

Визначено фактори, які виникають під час дугового розряду, та визначено можливість використання для прискорення роботи захисту від дугового замикання. Це дає можливість створення комбінованого пристрою для точного визначення місця дугового розряду. Зокрема, може бути розширено спектр чутливості оптичного датчика за рахунок використання ультрафіолетового випромінювання без його заміни.

Розглянуто можливість прискорення спрацьовування захисту від дугового замикання за рахунок відмови від його блокування з релейними схемами максимального струмового захисту та зменшення впливу сонячного випромінювання на роботу ЗДЗ (захисту від дугового замикання).

Обґрунтовано можливість розроблення більш досконалого пристрою для захисту від дугових замикань, який дозволяє розширити спектр оптичного датчика в область ультрафіолетового випромінювання.

Запропоновано вирішення задачі підвищення чутливості захисту від дугового замикання. Це можливо шляхом перетворення ультрафіолетового випромінювання у видиму частину оптичного спектру, що дозволить розширити спектр чутливості оптичного датчика в область ультрафіолетового випромінювання і відповідно дасть можливість підвищити його чутливість. Це пов'язано з тим, що 70 % випромінювання дугового розряду припадає на область ультрафіолету і тільки по 15% на видимий та інфрачервоний спектр оптичного випромінювання.

Отримані результати дають підстави стверджувати щодо можливості втілення у реальне промислове виробництво пристрою комбінованого захисту для визначення місця дугових замикань, а також розширення спектральної чутливості оптичних датчиків. Також розроблено комбінований пристрій для визначення місця дугового розряду за рахунок використання ультразвукової системи. Відомі розробки, які присвячені визначенню місця дугового розряду шляхом порівняння інтенсивності сигналу від спалаху на обох кінцях десятиметрового світлопроводу, відрізняються тим, що максимальна різниця часу надходження сигналів від точки спалаху до датчиків на кінцях світлопроводу становить 5нс. Це дуже низький часовий рівень у порівнянні довжини світлопроводу з швидкістю світла 300000 км/с.

Запропонована в даній роботі система, у якій для визначення місця дугового розряду використовується швидкість звуку, яка досягає 342 м/с, значно спрощує пристрій вимірювання часу для визначення місця короткого замикання та підвищує точність вимірювання часу на три порядки (103)

Ключові слова: захисту від дугового замикання, чутливість захисту, спектр випромінювання, перетворення ультрафіолетового випромінювання

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DESIGNING A COMBINED DEVICE FOR DETERMINING THE PLACE OF ARC DISCHARGE

R. Parkhomenko
Senior Lecturer*

E-mail: parchom@i.ua

O. Aniskov
Assistant*

Y. Tsibulevsky

PhD, Associate professor
LLC "Rudpromgeofizika"

Kryvbasivska str., 54, Kryvyi Rih, Ukraine, 50000

O. Melnik

PhD, Associate professor*

O. Shchokina

Senior Lecturer*

O. Kharitonov

Lecturer

Ukrainian Polytechnic College

Karla Marksa ave., 66, Kryvyi Rih, Ukraine, 50000

O. Kryvenko

PhD, Associate Professor, Senior Researcher
Research Institute of Labor Safety and Ecology in Mining
and Metallurgical Industry

Pershotravneva str., 12, Kryvyi Rih, Ukraine, 50000

O. Omelchenko

PhD

Department of general engineering disciplines and equipment

Donetsk National University of Economics and Trade named
after Mikhail Tugan-Baranovsky

Tramvayna str., 16, Kryvyi Rih, Ukraine, 50005

V. Chorna

PhD

Department of systems of

power consumption and energy management

Kremenchuk Mykhailo Ostrohradskyi National University

Pershotravneva str., 20, Kremenchuk, Ukraine, 39600

S. Tsvirkun

PhD

Department of Radiotechnics and Electromechanics

Krivorizky College of the National Aviation University

Tupolieva str, 1, Kryvyi Rih, Ukraine, 50045

*Department of power supply and energy management

Kryvyi Rih National University

Vitaliya Matusevycha str., 11, Kryvyi Rih, Ukraine, 50027

1. Introduction

Arc short circuits arise in complete distributive devices because of electrical breakdown of isolation between phases or between phases and earth. The spark is a short-circuited breakdown, and the arc is a continuous isolation breakdown at which a load supports current of leakage. At the same

time, temperature rises sharply; there is a sound shock wave, a light flash and electromagnetic radiation. A pillar of an electric arc can move along power lines at a speed up to 200 m/s, an amplitude of arc strength varies with a frequency of 100 Hz [1]. Arc circuits for up to 100 ms do not pose a high risk for equipment and personnel at 90 %, a discharge of $t < 1$ mc does not represent a threat at all [2], but if discharge

time increases, it can lead to considerable damage [3]. Burns from an electric arc caused 1,710 injuries according to the US statistics from 1992 to 2001 [4]. An arc-resistant wall between adjacent cells serves as passive arc protection used, but the mesh barrier of old cells will not provide necessary protection.

Possibility of acceleration of response of protection against arc circuit can significantly reduce a number of injuries from arc circuits in power supply systems. We determined factors that arise during the arc discharge and the possibility of using to accelerate response of protection against arc circuit in this study. This enables creation of a combined device for accurate determination of the location of an arc discharge. In particular, we will be able to extend a spectrum of sensitivity of an optical sensor by using ultraviolet radiation without its replacement.

2. Literature review and problem statement

Degradation of insulation is one of the most common reasons for failure of electrical components [5]. Experiments proved that a partial discharge is a reliable indicator. Its early diagnosis gives possibility to avoid a complete breakdown of an affected component of a power supply system. Usual measurement systems of partial discharges have some difficulty in measuring, especially in online environments and in noisy environments [6].

Consequences of a breakdown of insulation are well known. The trend implies a transition from conventional stand-alone testing to online monitoring to forecast an isolation resource, which results in the inclusion of high-frequency noise in trapped signals [7].

However, statistics show that it is not always possible to prevent accidents at a stage of partial discharges. Partial discharges often pass into a stage of arc circuits with a complete blocking of isolation with the development of a process of degradation of insulation. At this stage, it is necessary to use sensors to detect an electrical isolation breakdown to prevent further development of an accident. A document [8] provides a technological review of arc protection in distributive devices with an air-insulator. It covers the entire range from design aspects of distributive devices to the ultra-quick removal of an arc. A work [9] presents an assessment of a risk of an arc discharge in an electricity distribution system, including generation sources (GS).

There are four groups of sensors used to detect an electrical isolation breakdown [1]:

1. Protections in a function of pressure. Valve protection with end switches on pressure relief valves. Membrane protection, pneumatic switch with membrane tubes. Both protections are simple and cheap but hermiticity of a cell is necessary. In addition, mechanical protective devices do not fix an arc itself, but effects that arose after emergence of an electric arc. The valve protection works reliably on the short-circuit current $I > 3.5$ kA only.

2. Temperature protection. The disadvantage of protection is the need to position a sensor directly near arc discharge location, which necessitates installation of a large number of sensors in each cell.

3. An antenna sensor, which responds to ionization of air directly near a place of an arc discharge, is also not suitable for control of extended elements. There is a design

of a grounded antenna sensor that pulls an arc plasma into itself [5].

4. Optical sensors. Separate photocells or circular lenses, they send a signal through optical fiber to a detector unit or an open fiber-optic sensor without isolation of a length of 30–60 m, which covers the volume of several cells as a loop. The disadvantage of optical sensors is their false response to sunlight or to brilliance of an arc of an electric welding machine. Because there are many false responses of arc protection devices, additional relays of maximum current protection or error detectors on current transformers 1A/5A block them [4]. We believe that minimum condition for occurrence of an unstable arc is a current of about 0.5 A and a voltage of 15–20 V.

In addition to the above properties, sound, electromagnetic and gamma-radiation accompanies an arc discharge, and an explosion occurs at high discharge power.

We need to resolve the problem of acceleration of response of protection against an arc circuit. This is possible due to refusal of its blocking with relay circuits for maximum current protection and reducing of an influence of solar radiation on operation of PAC (protection against arc circuit).

The faster we detect and eliminate an arc, which arises in distributive devices, the less is a risk to receive a serious injury or death for personnel [10]. Other benefits of minimization of welding time include reducing of additional damage, reducing of downtime, and, consequently, reducing of requirements for individual protection means (IRM).

Typically, at registering of an arc discharge, photo thyristors record a narrow part of a visible optical spectrum at the infrared boundary. A time difference between moments of a light impulse coming to ends of a light guide determines location of an arc discharge. This causes low accuracy of determination of an arc discharge point.

A base of one of the new methods for detection of a fault type of an arc circuit in an AC electrical installation is a use of a single-phase active power filter (APF) [11]. The results obtained in this study show that it is possible to detect a series of arc disruptions using APF only by updating its digital control with a function of arc fail detection, instead of designing of a special arc failure detector ab origin.

Thus, we have to solve the problem of increasing of sensitivity of protection against arc circuit now. But it is possible by converting ultraviolet radiation into a visible part of the optical spectrum, which will make it possible to expand the spectrum of the optical sensor into the region of UV radiation and, accordingly, will increase its sensitivity.

3. The aim and objectives of the study

The objective of the study is to develop a combined optical sensor for arc protection, which means to determine a sound and optical spectrum radiated with arc discharges, which will enable to increase sensitivity of a device to protect against arc circuits.

We set the following tasks to achieve the objective:

- expansion of a sensitivity range of an optical sensor;
- development of a device for simultaneous measurement in ultraviolet, infrared and optical spectra;
- development of a device for a combined use of light and sound radiation of an arc discharge for determination of the place of appearance of an arc discharge.

4. Investigation of the optical spectrum of an arc discharge

Chemical elements radiate a spectrum, which is characteristic for each individual element, at combustion. We can obtain these spectra by combustion in an acetylene-air flame, or in conjunction with an electric arc, or at interaction with an electric spark. Large atlases of arc and spark optical spectra present these data, which proved to be very useful for decoding results of the optical research of an electric arc. Table 1 shows spectral lines for several chemical elements that are capable of being exposed to an electric discharge at a substation or at a distribution point [12]. We choose the six most commonly used elements for a detailed analysis. They are aluminum, tungsten, iron, copper, nickel and lead. Table 1 shows that the bulk of (15 sensitive lines) has an ultraviolet portion of the spectrum with wavelengths <380 nm, while a visible part (a background) of radiation consists of numerous low-intensity lines, as well as radiation of flame combustion products up to 670 nm. Fig. 1 shows total spectral characteristics. The spectrum of characteristics has an interval of 50–100 nm, and the interval in the region of the maximum is 10–20 nm. The analysis of the spectra showed that for quick detection of a spark discharge before it switches to an arc discharge it is necessary to choose an optical detector sensitive to ultraviolet radiation.

Existing arc circuit protection schemes have silicon photovoltaic cells. This is because the maximum of their differential characteristic falls on the maximum radiation of a flame of an electric arc in the region (0.7–1.1) nm. Basically, these are receivers with an internal amplification of the photocurrent: avalanche photodiodes, phototransistors, field phototransistors and photo thyristors, which became widely used in arc circuit protection schemes.

It is convenient to investigate an arc discharge electric welding machines. There are three spectra of ultraviolet radiation: UV-A (315–400) nm, UV-B (280–315) nm, UV-C (200–280) nm. At the same time, the most rigid is UV-C, which has an intensity of radiation up to 5 W/m² at a current of 200 A, which is harmful to a person at a distance larger than 60 meters [13]. The welding arc discharge spectrum consists of 70 % ultraviolet, 15 % visible and 15 % infrared radiation.

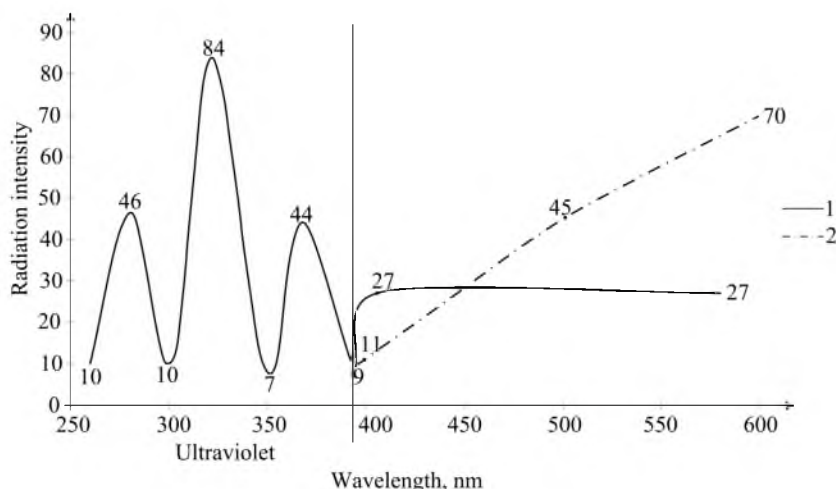


Fig. 1. Total spectral characteristics: 1 – spark and arc spectra of radiation of selected metals; 2 – spectral characteristic of relative sensitivity of a silicon photocell

Table 1
Wavelengths of radiation of arc and spark spectra of individual chemical elements [12]

Chemical element	Number of lines		Sensitive lines, nm	Intensity
	Arc	Spark		
Aluminum Al	23	19	308.2	8
			309.2	9
			394.4	9
			396.1	10
Hydrogen H ₂		1	656.2	(2,000) – Spark
Tungsten -W	34	49	289.6	7
			294.4	7
			291.6	7
			400.8	6
Iron Fe	15	10	259.9	10
			302.0	9
			358.1	9
			371.9	9
Copper – Cu	74	68	324.7	>10
			327.3	>10
Nickel – Ni	73	57	341.4	9
			349.2	7
			352.4	9
Tin – Sn	45	45	283.9	10
			300.9	10
			303.4	10
			317.5	10
			326.2	9
Lead – Pb	39	39	280.2	8
			283.3	8
			405.7	8
Carbon – C	1	12	247.8	400

The UV-C spectrum with a wavelength below 280 nm is absent in solar radiation on the Earth's surface [14]. Because the fact that the ozone layer absorbs this part of the spectrum completely and does not reach the surface of the Earth. There are wide-band materials based on gallium phosphide, nitrides of gallium and aluminum, flint carbide and diamond used for sensors of “hard” UV radiation. But mentioned devices are not widespread in the real cells or distribution points due to their high cost and insufficient information in technical literature. Therefore, we choose photochromic materials, crystallophosphors or fluorescent dyes for transition of non-visible ultraviolet radiation into the region of the visible optical spectrum. Typically, spectral shifts lie between an ultraviolet part and visible parts of the spectrum. The higher the power of radiation, the faster an output photoform will pass from an ultraviolet part to a visible part of the optical spectrum.

We chose photo thyristors TF 132-25-10 type for further research, which are used in protection schemes against

arc circuits for more than 20 years. Time of protection response is 10^{-5} sec. Nominal current is 25 A, voltage is 1,000 V. Power of a controlling light flow is from 1.0 to 1,000 MW.

Photo thyristors have a number of advantages over other semiconductor optical sensors, such as high load capacity at low power of a control signal, ability to memorize after removal of a control signal, high speed, and high sensitivity.

We selected the incandescent lamp BK 215-225-60 type with a voltage of 220 V and a power of 60 W with a light flow of 750 lm to record characteristics of a photo thyristor in a visible and infrared spectrum. A manufacturer recommends a similar lamp to control response of photo thyristors on a light signal. A photo thyristor starts operation from the light of a 60-watt lamp at a distance of 10 cm when powered by 12 Volts of direct current.

We used a red fluorophore dye to convert ultraviolet radiation of an arc discharge into a spectrum to which a sensitive photo thyristor is sensitive. We chose a mercury lamp with a bulb with UFS-3 light filter as a source of ultraviolet radiation. The resonance line of mercury has a wavelength of 253 nm. Lumino-phore covered the body of the lamp from the inside. It emits waves of (300–400) nm with a maximum of 350 nm. Fig. 2 shows excitation of the spectrum of fluorophore.

Fig. 3 shows location of devices during recoding of photo thyristor light characteristics

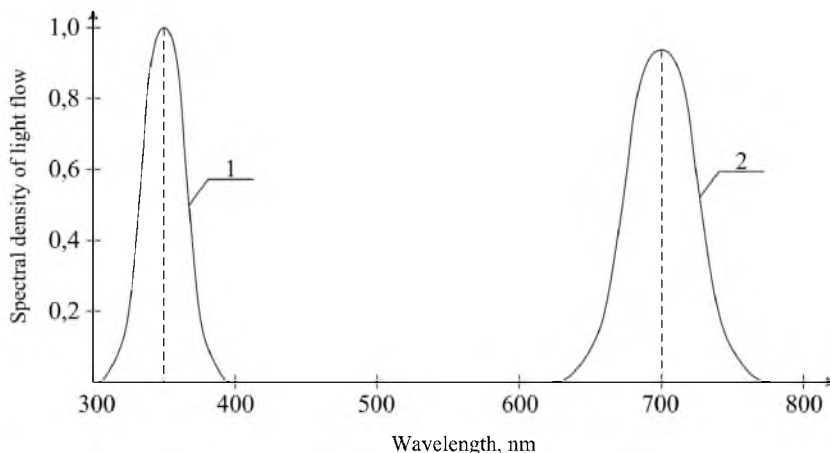


Fig. 2. Dependence of intensity of radiation on a wavelength: 1 – spectrum of mercury lamp; 2 – spectrum of radiation of fluorophore

Curve on Fig. 4 illustrates characteristics of the control of photo thyristor: from the threshold minimum of insensitivity to lighting to the minimum threshold resistance of the photo thyristor switching on. The control area is between the curve and the coordinate axes. The greater illumination of a light input of the photo thyristor, the less its resistance: switching on current remains constant, and the voltage decreases to almost zero. A light flow from fluorophore causes an additional reduction of internal electrical resistance, which increases sensitivity of the photo thyristor.

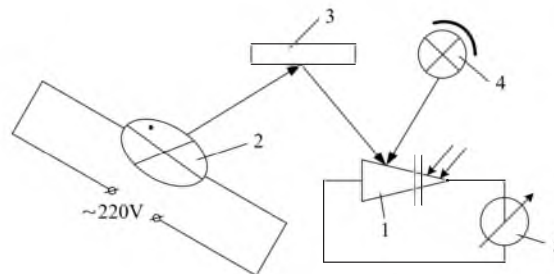


Fig. 3. Location of devices for recoding of light characteristics of a photo thyristor: 1 – photo thyristor; 2 – source of ultraviolet radiation; 3 – fluorophore; 4 – incandescent lamp; 5 – measuring equipment

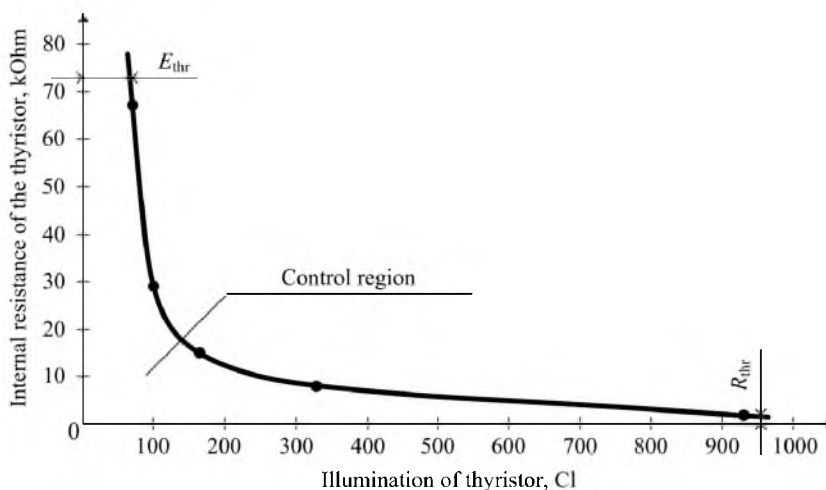


Fig. 4. Dependence of internal electrical resistance of the photo thyristor on a magnitude of a light flow, where E_{thr} is a threshold of illumination, Cl; R_{thr} – internal threshold resistance of the thyristor, kOm

We can determine a light flow emitted by fluorophore under the action of ultraviolet radiation by the expression

$$\Phi_{ef} = \int_{\lambda_1}^{\lambda_2} \phi_r(\lambda) \cdot \alpha(\lambda) \cdot \eta_e(\lambda) \cdot d\lambda, \quad (1)$$

where $\phi_r(\lambda)$ is the function of spectral density of the flow of fluorophore excitation; $\alpha(\lambda)$ are the spectral values of an absorption coefficient of fluorophore; $\eta_e(\lambda)$ are the spectral values of an energy output of fluorophore; λ_1 and λ_2 are the limits of the spectrum of excitation.

We can see from formula (1) that the light flow of fluorophore is a function of spectral density of an excitation flow from a source of ultraviolet radiation. The formula provides an opportunity to determine a light flow from a specific fluorescent surface, depending on efficiency of converting the ultraviolet radiation of an arc discharge into a visible part of the optical spectrum.

5. Investigation of the electromagnetic spectrum of arc discharge radiation

Transient processes, impulse overvoltage, current throttles accompany an arc discharge. A prerequisite for

formation of powerful electromagnetic waves is a sufficiently high frequency of electrical oscillations. Necessary much higher frequencies than 50Hz of industrial frequency. The electromagnetic spectrum of an electric welding arc has three resonance bands; their centers are at a frequency of 750 kHz, 3 MHz, and 20 MHz [13, 14]. Absorbing pincers and vertically polarized antennas are used at a height of 3 m and at a distance of up to 10 m (GOST 11001-69) to control interferences of arc discharge for radio communications. Measuring takes place at a distance of 20 m from the extreme wire on air lines. Electromagnetic radiation of a corona discharge of an air line is 0.154–100 MHz. We should note that its own resonance frequency of an oscillatory circuit depends on a magnitude of its reactive resistance and can reach 5–100 kHz. We can calculate a period of resonant frequency of a power line by the formula

$$T = 2\pi\sqrt{L \cdot C}, \text{ s}, \tag{2}$$

where L is the inductance in H, and C is the capacitance in μF .

Based on the analysis of given data we can conclude that the electromagnetic spectrum of an arc discharge is not suitable for diagnostics of an arc discharge at high frequencies because it is impossible to determine precisely a place where an arc discharge occurs. However, we can control it at low frequencies, when the power of an electric arc changes with doubling frequency of the supply voltage (100 Hz), and the electromagnetic field is more local in nature.

The disadvantage of the method is that the electromagnetic field of each power supply depends on load capacity of surrounding transformers, tires, and adjacent cell lines. We used a wavelength meter of a bridge type to determine electromagnetic parameters of an arc discharge. Fig.5 shows its functional diagram.

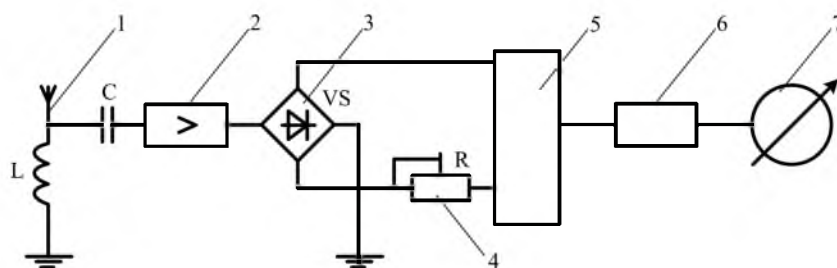


Fig. 5. Functional diagram of a wavelength meter

The wavelength meter consists of ultra-high frequency antenna 1, which is connected to diode bridge 3 via aperiodic amplifier 2, one of which has amplitude detector 5 connected to the output at which galvanometer 7 is connected through repeater 6. Before starting measurements, the wavelength is set to zero using potentiometer 4.

We used arc discharges of a welding transformer (voltage 60 V, current 100 A), electrical lighters for gas appliances, a high-voltage battery (voltage 4,500 V), and a pulsed photoluminescope (power 100 W) as arrays of electromagnetic radiation. We determined that intensity of electromagnetic radiation of an arc discharge is directly proportional to the power of a radiation source.

6. Investigation of the sound spectrum of arc discharge radiation

A level of arc discharge sound pressure can reach more than 140 dB. Electrical spark discharges, which are accompanied by hiss, are a manifestation of waves of the ultrasound range. Ultrasonic waves are very similar to sound ones and differ from them only by frequency because they occupy a frequency range above 20 kHz. Discharge activity of ultrasonic oscillations is particularly manifested in the frequency range (37–43) kHz at wavelength (100–400) nm. For measurements, piezoelectric structures, which have the required resonant frequency in the range of ultrasound, are used [14]. The advantage of ultrasound is a greater direction of radiation than in sound, which has properties close to light radiation. If we know velocity of light and sound waves, measurement of a time difference gives possibility to calculate a distance to an electric arc that caused their appearance accurately.

Microphones are the most commonly used devices that convert sound into an electrical signal: electrodynamic, tape, condenser and electromagnetic ones. For acoustic measurements, the most suitable is MK-6 non-directional condenser microphone: frequency 40,000 Hz, sound pressure level 9 dB. According to the National Standard of the Russian Federation GOST R55191-2012 (IEC 60270: 2000) High voltage test methods: “Partial discharge measurements: we cannot use acoustic and optical methods to determine quantitative characteristics of partial discharges: only to determine location of partial discharges. An arc discharge can emit sound with the frequency of industrial electric current.” In comparison, in Ukraine there is an intergovernmental standard “Electrical equipment and electrical installations of the voltage of 3 kV and above. General methods for testing of electrical strength of insulation”, which started its action as a state standard of Ukraine by the order of the State Standard of Ukraine of June 18, 1999, No. 354 as of 01.01.2000. This standard establishes general methods for testing of isolation of electric equipment by the voltage of lightning and switching impulses, short-term alternating voltage, constant voltage, conditions for conduction of these tests and requirements for an object of the test, as well as recommendations for the evaluation of test results.

Work [15] considers determination of location of an arc discharge by comparison of intensity of a signal from a flash on both ends of a ten-meter light conductor.

The maximum time difference between arrivals of signals from the point of flash to sensors at the ends of the lightning conductor is 5ns. This is a very low temporal level compared to the light conductor of a light velocity of 300,000 km/s. In contrast to this, the system proposed here has the feature that velocity of sound, which reaches 342 m/sec, determines arc discharge location, which simplifies a device for measurement of time and determination of the damaged cell greatly.

We install a relay for arc protection in a cell, which contains a tire system A, an electric cable of “ l ” length, a high-voltage switch Q, which is disconnected by YAT electromagnet. PAC consists of a piezoelectric ultrasound sensor US, a flash sensor in the form of several photo thyristors PT,

a timer T, a logic element "I". The US sensor is mounted in a focal cone under the cell's ceiling. Optical input of photo thyristors can be connected to open optical light conductors.

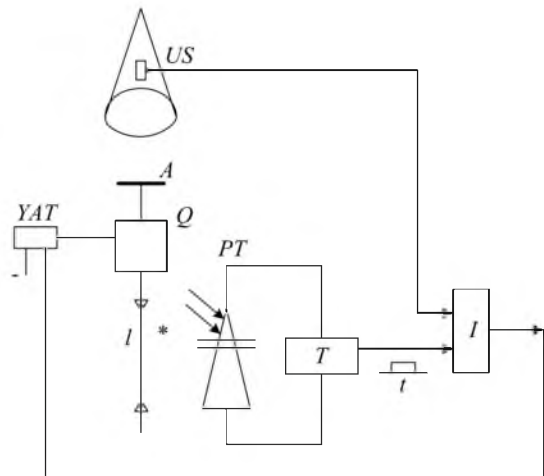


Fig. 6. System for determination of location of an arc discharge: A – tire system; Q, YAT – high-voltage switch with a disconnecting electromagnet; /– power cable; PT – photo thyristor; T – timer; I – logic element, US – ultrasound sensor; t – impulse length of a timer

The device works as follows: we set an impulse length [t] to the timer T. The length is equal to the time necessary for ultrasound to reach US sensor from the bottom of the cell, the output of which is connected to the input of the logical element "I".

In the case of an electric discharge appearance in the middle of the cell, the signal from flash sensors PT enters the timer T input, which outputs a signal by length "t". If the signal from the acoustic sensor US enters the logic element "I" at the same time as the "t" signal, then the system triggers and disconnects the high-voltage switch Q via its YAT electromagnet. If the signal from the acoustic US sensor arrives at the end of the timer signal "t", then the system does not react to it because it is a sound signal from a third party object. The system will not respond to sunlight and an electric arc of a welding machine because their appearance is not accompanied by a synchronous ultrasonic signal at a frequency of 20–50 kHz.

7. Investigation of radioactive radiation of an arc discharge

We know that gamma quanta appear as a result of corona discharges and arc discharges. The basic sanitary rules of Ukraine allocate a whole class of radio-electric devices with unused X-rays. This class includes welding, melting, zone cleaning materials, electronic microscopes, and others. We expect an output of X-rays at a voltage of 10 kV or more. Table 2 shows the dependence of the power of the exposure dose on supply voltage.

We tested the arc of a 150-ampere welding device was for gamma-quantum radiation using a dose-radiometer of MKS-03D «Strizh» type (factory number of the device 27). In the range of 0.1 μSv/h to 0.1 Sv/h, determination error of the dose does not exceed 15 %. Dosimetric control did not detect a significant deviation of gamma radiation of the

welding arc from background radiation. We obtained data using the specified device.

Table 2

Dependence of the power of the exposure dose on supply voltage

Voltage, kW	10–30	30–50	50–100	100–150
Power of exposure dose, μR/s	3 · 3·10 ²	30·10 ²	3·10 ³	10 ⁵

8. Discussion of the results of investigation of the spectrum of radiation of arc circuits

Investigation of the optical spectrum of radiation of metals under the action of an arc discharge showed that 70 % of the radiation falls on the ultraviolet part and 15 % on the visible and infrared parts of the spectrum [14]. Arc protection sensors are made based on silicon semiconductors that do not react to ultraviolet light because their maximum sensitivity is in the infrared zone and in the visible optical spectrum [16]. We used fluorescent dye to convert ultraviolet radiation into the spectrum of visible arc protection sensors, which, under the action of UV radiation, glowed in red light. We used an electric lamp as an UV source. Radiation of fluorophore under its action increased a signal at the output of the photo thyristor by 15 %. We can explain low efficiency of the proposed method by the fact that the power of the ultraviolet lamp was 10 times less than the power of the incandescent control lamp.

The author's development differs by the method for determination of contribution of converted ultraviolet radiation to the visible part of the spectrum, which gives an additional reduction of internal resistance of the photo thyristor and, accordingly, increases its sensitivity when we introduce a fluorescence screen. Authors of works [14] and [16] developed ultraviolet sensors that do not react to the visible part of the spectrum.

Investigation of the sound spectrum of an arc discharge.

Propagation of sound oscillations is in the inverse quadratic dependence of wave frequency. Ultrasound has a property of direction. Based on these two parameters, we used ultrasound to localize location of an electric discharge. When we know velocity of sound and light, it is quite easy to determine a distance to an arc discharge location by the difference in time of receipt of these two signals. Fig. 6 presents a functional diagram for detection of a single cell, where an arc discharge appears. The mentioned features of the scheme simplify the device for measurement of time to determine short-circuit location and increase accuracy of measurement of time by three orders (10³).

Investigation of radioactive radiation of an arc discharge.

We know that gamma-quantum appear due to corona and arc discharges, as well as at operation of powerful welding machines. Gamma radiation of powerful electrical installations becomes noticeable at a voltage over 10 kV. Uneven scattering of gamma quanta-quantum, in dependence on the location geometry of equipment and an effective atomic number of scattering surfaces, makes difficult to use gamma radiation to determine location of an arc discharge. In addition, it is necessary to take into account complexity of equipment, its dependence on vibration, an influence of atmospheric conditions and the electromagnetic field.

We proposed the solution of the problem of increasing of sensitivity of protection against arc circuit. This is possible by converting the ultraviolet radiation into the visible part of the optical spectrum, which will expand the spectrum of sensitivity of the optical sensor to the region of ultraviolet radiation and, accordingly, will increase its sensitivity. This is because of the fact that 70 % of radiation of an arc discharge falls on the region of ultraviolet radiation and only 15 % on the visible and infrared spectra of optical radiation.

The disadvantage of the development is a lack of tests on real power supply lines at high arc discharges. Lack of substantiation for choice of fluorophore; in terms of maximum light output. We did not select location of the photo sensor in cells, but there are works, which elaborate this issue [17]. In the future, it is necessary to use devices that control the state of electric isolation under voltage, which greatly reduces possibility of arc discharges [18].

9. Conclusions

1. We developed the method of expansion of the optical range of sensitivity of photo sensors by means of registra-

tion of an additional light flow from fluorophore, which causes additional reduction of internal electrical resistance and promotes increase of sensitivity of photo thyristor. We determined the necessary optical range of photosensitivity of photosensors and proved possibility of its expansion in the UV range. We obtained a characteristic of a photo thyristor control: from the threshold minimum of insensitivity to illumination to the minimum threshold resistance of the switching on the photo thyristor. The greater illumination of the light input of the photo thyristor, the less its resistance: switching on current remains constant, and the switching on voltage decreases to almost zero.

2. We developed a device for simultaneous control of transformed ultraviolet, visible, and infrared optical radiation by one sensor. We used a screen covered with fluorophore to convert UV radiation of an arc discharge to the spectrum, to which the photo thyristor is sensitive.

3. We developed a device with combined use of light and sound radiation of an arc discharge. It uses the velocity of sound, which is three orders of magnitude less than the velocity of light, to determine location of an arc discharge, which simplifies a device for time measurement and determination of location of short circuit greatly.

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ANALYSIS OF INRUSH CURRENTS OF THE UNLOADED TRANSFORMER USING THE CIRCUIT-FIELD MODELLING METHODS (p. 6-11)

Dmytro Yarymbash

Zaporizhzhia National Technical University, Zaporizhzhia, Ukraine

ORCID: <http://orcid.org/0000-0003-2324-9303>

Serhiy Yarymbash

Zaporizhzhia National Technical University, Zaporizhzhia, Ukraine

ORCID: <http://orcid.org/0000-0003-4661-7076>

Mykhailo Kotsur

Zaporizhzhia National Technical University, Zaporizhzhia, Ukraine

ORCID: <http://orcid.org/0000-0002-0072-5437>

Tetyana Divchuk

Zaporizhzhia National Technical University, Zaporizhzhia, Ukraine

ORCID: <http://orcid.org/0000-0002-9947-8527>

We studied theoretically the transition processes that occur during tests of power transformers in the mode of experimental idling. A circuit-field model of electromagnetic processes is developed, based on a three-dimensional dynamical model of the magnetic field in a three-phase power transformer at idling.

Using a finite element method, we divided the region of field simulation into estimated zones with the magnetic field symmetry conditions for vertical and horizontal cross sections. The number of finite elements and the time for computing was reduced by four times without compromising the accuracy of our results.

It was established that in the circuit of the windings, connected into a triangle, there occurs a transitional levelling current, which fades over the initial switching time. The multiplicity of this current may reach 60–70 % of the multiplicity of the input surge current.

We have developed relations for the approximation of transitional phase currents, which are represented by the aperiodic, periodic components and series with the basis Gaussian functions for phase current discrepancies between the circuit-field and circuit models.

We have proposed and implemented a refined approach for the calculation of input surge current based on the specifications for an idling mode of the transformer and a surge current coefficient, which is characterized by the high efficiency and accuracy of numerical realization.

To determine a functional dependence of the multiplicity coefficient for an input surge current on the input resistances, we applied a method of sorting out specialized functions. The approximation coefficients calculation was carried out based on the method of least squares. This allowed us to significantly reduce the level of error when calculating the multiplicity coefficient of input surge current based on the specifications of the transformer and testing equipment, by 2.1 %.

Using the 3D modeling reduces the calculation error of idling mode current surges by 2.4 % using a simplified procedure that employs specifications of the transformer.

Keywords: circuit-field model, three-phase transformer, idling mode, magnetization inrush currents.

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DESIGNING A COMBINED DEVICE FOR DETERMINING THE PLACE OF ARC DISCHARGE (p. 12-18)

Roman ParkhomenkoKryvyi Rih National University, Kryvyi Rih, Ukraine
ORCID: <http://orcid.org/0000-0003-1770-1631>**Olexandr Aniskov**Kryvyi Rih National University, Kryvyi Rih, Ukraine
ORCID: <http://orcid.org/0000-0001-9605-2304>**Yuri Tsibulevsky**LLC «Rudpromgeofizika», Kryvyi Rih, Ukraine
ORCID: <http://orcid.org/0000-0002-2032-2782>**Olga Melnik**Kryvyi Rih National University, Kryvyi Rih, Ukraine
ORCID: <http://orcid.org/0000-0002-7517-6815>**Olga Shchokina**Kryvyi Rih National University, Kryvyi Rih, Ukraine
ORCID: <http://orcid.org/0000-0002-0275-8646>**Olexander Kharitonov**Ukrainian Polytechnic College, Kryvyi Rih, Ukraine
ORCID: <http://orcid.org/0000-0002-4638-6055>**Oleksii Kryvenko**Research Institute of Labor Safety and Ecology in Mining and Metallurgical Industry, Kryvyi Rih, Ukraine
ORCID: <http://orcid.org/0000-0001-9186-9104>**Oleksandr Omelchenko**Donetsk National University of Economics and Trade named after Mikhail Tugan-Baranovsky, Kryvyi Rih, Ukraine
ORCID: <http://orcid.org/0000-0003-0704-5909>**Viktorii Chorna**Kremenchuk Mykhailo Ostrohradskyi National University, Kremenchuk, Ukraine
ORCID: <http://orcid.org/0000-0003-3641-4152>**Sergij Tsvirkun**Krivorizky College of the National Aviation University, Kryvyi Rih, Ukraine
ORCID: <http://orcid.org/0000-0001-5430-3427>

We determined factors that arise during an arc discharge and detected possibility of their use to accelerate protection against arc closure. This enables creation of a combined device for accurate determination of an arc discharge. In particular, we can expand the spectrum of sensitivity of an optical sensor by the use of ultraviolet radiation without its replacement.

We considered possibility of acceleration of response of protection against arc closure operation due to refusal of its blocking with relay circuits for maximum current protection and reduction of an influence of solar radiation on operation of PAC (protection against arc closure).

We substantiated possibility of development of a more advanced device for protection against arc circuits, which gives possibility to expand the spectrum of the optical sensor in the region of ultraviolet radiation.

We proposed the solution of the problem of increasing of sensitivity of protection against arc closure. This is possible by converting the ultraviolet radiation into a visible part of the optical spectrum, which will expand the spectrum of sensitivity of the optical sensor to the region of ultraviolet radiation and, accordingly, increase its

sensitivity. This is due to the fact that 70 % of an arc discharge radiation falls on the ultraviolet region and only 15 % on the visible and infrared spectra of the optical radiation.

The obtained results give grounds to assert about possibility of realization of a device of combined protection for determination of arc circuits in industrial production, as well as expansion of spectral sensitivity of optical sensors. In addition, we developed a combined device for determination of an arc discharge through a use of an ultrasound system. Known developments devoted to determination of location of an arc discharge by comparing intensity of a signal from a flash at both ends of the ten-meter optical light conductor are characterized by the fact that the maximum difference between the arrival time of signals from a flash point to sensors at the ends of the optical fibers is 5ns. This is a very low temporal level compared to the light conductor length at the velocity of 300,000 km/s.

The system proposed in this study uses the sound velocity, which reaches 342/s, to determine an arc discharge, which simplifies a time measurement device for determination of a short circuit greatly and increases accuracy of time measurement by three orders of magnitude (10^3).

Keywords: protection against arc circuit, protection sensitivity, radiation spectrum, ultraviolet radiation transformation.

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DEVELOPMENT OF DIODE TEMPERATURE SENSORS WITH OPERATING RANGE UP TO 750 K (p. 19-25)

Vasily Krasnov

V. E. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, Kherson, Ukraine

ORCID: <http://orcid.org/0000-0002-7019-5769>

Sergey Yerochin

V. E. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, Kherson, Ukraine

ORCID: <http://orcid.org/0000-0003-1719-3016>

Oleksii Demenskiy

V. E. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine, Kherson, Ukraine

ORCID: <http://orcid.org/0000-0003-3893-3861>

Gennadii Krapyvko

Kherson state maritime academy, Kherson, Ukraine

ORCID: <http://orcid.org/0000-0002-8165-1213>

The problem of expansion of the range of functioning of diode thermosensors in the region of high temperatures is considered and some of the results of the author's research in this area are given. To solve this problem, it is proposed to use diode structures based on wide bandgap semiconductor compounds in the III-V system. The technological method of producing prototypes of high-temperature diode temperature sensors based on GaP is developed. The presented method allows manufacturing samples of diode temperature sensors, the high-temperature limit of which exceeds the limit of functioning of commercial silicon diode temperature sensors by about 200–300 K. The experimental methods of obtaining epitaxial structures of solid solutions of AlGaAs and fabricating diode temperature sensors based on them are developed. It is shown that the approach chosen in this work allows extending the thermometric characteristics of such diodes in the high-temperature region by approximately 150–250 K. The paper presents the methodology for forming InGaN device structures and production of prototype high-temperature diode temperature sensors based on them. This technique with revisions can be used for the manufacture of diode temperature sensors and other devices for high-temperature applications, the entire range of solid solutions in the InN-GaN system. The parameters and characteristics of the obtained diode temperature sensors are investigated. The results of the research can be used by specialists in the field of electronics and optoelectronics in the development and production of semiconductor devices.

Keywords: diode temperature sensors, diode thermometry, thermometric characteristic, thermal sensitivity, liquid-phase epitaxy.

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DEVELOPMENT OF A MINIATURE MICROWAVE RADIOTHERMOGRAPH FOR MONITORING THE INTERNAL BRAIN TEMPERATURE (p. 26-36)

Mikhail Sedankin

Main research and testing robotics centre of the Ministry of defence of the Russian Federation (MRTRC), Moscow, Russia
ORCID: <http://orcid.org/0000-0001-9875-6313>

Daria Chupina

Bauman Moscow State Technical University, Moscow, Russia
ORCID: <http://orcid.org/0000-0002-4678-0298>

Sergey Vesnin

LLC "RTM Diagnostics", Moscow, Russia
ORCID: <http://orcid.org/0000-0003-4353-8962>

Igor Nelin

Moscow Aviation Institute, Moscow, Russia
ORCID: <http://orcid.org/0000-0003-0469-6650>

Victor Skuratov

VNIIRT, Moscow, Russia
ORCID: <http://orcid.org/0000-0003-1526-1505>

To improve efficiency of non-invasive monitoring of the internal brain temperature, a small-size single-channel microwave radiothermograph consisting of a miniature radiometer and a radiometric sensor based on a printed antenna was developed. Such solution is necessary to provide physicians with a system of non-invasive monitoring of diagnosis and treatment processes. Mathematical modeling and experimental verification of the technical solutions obtained are described in this paper. A miniature radiothermograph was developed. It is a balance modulation radiometer designed on the basis of the R. H. Dicke's circuit with two loads. Taking into account the requirements of miniaturization, a radiometric sensor was developed by means of numerical simulation. As a result of calculations, optimum antenna dimensions were determined (the

total size: $\varnothing 30$ mm, the size of the foil dielectric substrate: $\varnothing 23$ mm, dimensions of the emitter slot: $16 \text{ mm} \times 2 \text{ mm}$). According to the mathematical modeling, the depth of detection of thermal anomalies was not less than 20 mm for the printed antenna which is practically the same as for the waveguide antenna successfully used at present in brain radiometry.

The standing wave coefficient was determined for various head regions: frontal, temporal, parietal, occipital and the transient between the occipital and parietal regions. Experimental tests of the radiothermograph on water phantoms and biological objects have been carried out. A very good coincidence between the data of numerical simulation and the physical SWR experiment in a range of 1.04–1.8 was obtained. As a result of the study, it has been found that the radiothermograph with a printed slot antenna enabled measurement of internal brain temperature with an acceptable accuracy (± 0.2 °C). This will ensure control of craniocerebral hypothermia in patients with brain stroke and allow doctors to promptly change the hypothermia tactics. Small size of the created unit will make it possible to combine it with medical robotic systems to improve treatment effectiveness.

Keywords: microwave radiometry, temperature monitoring, printed antenna, medical radiothermograph, brightness temperature, medical robotics.

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ANALYSIS OF CONDITIONS FOR THE PROPAGATION OF INTERNAL WAVES IN A THREELAYER FINITE-DEPTH LIQUID (p. 37-46)

Yurii Hurtovyi

Volodymyr Vynnychenko Central Ukrainian State Pedagogical University, Kropyvnytskyi, Ukraine

ORCID: <http://orcid.org/0000-0002-1499-7089>

Volodymyr Naradovyi

Volodymyr Vynnychenko Central Ukrainian State Pedagogical University, Kropyvnytskyi, Ukraine

ORCID: <http://orcid.org/0000-0001-5187-8831>

Volodymyr Bohdanov

Volodymyr Vynnychenko Central Ukrainian State Pedagogical University, Kropyvnytskyi, Ukraine

ORCID: <http://orcid.org/0000-0001-7641-2616>

The problem of propagation of internal waves for an ideal incompressible fluid was considered. The hydrodynamic system consisted of three layers of a finite thickness that did not mix and were bounded with a solid cover from above and a solid bottom from below. The surface tension force acted on the interfaces of liquid media.

The problem was formulated in a dimensionless form. The nonlinearity coefficient equal to the ratio of the characteristic amplitude to the characteristic wavelength was used as a small parameter.

Solutions of the linear problem were sought in the form of progressive waves. On the basis of these solutions, the dispersion relation was obtained as a condition of solvability of the system of linear differential equations. Existence of two characteristic modes (the real roots of the dispersion relation) was revealed. The graphs of the roots of the dispersion relation were analyzed depending on various physical and geometric parameters of the system. It has been established that thickness of the layers did not affect dispersion of the waves while the change of the surface tension and the ratio of densities had a significant effect on the wave propagation conditions. Wave packets were considered in a linear formulation which was a superposition of harmonic waves of close lengths. It was found that amplitude of the envelope of the wave packet on the lower contact surface remained sinusoidal while it varied on the upper contact surface according to a more complicated law.

The problem of propagation of internal waves along the surface of three liquid layers can simulate a strongly stratified thermocline in the ocean. The study of influence of surface tension can also be used to develop new technologies associated with the use of three liquid layers that do not mix.

Keywords: ideal incompressible fluid, internal waves, three-layer hydrodynamic system, dispersion relation.

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EXPERIMENTAL INVESTIGATION OF THE FIRE-EXTINGUISHING SYSTEM WITH A GAS-DETONATION CHARGE FOR FLUID ACCELERATION (p. 47-54)

Kostyantyn Korytchenko

National Technical University “Kharkiv Polytechnic Institute”,
Kharkiv, Ukraine

ORCID: <http://orcid.org/0000-0002-1100-5435>

Oleksandr Sakun

National University of Civil Defence of Ukraine, Kharkiv, Ukraine

ORCID: <http://orcid.org/0000-0002-2964-071X>

Dmytro Dubinin

National University of Civil Defence of Ukraine, Kharkiv, Ukraine

ORCID: <http://orcid.org/0000-0001-8948-5240>

Yurij Khilko

National University of Civil Defence of Ukraine, Kharkiv, Ukraine

ORCID: <http://orcid.org/0000-0003-4185-8188>

Evgen Slepuzhnikov

National University of Civil Defence of Ukraine, Kharkiv, Ukraine

ORCID: <http://orcid.org/0000-0002-5449-3512>

Andriy Nikorchuk

National Academy of National Guard of Ukraine, Kharkiv, Ukraine

ORCID: <http://orcid.org/0000-0003-2683-9106>

Ivan Tseabriuk

National Academy of National Guard of Ukraine, Kharkiv, Ukraine

ORCID: <http://orcid.org/0000-0002-4246-8854>

To improve the parameters of pulsed fire-extinguishing plants for long-range and mass and dimensional indicators, it was proposed to replace the pneumatic propellant charge with the gas-detonation charge. The charge is formed based on the technical propane-butane mixture with oxygen, and detonation combustion of the mixture was achieved through the application of the electric discharge system of detonation initiation.

It was experimentally proved that the use of the gas-detonation charge instead of the pneumatic charge in pulsed fire-extinguishing plants makes it possible to improve their parameters. An increase in long-range of a water jet, which was achieved in the developed plant, decreases the impact of heat radiation on a rescuer, which ensures the feasibility of application of such systems for fighting large-scale fires. A decrease in gas pressure in cylinders due to transition from compression energy to chemical combustion energy ensures a decrease in the equipment weight and an increase in the number of shots with the extinguishing agent with the same dimensions of similar plants with the pneumatic charge. Specifically, in the plant with the gas-detonation charge, effective fire extinguishing distance, depending on the initial pressure of the charge within 0.1–0.3 MPa was from 8 to 19 meters for the mass of the extinguishing agent of 1 kg and from 5 to 14 meters for the mass of the extinguishing agent of 2 kg.

The parameters of the electric discharge system, which ensure detonation initiation with minimal electricity consumption, were determined. Specifically, in the case of the use of a special spark plug by two synchronized spark discharges, at complete energy of the charge of 15 J and application of the capacitor of 1.75 μF and inductivity of the discharge circuit of 400 nH, detonation occurs in the pipe of the diameter of 73 mm under conditions of the conducted research at the distance of not more than 180 mm.

The obtained results could be used in designing the plants with a gas-detonation charge.

Keywords: pulsed fire-extinguishing plant, extinguishing agent, gas-detonation charge, fire extinguishing distance, dispersion of atomization.

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INVESTIGATION OF THE ELECTROCHROMIC PROPERTIES OF Ni(OH)₂ FILMS ON GLASS WITH ITO-Ni BILAYER COATING (p. 55-61)

Valerii Kotok

Ukrainian State University of Chemical Technology, Dnipro, Ukraine

Vyatka State University, Kirov, Russian Federation

ORCID: <http://orcid.org/0000-0001-8879-7189>

Vadym Kovalenko

Ukrainian State University of Chemical Technology, Dnipro, Ukraine

Vyatka State University, Kirov, Russian Federation

ORCID: <http://orcid.org/0000-0002-8012-6732>

Electrochromic films have been deposited onto glass coated with indium-tin oxide (ITO) and glass with ITO and a thin layer of metallic nickel deposited onto it. Nickel was deposited onto the surface of the ITO coating from nickel electroplating solution. The metallic nickel was deposited onto the surface of ITO at the following parameters – cathodic current density 0.5 A/dm², deposition time 3 s. Such deposition parameters were chosen, because at longer deposition time and (or) higher current density, the deposited layer of metallic nickel became opaque. The two substrates were then used in the deposition of Ni(OH)₂ electrochromic films using the cathodic template synthesis method. As a result, it was revealed that the electrochromic film deposited onto glass with ITO-Ni coating possesses higher specific characteristics than that deposited on bare ITO-coated glass: higher coloration degree and higher oxidation-reduction currents on the cyclic voltamperogram. However, it was also revealed that the film possessing better characteristics, on the contrary, has lower reversibility of the coloration-bleaching process. Based on the obtained data, the mechanism that explains the role of the intermediate metal layer was proposed. The mechanism is that the deposited layer of metallic nickel forms additional contacts between the substrate surface and the electrochromic film. The nickel layer can also assist in securing the electrochromic film, and during film deposition has a positive effect on current distribution. On the other hand, the lower reversibility of the coloration-bleaching process of the film on ITO-Ni coating can be explained by gradual oxidation of metallic nickel in the basic medium. At the same time, it was revealed that deposition of metallic nickel leads to some decrease of the substrate transparency.

Keywords: electrochromism, electrodeposition, thin films, Ni(OH)₂, nickel, indium-tin oxide, nickel hydroxide.

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DETERMINING THE PARAMETERS OF THE ACOUSTIC SYSTEM FOR THE PRIMARY TREATMENT OF WOOL (p. 61-68)

Lyudmyla Mikhailova

State Agrarian and Engineering University in Podilya,
Kamianets-Podilskyi, Ukraine

ORCID: <http://orcid.org/0000-0002-3419-5446>

Oleksandr Kozak

State Agrarian and Engineering University in Podilya,
Kamianets-Podilskyi, Ukraine

ORCID: <http://orcid.org/0000-0002-0919-0344>

Natalia Kosulina

Kharkiv Petro Vasylenko National Technical University of
Agriculture, Kharkiv, Ukraine

ORCID: <http://orcid.org/0000-0003-4055-8087>

Pavel Potapsky

State Agrarian and Engineering University in Podilya,
Kamianets-Podilskyi, Ukraine

ORCID: <http://orcid.org/0000-0003-4792-8992>

Aleksandr Cherenkov

Kharkiv Petro Vasylenko National Technical
University of Agriculture, Kharkiv, Ukraine

ORCID: <http://orcid.org/0000-0003-1244-8104>

We have studied the process of primary treatment of wool in order to remove soil and manure contaminants, vegetable impurities, fat, and sweat. The primary treatment of wool performs a key role in retaining the natural properties of wool fiber and makes it possible to obtain high-quality raw materials for textile industry. It was found in the course of research that the intensification of the processes of primary treatment of wool requires the application of

acoustic oscillations. Acoustic oscillations act on the system wool-washing solution. The system wool-washing solution is in between grating conveyors. Conveyors form a grating of metal rods. To determine parameters of the acoustic system for the primary treatment of wool, we performed an analysis of three problems. The problems related to: the scattering of acoustic oscillations on a metal grating, on a layer of wool-washing solution, and combining the solutions to two problems into one using a scattering matrix method. Our study allowed us to define parameters for the system of primary treatment of wool with acoustic oscillations, which makes it possible to achieve greater effectiveness in cleaning wool compared to existing analogues. It was established in the course of theoretical and experimental studies that the washing of wool should be carried out at the following parameters of acoustic oscillations in a washing solution: frequency of the sound field is 1.1 ± 0.1 kHz; the sound intensity is 1.1 ± 0.01 W/cm². In this case, the thickness of a layer of wool at the conveyor is 0.06 ± 0.01 m; the motion speed of conveyor is 0.1 m/s; the number of converters per bath is 8 ± 1 pieces.

The application of optimal parameters in process of continuous washing of wool fibers in an aqueous solution makes it possible to obtain the residual fat on wool within 1.5 % of the amount of fat in the unwashed wool while GOST of Ukraine permits up to 2 %.

Keywords: primary treatment of wool, parameters of acoustic oscillations, coefficient of reflection of acoustic wave.

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