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HAL Id: hal-00475767

https://hal.science/hal-00475767

Submitted on 23 Apr 2010

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Keywords

<<Industrial application>>, <<Uninterruptible Power Supplies (UPS)>>, <<Estimation technique>>, <<Maintenance>>, <<Real time processing>>.

Abstract

This paper presents a work used for a low cost method to create a real time condition monitoring and a predictive maintenance system of an electrolytic capacitor in Uninterrupted Power Supplies (UPS). It consists of evaluating the evolution laws for equivalent series resistance (ESR) and the capacitance C values of the electrolytic capacitors versus operating time. Experimental results of parameter evolutions and the law estimations are presented. The laws funded are used in UPS where waveforms are continuously varying in amplitude, frequency and versus temperature. The estimated laws are used for the on line failure prediction method which has the merits of using only the existent resources in UPS.

Introduction

Electrolytic capacitors have been widely used in power electronic systems because they can achieve high capacitance and voltage ratings with volumetric efficiency and low cost. This type of capacitors have been traditionally used for filtering, coupling, timing networks, by-pass and other many applications in power electronics requiring a cost effective and volumetric efficiency components. We know that the common faults in electrolytic capacitor include initial catastrophic failures due to manufacturing or mis-application defects, and wear-out faults which can't be avoid. Unfortunately, electrolytic capacitors are some of the weakest components in power electronic converters [1-12]. Many papers have proposed different methods or algorithms to determinate the ESR and/or capacitance C of the electrolytic capacitor [2-12]. However, many parameters such as additional measurements and many computations are required, which makes it complicated, difficult, expensive and impractical for actual application. Nowadays, a UPS disposes of many accurate sensors, numerical treatment systems and powerful computation

resources which are used to control and regulate the UPS in order to improve its performance and efficiency. The proposed method has the merits of making a real time predictive maintenance system of electrolytic capacitors with using existing resources in the UPS. This predictive maintenance system works in background task and without perturbing operating system. Also this document presents studying the ageing of electrolytic capacitors to determine the evolution laws of the internal parameters: equivalent series resistance (ESR) and capacitance (C). These evolution laws will be used for the ageing algorithm that will be integrated on DSP as a part study of the real time predictive maintenance system of aluminium electrolytic capacitors used in UPS [1]. This part of work is divided into two main steps to determine all the evolution laws versus temperature, frequency and operation time. First, the capacitors are characterized at different temperatures (-20 °C, 0 °C, 10 °C, 25 °C, 40 °C, 55 °C and 85 °C). This allows us to determine the evolution laws of ESR and C versus temperature. After, two standards ageing are launched at two different temperatures (85 °C and 90 °C). This type of ageing consists of supplying the components under nominal voltage (normally used on UPS) and the maximum operating temperature allowed with the use of a climatic chamber. This allows us to analyze the capacitors internal parameter behaviors versus operating time and determine the ageing laws of parameters ESR and C of each component. This paper presents the experimental results of temperature characterization and standard ageing at 90C after 3390 hours (about 5 months) of ageing for different types and manufacturers of electrolytic capacitors.

Electrolytic capacitors monitoring

Estimation of ESR and C

The electrolytic capacitors can be modelled as a series combination of a capacitance, inductance, and resistance as showing in Fig.1
As it can be observed from bode-plot in Fig. 2, there exists three widely separated frequency bands.

Figure 1: Electrical equivalent circuit of an aluminium electrolytic capacitor

Capacitance of the capacitor is dominant in low frequency band. ESL is dominant in high frequency band and ESR is dominant in the mid frequency band.
The resonant frequency of the capacitor is given by this equation.

$$f_r = \frac{1}{2.\pi.\sqrt{ESL.C}} \tag{1}$$

Therefore, generally converters in UPS works at low frequency band compared to the resonant frequency's one, so ESL is usually neglected and the equivalent model of the capacitor is RC series equivalent circuit.
The transfer function of this model is given by:

$$H(p) = \frac{Uc(s)}{Ic(s)} = \frac{ESR.C.s + 1}{C.s} \tag{2}$$

However, converters are controlled with using digital treatments; we consider the z-transform corresponding of Equation (2) to represent the discrete time domain with using the Tustin bilinear method which is given by the following equation (3).

$$H\left(z^{-1}\right) = \frac{b_0 + b_1.z^{-1}}{1 - z^{-1}}$$
$$= \frac{\left(ESR + \frac{Ts}{2.C}\right) + \left(\frac{Ts}{2.C} - ESR\right).z^{-1}}{1 - z^{-1}} \tag{3}$$

Ts is the sampling period.
The bode-plot in Fig.2 shows that the continuous and discrete time domains are equivalent if we use the bilinear method discrete time. Also, we can see the temperature change effect on the different parameters of the capacitor.
To identify b0 and b1 (cf. equation (3)), so the two parameters ESR and C, we use a least square algorithm.
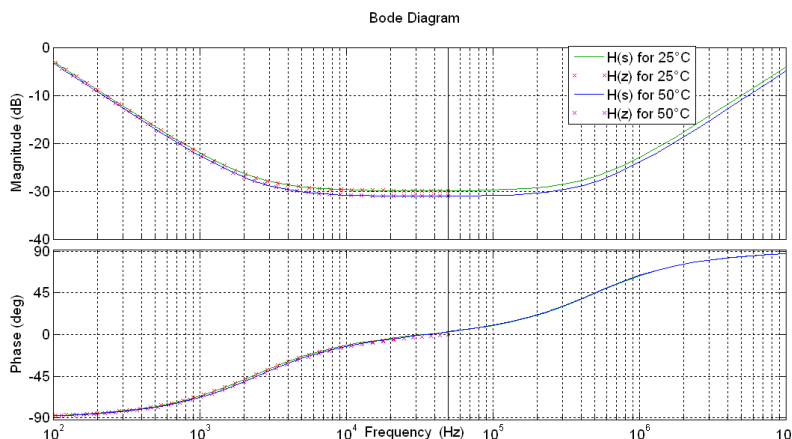
Figure 2: Bode-plot of electrolytic capacitor in continuous and discrete time domain

Compared to [1], this paper presents the implementation of the predictive maintenance system on an AC / DC converter. Also we discuss on this paper how to improve the precision identification of capacitor parameters (ESR and C). In fact, the identification of these two parameters is made separately by using simple frequency adjusting channel measurements needed to identify each of these two parameters.
A Matlab simulation was performed using dynamic equation from equivalent circuit shown in Fig. 3 of an AC/DC converter with 230V AC voltage input, for a switching frequency of 5 kHz and which is regulated to have 400V DC voltage output.
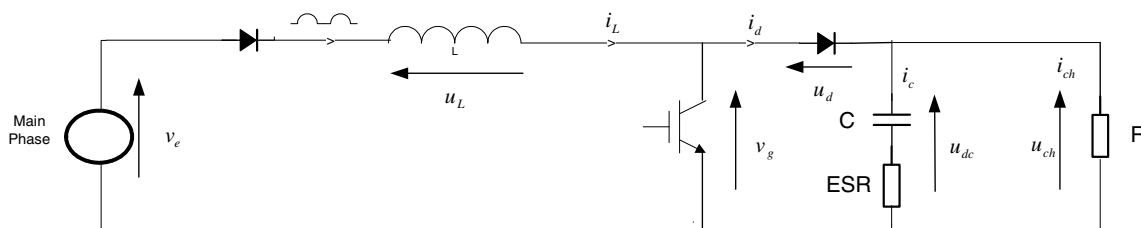 A Recursive Least Square algorithm which is a particular case of Kalman filters [14] was used.

Figure 3: Schematic of an AC/DC converter circuit with a DC capacitor circuit

In practice, we don't have a capacitor current sensor; because it's difficult and expansive to implement it in UPS. To perform and regulate the output voltage, we have only one current sensor used to measure the input inductance L current of the boost converter.
However, we can identify the capacitor current [1] with using Kirchhoff laws referencing to the schematic of a boost converter given in Fig. 3 and the PWM generated to control the converter.

$$i_c = \left(i_L . \overline{PWM}\right) - avg\left(i_L . \overline{PWM}\right) \tag{4}$$

Simulation results presented for the parameters identification are summarized in Table I.
The %Error presented on this table are the ones calculated between ESR and C values fixed on simulation and the estimated values given by the least square algorithm.

Table I: Simulation results for fixed parameters

	fixed	estimated	% error
ESR	32 mΩ	32.6 mΩ	0.2
C	2200 μF	2184 μF	0.7

Experimental study for online monitoring method

Experimental setup

To verify the validity of the proposed method, an experimental study was performed on an AC/DC converter with input AC voltage of 230 V, 2200 μF - 450 V filtering capacitor, an R-load of 100 Ω, a switching frequency of 5 kHz. Then a fixed point DSP controller (TMS320F2812) was used for i_L, u_c, i_c and capacitor ripple voltage ΔUc acquisition measurements and switching operations required to produce a 400 V DC output voltage. Moreover, a recursive least square algorithm (a particular case of Kalman filter) had been implemented to work in background task and to identify the two parameters ESR and C. As existing literature shows [13], we know that using different cases of Kalman filter provides centred input and output system measurements which are respectively capacitor current and capacitor voltage. Then, the capacitor voltage and the capacitor current are passed through a high-pass filter with cut-off frequency of around $f_c = 200\ Hz$ to suppress DC component of voltage measurements and without including phase shift. Consequently, we have only the capacitor ripple voltage which is in phase with capacitor current.
An FFT analysis respectively on the capacitor ripple voltage and capacitor current is made and we conclude that the bandwidth of the system is about 40 kHz, therefore and to respect Shannon theorem we choose a sampling frequency $f_s = 80\ kHz$.

To eliminate signal distortion anti-aliasing filters with a cut-off frequency of $f_c = \frac{f_s}{2} \approx 40kHz$ are used like showing in the global capacitor condition monitoring scheme Fig.4.
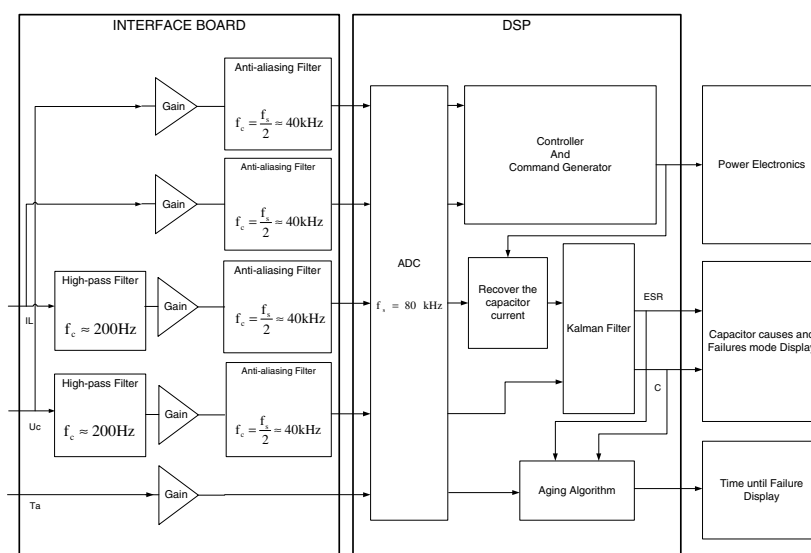

Figure 4: Real time electrolytic capacitor condition monitoring in UPS

Experimental results

Experimental results for online estimated parameters are summarized in Table II.
 The least square algorithm implemented on DSP to work in background task without perturbing operat-

Table II: Experimental results for estimated parameters

	actual	estimated[min, max]	% error
ESR	31.2 mΩ	[29.6 mΩ,32.5 mΩ]	$+/-5$
C	2200 μF	[2289μF, 2585μF]	$+/-6$

ing system use about 1K x 16bits of DSP memory and take about two seconds to converge and gives the ESR and C estimated values. This time is too small compared to the life time of a capacitor.
It can be seen that there is a small and less error between estimated and actual values of ESR and C compared to experimental results presented in[1] due to the fact that we identify the two parameters separately. These results are consistent with the measured value using an impedancemeter.

Ageing algorithm

Ageing laws

To deduce the number of hours before failure with knowing the ambient temperature measurement and the ESR and C values found in real time with the least square algorithm, we implement an ageing algorithm (Fig.4).
This algorithm uses the limit values to consider that the capacitor is at the end of life and which are fixed at:

- An increase of 100% of the ESR value compared to the initial one: $ESR_{limit}=2.ESR(0)$
- A decrease of 20% of the capacitance value compared to the initial one: $C_{limit} = 0.8.C(0)$

The parameters ESR and C depend on the inverter switching frequency and the ambient temperature.
The experimental tests carried out off-line and presented latter allow us to highlight the following laws:
Parameters evolutions versus temperature T' by knowing the ambient temperature: these laws allow us to determine the values of ESR (0) and C (0) using the following laws [15]:

$$ESR(0) = \alpha + \beta . \exp\left(\frac{-T'}{\gamma}\right) \tag{5}$$

$$C(0) = \chi + \lambda . T' \tag{6}$$

with α, β, χ and λ coefficients depend of type of capacitor.
The evolution curve parameters of experimental results allow us to determine the parameter evolution laws as a function of operating time (t_{op}) [15].

$$ESR\left(t_{op\_ESR}\right) = \left(ESR\left(0\right) + A_1\right) . \exp\left(B_1 . t_{op\_ESR}\right) \tag{7}$$

$$C\left(t_{op\_C}\right) = \left(E.C(0) + F.t_{op\_C}\right) \tag{8}$$

with A_1, B_1, E and F coefficients depend of type of capacitor.
From these evolution laws, we determine the ageing time (ta) corresponding to the two ageing temperatures (85 °C and 90 °C) using the following equations:

$$ta_{ESR} = \frac{\log\left(\frac{ESR_{limit}}{ESR(0) + A_1}\right)}{B_1} \tag{9}$$

$$ta_C = \frac{C_{limit} - E.C\left(0\right)}{F} \tag{10}$$

After having calculated the ageing time for two temperatures (85 °C and 90 °C for example), we calculate the activation energies (Ea_{ESR} and Ea_C) used in the Arrhenius law as follows:

$$Ea_{ESR} = k.\frac{\log\left(\frac{ta_{ESR(85°C)}}{ta_{ESR(90°C)}}\right)}{\frac{(90-85)}{(273+90).(273+85)}} \tag{11}$$

$$Ea_{ESR} = k.\frac{\log\left(\frac{ta_{ESR(85°C)}}{ta_{ESR(90°C)}}\right)}{\frac{(90-85)}{(273+90).(273+85)}} \tag{12}$$

ta_{ESR}: Ageing time corresponding to the ESR limit at T_a.
ta_C: Ageing time corresponding to the C limit at T_a.
k = Boltzmann constant (8,617.10^{-5} eV/°K).
Ea_{ESR}: Activation energy with taking into account ESR as an indicator of ageing.
Ea_C: Activation energy taking into account C as an indicator of ageing.
The procedure to determinate different laws and different parameters off-line is illustrated in Fig. 5 below:
 In real time and online, we have three values which are the equivalent series resistance (ESR), the capacitance (C) emerged by the identification algorithm and the ambient operating temperature T' (Fig.4).
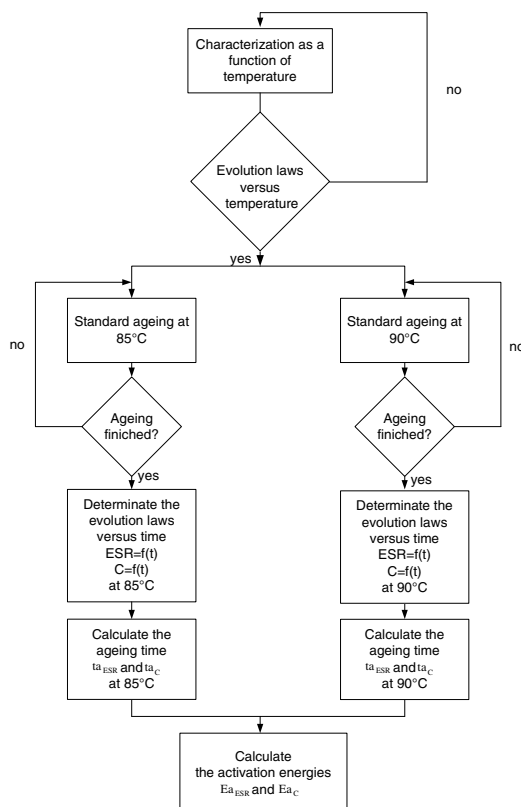
Figure 5: Off-line procedure to determinate the parameter evolution laws

The value of temperature T' allows us also to determine the time needed for the ageing with the use of following equations:13

$$t'_{ESR} = ta_{ESR}.\exp\left[\frac{Ea_{ESR}}{k} \cdot \frac{T_a - T'}{(T_a + 273).(T' + 273)}\right] \quad (13)$$

$$t'_C = ta_C.\exp\left[\frac{Ea_C}{k} \cdot \frac{T_a - T'}{(T_a + 273).(T' + 273)}\right] \quad (14)$$

T_a: Ageing temperature (85 °C for example).
T': Ambient temperature (25 °C for example).
T'_{ESR}: Extrapolated time at with ESR as an ageing indicator.
T'_C : Extrapolated time at with C as an ageing indicator.
The ESR and C values identified in real time and also the ESR (0) and C (0) will be used in the equations (9) and (10) to determine the respective operating time as shown in following equations:

$$t_{op\_ESR} = \frac{\log(\frac{ESR}{ESR(0)+A_1})}{B_1} \quad (15)$$

$$t_{op\_C} = \frac{C - E.C(0)}{F} \quad (16)$$

The time until failure $t_{failure}(ESR)$ with the use of equations (13) and (14) is given by:

$$t_{failure}(ESR) = \left(ta_{ESR}.\exp\left[\frac{Ea_{ESR}}{k} \cdot \frac{T_a - T'}{(T_a + 273).(T' + 273)}\right] - \frac{\log\left(\frac{ESR}{ESR(0)+A_1}\right)}{B_1}\right) \quad (17)$$

The figure below explains the different times given by equations (13), (15) and (17): The time until fail-
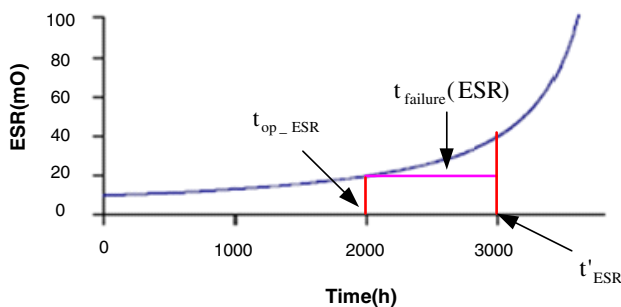
Figure 6: ESR evolution versus operating time

ure corresponding of the capacitance C with the use of equations (14) and (16) is given by:

$$t_{failure}(C) = \left(ta_C . \exp\left[\frac{Ea_C}{k} . \frac{T_a - T'}{(T_a + 273).(T' + 273)}\right] - \frac{C - E.(0)}{F}\right) \tag{18}$$

The capacitor time until failure is the less time between the two ones:

$$t_{failure} = Min(t_{failure}(ESR), t_{failure}(C)) \tag{19}$$

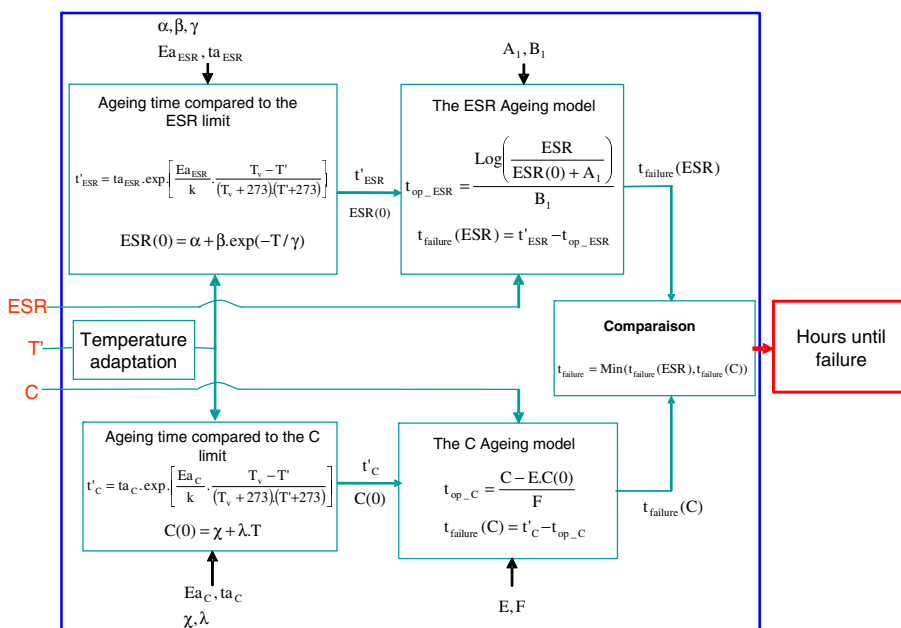The figure bellows shows the ageing algorithm used on line

Figure 7: Ageing algorithm

Experimental results used for ageing algorithm

We have for these work different types of capacitors according to four different manufacturers. For each one, we have 4 to 5 components indicated by the letters A, B ... Q and for each series we have 3 components of the same electrical characteristics with a capacitance tolerance of about ±20%.
Each component has an index of 1, 2 or 3 (e.g. A1, A2 and A3) since they have the same nominal capacitance and voltage.
All capacitors are first characterized versus temperature to determine the parameter evolution laws versus temperature (cf. figure 8 as example).
The parameters of the equation (4) are determined by the non-linear least squares method of Levenberg Marquardt which allows a very close approximation of the model.
For the example presented in Fig. 8, the method gives the following values:

$\alpha = 0.013055\Omega$ $\beta = 0.75844\Omega$ and $\gamma = 14.888386$ °C

The parameters of the equation (6) are determined in the same way as those identified in ESR. For the example presented in Fig.8, we have the following values:
$\chi = 0.000812$F $\lambda = 4,600790.10^{-0.007}$F/°C

The index 1 capacitors are used for the first ageing at 85 °C and those of index 3 are used for the ageing at 90 °C.
Some experimental results show the parameter evolutions of ESR and C after 3390 hours of ageing (about 5 months) for capacitors with index 3 (ageing at 90 °C).
Also we use a Matlab algorithm to make a linear interpolation and extrapolation with the use of experimental data. This allows us to find the parameters evolution laws and also the time until failure corresponding of ESR and the capacitance C limit like presented in Table III.
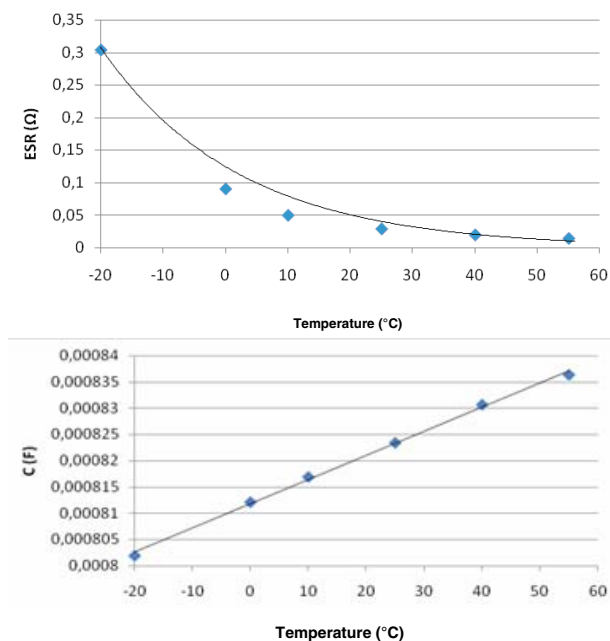The ESR and C variations versus temperature for a capacitor $1000\mu F$ / $450\ V$ are shown in Fig. 8.

Figure 8: Electric parameter variations versus temperature of one capacitor ($1000\mu F$ / $450\ V$)

We present bellow the interpolated and extrapolated data with the use of experimental measurements for ESR and C parameters of one capacitor ($1000\mu F$ / $450\ V$).
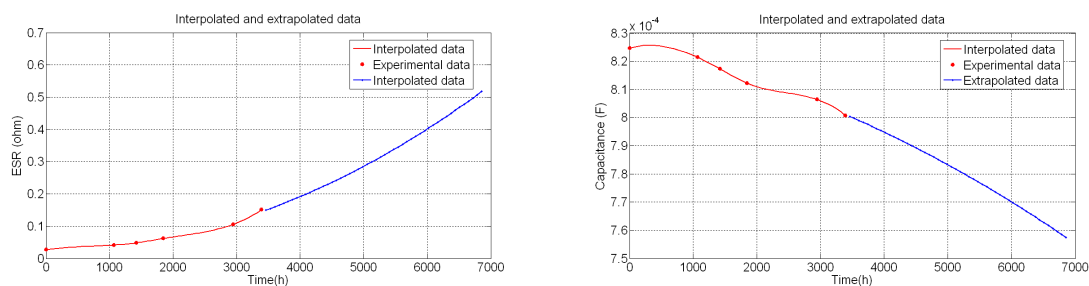

Figure 9: ESR evolution at 20 kHz and C evolution at 20 Hz for one capacitor($1000\mu F$ / $450\ V$)

Table III: Estimated ageing time compared to ESR and C limits for a capacitor($1000\mu F$ / $450\ V$)

Initial ESR(Ω)	ESR Limit=(2xInitial ESR)(Ω)	Ageing time(h)
0.0268	0.0536	1720
Initial Capacitance(μF)	Capacitance Limit=(0.8xInitial Capacitance)(μF)	Ageing time(h)
0.000824	0.000659	11913

Conclusion

Due to the large capacity and low cost, electrolytic capacitors capable of energy storage and voltage regulation are used for almost all types of power electronics system. Electrolytic capacitor, which is usually affected by wear-out faults, plays a very important role for the power-electronic systems quality and reliability. Therefore it is important to monitor the condition of an electrolytic capacitor in real-time to predict the failure. A new method is proposed to detect in real time the changes in ESR and capacitance C value of an electrolytic capacitor in order to realize a real-time failure prediction of an electrolytic capacitor. For the proposed method, capacitor current and capacitor ripple voltage measurements using cheap and simple analog circuits are required. Simulation results and hardware experimental implementation show that the proposed electrolytic capacitor failure-prediction technique can be applied to power-electronic systems successfully. Also, in continuation of our research and to improve the parameter estimation, we decide to implement adjustable gains used for the capacitor current and capacitor voltage measurements and which allow us to minimize the dynamic numerical errors.

In this paper, we have also presented the experimental results achieved on different electrolytic capacitors to find the different evolution laws of electrical parameters ESR and C as a function of temperature. Then we discussed the results of the ageing of these standard components to 90 °C after about 5 months of ageing. These results enabled us to compare the capacitors from different manufacturers and conclude on their quality. As perspective to our work, we will finish the ageing standard 85 °C to determine all the laws of ageing capacitors over time. The final objective is to determine these laws directly from well detailed data sheets provided by manufacturers without having to make these experimental tests used for each capacitor. These laws of evolution are used in the ageing algorithm implemented in real time to determine the remaining time before failure of electrolytic capacitors used in UPS.

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