Aging laws of electrolytic capacitors

Antoine EL HAYEK[1,2], Pascal VENET[1], Radoslava MITOVA[2], Miao-xin WANG[2], Guy CLERC[1], Ali SARI[1]

[1]Université de Lyon – Ampère (CNRS UMR 5005, Ecole Centrale de Lyon, INSA-Lyon, Université Claude Bernard Lyon 1)
Bâtiment Oméga – 43, Boulevard du 11 Novembre 1918
69100, Villeurbanne, France

[2]Schneider Electric – Power Conversion – Industry Business
38TEC – 37, quai Paul Louis Merlin
38000 Grenoble, France
Email: antoine.elhayek@schneider-electric.com

Abstract

Many techniques deal with life forecast and failure detection of aluminum electrolytic capacitors which are utilized as a part of power electronic converters. The main idea of these techniques is to estimate the values of Equivalent Series Resistance (ESR) and Capacitance (C). Observing the ESR and C values changes of an electrolytic capacitor can provide its remaining useful life. The drawback of these methods is that they all need a prior offline phase to construct the ageing model before being able to estimate the RUL (Remaining Useful Lifetime) of the capacitor. We are working on a method that gives an estimate of the RUL without the need of the offline phase. This, nonetheless, requires the knowledge of the shape of aging laws. The parameters of the laws will be determined automatically online. In order to know the shape of these laws, accelerated aging tests are set up to test the effect of the operational conditions (temperature, voltage, current) on the aging of the capacitor. Early results show that a cubic regression has the best fit with the experimental aging data.

Keywords— Electrolytic capacitors, accelerated ageing test, aging law, health monitoring, predictive maintenance.

I. Introduction

Because of their high capacitance and voltage ratings with their cost-effective and volumetric efficiency, electrolytic capacitors have been widely used in power-electronic systems. However, this type of capacitors are one of the weakest components in power-electronic converter [1], [2]. Electrolytic capacitors are used for filtering, coupling and many other applications in power electronics. Nowadays, systemic preventive maintenance is used in many companies; the capacitors are being replaced every 5 to 7 years. In several cases, Schneider Electric SA analyzed the replaced capacitors and the results showed that these capacitors are far from being actually aged. Thus, a better maintenance may be required: a predictive maintenance.

An electrolytic capacitor has several failure modes and causes. Electrical, thermal, mechanical, and environmental stresses cause the degradation of this component. The main failure mechanism is the evaporation of the electrolyte, which is accelerated with temperature rise during the operation, mainly due to ripple currents. This causes a decrease of capacitance (C) and an increase of the equivalent series resistance (ESR) which further increase the losses and, consequently, the temperature. The authors in [3]–[5] suggest that the capacitor should be considered as failed if the ESR value doubles from its initial value and the capacitance value decreases by 20%.

Therefore, it is critical, in a predictive maintenance, to monitor the conditions (temperature, ripple current and voltage) of electrolytic capacitors in order to estimate the ESR and the capacitance evolution of the electrolytic capacitor.

The purpose of this paper is to expose the previous works and methods done to achieve a real-time predictive system of electrolytic-capacitor failures. Then, after showing their disadvantages, a new method that estimate the remaining useful lifetime of the capacitors will be announced. The method requires knowledge of the shape of aging laws. The parameters of these laws will be automatically determined online. In order to know the shape of aging laws, accelerated aging tests were carried out. This paper presents the early results obtained from these aging tests.

II. Predictive Maintenance

1. Previous Works

Many papers have proposed different methods or algorithms that determine the ESR and/or C of the electrolytic capacitor [3], [6]–[8]. However, many offline measurements, and many computations and hardware are required, which makes them complicated, expensive, and unsuitable for industrial application. For instance, in order to estimate the RUL (Remaining Useful Lifetime) in the predictive-maintenance system, ageing models of ESR and C must be constructed. The ageing models of these indicators are constructed offline ([7]–[9]). These models are created through accelerated ageing tests that are time consuming. And it should also be noted that the ageing models constructed are dependent of the version of the capacitor. Thus, every time, a new version of capacitor is used, the accelerated ageing tests should be run again to get the new ageing models.

The objective is to generate parametrized models of the time-dependent ESR(t) and C(t) called aging laws. Parameters of these laws are identified offline in previous works. These parameters will be identified online in our work. Thus, the long and expensive accelerated tests could be bypassed in order to get the degradation models.

2. Proposed Work

With the advance of new technologies, uninterruptible power supply (UPS) can use a variety of accurate sensors, numerical treatment systems, and powerful computation resources thanks to the cloud computing. These features can be used not only for the control of the UPS (in order to improve its performance and efficiency) but also for predictive maintenance system. The suggested method makes a real-time predictive-maintenance system of electrolytic capacitors by using existing resources in the UPS. This method can detect, in real time, the changes in the value of the ESR and C, even in nonstationary systems, such as UPS, where ambient temperature, capacitor ripple voltage and current are continuously varying, and construct the aging model online. Our method requires a lifetime model as well as the aging law shape. Thus, in this paper, the lifetime estimation model used will be presented. The experimental setup used to identify the aging law shape of the indicators as well as the early results will also be discussed in this paper

III. Lifetime Model

The lifetime of electrolytic capacitors is largely dependent on the application conditions: environmental factors (temperature, humidity and vibrations), as well as electrical factors (operating voltage, ripple current and charge-discharge). When the capacitors are used for filtering purpose, ambient temperature and heating due to the ripple current are crucial factors for determining the lifetime of the capacitors. Therefore, the major factors affecting the lifetime of electrolytic capacitors in the power applications will be the operating temperature, the ripple current and the operating voltage. Other factors have minor affect to the lifetime and can be ignored in the calculation.

1. Influence of temperature on the lifetime model

The Arrhenius life-stress model is probably the most common life-stress relationship utilized when the stimulus or acceleration variable (or stress) is temperature. The lifetime of electrolytic capacitors follows the equation derived from Arrhenius law (1) [10].

$$L_x = L_0 . e^{\frac{E_a}{k}\left(\frac{1}{T_x} - \frac{1}{T_0}\right)} \tag{1}$$

Symbols	Parameters
L_0	Specified lifetime (hour) with the rated ripple current and the rated voltage applied at the upper limit of the operating temperature. Refer to the lifetime specifications datasheets of individual products.
L_x	Estimated life on actual usage (hour)
T_0	Maximum category temperature (K)
T_x	Actual ambient temperature (K)
E_a	Activation energy
k	Boltzmann constant

From equation (1) due to further analysis of the complete lifetime model, we will define the temperature factor with the following formula:

$$K_T = e^{\frac{E_a}{k}\left(\frac{1}{T_x} - \frac{1}{T_0}\right)} \tag{2}$$

Such as:

$$L_x = L_0 . K_{\mathrm{T}} \tag{3}$$

2. Influence of ripple current on the lifetime model

The ripple current causes power dissipation and heating. The capacitor produces more internal heat when a ripple current flows through it. The temperature rise due to this heat may significantly shorten the lifetime of the capacitor. Power consumption by the ripple current can be expressed as follows:

$$P = ESR . I_{RMSx}^2 \tag{4}$$

Symbols	Parameters
P	Internal power dissipation
I_{RMS}	RMS current
ESR	Equivalent series resistance at a given temperature

The core temperature, at which equilibrium is achieved between heat generation and dissipation, derive from equation:

$$ESR . I_{RMS}^2 = \frac{\Delta T}{\mathcal{R}_{th}} \tag{5}$$

Symbols	Parameters
$\mathcal{R}_{th}$	Thermal resistance
ΔT	Temperature rise due to RMS current

An approximate equation between temperature rise and ripple current can be calculated using the equation:

$$\frac{\Delta T_x}{\Delta T_0} = \frac{\mathcal{R}_{th} . ESR . I_{RMSx}^2}{\mathcal{R}_{th} . ESR . I_{RMS0}^2} = \left(\frac{I_{RMSx}}{I_{RMS0}}\right)^2 \tag{6}$$

Symbols	Parameters
I_{RMSx}	Operating RMS current flowing in capacitor
I_{RMS0}	Rated RMS current of capacitor

ΔT_0	Rise in internal temperature due to the rated RMS current ([K-273] °C)
ΔT_x	Rise in internal temperature due to the actual RMS current ([K-273] °C)

The impact of the applied ripple current on the temperature rise and on the electrolytic capacitor's lifetime can be expressed with the use of Arrhenius law by:

$$L_x = L_0 . e^{\frac{E_a}{k}\left(\frac{1}{273+\Delta T_x} - \frac{1}{273+\Delta T_0}\right)} \tag{7}$$

Then we factor out the [°C to K; 273] constant:

$$L_x = L_0 . e^{\frac{E_a}{k.273}\left(\frac{1}{1+\frac{\Delta T_x}{273}} - \frac{1}{1+\frac{\Delta T_0}{273}}\right)} \tag{8}$$

For the term within the exponential, a linear approximation around the zero of the variables ΔT_x and ΔT_0 (first-order Taylor series approximation) gives the following approximation:

$$\frac{E_a}{k.273}\left(\frac{1}{1+\frac{\Delta T_x}{273}} - \frac{1}{1+\frac{\Delta T_0}{273}}\right) \approx \frac{E_a}{k.273}\left(\left(1-\frac{\Delta T_x}{273}\right) - \left(1-\frac{\Delta T_0}{273}\right)\right) \tag{9}$$

Taking into account this change of variables and this approximation, the lifetime equation can then be written in the following form:

$$L_x = L_0 . e^{\frac{E_a}{k.273}\left(1-\frac{\Delta T_x}{273} - 1 + \frac{\Delta T_0}{273}\right)} \tag{10}$$

After factoring equation (10), we get:

$$L_x = L_0 . e^{\frac{E_a}{k.273^2}(\Delta T_0 - \Delta T_x)} \tag{11}$$

If we replace $\frac{E_a}{k.273^2}$ by a constant $\frac{1}{M}$ and $(\Delta T_0 - \Delta T_x)$ by Δx we get:

$$L_x = L_0 . e^{\frac{\Delta x}{M}} \tag{12}$$

This equation makes it possible to express an empirical concept often used for storage components such as electrolytic capacitors: a system whose lifetime is divided by 2 for any increase of 10 ° C. Such a tendency is respected only if the constant is chosen such that:

For $\Delta x = 10°C$, $e^{\frac{\Delta x}{M}} = \frac{1}{2}$ implies that $M = \frac{10}{\ln(2)}$

Replacing the constant M by its empirical tendency gives the following simplified equation:

$$L_x = L_0 . 2^{\frac{1}{10}(\Delta T_0 - \Delta T_x)} \tag{13}$$

An industrial well-established version of this equation is as follows:

$$L_x = L_0 . K_r^{\frac{1}{10}(\Delta T_0 - \Delta T_x)} \tag{14}$$

Where K_r is an empirical safety factor [11], [12]:

- $K_r = 2\ if\ I_{RMSx} \leq I_{RMS0}$
- $K_r = 4\ if\ I_{RMSx} > I_{RMS0}$ (in this case lifetime is divided by 4)

By factoring ΔT_0 and replacing the term $\frac{\Delta T}{\Delta T_0}$ with equation (6), we obtain the following formula of ripple current factor [11], [12]:

$$K_I = K_r^{\left(1-\left(\frac{I_{RMSx}}{I_{RMS0}}\right)^2\right)\frac{\Delta T_0}{10}} \tag{15}$$

Such as:

$$L_x = L_0.K_I \tag{16}$$

3. Influence of voltage on the lifetime model

For medium and large sizes electrolytic capacitors, the applied voltage can affect their lifetime, because operating voltages cause stress to the dielectric layer. The closer the operating voltage approaches the rated voltage, the more the ions in the electrolyte are consumed for the healing of small flaws within the dielectric layer called self-healing. Thus, an operating voltage lower than the rated can extend the lifetime of capacitors. In practice, operating voltages are higher than the half of the rated voltage and therefore only they are covered by the proposed lifetime estimation model. The voltage factor can be expressed as follows [13]:

$$K_V = \left(\frac{V_0}{V_x}\right)^n \tag{17}$$

Such as:

$$L_x = L_0.K_V \tag{18}$$

Symbols	Parameters
V_x	Actual operating voltage
V_0	Rated voltage

and n is fixed by the following conditions:

$$\begin{gathered} 0.5 \leq \frac{V_0}{V_x} \leq 0.8 \ \rightarrow n = 3 \\ 0.8 < \frac{V_0}{V_x} \leq 1 \ \rightarrow n = 5 \end{gathered} \tag{19}$$

Note: for smaller size radial electrolytic capacitors, voltage coefficient $K_V = 1$.

4. Lifetime estimation model for electrolytic capacitors

The complete equation of the lifetime estimation model for electrolytic capacitors is based on previous described factors. The final formula with the previously defined factors can be expressed as following [4], [11], [13]:

$$L_x = L_0 . K_T . K_I . K_V \tag{20}$$

Note: this lifetime model can be derived from Eyring model which generalize the Arrhenius law to integrate multiple stresses (other than the temperature) in the calculation of the degradation rate [14]. The model for temperature and two additional stresses takes the general form:

$$L = A . T^{\alpha} e^{\left[\frac{E_a}{kT} + \left(B + \frac{C}{T}\right) S_1 + \left(D + \frac{E}{T}\right) S_2\right]} \tag{21}$$

Symbols	Parameters
A	Constant related to the specific process being modeled
T	Absolute temperature (K)
α, B, C, D, E	Acceleration and interaction constants
S_1, S_2	Stresses; functions of current and voltage in this case of study

In our application, there no correlation between absolute temperature and the current or voltage stresses, thus $\alpha, C, E = 0$. The lifetime estimation model derived from (21) will be as following:

$$\frac{L_x}{L_0} = \frac{A . e^{\left[\frac{E_a}{kT_x} + B . S_{1x} + D . S_{2x}\right]}}{A . e^{\left[\frac{E_a}{kT_0} + B . S_{1o} + D . S_{2o}\right]}}$$

$$= e^{\frac{E_a}{k}\left(\frac{1}{T_x} - \frac{1}{T_0}\right)} e^{B(S_{1x} - S_{1o})} e^{D(S_{2x} - S_{2o})} \tag{22}$$

In order to fit equation (22) to the final formula of (20) describing the aging process of our application, the parameters $B, S_{1x}, S_{10}, D, S_{2x}, S_{2o}$ are identified and resumed in the Table 1 below.

$$e^{B(S_{1x} - S_{1o})} = K_r^{\frac{1}{10}(\Delta T_0 - \Delta T_x)}$$

$$e^{D(S_{2x} - S_{2o})} = \left(\frac{V_0}{V_x}\right)^n \tag{23}$$

Symbols	Identified parameter
B	$-\frac{ln(K_r)}{10}$
S_{1x}	ΔT_x
S_{1o}	ΔT_0
D	$-n$
S_{2x}	$ln(V_x)$
S_{2o}	$ln(V_0)$

Table 1 Identified constants and stresses

Replacing the terms identified in equation (21), we get:

$$L = A.e^{\left[\frac{E_a}{kT} - \frac{ln(K_r)}{10}\Delta T - n.ln(V)\right]} \tag{24}$$

IV. Experimental Setup

In order to know the shape of aging laws, accelerated aging tests are done in our work to assess the effects of the degradation process through time on real electrolytic capacitors. These tests apply thermal and electrical overstresses to commercial capacitors, in order to observe and record the degradation process and identify performance conditions until the failure criteria is reached in a considerably reduced time frame. The values of the stresses are chosen depending on the upper limit specifications of the capacitor under test. Two capacitor manufacturers are chosen for our tests to study the effect of different manufacturing processes on the degradation models. Based on Schneider industry UPS applications, two types of capacitors, with parameters shown in Table 2, were selected.

Items	Manufacturer A and B
Capacitance (±20%)	390 µF
Operating temperature range	-25 / 85 °C
Rated voltage	500 V
Rated ripple current (at 120 Hz)	2.3 A
Max leakage current (500V, 5min, 20°C)	1.5 mA

Table 2 Parameters of the selected capacitors found in their datasheets

A total of 47 capacitors under test are used for this accelerated aging study. Measurements using an impedancemeter are done periodically during the accelerated aging test to characterize the frequency response of the capacitor's impedance. Measurement of leakage current and physical degradation (weight loss, volume gain…) are also made.

A table of the actual experiments setup is presented in Table 3.

Test type	# Test	Temperature	Voltage	Effective current	Freq.	Nb Cap
Floating	f(85 ; 0)	85°C	0 V	0 A	0 Hz	3 manufacturer A 3 manufacturer B
	f(85 ; 500)	85°C	500 V	0 A	0 Hz	3 manufacturer A 3 manufacturer B
	f(75 ; 500)	75°C	500 V	0 A	0 Hz	3 manufacturer A 3 manufacturer B
	f(95 ; 500)	95°C	500 V	0 A	0 Hz	3 manufacturer A 3 manufacturer B
	f(85 ; 400)	85°C	400V	0 A	0 Hz	3 manufacturer A 3 manufacturer B
	f(95 ; 400)	95°C	400V	0 A	0 Hz	2 manufacturer A 3 manufacturer B
Ripple current	c(85 ; 500)	85°C	500 V	2,3 A	120 Hz	6 manufacturer A 6 manufacturer B

Table 3 Experimental plan of the accelerated ageing tests

Seven tests are run simultaneously. With these tests, aging law shapes will be extracted. This will also allow a better understanding of the effect of different conditions on the aging of the capacitors. While similar experiments applying voltage at different temperatures were already performed in previous studies [7], [8], [15]–[17] , the test labeled c(85 ; 500) including ripple current is more original. The latter emulates the filtering function of the capacitors in the UPS application. The test was neglected in the previous works because it was assumed that the ripple current only induces an overall temperature rise. To verify this assumption, thermo-couples were added to the core and the surface of some capacitors. A 10°C rise of core temperature was observed. So, test f(95 ; 500) was added to study and compare the effect of the ripple current and the overheating.

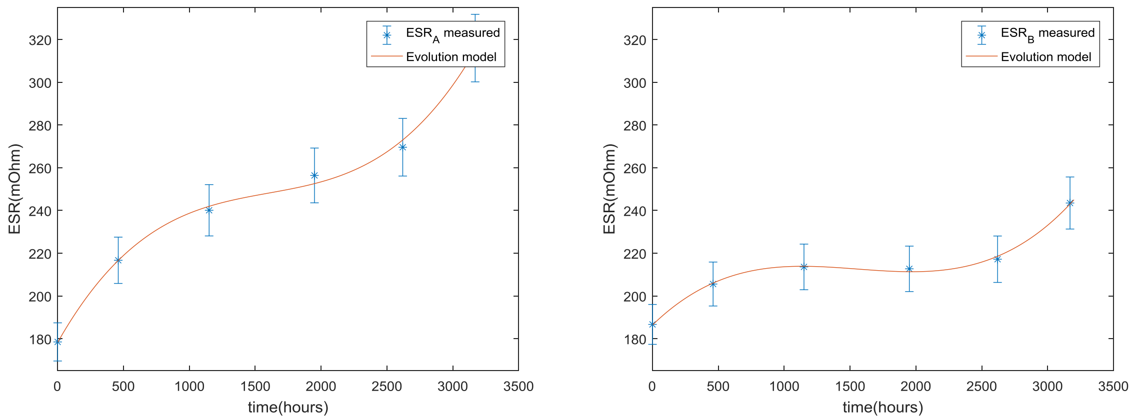
V. Experimental Results and Analysis

1. Aging shape of the indicators

After 5 months (3200 hours of aging) of launching the accelerated aging test, 6 measurements showing the evolution of ESR and C are already available. All the data collected were analyzed to observe how ESR and C were changing over the period of time. The tests are still running until at least the end of life criteria are reached (ESR value doubles or C value decreases by 20%).

In this paper, we are going to present the results obtained after 3200 hours of operation in the test c(85 ; 500). Since six capacitors per manufacturer were subjected to similar conditions of temperature, input voltage and ripple current, we averaged the collected data.

Figure 1 shows the plot for the average increase in the ESR values for all the six capacitors per manufacturer for the experimental period.

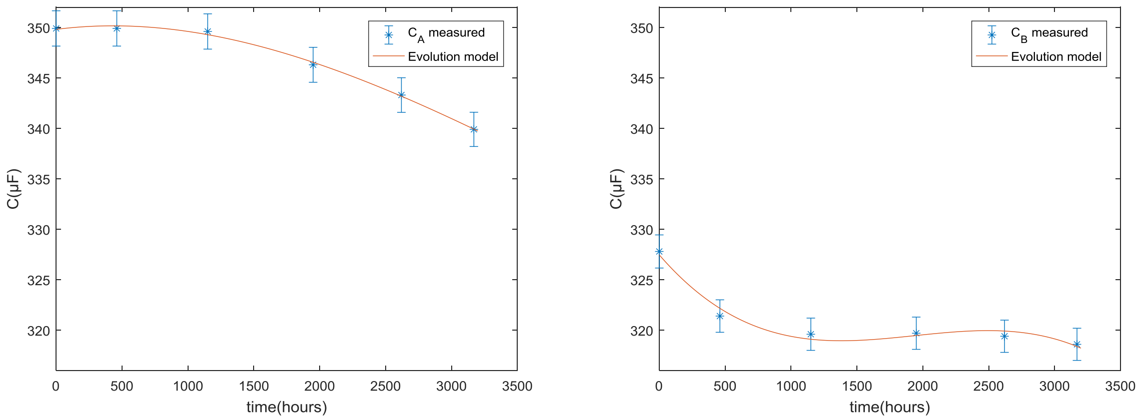


(a) manufacturer A *(b) manufacturer B*

Figure 2 Evolution of ESR with time – test c(85 ; 500)

At the end of 3200 hours of operation, the average capacitors ESR value for manufacturer A has increased by approximately 77% of the initial value and by 30% for manufacturer B.

Figure 3 shows the plot for the average decrease in the C values for all the six capacitors per manufacturer for the experimental period.



(a) manufacturer A *(b) manufacturer B*

Figure 4 Evolution of C with time – test c(85 ; 500)

At the end of 3200 hours of operation, the average capacitor C value for manufacturer A has decreased by approximately 2.9% of the initial value and by 3% for manufacturer B.

At present, all the experiments are still in progress and the parameters are being monitored to observe further degradation phenomena.

While the literatures [17], [18] show an exponential evolution of ESR and a linear evolution of C, our experiments are revealing a nonlinear evolution for both ESR and C. Implementing a curve fitting for the data, we can then use the equations for approximate evolution of the indicators. A quadratic fit (second order), cubic fit (third order) and exponential fit were done for the average ESR and C data. From the least squares calculation, we found that the cubic fit matched the experimental data in the best manner. The general form for the degradation data approximation is:

$$y = a + bt + ct^2 + dt^3 \tag{25}$$

Symbols	Parameters
y	ESR or C value at time t
t	Time in hours

The equations of the degradation models of the indicators ESR and C of the capacitors from manufacturers A and B (shown in Figure 5 and 6) are given below:

$$\begin{gathered} ESR_A(t) = 178 + 0.11t - 6.1e^{-5}t^2 + 1.3e^{-8}t^3 \\ ESR_B(t) = 186 + 0.06t - 4.2e^{-5}t^2 + 0.9e^{-8}t^3 \\ C_A(t) = 350 + 1.7e^{-3}t - 2e^{-6}t^2 + 1.7e^{-10}t^3 \\ C_B(t) = 327 - 15.1e^{-3}t + 8.5e^{-6}t^2 - 1.5e^{-9}t^3 \end{gathered} \tag{26}$$

Since the capacitor has not reached its end of life, perhaps, the overall shape will change and another fitting curve will be adopted.

2. Validation of the lifetime model acceleration factor

To validate the influence of temperature on the lifetime of the capacitors, tests f(85 ; 500) and f(75 ; 500) are given to make a comparison. The value of C for manufacturer B at 2200 hour for test f(75 ; 500) go through the same value of C at 1400 hour for test f(85 ; 500). By replacing the value of L_x by 2200h, L_0 by 1400h, T_x by 348K and T_0 by 358K in equation (1), we obtain $E_a$equals to 0.485 eV. The aging of 500 capacitors for the period of 10000 hours done by Rhoades [19] gave an $E_a$value equal to 0.405 eV. The value of E_a obtained from our aging tests validates the temperature life-stress model.

To validate the influence of ripple current on the lifetime of the capacitors, tests f(85 ; 500) and c(85 ; 500) are compared. The value of C for manufacturer B at 2200 hour for test f(85 ; 500) go through the same value of C at 1150 hour for test c(85 ; 500). By replacing the value of L_x by 2200h, L_0 by 1150h, I_{RMSx} by 0 A and I_{RMS0} by 2.3A in equations (14) and (15), we obtain K_r equals to 1.9 wich is so close to the empirical value of K_r ($K_r = 2\ if\ I_{RMSx} \leq I_{RMS0}$).

No major difference of the capacitor lifetime was observed until now between tests f(85 ; 500) and f(85 ; 400). The voltage has apprently little effect on the lifetime of the capacitors. It is probably because the capacitors under test have small size case. Thus, the voltage coefficient $K_V = 1$. Yet, nothing is conclusive because tests f(85 ; 400) was lauched not long ago.

Factor/lifetime model	Empirical value	Identified value
$L_x = L_0 . e^{\frac{E_a}{k}\left(\frac{T_0 - T_x}{T_0 T_x}\right)}$	$E_a = 0.405\ eV$	$E_a = 0.485\ eV$
$L_x = L_0 . K_r^{\left(1-\left(\frac{I_{RMSx}}{I_{RMS0}}\right)^2\right)\frac{\Delta T_0}{10}}$	$K_r = 2$	$K_r = 1.9$
$L_x = L_x . K_V$	$K_V = 1$	$K_V \approx 1$

Table 4 Empirical VS estimated parameters

V. Conclusion

The present work shows the ESR and capacitance of the electrolytic capacitor as ageing indicators. It also shows how previous works intended to use these indicators to predict the lifetime. The disadvantages of the offline step in these works made it crucial to rethink a new 100% online method. This method will identify the coefficient parameters of the aging laws shapes. The final aging laws shapes are chosen after the end of the accelerated aging tests. Major factors influencing lifetime of electrolytic capacitors used in power converters were also described. Results will allow us to perform a lifetime expectancy of the electrolytic capacitor in any application (various operating conditions).

References

[1] U. S. of A. D. of Defense, *Military Handbook: Reliability Prediction of Electronic Equipment: MIL-HDBK-217F: 2 December 1991*. Department of defense, 1991.

[2] S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, et P. Tavner, « An industry-based survey of reliability in power electronic converters », in *2009 IEEE Energy Conversion Congress and Exposition*, 2009, p. 3151‑3157.

[3] P. Venet, H. Darnand, et G. Grellet, « Detection of faults of filter capacitors in a converter. Application to predictive maintenance », in *Proceedings of Intelec 93: 15th International Telecommunications Energy Conference*, 1993, vol. 2, p. 229‑234 vol.2.

[4] N. Chemi-con, « Aluminum capacitors catalogue-Technical note on judicious use of aluminum electrolytic capacitors, 2013 », *Online Httpwww Chemi-Con Com2013AluminumElectrolyticCatalog Pdf*.

[5] A. EPCOS, *Aluminum Electrolytic Capacitors-General technical information, Application Note*. 2009.

[6] K.-W. Lee, M. Kim, J. Yoon, S. B. Lee, et J.-Y. Yoo, « Condition monitoring of DC-link electrolytic capacitors in adjustable-speed drives », *IEEE Trans. Ind. Appl.*, vol. 44, n° 5, p. 1606–1613, 2008.

[7] J. R. Celaya, C. Kulkarni, S. Saha, G. Biswas, et K. Goebel, « Accelerated aging in electrolytic capacitors for prognostics », in *2012 Proceedings Annual Reliability and Maintainability Symposium*, 2012, p. 1‑6.

[8] K. Abdennadher, P. Venet, G. Rojat, J.-M. Rétif, et C. Rosset, « A real-time predictive-maintenance system of aluminum electrolytic capacitors used in uninterrupted power supplies », *IEEE Trans. Ind. Appl.*, vol. 46, n° 4, p. 1644–1652, 2010.

[9] P. Venet, F. Perisse, M. H. El-Husseini, et G. Rojat, « Realization of a smart electrolytic capacitor circuit », *IEEE Ind. Appl. Mag.*, vol. 8, nº 1, p. 16‑20, janv. 2002.

[10] W. Nelson, « Analysis of Accelerated Life Test Data - Part I: The Arrhenius Model and Graphical Methods », *IEEE Trans. Electr. Insul.*, vol. EI-6, nº 4, p. 165‑181, déc. 1971.

[11] A. R. Khandebharad, R. B. Dhumale, S. S. Lokhande, et S. D. Lokhande, « Real time remaining useful life prediction of the electrolytic capacitor », in *2015 International Conference on Information Processing (ICIP)*, 2015, p. 631‑636.

[12] P. Spanik, M. Frivaldsky, et A. Kanovsky, « Life time of the electrolytic capacitors in power applications », in *2014 ELEKTRO*, 2014, p. 233‑238.

[13] A. Albertsen, « Electrolytic capacitor lifetime estimation », *Jianghai Eur. GmbH*, 2010.

[14] H. S. Endicott, B. D. Hatch, et R. G. Sohmer, « Application of the Eyring Model to capacitor aging data », in *Annual Report 1962 Conference on Electrical Insulation*, 1962, p. 47‑50.

[15] R. Cousseau, « Contribution à la modélisation et à l'étude du vieillissement des condensateurs électrolytiques aluminium dédiés à des applications à hautes températures », PhD Thesis, Université de Technologie de Compiègne, 2015.

[16] F. Salameh, A. Picot, M. Chabert, E. Leconte, A. Ruiz-Gazen, et P. Maussion, « Variable importance assessment in lifespan models of insulation materials: A comparative study », in *2015 IEEE 10th International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*, 2015, p. 198‑204.

[17] F. Perisse, « Etude et analyse des modes de défaillances des condensateurs électrolytiques à l'aluminium et des thyristors, appliquées au système de protection du LHC (Large Hadron Collider) », PhD Thesis, Université Claude Bernard-Lyon I, 2003.

[18] K. Abdennadher, « Etude et Elaboration d'un système de Maintenance Prédictive Pour les condensateurs et les Batteries Utilisés dans les Alimentations sans Interruptions (ASI) », PhD Thesis, PhD thesis, Universite de LYON 1, 2010.

[19] G. E. Rhoades et A. W. H. Smith, « Expected life of capacitors with nonsolid electrolyte », in *34th Component Conf. Proc*, 1984, p. 156–161.