



Designing Accelerated Life Test Setup for Aluminium Electrolytic Capacitors

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Aluminium electrolytic capacitors have been vital components for various electrical devices and machines for decades. Accelerated life testing (ALT) for capacitors provides important data of their lifetime, aging, and performance in various environments. With accelerated life testing both lifetime of capacitors and lifetime of devices using these capacitors can be improved. This also helps designing whole new applications and devices using aluminium electrolytic capacitors. By using accelerated life testing for aluminium electrolytic capacitors, and by calculating the lifetime in different environments, capacitors' lifetime in field can be evaluated to anticipate and prevent their end-of-life failure. The ALT test setup was designed to accelerate loss of capacitance and ESR increase. This end-of-life failure mode can be accelerated by amplifying the normal operating conditions to achieve the failure sooner. This gives data that can be compared to the normal application conditions by using factors. The factors can be calculated and applied with different lifetime equations. Creating a tool where these factors are calculated in various situations. a plot can be drawn and see how an upcoming test batch will age, or directly compare the aging against normal operating conditions of the tested capacitors.

This thesis will introduce an accelerated life test setup for aluminium electrolytic capacitors, introduce ALT methods, capacitors' failure modes and failure mechanism as well as a method how capacitors' lifetime can be calculated in various environments. The ALT test setup was built into ABB Drives Helsinki laboratory with support of their engineers.

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Kiihdytetyn Elinikä Testausjärjestelmän Suunnittelu Alumiini Elektrolyytti Kondensaattoreille

Sähkötekniikan diplomi tutkielma

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Alumiini elektrolyytti kondensaattorit ovat olleet yksi tärkeimmistä komponenteista eri tehoelektroniikan sovelluksissa jo pitkään. Kondensaattoreiden kiihdytetty elinikä testaus tuottaa tärkeää tietoa kondensaattoreiden eliniästä, ikääntymisestä sekä suorituskyvystä eri olosuhteissa. Kiihdytetyllä elinikä testauksella voidaan parantaa niin kondensaattoreiden elinikää kuin näiden sovelluksienkin, jotka kondensaattoreita hyödyntävät. Kiihdytetyn elinikä testauksen avulla voidaan myös suunnitella uusia sovelluksia kondensaattoreille. Kondensaattoreille voidaan testauksen avulla myös laskea ja arvioida elinikää eri olosuhteissa kentällä sekä näin ennakoida tulevaisuudessa kondensaattoreiden eliniän kestoa. Testi on suunniteltu kiihdyttämään kondensaattoreiden kapasitanssin tippumista sekä ESR arvon nousua. Tätä elinkaaren loppumisen vikamoodia voidaan kiihdyttää nostamalla normaaleja operoinnin olosuhteita, jotta vikaantumisen tapahtuu nopeammin. Tällaisesta testistä saatua dataa voidaan verrata normaalien olosuhteiden vikaantumisiin kertoimien avulla. Kertoimet sekä elinikä eri olosuhteissa ovat laskettavissa kaavojen kautta. Luomalla työkalu, jonka avulla nämä kertoimet sekä elinikä voidaan laskea eri olosuhteissa, saadaan luotua kuvaaja, joka kertoo eliniän eri olosuhteissa. Kuvaajan avulla voidaan suoraan arvioida eri olosuhteissa tapahtuvien testien kestoa tai verrata tapahtuvaa ikääntymistä normaalien olosuhteiden ikääntymiseen.

Tämä diplomityö esittää tavan toteuttaa kiihdytettyä elinikä testausta alumiini elektrolyytti kondensaattoreille, esittelee ALT metodeja, kondensaattoreiden vikamekanismeja sekä moodeja, tavan kondensaattoreiden eliniän laskentaan ja arviointiin eri olosuhteissa. Testi rakennettiin ABB Drives Helsingin laboratorioon heidän työntekijöidensä avulla.

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This thesis concludes, for now, my time in the University. My journey from elementary school to now graduating from university has been inspiring. I'd like to acknowledge my parents and family for supporting and helping me in various ways during these years. The journey has seen its highs and lows, but the support has always been there. I would also like to thank everybody who has been involved in making this thesis possible. Special thanks to everybody at the laboratory and especially to Kjell Ingman for giving me the opportunity and Hermanni Tervo, Pertti Silventoinen and Tommi Kärkkäinen for the guidance during the process.

Kiitos!

SYMBOLS AND ABBREVIATIONS

Roman characters

<i>C</i>	capacitance	[F]
<i>f</i>	frequency	[Hz]
<i>R</i>	resistance	[Ohm]
<i>T</i>	temperature	[°C, K]
<i>U</i>	voltage	[V]
<i>L</i>	inductance	[H]

Abbreviations

ABB	refers to ABB Ltd, a company
AC	Alternative current
ALT	Accelerated life testing
DC	Direct current
ESL	Equivalent series inductance
ESR	Equivalent series resistance
LCR	Inductance, capacitance, resistance
RMS	Root mean square

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1. Introduction

Capacitors are among the simplest and oldest electrical components as well as among the most used. Capacitors have been key components in different electrical applications for decades. The electrolytic capacitor is one of the main components in filtering applications in variable-frequency drives, where they are used in DC-link circuits. This thesis focuses on the aluminium electrolytic capacitors in the DC-link circuit applications and accelerated life testing (ALT) of these capacitors.

Accelerated life testing is often used to test components in various environments, and to evaluate the expected lifetime of the component in the given environment. To accelerate a component lifetime, it is a must to know how the tested component is used and in what kind of environment. Accelerated life test is done in an environment that is as close as possible to normal operating conditions, excluding those specific factors that are used to accelerate the lifetime. The capacitance loss and ESR value increase are considered as normal aging and, in these tests, as the normal end-of-life failure mode that is targeted thru the accelerated testing.

The failure mode is dependent on the failure mechanisms. The failure mechanisms are then dependant on either production related errors or application environment. In different environments capacitors will degrade and fail differently. To trigger the targeted failure mode based on capacitance loss and ESR value increase, AC ripple current over the capacitors and temperature levels are increased to heat up the capacitor and to accelerate the electrolyte loss.

Accelerated life testing only tells the exact time that is used to test the component. To evaluate lifetime under the various operating conditions and get the most out of accelerated life testing, calculations are needed. Lifetime evaluation considers the different environments and how it affects to the lifetime of the capacitor by factoring the increased parameters. This thesis examines a method for lifetime calculations.

The calculations are done using a factor for each of the accelerated parameter. From the equations, a lifetime evaluation for the capacitors tested is conducted and a calculator tool created to use for later tests and evaluations. Lifetime evaluation can be used to either

develop a better capacitor, or to improve existing electrical devices using the capacitors, or to extend lifetime of machines using these capacitors. The lifetime evaluation of capacitors shall be done in different environments with the ALT test setup. The test results in different test environments can be normalized to real life conditions by using the calculator tool.

The practical part of this thesis focuses on the lifetime evaluation and the building of the ALT setup. The first results will be analysed, and the means to create a more scalable and universal testing setup will be introduced. The first initial testing results prove that the suggested method for ALT of capacitors is worth of developing and researching more. By developing the setup further, more accurate and longer duration testing can be conducted. The data that can be collected from the testing would be utilized in the design of next generation DC-link as well as developing the current DC-link circuits to last longer and perform better.

This thesis suggests a method to conduct lifetime evaluation and accelerated life testing for aluminium electrolytic capacitors.

2. Capacitors

Capacitor is a passive electronic component that is used to store energy. The capacitor was invented by Ewald Georg von Kleist in 1745. His capacitor was made from a glass jar, mercury and an iron nail that was used as a connector. Nowadays a capacitor is constructed from two electrodes that both store an equal amount of energy but with opposite charges. This creates an electrical field that stores energy. Capacitor's capacitance is directly proportional to the area of the electrodes and the permittivity of the dielectric. Capacitance is inversely proportional to the distance between the electrodes.

In capacitors there is no galvanic current. The current in capacitors is displacement current, defined by Maxwell's equations. The dielectric between two electrodes, for example aluminium oxide in aluminium electrolytic capacitors, is acting as an enabler for the different distributions of electric charge in AC voltage. Due to the polarization of the dielectric material, it appears like current is flowing in the capacitor. Capacitors oppose the changes in voltages. The sinusoidal alternative current curve of the capacitor is ideally always 90° ahead of the sinusoidal AC voltage curve of its terminals. (Mäkelin, A. 2018)

$$u_c = \frac{1}{C} \int i_c dt. \quad (2.1)$$

The capacitors equivalent series inductance, *ESL*, and the equivalent series resistance, *ESR*, are formed out of the resistance and inductance of the capacitors structure. The terminals, for example, cause equivalent series resistance and equivalent series inductance to the capacitor. Impedance for capacitors is calculated through equivalent series resistance and equivalent series inductance. Formula for equivalent series resistance:

$$X_c = \frac{1}{2\pi f C}. \quad (2.2)$$

And for the equivalent series inductance respectively

$$X_L = 2\pi f L. \quad (2.3)$$

With ESL and ESR the impedance for a capacitor can be calculated as follows

$$|Z| = \sqrt{ESR^2 + \left(\frac{1}{2\pi fC} - 2\pi fESL\right)^2}. \quad (2.4)$$

All the parameters in the formula for the impedance of the capacitor are dependent on frequency. ESL and ESR are the cause for the electrical potential energy to be dissipated in the capacitor. Capacitors have only one dissipation factor, which includes all the potential energy losses in the capacitor. The formula for the dissipation factor, $\tan \delta$, is

$$\tan \delta = \frac{ESR}{X_c} = \omega C \times ESR = 2\pi fC \times ESR. \quad (2.5)$$

Capacitors are divided into different groups. This thesis focuses on the electrolytic capacitors, and mainly to the aluminium electrolytic capacitors.

2.1 Electrolytic capacitors

Electrolytic capacitors are capacitors that use an electrolyte as a cathode or negative plate of the capacitor. Electrolytic capacitors are polarized capacitors that use an oxide layer as the dielectric of the capacitor. Electrolytic capacitors tend to have a large capacitance value compared to the ceramic or film capacitors. The electrolytic capacitors are divided into three different subcategories: aluminium electrolytic capacitors, tantalum electrolytic capacitors and niobium electrolytic capacitors. Due to their large capacitance the electrolytic capacitors are often used in DC link circuits in variable-frequency drives as well as in storing and filtering applications. This thesis focuses on the aluminium electrolytic capacitors and its properties. Other electrolytic capacitors are only introduced in this thesis and their properties will not be profoundly researched.

Electrolytic capacitors use a chemical feature of specific metals, so-called *valve metals*. These specific metals are tantalum, niobium, manganese, titanium, zinc, cadmium, and aluminium. These *valve metals* can form an oxide layer in an electrochemical process which can block electrical current from flowing in one direction but allow it to flow into the opposite direction. Polish electrotechnician Karol Pollak was the first one to notice that the

oxide layer on an aluminium anode remains. much more stable when it was submerged into an electrolyte (Both. J, 2015.)

2.2 Aluminium electrolytic capacitors

Aluminium electrolytic capacitors are capacitors that have an anode electrode made from aluminium foil. The aluminium foil is etched and forms a thin insulate layer of aluminium oxide by anodization, and thus acts as the dielectric of the capacitor. Aluminium electrolytic capacitors are divided into three different categories: non-solid aluminium electrolytic capacitors, solid polymer aluminium electrolyte capacitors and solid manganese dioxide electrolytic capacitors. In non-solid, so-called wet or liquid, aluminium electrolytic capacitors the non-solid electrolyte is a liquid or gel like substance that covers the surface of the oxide layer. Non-solid electrolytic capacitors are widely used in a variety of different electrical applications. Aluminium electrolytic capacitors can only be operated with DC voltage due to the polarization caused by the anodization. Polarization causes the capacitors to breakdown due to negative voltage.

Aluminium electrolytic capacitors that have a non-solid electrolyte are the cheapest type of electrolytic capacitors, but also the electrolytic capacitors that have the widest possible range regarding their attributes. Aluminium electrolytic capacitors have, like film capacitors, a self-healing property. The liquid electrolyte can provide oxygen when needed for the self-healing of the dielectric oxide layer. The self-healing property can help the capacitor to stay in an operational condition a bit longer, but it can also cause the electrolyte to evaporate or dry out the capacitor. The evaporation of the electrolyte causes slowly breakdown of a capacitor. Evaporation of the electrolyte causes the ESR value of the capacitor to rise and the capacitance to drop.

3. Accelerated life testing

Development of new products has been steadily increasing, and it has got faster in the recent decades as product lifetime has got shorter, both in consumer and industrial electronics. To assure the customers of the product quality, and to estimate cost of ownership, and even potential warranty costs, there is a need to test and evaluate lifetime of products introduced to the markets. Lifetime testing in normal operating conditions would take too long time. This has led to the development of accelerated life testing (ALT) where units are subjected to a more severe environment (increased or decreased) than the normal operating environment so that failures can be induced in a short period of test time. (Elsayed, A.E. 2003.) When the units are under a stress that exceeds the normal field operating conditions or stress levels of the unit, the failure rate of the unit can be increased, and lifetime shortened. The shortened lifetime of the unit can be evaluated with different models.

To conduct an accelerated life test a detailed plan is required. Determination of stresses, number of units and stress levels all need to be considered. Accuracy of ALT depends on the carefully determined stress factors and their stress levels. Tested units need to fail to a failure mode that can be considered as an end-of-life failure. When the tested units are subject to a stress level that is not seen in normal field operating conditions, the failure mode of the tested unit can be something else than an end-of-life failure. The ALT should be planned so that all other stresses and parameters, excluding those factors that are used to accelerate lifetime, are as close as possible to the normal field operating conditions. Stresses can be applied in various ways. Typical loadings include constant, cyclic, step, progress, random stress loading and combinations of such loadings. (Elsayed, A.E. 2003.) Loading modes are shown in figure 1.

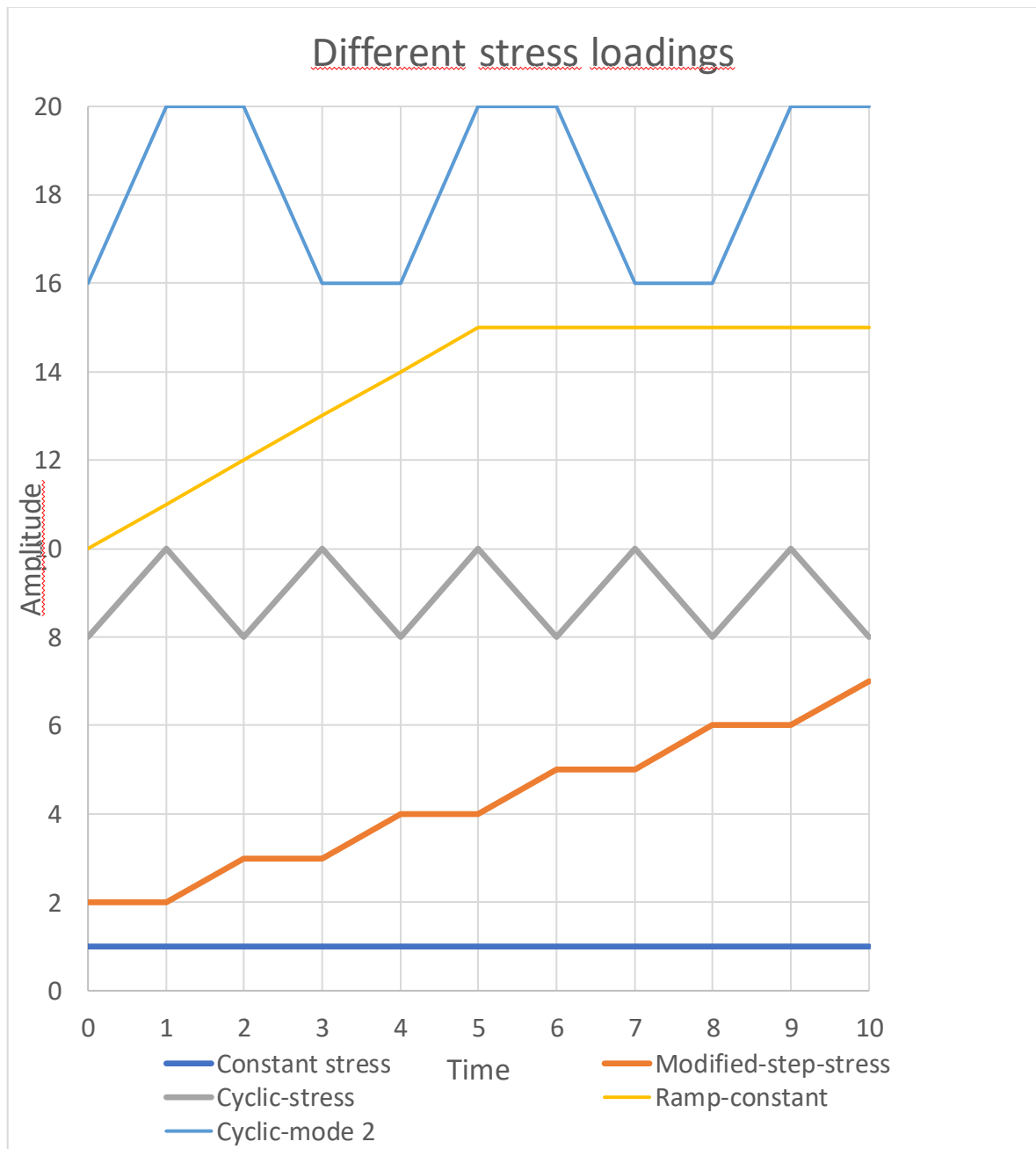


Figure 1. Different loading methods for stresses. (Elsayed E. A. 2003)

3.1 Methods of Acceleration

Accelerated life testing can be performed under different methods and stresses. Stresses are generally divided into three categories:

1. Mechanical stress
2. Environmental stress
3. Electrical stress.

The chosen type of stress is intended to lead to the eventual failure mechanism for the tested unit or product with the applied loading mode of the stress. Stresses can be applied various ways. The combination of environmental stress, for example heat and cyclic mode of applying heat, can simulate the environment under the field operating conditions when the temperature rises during the day and decreases in the night. It is also possible to accelerate product failures by using combinations of the above acceleration stresses (Pascual, F. Meeker, W. Escobar, L., 2006)

The aim with the stress is to induce a wanted product failure mode more quickly than it would occur under the normal field operating conditions. The methods to conduct accelerated life test is dependent on the nature of the subject that is tested. With accelerated life testing, actual acceleration can be induced by increasing product use rate, by accelerating product aging, or by increasing product stress. Increased product use rate is an appropriate way when the product under testing is not normally used continuously. Accelerating product aging happens when you change the environmental conditions of the operation, for example by increasing temperature. Increasing product stress happens for example by increasing voltage, then voltage is amplifying product stress.

All three of these methods include a stress that is introduced to the subject. In this thesis, the ALT testing of the capacitors will be carried out by accelerating product aging under increased temperature levels, and by increasing product stress by applying ripple current over the capacitors.

3.1.1 Mechanical Stress

Mechanical stress is usually applied in ALT for mechanical components. Mechanical stresses are applied to components for example in elevated temperatures to see how the temperature affects the tested parts' ability to handle fatigue. A test where fatigue and temperature are applied to the object under stress is called a creep test. Typical mechanical stresses are fatigue, shock, and vibration. Shock and vibration testing is suitable to products which are exposed to such conditions, for example such as bearings, shock absorbers, tires and circuits in airplanes, automobiles, and is part of typical type tests for frequency converters (Elsayed, A.E. 2003.)

3.1.2 Environmental stress

Environmental stresses are commonly categorized as temperature, humidity, and impurities of the air e.g., dirt and fine particles. Most accelerated life tests commonly use thermal cycling and increased or decreased temperatures in the tests. When environmental stress is introduced to the test, it is critical to use appropriate levels of environmental stress. If the applied stress is too harsh, there is a high and unwanted risk of introducing different failure mechanisms compared to what happens under normal field conditions. Temperature and humidity are the most critical stresses. Challenge with humidity is that often a long-time exposure, like with corrosion, is needed before failure. Of course, humidity can cause fast failure mechanisms in electrical applications, but instead of humidity, corrosion of electrical components or product corrosion can be tested with other environmental stresses like ultraviolet lights and different kind of gases or chemical concentrations. Radiation can also be used as an environmental stress but using radiation in accelerated life testing can be considered problematic due to the constraints of the testing environments. Also, radiation is seldom a likely cause of the failure in the field.

3.1.3 Electrical stress

Electrical stress can be constant or cycling. Electric stress can be used for both non-electrical and electrical components. For non-electrical components, like bearings, electric field is used to accelerate aging. Electrical stress can be overvoltage, ripple voltage or current, overcurrent, electric field, and electromigration (Elsayed, A.E. 2003.) (Nelson, W. 1980)

3.2 Accelerated life testing models

Accelerated life testing models are classified to procedures, which relate to life under stress conditions. (Elsayed, A.E. 2003.) Many of the procedures are based on the Arrhenius equation. The Arrhenius equation is a formula where the accelerating variable is temperature, and it is often used in ALT. The Arrhenius equation describes the relation rate of reaction and temperature for physical and chemical reactions. The Arrhenius equation was first introduced by Svante Arrhenius in 1889 on his article (Arrhenius, S. 1899). The Arrhenius equation is given as

$$k = Ae^{\frac{-E_a}{RT}} \quad 3.1$$

where k is rate constant, T is the absolute temperature, R is the universal gas constant defined by the Avogadro constant and multiplied by Boltzmann constant. E_a is the activation energy for the reaction.

As mentioned, the Arrhenius equation only uses temperature as the accelerating factor causing failures. When there is more than one factor or stress accelerating the test, the Eyring equation can be used where the Arrhenius equation is a part of the equation.

$$\lambda = A * e^{\frac{-B}{kT}} * e^{S(c + \frac{D}{kT})} \quad 3.2$$

where A , B , C , D are measured and estimated constants, k is the Boltzmann constant, T temperature and S is the accelerating factor other than temperature. The Eyring equation can be divided into sectors where the second part is the accelerating factor, and the third part is their cumulative damage in the test. These three parts are the three different exponential parts of the equation.

Weibull distribution is a continuous probability distribution that is widely used in probability theory and statistics. Named after the Swedish mathematician Waloddi Weibull in his paper *A statistical Distribution Function of Wide Applicability* 1951. The Weibull distribution is used to estimate product reliability, model failure times and to analyse life data in the engineering field. Weibull distribution has two different versions, the two and three parameter versions. The two-parameter version is

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x}{\alpha}\right)}. \quad 3.3$$

For $x \geq 0$, the $\beta \geq 0$ is the shape parameter, $\alpha > 0$ is the scale parameter. The three-parameter version is only extended from the two-parameter version

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x - \gamma}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x - \gamma}{\alpha}\right)^\beta} \quad 3.4$$

For $x \geq \gamma$, $\beta > 0$ and $\alpha > 0$. The β and α are still shape and scale parameters. (Jensen, W. A. 2013).

The Weibull analysis is using Weibull distribution to study the time to failure on e.g., electrical components. The Weibull analysis is often used to study time to failure in warranty analysis and lifetimes of different electrical and mechanical components. Weibull analysis is a completed approach of determining reliability characteristics and reliability trends of a population.

3.3 Capacitor reliability

Aluminium electrolytic capacitor's reliability has been long time of vital importance for electronic applications. The variations of electrical performance and lifetime can be crucial. Over time the performance of the capacitor starts to change and degrade. Eventually the capacitors capacitance starts to drop, tangential loss angle increases, and the leakage current begins to drop. When approaching the end-of-life, the capacitor normally enters open circuit mode, and the dielectric dehydrates. (ELNA America INC. 2011)

To design the device with aluminium electrolytic capacitors, it is necessary to consider a failure rate and expected life in order to understand reliability. (Nippon Chemi-Con. 2021.) As mentioned, the failure rate for capacitors are usually approximated with the “bathtub curve” of the Weibull distribution. In the curve, the failure rates are categorized into three categories based on the product life cycle: early failure period (EFR), random failure period (increased failure rate IFR), and wear-out failure period. The Weibull distribution bathtub curve is shown in figure 2.

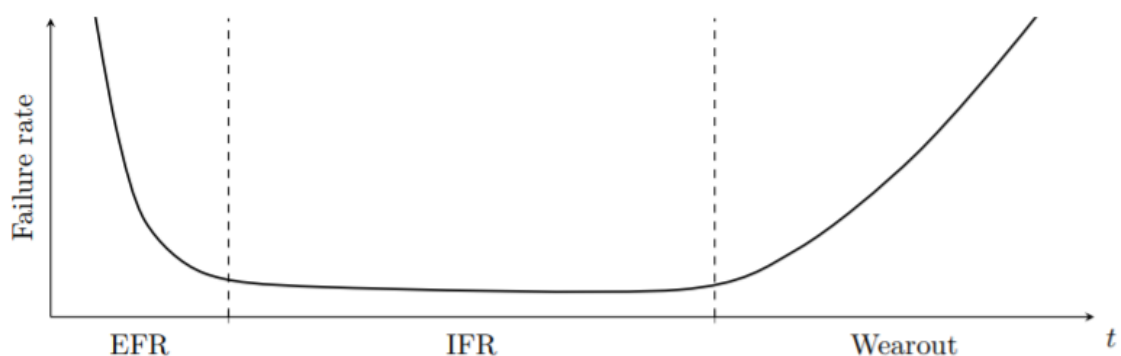


Figure 2. Weibull distribution bathtub curve. (Vulli, A. 2018)

In the early failure period capacitors tend to reach breakdown due to incompatible operation conditions, or due to errors that have happened in the manufacturing process. The early

failure period, EFR in figure 2, is also typically called as “infant mortality”. In random failure period, IFR in figure 2, the failure rate is normally low and stable. The failures are sporadic and are not dependent on serving time or anything else. In random failure period the failures tend to be catastrophic failures. The wear-out failure period is at the other end of the bathtub curve. The failure rate starts to rise exponentially the longer the serving time is. In this period the electrolyte has started to gradually evaporate causing significant capacitance loss and ESR increase, thus leading eventually to an end-of-life failure of the capacitor.

3.4 Electrolytic capacitor failure mechanisms and modes

Electrolytic capacitors have a finite life span. Capacitors can be determined to have failed in various ways. The failure mode is determined by the failure mechanism. Failure mechanisms are the trigger for the failure, that originates from either production or application related source. Failure mechanisms that can be traced back to production related causes are usually caused by impurities. In the field, production-related failures are rarely observed, because the purity of the base materials and the quality level of the mechanical production processes have been continuously improved over the past years (Albertsen, A. 2012). The failure mechanisms originating from unfavorable application or operating conditions are more common. These mechanisms are usually voltage, current, or temperature dependent. These are mechanism that are also hard to predict or prevent due to their character. The normal end-of-life or the wanted failure mechanism for electrolytic capacitors is electrolyte loss. This is an application dependent failure mechanism that is caused by an electromechanical reaction. The failure mode for electrolytic capacitor can be triggered by multiple failure mechanisms. For example, when the failure mode is the capacitance loss and increase of the ESR, the mechanism can be electromechanical degradation, but it can also be thermal decomposition of the electrolyte, or capacitance drop in either anode or cathode.

Electrolytic capacitors possess a unique failure mechanism, the safety vent failure. The purpose of the safety vent is to release internal pressure and prevent an explosion. Capacitor’s anode can free hydrogen and oxygen when operated. The hydrogen must be able to diffuse or exit the package or it will rupture (European Passive Components Institute. 2020). The buildup of gases can cause overpressure to the capacitor and open the safety

valve to prevent an explosion. Electrolytic capacitor is not hermetically sealed due to the gas build up. Hydrogen gas has a low viscosity, and it can escape the capacitor also from the rubber gaskets or other sealing of the capacitor than the safety vent. Collective cause and relation table (table 1.) is given beneath. The failure mode that is wanted in this ALT setup is the capacitance loss and ESR increase.

Electrolytic capacitor failure mechanisms and modes are summarized the in the Table 1.

Application	Production	Failure Mechanism	Failure Mode
Mechanical overstress, overvoltage, reverse voltage.	Impurities, weak spots, mechanical stress, bad contact	Short circuit between electrodes, Dielectric breakdown (either oxide or paper)	Short circuit
Mechanical overstress	Mechanical stress, bad contact	Broken terminal, bad terminal contact, corrosion, electromechanical reaction	Open circuit
Normal aging, thermal overload, overvoltage, reverse voltage, overcurrent, overload, haline contamination	Haline contamination, instable electrolyte system	Electrolyte loss, thermal decomposition, Capacitance drop (either anode or cathode), electromechanical reaction	Capacitance loss, ESR increase
Normal aging, thermal overload, overvoltage, reverse voltage, overcurrent, overload, haline contamination	Haline contamination, instable electrolyte system	Decomposition of oxide layer, corrosion electromechanical reaction	Leakage current increase
Normal aging, thermal overload, overvoltage, reverse voltage, overcurrent, overload, haline contamination	Haline contamination, instable electrolyte system	Internal pressure rise, Electromechanical reaction	Safety vent opening
-	Bad sealing	Insufficient sealing	Electrolyte spilling

Table 1. Failure mechanism and Failure modes with causes leading to them.

(ELNA 2012) (Albertsen 2012)

4. ALT setup for aluminium electrolytic capacitors

Part of this thesis was to create a test setup and conduct an accelerated life test for selected aluminium electrolytic capacitors. The test setup was built into the ABB test laboratory, with assistance from the laboratory team especially what comes to the safety of the test setup. The practical part of this thesis will show the simulation work that was done to get the basic design and dimensioning to the test setup. The latter part of this chapter will go through the chosen models, which will be used to accelerate the lifetime of tested aluminium electrolytic capacitors and to analyse the results. The principal stresses that were selected to accelerate the lifetime are temperature and ripple current. With these stresses, it is possible to accelerate the wanted end-of-life failure mode of capacitance loss and ESR value increase.

When applied with ripple current and elevated temperature the electrolytic capacitors are heated which cause the electrolytic substance to evaporate. The internal pressure caused by the heating electrolytic substance facilitates the electrolytic gas to escape between the rubber bung and case, or simply from the pressure valve on top of the capacitor. This causes drop of capacitance and rise of the ESR value. When electricity and heat is turned off and the sample capacitors have cooled down to room temperature, the LCR scope measurement will tell if the sample capacitors have reached their end-of-life. If the sample capacitors have not reached their end-of-life yet, the samples can be placed back to the tester, and continue testing until end-of-life will be reached can be evaluated from the done measurements. There is a possibility that catastrophic failures like explosion of an electrolytic capacitor happens during tests, but these failures should still follow the Weibull distributions i.e., “bathtub curve”.

4.1 Simulation

The simulation work was done with Matlab Simulink software. The block diagram of the simulations was based on the test setup circuit, and that is shown the Figure 3. The test circuit was based on Wang et als, 2017 “Reliability Test Setup for Liquid Electrolytic Capacitor Testing” article.

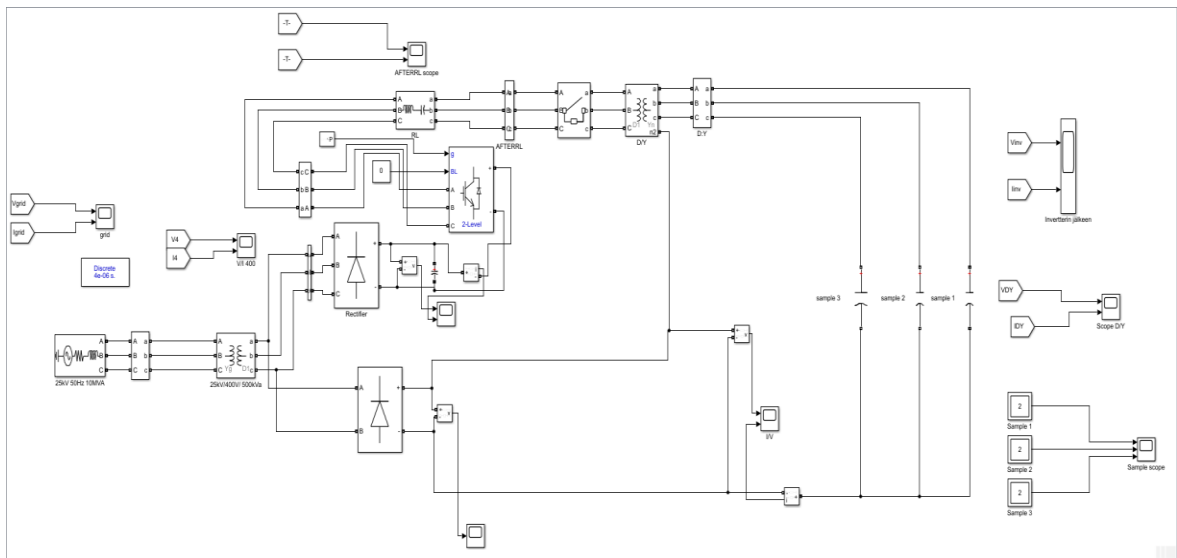


Figure 3. Simulink block diagram of the simulation. The circuit has AC-voltage source, frequency converter, sine filter, delta-wye transformer, and a rectifying bridge to load capacitors on the right. The diagram also has multiple measuring points.

The simulation was done to help dimensioning the hardware setup that would be built, and to help understanding what the sample capacitors would undergo during the planned tests. The simulation currents (figure 4) were found to be high. The current spike in the simulation was found to be around 750A when the contactor was closed and the wanted ripple current level introduced instantly to the circuit. In the real test setup this can be avoided by rising the ripple current level manually step by step. The high current level was also probably due to some not ideal components that were used in the simulation. Simulation still provided much needed information about the behaviour of the circuit and indicated the base values of what to expect in the actual tests.

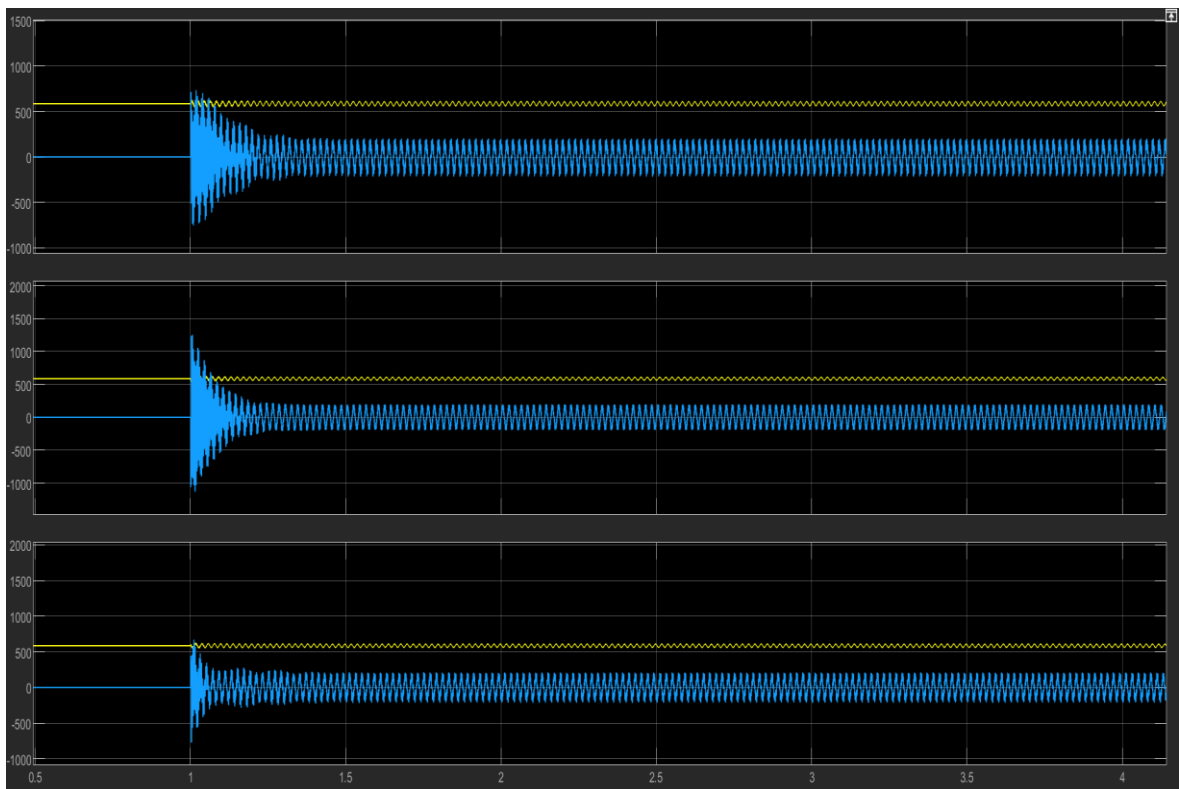


Figure 4. Measurements from the simulation “sample scope”. Yellow line being voltage across the capacitors and blue being the current. Each phase has $21 \cdot 10^{-6} \text{F}$ of capacitance.

4.2 Test setup

The test setup was built into ABB Drives Helsinki Laboratory with the help of ABB’s laboratory engineers. In the setup the sample capacitors are placed into an environmental chamber (figure 5) that can produce the planned temperatures and humidity for the accelerated life test. The first test setup was simplified from the setup that was simulated. The DC rectifying bridge was replaced by a DC power supply and a power resistor was dimensioned to go parallel with the sample capacitors to discharge the electric charge from the capacitors. The electrical wiring diagram (figure 6.) shows how the setup that was built and how it has changed from the simulation block diagram. Wiring diagram also shows how the setup has changed from the original proposed setup (Wang, X. et al. 2019). The power resistor was connected parallel to the capacitors with a contactor to disconnect and connect the discharging circuit when needed and stationed into electrical cabinet next to the environmental chamber (figure 7).

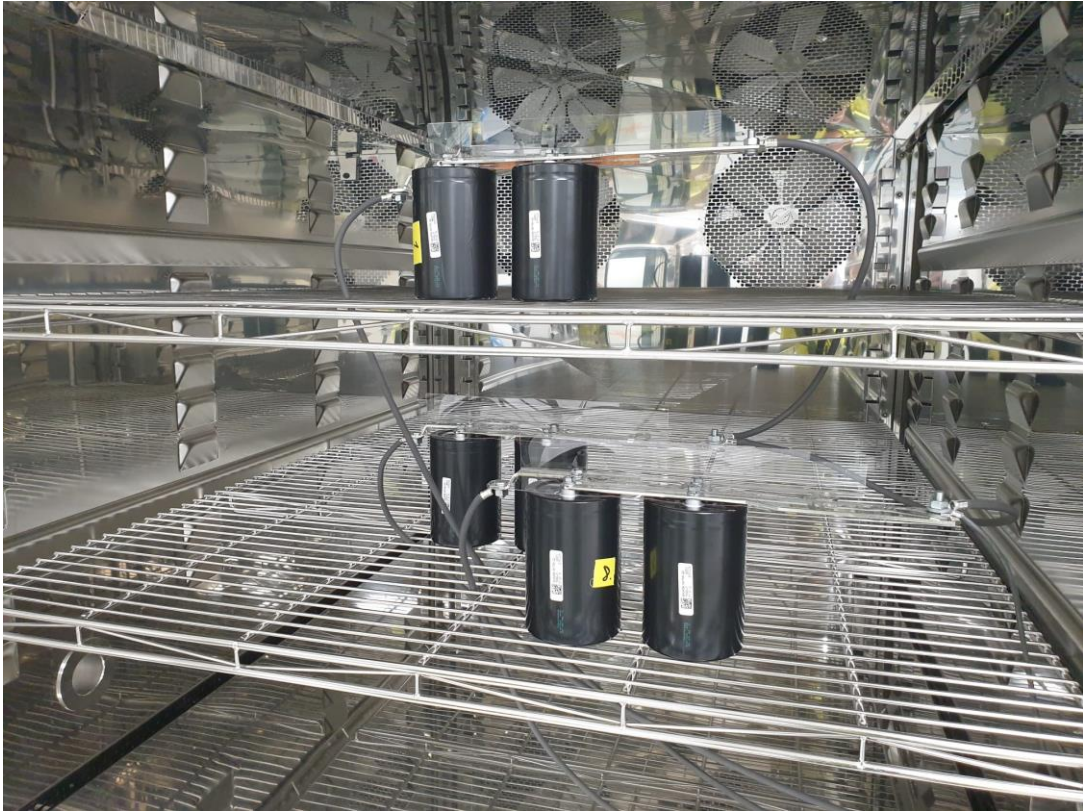


Figure 5. Two aluminium electrolytic capacitors on each phase connected to busbars.

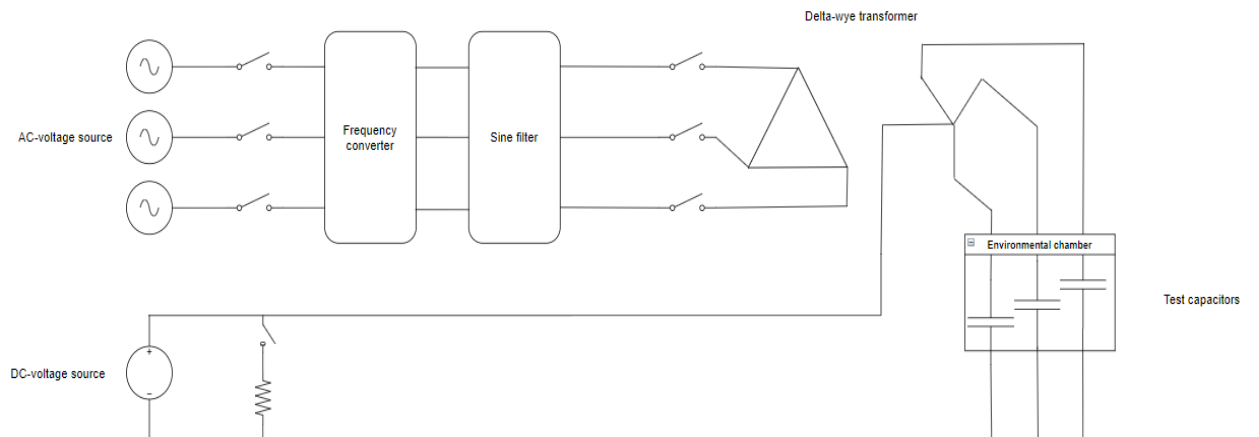


Figure 6. Electrical wiring diagram of the test setup.



Figure 7. Picture of the whole test setup. Environmental chamber with the capacitors. Cabinet with the VSD, power resistor and contactors. On the table DC-power supply and an oscilloscope and on the far right a variable AC power source.

All other parts of the circuit than the sample capacitors were installed into the electrical cabinet next to the environmental chamber. This allows a wider temperature and humidity range when needed inside the environmental chamber without worrying of breaking other components than the sample capacitors. This is also a safety factor, due to the risk of sample capacitor exploding and causing harm to other components. With this arrangement, the test setup can be started and stopped safely, and minimizing risks to other devices or human electrical hazards.

The first test was decided to conduct with very high temperature and ripple current to reach the results in a short period, given that it is easier to come down in the accelerating factor values than possibly wait for several months for a first failure. The accelerating test values were selected according to the datasheet maximum values of the selected capacitors, and

then approximated accelerating value where the test would be conducted. The temperature was set to 100 degrees of Celsius and 300Hz of frequency. The frequency was selected to be the same what the capacitors would normally undergo in the DC-circuit of variable speed drives due to six pulse rectifier. The transformer used in the setup is rated as 400V and 12A in the primary side, and with 30-50V, 100A and 125Hz in the secondary side. This allows to push 300Hz with around 9V output still in the secondary winding, without exceeding the current limits on the transformer output. The 9V ripple voltage is not ideal considering reliable accelerating life tests, but the transformer will be upgraded to a new one for the later version of the test setup. The AC voltage drops low due to the high frequency. The fast-changing rate of the voltage leads to higher current levels. To create an ideal accelerating life test setup, the ripple voltage should be around 50VAC.

4.3 Acceleration model and stress

The accelerating factors will be temperature and high frequency alternative ripple current over the capacitors. This is to simulate the capacitor being under use and stress in a frequency converter. For this setup, there will be only one temperature used. In the future the environmental chamber allows the test to simulate more various situations and environments. The high frequency alternative ripple current will cause hot spots to the capacitors in the test. The stress loading method will be the constant stress. This constant stress loading is the same that is used in the lifetime evaluation calculations. The stress loading method can be changed and varied in later test batches to match the test needs.

The sample capacitors are confirmed to be failed, according to datasheet values, when the ESR has risen over 30% and the capacitance has dropped below 90% from the nominal given datasheet values. Evaluation of these values is done by measuring the sample capacitors with an LCR scope. To measure the sample capacitors safely and to keep the measurements comparable the measurements must be made in closed relative environments. This means that the test setup will be stopped before measuring the sample capacitors, and the samples are given time to cool down and set into room temperature before measuring them. After measuring the sample capacitors, the setup can be normally started again safely.

4.4 Lifetime evaluation

Lifetime of a capacitor is the time from start to failure, where failure is defined as the lack of ability of a component to fulfill its specified function (Gallay, R. 2014). The loss of capacitance in an electrolytic capacitor is caused by either temperature, humidity, or voltage, and it can be calculated. When temperature is the accelerating stress, the evaluation will be done with the Arrhenius law. The voltage dependency of the capacitor can be calculated through exponential law as follows

$$t = t_{U_n} e^{-a \frac{(U-U_n)}{U_n}} \quad 4.1$$

where t_{U_n} is the expected lifetime at the nominal voltage. t/t_{U_n} being the voltage acceleration factor and the a is manufacturer specific acceleration factor. The failure modes are classified into two main categories: “early failures” and “wear out failures” (Gallay, R. 2014)

Electrolytic capacitor manufacturers offer lifetime calculations on the datasheets and even lifetime calculator tools to calculate the lifetime of the capacitor under different circumstances. Electrolytic capacitors are known to have a finite lifetime and causing problems what comes to reliability of power electronics if not well dimensioned. The calculations and calculation tools that manufacturers offer are based on the Arrhenius equation for temperature dependance of reaction rates. When applying ripple current and frequency to the operation, the core of the electrolytic capacitor will heat up more than just by accelerating only with temperature. The power dissipated by the capacitor is determined by the RMS ripple current and the capacitor ESR at the applied frequency. (Bocock, G. 2021) These acceleration values are usually determined by the capacitor manufacturer. The simplest way to calculate the life expectancy of an electrolytic capacitor can be given as

$$T = T_0 * 2^{\left(\frac{T_{\max} - T_a}{10}\right)} \quad 4.2$$

where T is estimated lifetime, T_0 lifetime at the rated temperature, T_{\max} rated temperature and T_a the ambient temperature, in this case the set temperature in the environmental chamber. (Huang, S. Xiong, S. Zeng, D. Qu, L. Zhu, L. Zhu, G. 2018.) The number 10 is the rule of thumb for biological and chemical reactions and could be a component or supplier specific on experimental results.

In our first test, the above equation gives $T=4242,62$ hour for the lifetime, where $T_0=12000\text{H}$, $T_{\max}=85^\circ\text{C}$ and $T_a=100^\circ\text{C}$. The radical drop on the lifetime is the result of the extreme temperature set in the environmental chamber where the capacitors were. In this case the calculated lifetime does not include the stress caused by the AC current ripple, only the temperature effect on the lifetime. The lifetime calculations used for this accelerated life test setup are proposed in the next chapter.

4.5 Lifetime modelling

To understand and conduct lifetime modelling we need to have a knowledge of the capacitor's datasheet specification and the application specific or test specific parameters like temperature, current load, and voltage levels. Equivalent series resistance ESR can also be considered as vital for lifetime models. With ESR thermal losses during operation can be calculated. Total ESR can be calculated as follows

$$ESR = R_0 + R_f + R_t \quad 4.3$$

where the R_0 is the capacitors constant resistance value, R_f is frequency dependent resistance of the dielectric layer of the capacitor, and R_t is the temperature dependent resistance of the electrolyte.

Electrolytic capacitors self-healing mechanism can save and keep the capacitor in a better condition, but it also causes heat buildup inside the capacitor. When operated the capacitors

temperature rises above the ambient temperature. In electrolytic capacitors their core heats up more and, thus, need to be estimated in lifetime calculation. Capacitors core temperature can be estimated with a given formula

$$T_c = \Delta T * \frac{R_{th}^{in}}{R_{th}} + T_s \quad 4.4$$

where ΔT is the temperature rise of the capacitors surface area when ripple current is applied, R_{th} is overall temperature resistance, T_s is the surface temperature of the capacitor and R_{th}^{in} is the combined thermal resistances of the capacitor in axial and radial direction. The mathematics behind combined and axial and radial thermal resistance can be excessive nowadays. To evaluate the core temperature properly for accurate results, special made capacitors with mounted thermocouples were ordered to conduct tests. Radial and axial thermal conductivity is widely introduced in the S. Parler “Thermal Modeling of Aluminium Electrolytic Capacitors”. The core temperature of the capacitor is possibly the most critical parameter for lifetime evaluation, but it is also dependent on ripple current. In this test, ripple current is introduced to the circuit through a VSD and a transformer. Ripple current causes the capacitor to self-heat. Effects of the ripple current can be calculate as given

$$I_R = \sqrt{\left(\frac{I_{f1}}{F_{f1}}\right)^2 + \left(\frac{I_{f2}}{F_{f2}}\right)^2 + \dots + \left(\frac{I_{fn}}{F_{fn}}\right)^2} \quad 4.5$$

where I_R is the RMS value of rated ripple current, I_{fn} is the RMS value of rated ripple currents at frequencies $f_1 \dots f_n$, F_{fn} is the correction factor for the current at the same frequencies. Correction factors can be usually obtained from datasheets as they are dependent from the ESR.

The liquid electrolyte inside the capacitor is the main cause for capacitor’s finite lifetime and the continuous change of its parameters (Albertsen, A. 2018). The end-of-life failure for electrolytic capacitors can be estimated by use of semi-empirical lifetime model that gives out the resulting lifetime

$$L = L_0 * K_R * K_T * K_V \quad 4.6$$

where L_0 is the nominal lifetime given in the datasheet, K_R is the ripple current factor, K_T is the temperature factor and K_V is the voltage factor. All the parameters are factors because they are calculated. Temperature factor K_T is given as

$$K_R = 2^{\frac{T_0 - T_A}{10K}} \quad 4.7$$

where T_0 is the datasheet max temperature, and T_A is the application temperature, here the environmental chambers set temperature. $10K$ is the rule of thumb for biological and chemical reactions and could be a component or supplier specific on experimental results. The life of an aluminium electrolytic capacitor varies exponentially with temperature, approximately doubling for each 10 degrees cooler the capacitor is operated (S.G. Parler 1999)

Ripple current factor can be calculated through given formula

$$K_R = K_i^{A * \frac{\Delta T_0}{10K}} \quad 4.8$$

where

$$A = 1 - \left(\frac{I_A}{I_R} \right)^2 \quad 4.9$$

and I_A is the ripple current of the application, I_R nominal ripple current of the capacitor, ΔT_0 is core temperature increase of the capacitor due to ripple current, and K_i is the empirical safety factor (defined in the appendix). The voltage factor is dependent on the self-healing phenomena. Self-healing consumes the electrolyte every time it happens, and self-healing

phenomena is depending on temperature. Thus, lower operating voltage than rated voltage may extend the lifetime of capacitors significantly (S.G. Parler 2004)

$$K_V = \left(\frac{U_A}{U_R}\right)^{-n} \quad 4.10$$

Where U_A is the application operation voltage, U_R is the capacitor rated voltage and n is the exponent defined in the appendix.

Humidity also effects the lifetime of the capacitors. Moisture presence can damage electrolytic capacitor due to electrolytic corrosion causing the capacitance to drop. Few articles suggest a method to factor humidity the same way to the equations. The same principle can also be applied to vibration. (Bhargava, C. et als 2018)

4.6 Pre-test lifetime estimation

Before the tests, a lifetime estimation is conducted to get a preliminary grasp of at which level the stresses for the capacitors should be applied. The estimation is done based on the calculations above, and with the tools that are given by the different manufacturers, for example websites of TDK Epcos. The lifetime estimation was done with above mentioned equations that include the negative effect on lifetime by ripple current. The equations and paragraphs were done with Matlab. The lifetime calculations on different temperatures and ripple current are shown in the figure 7. The figure 7 shows us that the lifetime estimation 12000H that was given in the capacitor datasheet (appendix 1.) is very close to our own calculation results. In figure 7 the lifetime of the capacitors in 20A ripple current at 85°C temperature is about 525 days. The 12000H lifetime in 21,6 A ripple current and at 85°C equals for 500 days. For a similar capacitor the TDK Epcos lifetime calculation tool gives a 12000H lifetime in 20A and at 85°C.

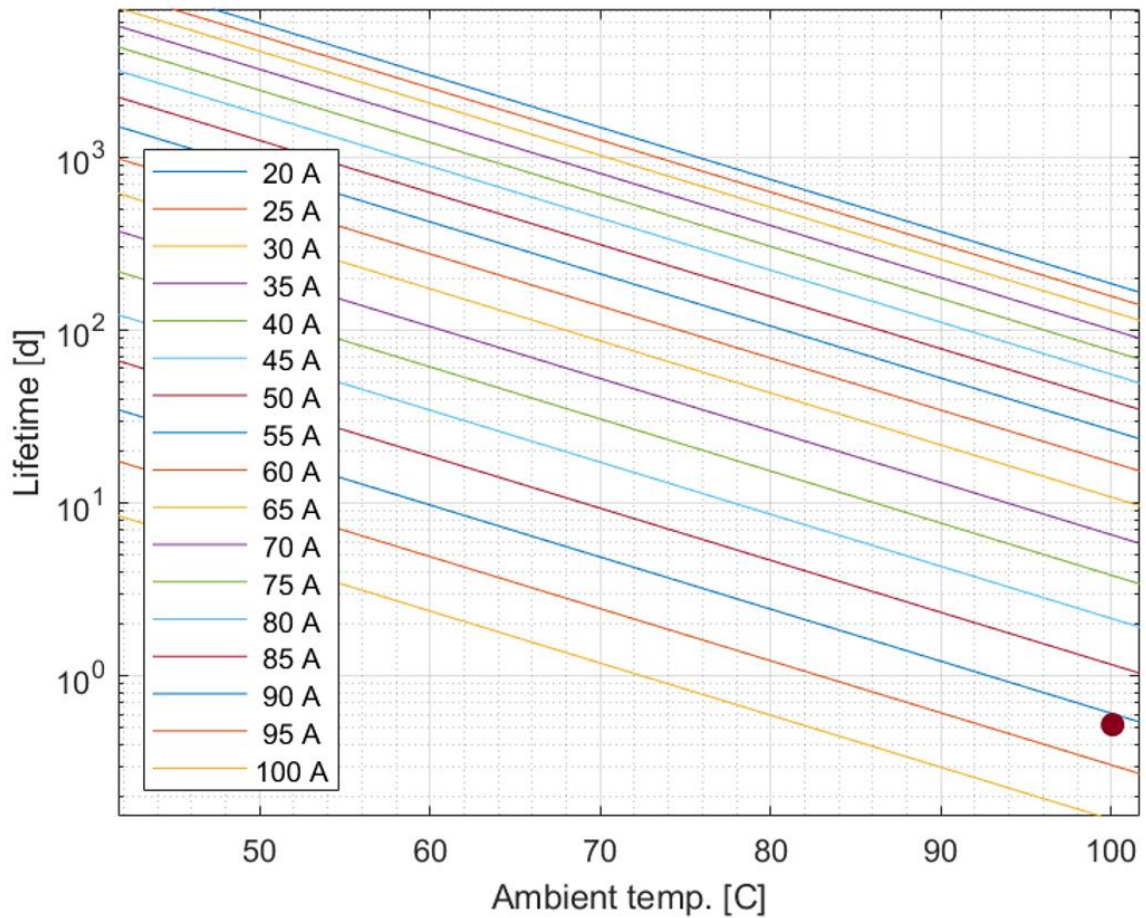


Figure 7. Capacitor's lifetime estimation in different temperatures and ripple current levels.

The first initial testing was conducted in extreme condition in roughly 90A ripple current and 100°C temperature would only give the capacitors a 15 Hour lifetime in 50Hz system. Our test setup uses 300Hz ripple current that prolongs the lifetime. The capacitors ESR decreases as the frequency increases (Bocock, G. 2021), giving us a longer lifetime in the test conditions than in the paragraph given above. This also works vice versa; low frequencies shorten the capacitors lifetime and thus cause faster aging of the capacitors.

5. Results

The target of this master's thesis was to create an accelerated lifetime test setup and conduct preliminary testing for aluminium electrolytic capacitors. During this thesis the test setup was simulated, designed, and built. It was tested to be suitable for accelerated life testing purposes and it performed as specified in the simulation. The designed ALT test setup can be used to conduct reliable testing under various stress levels. The variable speed drive can be used to create various stress levels with different frequencies, voltage levels and current levels. The three-phase transformer determines the highest possible current and voltage levels, and if needed, the transformer can be change in order to create more possible stress levels to the match the planned test setup. Environmental chamber allows the test setup to have a broad temperature and humidity range where the aluminium electrolytic capacitors can be tested in. The first test was conducted in extremely harsh conditions to see how quickly the aluminium electrolytic capacitors would start to degrade.

The loading method that is used is the constant stress. When the test is started the temperature of the environmental chamber was set to constant, 100° Celsius in this first test, and the ripple current was introduced also as a constant value being roughly 92A RMS for each phase and capacitor.

5.1 Analysis

The first tested aluminium electrolytic capacitors had a capacitance of 7000 μ F. The relevant specifications for the capacitors will be given in the appendix. The capacitors were measured with Keysight E4990A Impedance analyzer. Each capacitors C_s and R_s values were measured with the Keysight from 0-10000Hz range. Measurement data is available in the appendix. The first test only included one capacitor on each phase, totaling three capacitors. The capacitors were then connected to the busbars the environmental chamber. The test setup was running for 10Hours with the cabinet temperature being 100° of Celsius, direct current voltage of 400V and the alternative current ripple being 8 Volts and 92 Amperes on each phase and capacitor. The ten-hour long test showed that the capacitance had dropped

according to the Figure 8. The capacitance drop is not enough to conclude that the capacitor is already at end-of-life, but the harsh test and clear results have proven the test setup is working and performing as planned. The test setup is worth developing further to support more versatile testing and to verify the results, that was not possible due to time limitations on the project.

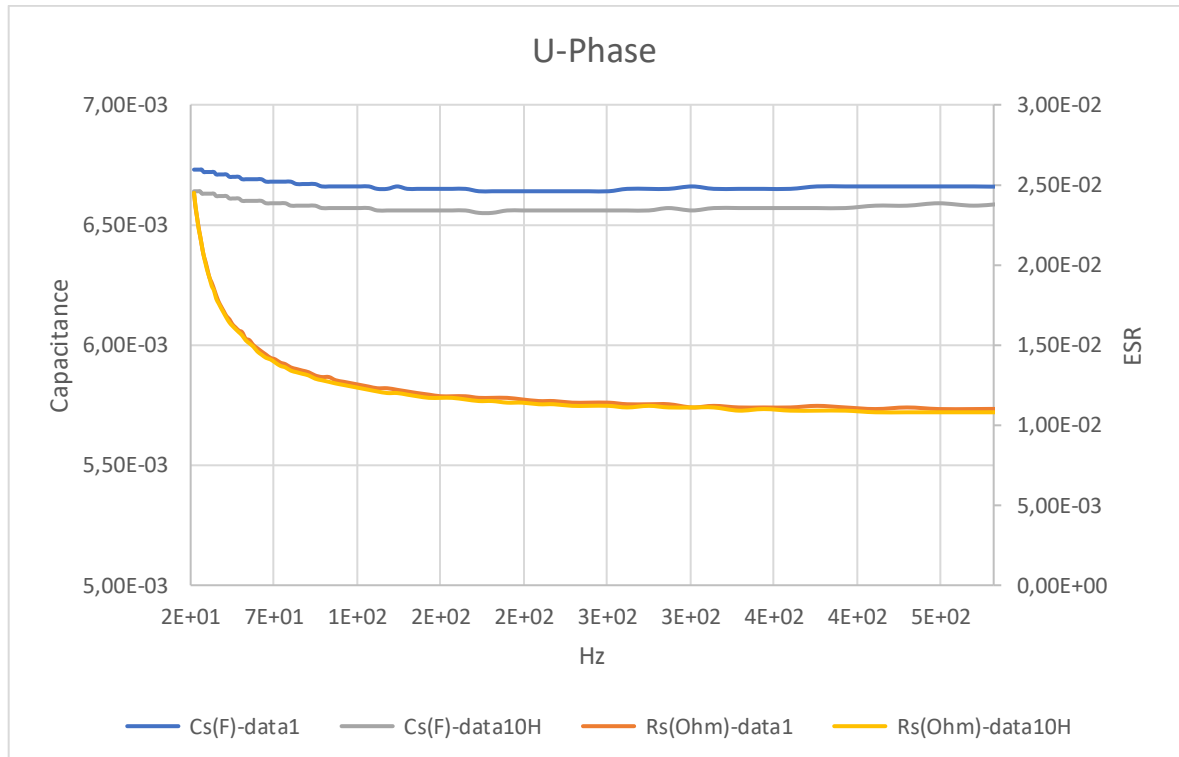


Figure 8. The U-phase capacitor's C_s and R_s data plotted before and after the 10hour long test.

From the measurement data and from the figure 8 we can estimate that the capacitance has dropped about 1,4% in the 50Hz region. The difference between ESR values is still minimal and no clear aging or variation is yet visible. If the aging is linear the capacitor would be crossing the line on manufacturers defined 10% capacitance loss after 80 hours of testing. This would then be considered as the end-of-life failure mode due to capacitance loss and ESR value increase. Every time the capacitance and ESR value are measured from the tested capacitors, the results will be easy to analyze and compare to the original measured values and to the lifetime chart. The lifetime chart provides great evaluation to the duration of the

test and how rapidly the capacitors are aging. When the capacitors are measured either during the test or every time the setup is being stopped for measurements, the data gathered can also be plotted to the lifetime evaluation chart (figure 7.) When the data is plotted to the lifetime chart, we can see how the actual data compares to the calculated aging. When the test setup works as specified the gathered measurement data should be alike with the calculated lifetime evaluation charts. When plotted to the logarithmic chart the gathered data should also perform linear.

The first test showed that ALT setup can age the capacitors in a short time. The initial testing was done to see how fast the aging would be visible on the capacitors, and if the setup is worth developing further. The results are positive, and the next real tests will be done with more capacitors and more suitable stress levels. Before the next test batch, the current ALT setup will be upgraded with a new transformer and a better sine filter to increase the amount of capacitors that can be under test and to support new test protocols.

6. Summary

The target of this thesis was to design a tool for lifetime calculation and ALT test setup for electrolytic aluminium capacitors. Targets were achieved and both the calculations and test setup proved to be successful.

The accelerated life test setup designed in this thesis will be further developed based on this thesis at the ABB laboratory. The setup will be upgraded to make it more suitable for different kinds of capacitors and a measurement circuit for the capacitor will be created. For example, the transformer will be upgraded to more robust with higher currents, and more busbars will be designed in order to use the tester for example to test snap-in capacitors. A critical factor is safety of the test setup which need special attention. Ideally there should be a way to measure and detach every single capacitor all the time. The measurement circuit would monitor the capacitance values and ESR values for single capacitor during the test and when the critical point on one or more capacitors is reached, the system would automatically trigger the safety measurements either to stop the test altogether, or to detach a single capacitor off from testing circuit and continue the test on other capacitors. The stress loading method was chosen to be constant stress in these first tests. This simulates well the situation where the capacitors are in constant use for long periods of time. With different stress loading method, the setup can also simulate different situations. When the loading method chosen is cyclic-stress the setup can simulate the aging of capacitors that are used in devices that only work e.g., 8 hours a day or similar.

The lifetime calculations have proved to be useful for many capacitors and the Matlab code created for them is useful for both product engineering and product development in making decision on components and their dimensioning. To make the lifetime calculations even more useful, adding more lifetime affecting factors like vibration, frequency and humidity should be added to the equation for even more precise and prognostic approach. With precise lifetime calculations on different power electronics components, especially on the capacitors, the service intervals for the devices can be estimated. When the field operating conditions are known, the lifetime can be precisely evaluated, and the service intervals adjusted accordingly. With precise lifetime calculations the failure of the product in the field

can be prevented. The ultimate developing goal for the lifetime calculations and ALT test setup would be to use the data to create a prognostic approach to the capacitors lifetime in order to prevent the failures, and to find a point where capacitors would start degrading before any lack of operational performance.

The ALT setup for capacitors can be useful in product engineering, product development, reliability engineering and with supplier comparison. With upgrading the setup to make it more scalable and suitable for different kinds of electrolytic capacitors, the setup should provide meaningful data that can be used to create more customer value and more robust frequency converters and drives.

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Appendix 1.

Tested capacitors datasheet values.

Capacitance	100Hz 20°C	7000 μ F
Capacitance tolerance		-10/+30%
Rated Voltage	V_r	400
Surge Voltage	V_s	440
Operating Temperature	°C	-25/+85
Maximum Leakage Current	5min 20°C	9,8mA
Typical ESR	100Hz 20°C	15m Ω
Maximum ESR	100Hz 20°C	23m Ω
Rated Ripple Current $I_{ac,r}$	100Hz 20°C	21,6A
Maximum Ripple Current	100Hz 100°C	60,2A
$I_{ac,max}$		
Useful Life	85°C, V_r , $I_{ac,r}$	12000H

Appendix 2.

Lifetime calculation variables K_i and n definitions

K_i is an empirical safety factor for the ripple current defined as

When $T_0=85^\circ\text{C}$, $K_i=2$

When $T_0=105^\circ\text{C}$ and $I \geq I_R$, $K_i=4$ when $I \leq I_r$, $K_i=2$

n is an exponent to the voltage factor defined as

$$0.6 \leq \frac{U_A}{U_R} \leq 1, n=2,5$$

And

$$0 \leq \frac{U_A}{U_R} \leq 0.6, K_v = 3,59$$