PROGNOSTICS TECHNIQUES FOR CAPACITOR DEGRADATION AND HEALTH MONITORING

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Abstract
This paper discusses our initial efforts in constructing physics of failure models for electrolytic capacitors subjected to electrical stressors in DC-DC power converters. Electrolytic capacitors and MOSFET's are known to be the primary causes for degradation and failure in DC-DC converter systems. We have employed a topological energy based modeling scheme based on the bond graph (BG) modeling language for building parametric models of multi-domain systems, such as motors and pumps. In previous work, we have conducted experimental studies to validate an empirical physics of failure model based on Arrhenius Law for equivalent series resistance (ESR) increase in electrolytic capacitors operating under nominal conditions. In this paper, our focus shifts to deriving first principle models of capacitor degradation that explain both the ESR increase and the decrease in capacitance over time when the capacitor is operated under electrical stress conditions. Experimental studies are run in parallel, and data collected from these studies are used to validate the generated models. In the future, they will also be used to compute model parameters, so that the overall goal of deriving accurate models of capacitor degradation, and using them to predict performance changes in DC-DC converters is realized.

Key words: DC-DC converters; ESR; capacitance, electrolytic capacitors; degradation; avionics; prognostics; health management

INTRODUCTION

This paper proposes a model based approach to study the degradation effects of power supply converters used in avionics systems. Avionics systems combine physical components, computational hardware, and software systems, and present unique challenges to performing root cause analysis when faults occur, and for establishing the effects of faults on overall system behavior and performance. However, systematic analysis of these conditions is very important for analysis of safety and also to avoid catastrophic failures in navigation systems.

Electrolytic capacitors and MOSFET's have higher failure rates than other components in DC-DC converter systems [1, 2]. Currently our work focuses on analyzing and modeling electrolytic capacitors degradation and its effects on the performance and efficiency of DC-DC converter systems. The degradation typically manifests as increases in ripple current and the drop in output voltage at the load. Typically the ripple current effects dominate, and they can have adverse effects on downstream components. For example, in avionics systems where the power supply drives a GPS unit, ripple currents can cause glitches in the GPS position and velocity output, and this may result in errors in the Inertial Navigation (INAV) computations of position and heading, causing the aircraft to fly off course [3, 4].

The performance of electrolytic capacitors is strongly affected by operating conditions, such as voltage, current, frequency, and working temperature. Under stress conditions the ESR gradually increases and capacitance of the capacitor gradually decreases with time thus resulting in the capacitors ability to filter out AC components in the output voltage [5]. This degradation can be attributed to evaporation of electrolyte, degradation in the electrolyte oxide layer, and chemical reactions that result in increase in the internal pressure. These processes are discussed in detail in the later sections of the paper. Continued degradation of the capacitor results in the converter output voltage to also drop below specifications and in some cases the combined effects of the voltage drop and the ripple currents may damage the converter as well as downstream avionics subsystems.

A physics of failure model based approach to studying degradation phenomena enables us to combine the energy based modeling of the DC-DC converter with physics of failures models of capacitor degradation, and predict using stochastic simulation methods how system performance deteriorates with time. This systematic analysis not only provides a general and accurate method for computing the remaining useful life (RUL) of the component but one can also track the degradation in converter performance over time. This paper develops a methodology for studying degradation of electrolytic capacitors under high electrical stress. We develop a methodology for characterizing the physical phenomena that cause degradations and in parallel conduct experiments where we study a set of capacitors that are subjected to electrical stress in the form of continuous charge/discharge cycle. Electrical stressors accelerate the degradation process thus shortening the experiment time for analyzing the degradation and failure phenomena.

The rest of this paper is organized as follows. Section 2 discusses the DC-DC converter model, and Section 3 briefly covers the general notion of *physics of failure* (POF) modeling. Section 4 discusses in detail the mechanisms that govern the degradation process in capacitors. Section 5 discusses the accelerated degradation experiments conducted on electrolytic capacitors. The last section discusses data analysis for the data collected from the measurements and mapping it with the physics of failure models.

DC-DC CONVERTERS

Switched-mode power supplies are widely used in DC-DC converters because of their high efficiency and compact size. DC-DC converters are important in portable electronic devices, which derive their power primarily from batteries. Such electronic devices often contain several sub-circuits with different voltage requirements (sometimes higher and sometimes lower than the supply voltage, and possibly even negative voltage). DC-DC converters provide additional functionality for boosting the battery voltage as the battery charge declines.

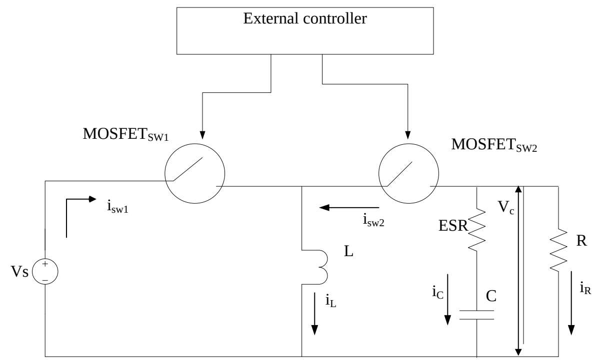


Figure 1: Buck Boost Converter Circuit

A typical buck-boost DC-DC converter circuit is illustrated in Fig. 1. Such converters step the voltage up or down, by storing the input energy temporarily in inductors when switch sw1 is ON and switch sw2 is OFF, and then releasing that energy to the output at a different voltage value when sw2 is ON and sw1 is turned OFF. The efficiency of conversion ranges from 75% to 98%. This high efficiency is typically achieved by using power MOSFET's (metal oxide semiconductor field-effect transistor), which can provide high frequency switching more efficiently than power bipolar transistors, which, in addition to greater switching losses require more complex drive circuits. Overall, MOSFET switches increase the battery life in such devices. A buck boost approach is used for conversion to the required dc voltage output. Our particular application has an input of 28V DC from a battery source, and the required output voltage is 5V. The switches sw1 and sw2 are power MOSFET's, which are controlled by an external controller. Fig. 2 shows the external controller box, which controls the switching of the MOSFET's to maintain the required output voltage

We develop a systematic approach for reliable diagnostics and prognostics for the converter system. For this we need to capture the topological and functional dependence of the system in addition to component level faults and capturing the causal flow in time to account for transient failures.

PHYSICS OF FAILURE (POF) MODELS

Physics-of-failure models capture failure phenomenon using a first principles approach, i.e., in terms of component geometry and energy based principles that define the effect of stressors on the component behavior. This is in contrast to the traditional approach of deriving degradation models from empirical data. Physics-of-failure techniques present a general methodology for estimating lifetimes due to specific failure mechanisms [6, 7]. The failure rate models can be tuned to include parameters that relate to the present health of the device/system and the expected conditions under which it will be operated [8].

Prognostics methods relate to detecting failure precursors followed by the prediction of remaining useful life (RUL). For end-of-life predictions of critical systems, it is necessary to establish the accuracy and reliability of the prognostic approach before the predictions can be used for decision-making. The aerospace industry is at the forefront of model- and data-driven prognostics methods and their applications. Health inspections and monitoring of systems on spacecraft and aircraft are often difficult and costly. The consequences of premature failures can be catastrophic for these systems. Prognostics methods are being applied to monitoring the condition of aircraft structures, avionics, wiring, control actuators, power supplies, and propulsion systems. Prognostic functionality is being incorporated into the mechanical and fluid health management systems of the latest military and civilian aircraft [9] to reduce the overall lifecycle cost and improve flight readiness. But prognostics research for electronics is less advanced than methods that have been developed for mechanical systems [8, 10, 11].

In this work, we hope to reduce this gap by focusing our prognostics studies on electrical and electronic components in DC-DC power supply converters. A detailed study on electrolytic capacitors used to filter the output signal in the converter is being performed. To accelerate the degradation process in capacitors, and to study end of life issues we have developed an experimental testbed where a suit of capacitors can be subjected to different stress conditions. The degradation data collected provides estimations of the damage parameters of the POF model. Simultaneously, we are also developing procedures to validate the POF model.

Component Degradation/Failure: It has been reported in the literature that electrolytic capacitors are the leading cause for breakdowns in power supply systems [12]. Electrolytic capacitor performance is strongly affected by its operating conditions, such as voltage, current, frequency, and ambient temperatures. For degraded electrolytic capacitors, the impedance path for the ac current in the output filter keeps increasing and the capacitance decreases, thus introducing a ripple voltage on top of the desired DC voltage. Continued degradation of the capacitor leads the converter output voltage to also drop below specifications affecting downstream components. In some cases, the combined effects of the voltage drop and the ripples may damage the converter. Our approach to designing degradation models for electrolytic capacitors is discussed next.

ELECTROLYTIC CAPACITOR DEGRADATION

This section discusses in detail the conditions under which the capacitor degrades leading to faults in the system. We study the effect of voltage overstress on capacitors i.e., Vapplied ≥ $V_{rated,}$ where $V_{applied}$ is the applied overstress voltage and V_{rated} is the rated voltage for the capacitor. This accelerates the nominal degradation process, because of the higher temperatures in the capacitor core.

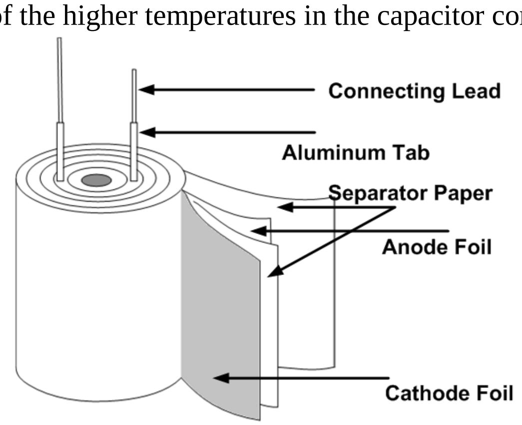


Figure 2: Construction of Electrolytic Capacitor [1]

Physical Model of the Capacitor: An aluminum electrolytic capacitor, illustrated in Fig. 2 consists of a cathode and anode made of aluminum foil, separator (electrolytic) paper, electrolyte, and an aluminum oxide layer on the anode foil surface, which acts as the dielectric. When in contact with the electrolyte, the oxide layer possesses excellent insulation properties in the forward direction. Etching the foil magnifies the effective surface area, allowing for high capacitance in a small volume [13].

Since the oxide layer has rectifying properties, a capacitor has polarity. If both the anode and cathode foils have an oxide layer, the capacitor is bipolar. In this paper we analyze 'non-solid' aluminum electrolytic capacitors in which the electrolytic paper is impregnated with liquid electrolyte. Another type of aluminum electrolytic capacitor uses a solid electrolyte, but we do not study them in this work [13, 14].

Degradation Mechanisms: There are several factors that cause electrolytic capacitors to degrade. Continued degradation, i.e., gradual loss of functionality over a period of time results in the failure of the component. Complete loss of function is termed a *catastrophic* failure. Typically, this results in a short or open circuit in the capacitor. For capacitors, degradation results in a gradual increase in the equivalent series resistance (ESR) and decrease in capacitance over time.

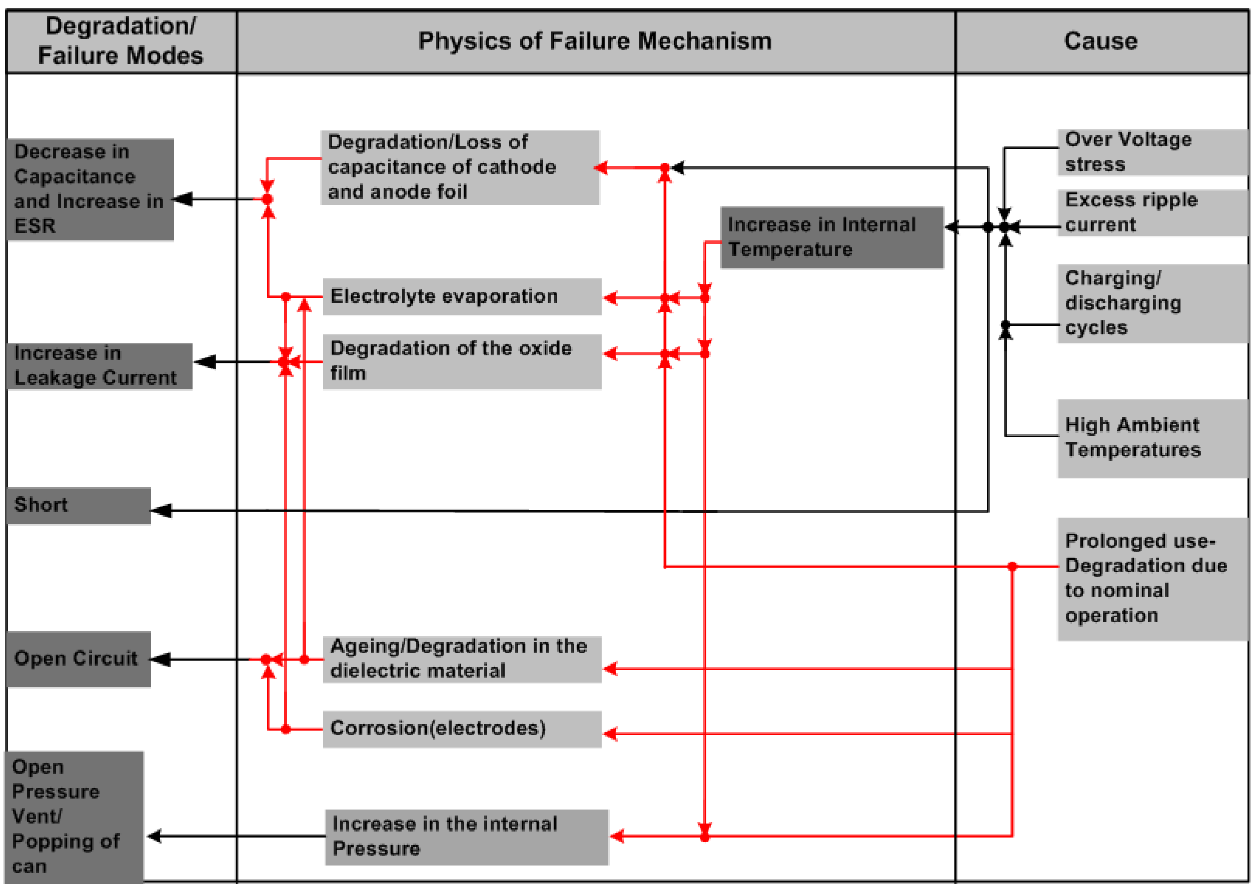


Figure 3: Causes, failure mechanisms and Failure modes in Aluminum Electrolytic Capacitor

Figure 3 shows the most common set of failure modes for electrolytic capacitors that have been reported in the literature [15]. The figure links the failure modes to the identified physics of failure mechanisms and then the root cause for the degradation. For example, over voltage stress, which results in an increase in the capacitor internal temperature can cause loss of electrolyte and also degradation in the oxide film leading to increased leakage currents. This in turn causes increased ESR and decreased capacitance over time, which can have a number of adverse effects on the system that the capacitor is a part of. ,

PHYSICS OF FAILURE MODELS

In this work, we study the degradation of electrolytic capacitors operating under high electrical stress, i.e., $V_{applied} \geq V_{rated}$. During operation, the capacitors are charged and discharged continuously and a number of measurements are made at periodic intervals. Before we discuss our experimental studies, we develop our approach to building the physics of failure models of capacitor degradation. A study of the literature [16, 17] indicated that the degradation could be primarily attributed to three phenomena:

1) Electrolyte evaporation,
2) Leakage Current, and
3) Increase in internal Pressure

Figure 4 shows a detailed view of the cross section of an electrolytic capacitor structure along with its equivalent electrical circuit diagram. To get higher capacitance values for the same surface area of the anode and cathode foils, the foil is etched by a chemical process. After etching, the plates are anodized by coating them with a thin aluminum oxide layer on the surface of the foil. This layer of aluminum oxide acts as the dielectric (insulator) and serves to block the flow of direct current between the two capacitor plates. When a DC voltage is applied to a discharged capacitor there is an initial surge of current. As the voltage across the terminals of the capacitor increases due to the capacitor charging, the current flow drops exponentially, and trends to zero as the capacitor terminal voltage equals the applied voltage [24]. The flow of current during the charge / discharge cycle of the capacitor causes the internal temperature to rise (because of the internal resistance). The trapped heat inside the capacitor body causes the electrolyte to evaporate, and gradually deplete.

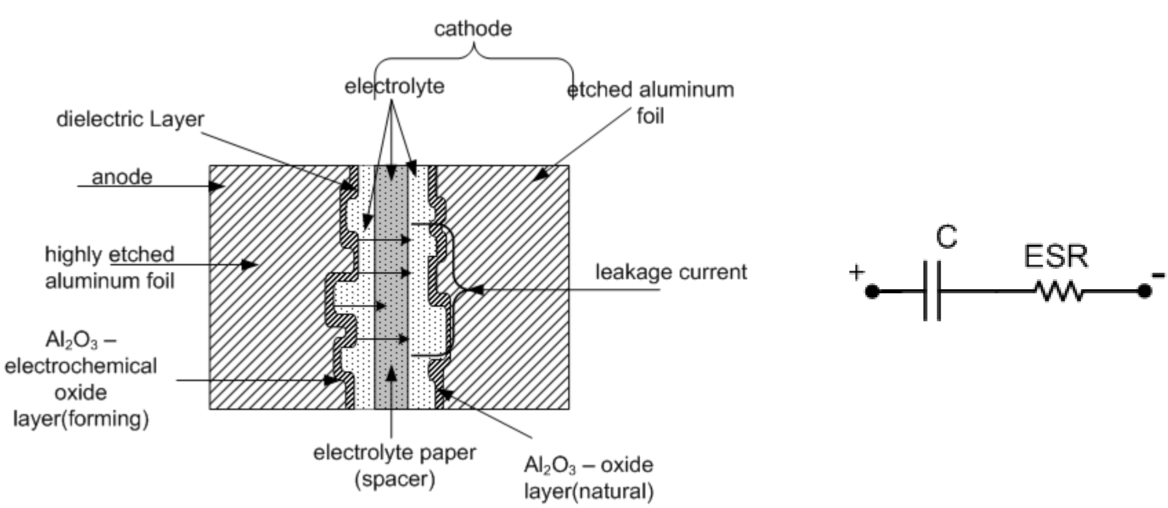


Figure 4: Capacitor Structure and Equivalent circuit diagram

An ideal capacitor would offer no resistance to the flow of current at its leads. However, the electrolyte, aluminum oxide, space between the plates and the electrodes produces a small equivalent internal series resistance (ESR) as shown in the right part of Figure 4. The ESR dissipates some of the stored energy in the capacitor. Inspite of the dielectric insulation layer between a capacitor's plates, a small amount of 'leakage' current flows between the plates. For a good capacitor operating nominally this current is not significant, but it becomes larger as the oxide layer degrades during operation. Degradation in the oxide layer can be attributed to crystal defects that occur because of the periodic heating and cooling during the capacitor's duty cycle, as well as stress, cracks, and installation-related damage. High electrical stress is known to accentuate the degradation of the oxide layer due to localized dielectric breakdowns on the oxide layer [18, 26]. These breakdowns, which accelerate the degradation, have been attributed to the duty cycle, i.e., the charge/discharge cycle during operation [18, 19].

The literature on capacitor degradation shows a direct relationship between electrolyte decrease and increase in the ESR of the capacitor [20]. We have also modeled this phenomenon, and demonstrated in the effectiveness of our model through experiments in previous work [21]. ESR increases imply greater dissipation, and, therefore, a slow decrease in output voltage at the capacitor leads. The combination of ESR increases and capacitance decreases also produces ripples of greater magnitude when these capacitors are used as filters at the output of DC-DC converters.

A third simultaneous phenomenon is the increase in the internal pressure due to an increased rate of chemical reactions, which can again be attributed to the internal temperature increase in the capacitor. Under normal operating conditions the chemical reactions between the dielectric and electrolyte releases hydrogen gas, which is then absorbed by the anode and cathode surfaces. The absorption of the gas keeps the pressure inside the capacitor from increasing too much. However, as the internal temperature increases the chemical reaction rate increases producing more hydrogen, but the absorption rate is unable to keep up. Thus the excess hydrogen gas that builds up inside causes the pressure to increase. This pressure increase can ultimately lead to the capacitor popping. We provide a more detailed qualitative description of each of these phenomena in greater detail below.

Electrolyte evaporation: Operation of the capacitors under $V_{applied} \geq V_{rated}$ results in rise of the internal core temperature of the capacitor. The current flow through the capacitor during the charge/discharge cycle has an exponential temporal relation with the applied voltage [24]. When the applied voltage is within the range of V_{rated} the amount of heat generated because of the current and internal resistance of the capacitor is relatively low. Therefore, a lot of this heat is conducted or radiated out through the capacitor body and leads, and the internal temperature rise is small. This has been demonstrated by a physics model we have built in previous work [22]. When the applied voltage, $V_{applied}$ is above V_{rated} the rate of current flow increases at a much faster rate, thus increasing the amount of heat generated. Lesser amounts of this heat gets dissipated to the outside, which leads to a rise in the core temperature of the capacitor. The increase in temperature accelerates the electrolyte evaporation, thus increasing the ESR of the capacitor. The details of the work can be referred to our earlier work in [22].

Leakage Current: Changes in the electrical parameters due to degradation in the oxide layer and electrolyte depletion causes changes in the leakage current of the capacitors. Leakage current (I_L) is defined as the current that flows between the capacitor plates subsequent to the charging of the capacitor

[15]. It has been shown that the leakage current becomes more pronounced as the dielectric layer on the capacitor plates is damaged. The leakage current value is very much dependent on the effective/healthy surface area of the etched aluminum foil (capacitance of the capacitor), and the type of electrolyte used.

The overall breakdown process can be described as a chain of individual sparks which travel over the electrode. This leads to trails of thicker crystalline oxide being embedded on the amorphous oxide film [24]. When this crystalline oxide layer breaks away, some of the insulating oxide layer also peels off, and this increases the electrical conductivity between the plates because of the impregnation of these defects by electrolytes. The electronic conduction mechanism is explained by an avalanche multiplication of electrons by the impact ionization. The high electronic current across the oxide which increases exponentially with voltage gives rise to scintillation process for the values corresponding to the values higher than $V_{rated.}$ Thus leakage currents depends of several affecting factors, such as time, voltage, temperature, type of electrolyte, and operating 'history' of the capacitor [15].

Increase in Pressure: Internal pressure increases due to increase in the core temperature and chemical reactions taking place during the charge/ discharge cycle. Gas generation in capacitors [23] when subjected to $V_{applied} \geq V_{rated}$, is principally controlled by two processes outlined below:

The first process is based on Faradays first law of electrolysis. The law states that "*Mass of any substance deposited or liberated at any electrode is directly proportional to the quantity of electricity (charge) passed*". The quantity of charge passed is the product of current (A) and time (sec) which is the polarization time. The mass (W) of ions librated, is directly proportional to the amount of charge passed through the electrolyte (Q) [23].

During the charging cycle, a charge q, equal to C_A. $V_{applied}$, is built up on the anode, where C_A is the anode capacitance and $V_{applied}$ the applied voltage. This applied charge leads to oxidation at the anode and will cause a reduction reaction at the cathode resulting in the generation of hydrogen. As studied from the first law the number of moles of gas generated is linearly dependent on the polarization time. Similarly during the discharge cycle, on discharge of the anode, electron transfer from the solution to the aluminum cathode takes place which causes discharge of hydrogen to produce either molecular oxygen or anodic aluminum oxide. These observations suggest that, under any condition, we would observe gas evolution and damage on the oxide layer due to oxidation [23].

The simultaneous process going during the operation is the absorption of the generated gas. The continuous evolution of the gas during the operation is diminished by the absorption of hydrogen by the depolarizer. Hydrogen absorption takes place at a constant rate through the reduction reaction of the quinone and picric acid (components in the electrolyte) [19, 23]. The reduction reaction follows the first order of kinetics where, the rule states that in a chemical reaction in which the rate of decrease in the number of molecules of a substrate is proportional to the concentration of substrate molecules remaining.

Under normal operating conditions the amount of gas generated is small and all to it is absorbed by the depolarizer. At high temperatures caused by the over stress voltage, conditions rate of reaction accelerates leading to increase in the generation of hydrogen gas. With increase in internal temperature the electrolyte depletes and thus the amount of depolarizer present reduces. This leads to decrease in the rate at which hydrogen gas is absorbed causing some of the hydrogen to be left unused and results increase in the internal pressure. Though this is a very slow process and is secondary to the previous two phenomenons's described the end result causes the capacitor cap to *"pop"* and complete failure of the device.

From the above described qualitative models we hypothesize the sequence of the phenomenon's as they occur during the charge/discharge overstress. Our hypothesized sequences of the processes that explain degradation cause by the overstress voltage condition are listed below:

a. Overvoltage operation results in higher internal temperatures.
b. *Operation under higher internal temperature increases the electrolyte evaporation rate* [24].
c. Operating at high voltages degrades and weakens the oxide layer. Changes in the dielectric parameters lead to changes in the transient shape of leakage current [15].
d. *Leakage current increase as oxide layer degrades*
e. *As the electrolyte decreases, this results in a steady decrease in C and a steady increase in ESR* [25].
f. Increase in internal temperature also accelerates the rate of chemical reactions occurring inside the capacitor. The combination of electrolyte evaporation and the hydrogen produced by the chemical reaction results in increases in pressure inside the can [19, 23].
g. Typically, when the ESR value of the capacitor goes above 2-2.5 times of its nominal value, the capacitor is said to be degraded, and replaced.
h. *One way a capacitor fails if there is a short circuit internally due to a weak oxide layer.*

   In case of high voltage impulses are applied leading to weakening or breakdown and this could lead to a short internally damaging the capacitor.
i. *Another more drastic failure occurs when excessive pressure buildup in the capacitor can cause it to "pop".*

ACCELERATED CAPACITOR DEGRADATION EXPERIMENTS

Experiments were conducted where capacitors were subjected to high electrical stress as discussed earlier and the data was collected approximately once every 8-10 hours for a period of 180 hours. For this experiment a set of six electrolytic capacitor devices were considered. Electrolytic capacitors of 2200μF capacitance, with a maximum rated voltage of 10V, maximum current rating of 1A and maximum operating temperature of 85°C was used for the study. This was the suggested type of capacitor by the manufacturer of the DC-DC converters. The capacitors used for the experiments were picked from the same lot of one manufacturer, and all the capacitors in the lot had similar specifications. The electrolytic capacitors under test were measured for the initial ESR and capacitance value with other related measurement details before the start of the experiment at room temperature. The ESR and capacitance values were measured using an SP-150 Biologic SAS measuring instrument. The average initial ESR value was measured to be around 0.056mΩ and average capacitance of 2123μF for the set of capacitors under test. ESR value is real impedance measured through the terminal software of the instrument. Similarly the capacitance value is computed from the imaginary impedance using Electrochemical Impedance Spectroscopy Z-Fit. The details of the method are presented in [21]

Figure 5: Hardware setup for the experiment.

Since we were studying the effect of high voltage on degradation of the capacitors, we did not use the capacitors within DC-DC converters, only the capacitors were subjected to high voltage stress through an external supply source. Figure 5 shows the entire setup for the experiment which includes the test board with capacitors, power supply, signal generator and the NI data acquisition system. A constant voltage source with a square wave of 200 mHz frequency and 1V output was used for generating the required signal. The output voltage from the source was then ramped up to the required voltage of 15V using an external hardware circuit. This ramped up voltage was selected to be higher than the rated voltage of 10V to observe accelerated degradation in the capacitor. The 200 mHz square wave frequency output subjects the capacitor to a continuous charge/discharge cycle. A load of 100Ω was connected at capacitor terminal to discharge the capacitor completely within the specified cycle time.

The measurements were recorded approximately at every 8- 10 hours of the total 180 plus hours of operation time to capture the rapid degradation phenomenon in the ESR and capacitance values. The ambient temperature for the experiment was controlled and kept at 25°C. During each measurement the voltage source was shut down, the capacitors were discharged completely and then measurements for the ESR and capacitance were made. This was done for all the six capacitors under test. Keeping all of the conditions according to specification, the experiment was started again till the next measurement time. This procedure was followed and recorded for all the readings taken during the time of the experiment.

ANALYSIS BASED ON POF MODEL

After conducting the experiments, the collected data was analyzed and interpreted using the failure models discussed earlier. Our goal in this paper was to create a mapping between the physics of failure phenomenon and the data to ensure there was a qualitative match in the trends predicted and observed.

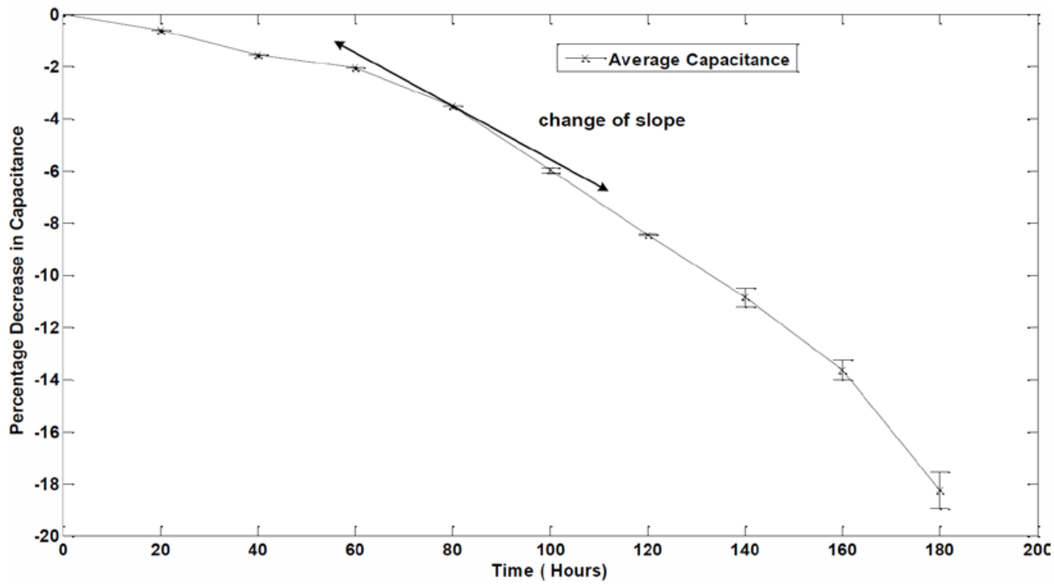


Figure 5 : Capacitance decrease

As discussed earlier operating the capacitors at $V_{applied} \geq V_{rated}$, results in increase in core temperature of the capacitor. High core temperature causes faster depletion in the electrolyte contents and degradation of the oxide layer leading to the observed changes in the electrical parameters of the capacitor as shown by the plots in figures 5 and 6. We observe that the capacitance decreases and ESR increases. This phenomenon can be mapped to the electrolyte depletion and oxide peeling physics of failure phenomena discussed earlier in the paper.

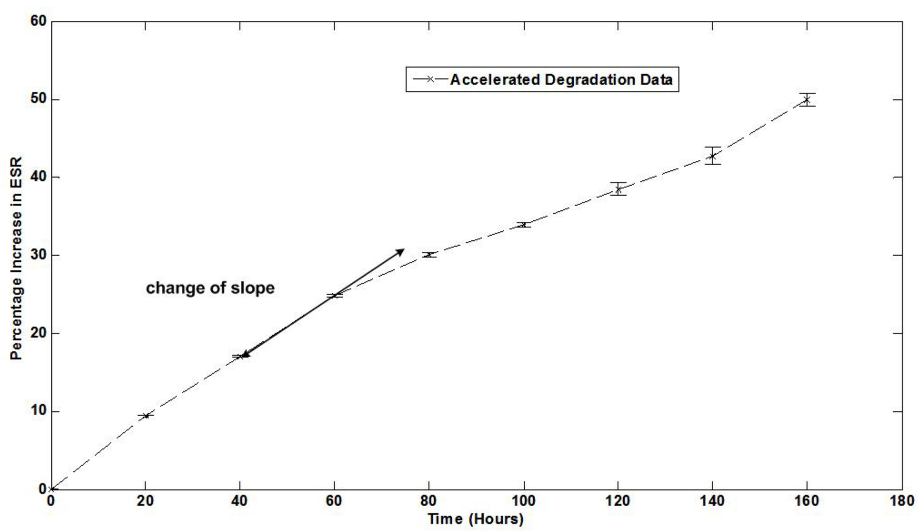
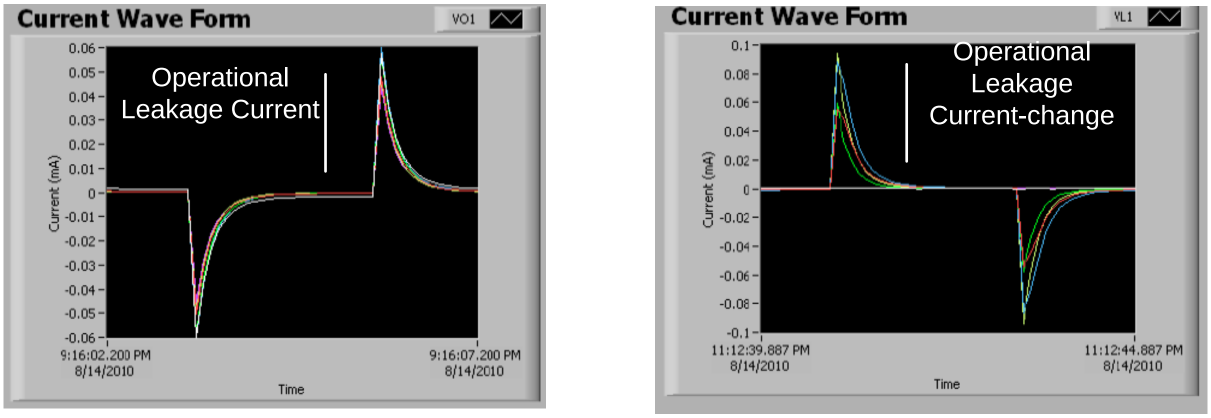


Figure 6 : ESR Increase

Continued increase in the internal core temperature due to electrical overstress causes further depletion of electrolyte and degradation of the oxide layer. As the amount of peeling off in the oxide layer increases the amount of leakage current flowing through the capacitor starts going up at a faster rate. In turn the core temperature increases at a faster rate. Thus this triggers a cyclic process of increase in temperature and increase in the leakage current.



a) **Leakage Current on Pristine devices** b) **Leakage Current at 120 hrs operation**

Figure 7: Experimental Leakage current Data

The increase in leakage current over time is shown by the measurements in Figure 7. Figure 7a shows the operational leakage current when the capacitors under test are behaving nominally early in the experiment. Figure 7b shows the leakage current observed after 120 hours of over voltage stress. As the degradation process accelerates, there is also a significant increase in the rate of leakage current increase.

Eventually, the faster increase in temperature leading to higher and higher leakage current causes a breakdown effect [18, 26]. The significant increase in the rate of leakage current produces a faster rate of capacitance decrease (because less charge remains on the plates), and a faster increase in ESR because of the increased rate of electrolyte evaporation. This is indicated by a change of slope in Figures 5 and 6.

The third underlying physics of failure phenomenon, i.e., the generation of gases which is activated due to accelerated chemical reactions at increased temperature resulting in the increase in the internal pressure. As discussed earlier the pressure increase can be related to 1) generation of gas due to faradays first law and 2) absorption of the gas due to the reduction reaction depolarizers present on the surface of the cathode. We hypothesize that this phenomena also adds to the accelerated degradation of the capacitance and ESR that we observe in the plots in figures 5 and 6. The process of pressure build up is slower than the first two failures discussed. But in certain cases it may cause catastrophic failure because of the popping of the capacitor.

CONCLUSIONS:

This work discussed in the paper proposes a model-based approach to study electrolytic capacitor degradation in DC-DC converters. The physics of failure model derived expressed the change in ESR values as a function of applied voltage for given operating conditions. According to industry standards, an electrolytic capacitor is considered unworthy of being used in the system when their ESR value exceeds 2.8 times its initial value. With our experiments we are developing a systematic method for predicting this ageing time of components. We will be able to recalculate some of the model parameters more accurately from the experimental data and improve the model. Thus in this work we were able to map physics of failure models with a quantitative by relating the different phenomenon's occurring when the capacitor is subject to high electrical stress which causes accelerated degradation in the device.

In future we plan to conduct develop more precise qualitative physics of failure models based on this work which will help in estimating the degradation parameters. These updated parameter estimation results for the model will help in predicting the failures and degradation in the capacitor elements with higher accuracy and precision. The work will provide a methodology for more accurate estimation of model parameters, and therefore, the capability to build more accurate degradation models.

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