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The use of shape memory alloys in fuses for the protection of electrical installations

Problem. *The degree of damage to electrical installations during short circuits depends on the response time of the protection. An effective way to enhance the current-limiting effect in electrical fuses (reducing their response time) may be the use of shape memory alloy (SMA) elements. However, this requires careful study and research. The* ***goal*** *of the work is to establish the patterns of strengthening the current-limiting effect of a fuse (reducing the response time) when using thermosensitive elements made of shape memory alloys. The achievement of this goal is based on the analysis of experimental studies conducted by the authors and mathematical models of the characteristics of a fuse containing an SMA element.* ***Methodology***. *The article presents mathematical modelling of the parameters and characteristics of fuses with thermomechanical destruction of the fuse element, as well as a thermophysical model of a fuse with a thermosensitive SMA element. The article presents the* ***results*** *of experimental studies of a traditional fuse and a fuse equipped with a thermosensitive SMA element. For each current, the response time of the modified fuse was shorter than that of the traditional fuse. The use of a thermosensitive element reduced the response time by more than 20 times for a current of 10 A and approximately 10 times (from 0.257 s to 0.0244 s) for a current of 20 A. For the highest tested current (90 A), the fuse response time was half that of a traditional fuse. The article also presents the results of calculations of fuse characteristics using a mathematical model and a comparison with the results of experimental studies.* ***Scientific novelty***. *The developed mathematical models of the characteristics of electrical fuses containing SMA elements made it possible for the first time to substantiate the interrelationships between the parameters (geometric dimensions and characteristics of SMA elements, fuse links) with current loads of electrical installations. The* ***practical value*** *of the work lies in the proposed use of thermosensitive elements made of functional materials to increase the current-limiting effect of electrical fuses for protecting electrical installations during short circuits.* References 19, tables 2, figures 7.

Key words: **functional materials, fuse, shape memory alloy, thermosensitive element**.

Проблема. *Ступінь пошкодження електроустановок при коротких замиканнях залежить від часу спрацювання захисту. Ефективним способом покращення струмообмежуючого ефекту в електричних запобіжниках (зменшення часу їх спрацювання) може бути застосування елементів із сплавів з ефектом пам'яті форми. Проте, це потребує ретельного вивчення та дослідження.* ***Метою*** *роботи є встановлення закономірностей покращення струмообмежувального ефекту запобіжника (зменшення часу спрацьовування) при застосуванні термочутливих елементів із сплаву з пам'яттю форми (SMA – shape memory alloy). Досягнення мети базується на аналізі проведених авторами експериментальних досліджень і побудованих математичних моделях характеристик запобіжника, що містить елемент SMA.* ***Методика.*** *У статті представлено математичне моделювання параметрів і характеристик запобіжників з термомеханічним руйнуванням запобіжного елемента, а також теплофізичну модель запобіжника з термочутливим елементом SMA. У статті представлені* ***результати*** *експериментальних досліджень традиційного запобіжника та запобіжника, оснащеного термочутливим елементом SMA. Для кожного струму час спрацьовування модифікованого запобіжника був коротшим, ніж у традиційного запобіжника. Використання термочутливого елемента скоротило час спрацьовування більш ніж у 20 разів для струму 10 А і приблизно в 10 разів (з 0,257 с до 0,0244 с) для струму 20 А. Для найбільшого випробуваного струму (90 А) час спрацьовування запобіжника був удвічі меншим, ніж у традиційного запобіжника. Наведено результати розрахунків характеристик запобіжника за допомогою математичної моделі та порівняння з результатами експериментальних досліджень.* ***Наукова новизна.*** *Розроблені математичні моделі характеристик запобіжників, що містять елементи SMA, дозволили вперше обґрунтувати взаємозв'язки параметрів (геометричних розмірів і характеристик елементів SMA, плавких вставок запобіжників) зі струмовими навантаженнями електроустановок.* ***Практична значимість*** *роботи полягає у пропонованому використанні термочутливих елементів з функціональних матеріалів для підвищення струмообмежувальної дії запобіжників для захисту електроустановок при коротких замиканнях.* Бібл. 19, табл. 2, рис. 7.

Ключові слова: **функціональні матеріали, запобіжник, сплав з пам'яттю форми, термочутливий елемент.**

Introduction. A number of electrical devices are particularly sensitive to overload (for example, voltage transformers [1] in automatic reserve input and sectioning devices [2]), respectively, fuses with a current-limiting effect are used for their protection. The current-limiting effect in modern fuses is created by dissolving more refractory metals in less refractory ones, using an alloy of fusible inserts, pointwise reduction of the cross-sectional area of fusible inserts, accelerated extinguishing of the electric arc with a quartz filler, etc.

An effective way to improve the current-limiting effect can be the use of elements made of shape memory alloys (SMA) [3]. The basic physical essence of the shape memory effect can be interpreted as the property of a technical element made of an alloy containing thermoelastic martensite in its structure to restore its original shape when heated (Fig. 1).

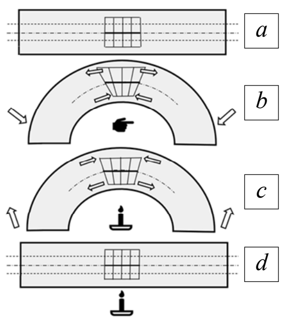

Fig. 1. Interpretation of the properties of a product made of an alloy with a shape memory effect: *a* – the initial shape of the product; *b* – forced deformation of the product (deformation of the martensite structure); *c* – heating of the product and the beginning of the recovery of the shape (thermoelastic reverse deformation of the martensite structure); *d* – completion of the recovery of the shape to the initial state

The SMA alloy element can perform the functions of both a sensor and an actuator [3, 4].

The two most common SMAs in terms of application and research are Ni-Ti, also known as Nitinol, and copper-based alloys such as Cu-Al-Mn [4–6]. One variant of copper-based SMA is Camital [7].

The shape recovery of SMA products can be achieved by indirect heating with a heat source and directly by the action of an electric current. A SMA product can convert thermal energy into mechanical work, the value of which depends mainly on the alloy composition and the geometry of the product [3, 8, 9].

The shape memory process involves two types of martensitic transformations: direct and reverse. Each of them manifests itself in a certain temperature range: M_S and M_F – the initial and final temperatures of the martensitic transformation during cooling; A_S and A_F – the initial and final temperatures of the reverse martensitic transformation during heating, respectively. The martensitic transformation temperatures are a function of the alloy grade (alloy system) and its chemical composition. Minor changes in the chemical composition of the alloy (intentional or due to defects) cause a change in the characteristic transformation temperatures. This leads to the need to maintain the exact chemical composition for the functional manifestation of the shape memory effect with programmed parameters and characteristics, which puts the metallurgical production of SMA in the field of high technology [3, 4].

Experimental studies of SMA products have shown [3, 10, 11] that from the point of view of economic indicators, as well as physical properties and characteristics, the copper-based alloy Cu (83 %)-Al (12 %)-Mn (5 %) is the most suitable for solving various engineering problems, for example, in electrical installations and other areas. Of great importance is its cost, which is almost 20 times lower compared to Ni-Ti Nitinol.

A unique physical feature of SMA is the time-dependent characteristic of shape recovery during direct heating of products with electric current, which allows creating highly sensitive electrical devices for protecting electrical installations from overloads and short circuits [9, 12].

The indicators obtained by the authors during previous experimental studies of the shape recovery time of a thermosensitive element heated directly by electric current, as well as the reactive power and its behavior during an increase in electric current, confirm the possibility of designing protection and control devices [3].

There are two classical principles of fuse design: a fusible type with thermal destruction of the fuse element and a multiple contact type with a bimetallic thermosensitive element [13].

Based on the electrothermomechanical properties of the SMA application, a new principle of fuse design was implemented in this study (Fig. 2). The operation of this fuse is based on the forced mechanical destruction of the fuse element by a thermosensitive tension element at a given current value [14].

The current flowing through the fuse element and the thermal element heats them. The thermal element 1 changes (restores) its shape under the influence of temperature, causing mechanical tension in the fuse element 2. If the tension reaches the mechanical strength limit, the fuse element first breaks mechanically and then thermally due to the electric arc that stretches between the parts of the torn fuse element, which reduces the fuse response time.

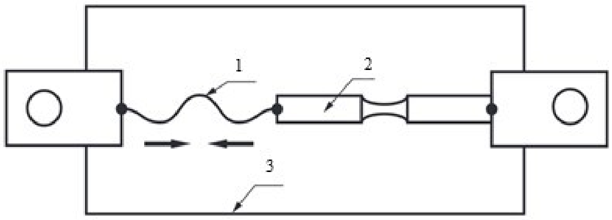

Fig. 2. Schematic representation of a fuse with forced destruction of the fuse element: 1 – SMA thermosensitive element; 2 – fuse element; 3 – housing [14]

Therefore, **the goal of the work** is to establish the patterns of strengthening the current-limiting effect of a fuse (reducing the response time) when using thermosensitive elements made of shape memory alloys. The achievement of the goal is based on the analysis of the experimental studies conducted by the authors and the mathematical models of the characteristics of the fuse containing the SMA element.

Mathematical modelling of parameters and characteristics of fuses with thermomechanical destruction of the fuse element. Let us assume that the thermosensitive element is located in a homogeneous confined medium with low thermal resistance in such a way that the temperature gradient in the middle of this element is very small, and there is an ideal thermal contact between the thermosensitive element and its medium. The heat transfer coefficient does not depend on temperature [15, 16]. When current flows, the heat produced in the thermosensitive element is spent on heating both this element and its contact medium. In this case, the heat balance equation has the form [17, 18]:

$$\left(c_1 m_1 + c_2 m_2\right)\frac{\mathrm{d}\theta}{\mathrm{d}t} + \alpha S\left(\Theta - \Theta_0\right) = I^2 R_0\left(1 + \beta\Theta\right), \quad (1)$$

where θ is the temperature of the thermosensitive element, °C; c_1 is the specific heat capacity of the alloy of the thermosensitive element, J/(kg·K); c_2 is the specific heat capacity of the medium in which the thermosensitive element is located, J/(kg·K); m_1 is the mass of the thermosensitive element, kg; m_2 is the mass of the medium, kg; R_0 is the electrical resistance of the thermosensitive element at 0 °C; S is the cooling surface, m^2; I is the current flowing through the thermosensitive element, A; β is the coefficient of temperature resistance, K^{-1}; α is the heat transfer coefficient, W/(m^2·K); θ_0 is the ambient temperature, °C.

Under these conditions, the solution of the differential equation (1) for a direct current I and the initial condition $\theta|_{t=0} = \theta_0$ is as follows [3]:

$$\theta = \frac{\dfrac{I^2 R_0}{\alpha S} + \theta_0}{1 - \dfrac{I^2 R_0}{\alpha S}\beta} - \frac{\dfrac{I^2 R_0}{\alpha S}\left(1 + \beta\theta_0\right)}{1 - \dfrac{I^2 R_0}{\alpha S}\beta}\exp\left[-\frac{t\left(1 - \dfrac{I^2 R_0}{\alpha S}\beta\right)\alpha S}{c_1 m_1 + c_2 m_2}\right]. \quad (2)$$

Fuse characteristics in steady state if $\frac{I^2 R_0}{\alpha S}\beta < 1$, then according to (2), when $t \to \infty$, the temperature of the thermosensitive element will approach the value θ_{es}, which is expressed as:

$$\theta_{es} = \left(\frac{I^2 R_0}{\alpha S} + \theta_0\right) \Bigg/ \left(1 - \frac{I^2 R_0}{\alpha S}\beta\right). \quad (3)$$

If in (3) the temperature coefficient of resistance $\beta = 0$, then the dependence of the given temperature on the current will be determined by the expression:

$$\theta_{es} = \frac{I^2 R_0}{\alpha S} + \theta_0 . \quad (4)$$

The rated fuse current I_N is determined from (3) provided that:

$$\theta_{es} = A_S, \quad (5)$$

where A_S is the temperature at which the thermosensitive element begins to recover its shape, °C.

Therefore, the rated current of the fuse is:

$$I_N = \sqrt{\frac{\alpha S(A_s - \theta_0)}{R_0(1 + \beta A_s)}} . \quad (6)$$

The limit current ($I_{\lim}$) for this type of fuse will be determined by the critical temperature level θ_{kr} at which the condition will be fulfilled:

$$\sigma_{ad} = \sigma_{in}, \quad (7)$$

where σ_{ad} is the ultimate mechanical tensile stress of the fuse element, Pa; σ_{in} is the mechanical stress in the fuse element when the therm0sensitive element is heated, Pa:

$$I_{\lim} = \sqrt{\frac{\alpha S(\theta_{kr} - \theta_0)}{(R_0(1 + \beta\theta_{kr})}} . \quad (8)$$

The ratio of the limiting current to the rated current will be determined by the critical temperature and the shape recovery temperature of the SMA thermosensitive element.

$$I_{\lim} / I_N = \sqrt{\frac{(\theta_{kr} - \theta_0)(1 + \beta A_s)}{(A_s - \theta_0)(1 + \beta A_{kr})}} . \quad (9)$$

Fuse characteristics in unstable mode. The differential equation describing the cooling process of the thermosensitive element has the form:

$$(c_1 m_1 + c_2 m_2)\frac{\mathrm{d}\theta}{\mathrm{d}t} + \alpha S(\theta - \theta_0) = 0 , \quad (10)$$

and its solution for the initial condition $\theta|_{t=0} = \theta_{es}$ is [3]:

$$\theta - \theta_0 = (\theta_{es} - \theta_0) e^{-t/\left[\frac{(c_1 m_1 + c_2 m_2)}{\alpha S}\right]} . \quad (11)$$

Since formula (2) shows the dependence of the temperature of a thermosensitive element on the time of current flow, it can be transformed to determine the time required to heat the element to a given temperature and, in particular, to the critical temperature:

$$t_{kr} = \frac{c_1 m_1 + c_2 m_2}{\alpha S\left(\frac{I^2 R_0}{\alpha S}\beta - 1\right)} \ln\left[\frac{1 + \beta\theta_{kr}}{1 + \beta\theta_0} - \frac{\theta_{kr} - \theta_0}{\frac{I^2 R_0}{\alpha S}(1 + \beta\theta_0)}\right] . \quad (12)$$

The formula for the time-current characteristic of a fuse with any SMA thermosensitive element is:

$$\frac{t_{kr}}{\tau} = \frac{I_{\lim}^2(1 + \beta\Theta_{kr})}{I^2(\theta_{kr} - \theta_0) - I_{\lim}^2(1 + \beta\theta_{kr})} \ln\left[\frac{1 + \beta\theta_{kr}}{1 + \beta\theta_0}\left(1 - \frac{I_{\lim}^2}{I^2}\right)\right], \quad (13)$$

where the time constant is:

$$\tau = \frac{c_1 m_1 + c_2 m_2}{\alpha S} .$$

The thermomechanical characteristics of the thermosensitive SMA element and the mechanical strength characteristics of the fuse, the protective characteristics of the fuse with thermomechanical fuse failure can be obtained by fulfilling condition (7).

Since the fuse uses the principle of mechanical failure of the fuse element, the equation of the maximum mechanical strength limit of the fuse element will be as follows:

$$F_{ad} = \sigma_{AD}\pi\frac{d_{fe}^2}{4} , \quad (14)$$

where d_{fe} is the diameter of the fuse element, m.

Accordingly, the force generated in the thermosensitive element (SMA) of the fuse is equal to:

$$F_{te}(t, I) = ab\sigma_{te}(t, I) , \quad (15)$$

where a, b are the width and thickness of SMA, respectively, m; $\sigma_{te}(t, I)$ is the thermomechanical stress arising in the thermosensitive element during direct heating (function of time t and current I), Pa.

Then the balance equation of the mechanical strength limit will be as follows:

$$\sigma_{te}(t, I)ab - \sigma_{ad}\pi\frac{d_{fe}^2}{4} = 0 . \quad (16)$$

Modelling of thermomechanical strength in a SMA thermosensitive element can be performed using the following equations:

$$\sigma_{te}(t) = \mathrm{if}[\theta(t) \ge 90, M_{te}(t), K_{te}(t)]; \quad (17)$$

$$M_{te}(t) = (1 - e^{-\theta(t)A_1})A_2 L_0 - A_3 L_0 ; \quad (18)$$

$$K_{te}(t) = A_4\theta(t)^4 L , \quad (19)$$

where σ_{te} is the thermomechanical stress, Pa; t is the time, s; θ is the temperature, °C; $A_1 - A_4$, L_0, L are the coefficients calculated based on experimental measurements of thermomechanical characteristics of SMA samples. Dimensions of coefficients: L – [Pa/K^4]; L_0 – [Pa]; A_1 – [1/K]; $A_2 - A_4$ – dimensionless quantities.

The dependence of the temperature of the thermosensitive element on the current and its flow time is based on the well-known dependence [3, 9]:

$$\theta = \frac{\rho}{C}10^6(I/q)^2 t , \quad (20)$$

where ρ is the specific electrical resistance of the SMA, Ω·m; C is the specific volumetric heat capacity of the conductor material, J/(m^3·K); I is the current, kA; q is the cross-sectional area of the conductor, m^2; t is the time, s.

For the Camital alloy, the change in the temperature of the SMA over time when heated by a short-circuit current can be represented by the expression [3]:

$$\theta(t,I)=5{,}328\cdot10^{-7}\frac{W(t)}{q^2}+1{,}28\cdot10^{-18}\frac{W(t)^2}{q^4}+ +4{,}014\cdot10^{-29}\frac{W(t)^4}{q^6}+\theta_0, \quad (21)$$

where $W(t)$ is the thermal impulse, $A^2\cdot s$; q is the cross-sectional area of the thermally sensitive element, m^2.

The thermal impulse generated in the thermosensitive element during the flow of a short-circuit current is calculated by the formula [3, 9]:

$$W(t)=\int_0^t\left[I_{pm}\sin(\omega t)+I_{am}e^{-t/T_a}\right]^2 dt, \quad (22)$$

where I_{pm}, I_{am} are the periodic and aperiodic components of the short-circuit current, respectively, kA; T_a is the time constant of the decay of the aperiodic component of the short-circuit current, s.

To obtain a generalized equation of the protective characteristics of the fuse, the relationship between the heating temperature of the thermosensitive element and the current and its flow time is approximated by the following polynomial (based on experimental measurement data):

$$\theta(t,I)=5{,}328\cdot10^{-7}I^2\frac{t}{q^2}+1{,}28\cdot10^{-18}I^4\frac{t^2}{q^4}+ +4{,}014\cdot10^{-29}I^6\frac{t^4}{q^6}+\theta_0. \quad (23)$$

Since the second and third terms in (23) take values close to zero, we can use a simplified dependence with an error of <1 %:

$$\theta(t,I)=5{,}328\cdot10^{-7}I^2\frac{t}{q^2}+\theta_0. \quad (24)$$

Then the model of thermomechanical characteristics takes the following form:

$$\sigma_{te}(t,I)=\mathrm{if}\left[\theta(t,I)\geq 90, M_{te}(t,I), K_{te}(t,I)\right]; \quad (25)$$

$$M_{te}(t,I)=\left[1-e^{-(5{,}328\cdot10^{-7}I^2\frac{t}{q^2}+\theta_0)A_1}\right]A_2L_0-A_3L_0; \quad (26)$$

$$K_{te}(t,I)=A_4(5{,}328\cdot10^{-7}I^2\frac{t}{q^2}+\Theta_0)^4L. \quad (27)$$

After transforming (24) with respect to time t and taking into account the equation of thermomechanical characteristics of the thermosensitive element, we obtain the ampere-second characteristic (mathematical model) of a fuse with a tension element made of a shape memory alloy:

$$t(I)=1{,}87\cdot10^6\frac{q_{te}^2}{I^2}\left[\sqrt[4]{\pi\sigma_{fe}\frac{d_{fe}^2}{ALq}}-\theta_0\right], \quad (28)$$

where $A = 4\cdot A_4$ is the dimensionless quantity.

In the case of SMA in the form of a coiled spring, we obtain:

$$t(I)=1{,}87\cdot10^6\frac{q_{te}^2}{I^2}\left[\sqrt{d_{fe}d_{te}\sqrt{\sigma_{fe}\pi\frac{D_{te}}{2A_4LL_{te}\ln(1+\varepsilon)}}}-\Theta_0\pi^2d_{te}\right], (29)$$

where d_{te} is the diameter of the SMA wire, m; L_{te} is the length of the SMA wire, m; D_{te} is the diameter of the SMA spring, m; ε is the relative deformation of the spring, a dimensionless quantity; $C/\rho = 1.87\cdot10^6$ [$A^2\cdot s/(m^4\cdot K)$].

Test bench design. A special test bench was created to conduct tests to verify the developed mathematical model. Its functional diagram is shown in Fig. 3; Fig. 4 shows the measuring unit, and Fig. 5 shows the general view.

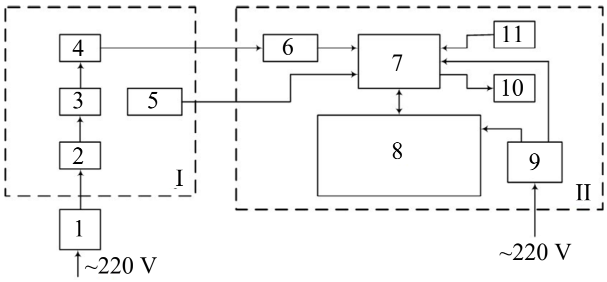

Fig. 3. Functional diagram of the test bench: I – measuring device; II – information display and storage unit; 1 – regulated power supply; 2 – fuse; 3 – strain gauge; 4 – current sensor; 5, 6 – analog-to-digital converters; 7 – microcontroller; 8 – touch screen; 9 – power supply; 10 – information storage device; 11 – ambient temperature sensor

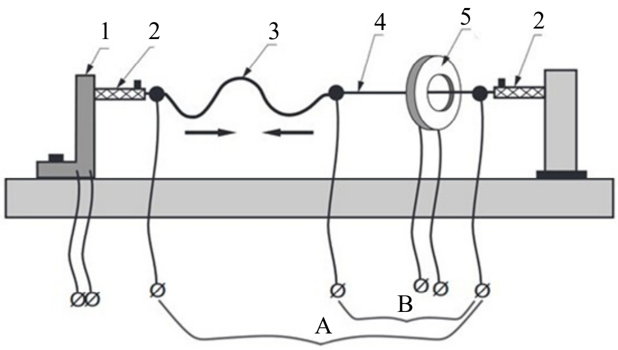

Fig. 4. Measuring unit of the test bench: 1 – strain gauge mounting; 2 – insulating mountings; 3 – SMA thermosensitive element; 4 – fuse element; 5 – induction coil, current measuring element; A – power supply circuit when testing a fuse with a SMA thermosensitive element; B – power supply circuit when testing a traditional fuse

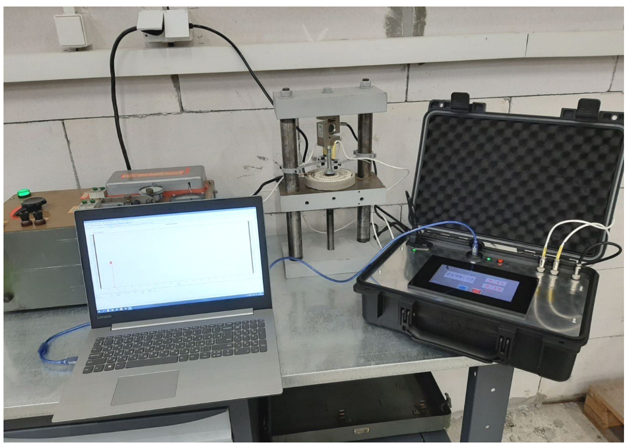

Fig. 5. General view of the experimental setup for studying thermosensitive elements with shape memory and fuses [19]

The stand can be used to test both traditional fuses and fuses with an SMA element. In the first case, voltage is applied to circuit B, and current flows only through element 4. In the second case, voltage is applied to circuit A, and current flows through both the traditional fuse element 4 and the thermosensitive element 3. The thermosensitive element heats up and, changing its shape, increases the mechanical load on part 4 of the fuse. The strain gauge system measures the increase in tensile force until the tensile strength is exceeded and the fuse element breaks. The current is measured using an inductive sensor YTT-6M2 with an accuracy class of 0.2 (5) and a control and measurement system. The accuracy of the breaking force measurement is 2 %.

The characteristics of a fuse with a rated current of 7 A, which assume thermomechanical destruction of the safety element, can be analyzed using an example with the following initial data: geometry of the thermosensitive element a = 0.005 m (width), b = 0.00035 m (thickness); copper safety element – wire with a diameter of d = 0.0002 m; mechanical tensile strength limit of the safety element σ_{fe} =$2\cdot10^8$ Pa (tensile strength 6.28 N); current I = 40 A; A_4 = $5.8\cdot10^{-5}$; L = $2\cdot10^5$ Pa/K^4. The results of the calculations are shown in Fig. 6, 7.

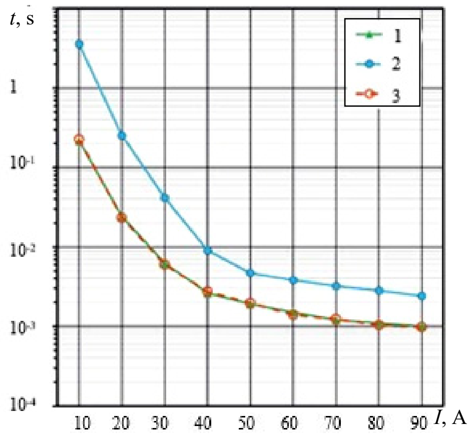

Fig. 6. Ampere-second characteristics of fuses:
1 – thermomechanical destruction of the fuse element (calculated); 2 – experimental protective characteristics of a traditional fuse; 3 – experimental protective characteristics of a fuse with a thermosensitive SMA element

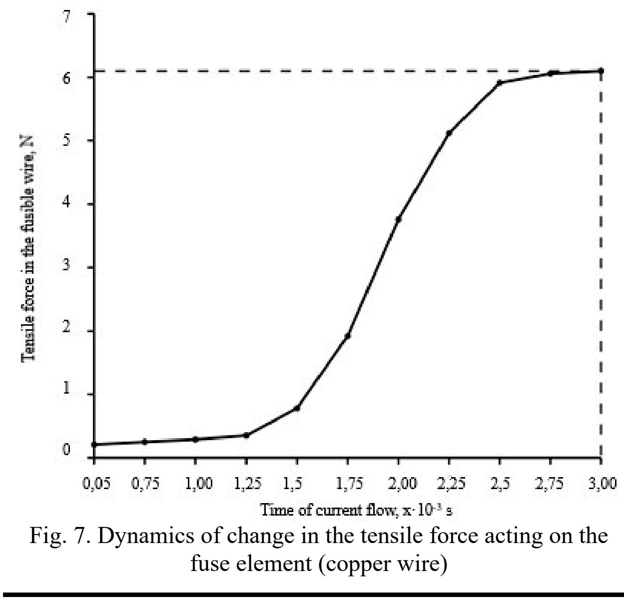

Fig. 7. Dynamics of change in the tensile force acting on the fuse element (copper wire)

Results and discussion. Table 1 shows the measurement results for a conventional fuse and an SMA fuse equipped with a thermally sensitive element. For each current value, the responce time of the modified fuse was shorter than that of the conventional fuse. The use of a thermosensitive element reduced the response time by more than 20 times for a current of 10 A and by about 10 times (from 0.257 s to 0.0244 s) for a current of 20 A. The reduction in response time decreased with increasing current. For the highest current tested (90 A), the response time of the fuse was less than half that of the conventional fuse.

Table 1

Fuse response time for different current values (SD – standard deviation)

Current, A	Traditional fuse	Fuse with SMA element	Values calculated for a fuse with an SMA element
	Safety element destruction time, average value (±SD), s		
10	3,579 (±0,0224)	0,2158 (±0,0041)	0,2266
20	0,254 (±0,0044)	0,0244 (±0,0005)	0,02338
30	0,0416 (±0,0003)	0,0063 (±0,0002)	0,00602
40	0,0091 (±0,0002)	0,0026 (±0,0001)	0,00272
50	0,0047 (±0,0003)	0,0022 (±0,0001)	0,00196
60	0,0038 (±0,0001)	0,0015 (±0,0001)	0,00139
70	0,0032 (±0,0003)	0,0012 (±0,0002)	0,00104
80	0,0028 (±0,0001)	0,0011 (±0,0001)	0,00104
90	0,0024 (±0,0001)	0,0010 (±0,00002)	0,00098

Table 2 contains calculated values from the mathematical model described in the research methodology, which are close to the measurement results. The dependencies of the fuse response time for different current values in three variants are shown in Fig. 6.

Table 2

Dynamics of changes in the tensile force acting on the fusible wire (SD – standard deviation)

Current flow time, ms	Force acting on the fusible wire
	Average value (±SD), N
0,5	0,21 (±0,006)
0	0,25 (±0,002)
1	0,29 (±0,002)
1,25	0,35 (±0,002)
1,5	0,78 (±0,004)
1,75	1,92 (±0,003)
2	3,76 (±0,004)
2,25	5,12 (±0,004)
2,5	5,91 (±0,004)
2,75	6,06 (±0,013)
3	6,12 (±0,000)

In experimental studies, the same fuse element (copper wire with a diameter d = 0.0002 m) was used. The positions of the characteristics obtained from calculations and experiments in the coordinate grid (Fig. 6) confirm the positive effect of the SMA thermosensitive element on the fuse sensitivity and the increase in the current-limiting effect. The discrepancy between the calculated (1) and experimental results (3) in Fig. 6, estimated by the least squares method, does not exceed 5 % on average.

According to the research methodology, measurements of the change in the tensile force at different currents were carried out. The results are given in Table 2 and shown in Fig. 7. Under these conditions, at a current $I = 40$ A, the tensile force reached the limit value after ≈3 ms. Such a fuse response time is achieved due to the use of the SMA thermally sensitive element and significantly increases the current protection class, ensuring satisfactory safety for most electrical equipment. The tensile strength of the safety element was ≈6 N and was slightly lower than the calculated tensile strength given above (6.28 N). This difference is due to the heating of the safety element and the change in its mechanical characteristics.

Conclusions.

1. Using a thermosensitive shape memory alloy (SMA) element to ensure thermomechanical destruction of the fuse element is a highly effective way to improve its current-limiting effect. It is experimentally proven that the modified fuse exhibits a significantly shorter response time compared to the traditional one: the response time reduction was more than 20 times for a current of 10 A and about 10 times for a current of 20 A.
2. The developed mathematical model adequately describes thermal, electrical and thermomechanical processes in a fuse with an SMA element; the discrepancy between the calculated and experimental ampere-second characteristics does not exceed 5 %, which confirms the possibility of its use for engineering design and optimization of fuse parameters.
3. To implement the new fuse design principle, it is advisable to use a functional copper-based alloy, for example Cu-Al-Mn (Camital). This choice is due not only to its suitable physical properties and characteristics, but also to its significantly lower cost compared to Ni-Ti Nitinol, which increases the practical significance of the proposed solution.

Conflict of interest. The authors declare no conflict of interest.

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The use of shape memory alloys in fuses for the protection of electrical installations.

Problem*. The degree of damage to electrical installations during short circuits depends on the response time of the protection. An effective way to enhance the current-limiting effect in electrical fuses (reducing their response time) may be the use of shape memory alloy (SMA) elements. However, this requires careful study and research. The* ***goal*** *of the work is to establish the patterns of strengthening the current-limiting effect of a fuse (reducing the response time) when using thermosensitive elements made of shape memory alloys. The achievement of this goal is based on the analysis of experimental studies conducted by the authors and mathematical models of the characteristics of a fuse containing an SMA element.* ***Methodology****. The article presents mathematical modelling of the parameters and characteristics of fuses with thermomechanical destruction of the fuse element, as well as a thermophysical model of a fuse with a thermosensitive SMA element. The article presents the* ***results*** *of experimental studies of a traditional fuse and a fuse equipped with a thermosensitive SMA element. For each current, the response time of the modified fuse was shorter than that of the traditional fuse. The use of a thermosensitive element reduced the response time by more than 20 times for a current of 10 A and approximately 10 times (from 0.257 s to 0.0244 s) for a current of 20 A. For the highest tested current (90 A), the fuse response time was half that of a traditional fuse. The article also presents the results of calculations of fuse characteristics using a mathematical model and a comparison with the results of experimental studies.* ***Scientific novelty****. The developed mathematical models of the characteristics of electrical fuses containing SMA elements made it possible for the first time to substantiate the interrelationships between the parameters (geometric dimensions and characteristics of SMA elements, fuse links) with current loads of electrical installations. The* ***practical value*** *of the work lies in the proposed use of thermosensitive elements made of functional materials to increase the current-limiting effect of electrical fuses for protecting electrical installations during short circuits.* References 19, tables 2, figures 7.

Key words: **functional materials, fuse, shape memory alloy, thermosensitive element**.

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