



## Electrolytic capacitor: Properties and operation

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# Electrolytic capacitor: properties and operation

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## Highlights:

- A comprehensive review on the properties of electrolytic capacitor are presented
- Characteristics of three different types of electrolytic capacitors are explained
- The article reviews the study of predictive maintenance to anticipate breakdowns
- 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 fields of power electronics, mainly for filtering and energy storage functions. Their characteristics change strongly with frequency, temperature and aging time. Electrolytic capacitors are among the components whose lifetime has the greatest influence on the reliability of electrical systems. Over the past three decades, many efforts in academic research have been devoted to improving reliability capacitor. Industrial applications require more reliable power electronic products. It is in this context that the different electrolytic capacitors and their characteristics are discussed. The aging process of aluminum electrolytic capacitors is explained. Finally, this paper reviews existing methods of failure prognosis of electrolytic capacitors.

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

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## 1. Electrolytic capacitors

Capacitors are used in many fields of electronics and their main uses are the following:

- Energy storage (data backup, system protection...),
- Power factor correction,
- Regulation of the output voltage of switch mode power supplies,
- Input or output filtering of static converters,
- Starting of electric motors.

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

**Section 1** presents the principles of electrolytic capacitors, the construction and the different types of electrolytic capacitors. **Section 2** describes the characteristics, the maintenance that can be applied on 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 are presented in **Section 4**.

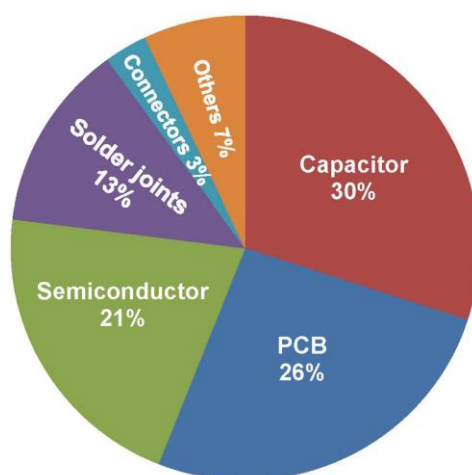


Figure 1: Failure distribution in power electronic systems [6].

### 1.1 Principle of electrolytic capacitors

Electrolytic capacitors consist of two electrodes (anode and cathode), a film oxide layer acting as a dielectric and an electrolyte. The electrolyte brings the negative potential of the cathode closer to the dielectric via ionic transport in the electrolyte [7] (see **Figure 2**). The electrolyte is either a liquid or a

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

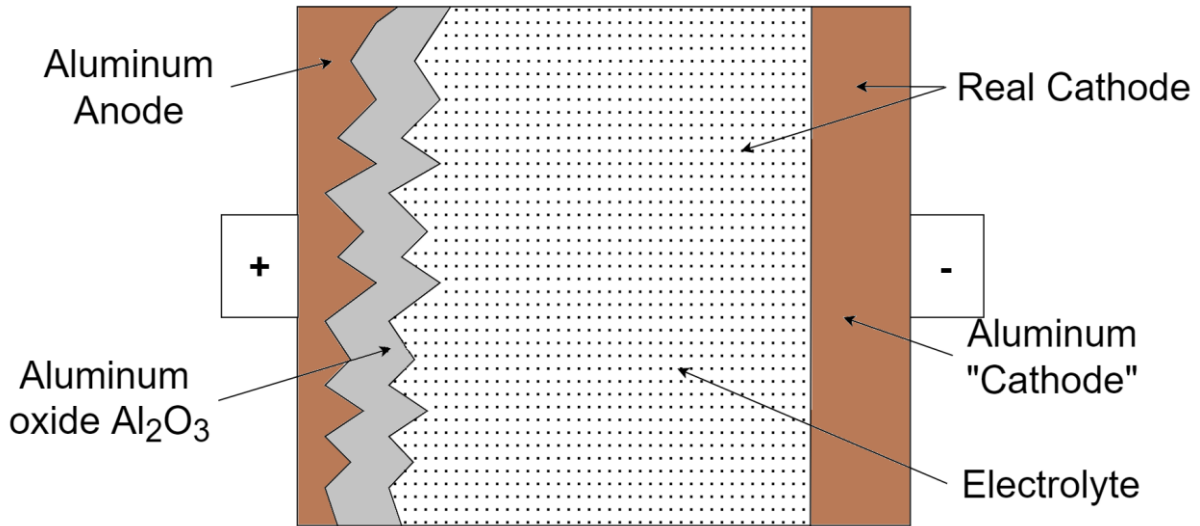


Figure 2: Simplified diagram of the constitution of an aluminum electrolytic capacitor consisting of aluminum electrodes, an alumina dielectric and an electrolyte.

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 capacitance value can be calculated as follows:

$$C = \frac{\epsilon_0 \epsilon_r S}{e} \quad (1)$$

With:

- $\epsilon_0 (= 8,854.10^{-12} F \cdot m^{-1})$  the vacuum permittivity,
- $\epsilon_r$  the relative permittivity of the dielectric,
- $S [m^2]$  the surface of the electrodes,
- $e [m]$  the thickness of the dielectric.

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

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

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

## 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].

Until the wound construction of aluminum foil capacitors, this type of capacitor was bulky and heavy. There are different sizes of capacitor ranging from 3 mm in diameter for 5 mm in height up to 90 mm for 210 mm [19]. Now, AEC became the model for all modern electrolytic capacitors due to their range of voltage ratings and capacitances. This advantage is useful in power supply filters where they are the most common component [15]. This type of capacitor offers high power density but has high leakage current and high sensitivity to reverse polarity. It is necessary to use temperature sensors and current limiters due to their risky failure mode. Indeed, in the event of a power surge there is a high risk of fire. This type of capacitor has an operating temperature of up to 150°C in some cases, allowing a wide range of operating temperatures. Moreover, compared to other electrolytic capacitors, they are less expensive not only because of the materials used but also because of the manufacturing process. They offer good stability and a long service life. In addition, the article indicates that today some components have a theoretical life of about 15 years at 65°C compared to an estimated life of half a year 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,
- 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),  $\gamma$ -butyrolactone (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].

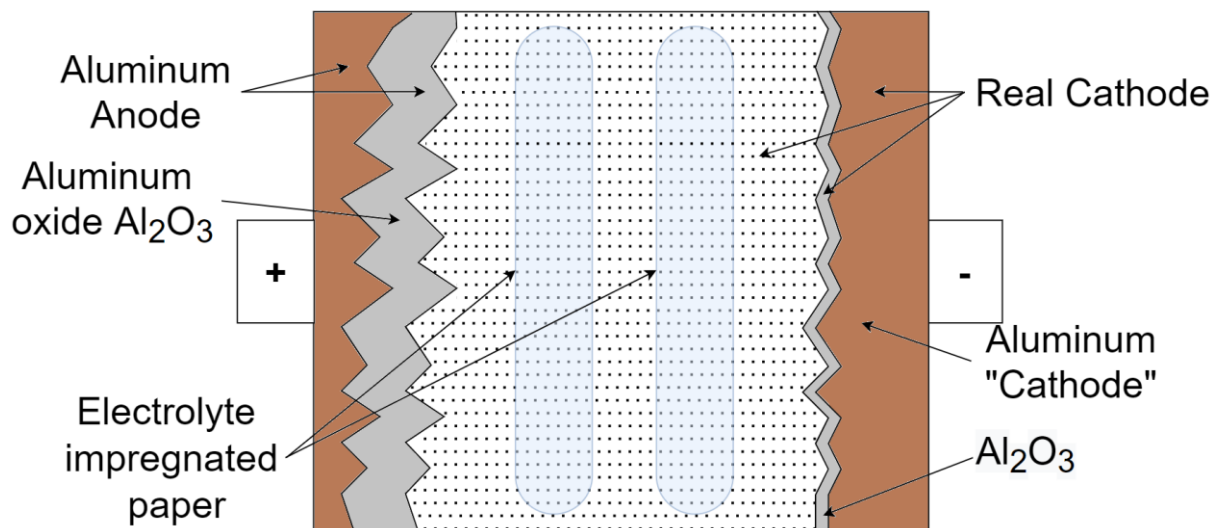
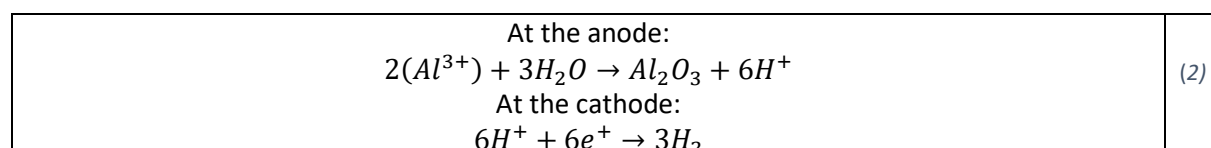


Figure 3: Detailed diagram of the constitution of an AEC consisting of etched aluminum electrodes, an alumina dielectric and an electrolyte support with sheets of paper impregnated with this electrolyte.

In addition, the majority of AEC have an anode etch [32], as shown in **Figure 3**. Etching will increase the surface area of the anode, and therefore the capacitance, by controlled deposition of the dielectric. Etching is used to chemically remove layers from the surface, a portion of the surface is protected from

etchant by a mask material that resists etching, and then the mask is removed. For example, if the aluminum electrode is the material to be etched, then the etchants are phosphoric acid ( $H_3PO_4$ ), water, acetic acid and nitric acid ( $HNO_3$ ) [33]. It should be noted that the quality of the etching has an important influence on the capacitance of the capacitor and largely determines its tolerance. As it has been seen above, the thickness of the oxide layer (a few nm to a few hundred nm) and the etching of the aluminum foil constituting the anode (allowing the effective surface to be 20 to 200 times wider) allows important capacitance [19], [34]. The use of a liquid electrolyte will allow the exploitation of a specific surface area greater than a flat electrode surface. Indeed, the increase in surface area will allow a significant increase in capacitance. It is then understood that the AEC has an all the greater capacitance. A more detailed sketch of ACE is shown in **Figure 3**. In this figure, sheets of paper impregnated with electrolyte can be seen. Electrolyte impregnated paper serves as physical separator limiting the risk of short circuits between the two electrodes. The thin layer of  $Al_2O_3$  (alumina) on the cathode is caused by natural oxidation of aluminum which limits corrosion as shown in **Figure 3**. However, the aluminum oxide layer present on the anode is caused during the construction of the capacitor by the application of a potential according to the equation below [20]:



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

AEC that have been stored for long periods of time should go through a voltage treatment process that will reform the dielectric ( $Al_2O_3$ ) through the electrolyte and bring the leakage current back to the original level. The increase in leakage current during storage varies with the holding voltage of a capacitor. In general, the higher the voltage rating, the greater the increase in leakage current tends to be. Also, since storage for a long period of time can reduce the life of capacitors, storage conditions should be considered in relation to the life requirements of the device. When an AEC is stored under no load conditions for a long period of time, the electrolyte may have degraded the oxide layer of the anode. Since the dielectric strength has been reduced by the electrolyte, the capacitor has a higher



leakage current than originally. The voltage applied to the capacitor will allow the oxide layer to reform. This is why, many technical guides [17], [37] advise charging the capacitor to its nominal voltage for one hour through a resistor to prevent the capacitor from overheating. Thus, the leakage current returns to its initial value due to the reformation of the dielectric. It can be found in [38], for an AEC stored a temperature between  $-5^{\circ}\text{C}$  and  $+50^{\circ}\text{C}$ , we must reform the dielectric of the AEC by applying a voltage. This voltage will be different depending on the storage time according to the following criteria:

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

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

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

**Slitting:** According to the capacitance value and geometric dimensions desired, the formed 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**).



Reforming: This process permits to repair the oxide film, that could have been broken during the assembly step, by applying a continuous voltage. This voltage needs to be superior to the forming voltage of oxide (**Figure 4. 7**).

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

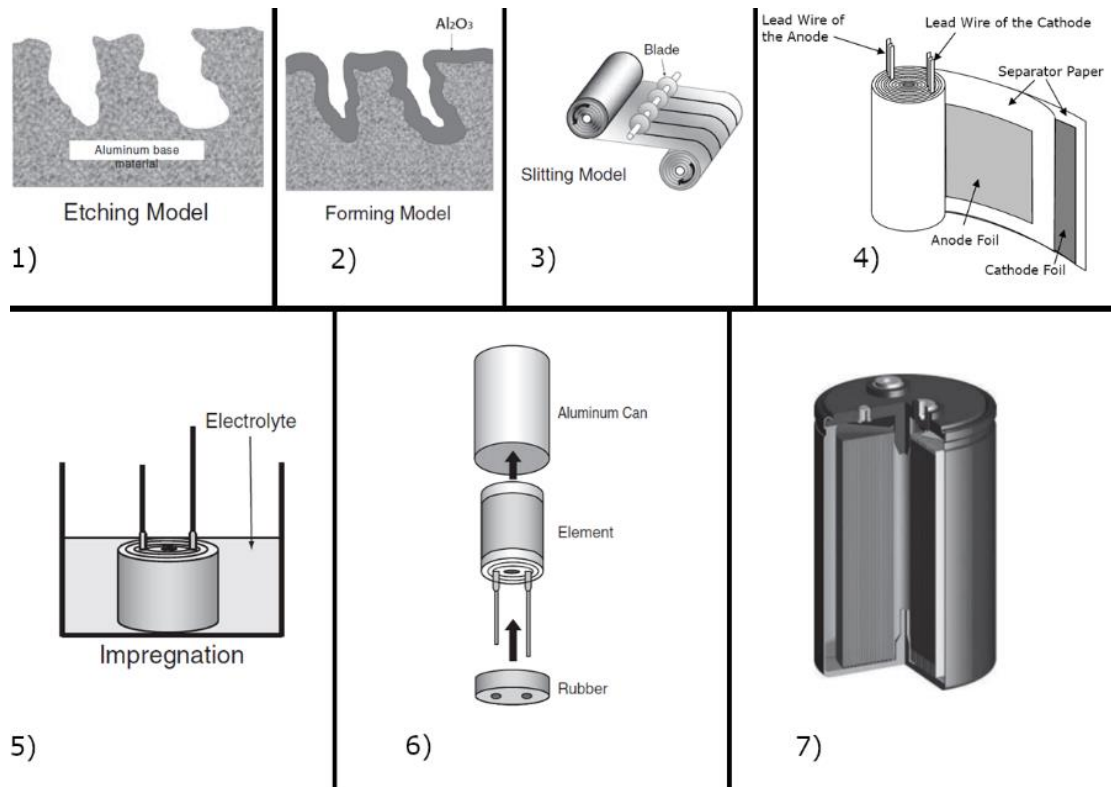


Figure 4: 1) Etching of an aluminum sheet. 2) Formation of oxide layer. 3) Slitting of the aluminum sheets. 4) Winding. 5) Impregnation. 6) Assembly. 7) Final Product. [39]–[41]

### 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.

#### 1.3.1 Comparison of electrolytic capacitor types

##### Tantalum electrolytic capacitor:

There is a multitude of electrolytic capacitors such as tantalum that have better stability, a wider operating temperature range and a longer service life than others [42] but who are considerably more expensive. They consist of metallic tantalum which acts as an anode covered by an oxide layer of tantalum pentoxide ( $\text{Ta}_2\text{O}_5$ ), surrounded by a conductive solid or liquid electrolyte which acts as the cathode. The dielectric, made of tantalum pentoxide, has a minimum thickness of 1.4 nm/V. Indeed, this type of capacitor generally has a larger capacitance value since it has a very thin dielectric layer with higher permittivity than aluminum capacitor (see **Table 2**). They are polarized, which means that electrolytic capacitors cannot be connected to an AC supply. Compared to many types of capacitors, they have excellent stability, high cut-off frequency characteristics and higher energy density [43]. Their benefits include low impedance and low leakage current with high frequency performance [44]. 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.

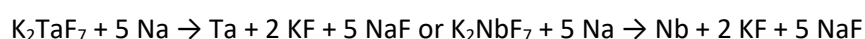
In terms of applications, tantalum capacitors are widely used in laptops, the automotive industry and mobile phones. In the past, tantalum capacitors were built with axial anode capacitors with liquid electrolyte that made them heavy and expensive [16]. Now, they are widely used in power filters, by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

#### Niobium electrolytic capacitor:

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

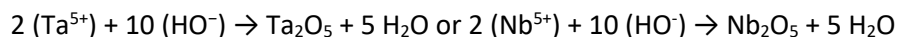
#### Basic construction of Tantalum and Niobium electrolytic capacitors:

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]:



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:



Immersed in an aqueous solution of manganese nitrate ( $\text{Mn}(\text{NO}_3)_2$ ), 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:



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

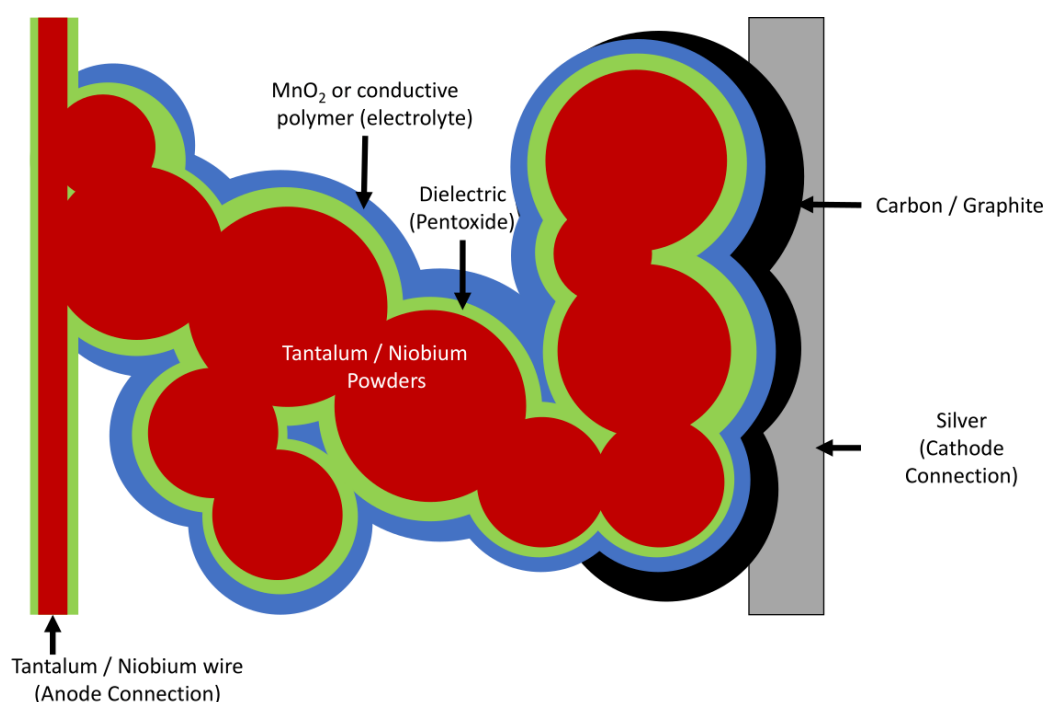


Figure 5: Sketch of the structure of a sintered tantalum or niobium electrolytic capacitor.

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.

### 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].

Dielectric	Electrolyte	Capacitance ( $\mu\text{F}$ )	Maximum temperature ( $^{\circ}\text{C}$ )	Operating voltage (V)

<b>Alumina oxide (Al<sub>2</sub>O<sub>3</sub>)</b>	GBL, DMF, DMA	0.1 to 10 <sup>6</sup>	150	550
	Borax, glycol	0.1 to 10 <sup>6</sup>	105	630
	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>Tantalum oxide (Ta<sub>2</sub>O<sub>5</sub>)</b>	Sulfuric acid	0.1 to 2.10 <sup>4</sup>	200	650
	Solid, Manganese dioxide	0.1 to 3x10 <sup>3</sup>	150	120
	Solid, Polymer	5 to 10 <sup>3</sup>	125	10
<b>Niobium oxide (Nb<sub>2</sub>O<sub>5</sub>)</b>	Solid, Manganese dioxide	1 to 10 <sup>3</sup>	125	10
	Solid, Polymer	5 to 500	125	16

Table 1: Operating properties of electrolytic capacitors

In order to compare these three main categories of capacitor and to sum up some characteristics of 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
<b>Alumina oxide (Al<sub>2</sub>O<sub>3</sub>)</b>	8 to 10	6600 to 7700	1.1 – 1.5	- Volume Ratio - Less expensive - Better range of Voltage and Capacitance	- High Leakage current - Risky failure mode
<b>Tantalum oxide (Ta<sub>2</sub>O<sub>5</sub>)</b>	10 to 27	6250 to 10 000	1.4	- Low impedance - Low Leakage current - High Frequency	- Risky failure mode
<b>Niobium oxide (Nb<sub>2</sub>O<sub>5</sub>)</b>	41	4000	2.5	-High dielectric constant - Good balance - Common materials	- Low capacitance per volume - Low Voltage

Table 2: Characteristics of electrolytic capacitors.

Although there are many electrolytic capacitors, they have some common characteristics. Electrolytic capacitors are the cheapest and most requested capacitors thanks to their high storage densities and

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

## 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**:

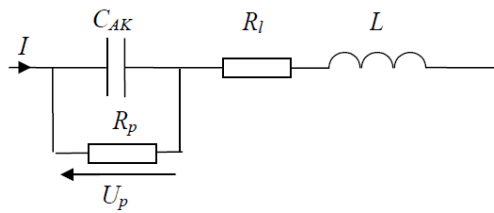


Figure 6: Equivalent circuit of a capacitor [63].

As stated in [39]:

- $R_p$ : Resistance due to electrolyte and dielectric losses. This element represents the insulation resistance of the capacitor that induces a leakage current.
- $C_{AK}$ : Ideal capacitance between the cathode and the anode.
- $L$ : Equivalent series inductance of connections and windings.
- $R_l$ : Series resistance of connections, impregnated paper and electrodes.

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

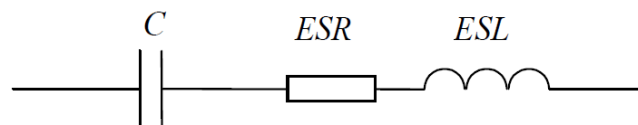


Figure 7: Normalized equivalent circuit of a capacitor [63].

- ESL: Equivalent series inductance.

- C: Equivalent capacitance.
- ESR: Series equivalent resistance representing all losses.

By identifying the impedances of the circuit, it is possible to deduce:

- $C = C_{AK} \left( 1 + \frac{1}{R_p^2 C_{AK}^2 \omega^2} \right)$
- $ESR = R_l + \frac{R_p}{1 + R_p^2 C_{AK}^2 \omega^2}$
- $ESL = L$

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:

$$f_r = \frac{1}{2\pi\sqrt{ESL \cdot C}} \quad (3)$$

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 ( $P_d$ ) and losses created by Joule Heating:

$$P = P_d + R_l I_r^2 = ESR \cdot I_r^2 \quad (4)$$

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:

$$\Delta T = \frac{ESR \cdot I_r^2}{hS} \quad (5)$$

With  $h$ : Thermal convection coefficient and  $S$ : the external surface of heat exchange between the 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 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:

$DF = \tan \delta = ESR \cdot C \cdot \omega$	(6)
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430 The Dissipation Factor allows to determine the total losses P in the component according to the total  
 431 reactive power Q:

$P = \tan \delta \frac{I^2}{C\omega} = Q \cdot \tan \delta$	(7)
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## 432 2.2 Maintenance

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

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

443 2) Corrective maintenance is a strategy based on the idea that the costs sustained for breakdown and  
 444 repair are lower than the investment required for a maintenance program. Indeed, the maintenance  
 445 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.

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

463 Hence, there are different methods that can detect in real time the evolution of the ESR and the  
 464 capacitance C in order to realize a system of monitoring and predictive maintenance of electrolytic  
 465 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.

Based on this diagnostic and prognostic work, optimizations can be performed. A selection of the potential failure mechanism is necessary to reduce the number of indicators used in aging models. 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 have an estimate of the remaining lifetime (and consequently the health status) of the capacitor.

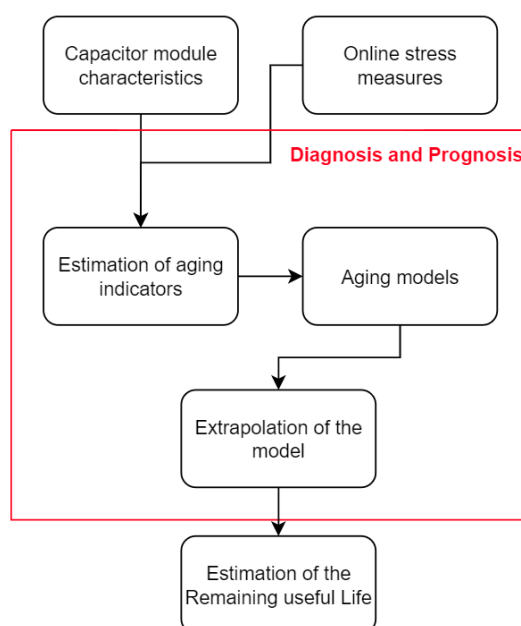


Figure 8: Electrolytic capacitor failure prognosis method diagram.

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

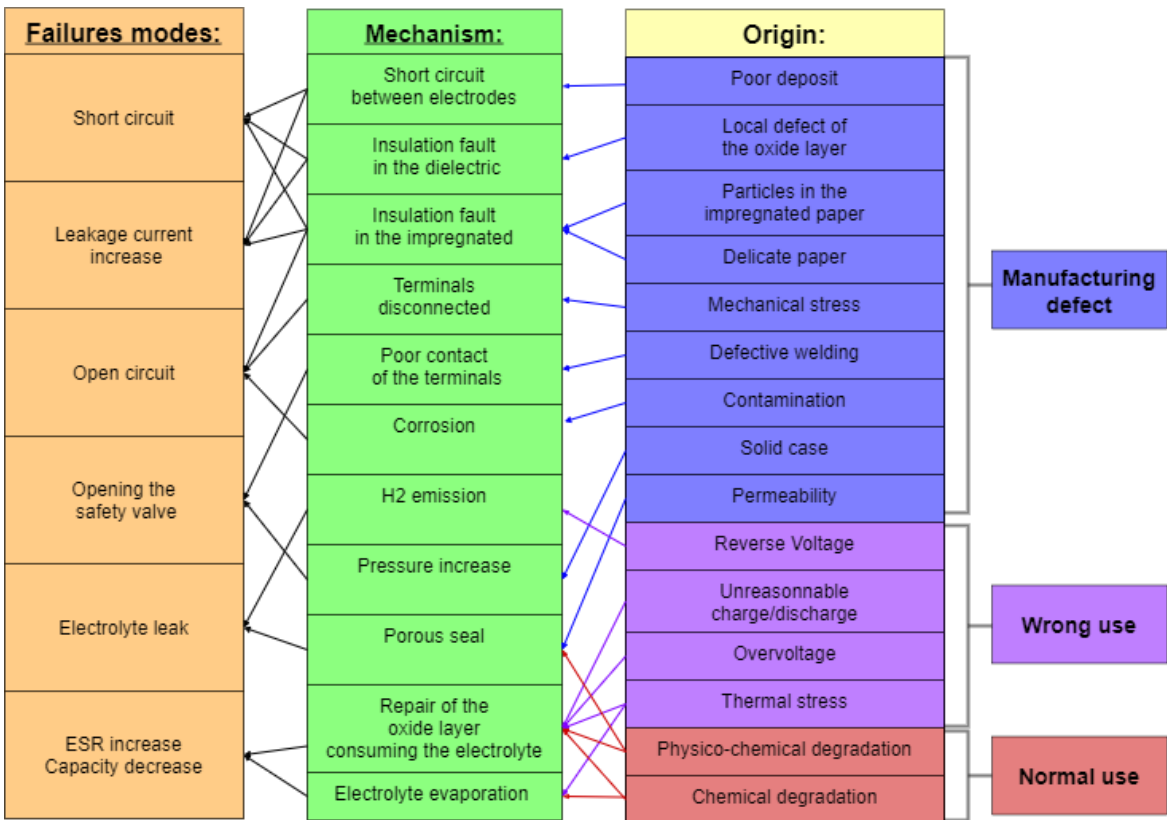
At low temperatures, a phenomenon of electrolyte thickening [81] induces less mobility of ions and leads to an increase in ESR.

All of electrolytic capacitors are frequency and temperature sensitive [82], have a fairly short lifespan and have a fairly high failure rate [83]. There are many studies on the failure modes of electrolytic capacitors, and mainly aluminum electrolytic capacitors. Indeed, from the understanding of the mechanisms and failure modes of a capacitor, it is possible to apply a maintenance in order to know the remaining lifetime of the component.

### 2.3 Mechanisms and failure modes

#### 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



capacitors. Evaporation of the electrolyte creates an overpressure inside the component. It can be 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

Figure 9: Mechanisms and failure modes according to the stress in an electrolytic capacitor.

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

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

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

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

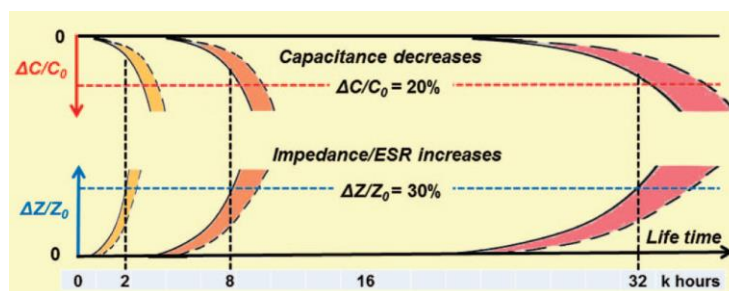


Figure 10: Endurance tests under 85°C (red), 105°C (orange), 125°C (yellow) of an AEC [19].

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

### 2.3.2 Solid and polymer electrolytic capacitor failure modes

- Polymer Tantalum and Niobium capacitor

Solid polymer tantalum electrolytic capacitors do have a life time specification. Indeed, the polymer electrolyte has a slight deterioration of conductivity by a thermal degradation mechanism of the conductive polymer. The electrical conductivity decreases, as a function of time, in agreement with a granular metal type structure, in which aging is due to the shrinking of the conductive polymer grains [97]. The main advantage of polymer electrolytic capacitors over wet electrolytic and  $\text{MnO}_2$  capacitors is their low temperature dependence coupled with their non-ignition failure mode. These capacitors can avoid ignition because the conductive polymer cathode does not contain active oxygen that could ignite the tantalum anode. The no-ignition failure mode is an important safety feature, especially in low ESR circuits. Concerning the self-healing of polymer-based capacitors, they have a polymer playing the role of an electrolyte. There is also the phenomenon of self-healing for this type of electrolytic capacitor. As seen previously, the leakage current will generate a rise in temperature. This will allow the vaporization of the polymer present in contact with the dielectric and the inhibiting of the conductive contact of the defects. Or the leakage current will generate an oxidation of the polymer increasing then the resistivity and limiting/blocking the leakage current. In both cases, the reduction of the contact area causes a decrease of the capacitance.

- Solid Tantalum and Niobium capacitor

The typical failure mode of solid  $\text{MnO}_2$  tantalum and niobium capacitors is a short circuit, and in some cases the failed capacitors ignite. The tantalum/niobium capacitor structure uses an extremely thin, glass-like material for its dielectric. Throughout the process, foreign matter can enter the structure. The soaking and drying process introduces multiple thermal exposures. Combined with the huge surface area of the electrolytic capacitor, this leads to the formation of defects in the capacitor structure. This is because when a large amount of stored energy is rapidly released through a small break channel, micro-cracks or pores [98] in the dielectric, it causes a rapid increase in temperature and release of oxygen from the  $\text{MnO}_2$  cathode. Ignition is an important phenomenon to keep in mind. It occurs if the resistivity of the defective dielectric is too low and when the leakage current which is too high and overrides the self-healing phenomenon. For solid niobium capacitors, when the main dielectric is broken, the capacitor goes to high resistance, typically about 34 k $\Omega$  [99]. Indeed, at 450°C the transformation of  $\text{MnO}_2$  into  $\text{Mn}_2\text{O}_3$  is not instantaneous. This is why it is necessary to have a leakage current that is not too high for the  $\text{MnO}_2$  to heat up and transform, otherwise there is a risk of deterioration of the  $\text{Ta}_2\text{O}_5$  /  $\text{Nb}_2\text{O}_5$  and ignition in the fault. Nevertheless, a possibility of ignition in the event of failure as well as a high ESR compared to the ESR of ceramic and film capacitors with metal 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  $\text{MnO}_2$  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  $\text{MnO}_2$  adjacent to the fault. This current causes local heating of the  $\text{MnO}_2$  at the fault current entry point. When the  $\text{MnO}_2$  heats up to  $500^\circ\text{C}$  [98], it transforms into a less oxygenated state,  $\text{Mn}_2\text{O}_3$ . The more conductive manganese oxide combination is  $\text{MnO}_2$ , 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

Tantalum and niobium capacitors are as reliable as other electronic components, with very low failure rates. However, they have a unique failure mode called "field crystallization". Field crystallization occurs only at certain sites on the metal-oxide interface that are favorable for the formation of crystalline nuclei. These sites can be areas with high impurity content in the metal. Field crystallization 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 risk of potential ignition is reduced. Indeed, it is recommended by the manufacturers of tantalum and niobium capacitors to reduce voltage by 50% and 20% respectively for temperatures below  $85^\circ\text{C}$  [55]. There is a correlation between the time to failure and the conditions according to [102]. The effect of 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)
--	-----

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 2,  $T_1$  and  $T_2$  for absolute temperature 1 and 2,  $n$  for the voltage stress exponential,  $E_a$  for the activation 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].

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

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

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

#### 3.1 Characterization of aging indicators of electrolytic capacitors

It is important to have models of the variation of ESR and C as a function of influencing factors other 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 temperatures, the electrolyte is thick, induces less mobility of ions and leads to an increase in ESR [81]. The variation of ESR as a function of temperature can be approximately expressed by an exponential law of the form [104]:

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

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.

In order to facilitate the understanding of the physical principles involved in the capacitor and to confirm theoretical models, it is interesting to perform characterizations. These characterizations will make it possible to obtain macroscopic data and to highlight the influence of this data according to certain parameters (voltage, temperature, frequency...) on the ESR and C. Throughout the characterization of the capacitor, it will be essential to perform a metric characterization. This consists of recording dimensions and weight for later comparison in the event that testing degrades the sample. For example, the evaporation of the electrolyte can modify the structure, the weight and the behavior of the capacitor under test.

- Frequency Characterization:

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 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 modulus of impedance as a function of frequency is represented. The characteristics of the capacitors 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 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  $f_h$ . The real part represents all the losses in the component, and is identified with the resonance frequency where the total impedance  $Z$  of the capacitors is equivalent to its resistive part. The latter gives a global view of the variation of the losses in the component, but does not allow to study the individual evolution of the parameters ( $R_l$  and  $R_p$  from **Figure 6**) with respect to the applied constraints. This is how the capacitance, the ESR and the ESL are defined:

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

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



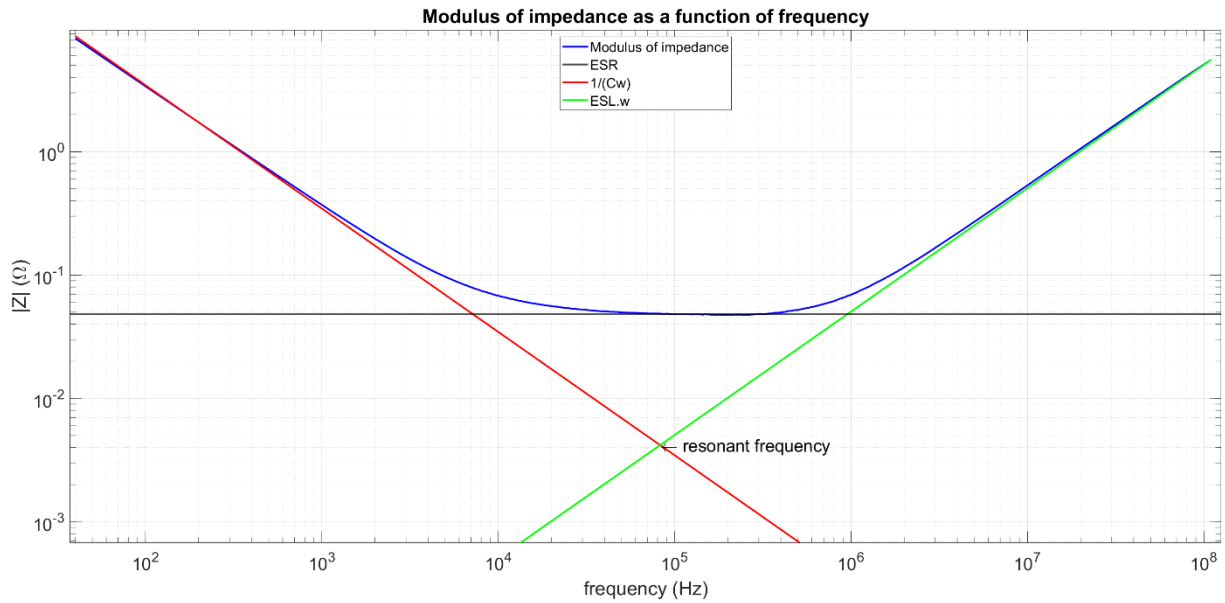


Figure 11: Bode diagram for an aluminum electrolytic capacitor ( $470 \mu\text{F} / 50 \text{ V}$ ) with:  $\text{ESL} = 8.05 \cdot 10^{-9} \text{ H}$  and  $\text{ESR} = 48.2 \text{ m}\Omega$ .

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.

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



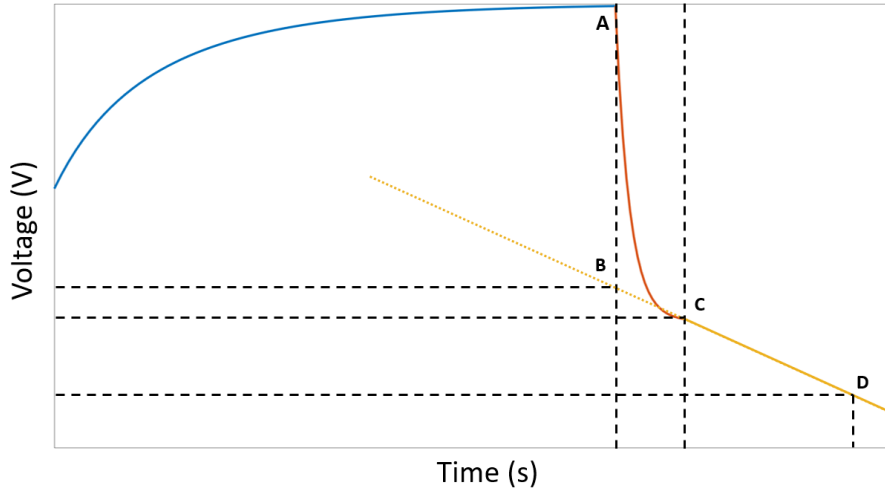


Figure 12: Diagram of the variation of the voltage of a capacitor during a charge and discharge. Blue curve: charging voltage. Orange curve: transient discharge. Yellow curve: constant discharge.

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:

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

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.

### 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:

$$k_T = A \cdot e^{\left(-\frac{E_a T}{k_B}\right)} \quad (12)$$

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

the acceleration stress is temperature [75], [106]–[108]. To estimate the lifetime at the temperature  $T$ , the following equation can be used:

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

where:  $t$  is the time of appearance of failure;  $t_0$  is the specified lifetime given by the individual datasheets of products;  $T_0$  is the specified temperature;  $v$  is the reaction speed according to the expected conditions of use;  $v_0$  is the reaction rate under extreme conditions operation;  $K_{T \text{ Arrhenius}}$  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:

$$t_{Eyring} = A \cdot T^n \cdot e^{\left(\frac{E_a}{T k_B} + S_1 \left(B + \frac{C}{T}\right) + S_2 \left(D + \frac{E}{T}\right)\right)} \quad (14)$$

Where  $A, B, C, D, E, T$  and  $n$  are coefficients depending on the test and the failure with  $S_1, S_2$  the 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]:

$$L = L_0 \cdot K_T \cdot K_I \cdot K_V \quad (15)$$

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;

$$\begin{aligned} K_T &= 2^{\frac{\theta_0 - \theta_x}{10}} \\ K_I &= K_r \left(1 - \left(\frac{I_{RMSx}}{I_{RMS0}}\right)^2\right)^{\frac{\Delta\theta_0}{10}} \\ K_V &= \left(\frac{V_0}{V_x}\right)^n \end{aligned} \quad (16)$$

where:  $K_r$  is an empirical factor;  $\theta_0$  is the maximum temperature;  $\theta_x$  is the ambient temperature;  $\Delta\theta_0$  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;  $I_{I_{RMSx}}$  is the operating RMS current flowing in the capacitor;  $I_{RMS0}$  is the rated RMS current of the capacitor;  $n$  is an empirical constant of security.

Where  $K_r$  is an empirical safety factor [99], [100]:

- $K_r = 2$  if  $I_{RMSx} \leq I_{RMS0}$
- $K_r = 4$  if  $I_{RMSx} > I_{RMS0}$  (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]:

$$0.5 \leq \frac{V_0}{V_x} \leq 0.8 \rightarrow n = 3$$

$$0.8 < \frac{V_0}{V_x} \leq 1 \rightarrow n = 5$$

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].

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

$C(t) = \alpha_1 + \alpha_2 \cdot t$	(17)
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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:

$\frac{1}{ESR(t_x)} = \frac{1}{ESR(t=0)} (1 - A_0 t_x e^{-\frac{Ea}{k_B T_x}})$	(18)
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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  $t = 0$ ;  $A_0$  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 giving the value of the ESR is not defined at all points. Indeed if  $A_0 t_x e^{-\frac{E_a}{T_x}}$  tends to be equal to 1 then the ESR tends towards infinity. Therefore, one of the signs of failure is the rise of the ESR which is faster towards the end of the capacitor's life. There are also other assumptions on the variation of the ESR as a function of temperature and time. Indeed, in [90], they supposed different models, here is an example:

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

Where:  $A_1 C_1$  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:

$$ESR_2(t', T') = (ESR(t = 0, T') + A_1). e^{C_1 \cdot t' \cdot e^{\frac{4700 \cdot (T' - T_v)}{(T_v + 273) \cdot (T' + 273)}}} \quad (20)$$

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

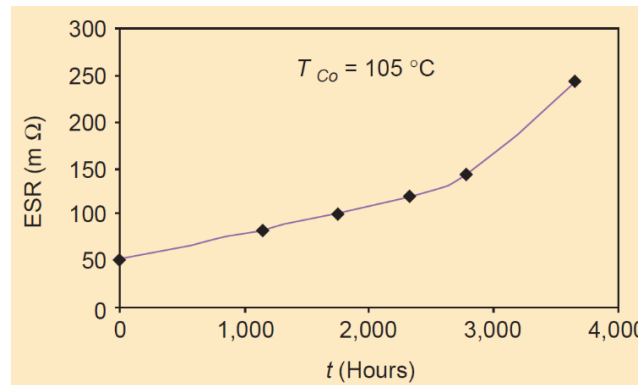


Figure 13: ESR versus aging test of electrolytic capacitors at  $T=105^\circ\text{C}$  [104].

### 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.

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

It is possible to observe methods that include the impact of voltage in addition to using temperature as a stress. Temperature is considered a major constraint, but it is not the only one. Some works try to 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 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 combined (using voltage and temperature constraint) in order to give a higher accuracy lifetime prediction algorithm. A new method of predicting the life of capacitors is introduced. The service life 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 influencing the lifetime of electrolytic capacitors used in power converters. In order to know the shape of aging laws, accelerated aging tests are done in this work to assess the effects of thermal and electrical overstresses through time. Early results show that a cubic regression has the best fit with the 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 core temperature estimation derived from ESR deterioration and operating conditions is shown.

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

Finally, a last category of stress is the one under nominal condition, which means below the operating temperature and voltage. In [105], under nominal condition, the drift of ESR with time is determined by the Arrhenius model. A third-degree regression model is proposed for the degradation of the mean capacitance as a function of time. This type of stress under nominal condition can be seen in [128], this work tries to determine all the evolution laws versus temperature, frequency and operation time. To do so, the components are under nominal voltage at the maximum operating temperature allowed with the use of a climate chamber. Then, the capacitors internal parameter behavior can be analyzed against operating time and determine the aging laws of parameters as ESR and C of AEC.

There are disadvantages to these methods, it is necessary to have models of degradation of the capacitors in real time considering the operating conditions (ambient temperature, voltage, frequency...) to predict the lifetime of the capacitors. In addition, physical models and models of degradation based on data regression are then combined. But these regression-based models require large sets of samples to increase estimation precision. These different methods all use accelerated aging tests. These methods constitute an essential learning phase, to be carried out offline, before any online evaluation of the life of the capacitors. It is important to note that the accelerated aging tests are carried out with each new version of the capacitor before it is integrated into the model. This is why this method is costly in terms of time and money, which makes this step not very viable at the industrial level. It would be interesting to design a strategy that uses the least amount of offline resources. This strategy will not only improve the fit of the model, but also the prediction of health status. In [74] the invention relates to a method for determining a value representative of the remaining useful life (RUL) of a capacitor, based on specific values such as a maximum temperature value and a maximum voltage value of the capacitor. The method is in two parts. The first one consists in identifying in real time indicators of aging ESR and C of any capacitors integrated in a power converter. The second phase is the implementation of an algorithm capable of constructing, thanks to the estimations of ESR and C, a model of aging in real time and capable of deducing the remaining life of the capacitors. As discussed, the offline learning phase where accelerated aging tests are performed is a costly and time-consuming method. This invention is relevant because it allows an online evaluation of the capacitor lifetime without performing an offline learning phase.

## 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



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

## References

- [1] E. Wolfgang, "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.
- [3] H. Wang *et al.*, "Transitioning to Physics-of-Failure as a Reliability Driver in Power Electronics," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2014, doi: 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.
- [5] D. Ton and W. Bower, "Summary Report on the DOE High-tech inverter workshop," *US Department of Energy*, 2005. Accessed: Nov. 01, 2022. [Online]. Available: [https://www1.eere.energy.gov/solar/pdfs/inverter\\_II\\_workshop.pdf](https://www1.eere.energy.gov/solar/pdfs/inverter_II_workshop.pdf)
- [6] H. Wang, Y. Yang, and H. Sangwongwanich, "Design for Reliability of Power Electronic Systems," *Power electronics handbook. Butterworth-Heinemann*, 2018, doi: 10.1109/IECON.2012.6388833.
- [7] M. E. Orazem and B. Tribollet, *Electrochemical impedance spectroscopy*. The Electrochemical 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.
- [10] Nichicon corporation, "Conductive Polymer Hybrid Aluminum Electrolytic Capacitors." Datasheet. Accessed: Nov. 01, 2022. [Online]. Available: [https://www.nichicon.co.jp/english/products/pdf\\_x/e-gya.pdf](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.
- [12] E. Manla, G. Mandic, and A. Nasiri, "Development of an Electrical Model for Lithium-Ion Ultracapacitors," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2015, doi: 10.1109/JESTPE.2014.2383955.



- [13] D. S. Campbell, "Electrolytic Capacitors," *Components and Circuits Group Symposium on Capacitors 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.
- [17] Nichicon corporation, "General Descriptions of Aluminum Electrolytic Capacitors, Technical Notes." 2015. Accessed: Nov. 01, 2022. [Online]. Available: <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.htm#index](https://web.archive.org/web/20160617163728/http://www.faradnet.com/deeley/chapt_10.htm#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.
- [23] H. O. Siegmund, "The Aluminum Electrolytic Condenser," *Bell System Technical Journal*, 1929, doi: 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.
- [25] Z. Dou and R. Xu, "Development of Electrolytes in Aluminium Electrolytic Capacitors for 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 Al<sub>2</sub>O<sub>3</sub>/Al in ionic liquid BMI.BF<sub>4</sub>/γ-butyrolactone electrolytes for use in electrolytic capacitors," *Ionics*, 2017, doi: 10.1007/s11581-016-1912-x.
- [27] J. Barthel, H.-J. Gores, G. Schmeer, and R. Wachter, "Non-aqueous electrolyte solutions in chemistry and modern technology," in *Physical and Inorganic Chemistry*, Springer Berlin Heidelberg, 1983. doi: 10.1007/3-540-12065-3\_2.
- [28] J. D. Dale-Lace, "Capacitors for power supplies," *Electronics and Power*, 1986, doi: 10.1049/ep.1986.0146.
- [29] D. Petrov and U. Hilleringmann, "Water-based primary cell for powering of wireless sensors," in *IEEE SENSORS*, 2020. doi: 10.1109/SENSORS47125.2020.9278891.
- [30] J. Menzel, E. Frackowiak, and K. Fic, "Electrochemical capacitor with water-based electrolyte operating at wide temperature range," *Journal of Power Sources*, 2019, doi: 10.1016/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.
- [33] S. Wolf and R. N. Tauber, "Silicon Processing for the VLSI Era: Process Technology." Process Technology, 1999.

- [34] D. G. W. Goad and H. Uchi, "Modelling the capacitance of d.c. etched aluminium electrolytic capacitor foil," *Journal of applied electrochemistry*, 2000, doi: <https://doi.org/10.1007/s10854-015-3280-0>.
- [35] M. Makdessi, A. Sari, and P. Venet, "Improved model of metalized film capacitors," *IEEE Transactions on Dielectrics and Electrical Insulation*, 2014, doi: 10.1109/TDEI.2013.004158.
- [36] O. G. Gnonhoue, A. Velazquez-Salazar, É. David, and I. Preda, "Review of Technologies and Materials Used in High-Voltage Film Capacitors," *Polymers*, 2021, doi: 10.3390/polym13050766.
- [37] TDK Electronics, "Aluminum Electrolytic Capacitors - General technical information," 2019, Accessed: Nov. 01, 2022. [Online]. Available: <https://www.tdk-electronics.tdk.com/download/185386/e724fb43668a157bc547c65b0cff75f8/pdf-generaltechnicalinformation.pdf>
- [38] Exxelia, "Electrolytic Aluminum Capacitors Technical data." 2017. Accessed: Nov. 01, 2022. [Online]. Available: <https://exxelia.com/uploads/PDF/aluminum-electrolytic-capacitors-catalog-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.
- [40] A. E. Hayek, "Analyse de vieillissement, estimation de la durée de vie et méthode de surveillance de l'état de santé des condensateurs électrolytiques." Doctoral dissertation, Université de Lyon, 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.
- [47] E. K. Reed, "Characterization of Tantalum Polymer Capacitors." NASA Electronic Parts and Packaging Program, NEPP Task, 2006.
- [48] V. Sprague, "Solid Tantalum Surface Mount Chip Capacitors TANTAMOUNT™, Molded Case, Standard Industrial Grade," 2021, Accessed: Nov. 01, 2022. [Online]. Available: <https://www.tme.eu/Document/b7b423fee79a0baa3802818aefa8a73f/293d.pdf>
- [49] I. Bishop and J. Gill, "Reverse voltage behavior of solid tantalum capacitors, Technical 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: 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>.
- [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.
- [56] A. Shrivastava, "RELIABILITY EVALUATION OF LIQUID AND POLYMER ALUMINUM ELECTROLYTIC CAPACITORS," p. 113.
- [57] J. Yoo, "Liquid electrolyte-free cylindrical Al polymer capacitor review: Materials and characteristics," *Journal of Power Sources*, 2015, doi: <https://doi.org/10.1016/j.jpowsour.2015.03.023>.
- [58] M. Agrawal, R. Singh, M. Ranitović, Z. Kamberovic, C. Ekberg, and K. K. Singh, "Global market trends of tantalum and recycling methods from Waste Tantalum Capacitors: A review," *Sustainable Materials and Technologies*, 2021, doi: 10.1016/j.susmat.2021.e00323.
- [59] A. Dehbi, W. Wondrak, Y. Ousten, and Y. Danto, "High temperature reliability testing of aluminum and tantalum electrolytic capacitors," *Microelectronics Reliability*, 2002, doi: 10.1016/S0026-2714(02)00021-5.
- [60] V. Sprague, "AC Ripple Current Calculations." Application Notes, 2002. Accessed: Nov. 01, 2022. [Online]. Available: <https://www.vishay.com/docs/40031/appripppl.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.
- [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.
- [63] K. Abdennadher, P. Venet, G. Rojat, J.-M. Retif, and C. Rosset, "A Real-Time Predictive-Maintenance System of Aluminum Electrolytic Capacitors Used in Uninterrupted Power Supplies," *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.
- [65] J. Čuntala, M. Frivaldský, and A. Kondelová, "Thermal simulation of electrolytic capacitor during impulse operation," 2014.
- [66] A. L. d'Entremont, "Thermal modeling of electrochemical capacitors." Doctoral dissertation, Univeristy of California, Los Angeles, 2015.
- [67] S. G. Parler, "Thermal modeling of aluminum electrolytic capacitors," in *Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Forth IAS Annual Meeting (Cat. No.99CH36370)*, 1999. doi: 10.1109/IAS.1999.799180.
- [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/s00202-004-0265-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: 10.1016/0379-6779(94)90093-0.
- [81] B. Alvsten, *Electrolytic capacitors theory and application*, RIFA Electrolytic Capacitors. Sweden, 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/ijphm.2013.v4i1.1448.
- [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.
- [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," *Microelectronics Reliability*, 2002, doi: [https://doi.org/10.1016/S0026-2714\(02\)00013-6](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.
- [93] U.S. of A. D. of Defense, "Military HandBook - Reliability prediction of electronic equipment," p. 150, 1991.

- [94] J. Renwick, C. S. Kulkarni, and J. R. Celaya, "Analysis of Electrolytic Capacitor Degradation under Electrical Overstress for Prognostic Studies," 2015, doi: <https://doi.org/10.36001/phmconf.2015.v7i1.2713>.
- [95] Fixed Electrolytic, "General specification for capacitors (MIL-C-62F)," 2008.
- [96] International Electrotechnical Commission, "IEC 60068-1 : Environmental testing," 1988.
- [97] E. Vitoratos *et al.*, "Thermal degradation mechanisms of PEDOT:PSS," *Organic Electronics*, 2009, doi: 10.1016/j.orgel.2008.10.008.
- [98] Y. Pozdeev, "Reliability comparison of tantalum and niobium solid electrolytic capacitors," *Quality and Reliability Engineering International*, 1998, doi: 10.1002/(SICI)1099-1638(199803/04)14:2<79::AID-QRE163>3.0.CO;2-Y.
- [99] T. Zednicek, "Voltage Derating Rules for solid tantalum and niobium capacitors." 2003. Accessed: Nov. 01, 2022. [Online]. Available: <https://www.kyocera-avx.com/news/voltage-derating-rules-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. Troler-McKinstry, and M. T. Lanagan, "MnO<sub>2</sub> Thin Film Electrodes for Enhanced Reliability of Thin Glass Capacitors," *Journal of the American Ceramic Society*, 2015, doi: 10.1111/jace.13774.
- [102] J. Prymark, "Derating review of Ta MnO<sub>2</sub> vs. Ta polymer vs. Al polymer vs. NbO MnO<sub>2</sub>," 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. Iuculano, 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.
- [112] P. Spanik, M. Frivaldsky, and A. Kanovsky, "Life time of the electrolytic capacitors in power applications," in *ELEKTRO*, 2014. doi: 10.1109/ELEKTRO.2014.6848893.
- [113] S. G. Parler, "Deriving Life Multipliers for Electrolytic Capacitors." IEEE Power Electronics Society Newsletter, 2004.
- [114] Technical Notes, "Judicious Use of Aluminum Electrolytic Capacitors." Nippon Chemi-Con. Accessed: Nov. 01, 2022. [Online]. Available: <https://chemi-con.com/wp-content/uploads/2021/04/Technical-Notes.pdf>
- [115] H. Gualous *et al.*, "Supercapacitor ageing at constant temperature and constant voltage and 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.
- [118]G. E. Rhoades and A. W. H. Smith, "Expected life of capacitors with nonsolid electrolyte." 34th 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.
- [128]K. Abdennadher, P. Venet, G. Rojat, J.-M. Rétif, and C. Rosset, "Online monitoring method and 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/mm<sup>2</sup>," 2019.
- [131]H. Choi and H. Yoon, "Nanostructured Electrode Materials for Electrochemical Capacitor Applications," *Nanomaterials*, 2015, doi: 10.3390/nano5020906.