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Entropy characterisation of overstressed capacitors for lifetime prediction

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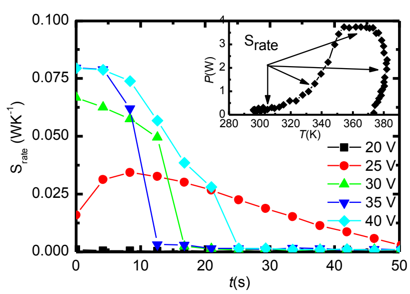
HIGHLIGHTS

- Introduction of entropy generation rate for capacitor lifetime determination.
- Entropy generation rate dependence on capacitor parameters (capacity and ESR).
- Relationship between entropy generation rate and failure mechanism.

GRAPHICAL ABSTRACT



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ABSTRACT

We propose a method to monitor the ageing and damage of capacitors based on their irreversible entropy generation rate. We overstressed several electrolytic capacitors in the range of 33 μF–100 μF and monitored their entropy generation rate $\dot{S}(t)$. We found a strong relationship between capacitor degradation and $\dot{S}(t)$. Therefore, we proposed a threshold for $\dot{S}(t)$ as an indicator of capacitor time-to-failure. This magnitude is related to both capacitor parameters and to a damage indicator such as entropy. Our method goes beyond the typical statistical laws for lifetime prediction provided by manufacturers. We validated the model as a function of capacitance, geometry, and rated voltage. Moreover, we identified different failure modes, such as heating, electrolyte dry-up and gasification from the dependence of $\dot{S}(T)$ with temperature, T. Our method was implemented in cheap electrolytic capacitors but can be easily applied to any type of capacitor, supercapacitor, battery, or fuel cell.

1. Introduction

Capacitors are energy storage components ubiquitous in electronic and electrical engineering applications. Several types of capacitors are available: ceramic, film, aluminium electrolytic, laminated ceramic, tantalum electrolytic, supercapacitors or flow supercapacitors. Electrolytic and supercapacitors have the largest capacities. They are manufactured in many foundries worldwide, and some of the largest producers are Panasonic, Vishay, Kemet, and Murata.

In this contribution, we are interested in capacitor ageing and failure characterisation. Capacitors are exposed to wear or damage

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while in use, which jeopardizes circuit performance. Degradation can be caused by different mechanisms. Typical failure modes and their causes are shown in Table 1.

In the scientific literature, there are many models regarding capacitor ageing and reliability, from different approaches: physicochemical, which characterises dielectric material properties [2,3]; statistical, which evaluates failure distributions [4–6]; electrical [7], with a special focus on equivalent series resistance (ESR) evolution [8,9] or impedance spectroscopy [10,11] and thermal [12–15]. From the thermal viewpoint, reversible entropy in supercapacitors has been considered in similar terms as in batteries [16,17]. In this case, reversible heat is related to ion movement in the electrolyte [12,14]. Moreover, the industry has also produced a large literature of information about ageing. International standards specify how ageing tests must be conducted [18–20], i.e., capacitors are biased at their nominal DC voltage with or without a superimposed AC signal. From these tests, empirical data to predict the capacitor lifetime is obtained. Panasonic provides the expected life L ratio for its parts as a function of temperature [1] by the following equation:

$$L = L_0 2^{T_0 - T/10} \tag{1}$$

where T and T_0 are the capacitor temperature and the maximum guaranteed capacitor temperature respectively, and L_0 is the guaranteed life of the capacitor. Moreover, the typical random failure rate, λ can be determined. It relates the expected capacitor life (L in hour) to its operating performance [21] by the following equation:

$$\lambda = \frac{4 \cdot 10^6 N V_a^3 C^{1/2} 2^{(T_a - T_m)/10}}{L_0 V_r^2} \tag{2}$$

N is the number of the studied capacitors, V_a is the applied voltage, C the capacitance of a single capacitor, T_a and T_m are the actual and the maximum permitted core temperatures respectively, L_b is the base life in hours at T_m and V_r is the rated voltage. The expressions given by (1) and (2) are typically empirical and provided by the manufacturers.

We suggest that the available models and relationships are either not directly dependent on intrinsic capacitor parameters (such as capacitance, ESR, EPR, dielectric permittivity or loss tangent) or they are statistical fits. However, in both cases they suggest the critical effect of temperature on operating performance. An ageing description that considers the physical parameters of the capacitor beyond a statistical approach and that is able to predict the lifetime and internal capacitor degradation, could be very useful. This type of description is true not only for capacitors but also for other energy storage systems, e.g. batteries or fuel cells.

Thus, looking at Table 1 we observe that the capacitors either evolve to open or short circuit conditions depending on the degradation mechanism. However, in both cases the capacitor ages, so an ageing model must simultaneously consider both the increase and decrease of internal parameters, such as current, voltage, capacitance or ESR for a positive ageing. We can infer that ageing and the internal parameters must be related, at least, through a quadratic relation. Dissipated power is the first quadratic option, but it is not a function of state. Conversion from power dissipation to ageing degradation can be achieved through entropy generation. Because ESR depends on temperature and ageing and dissipates power when biased, we consider that entropy can become a bridge between these parameters. We previously characterised the irreversible entropy generation rate σ_s for resistors [22], which here we extend to capacitors. Moreover, entropy has already been applied to damage characterisation [23–26] and was suggested as a valuable parameter for instrumentation and measurement [27]. Thus, we aim at finding a simple method to predict their ageing evolution to foresee their lifetimes. We investigate entropy evolution to characterise commercial capacitor damage and to find the relationship between failure mechanisms and time-to-failure (L in (1)). The final aim is to explain capacitor degradation in terms of positive irreversible entropy generation. Thus, a threshold for maximum allowable damage will be established.

2. Theoretical approach

We took a thermodynamic approach to capacitor failure, using the first and second laws of thermodynamics [28]

$$dU = dW + dQ + dE_{\text{irr}} \tag{3}$$

$$\dot{S} = \dot{S}_e + \dot{S}_i \tag{4}$$

with

$$\dot{S}_i \geq 0 \tag{5}$$

in a non-equilibrium system considering the approximation of local equilibrium. The dot over the variable represents a time derivative, i.e., $\dot{S} = dS/dt$. In (3), U, W, Q, and E_{irr} are the internal, stored, heat and irreversible damage energies, respectively. In (4), subindices e and i refer to external (entropy exchange) and internal entropy (entropy generation), respectively [29]; thus, entropy remains a valuable state function. We are interested in $\dot{S}_i$, includes thermal dissipation and ageing, and must be positive. The stored energy (dW) for a capacitor is well-known and described by the following:

$$W = \frac{1}{2} C V^2 \tag{6}$$

Heat is dissipated at the series resistance due to the Joule effect:

$$Q = R_s \cdot I^2 \tag{7}$$

No literature about E_{irr} was found; thus, its form is unknown at present. In terms of the entropy generation rate $\dot{S} = dS/dt$, for electrical systems, it is commonly written as [28]:

Table 1
Failure modes and mechanisms of Aluminum electrolytic capacitors (simplified from Ref. [1]).

Causes	Failure mechanisms	Effects
• Overvoltage impressed • Excessive ripple • Reverse voltage applied • Severe charging/discharging • AC voltage applied	• Increase in internal temperature • Increase in internal pressure • Reduction in anode foil capacitance • Reduction in cathode foil capacitance • Deterioration of oxide film • Electrolyte dry-up	• Air tightness failure of sealing • Capacitance reduces • Losses increases • Leakage current increase • Short circuit • Open circuit
• Used at high temperatures • Used for a long period	• Insulation breakdown • Corrosion	