CHEMICAL ENGINEERING TRANSACTIONS
VOL. 33, 2013
Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1333185

Health Monitoring of DC link Capacitors

Maawad Makdessi*, Ali Sari, Pascal Venet

Laboratoire Ampère UMR 5005 CNRS, Université Claude Bernard - Lyon 1, 69622 Villeurbanne Cedex, France
maawad.makdessi@univ-lyon1.fr

Electrolytic and metallized polypropylene film (MPPF) capacitors are among the most popular capacitors used in electronic equipments. The choice of capacitors is of major importance because one of the most frequent causes of the equipment breakdowns results from the failure of capacitors, and will therefore determine the overall lifetime of the system. Electrolytic capacitors present higher capacity per volume unit and lower cost than MPPF capacitors; however, they appear as the most life-limiting components exhibiting a high failure rate. MPPF are a good alternative to electrolytic capacitors thanks to their high dielectric breakdown strengths, low dissipation factors and good stability over a wide range of frequencies and temperatures. Even though MPPF capacitors are very reliable components due to their unique self-healing capability, they are not free of failures and they release noxious gases in this case. Therefore, suitable diagnostic techniques are needed to prevent catastrophic failures. The typical failure mode of electrolytic and polypropylene film capacitors lays on the increase of the capacitor Equivalent Series Resistance (ESR) and the decrease of its capacitance. This paper presents an approach for the monitoring of the capacitor's electrical parameters in function of the ageing time when used as DC-link capacitors. A comparison between the film and electrolytic technologies will be also made in this paper.

1. Introduction

Capacitors are one of the key components in power electronics equipments; their use extends over wide domains of applications and reaches the most critical operating systems. Electrolytic capacitors (EC) assume a special position among the various types of capacitors since their principle of operation relies, in part, on electrochemical processes. This structure, despite being sensitive to frequency and temperature variations, provides electrolytic capacitors higher capacitance values, higher volumetric efficiency and an excellent price over performance ratio (Joubert et al., 2007). Therefore, EC becomes the usual and the best choice for low-frequency applications such as in power supply filters. Metallized polypropylene films (MPPF) capacitors on the other hand, in view of their good dielectric breakdown strengths, low dissipation factors and good stability over a wide range of frequencies and temperatures, becomes the preferred polymer materials for capacitive energy storage-devices. They proved to be more reliable components than EC thanks to their unique self-healing proprieties and are favored for high voltage applications and applications where high capacitances are not required such as in high frequency filtering, snubbers and resonant circuits.
However, capacitors, whether belonging to electrolytic or metallized films technologies, remain one of the most unreliable components since they are responsible of more than 30 % of the equipments breakdowns (Venet et al., 1999). Health monitoring of these passive components becomes of paramount importance; a good acquaintance of their deterioration over time would enable us to perform a predictive maintenance on the component and thus to improve the availability of the whole system.
The object of the present paper is to focus on the monitoring of both electrolytic and MPPF capacitors when used as DC-link capacitors. This operation, through adequate measurements and techniques must ensure analysis of the components degradation, an essential step to predict the capacitor performance and its remaining lifetime; the final interest would be to provide warnings in advance of catastrophic failures.

Please cite this article as: Makdessi M., Sari A., Venet P., 2013, Health monitoring of dc link capacitors, Chemical Engineering Transactions, 33, 1105-1110 DOI: 10.3303/CET1333185

2. Principles and Technologies

2.1 Aluminum electrolytic capacitors

Aluminum electrolytic capacitors are composed of two aluminum foils, an electrolyte support (also called separator) and an aluminum oxide (AL_2O_3) layer constituting the dielectric (Martinez-Vega, 2010). The composition of such a capacitor is represented in Figure 1 (a).

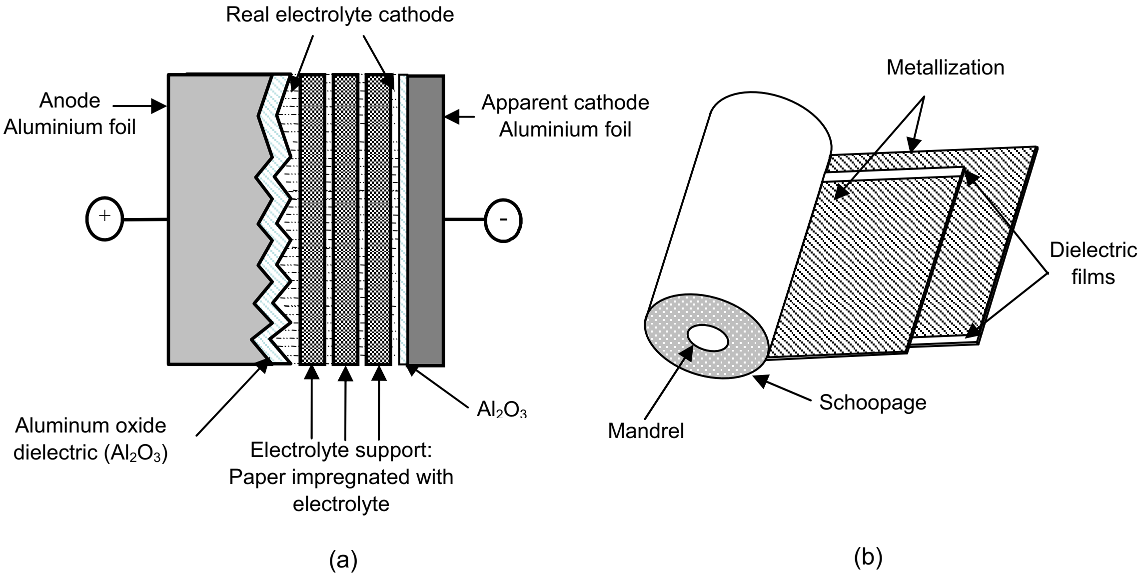

Figure 1: Composition of aluminum electrolytic capacitors (a), and MPPF capacitors (b)

As mentioned previously, due to the thin oxide layer and the engraving structure of the aluminum foil constituting the anode, capacitance values for this type of capacitors can be very high.
The aluminum oxide, constituting the dielectric, is formed by electrolysis on the anode during manufacturing processes. The electrolyte imbibing the paper has two main functions, it will, in the first hand, ensure electric conduction between the aluminium foil (brought to the negative potential) and the aluminium oxide, and on the other hand, it will regenerate the integrity of aluminium oxide in case of default.

2.2 Metallized polypropylene films capacitors

Capacitors using a plastic film as dielectric are widespread and their characteristics depend on the material that has been used. Plastic films are themselves coated with zinc or aluminum of a few nanometers thickness to constitute the electrode (see Figure 1 (b)). Metallized films are then wrapped together on a cylindrical insulated base called mandrel. To assure connections with an external circuit, a sprayed metal technique known as ‘Schoopage’ is used on both sides of the winding.
Metallized films capacitors have been used since the 1950’s (Tortai et al., 2004) and were coveted for their abilities of self-healing; defects such as pinholes, embedded foreign particles or even micro-flaws in the dielectric material can lead to a localized breakdown of the film. Such a breakdown event results from a sudden and localized discharge of a portion of the stored charge under the influence of temperature and pressure. During this intense discharge, a puncture is developed in the dielectric material and the thin metallization layer near the defected site will be rapidly vaporized and blown away and the site becomes electrically isolated. Thus, metallized film capacitors can undergo a large number of breakdowns with as only visible impact a slight drift of its electrical parameters.
Unlike electrolytic capacitors, plastic films capacitors do not require a given polarization and behave well under high current and voltage conditions (El-Husseini et al., 2003). Metallized films capacitors are a very interesting alternative to electrolytic capacitors (Buiatti et al., 2010) and present higher reliability, higher RMS currents and small capacitance change regardless of the applied voltage.

2.3 Equivalent electrical circuit

All real components including capacitors have parasitic parameters not taken into account in ideal models. These factors can have a major impact on electrical behaviour within a circuit. A model which is simple and takes into account parasitic parameters involved is showed in Figure 2.

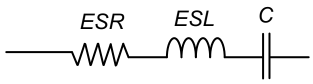

Figure 2: Simplified electrical model of EC and MPPF capacitors

ESR is the Equivalent Serial Resistance taking into account all losses in the component; ESL represents the equivalent serial inductance due to the capacitors windings and electrodes, while C is the nominal capacitance of the capacitor.

3. Mode and failure rates of capacitors

3.1 Failure mode

Failures are classified into two main parts, parametric and catastrophic modes:

- Parametric failures, e.g. devices degradation are defined as the change of the component characteristics which drifts out of its specific tolerances. The most current degradations of capacitors are the increase of the equivalent series resistance ESR or of the loss factor $\tan\delta$ and the decrease in the capacitance C.
- Catalectic or catastrophic failures represent sudden failures corresponding to the disappearance of the component function. They are most often characterised by a short or open circuit of the capacitor.

3.2 Failure rate

The failure rate $\lambda(t)$ is the conditional failure probability of a component by unit of time; it gives an indication on the risks for a device to breakdown during a time interval $]t, t+\Delta t]$ when Δt tends to zero and by considering that this device lasted until time t. The failure rate $\lambda(t)$ is expressed in 10^{-6}/hour or 10^{-9}/hour (implied: failure/10^6 h or failure/10^9 h) or in FIT (Failure In Time with 1 FIT = 1 failure/10^9h).
The failure rate $\lambda(t)$ follows for many components the bathtub curve represented in Figure 3.

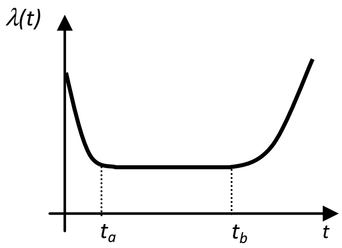

Figure 2: Failure rate $\lambda(t)$ as a function of time

As it can be seen, the curve can be divided into three parts:

– The early failure period ($t \le t_a$), which is due to the youth defects of capacitors, during this phase the failure rate $\lambda(t)$ decreases;
– The intermediary period ($t \in\ ]t_a, t_b[$), where the failure rate is approximately constant, it corresponds to the normal lifetime period;
– The wear out period ($t \ge t_b$) where the failure rate $\lambda(t)$ increases drastically. In this period, the failures take a systematic character. Generally, they correspond to the failures by degradation.

4. Accelerated Ageing tests

Accelerated ageing tests methods are often used as a way to assess the effects of the degradation process through time. Monitoring and analyzing the degradation of these test components provides information on their behaviour under specific stresses and allows the identification of different failure mechanisms. These information can also be used as a way to retroact on the conception of the component and thus to improve its reliability (El-Husseini et al., 2003). Very often, for energy storage devices including capacitors, it is well recognized that failure process is equivalent to a chemical reaction. Its rate constant, according to Arrhenius law, is function of the absolute temperature T (Lahyani et al., 1998). The typical failure mode of capacitors lays on the gradual increase of the capacitor Equivalent Series Resistance (ESR) and a decrease of its main capacitance C; a capacitor is considered at its end of life when ESR becomes at least two times higher than its initial value and/or when its capacitance C decreases of 20 % from its original value. Monitoring the evolution of these parameters through time is of a major importance and will serve us as database to track the capacitors ageing.

4.1 Ageing of aluminium electrolytic capacitors

As mentioned previously, accelerated ageing tests allow studying C and ESR evolution as function of time. For a 1000 µF, 400 V aluminium electrolytic capacitor, floating ageing test at 85 °C and 400 V was realized. It consists on applying constant voltages and temperatures across the component terminals. Figure 4 represents the interpolated and extrapolated data with the use of experimental measurements for ESR and C parameters (Abdennadher et al., 2010).

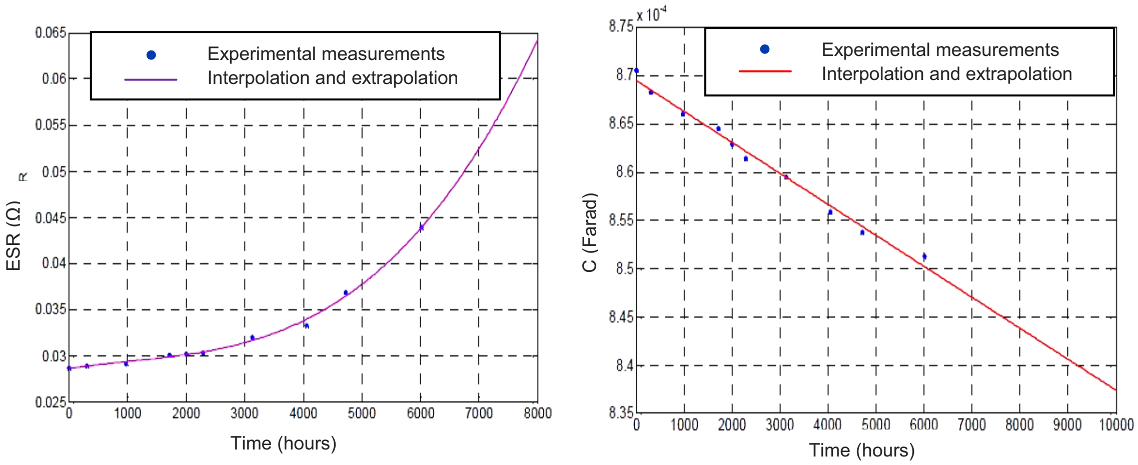

Figure 3: Evolution of ESR and C as function of ageing time for an electrolytic capacitor (1000µF / 400 V)

These evolutions are mainly due to the ageing of the electrolyte. In fact, like all components based on liquid electrolyte, aluminium electrolytic capacitor present a wear out period, when $t \geq t_b$ (see Figure 3), failure occurs since it becomes inevitable. As it can be seen from Figure 4, the equivalent series resistance ESR is the parameter which is the most affected by the component ageing. It mainly depends on the resistance of the electrolyte imbibing the papers; when the electrolyte evaporates, the equivalent surface of this latter decreases, leading to an increase of ESR and a decrease of C. It is of interest to note that ESR and C variation as a function of time depends on the electrolyte type, on the component package and more particularly on its watertightness. Several models describe ESR and C evolutions as a function of ageing time. For example, for C, a linear model can describe its decrease versus ageing time. While for ESR more precise models describe these variations according to exponential laws (Perisse, 2003).

4.2 Ageing of metallized polypropylene films capacitors

Since most of the research done in the field of ageing laws of capacitors deals with the electrolytic type, we will focus in this section on the identification of MPPF capacitors ageing law. It is based on the analyse of the degradation of the capacitors parameters over the ageing time; with respect to Figure 3, we will be in this case in the third zone of the bathtub. Although Arrhenius model gives a good approximation of the operating life of a component, it is limited to a temperature effect. In fact, during their operation, capacitors are not only subjected to temperature stresses but also to critical operating conditions such as voltages and currents that may affect their lifetime. In order to improve the knowledge of the ageing law of MPPF capacitors, a more sophisticated one must be established. Eyring theory generalizes Arrhenius law to many factors besides the temperature (Endicott et al., 1965). Equation (1) describes Eyring law when two supplementary stresses are considered:

$$\tau_{f\_Eyring}(T_i, S_{1i}, S_{2i}) = A_E T_i^{\alpha}.exp\left(\frac{E_a}{kT_i} + \left(B_E + \frac{C_E}{T_i}\right).S_{1i} + \left(D_E + \frac{E_E}{T_i}\right).S_{2i}\right) \tag{1}$$

Where, τ_{f_Eyring} is the useful life of the component (s), T_i the temperature stress in Kelvin (K), E_a the activation energy (eV), k Boltzmann constant ($8.617.10^{-5}$ $eV.K^{-1}$), S_{1i} and S_{2i} are the supplementary considered stresses, A_E, B_E, C_E, D_E, E_E and α are different constants. By considering the DC voltage as the only supplementary stress for our tests, Eq (1) can be simplified as shown in equation (2):

$$\tau_{Eyring}(\theta_i, U_i) = \tau_0 . exp(-\theta_i/\theta_0 - U_i/U_0) \quad (2)$$

Where, τ_{Eyring} represent the useful life of a component at a given temperature θ_i (ºC) and a given voltage U_i; θ_0 and U_0 are respectively the accelerating coefficients of the temperature and voltage, while τ_0 is the theoretical useful life of the component at 0 ºC and 0 V.

In order to determine τ_0, θ_0 and U_0, three floating ageing tests, have been achieved respectively on a set of ten metallized polypropylene films capacitors (1µF-630V). The realized accelerated tests are listed below:

- Floating ageing 1: at 85 ºC – 692 V
- Floating ageing 2: at 100 ºC – 692 V
- Floating ageing 3: at 85 ºC – 820 V

This method is used to quantify both temperature and voltage effects on the ageing of capacitors. From the floating ageing tests 1 and 3 we would be able to determine U_0, whereas from the floating ageing tests 1 and 2, θ_0 can be identified. Figure 5 represent the evolutions of ESR and C of MPPF capacitors as function of ageing time when subjected to different stresses.

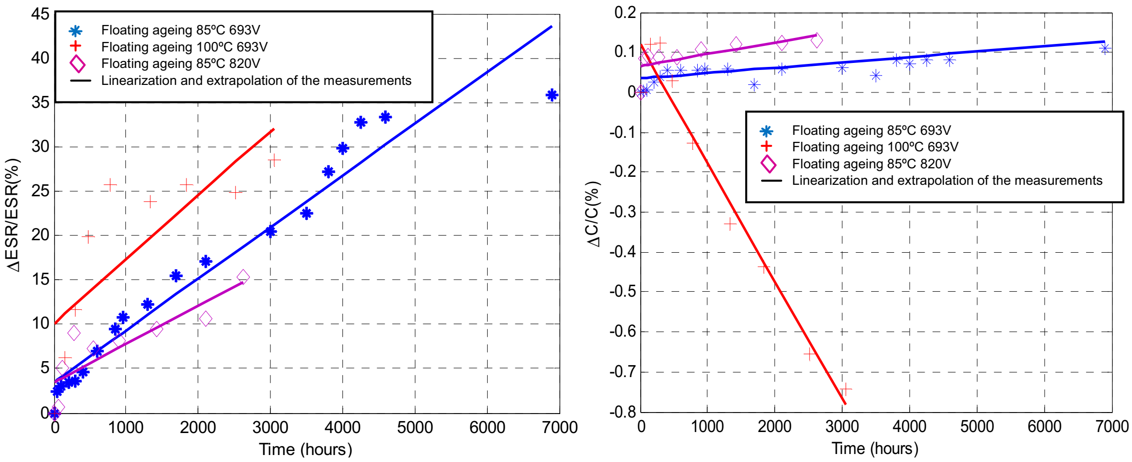

Figure 4: ESR and C evolution as function of ageing time for MPPF capacitors

These evolutions are mainly due to the self-healing capabilities of MPPF capacitors; when the metallization evaporates, the equivalent surface area of this latter decreases, which leads to an increase of ESR and a slight decrease of C. With respect to the experimental plots shown in Figure 5, τ_0, θ_0 and U_0 can be identified by extrapolation of the measurements. By considering an increase of ESR of 100 % we can note 50 % reduction of the lifetime o MPPF capacitors for an increase of 10 ºC or an increase of 170 V on the applied voltage (U_0 = 245 V; θ_0 = 14.4 ºC). Assuming this trend faithful, we can establish an expectation lifetime of MPPF capacitors in function of voltage and temperature as shown in Figure 6.

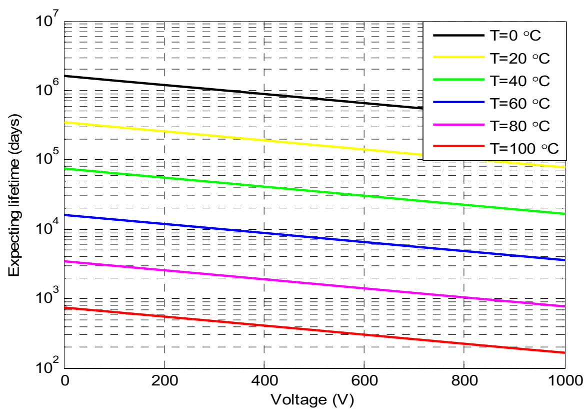

Figure 5: Expecting useful life of MPPF capacitors as function of temperature and DC voltage stresses

5. Health monitoring of capacitors

Since the drifts of the different parameters are known and can be expressed as equations, predictive maintenance systems can be elaborated (Abdennadher et al., 2010). Some authors propose an individual supervision of the capacitors: by measuring their impedance near the resonance frequency, the equivalent series resistance ESR can be determined whilst functioning and compared to that of a healthy component. An example of such “smart” device is given on Figure 7 (Venet et al., 2002).The actual value of the ESR is computed from the current flowing in the capacitor and the voltage ripple. It is compared to the value of ESR for a healthy capacitor at the measured case temperature T_c of the component. If the difference is too high, a signal indicates that the capacitor is near its end-of-life and should be replaced.

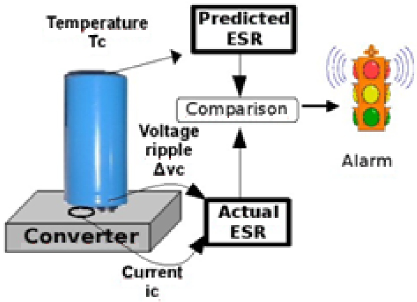

Figure 6: Smart electrolytic capacitor

6. Conclusion

This paper presents a monitoring approach for the capacitor’s electrical parameters in function of the ageing time for both electrolytic and MPPF capacitors. Furthermore, MPPF capacitors ageing laws were identified using Eyring law as function of the applied DC voltage and temperature. This latter can be implemented in an algorithm allowing us to perform a predictive maintenance on the test capacitors. However, since DC-link capacitors are subjected to gradients of temperature due to the electrical stresses encountered during their normal operation of the component, improvements in Eyring law should be made in order to take into account the impact of RMS current on the capacitor ageing.

References

Abdennadher K., Venet P., Rojat G., Retif J.M., Rosset C., 2010, A Real-Time Predictive-Maintenance System of Aluminum Electrolytic Capacitors Used in Uninterrupted Power Supplies. *Industry Applications, IEEE Transactions on,* 46**,** 1644-1652.

Buiatti G.M., Martin-Ramos J. A., Garcia C.H.R., Amaral A.M.R., Cardoso A.J.M., 2010, An Online and Noninvasive Technique for the Condition Monitoring of Capacitors in Boost Converters. *Instrumentation and Measurement, IEEE Transactions on,* 59**,** 2134-2143.

El-Husseini M.H., Venet P., Al-Majid A., Fathallah M., Rojat G., Ferreira J.A., 2003, Manufacturing technology effect on current pulse handling performance of metallized polypropylene film capacitors. *Journal of Physics D: Applied Physics,* 36**,** 2295.

Endicott H., Hatch B., Sohmer R., 1965, Application of the Eyring Model to Capacitor Aging Data. *Component Parts, IEEE Transactions on,* 12**,** 34-41.

Joubert C., Rojat G., Venet P., 2007, Capacitors: revisiting a classical technology to face new challenges. *2nd edition of the international conference Automotive Power Electronics, Paris*.

Lahyani A., Venet P., Grellet G., Viverge P.J., 1998, Failure prediction of electrolytic capacitors during operation of a switchmode power supply. *Power Electronics, IEEE Transactions on,* 13**,** 1199-1207.

Martinez-Vega J., 2010, Dielectric Materials for Electrical Engineering. *John Wiley & Sons Inc,* Chapter 18 Electrolytic capacitors, P. Venet**,** 403-434.

Perisse F., 2003, Etude et analyse des modes de défaillances des condensateurs électrolytiques à l’aluminium et des thyristors, appliquées au système de protection du LHC (Large Hardon Collider). *Thesis* University of Lyon.

Tortai J.H., Bonifaci N., Denat A., 2004, Diagnostic of the self-healing of metallized polypropylene film by modeling of the broadening emission lines of aluminum emitted by plasma discharge. *Journal of Applied Physics*.

Venet P., Lahyani A., Grellet G., Ah-Jaco A., 1999, Influence of aging on electrolytic capacitors function in static converters: Fault prediction method. *The European Physical Journal - Applied Physics,* 5**,** 71-83.

Venet P., Perisse F., El-husseini M.H., Rojat G., 2002, Realization of a smart electrolytic capacitor circuit. *Industry Applications Magazine, IEEE,* 8**,** 16-20.