ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2012. No. 7(123)
ELEKTRONIKA IR ELEKTROTECHNIKA

ELECTRICAL ENGINEERING
ELEKTROS INŽINERIJA

Investigation of Heat Transfer of Electronic System through Utilization of Novel Computation Algorithms

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crossref http://dx.doi.org/10.5755/j01.eee.123.7.2371

Introduction

Looking towards modern electronic development, it can be seen that tendencies are focused on efficiency and reliability. Simultaneously higher integration and minimization of electronic systems are more and more utilized almost in every industrial and commercial sphere. Together with these phenomenons the higher emphasis has to be putted on the thermal management of modern electronics. Manufacturers of semiconductor devices are targeting optimal thermal properties of their devices in the way of utilization of modern materials, technologies, or packaging processes. Thinking about complex electronic system, it is necessary to focus almost on proper design of thermal management in post-prototype stage. This is also due to fact that each consumer's electronic device has to fulfill special international electronic standards, mainly from the EMC and thermal point of view. The optimization process of heat transfer can be based on experimental verification of proposed system or a special computation technique, which will be able to determine the temperature distribution can be utilized. First technique (experimental) is mostly time consuming due to repeatable test after each modification of functional sample (geometry reassembly, utilization of different materials – PCB, devices etc.). Therefore targeting accurate and fast optimization process, the computation algorithm of heat distribution seems to be better solution. The only need is design of COMSOL simulation model, which is multiphysics software based on FEM analysis methodology [1–4].

In this paper we will present process of development of computation algorithm, which is designed in MATLAB software. Two possible approaches will be shown, whereby first will be based on resistance matrix computation (algorithm implemented into m-file), and second on COMSOL - Simulink interface.

Computation algorithms

Nowadays, simulation programs used for determination of heat transfer and temperature distribution use power dissipation of each component in electronic device as input value and outputs a component's temperature of each element in investigated system. If electronic system which is not well known in detail is being investigated (you do not know properties of utilized ICs, passive and active devices) the analysis of heat transfer and temperature distribution is acting as too lengthy. That means, if designer of simulation model is targeting close accordance to real temperature distribution of investigated system (real physical sample of model can be analyzed through thermovision measurements) whole process of simulation must be performed repeatedly. If simulated temperature corresponds with measured data (accepting defined tolerance), then the simulation model can be considered as acceptable. Utilization of mentioned methodology is too much time consuming and is not effective in cases, when fast solution is awaited. Only advantage of this methodology is in good representation of physical system and its inner components, because each time designer is operating with simulation model and physical properties which are related to it. Determination of heat transfer and temperature distribution of investigated system is from time point of view lasting from several tens of minutes to tens of hours what is based on number of degrees of freedom (DOFs). Also it is dependent on hardware configuration of computation machine (PC), whereby more complex model requires more powerful PC.

Computation algorithm based on resistance matrix of investigated system. The aim of proposed computation algorithm is determination of power dissipation of active components of investigated system, based on thermovision measurement of this system. For initial verification of proposed methodology we had select test simulation model (Fig. 1) which consist of printed circuit board (PCB) and six active dissipative components A-F (ICs). The geometry of model is designed in Comsol Multiphysics software and all necessary physical properties are also defined through utilization of predefined libraries of software.

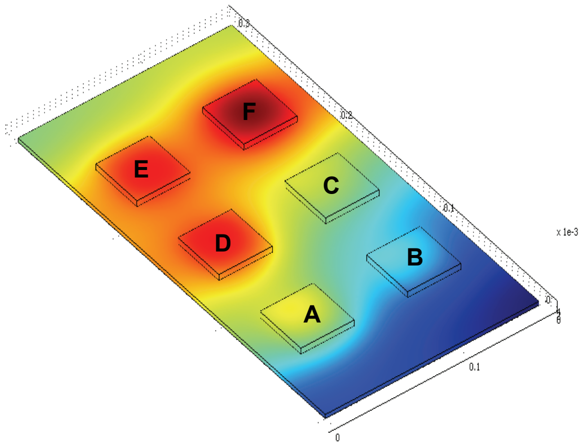

Fig. 1. Test simulation model (6-IC-PCB)

As was mentioned earlier two possible approaches of power dissipation identification and then thermal distribution of investigated system will be shown. Both can be utilized on the electronic system with various complexities. First methodology is based on identification of resistance matrix of investigated system. We assume that six components of testing model are heated independently by power losses $P_1 - P_6$. Then the matrix of power dissipation of 6 components on PCB is:

$$\begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \end{Bmatrix}, \quad (1)$$

where sum of this power dissipation is equal to total power loss of investigated system $P_1 + P_2 + P_3 + P_4 + P_5 + P_6 = P_{total}$.

The aim of the analysis is determination of temperature of each component and thus of total investigated system. Then the relationship of the investigated temperature is given by next formula:

$$\begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{Bmatrix} = \begin{Bmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\ R_{21} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\ R_{31} & R_{32} & R_{33} & R_{34} & R_{35} & R_{36} \\ R_{41} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\ R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66} \end{Bmatrix} \times \begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \end{Bmatrix}, \quad (2)$$

where R_{ij}, $i \neq j$ are thermal resistance values between reference points of components i and j, and R_{ii} is thermal resistance values between reference point of selected unity dissipative component and ambient (Fig. 2).

Now we will describe process of determination of values of resistance matrix (R_{ij}, and R_{ii}) what will be based on "*unity power criterion*". In Comsol simulation model we set power dissipation of first component – A to $P_1 = 1$ W, and together with this setting all other components will have zero power dissipation ($P_2 = P_3 = P_4 = P_5 = P_6 = 0$).

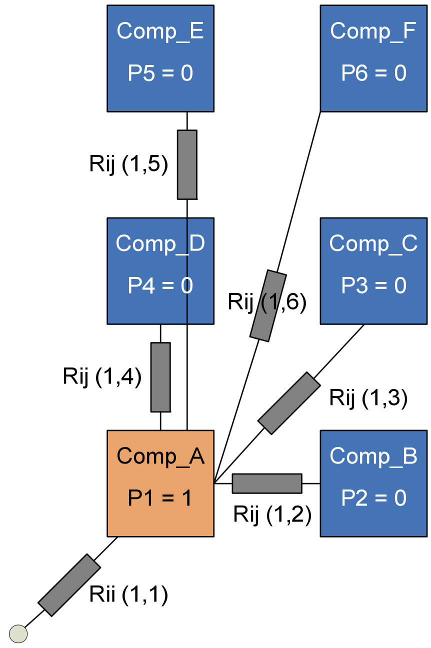

Fig. 2. Unity power criterion (A component is heated)

For calculation of each resistance, next equations have to be used:

$$R_{ii} = \left(\frac{T_{is} - T_a}{P_i} \right) \text{ for } P_k = 0, \text{ where } k \neq 1, \quad (3)$$

$$R_{ji} = \left(\frac{T_{js} - T_a}{P_i} \right) \text{ for } P_k = 0, \text{ where } k \neq 1, \quad (4)$$

where T_{is}, T_{js} are temperatures in the reference points of i-th and j-th component. T_a is ambient temperature.

The same process is then valid for computation of next set of resistance values which are related to setting where $P_2 = 1$ W, and all other components will have zero power dissipation. After computation of resistance matrix is done, the designed computation algorithm will start to determine power losses of each component:

$$\begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{Bmatrix}_m - \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{Bmatrix}_s = \begin{Bmatrix} \Delta T_1 \\ \Delta T_2 \\ \Delta T_3 \\ \Delta T_4 \\ \Delta T_5 \\ \Delta T_6 \end{Bmatrix}. \quad (5)$$

Optimization task of computation algorithm is to find solution which will be characterized with minimal difference between measured (T_m) and simulated temperatures (T_s), formula (5). That means that form the computation speed point of view it is necessary to achieve as lowest number of iteration as possible, whereby convergence of solution has to be limited to acceptable level. For determination of power dissipation in each iteration next formula is valid:

$$\begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \end{Bmatrix}_{i+1} = \begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \end{Bmatrix}_{i} + \alpha\nabla\left(\begin{bmatrix} R_{11} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\ R_{21} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\ R_{31} & R_{32} & R_{33} & R_{34} & R_{35} & R_{36} \\ R_{41} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\ R_{51} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66} \end{bmatrix} \times \begin{Bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \end{Bmatrix}_{i} \right), \quad (6)$$

where α is parameter of gradient search and i is step of iteration.

This methodology was implemented into MATLAB software, whereby we have utilized m-file function for code generation. After algorithm finishes computation of power dissipation, the determined values of each component is defined in COMSOL model. In this way we are checking, what is the amount of temperature difference, when physical properties of simulation model are also considered. Advantage of this approach is very fast computation time (several minutes) but on the other side lower accuracy. Higher differences (between measurement and simulation) are caused due to fact that algorithm is not operating with physical conditions but just with resistance matrix.

Computation algorithm based on COMSOL – simulink interface. COMSOL – simulink methodology is based on development of COMSOL simulation model of investigated system and then on its export as simulink library. As input variables, the power dissipation of selected active (lossy) components are defined. As output variables, the temperatures of active components are monitored. The advantage of this approach is that proposed algorithm is always counting with equations of physical properties which are defined in COMSOL simulation model. On the other side, computation time is dependent on factors like: model complexity (number of mesh elements), and solver settings. The time of power dissipation determination and consequently of heat distribution is much higher compared to previous methodology (m-file), but the accuracy should be due to continuous operation with simulation-physical model very tight compared to real measurement. Next figure (Fig. 3) is showing inner regulation loop of power dissipation for one active component for COMSOL – simulink approach.

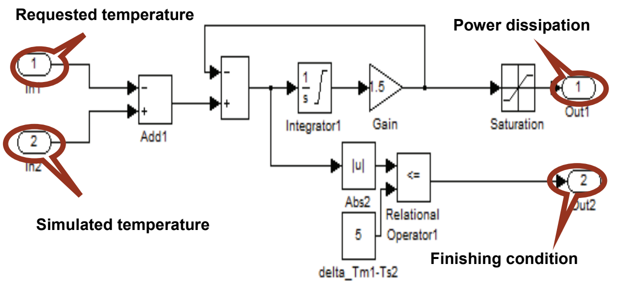

Fig. 3. Inner regulation loop of COMSOL – simulink computational algorithm

The second proposal of computational algorithm is comparing simulated and measured temperature. Then the variable which is influencing their difference is power dissipation which is increased or decreased (based on input temperature condition) during every iteration by defined dissipation step. The algorithm finishes computing when all of inner regulation loops fulfill condition of temperature difference which should be lower than 5 ºC. In the next chapter we will describe simulation results and their comparisons between both proposed computational algorithms.

Implementation

Matrix – resistance model (m-file). As was previously mentioned we have utilized MATLAB m-file for implementation of our proposed algorithm. First we have defined variables and constants in code. The aim of algorithm is to fulfill final condition. It is defined that each component has to have predefined temperature difference which should be lower than 5 Celsius degrees. After algorithm finishes computation of power dissipation, the determined values of each component is defined in COMSOL model. In this way we are checking, what is the amount of temperature difference, when physical properties of simulation model are also considered.

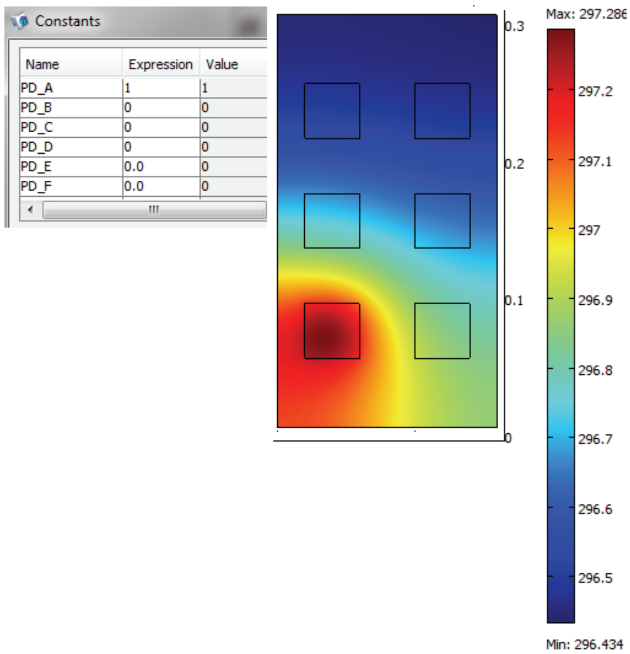

Fig. 4. Simulation results from COMSOL model (situation: P_1 = 1W, P_2 = 0W, P_3 = 0W, P_4 = 0W, P_5 = 0W, P_6 = 0W)

The validation of m-file algorithm robustness and accuracy was done as follows. First we put power dissipations of components into COMSOL model (P_1 = 1 and other power dissipations are equal to zero). Then we had subtracted temperature values of components (Fig. 4) from their reference points (middle of components). These temperature have been then defined as measured /requested temperature into m-file computation algorithm. After that computation started and determination of power dissipation was received (Fig. 5).

It can be seen that the results of power dissipation calculation from m-file is in very close accordance to COMSOL defined values. Thus based on this result, it can be said that matrix - resistance model shows acceptable level of accuracy because temperature difference (between measured and simulated temperature) is lower than 1 Celsius degree (see also Fig. 5 T – measured temperature and Tsa – simulated temperature, dT – their difference).

P	[0.9720;0.0070;0.0260;0.0090;-0.0050;-0.0080]
R	<6x6 double>
T	[297.2741;296.8519;296.6566;296.7408;296.5039;296.4859]
Tmc	[24.1241;23.7019;23.5066;23.5908;23.3539;23.3359]
Ts	[4.1145;3.7085;3.5226;3.5973;3.3566;3.3394]
Tsa	[297.2645;296.8585;296.6726;296.7473;296.5066;296.4894]
dT	[0.0096;-0.0066;-0.0159;-0.0065;-0.0026;-0.0034]
i	1599
max	0.0100
stepP	1.0000e-03
x	[1,1,1,1,1,1]
y	1

Fig. 5. Results carried out by m-file computation algorithm

In next subchapter the implementation of computation into COMSOL - simulink model will be described.

COMSOL – simulink interface. The procedure of computation using COMSOL - simulink interface is similar to previous one. First we define measured temperatures. These were - Tm_A = 306 K, Tm_B = 305.5, Tm_C = 304, Tm_D = 304, Tm_E = 303, Tm_F = 302.5, where Tm - is measured temperature of selected component in reference point in Kelvins.

Fig. 6 is showing results from COMSOL - simulink simulation. Highlighted are values of power dissipation (left side) and values of simulated temperatures (right side from top to bottom - Component A to Component F). When we compared these values with requested temperature values it can be seen again that temperature difference at each reference point is lower than 1 Celsius degree. Thus based on these results we can say that both algorithms are showing very good performance. The advantage or disadvantage of each compared themselves will be better validated on more complex systems (for example small brick DC-DC converter). The initial model of such complex system is shown on next figure. These model has 29 active - dissipative components.

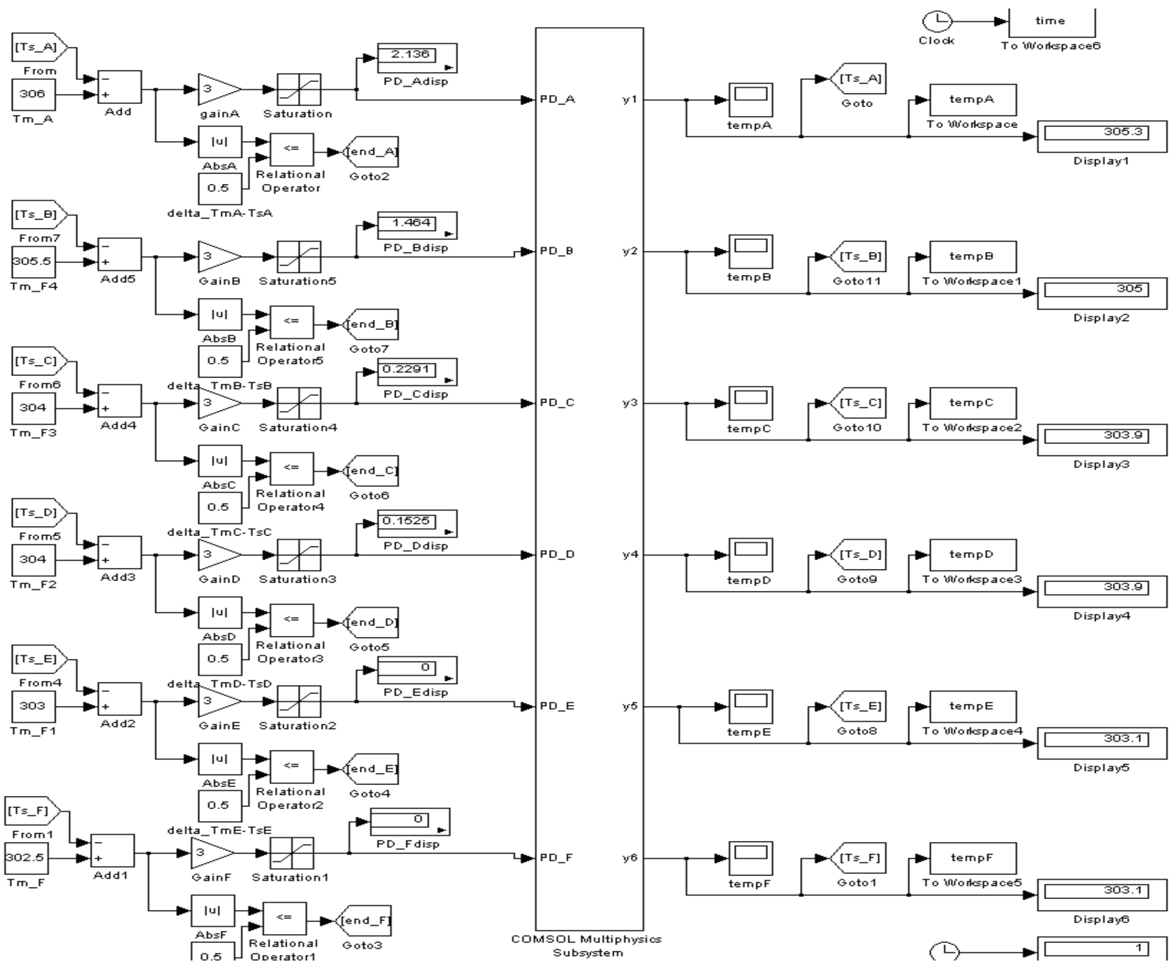

Fig. 6. Results from COMSOL - simulink interface

Trial determination of requested temperatures and selection of most dissipative components were done through termovision measurements. After that, implementation both for m-file and COMSOL - simulink algorithms were made. Next figure is showing comparisons between both computation algorithms. The y-axis of graphs shows relative error in [%] and x - axis shows number of dissipative component.

The computation of relative error was based according to next formula

$$rel.error = \frac{T_{measured} - T_{simulated}}{T_{measured}}, [\%]. \qquad (7)$$

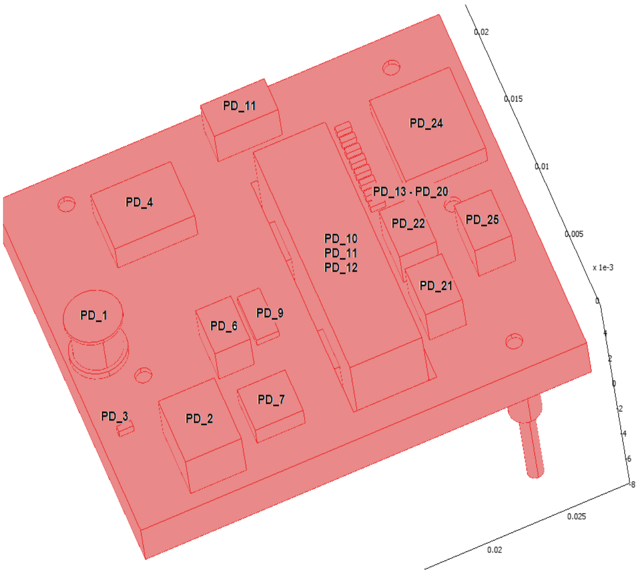

Fig. 7. DC-DC brick converter 15 W showing selected dissipative (active) components

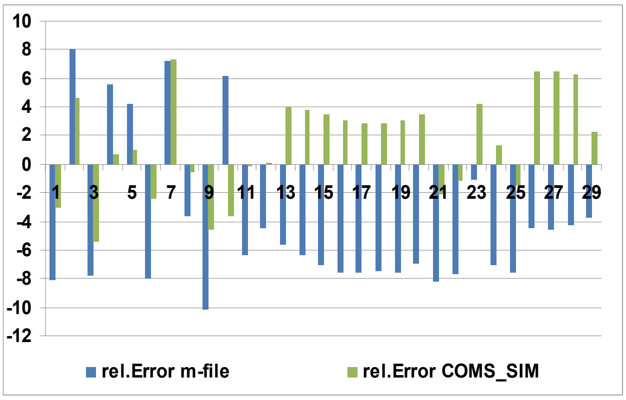

Fig. 8. Comparisons of relative errors of COMSOL - simulink and m-file algorithm for DC-DC brick converter

Conclusions

It can be seen that COMSOL - simulink based computation algorithms shows lower temperature difference and is acting as more accurate. On the other side m-file algorithm is much faster, but requires detailed identification of resistance matrix. During various experiments we have found out that resistance matrix is very sensitive on value of power dissipation and is in nonlinear dependency with power. Therefore in future steps the nonlinearity of more complex systems will be investigated together with development of proper selection methodology of most dissipative components which are influencing temperature distribution by the highest effect.

Acknowledgements

The authors wish to thank to Slovak grant agency APVV for project no. LPP - 0366 - 09, and also to Slovak grant agency VEGA for project no. 1/0943/11. Our thank also belongs to R&D operational program Centre of excellence of power electronics systems and materials for their components No. ITMS 2622012003.

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Received 2012 01 03
Accepted after revision 2012 02 23

P. Spanik, J. Cuntala, M. Frivaldsky, P. Drgona. Investigation of Heat Transfer of Electronic System through Utilization of Novel Computation Algorithms // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 7(123). – P. 31–36.

This paper deals with the development of methodology suited for design of computation algorithm which is able to determine power losses of electronic systems based on measured temperature distribution - thermovision measurement. The scope of application would be focused mostly on consumer electronics, where temperature distribution and its maximal value on the surface of investigated system is critical for end consumer. Through application of the proposed algorithm it will be more simple to optimize thermal management of investigated system. Even though, the algorithm shall also be able to used for industrial applications like power supply systems - DC/DC, AC/DC converters. In this paper, first the current tendencies in the field of power loss estimation will be described. Next, the proposed methodology together with proposal of testing model is described. Finally application of two approaches of computational algorithms on proposed testing system will be done together with evaluation of results and their comparisons with results from precise simulation tools (COMSOL 3.5a) of thermal processes will also be provided. Ill. 8, bibl. 4 (in English; abstracts in English and Lithuanian).

P. Spanik, J. Cuntala, M. Frivaldsky, P. Drgona. Elektroninių sistemų šilumos perdavimo tyrimas naudojant naujus skaičiavimo algoritmus // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 7(123). – P. 31–36.

Nagrinėjama, kaip kuriama metodologija, tinkanti skaičiavimo algoritmui, kuris leistų nustatyti elektroninės sistemos šiluminius nuostolius atlikus sistemos temperatūrinio pasiskirstymo matavimą. Tyrimų objektas – elektronikos įtaisai, kurių temperatūros pasiskirstymas paviršiuje ir maksimali vertė yra labai svarbūs vartotojui. Įdiegus pasiūlytąjį algoritmą, būtų galima paprasčiau optimizuoti tiriamosios sistemos temperatūros valdymą. Algoritmas galėtų būti naudojamas pramoniniams tinklams – DC/DC, AC/DC keitikliuose. Pradžioje apžvelgiamos dabartinės galios nuostolių vertinimo tendencijos, paskui aprašoma siūloma metodologija bei testinis modelis. Pabaigoje pateikiamas skaičiavimo algoritmų siūlomai testinei sistemai rezultatų palyginimas su tikslios modeliavimo programos (COMSOL 3.5a) rezultatais. Il. 8, bibl. 4 (anglų kalba; santraukos anglų ir lietuvių k.).