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A multistage equivalent circuit for pyroelectric transducer modelling

I. Klyuchnyk, A. Bondarenko, I. Kliuchnyk, O. Degtiarov, P. Galkin

Kharkiv National University of Radio Electronics, Nauky Ave., 14, 61166, Kharkiv, Ukraine
ihor.kliuchnyk@nure.ua; pyrodetector@gmail.com; oleksandr.degtiarov@nure.ua

Abstract

The paper addresses the application of equivalent circuits to describe pyroelectric transducers (PETs) and measuring modules based on them. The scope and areas of use of equivalent circuit models are analyzed, their suitability for theoretical study, performance prediction, and parameter identification of commercial pyroelectric detectors is demonstrated. Special attention is paid to the requirements imposed on equivalent circuits used as the basis for PET models implemented in electrical circuit simulators. Modified equivalent circuits that meet these requirements are proposed. Their dimensional consistency is verified, and the adequacy of the models for determining the main characteristics of pyroelectric transducers is substantiated. A multistage equivalent circuit in the form of an active band-pass filter is proposed, which can be implemented as a standard library component in circuit simulation software. The model is based on the application of the operational method to the main stages of energy conversion inherent in pyroelectric detectors. The equivalent circuit consists of four functional blocks based on ideal operational amplifiers and ensures sufficient simulation accuracy. It enables modelling of specific commercial pyroelectric transducers in the form of equivalent electrical schematic diagrams using standard simulator components. It is shown that the minimum set of parameters required for adequate modelling includes the thermal and electrical time constants, as well as the sensitivity of the pyroelectric transducer. Integration of the proposed model into standard simulation environments expands the possibilities for analysing time-domain and frequency-domain characteristics of measuring modules that include PETs.

Keywords: pyroelectric transducer; measuring module; transfer function; equivalent circuit diagram; simulators of electric circuits; modelling; prediction of characteristics.

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Introduction

Pyroelectric transducers are thermal sensors, but they respond exclusively to temperature changes, not to its stable level. However, modelling and analysis of characteristics of pyroelectric detectors, like of any other thermal measuring transducers, is usually based on the use of an analogy between descriptions of thermal transformation processes and processes occurring in electrical circuits, for which the theory of analysis is well-developed and has been confirmed by many experimental studies. Pyroelectric detectors are widely used in control and measuring instruments of various frequency ranges, but to date their representation in common electrical circuit simulators is limited.

This study addresses significant theoretical and applied challenges in the circuit-level modelling of primary pyroelectric transducers and the analysis of their performance characteristics.

This study aims to develop metrological assurance applied to pyroelectric measurements by improving the equivalent circuits of pyroelectric detectors to identify the parameters with better accuracy.

Enhancing the equivalent circuit representations of pyroelectric detectors enables more accurate determination of technical and metrological parameters of a broad range of modules, while also improving the reliability of simulations for information and measurement systems that incorporate pyroelectric detectors.

That is why there are still studies in different countries related to improving the representation of pyroelectric transducers in the form of their equivalent circuits, the need for which arises when considering many issues related to both the development of the theory of PETs and their practical application [1–6].

One of the first schematic representations of a pyroelectric transducer is the Thevenin equivalent circuit (Fig. 1), which points to the fact that the polarization change in pyroelectrics is electrically equivalent to a voltage source V_0 connected in series with the volume capacitance of the sensing element C_E, which in turn is shunted by the leakage resistance R_E of this element.

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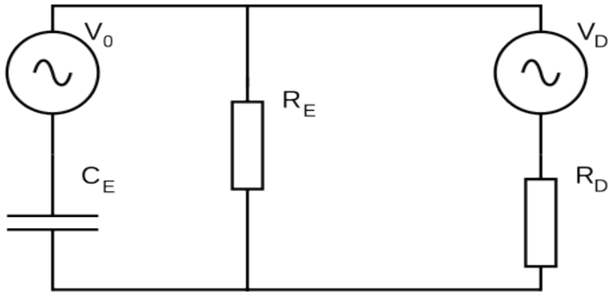


Fig. 1. Thevenin equivalent circuit with a voltage generator reflecting the thermoelectric and electrical stages of the PET transformations

The external circuit to which the sensing element is connected is represented by a source of bias voltage V_D with resistance R_D. Such a schematic representation of the PET allows us to state the presence of the influence of the external circuit on the polarization of the sensing element, to obtain a theoretical expression for the equivalent noise power, and to estimate the noise levels, as well as the sensitivity of the PET [4, 5]. The same equivalent circuit has been successfully used to determine the pyroelectric coefficients of pyromaterials [7], to calculate the specific detectivity [5], etc. In general, the output signal from the pyroelectric converter can be represented in the form of voltage or current, depending on its application. Therefore, in many cases, the equivalent circuit of the PET is represented not by a voltage generator, but by a current generator, for example, as in the Norton circuit [5] shown in Fig. 2.

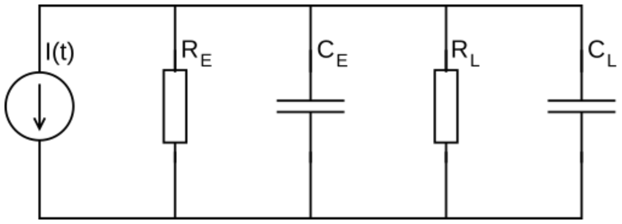


Fig. 2. Norton equivalent circuit with a current generator reflecting the thermoelectric and electrical stages of PET transformations

There are a lot of modifications of this type of equivalent circuits, which mostly reflect only the thermoelectric and electrical stages of PET transformations [8, 9]. Still, the equivalent circuit can be a starting point when analysing any of the three transformation processes that are distinguished during the operation of PETs: not only thermoelectric or electrical ones, but also the thermal one that precedes them [6, 9]. In this case, the thermal stage refers to the process of thermal conversion – the transformation of incident thermal radiation $\Delta\Phi(t)$ into a change in temperature $\Delta T(t)$ of the pyroelement. The thermoelectric stage is the transformation of the temperature change $\Delta T(t)$ into a change in polarization, and the current flowing $I(t)$ into the pyroelement. The third stage – electrical conversion – is the formation of the output voltage $V(t)$ at the amplifier input through an equivalent capacitor with a capacitance C_L and a resistor with a resistance R_L.

To implement this approach, when constructing a complete equivalent circuit of any thermal converter, the electrothermal analogy method is used, which is based on the similarity of the expressions of the laws of heat propagation (thermal conductivity) and current flow in an electric circuit. This allows the graphical interpretation of Fourier's law for thermal conductivity and Ohm's law for electric circuits to be carried out using the same components of the electrical circuit diagram, which makes it possible to represent all stages of the conversion process in the PET in a single system of symbols for the elements of the electrical circuit. Thus, the method of electrothermal analogy allows modelling thermal and electrical processes in a unified form using a single equivalent electrical circuit. The similarity between the laws of thermal and electrical conductivity leads to the following correspondences:

- temperature (T) corresponds to electric potential (U);
- heat flow (Φ) corresponds to electric current (I);
- thermal resistance (R_T) corresponds to electrical resistance (R) and is defined as:

$$R_T = \Delta T \,/\, \Delta\Phi,$$

where ΔT is the temperature difference.

The diagram of a pyroelectric converter built on this principle is called the basic equivalent circuit and is shown in Fig. 3.

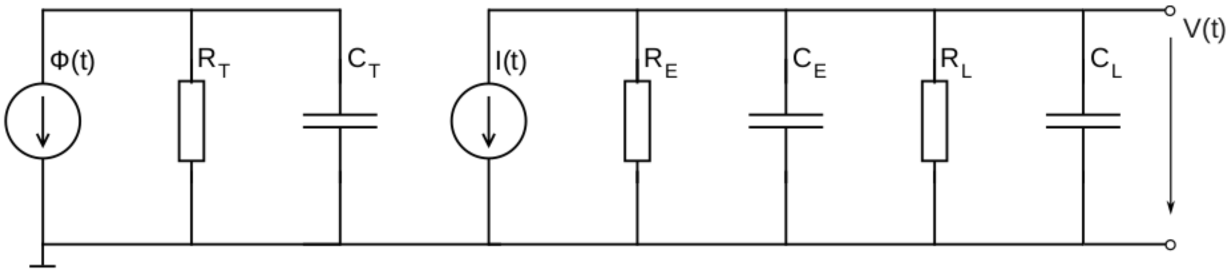


Fig. 3. Basic equivalent thermoelectric circuit of the primary measuring pyroelectric transducer: $\Phi(t)$ – radiation power flux incident on the pyroelectric sensing element; $I(t)$ – pyroelectric current; $V(t)$ – output voltage; R_T – total thermal resistance of the sensing element; C_T, C_E – thermal and electrical capacitances of the sensing element; R_E, R_L – electrical resistance of the sensing element and input stage; C_L – electrical capacitance of the input stage

Using these correspondences, it is possible to model thermal systems using electrical circuits, which simplifies the analysis and calculation of thermal processes. In the case of pyroelectric converters, such an equivalent circuit is used to visually demonstrate the principle of operation of a pyroelectric detector, since it allows modelling the process of converting the incident radiation heat flow $\Phi(t)$ through the pyroelectric response and to the output voltage $V(t)$ supplied to the amplifier input. The analysis of such a circuit immediately indicates that the PET obviously requires a charge amplifier, an integrating stage or a high-impedance amplifier, for example, on a field-effect transistor with an input resistance of the order of 10^{12} Ohms, to avoid shunting of the pyroelectric signal, etc. It is this level of equivalent circuit that can be reproduced by a mathematical model that provides the creation of a specialized, object-oriented simulator of a pyroelectric converter, in the form of a structural diagram element (E1) with the corresponding transfer function (E1 level simulators) [10].

Unfortunately, the use of the basic circuit as a pyroconverter model in an electrical circuit simulator is impossible for reasons that are primarily related to the incorrectness of the circuit solution, which is the parallel connection of the corresponding components of the simulator: a DC current source and a capacitor. Usually, such a combination of elements can lead to the destruction of the capacitor. That is why standard simulators, such as TINA, diagnose such a circuit as defective, which is confirmed by the corresponding notification (irregular circuit).

Synthesis of a multistage equivalent circuit (MEC) for PETs

At the same time, the widespread use of PETs as an element of various control and measuring circuits necessitates the representation of a pyroelectric transducer as a component of an electronic circuit with predicted parameters. An adequate model of a pyroelectric detector shall meet the same requirements as models of other common components of electrical circuit diagrams do such as resistors, capacitors, diodes, transistors, microcircuits or functional units based on them.

Converting a basic equivalent circuit into an electrical schematic diagram is possible using the operator method, which is widely used for analysing electrical circuits.

The dynamics of a pyroelectric converter can be represented by its general transfer function $F(s)$, which is formed based on the transfer functions of all stages of transformations that are characteristic of a PET. This function $F(s)$ is usually a complex expression that can contain the sum, difference, and product of elementary (partial) operator images $F_I(s)$ that correspond to typical links or filters. The complex transfer function $F(s)$ is decomposed into the sum, difference and/or product of simpler transfer functions, each of which can be implemented by a standard active filter on operational amplifiers (OAs). If $F(s) = F_I(s) \pm F_J(s)$, then such an operation is implemented by connecting the links (filters) in parallel. If the complex transfer function is the product $F(s) = F_I(s) \cdot F_J(s)$, then this is implemented by connecting the links (filters) with the transfer functions $F_I(s)$ and $F_J(s)$ in series.

This paper considers only the main stages of the transformation. The electrocaloric effect, secondary and tertiary pyroelectric additions, the manifestations of which are much weaker than the main pyroelectric effect, are not accounted for. Therefore, in the small signal range, it is advisable to represent a pyroelectric detector as an object, the structural diagram of which shall include a source of thermal radiation with power $\Phi(t)$, linear links and filters that will describe the main stages of transformations in the PET.

At the first stage – the stage of thermal transformation, the heat balance equation for the sensing element is formulated, which describes the change in its temperature being exposed to the radiation power flux $\Phi(t)$ falling on the pyroelectric:

$$\tau_T \frac{d\Delta T(t)}{dt} + \Delta T(t) = \frac{\alpha}{G_T}\Delta\Phi(t) \ \ [\mathrm{K}], \qquad (1)$$

where τ_T is the thermal constant of the pyroelectric element, α is the absorptive capacity of the surface of the sensing element, G_T is the heat loss.

The transfer functions ($\Delta T(s)$, $\Delta I(s)$, $\Delta V(s)$) can be obtained by replacing the differential d/dt with the Laplace variable s.

In this regard, the heat balance equation (1) in the operator domain is represented as:

$$\Delta T(s) = \Delta\Phi(s)\frac{\alpha}{G_T}\frac{1}{\tau_T s + 1} \ \ [\mathrm{K}]. \qquad (2)$$

In terms of circuit engineering point, expression (2) is identical to the transfer function of a low-pass filter, which can be represented by the corresponding structural diagram shown in Fig. 4.

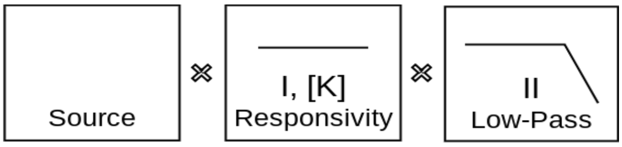


Fig. 4. Block diagram of the pyroelectric transducer heating process

When transitioning to the rate of temperature change, a derivative is applied to expression (2), which creates the conditions for converting the low-pass filter into a high-pass filter:

$$\Delta\Psi(s) = \Delta\Phi(s)\frac{\alpha}{C_T}\frac{\tau_T s}{\tau_T s + 1} \ \ [\mathrm{K/s}]. \qquad (3)$$

Expression (3) can be matched with the structural diagram shown in Fig. 5.

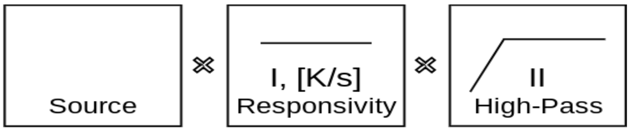


Fig. 5. Block diagram of the process of a rapid change in the heating of a pyroelectric transducer

The further transition to pyroelectric current generation finally forms the transfer function of the high-pass filter with the thermal time constant τ_T:

$$\Delta I(s) = \Delta\Phi(s)\frac{\alpha}{C_T}\rho A\frac{\tau_T s}{\tau_T s+1} \ \ [\text{A}], \qquad (4)$$

where ρ is the pyroelectric coefficient, A is the area of the absorbing electrode of the pyroelectric sensing element.

The transfer function (4) is displayed by the structural diagram presented in Fig. 6.

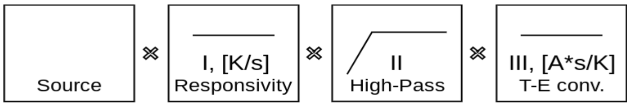


Fig. 6. Block diagram of the pyroelectric current generation process

The pyroelectric coefficient is the ratio between the output current, Equation (4) and the rate of temperature change, Equation (3):

$$\frac{\Delta I(s)}{\Delta\Psi(s)} = \rho A \ \ [\text{C/K}]. \qquad (5)$$

The general process of converting thermal radiation into a pyroelectric voltage response is represented by the transfer function (6) and corresponding block diagram (Fig. 7).

$$\Delta V(s) = \Delta\Phi(s)\frac{\alpha}{C_T}\rho A R_E\frac{\tau_T s}{\tau_T s+1}\frac{1}{\tau_E s+1} \ \ [\text{V}], \qquad (6)$$

where $\alpha\rho A R_E/C_T$ is the theoretical sensitivity of the pyrodetector, in which ρA is the transfer function of the sensing element itself and is calculated by formula (5).

Thus, to represent the pyroelectric converter (under the above assumptions) a sequential multiplication of five elements is used, including three coefficients (I, III, IV) and two filters (II, V). This scheme can be optimized by multiplying all the coefficients and representing the result by a single coefficient (link I) of the corresponding dimension $[V/W]$, as shown in Fig. 8.

Fig. 8 demonstrates an optimized schematic diagram after the virtual multiplication of coefficients. This diagram represents a bandpass filter limited by the two cut-off frequencies. It can be transformed into a multistage equivalent circuit diagram for further analysis. The transition from the structural diagram to the electrical schematic diagram is carried out by establishing compliance with the functional purpose of a particular link (transfer function) of its circuit implementation based on ideal operational amplifiers (OPs), which are connected by connections according to the diagram shown in Fig. 9.

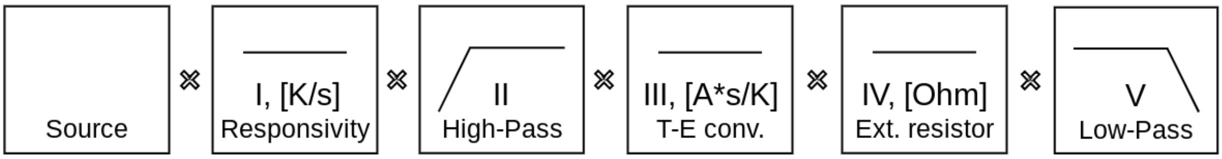


Fig. 7. General block diagram of a pyroelectric converter as a set of elements – transfer functions of links and filters

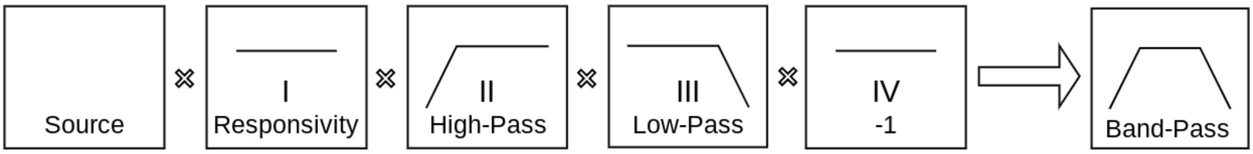


Fig. 8. General optimized block diagram (E1) of the pyroelectric transducer

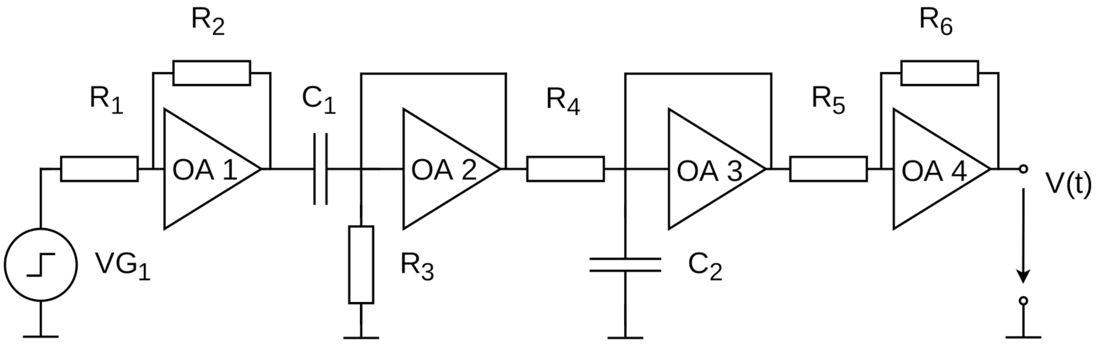


Fig. 9. Multistage equivalent circuit (E3) of a pyroelectric converter for modelling the operation of a PET in circuit simulators

The voltage source VG1 in Fig. 9 is an electrothermal analogy of the heat radiation source link with power $\Phi(t)$ in Fig. 8.

The first stage in Fig. 9 displays the schematic implementation of the first link of the structural diagram (Fig. 8), to which the transfer coefficient of the transfer function (6) corresponds (but without $\Delta\Phi(t)$), which represents the response value of the pyroelectric detector in a dimensionless form, and which in numerical value can be given through the ratio of resistors R_2/R_1 in the repeater switching circuit based on the operational amplifier OA1. In practice, it is advisable to equate R_1 to unit one, then the value of the sensitivity of the PET (with the dimension $[V/W]$) is numerically equal to R_2. It should be noted that this is a theoretical sensitivity of the pyrodetector, which the latter would have in the case of an ideal inertialess link. An approximate numerical value of this sensitivity can be obtained, for example, experimentally – by approximating the transient process using the corresponding equation. In this case, the catalogue values of sensitivities $R_{V/W}(s)=V(s)/\Phi(s)$ are incorrect to use, since manufacturers provide them as frequency-dependent. Subsequent links are schematically formalized in a similar way.

The second stage (Fig. 8) is characterized by the ratio $\tau_T s/(\tau_T s + 1)$ in (6) which corresponds to a high-pass filter that is implemented in Fig. 9. In this case, the thermal time constant is a product of the thermal capacitance C_T and the thermal resistance R_T. Hence, C_T equals C_1 while R_T does R_3.

By the analogy, the third stage is a low-pass filter with a transfer function of $1/(\tau_E s + 1)$ in expression (6). In general, when connecting a sensing element with a high-impedance resistor, the product of this resistor and the transfer function of a low-pass filter is obtained. Here, it is obvious that the components shall be applied separately. Thus, the high-impedance resistor is included in the third stage while its dimension (link IV, Fig. 7) is multiplied with the other coefficients. The third stage includes a low-pass filter only. This filter time constant is the product of the resistor R_L (R_4) and the capacitor C_E (C_2).

The fourth stage based on OA4 is a voltage repeater, the parameters of which are determined by several conditions.

First, the construction of the final equivalent circuit (when implementing the product of transfer functions) is completed by installing buffer OPs (voltage repeaters) between the filter stages, which prevent the mutual influence (loading) of the stages on each other, thereby ensuring that the entire transfer function equals the product of the individual transfer functions. Here, the buffer amplifier OP performs a “virtual multiplication”. When modelling, it should also be noticed that the first stage (responsivity) has the negative input pin. Accordingly, the mathematical description of the functioning of the last link shall also provide for signal inversion (multiplication by minus one).

In addition, single-element pyroelectric detectors in transistor housings are typically manufactured in such a way that when heated they generate a signal of positive polarity, and when cooled – negative. Therefore, if in a single-element PET the sensing element is structurally inverted, it will generate a signal of the opposite polarity compared to the standard configuration, which will also influence the polarity of the output signal to the module and may require or, conversely, make it impossible to use inverting. It is also worth noting that in most cases, PETs are used as part of non-radiometric devices, such as passive infrared motion sensors, heat detectors in security systems, flame sensors, spectroscopic sensors (for gas detection), etc. In these cases, two-element pyrodetectors are often used, the sensing elements of which can be either physically separated (manufactured by Kube, Eltec) or integrated on one substrate (all other manufacturers). When heating one of the sensing elements (provided that the other is shielded from radiation), the output signal can have both positive and negative polarity, depending on which exactly element has been exposed to temperature effects. Accounting for such features of two-element PETs, when modelling modules based on them, the sign of “virtual circuit multiplication” of the fourth link is optional.

Therefore, in the proposed MEC, the fourth stage has a conditional and formal character: the numerical values of R_5 and R_6 shall be the same, and the presence of an inverting function is due to the features of the switching on scheme of one sensing element or some.

Finally, the multistage equivalent circuit is presented as an electric circuit diagram consisting of a series of sub-stages each having a unique transfer function. This MEC allows simulating a set of responses using the standard library components widely available in any software like LTspice, PSpice, TINA-TI, Micro-Cap, etc.

The constructed PET model in the form of a multistage circuit can be considered as a user library component that functionally emulates the operation of a pyrodetector, and which can be easily integrated into many well-known electrical circuit simulators. Moreover, today in many commonly used electronic circuit simulators, pyroelectric converters, as specific thermoelectric detectors, are not very common and are not included in their standard libraries. Multiphysics simulators (COMSOL, ANSYS, Modelica, MATLAB Simscape, SolidWorks, FreeCad, Salome) do not have PETs in their libraries either, although they are best suited for realistic modelling of PETs at the level of study into the dependence of the charge magnitude on the temperature change ΔT (thermoelectric stage of transformations), for example, accounting for the non-uniform heating of the pyroelectric material of the sensing element, etc. Multiphysics modelling allows one to implement user elements based on basic blocks.

Such modelling environments include Simulink, LTspice, Multisim, Modelica, etc. However, as a rule, the use of such paid packages is not cost-effective when addressing most engineering problems, which are usually associated with predicting (modelling) the behaviour of circuits of various types of control and measuring modules based on serially produced pyroelectric detectors.

To represent a pyroelectric detector as an identified library component of the circuit, it is sufficient to have data that determine the parameters of the multistage PET model shown in Fig. 9. These minimally required parameters include sensitivity and time constants. The pyrodetector true responsivity numerically equals to the dimensionless gain (virtual responsivity) of the first stage. The second stage is provided with the thermal time constant of a high-pass filter (high-pass cut-off frequency, $f_{HP} = 1/2\pi\tau_T$). The low-pass cut-off frequency $f_{LP} = 1/2\pi\tau_E$ of the third stage forms the electric time constant.

In the absence of complete catalogue information, the above parameters can be obtained by the method of approximate identification [6, 11, 12].

Fig. 10 shows an example of implementing a multistage electrical circuit equivalent to a specific commercial pyroelectric sensor, accounting for its parameters, performed in the Micro-Cap 12 electrical circuit modelling environment.

Fig. 11 shows the amplitude response (AR) obtained in Micro-Cap 12 for the circuit presented in Fig. 10. For the same pyroelectric sensor PE10-S-Q, the authors of [6] obtained its AR experimentally. The amplitude response, constructed from the measurement points obtained in the physical experiment (dotted curve), and the AR of the circuit E3 simulated in Micro-Cap (solid curve) are given in Fig. 11 in a single coordinate system. The graphs demonstrate acceptable qualitative and quantitative similarity.

To confirm the adequacy of the functioning of the multistage equivalent circuit in the time domain

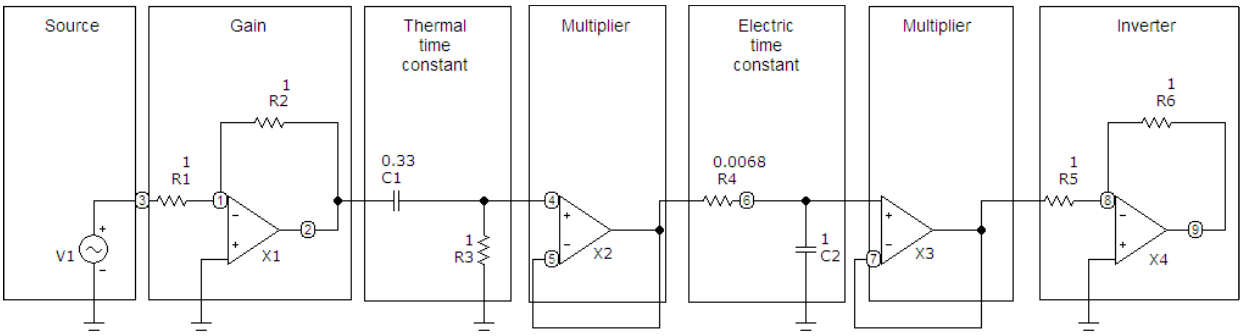


Fig. 10. Equivalent electrical schematic diagram (E3) of the pyrodetector laser energy sensor from the PE10-S series from Ophir Optronics PE10-S-Q with a single transmission coefficient ($R_1 = R_2 = R_3 = R_4 = R_5 = R_6 = 1$ Ohm), thermal time constant $\tau_T = C_1 \cdot R_3 = 0.33$ s, and electrical time constant $\tau_E = C_2 \cdot R_4 = 0.0068$ s, simulated in the Micro-Cap 12 environment

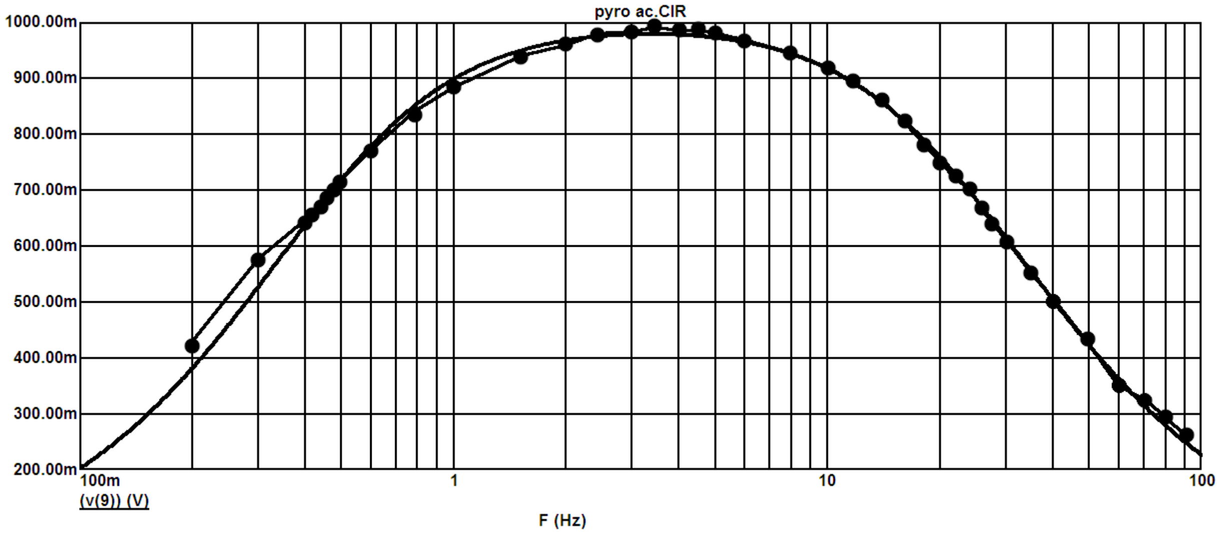


Fig. 11. Amplitude characteristic of the electrical equivalent circuit E3 of the PE10-S-Q pyroelectric sensor, simulated in Micro-Cap 12 (solid curve), and the experimental frequency response of the same sensor (dotted curve), reproduced according to the data of [6]

in the Micro-Cap 12 environment, the E3 circuit of the commercial pyroelectric converter LHI958 (manufactured by PerkinElmer Optoelectronics) was also simulated, which is shown in Fig. 12. For this circuit, its transient characteristic was obtained (Fig. 13, *a*). The experimental transient characteristic of the converter LHI958, obtained using the method given in [12], is shown in Fig. 13, *b*.

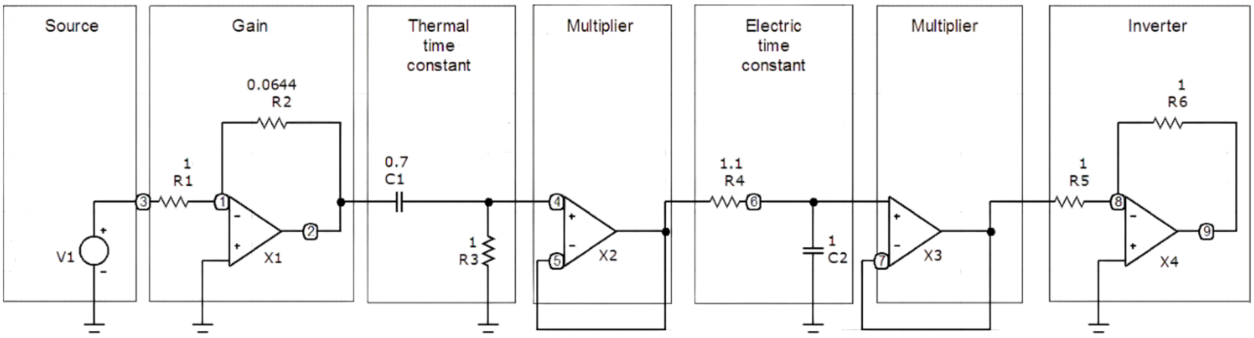
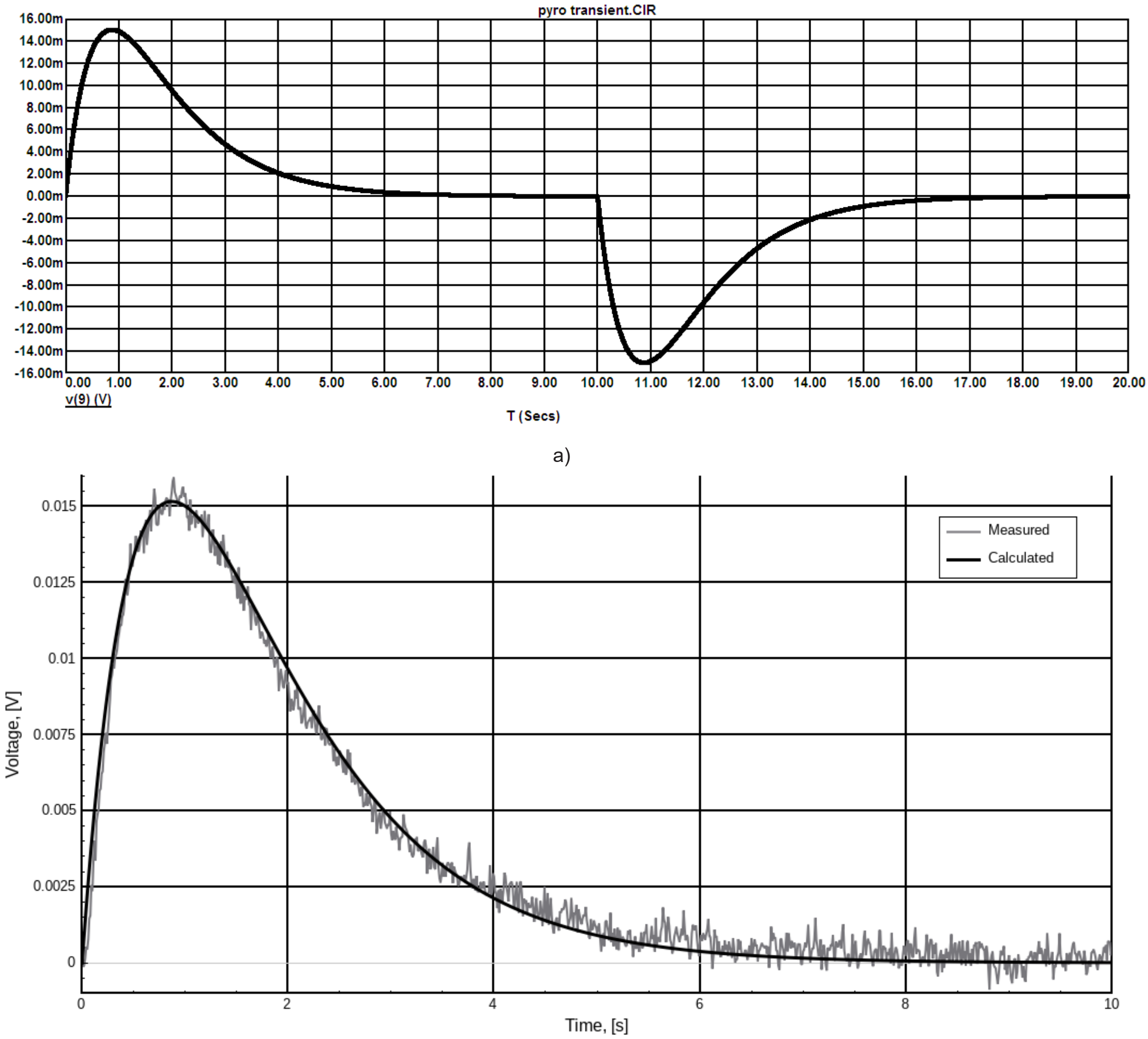


Fig. 12. Multistage equivalent circuit of E3 pyroelectric detector LHI958



a)

b)

Fig. 13. Transient response (TR) of the LHI958 pyrodetector. Identified parameters: transmission coefficient 0.092, thermal constant $\tau_T = C_1 \cdot R_3 = 0.7$ s, electrical constant $\tau_E = C_2 \cdot R_4 = 1.1$ s; a) TR obtained in the Micro-Cap 12 environment based on a multi-stage model during heating and cooling of the pyrodetector; b) TR obtained experimentally during heating of the PET

As can be seen from Fig. 11, 13, the degree of coincidence of the model and experimental curves for addressing engineering problems is satisfactory. The suitable coincidence of the dependencies proves the correctness of the proposed model.

Conclusions

The modified equivalent circuit of a pyroelectric converter, proposed in the form of a multistage sequence of filters and buffers based on operational amplifiers, can be recommended for use as a standard library component in electronic circuit simulators. This approach to modelling is appropriate during the synthesis and analysis of circuits of functional units, devices and measuring modules, which include pyroelectric converters.

The representation of a pyrodetector in the form of the proposed equivalent circuit provides adequate reproduction of dynamic processes and makes it possible to perform frequency and time analysis of circuits of control and measuring modules based on PETs. This, in turn, allows for the optimal selection of pyroelectric detectors for measuring equipment, accounting for the specified criteria and operating conditions.

The results of testing the equivalent circuit, carried out using the Micro-Cap 12 electric circuit simulator, are consistent with experimental data and simulation results on a specialized E1 simulator [10]. Additional confirmation of the correctness of the proposed model in the form of a multistage equivalent circuit (E3 simulator) is the analysis of the dimensions of the mathematical model (Fig. 7), on which it is based.

A feature of the presented model is that the heat balance equation (1) is not introduced directly into the description of the circuit, which reflects the set of transfer functions of energy transformations in the PET (6). This distinguishes it from traditional models based on the heat balance equation and provides the possibility of using the model in any simulators of electrical circuits, even in the absence of Laplace transform blocks. In addition, this allows one to apply a full set of analysis methods available in the simulator environment itself.

Thus, the use of the proposed multistage equivalent circuit makes it possible to increase the efficiency and quality of the design of electronic circuits of measuring modules containing pyroelectric converters.

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І.І. Ключник, О.Ю. Бондаренко, І.І. Ключник, О.В. Дегтярьов, П.В. Галкін

Харківський національний університет радіоелектроніки, просп. Науки, 14, 61166, Харків, Україна
ihor.kliuchnyk@nure.ua; pyrodetector@gmail.com; oleksandr.degtiarov@nure.ua

Анотація

Розглянуто застосування еквівалентних схем для опису піроелектричних перетворювачів (ПЕП) та вимірювальних модулів на їх основі. Проаналізовано призначення й області застосування таких схем, показано їхню придатність для теоретичних досліджень, прогнозування характеристик і визначення параметрів комерційних піроелектричних детекторів. Окрему увагу приділено вимогам до еквівалентних схем як основи моделей ПЕП, що використовуються у спеціалізованих симуляторах електричних кіл. Запропоновано модифіковані еквівалентні схеми, що задовольняють зазначені вимоги; перевірено коректність їхніх розмірностей та наведено результати досліджень адекватності щодо визначення основних характеристик ПЕП. Запропоновано багатокаскадну еквівалентну схему у вигляді активного смугопропускного фільтра, що може використовуватися як стандартний бібліотечний елемент у програмних пакетах моделювання електричних схем. Схему побудовано на основі застосування операторного методу до всіх основних етапів енергетичних перетворень, характерних для піроелектричних детекторів. Вона складається з чотирьох функціональних вузлів на базі ідеальних операційних підсилювачів, забезпечує високу точність моделювання та створює підґрунтя для подальшого розвитку систем проєктування модулів на основі ПЕП із використанням стандартних симуляторів. Показано можливість моделювання конкретних комерційних піроелектричних перетворювачів у вигляді їх еквівалентних електричних принципових схем із використанням компонентів стандартних симуляторів, з якими запропонована схема коректно інтегрується. Обґрунтовано, що мінімально необхідними параметрами для адекватного моделювання є теплова та електрична сталі часу, а також чутливість ПЕП. Інтеграція схеми заміщення піродетектора до стандартних симуляторів розширює можливості аналізу часових, частотних і фазових характеристик функціональних модулів різного призначення, що містять ПЕП.

Ключові слова: піроелектричний перетворювач; вимірювальний модуль; передавальна функція; еквівалентна схема заміщення; симулятори електричних кіл; моделювання; прогнозування характеристик.

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