

THERMAL SIMULATION OF ELECTROLYTIC CAPACITOR DURING IMPULSE OPERATION

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Abstract

The article is focused on thermal analysis of electrolytic capacitors with repeated cycles of charging and discharging. In the introduction, we present the theory necessary to a capacitors analysis. The particular aluminum electrolytic capacitor Nichicon is examined in the paper. There is described Implementation of real model in COMSOL Multiphysics and simulation solutions too. In conclusion, the model is verified by experimental measurements on a real capacitor and deviations between measured and simulated data are identified.

1 Introduction

Electrolytic capacitors play an irreplaceable role in power electronics. They are mainly used as smoothing, filtering or storage components. Currently, the emphasis is on devices efficiency increase. Therefore, it is necessary to reduce its losses of energy in separate components. Thorough thermal analysis of components can help. The capacitor like any real component has parasitic elements that cause energy losses. These losses are manifested in the form of heat, which is undesirable because it causes warming of components. Component parameters change and component life shortens under warming. The capacitor could be damaged inside by press of electrolyte after over run of permitted operating temperature values.

2 Analysis of capacitor problems

Capacitor is a passive frequency-dependent component. The technical design of capacitor is also called a condenser. The basic characteristic of the capacitor is the ability to keep the energy in the form of electrical charge and pass it, if necessary, back to the circuit. As a result of charging, difference of electrical potential or voltage arises on its contacts. Capacitors are composed of two or more conductive plates separated by a non-conductive material which is called a dielectric. Dielectric may include a vacuum, paper, mica, plastic, glass or ceramics. The basic parameter of the condenser is capacity, expressed in farad. Capacity of the planar electrode arrangement in Fig. 1 is given by:

$$C = \varepsilon_r \varepsilon_0 \frac{S}{d} F \quad , \quad (1)$$

where C - the capacitance of capacitor, ε_r - relative permittivity of dielectric, ε_0 - vacuum permittivity, S - surface of electrodes, d-distance of electrodes. On the basis of that formula, we see that the value of capacity is directly proportional to the relative permittivity of the dielectric ε_r and to the electrode surface S. Capacity is inversely proportional to the distance of electrodes. Permittivity of vacuum is a constant which value is equal to $\varepsilon_0 = 8,854187 \cdot 10^{-12} \text{F/m}$.

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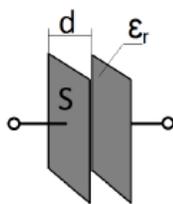


Fig.1 Planar plate capacitor

Tab 1.The relative permittivity of some materials

Material at 20° C	Glass	Mica	Paraffin wax	China	Rubber	Air
ϵ_0	5 to 10	5,6 to 8	2 to 2,4	4,5 to 6,7	2 to 2,3	1,000528

The values of relative permittivity of the dielectric shown in Table1 are given for static electric field or a field with low frequency. Values are changing with increasing frequency and temperature. However the rate of change is dependent on the material. Therefore, material selection should be considered according to the requirements of the particular application. Energy, which can be accumulated in the capacitor, is calculated as follows:

$$E = \frac{1}{2} C * V^2. \quad (2)$$

The formula implies that the energy accumulated in the capacitor increases with increasing capacity and with the square of the voltage which is connected to the capacitor. If we want to draw energy from the capacitor or to supply energy to capacitor, this energy is calculated according to

$$E = \frac{1}{2} C * V_1^2 - V_2^2, \quad (3)$$

Where V_1 is the initial and V_2 is the result capacitor voltage. Energy that we want to drain from the capacitor or supply into the capacitor depends directly proportional to the capacity of the capacitor and the difference of the voltage squares before change and after change of energy state.

The basic structural component of aluminum electrical capacitors in Fig. 2 is aluminum foil. The foil may be adjusted during production by etching. Etched foil has the advantage that it has a greater surface area and therefore can, while maintaining the same size to create a capacitor with a higher value of the capacity. The foil is then anodized by boric acid. The foil was then anodized boric acid. The process creates on the aluminum foil a layer of aluminum oxide, which acts as a dielectric, and at the same time creates a surface of the anode foil. Dielectric is then formed by DC power.

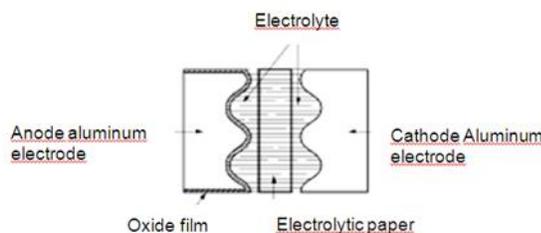


Fig. 2. Structure of the aluminum electrolytic capacitor

(Source: <http://www.nichicon.co.jp/english/products/pdf/aluminum.pdf>)

The detail of construction of aluminum capacitors in Fig. 2 shows that on the anode foil is a condenser paper and cathode foil. Everything is then rolled up, impregnated with liquid electrolyte and encased in a package which protects the electrolyte from drying out. Composition of the capacitor is shown in Fig. 3. Oxide layer has a rectifier character. Capacitor has polarity that must be followed to avoid damage.

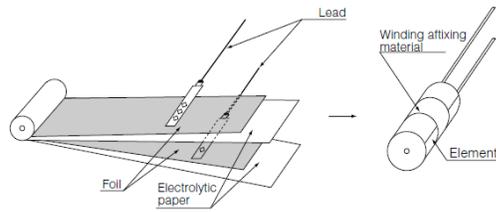


Fig. 3.Composition ofthe capacitor

(Source: <http://www.nichicon.co.jp/english/products/pdf/aluminum.pdf>)

When choosing a capacitor, we find the basic parameters of capacitors:

- The capacity of the capacitor and its tolerance - shows the total capacity of the capacitor with a given maximum permissible deviation.
- Maximum operating voltage - indicates the highest voltage which can be connected to the capacitor, to avoid electrical breakdown of the dielectric what leads to a capacitor irreversible destruction.
- Operating temperature range - indicates in what temperature range can operate a capacitor while maintaining the required parameters.
- Leakage current - current that passes through a capacitor after a certain time after connecting to a source of DC voltage. It is a source of loss, and therefore is undesirable.
- Equivalent series resistance - parasitic capacitor element, which is the main source of heat loss when electrical current passes through a capacitor.

3 Capacitor during repeated charge and discharge cycles

In practice, the capacitor is typically used as a temporary source of power. It is therefore cyclic charged and discharged. His energy is repeatedly decanted from the circuit to the capacitor and vice versa. The amount of the energy that can be stored in the capacitor is represented by the amount of electric charge in the capacitor. The charge is given by:

$$Q = C * V , \quad (4)$$

where Q is the electric charge, C-capacity of an ideal capacitor, U-voltage of capacitor.

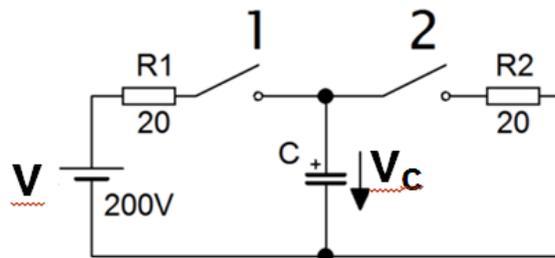


Fig. 4. The replacement model for repeated charging and discharging of an ideal capacitor

Fig. 4 shows the circuit diagram of an ideal capacitor in a circuit, which performs its repeated charging and discharging. If switch 1 is closed the capacitor is charging. The value of the charging current is limited by resistor R_1 . When the capacitor is charged to a voltage of source a capacitor current dropped to zero. This means that it is fully charged. Then switch 1 is switched off and switch 2 is switched on. Energy accumulated in the capacitor is converted into heat through the resistor R_2 , thereby discharges the capacitor. With repeated charging and discharging a current constantly flows through a capacitor. This current flows through the parasitic capacitor elements and thereby causes losses that will cause warming of capacitor. The point is that in the large storage capacitors (about 25 mm diameter), a difference arises between the temperature in the core of the capacitor and its surface. When designing a specific application, it is therefore necessary to take into account this fact. For smaller capacitors, this difference is negligible.

For a thorough analysis of the capacitor is necessary to know the mathematical description of the electrical parameters during charging and discharging. It is clear that this is a first-order linear circuit. Mathematically it is described with a linear differential first-order equation with constant coefficients, because the values of elements are not changing. Diagram in Fig. 4 is used. The process was divided into two intervals i.e. charging interval, and discharging interval. Then we described the circuit using the 1st and 2nd Kirchhoff's law and modified the equations. The solution is the sum of the homogeneous and particular solutions. After editing we get the following equations:

Charging process:

$$\begin{aligned} i_C t &= C \frac{dv_C}{dt} = 10e^{-\frac{100}{3}t} \text{ A} \\ v_C t &= 200 \left(1 - e^{-\frac{100}{3}t}\right) \text{ V} \end{aligned} \quad (5)$$

Discharging process:

$$\begin{aligned} i_C t &= -10e^{-\frac{100}{3}t} \text{ A} \\ v_C t &= 200e^{-\frac{100}{3}t} \text{ V} \end{aligned} \quad (6)$$

Substituting the values for time variable, we get instantaneous value of voltage and current at any given time. Speed of time change of waveforms depends on the time constant τ . We can calculate it as follows:

$$\tau = R * C = 20 * 1500 * 10^{-6} = 0,03 \text{ s} \quad (7)$$

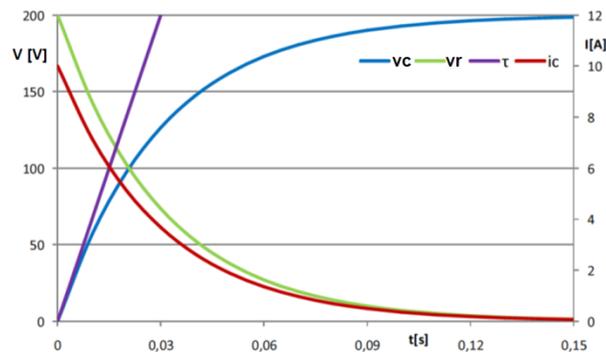


Fig. 5. Calculated waveforms at capacitor charging

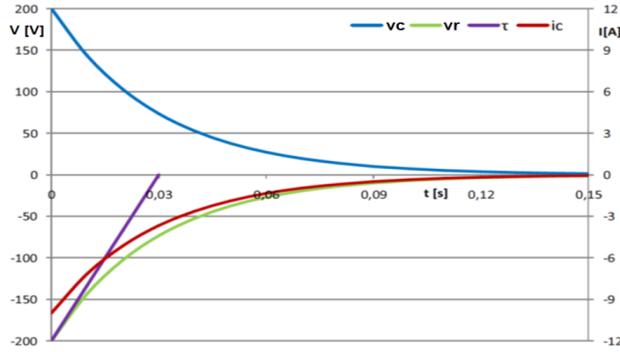


Fig. 6. Calculated waveforms at capacitor discharging

From the waveforms in Fig. 5 and Fig. 6 we see that the transient can be considered completed around the time:

$$t_u = 5 * \tau = 5 * 0,03 = 0,15 \text{ s} \quad (12)$$

4 Thermal model of capacitor

The thermal model is a digital copy of a particular element, which respects its structure, composition and mechanisms of heat generation and heat transfer in conformity with reality. The thermal model allows us to fold the temperature analysis in a particular structure using simulation programs. In this work we use COMSOL simulation environment. The advantage of this solution is the speed and accuracy of calculation in comparison with the numerical methods. Calculated values then can be monitored in time and space and display the results graphically. It is particularly preferred for purposes of illustration, because at first glance we see the time changes of the temperature in each area of the element. The results can then be interpreted either as a specific numerical value for the selected point of body or in graphical form through pictures or videos. In addition to thermal analysis, this program also allows the study of other physical fields and their interaction. To analyze the thermal model of a specific capacitor we need to know the exact design, used materials, their properties and loss in the element. The problem is to know perfectly the design of the capacitor, because the manufacturer does not mention it. It is therefore necessary to analyze a particular physical model, to cut it in an appropriate way and determine dimensions and materials of the individual layers. Geometric model examined capacitor was treated at work [16]. Fig.7 presents the resulting geometric model and the picture of a real capacitor.



Fig. 7. Left - geometric model of the capacitor, right - examined capacitor with glued temperature sensor

5 Simulation results

COMSOL program after the calculation allows viewing a simulated model in post processing mode. Displayed information can be changed via the Plot parameters menu. We can also show simulation results

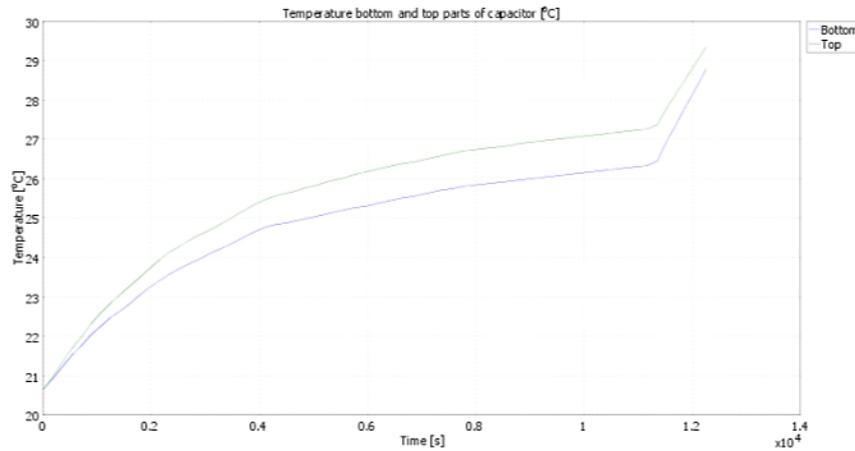


Fig. 8. Time diagram of the temperature at the bottom and the top of the capacitor [17]

at the selected time, where the model is solved. Besides showing the temperature distribution on the surface of the model we can also display the temperature inside the model at the selected point, on any edge, show places with the maximum and minimum temperatures, or create animation, etc. Fig. 8 presents the simulated time waveforms of temperature in the middle of the top and bottom base of the capacitor. From the waveforms we see that the top of the capacitor during

cyclic operation warmed more than the bottom. This is because the heat tends to rise and also by designing the capacitor, because the aluminum strips of capacitor core are output on the top and they are connected to screw contacts for connecting the wires that conduct heat well.

6 Experimental verification of simulation

To verify the accuracy of the simulation results, we performed experimental measurements under conditions that are as close as possible to the conditions in the simulation. We need the capacitor to be repeatedly charged and discharged and investigate its warming in defined respectively accessible places until we reach a steady state. The results of measurement and simulation files are completely processed in Fig. 9.

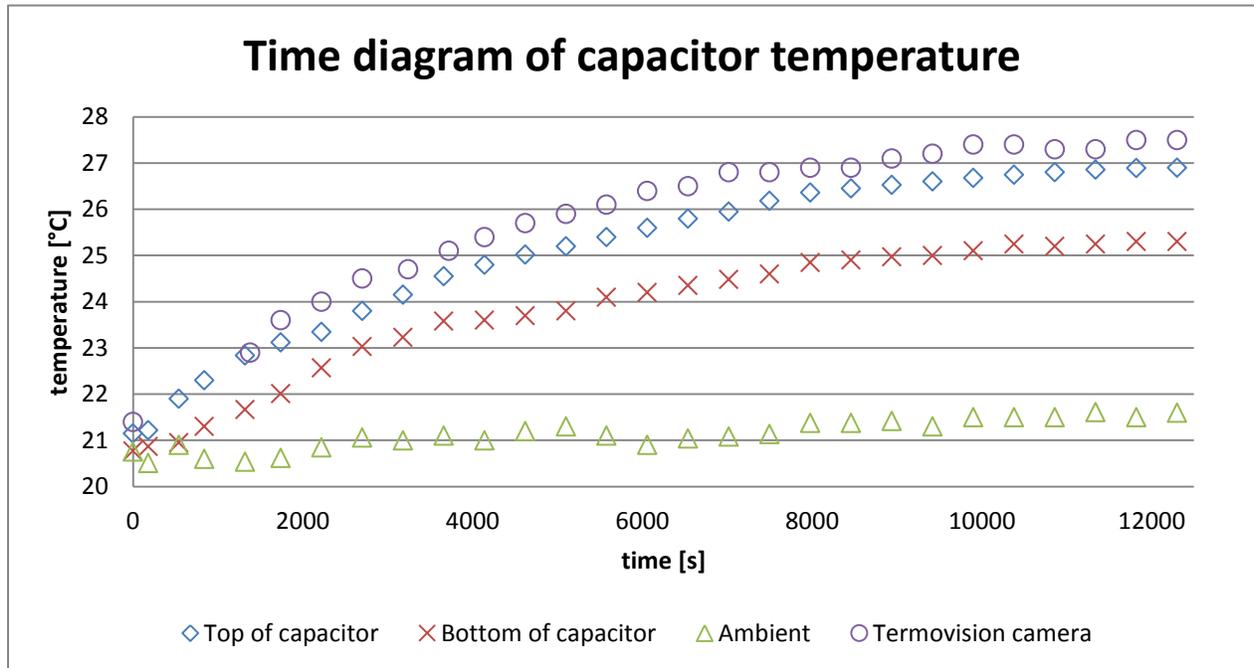


Fig. 9. Time diagrams of temperature on the top, bottom of simulated capacitor and thermo-visual temperature of top and surroundings of capacitor

Conclusion

The aim of this study was to design, analyze and verify the simulation model of electrolytic capacitor Nichicon capacity $1500\mu\text{F}$ and maximum allowable voltage of 450V. The model was implemented in COMSOL Multiphysics. Setting of physical parameters of the model was performed on the basis of actual knowledge acquired by capacitor disassembling and from the manufacturer data. These include determining the materials and boundary conditions. We did the simulation for vertically or horizontally oriented capacitor in the laminar flow of ambient air. After setting all the parameters, we performed time simulation model of the capacitor which is warmed by power loss at periodic charging and discharging.

We used two methods for temperature measurement: contact measurement using sensors placed on the capacitor and contactless measurement of thermo-vision camera. With this solution, we achieved a relatively accurate temperature values.

It was necessary to use the precise sensors with sufficient resolution up because warming of capacitor was not great. Overall it was a very time-consuming measurement, because capacitor was warming very slowly. The diagram of the temperature can be seen in Fig. 9.

We compared the results and evaluate the percentage deviation in temperature. In both cases, we found a greater deviation from the sensor placed on the bottom of the capacitor.

Practical contribution of this thesis is validated simulation model of the specified capacitor. If necessary, the model can be adjusted according to the requirements of the particular application and thus get relevant results without the need for physical measurements on real samples.

Acknowledgement

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References

- [1] AB., COMSOL. 2008. COMSOL Multiphysics User's Guide. s.l. : COMSOL AB., November 2008.
- [2] Heat Transfer Module User's Guide. s.l. : COMSOL AB., 2008.
- [3] Coulson, J.M. a Turgeon, É. 1990. Chemical Engineering. New York :Pergamon Press, 1990.
- [4] Elberg, Salomon a Mathonnet, Pierre. :Odvod tepla z elektronických zařízení, Praha : SNTL – Nakladatelství technické literatury, 1983.
- [5] Ellison, Gordon N., Thermal Computationsfor Electronics, Boca Raton : CRC Press, 2011. 978-1-4398-5017-6.
- [6] Fukátko, T., Fukátko, J.: Teplo a chlazení v elektronice II. Praha, BEN – technická literatura, 2006. 80-7300-199-3.
- [7] <http://www.illinoiscapacitor.com/>. [Online]
- [8] <http://www.illinoiscapacitor.com/tech-center/life-calculators.aspx>
- [9] <http://www.radio-electronics.com/>. [Online]
- [10] <http://web.tuke.sk/>. <http://web.tuke.sk/>. [Online]
- [11] Kúdelčík, J.,Hockicko, P.: Základy Fyziky, Žilina: Žilinská univerzita v Žiline, 2011. 978-80-554-0341-0.
- [12] NIC COMPONENTS CORP. General Information For Non Solid Aluminum Electrolytic Capacitors. [Online]
- [13] <http://www.niccomp.com/help/techinfo/AlumApplInfoCautions.pdf>
- [14] Nichocon Corporation. General Descriptionsof Aluminum Electrolytic Capacitors.[Online]
- [15] <http://www.nichicon.co.jp/english/products/pdf/aluminum.pdf>.
- [16] Varačka, Lukáš. Analýza vplyvu elektrických strát elektrolytického kapacitora na jeho rozloženie teploty, Diplomová práca, Žilina, 2013.
- [17] Brigant Michal. Simulácia teplotného poľa v elektrolytickom kapacitore v opakovaných cykloch nabíjania a vybíjania, Diplomová práca. Žilina, 2014.