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A new method for calculation of high-temperature capacitors thermal resistance

Key words: High-temperature capacitors, heat profiles, thermal resistance

Introduction

Commercially available high-temperature passive devices are designed to operate in the temperature range up to 200°C and are offered e.g. by Vishay or Kemet corporation.

The demand for temperature-resistant components is a result of rapid development of power systems, which should operate with high power densities and in the wide range of temperature. A possibility of high power dissipation enables the designers to minimize the size of electronic circuits.

Simulation of transient states is an integral part of designing of modern power systems. In the case of operation in the wide range of internal and ambient temperature, proper prediction of current and voltage waveforms, with electro-thermal interactions taken into account is very important. Changes of internal temperature are observable in the case of self-heating phenomenon occurrence, and the ambient temperature is one of the externally forced operation conditions. Methods of acquiring the necessary data for capacitors models differ substantially from the methods used in the case of semiconductor devices.

Power dissipation in capacitors is mainly related to an Equivalent Series Resistance (ESR), resulting from leads and electrodes resistance and dielectric loss. Changes of internal temperature of a capacitor may be predicted, when the thermal impedance curve or, at least thermal resistance value is known.

Measurements of capacitors thermal resistance or transient thermal impedance are much more complicated than measurements performed for active devices. Choosing of temperature-sensitive parameter and further calibration of measuring set-up is not obvious. In the presented investigations, thermal resistance of high-temperature capacitors is indentified indirectly.

A temperature – dependent electrical model of a capacitor

In the standard approaches to modelling of electro-thermal interactions in capacitors (e.g. in multi-purpose simulators), an equivalent circuit for capacitor consists of a pure capacitance, leakage and equivalent series resistance. In the more complicated models, various equivalent RC ladders, with resistance and capacitance distribution taken into account, are considered [1–3]. A parasitic inductance of the leads and pads, determining the resonance frequency is also sometimes taken into account. The parasitic resistances in capacitors result from various causes. Dielectric materials placed between the capacitor pads are not perfect insulation, so the flow of a small amount of charge stored on the plates of capacitors dielectric layer occurs. Leakage resistance is a parameter related to this phenomenon. Resistance of the leads, electrodes and dielectric loss contribute to occurrence of series resistance losses.

In the case of electro-thermal simulation, each of assumed components depend on the temperature in a different way and the origin of losses distribution in ceramic and electrolytic capacitors should differ. However, it is appropriate to assume reasonable substitute parameters and find a compromise between the complexity of the model and its accuracy.

In the presented work, a simple model, consisting of capacitance and ESR has been assumed (Fig. 1).

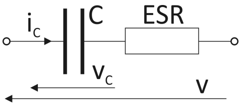

Fig. 1. A simple equivalent model of a capacitor

An easiest way to identify the influence of frequency and temperature on electrical parameters of considered devices is the use of RLC bridge. The accuracy of used bridge, provided by the manufacturer is 0.05%. Measurements of temperature- and frequency-dependent series and parallel resistances, as well as capacitances, in the temperature range from 22°C up to 300°C has been performed [4] and the exemplary results for a high-temperature 120μF Vishay capacitor from 135D series [5] are shown in Fig. 2. The setted values of frequency was from 50Hz up to resonance, so it may be also observed, how the rise of temperature restricts the range of operating frequency.

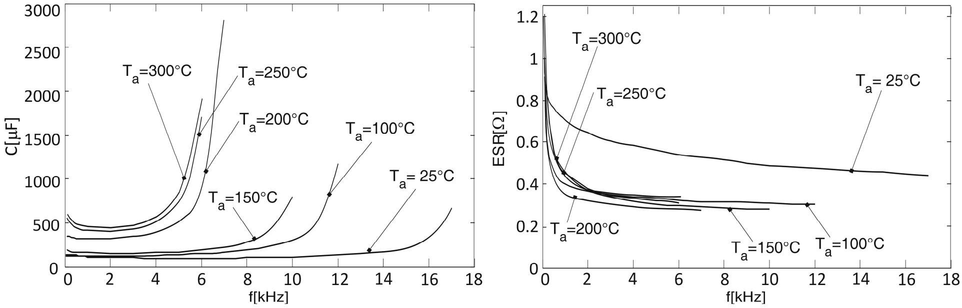

Fig. 2. Influence of frequency and temperature on capacitance and equivalent series resistance of 120μF Vishay capacitor

During the measurements, sufficiently low amplitudes of current and voltage in the capacitor has been ensured – to avoid the occurrence of self-heating phenomenon. In such case – for each of setted frequency values, only the ambient temperature is a factor influencing capacitance and ESR.

From the set of measurements shown in Fig. 2, the C(T) and ESR(T) dependencies for various values of frequency has been extracted and the equations for an analytical representation of those dependencies has been assumed:

$$C(T_a) = C_0 \cdot \left(a \cdot T_a^b + c\right) \tag{1}$$

$$ESR(T_a) = R_0 \cdot \left(p_1 \cdot T_a^2 + p_2 \cdot T_a + p_1\right) \tag{2}$$

Coefficients a, b, c, p_1, p_2, p_3 in (1), (2) have been identified with the use of standard curve-fitting methods and their values for chosen frequencies (500Hz and 3kHz) are given in Table I.

Table I. Coefficients in the analytical representations of C(T) and ESR(T)

	C(T)				ESR(T)			
f [kHz]	C_0[μF]	a[1/°C^2]	b	c	R_0[Ω]	p_1[1/°C2]	p_2[1/°C]	p_3
0.5	116	0.14	3.06	$0.93 \cdot 10^6$	0.83	$0.2 \cdot 10^{-6}$	-0.007	1.16
3	99	46.84	2.04	$0.86 \cdot 10^6$	0.68	$0.14 \cdot 10^{-6}$	-0.006	1.12

Goodness of fits is represented by an adjusted R-square (ARS):

$$ARS = \frac{\sum_{n=1}^{N}\left(\hat{y}_n - \bar{y}\right)^2}{\sum_{n=1}^{N}\left(y_n - \bar{y}\right)^2} \tag{3}$$

where: y_n – the real (measured) value, $\hat{y}_n$- the value calculated from analytical model, $\bar{y}$- the average value of empiric data. Accuracy of parameters identification is better, when the ARS value (always between 0 and 1) is closer to 1.

In Fig. 3, the influence of ambient temperature on C and ESR, represented by (1) and (2) is shown and compared to measurement results.

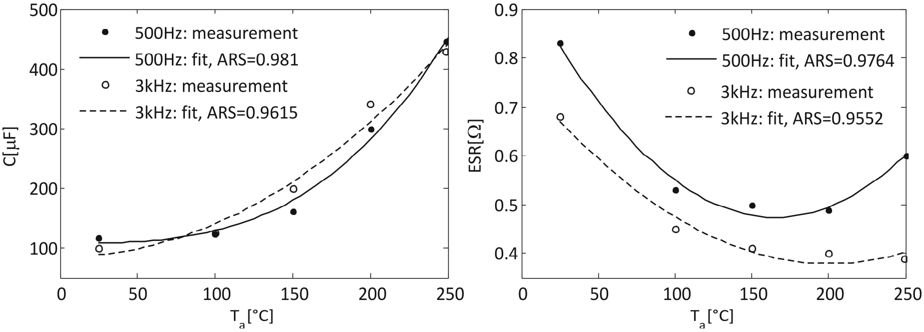

Fig. 3. Influence of the ambient temperature on capacitance and ESR of “120μF” capacitor for 500Hz and 3kHz

Calculation of capacitors heat profiles

In the presented approach, for the calculation of capacitors heat profiles, waveforms of current and voltage in the capacitor are needed. Such waveforms, has been measured with the use of digital oscilloscope, with accuracy 0.05%, and samples of data has been stored for further processing. This time, the amplitude of forced voltage was high enough (35V) to induce self-heating. The exemplary voltage and current waveforms for f=500Hz are given in Fig. 4(a).

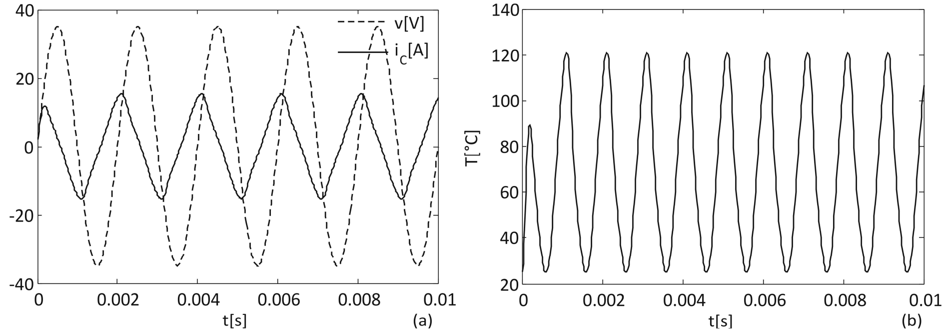

Fig. 4. 500Hz voltage forced in the capacitor and its current response (a) and its heat profile (b) in the electro-thermal steady-state

In the discrete-time domain, for the equivalent circuit given in Fig. 1:

$$v_{[n]} = v_{C[n]} + ESR \cdot i_{C[n]} \tag{4}$$

For the discretization of a pure capacitance appearing in the model from Fig. 1, one may use any of algorithms for numerical integration [6]. In the presented case, a second-order Adams Moulton (trapezoid) algorithm has been used:

$$v_{C[n]} = v_{C[n-1]} + \frac{h}{2 \cdot C} \cdot \left(i_{C[n]} + i_{C[n-1]} \right) \tag{5}$$

where h is the discretization step.

After including the analytical representations of C(T) (1) and ESR(T) (2), one obtains:

$$\begin{aligned} &\frac{h}{2 \cdot C_0 \cdot \left(a \cdot T^b + c \right)} \cdot \left(i_{C[n]} + i_{C[n-1]} \right) + \\ &+ R_0 \cdot \left(p_1 \cdot T^2 + p_2 \cdot T + p_3 \right) \cdot i_{C[n]} + v_{C[n-1]} - v_{[n]} = 0 \end{aligned} \tag{6}$$

The temperature T in (6) is now an internal temperature of a capacitor. Equation (6) is a simple nonlinear issue to solve numerically with the use of Newton-Raphson algorithm [6]. In the presented case, the accuracy of Newton procedure was 1·10-6 [5]. Heat profiles of considered capacitor, calculated for f=500Hz are given in Fig. 4(b). A lower amplitude in the first half-period is a result of starting error, which is compensated for every numerically stable algorithm.

If one consideres an electro-thermal steady-state, a thermal resistance of a device may be represented as a quotient of an average rise of internal temperature (over the ambient) and average power dissipated in the device [7]:

$$R_{th} = \frac{\Delta T}{P} \tag{7}$$

In the case of capacitor represented by the model from Fig. 1, the power dissipation occurs in ESR. The average values of temperature rise and power may be easily calculated numerically. In the performed experiments, the obtained values of thermal resistance were: R_{th}=0.79°C/W for f=500Hz and R_{th}=0.8°C/W for f=3kHz. Unfortunately, the manufacturers data sheets for investigated capacitor (and for other from the high-temperature series) do not contain any information about thermal resistance. Other capacitors offered by Vishay are characterized by the thermal resistance from 0.5 to 0.8°C/W.

Estimation of numerical error

The numerical inaccurracy of proposed method may be estimated by the use of following procedure: the calculated temperature transient (Fig. 4(b)) and value of R_{th} are taken as a priori known and used for calculation of "reference" power, absolute of capacitors current and voltage drop on ESR. The mentioned operations do not involve the numerical algorithms and have got a pure analytical form:

$$p_{ref}(t) = \frac{T(t)}{R_{th}} \tag{8}$$

$$\left|i_{Cref}(t)\right| = \sqrt{\frac{p_{ref}(t)}{ESR}} \tag{9}$$

$$\left|v_{ESRref}(t)\right| = ESR \cdot \left|i_{Cref}(t)\right| \tag{10}$$

Values of error related to the numerical algorithms (5), (6) are calculated from equation:

$$\xi_{[n]} = \frac{\left|\left|v_{ESR[n]}\right| - \left|v_{ESRref[n]}\right|\right|}{\bar{v}_{ESR}} \cdot 100\% \tag{11}$$

where: $|v_{ESR[n]}|$ - absolute of voltage drop on ESR calculated with the use of procedure based on equations (4), (5), (6), $|v_{ESR[n]}|$ - absolute of reference voltage drop on ESR, calculated analytically, $\bar{v}_{ESR}$ - average value of v_{ESR}. The percentage error of numerical operations in the procedure for R_{th} calculation, for various values of discretization step is shown in Fig. 5.

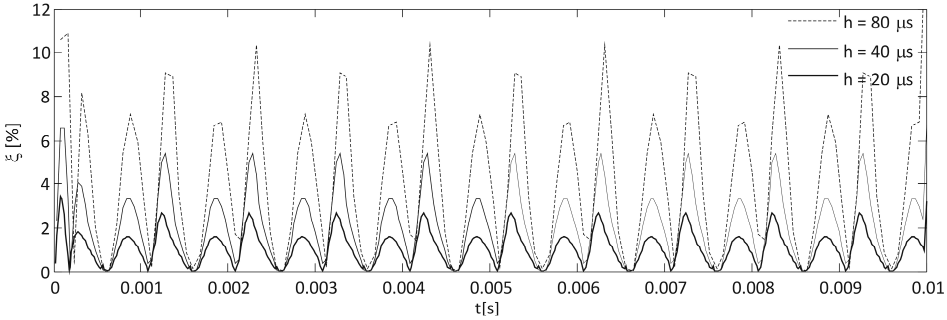

Fig. 5. Estimation of numerical error for various discretization step values

It should be pointed out, that the voltage drop on ESR is not an output value in the procedure for R_{th} calculation, so the error shown in Fig. 5 is only approximate.

Conclusions

The comprehensive measurements of the influence of the temperature on the capacitors electrical parameters are a very useful tool in the modeling of electro-thermal processes. Performed measurement test show a meaningful derating of capacitance, caused by the temperature rise (Fig. 2, 3). The analytically represented influence of the temperature on assumed capacitors electrical parameters gives a possibility of calculation of its heat profiles and thermal resistance. The error of calculation of thermal resistance results from a few different sources: inacurracy of measurements performed by RLC bridge and oscilloscope, error of curve fitting method, used for identification of parameters in C(T) and ESR(T) analytical description, and error of the numerical procedure. But the total percentage error of whole method should not exceed 20%. The presented results are for now preliminary and it is obvious that the more expanded (than the one given in Fig. 1) equivalent circuits should be considered and tested. In the further work, the numerical procedures for calculation of capacitors transient thermal impedance will be developed.

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Abstract

In this paper, issues related to the self-heating phenomenon in high-temperature capacitors are described. Measurements of capacitance and parasitic resistance, as a function of frequency and ambient temperature of considered capacitors are presented. Novel procedures for calculation of internal temperature changes are proposed and a novel method for acquiring thermal resistance values is developed and its numerical error is estimated.

Streszczenie

W niniejszej pracy, opisano zagadnienia związane ze zjawiskiem samonagrzewania w kondensatorach wysokotemperaturowych. Przedstawiono wyniki pomiarów pojemności i oporności pasożytniczej wybranych kondensatorów w funkcji częstotliwości i temperatury otoczenia. Zaproponowano nową metodę obliczania zmian temperatury wewnątrz elementu oraz wyznaczania jego rezystancji termicznej. Oszacowano błędy numeryczne proponowanej metody.

Słowa kluczowe: Kondensatory wysokotemperaturowe, profile cieplne, rezystancja termiczna.