

# Electrolytic capacitor: Properties and operation

Jami Torki, Charles Joubert, Ali Sari

## ▶ To cite this version:

Jami Torki, Charles Joubert, Ali Sari. Electrolytic capacitor: Properties and operation. Journal of Energy Storage, 2023, 58, pp.106330. 10.1016/j.est.2022.106330. hal-04045102

# HAL Id: hal-04045102 https://hal.science/hal-04045102

Submitted on 9 Jun2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers. L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## Electrolytic capacitor: properties and operation

- 2 Jami TORKI<sup>1</sup>, Charles JOUBERT<sup>1</sup> and Ali SARI<sup>1</sup>
- 3 4

5

1

- <sup>1</sup>Université de Lyon, Université Claude Bernard Lyon 1, Ecole Centrale de Lyon, INSA Lyon, CNRS UMR5005, Ampère, Villeurbanne 69622, France
  - jami.torki@univ-lyon1.fr; charles.joubert@univ-lyon1.fr; ali.sari@univ-lyon1.fr
- 6 Highlights:
- 7 A comprehensive review on the properties of electrolytic capacitor are presented
- 8 Characteristics of three different types of electrolytic capacitors are explained
- 9 The article reviews the study of predictive maintenance to anticipate breakdowns
- 10 Methods based on the variation of aging indicators for aging laws are listed

Abstract: Due to their high specific volumetric capacitance, electrolytic capacitors are used in many 11 12 fields of power electronics, mainly for filtering and energy storage functions. Their characteristics 13 change strongly with frequency, temperature and aging time. Electrolytic capacitors are among the 14 components whose lifetime has the greatest influence on the reliability of electrical systems. Over the 15 past three decades, many efforts in academic research have been devoted to improving reliability 16 capacitor. Industrial applications require more reliable power electronic products. It is in this context 17 that the different electrolytic capacitors and their characteristics are discussed. The aging process of 18 aluminum electrolytic capacitors is explained. Finally, this paper reviews existing methods of failure 19 prognosis of electrolytic capacitors.

20 Keywords: Electrolytic capacitor, failure modes, aging law, predictive maintenance.

### 21 Contents

22	1. Elec	ctrolytic capacitors	2
23	1.1	Principle of electrolytic capacitors	2
24	1.2	Aluminum electrolytic capacitors	4
25	1.3	Types and features of electrolytic capacitors	8
26	1.3.1	Comparison of electrolytic capacitor types	8
27	1.3.2	Comparison of electrolytic capacitor parameters	10
28	2. Fea	tures and Failure modes	12
29	2.1	Series equivalent circuit model of a capacitor and characteristic	12
30	2.2	Maintenance	14
31	2.3	Mechanisms and failure mode	16
32	2.3.1	Non-solid electrolytic capacitor failure modes	16
33	2.3.2	Solid and polymer electrolytic capacitor failure modes	
34	3. Agir	ng process of non-solid electrolytic capacitor	19
35	3.1	Characterization of aging indicators of electrolytic capacitors	19
36	3.2	Aging models for electrolytic capacitors	22
37	3.3	Detect the aging of electrolytic capacitors	

38	4.	Conclusion	27
39	Refe	rences	28

40

## 41 1. Electrolytic capacitors

- 42 Capacitors are used in many fields of electronics and their main uses are the following:
- 43 Energy storage (data backup, system protection...),
- 44 Power factor correction,
- Regulation of the output voltage of switch mode power supplies,
- 46 Input or output filtering of static converters,
- Starting of electric motors.

48 There are different types of capacitors to meet the different electrical, thermal and mechanical 49 constraints associated with their use. Moreover, each capacitor will meet certain criteria such as 50 capacitance, voltage and size. There are therefore three different types of capacitors that can cover all 51 user needs: ceramic, film and electrolytic capacitors. Choosing the right capacitor for the system can 52 be very important because in some applications it is responsible for most of the failures. Figure 1 shows 53 the distribution of failures among power electronic components [1] [2]. Among all the electric 54 components, capacitors are the most vulnerable in terms of level and time of failure, as analyzed in 55 [3]–[5]. They are considered as reliability critical components in power electronic converters, especially 56 capacitors for DC link applications. This literature focuses on one of the three main types of capacitors: 57 electrolytic capacitors. The remainder of this paper is organized as follows:

- 58 **Section 1** presents the principles of electrolytic capacitors, the construction and the different types of
- 59 electrolytic capacitors. **Section 2** describes the characteristics, the maintenance that can be applied on
- 60 capacitors and the failure indicators. **Section 3** discusses general characterization, aging laws, variation
- of aging indicators and methods for detecting the aging of electrolytic capacitors. Finally, conclusions
- 62 are presented in **Section 4**.



63

64

Figure 1: Failure distribution in power electronic systems [6].

## 65 1.1 Principle of electrolytic capacitors

66 Electrolytic capacitors consist of two electrodes (anode and cathode), a film oxide layer acting as a 67 dielectric and an electrolyte. The electrolyte brings the negative potential of the cathode closer to the 69 dielectric win in the electrolyte brings the negative potential of the cathode closer to the

68 dielectric via ionic transport in the electrolyte [7] (see **Figure 2**). The electrolyte is either a liquid or a

69 polymer containing a high concentration of any type of ion, although generally some ions are preferred 70 for electrolyte stability. There are mixtures of electrolyte with polymers [8] that provide better 71 conduction and stability performance [9]–[11]. There are many different electrolytes, which can be 72 separated into three categories: "Wet electrolytic capacitor", which are electrolytic capacitors without 73 electrolytic paper; "solid electrolyte" using a polymer, usually polythiophene, conducting electrons; 74 "dry electrolytic" capacitors which still use a liquid electrolyte balancing the charge by ions.

75



76

Figure 2: Simplified diagram of the constitution of an aluminum electrolytic capacitor consisting of aluminum electrodes, an
 alumina dielectric and an electrolyte.

The only physics that can store energy in a capacitor is electrostatics, allowing rapid and reversible processes. It is estimated that a capacitor has an efficiency of over 95% and can perform over one million charge and discharge cycles over its lifetime [12]. In the case of an ideal planar capacitor, the

82 capacitance value can be calculated as follows:

 $C = \frac{\varepsilon_0 \varepsilon_r S}{e} \tag{1}$ 

83 With:

•  $\varepsilon_0$  (= 8,854.10<sup>-12</sup> F.  $m^{-1}$ ) the vacuum permittivity,

85

84

86 87

- ε<sub>r</sub> the relative permittivity of the dielectric,
  S [m<sup>2</sup>] the surface of the electrodes,
- *e* [m] the thickness of the dielectric.

88 Thus, it can be concluded that increasing the surface of the electrodes will allow the increase in 89 capacitance. It is also possible to increase the capacitance by changing the relative permittivity of the 90 dielectric used but also its thickness, which is why there is a multitude of capacitors classified into 91 subgroups. As detailed below, electrolytic capacitors have a large electrode surface. Moreover, they 92 have a thin oxide layer less than 1500 nm thick (see Table 2) [13]. One can understand that the 93 electrolytic capacitors has a specific capacitance that is significantly greater than all the other 94 capacitors. An electrolytic capacitor is a polarized capacitor whose anode is a positive plate where an 95 oxide layer is formed through electrochemical principles that limit the use of reverse voltage. Indeed, 96 reverse voltage would cause a chemical reaction (the reduction of the oxide and a release of gaseous 97 dihydrogen), destroying the dielectric at the anode, which would create on one hand a short circuit 98 and on the other hand would generate the creation of a layer of dielectric at the cathode releasing

- 99 dihydrogen and strongly increasing the internal pressure leading to an explosion. In order to maintain
- 100 the stability of the oxide, the voltage on the positive terminal should always be higher than the voltage
- 101 on the negative terminal.

102 The electrical, thermal and mechanical constraints related to the use of these components are very 103 diverse. There are different types of capacitors that can cover all the needs of users. Three main types 104 of capacitors can cover all the needs of users. Generally, electrolytic capacitors contain aluminum, 105 tantalum or niobium [14]-[16]. In this article, a review of the operation and properties of the 106 electrolytic capacitor (Aluminum, Tantalum and Niobium) is presented. The paper also proposes a 107 review on maintenance to anticipate failures with non-intrusive diagnosis. In order to overcome these 108 problems and to be able to estimate the remaining lifetime with predictive maintenance, the 109 identification of failure mechanisms and modes is reviewed. Information on different methods and 110 algorithms based on the variation of aging indicators with constraints, which can lead to aging laws, is 111 provided. Finally, an overview of several significant methods existing in the literature is summarized, 112 based on failure prognosis.

### 113 1.2 Aluminum electrolytic capacitors

One of the major axes of research on electrolytic capacitors is the aluminum electrolytic capacitor (AEC). They have higher volume efficiency due to a significantly lower minimum dielectric thickness than all the other capacitors. However, they have a high internal resistance as well as an inductance limiting high frequency performance and low temperature stability [17], [18].

- 118 Until the wound construction of aluminum foil capacitors, this type of capacitor was bulky and heavy. 119 There are different sizes of capacitor ranging from 3 mm in diameter for 5 mm in height up to 90 mm 120 for 210 mm [19]. Now, AEC became the model for all modern electrolytic capacitors due to their range 121 of voltage ratings and capacitances. This advantage is useful in power supply filters where they are the 122 most common component [15]. This type of capacitor offers high power density but has high leakage 123 current and high sensitivity to reverse polarity. It is necessary to use temperature sensors and current 124 limiters due to their risky failure mode. Indeed, in the event of a power surge there is a high risk of fire. 125 This type of capacitor has an operating temperature of up to 150°C in some cases, allowing a wide 126 range of operating temperatures. Moreover, compared to other electrolytic capacitors, they are less 127 expensive not only because of the materials used but also because of the manufacturing process. They 128 offer good stability and a long service life. In addition, the article indicates that today some 129 components have a theorical life of about 15 years at 65°C compared to an estimated life of half a year 130 in the 1960s [20]. Aluminum electrolytic technology tends to be more and more reliable.
- AEC consists of two aluminum electrodes, a film oxide layer (alumina) acting as a dielectric, and an electrolyte which consists of a mixture of solvents and additives to meet given requirements. The main electrical property of the electrolyte is its conductivity. In addition to good conductivity of the operating electrolytes, other requirements include:
- chemical stability,
- 136 high flash point/flammability point,
- chemical compatibility (e.g. with aluminum).

And in some cases, it may be interesting to have a low viscosity, a minimal negative impact on the environment and a low cost. The electrolyte must, if possible, be able to carry out the formation and self-repair processes of alumina, this will be detailed below. This is why there is a wide variety of solutions for different requirements for the liquid electrolyte [21]. These chemical mixtures allow the electrolyte to be a very good conductor over a wide range of temperatures. Three main groups of"wet" electrolytes are used today:

- Electrolytes based on boric or benzoic acid dissolved in ethylene glycol or glycerin and water.
   But in these electrolytes, an undesirable chemical reaction occurs between the crystal and the
   water: the acid with the alcohol gives ester and water [22]. This constitutes the degradation of
   the electrolyte. These "borax" electrolytes are standard electrolytes, which have long been
   used for their low cost, and have a water content of between 5 and 20%. They operate at a
   maximum temperature of 85 °C or 105 °C over the entire voltage range up to 500 V [23], [24].
- Anhydrous electrolytes based on organic solvents, such as dimethylformamide (DMF), γbutyrolactone (GBL) or dimethylacetamide (DMA). These capacitors with organic solvent electrolytes are suitable for temperature ranges up to 150 °C, have low leakage current values and age well. In order to have the best performance, it is recommended to use picric acid (DMA) and a lactone-based solvent such as GBL, however this comes at a price. A second possibility is to use DMF in order to keep good performances at a lower cost, although this chemical is carcinogen and can be injurious to health [25]–[28].
- Water-based electrolytes with high water content, up to 70% water for low impedance, low ESR or high ripple current electrolytic capacitors with voltage ratings up to 100 V for low cost applications [29]. ESR and ripple current will be described below, in capacitors these parameters are linked to internal heating. The corrosion potential of water on aluminum should be avoided with appropriate additives [30].

Non-solid electrolytes can easily fit in the rough structure due to the liquid medium which has ion conductivity due to the ions [31]. However, the electrolyte is not a perfect conductor like a metal: an electrolytic capacitor has a non-negligible series resistance. In addition, there is an inductance effect which is more important the higher the frequency. This is due to the overall volume of the capacitor, and the more inductive connections than some types of film or ceramic capacitors. Originally, these capacitors were not designed to be used for decoupling or filtering signals. AEC are mainly used in the filtering part of power supply circuits [14].



- 169
- 170 171

Figure 3: Detailed diagram of the constitution of an AEC consisting of etched aluminum electrodes, an alumina dielectric and an electrolyte support with sheets of paper impregnated with this electrolyte.

172 In addition, the majority of AEC have an anode etch [32], as shown in **Figure 3**. Etching will increase 173 the surface area of the anode, and therefore the capacitance, by controlled deposition of the dielectric.

174 Etching is used to chemically remove layers from the surface, a portion of the surface is protected from

175 etchant by a mask material that resists etching, and then the mask is removed. For example, if the 176 aluminum electrode is the material to be etched, then the etchants are phosphoric acid ( $H_3PO_4$ ), water, 177 acetic acid and nitric acid ( $HNO_3$ ) [33]. It should be noted that the quality of the etching has an 178 important influence on the capacitance of the capacitor and largely determines its tolerance. As it has 179 been seen above, the thickness of the oxide layer (a few nm to a few hundred nm) and the etching of 180 the aluminum foil constituting the anode (allowing the effective surface to be 20 to 200 times wider) 181 allows important capacitance [19], [34]. The use of a liquid electrolyte will allow the exploitation of a 182 specific surface area greater than a flat electrode surface. Indeed, the increase in surface area will 183 allow a significant increase in capacitance. It is then understood that the AEC has an all the greater 184 capacitance. A more detailed sketch of ACE is shown in Figure 3. In this figure, sheets of paper 185 impregnated with electrolyte can be seen. Electrolyte impregnated paper serves as physical separator 186 limiting the risk of short circuits between the two electrodes. The thin layer of Al<sub>2</sub>O<sub>3</sub> (alumina) on the 187 cathode is caused by natural oxidation of aluminum which limits corrosion as shown in Figure 3. 188 However, the aluminum oxide layer present on the anode is caused during the construction of the 189 capacitor by the application of a potential according to the equation below [20]:

At the anode:	
$2(Al^{3+}) + 3H_2O \rightarrow Al_2O_3 + 6H^+$	(2)
At the cathode:	
$6H^+ + 6e^+ \to 3H_2$	

190

191 The electrolytic capacitors have a specific characteristic, a DC leakage current. This leakage current 192 includes the imperfection of the dielectric due to chemical processes which happens during the storage 193 time when there is no applied voltage. In order to dramatically reduce the leakage current of the 194 capacitor, researchers found a way to reform the dielectric. When a voltage is applied to the capacitors, 195 the same electrochemical reaction seen previously generates a natural oxidation of the aluminum. This 196 same reaction takes place even with slight defects in the dielectric and regenerates the alumina oxide 197 layer. The leakage current drops within the first minutes of voltage application, reflecting the repair 198 phenomenon of the dielectric layer due to the oxidation reduction reactions (2). The time required for 199 the leakage current to decrease generally depends on the type of electrolyte. For example, the leakage 200 current of solid electrolytes drops much faster than for non-solid electrolytic capacitors, but it remains 201 at a higher level. Non-solid electrolytic capacitors with highly concentrated water electrolytes, in the 202 first minutes, generally have a higher leakage current than those with an organic electrolyte, but after 203 several minutes they reach the same level. Once the dielectric layer has completely reformed, the 204 leakage current tends to a stable nominal value. If the capacitors still do not meet the leakage current 205 requirements after self-repair, this can be an indication of permanent damage. This phenomenon is 206 called "self-healing" or "self-repair" and should not be mixed up with the self-healing of a metalized 207 film capacitors [35], [36]. This occurs thanks to an electrochemical phenomenon of electrolysis of water 208 transforming it into oxygen and hydrogen allowing the generation of alumina by the chemical formula 209 above. Self-healing of the dielectric prevents the risk of electrical breakdown.

210 AEC that have been stored for long periods of time should go through a voltage treatment process that 211 will reform the dielectric  $(Al_2O_3)$  through the electrolyte and bring the leakage current back to the 212 original level. The increase in leakage current during storage varies with the holding voltage of a 213 capacitor. In general, the higher the voltage rating, the greater the increase in leakage current tends 214 to be. Also, since storage for a long period of time can reduce the life of capacitors, storage conditions 215 should be considered in relation to the life requirements of the device. When an AEC is stored under 216 no load conditions for a long period of time, the electrolyte may have degraded the oxide layer of the 217 anode. Since the dielectric strength has been reduced by the electrolyte, the capacitor has a higher 218 leakage current than originally. The voltage applied to the capacitor will allow the oxide layer to 219 reform. This is why, many technical guides [17], [37] advise charging the capacitor to its nominal 220 voltage for one hour through a resistor to prevent the capacitor from overheating. Thus, the leakage 221 current returns to its initial value due to the reformation of the dielectric. It can be found in [38], for 222 an AEC stored a temperature between -5°C and +50°C, we must reform the dielectric of the AEC by 223 applying a voltage. This voltage will be different depending on the storage time according to the 224 following criteria:

- For U < 100 V, the storage time is 5 years.
- For 100 V < U < 360 V, the storage time is 3 years.
- For 360 V < U < 500 V, the storage time is 1 years.
- For U > 500 V, the storage time is 6 months.

In this section, the various steps in the construction of an aluminum electrolytic capacitor aredescribed. There are several steps to build an AEC:

231 Etching: The anode foil is made of an almost pure aluminum foil, 40 to 110  $\mu$ m thick. In order to 232 increase its effective surface area, the use of a direct or alternating current with a solution of chloride 233 can transform the smooth surface into a rough surface. Etching is performed on high-purity aluminum 234 foil by an electrochemical process in a chloride solution with either direct or alternating current. AC 235 electrolysis is generally used for low voltage capacitors, and DC electrolysis is used for medium and 236 high voltage capacitors. The multiplication factor is the ratio of the capacitance of the smooth surface 237 to the etched surface and, usually, it reaches values ranging from 10 to 100. Sometimes, in order to 238 enhance the exchange of the cathode with the electrolyte, the cathode foil, 20 to 50  $\mu$ m thick, is also 239 etched (Figure 4. 1).

Formation: By electrolysis under a continuous voltage, higher than the nominal voltage, the aluminum oxide layer is formed on the aluminum foil surface. The advantage of AEC is the ability to change the thickness of the oxide film by changing the voltage (**Figure 4. 2**).

243 Slitting: According to the capacitance value and geometric dimensions desired, the formed 244 electrode foils are cut (**Figure 4. 3**).

Winding: The anode foil is wound up with the cathode sheet and the impregnated electrolytic paper (separator) to form a cylinder. This paper serves to avoid short circuit and to maintain the uniform thickness, density and absorption of the electrolyte. Connection strips distributed on the winding are assembled (**Figure 4. 4**).

Impregnation: Impregnation is the process of saturating the winding with electrolyte to make sure that there is a good contact between the oxide layer and the real cathode. With or without heat, the mechanism of impregnation consists in the immersion of the winding with pressure and vacuum cycle in the electrolyte. The electrolyte must adhere to the whole surface of the anode and cathode foils to have a higher capacitance. It can also repair defects in the anode oxide film as seen before. The nature of the electrolyte influences the temperature and frequency characteristics response of the capacitor (**Figure 4. 5**).

Assembly: To avoid the deterioration from evaporation or moisture absorption of the electrolyte, the winding needs to be inserted in a metal case and sealed-off. Finally, a safety valve is added which allows the evacuation of a possible overpressure, in the event of evaporation of the electrolyte (**Figure 4.6**). 260 Reforming: This process permits to repair the oxide film, that could have been broken during the 261 assembly step, by applying a continuous voltage. This voltage needs to be superior to the forming 262 voltage of oxide (**Figure 4. 7**).

Inspection: After the sealing, products are inspected for capacitance, leakage current, externalappearance and performances as required before packaging.



Figure 4: 1) Etching of an aluminum sheet. 2) Formation of oxide layer. 3) Slitting of the aluminum sheets. 4) Winding. 5)
 Impregnation. 6) Assembly. 7) Final Product. [39]–[41]

## 268 1.3 Types and features of electrolytic capacitors

Although the aluminum electrolytic capacitor has been the focus of research in recent years, it is not the only one. It can be interesting to classify the different electrolytic capacitors because each of them has preferential characteristics according to the applications and its environment.

272 1.3.1 Comparison of electrolytic capacitor types

### 273 <u>Tantalum electrolytic capacitor:</u>

265

274 There is a multitude of electrolytic capacitors such as tantalum that have better stability, a wider 275 operating temperature range and a longer service life than others [42] but who are considerably more 276 expensive. They consist of metallic tantalum which acts as an anode covered by an oxide layer of 277 tantalum pentoxide ( $Ta_2O_5$ ), surrounded by a conductive solid or liquid electrolyte which acts as the 278 cathode. The dielectric, made of tantalum pentoxide, has a minimum thickness of 1.4 nm/V. Indeed, 279 this type of capacitor generally has a larger capacitance value since it has a very thin dielectric layer 280 with higher permittivity than aluminum capacitor (see Table 2). They are polarized, which means that 281 electrolytic capacitors cannot be connected to an AC supply. Compared to many types of capacitors, 282 they have excellent stability, high cut-off frequency characteristics and higher energy density [43]. 283 Their benefits include low impedance and low leakage current with high frequency performance [44]. 284 Initially, tantalum capacitors were low voltage and unreliable. The failure rate and the operating life of tantalum capacitors have been improved nowadays due to the decrease in DC leakage current. The
 article [45] shows a comparison between a tantalum polymer capacitor from the 1990s and one from
 today. However, the risk associated with this kind of capacitors is their failure mode that generates
 fires and explosions. Therefore, their use requires additional safety devices such as overvoltage
 protection or reverse polarity protection.

290 In terms of applications, tantalum capacitors are widely used in laptops, the automotive industry and 291 mobile phones. In the past, tantalum capacitors were built with axial anode capacitors with liquid 292 electrolyte that made them heavy and expensive [16]. Now, they are widely used in power filters, by 293 pass channel circuit, for coupling and decoupling [46]. As SMD (Surface Mounted Devices), they take 294 up much less space on the PCB (Printed Circuit Board) and allow higher energy densities. They are 295 manufactured with capacitance values ranging from 100 nF to 10 mF and are smaller compared to 296 aluminum capacitors. The rated voltage can range from few volts to 100 V. They have a high ESR 297 (Equivalent Series Resistance) but that is still ten times smaller than the ESR of aluminum capacitors 298 [47]. Compared to AEC, high currents can be obtained without creating much heat. When handled 299 correctly, this type of capacitor can be stored for a long time due to its stability. Tantalum capacitor 300 manufacturers advise that tantalum capacitors should never be used in a circuit where a reverse 301 voltage may be applied, but indicate that tantalum capacitor have been shown to be capable of 302 withstanding momentary reverse voltage peaks of up to 10 % of the DC rating at 25°C [48]. Indeed, 303 researchers have obtained that leakage currents of a tantalum capacitor rapidly increase if the applied 304 reverse voltage exceeds 10% of the DC rating [49].

### 305 <u>Niobium electrolytic capacitor:</u>

306 Niobium electrolytic capacitors are made of passivated niobium metal or monoxide and a non-liquid 307 electrolyte (Polymer or MnO<sub>2</sub>). The materials and processes used to produce niobium capacitors are 308 essentially the same as for tantalum capacitors which means they show similar chemical properties. 309 Electrochemical etching of niobium foil is possible in order to enlarge the surface area for the 310 application in electrolytic capacitors [50]. Niobium pentoxide has a greater dielectric constant than 311 tantalum pentoxide but a lower voltage, it allows to obtain the same amount of energy [15]. However, 312 the energy density is lower than the one of tantalum due to its large size. The maximum temperature 313 of operation is limited to 105°C, the leakage current is 5-10 times higher than for tantalum capacitors 314 [16]. Niobium can be found in abundance in the nature compared to tantalum and it is less expensive. 315 But the high melting point obstructed the industrial development of this one until 2000 when the price 316 increase for tantalum encouraged the development of niobium electrolytic capacitors with manganese 317 dioxide and polymer electrolyte [51].

### 318 Basic construction of Tantalum and Niobium electrolytic capacitors:

The positive terminal consists of tantalum or niobium powder pressed and sintered into a pellet. The process of creating the powder takes place in a liquid phase at about 600°C under agitation. The chemical process is [52]:

322

#### $K_2$ TaF<sub>7</sub> + 5 Na → Ta + 2 KF + 5 NaF or $K_2$ NbF<sub>7</sub> + 5 Na → Nb + 2 KF + 5 NaF

The reduction of sodium generates heavy tantalum or niobium particles that fall to the bottom of the reactor while the potassium and sodium fluoride salts go to the surface. There is a mixture reduction set (KCl, KF, NaCl, Na) that depends on the manufacturer. The powder is evaluated for its "CV/g", this is the value of the capacitance multiplied by the voltage obtained per gram. These values depend on conditions such as: press density range, anodizing voltage and sintering quality. The porosity of the positive terminal is generally higher than 50% of the total volume [53]. The dielectric is formed by an electrochemical process called anodization. It forms the insulating oxide layer that covers the anode
over the tantalum particles [54]. As with other electrolytic capacitors, the thickness of the dielectric
layer depends on the total applied voltage. The chemical equations are shown below:

332 2 
$$(Ta^{5+}) + 10 (HO^{-}) \rightarrow Ta_2O_5 + 5 H_2O \text{ or } 2 (Nb^{5+}) + 10 (HO^{-}) \rightarrow Nb_2O_5 + 5 H_2O$$

Immersed in an aqueous solution of manganese nitrate (Mn(NO<sub>3</sub>)<sub>2</sub>), followed by pyrolysis (at about 250 °C) of the manganese nitrate into solid manganese dioxide and nitrogen oxide gas [55]. The manganese dioxide coats the dielectric surface inside and outside the porous anode while the nitrogen oxide gas evaporates from the capacitor body. The chemical equations are shown below:

337 
$$Mn(NO_3)_2 \rightarrow MnO_2 + 2 NO_2$$

338 The procedure is repeated until the pellet has a dense coating on the inner and outer surfaces. To

ensure a solid connection, the pellet is dipped in graphite and silver. The final result is represented in

340 **Figure 5** showing an illustration of a solid Niobium or Tantalum electrolytic capacitor.



341 342

Figure 5: Sketch of the structure of a sintered tantalum or niobium electrolytic capacitor.

Instead of graphite and silver, the tantalum polymer electrolytic capacitor uses a conductive polymer.
For wet tantalum capacitors, the anode is immersed in a liquid electrolyte inside an enclosure after it
has been sintered and a dielectric layer has been formed as for an aluminum electrolytic capacitor.
Finally, the product is inspected and performance is tested to verify the specifications before being
packaged.

### **348** 1.3.2 Comparison of electrolytic capacitor parameters

Depending on the nature of the used anode metal and electrolyte, there is a wide variety of electrolytic capacitors. An overview of the main characteristics of the different types is listed in **Table 1** [56]–[60].

	GBL, DMF, DMA	0.1 to 10 <sup>6</sup>	150	550
	Borax, glycol	0.1 to 10 <sup>6</sup>	105	630
Alumina oxide (Al <sub>2</sub> O <sub>3</sub> )	Water based	1 to 2x10 <sup>4</sup>	105	100
	Solid, Polymer	10 to 2x10 <sup>3</sup>	100	25
	Hybrid polymer solid and non-solid	6 to 10 <sup>3</sup>	125	125
<b>T</b>	Sulfuric acid	0.1 to 2.10 <sup>4</sup>	200	650
oxide (Ta₂O₅)	Solid, Manganese dioxide	0.1 to 3x10 <sup>3</sup>	150	120
	Solid, Polymer	5 to 10 <sup>3</sup> 125		10
Niobium oxide	Solid, Manganese dioxide	1 to 10 <sup>3</sup>	125	10
(Nb2O5)	Solid, Polymer	5 to 500	125	16

351

Table 1: Operating properties of electrolytic capacitors

352 In order to compare these three main categories of capacitor and to sum up some characteristics of

353 electrolytic capacitors, the different modern electrolytic capacitors present in the market along with

their dielectric properties are listed in **Table 2** [58], [61].

Dielectric	Dielectric constant	Dielectric strength (kV/cm)	Electric layer thickness (nm/V)	Benefits	Drawbacks
Alumina oxide (Al <sub>2</sub> O <sub>3</sub> )	8 to 10	6600 to 7700	1.1 - 1.5	<ul> <li>Volume Ratio</li> <li>Less expensive</li> <li>Better range of Voltage and Capacitance</li> </ul>	- High Leakage current - Risky failure mode
Tantalum oxide (Ta <sub>2</sub> O <sub>5</sub> )	10 to 27	6250 to 10 000	1.4	- Low impedance - Low Leakage current - High Frequency	- Risky failure mode
Niobium oxide (Nb₂O₅)	41	4000	2.5	-High dielectric constant - Good balance - Common materials	- Low capacitance per volume - Low Voltage

355

Table 2: Characteristics of electrolytic capacitors.

356 Although there are many electrolytic capacitors, they have some common characteristics. Electrolytic

357 capacitors are the cheapest and most requested capacitors thanks to their high storage densities and

358 low rated currents. However, their ESR and ESL value limits their maximum operating frequency. Their 359 low current and temperature management limitations restrict their integration in some applications, 360 but recent work has been done in recent years to integrate electrolytic capacitor technology [25], [62]. 361 Electrolytic capacitors offer very high capacitance, but this type of capacitor has drawbacks such as 362 high leakage current and high ESR. Some electrolytic capacitors may experience a gradual loss of 363 capacitance when subjected to heat. Indeed, capacitors can suffer catastrophic failures when stressed 364 beyond their rated capacity or when they reach the end of their normal life. By understanding the 365 physical mechanisms that lead to capacitor failure, the life of the next generation of electrolytic 366 capacitors can be improved. Therefore, the characteristics and failure modes in the rest of this article 367 are presented.

## 368 2. Features and failure modes

In conversion systems, electrolytic capacitors, which ensure a stable DC network, are an important part of the electrical energy conversion chain. During operation, they are subject to electrical and environmental stresses (ambient temperature, current ripple, applied voltage, humidity, vibrations, etc.) and their lifetime is affected. In order to estimate the remaining life of electrolytic capacitor, a model that can characterize the system is presented in a first part. Thus, a low-cost maintenance operation such as predictive maintenance is detailed. Finally, the failure modes of electrolytic capacitors are studied since maintenance requires the use of failure indicators.

## 2.1 Series equivalent circuit model of a capacitor and characteristic

There are several equivalent circuits representing the frequency behavior of capacitors. The most used
 model combining simplicity and relatively good precision is shown in the following Figure 6:



379 380

Figure 6: Equivalent circuit of a capacitor [63].

381 As stated in [39]:

- R<sub>p</sub>: Resistance due to electrolyte and dielectric losses. This element represents the insulation
   resistance of the capacitor that induces a leakage current.
- C<sub>AK</sub>: Ideal capacitance between the cathode and the anode.
- L: Equivalent series inductance of connections and windings.
- R<sub>i</sub>: Series resistance of connections, impregnated paper and electrodes.

387 More or less complex models of the capacitor can be found in the literature, but they are built for a 388 specific environment [64]. this schematic can be simplified which yields to the normalized 389 representation **Figure 7**. It is composed of elements depending on the frequency:



**392** • ESL: Equivalent series inductance.

- C: Equivalent capacitance.
- ESR: Series equivalent resistance representing all losses.
- 395 By identifying the impedances of the circuit, it is possible to deduce:

396 • 
$$C = C_{AK} \left( 1 + \frac{1}{R_p^2 C_{AK}^2 \omega^2} \right)$$

$$\bullet \quad ESR = R_l + \frac{R_p}{1 + R_p^2 C_{AK}^2 \omega^2}$$

$$\bullet ESL = L$$

This representation is important because it can be deduced from the characterization of the capacitor during the frequency measurements of the impedance. Indeed, the resistor ESR represents the real part of the impedance while the imaginary part is comparable to reactance  $\frac{1}{C\omega}$  at low frequencies and  $ESL\omega$  at high frequencies. The resonant frequency can be written as:

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

Regarding the Equivalent Series Resistance (ESR), this is a characteristic representing the total ohmic
 losses of a capacitor. The current research consists in reducing the ESR because it leads to overheating
 and to a decrease of the filtering performances. The ESR in an electrolytic capacitor is mainly due to
 the finite conductivity of the electrolyte. The ESR is connected to the dielectric losses (P<sub>d</sub>) and losses
 created by Joule Heating:

$$P = P_d + R_l I^2 = ESR. I_r^2 \tag{4}$$

(3)

408 With  $I_r$ : Ripple Current value

Ripple current results in increased dissipation in parasitic resistive portions of circuits like the ESR of capacitors. This information can lead to a thermal analysis [65], [66]. The self-heating due to the power loss of a capacitor where it depends on the ESR, the ripple current and the thermal resistance between the package and the environment can be considered. The maximum power that a capacitor can dissipate without degradation depends on its thermal dissipation properties (size of the component, materials, geometry, condition of use...). If thermal radiation and thermal conduction are neglected, it can be found that the self-heating can be expressed as:

$$\Delta T = \frac{ESR.{I_r}^2}{hS} \tag{5}$$

416 With h: Thermal convection coefficient and S: the external surface of heat exchange between the 417 capacitor and the ambient air.

Heat generation affects the lifetime of the capacitor, as it will be seen below, by evaporation of electrolytes. If the dimensions of the capacitor are known, the maximum ripple current value can be deduced from the maximum specified temperature. The lower the ESR, the higher the ripple current and the better the functionality of the capacitor. There are various studies on the thermal behavior of capacitors [67]–[69] but this will not be detailed in this paper.

The larger the ESR decrease of a capacitor, the more the efficiency can be improved. Near the resonance, the impedance is close to the ESR. Therefore, the ESR is a factor that limits the filtering performance of the capacitor. In addition, the ESR is proportional to the heating caused by the losses

426 by the Joules effect. Therefore, in order to decrease voltage fluctuations, low ESR values are needed.

- 427 For high current circuit uses, designers should obtain capacitors with a minimum ESR [70] in order to
- 428 maintain power levels.
- 429 The Dissipation Factor (DF) which is given by the manufacturer:

$$DF = \tan \delta = ESR.C.\omega$$

(6)

The Dissipation Factor allows to determine the total losses P in the component according to the totalreactive power Q:

$$P = \tan \delta \, \frac{l^2}{C\omega} = Q. \tan \delta \tag{7}$$

### 432 2.2 Maintenance

There is an electrical model of the capacitor in which the usual properties (Losses, Joule heating, DF...) are defined by parameters such as ESR, ESL, C. By studying the evolution of some parameters such as the ESR and the capacitance under different operating conditions (temperature, voltage, frequency...), the evolution of the mode of operation and the degradation state of the capacitor can be determined. In order to improve the reliability and availability of industrial equipment by reducing the number of breakdowns, with a non-intrusive diagnosis, there are three types of maintenance:

1) Preventive maintenance is a maintenance carried out at predetermined intervals without
considering the instantaneous conditions of the use of the machine [71]. Waiting for failure can be a
costly strategy because failure of capacitors can lead to accidents which can cause financial loss and
damage.

2) Corrective maintenance is a strategy based on the idea that the costs sustained for breakdown and
repair are lower than the investment required for a maintenance program. Indeed, the maintenance
is realized after the detection of an anomaly and normal operating conditions have to be restored [72].

446 3) Predictive maintenance detects the appearance of aging or progressive failure in order to anticipate 447 breakdowns. To make a non-destructive or non-intrusive diagnosis, it is necessary to set up a periodic 448 monitoring of parameters on the equipment in operation. It uses sensor data to monitor a system and 449 then evaluates it to predict failure before it occurs. Thanks to that the reliability and availability of 450 industrial equipment can be improved by reducing the number of breakdowns. It also reduces the cost 451 of preventive maintenance by providing the best time to change parts, neither too early (preventive 452 maintenance) and neither too late (maintenance corrective) [73]. In order to apply conditional 453 preventive maintenance, it is necessary to identify the causes, mechanisms and modes that govern 454 capacitor failures. Then, it is necessary to select aging indicators that reflect the wear of the component 455 associated with these failures. Thanks to the evolution of aging indicators, it is possible to establish 456 aging models. Based on these aging models, the estimation of the remaining useful life and the health

457 status of the component can be performed.

In order to be able to apply predictive maintenance (summarized in **Figure 8**) it is necessary to identify the causes, mechanisms and modes that govern capacitor failures. By knowing the characteristics of the capacitors (state of the art or datasheet) and their evolution over time according to the different constraints applied (temperature, current and voltage), it is then possible to estimate the aging indicators.

Hence, there are different methods that can detect in real time the evolution of the ESR and the capacitance C in order to realize a system of monitoring and predictive maintenance of electrolytic capacitors [63], [74], [75]. To do so, it is necessary to create a method that can identify in real time

- aging indicators of any capacitors and then to create an algorithm. This algorithm needs to be able to build a model of aging in real time and to deduce the remaining life of the capacitors, due to the estimations of the ESR and C. There are also other methods and algorithms to determine the ESR and C of the electrolytic capacitor [76]–[78]. But they are expensive to use due to the many measurements and computations required. Indeed, The aging models based on offline method [63], [78] require accelerated aging tests which takes time for each new version of the capacitor.
- 472 Based on this diagnostic and prognostic work, optimizations can be performed. A selection of the
- 473 potential failure mechanism is necessary to reduce the number of indicators used in aging models.
- 474 These models are used to estimate the remaining life and to monitor the health of the capacitors. Once
- the aging model can be built and optimized, the model can be extrapolated into the future in order to
- 476 have an estimate of the remaining lifetime (and consequently the health status) of the capacitor.



477

478

#### Figure 8: Electrolytic capacitor failure prognosis method diagram.

479 Electrolytic capacitors are known to be sensitive to temperature and frequency variations. In fact, an 480 electrolytic capacitor has several modes and causes of failure. The main reason for temperature 481 dependence is due to the electrolyte and for the frequency it is due to the dielectric oxide [79]. This 482 frequency effect can be seen in the ripple current multipliers provided by capacitor manufacturers 483 [41]. It is due to energy losses in the temporal variation of the alignment of dipoles. It becomes even 484 more significant for capacitors with a thicker oxide layer. Regarding the increase in the temperature 485 of the capacitor, this one decreases the resistivities of the system. An increase in temperature also 486 increases the effective area of the electrode due to thermal expansion and results in an increase in C 487 and decrease in ESR with a temperature increase as it can be seen in [77], [80]. If the temperature 488 increases enough, the electrolyte can evaporate and the main mechanism of failure is the evaporation 489 of the electrolyte due to the ripple currents. This leads to an increase of the equivalent series resistance 490 (ESR) which increases the losses and, then, the temperature. This rise of temperature accelerates the 491 mechanism of evaporation and so on [79]. As the electrolyte solution dries up, the amount of 492 electrolyte decreases and the effective contact area between electrodes decreases. This results in a 493 decrease of the capacitance [78] and an increase in ESR which accelerates the degradation process and 494 can cause damage. The properties of the electrolyte constituting much of this resistance are the cause.

- 495 At low temperatures, a phenomenon of electrolyte thickening [81] induces less mobility of ions and496 leads to an increase in ESR.
- 497 All of electrolytic capacitors are frequency and temperature sensitive [82], have a fairly short lifespan 498 and have a fairly high failure rate [83]. There are many studies on the failure modes of electrolytic 499 capacitors, and mainly aluminum electrolytic capacitors. Indeed, from the understanding of the 500 mechanisms and failure modes of a capacitor, it is possible to apply a maintenance in order to know 501 the remaining lifetime of the component.
- 502 2.3 Mechanisms and failure modes

## 503 2.3.1 Non-solid electrolytic capacitor failure modes

As it has been seen in this paper, the capacitance and the ESR depend on the temperature, frequency and voltage. There is a lot of papers concerning the thermal influence [83]–[88], the current influence [56], [83]–[85], [87], [88], voltage influence [85], [88], [89] on these characteristics of the capacitor. A charge/discharge influence can be seen in some studies [85], [89], where excessive charging and discharging cycles at high currents will accelerate the degradation of the oxide shower and increase the leakage current. Here, the current being important in the capacitor at the time of the discharge, it

- will prevent the auto-regeneration of the layer of alumina oxide and thus increase the leakage current[90]. Indeed, there are many failure origins that can lead to various failure modes in electrolytic
  - Failures modes: Mechanism: Origin: Short circuit Poor deposit between electrodes Short circuit Local defect of Insulation fault the oxide layer in the dielectric Particles in the impregnated paper Insulation fault Leakage current in the impregnated increase Delicate paper Manufacturing Terminals Mechanical stress defect disconnected Defective welding Poor contact Open circuit of the terminals Contamination Corrosion Solid case Opening the H2 emission Permeability safety valve Reverse Voltage Pressure increase Unreasonnable charge/discharge Wrong use Electrolyte leak Porous seal Overvoltage Thermal stress Repair of the oxide layer ESR increase consuming the electrolyte Physico-chemical degradation Capacity decrease Normal use Electrolyte evaporation Chemical degradation
- 512 capacitors. Evaporation of the electrolyte creates an overpressure inside the component. It can be
- 513 assumed that the rate of electrolyte loss is directly proportional to the vapor pressure of the
- electrolyte. Ref. [79] gives element to connect the core temperature to the vapor pressure of the
- electrolyte, which is mainly ethylene glycol. These elements are used to characterize the quality of the



end seal. The more the evaporation progresses, the greater the overpressure becomes and, beyond a

517 certain threshold, it can cause an explosion. An increase in the leakage current of the various 518 components has been observed during aging. This phenomenon is due to a degradation of the 519 dielectric. A degradation of the oxide layer facilitates the appearance of dielectric breakdown which 520 can short-circuit the capacitor. Indeed, the oxide layer (dielectric) determines the voltage withstand 521 (see Table 2). The leakage current in capacitors depends on the dielectric characteristics. Its density 522 must be homogeneous over the whole surface of the electrodes in order to obtain the lowest possible 523 leakage current. However, the self-healing phenomenon generates hydrogen ions (2) which will react 524 with the electrons supplied by the cathode to create gaseous dihydrogen. This dihydrogen will increase 525 the internal pressure of the system and is a flammable and reactive gas.

526 Figure 9 summarizes the impact of the different stresses on the capacitor. The causes are generally 527 related to manufacturing defects, wrong use or aging of the component. It appears that the prediction 528 of failure of these components other than that due to wear can only be statistical given the many 529 causes of failure leading to various failure modes. Therefore, in this case, the increase of the ESR and 530 the decrease of C are aging modes that occur after applied stress. Indeed, a thermal stress that can 531 cause the evaporation of the electrolyte or the rise of the pressure can generate the increase of the 532 ESR and the decrease of the capacitance. Similarly, a voltage stress that can degrade the oxide film of 533 the anode or cathode can also generate an increase in ESR, a decrease in capacitance and an increase 534 in leakage current. According to Figure 9, it would not be possible from the leakage current to estimate 535 the health status of the component since the origin of the failure is due to a manufacturing defect. 536 Indeed, it is difficult to quantify this parameter by online methods. In addition, according to certain 537 aging tests, this current has a stable then violent evolution when a fault appears. Therefore, the 538 leakage current will not be considered as an indicator of failure and aging, unlike ESR and C, although 539 there is some work on this subject [91], [92].

540 A normal use of the capacitor leads to the evaporation of the electrolyte and the repair of the oxide 541 layer. These are two causes of electrolyte disappearance, which is the main cause of capacitor 542 degradation under normal conditions. Voltage and temperature, even without exceeding the limit 543 values (wrong use), are important contributing factors to aging. An aging indicator is a parameter which 544 can quantify and monitor the overall aging of a capacitor. However, the ESR and the capacitance C are 545 two electrical parameters making it possible to monitor the degree of degradation of an electrolytic 546 capacitor. This is why these two parameters are considered as indicators of aging. The moments when 547 the aging indicators reach their limit value set by the user or by the standard correspond to the end-548 of-life of the capacitor. The end of life of an electrolytic capacitor under thermal and electrical 549 constraints is defined by a 20% decrease in capacitance or a 100% increase in ESR [93]–[96]. Common 550 lifetime specifications derived from endurance tests at 85, 105, and 125°C are shown in Figure 10. In 551 this figure, the variation of capacitance and impedance with respect to its origin during aging tests 552 under different temperatures is shown. As it is presented below, temperature is an aging factor for

553 capacitors.



554



Figure 10: Endurance tests under 85°C (red), 105°C (orange), 125°C (yellow) of an AEC [19].

556 Concerning other non-liquid electrolytic capacitors, as there is no liquid electrolyte such as in the 557 niobium or tantalum capacitor, the phenomena of wear related to electrochemical reactions cannot 558 take place. However, it is possible to use manufacturers' recommendations to extend the life of this 559 type of component. Polymer, solid tantalum, and solid niobium electrolytic capacitors also have a 560 lifetime specification. However, they do not have a lifetime specification in the non-solid AEC sense. 561 The many types of electrolytic capacitors exhibit different electrical aging behaviors and intrinsic 562 failure modes. In order to ensure long life and high reliability of the electrolytic capacitor, some 563 application rules are detailed below for each electrolytic capacitor.

- 564

### **565** 2.3.2 Solid and polymer electrolytic capacitor failure modes

• Polymer Tantalum and Niobium capacitor

567 Solid polymer tantalum electrolytic capacitors do have a life time specification. Indeed, the polymer 568 electrolyte has a slight deterioration of conductivity by a thermal degradation mechanism of the 569 conductive polymer. The electrical conductivity decreases, as a function of time, in agreement with a 570 granular metal type structure, in which aging is due to the shrinking of the conductive polymer grains 571 [97]. The main advantage of polymer electrolytic capacitors over wet electrolytic and MnO<sub>2</sub> capacitors 572 is their low temperature dependence coupled with their non-ignition failure mode. These capacitors 573 can avoid ignition because the conductive polymer cathode does not contain active oxygen that could 574 ignite the tantalum anode. The no-ignition failure mode is an important safety feature, especially in 575 low ESR circuits. Concerning the self-healing of polymer-based capacitors, they have a polymer playing 576 the role of an electrolyte. There is also the phenomenon of self-healing for this type of electrolytic 577 capacitor. As seen previously, the leakage current will generate a rise in temperature. This will allow 578 the vaporization of the polymer present in contact with the dielectric and the inhibiting of the 579 conductive contact of the defects. Or the leakage current will generate an oxidation of the polymer 580 increasing then the resistivity and limiting/blocking the leakage current. In both cases, the reduction 581 of the contact area causes a decrease of the capacitance.

### • Solid Tantalum and Niobium capacitor

583 The typical failure mode of solid MnO<sub>2</sub> tantalum and niobium capacitors is a short circuit, and in some 584 cases the failed capacitors ignite. The tantalum/niobium capacitor structure uses an extremely thin, 585 glass-like material for its dielectric. Throughout the process, foreign matter can enter the structure. 586 The soaking and drying process introduces multiple thermal exposures. Combined with the huge 587 surface area of the electrolytic capacitor, this leads to the formation of defects in the capacitor 588 structure. This is because when a large amount of stored energy is rapidly released through a small 589 break channel, micro-cracks or pores [98] in the dielectric, it causes a rapid increase in temperature 590 and release of oxygen from the MnO<sub>2</sub> cathode. Ignition is an important phenomenon to keep in mind. 591 It occurs if the resistivity of the defective dielectric is too low and when the leakage current which is 592 too high and overrides the self-healing phenomenon. For solid niobium capacitors, when the main 593 dielectric is broken, the capacitor goes to high resistance, typically about 34 k $\Omega$  [99]. Indeed, at 450°C 594 the transformation of  $MnO_2$  into  $Mn_2O_3$  is not instantaneous. This is why it is necessary to have a 595 leakage current that is not too high for the  $MnO_2$  to heat up and transform, otherwise there is a risk of 596 deterioration of the  $Ta_2O_5/Nb_2O_5$  and ignition in the fault. Nevertheless, a possibility of ignition in the 597 event of failure as well as a high ESR compared to the ESR of ceramic and film capacitors with metal 598 electrodes have limited the military applications of tantalum and niobium solid capacitors [100].

Aging is a process that activates the self-healing mechanism of the MnO<sub>2</sub> to remove defect sites from the capacitor structure. It happens when the application of an electric field generates a current through a defect site and causes a breakdown of the dielectric as well as the appearance of higher currents. At

- the fault site, there is a concentration of current in the MnO<sub>2</sub> adjacent to the fault. This current causes local heating of the MnO<sub>2</sub> at the fault current entry point. When the MnO<sub>2</sub> heats up to 500°C [98], it transforms into a less oxygenated state, Mn<sub>2</sub>O<sub>3</sub>. The more conductive manganese oxide combination is MnO<sub>2</sub>, and the reduction in oxygen content results in an increase in ESR. This conversion thus limits the current in the fault site and decreases the contact area thereby reduces the capacitance. These conversions are permanent, sealing these fault sites for the rest of the life of the capacitor.
- Derating voltage for Niobium and Tantalum capacitors

609 Tantalum and niobium capacitors are as reliable as other electronic components, with very low failure 610 rates. However, they have a unique failure mode called "field crystallization". Field crystallization 611 occurs only at certain sites on the metal-oxide interface that are favorable for the formation of 612 crystalline nuclei. These sites can be areas with high impurity content in the metal. Field crystallization 613 is a main reason for the degradation and catastrophic failures of solid niobium and tantalum capacitors. By reducing the maximum operating voltage from the rated voltage, the risk of failure as well as the 614 615 risk of potential ignition is reduced. Indeed, it is recommended by the manufacturers of tantalum and 616 niobium capacitors to reduce voltage by 50% and 20% respectively for temperatures below 85°C [55]. 617 There is a correlation between the time to failure and the conditions according to [102]. The effect of 618 voltage derating can be estimated from the following empirical component dependent equation:

$$\frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^n \exp\left(\frac{E_a}{KT}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right)$$

(8)

619 where:  $t_1$  and  $t_2$  stand for the time to failure under condition 1 and 2,  $V_1$  and  $V_2$  for the voltage 1 and 620 2,  $T_1$  and  $T_2$  for absolute temperature 1 and 2, n for the voltage stress exponential,  $E_a$  for the activation 621 energy for dielectric wear out and  $k_B$  is the Boltzmann constant.

The parameters n and  $E_a$  in this equation are typically determined from the distribution of failure time data in accelerated tests with several voltage combinations. The large surface area of tantalum or niobium pentoxide impurity sites exist in all capacitors. To minimize the possibility of providing enough activation energy to convert these impurity sites from an amorphous to a crystalline state that will conduct energy, it is recommended to use derating. By reducing the electric field inside the anode at these sites, the reliability of the tantalum or niobium capacitor can be greatly increased [103].

628 The knowledge of the physical mechanisms degrading the state of health of a component has allowed

the establishment of empirical law to relate the life of the component according to certain constraints.
 Just like derating in the case of tantalum and niobium capacitors, there are also laws linking the life of

631 a component and the aging indicators for non-solid electrolytic capacitors.

## 632 3. Aging process of non-solid electrolytic capacitors

633 It has been seen that normal use leads to the evaporation of the electrolyte and the repair of the oxide 634 layer. These are two causes of electrolyte disappearance, which is therefore the essential cause of 635 capacitor degradation under normal conditions. The physical consequences are: increase of ESR and 636 decrease of C. These two parameters are therefore essential both to measure the health of capacitors, 637 but also to build aging models. The objective in this chapter will be to determine the health of a non-638 solid electrolytic capacitor from physical measurements of ESR and C.

- 639 3.1 Characterization of aging indicators of electrolytic capacitors
- 640 It is important to have models of the variation of ESR and C as a function of influencing factors other
- 641 than aging, if they are for use as an aging indicator for predictive maintenance.

- The properties of the electrolyte constituting much of this resistance are the cause. For example at low
- 643 temperatures, the electrolyte is thick, induces less mobility of ions and leads to an increase in ESR [81].
- 644 The variation of ESR as a function of temperature can be approximately expressed by an exponential
- 645 law of the form [104]:

$$ESR(T) = \alpha + \beta \cdot e^{-\frac{T}{\gamma}}$$
<sup>(9)</sup>

646 With:  $\gamma$ ,  $\beta$ ,  $\alpha$  component dependent coefficients.

To have an accurate model, it can be, for example, adjusted by the least-squares method to fit the ESR drift for one type of capacitor. Levenberg Marquardt's non-linear least squares method allows a fine approximation of the model. However, there are more accurate models to describe the evolution of ESR as a function of temperature and time, detailed below.

- In [74], the method presented consists in parameterizing laws directly from datasheets provided by the manufacturers, without having to perform experimental tests for each capacitor. These evolution laws are self-parameterized by the implemented aging algorithm monitoring the aging indicators in real time and thus making it possible to determine the time before the failure of the capacitors used in the considered converters.
- 656 In order to facilitate the understanding of the physical principles involved in the capacitor and to 657 confirm theoretical models, it is interesting to perform characterizations. These characterizations will 658 make it possible to obtain macroscopic data and to highlight the influence of this data according to 659 certain parameters (voltage, temperature, frequency...) on the ESR and C. Throughout the 660 characterization of the capacitor, it will be essential to perform a metric characterization. This consists 661 of recording dimensions and weight for later comparison in the event that testing degrades the sample. 662 For example, the evaporation of the electrolyte can modify the structure, the weight and the behavior 663 of the capacitor under test.

### • Frequency Characterization:

665 Offline characterizations can be performed, the interest is to define some parameters before the aging of the capacitor. Using an impedance analyzer, it is possible to inject a sinusoidal signal of low 666 667 amplitude under continuous bias in order to study the modulus and phase of the response. This characterization will give the evolution of the impedance as a function of frequency. In Figure 11, the 668 modulus of impedance as a function of frequency is represented. The characteristics of the capacitors 669 670 are clearly divided into two areas. At low frequencies  $(f_l)$ , capacitors behave mainly capacitively and their imaginary parts can be likened to  $\frac{-1}{C\omega}$  reactance. However, with increasing frequency, the 671 672 inductive effect grows on the rest of the parameters until it dominates the behavior of these components. In this case, the reactance of the capacitors is assimilated to  $L\omega$  at high frequencies  $f_h$ . 673 674 The real part represents all the losses in the component, and is identified with the resonance frequency 675 where the total impedance Z of the capacitors is equivalent to its resistive part. The latter gives a global 676 view of the variation of the losses in the component, but does not allow to study the individual 677 evolution of the parameters ( $R_I$  and  $R_p$  from **Figure 6**) with respect to the applied constraints. This is 678 how the capacitance, the ESR and the ESL are defined:

$$C = \frac{1}{2.\pi.f.Z(f_l)}; \ ESR = Z(f_r); \ ESL = \frac{Z(f)}{2.\pi.f_h}$$
(10)

679 With:  $f_l$  a low frequency;  $f_r$  the resonant frequency;  $f_h$  a high frequency



680

**681** Figure 11: Bode diagram for an aluminum electrolytic capacitor (470  $\mu$ F / 50 V) with: ESL = 8.05.10<sup>-9</sup> H and ESR = 48.2 m $\Omega$ .

A complementary characterization to the proposed frequency characterization is possible. This consists of placing the capacitor under test in a climatic chamber and performing the same procedure in order to obtain several evolutions of the impedance as a function of frequency for different temperature values. Indeed, the state of life of a capacitor or the temperature can modify the behavior of the capacitor and thus the frequency response. As It has been seen, ESR and C depend on the temperature. The use of an environmental chamber is then required in order to get accurate values.

688 Characterizations under different voltages will allow us to study the dependence of the electrical 689 quantities, previously identified, according to the DC voltage. An impedance analyzer can be used for 690 the frequency characterization of components. In addition, an experimental model can be made to 691 reach nominal voltages of several hundred volts if necessary while protecting the impedance meter. 692 However, this configuration can limit the study frequency range.

• Temporal Characterization:

In this type of characterization, the interest is to be able to perform online measurements. Using the measurements previously made, it is then possible to define an equivalent model. The analyzer will give the values of the identified electrical parameters by considering a final model of the capacitor under test. Thus, the values of the capacitance C, the ESR and the ESL can be drawn. For example, the equivalent RLC schematic (**Figure 6**) is, at first, a good approximation. However, depending on whether it is placed before or after the resonance frequency, or whether there is more or less precision, this scheme can evolve later.



701

702 703

Figure 12: Diagram of the variation of the voltage of a capacitor during a charge and discharge. Blue curve: charging voltage. Orange curve: transient discharge. Yellow curve: constant discharge.

11 It is possible to determine the capacitance and the ESR of a capacitor under test thanks to a temporal characterization. The capacitor is charged using a DC voltage. Then, a discharge is carried out by measuring the variation of the voltage perceived by the capacitor. Graphically in **Figure 12**, four important points can be obtained. The voltage at the moment of discharge (A), two points (C and D) during the discharge and the point (B) obtained by the intersection between the moment of discharge and the extension of the linear regression line of the curve related to the decrease of the voltage during the discharge. One can obtain:

$C = L \frac{t(D) - t(C)}{c = L} \frac{v(A) - V(B)}{v(A) - V(B)}$	(11)
$C = I \cdot \frac{V(C) - V(D)}{V(C) - V(D)}$ and $ESR = \frac{I}{I}$	

711

Thus, all these experiments of the complete cell will allow to characterize the aging indicator. It is then
 possible to carry out the aging of the studied capacitor and to compare these precise results with the
 aging models in order to better understand the degradation of the latter.

715 3.2 Aging models for electrolytic capacitors

Accelerated aging tests applied to components aim to reveal their failure mechanisms in order to assess their reliability and useful life in a relatively short time. The main constraint to consider for electronic components is temperature because it has a major influence on their failure rate. The temperature of the component to be considered is a function of the ambient temperature and the power dissipation in the component. But the chemical reaction rate constant is dependent on the absolute temperature T which is given by the Arrhenius equation:

$$k_T = A. \, e^{\left(-\frac{E_a T}{k_B}\right)} \tag{12}$$

where:  $k_T$  is the rate constant; T is the absolute temperature; A is a pre-factor;  $E_a$  is the activation energy for the reaction.

The main effect of this type of aging is the evaporation of the electrolyte. Since this aging is comparable to a chemical reaction, Arrhenius' law can be used. It has been found that the activation energy  $(E_a)$  is of the order of 0.4 eV for AEC ([83], [105]) and 1.2 eV for tantalum capacitors [100]. The degradation rate of a capacitor is proportional to this exponential, whereas, the time of appearance of the failure *t* is inversely proportional to it. In order to determine the lifetime of electrolytic capacitors, the Arrhenius life-stress model can be used. It is the most common life-stress relationship utilized when 730 the acceleration stress is temperature [75], [106]–[108]. To estimate the lifetime at the temperature 731 T, the following equation can be used:

$$K_{T\,Arrhenius} = \frac{t}{t_0} = \frac{v_0}{v} = e^{\left(\frac{E_a}{k_B}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right)}$$
(13)

732 where: *t* is the time of appearance of failure;  $t_0$  is the specified lifetime given by the individual 733 datasheets of products;  $T_0$  is the specified temperature; *v* is the reaction speed according to the 734 expected conditions of use;  $v_0$  is the reaction rate under extreme conditions operation;  $K_{T Arrhenius}$ 735 is the temperature multiplying factor.

This law is interesting but it only involves temperature. Therefore, other aging laws involving several constraints exist. It gives a good approximation of the service life of a component, but it is limited to the effect of temperature alone. This estimate also depends on the range of the extrapolation (of the temperature); the values of life being all the more precise as the difference between the two temperatures is weak. It is possible to give an example in which the following aging equivalences have been obtained for an aging at 85°C extrapolated to 25°C: 2 years at 25°C is equivalent to 620h at 85°C and 5 years at 25°C is equivalent to 3115h at 85°C.

A second most common life-stress relationship is the general Eyring model [18], [109], [110]. Eyring's model improves Arrhenius's law because it can consider other constraints than temperature (humidity, voltage...). But, the downside of this model is the large number of parameters to identify. On the other hand, in a very large number of cases, this model can be simplified by considering some zero coefficients. So, the relationship of the time of appearance of failure can be found:

$$t_{Evring} = A.T^n.e^{\left(\frac{E_a}{Tk_B} + S_1\left(B + \frac{C}{T}\right) + S_2\left(D + \frac{E}{T}\right)\right)}$$
(14)

748 Where A, B, C, D, E, T and n are coefficients depending on the test and the failure with  $S_1, S_2$  the 749 constraints 1 and 2.

The prediction of capacitor life is mainly based on empirical models based on failure physics. The most commonly used model for electrolytic capacitors is based on Arrhenius' law, which describes the influence of the constraints related to the ambient temperature and the current flowing through the capacitors, and on the Coffin-Manson empirical law for the consideration of the applied voltage. Capacitor manufacturers offer, in their catalogs, a formula to estimate the lifespan of capacitors (*L*) according to the various constraints [18], [87], [111]:

$$L = L_0. K_T. K_I. K_V$$

with:  $L_0$  is the specified life (hours) under extreme operating conditions (maximum allowable temperature, maximum allowable current ripple, rated voltage);  $K_T$  is the temperature factor;  $K_I$  is the ripple current factor;  $K_V$  is the voltage factor;

$$K_{T} = 2^{\frac{\Theta_{0} - \Theta_{\chi}}{10}}$$

$$K_{I} = K_{r}^{\left(1 - \left(\frac{I_{IRMS_{\chi}}}{I_{RMS_{0}}}\right)^{2}\right)\frac{\Delta\Theta_{0}}{10}}{K_{V}} \qquad (16)$$

$$K_{V} = \left(\frac{V_{0}}{V_{\chi}}\right)^{n}$$

(15)

759 where:  $K_r$  is an empirical factor;  $\Theta_0$  is the maximum temperature;  $\Theta_x$  is the ambient temperature;  $\Delta \Theta_0$ 760 is the rise in internal temperature due to the rated RMS current;  $V_0$  is the rated voltage;  $V_x$  is the actual

- operating voltage;  $I_{IRMS_x}$  is the operating RMS current flowing in the capacitor;  $I_{RMS_0}$  is the rated RMS current of the capacitor; n is an empirical constant of security.
- 763 Where  $K_r$  is an empirical safety factor [99], [100]:
- 764  $K_r = 2$  if  $I_{RMSx} \le I_{RMSo}$
- $K_r = 4$  if  $I_{RMSx} > I_{RMSo}$  (lifetime is divided by 4)

The exponent *n* can vary between 1 and 6 although for most suppliers [87], [113], the exponent is fixed by the following conditions [100]:

768

$$0.5 \le \frac{V_0}{V_x} \le 0.8 \rightarrow n = 3$$
$$0.8 < \frac{V_0}{V_x} \le 1 \rightarrow n = 5$$

769

For small electrolytic capacitors, the lifetime is governed mainly by the temperature (consumption of the electrolyte) so the voltage factor  $K_V$  is estimated at 1 [18]. For every 10 °C increase in operating temperature, the life of the electrolytic capacitor reduces by half [113], [114]. But, there is a temperature range where the theory of lifetime is not applicable. Indeed, for a temperature higher than 100 °C, the temperature acceleration factor is different. Depending on temperature ranges of the lifetime estimation, the temperature acceleration factor needs to be modified [114].

776 In the literature, different models slightly modified can be found. Indeed, Gualous and Gallay [115] 777 gave a model where they assumed that the supercapacitor life is proportional to the inverse reaction 778 rate and proposed a modified Arrhenius equation. Dehbi and Wondrak [59] modified the temperature 779 factor (14) to account for the applied voltage. And then, Jánó and Pitica [116] proposed a model taking 780 into account the [115] [59] models. Cycling has an impact on the degradation of a supercapacitor and 781 therefore on its lifetime. Using temperature, voltage and current for accelerated cycling tests, [117] 782 this paper proposes a method to quantify the acceleration of aging during a cycling phase and a new 783 equation to estimate the lifetime in order to integrate the influence of the RMS current.

Capacitance depends mainly on the condition of the dielectric in aluminum electrolytic capacitors.
Indeed, the capacitance depends on the quality of the etching and the actual surface of the dielectric.
Moreover, the phenomenon of self-healing of the dielectric has an influence on the quality of the
dielectric and consequently on the capacitance. A linear model of the evolution of capacitance C as a
function of aging time represents well the experimental evolutions of capacitance shown [68]:

$$C(t) = \alpha_1 + \alpha_2 \cdot t \tag{17}$$

789 With:  $\alpha_1, \alpha_2$  the time evolution coefficients of C depending on the component.

The ESR primarily depends on the resistivity of the electrolyte in AEC. The variation in this resistance over time depends on the electrolyte and the aging temperature. A linear model of the evolution as a function of the aging time of the inverse ESR has been developed by Rhoades and Smith [118]. This linear model, model 1, in reverse was designed by Cathey and Joyner [119]. It provides a prediction of the evolution of the ESR as a function of aging time and temperature. The proposed relationship is as follows:

$$\frac{1}{ESR(t_x)} = \frac{1}{ESR(t=0)} \left(1 - A_0 t_x e^{-\frac{Ea}{k_B T_x}}\right)$$
(18)

796 With:  $t_x$  the aging time at temperature  $T_x$ ;  $ESR(t_x)$  the value of ESR at  $t_x$ ; ESR(0) the value of ESR at 797 t = 0;  $A_0$  a constant depending on the component;  $E_a$  the activation energy of an AEC.

The activation energy ( $E_a$ ) is of the order of 0.4 eV for AEC and this value is usually written as E the activation energy per Boltzmann's constant equals 4700 K [83], [105]. Although the model respects that the ESR is always positive and increases with aging, one can notice that in this model, the function

801 giving the value of the ESR is not defined at all points. Indeed if  $A_0 t_x e^{-\frac{Ea}{T_x}}$  tends to be equal to 1 then 802 the ESR tends towards infinity. Therefore, one of the signs of failure is the rise of the ESR which is faster 803 towards the end of the capacitor's life. There are also other assumptions on the variation of the ESR as 804 a function of temperature and time. Indeed, in [90], they supposed different models, here is an 805 example:

$$ESR_1(t_x) = (ESR(t=0) + A_1) \cdot e^{C_1 \cdot t_x}$$
(19)

806 Where:  $A_1C_1$  is a constant depending on the component.

From the particular equation of the ESR **(19)** and using the law of Arrhenius **(13)**, one can thus find the evolution of the ESR according to the time and the temperature of aging:

$$ESR_{2}(t',T') = (ESR(t=0,T')+A_{1}) \cdot e^{C_{1} \cdot t' \cdot e^{\frac{4700 \cdot (T'-T_{\nu})}{(T_{\nu}+273) \cdot (T'+273)}}}$$
(20)

809 With: t' the aging time at temperature T';  $T_v$  the aging temperature accelerated; T' the aging 810 temperature extrapolated; ESR(t', T') the value of ESR at t' at T'; ESR(0, T') the value of ESR at t = 0811 at T'.

The value of ESR(t=0) at a temperature T' is obtained by the equation (19) giving the variation of ESR as a function of temperature. The rate of the chemical reaction leading to the degradation of ESR depends on the aging temperature of the component [84]. Indeed, this dependence is expressed by the relation (13) which makes it possible to obtain an aging time t' at temperature T' from measurements made during another aging of time  $t_v$  and temperature  $T_v$ .

An example of the rise of the ESR during time is shown in **Figure 13** where the experimental values of the ESR are measured at 66 kHz and 25 °C and the temperature of the capacitor is being kept at 105 °C during the aging. The capacitors used in this study are aluminum electrolytic capacitors used in a dc/dc forward type converter to filter the output voltage. As it has been seen, the rise of the ESR increases more rapidly toward the end of the life of the capacitor. The evolution of the ESR follows a linear inverse ESR model versus time [104], [120], [121]. As it has been shown before, the determination of this model is necessary to predict the lifetime of the capacitor online.





Figure 13: ESR versus aging test of electrolytic capacitors at T=105°C [104].

### 826 3.3 Detect the aging of non-solid electrolytic capacitors

There are several methods existing, in the literature, in order to detect the electrolytic capacitor aging.
In practice, they require accelerated aging tests and these methods can be grouped in different
categories depending on the type of stress applied.

830 A first type of stress used in most cases is the temperature using the Arrhenius equation. Temperature 831 is considered as the main constraint to be considered for electronic components because it has a major 832 influence on their failure rate. The temperature to consider is the temperature at the heart of the 833 component, which is a function of the ambient temperature and its heating created by dissipation. In 834 [84], a life model of AEC that is based on the mechanism of electrolyte vaporization and loss through 835 the seal has been developed. This physical failure model makes it possible to calculate the lifetime of 836 capacitors as a function of temperature using Arrhenius' law. The model incorporates relationships for 837 ESR change with electrolyte loss, ESR change with temperature, and heat transfer value using 838 temperature stress. These results are then compared with the lifetimes obtained using a law used in 839 industry which gives substantially more liberal predictions. Indeed, this method of detecting the aging 840 of electrolytic capacitors is quite accurate and allows the agreement between the prediction and the 841 experiment as in [104]. The method predicts the life of an electrolytic capacitor by estimating the 842 current state ESR and comparing it to its new condition with temperature constraint. The ESR, defined 843 by the ratio of the voltage ripple by the ripple current, is compared to the ESR theorical. Test results mostly 844 agree with the prediction and the mean difference is less than 10 %. It is also possible to quote [63], 845 [122] where the remaining life is estimated by subtracting the operating life obtained by regression 846 equations from the total life by using temperature stress. Indeed, this operating life is obtained using 847 regression (the least square fitting method) equations characterizing the temporal variations of the 848 capacitance C and of the ESR as a function of temperature. And from the Arrhenius equation for a fixed 849 temperature of the capacitor, the total lifetime can be deduced. The method used is to measure the 850 current and ripple voltage of the capacitors using cheap and simple analog circuits. This same method 851 can be seen in [123], it allows to obtain the operating lifetime of a capacitor by regression equations. 852 In this paper, a combined experimental and numerical approach, using multi-physics modeling 853 techniques to extract relevant physical parameters, at the component level, is proposed for lifetime 854 prediction using temperature stress. A degradation modeling approach is proposed in which the 855 parameters of the regression equations characterizing the capacitance and the ESR over time follow 856 Arrhenius' law. Increased current ripple in capacitors is considered a criterion for failure. Time to failure 857 can be calculated under variable temperature operating conditions.

858 It is possible to observe methods that include the impact of voltage in addition to using temperature 859 as a stress. Temperature is considered a major constraint, but it is not the only one. Some works try to 860 prove that it is not the majority compared to tension. In fact, many works deal with aging tests using temperature and voltage as a type of stress. There is therefore a second type of stress, that is 861 862 temperature used with voltage. In [116], [124], it has been decided that current prediction algorithms are not accurate enough to precisely estimate lifetime for AEC. Consequently, prediction methods are 863 864 combined (using voltage and temperature constraint) in order to give a higher accuracy lifetime 865 prediction algorithm. A new method of predicting the life of capacitors is introduced. The service life 866 obtained is more precise than the previous models because the capacitors are affected by the applied voltages. Another work [18] shows the ESR and capacitance as aging indicators and major factors 867 868 influencing the lifetime of electrolytic capacitors used in power converters. In order to know the shape 869 of aging laws, accelerated aging tests are done in this work to assess the effects of thermal and 870 electrical overstresses through time. Early results show that a cubic regression has the best fit with the 871 experimental aging data.

- The combination of temperature and current as a type of stress is presented in [125]. It is a new
  method which predicts the life of an electrolytic capacitor by estimating the ESR and the ripple current
  flowing through the capacitor using temperature and current as a constraint. A life model employing
- 875 core temperature estimation derived from ESR deterioration and operating conditions is shown.

876 As seen previously, the voltage can influence the aging of the capacitors by applying a voltage 877 overstress in order to subject the capacitor to continuous charge and discharge cycles. The purpose of 878 this experiment is to study the effect of high voltage stress on degradation of the capacitor in [126]. 879 Using voltage stress, a methodology to predicting the remaining useful life for electrolytic capacitors 880 based on a Kalman filter is presented. It focuses on condition-based health assessment by estimating 881 the current state of health. In addition, this type of aging can be applied to tantalum electrolytic 882 capacitors as shown in [127] where a substantial number of samples have been life-tested under 883 voltage stress at temperatures from 25°C to 85°C.

- 884 Finally, a last category of stress is the one under nominal condition, which means below the operating 885 temperature and voltage. In [105], under nominal condition, the drift of ESR with time is determined 886 by the Arrhenius model. A third-degree regression model is proposed for the degradation of the mean 887 capacitance as a function of time. This type of stress under nominal condition can be seen in [128], this 888 work tries to determine all the evolution laws versus temperature, frequency and operation time. To 889 do so, the components are under nominal voltage at the maximum operating temperature allowed 890 with the use of a climate chamber. Then, the capacitors internal parameter behavior can be analyzed 891 against operating time and determine the aging laws of parameters as ESR and C of AEC.
- 892 There are disadvantages to these methods, it is necessary to have models of degradation of the 893 capacitors in real time considering the operating conditions (ambient temperature, voltage, 894 frequency...) to predict the lifetime of the capacitors. In addition, physical models and models of 895 degradation based on data regression are then combined. But these regression-based models require 896 large sets of samples to increase estimation precision. These different methods all use accelerated 897 aging tests. These methods constitute an essential learning phase, to be carried out offline, before any 898 online evaluation of the life of the capacitors. It is important to note that the accelerated aging tests 899 are carried out with each new version of the capacitor before it is integrated into the model. This is 900 why this method is costly in terms of time and money, which makes this step not very viable at the 901 industrial level. It would be interesting to design a strategy that uses the least amount of offline 902 resources. This strategy will not only improve the fit of the model, but also the prediction of health 903 status. In [74] the invention relates to a method for determining a value representative of the 904 remaining useful life (RUL) of a capacitor, based on specific values such as a maximum temperature 905 value and a maximum voltage value of the capacitor. The method is in two parts. The first one consists 906 in identifying in real time indicators of aging ESR and C of any capacitors integrated in a power 907 converter. The second phase is the implementation of an algorithm capable of constructing, thanks to 908 the estimations of ESR and C, a model of aging in real time and capable of deducing the remaining life 909 of the capacitors. As discussed, the offline learning phase where accelerated aging tests are performed 910 is a costly and time-consuming method. This invention is relevant because it allows an online 911 evaluation of the capacitor lifetime without performing an offline learning phase.

## 912 4. Conclusion

In this paper, a review of operation and properties of electrolytic capacitors is presented. A focus has
been done on the respective characteristics of three different types of electrolytic capacitors
(Aluminum, Tantalum and Niobium), the series equivalent circuit model of an electrolytic capacitor
and some information that can be deduced. The paper also proposed a review on predictive

917 maintenance in order to anticipate breakdowns with a non-intrusive diagnosis, neither too early as the 918 preventive maintenance nor too late as the corrective maintenance. In order to overcome these 919 problems and to be able to estimate the remaining life with the predictive maintenance, it is necessary 920 to identify the mechanisms and failure mode to limited the number of aging indicators. Different 921 methods and algorithm based on the variation of aging indicators as a function of constraint that can 922 lead to aging laws are proposed. Finally, an overview of several significant methods existing in

923 literature is presented, based on failure prognosis.

In order to predict the trend of electrolytic capacitors, one can imagine a hybrid electrolytic capacitor, a technology that would combine the advantages of electrolytic capacitors such as high electrode surface (pressed and sintered, porous, ...) with a composite hybrid dielectric structure to achieve greater specific energy [129]. Carbon nanostructures can help to reach higher capacitance density than the use of porous electrode [130]. Therefore, future developments will certainly always focus on optimizing existing electrode materials and creating new materials with energy densities close to those of batteries [131].

## 931 References

- [1] E. Wolfang, "Examples for failures in power electronics systems," *ECPE Tutorial on Reliability of Power Electronic Systems*, 2007.
- [2] S. Yang, A. Bryant, P. Mawby, Dawei Xiang, Li Ran, and P. Tavner, "An Industry-Based Survey of Reliability in Power Electronic Converters," *IEEE Transactions on Industry Applications*, 2011, doi: 10.1109/TIA.2011.2124436.
- 937 [3] H. Wang *et al.*, "Transitioning to Physics-of-Failure as a Reliability Driver in Power Electronics,"
  938 *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2014, doi:
  939 10.1109/JESTPE.2013.2290282.
- [4] U.-M. Choi, F. Blaabjerg, and K.-B. Lee, "Study and Handling Methods of Power IGBT Module
   Failures in Power Electronic Converter Systems," *IEEE Transactions on Power Electronics*, 2015, doi: 10.1109/TPEL.2014.2373390.
- 943 [5] D. Ton and W. Bower, "Summary Report on the DOE High-tech inverter workshop," US Department
  944 of Energy, 2005. Accessed: Nov. 01, 2022. [Online]. Available:
  945 https://www1.eere.energy.gov/solar/pdfs/inverter\_II\_workshop.pdf
- 946 [6] H. Wang, Y. Yang, and H. Sangwongwanich, "Design for Reliability of Power Electronic Systems,"
   947 *Power electronics handbook. Butterworth-Heinemann*, 2018, doi: 10.1109/IECON.2012.6388833.
- 948 [7] M. E. Orazem and B. Tribollet, *Electrochemical impedance spectroscopy*. The Electrochemical
   949 Society series. Wiley, 2008.
- [8] B. E. Conway, "Chapter 12: Capacitance Behavior of films of conducting, electrochemically
   reactive polymers," in *Electrochemical Supercapacitors Scientific Fundamentals and Technological Applications*, Springer, 1999.
- [9] J. R. Miller, D. A. Evans, and E. Company, "Properties and performance of hybrid aluminum
   electrolytic / electrochemical capacitors," presented at the CARTS conference. Components
   Technology Institute, 1996.
- 956 [10] Nichicon corporation, "Conductive Polymer Hybrid Aluminum Electrolytic Capacitors." Datasheet.
   957 Accessed: Nov. 01, 2022. [Online]. Available:
   958 https://www.nichicon.co.jp/english/products/pdf\_x/e-gya.pdf
- [11] K. Nogami, K. Sakamoto, T. Hayakawa, and M. Kakimoto, "The effects of hyperbranched
   poly(siloxysilane)s on conductive polymer aluminum solid electrolytic capacitors," *Journal of Power Sources*, 2007, doi: 10.1016/j.jpowsour.2007.01.030.
- 962 [12] E. Manla, G. Mandic, and A. Nasiri, "Development of an Electrical Model for Lithium-Ion
   963 Ultracapacitors," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2015, doi:
   964 10.1109/JESTPE.2014.2383955.

- 965 [13] D. S. Campbell, "Electrolytic Capacitors," Components and Circuits Group Symposium on Capacitors
   966 held in London, 1970.
- [14] J. Both, "Electrolytic capacitors, 1890 to 1925: early history and basic principle," *IEEE Electrical Insulation Magazine*, 2015, doi: 10.1109/MEI.2015.6996675.
- [15] J. Ho and R. T. Jow, "Historical Introduction to Capacitor Technology," *IEEE Electrical Insulation Magazine*, 2010, doi: 10.1109/MEI.2010.5383924.
- [16] J. Both, "Electrolytic capacitors from the postwar period to the present," *IEEE Electrical Insulation Magazine*, 2016, doi: 10.1109/MEI.2016.7414227.
- 973 [17] Nichicon corporation, "General Descriptions of Aluminum Electrolytic Capacitors, Technical
   974 Notes." 2015. Accessed: Nov. 01, 2022. [Online]. Available:
   975 https://www.nichicon.co.jp/english/products/pdf/aluminum.pdf
- [18] A. E. Hayek, P. Venet, R. Mitova, M.-X. Wang, G. Clerc, and A. Sari, "Aging laws of electrolytic
  capacitors," p. 14, 2018.
- [19] J. Both, "The modern era of aluminum electrolytic capacitors," *IEEE Electrical Insulation Magazine*,
  2015, doi: 10.1109/MEI.2015.7126071.
- [20] R. S. Alwitt and R. G. Hills, "The Chemistry of Failure of Aluminum Electrolytic," *IEEE Transactions on Parts, Materials and Packaging*, 1965, doi: 10.1109/TPMP.1965.1135396.
- [21] P. McKnight Deeley and The FaradNet Staff, "Part 3 Chapter 10 : Non-Aqueous Electrolytes and
   Their Characteristics," Accessed: Nov. 01, 2022. [Online]. Available:
   https://web.archive.org/web/20160617163728/http://www.faradnet.com/deeley/chapt\_10.ht
   m#index
- [22] A. Berduque, Z. Dou, and R. Xu, "Electrochemical Studies for Aluminium Electrolytic Capacitor
   Applications: Corrosion Analysis of Aluminium in Ethylene Glycol-Based Electrolytes," *CARTS- Europe Virtual Conference.*, 2009.
- 989 [23] H. O. Siegmund, "The Aluminum Electrolytic Condenser," *Bell System Technical Journal*, 1929, doi:
   990 10.1002/j.1538-7305.1929.tb02305.x.
- [24] J. L. Stevens, J. S. Shaffer, and J. T. Vandenham, "The service life of large aluminum electrolytic
   capacitors: effects of construction and application," *IEEE Transactions on Industry Applications*,
   2002, doi: 10.1109/TIA.2002.802922.
- 994 [25] Z. Dou and R. Xu, "Development of Electrolytes in Aluminium Electrolytic Capacitors for
   995 Automotive and High Temperature Applications," *Conference Proceedings*, 2008.
- [26] K. N. Borba, F. Trombetta, R. F. de Souza, and E. M. A. Martini, "Stability of Al2O3/Al in ionic liquid
   BMI.BF4/γ-butyrolactone electrolytes for use in electrolytic capacitors," *Ionics*, 2017, doi: 10.1007/s11581-016-1912-x.
- 999 [27] J. Barthel, H.-J. Gores, G. Schmeer, and R. Wachter, "Non-aqueous electrolyte solutions in
  1000 chemistry and modern technology," in *Physical and Inorganic Chemistry*, Springer Berlin
  1001 Heidelberg, 1983. doi: 10.1007/3-540-12065-3\_2.
- 1002 [28] J. D. Dale-Lace, "Capacitors for power supplies," *Electronics and Power*, 1986, doi: 10.1049/ep.1986.0146.
- 1004 [29] D. Petrov and U. Hilleringmann, "Water-based primary cell for powering of wireless sensors," in
   1005 *IEEE SENSORS*, 2020. doi: 10.1109/SENSORS47125.2020.9278891.
- 1006 [30] J. Menzel, E. Frackowiak, and K. Fic, "Electrochemical capacitor with water-based electrolyte
  1007 operating at wide temperature range," *Journal of Power Sources*, 2019, doi:
  101016/j.jpowsour.2018.12.080.
- [31] J. H. Masliyah and S. Bhattacharjee, *Electrokinetic and colloid transport phenomena*. Wiley Interscience, 2006.
- [32] H.-J. Butt, K. Graf, and M. Kappl, *Physics and chemistry of interfaces*. Physics textbook: Wiley-VCH,
   2003.
- 1013 [33] S. Wolf and R. N. Tauber, "Silicon Processing for the VLSI Era: Process Technology." Process1014 Technology, 1999.

- 1015 [34] D. G. W. Goad and H. Uchi, "Modelling the capacitance of d.c. etched aluminium electrolytic
  1016 capacitor foil," *Journal of applied electrochemistry*, 2000, doi: https://doi.org/10.1007/s108541017 015-3280-0.
- 1018 [35] M. Makdessi, A. Sari, and P. Venet, "Improved model of metalized film capacitors," *IEEE* 1019 *Transactions on Dielectrics and Electrical Insulation*, 2014, doi: 10.1109/TDEI.2013.004158.
- 1020 [36] O. G. Gnonhoue, A. Velazquez-Salazar, É. David, and I. Preda, "Review of Technologies and 1021 Materials Used in High-Voltage Film Capacitors," *Polymers*, 2021, doi: 10.3390/polym13050766.
- 1022[37] TDK Electronics, "Aluminum Electrolytic Capacitors General technical information," 2019,1023Accessed: Nov. 01, 2022. [Online]. Available: https://www.tdk-1024electronics.tdk.com/download/185386/e724fb43668a157bc547c65b0cff75f8/pdf-1025generaltechnicalinformation.pdf
- 1026 [38] Exxelia, "Electrolytic Aluminum Capacitors Technical data." 2017. Accessed: Nov. 01, 2022.
   1027 [Online]. Available: https://exxelia.com/uploads/PDF/aluminum-electrolytic-capacitors-catalog 1028 6298a1c93f65a.pdf
- [39] P. Venet, "Amélioration de la sûreté de fonctionnement des dispositifs de stockage d'énergie."
   (Doctoral dissertation, Université Claude Bernard-Lyon I), 2007.
- 1031 [40] A. E. Hayek, "Analyse de vieillissement, estimation de la durée de vie et méthode de surveillance
  1032 de l'état de santé des condensateurs électrolytiques." Doctoral dissertation, Université de Lyon,
  1033 2020.
- [41] United Chemi-Con, "Aluminum electrolytic capacitors." Rosemont, 2021. Accessed: Nov. 01, 2022.
   [Online]. Available: https://www.chemi-con.co.jp/en/catalog/pdf/al-e/al-all-e1001u-2020.pdf
- [42] Y. Freeman, P. Lessner, and I. Luzinov, "Reliability and Failure Mode in Solid Tantalum Capacitors,"
   *ECS Journal of Solid State Science and Technology*, 2021, doi: 10.1149/2162-8777/abf728.
- [43] F. Larmat, J. R. Reynolds, and Y.-J. Qiu, "Polypyrrole as a solid electrolyte for tantalum capacitors,"
   *Synthetic Metals*, 1996, doi: 10.1016/0379-6779(96)80198-6.
- [44] YAGEO Corporation, "MLCC replacements for tantalum capacitors." 2002. [Online]. Available:
   https://studylib.net/doc/18038548/mlcc-replacements-for-tantalum-capacitors
- [45] Y. Freeman and P. Lessner, "Evolution of Polymer Tantalum Capacitors," *Applied Sciences*, 2021,
   doi: 10.3390/app11125514.
- [46] Jiaoying Huang, Yongkang Wan, Cheng Gao, and Yuanyuan Xiong, "Discussion on multilayer
   ceramic replacements for tantalum capacitors," in *Prognostics and System Health Management Conference (PHM)*, 2015, pp. 1–5. doi: 10.1109/PHM.2015.7380064.
- 1047 [47] E. K. Reed, "Characterization of Tantalum Polymer Capacitors." NASA Electronic Parts and1048 Packaging Program, NEPP Task, 2006.
- [48] V. Sprague, "Solid Tantalum Surface Mount Chip Capacitors TANTAMOUNT<sup>™</sup>, Molded Case,
   Standard Industrial Grade," 2021, Accessed: Nov. 01, 2022. [Online]. Available:
   https://www.tme.eu/Document/b7b423fee79a0baa3802818aefa8a73f/293d.pdf
- 1052 [49] I. Bishop and J. Gill, "Reverse voltage behavior of solid tantalum capacitors, Technical 1053 information." AVX Ltd, 2013.
- [50] K. Kim, J. Park, G. Cha, J. E. Yoo, and J. Choi, "Electrochemical etching of a niobium foil in
   methanolic HF for electrolytic capacitor," *Materials Chemistry and Physics*, 2013, doi:
   10.1016/j.matchemphys.2013.06.008.
- [51] E. N. Tarekegn, W. R. Harrell, I. Luzinov, P. Lessner, and Y. Freeman, "Environmental Stability of Polymer Tantalum Capacitors," *ECS Journal of Solid State Science and Technology*, 2022, doi: 1059 10.1149/2162-8777/abba02.
- [52] T. S. Kumar, S. R. Kumar, M. L. Rao, and T. L. Prakash, "Preparation of Niobium Metal Powder by
   Two-Stage Magnesium Vapor Reduction of Niobium Pentoxide," *Journal of Metallurgy*, 2013, doi: https://doi.org/10.1155/2013/629341.
- 1063 [53] T. Kárník, "NIOBIUM OXIDE FOR CAPACITOR MANUFACTURING," *Metal*, 2008.
- [54] H. Zillgen and M. Stenzel, "New Niobium Capacitors with stable electrical parameters," *Active and Passive Electronic Components*, 2001.

- [55] Y. Freeman, *Tantalum and Niobium-Based Capacitors*. Springer International Publishing, 2018. doi:
   10.1007/978-3-319-67870-2.
- 1068 [56] A. Shrivastava, "RELIABILITY EVALUATION OF LIQUID AND POLYMER ALUMINUM ELECTROLYTIC
   1069 CAPACITORS," p. 113.
- 1070[57] J. Yoo, "Liquid electrolyte-free cylindrical Al polymer capacitor review: Materials and1071characteristics," Journal of Power Sources, 2015, doi:1072https://doi.org/10.1016/j.jpowsour.2015.03.023.
- 1073 [58] M. Agrawal, R. Singh, M. Ranitović, Z. Kamberovic, C. Ekberg, and K. K. Singh, "Global market trends
   1074 of tantalum and recycling methods from Waste Tantalum Capacitors: A review," *Sustainable* 1075 *Materials and Technologies*, 2021, doi: 10.1016/j.susmat.2021.e00323.
- 1076 [59] A. Dehbi, W. Wondrak, Y. Ousten, and Y. Danto, "High temperature reliability testing of aluminum
  1077 and tantalum electrolytic capacitors," *Microelectronics Reliability*, 2002, doi: 10.1016/S00261078 2714(02)00021-5.
- 1079 [60] V. Sprague, "AC Ripple Current Calculations." Application Notes, 2002. Accessed: Nov. 01, 2022.
   1080 [Online]. Available: https://www.vishay.com/docs/40031/apprippl.pdf
- [61] R. U. A. Shaikh, A. Saeed, and R. Kumar, "Review on present and future integration techniques for
   capacitors in motor drives," in *2018 International Conference on Computing, Mathematics and Engineering Technologies (iCoMET)*, Mar. 2018. doi: 10.1109/ICOMET.2018.8346442.
- 1084 [62] O. Ondel, E. Boutleux, and P. Venet, "A decision system for electrolytic capacitors diagnosis," in
   35th Annual Power Electronics Specialists Conference, 2004. doi: 10.1109/PESC.2004.1354771.
- 1086 [63] K. Abdennadher, P. Venet, G. Rojat, J.-M. Retif, and C. Rosset, "A Real-Time Predictive 1087 Maintenance System of Aluminum Electrolytic Capacitors Used in Uninterrupted Power Supplies,"
   1088 *IEEE Transactions on Industry Applications*, 2010, doi: 10.1109/TIA.2010.2049972.
- [64] D. A. John and K. Biswas, "Electrical equivalent circuit modelling of solid state fractional capacitor,"
   *AEU International Journal of Electronics and Communications*, 2017, doi:
   10.1016/j.aeue.2017.05.008.
- 1092 [65] J. Čuntala, M. Frivaldský, and A. Kondelová, "Thermal simulation of electrolytic capacitor during
   1093 impulse operation," 2014.
- 1094 [66] A. L. d'Entremont, "Thermal modeling of electrochemical capacitors." Doctoral dissertation,
   1095 University of California, Los Angeles, 2015.
- 1096 [67] S. G. Parler, "Thermal modeling of aluminum electrolytic capacitors," in *Conference Record of the* 1097 *1999 IEEE Industry Applications Conference. Thirty-Forth IAS Annual Meeting (Cat.* 1098 *No.99CH36370)*, 1999. doi: 10.1109/IAS.1999.799180.
- 1099 [68] F. Perisse, P. Venet, G. Rojat, and J. M. Rétif, "Simple model of an electrolytic capacitor taking into
  account the temperature and aging time," *Electrical Engineering*, 2006, doi: 10.1007/s00202-004101 0265-z.
- [69] P. Freiburger, "Transient thermal modeling of aluminum electrolytic capacitors under varying mounting boundary conditions," in 2015 21st International Workshop on Thermal Investigations of ICs and Systems, 2015. doi: 10.1109/THERMINIC.2015.7389619.
- [70] Z. Fan, N. Islam, and S. B. Bayne, "Towards kilohertz electrochemical capacitors for filtering and pulse energy harvesting," *Nano Energy*, 2017, doi: 10.1016/j.nanoen.2017.06.048.
- [71] H. Soliman and H. Wang, "A Review of the Condition Monitoring of Capacitors in Power Electronic
   Converters," *IEEE Transactions on Industry Applications*, 2016, doi:
   10.1109/OPTIM.2015.7427012.
- [72] M. Catelani, L. Ciani, R. Singuaroli, and A. Mannucci, "Electrolytic Capacitor Lifetime Prediction in
   Ground Mobile Applications." 13th IMEKO TC10 Workshop on Technical Diagnostics, 2014.
- [73] S. R. McCormick, K. Hur, S. Santoso, A. Maitra, and A. Sundaram, "Capacitor bank predictive maintenance and problem identification using conventional power quality monitoring systems," in *Power Engineering Society General Meeting*, 2004. doi: 10.1109/PES.2004.1373199.
- [74] A. E. Hayek, P. Venet, G. Clerc, M. Wang, R. Mitova, and A. Sari, "Estimation of the remaining Useful
   Life of capacitors." U.S. Patent Application No 16/878,499, 2020.

- [75] H. Malek, S. Dadras, and Y. Chen, "Fractional order equivalent series resistance modelling of
   electrolytic capacitor and fractional order failure prediction with application to predictive
   maintenance," *IET Power Electronics*, 2016, doi: 10.1049/iet-pel.2015.0636.
- [76] P. Venet, H. Darnand, and 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. doi: 10.1109/INTLEC.1993.388568.
- [77] Kwang-Woon Lee, Myungchul Kim, Jangho Yoon, Sang Bin Lee, and Ji-Yoon Yoo, "Condition
   Monitoring of DC-Link Electrolytic Capacitors in Adjustable-Speed Drives," *IEEE Transactions on Industry Applications*, 2008, doi: 10.1109/TIA.2008.2002220.
- [78] J. R. Celaya, C. Kulkarni, S. Saha, G. Biswas, and K. Goebel, "Accelerated aging in electrolytic
  capacitors for prognostics," in *Proceedings Annual Reliability and Maintainability Symposium*,
  2012. doi: 10.1109/RAMS.2012.6175486.
- [79] M. L. Gasperi, "Life Prediction Modeling of Bus Capacitors in AC Variable-Frequency Drives," *IEEE Transactions on Industry Applications*, 2005, doi: 10.1109/TIA.2005.858258.
- [80] Y. Kudoh, M. Fukuyama, and S. Yoshimura, "Stability study of polypyrrole and application to highly
  thermostable aluminum solid electrolytic capacitor," *Synthetic Metals*, 1994, doi: 10.1016/03796779(94)90093-0.
- 1134 [81] B. Alvsten, *Electrolytic capacitors theory and application*, RIFA Electrolytic Capacitors. Sweden, 1135 1995.
- [82] C. Joubert, G. Rojat, and P. Venet, "Capacitors: revisiting a classical technology to face new challenges," International conference Automotive Power Electronics, Paris, 2007.
- [83] A. Lahyani, P. Venet, G. Grellet, and P.-J. Viverge, "Failure prediction of electrolytic capacitors during operation of a switchmode power supply," *IEEE Transactions on Power Electronics*, 1998, doi: 10.1109/63.728347.
- [84] M. L. Gasperi, "Life prediction model for aluminum electrolytic capacitors," in *IAS '96. Conference Record of the Industry Applications Conference Thirty-First IAS Annual Meeting*, 1996. doi:
   10.1109/IAS.1996.559241.
- [85] C. S. Kulkarni, "A Physics-Based Degradation Modeling Framework for Diagnostic and Prognostic
   Studies in Electrolytic Capacitors." Doctoral dissertation, Vanderbilt University, 2013.
- [86] C. S. Kulkarni, G. Biswas, J. R. Celaya, and K. Goebel, "Physics Based Degradation Models for
   Electrolytic Capacitor Prognostics under Thermal Overstress Conditions," *International Journal of Prognostics and Health Management*, 2012, doi: 10.36001/jjphm.2013.v4i1.1448.
- 1149 [87] D. A. Albertsen, "Electrolytic Capacitor Lifetime Estimation." JIANGHAI Eur. GmbH, 2010.
- [88] A. Shrivastava *et al.*, "Detection of capacitor electrolyte residues with FTIR in failure analysis," J
   *Mater Sci: Mater Electron*, vol. 25, no. 2, pp. 635–644, Feb. 2014, doi: 10.1007/s10854-013-1146 x.
- [89] A. M. Imam, D. M. Divan, R. G. Harley, and T. G. Habetler, "Electrolytic Capacitor Failure
  Mechanism Due to Inrush Current," *IEEE Industry Applications Annual Meeting*, 2007, doi:
  10.1109/07IAS.2007.115.
- 1156 [90] 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." Doctoral dissertation, Université Claude Bernard Lyon 1, 2003.
- [91] J. Pavelka, J. Sikula, P. Vasina, V. Sedlakova, M. Tacano, and S. Hashiguchi, "Noise and transport characterisation of tantalum capacitors capacitors," *Microelectronics Reliability*, 2002, doi: https://doi.org/10.1016/S0026-2714(02)00013-6.
- [92] K. Hasegawa, K. Tsuzaki, and S. Nishizawa, "DC-bias-voltage dependence of degradation of aluminum electrolytic capacitors," *Microelectronics Reliability*, 2018, doi: 10.1016/j.microrel.2018.02.012.
- 1165 [93] U.S of A. D. of Defense, "Military HandBook Reliability prediction of electronic equipment," p.1166 150, 1991.

- 1167[94] J. Renwick, C. S. Kulkarni, and J. R. Celaya, "Analysis of Electrolytic Capacitor Degradation under1168ElectricalOverstressforPrognosticStudies,"2015,doi:1169https://doi.org/10.36001/phmconf.2015.v7i1.2713.
- 1170 [95] Fixed Electrolytic, "General specification for capacitors (MIL-C-62F)," 2008.
- 1171 [96] International Electrotechnical Comission, "IEC 60068-1 : Environmental testing," 1988.
- 1172 [97] E. Vitoratos *et al.*, "Thermal degradation mechanisms of PEDOT:PSS," *Organic Electronics*, 2009, doi: 10.1016/j.orgel.2008.10.008.
- 1174[98] Y. Pozdeev, "Reliability comparison of tantalum and niobium solid electrolytic capacitors," Quality1175and Reliability Engineering International,1998,doi:10.1002/(SICI)1099-11761638(199803/04)14:2<79::AID-QRE163>3.0.CO;2-Y.
- 1177 [99] T. Zednicek, "Voltage Derating Rules for solid tantalum and niobium capacitors." 2003. Accessed:
   1178 Nov. 01, 2022. [Online]. Available: https://www.kyocera-avx.com/news/voltage-derating-rules 1179 for-solid-tantalum-and-niobium-capacitors/
- [100]B. Goudswaard, F. J. J. Driesens, N. V. Philips, and P. D. Elcoma, "Failure mechanism of solid
   tantalum capacitors," 1976, doi: 10.1155/APEC.3.171.
- [101]B. Akkopru-Akgun, S. Trolier-McKinstry, and M. T. Lanagan, "MnO2 Thin Film Electrodes for
  Enhanced Reliability of Thin Glass Capacitors," *Journal of the American Ceramic Society*, 2015, doi:
  10.1111/jace.13774.
- 1185 [102]J. Prymark, "Derating review of Ta MnO2 vs. Ta polymer vs. Al polymer vs. NbO MnO2," 2004.
- [103]AVX, "Surface Mount Tantalum Capacitors." 2013. Accessed: Nov. 01, 2022. [Online]. Available:
   https://www.farnell.com/datasheets/2613.pdf
- [104] P. Venet and F. Perisse, "Realization of a smart electrolytic capacitor," *IEEE Industry Applications Magazine*, 2002, doi: 10.1109/2943.974353.
- [105]C. Kulkarni, G. Biswas, X. Koutsoukos, J. Celaya, and K. Goebel, "Experimental Studies of Ageing
   in Electrolytic Capacitors." Vanderbilt University Nashville, Dept of Electrical Engineering and
   Computer Science, 2010.
- [106]A. Zanobini, G. luculano, and A. Falciani, "Automatic-Test Equipment for the Characterization of
   Aluminum Electrolytic Capacitors," *IEEE Transactions on Instrumentation and Measurement*, 2006,
   doi: 10.1109/TIM.2006.870333.
- [107]C. Bhargava, V. K. Banga, and Y. Singh, "An intelligent prognostic model for electrolytic capacitors
   health monitoring: A design of experiments approach," *Advances in Mechanical Engineering*, 2018,
   doi: 10.1177/1687814018781170.
- [108]H. Qingchuan, C. Wenhua, P. Jun, and Q. Ping, "Improved step stress accelerated life testing
  method for electronic product," *Microelectronics Reliability*, 2012, doi:
  10.1016/j.microrel.2012.04.003.
- [109]H. S. Endicott, B. D. Hatch, and R. G. Sohmer, "Application of the Eyring Model to capacitor Aging
   Data," *IEEE Transactions on Component Parts*, 1965, doi: 10.1109/EIC.1962.7466672.
- [110]N. Delmonte, D. Cabezuelo, I. Kortabarria, D. Santoro, A. Toscani, and P. Cova, "A method to
   extract lumped thermal networks of capacitors for reliability oriented design," *Microelectronics Reliability*, 2020, doi: 10.1016/j.microrel.2020.113737.
- [111]A. R. Khandebharad, R. B. Dhumale, S. S. Lokhande, and S. D. Lokhande, "Real time remaining useful life prediction of the electrolytic capacitor," in *International Conference on Information Processing (ICIP)*, Pune, India, 2015. doi: 10.1109/INFOP.2015.7489460.
- 1210 [112]P. Spanik, M. Frivaldsky, and A. Kanovsky, "Life time of the electrolytic capacitors in power 1211 applications," in *ELEKTRO*, 2014. doi: 10.1109/ELEKTRO.2014.6848893.
- 1212 [113]S. G. Parler, "Deriving Life Multipliers for Electrolytic Capacitors." IEEE Power Electronics Society
   1213 Newsletter, 2004.
- 1214 [114]Technical Notes, "Judicious Use of Aluminum Electrolytic Capacitors." Nippon Chemi-Con.
   1215 Accessed: Nov. 01, 2022. [Online]. Available: https://chemi-con.com/wp 1216 content/uploads/2021/04/Technical-Notes.pdf
- 1217 [115]H. Gualous *et al.*, "Supercapacitor ageing at constant temperature and constant voltage and 1218 thermal shock," *Microelectronics Reliability*, 2010, doi: 10.1016/j.microrel.2010.07.144.

- [116]R. Jano and D. Pitica, "Accelerated ageing tests of aluminum electrolytic capacitors for evaluating
   lifetime prediction models," p. 6, 2012.
- [117]P. Kreczanik, P. Venet, A. Hijazi, and G. Clerc, "Study of Supercapacitor Aging and Lifetime
   Estimation According to Voltage, Temperature, and RMS Current," *IEEE Transactions on Industrial Electronics*, 2014, doi: 10.1109/TIE.2013.2293695.
- 1224 [118]G. E. Rhoades and A. W. H. Smith, "Expected life of capacitors with nonsolid electrolyte." 34th 1225 Component conf. Proc., 1984.
- [119]L. Cathey and K. A. Joyner, "Investigation of the Dissipation Process in Electrolytic Capacitors,"
   *ElectroComponent Science and Technology*, 1980, doi: 10.1155/APEC.6.49.
- [120]K. Harada, A. Katsuki, and M. Fujiwara, "Use of ESR for Deterioration Diagnosis of Electrolytic
   Capacitor," *IEEE Transactions on Power Electronics*, 1993, doi: 10.1109/63.261004.
- [121]Hao Ma and Linguo Wang, "Fault diagnosis and failure prediction of aluminum electrolytic
   capacitors in power electronic converters," in *31st Annual Conference of IEEE Industrial Electronics Society*, 2005. doi: 10.1109/IECON.2005.1569014.
- [122]Y. Yu, T. Zhou, M. Zhu, and D. Xu, "Fault Diagnosis and Life Prediction of DC-link Aluminum
   Electrolytic Capacitors Used in Three-phase AC/DC/AC Converters," in 2012 Second International
   Conference on Instrumentation, Measurement, Computer, Communication and Control, 2012. doi:
   10.1109/IMCCC.2012.199.
- [123]B. Sun, X. Fan, C. Qian, and G. Zhang, "PoF-Simulation-Assisted Reliability Prediction for
   Electrolytic Capacitor in LED Drivers," *IEEE Transactions on Industrial Electronics*, 2016, doi:
   10.1109/TIE.2016.2581156.
- [124] V. N. A. Naikan and A. Rathore, "Accelerated temperature and voltage life tests on aluminium
   electrolytic capacitors: A DOE approach," *International Journal of Quality & Reliability Management*, 2016, doi: 10.1108/IJQRM-12-2014-0201.
- [125]H. M. Pang and P. M. H. Bryan, "A life prediction scheme for electrolytic capacitors in power
   converters without current sensor," in *Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Feb. 2010. doi: 10.1109/APEC.2010.5433384.
- [126]J. R. Celaya, C. Kulkarni, G. Biswas, S. Saha, and K. Goebel, "A Model-based Prognostics
   Methodology for Electrolytic Capacitors Based on Electrical Overstress Accelerated Aging." Annual
   Conference of the PHM Society, 2011.
- [127] D. McLean and F. Power, "Tantalum Solid Electrolytic Capacitors," *Proceedings of the IRE*, 1956,
   doi: 10.1109/JRPROC.1956.275141.
- 1251 [128]K. Abdennadher, P. Venet, G. Rojat, J.-M. Rétif, and C. Rosset, "Online monitoring method and 1252 electrical parameter ageing laws of aluminium electrolytic capacitors used in UPS." EPE, 2009.
- [129]M. Randall, T. Kinard, J. Qazi, R. Hahn, and P. Lessner, "The Battle for Maximum Volumetric
   Efficiency Part 2: Advancements in Solid Electrolyte Capacitors," *CARTS Europe 2007 Symposium*,
   2007.
- [130]R. Andersson, M. Bylund, S. Krause, A. M. Saleem, and V. Desmaris, "Integrated and Discrete
   Capacitors Based on Carbon Nanostructures with Capacitance Densities in Excess of 200 nF/mm2,"
   2019.
- [131]H. Choi and H. Yoon, "Nanostructured Electrode Materials for Electrochemical Capacitor
   Applications," *Nanomaterials*, 2015, doi: 10.3390/nano5020906.