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Application of Electro-Thermal Analogy for Complex Simulation of Hybrid Power Controllers

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Abstract – **Temperature plays a very important role in proper operation of microelectronic circuits. It determines exploitation parameters and – in the most cases – reliability of circuit or whole system. From this reason, taking into consideration the thermal problems is strongly recommended on the beginning of design process. The paper presents some aspects of describing of thermal model of the thick-film microcircuits with equivalent models (based on RC elements) as well as example of the complex analysis of hybrid power controller of household equipment in PSPICE program.**

Keywords – **temperature field, PSPICE simulation**

I. Introduction

Temperature plays a very important role in proper operation of microelectronic circuits. It determines exploitation parameters and – in the most cases – reliability of circuit or whole system [2]. From this reason, taking into consideration the thermal problems is strongly recommended on the beginning of design process.

The thick-film microcircuits are very complicated objects to their formal description from point of view of heat transfer. The complexity of heat exchange mechanism makes the mathematical analysis only approximation of the real-world conditions. In reality, only numerical calculations can solve the systems of differential equations with very complicated boundary and initial conditions.

Using the mathematical analogy of equations (in stationary and dynamic states) which describe the temperature field and electric potential field, it is possible to create the electrical equivalent circuit of thermal system which can be simulated in PSPICE program. The proposed method of temperature simulation using equivalent RC models is based on well – known Beuken theory and is much more easier and "intuitive" for designers of the electronic equipment. [1-7].

II. RC modelling procedure

Based on Fourier theory of heat conduction, Beuken in 1934 proved that using electrical model of the analyzed structure is possible to obtain the information about its temperature. In such idea (based on combined connections of the RC elements) voltage is the analogue of temperature, and resistance and capacitance are analogous of thermal resistance and capacitance, respectively.

The division of real-world circuit on differential elements in the modeling procedure is required. It is nearly the same to finite differences method.

The next step is concentration of thermal capacity in the node and thermal resistances between particular nodes. As results the resistors' network is created with terminated capacitors.

Thermal resistance is determined by thermal conductivity in the selected area of analyzed object and it can be expressed by formula:

$$R_{T\lambda}(\lambda(T)) = \frac{l}{\lambda(T) \cdot F} \tag{1}$$

where: $\lambda(T)$ is the material thermal conductivity dependent on temperature, l – material length and F means material area excited by heat flux.

For boundary elements in RC thermal model of the microcircuit the calculation of thermal resistance which characterized the heat exchange with environment is required. In general case it can be calculated from equation:

$$R_T(\alpha(T)) = \frac{1}{\alpha(T) \cdot F} \tag{2}$$

where: $\alpha(T)$ is the total coefficient of heat exchange with environment (by convection and radiation).

The value of α coefficient is very hard to determination because it is strongly dependent on many physical parameters. The most often it is determined from experimental measurements or calculated from criterion numbers (Nusselt and Rayleigh).

Thermal capacitance is determined by specific heat of the selected area of analyzed object as well as density of material. In the general case it can be calculated from expression:

$$C_T(T) = c_p(T) \cdot \rho \cdot V \tag{3}$$

where: c_p is specific heat, ρ – material density and V means volume.

Such defined elementary RC elements are the basis for creation RC network which represents analyzed thermal object. The main idea of the multilayer microcircuits modeling is presented in Fig. 1.

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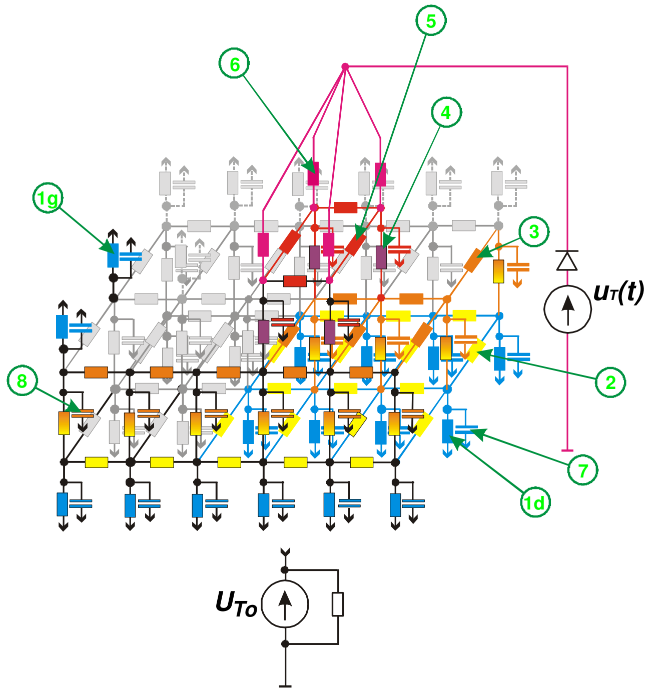

Fig. 1. RC model of multilayer structure: 1d and 1g - thermal resistances of heat exchange by lower and upper surface, respectively, 2,3 and 5 - thermal resistances of substrate and layers, respectively, 4 – thermal contact resistance (between layers), 6 – resistance which connects heat source with layer node, 7 – thermal capacitance of substrate, 8 – thermal capacitance of layer, UTo – voltage source which represents ambient temperature, uT(t) – voltage source which represents heat source.

The majority of physical parameters (important from the thermal point of view) of particular thick-film components are strongly dependent on temperature. For proper model creation the very good knowledge about such temperature relations is required.

For simulation of temperature field distribution using equivalent RC models the PSPICE program was applied. The non-linear thermal resistances and capacitances (with taking into consideration their dependence on temperature) were modeled in PSPICE program as special “subcircuits” – so-called controlled resistances and capacitances.

III. Example of Simulations

As example of complex electro-thermal simulation the hybrid power controller HR093 was chosen (see the picture in Fig.1). It is manufactured by HYBRES factory (Rzeszow, Poland) for controlling of power in household equipment (especially in vacuum cleaners).

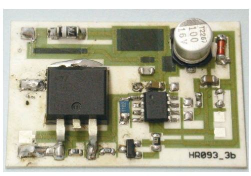

Fig. 2. Picture of controller.

The block and schematic diagrams (with topology) of the above-mentioned controller are presented in Fig. 3 and 4, respectively.

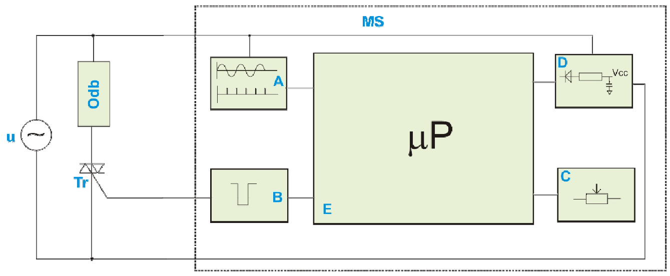

Fig. 3. Block diagram of power controller: A-zero detection module, B-pulse forming circuit, C-control of supplied power, D-supplier, E-microprocessor control unit, Tr-triac T1635, Odb-power receiver, u-voltage source.

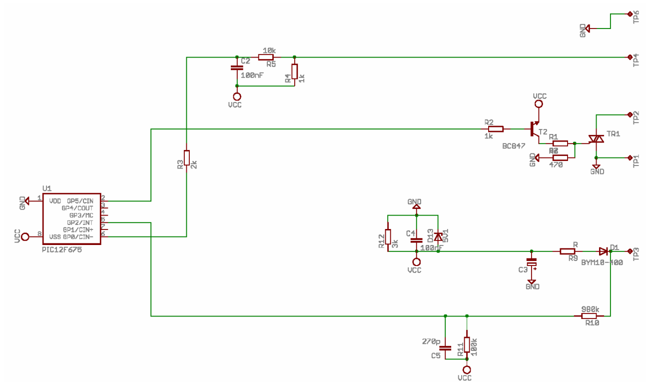

Fig. 4. Schematic diagram of power controller.

Such device was simulated in PSPICE program as typical electrical circuit, as RC model of thermal object (for temperature field determination) and again electrically simulated with taking into account the temperature changes in particular points of analyzed circuit.

A. *Electrical simulation*

Transient analysis was conducted for different power levels with taking into consideration the resistance and inductance of windings. The results of simulations are presented in Fig. 5. and 6.

Those results were basis for determination of average value of power for particular components of microcircuit (necessary to the thermal analysis – estimation of heat fluxes density).

B. *Thermal simulation*

The main heat sources in analyzed controller are supplying resistor R and triac Tr. The simulations of temperature distribution were made using EQ Term program. It allow to create RC elements network (on the basis of geometrical data and grid size) in the acceptable form for PSPICE program. After simulation it is possible to view the all temperature in each layer (in grid points) of microcircuit in analyzed time steps.

The heat fluxes density (as results of electrical simulation) were equal 6016 W/m^2 (for triac) and 5000 W/m^2 (for resistor). The results are shown in Fig. 7.

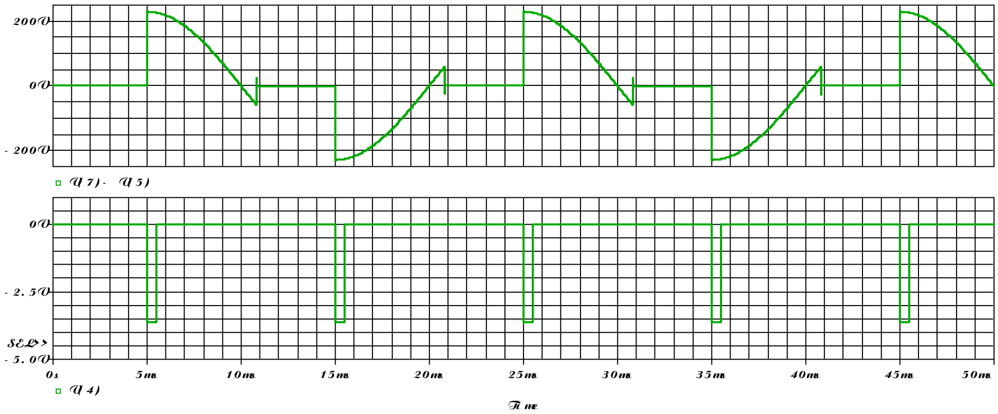

Fig. 5. Voltage courses on load (upper) and triac gate (lower) for average motor power.

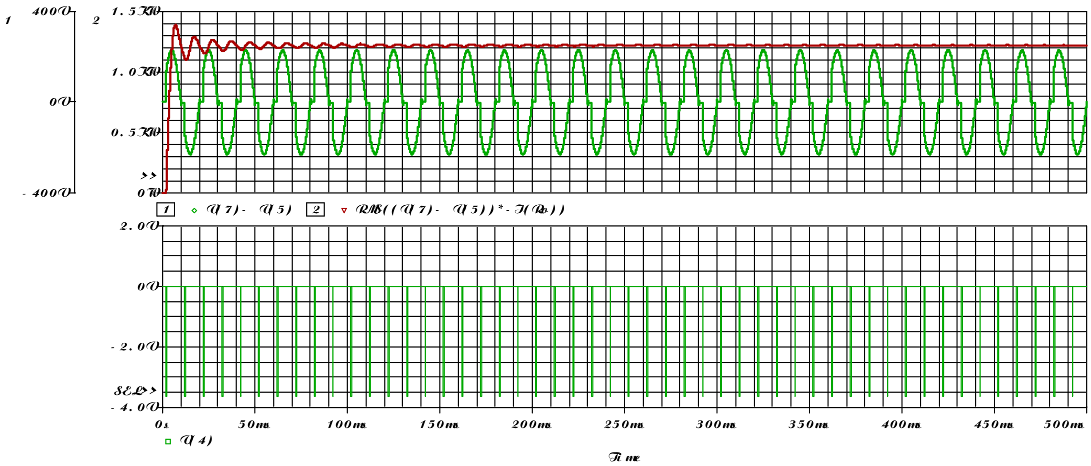

Fig. 6. Voltage courses and average power on load (upper) and triac gate (lower) for maximal motor power.

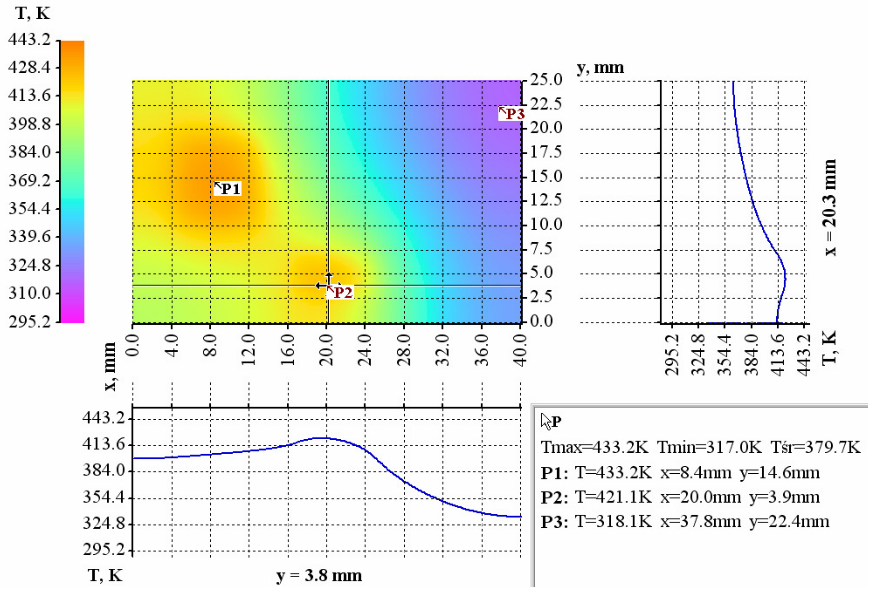

Fig. 7. Temperature field distribution in controller substrate for maximal power of motor.

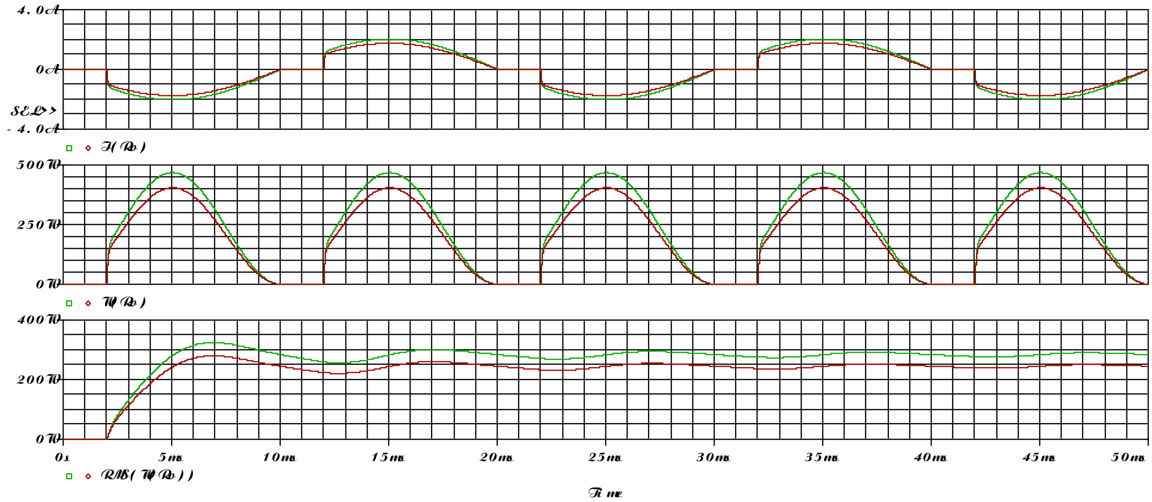

Fig. 8. . Results of transient analysis with (red color) and without (green color) taking into account the local values of temperature (courses on load): current (upper), pulse power (middle), average power (lower).

C. *Electrical simulation with temperature influences*

The newest versions of PSPICE program allow to introduce to the simulated circuit temperature gradient (by definition of different local temperature on each element important from the thermal point of view).

In the case of analyzed controller the local temperature was given for supplying resistor and triac only (values obtained from thermal simulations using equivalent RC network). The results of calculations (transient analysis) are presented in Fig.8.

IV. Experimental verification

The measurements were made using thermovision camera V–20ER005-25 (Vigo Warszawa). They are carried out for open system with natural convection and cooling by one area. The series commutator motor was used as load. Thermogram for maximal motor power is presented in Fig. 9.

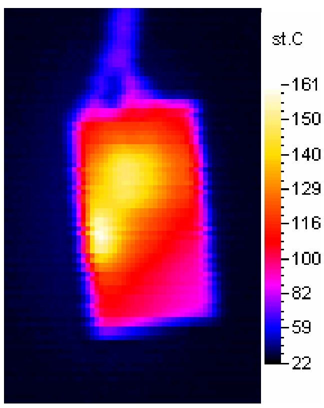

Fig. 9. Temperature distribution on controller substrate (maximal motor power).

V. Conclusions

The presented method of complex simulation using electro-thermal analogy (equivalent RC models based on Beuken theory) is very useful (and more easier) for designers of the electronic equipment. The big advantage of such method is possibility of its application not only for thick-film microcircuits. The main disadvantage is necessity of well knowing of the complete thermal characteristic of the analyzed object.

References

[1] Beuken D.L. *Wärmeverluste bei periodisch betriebenen Öfen*, Dissertation, 1936 Freiburg, Germany.

[2] Andonova A., Ph. Philippov, N. Atanasova, Methodology of Estimate Reliability of Highly Reliable Components by Monitoring Performance Degradation, *Proceedings of 24th ISSE,* May 5-9, Bulgaria, 2004, pp. 125-128.

[3] Błąd G., D. Klepacki , J. Potencki , Simulation of Temperature Distribution in Thick-Film Sensors, *Proceedings of 8th International Symposium For Design And Technology In Electronic Modules SIITME'2002*, Cluj-Napoca, September 19-22, 2002, pp.34-37.

[4] Błąd G., D. Klepacki , Modelowanie pól temperatury w grubowarstwo-wych strukturach sensorowych; *ELEKTRONIZACJA* No 7-8, 2002, pp. 39-42 (in Polish).

[5] Błąd G., Z. Hotra ., D. Klepacki., J. Potencki , Modelling of Temperature Field Distribution in Thick-Film Sensor Structures, *Proceedings of XXVI Conference of IMAPS Poland Chapter, Warszawa,* 25-27 September 2002, pp. 109-112.

[6] Potencki J., A. Pietrikova, Possibilities of Temperature Fields Shaping in Multilayer Thick-Film Heating Systems, *SPIE*, vol. 3730, 1999, pp. 130-138.

[7] Błąd G., D. Klepacki, J. Potencki, Nonlinear Discrete Elements in Electro-Thermal Model of Thick-Film Structure, *28th International Spring Seminar on Electronic Technology ISSE 2005*, Wiener Neustadt, Austria, May 18-22, pp.231-236, 2005.