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FUNCTIONING FEATURE ANALYSIS OF VOLTAGE LIMITERS BASED ON A COMBINED VARISTOR-POSISTOR STRUCTURE

Abstract. Modeling and analysis results concerning the influence of the electrical and thermal conditions on the functioning of series-connected and thermally contacted layers of varistor ceramics and a posistor composite are presented. Such structures may be useful for the development of a promising limiter of constant and slowly varying voltages. The main attention is paid to the behavior of their functional electrical and thermal characteristics with changes in the internal resistance of the input voltage source and in heat flow intensity to the environment as well as in its temperature. It is shown that a change in the internal resistance of the input voltage source can only lead to a shift towards higher input voltage values ensuring the posistor element actuation. At a low intensity of heat exchange between such a voltage limiter and the environment, it may operate at voltages lower than the classification voltage of the varistor layer, and thus the device under consideration is not capable of fixing a constant voltage at the output and can function as a self-resetting high voltage fuse. In the case of an increase in the ambient temperature (up to the temperature of the phase transition in the posistor layer material), the temperature of the structure and the output voltage of the device change insignificantly around the temperature limitation point, and the current value and dissipation power of the structure are much reduced. For structures based on varistor ceramics with a strong temperature dependence of low-voltage resistance (high activation energies of its temperature sensitivity), the output voltage decrease (to values of one volt order) takes place.
Key words: varistor ceramics; polymeric positive temperature coefficient (PPTC) nanocomposite; varistor-posistor structure, voltage limiter; voltage source internal resistance, heat transfer intensity.

1. Problem statement

Inhomogeneous dielectrics, in particular posistor nanocomposite materials and varistors, have found wide and effective use in modern technology as elements of protection devices against current and impulse overloads of various electrical systems [1-6]. A promising application of inhomogeneous dielectrics of this type is the implementation of protection of solar cells from overvoltage in their series connections (rows) in photovoltaic modules [7].

Therefore, it is very important to model and analyze the influence of the electrical and thermal conditions on the operation of voltage limiters – combined structures based on metal oxide ceramics and a polymer posistor composite used in well-known self-healing fuses of the PolySwitch technology. Hence, relevant is the study of behavior patterns of their functional electrical and thermal characteristics with a change in the internal resistance of the input voltage source, the heat transfer to the environment and its temperature.

2. Analysis of recent research and publications

The analysis of literature data showed that the use of the construction described in [8, 9] in the form of a combined two-layer structure of varistor and posistor layers in thermal contact to limit overvoltage is a promising directional protection against current and impulse overloads. The input voltage is applied to the entire structure (sequential connection of specified layers).

The varistor layer determines the output voltage of such a quadripole and is connected in parallel to the object of protection. When an input overvoltage occurs, the heat generated by the varistor layer initializes the heating of the series-connected posistor layer and causes an increase in its resistance. As a result, there is a redistribution of the input overvoltage between the layers, which can ensure the limitation of the output voltage on the varistor layer and, accordingly, on the load connected in parallel to it.

A number of works are devoted to the study of the electrical characteristics of the considered two-layer varistor-posistor structures [9, 10, 11]. At the same time, the main attention was paid to the research on the substantiation of the very principle of operation of such an overvoltage protection element and the possibility of its application in solar photovoltaic systems [7].

The tasks of developing the devices under consideration as voltage limiters (VL) both for general multi-purpose use and for use as self-resetting surge protectors in solar photovoltaic systems [7, 12] require detailed knowledge of their electrical and thermal characteristics and their behavior under various conditions.

3. The purpose of study

The purpose of the work is to determine the patterns of behavior of the functional electrical and thermal characteristics for such structures with a change in the internal resistance of the input voltage source, in the heat transfer intensity to the environment and its temperature.

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4. Description of the main material of research.

4.1. Model equations

The analyzed two-layer structure, consisting of layers of varistor ceramics and a nanocomposite with a positive temperature coefficient of resistance connected in series and in direct thermal contact, can be represented by the scheme in Fig. 1.

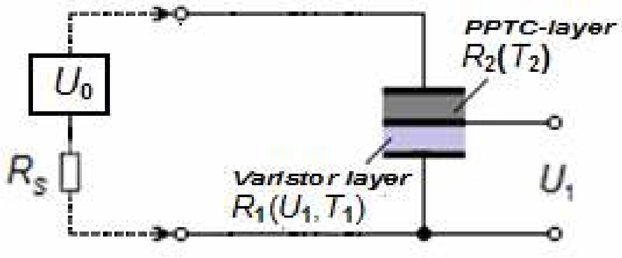

Figure 1 - The structure under study and the circuit for supplying electric voltage to it: U_0 and U_1 are the input and output (to be limited) voltage; $R_1(U_1, T_1)$, $R_2(T_2)$ and R_s are the electrical resistances of the varistor and posistor layers and the internal resistance of the input voltage source

When voltage U_0 is applied to the structure under consideration, it is initially applied to the varistor layer, since the posistor layer at temperatures below the actuation temperature $T_{tr} \approx 398$ K [13, 14] has a low resistance (close to metal). Because of this, the varistor layer begins to heat up due to the increase in the flowing current and its temperature increases. The posistor layer also heats up due to contact with the varistor layer, as well as due to the current flowing through it (self-heating). Its resistance increases sharply as it approaches the actuation temperature T_{tr} (this designation is used because of the traditional term "tripping"). The current flowing through the structure and, accordingly, through the layer of varistor ceramics, slightly decreases, and the structure temperature drops. As a result of such a transient process, the output voltage on the varistor layer and the structure temperature are stabilized.

The set of equations for determining and analyzing the steady-state stationary values of the main parameters of the considered electrothermal voltage limiter can be written in the following form:

$$P_1(T_1,T_2)=\frac{T_1-T_0}{RT_{dis}}-\frac{T_1-T_2}{RT_{con}}, \tag{1}$$

$$P_2(T_1,T_2)=\frac{T_2-T_0}{RT_{dis}}-\frac{T_2-T_1}{RT_{con}} \tag{2}$$

where $P_1(T_1,T_2)=I(T_1,T_2)\cdot U_1(T_1,T_2)$ and $P_2(T_1,T_2)=I(T_1,T_2)^2\cdot R_2(T_2)$ – electrical (converted into thermal) power dissipation of the varistor and posistor layers;

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$T_1(t)$ и $T_2(t)$ – temperatures; T_0 – ambient temperature (assumed to be 300 K);
RT_{dis} – temperature resistances of heat dissipation into the environment, which are related to the heat transfer coefficient $RT_{dis} \approx 1/(h_z S)$, h_z – coefficient of heat transfer per unit area of the plate surface with the environment, S – plate area [15] (taken the same for both layers of the structure); RT_{con} – temperature resistance of heat transfer of the contact between these layers.

Electrical resistance of the varistor layer, taking into account the temperature dependence of their conductivity in weak electric fields (in the ohmic part of the I–V characteristic) $G(T)$, was represented on the basis of the analytical equation given in [5] as

$$R_1(U,T) = \frac{1}{G(T) + \frac{I_c}{U} \cdot \left(\frac{U}{U_c}\right)^{\beta}}, \qquad (3)$$

where U_C – voltage (sometimes called breakdown voltage) across the varistor layer at current $I_C = 10^{-3}$A [1, 5]; β – non-linearity coefficient;

$G(T)=G_0 \cdot exp(-\Delta E_g/(kTn))$; k and ΔE_g are the Boltzmann constant and the activation energy of the considered temperature dependence (which for zinc oxide varistor materials ranges from 0.4 to 0.8 eV [16]; n is the correction factor for determining the activation energy of the considered temperature dependence (determined experimentally).

To approximate the temperature dependence of the posistor electrical resistance $R_2(T)$, the equation is used [9], which is known for describing phase transitions and suitable for nanocomposite materials based on PolySwitch technology

$$R_2(T) = \begin{cases} \frac{A_1}{(T_{trip} - T)^m}, T < \theta \\ A_2, \ T \geq \theta \end{cases}, \qquad (4)$$

where $A_1 = R_2(T_0)\cdot(T_{trip}-T_0)^m$; $R_2(T_0)$, A and m are values determined by the technical parameters of samples of PPTC composite of PolySwitch technology; $T_{trip} \approx 398$ K is the temperature of its operation (phase transition);

$R_2(T_0) = R_2(300\ K)$ (equals to R_{min} or R_{1max} [7]) is the resistance of the fuse layer in the conducting state; R_{min} is the minimum resistance of the posistor nanocomposite layer at 23 °C; R_{1max} is the maximum layer resistance after switching off and restoration within one hour at 23 °C;

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A_2 – resistance of the fuse in the insulating state (from 10^4 Ω to 10^{10} Ω) [5]; m is the approximation parameter (from 1 to 4); $\theta \approx T_{trip}$.

Determining the magnitude of the electrical voltage $U_1(T_1, T_2)$ on the varistor layer in a circuit from a series connection of the varistor and posistor layers, to which the voltage U_0 of a power supply with an internal electrical resistance R_S is applied, is carried out by solving the following non-linear equation, which can be obtained from the well-known Kirchhoff laws,

$$U_1(T_1,T_2) = \frac{U_0 \cdot R_1[U_1(T_1,T_2),T_1]}{R_1[U_1(T_1,T_2),T_1] + R_2(T_2) + R_s}\,. \tag{5}$$

The solution of a non-linear equation (5) can only be numerical (in the form of a two-dimensional array). To find it, the standard built-in root function of the Mathcad package [17] can be used. To represent the function $U_1(T_1,T_2)$ in the analytical form required for solving the set (1)-(3), two-dimensional spline interpolation was used (the interp and cpline functions of the Mathcad package).

The expression for the current passing through the structure under consideration has the form:

$$I(T_1,T_2) = \frac{U_0}{R_1[U_1(T_1,T_2),T_1] + R_2(T_2) + R_s}\,. \tag{6}$$

The temperatures T_1 and T_2 were found by solving the set of nonlinear equations (1)-(2), which was performed using the already mentioned standard built-in root function of the Mathcad package.

4.2. Modeling the influence of the features of the electrical and thermal conditions on the operation of a varistor-posistor voltage limiter

4.2.1. Influence of the internal resistance of the input circuit

The influence of the internal resistance of the input voltage source R_s on the steady state values of output voltage U_1, current I, and power dissipation of the varistor layer P_1 after the actuation of the analyzed VL is shown in Fig. 2.

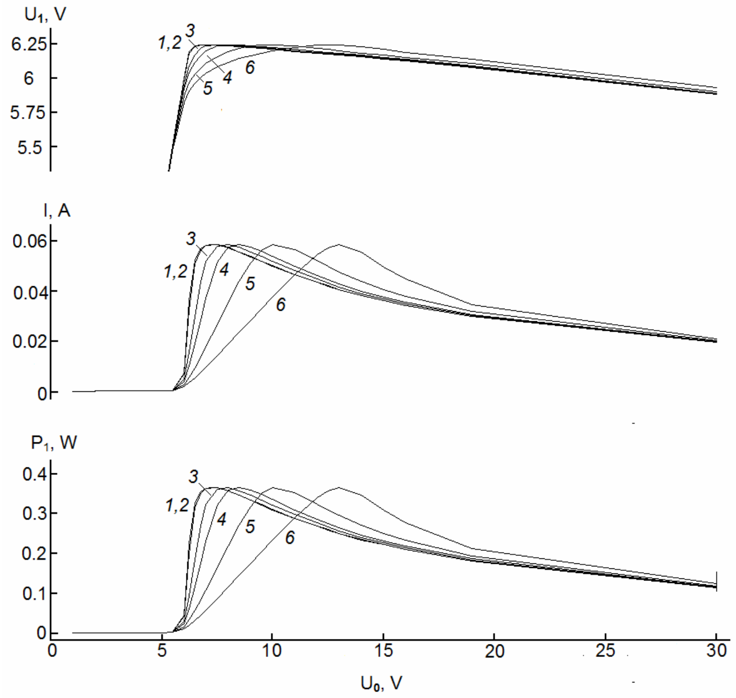

Figure 2 -Ansient $U_1(U_0)$ and input $I(U_0)$ characteristics, as well as dependences of the power dissipation of the varistor layer $P_1(U_0)$ of the varistor-posistor structure on the input voltage when using voltage sources with internal resistances R_s (Ω):
1 – 0.1: *2* – 1; *3* – 10; *4* – 20; *5* – 50; *6* – 100

In numerical experiments, the typical values of the quantities R_s=1 Ω; RT_{con}=1.15 K·W^{-1}; h_z=0.001 W·K^{-1}·cm^{-2} (RT_{dis}=318 K·W^{-1}) and of the physical parameters of the component materials of the structure under study, oriented for use in protection circuits of solar arrays, are accepted. For the varistor layer, the parameters of its working element – a layer assembled from several dozen parallel-connected commercial frameless low-voltage varistors V3.5MLA0603NH (U_C = 3.7-7 V, β = 30-50) [18] and for the posistor layer, that of a self-restoring fuse of the FRX110 60F type (element resistance in conductive state $R_2(T_0)$ ~ 0,3 Ω; T_{trip}=125 °C) [19] were used.

As can be seen, the dependences $U_1(U_0)$ and $I(U_0)$ presented in Fig. 2 correspond to the known ones [8, 9]: with an increase in the input voltage above the classification voltage of the varistor layer U_C, the output voltage is almost constant and the current and the dissipation power values, respectively, decrease.

These results are in full agreement with the existing ideas about the mechanism of electrothermal voltage limitation by the structure under consideration, which can be described as follows. When an input overvoltage is applied to the structure, the heat generated by the varistor layer heats the series-

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connected PTC layer and leads to an increase in its resistance. As a result, there is a redistribution of the input overvoltage between the layers, which ultimately can provide a limitation at a given level of the output voltage on the varistor layer and, naturally, on the load connected in parallel to it.

A change in the internal resistance of the input voltage source can only lead to a shift towards higher values of the input voltage that ensures the operation of the posistor element. This does not contradict the ideas about the allocation of some part of the electric power by the internal resistance of the source, that is, the achievement of the actuation temperature T_{trip} takes place at a higher input voltage (Fig. 3).

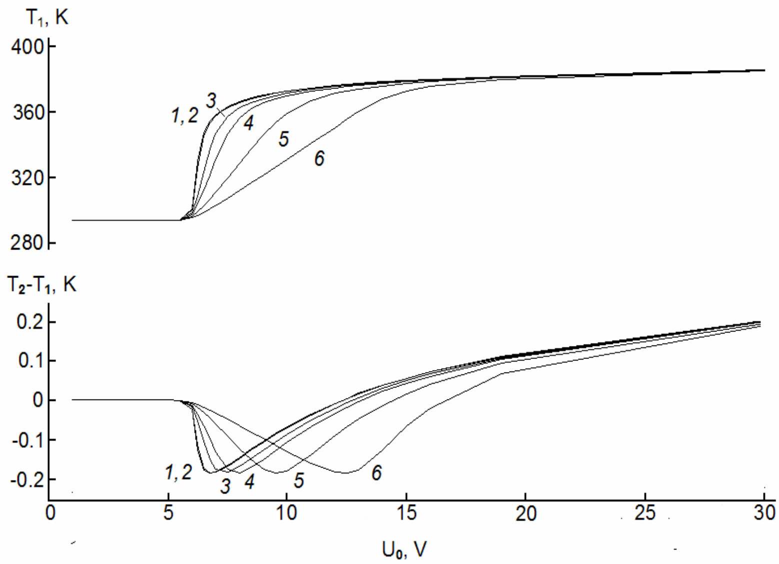

Figure 3 -Dependence of the temperature of the varistor layer T_1 and the temperature difference between the varistor and posistor layers (T_1 – T_2) after the VL operation on the applied input voltage for voltage sources with different internal resistances R_s (Ω): *1* – 0.1; *2* – 1; *3* – 10; *4* – 20; *5* – 50; *6* – 100

It should also be noted that at small U_0 the heating temperature of the varistor layer is higher than the temperature of the posistor one (T_1 – T_2) > 0, and for large U_0, the opposite pattern takes place (T_1 – T_2) < 0, which is the result of self-heating of the posistor layer by the passing current.

4.2.2 Influence of the intensity of heat exchange with the environment

The intensity of heat exchange with the environment is one of the essential factors that determine the temporal changes in the temperature of the considered two-layer varistor-posistor structure and, accordingly, its functional electrical characteristics. Such process can be regulated within certain limits, for example, by using special metal radiators; this allows to consider it as a regime process.

To simulate the effect of this heat transfer, the coefficient of heat exchange per unit surface of the outer electrode layers of the structure with the environment (h_z) can be used, which determines the thermal resistance of dissipation to the environment (RT_{dis}) in a specific mode of its functioning.

Presented in Fig. 4 data indicate a significant effect of this parameter on the transient response and the dependences of the dissipated electrical power and the temperature of the varistor layer in the active state (after actuation) for the device under consideration.

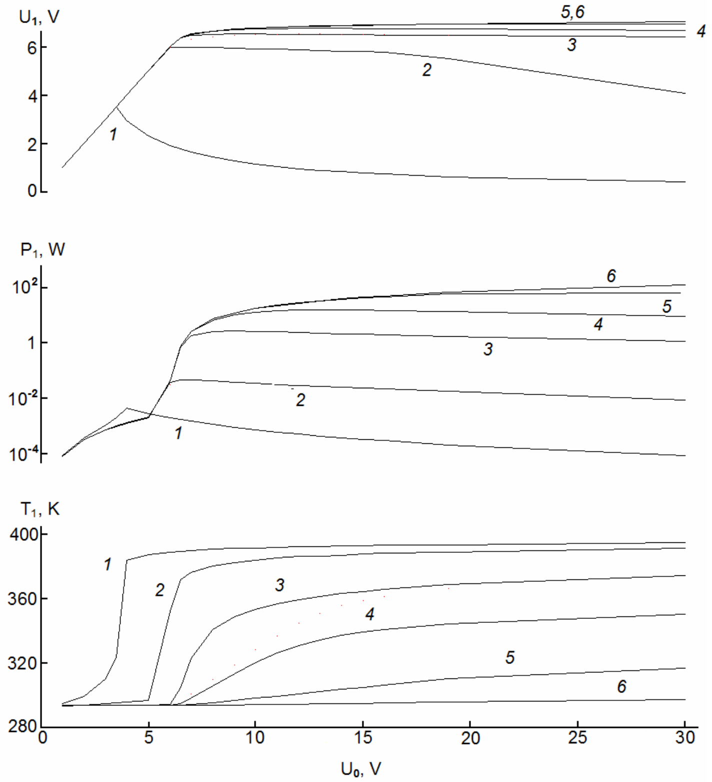

Figure 4 - Dependence of output voltage U_1, power dissipation P_1 and temperature of varistor layer T_1 after VL actuation on input U_0 at values of specific heat transfer coefficient h_z (W·K^{-1}·cm^{-2}): *1* – 0.00001; *2* – 0.0001; *3* – 0.001; *4* – 0.01; *5* – 1; *6* – 10

At low values of the heat transfer coefficient h_z, the VL actuation (at $T = T_{tr}$) takes place at relatively low ($U_0 < Uc$) input voltages U_0 (curves *1* and *2* in Fig. 4). In this case, the output voltage U_1 and the electrical power dissipated by the varistor layer are significantly reduced. It follows that the device under consideration in this mode is not capable of fixing a constant voltage at the output and can only function as a self-resetting high voltage fuse.

At large values of h_z, a significant electric power is required for the corresponding heating of the entire structure (curves *5* and *6* in Fig. 4) and,

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therefore, in the stationary state, large currents must flow through the structure, which will eventually lead to the degradation of the varistor layer [20] and the destruction of the voltage limiter. Regarding the accepted physical and technical parameters of the structure, the optimal value of the parameter h_z is within 0.001 – 0.01 $W \cdot K^{-1} \cdot cm^{-2}$.

4.2.3. Influence of ambient temperature

In the technical application of the studied combined electrothermal devices, detailed information is needed on their behavior under various conditions, in particular, in various temperature regimes. One of the urgent tasks is to study the influence of environmental factors on their electrical characteristics, first of all, such factor as ambient temperature.

The calculated dependences of the output voltage, current, and temperature of the structure under study on the applied input voltage in the open circuit mode are shown in Fig. 5.

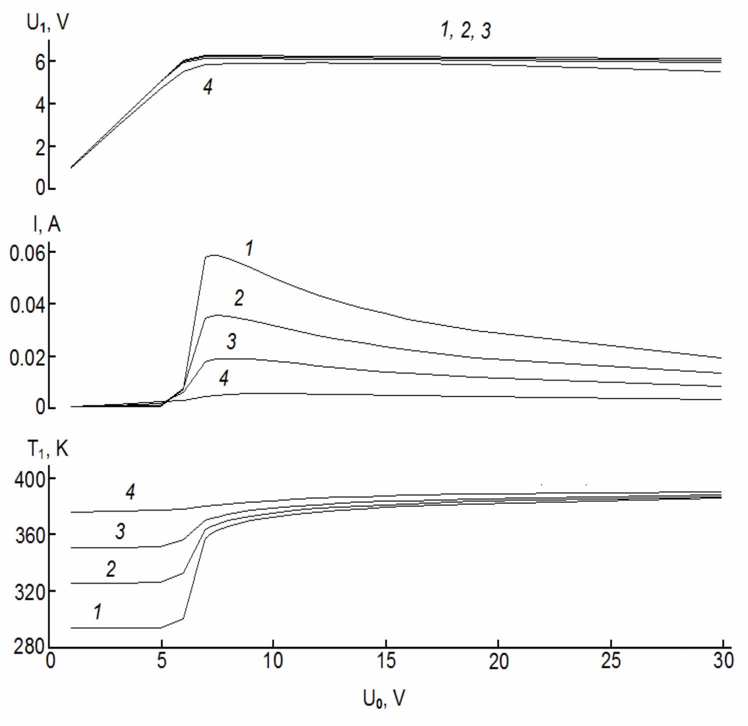

Figure 5 - Dependence of the output voltage U_1, current and temperature of the varistor layer T_1 after VL actuation on the input U_0 at the ambient temperature values T_0 (K): 1 – 293; 2 – 325; 3 – 350; 4 – 375

The presented patterns are in satisfactory agreement with the known data of the experimental studies [11].

The effect of ambient temperature on the absolute value of the limited output voltage is determined by a negligible thermal resistance factor.

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An increase in the ambient temperature T_0 leads to a slight increase in the temperature of the posistor layer of the structure in the output voltage range where the process of its limitation is implemented.

Input characteristics correspond to typical volt-ampere characteristics of posistors [21, 22]. It should be noted that the main function of the varistor – the limitation of the overvoltage pulse – takes only a short period of time at the beginning of its action when the varistor element heats the structure to the temperature of the phase transition of the posistor element, and then it performs only the function of a heater. After switching the posistor element to the low-conducting state, upon reaching T_{tr}, the current of the structure decreases to a value sufficient to keep it in this state [23]. According to the data in Fig. 4, an increase in the ambient temperature T_0 causes a significant decrease in the magnitude of the current I since such increase provides additional heating of the posistor element.

Accordingly, as the voltage U_0 increases, the current I flow through the combined structure under study increases and passes through its maximum (when the temperature of the structure approaches T_{trip} corresponding to the previously indicated phase transition). Further, this current decreases due to an increase in the resistance of the nanocomposite posistor layer.

Figure 6 shows the corresponding dependences of electrical power dissipation by layers of varistor ceramics and posistor polymer nanocomposite/

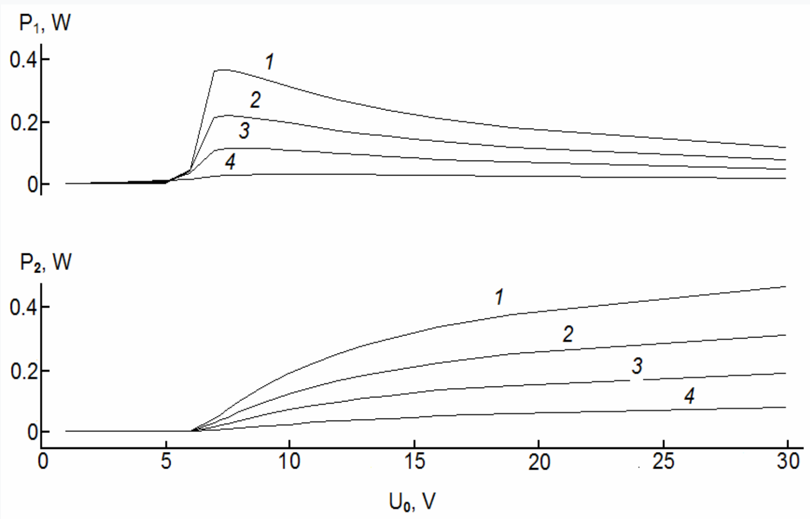

Figure 6 - Dependence of the electrical powers dissipated by the varistor P_1 and posistor P_2 layers of the structure under study after the VL actuation on the input voltage U_0 at the ambient temperature values T_0 (K):
1 – 293; 2 – 325; 3 – 350; 4 – 375

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After the transition of the posistor layer to a high-resistance state at T_{trip}, there is a redistribution of the input voltage and dissipated electrical power towards its posistor component increasing.

An increase in the ambient temperature leads to a decrease in the additional electric power required for the posistor layer to reach the phase transition temperature.

In conclusion, it should be noted that the current-voltage characteristics (CVC) of varistor, in particular, metal oxide ceramic materials, have sections that differ somewhat in electrical and thermal properties [24]. At low voltage values, there is a temperature-sensitive linear (ohmic) dependence of the current on voltage in the form of Ohm's law, and the electrical resistance of the varistor has a temperature activation dependence typical of a semiconductor. With a further increase in voltage, the current increases nonlinearly with increasing voltage, and there are sections of weak and varistor nonlinearity of the I–V characteristic, where there is practically no dependence on temperature. At very high voltages, the volt-ampere characteristic is also linear and has a temperature dependence of resistance with low activation energies (<0.05 eV). As a rule, this section of the CVC of varistors is not technically used.

Depending on the type of varistor material, as the temperature rises, its ohmic section and the section of intermediate fields can significantly move to the region of high currents. The activation energy of electrical conductivity in weak fields for different types of ceramics is 0.4–1 eV [16]. This feature of the I–V characteristics of the varistor layer, which is largely dependent on the activation energy of the low-voltage electrical conductivity of metal oxide ceramics, can lead to the effect of transformation of the transient characteristics of the considered LV, like those described in the previous subsection.

The results of the analysis of the effect of the temperature sensitivity of the varistor layer on the characteristics of the considered voltage limiting device within the framework of the adopted model of its CVC are presented below (Fig. 7).

As can be seen from this figure, when using a varistor layer with a significant temperature dependence of ohmic conductivity, a significant decrease in the output (limited voltage) can take place.

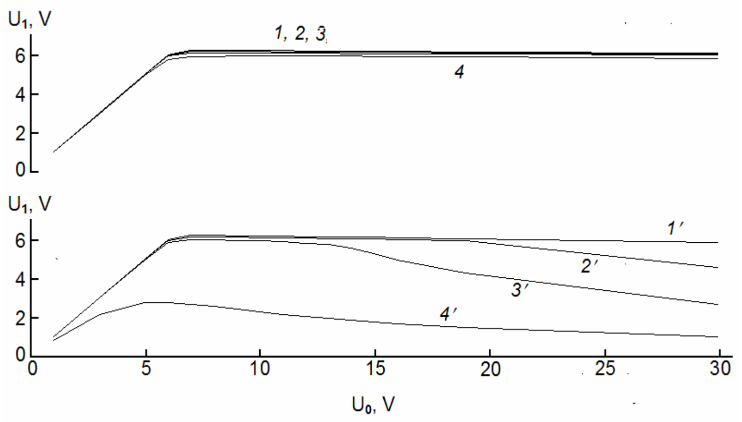

Figure 7 - Dependences of the output voltage U1 on the input U0 after actuation for VL based on varistor layers with conduction activation energies in the low-voltage (ohmic) section of their CVC: ΔE = 0 eV (1, 2, 3, 4) and ΔE = 0.4 eV (1′, 2′, 3′, 4′). Other designations correspond to those given in Fig. 6

5. Conclusions

The presented results of modeling and analysis of the influence of the features of the electrical and thermal conditions on the operation of a voltage limiter based on a combined structure of layers of metal oxide varistor ceramics and a posistor polymer nanocomposite made it possible to establish the following regularities.

A change in the internal resistance of the input voltage source may result in a shift towards higher values of the input voltage ensuring the posistor element actuation that corresponds to the loss of some part of the electric power spent for heating the structure on the internal resistance of the source.

Low levels of heat exchange intensity between the considered VL and environment cause it to actuate at voltages lower than the classification voltage of the varistor layer, and thus such a device is not capable of fixing a constant voltage at the output but can only function as a self-resetting high voltage fuse. At high intensity levels, significant currents are required for the appropriate heating of the entire structure, which can lead to the destruction of the VL itself.

If the ambient temperature rises, the structure temperature and the output voltage of the device change insignificantly in the section of the temperature limitation, and the current magnitude and the dissipation power of the structure are substantially reduced. For structures based on varistor ceramics with a strong dependence of low-voltage resistance on temperature (high activation energies of its temperature sensitivity), the output voltage decreases (to values of the order of one volt).

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Аналіз особливостей функціонування обмежувачів напруги на основі комбінованої варисторно-позисторної структури

У роботі наведено результати моделювання та аналізу впливу особливостей електричного та теплового режимів на функціонування структури з послідовно з'єднаних та термічно контактованих шарів варисторної кераміки та позисторного композиту, що становлять інтерес для розробки. перспективного обмежувача постійних і повільно змінних напруг. Основна увага приділена дослідженню закономірностей поведінки функціональних електричних і теплових характеристик таких структур при зміні внутрішнього опору джерела вхідної напруги та інтенсивності теплообміну з навколишнім середовищем, а також його температури.

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Показано, що зміна внутрішнього опору джерела вхідної напруги може призвести лише до зсуву в бік вищих значень вказаної напруги, що забезпечує спрацьовування позисторного елемента.

При низькій інтенсивності теплообміну між таким обмежувачем напруги та навколишнім середовищем він може працювати при напругах, нижчих за класифікаційну напругу варисторного шару, і, таким чином, розглянутий пристрій не здатний фіксувати постійну напругу на виході і може функціонувати тільки як самовідновлюваний запобіжник від перенапруги.. При підвищенні температури навколишнього середовища (до температури фазового переходу в матеріалі шару позистора) температура структури та вихідна напруга приладу змінюються несуттєво навколо точки обмеження температури, а значення струму і потужність розсіювання структури значно зменшуються. Для структур на основі варисторної кераміки з сильною залежністю низьковольтного опору від температури (високі енергії активації його температурної залежності) має місце зниження вихідної напруги (до значень порядку одного вольта).

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