UDC 614.8
DOI: 10.15587/1729-4061.2016.75063

INCREASE OF ACCURACY OF DEFINITION OF TEMPERATURE BY SENSORS OF FIRE ALARMS IN REAL CONDITIONS OF FIRE ON OBJECTS

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На основі аналізу узагальненої схеми теплового датчика розроблена його динамічна модель, що дозволила визначити напрями підвищення точності. Встановлені оптимальні параметри датчика для різних динамічних умов і випадкових збурень. Отримані результати дозволяють прогнозувати очікувану точність існуючих датчиків, а також розробляти оптимальні датчики для гарантованого виявлення загорянь на реальних об'єктах

Ключові слова: тепловий датчик, пожежний сповіщувач, точність, температура, динамічні умови, випадкові збурення

На основе анализа обобщенной схемы теплового датчика разработана его динамическая модель, позволившая определить направления повышения точности датчика. Установлены оптимальные параметры датчика в различных динамических условиях и случайных возмущениях. Полученные результаты позволяют прогнозировать точность существующих датчиков, а также разрабатывать оптимальные датчики для гарантированного обнаружения загораний на реальных объектах

Ключевые слова: тепловой датчик, пожарный извещатель, точность, температура, динамические условия, случайные возмущения

1. Introduction

The thermal sensors of fire alarms are primary sources of the information about an ambient temperature at fire on the object. They transform the information of thermal sensitive elements to corresponding voltage for its subsequent threshold or address and analogue processing. The warning signal about fire presence and the operating signal for automatic fire extinguishing systems are formed on the basis of this voltage in fire-prevention alarm system. Therefore the increased requirements to the accuracy of definition of an ambient temperature are imposed on the thermal sensors of fire alarms. Thus the ambient temperature has a dynamic character, which is accompanied by casual indignations in real conditions of fire on objects. Especially high requirements to the accuracy of definition of temperature are imposed on sensors of fire alarms used for early fire detection when initial dynamics of an ambient temperature growth is masked by casual temperature indignations. The thermal sensors are recently widely applied in the fire alarms of systems of fire protection of property and in life safety equipment in which smoke sensors cannot be used. The thermal sensors are irreplaceable for protection of zones in which fast changes of temperature take place or where there are high fluctuations of an ambient temperature [1], for example, warehouses, garages, technical premises, commercial kitchens and other service objects. The traditional method of increase of the accuracy of the thermal sensors of fire alarms in dynamic conditions is connected with increase of the level of a casual component of output voltage, which is the basic source of admissions and false detection of fire and is based on the inertance decrease of the thermal sensors of fire alarms [2].

The work urgency in the given direction consists in increase of accuracy of the thermal sensors of fire alarms in dynamic conditions at casual indignations. It will allow lowering the probability of admissions and false detection of fire by thermal fire alarms in real conditions during their use on objects.

2. Literature review and the problem statement

The thermal alarms, as is known, possess insufficient accuracy of definition of an ambient temperature for making the guaranteed decision on fire presence in real conditions. It is shown, that the guaranteed detection of fire on objects by the single fire alarms according to the criterion of admissible risk is possible only in the severe conditions characterized by negligibly small indignations and high accuracy of sensors. Therefore last year's intensive researches in the field of search of constructive ways to increase the accuracy of thermal and other types of sensors of modern fire alarms in dynamic conditions taking into account casual indignations are carried out [3–7]. The most part of these researches is devoted to increase of the accuracy of sensors on the basis of the use of a group (set) of identical or various types of sensors and multichannel processing of their output data on the basis of modern technologies use [2, 4–6]. So, for example, multicriteria detection technologies offer the most perspective means of increase of the accuracy of real fires detection [7, 13]. Modern technologies of multicriteria detection allow to process the output signals of sensors, which measure several factors of developing fire or various parameters of one of the factors (for example, absolute value, speed of increase or fluctuation).

The majority of works in this direction is focused on data processing of various types of sensors located in one area of the object of protection (detection by a set of fire factors) [9–11, 13, 15, 16]. Thus sensors work with regulated, but fixed threshold of detection. The issues of increase of the accuracy of the sensors are not considered in the specified works.

A considerable part of researches is aimed at working out of algorithms of the alarm system with the use of fuzzy logic and neural networks for recognition of the events connected with true and false fire on the object [14, 17]. The work [18] is devoted to development of multicriteria fire detection at the use of similar type (or types) of sensors of the group, placed in various areas of the object of protection. It is shown that grouping of sensors at the information reception taking into account topology of their placing, current time and realised technology allows to provide high indicators of quality of fire detection on the object.

The new technologies of fire detection on the basis of the DS-theory [4], neural networks [5], and also the co-ordinated optimisation of double detecting [6] appeared within the limits of the considered direction. Now the technologies of the sensor's special placing taking into account the features of various types of fire protection objects are also known [19, 20]. It is noted that it is possible to define the demanded technical parameters of systems of objects' fire protection and separate devices, and also the directions of their perfection on the basis of the received experimental data of sensors' placing influence on the efficiency of fire detection.

Despite the reached results, this direction of researches is based on introduction of corresponding redundancy and does not address a problem of increase of accuracy of separate sensors of the group. That is the problem of increase of accuracy and maintenance of the guaranteed fire detection on objects is solved only with the help of group principle and/or placing of group sensors at their set, usually low, realised accuracy. But the issues connected with increase of the accuracy of group sensors, and also optimisation of their accuracy in the set dynamic conditions taking into account casual indignations in the environment are beyond the frameworks of researches with this approach.

It is necessary to note especially that potential possibilities of fire detection in such conditions by technical means can be reached only at the use of sensors, which accuracy is optimum together with the group principle of information processing and sensors' optimum placing on the object of protection.

Considerably smaller part of researches in the considered direction is devoted to increase of the accuracy of fire detection on objects on the basis of the synthesis of optimum (on accuracy) thermal sensors of fire alarms [7]. It is shown that the existing thermal sensors used in fire alarms are not optimum and have low accuracy.

The main reason of increase in the number of false detections and admissions of fire on real objects is low accuracy of sensors at threshold decision-making on possible fire. The synthesis of the thermal sensor in a general form without regard to the sensitive element type, thermal conduction process and the measuring circuit is executed in the work [7].

It does not allow using the results in practice [7] at a choice of optimum parameters of thermal sensors with the thermoresistive sensitive element and the bridge measuring circuit for fire detection on objects in real conditions that requires additional researches in this direction.

3. The research purpose and problems

The work purpose is increase of the accuracy of thermal sensors of fire alarms with the thermoresistive sensitive element and the bridge measuring circuit in dynamic conditions of fire at casual indignations.

The following problems have been formulated for achievement of the overall work purpose:

– the theoretical analysis of the generalised circuit of the thermal sensor of fire alarm with a thermoresistive sensitive element;

– working out of a dynamic model of the thermal sensor with the thermoresistive sensitive element in the form of a thin plate in the state space;

– the analysis of accuracy and optimisation of parameters of the thermal sensor with the thermoresistive sensitive element and the bridge measuring circuit in dynamic conditions in the presence of casual indignations.

4. The theoretical analysis of the thermal sensor generalised circuit

The greatest distribution as the thermal sensors of fire alarms was received by parametrical measuring circuits. Such circuits transform an impedance of sensitive elements to a corresponding electric signal in the form of voltage or a current. The resistive elements are often used as sensitive elements, and as measuring bridge circuits, for example, Wheatstone bridge circuit [21] are often used. One of the bridge's diagonals is connected to a source of constant voltage E, and loading is connected to another one in the form of the amplifier. Usually the internal resistance of a source is much less than the resistance of loading. Thus sensitivity of the measuring bridge is maximum in case of its balance. If the resistance of shoulders of the bridge is identical and equal to R_0 then the model of the thermal sensor will be defined by function of transformation in the form of output voltage

$$u = \frac{E\Delta R}{4R_0(1+\Delta R/2R_0)}, \qquad (1)$$

where $\Delta R = R_{T0}\bar{\alpha}\theta$ – increment of resistance of the thermoresistive sensitive element, caused by its gain by the medium-volume temperatures by Θ, RTO – resistance of the sensitive element at the initial temperature corresponding to conditions of the bridge balancing, $\bar{\alpha}$ – temperature coefficient of the sensitive element material resistance.

The value θ is small at the initial stage of fire and so is the value ΔR. Therefore the following model is fair for the thermal sensor taking into account (1)

$$u=\frac{E R_{T0}\bar{\alpha}\theta}{4R_0}. \qquad (2)$$

The value θ in the model (2) will be defined by the form of the thermoresistive sensitive element. The thermal processes in such sensitive element are described by the equation of non-stationary thermal conductivity with corresponding initial and boundary conditions [22]. It is often possible to believe that one size x of the sensitive element is much less than its other sizes y and z. In such a case, the thermal processes T (x, t) in this element are similar to the processes of non-stationary thermal conductivity in a plate of the unlimited sizes described by the equation

$$\frac{\partial T(x,t)}{\partial t}=a\frac{\partial^2 T(x,t)}{\partial x^2} \qquad (3)$$

with the initial condition T(x, 0)=T_0=const and boundary conditions

$$\left(\frac{\partial T(x,t)}{\partial t}\right)_{x=\delta}=-\frac{\alpha}{\lambda}\left(T_{x=\delta}-T_C\right);\ \left(\frac{\partial T(x,t)}{\partial t}\right)_{x=0}=0, \qquad (4)$$

where a – coefficient of temperature conductivity of the sensitive element material; α – coefficient of thermal exchange of a material; δ – thickness of a plate material; λ – coefficient of thermal conductivity of the sensitive element wall; T_0 – initial temperature of the sensitive element material (temperature of balancing of the sensor's measuring bridge); T_C – ambient temperature in a place of the fire alarm location.

Introducing dimensionless (relative superfluous) temperature $\bar{\theta}=(T_C-T)/(T_C-T_0)$ and dimensionless co-ordinate $\bar{x}=x/\delta$, and also Biot criteria B_i=αδ/λ and Fourier criteria F_O=at/δ² the solution of the equation (3) taking into account (4) will be defined by

$$\bar{\theta}(\bar{x},Fo)=\sum_{i=1}^{\infty}\frac{2\sin(K_i)\cos(K_i\bar{x})\exp(-K_i^2 Fo)}{K_i+\sin(K_i)\cos(K_i)}, \qquad (5)$$

where K_i – solutions of the transcendental equation ctg(K)=K/B_i, which defines K_i as a function of numerical parameter B_i for all i=1, 2, 3,…,∞.

Following (5), an increment of dimensional temperature of the sensitive element for any values $\bar{x}$ and F_O

$$\theta(\bar{x},Fo)=T_C-T(\bar{x},Fo)=$$
$$=(T_C-T_0)\sum_{i=1}^{\infty}\frac{2\sin(K_i)\cos(K_i\bar{x})\exp(-K_i^2 Fo)}{K_i+\sin(K_i)\cos(K_i)}. \qquad (6)$$

The expression under the sign of the sum in (6) defines the dimensionless space and time characteristic of the researched thermoresistive sensitive element. Averaging (6) on the parameter $\bar{x}$, it is possible to get an increment of dimensional average temperature for the sensitive element

$$\theta(Fo)=(T_C-T_0)\sum_{i=1}^{\infty}\frac{2\sin^2(K_i)\exp(-K_i^2 Fo)}{K_i^2+K_i\sin(K_i)\cos(K_i)}. \qquad (7)$$

The dynamic vector process described in the state variables will correspond to the average temperature of the sensitive element for the limited number n summands in (7)

$$B\frac{d\Theta(at/\delta^2)}{dt}+\Theta(at/\delta^2)=A(T_C-T_0), \qquad (8)$$

where Θ(at/δ²) – vector of the state variables defined by a private increment of temperature of the sensitive element caused by each root K_i in the equation (7); B – diagonal matrix of private time constants of the sensitive element of the corresponding size with elements $B_{i,i}=\delta^2/K_i^2 a$; A – diagonal matrix of private static coefficients of transfer of the sensitive element of the corresponding size with elements

$$A_{i,i}=\frac{2\sin^2(K_i)\delta^2}{[K_i^2+K_i\sin(K_i)\cos(K_i)]K_i^2 a}.$$

Transition from the considered state variables Θ(at/δ²) (8) to initial temperature θ(at/δ²) in the equation (7) will be defined by the supervision equation

$$\theta(at/\delta^2)=H\,\Theta(at/\delta^2), \qquad (9)$$

where H – row vector of the corresponding size with the elements equal to unit.

Equations (8) and (9) define the model of increment of the average temperature of the researched thermoresistive sensitive element in the state variables. It is possible to be limited only by the first component of the thermoresistive sensitive elements with a sufficient degree of accuracy for values Bi≤1 in models (8), (9). In this case, the model (8), (9) can be presented by the following differential equation

$$B_{1,1}\frac{d\theta(at/\delta^2)}{dt}+\theta(at/\delta^2)=A_{1,1}(T_C-T_0). \qquad (10)$$

Taking into account (10) and models (2) the output voltage of the thermal sensor with the researched thermoresistive sensitive element will be described by the following differential equation

$$B_{1,1}\frac{du(at/\delta^2)}{dt}+u(at/\delta^2)=\frac{E R_{T0}\bar{\alpha}}{4R_0}A_{1,1}(T_C-T_0), \qquad (11)$$

where $B_{1,1}=\delta^2/K_1^2 a$, and value

$$A_{1,1}=\frac{2\sin^2(K_1)\delta^2}{[K_1^2+K_1\sin(K_1)\cos(K_1)]K_1^2 a}.$$

The equation (11) defines the dynamic model of the first approximation for the generalised thermal sensor of fire alarm in the case of use of the thermoresistive sensitive element of the considered type. This model allows to research the accuracy of the thermal sensor in various conditions of use of fire alarm taking into account casual indignations.

5. The analysis of accuracy of the thermal sensor in dynamic conditions in the presence of casual indignations

The dynamic conditions of use of the thermal sensor, characterised by the linear law of temperature increase of $T_C(t)=T_H+bt$, where T_H – initial value of ambient temperature, a and b define the rate of its increase at fire are important for early fire detection. Parameters T_H and b usually are considered set, characterising the character of fire on the object. We will believe that at/δ²=1, and the dynamics of the ambient temperature of $T_C(t)$ is accompanied by influence of casual temperature indignations N(t), described by Gaussian white noise with a zero average value of intensity G. Let the initial voltage u(0) on an exit of the thermal sensor be a random variable with a mathematical expectation m_0 and dispersion D_0. In these conditions the required output voltage of the thermal sensor should be equal to $u_T(t)=T_H+bt-T_0$.

Let's define the second initial moment of an error. The mathematical expectation of an output signal is defined by the equation

$$B_{1,1}\frac{dm_u}{dt}+m_u=\frac{ER_{T0}\bar{\alpha}}{4R_0}A_{1,1}(T_C-T_0),\quad m_u(0)=m_0.$$

Solving this equation, we will receive

$$\begin{aligned}m_u(t)&=m_0e^{-\frac{t}{B_{1,1}}}+\xi\{(T_H-T_0)\times\\&\times(1-e^{-\frac{t}{B_{1,1}}})+b\,B_{1,1}[e^{-\frac{t}{B_{1,1}}}+(\frac{t}{B_{1,1}}-1)]\},\end{aligned}\tag{12}$$

where

$$\xi=\frac{ER_{T0}\bar{\alpha}A_{1,1}}{4R_0}.$$

In the steady state

$$m_u(t)=\xi[(T_H-T_0)+b(t-B_{1,1})].\tag{13}$$

Aligning the equation (11) and using the known general equation for definition of the correlation moments [23], we have the following equation for dispersion D_u of the output voltage in a considered case

$$B_{1,1}\frac{dD_u}{dt}+2D_u=\xi^2\frac{G}{B_{1,1}},\quad D_u(0)=D_0.$$

Integrating this equation, we will receive a dispersion of the output voltage

$$D_u(t)=D_0e^{-\frac{2t}{B_{1,1}}}+\xi^2\frac{G}{2B_{1,1}}.\tag{14}$$

The dispersion of the required voltage and the mutual correlation moment of output and required output voltage are equal to zero in the considered case. Accordingly the error variance of the thermal sensor is equal to the dispersion of the output voltage (13).

Taking into account the equation (12) the mathematical expectation of an error of the thermal sensor $m_\varepsilon(t)$ at required output voltage u_T (t) $=T_H+bt-T_0$ will be defined as follows

$$\begin{aligned}m_\varepsilon(t)&=m_u(t)-u_T(t)=\\&=[m_0-\xi(T_H-T_0-b\,B_{1,1})]e^{-\frac{t}{B_{1,1}}}+\\&+(\xi-1)(T_H-T_0)-\xi b\,B_{1,1}+bt(\xi-1).\end{aligned}\tag{15}$$

The required second initial moment of an error of the thermal sensor characterising its accuracy in dynamic conditions at casual ambient temperature indignations will be equal to the following value taking into account the described conditions

$$\alpha2_\varepsilon(t)=m_\varepsilon(t)^2+D_0e^{-\frac{2t}{B_{1,1}}}+\xi^2\frac{G}{2B_{1,1}}.\tag{16}$$

Generally the value $\alpha2_\varepsilon(t)$, following (14) and (16), depends on time and some characteristic parameters of the thermal sensor and ambient temperature conditions at fire on the object.

In that specific case, when the characteristic parameter of the sensor ξ is equal to one, the second initial moment $\alpha2_\varepsilon(t)$ of an error of the thermal sensor in the established mode, characterising its accuracy, does not depend on time and is defined by the value

$$\alpha2_\varepsilon=(bB_{1,1})^2+\frac{G}{2B_{1,1}}.\tag{17}$$

The equation (17) shows that there are optimum values of the characteristic parameter $B_{1,1}$ of the sensor for the set dynamic ambient temperature conditions at which the value $\alpha2_\varepsilon$ is minimum.

The optimum values of the characteristic parameter $B_{1,1}$ of the thermal sensor, are defined as follows taking into account (17)

$$B_{1,1opt}=\left[\frac{G}{4b^2}\right]^{1/3}.\tag{18}$$

The equation (18) shows that the optimum characteristic parameter $B_{1,1opt}$ of the thermal sensor is unequivocally defined by ambient temperature dynamics from a fire source on the object and also by the intensity of casual temperature indignations.

6. Results of modelling of the thermal sensor in various conditions and their analysis

Generally, following (14) and (16), the value $\alpha2_\varepsilon(t)$ depends on time and some characteristic parameters of the thermal sensor, and also ambient temperature conditions at fire detection on the object. As an example, the dynamics of the value $\lg(\alpha2_\varepsilon)$ depending on the characteristic parameter ξ of the thermal sensor under the condition $at/\delta^2=1$ and casual ambient temperature indignations by intensity G=1 for dynamics of temperature 29+0.1t in degrees, caused by the fire centre is presented in Fig. 1. The initial temperature of the sensitive element of the sensor $T_0=25$ degrees.

From the analysis of data in Fig. 1 it follows that the maximum accuracy of the thermal sensor in the considered dynamic conditions in the presence of casual indignations for any values of the parameter ξ is equal to the beginning of fire development. If the parameter ξ is equal to one, the accuracy of the sensor practically does not depend on time. Therefore it is expedient to choose corresponding parameters of the thermal sensor, at which the characteristic parameter ξ=1 for exception of the accuracy dependence on time.

The results of the analysis of dependence of the accuracy $\lg(\alpha2_\varepsilon)$ on the characteristic parameters ξ and $B=B_{1,1}$ of the thermal gauge in the case $at/\delta^2=1$ for the time moment t=10 s in similar conditions, but at various values of speed b of ambient temperature increase, equal to, accordingly 0.5

and 0.017 degrees per second are presented in Fig. 2, 3. The specified above values of speed define the maximum and minimum standard speed of increase of the ambient temperature from the fire centre on the object for various classes of fire alarms. The norms of time of the thermal fire alarms operation are defined for the given speeds.

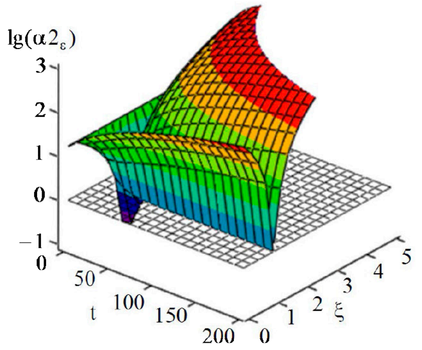

Fig. 1. Dynamics $\lg(\alpha 2\varepsilon)$ from the characteristic parameter ξ of the thermal sensor

Thus increase of the speed of the ambient temperature rising from the fire centre leads to increase in the number of local zones of the raised accuracy and also to reduction of values of the characteristic parameter B corresponding to these zones at the initial stage. The decrease in absolute potential accuracy of the thermal sensor in the specified local zones is observed (Fig. 2).

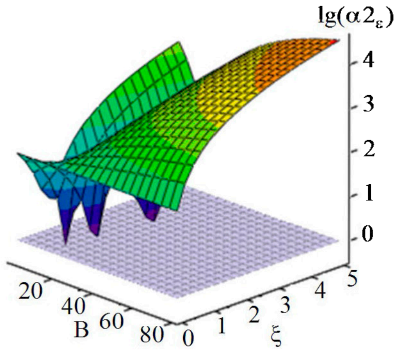

Fig. 2. Dynamics $\lg(\alpha 2_\varepsilon)$ from the characteristic parameters ξ and B of the thermal sensor at the maximum speed of temperature increase

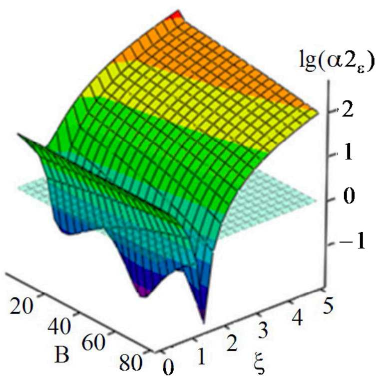

Fig. 3. Dynamics $\lg(\alpha 2_\varepsilon)$ from the characteristic parameters ξ and B of the thermal sensor at the minimum speed of temperature increase

Fig. 4, 5 contain as an example dependences $B_{1,1opt}$ defined by (16) for various dynamic conditions of the use of the thermal sensor.

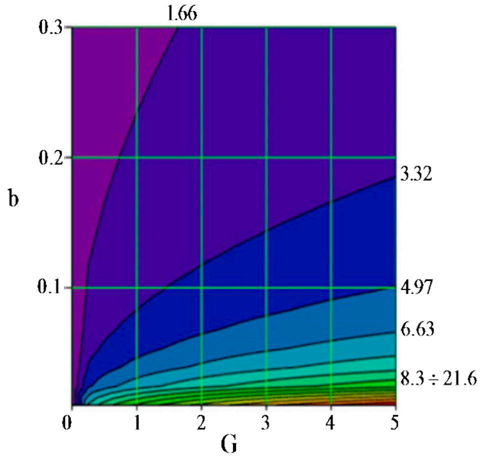

Fig. 4. Dependences $B_{1,1}$ for high dynamics of the ambient temperature from the centre of fire against casual indignations

The analysis of data presented in Fig. 4, 5 shows that the characteristic parameters $B_{1,1}$ of the thermal sensors of fire alarms, equal to 20 s and 60 s, accepted according to EN54, are not optimum for fire detection by the standard speed of ambient temperature increase from the fire centre. Following the presented data, the existing standard requirements to the characteristic parameter $B_{1,1}$ are close to optimum ones only for detection of casual ambient temperature indignations of high intensity. This, apparently, is due to the low accuracy of real fire detection and high probability of false alarms from fire sensors and various existing fire alarm systems. It is probable that the specified standard values of the time constants of alarms were chosen taking into account only the condition of the maximum smoothing of casual ambient temperature fluctuations without the first component of the sum (15).

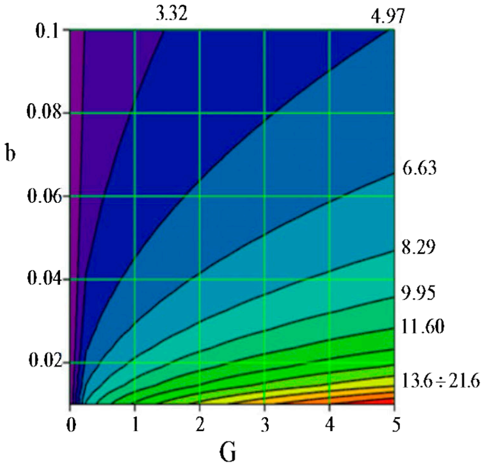

Fig. 5. Dependences $B_{1,1opt}$ for weak dynamics of the ambient temperature from the centre of fire against casual indignations

The dependences shown in Fig. 4, 5 allow practical defining of $B_{1,1opt}$ for the considered type of a thermoresistive sensitive element of the thermal sensors of fire alarms depending on temperature conditions of their use on objects (speed of ambient temperature increase from fire and intensity of casual temperature indignations).

7. Conclusions

1. The theoretical analysis of the generalised circuit of the thermal sensor of fire alarm has shown that it represents the parametrical measuring circuit of transformation of an impedance of the sensitive element in the corresponding voltage. Thus the thermoresistive element is considered as a typical sensitive element, and the Wheatstone bridge circuit – as the measuring circuit.

2. The dynamic model of the generalised circuit of the thermal sensor of fire alarm is presented in the form of the differential equations in the state space for the thermoresistive sensitive element in the form of a thin plate. The private model of the thermal sensor of the first approximation in the state space is received for values Bi≤1. The given model allows researching the dynamic accuracy of the thermal sensor in various conditions of the fire alarm use taking into account the casual ambient temperature indignations. The influence of parameters of the bridge circuit and also of the sensitive element of the thermal sensor on dynamic accuracy in various conditions is investigated on the basis of this model.

3. The analysis of dependence of the value of the second initial moment of an error on the considered characteristic parameters of the thermal sensor in dynamic conditions in the presence of casual temperature indignations of various intensity has shown, that there are minimum values of the second initial moment of an error. Generally the minimum values of the second initial moment of an error depend on the characteristic parameters of the thermal sensor, current time and temperature conditions in the environment, characterised by the fire centre. There are possibilities of maintenance of invariance in time of the second initial moment of an error. The dependences of the optimum value of the characteristic parameter $B_{1,1opt}$ of the thermal sensor on the speed of temperature increase caused by the fire centre, and also the intensity of masking casual temperature indignations on the object are received for this case.

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