Numerical Simulation of Electro-Thermal Processes in Multilayer Ceramic Capacitors

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***Abstract* — Electro-thermal processes in multilayer ceramic capacitors were studied. Using COMSOL Multiphysics software the digital twin of multilayer ceramic capacitor was developed. Numerical model of capacitor takes into account nonlinear electric and thermal properties of materials. The digital twin allows to analyze capacitor's operating under different electrical and thermal regimes. Electrical stress, current density and temperature can be calculated in all parts of capacitor. The heating process of testing capacitor under AC load and its dielectric parameters was experimentally studied. The simulation results are in good agreement with the experimental data.**

Keywords — multilayer ceramic capacitor; digital twin; numerical modeling; COMSOL Multiphysics

I. INTRODUCTION

The important components of modern electronic devices are multilayer ceramic capacitors (MLCCs). Small size, high volumetric capacitance and relatively high operating temperature determine its widespread use. The main MLCC's element is monolithic sintered package that consists of ceramic dielectric and electrodes layers. As a rule, external terminals connected to the multilayer package and then it is epoxy coated (Fig. 1). There are low voltage and high voltage MLCCs. Low voltage MLCC single dielectric layer thickness is several micrometers and total layer's number is several tens – hundreds. The single dielectric layer thickness of high voltage MLCCs is several tens of micrometers and total layer's number varies within a several tens [1-4].

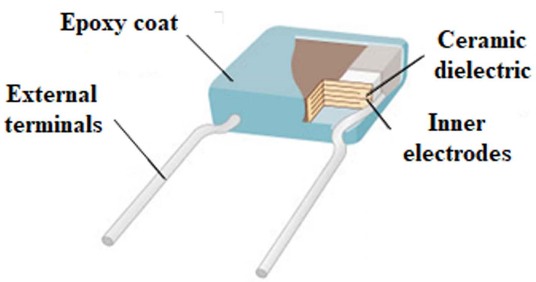

Fig. 1. Multilayer ceramic capacitor [5].

MLCC's dielectric parameters, such as capacitance and dissipation factor are very sensitive to temperature impact. The operating temperature mainly determines MLCC's performance. The most intense capacitors heating is due to operating under AC voltage. Numerical modeling of electrical and thermal MLCC's operating modes helps to determine its performance under different loads and cooling conditions. The digital twin is a convenient tool in the design of MLCCs and checking its performance. Simple geometry sizes, electric and thermal parameters changing allow to determinate capacitor's design with specified characteristics and operating mode.

II. EXPERIMENTAL SETUP

The investigated objects were MLCCs X7R type. The nominal capacitance is 1 μF and operating voltage is 50 V. Investigated capacitors were stressed by AC voltage of different amplitude and frequency. Simplified view of experimental setup is shown in Fig. 2. Voltage and current were measured by digital oscilloscope GW Instek GDS-72072. Surface temperature was measured by infrared pyrometer Optris LS LT and temperature inside of test cell by thermocouple.

The heating process of MLCCs under AC voltage in the range 50 – 125 V and frequency range 0.1 – 1 kHz were investigated to verify the digital twin model. Such high operating voltage was used to make wide range of measuring temperature on the capacitors surface. Nevertheless, generated heat was not enough for development of thermal breakdown during experiment.

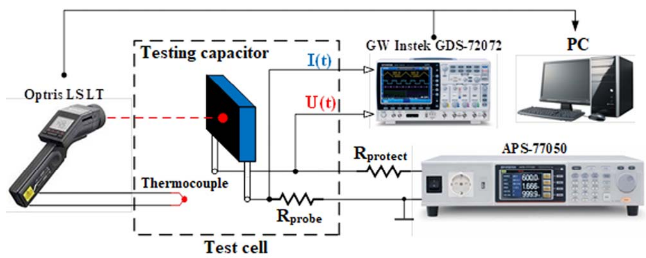

Fig. 2. Experimental setup

III. NUMERICAL MODEL

The model of MLCC's digital twin was developed using COSOL Multiphysics software. The main task was to develop the most detailed model, that takes into account the nonlinear electrical and thermal properties of dielectric materials. Numerical model geometry is shown in Fig. 3. The digital twin geometry replicated the design of X7R type MLCC.

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To optimize calculation process the finite elements of 2 types were used: rectangular mesh in dielectric-electrode multilayer and ceramic shell, and tetrahedral mesh in other elements. Mesh size was ranged in 10 – 100 μm.

Software modules «Electric Currents» and «Heat Transfer in Solids» were used to calculate this multiphysics task. The task consisted of Maxwell's equations

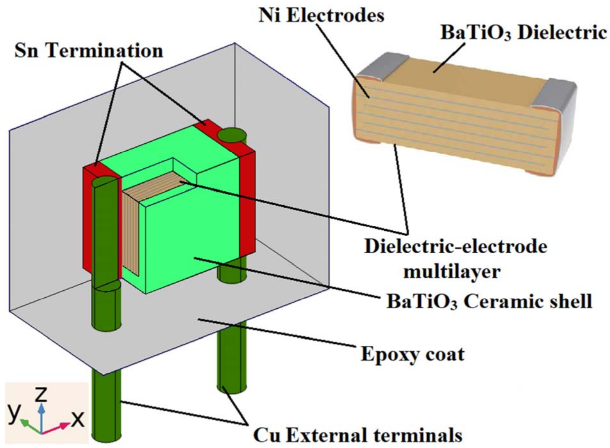

Fig. 3. Numerical model geometry. Several boundaries are hidden

$$\begin{aligned} &\nabla \bar{J} = 0 \\ &\bar{J} = \sigma(T)\bar{E} + j\omega\bar{D} \\ &\bar{E} = -\nabla\varphi \end{aligned} \qquad (1)$$

and heat transfer equation

$$\rho(T)C(T)\cdot\frac{\partial T}{\partial t} = \lambda(T)\cdot\nabla^2 T + Q_J + Q_D, \qquad (2)$$

were $\bar{J}$ – current density vector, $\bar{E}$ – electric strength vector, $\sigma(T)$ – electric conductivity, φ – electric potential, ω – angular frequency, $\bar{D}$ – electric displacement vector, j – imaginary unit, $\rho(T)$ – density, $\lambda(T)$ – thermal conductivity, $C(T)$ – specific heat, T –temperature, Q_J and Q_D – volumetric power densities due to Joule heating and dielectric losses respectively. Q_J and Q_D were determined by equations

$$Q_J = \frac{\bar{J}^2}{\sigma(T)}, \qquad (3)$$

$$Q_D = \omega\varepsilon(T,E)\varepsilon_0\bar{E}^2 tg\delta(T,E), \qquad (4)$$

where $\varepsilon(T,E)$ – relative permittivity, ε_0 – dielectric constant, tgδ(T,E) – dissipation factor.

The boundary conditions for equations (1) were: certain electric potential on the bottom of external terminals and zero value of normal current density on other boundaries $\bar{J}_n = 0$. The boundary conditions for equation (2) were: constant temperature value on the bottom of external terminals and convective heat flux on other boundaries. The convective heat flux determined by equation

$$q_s = h(T - T_0), \qquad (5)$$

where T_0 – temperature inside the test cell, h – heat transfer coefficient depending on geometry and heat flux direction.

The values of $\varepsilon(T,E)$ and $tg\delta(T,E)$ were experimentally determined in [6]. Temperature dependent parameters $\sigma(T)$, $\rho(T)$, $\lambda(T)$, $C(T)$ were taken from [7] and software material library. Taking into account all used materials the model has 17 nonlinear parameters.

Study type «Frequency-Stationary» was used to analyze the steady-state solution and study type «Frequency-Transient» to analyze capacitor's operating in time range. The latter requires large computing resources.

IV. RESULTS AND DISCUSSION

Developed model of the MLCC digital twin allows to determine electric field, current density and temperature in every point of calculation area. Typical 3D temperature distribution under U = 50 V and f = 1 kHz mode is shown in Fig 4. Maximum temperature value in the center of capacitor is 116 deg C, meanwhile temperature value on its surface ranged within 70 – 90 deg C.

Experimental and calculated dependencies of maximum temperature on capacitor's surface under different load regimes are shown in Fig 5. The difference between experimental and calculation results can be explained by approximate method of convective cooling calculation. Using software module «Laminar Flow» convective heat flux calculation is more correct. It allows to determine the temperature field and air velocity field around the capacitor.

Capacitance of modeled MLCC was calculated according to equation

$$C = \frac{\mathrm{Im}(\dot{Y})}{\omega}, \qquad (6)$$

where $\mathrm{Im}(\dot{Y})$ – imaginary part of admittance. The difference between experimental and calculated capacitances was less than 5%. Such difference can be explained by the complicated dependence of dielectric relative permittivity on temperature, electric field and voltage frequency.

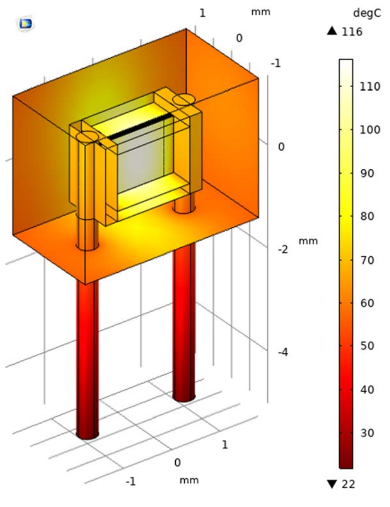

Fig. 4. Temperature distribution. Load parameters U = 50 V and f = 1 kHz.

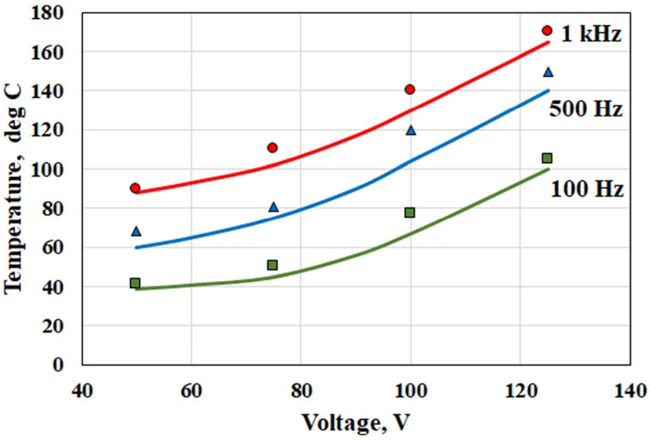

Fig. 5. Maximum temperature on capacitor's external boundary. Markers – experimental results, lines – calculation results.

Developed model of MLCC digital twin can be improved. Magnetic fields can be included in calculation using by software module «Magnetic Fields». Software module «Solid Mechanics» allows to calculate mechanical stress inside of capacitor due to heating and electrodynamic forces. However, adding other software modules in calculation model requires much more computing resources.

V. CONCLUSION

The digital twin (numerical model) of MLCC was developed. The digital twin is a convenient and effective tool for design of new capacitor types and operating analyze. The model of digital twin allows evaluating the electric and temperature fields inside the capacitor. The model takes into account nonlinear electric and thermal properties. The adequacy of designed model was experimentally verified.

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