Виконано узагальнений аналіз алгоритму самоналагоджуваних пожежних сповіщувачів. Відмінною рисою є нелінійний характер алгоритму і умови гарантованого виявлення загорянь. Ознакою негарантованого виявлення загорянь може служити зростання самоналагоджувального порога. Досліджено динаміку самоналагоджувального порога і ймовірності виявлення загорянь, які свідчать про здатність пожежних сповіщувачів здійснювати раннє гарантоване виявлення загорянь в невідомих умовах

Ключові слова: самоналагоджувальний пожежний сповіщувач, самоналагоджувальний поріг, гарантоване виявлення загорянь, горючий матеріал

Выполнен обобщенный анализ алгоритма самонастройки пожарных извещателей. Отличительной чертой являются нелинейный характер алгоритма и условия гарантированного обнаружения загораний. Признаком негарантированного обнаружения загораний может служить возрастание самонастраивающегося порога. Исследована динамика самонастраивающегося порога и вероятности обнаружения загораний, которые свидетельствуют о способности пожарных извещателей осуществлять раннее гарантированное обнаружение загораний в неизвестных условиях

Ключевые слова: самонастраивающийся пожарный извещатель, самонастраивающийся порог, гарантированное обнаружение загораний, горючий материал

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RESEARCH INTO DYNAMICS OF SETTING THE THRESHOLD AND A PROBABILITY OF IGNITION DETECTION BY SELF-ADJUSTING FIRE DETECTORS

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1. Introduction

Modern technical solutions, related to the widespread introduction of microprocessor technology, are actively implemented in the sphere of construction of plants and systems of fire alarm. Over the past few years, the market of technical fire alarm facilities underwent major changes, associated primarily with the introduction of "intelligent" fire detectors (FD). The main special feature of these technical means is their ability to not only control fire-generated physical factors, but also to track dynamics. These functions of facilities, along with special "intelligent" algorithms make it possible to provide self-adjustment of FD to unknown beforehand ignition conditions on sites, as well as early and guaranteed ignition detection [1, 2]. Modern FD generate information about ignition, based on different physical components of combustion [3, 4]. That is why it is particularly expedient to research quantitative characteristics of FD, self-adjusting by ignition (SFD) in circumstances, unknown in advance, of ignition of different combustible materials.

The relevance of present work is in studying quantitative characteristics of SFD under conditions of application unknown in advance.

2. Literature review and problem statement

Proposed in [5], the algorithms for SFD can be considered in the class of well-known adaptive algorithms of least squares (LMS). LMS properties substantially depend on original conditions and selection of parameter of algorithm convergence [6]. In a discrete version, this refers to dependence of properties of the algorithm on the original value and magnitude of step of adaptation of recurrent procedure. That is why original value and step size in discrete adaptation algorithms require careful setting. In this case, a small step size is known to lead to slowing down of convergence of the procedure, and a large step size – to volatility and disruption of the adaptation process. In the latter case, SFD under consideration may appear incapable of providing guaranteed ignition detection. In this regard, various modifications of algorithms, in which a step size changes in the process of adaptation, continue to evolve and remain relevant [6–11].

Paper [7] reviews known methods for selection of the step variable in adaptation algorithms. Such algorithms can be grouped according to the methods of step size setting. One method of step size regulation is based solely on the input signal. Another method is based on connection between a step size and adaptation error. The essence of this method is that the step size for providing small magnitude of adaptation error should be small, while in case of large adaptation error, the step size must be large in order to accelerate the adaptation process [8]. We also know the combined method, combining the use of an input signal and adaptation error for step size correction. This method is used in most modern adaptation algorithms [9].

The known modifications of adaptation algorithms can be grouped based of the number of regulation parameters, necessary to run each of them [7]. The first group includes the algorithms that do not need parameter adjustment before running. The algorithms of this group operate autonomously and have only two assigned parameters (algorithms of Michael and Vaughn [9]). The second group is characterized by a single setting parameter and includes only learning algorithm for identification of systems. The third most numerous group includes the algorithms, requiring regulation of the upper boundary of a step size and additional setting of one or two parameters (algorithms of Carney, Benvenist and Matthews). Three adjustable parameters without regulation of the upper boundary of step size are determined by the Benisty algorithm. Other algorithms of this group are characterized by regulation of more than three parameters. Modified adaptation algorithm with five adjustable parameters of adaptation step allows improvement of performance of the adaptation process under non-stationary conditions [10]. However, such a number of adjustable parameters significantly limits the scope of its practical use, including for SFD. Certain simplification of the algorithm is possible by selecting the upper boundary of a step size, based on the conditions of algorithm stability [11].

Paper [12] presents test results of various adaptation algorithms in three typical applications: identification, adaptive amplification and noise suppression. Adaptation algorithms for applications of ignition detection by the data of registration of physical components of the ignition site are not considered. In article [12], it is noted that the main problem in testing concerned mainly the algorithms with more than two regulated parameters. This problem was related to difficulties in adjusting parameters due to their interconnection. However, this comment does not relate to regulation of maximum and minimum step sizes. The known research in characteristics of adaptation algorithms for other applications is limited mostly to problems of assessment of instantaneous frequency, spectral analysis and amplification of speech signals [13]. In this case, research in quantitative characteristics of adaptive algorithms of SFD for the conditions unknown in advance is not addressed in the scientific literature.

Paper [7] presented results of analysis of seventeen most popular modifications of the algorithm with an alternating adaptation step. It was noted that different methods of dynamic step size regulation are required for effective adaptation. This is particularly noticeable at registration of stationary input data, unlike non-stationary. In addition, it is noted that for non-stationary data, considering simplicity and performance, the normalized algorithm still has no rivals. According to the authors of paper [7], despite constant efforts to develop new modifications of adaptation algorithms for a variety of applications, this algorithm will dominate adaptive solutions for many years. In this case, normalized algorithm can be considered as a standard algorithm, appropriate for most applications of adaptive input data processing. Normalization of step size in accordance with assessment of power of input data makes this algorithm invulnerable when the level of input data changes. In this regard, the algorithm does not require additional step size adjustment in non-stationary applications.

Paper [14] deals with algorithms and structural schemes of SFD of guaranteed detection of ignition center on sites, based on registration of one of the major physical components of ignition. In this case, quantitative characteristics of SFD under conditions unknown in advance for the registration of a physical ignition component are not considered. However, it is known that specified characteristics of SFD will substantially depend on the original value and magnitude of step of recurrent adaptation procedure.

Lack of data on quantitative characteristics of adaptation procedure remains the unresolved part of SFD creation.

3. The aim and objectives of the study

The aim of present work is to determine the main quantitative characteristics of SFD depending on the original value and step magnitude of recurrent adaptation procedure.

To accomplish the set goal, the following objectives were formulated:

– to give general characteristic of the algorithm of adaptation of SFD of early guaranteed ignition detection;

– to consider peculiarities of algorithm of SFD adaptation taking into account actual conditions of ignition detection;

– to explore characteristics of SFD according to data of registration of actual physical components of ignition of tested combustible materials.

4. General characteristics of adaptation algorithm of fire detectors, self-adjusted by ignitions

An ignition source at the initial stage of development is generally considered as a source of basic physical components in the form of ambient temperature, smoke density and carbon monoxide concentration. That is why early ignition detection on the site can be based on registration of one of the components of the source.

Papers [5, 14] introduced the concept and formulated the criterion of guaranteed ignition detection on fire protection sites, having the sense of equality of probabilities of false ignition and failure to detect actual ignition for its arbitrary component

$$P(x \in X_1 : f = 0) = P(x \notin X_1 : f \neq 0), \tag{1}$$

where x is the magnitude of the observed ignition component on a site (temperature, concentration of smoke and carbon monoxide); X_1 is the region of values of magnitudes of the observed ignition component, corresponding to existence of ignition source and FD actuation; f is the actual state of ignition source on the site, which can take value $f \neq 0$ (the source exists) or $f=0$ (the source does not exist).

Due to threshold rule of solution, at guaranteed ignition detection by FD, characteristic function is introduced

$$\theta(x,c) = \mathrm{sgn}(x-c) = \begin{cases} 1, \text{ if } x \geq c, \\ 0, \text{ if } x < c, \end{cases}$$

where c is the arbitrary value of threshold of making decision about ignition. In this case, mathematical expectation of this characteristic function will be numerically equal to probability of existence of actual ignition. Given the actual statistics of specific frequency of ignition appearance, for example, for industrial buildings and warehouses of various industries, it can be argued that existence of ignitions on the specified sites is a rather rare event. This means that probability $P(x \notin X_1 : f \neq 0)$ of missing actual ignition on these sites in close to zero. In this case, magnitude of mathematical expectation $M\{\mathrm{sgn}(x-c)\}=0$. Based on this, the algorithm of FD, self-adjusted by arbitrary physical component x, in the case of discrete registration of data $x[i]$ can be represented as recurring algorithm of adaptation of threshold of making decision on ignition:

$$c[i]=c[i-1]+g[i](\mathrm{sgn}(x[i]-c[i-1])), \quad c[0]=c0, \tag{7}$$

where $g[i]$ is the magnitude of current step of adaptation algorithm; $c0$ is the original threshold value. In the general case, adaptation step $g[i]$ must meet the known general conditions of convergence of adaptation algorithms

$$g[i]>0, \quad \sum_{i=1}^{\infty} g[i], \quad \sum_{i=1}^{\infty} g^2[i]<\infty, \tag{8}$$

that are more of theoretical than of practical interest, because of the lack of specific recommendations on its choice. This means that in terms of selection of step $g[i]$ in adaptation algorithm (7) there is some arbitrariness. Thus, this parameter can be fixed or depend on the moment and the level of registered data $x[i]$ on the monitored component of ignition of material. Effectiveness of adaptation algorithm (7) depends primarily on its convergence rate. Using the methods of functional analysis, it was shown that at $g[i]$=const, convergence rate is determined by index law, and at step $g[i]=g0/i$, which satisfies (8), it is determined by exponential law. Therefore, convergence rate at $g[i]=g0/i$ is lower than at $g[i]$=const. This phenomenon is explained by the fact that constant feedback provides more fast-responding process than the feedback, disappearing over time. That is why in the absence of interference, it is preferable to use $g[i]$=const.

5. Specific features of algorithm of adaptation of self-adjusted fire detectors considering actual conditions of ignition detection

An important feature of FD adaptation algorithm is its non-linear character. A certain difficulty of its analysis considering actual conditions is related to this fact. To analyze specific features of adaptation algorithm (7), we will represent it as differences and sums, respectively

$$\Delta c[i-1]=c[i]-c[i-1]=g[i](\mathrm{sgn}(x[i]-c[i-1])), \tag{9}$$

$$c[i]=c[0]+\sum_{m=1}^{i} g[m]\mathrm{sgn}(x[m]-c[m-1]). \tag{10}$$

Let us consider convergence of adaptation algorithm (7). According to conditions (8) and ratio (9), for $c[i]$ to tend to the optimal value almost surely, it is necessary, at least, that at $i\to\infty$ the right part (9) should tend to zero, i. e.

$$\lim_{i\to\infty} g[i]\mathrm{sgn}(x[i]-c[i-1])=0. \tag{11}$$

In a general case, characteristic function in (11) can accept zero and unit values. This means that for convergence (7), it is necessary that step $g[i]$ with an increase of i should tend to zero. If adaptation step is constant, convergence (7) will be determined by values of characteristic function at an increase of i. In this case, zero values of characteristic function will exist at all i, for which condition $x[i]<c[i-1]$ is satisfied. In this case, the rate of threshold change, according to (9), will be equal to zero, and the process of threshold adaptation will cease. If this condition is violated, characteristic function takes unit value, determining a positive sign of the rate of threshold change (i. e. its increase) and adaptation step – its absolute value.

It should be noted that conditions $x[i]<c[i-1]$ at assigned $c[i-1]$ can be violated only due to a change in the level of registered data $x[i]$, caused, for example, by ignition on the site or through other reasons. In this case, threshold magnitude starts to increase at the rate, proportional to the current adaptation step. This will occur until condition $x[i]<c[i-1]$ is met. The total magnitude of threshold increments relative to original threshold value, according to (10), will be determined from

$$\sum_{m=1}^{i} g[m]\mathrm{sgn}(x[m]-c[m-1]).$$

Obviously, the closer the original threshold value to the level of registered data in the absence of ignitions, the fewer steps are required for threshold adaptation. That is why original threshold value in adaptation algorithm (7) must be selected in accordance with the level of registered data in the absence of ignition, taking into account that condition $x[i]<c[i-1]$ is satisfied. For this purpose, it is proposed to use the procedure of parametric median filtration of registered data with adjustable parameters A and d. In this case, original threshold value

$$c0(A,d)=A+\frac{1}{d+1}\sum_{m=0}^{d} x[m].$$

Another feature of algorithm (7) is the selection of an adaptation step. According to the results of study [7], if data about ignition components in algorithm (7) are non-stationary, a step size can be chosen, taking into account normalization in accordance with evaluation of input data capacity. This provides for invariance of properties of adaptation algorithm (7) to changing the level of registered data. This property of the algorithm makes it possible to use it effectively for detection of ignition of various combustible materials when registering arbitrary physical components of a source. In this case, algorithm (7) does not require additional adjustment of step size at the specified changes.

It should be noted that resulting dynamics of threshold magnitude, or rather a moment of threshold increase, is a sign of the presence of an undesirable positive tendency of increasing the level of registered data, resulting from the initial stage of ignitions. To give probabilistic coloring to this feature, it is necessary to assess magnitude of mathematical expectation by characteristic function $M\{\mathrm{sgn}(x-c)\}$. This function will determine its probability and guarantee the fact of ignition detection in this case.

To evaluate P_i of mathematical expectation by characteristic function $M\{\mathrm{sgn}(x-c)\}$, it is possible to use the operator of exponential smoothing, determined in the form of

$$P[i]=\frac{1}{N}\sum_{m=0}^{i}\left[\frac{N-1}{N}\right]^{i-m}\mathrm{sgn}\left(x[m]-c[m-1]\right),$$

where N is the parameter of smoothing.

Operator of exponential smoothing can be represented in the equivalent recurring form

$$P[i]=(1-\alpha)P[i-1]+\alpha\,\mathrm{sgn}(x[i]-c[i-1]),$$

where $\alpha=1/N$ is the coefficient of smoothing. In this case, $P[0]=0$, and $P[1]=\alpha\mathrm{sgn}(x[1]-c[0])$.

Thus, peculiarities of considered FD adaptation algorithm relate to its nonlinear nature and conditions of early guaranteed detection of actual ignitions. To provide convergence of the adaptation algorithm, it is necessary to set the original threshold value in accordance with actual registered data for each physical ignition component, considering specific combustible material. Since under actual conditions this information is not available, original threshold value should be determined by registered data, corresponding to the absence of ignitions. At the same time, it is necessary to choose the appropriate step of threshold adaptation. It should be noted that the moment of the threshold increase is the sign of starting ignition without specifying the probability of this fact. For probabilistic assessment of this ignition sign, it is necessary to perform exponential smoothing of magnitude $\mathrm{sgn}(x[i]-c[i-1)$ simultaneously with the threshold adaptation.

6. Research into characteristics of fire detectors, self-adjusting by data of ignition components registration

For the studied SFD, it is of paramount importance to study the influence of adaptation step on threshold dynamics and probability of ignition detection for different physical components and combustible materials. For this purpose, we conducted an experiment, in the course of which we recorded actual data about ambient temperature, concentration of smoke and carbon monoxide concentration in the test chamber at setting fire and ignition of tested materials [5].

Alcohol, paper, wood and textiles were used as tested combustible materials. Data registration was carried out using appropriate sensors, placed in the test chamber. Data were collected with the interval of 0.1 s within monitoring interval equal to 300 s. Ignition of tested flammable materials was carried out approximately at the 24th second from the start of the interval of observation and recording of data. The form, dimensions and conditions of the experiment are described in more detail in [14]. In these studies, the original threshold value $c0(A,d)$ was determined automatically for $A=0.5$ and $d=2$. This method of determining original threshold value in adaptation algorithm (7) provided satisfaction of condition of $x[i]<c[i-1]$), at which zero probability of detection ignition corresponds to true absence of ignition.

The study of the specified characteristics of SFD was performed for two classes of adaptation algorithms. The first class includes algorithms with different, but fixed adaptation step: $GA=0.5$, $GAa=0.05$ and $GAb=0.2$. The second class was presented by the algorithm with an alternating adaptation step

$$g[i]=GMi=\left(\sum_{m=0}^{i}x^2[m]\right)^{-1}.$$

Thresholds of adaptation and probabilities of ignition detection, correspondent to classes of adaptation algorithms under consideration were designated respectively c_i, ca_i, cb_i, cd_i and P_i, Pa_i, Pb_i, Pd_i

According to acquired results, it was found that for all the studied adaptation algorithms of SFD, after 2–3 s after setting fire to tested flammable materials, an increase in threshold magnitude relative to its initial value (no ignition) was observed. In this case, the nature of dynamics of threshold increase is influenced by the type of combustible material and a registered ignition factor. However, character of dynamics of magnitude of ignition detection probability appears to be different.

As an illustration, Fig. 1, 2 shows the fragments of the most characteristic examples of dynamics of threshold and probability of ignition detection for studied combustible materials in the process of FD self-adjustment according to algorithm (7) at fixed steps GA, GAa and GAb, as well as in the case of alternating adaptation step $g[i]=GMi$. In this case, the best indicators at a fixed step of self-adjustment were observed for step magnitude $GAa=0.05$.

It should be mentioned that Fig. 1, 2 show only particular and the most characteristic results of conducted comprehensive research into basic FD characteristics. Integrated studies included analysis of dynamics of threshold and probability of ignition detection by FD for all types of tested flammable materials, specified in this study.

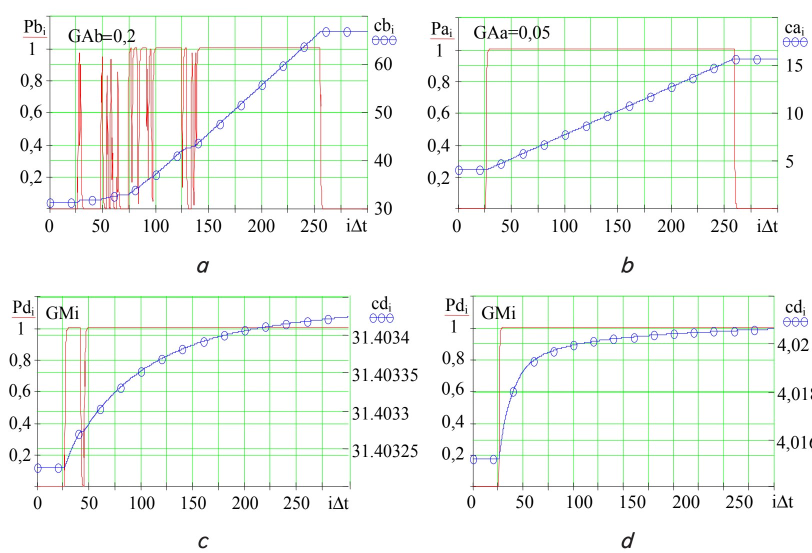

Fig. 1. Dynamics of threshold and probability of ignition detection in the process of FD self-adjustment for algorithms under consideration with wood as tested flammable material at registration of ambient temperature and concentration of carbon monoxide: *a, b* – algorithms of first class for temperature and concentration of carbon monoxide respectively; *c, d* – algorithms of the second class with alternating step

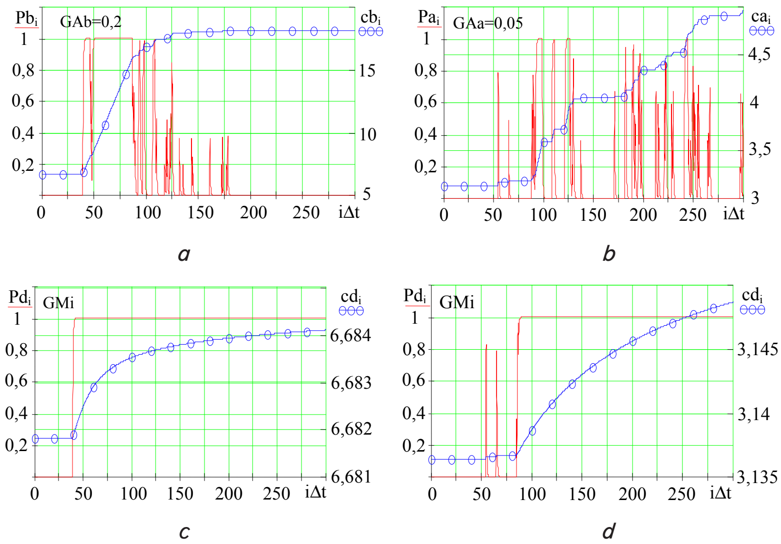

Fig. 2. Dynamics of threshold and probability of ignition detection in the process of FD self-adjustment for textiles as tested flammable material at registration of concentration of carbon monoxide and smoke: *a, b* — algorithms of first class for concentration of carbon monoxide and smoke respectively; *c, d* — algorithms of the second class with an alternating step

compared with the case of SFD self-adjustment by temperature (Fig. 2, *d*). Ignition detection by ambient temperature and smoke concentration at a fixed step was found to have the highest irregularity of ignition detection probability.

In the case of FD self-adjustment at an alternating step of adaptation by ambient temperature and carbon monoxide concentration, early guaranteed detection of fire, caused by the ignition of tested flammable materials, is provided. That is why ambient temperature and concentration of carbon monoxide are more preferable factors at guaranteed ignition detection for the considered types of combustible materials.

Experiment results proved that guaranteed ignition detection is possible in the case of actual data of registration of ignition factors in the environment. In this case, effectiveness of such ignition detection significantly depends on regulation of adaptation step in the implemented algorithm of FD self-adjustment.

Based on all obtained results, it is possible to argue that SFD under consideration, in contrast to the known ones, can actually provide effective early guaranteed detection of ignition of various types of combustible materials under conditions unknown in advance.

7. Discussion of results of research into fire detectors, self-adjusting by ignition

According to results of research in basic characteristics of SFD, such as dynamics of threshold and probability of ignition detection, we established the following.

SFD under consideration are capable to provide early guaranteed detection of ignition sources for flammable materials under circumstances unknown in advance. In this case, ignition detection is guaranteed only when using the algorithm of threshold self-adjustment with alternating adaptation step $g[i]=GMi$. Adaptive selection of original threshold is carried out in accordance with the proposed algorithm.

In the case of using the algorithm of threshold adaptation with fixed values of adaptation step at adaptive selection of the original threshold value, guaranteed ignition detection is not provided. In this case, probability of ignition detection is random in nature and does not provide reliable ignition detection. However, at the moment of ignition, an increase in threshold is registered, but in this case, the correspondent probability appears to be low, which does not allow us to consider the fact of a threshold increase as a guaranteed ignition.

It was established that in the case of SFD adjustment by smoke concentration, guaranteed detection of the ignition source occurs at later moments after ignition of materials

8. Conclusions

1. A general analysis of SFD adaptation algorithm for early guaranteed ignition detection was carried out. It was shown that in terms of selection of adaptation step in the algorithm of FD self-adjustment, there is some arbitrariness. For example, adaptation step can be fixed or depend on the level of registered data on the factor of ignition of combustible material.

2. Peculiarities of SFD adaptation algorithm are related to its nonlinear nature and conditions of early guaranteed ignition detection. To provide convergence of nonlinear adaptation algorithm and guaranteed ignition detection, it is necessary to set the original threshold value in accordance with registered data on the physical component of ignition (considering conditions of observations) and the type of combustible material. In this case, it is necessary to determine original threshold value according to the data, corresponding to the absence of ignition, at simultaneous selection of adaptation step size.

The fact of an increase in self-adjusted threshold relative to its original value can be a sign of ignition detection without specifying probability. For probabilistic assessment of the ignition fact, it was proposed to use exponential smoothing of characteristic function, which allows generation of assessment of probability of ignition detection.

3. Results of research into dynamics of the threshold and the probability of ignition detection by SFD indicate capability to provide early detection of ignition sites under conditions unknown in advance. In this case, it should be noted that FD, self-adjusted by ambient temperature and carbon monoxide concentration, appear to be more preferable for the studied types of combustible materials.

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