

Condition monitoring of electrolytic capacitors

Acácio M. R. Amaral · A. J. Marques Cardoso

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Abstract This paper presents a very simple and cheap *off-line* technique that is able to evaluate the aluminum electrolytic capacitors condition. Aluminum electrolytic capacitors equivalent circuit is composed by an internal resistance and a capacitance. The capacitors internal resistance increases with aging while the capacitance decreases. Manufacturers define the end of life limit of the capacitor when its internal resistance doubles its initial value or the capacitance changes more than 20% when it is compared with the initial one. The proposed technique evaluates the capacitor condition through the identification of both capacitor internal resistance and capacitance. To compute both capacitor internal resistance and capacitance a very simple, cheap, and practical experimental setup is proposed.

Keywords Technologies and methodologies for diagnostics and prognostics · Aluminum electrolytic capacitors · *LMS* algorithm

1 Introduction

In the last years several researchers have been working on the subject of fault diagnosis of aluminum electrolytic

capacitors (Harada et al. 1993; Lahyani et al. 1998; Venet et al. 2002; Gasperi 2005; Amaral and Cardoso 2009). This is mainly due to the fact that these capacitors are one of the preferred capacitors in electronics and simultaneously one of the weakest elements. Figure 1 shows the distribution of faults in a common switch mode power supply (half-bridge DC–DC forward-type power supply) (Lahyani et al. 1998; Venet et al. 2002).

From the analysis of Fig. 1 it is possible to conclude that these capacitors represent the weakest element of power supplies. In this way, it becomes of paramount importance the development of fault diagnostic techniques that are able to evaluate the state condition of aluminum electrolytic capacitors, in order to avoid unexpected breakdowns of the equipment.

2 Capacitors

A capacitor is an electronic component that is able to store electrical energy in a form of an electrical field. It is constituted by a pair of conductors (two plates) separated by an insulator (dielectric).

When a voltage source is connected to the capacitor some rearrangements occur in the electrical charge of both capacitor plates. The positive terminal of the power supply attracts the electrons of the capacitor plate that is closest to it. The other terminal of the power supply, which is connected to the other plate, repels the plate electrons. During this process the capacitor is charging.

To discharge the capacitor it is necessary to connect a conductor between both plates in order to achieve the charge equilibrium between both plates.

A. M. R. Amaral (✉)
Polytechnic Institute of Coimbra, ISEC–DEIS,
Rua Pedro Nunes, 3030-199 Coimbra, Portugal
e-mail: acacio@isec.pt

A. M. R. Amaral · A. J. Marques Cardoso
Instituto de Telecomunicações, DEEC, University of Coimbra,
Pólo II–Pinhal de Marrocos, 3030-290 Coimbra, Portugal
e-mail: ajmcardoso@ieee.org

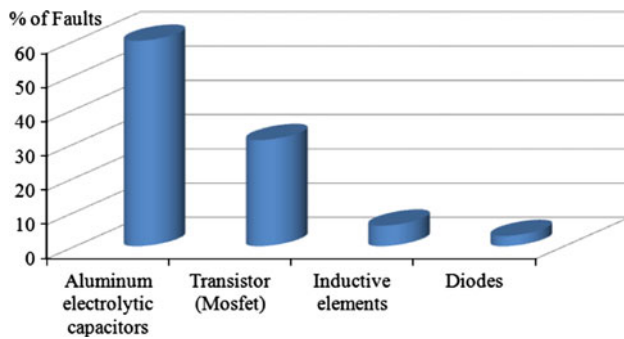


Fig. 1 Distribution of failures for each power component, for a common used half-bridge forward-type power supply (Lahyani et al. 1998; Venet et al. 2002)

The capacitor capacitance, C , can be defined as:

$$C = \frac{Q}{V} \quad (1)$$

where Q and V represent the capacitor electrical charge and capacitor voltage, respectively. However, the capacitance can also be defined in a geometrical way as:

$$C = \epsilon_0 \times \epsilon_r \times \frac{S}{d} \quad (2)$$

where ϵ_0 , ϵ_r , S , and d represent the dielectric constant of the free space (8.854×10^{-12} F/m), the relative dielectric constant of the dielectric material, the surface area of the dielectric (m^2) and the thickness of the dielectric (m).

The capacitor current, i_C , due to charge rearrangements in the capacitor plates during the charge or discharge process can be obtained by differentiating (1):

$$i_C = C \times \frac{dv}{dt} \quad (3)$$

where $\frac{dv}{dt}$ represent the rate of change of capacitor voltage with time.

3 Capacitors technologies

Capacitors are available in three basic technologies:

1. Electrolytic capacitors;
2. Film capacitors;
3. Ceramic capacitors.

The electrolytic capacitors have very high volumetric efficiency, an excellent price/performance ratio and a very wide range of voltage and capacitance ratings, which make them the preferred capacitor type for power electronic applications (Fodor et al. 2006). However, they have high losses and are polarity dependent, so they are essentially used in DC circuits (Sarjeant et al. 1998). These capacitors can be subdivided into, tantalum electrolytic capacitors and

aluminum electrolytic capacitors. The first ones have a higher dielectric constant; however, they are more expensive when compared with the second ones (Poole 1981). Besides, their maximum voltage rating is limited to 50 V, which limits their application to low and medium voltage ranges. Aluminum electrolytic capacitors have a much higher range of capacitances (0.1 μ F–3 F), and voltages (5–500 V) (Application guide, Cornell Dubilier). The very high volumetric efficiency of electrolytic capacitors is achieved due to the very thin dielectric and to a process of etching the foils that can enlarge the surface area of the foil in 100 times (Application guide, Cornell Dubilier).

Film capacitors offer tight capacitance tolerance, which does not change much with temperature, low losses, and are polarity independent. However, they are expensive, large, and weight (Application guide, Cornell Dubilier); the most popular polymer is the polypropylene.

Ceramic capacitors are used in very high frequency applications due to their non-inductive behavior. These capacitors can be sub-divided in classes 1 and 2. The first ones are very precise, stable, and have very low losses; however, they have low volumetric efficiency when compared with class 2 ones. Class 1 capacitors are used in circuits that operate close to 1 GHz. Class 2 capacitors are especially suited for AC applications that operate till 1 MHz (Dai et al. 2005).

4 Aluminum electrolytic capacitors

According to the Industrial Technology Research Institute of Taiwan (Tsai et al. 2002), the demand of aluminum electrolytic capacitors is estimated to growth by 8–10% per year, due to their excellent characteristics. Besides, some of their disadvantages can be overcome. For instance, the fact of this capacitor be polarity dependent, do not avoid it from being used in AC applications, if two aluminum electrolytic capacitors are connected in anti-series (back-to-back with the positive terminals or the negative terminals connected). The result is a non-polarity single capacitor with half of the capacitance (Application guide, Cornell Dubilier). The high losses can be reduced if low resistivity electrolytes are used (Efford et al. 1997), and the capacitor inductive effects can be reduced if a smaller capacitor with lower inductive effect is connected in parallel with the first one or if special design terminal electrolytic capacitors are used instead (Will and Fischer 2000).

4.1 Composition

An aluminum electrolytic capacitor consists of a wound element, impregnated with liquid electrolyte, connected to the terminals and sealed in a can (Fig. 2).

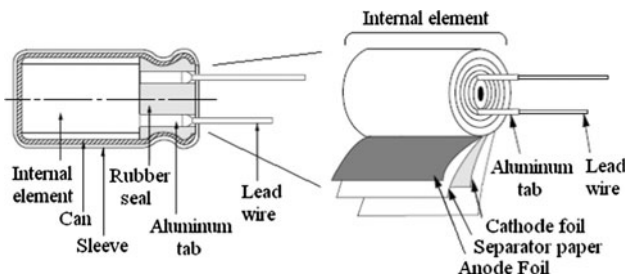


Fig. 2 Aluminum electrolytic capacitor composition ([Precautions and guidelines, Nippon Chemi-con](#))

The internal element comprises two foils (anode and cathode foils) that are separated by separator paper impregnated in the electrolyte. The foils are etched with billions of microscopic tunnels to increase their surface (Fig. 3) ([Application guide, Cornell Dubilier](#)).

This construction gives an enormous capacitance, since the dielectric surface can increase more than hundred times, which can be easily understood through (2).

4.2 Equivalent circuit

Real capacitors have some parasitic elements that influence their behavior, like the internal equivalent series resistance (*ESR*) or the equivalent series inductance (*ESL*).

Figure 4 models the behavior of an aluminum electrolytic capacitor under normal operation, as well as over-voltage and reverse-voltage behavior.

The capacitance of the capacitor is represented by C .

ESL models the inductive effect of the capacitor, and is mainly due to the loop formed by the terminals and tabs. Its value is typically 1–2 nH/mm for terminal spacing (Parler 2003).

The resistance R_S represents the sum of terminals resistance, foils resistance, tabs resistance, paper resistance, and electrolyte resistance.

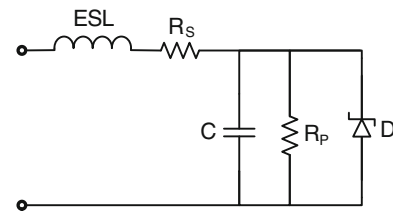


Fig. 4 Aluminum electrolytic capacitor equivalent circuit ([Application guide, Cornell Dubilier](#))

The resistance R_p models the leakage current in the capacitor, and its typical value is $100/C$ M Ω with C in μF ([Application guide, Cornell Dubilier](#)).

The *zener* diode D models the reverse and under voltage behavior of the capacitor. So, if the capacitor is submitted to a voltage higher than its nominal value, the leakage current will increase significantly; similar behavior has a *zener* diode when reverse biased over its *zener* voltage. On the other side, an application of a reverse voltage to the capacitor would lead to a behavior very similar to the *zener* diode when forward biased.

However, if the capacitor is working under normal operation, the circuit of Fig. 4 can be simplified to the one shown in Fig. 5.

ESR represents the influence of R_p and R_s and represents the ohmic losses in the capacitor:

$$ESR = R_S + \frac{1}{\omega^2 \times R_p \times C^2} \quad (4)$$

The *ESR* value decreases with temperature and frequency. Higher temperatures make the electrolyte conductivity increase which explains the decrease of *ESR*. This effect can be modeled through:

$$ESR(T) = \alpha + \beta \times e^{-\frac{T}{\delta}} \quad (5)$$

where T represents the operating temperature and α , β , and δ are constants that depend on the capacitor type (Venet et al. 2002).

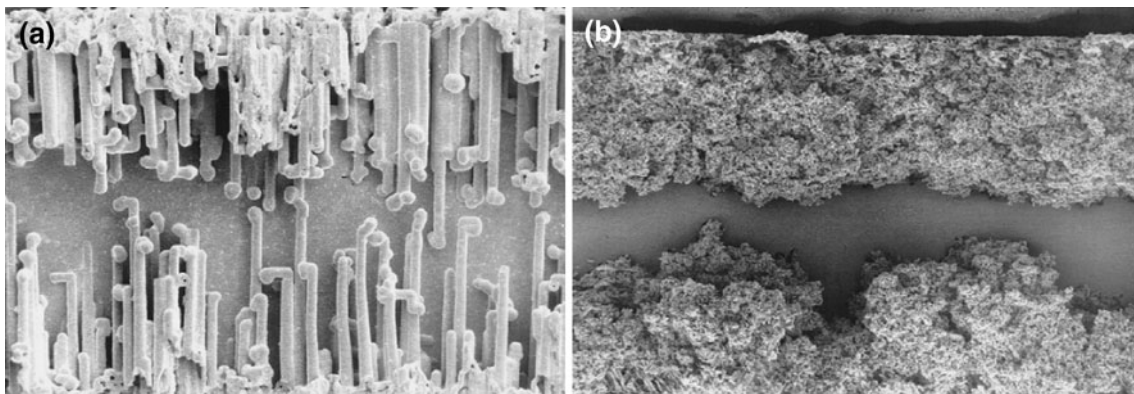


Fig. 3 Anode foil for high voltage (a) and low voltage (b) aluminum electrolytic capacitors (magnification of $\times 400$) (Epcos and January 2008)



Fig. 5 Simplified model of an aluminum electrolytic capacitor equivalent circuit (Application guide, Cornell Dubilier), under normal operation

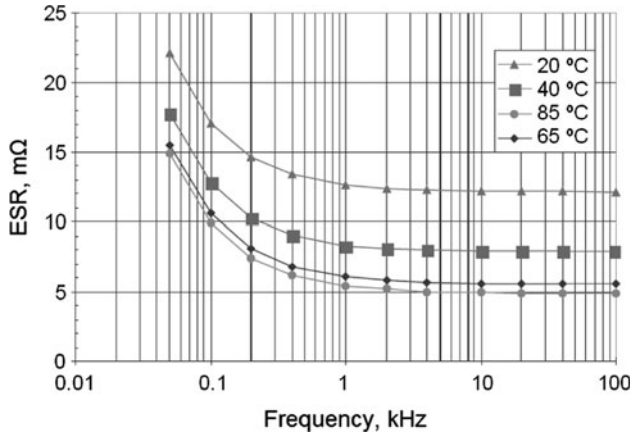


Fig. 6 ESR versus frequency and temperature for a capacitor of 4700 μF, 450 V (Application notes, BHC Components)

On the other hand, the decrease of ESR with frequency can be justified by (4). Both effects can be observed in Fig. 6.

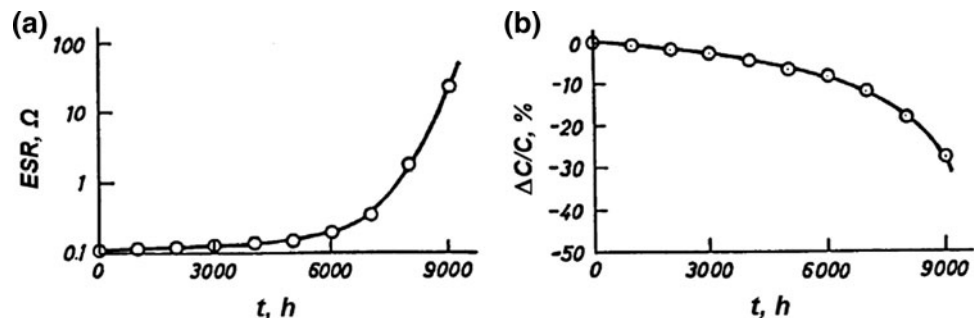
4.3 Aging process

The aging of aluminum electrolytic capacitors is expressed by the increase of their ESR and a decrease of C. This phenomenon can be explained by the reduction of the electrolyte volume which decreases the conductivity as well as the effective area between the dielectric and the electrolyte (Fig. 7).

In fact, the evolution of ESR with aging time, *t*, for a constant temperature, *T*, can be modeled through Arrhenius law:

$$\frac{1}{ESR(t)} = \frac{1}{ESR(0)} \times \left(1 - k \times t \times e^{-\frac{4700}{T+273}} \right) \quad (6)$$

Fig. 7 ESR (a) and ΔC/C (b) characteristics under high temperature load tests (Harada et al. 1993)



where *k* represents a constant which depends on the design and construction of the capacitor (Lahyani et al. 1998).

The dielectric formed on the anode side is not uniform, thus there are regions where the thickness is lower than the medium one. Those regions do not stand voltages close to the nominal one, and so a leakage current will be created. However, these capacitors have a mechanism to restore the dielectric defects, the so called self-repairing mechanism (Technical guide, Panasonic). This mechanism consists in the formation of dielectric in the affected regions. For that, the oxygen of the electrolyte combines with the aluminum of the foils to form aluminum oxide. During this process some hydrogen will be released on the cathode side. The self-repairing mechanism increases with time, since the dielectric defects will increase with the aging process, and it is necessary to repair them. Therefore, the electrolyte reduces its volume, and consequently *C* decreases and *ESR* increases. Eventually, if the capacitor is not replaced in due time the electrolyte volume is so reduced that will lead to an open circuit failure.

5 Previous work

In the last years many authors have been working in the area of fault diagnosis of aluminum electrolytic capacitors. The major contributions are related to on-line diagnostic techniques, which are very complex, many times difficult to be implemented and dependent on the application. This is mainly due to the fact that capacitor ESR and *C* change considerable with temperature, frequency, voltage, current ripple, among other factors. To develop an accurate on-line fault diagnostic technique it is required to consider all these factors (Lahyani et al. 1998; Venet et al. 2002; Gasperi 2005).

Other solutions that do not have to consider the previous factors are the off-line diagnostic techniques, since the measurements can be performed always under the same operating conditions.

In (Amaral and Cardoso 2008) the authors presented an experimental technique that allows the computation of both ESR and reactance (*X_C*) intrinsic values of aluminum electrolytic capacitors for a wide range of frequencies.

The proposed technique requires the use of a *RC* circuit connected to a signal generator followed by a power amplifier. The objective is to create a sinusoidal waveform with enough power and the desired frequency to feed the *RC* circuit, in order to extract both *ESR* and X_C . The *ESR* and X_C are obtained from a graphical analysis. In (Amaral and Cardoso 2009; Amaral and Cardoso 2008) the previous technique was made automatic through the use of the discrete Fourier transform and of the least mean squares algorithm, respectively. In this approach, the capacitor current and voltage were used instead. In (Amaral and Cardoso 2009) a very simple alternative charge–discharge circuit is also proposed to extract both *ESR* and X_C of aluminum electrolytic capacitors.

The previous off-line diagnostic techniques are quite accurate and precise; however, they require the use of a digital oscilloscope connected to a *PC*.

In this paper the authors propose a simple fault diagnostic technique that is able to evaluate the capacitor condition without the need of a digital oscilloscope; instead a digital multimeter is used.

6 Proposed technique

The proposed technique uses only the capacitor impedance to estimate both *ESR* and *C*.

If the operating frequency is lower than the capacitor resonance frequency, the equivalent circuit of the capacitor can be simplified to the series of an ideal capacitor, *C*, and a resistor, *ESR*. Therefore, the impedance of the capacitor, Z_{CAP} , can be defined as:

$$Z_{CAP} = \sqrt{ESR^2 + \left(\frac{1}{w \times C}\right)^2} \tag{7}$$

Using (7), the least mean squares algorithm, and several values of Z_{CAP} at different frequencies, it is possible to estimate the *C* and the *ESR* values that best fit Z_{CAP} .

To obtain the Z_{CAP} values at different frequencies a very simple, cheap, and practical experimental setup is used: a *RC* circuit, composed by the capacitor under test in series with a non-inductive thick film resistor, connected to a signal generator followed by a power amplifier. Following, the root mean square values of the capacitor current, i_{crms} , and voltage, v_{crms} , are measured using a digital multimeter, a *Tektronix TX3 True RMS*. The impedance is then obtained through:

$$Z_{CAP} = \frac{v_{crms}}{i_{crms}} \tag{8}$$

After the computation of Z_{CAP} for several frequencies, the least mean squares algorithm, *LMS*, is used to compute the values of *ESR* and *C* that better fit Eq. 7.

6.1 Least mean squares algorithm

One strategy for fitting a “best” line through the data would be to minimize the sum of the squares of the residuals, S_r :

$$S_r = \sum_{i=1}^n \left(\frac{v_{crms}}{i_{crms}} - \sqrt{ESR^2 + \left(\frac{1}{w \times C}\right)^2} \right) \tag{9}$$

In order to simplify the process of estimating *ESR* and *C*, Eq. 7 is rewritten as:

$$f(w) = Z_{CAP}^2 = ESR^2 + \left(\frac{1}{w \times C}\right)^2 = K_X + K_Y \times \frac{1}{w^2} \tag{10}$$

In order to minimize the sum of the square of the S_r (9) is minimized with respect to the coefficients (K_X , K_Y). Thus, the coefficients can be computed through:

$$\begin{bmatrix} N & \sum_{i=1}^N \frac{1}{w_i^2} \\ \sum_{i=1}^N \frac{1}{w_i^2} & \sum_{i=1}^N \frac{1}{w_i^4} \end{bmatrix} \times \begin{bmatrix} K_X \\ K_Y \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^N Z_{CAPi} \\ \sum_{i=1}^N \left(\frac{1}{w_i^2} \times Z_{CAPi}\right) \end{bmatrix} \tag{11}$$

where *N*, Z_{CAPi} and w_i represent the number of tested frequencies, the capacitor impedance at the different tested frequencies, and the corresponding angular frequencies at the different test frequencies.

The values of *ESR* and *C* can be computed using:

$$ESR = \sqrt{K_X} \tag{12}$$

$$C = \frac{1}{\sqrt{K_Y}} \tag{13}$$

7 Experimental results

In these experiments three different capacitors with different degrees of aging were used. Thus, capacitor C_A represents a sound capacitor, while C_B and C_C represent two aged capacitors, of the same type of C_A , however, with different degrees of aging. Capacitor C_C was submitted to a more severe aging test than C_B .

Table 1 shows the capacitor characteristics given by the manufacturer:

Table 2 shows the i_{crms} and v_{crms} values obtained through a digital multimeter, for different tested frequencies.

From Table 2 it is possible to compute the Z_{CAP} , at the different tested frequencies, using (8). In this way, using Table 2 together with (11), it is possible to estimate the values of *ESR* and *C* that better fit Eq. 7, as can be seen in Table 3.

Figures 8, 9, and 10 show the experimental values Z_{CAP} obtained from Table 2, as well as the fitting Z_{CAP} based on

Table 1 Capacitor C_A specifications

Capacitance ($\pm 20\%$)	ESR max	DF max
4,700 μF	56.4 $\text{m}\Omega$	0.2

Table 2 Experimental results

f (Hz)	C_A		C_B		C_C	
	i_{crms} (A)	v_{crms} (mV)	i_{crms} (A)	v_{crms} (mV)	i_{crms} (A)	v_{crms} (mV)
100	0.416	144.9	0.413	153.5	0.412	161.2
500	0.498	38.9	0.498	44.6	0.496	56.8
1,000	0.503	22.4	0.502	22.8	0.501	41.3
5,000	0.504	12.6	0.503	20.2	0.500	32.5
10,000	0.500	12.5	0.499	19.9	0.497	31.7
15,000	0.494	12.7	0.492	19.9	0.491	31.1
20,000	0.484	12.9	0.482	19.7	0.482	30.4

Table 3 Estimated values of ESR and C

Capacitor	ESR (Ω)	C (μF)
C_A	0.0262	4,406
C_B	0.0422	4,225
C_C	0.0688	4,050

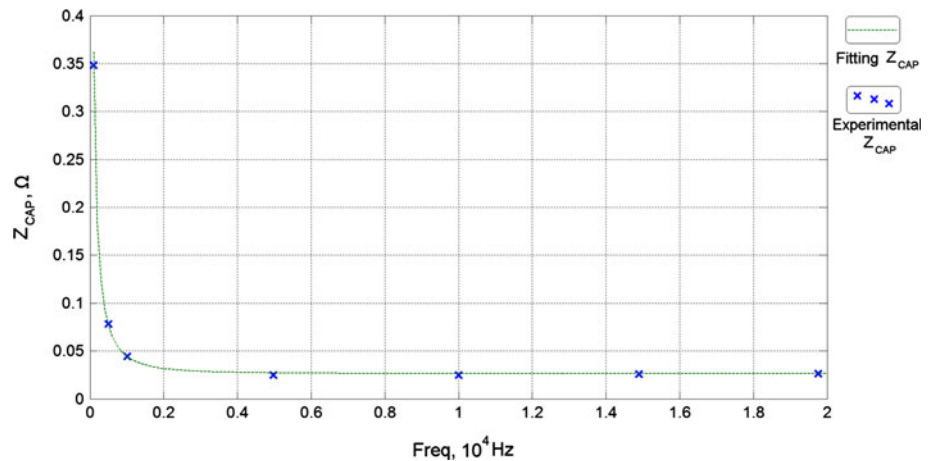
the estimated ESR and C values (Table 3), for C_A , C_B , and C_C , respectively.

Figures 8, 9, and 10 show a very good fitting of the experimental values of Z_{CAP} .

7.1 Accuracy of the proposed technique

In order to evaluate the accuracy of the proposed technique both ESR and C values were obtained at 20 kHz and

Fig. 8 Evolution of Z_{CAP} with frequency, for capacitor C_A



100 Hz, respectively, with an Impedance Gain Phase Analyzer *Agilent HP 4294* (Table 4).

Afterwards the results of Table 3 and 4 were compared in order to evaluate the accuracy of the proposed technique.

Table 5 clearly shows that the proposed technique is sufficiently accurate. Particularly, it can be observed that the ESR value doubles, and C almost changes 20% when the capacitor is close to its end of life limit. Besides, the error increases with aging, so it is possible to conclude that the proposed technique is conservative.

7.2 Fault diagnosis

In order to evaluate the capacitors condition the experimental results obtained from the proposed technique were analyzed (Table 3).

Figure 11 compares the ESR and C values of C_B and C_C , with the typical ones for a sound capacitor, and for that a new capacitor was used (C_A).

From Fig. 11 it is clear that the ESR of capacitor C_C is greater than twice the ESR of a sound capacitor of the same type, and so, capacitor C_C should be replaced. However, the ESR of capacitor C_B is lower than the limit, thus, it can still be used. Anyway, some attention should be given to this capacitor since the aging process is faster nearby the end of life period.

The capacitance of both aged capacitors (C_B and C_C) is lower than the limit, which could lead to the opposite conclusion with respect to C_C . However, to warrant the reliability of the equipments, when one of the two conditions related to the ESR or C limit is satisfied, the capacitor should be removed.

The proposed technique can also be used to predict the capacitor remaining useful life. For that, the following steps should be implemented:

1. First, several measurements at different aging time periods should be made using the proposed technique,

Fig. 9 Evolution of Z_{CAP} with frequency, for capacitor C_B

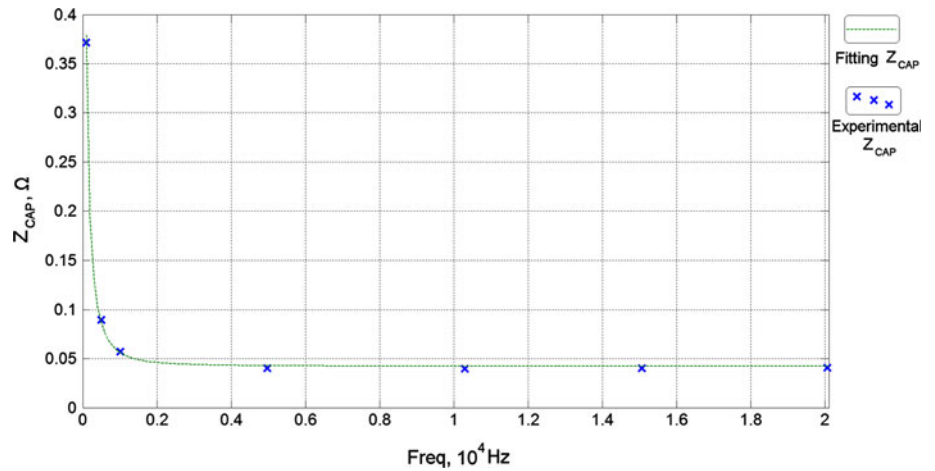


Fig. 10 Evolution of Z_{CAP} with frequency, for capacitor C_C

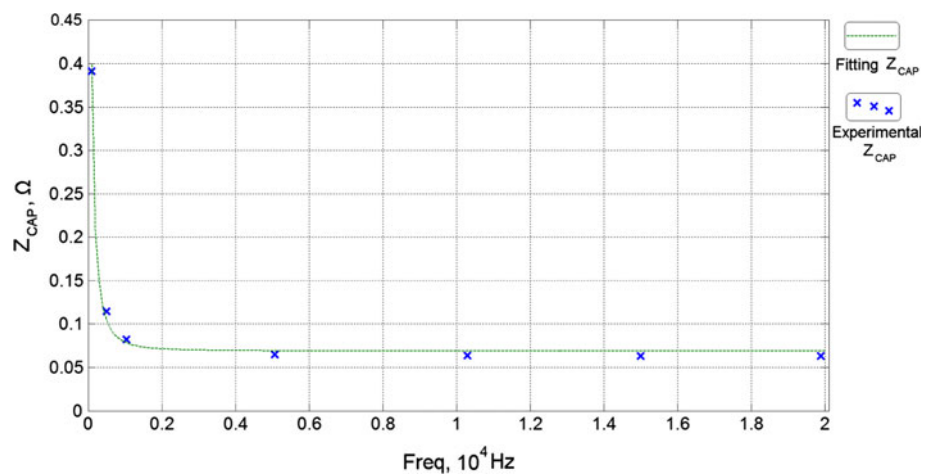


Table 4 ESR and C values obtained with the Agilent HP 4294

Capacitor	ESR (Ω) at 20 kHz	C (μF) at 100 Hz
C_A	0.0265	4,400
C_B	0.0404	4,238
C_C	0.0636	4,080

Table 5 Comparison of ESR and C values estimated by the proposed technique with ones obtained with the Agilent HP 4294

Capacitor	Error	
	ESR (%)	C (%)
C_A	1.1	0.1
C_B	4.5	0.3
C_C	8.2	0.7

during the initial lifetime. This allows the representation of function (6).

- In a second step, by using the previous curve together with a fitting algorithm it would be possible to compute K_X :

$$K_X = k \times e^{-\frac{4700}{T+273}} \tag{14}$$

- Finally, the capacitor remaining useful lifetime can be estimated from (6).

This methodology assumes that the capacitors average operating temperature is almost constant between the measurement periods, so that when computing K_X it is assumed a capacitor average operating temperature.

8 Conclusions

In this paper a very simple and cheap off-line technique that is able to evaluate the aluminum electrolytic capacitors condition was proposed.

Aluminum electrolytic capacitors equivalent circuit changes considerable with the operating conditions and aging.

The capacitors internal resistance increases with aging while the capacitance decreases. However, the operating conditions can also influence their values; so, the

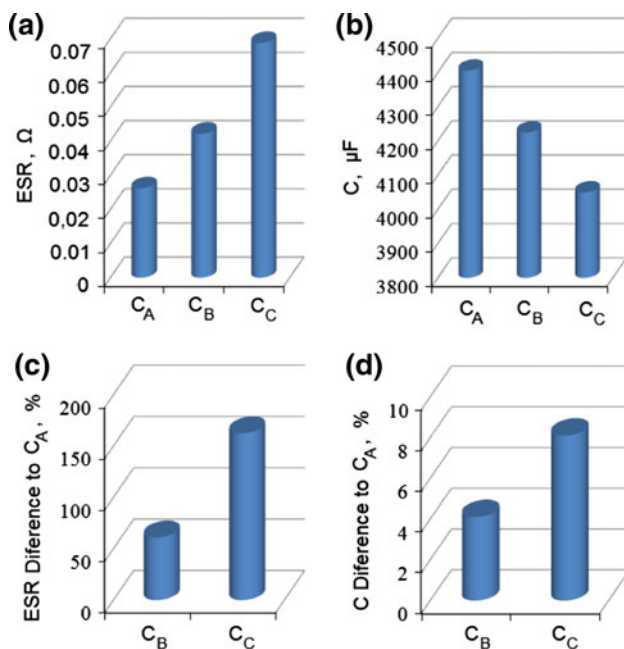


Fig. 11 Capacitors equivalent circuit obtained with the proposed technique: (a) ESR, (b) C, (c) ESR difference between the aged capacitors (C_B and C_C) and the sound one (C_A), and (d) C difference between the aged capacitors (C_B and C_C) and the sound one (C_A)

development of on-line fault diagnostic techniques is many times difficult, expensive, and complex.

Manufacturers define the end of life limit of a capacitor when its internal resistance doubles its initial value or the capacitance changes more than 20% when it is compared with the initial one.

The proposed technique evaluates the capacitor condition through the identification of both capacitor internal resistance and capacitance. To determine both values, the capacitor impedance values at different frequencies are computed using a digital multimeter. Afterwards, using the least mean squares algorithm it is possible to estimate the values of ESR and C that better fit the capacitor impedance.

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