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ANALYSIS OF TEMPERATURE DISTRIBUTION IN A SOLAR ELEMENT WITH POSISTOR LAYER IN THE PRESENCE OF LOCAL ELECTRIC HEAT SOURCE

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The temperature distribution in a model structure in the form of a solar photovoltaic cell plate with an additional posistor layer based on a polymer matrix with nanocarbon fillers being in thermal contact is determined and investigated in the presence of overvoltages leading to the occurrence of local overheating regions. It is found that the regions of local overheating expand over time and, as a result, they spread over the entire plate of such a structure. The entire structure is heated above the phase transition temperature of the posistor layer for a time interval of the order of several seconds. The posistor layer goes into a low-conductivity state and most of the voltage drops across it. These results substantiate the prospects of using a posistor layer for electrical and thermal protection of solar photovoltaic cells from reverse overvoltages.

Keywords: **solar photovoltaic cell, overvoltage, electrical characteristics, modeling, posistor, PPTC fuse, tripping temperature.**

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1. Introduction

One of the ways to solve the problem of protecting photovoltaic cells of solar arrays from electrical overloads and preventing local overheating (the appearance of “hot spots” [1-6]) is based on the use of posistor composites based on nanocarbon fillers in a polymer matrix and manufactured using the “PolySwitch” technology [7-9]. The basic functional property of such polymeric positive temperature coefficient devices (PPTC resettable fuses) is an abrupt increase in resistance by several orders of magnitude upon reaching a certain limiting temperature and returning to the initial highly conductive state when the temperature drops. Analysis of the prospects for the creation and application of such thermal sensor fuses is relevant. The possibility of implementing protection against reverse electrical overvoltages and thermal breakdown of photovoltaic cells of a small area with built-in layers of a posistor polymer nanocomposite with a carbon filler for which the inhomogeneity of pre-breakdown heating can be neglected was established [10]. However, it should be taken into account that modern solar photovoltaic cells are distributed film type structures (thickness 0.1-0.2 mm, area up to 15×15 cm^2). The processes of heat propagation in the longitudinal direction (in particular, thermal breakdown) must be considered in a detailed study of electrothermal processes in such structures. This is the subject of this work. The results of modeling the temperature distribution in the structure, which is a solar photovoltaic cell with an additional posistor layer (PPTC resettable fuse of “PolySwitch” technology) being in thermal contact in the presence of overvoltage are given. The equations of heat conduction with a local source of heat of electrical origin varying in space and time are the basis of the model.

2. Physical fundamentals

At the initial moment of the appearance of a reverse voltage, which biases the p-n junction of the photovoltaic cell, the PPTC fuse layer has a temperature close to the ambient temperature T_0 and is in a highly conductive state. Significant current begins to flow in the region with low electrical resistance of the photovoltaic cell, which is able to heat the specified area and the adjacent part of the PPTC fuse layer to temperatures equal to or higher than the temperature of its transition to the insulating state (tripping temperature). As a result, the region of the PPTC fuse layer adjacent to the region of local heating of the solar photovoltaic cell plate becomes insulating and the current of the reverse biased p-n junction of the photovoltaic cell is forced to flow around it, which leads to spatial expansion (“spreading”) of the initially formed heat source (Fig. 1).

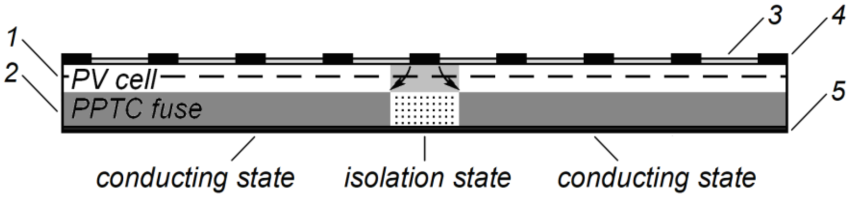

Fig. 1. The analyzed structure in the state of heating the local region of the PPTC fuse layer by electric current with its transition to a low-conductive state. The arrows show the directions of the maximum currents flow.
1 **- p-n junction of photovoltaic cell;** ***2*** **- posistor nanocomposite layer;** ***3*** **and** ***4*** **- antireflection coating and metal mesh (electrode) of photovoltaic cell layer;** ***5*** **– electrode layer.**

As this “spreading” occurs, all new regions of the PPTC fuse layer are heated and pass into a low-conductive state. After such a transition of the entire PPTC fuse, the overvoltage of the p-n junction of the photovoltaic cell is redistributed to this layer and, thus, the possibility of thermal breakdown and degradation of the solar photovoltaic cell in the considered abnormal situation is prevented.

3. Model equations

The solution to the problem of finding the temperature distribution $u(r,t)$ along the coordinate r and in time t can be realized using the heat conduction equation in a polar coordinate system taking into account axial symmetry [11, 12], where the above-described effect of “spreading” of an electric heat source is necessary take account

$$\frac{\partial u(r,t)}{\partial t}=\frac{k}{\rho\cdot c}\left[\frac{\partial^2 u(r,t)}{\partial r^2}+\frac{1}{r}\frac{\partial u(r,t)}{\partial r}\right]+\frac{p[u(r,t),r_s]}{\rho\cdot c\cdot d}-\frac{2h_z[u(r,t)-T_0]}{\rho\cdot c\cdot d}, \tag{1}$$

where r is a point in the plane of the plate, which has the shape of a thin disk of radius r_0 and thickness d; ρ, c, k and h_z are density, specific heat capacity, thermal conductivity and heat transfer coefficient of the unit surface of the plate bases with the environment.

The left term of equation (1) corresponds to the processes of heat accumulation spent on heating the plate, the right terms correspond to the processes of heat propagation in the longitudinal direction, heat creation by internal sources and its dissipation according to the Newton-Richman law [13] through the surfaces of the bases in the transverse direction, respectively.

The density of electrical power, which is spent on heating a plate element with an area $dS = 2\pi\, r\, dr$, is determined by the expression [14]

$$p[u(r,t),r]=U(T)^2 g_{p-n}(T)\, f(r,\sigma), \tag{2}$$

where $U(T)=U_0 R_{p\text{-}n}(T)/[R_{p\text{-}n}(T)+R_s]$ is the reverse electrical voltage applied to the p-n junction of the solar photovoltaic cell; U_0 is the overvoltage amplitude; R_s and $R_{p\text{-}n}(T)$ are the internal resistance of the overvoltage source of the photovoltaic cell and the experimentally determined resistance of the p-n junction; $f(r,\sigma)=1/\left(\sigma\sqrt{2\pi}\right)\exp\left[-r^2/\left(2\sigma^2\right)\right]$ is the power distribution function along the coordinate (radius) of a local heat source with axial symmetry [15]; σ is the parameter related to the effective value of the radius of the heat source r_s by the equation $f(r_s,\sigma)/f(0,\sigma)=0.5$;

$g_{p-n}(T) = G_{p-n}(T) \Big/ \left\{ \sigma\sqrt{2\pi}\left[1-\exp\left(-\frac{r_0^{\,2}}{2\sigma^2}\right)\right]\right\}$ and $G_{p-n}(T)=1/R_{p-n}(T)$ are the differential and integral electrical conductivity of the reverse biased p-n junction of the photovoltaic cell plate.

The problem under consideration has axial symmetry and the boundary condition for it can be written using the Newton-Richman law for the end surface of the plate, which, in accordance with the adopted approximations, has a circular shape

$$\frac{\partial u(r_0,t)}{\partial t} = h_r\left[u(r_0,t) - T_0\right], \tag{3}$$

where h_r is the heat exchange unit of the end surface of the plate with the environment.

The initial condition is

$$u(r,0) = T_0\,. \tag{4}$$

In this case, the influence of longitudinal heat transfer in the posistor layer is neglected. To a certain extent, such a simplification can be considered correct, since the specific thermal conductivity of a silicon plate (at room temperatures 0.84-1.50 $\mathrm{W\,cm^{-1}\,K^{-1}}$) [16] is several times higher than the value of a similar parameter for polyethylene (0.0033 $\mathrm{W\,cm^{-1}\,K^{-1}}$) [17].

In this case, the solution algorithm is as follows.

1. Solution of problem (1)-(4) for a small-time interval Δt_1 (from $t_0 = 0$ to $t_1 = \Delta t_1$). The time of the heat propagation process is taken equal t_1.

Fixation of the obtained temperature distribution in the plate $u(r, t_1)$ and determination of the boundary value of the radius of the polar coordinate system, where the temperature is not lower than the tripping temperature of the PPTC layer, i.e. limits the region of this layer, which has passed into a low-conductivity state (Fig. 1) by solving the equation $u(r_{trip}, t_1) = T_{trip}$.

2. Solution of the problem of point 1 for the next small time interval Δt_2, taking into account that

– the radius of the heat source changed $r_s = r_{trip}$ and, accordingly, the value of the distribution density parameter σ changed;

– right party of the initial condition of the temperature distribution is replaced by $u(r, t_1)$;

– the electric heat source “spreads” and the area of the posistor layer, which turns into an isolating state, increases. As a result, the integral conductivity of the plate of the reverse biased p-n junction of the photovoltaic cell decreases in accordance with the formula

$$G_{p-n}(T) = g_{p-n}(T)\left\{\sigma\sqrt{2\pi}\left[\exp\left(-\frac{r_{trip}^2}{2\sigma^2}\right) - \exp\left(-\frac{r_0^{\,2}}{2\sigma^2}\right)\right]\right\}. \tag{5}$$

In the following numerical experiments taken

$$g_{p-n}(T) = g_{p-n}(T_0)\exp\left[\frac{\Delta E_g}{nkT}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right],$$

where ΔE_g is the band gap of the semiconductor material of the photovoltaic cell (silicon); k is the Boltzmann constant; n is the correction coefficient for determining the activation energy of the considered temperature dependence, which is determined empirically; T is the temperature of the solar photovoltaic cell plate.

After executing this step of the calculation, analogically, the total time of the heat propagation process $t_2 = t_1 + \Delta t_2 = \Delta t_1 + \Delta t_2$ and the obtained temperature distribution in the plate $u(r, t_2)$ are fixed, and also the boundary value of the radius r_{trip} is determined from the equation $u(r, t_{trip}) = T_{trip}$.

Algorithm point 2 is repeated until $r_{trip} = r_0$ is satisfied.

4. Temperature distribution in the structure of the photovoltaic cell - posistor

The problem was solved by a numerical method using the built-in library programs *pdesolve* of the Mathcad package [18].

The temperature distribution profiles along the r coordinate are shown in Fig. 2

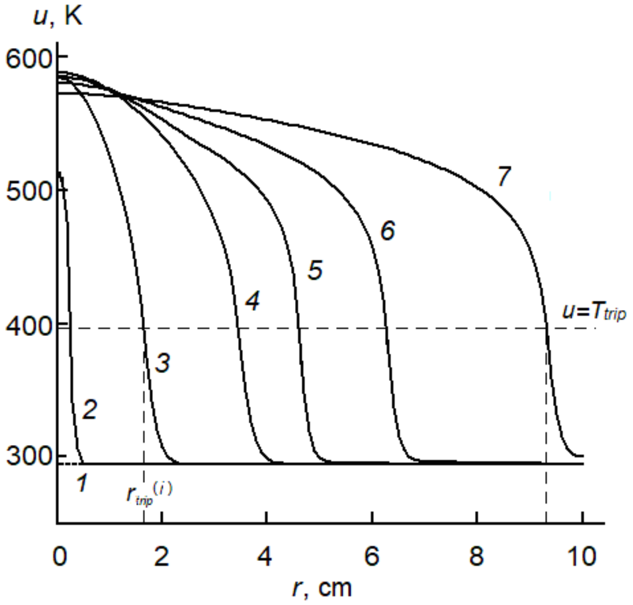

Fig. 2. Temperature distribution along the coordinate in the solar photovoltaic cell plate after the application of electric overvoltage ($U_0 = 12$ V) at times t_i, s: *1* – 0; *2* – 0.04; *3* – 0.34; *4* – 0.74; *5* – 0.94; *6* – 1.29; *7* – 2.04.

As can see, the width of the local heating region increases with time, as a result it spreads to the entire plate of the solar photovoltaic cell, after which the circuit should open and the photovoltaic cell should be disconnected from the overvoltage source. With repeated closings of the circuit (for example, due to cooling of the posistor layer), the process under consideration will be repeated until a metastable state is reached. However, the process of uncontrolled heating of the photovoltaic cell will be excluded.

5. Conclusions

The results of the theoretical analysis of the temperature distribution in a solar photovoltaic cell plate in the presence of a posistor layer at local (point) heating of the electrical nature are presented.

In the structure, which is a photovoltaic cell with an additional built-in posistor layer of the PolySwitch technology, which is in thermal contact, within the framework of the concept of a “spreading” heat source, it is established that in the presence of overvoltages, the local heating region expand over time, spreading to the entire plate of such a structure. During a time interval of the order of several seconds, the entire structure heats up above the phase transition temperature of the PPTC layer. The posistor layer goes into a low-conductivity state and most of the voltage drops across it.

Taking into account that the process of reaching temperatures sufficient for thermal breakdown of the considered silicon solar cells lasts about several tens of seconds [19], and the stay of such photovoltaic cells at temperatures below 300 °C for several hours does not lead to their significant degradation [19-22], the obtained results substantiate the prospects of using the built-in posistor layer for electrical and thermal protection of solar photovoltaic cells from reverse overvoltages.

References

1. **Herrmann, W.** Operational behaviour of commercial solar cells under reverse biased conditions / W. Herrmann, M. Adrian, W. Wiesner // Second World Conference on Photovoltaic Solar Energy Conversion: International Conference, Wien, Austria, 6–10 July 1998. Proceedings. –1998. – P. 2357 – 2359.
2. **Köntges, M.** Review of failures of photovoltaic modules / M. Köntges, S. Kurtz, C. Packard, U. Jahn, K.A. Berger, K. Kato, T. Friesen, H. Liu, M. Van Iseghem // IEA PVPS Task 13. – 2014. – 132 p.
3. **Kim, K.A.** Reexamination of photovoltaic hot spotting to show inadequacy of the bypass diode / K.A. Kim, P.T. Krein // IEEE Journal of Photovoltaics. – 2015. – Vol. 5, No. 5. – P. 1435 – 1441.
4. **Tonkoshkur, A.S.** Problemy nadiinosti fotoelektrychnykh komponentiv soniachnykh batarei / A.S. Tonkoshkur, L.V. Nakashydze // Vidnovliuvana enerhetyka. – 2018. – No. 3. – P. 21 – 31. (in Ukrainian).
5. **Santhakumari, M.** A review of the environmental factors degrading the performance of silicon wafer-based photovoltaic modules: Failure detection methods and essential mitigation techniques / M. Santhakumari, N. Sagar // Renewable and Sustainable Energy Reviews. – 2019. – Vol. 110. – P. 83 – 100.
6. **Guerriero, P.** A bypass circuit for avoiding the hot spot in PV modules / P. Guerriero, P. Tricoli, S. Daliento // Solar Energy. – 2019. – Vol. 181. – P. 430 – 438.
7. **Tonkoshkur, A.S.** Electrical properties of structures based on varistor ceramics and polymer nanocomposites with carbon filler / A.S. Tonkoshkur, A.V. Ivanchenko // Journal of Advanced Dielectrics. – 2019. – Vol. 9, No. 3. – Article ID 1950023.
8. **Tonkoshkur, A.S.** Modeling of electrical characteristics of photovoltaic solar arrays with protection against current overloads based on PolySwitch elements / A.S. Tonkoshkur, A.V. Ivanchenko // Multidiscipline Modeling in Materials and Structures. – 2020. – Vol. 16, No. 3. – P. 425 – 438.
9. **Ivanchenko, A.V.** Application of a polymer nanocomposite with carbon filler to limit overvoltages in a photovoltaic element / A.V. Ivanchenko, A.S. Tonkoshkur // Journal of Advanced Dielectrics. – 2020. – Vol. 10, No. 5. – Article ID 2050020.
10. **Ivanchenko, A.V.** Elektricheskiye svoystva fotogalvanicheskogo elementa so vstroyennym pozistornym sloyem na osnove polimernogo nanokompozita s uglerodnym napolnitelem / A.V. Ivanchenko, A.S. Tonkoshkur // Tekhnologiya i Konstruirovanie v Elektronnoy Apparature. – 2020. – No. 1–2. – P. 30 – 36. (in Russian).
11. **Chumakov, V.I.** K nelineynoy teplovoy modeli povrezhdeniy poluprovodnikov / V.I. Chumakov // Radioelektronika i informatika. – 2000. – No. 1. – P. 33 – 36. (in Russian).
12. **Zarubin, V.S.** Variatsionnyiy variant modeli teplovogo proboya sloya tverdogo dielektrika pri postoyannom napryazhenii / V.S. Zarubin, G.N. Kuvyirkin, I.Yu. Saveleva

// Radiooptika. MGTU im. N.E. Baumana. Elektronnyiy zhurnal. – 2016. – No. 5. – P. 38 – 50. (in Russian).

13. **Kudinov, V.A.** Tehnicheskaya termodinamika i teploperedacha: uchebnik dlya akademicheskogo bakalavriata / V.A. Kudinov, E.M. Kartashov, E.V. Stefanyuk, 3rd edn. – Moscow: Yurayt, 2016. – 442 p. (in Russian).

14. **Tonkoshkur, A.S.** Modelling of overheating in solar photovoltaic cell plates with local electric heat sources / A.S. Tonkoshkur, A.V. Ivanchenko // Journal of Physics and Electronics. – 2020. – Vol. 28(1). – P. 63 – 70.

15. **Reznikov, A.N.** Teplofizika protsessov mehanicheskoy obrabotki materialov / A.N. Reznikov. – M.: Mashinostroyeniye, 1981. – 279 p. (in Russian).

16. Handbook of silicon based MEMS materials and technologies / eds. M. Tilli, M. Paulasto-Kröckel, M. Petzold, H. Theuss, T. Motooka, V. Lindroos. – Elsevier, 2020. – 996 p.

17. **Gudkova, A.V.** Termostabilizatsiya fotoelektricheskih preobrazovateley dlya izmereniya VAH s impulsnym istochnikom sveta / A.V. Gudkova, S.V. Gubin, V.I. Belokon // Otkrytyye informatsionnyye i kompyuternyye integrirovannyye tekhnologii. – 2012. – No. 57. – P. 87 – 196. (in Russian).

18. **Tonkoshkur, O.S.** Metody matematychnoi fizyky u radioelektronitsi. Praktykum: navchalnyi posibnyk / O.S. Tonkoshkur, V.U. Ihnatkin, O.V. Kovalenko, K.M. Levkivskyi. – Dnipropetrovsk: Vydavnytstvo DNU, 2013. – 120 p. (in Ukrainian).

19. **Ivanchenko, A.V.** Izmeneniya harakteristik kremnievyih fotoelektricheskih preobrazovateley solnechnyih batarey posle tokovyih peregruzok / A.V. Ivanchenko, A.S. Tonkoshkur // Tekhnologiya i Konstruirovanie v Elektronnoy Apparature. – 2019. – No. 3–4. – P. 19 – 25. (in Russian).

20. **Ivanchenko, A.V.** Issledovanie harakteristik kremnievyih fotoelektricheskih preobrazovateley solnechnyih batarey pri peregreve / A.V. Ivanchenko, S.V. Mazurik, A.S. Tonkoshkur // Tekhnologiya i Konstruirovanie v Elektronnoy Apparature. – 2018. – No. 4. – P. 14 – 20. (in Russian).

21. **Radziemska, E.** Effect of temperature on dark current characteristics of silicon solar cells and diodes / E. Radziemska // International Journal of Energy Research. – 2006. – Vol. 30, No. 2. – P. 127 – 134.

22. **Flammini, M.** The influence of heating time and temperature on the properties of CIGSSe solar cells / M.G. Flammini, N. Debernardi, M. Le Ster, B. Dunne, J. Bosman, M. Theelen // International Journal of Photoenergy. – 2016. – Vol. 2016. – Article ID 4089369.