**Panagiotis CHATZIPANAGIOTOU** [1], Maria STRĄKOWSKA [2], Gilbert DE MEY [3],
Vasilis CHATZIATHANASIOU [1], Bogusław WIĘCEK [2], Michał KOPEĆ [2]
[1] ARISTOTLE UNIVERSITY OF THESSALONIKI, DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING, 54 124 Thessaloniki, Greece
[2] LODZ UNIVERSITY OF TECHNOLOGY, INSTITUTE OF ELECTRONICS, 211/215 Wólczańska St., 90 924 Lodz, Poland
[3] GENT UNIVERSITY, DEPARTMENT OF ELECTRONICS AND INFORMATION SYSTEMS, Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium

# A new software tool for transient thermal analysis based on fast IR camera temperature measurement

**Abstract**

A new software tool for transient thermal analysis based on thermographic measurement of temperature is presented. In the proposed approach, temperature change after applying or removing power can be measured by a thermal camera or any contact temperature sensor. The software calculates thermal impedance in frequency domain and represents it in the form of the Nyquist plot. In addition, thermal time constant spectrum and cumulative structure function are evaluated. The software was developed in Matlab environment using in-built procedures for transfer function estimation. For the validation of the proposed tool, the results are compared with ones obtained using commercially available software.

**Keywords**: transient thermal analysis, IR thermography, Nyquist plot, time constant, cumulative structure function.

## 1. Introduction

The transient thermal process modelling is now of the growing interest due to the developments of new methods and measurement tools, especially IR contactless thermography [1, 2]. Measurement of temperature evolution in time provides enough information on the object's structure and its thermal parameters. Very popular modelling in time domain using FEM, in some cases, can be replaced by the modelling in frequency domain. It allows the simplification of modelling and significant reduction of the required computational power. Sometimes the models have analytical solutions [2, 3].

The very useful tool for transient thermal processes analysis is based on thermal impedance $Z_{th}(\mathrm{j}\omega)$ and time-constant spectrum $\varphi(\tau)$ [3, 4]. There are different approaches to calculate $Z_{th}(\mathrm{j}\omega)$ and $\varphi(\tau)$. Many of the research is now referring to so-called Network Identification by Deconvolution (NID) which is one among the many other known methodologies [1, 2, 4 - 7]. Thermal impedance in frequency domain is simple calculated by using the Fourier transforms of the temperature response and the power excitation. The time constant spectrum can be calculated using different methods e.g. Gardner [5] and Pade-Laplace [6] transforms or Prony algorithm for the transfer function estimation [4].

In this paper, a simple tool based in Matlab environment is presented which is mainly dedicated to transient thermography measurements. It calculates Nyquist plot of thermal impedance in frequency domain, thermal time constant spectrum using Peeling method [7] and cumulative structure function using Foster to Cauer network transformation [8].

## 2. Theoretical background

Extensive research has been conducted in the area of thermal modelling, simulation and experimental analysis of electronic and electric systems [4-6]. Elaborated thermal characterization methods have been used for the study of thermal problems in microelectronics [1, 2] as well as in high voltage overhead and underground power lines [9, 10].

Physical quantities, such as thermal transient response $T$ and dissipated power $P$, are processed to have mathematical representations appropriate for the thermal characterization, such as thermal impedance and time-constant distribution.

Thermal impedance is a quantity that can help to characterize the dynamic behaviour of a system. The thermal impedance versus frequency can be defined by the temperature response $T(t)$ to a power step function $P(t)$ presented using Laplace transforms:

$$Z_{th}(s) = \frac{T(s)}{P(s)}, \frac{\mathrm{K}}{\mathrm{W}} \tag{1}$$

If the power has the step function form, the thermal impedance $Z_{th}$ in frequency domain can be obtained by evaluating the following integral

$$Z_{th}(\mathrm{j}\omega) = \frac{\mathrm{j}\omega}{P}\int_0^\infty T(t)e^{-\mathrm{j}\omega t}\mathrm{d}t,\ \frac{\mathrm{K}}{\mathrm{W}} \tag{2}$$

where $P$ is the power of step function excitation, $\omega$ is the angular frequency, rad/s, and $\mathrm{j}=\sqrt{-1}$ the imaginary unit.

From the thermal impedance function (2) one can determine the time constant distribution $\varphi(\tau)$. In another approach, time constant distribution can be derived from temperature curves that contain sections of different slopes corresponding to the different time constants [12]. Szekely [3, 13] proposed an advanced thermal analysis and characterization methodology based on NID. The final result of this method is the continuous time spectrum whose integral is the thermal resistance $R_{th}$ in DC state.

Büttner [14] proposed an algorithm for gradual identification and elimination using the function (3) containing the exponential terms. This approximation method, known as the Peeling method, is based on the recursive elimination of dominant time constants $\tau_i$.

$$Z_{th}(t) = \sum_{i=1}^{n} R_i \cdot \left(1 - e^{-\frac{t}{\tau_i}}\right),\ \frac{\mathrm{K}}{\mathrm{W}} \tag{3}$$

The sum of identified thermal resistances $R_i$ of the corresponding Foster network equals the DC value of the measured transient thermal impedance:

$$Z_{th}(\infty) = \sum_{i=1}^{n} R_i \tag{4}$$

It has been proved [14] that the function

$$F_1(t) = Z_{th}(\infty) - Z_{th}(t) \tag{5}$$

has an asymptote for $t \to +\infty$

$$a_1(t) = -\frac{t}{\tau_1} + \ln(R_1) \tag{6}$$

Consequently, by determining the asymptote, the first parameter pair ($R_1$ and $\tau_1$) is also calculated. Eliminating the influence of the calculated time constant it is possible to obtain

$$F_2(t) = Z_{th}(\infty) - Z_{th}(t) - R_1 \cdot \left(1 - e^{-\frac{t}{\tau_1}}\right) \tag{7}$$

whose asymptote for $t \to +\infty$ is

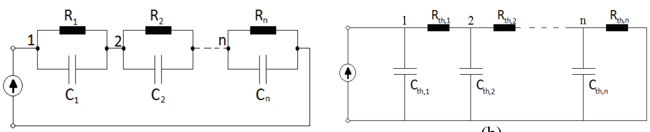
$$a_2(t) = -\frac{t}{\tau_2} + \ln(R_2) \tag{8}$$

All other time constants are evaluated by the gradual identifying and eliminating. The main difficulty of this procedure concerns a correct numerical evaluation of the asymptotes and the right values of $R_i$ selection for thermal time constant identification [15].

During the development of this tool, various software procedures for automatic estimation of parameters values of thermal models have been examined [7, 11, 16].

The distribution of thermal time constants corresponds directly to the Foster network representing the analysed heat sink, Fig. 1a. Although the electrical input impedance of the Foster network correctly represents the thermal impedance $Z_{th}(j\omega)$, this representation cannot model the heat spreading inside the structure. The reason is that the node-to-node capacitors have no physical meaning in the thermal context [2].

After applying the Foster to Cauer transformation, the Cauer network can be derived, as shown in Fig. 1b. This cascade network is physically acceptable to carry out further interpretation of a thermal system. If the heat flow in the structure under investigation is quasi one-dimensional, then the different RC sections of the resulting Cauer network will correspond well to the different parts of the physical structure.



(a) (b)

Fig. 1. Foster (a) and Cauer (b) networks of a thermal system

As heat spreads from the heat source through an object along this path, it penetrates consecutive resistive segments, until it finally reaches the ambient. For the Cauer network in Fig. 1 there is a stepwise increase of the cumulative thermal resistance $R_\Sigma$ each time a new node is reached. When ambient is reached it applies $R_\Sigma = Z_{th}(\infty)$. Similarly, one can define the cumulative thermal capacitance $C_\Sigma$.

## 3. Program for transient thermal analysis

In this research, a new software package *IRimp* has been developed in Matlab environment. This software is for analyzing transient thermal data obtained by thermography or any contact temperature sensor measurements, and it consists of the following processing parts.

1. The thermal image sequence wizard to import temperature and power from the camera and/or other measurement systems (Fig. 2a)
2. Transient response package to visualize the temperature and power vs. time (Fig. 2b)
3. Thermal time constant package (Figs. 3)
4. Cumulative structure function estimation package (Fig. 4a) and
5. Thermal impedance calculation package (Fig. 4b).

Using the main window (Fig. 2a), user prepares the temperature and the power data for further analysis. In the input wizard, transient thermal image sequences (videos) from IR thermal camera or any temperature sensor are loaded and are converted to the processable form. Then, the average temperature is calculated by a user-specified rectangle region of interest.

In the transient time response window (Fig. 2b), the input temperature curve is plotted. The x-axis is either of linear or logarithmic time scale. The y-axis represents the relative temperature change, starting from zero (ambient temperature).

Thermal time constant estimation window consists of three subforms. The initial window presents how the thermal time constants are estimated using gradual identifying and eliminating algorithm (Fig. 3a). At this stage, the temperature measurement normalized by the applied power is processed. User can smooth the input data applying the Savitzky-Golay filtering method [17]. This digital filter is based on the moving average technique. It increases the signal-to-noise ratio without significant distortion of the signal. Values of the filter order and the frame length are pre-determined by the user. The polynomial order must be less than the frame length and in turn, the frame length must be odd.

Hence, the thermal data are evaluated in order to get the Foster network. Then, the thermal resistances and the time constants can be identified after the iterative procedure. Fig. 3a presents the resulting plots for an experimental case of a steel conductor. Dash-dot line is the thermal transient response in time $Z_{th}(t)$ (eqn. 3), dashed line is the function $F_1(t)$ as the result of $Z_{th}(\infty)$ - $Z_{th}(t)$ (eqn. 5), dotted line is $\ln F_1(t)$ vs. time and solid line is the asymptote – tangent line in a chosen point. This point is defined by minimising the difference between the asymptote and function $\ln F_1(t)$ for a selected time period using the least square method.

The calculated pairs of thermal resistances and time constants are plotted in the form of graph as shown in Fig. 3b. The x-axis is time in the logarithmic scale, while the y-axis is the Foster thermal resistance in K/W.

Fig. 4a shows the cumulative structure function. The x-axis and y-axis represent the cumulative Cauer thermal resistances and heat capacitances, starting from the heat source, respectively. This curve can be regarded as a visual representation of the heat flow path. Substantial information about the physical structure can be revealed from the cumulative structure function. Logarithmic scale of the vertical axis is used in order to present the large range of capacitance values.

Thermal impedance calculation window (Fig. 4b) contains the Nyquist plot graphic representation. The complex locus plot demonstrates the thermal impedance in the frequency domain, on the complex plane – the imaginary versus the real part of $Z_{th}$ is plotted using the angular frequency $\omega$ as parameter. This curve exhibits some interesting and powerful properties of the investigated object.

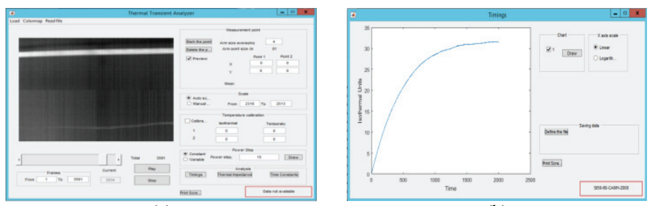

(a) (b)

Fig. 2. a) The main window with a thermal image from a long sequence, b) the corresponding thermal step response

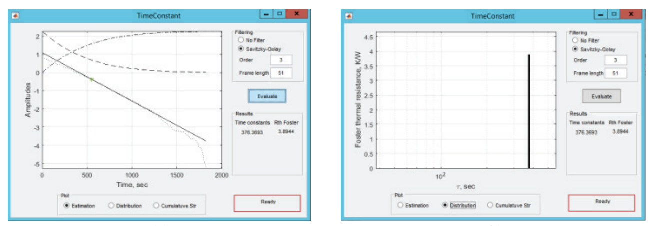

(a) (b)

Fig. 3. Thermal time constant estimation, a) intermediate result for asymptote calculation, b) – final result

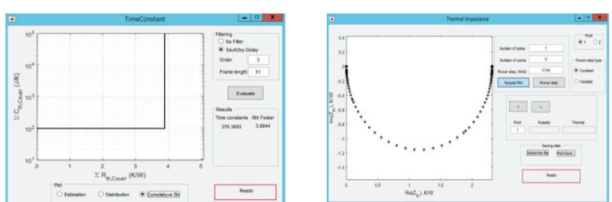

(a) (b)

Fig. 4. a) Window of cumulative structure function, b) thermal impedance

## 4. Exemplary results – comparison of two approaches

For the validation of the developed transient thermal analysis tool *IRimp* two cases are examined: a) a simulated Foster network and b) an experimental temperature measurement of an overhead steel conductor.

For the purpose of this study, a 4-stage Foster network was considered (Fig. 5). From a known electro-thermal Foster network, the corresponding temperature response can be extracted. The thermal resistance $R_i$ of each stage was equal to 10 K/W while the corresponding time constants $\tau_i$ were 1, 40, 100 and 800 seconds. Dissipating the power step $P(t)$ of 1 W the thermal impedance $Z_{th}(t)$ is identical to the temperature response $T(t)$. Hereupon, the temperature function was sampled uniformly per 0.1 s.

Processing the imported Foster temperature curve with the proposed system, the Nyquist plot of the thermal impedance, time constant distribution and the cumulative structure function were obtained. Then, the results were compared with the ones theoretically assumed. As it can be seen in the Fig. 6, there are negligible differences between the two Nyquist plots. Concerning the time constants, the difference between the calculated by the proposed method and the equivalent theoretical ones increases as the time value of the time constant decreases (Fig. 7). Fig. 8 presents the calculated and the theoretical cumulative structure functions.

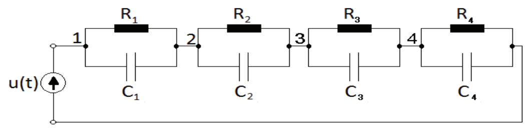



Fig. 5. 4-stage Foster network

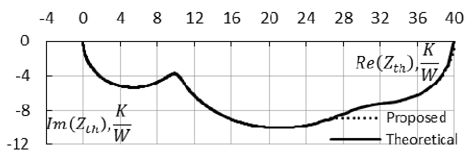



Fig. 6. Nyquist plots of Foster network

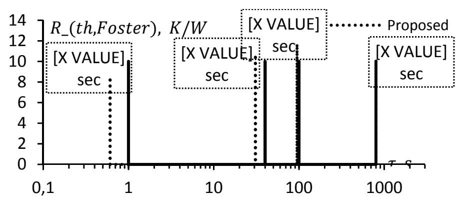



Fig. 7. Time constants of Foster network

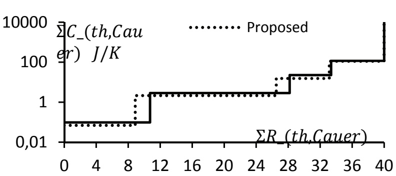



Fig. 8. Cumulative structure plots of Foster network

A comparison between the proposed analysis tool and the results provided by the commercially available NID software [18] was also made. For this reason. An experiment with heating a conductor was performed. A steel conductor (diameter $D$=8 mm and length $l$ =2.90 m) was fed with a constant DC electrical current ($I$=50 A). The temperature curve of the conductor was measured using an IR camera. The thermal steady state condition was achieved after a few tens of minutes. Meanwhile, the ambient conditions were maintained constant. During the experiment, surface temperature of the conductor was measured every 1 second directly by an infrared camera Cedip Titanium 560M with error less than ±0.5 K.

After recording video using the thermal camera by the proposed tool and selecting the measurement area, the temperature heating curve was generated. Consequently, the Nyquist plot of the thermal impedance, the time constant and the cumulative structure function were calculated. Importing and evaluating the same heating curve in the NID software, the corresponding functions were also obtained.

In Figs 9-11 the results are compared. As it can be observed, there is a minor difference between the results obtained by the proposed method and the corresponding evaluation performed by using standardized measurements. This difference of time constant and thermal capacity does not exceed the level of 14%.

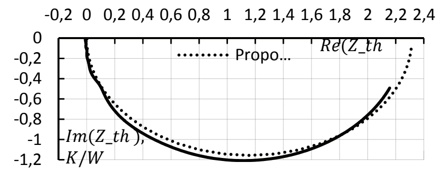



Fig. 9. Nyquist plots of experimental data

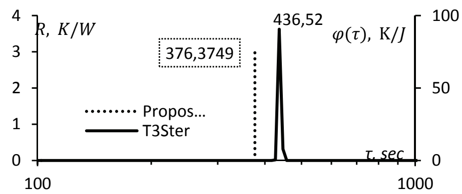



Fig. 10. Time constant distributions of experimental data

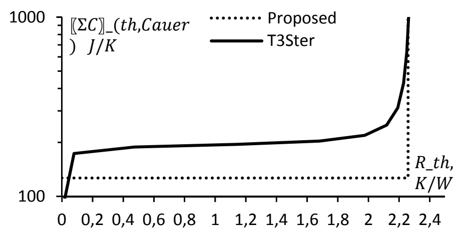



Fig. 11. Cumulative structure functions of experimental data

## 5. Conclusions

A new tool *IRimp* for transient thermal analysis based on fast thermal camera temperature measurement has been presented. Input data in this evaluation tool is temperature and power curves vs. time. The results concern Nyquist plot, time constant distribution and cumulative structure function.

Experimental temperature measurements and theoretical thermal networks were used to testify the validity of the performed evaluations. Comparison between the obtained data and the corresponding results calculate by the commercial T3Ster software has been also performed. Authors have to emphasize that the presented software can still be improved by using more advanced methods of signal processing and transfer function identification. It means that this research will continue.

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**Panagiotis CHATZIPANAGIOTOU, eng.**

Eng. Panagiotis Chatzipanagiotou received the Diploma degree in Electrical Engineering from the Aristotle University of Thessaloniki, Greece, in 2012, where he is pursuing the PhD degree in electrical engineering since February 2013. His research interests lie in the fields of thermal characterizations of power lines and cables.

*e-mail: chatzipa@auth.gr*

**Maria STRĄKOWSKA, PhD**

Maria Strąkowska was born in 1986. In 2010 she graduated of Faculty of Electrical, Electronic, Computer and Control Engineering and started her PhD study. In Medical Electronics Division she does her research on heat transfer in human tissue. Her field of interest is thermographic image processing, thermovision measurement, and computer modelling of heat transfer phenomena in medicine and electronic.

*e-mail: strakowska.m@gmail.com*

**Prof. Gilbert De MEY**

Gilbert De Mey was graduated at University of Ghent, where he is now a professor. He conducts research on thermal problems in electronic systems. The main area of the research regards problems of heat exchange in electronic components and systems. It includes theoretical modelling and studies on heat transfer by convection and radiation.

*e-mail: gilbert.demey@ugent.be*

**Prof. Vasilis CHATZIATHANASIOU**

Vasilis Chatziathanasiou was graduated at Electrical and Computer Engineering Faculty in Aristotle University of Thessalonica in Greece. He is now assistant professor there. His interests are in coupled electrothermal problems in power transmission systems.

*e-mail: hatziath@eng.auth.gr*

**Prof. Bogusław WIĘCEK**

Bogusław Więcek specializes in the field of thermal imaging and computer modeling of complex heat transfer phenomena in electronics. He is a member of Scientific Committees for Quantitative Infrared Thermography, International Thermology, Thermal Engineering and Thermometry and Mixed Design of Integrated Circuits and Systems. He is organizing the conference "Thermography and Thermometry in the Infrared".

*e-mail: bogusław.wiecek@p.lodz.pl*

**Michał KOPEĆ, MSc**

Michał Kopeć graduated from the Faculty of Electrical, Electronic, Computer and Control Engineering (2014), in Electronics and Telecommunications. Currently he is a PhD student at the Electronic Circuits and Thermography Department of Lodz University of Technology. He is author or co-author of 8 papers. His areas of research are non-destructive testing using thermography, heat transfer problems and widely defined electronics.

*e-mail: michal.kopec@dokt.p.lodz.pl*