be observed in Fig. 10, these changes are linear but occur at a faster rate than that demonstrated in other configurations within the 105°C environmental chamber. This can be associated with the self-heating of the capacitor when excited by a square wave. While it is impractical to measure the core temperature of these capacitors without modifying their structure, it is possible to measure the case temperature. By considering the case temperature it is possible to assess the level of self-heating which is occurring and therefore comment on its likely influence. The case temperature increased by an average of 2°C. Considering the size of the capacitor can it is reasonable to assume that the core temperature is not significantly higher than the case temperature [2]. The estimated core temperature is supported by the fact that the ESR increases at a higher rate than the other capacitors within this chamber, but is slower than the capacitors within the 115 °C chamber suggesting that the internal temperature is somewhere between these two values.

Fig. 11 and Fig. 12 show the results of the capacitors excited by a square wave voltage within the 115°C chamber. Again, using an ageing temperature of 115°C yields comparable results to the capacitors under the same test regime at 105°C chamber, but at an increased rate. One point which must be noted within this particular dataset is that one of the capacitors failed under test relatively early on within the test (1200 hours). Prior to this failure the capacitor was degrading in a similar manner to the other capacitors within this batch and gave no significant indication that failure was imminent. As this failure occurred at a far earlier time than any of the other capacitors it has been concluded that it was premature.

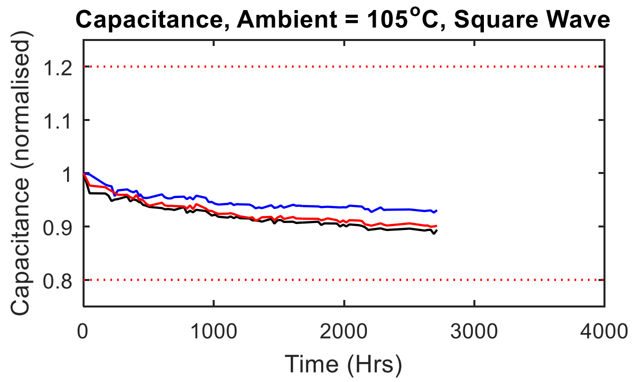

Fig. 9 Change in capacitance, 105°C, 0.2 Hz square wave, 1 kHz measurement

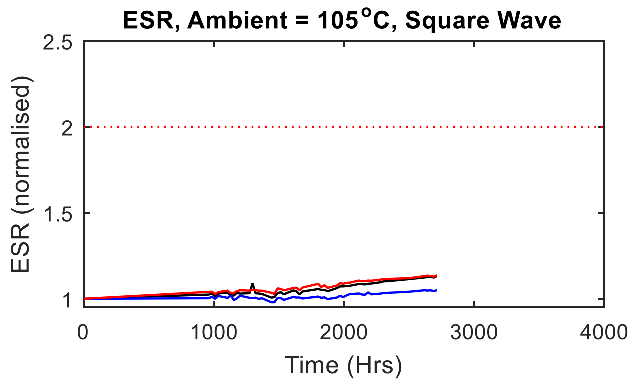

Fig. 10 Change in ESR, 105°C, 0.2 Hz square wave, 1 kHz measurement

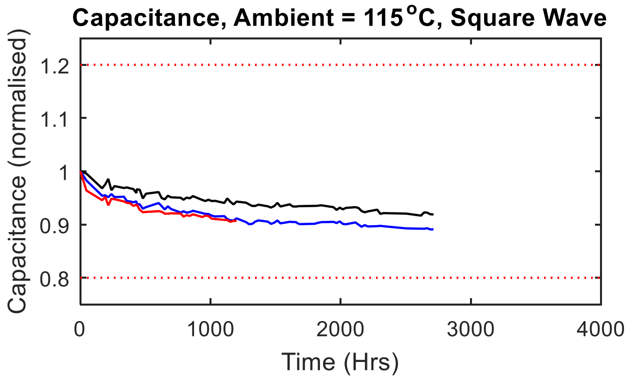

Fig. 11 Change in capacitance, 115°C, 0.2 Hz square wave, 1 kHz measurement

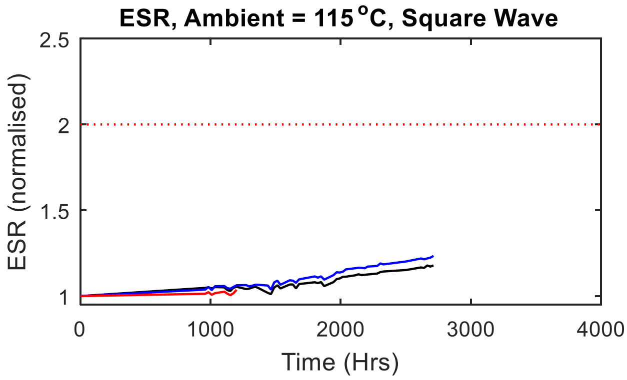

Fig. 12 Change in ESR, 115°C, 0.2 Hz square wave, 1 kHz measurement

It is important to note that the change in capacitance values observed during capacitor failure is dependent upon the conditions which it is placed. Conversely the ESR is always seen to increase, regardless of test conditions. For this reason, the ESR is the more suitable property for use in determining the age of a capacitor.

D. Failure point

From the results, it is evident that a sharp change in capacitance or ESR is a marker of forthcoming device failure. A summary of the state of the capacitors at the point at which the sudden change in parameters starts to occur is outlined in Table II. From this it can be observed that this sudden change occurs well before the parameters reach the values defined for failing capacitors by (**1**) and (**2**). Therefore prognostic systems must consider this stage of the capacitor's lifespan.

TABLE II CAPACITOR REGION THRESHOLD VALUES

Configuration	**Capacitance change**	**ESR Change**
105 °C, No Bias	- 3 %	+ 15 %
115 °C, No Bias	- 3 %	+ 17 %
105 °C, 50.4 V Bias	- 4 %	+ 8 %
115 °C, 50.4 V Bias	TBD	TBD
105 °C, Square wave	TBD	TBD
115 °C, Square wave	TBD	TBD

E. Effect of temperature on ageing

The Arrhenius rule is frequently used to describe electrolytic capacitor degradation. For this work, as the capacitors were aged at different temperatures it should be possible to validate Arrhenius rule with the experimental data generated. Based on the rule, if an appropriate scale factor is applied to the time axis of the data, data obtained at different temperatures can be compared. The graphs shown in Fig. 13 to Fig. 16 are produced for this purpose. In these figures, the experimental results obtained at 115°C are used as the reference data (and are plotted as solid lines within the figure). The data obtained at 105°C is normalised to this data. This is achieved by dividing the measurement times for the 105°C data by a factor of 2. This factor is derived from the fact that the Arrhenius rule states that an increase in temperature by 10°C halves the lifetime of the capacitor. The resulting data is plotted in the figures represented by the 'x' symbol. It can be observed from these figures that the normalised 105°C data matches well with the 115°C reference data within the linear degradation region of the curves, validating the applicability of this rule. It should be note however that deviation between the results can be seen when the capacitors enter the exponential region. This can be attributed to the fact that the time at which the components enter this region is based on probability, and therefore the timing of this event will possess some degree of statistical variation.

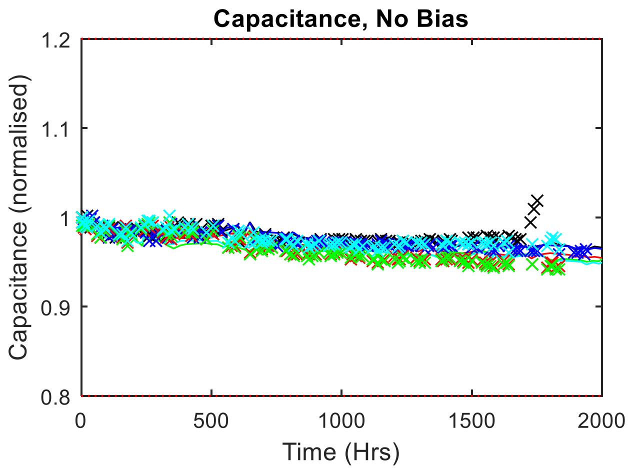

Fig. 13 Change of capacitance over time, no bias. Capacitors in oven at 115 °C ('-') used as reference. Capacitors in oven at 105 °C ('x') have had times halved.

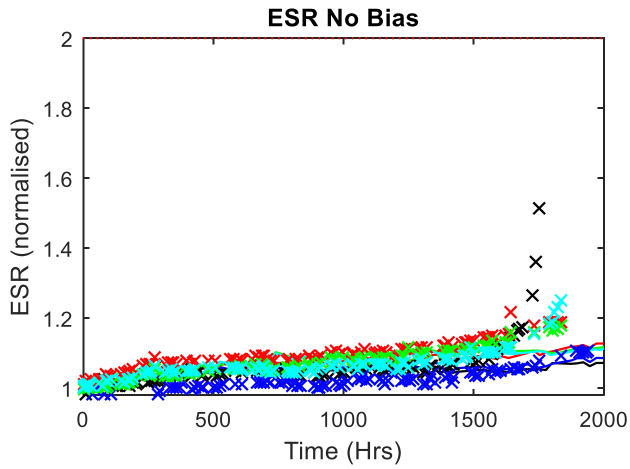

Fig. 14 Change of ESR over time, no bias. Capacitors in oven at 115 °C ('-') used as reference. Capacitors in oven at 105 °C ('x') have had times halved.

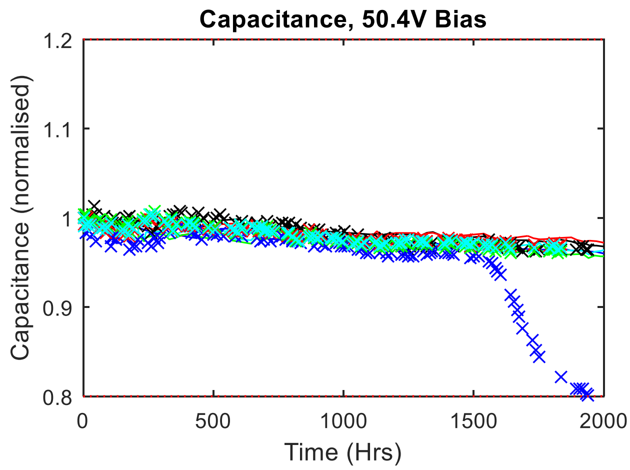

Fig. 15 Change of Capacitance over time, no bias. Capacitors in oven at 115 °C ('-') used as reference. Capacitors in oven at 105 °C ('x') have had times halved.

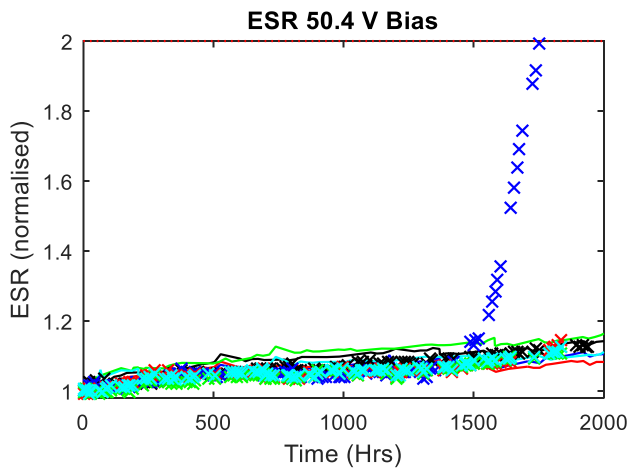

Fig. 16 Change of ESR over time, no bias. Capacitors in oven at 115 °C ('-') used as reference. Capacitors in oven at 105 °C ('x') have had times halved.

V. Conclusion

In this work we set out to establish the shape of electrolytic capacitor electrical property curves as a result of ageing under a variety of test conditions. From these curves, it is possible to identify capacitors in which failure is imminent by considering the change in electrical parameters. It has also been established that the point of particular interest for the purpose of life determination is the point at which the capacitors exhibit sudden changes in capacitance and ESR. Such a change suggests that the capacitors are approaching end of life.

Consideration has also been given to Arrhenius rule which relates capacitor life to temperature and states that capacitor lifetime is halved when temperature is increased by 10°C. The experimental results obtained at different temperatures appear to support this rule. This is useful as it allows the ageing data obtained at a single temperature to be utilised to predict the lifetime of a capacitor at multiple operating temperatures, reducing the quantity of data which has to be determined for a given capacitor type.

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