Information technologies for calculating the effect of wire thickness and insulation material on its heating temperature during operation

Albert Katunin
Department of fire and technological safety of facilities and technologies, National University of Civil Defence of Ukraine
Kharkiv, Ukraine
lightsymboll@gmail.com

Oleg Kulakov
Scientific Department on Problems of Civil Protection and Technogenic and Ecological Safety, National University of Civil Defence of Ukraine
Kharkiv, Ukraine
olegkov1963@gmail.com

Oleksii Kolomiitsev
Computer Engineering and Programming Department, National Technical University "Kharkiv Polytechnic Institute"
Kharkiv, Ukraine
alexus_k@ukr.net

Hennadii Heiko
Computer Engineering and Programming Department, National Technical University "Kharkiv Polytechnic Institute"
Kharkiv, Ukraine
gennady1752@gmail.com

Ihor Rudakov
Computer Engineering and Programming Department, National Technical University "Kharkiv Polytechnic Institute"
Kharkiv, Ukraine
ihor.rudakov@cit.khpi.edu.ua

***Abstract*— The paper evaluates the influence of wire thickness and insulation material on its heating temperature during operation. The temperature and time characteristics of wire exploitation under conditions of different load currents are analysed. The ranges of the wire temperature increase during operation are determined for wires with insulation made of polyethylene, polyvinyl chloride, enamel, and rubber.**

***Keywords*— wire, heating temperature, insulation material, insulation thickness, load current, temperature and time characteristics of operation.**

I. INTRODUCTION

The issue of improving fire and environmental safety has become particularly relevant in the context of the Russian invasion of Ukraine. Air strikes on chemical, oil refining and energy facilities could result in the release of hazardous chemicals into the environment and cause fires of various sizes.

Various methods and tools are used to detect dangerous elements in the atmosphere, which allow determining the composition and concentration of harmful substances [1-5].

It is advisable to simultaneously solve the problems of detecting fires by signs [6-9] and predicting the scale and consequences of fires in different conditions [10-12], in the case of conflagrations.

At the same time, solving the problem of effective conflagrations detection requires the development of new and improvement of existing fire detectors [13-15].

Particular attention should be paid to the functioning of the country's power system in the event of possible damage to electrical power facilities, when the entire power system is operating in an overload mode. Ensuring the level of fire safety of cable products as one of the main components of the power system is one of the priorities in such conditions.

Cables and wires that carry more current than the current they are designed to carry heat up and can reach temperatures that cause the insulation to ignite, which can lead to a fire [16-19]. Insulation is made of dielectric materials, such as polyethylene, polyvinyl chloride (PVC), enamels and rubber, which can burn or support combustion. Therefore, in practice, to determine fire safety, it is important to estimate the temperature to which the cable product will heat up before the protection devices are activated.

Thus, assessing the impact of wire insulation parameters, in particular, thickness and material, on its heating temperature during operation is an imperative task of ensuring fire safety.

II. SELECTION OF THE EVALUATION MODEL

In [20, 21], an improved model for assessing the heating of cable products during operation was proposed and tested. As shown, this model can be used to calculate the temperature and time characteristics of wire operation according to the following expressions:

$$T(t) = T_{\Pi} + \frac{T_{\Pi}}{\phi_2} \times \left[\phi_3(\omega-1)t + \phi_3^2\omega(\omega-1)\frac{t^2}{2!} + \phi_3^3\omega(\omega-1)(3\omega-2)\frac{t^3}{3!} \right], \quad (1)$$

$$\omega = \frac{\delta_1(\delta_3+\delta_5)}{(1+\delta_4)(\delta_6-\delta_2)} + 1, \quad (2)$$

$$\phi_2 = \frac{\delta_3+\delta_5}{1+\delta_4}, \quad (3)$$

$$\phi_3 = \frac{\delta_6-\delta_2}{1+\delta_4}, \quad (4)$$

$$\delta_1 = \frac{I^2 \rho_{g0}}{\pi^2 r_g^4 \gamma_g C_{g0} T_\Pi}, \quad (5)$$

$$\delta_2 = \frac{I^2 \rho_{g0} \alpha}{\pi^2 r_g^4 \gamma_g C_{g0}}, \quad (6)$$

$$\delta_3 = T_\Pi \phi_g, \quad (7)$$

$$\delta_4 = \frac{\gamma_{iz} \pi (\Delta r_{iz}^2 + 2 r_g \Delta r_{iz}) C_{iz0}}{\gamma_g \pi r_g^2 C_{g0}}, \quad (8)$$

$$\delta_5 = \frac{\gamma_{iz} \pi (\Delta r_{iz}^2 + 2 r_g \Delta r_{i3}) C_{iz0} \varphi_{iz} T_\Pi}{\gamma_g \pi r_g^2 C_{g0}}, \quad (9)$$

$$\delta_6 = \frac{2\pi (r_g + \Delta r_{i3}) a}{\gamma_g \pi r_g^2 C_{g0}}. \quad (10)$$

where I – electric current, A;
ρ_{g0} – the initial value of the electrical resistivity of the cable product core material according to the initial time $T = T_0$, Ohm;
r_g – cross-sectional radius of the lead, m;
γ_{iz} – insulation material density, kg/m^3;
Δr_{iz} – insulation layer thickness, m;
C_{iz0} – the initial value of the heat capacity of the insulation material, which corresponds to the initial moment of time $T = T_0$, J/grad.;
γ_g – density of the core material, kg/m^3;
C_{g0} – the initial value of the heat capacity of the core material, which corresponds to the initial moment of time $T = T_0$, J/grad.;
a – heat transfer coefficient from insulation to air, W/m^2 grad;
T_n – air temperature, grad.;
α, φ_g – thermal coefficients.

The model allows you to analyse the impact of cable product parameters, including insulation, on their heating temperature during operation at specified load currents.

III. ANALYSIS OF THE TEMPERATURE AND TIME CHARACTERISTICS OF THE OPERATION OF WIRES WITH DIFFERENT THICKNESSES OF INSULATION MATERIAL

The first step is to analyse the effect of insulation thickness on the heating temperature of a cable product. The corresponding characteristics are plotted for a polyvinyl (PV) wire (1x1.5) with PVC insulation for a given insulation layer thickness of $\Delta r_{iz} = 7\times10^{-4}$; 10^{-3}; $1{,}3\times10^{-3}$ m at load currents I = 19, 30, 40 A and the following input data:

$t = 300$ c;
$r_g = 8{,}9\times10^{-4}$ m;
$\varphi_g = 0.000257$;
$\varphi_{iz} = 0.0003$;
$\gamma_{iz} = 1350$ kg/m^3;
$\gamma_g = 8960$ kg/m^3;
$C_g = 373$ J/grad;
$C_{iz} = 1200$ J/grad;
$a = 0.003$ W/m^2;
$\alpha = 0.00433$;
$T_п = 20$°C;
$\rho_{g0} = 0.0000000189$ Ohm.

The analysis of the above graphs obtained during the calculation in the MATHCAD software package based on the model (1-10) and presented in Figures 1-3 allows us to formulate the following conclusions regarding the effect of insulation thickness on the heating temperature of the wire during operation:

- Increasing the thickness of the wire insulation layer allows to reduce the heating temperature of the wire during operation;
- for a significant reduction in the temperature of the wire during operation, the thickness of the wire insulation layer must be increased several times, namely (fig. 1 - 3):

when operated at a load current of I = 19 A in 100s, the temperature drop from 54.0°C to 30.5°C is recorded when the insulation layer increases 3 times from 0.0007 m to 0.0021 m, the temperature drop from 54.0°C to 24.9°C is recorded when the insulation layer increases 5 times from 0.0007 m to 0.0035 m;

in 200 s, a temperature decreases from 83.4°C to 40.6°C is recorded when the insulation layer is increased 3 times from 0.0007 m to 0.0021 m, a temperature decreases from 83.4°C to 29.7°C is recorded when the insulation layer is increased 5 times from 0.0007 m to 0.0035 m;

in 300 s, the temperature decreases from 108.5°C to 50.3°C is recorded when the insulation layer is increased by 3 times from 0.0007 m to 0.0021 m, the temperature decreases from 108.5°C to 34.4°C is recorded when the insulation layer is increased by 5 times from 0.0007 m to 0.0035 m;

- the degree of influence of the thickness of the wire insulation layer on the wire heating temperature in the time interval of 0...300 s increases with time for all given values of the load current of 19; 30; 40 A, namely:

when operated at a load current of I = 19 A, the wire heats up to a temperature of 24.9°C, 30.3°C, 53.7°C in 100 s;

in 200 s - to the temperature values of 29.7°C; 40.7°C; 83.4°C;

in 300 s - to the temperature values of 34.4°C; 50.3°C; 108.4°C, respectively, for the values of insulation thickness Δriz = 35×10-4; 21×10-4; 7×10-4m (Fig. 1);

when operating at a load current of I = 30 A in 100 s, the wire heats up to a temperature of 32.0°C, 45.5°C, 93.3°C;

in 200 s - to the temperature values of 43.5°C; 68.2°C; 149.4°C;

in 300 s - to the temperature values of 54.4°C, 88.7°C, 190.3°C, respectively, for the values of insulation thickness Δriz = 35×10-4, 21×10-4, 7×10-4m (Fig. 2);

when operating at a load current of I = 40 A, the wire heats up to a temperature of 43.1°C, 63.7°C, 139.0°C in 100 s;

in 200 s - to the temperature values of 60.2°C; 99.1°C; 211.6°C;

in 300 s - to the temperature values of 77.7°C; 128.6°C; 298.0°C, respectively, for the values of insulation thickness Δriz = 35×10-4; 21×10-4; 7×10-4m (Fig. 3);

- conductors with a small insulation thickness should be used only if measures are taken to limit the values of the load I currents during operation.

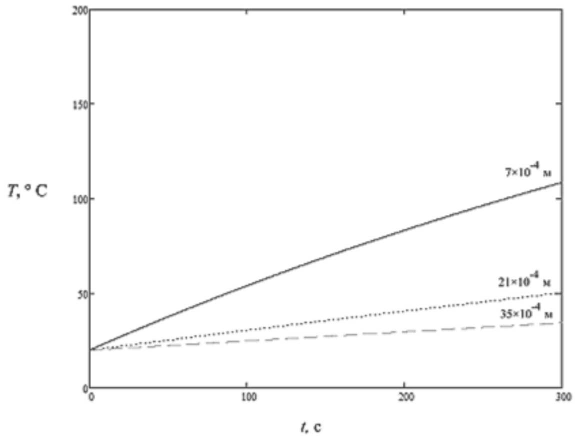

Fig. 1. Temperature-time characteristic of operation of PV wire (1x1.5) for load current I = 19 A at insulation thickness $\Delta r_{iz} = 7\times10^{-4}$; 21×10^{-4}; 35×10^{-4} m

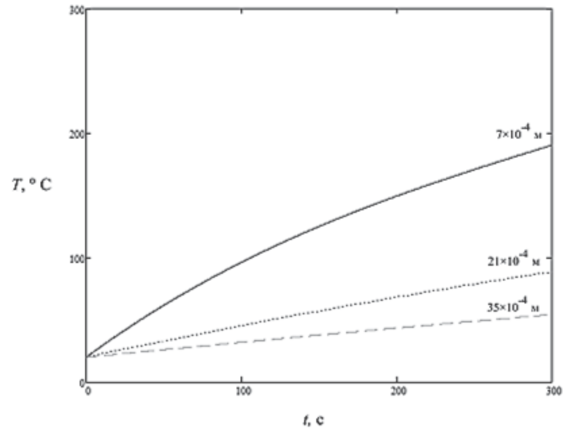

Fig. 2. Temperature-time characteristic of operation of PV wire (1x1.5) for load current I = 30 A at insulation thickness $\Delta r_{iz} = 7\times10^{-4}$; 21×10^{-4}; 35×10^{-4} m

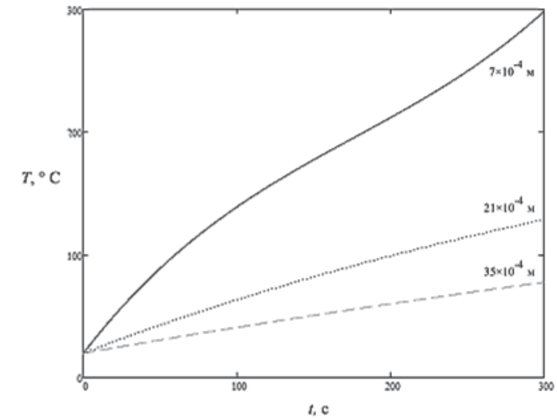

Fig. 3. Temperature-time characteristic of operation of PV wire (1x1.5) for load current I = 40 A at insulation thickness $\Delta r_{iz} = 7\times10^{-4}$; 21×10^{-4}; 35×10^{-4} m

IV. ANALYSIS OF TEMPERATURE AND TIME CHARACTERISTICS OF OPERATION OF WIRES WITH DIFFERENT INSULATION MATERIALS

At the second stage, we analyse the effect of the insulation material on the heating temperature of the cable product. The relevant estimates were made for a wire with a nominal copper core cross-section of 1.5 mm^2 for an insulation layer thickness of $\Delta r_{iz} = 7\times10^{-4}$ m and a load current of $I = 30$ A.

The following insulation materials were evaluated: polyethylene, PVC, enamel and rubber. The parameters γ_{iz}, φ_{iz} and C_{iz} are determined by the insulation material according to the data presented in Table 1.

Analysis of the above graphs obtained in the MATHCAD software package and presented in Figures 4-7, respectively, allows us to formulate the following conclusions regarding the effect of different wire insulation materials on the temperature of its heating during operation:

- the heating temperature of the wire during operation significantly depends on the parameters of the insulation material;
- the temperature and time characteristics of the operation of wires with different insulation materials are similar and non-linear;
- the lowest temperature values were recorded when enamel was used as an insulation material, the highest - when rubber was used as an insulation material (Fig. 5-7);
- range of temperature rise of a wire with a copper core cross-section of 1.5 mm^2 during operation in 300 c at a load of $I = 30$ A:

for polyethylene insulation corresponds to the following values - 20.0...169.6°C (Fig. 5);

for PVC insulation - 20.0...189.9°C (Fig. 6);

for enamel insulation - 20.0...128.5°C (Fig. 6);

for rubber insulation - 20.0...210.7°C (Fig. 7).

TABLE 1. Insulation material parameters

Material	Density, kg/m^3	Conduction, W/(m·grad)	Heat capacity, L/(kg·grad)
Enamel	1030 ... 2045	0,18…0,4	650…2000
Polyvinyl chloride (PVC)	1400 ... 1600	0,15…0,2	-
Polychlorovinyl	1290 ... 1650	0,15	1130 ... 1200
High-density polyethylene	955	0,35…0,48	1900 ... 2300
Low-density polyethylene	920	0,25…0,34	1700
Soft rubber	-	0,13…0,16	1380
Hard rubber	900 ... 1200	0,16…0,23	1350 ... 1400
Porous rubber	160 ... 580	0,05…0,17	2050

For practical use, the modelling results obtained must be supplemented with the values of permissible wire temperatures in the event of a short circuit in order to make decisions on the feasibility of using a particular cable product in given operating conditions.

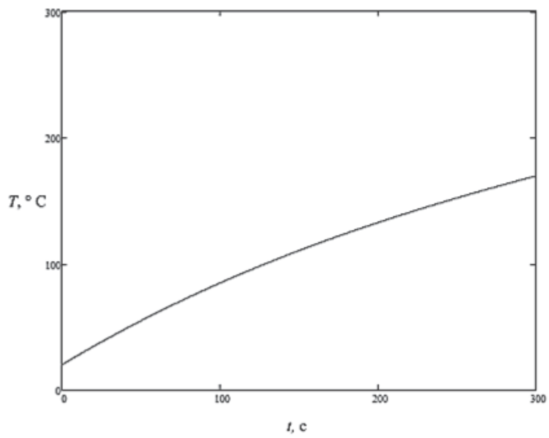

Fig. 4. Temperature and time characteristics of operation of a wire with polyethylene insulation for load current I = 30 A at insulation thickness $\Delta r_{iz} = 7\times10^{-4}$ m

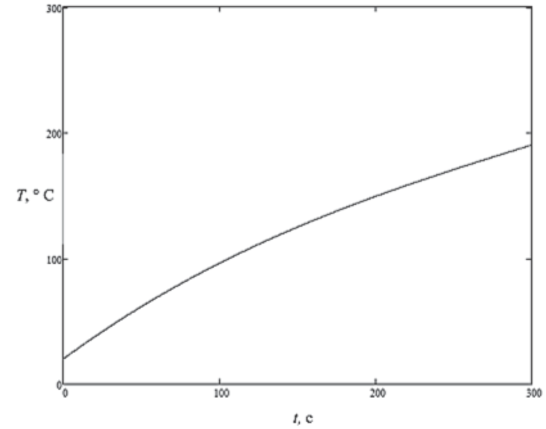

Fig. 5. Temperature and time characteristics of operation of a wire with PVC insulation for load current I = 30 A at insulation thickness $\Delta r_{iz} = 7\times10^{-4}$ m

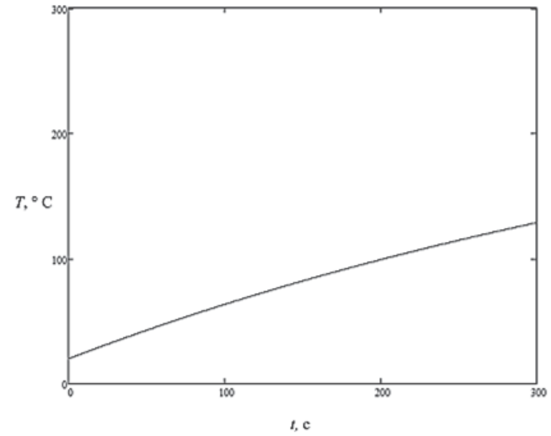

Fig. 6. Temperature and time characteristics of operation of a wire with emanol insulation for load current I = 30 A at insulation thickness $\Delta r_{iz} = 7\times10^{-4}$ m

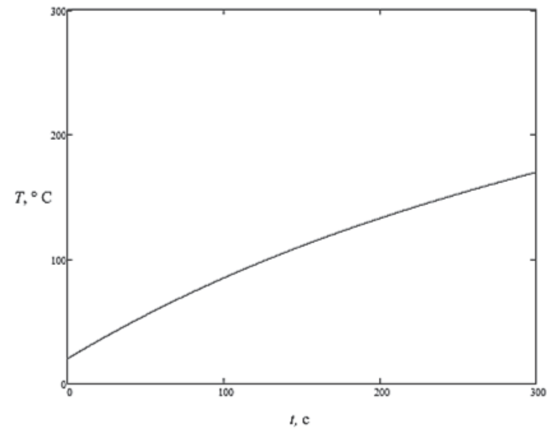

Fig. 7. Temperature and time characteristics of operation of a wire with rubber insulation for load current I = 30 A at insulation thickness $\Delta r_{iz} = 7\times10^{-4}$ m

V. Conclusions

The fire safety of cable products depends on the ability of the insulation to ignite when the conductor is heated and create sources of fire.

Cable products are insulated with dielectric materials, such as polyethylene, PVC, rubber and enamels, which can combust or support combustion. Therefore, in practice, to determine fire safety, it is important to estimate the temperature to which the cable product will heat up before the protection devices are activated.

The results of mathematical modelling show that in order to significantly reduce the temperature of the wire during operation, the thickness of the wire insulation layer must be increased several times, which indicates the cost and material intensity of this method of improving fire safety. It should also be taken into account that the degree of influence of the thickness of the cable insulation layer on the heating temperature of the wire increases with time for all specified values of the load current. Therefore, the method of improving fire safety by increasing the thickness of the wire insulation layer may be appropriate for long-term overloading of cable products.

Based on the obtained results of mathematical modelling, it is possible to conclude that the parameters of the insulation material have a significant impact on the heating temperature of the wire during operation. At the same time, the lowest temperature values were recorded when enamel was used as an insulation material, and the highest - when rubber was used as an insulation material. Such data indicate the prospects of the method of improving fire safety by selecting the insulation material, which is in line with international practice.

References

[1] Usage of Lidar Systems for Detection of Hazardous Substances in Various Weather Conditions / O. Kulakov, A. Katunin, Ya. Kozhushko, S. Herasymov, O. Roianov, T. Gorbach // IEEE 6th International Symposium on Microwaves, Radar and Remote Sensing (MRRS). 2020. P. 360–363.

[2] Construction of a method for detecting arbitrary hazard pollutants in the atmospheric air based on the structural function of the current pollutant concentrations / Sadkovyi V., Pospelov B., Andronov V., Rybka E., Krainiukov O., Rud A., Karpets K., Bezuhla Yu. // Eastern-European Journal of Enterprise. 2020. V. 6/10 (108). P. 14–22.

[3] Use of uncertainty function for identification of hazardous states of atmospheric pollution vector / Pospelov B., Rybka E., Meleshchenko R., Krainiukov O., Harbuz S., Bezuhla Yu., Morozov I., Kuruch A., Saliyenko O., Vasylchenko R. // Eastern-European Journal of Enterprise. 2020. V. 2/10 (104). P. 6–12.

[4] Pospelov B., Rybka E., Krainiukov O., Yashchenko O., Bezuhla Y., Bielai S., Kochanov E., Hryshko S., Poltavski E., Nepsha O. Short-term forecast of fire in the premises based on modification of the Brown's zero-order model. EEJET. 2021. V. 4/10 (112). P. 52–58.

[5] Pospelov B., Rybka E., Meleshchenko R., Borodych P., Gornostal S. Development of the method for rapid detection of hazardous atmospheric pollution of cities with the help of recurrence measures // Eastern-European Journal of Enterprise. 2019. V. 1/10 (97). P. 29–35.

[6] Sadkovyi V., Pospelov B., Rybka E., Kreminskyi B., Yashchenko O., Bezuhla Y., Darmofal E., Kochanov E., Hryshko S., Kozynska I. Development of a method for assessing the reliability of fire detection in premises. Eastern-European Journal of Enterprise Technologies. 2022. 3 (10 (117)). P. 56–62.

[7] Pospelov B., Rybka E., Samoilov M., Morozov I., Bezuhla Y., Butenko T., Mykhailovska Y., Bondarenko O., Veretennikova J. Defining the features of amplitude and phase spectra of dangerous factors of gas medium during the ignition of materials in the premises. Eastern-European Journal of Enterprise Technologies. 2022. 2 (10 (116)). P. 57–65.

[8] Experimental study of the fluctuations of gas medium parameters as early signs of fire / Pospelov B., Andronov V., Rybka E., Popov V., Romin A. // Eastern-European Journal of Enterprise Technologies. 2018. Vol. 1, Issue 10 (91). P. 50–55.

[9] Analysis of correlation dimensionality of the state of a gas medium at early ignition of materials / Pospelov B., Andronov V., Rybka E., Meleshchenko R., Gornostal S. // Eastern-European Journal of Enterprise Technologies. 2018. V. 5/10 (95). P. 25–30.

[10] Development of the method of operational forecasting of fire in the premises of objects under real conditions / Pospelov B., Andronov V., Rybka E., Samoilov M., Krainiukov O., Biryukov I., Butenko T., Bezuhla Yu., Karpets K., Kochanov E. // Eastern-European Journal of Enterprise. 2021. V. 2/10 (110). P. 43–50.

[11] Short-term fire forecast based on air state gain recurrency and zero-order Brown model / Pospelov B., Rybka E., Meleshchenko R., Krainiukov O., Biryukov I., Butenko T., Yashchenko O., Bezuhla Yu., Karpets K., Vasylchenko R. // Eastern-European Journal of Enterprise. 2021. V. 3/10 (111). P. 27–33.

[12] Pospelov B., Rybka E., Krainiukov O., Yashchenko O., Bezuhla Y., Bielai S., Kochanov E., Hryshko S., Poltavski E., Nepsha O. Short-term forecast of fire in the premises based on modification of the Brown's zero-order model. EEJET. 2021. V. 4/10 (112). P. 52–58.

[13] Design of fire detectors capable of self-adjusting by ignition / Pospelov B., Andronov V., Rybka E., Skliarov S. // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 4, Issue 9 (88). P. 53–59.

[14] Research into dynamics of setting the threshold and a probability of ignition detection by self-adjusting fire detectors / Pospelov B., Andronov V., Rybka E., Skliarov S. // Eastern-European Journal of Enterprise Technologies. 2017. V. 5/9 (89). P. 43–48.

[15] Examining the learning fire detectors under real conditions of application / Andronov V., Pospelov B., Rybka E., Skliarov S. // Eastern-European Journal of Enterprise Technologies. 2017. Vol. 3, Issue 9 (87). P. 53–59.

[16] Definition of Accumulated Operating Time Distributions for a Cable Product Insulation Within the Defined Life Cycles / O. Kulakov, A. Katunin, Y. Kozhushko, S. Herasymov, I. Vasil'eva and O. Konovalenko // IEEE 2nd Ukraine Conference on Electrical and Computer Engineering (UKRCON), Lviv, Ukraine. 2019. P. 355–358.

[17] Катунін А.М., Олійник В.В., Кулаков О.В. & ін. (2022). Удосконалення моделі теплового старіння ізоляції кабельних виробів // INTERNATIONAL SCIENTIFIC JOURNAL GRAIL OF SCIENCE. № 17 (липень, 2022). – С. 181-185. http://repositsc.nuczu.edu.ua/handle/123456789/15692.

[18] Investigation of Reliability of Emergency Shutdown of Consumers in Electric Power Systems of Explosive Hazardous Zones / Oleg Kulakov, Maksym Kustov, Serhii Rudakov, Albert Katunin, Evgen Slepuzhnikov. IEEE 3rd KhPI Week on Advanced Technology (KhPIWeek). 2022, pp. 173–177.

[19] Катунін А.М., Роянов О.М. Аналіз особливостей теплового старіння ізоляції кабельних виробів // Матеріали Міжнародної науково-практичної конференції «Проблеми пожежної безпеки 2022» («Fire Safety Issues 2022»). – Х.: НУЦЗ України, 2022. – С. 20-21.

[20] Катунін А. М., Коломійцев О. В., Олійник В.В. & ін. (2023). Удосконалення моделі оцінки нагрівання кабельних виробів у процесі експлуатації // Матеріали III Міжнародної наукової конференції «Міжгалузеві диспути: динаміка та розвиток сучасних наукових досліджень». м. Хмельницький, Україна. – С. 164–167.

[21] Катунін А.М., Кулаков О.В., Рудаков С.В. & ін. (2023). Оцінка впливу струму навантаження на температуру нагрівання кабельних виробів у процесі експлуатації // INTERNATIONAL SCIENTIFIC JOURNAL GRAIL OF SCIENCE. № 24 (лютий, 2023). – С. 210–215.