

Prognostic Modeling and Experimental Techniques for Electrolytic Capacitor Health Monitoring

C. KULKARNI, J. CELAYA, G. BISWAS and K. GOEBEL

ABSTRACT

Electrolytic capacitors are used in several applications ranging from power supplies on safety critical avionics equipment to power drivers for electro-mechanical actuators, and this makes them good candidates for prognostics and health management research. Prognostics provides a way to assess remaining useful life of components or systems based on their current state of health and their anticipated future use and operational conditions. Past experiences show that capacitors tend to degrade and fail faster under high electrical and thermal stress conditions that they are often subjected to during operations. In this paper, we study the effects of accelerated ageing due to thermal stress on a set of capacitors. Our focus is on deriving first principles degradation models for thermal stress conditions. Data collected from simultaneous experiments are used to validate the desired models. Our overall goal is to derive accurate models of capacitor degradation, and use them to predict performance changes in DC-DC converters.

INTRODUCTION

This paper proposes a first principles physics of failure model for degradation analysis and prognosis of electrolytic capacitors in DC-DC power converters. It has been reported in the literature that electrolytic capacitors are the leading cause for breakdowns in power supply system's [1]. Our work has focused 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. For example, in avionics systems ripple currents in the power supply 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 [2, 3].

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In earlier work, we discussed studies related to capacitor degradation under nominal operation and accelerated degradation under high electrical stress [2, 4, 5]. In this paper, we focus on accelerated degradation caused by thermal stress. We have developed an experimental setup for measuring a number of parameters on capacitors as actual degradation occurs under thermal overstress conditions. Thermal stress occurs when the capacitors operate in high temperature environments. 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 the models of capacitor degradation, and predict (using stochastic simulation methods) how system performance deteriorates with time. This more systematic analysis may provide a more general and accurate method for computing the remaining useful life (RUL) of components and the converter system under different assumed operating conditions. Component degradation models are derived by studying degradation phenomena such as electrolyte evaporation, failure models that have been presented in the literature, and validating these models using data collected from accelerated degradation studies [4]. The physics of failure models provide mathematical formulations that are directly linked to component parameters. The data from these experiments is used to verify results from the models developed and also for refining the model parameters for more accuracy.

The rest of this paper is organized as follows. Section 2 briefly covers the general notion of *physics of failure* (POF) modeling. Section 3 discusses in detail the mechanisms that govern the degradation process in capacitors. Section 4 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. The paper concludes with comments and future work to be done.

PROGNOSTIC METHODOLOGY

Physics-of-failure models capture failure phenomenon 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 for deriving degradation models from empirical data. Physics-of-failure techniques present a general methodology for estimating lifetimes due to specific failure mechanisms [6, 7, 8]. 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 [9]. This approach is likely to provide more accurate estimates of the prediction of remaining useful life (RUL).

In this work, we focus our prognostics studies on electrical and electronic components in DC-DC power supply converters. Our research agenda includes a detailed study on electrolytic capacitors used to filter the output signal in the converter. To accelerate the degradation process in capacitors, and to study end of life issues we have developed experimental testbeds 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.

CAPACITOR FAILURE MODELS

We study the effect of thermal overstress on capacitors i.e., $T_{\text{applied}} \geq T_{\text{rated}}$, where T_{applied} is the applied overstress temperature in storage (i.e., not during actual operation when the capacitor may charge and discharge) and T_{rated} is the rated temperature at which the capacitor can be stored.

Thermal Model

When the storage temperature (controlled chamber temperature) is increased the core temperature of the capacitor also increases. The raised temperature in the capacitor core causes the electrolyte to start evaporating at faster than normal rates [10]. It has been observed that the temperature of the cartridge and casing remain almost constant across the diameter and along the length of the capacitor. Therefore, it is reasonable to assume that cartridge and casing are isothermal bodies. As a result, the capacitor can be treated as two concentric isothermal cylinders as shown in Fig. 1(a) with temperature values T_1 , T_2 respectively. Further heat flow can be considered to be radial. These assumptions hold for capacitors having cylindrical surface area much greater than the end areas [11].

High temperature on the surface causes heat flow radially towards the core of the capacitor (see Fig. 1(b)) [10, 12]. The heat flow is considered only in one direction from the outer surface to the core. The capacitor structure is made up of different layers through which the heat flows as shown in the Figure 1. In the thermal model these layers represent successive thermal capacitances and thermal resistances. In the capacitor, the anode and electrolyte layers are represented as the thermal capacitances, labeled as C_1 , C_2 respectively (see Fig. 1(b)). Similarly the dielectric and cathode layers are modeled as thermal resistances R_1 and R_2 , respectively.

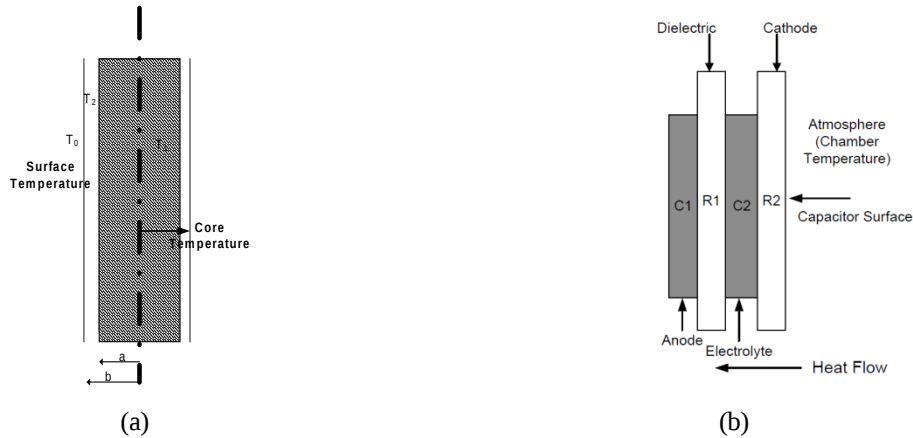


Figure 1: Capacitor Heat Transfer Model

Electrolyte Decrease

Exposure of the capacitors to temperatures $T_{\text{applied}} \geq T_{\text{rated}}$ results in accelerated aging of the devices [13, 14]. Higher ambient storage temperature accelerates the rate of electrolyte evaporation leading to degradation of the capacitance [15]. The depletion in the volume and thus the effective surface area is given by

$$\frac{V}{V_0} = 1 - \frac{W_w A_e j_{eo}}{V_0} t \quad (1)$$

where:

V : is the dispersion volume at time t

V_0 : is the initial dispersion volume

A_e : surface area of evaporation.

w_w : volume of water molecules.

j_{eo} : evaporation rate (1.5 mg m^{-1} at 125°C)

Details of the derivation of this equation can be found in [16, 17]. Evaporation also leads to increase in the pressure in the chamber, which decreases electrolyte evaporation. The equation gives us the decrease in the active surface area due to evaporation of the electrolyte, which results in a decrease in C and an increase in ESR [15, 18].

Physics of Failure Model

To study the degradation leading to failure we are working towards developing physics based models. The structure of electrolytic capacitors can be considered as a relatively long strip line structures which is cylindrically wound and packed in a case. Figure 2(a) shows the anode and cathode, the dielectric oxide layers, and electrolyte interconnecting layer (spacer). This configuration is equivalent to a transmission line, and its reduced electrical model is shown in Figure 2(b) [17]. The input impedance of the capacitor network is defined in terms of the total lumped series and parallel impedance of the simplified network [19] (Figure 2(a)). Key effects include: (a) capacitance of the structure doubles, (b) resistances associated with the electrolyte and oxide films of the structure becomes half [17]. These results are due to the cylindrical configuration of the structure where both the sides of each layer are used. The total lumped capacitance of the structure is given by

$$C = \frac{2 \epsilon_R \epsilon_0 A_0}{t_0} \quad (2)$$

where : ϵ_R : relative dielectric constant

ϵ_0 : permittivity of free space

A_0 : oxide area

t_0 : oxide thickness

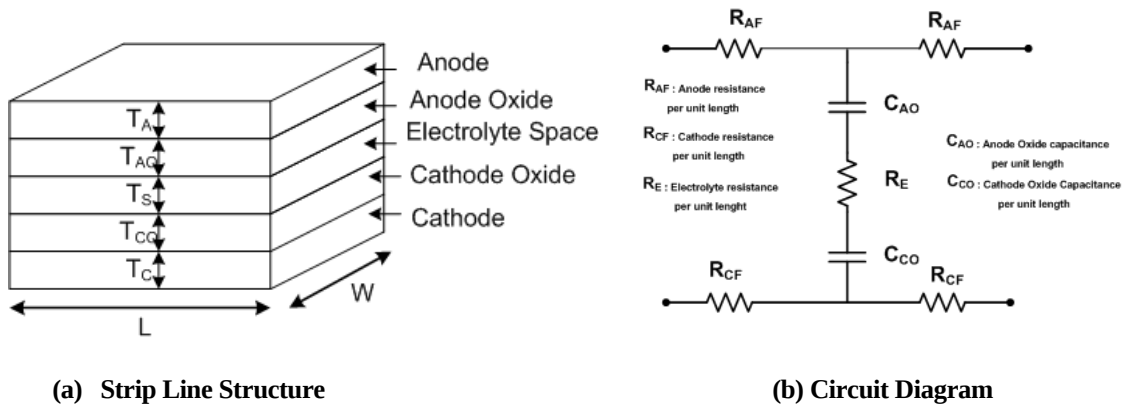


Figure 2: Strip Line Structure and Equivalent circuit Diagram of Electrolytic Capacitor

The capacitance value is directly proportional to the oxide layer area and inversely proportional to the oxide thickness. As we discussed earlier, the increase in the core temperature evaporates the electrolyte decreasing the oxide area (A_O) thus causing degradation. The rate at which the oxide layer degrades is directly related to the rate of evaporation of the electrolyte. The resultant decrease in the capacitance can be computed by solving for h , the dispersion height of the electrolyte, using equation (1):

$$h = h_0 - \frac{W_w A_e j_{eO}}{2\pi r} t \quad (3)$$

where: h_0 = initial height, and r : average radius of the electrolyte cylindrical surface.

The effective change of area can be calculated from h , which gives us the change in the capacitance from equation (2). Similarly, the total lumped electrolyte resistance (R_E) for a rolled configuration is

$$R_E = \frac{\rho_E t_0 P_E}{2 L W} \quad (4)$$

where: ρ_E : electrolyte resistivity ; t_0 : oxide thickness ; **L and W** = length and width of the anode surface area; and P_E = correlation factor related to electrolyte spacer porosity and average liquid pathway.

With decrease in the electrolyte due to high temperature the average liquid path length is reduced, which decreases P_E directly. The decrease in P_E reduces R_E as the electrolyte evaporates. Electrolytic capacitors have a leakage current associated with direct charge on its plates. For a healthy capacitor operating nominally leakage current is not significant, but it begins to increase as the oxide layer degrades, which can be attributed to crystal defects that occur due to electrolyte evaporation under high thermal stress conditions [20]. Under normal circumstances no damage or decrease in the life expectancy of the capacitor is observed. But in cases where the capacitors are stored under thermal stress conditions permanent damage is observed [18]. This can be explained by the decrease in R_E as we have derived above. Therefore, decrease in R_E increases the leakage current through the capacitor. In summary, the

degradation in the capacitor under thermal stress can be linked to two parameters: A_O and P_E , which directly affect the capacitance and leakage current, respectively.

ACCELERATED AGEING EXPERIMENTS

In this setup we emulated conditions similar to high temperature storage conditions, where capacitors are placed in a controlled chamber and the temperature is raised above their rated specification [13, 14]. Pristine capacitors were taken from the same lot rated for 10V and maximum storage temperature of 85°C.

The chamber temperature was gradually increased in steps of 25°C till the pre-determined temperature limit was reached. The capacitors were allowed to settle at a set temperature for about 15 min and then the next step increase was applied. This process was continued till the required temperature limit was attained. To decrease possibility of shocks due to sudden decrease in the temperature the above procedure was followed. For this experiment all the capacitors were subjected to a constant temperature of 125°C with no temperature variation. At the end of specific time interval the temperature was lowered in steps of 25°C till the required room temperature was reached. The ESR value is the real impedance measured through the terminal software of the instrument. Similarly the capacitance value is computed from the imaginary impedance using Electrochemical Impedance (EIS) Spectroscopy Z-Fit. Characterization of all the capacitors was done for measuring the impedance values using an SP-150 Biologic SAS instrument, twice a week. The details of the measurement procedure and calculation procedure are given in [2, 21].

As the devices degrade we observe a considerable decrease in the capacitance and while there is a considerably less change measured in the ESR. Under thermal stress it is observed that the degradation in the capacitors is primarily due to decrease in the capacitance [20, 22]. In this experiment the failure precursor is linked to the decrease in the capacitance value.

DATA ANALYSIS

As per the standards MIL-C-62F14 [20] a capacitor is considered unhealthy if under storage condition and high thermal stress its capacitance decreases by 10% or more below its pristine condition value.

Figure 3 shows the plots for all the six capacitors under test. The decrease in capacitance is plotted as a function of ageing time. The gradual decrease in the capacitance can be related to the physics of failure model derived earlier. As the temperature increases the electrolyte inside the capacitors evaporates and from equations (2) and (3) the decrease in the capacitance is directly linked to the decrease in the effective oxide area (A_O) of the capacitor. This decrease in the oxide area is in turn directly related to the rate of evaporation of the electrolyte given by (1). Till about 2200 hours of storage we observe a linear decrease in capacitance as predicted by the physics of failure model. As we continue beyond this time period, at around 2250 – 2400 hours we observe a step change in the capacitance indicating a sudden breakdown indicating a (sudden) breakdown phenomenon.

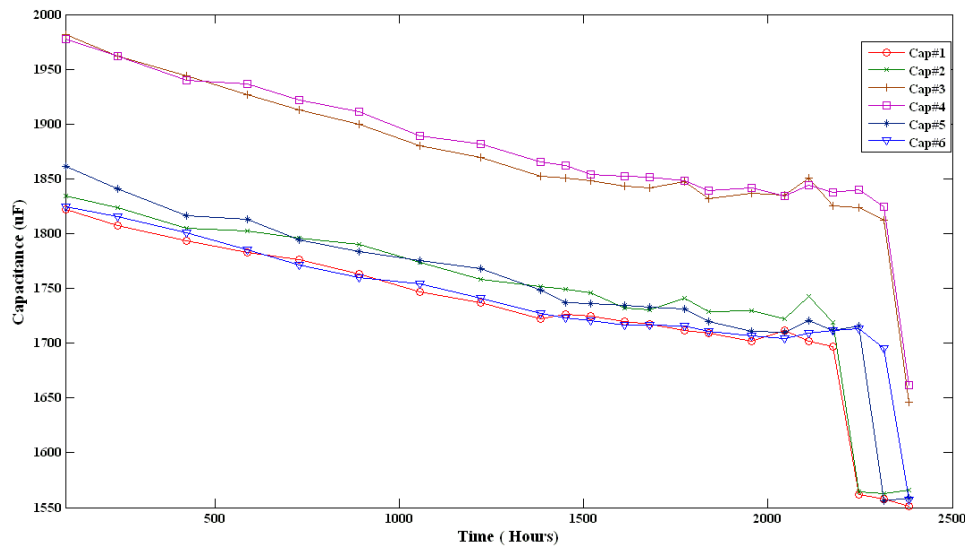


Figure 3: Capacitance Loss of all the six capacitor units

Presumably, after the electrolyte level falls below a certain value, breakdown occurs, which causes the leakage current to jump, leading to the sudden drop in capacitance. In future work, we will extend this qualitative analysis to methods where we estimate the parameters of the degradation model from data, and study the breakdown phenomenon in greater detail.

CONCLUSIONS

This paper proposed a model-based approach to study electrolytic capacitor degradation. We studied the possible physics of failure model that explained the degradation process leading to decrease in the capacitance. According to industry standards, an electrolytic capacitor is considered unworthy of being used in the system when under storage conditions its capacitance decreases by 10% of its initial value. With our experiments we are developing a systematic method for predicting this ageing time of components under different conditions. We will be able to recalculate some of the model parameters more accurately from the experimental data and improve the model.

The next steps are to extend the physics of failure model that also extends into the breakdown region for the capacitor. In future, we plan to develop more precise 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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