Для створення пожежних сповіщувачів, що навчаються, розглядається критерій виявлення загорянь у вигляді рівності ймовірностей помилкового виявлення та пропуску загорянь. Зазначений критерій дозволяє забезпечувати пристосування сповіщувачів до невідомих умов і гарантоване виявлення ними загорянь на об'єктах. Розроблено алгоритми та структури пожежних сповіщувачів, що навчаються, при дискретній і безперервній реєстрації даних

Ключові слова: пожежний сповіщувач, що навчається, гарантоване виявлення загорянь, апріорна невизначеність умови виявлення

Для создания обучающихся пожарных извещателей рассматривается критерий обнаружения загораний в виде равенства вероятностей ложного обнаружения и пропуска загораний. Указанный критерий позволяет обеспечивать приспособление извещателей к неизвестным условиям и гарантированное обнаружение ими загораний на объектах. Разработаны алгоритмы и структуры обучающихся пожарных извещателей при дискретной и непрерывной регистрации данных

Ключевые слова: обучающийся пожарный извещатель, гарантированное обнаружение загораний, априорная неопределенность условия обнаружения

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EXAMINING THE LEARNING FIRE DETECTORS UNDER REAL CONDITIONS OF APPLICATION

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1. Introduction

Considerable attention has been recently paid to the problem of creation of learning systems, which are capable of improving their functioning in the course of time. The need for applying learning systems appears when there are no a priori data about conditions of functioning of the systems. This means that a system must work under conditions of uncertainty.

Under such conditions, there is no possibility to design in advance an optimal system with fixed parameters. Such conditions are characteristic for the majority of contemporary and newly designed systems of fire automation [1]. Moreover, the actual conditions of applying fire automation systems are so diverse and unpredictable that it does not seem possible to create a system, which would provide the guaranteed fire-prevention protection of different sites within the framework of systems with fixed parameters.

In different systems of fire automation, fire detectors (FD) that react to different physical components of a fire are used as the main sources of primary information about a fire on sites [2]. Especially high demands are imposed on thermal FD, used in the systems of early fire detection when the initial dynamics of an increase in the ambient temperature is disguised by unpredictable random temperature disturbances.

In this connection, in order to provide a reliable fire-prevention protection of objects, the problem of creation of learning FD acquires special relevance. They are capable of improving their functioning and provide guaranteed fire detection on the sites under actual application conditions.

The relevance of the work in this direction is in the development of learning FD and in examining their dynamic properties under conditions of real dynamics of the mean temperature of medium taking into account the unpredictability of temperature disturbances when a fire starts.

2. Literature review and problem statement

Existing FD of fire automation systems do not provide guaranteed fire detection at facilities.

Considering this, the problems of creating FD, capable of effective functioning under real dynamic conditions, taking into account a priori information about random disturbances, have been studied recently.

Thus, for instance, article [3] addresses special features of creating multi-sensor detectors for fire automation systems, which function under conditions of uncertainty based on the theory of fuzzy logic. In this case, fuzzy logic is limited to the description of uncertainty in the form of fuzzy magnitudes with the assigned membership functions. Under actual conditions, there is no information of this kind. With this approach, the solution of the problem of the guaranteed fire detection under conditions of uncertainty also remains problematic. In addition, fuzzy logic of detection is a complex process of the generation of fuzzy rules, which are rather difficult to implement using modern computing devices that employ discrete logic.

Paper [4] considers one of the methods of fire detection under conditions of uncertainty based on neural technologies. Still unresolved is the problem on searching for an optimal solution (fire detection), which can be completed even if it is not determined in case of using a non-representative sample for training a neural network, or if there is no suitable function for learning. The realization of artificial neural networks is complicated, and learning proves to be lengthy. In this case, there is no solution in the above paper to the problem of guaranteed fire detection under conditions of uncertainty, which is important for applications.

Article [5] examines the method for improving the effectiveness of monitoring of critical states of the sites under conditions of uncertainty based on group detectors. In the given study, uncertainty of fire detection conditions is limited to the assigned probability characteristics of observations. In this case, learning and self-learning of FD to adapt to uncertain conditions and guaranteed fire detection are not explored.

Development of the new approach of enhancing effectiveness of the maximum FD under conditions of random background influence is represented in [6]. In this case, the principles of construction of learning and self-learning FD and the task of providing the guaranteed fire detection remain unresolved parts of the studied problem.

Consequently, papers [3–5] address the problem on improving the effectiveness of fire detection under conditions of uncertainty, which is limited to the cases of either assigned statistics of observations or disturbances, or assigned fuzzy magnitudes with the assigned membership functions. In this case, the problem of the guaranteed fire detection under conditions of uncertainty, characterized by the lack of data about observation statistics, is not examined in the above-mentioned studies.

Article [7] examines technology of multi-criteria detection taking into account several factors of a developing fire. In this case, the studies were performed for the assigned statistics of disturbances. The problems of guaranteed fire detection under conditions when there is no information about the kind of laws of distribution of the observed factors of a developing fire remain as the unresolved parts of the problem.

A number of studies focus on the development of new algorithms with the use of fuzzy logic and neural networks at the assigned statistics of observations for a more reliable recognition of events, connected with the true and false fire start on the site [8, 9]. In this case, the problems of providing the guaranteed fire detection under conditions when there is no information about the kind of laws of distribution of observed data, and the construction of learning fire detection devices under these conditions, remain unresolved.

Paper [10] argues that grouping FD at the known statistics of observations, as well as information about the topology of their arrangement, makes it possible to improve the indicators of fire detection quality on the site. In this case, the problem of providing the guaranteed indicators of fire detection quality on the site is not considered and solving it remains to be seen.

The problem of improving FD sensors accuracy under actual conditions of fire at facilities is explored in article [11]. In the article, however, the solution of the problem is limited to the known Gaussian statistics of background fluctuations while special features of the guaranteed fire detection are not examined.

The studies described in the scientific literature are based on the assigned statistics of data, observed or recorded by FD, and do not tackle the problem of the guaranteed detection and creation of FD capable of learning under uncertain conditions. This means that the problem of guaranteed fire detection by FD on actual sites is solved predominantly with complete a priori information based on known statistical technologies. In this case, the problems of creating the learning FD, which are capable to adapt in the course of time to the previously unknown application conditions and to provide the guaranteed fire detection on sites, remain unresolved.

Some advertising materials have recently mentioned the development of FD of the new type Acclimate 2251TMB (Canada) by the company System Sensor (with the headquarters in the USA). According to the developer (Canadian company Mircom), such FD is different from those known by the fact that it is a self-learning one. Sensitivity setting is not required while the intelligent capacities of FD make it possible to perform its self-tuning to the previously unknown application conditions. The Acclimate 2251TMB is a combined address FD that unites optical and temperature channels. In this case, the temperature channel of FD has a fixed threshold equal to 57 °C, and the sensitivity of the optical (photo-electronic) channel changes automatically. Embedded software analyses data from both channels and, based on a special self-learning algorithm, makes a decision about a fire starting on a site.

According to official statement from the Mircom company, a probability of false alarm from such FD tends to a negligibly low magnitude. In this case, the microprocessor of FD constantly analyzes the composition of air mixture on the premises, correcting the threshold indicator of its opacity, which makes it possible to avoid false triggering caused by the influence of dustiness. However, the realized intellectual algorithm is not described in the materials. It is only noted that FD is enabled only in the case of an actual fire. In this case, the guaranteed indicators of quality of fire detection are not examined and are not described.

There is also information from ZAO "PO "Spetsavtomatika" (Russia) about the development of new FD of the aspiration type for the earliest fire detection, which are capable of self-adjusting to the conditions of a particular site. However, the issues related to the guaranteed fire detection and the algorithms of self-adjustment of such FD are not examined.

Therefore, the unsolved tasks of the examined problem include development and study of learning FD, capable of providing the guaranteed fire detection under the actual conditions of their application on sites.

3. The aim and tasks of research

The aim of present research is to develop learning fire detectors, capable of automatic adaptation to the previously unknown application conditions and of providing the guaranteed fire detection.

To achieve the set goal, the following particular problems were formulated:

– theoretical substantiation of the criterion of guaranteed fire detection by FD;

– development of algorithms and the structure of learning FD at discrete and continuous data recording;

– research into basic characteristics of learning FD at discrete data recording, on the example of actual dynamics of the mean temperature of medium when alcohol is ignited and burned.

4. Theoretical substantiation of a criterion of guaranteed fire detection by fire detectors

Under conditions of the examined uncertainty, a certain arbitrary physical component of fire, for example, ambient temperature, concentration of carbon monoxide or smoke density, registered at an arbitrary moment of time at the output of the appropriate sensing element of FD, is characterized by a random magnitude x with an unknown distribution law.

A fire site has two possible states. The first one is characterized by the absence of fire site at a facility. Let us designate this state of the site through f=0 (there is no a fire site). The second one is characterized by the existence of a fire site at a facility. Let us designate this state of the site through f≠0 (there is a fire site).

Fire detection by FD is achieved based on the registered data x about the observed physical component of fire. Let us represent the space of possible values x in the form of two non-intersecting areas: X_0 is the area where there is no fire, and X_1 is the area where a fire site exists. Then the process of fire detection by FD is reduced to relating the registered data x to one of the indicated areas.

It is known that such data assignment procedure is accompanied by two types of errors: in the form of false detection and when the fire center is skipped. For the purpose of substantiation of the criterion of guaranteed fire detection by FD, let us require that the probabilities of false detection and skipping a fire center by FD are equal to each other. This requirement means that the probability of the false fire detection, determined by P(x∈X1/f=0), and the probability of skipping the fire P(x∈X1/f≠0) are equal, that is

$$P(x \in X_1 / f = 0) = P(x \in X_0 / f \neq 0). \quad (1)$$

Based on the formula of total probability, the following equation holds

$$P(x \in X_1) = P(x \in X_1 / f = 0) + P(x \in X_1 / f \neq 0). \quad (2)$$

In this case, a probability of fire starting on the site will be determined by magnitude

$$P(f \neq 0) = P(x \notin X_1 / f \neq 0) + P(x \in X_1 / f \neq 0). \quad (3)$$

Subtracting expression (3) from (2) considering relationship (1), we shall obtain

$$P(x \in X_1) = P(f \neq 0). \quad (4)$$

Relationship (4) means that probability of assigning the recorded data x to area X_1 in accordance with requirement (1) is equal to the probability of the state of the fire center that matches a real fire. Therefore, equality (1) may be considered as the criterion that provides the guaranteed fire detection under conditions of uncertainty in the absence of a priori information about the form of distribution of the recorded data. Consequently, the criterion of equality of probabilities of false detection and skipping a fire site is simultaneously a criterion of the guaranteed fire detection under conditions of uncertainty. This criterion will be subsequently used in the development of algorithms and the structure of learning FD.

5. Development of algorithms and structure of learning fire detectors at discrete and continuous data recording

Employing a general theory of learning systems by Y.Z. Tsypkin, in order to develop the algorithms and the structure of learning FD for the guaranteed fire detection, we shall introduce characteristic function

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

where c is the threshold number. Considering that

$$M\{\operatorname{sgn}(x - c)\} = P(x \in X_1),$$

as well as representation (4), we shall obtain equation for the case of a fire site in the following form

$$M\{\operatorname{sgn}(x - c) - y_o\} = 0, \quad (5)$$

where y_o defines directions of “trainer”, for which the representation $M\{y_o\}=P(f\neq 0)$ is correct.

This means that possible instructions of the “trainer” correspond to value 1 if there is a fire site, and 0 if there is no a fire site. Based on equation (5), we shall obtain discrete and continuous algorithms of learning for FD. If recorded data x[k] arrive discretely over time t_k, where k=1, 2,...n determines the appropriate moment of data arrival, then the algorithm for FD learning the guaranteed fire detection can be represented in the form of a discrete dynamic procedure of determining a threshold c[k] of the following form

$$c[k] = c[k-1] + g[k](\operatorname{sgn}(x[k] - c[k-1]) - y_o[k]), \quad (6)$$

where g[k] is the parameter that depends on the moment of data arrival and which is selected from the condition of convergence of a discrete dynamic procedure (6).

In case of arrival of recorded data x(t) continuously in time t, the continuous algorithm of FD learning the guaranteed fire detection can be presented based on (6) in the form of the corresponding differential equation

$$dc(t)/dt = g(t)(\operatorname{sgn}(x(t) - c(t)) - y_o(t)), \quad (7)$$

where g(t) is the assigned time function, selected from the condition of convergence of dynamic procedure (7).

The block diagram of FD learning the guaranteed fire detection considering expression (7) is represented in Fig. 1. By following this scheme, data x(t) arrive at the input of learning FD. Estimation $\hat{P}(x(t) \in X_1)$ (in the form of unities or zeros) of probability $P(x \in X_1)$ of the existence of a fire site for condition $M\{\hat{P}(x(t) \in X_1)\} = P(x \in X_1)$ is formed at the output.

It should be noted that such learning FD is capable through training to establish such a threshold value of c(t)=c* at which criterion (1) is satisfied. Following this criterion, there is a fire on the site if the registered data x exceed the threshold, and there is no a fire when x is lower than the threshold. In this case, a detection of the fire site is guaranteed in terms of quality indicators determined by criterion (1). The guarantee of the indicators of quality of fire detection by learning FD is a new property, which improves their effectiveness under conditions of uncertainty and expands the scope of their practical application.

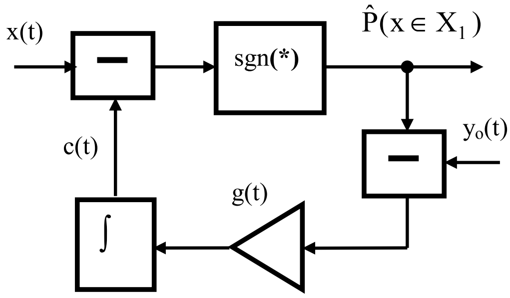

Fig. 1. Block diagram of the learning fire detector, at whose output the current estimation $\hat{P}$ ($x \in X_1$) of probability $P(x \in X_1)$ of the existence of a fire site is formed

Realization of the learning FD represented in Fig. 1 implies the existence of a command from "trainer" $y_\circ$ as to which of the situations (there is or there is no fire) the recorded data x correspond at the input. This means that training FD is conducted with participation of the trainer, who possesses precise information about a fire or its absence on the site. Under actual conditions, such information is missing.

In this case, it is possible to assume with high probability that the existence of fires on a site is a rather rare event. Therefore, most probably, in reality, the trainer's instructions will correspond to the situation when there is no fire, that is $y_\circ=0$. In this case, the algorithm for training a FD (6) is simplified and may be represented in the form of a discrete dynamic procedure for determining the threshold c[k] in the following form

$$c[k] = c[k-1] + g[k]\mathrm{sgn}(x[k] - c[k-1]). \tag{8}$$

Algorithm (8), in contrast to (6), does not require any additional information from the trainer and, therefore, it is a self-learning one. A block diagram of the self-learning FD considering expression (8) can be represented in the form, shown in Fig. 2.

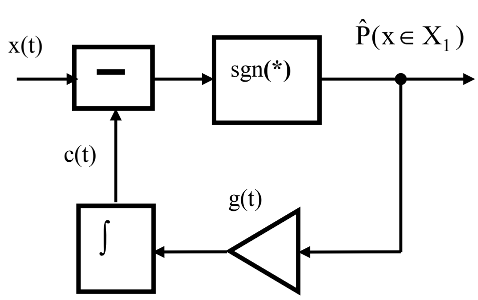

Fig. 2. Block diagram of the self-learning fire detector, at whose output the current estimation $\hat{P}$ ($x \in X_1$) of probability $P(x \in X_1)$ of the existence of a fire site on the object is formed

In the case of data arrival x(t) continuous over time t, the continuous algorithm of a self-learning FD can be represented based on (8) in the form of the corresponding differential equation

$$dc(t)/dt = g(t)\mathrm{sgn}(x(t) - c(t)). \tag{9}$$

The algorithms for self-learning (6)–(9) are nonlinear. Therefore, structural circuits that realize the given algorithms and which are outlined in Fig. 1, 2 will represent nonlinear systems, which correspond to the learning and self-learning FD for the guaranteed fire detection under conditions of uncertainty.

6. Results of examining the main characteristics of the learning fire detectors

As an example, Fig. 3 shows discrete data recorded at the output of the measuring scheme of thermal FD. Discrete data x_i were recorded in the time moments t_i, where i=1, 2,..., 3000, and matched the mean temperature of medium in the modeling chamber with openings when alcohol is ignited and, subsequently, burned. The interval of data arrival corresponded to 0.1 second.

An exterior view of the simulating chamber is shown in Fig. 3. The chamber is equipped with sensors to measure temperature, smoke density and content of carbon monoxide, the data from which were recorded by a PC using the specialized software that enables the registration of data at different frequency of requests from sensors. This made it possible to perform the subsequent re-processing of data from each sensor. Volume of the chamber was approximately 0.524 m^3. In the upper part of the chamber there were measuring sensors for registering the values of basic physical components of a fire center. Measuring sensors were placed above the fire site at height of about 80 cm. The chamber represented a model of non-hermetic premises with openings for letting in air from outside.

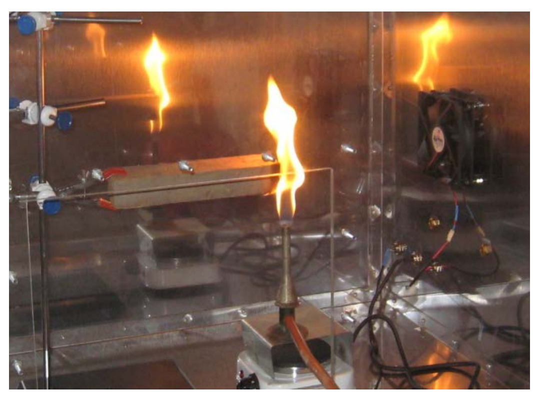

Fig. 3. Exterior view of the simulating chamber with openings

Experimental data about the mean temperature of medium in the simulating chamber, obtained when alcohol was ignited and then burned, were used for exploring the fundamental characteristics of the examined FD. Dynamics of the learning threshold and the output signal of the learning FD was explored.

Fig. 5 shows, as an illustration to the work, the operation of the learning FD with the trainer's instructions ($y_\circ=0$); dependences of establishment of the magnitude of the learning threshold (6) and experimental dependence of the mean temperature of medium in the chamber are represented.

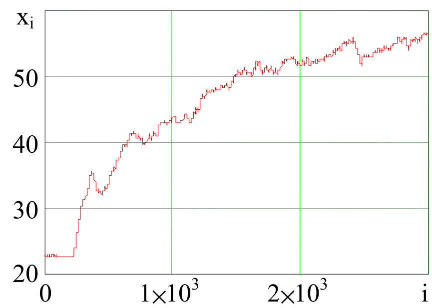

Fig. 4. Dynamics of the mean temperature of medium in the simulating chamber over the assigned registration interval (300 s)

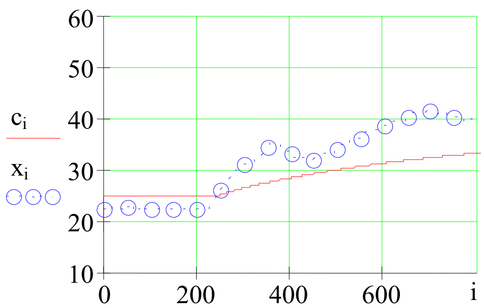

Fig. 5. Dynamics of the learning threshold and the mean temperature of medium in the chamber over the initial interval of data recording

Represented data correspond to the conditions of the initial stage of fire development: absence of burning, alcohol ignition, and subsequent burning. The ignition of alcohol was performed approximately at the 227th data count, which corresponded to the 23rd second of the registration process. Dependences, shown in Fig. 5, correspond to the initial threshold value for the learning FD, equal to 18 °C. In this case, the mean temperature of medium in the chamber before the alcohol ignition was 23 °C.

It is evident from an analysis of dependences in Fig. 5 that the learning FD, in accordance with the instruction from the trainer, automatically establishes the threshold whose value exceeds the mean temperature of medium in the chamber by 2 °C. In this case, the output signal of the learning FD will determine the probability of a fire site detection, which in this case must be equal to zero.

Next, when alcohol is ignited, the threshold automatically increases with an increase in the mean temperature of medium in the chamber, but turns out to be lower than the mean temperature of medium. In this case, the output signal of the learning FD that determines the probability of a fire detection must be equal to unity.

The magnitude of the learning threshold is established automatically as the one, at which criterion (1) is met. As the illustration of this fact, Fig. 6 shows dynamics of the output signal $cM_i=M\{sgn(x_i-c_i)\}=P(f\neq 0)$ of the learning FD for the given case.

It should be noted that for the existing thermal FD, for example of class A1, in accordance with DSTU EN 54-5:2003, the minimum static temperature of triggering (that is, fire detection on the site) is 54 °C. This means that FD under conditions, presented in Fig. 4, will be enabled (will detect alcohol ignition) at the 2317th count, which corresponds to the 231.7th second from the beginning of the registration process.

If one considers that the ignition occurred at the 23rd second, then the fire detection by standard FD in line with EN 54-5:2003 in the examined case would happen at the 208.7th second after the moment of alcohol ignition. In this case, there is no information regarding the standard FD about the probability of its triggering (fire detection), that is, fire detection by the regular FD is not guaranteed.

Analogous studies were carried out for the mean values of temperature of medium during ignition and burning of different types of flammables in the form of paper, wood and cloth.

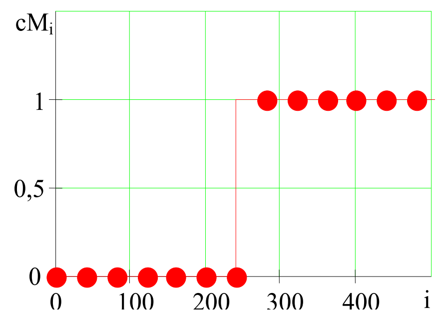

Fig. 6. Dynamics of output signal cM_i of the learning fire detector under examined conditions

Results of these studies testify to the fact that the examined learning FD can substantially faster detect fire (at the 239th count, that is, in 1.2 seconds after alcohol is ignited). In this case, in contrast to the standard FD, reliability of this detection is guaranteed in accordance with criterion (1). Fire detection after the moment the alcohol is ignited by the standard FD in accordance with EN 54-5:2003 in the examined case will occur only at the 208.7th second. The gain in time for the fire detection after its ignition exceeds 170 times.

Therefore, the examined learning FD (Fig. 2) provides early detection of the beginning of ignition of different flammables and, in addition, does not require any additional instructions from a trainer. That is why such learning FD may be considered self-learning. Taking into account modern level of development of electronics, technical realization of the learning and self-learning FD shown in Fig. 1, 2 does not seem problematic.

In this case, it should be noted that the primary task of any fire-detection system has been early and guaranteed fire detection independent on the specific conditions of application on the site. Effective solution of this task can be provided based on the use of the examined learning and self-learning FD, capable of automatically adapting to the previously unknown conditions of application.

In practice, transition to the self-learning FD makes it possible to provide a high and guaranteed protection level under difficult conditions of application and it is one of the directions, capable of bringing fire prevention systems to the higher qualitative level, which corresponds to the advanced European and world standards.

7. Discussion of results of examining the learning fire detectors

The present study shows that the output signal of the examined learning FD, in contrast to the traditional signal (EN 54-5:2003), characterizes not only the fact of fire detection on the site but also guarantees the magnitude of probability of such fact. This means that by employing the magnitude of the output signal it is possible to guarantee a probability of the existence of a fire site. Standard FD that comply with EN 54-5:2003 do not possess such a property.

It was established that the actual dynamics of temperature of medium on the site is the source of information for training a threshold – it adapts the learning FD to actual temperature conditions. FD that learns by such method provides meeting the criterion of the guaranteed fire detection (equality of probabilities of false fire detection and skipping a fire) for the arbitrary dynamics of temperature of medium on the site.

A distinguishing feature of the examined FD in comparison with the standard fire detectors is the presence in its structure and in its algorithm of a nonlinear converter of the difference between the recorded data and the learning threshold. Such processing algorithm makes it possible to form at the output of such nonlinear converter a signal, which simultaneously characterizes both the fact of fire detection and a guaranteed probability of this fact. This property of the examined FD is valuable for applications related to the realization of effective fire-prevention protection of sites with complex dynamics of physical components of ignition.

Present work demonstrates that the basic limitation of the examined learning FD is the need of using external information about the existence or the absence of a fire in the form of respective instructions from a trainer. However, it is possible to assume with high confidence that the existence of a fire on the protected site is a rather rare event. Therefore, in a real case, required commands from a trainer most probably will correspond to the absence of fire rather than its existence.

It was shown that the learning FD in this case becomes a self-learning FD. Such FD might be used for the guaranteed fire detection on the sites with complex conditions in the absence of a priori information about fire existence or absence. In this case, known standard FDs do not possess the indicated capabilities.

It was established in the course of the study that the self-learning FDs also possess a substantially higher performance speed. Given the indicated properties, self-learning FD might be recommended for the new systems of early and the earliest fire warning on the sites with complex operating conditions.

It is expedient to direct further studies in the field of the learning FD toward the development of design methods for obtaining current information about the fire existence (absence) on the site and its consideration while forecasting the current states of a site.

8. Conclusions

1. Theoretical substantiation of the criterion of guaranteed fire detection by FD showed that in order to create learning FD, capable of adjusting to unknown application conditions, it is expedient to consider the criterion of equality of probabilities of false detection and skipping a fire as a criterion of guaranteed fire detection. In this case, the given criterion allows providing the guaranteed fire detection under conditions of the absence of a priori information about the type of distribution law of the recorded data.

2. The algorithms and structures of learning FD were developed at discrete and continuous data recording. It was shown that the main limitation in the implementation of such algorithms is the need of using the additional instructions from a trainer about the existence or absence of fire on the site. To overcome this limitation, it was proposed to use the hypothesis about sufficient rarity of events related to a fire on the sites. This makes it possible to use the registered information about the absence of a fire as instructions from a trainer. The algorithm and the corresponding structural circuit of the learning FD that were modified in this way do not require instructions from a trainer and, in this sense, they are the self-learning ones.

3. Results of study into the examined FD on the example of real dynamics of the mean temperature of medium when alcohol is ignited and burned demonstrated their high efficiency. In comparison with the standard FD that comply with EN 54-5:2003 FD, there is an essential (exceeding 170 times) gain in fire detection time. In this case, the guaranteed fire detection is provided at the same time, under conditions of the absence of a priori information about the type of distribution of the recorded data. The ability of self-learning FD to adapt to previously unknown conditions makes it possible to apply them under non-stationary and indeterminate conditions to detect complex types of fire.

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OPTIMIZATION OF THERMAL MODES AND COOLING SYSTEMS OF THE INDUCTION TRACTION ENGINES OF TRAMS

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Розроблено методику оптимізації теплових режимів та параметрів системи охолодження асинхронних тягових двигунів трамваїв. Оптимізовано режими роботи за критерієм ефективності. Режими руху за встановленим графіком та профілем на ділянці колії оптимізовано за критерієм витрат енергії методом Гамільтона-Якобі-Беллмана. Оптимізовано параметри вентилятора тягових двигунів за критерієм ефективності системи охолодження методом Вейля

Ключові слова: трамвайний вагон, асинхронний двигун, оптимальні режими роботи, вентилятор охолодження

Разработана методика оптимизации тепловых режимов и параметров системы охлаждения асинхронных тяговых двигателей трамваев. Оптимизированы режимы работы по критерию эффективности. Режимы движения по установленному графику и профилю на участке пути оптимизированы по критерию расхода энергии методом Гамильтона-Якоби-Беллмана. Оптимизированы параметры вентилятора тяговых двигателей по критерию эффективности системы охлаждения методом Вейля

Ключевые слова: трамвайный вагон, асинхронный двигатель, оптимальные режимы работы, вентилятор охлаждения

1. Introduction

The processes of energy conversion in the traction engines of tram carriages are accompanied by its losses in the elements of design due to physical processes at energy conversion [1, 2]. Temperature of the elements of design of traction engines increases over the time of operation and can exceed permissible structural limits [2, 3]. This is especially true for temperature of the insulation of the motor windings, which is constrained by a class of the applied insulation [3, 4]. To reduce temperature in the elements of design of engines, the cooling systems are employed that increase the efficiency of heat exchange in the engine design elements through the application of ventilation by air [5, 6], by wa-