3.2. New construction and packaging process for highest voltage aluminium polymer electrolytic capacitor

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ABSTRACT

Polymer aluminium electrolytic capacitors exhibit high capacitance density while having lower ESR and higher reliability than capacitors with a liquid electrolyte. Their biggest disadvantage are the voltage limitations, with commercial devices only going up to 200 V. Increasing the voltage rating requires bigger can size, which is not possible due to difficult winding impregnation. In this work a process is shown to succesfully construct a high voltage polymer aluminium electrolytic capacitor with a rated voltage of 750 V. For that, a high voltage anodization process was developed, enabling formation up to 1500 V. Single aluminium anode foils were anodized and stacked in parallel into a fan-like cathode structure with paper separators. The structure was then impregnated inside an aluminium can and dried. The resulting capacitors showed high breakdown voltages of 835 V and a capacitance of 2 μF. The electrical performance was further demonstrated by leakage and ripple current measurements. In this study, flat aluminium foils were utilized as the anode material, so any subsequent increase in surface area could significantly enhance capacitor performance and capacitance density. With an improved capacitance density, this technology could have great potential in DC link applications that require high voltage, high ripple currents, and high capacitance. The drivetrain of an electric vehicle could be a potential application, where constant acceleration and recuperation lead to very high ripple currents.

INTRODUCTION

Capacitors are essential electrical components and are used in every electronic cuircuit. In the electrification they play an important role as the DC link capacitor, especially in the automotive use, where it can take up to 20% of the weight of a traction inverter [1]. An optimized DC link capacitor can significantly improve power density and efficiency. One widely used technology are aluminium electrolytic capacitors due to their advantages, such as high capacitance density and low manufacturing costs. However, they also have significant disadvantages, including a high equivalent series resistance (ESR) and failure caused by electrolyte evaporation [2]. To address these issues, improvements were made with the development of aluminium electrolytic capacitor, using a conductive polymer instead of the liquid electrolyte [3] [4]. These devices demonstrated substantially better reliability, lower ESR, better thermal stability, and reduced electrolyte loss and degradation [5] [6]. Despite these advances, the technology is still constrained by the maximum operating voltage and capacitance values, with commercially available capacitors typically limited to 100 V with exceptions going up to 200 V [7] [8] [9]. Recent publications in this field demonstrated high breakdown voltages going up to 700 V [10] [11]. However, rising DC link voltages going up to 800 V would still make it necessary to use multiple capacitors in series and parallel [12]. That increases the number of devices and introduces the need for voltage-balancing circuits. In order to use the high power density of polymer aluminium electrolytic capacitors in such applications, it is necessary to increase the breakdown and the resulting rated voltage. A higher rated voltage requires a thicker dielectric, which leads to lower capacitance values. To achieve high capacitances, the can size of high voltage capacitors has to be increased. That however is not trivial for capacitors that use a polymer electrolyte due to the limitations of the production. The typical structure of this technology today is a winding structure. The anode and cathode are wound up and then the oxide has to be formed in an acidic electrolyte [2]. After this, the acidic electrolyte has to be removed and replaced by the conducting polymer electrolyte, containing Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS). The impregnation of the winding is challenging up to today and windings diameter and height are mainly limited to a maximum of 1.2 cm [7] [8] [9]. A second way to increase capacitance is to increase the active area of the anode foil. In anodization voltages up to 1000 V this is done through an etching process, to produce tunnels on the surface. However, this process is not developed for anodization voltages above 1000 V, which is needed to get to rated voltages of 800 V. Since the oxide is much thicker at higher forming voltages, the oxide clogs the tunnels, lowering the active area. Since the etching process for a high voltage anodization is a whole study on its own, this work uses flat anode foils to concentrate on the high voltage formation and on the packaging of such a device. This study presents a possible solution for the impregnation and size limitation of a high voltage polymer aluminium electrolytic capacitor. Pure aluminium is anodized to the highest voltage of 1500 V. With the aluminium cathode foils a structure is prepared to accomodate the stacking of the anode foils. The structure is inserted into the can and is impregnated with PEDOT:PSS directly within. The seperate anode and cathode foils are then weld together with ultrasonic welding and the can is sealed with polyurethane. The

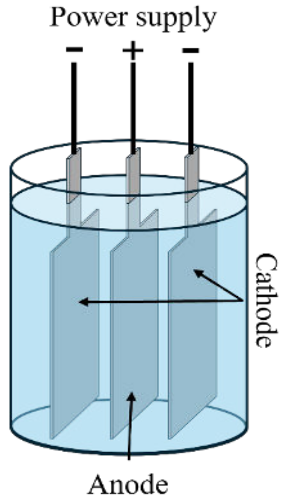
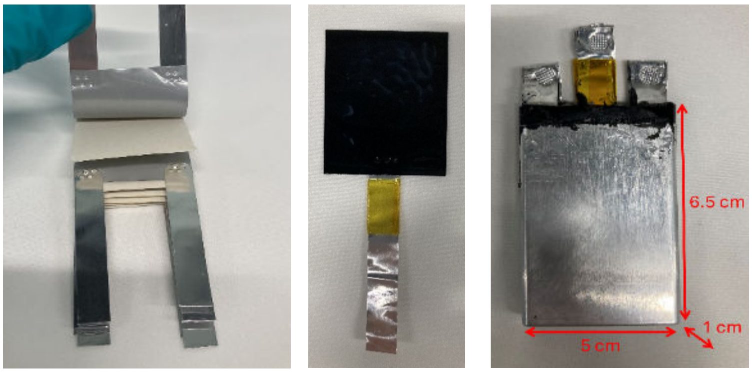


Figure 1: Electrochemical setup for electropolishing and anodization.



(a) *(b)* *(c)*

Figure 2: (a) Fan structure consisting of cathodes and paper seperators. Between the cathodes and papers, a total of 6 anode foils can be inserted. (b) PEDOT:PSS covered anode. (c) Capacitor stack after impregnation, encapsulation and welding

electrical characteristics including ESR, capacitance, leakage current, ripple current and breakdown voltage are measured and presented in this study. The next section is the experimental part. It describes the forming process, the construction of the capacitor with the formed foils and the measuring techniques. The third section presents the measured electrical characteristics and discusses the results and the fourth section concludes this study.

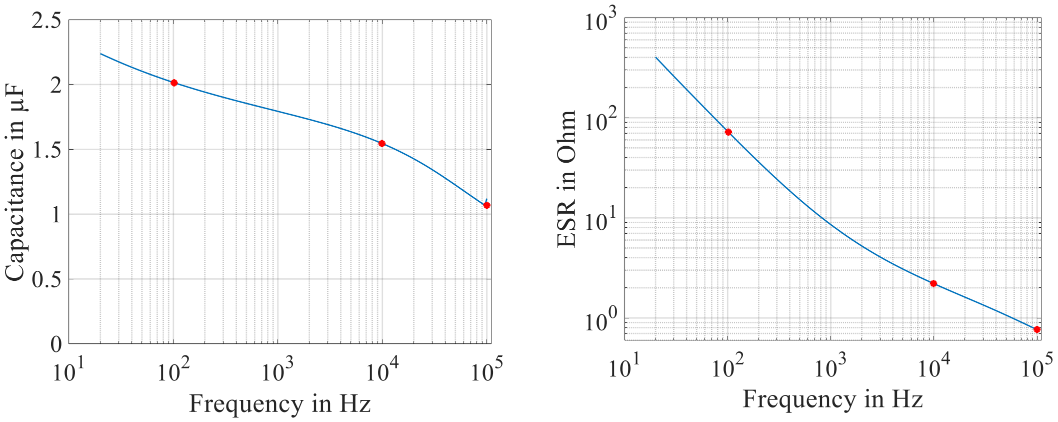
EXPERIMENTAL SECTION

Forming Process

A pure 99.99 % aluminium sheet with a thickness of 150 µm from TDK was used for the anodization. It was cut into 4 x 5 cm sections with a 1 cm wide tap and pressed flat with a mechanical press. The foils were cleaned by rinsing in 2-propanol and deionized water. Subsequently the foils were electropolished in an ethylene glycol and choline chloride solution. For that, the chemicals were mixed in a 2:1 ratio in a glass beaker, heated up to 70 °C and the heating was turned off immediatly after reaching 70 °C. The solution is cooled to room temperature and is then ready to be used for polishing. The polishing is done in an electrochemical cell, where the polished aluminium is the anode and two aluminium foils that are not polished are the cathode. Because of the high viscosity of the solution, the stirrer has to be turned on up to the point, where a whirl is forming at the surface. Then a voltage of 10 V is applied to the anode and cathode for 10 minutes. The current density is set by the electrochemical process itself. This is a sensitive process, where slight deviation might lead to a white layer, likely consisting of Al_2Cl_3 on top of the aluminium instead of a polished surface. The polishing setup is schematically shown in Figure 1. The process could be run for longer time for even smoother surface. It was found however, that a polishing time longer than 600 seconds does not improve the electrical characteristics further. After polishing, the oxide formation occurs in multiple steps: anodization, chemical depolarization, and thermal depolarization. Anodization is performed with the same setup used for polishing in Figure 1, with a 0.05 mol L^{-1} boric acid electrolyte. The total forming process with parameter details is listed below.

1) First anodization: H_3BO_3, 0.05 mol L^{-1}, 85 °C
2) Chemical depolarization: $(NH_4)_2HPO_4$, 70 °C
3) Thermal depolarization: 500 °C
4) Second anodization, H_3BO_3, 0.05 mol L^{-1}, 85 °C
5) Chemical depolarization: $(NH_4)_2HPO_4$, 70 °C
6) Thermal depolarization: 500 °C
7) Third anodization, H_3BO_3, 0.05 mol L^{-1}, 85 °C

For the first anodization the current density is set to 3.75 mA cm^{-2} and remains constant until 1500 V is reached. The voltage is 1500 V for all three anodization steps. The anodization process is stopped when the current density falls to 1.9 mA cm^{-2}. The anodized aluminium strips are then depolarized in a 0.3 mol dm^{-3} di-ammonium hydrogen phosphate



(a)

(b)

Figure 3: (a) Capacitance-frequency response of the capacitors. (b) ESR-frequency response of the capacitors. Both are an average of 4 samples.

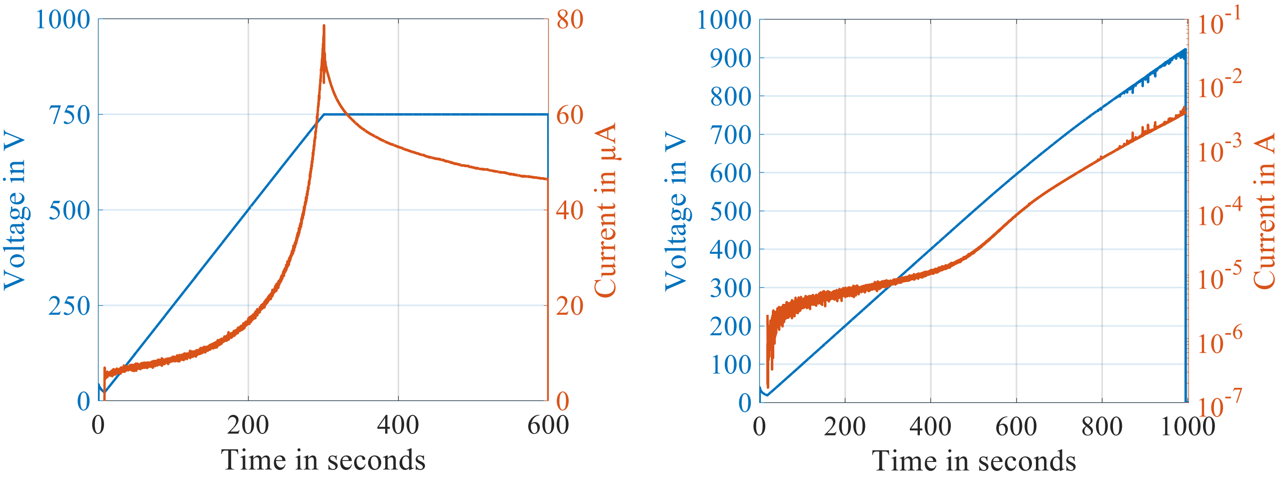
solution, at 70 °C. The high conductivity of the solution enables trapped charges from the oxide to be released, so that defects can be rearranged by the thermal depolarization [13]. For the thermal depolarization, the anodized aluminium strips are placed in an oven at 500 °C. Heat treatment is a widely used process after anodization. It can increase the resistance to high temperatures and improve the leakage current, and the breakdown voltage of the oxide layer [14]. The heat treatment enables trapped charges and crystal lattice defects to realign because of the increased thermal energy. To improve the oxide quality, these three steps are repeated one more time, followed by a third and last anodization step. For the second and third anodizations the initial current density is set to 2.5 mA cm^{-2} and the anodization is stopped once the current density falls to 1.2 mA cm^{-2} .

Capacitor construction

A capacitor cell consists of a cathode, a paper separator, and an anode with the grown dielectric oxide. To increase surface area, the usual construction is a long strip of anode, cathode, and paper, which are wound up to a cylinder. As described in the introduction, that leads to the problem of the impregnation of the PEDOT:PSS electrolyte as the forming electrolyte has to be removed and the PEDOT:PSS has to be impregnated into the tighthly wound foils afterward. An alternative way is to have multiple single flat capacitor cells each consisting of a cathode, paper, and anode and stack them on top of one another. All cells are in parallel, which increases the capacitance and reduces ESR and ESL values. This way, the impregnation is simplified and the active area can be increased. It would be possible to construct and impregnate every cell on its own and stack them afterward. However, the thick oxide layer on top of the anode foils is brittle and cracks easily upon handling. A crack leads to an early breakdown when the capacitor is in operation. It is thus necessary to reduce the steps where the anodes have to be physically handled as much as possible. For the cathode a 50 µm thick and highly etched aluminium foil from TDK was used. Both paper and cathode are cut into 5.3 cm x 4.2 cm pieces. The separate cathode foils are cold-welded together at one end, and between two cathodes, two paper seperators are placed. To form the electrical connections, two pure aluminium tap foils with a thickness of 120 µm are cold-welded to the edges of each cathode. The resulting structure is displayed in Figure 2 (a). Before the anodes can be inserted into the structure, they have to be precoated with the PEDOT:PSS dispersion. This step is necessary to ensure an electrical connection to the whole anode surface. If this step is not done, the electrolyte will only partially cover the anode, leading to reduced capacitance and an increased ESR. A PEDOT:PSS covered anode is shown in Figure 2 (b). The anodes are then carefully put in between the paper and cathode structure and then is placed inside a 1 cm x 5 cm x 6 cm aluminium can. For impregnation, the can is then filled with the PEDOT:PSS electrolyte, put under vacuum und is subsequently dried in an oven at 120 °C. After impregnation the can is encapsulated with polyurethane and the tap foils are weld together with ultrasonic welding. Figure 2 (c) shows the final capacitor after encapsulation and welding.

Characterization

The electrical characteristics of the resulting capacitors are measured through capacitance, ESR, leakage current and breakdown voltage. The capacitance and ESR are measured with a LCR meter FLUKE E4980AL which takes 200 measurements over a frequency range of 40 Hz – 100 kHz. The breakdown voltage is measured with a Vitrek 951i breakdown tester, which is set to apply a voltage sweep of 2 V s–1. The breakdown is detected, when a preset limited current exceeds 10 mA. The leakage current is measured through a power supply and two multimeters. For that, the rated voltage of 750 V is applied to the capacitor for 12 hours. The voltage is then turned off and on again. The leakage current is measured after 5 minutes.



(a)

(b)

Figure 4: (a) Exemplary leakage current measurement at 750 V. (b) Exemplary breakdown voltage measurement.

RESULTS AND DISCUSSION

Capacitance and ESR

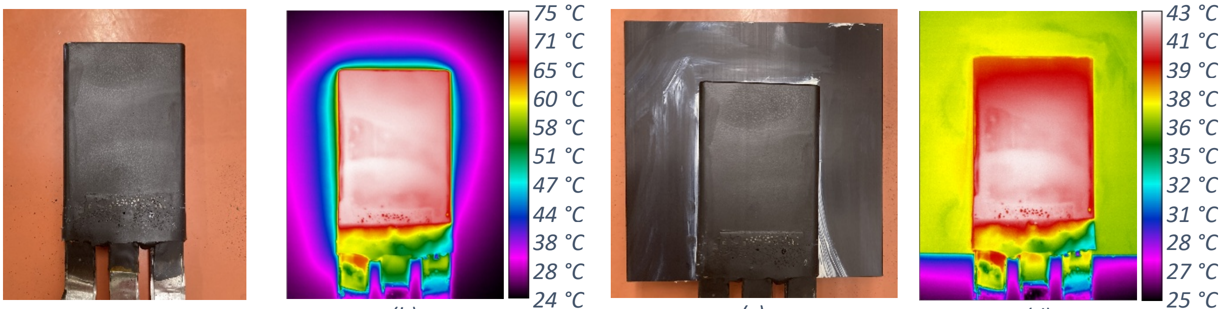
The capacitance and ESR measurements are shown in Figure 3. The capacitance is at around 2 µF at 100 Hz. It decreases with frequency, so that at 10 kHz it is at 1.5 µF and at 100 kHz it is at around 1.1 µF. The ESR values fall from of 70 Ω at 100 Hz to 1.1 Ω at 10 kHz, and 0.7 Ω at 100 kHz. Both the low capacitance and the high ESR are a result of the flat aluminium foils used for the anodes. This values represent a starting point of which any area increase of the anode foils would lead to greatly improved capacitance and ESR values.

Leakage current and breakdown voltage

Leakage current and breakdown voltage measurements are time dependent measurements. Because of this, an averaging of these measurements would lead to a distorted representation. In Figure 4 a representive measurement of the leakage current and breakdown voltage are displayed. The leakage current in Figure 4 (a) is at 45 µA after 5 minutes and shows the stable operation of the capacitor at rated voltage. The average of 4 prepared capacitors is 42 µA. The low leakage current indicates a good oxide quality and demonstrates the general feasibility of operating an electrolytic capacitor at high voltages. The breakdown voltage of the sample in Figure 4 (b) is at 900 V. However, from 830 V on, many small breakdowns are visible. They do not lead to a fatal breakdown during this measurement, but it can be assumed that if the voltage is kept for a longer time, the sample would break. Taking these small breakdown sites into account, the breakdown average of all samples is at 835 V. That is 55% of the forming voltage. Scientific publications that include investigations on formations below 1000 V frequently report breakdown voltage values that are in the range of 60 - 70% of the forming voltage [11] [15]. It is likely that the breakdown voltage of oxides formed at higher voltages is a little lower per µm due to more defects from the formation process [16]. With further improvement of the high voltage formation process, breakdown voltages of up to 1000 V are likely possible.

Ripple current test

One advantage of the polymer aluminium electrolytic capacitor technology is that it is coolable. This was demonstrated with a ripple current test. An ASR-2000 power supply was used which supplies an AC voltage with a DC offset. The cooling was done simply by attaching the capacitor with a thermal paste to a metal heat sink. An AC voltage with a DC offset was supplied to the capacitor with and without cooling. Under both conditions 300 VDC, 100 VAC and 0.6 AAC at 500 Hz was applied to the capacitor. The thermal images are shown in Figure 5 (b) and (d) and the setups are shown in Figure 5 (a) and (c). It can be seen that the both conditions inhibit a homogeneous housing temperature. In Figure 5 (b), without cooling, a surface temperature of around 75 °C is observed. In Figure 5 (d), with cooling, the temperature is significantly lower, at around 43 °C. It can also be seen that the temperature at the edges and at the end of the capacitor is a few degrees lower than on the surface. That makes sense, as at the end of the capacitor, the current density is the lowest and at the edges the heat conduction to the heatsink is optimal. The heat conduction is best in the horizontal direction due to the stacking structure of the capacitor. The results demonstrate the coolability of this technology and show its potential use in high ripple current applications.



(a) *(b)* *(c)* *(d)*

Figure 5: Cooling setup for thermal imaging of a capacitor with 300 VDC, 100 VAC and 0.5 AAC at 500 Hz applied. (a) and (b) show the thermal image and the test setup without cooling, (c) and (d) show the thermal image and test setup with cooling

Table 1: Comparison of electrical characteristics of different capacitor technologies at the

Technology	Rated voltage in V	Rated capacitance in μF	Capacitance density in μF/cm^2 @ 10 kHz	ESR in Ω @ 10 kHz
Polymer electrolytic	750	2	0.046	2.2
Liquid electrolytic[17]	400	4.7	2.49	1.7
Metallized film[18]	800	2	0.28	31 m

Comparison to existing technologies

To get a better understanding of the potential and performance of this technology, it is compared to existing technology of this voltage level and at the same rated capacitance. One main application of high voltage polymer electrolytic capacitors could be as a DC link capacitor. At this high voltage, either a series connection of liquid electrolytic capacitors or metallized film capacitors are used today. In Table 1 the three technologies are listed with their rated voltage, rated capacitance, capacitance density and ESR at 10 kHz. Liquid electrolytic capacitors are mostly only available at discrete voltage levels of up to 350 V, 400 V and 450 V. To match the 750 V and 2 µF rated voltage and capacitance, two devices in series connection are needed. Film capacitors are available at this voltage level and no series connections are needed. The datasheets of the capacitors chosen for the comparison are linked in the references [17] [18]. There are many capacitor producers and there are devices available with better or worse characteristics than the devices used here. But these values still give a good general representation of available devices. It can be seen that the capacitance density of the polymer capacitor is the lowest, with the liquid electrolytic having 54 times the capacitance density and metallized film capacitor having 6 times the capacitance density. The ESR values of the polymer electrolytic capacitor are only slightly higher than of the liquid electrolytic capacitor but still 36 times higher than metallized film capacitors. This comparison shows the possible niche for this technology. With every doubling in the active anode area, the capacitance is doubled and the ESR is reduced by half. This means, with a slight increase of the area the capacitance density will be better than of metallized film capacitors and the ESR values will be better than of liquid electrolytic capacitors, resulting in the electrical characteristics being in between metallized film and liquid electrolytic capacitors.

CONCLUSION

In this study an improved way to fabricate high voltage polymer aluminium electrolytic capacitors was presented. The typical winding structure of this technology restricts the maximum size because of the difficulties of impregnating the PEDOT:PSS electrolyte into the windings. This issue greatly limits the rated voltage of this technology. Thick oxides lower the capacitance density and for large anodes, the oxide cracks easily. The presented technique lowers the steps that require contact to the anodes to a minimum and in the same time greatly simplifies the impregnation. It was demonstrated that it is possible to build a stacked capacitor at high rated voltages up to 750 V. The functionality of the resulting capacitors were demonstrated by measurements of capacitance, ESR, leakage current, breakdown voltage, and ripple current capability. The capacitance and ESR values are not yet competitive to values achieved by other capacitor technologies. However, the comparison to existing technologies shows that there is a niche for this technology between liquid electrolytic capacitor and metallized foil capacitors. The low capacitance and ESR values are a result of the flat anode foil and any slight increase of surface area of the anode would greatly improve electrical characteristics. For this study it was decided to use flat anode foils because the development of an etching process for forming voltages up to 1500 V requires the effort of a seperate study. The leakage current, breakdown voltage and ripple current measurements demonstrate the functionality of the capacitors. With an improved capacitance density, this technology could have great potential in DC link applications that require high voltage, high ripple currents, and high capacitance. The drivetrain of an electric vehicle could be a potential application, where constant acceleration and recuperation lead to very high ripple currents.

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