MODELING OF TEMPERATURE STABILIZATION KINETICS OF SOLAR CELL WITH POSISTOR LAYER AT LOCAL OVERHEATING

A.V. Ivanchenko*, A.S. Tonkoshkur

Oles Honchar Dnipro National University, Dnipro, Ukraine
*e-mail: IvanchenkoAV@ukr.net

The kinetics of changes in the maximum temperature and voltage drop in the plate of a separate solar photocell of a large area, which is in thermal contact with an additional posistor layer, in the presence of an overvoltage displacing the p-n junction of the photocell in the opposite direction, are investigated by modeling. It is shown that due to the expansion of the region of local heating of such an element for a time of several seconds, the entire structure can be heated to temperatures above the temperature of the transition of the posistor layer to the low-conductivity state. In this case, almost all the applied voltage drops across it.

Keywords: solar photovoltaic cell, overvoltage, kinetics, electrical characteristics, posistor polymer nanocomposite, modeling.

Received 18.10.2021; Received in revised form 01.12.2021; Accepted 10.12.2021

1. Introduction

The creation and use of reliable switching devices to prevent electrical overvoltages, the appearance of local overheating, blocking solar defective and damaged solar cells (SC) is still considered as a promising way to improve the reliability and efficiency of solar power plants operation [1-4]. The currently available methods for solving these problems (for example, the use of transistor switches, electronic systems, etc.) either do not completely solve them, or are quite costly [5-9].

One of the directions in solving the problems of developing switching devices of this type is an approach based on the use of heterogeneous materials of modern solid-state electronics: new posistor elements such as PPTC (polymeric positive temperature coefficient) resettable fuses of the PolySwitch technology, varistors and phase change thermistors metal semiconductor [10-13].

The distinctive feature of fuses of this type is a sharp increase in resistance when they are heated to temperatures close to the phase transition temperature in polyethylene (~ 125 °C), which is called the response temperature T_{trip} [14, 15]. This shows the possibility of implementing a method of protection against local overheating of such devices, which is based on the actuation of a distributed resettable fuse, which is in direct contact with the surface of the photovoltaic converter, when the temperature rises.

As a first step in this direction, namely, to clarify the effectiveness and features of the overvoltage protection method considered here, experimental and theoretical studies of accompanying electrical effects were fulfilled with using small areas SC, for which the inhomogeneity of prebreakdown heating can be neglected [11, 12, 16, 17]. At the same time, the possibility of implementing protection against reverse electrical overvoltages and thermal breakdown of photovoltaic systems based on such SC with built-in layers based on posistor polymer nanocomposites with carbon fillers was established.

It should be noted that modern solar photovoltaic cells belong to the distributed film-type ones (thickness 0.1 – 0.2 mm, dimensions up to 15×15 cm^2). In a detailed study of electrothermal processes, in particular thermal breakdown, in such structures, it is necessary to consider the processes of heat distribution in the longitudinal direction, which ultimately leads to complex problems in the mathematical and experimental senses [17-19].

To advance in the indicated direction, it is relevant to study the temperature distribution in photovoltaic cells with large areas during local (point) heating and the impact of an additional protective posistor layer on this distribution.

The results of a theoretical analysis of the temperature distribution in a solar cell plate without and in the presence of a posistor layer with local (point) heating of an electrical nature are presented in [20, 21]. In particular, in such structure as a photovoltaic cell with an additional built-in posistor layer of the PolySwitch technology, which are in thermal contact, in the presence of overvoltages within the framework of the concept of a "spreading" heat source, it has been found that over time, the areas of local heating expand and spread onto the entire plate of the structure. During a time interval 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. The key point in the process under consideration is to determine the maximum temperature that occurs in the platinum SC and its time dependence. Our work is devoted to the study of this problem. The theoretical kinetic dependences of the maximum temperature and voltage drop in the plate of an individual solar photovoltaic cell with a built-in layer of a posistor polymer nanocomposite in thermal contact with it in the presence of an overvoltage displacing the p-n junction of the photocell in the opposite direction are presented in the paper.

2. Algorithm for solving

A disk structure of a solar cell with a built-in posistor layer (PPTC fuse) was used in the modeling.

In order to simplify the solution of the relatively complex problem of describing the kinetics of thermal and electrical processes occurring in the structure under consideration, it seems appropriate to divide it into two subproblems. The first of them corresponds to the situation before complete electrical insulation of the solar photovoltaic cell (which corresponds to some time t^*), and the second one corresponds to the situation in the presence of such insulation.

In accordance with the concepts of [21], in the region with a reduced electrical resistance of the reverse biased p-n junction of the SC, which has an ambient temperature T_0 and is in a highly conductive state, a significant current begins to flow, which can heat the indicated region and the adjacent part of the PPTC layer to temperatures equal to or higher than the temperature of its tripping to the insulating state T_{trip}. As a result, the section of the PPTC layer adjacent to the region of local heating of the SC plate becomes insulating. 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 originally arisen heat source. With this “spreading”, all new parts of the PPTC layer are heated and pass into a low-conductivity state. After the transition of the entire PPTC layer to the low-conductive state, the overvoltage initially applied to the p-n junction of the photovoltaic cell is redistributed and most of it drops across this layer.

The solution of the first subproblem (time range $t \le t^*$) can be implemented using the heat conduction equation in a polar coordinate system and the solution algorithm given in [21], where the change in the temperature distribution profile along the longitudinal coordinate of the SC plate (r) was considered. The maximum temperature T_{max} is realized directly at the point where the reverse resistance of the reverse biased p-n junction SC is minimal, i.e. at the point of initial heating ($r = 0$).

When analyzing the behavior of the temperature distribution during the transition of the SC to a stationary heated state, it should be taken into account that the main outflow of thermal energy of the SC plate, which has a relatively large area (~15×15 cm^2) and a small thickness (1 mm), goes through its surfaces of the bases in the transverse direction, and heat transfer in the longitudinal direction can be neglected. This suggests that the elementary sections of the plate with a temperature $T > T_{trip}$ change their temperature almost independently relative to each other, and this process for each of them can be approximately considered within the framework of a system with lumped parameters.

Thus, the solution of the second subproblem (in the time range $t > t^*$) can be realized on the basis of the indicated representations for an elementary section with T_{max} within the framework of the model developed in [12, 16]. This model is based on the use of heat balance equations considering the thermal contact between the layers of the structure.

3. Theoretical kinetic dependences of temperature and voltage drop across solar cell

The calculated kinetic dependences of the maximum temperature $T_{max}(t)$ and the voltage drop across the photovoltaic cell are shown in Fig. 1.

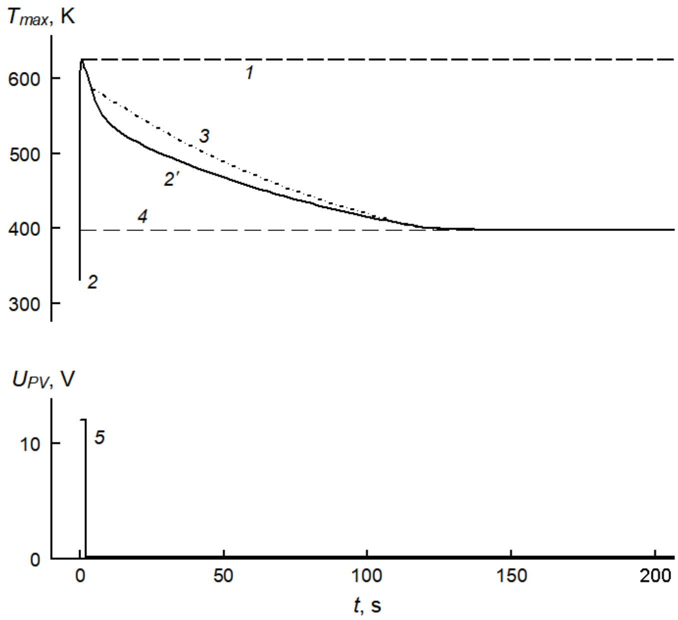

Fig. 1. Dependences of the maximum heating temperature of the plate T_{max} (curves *1–4*) and the voltage U_{PV} (5) of the solar cell on the duration of the constant reverse overvoltage (U_0= 12 V). Curves *1* and *2*, *2′* correspond to the dependences of $T_{max}(t)$ for solar cells without and with a posistor layer (*2* – before tripping, *2′* – after the posistor protection tripping); *3* – changes in the average temperature of the PPTC layer over time; *4* – corresponds to the level $T_{max}(t)=T_{trip}$.

After a few seconds of supplying the reverse voltage U_0, the entire structure heats up above the transition temperature T_{trip} to the insulating state (Fig. 1, curve *2*). The posistor layer goes into a low-conductivity state and most of the voltage drops across it. The temperature of the structure decreases to values close to T_{trip} (Fig. 1, curves *2′* and *3*).

The presented results indicate the possibility of using a built-in polymer nanocomposite posistor layer for limiting and subsequent stabilization of the temperature of the SC plate. Its use allows to convert the constant thermal influence of electrical overload into a fire safe relatively short (several seconds) thermal shock, which can lead to only minor degradation of the solar cell. Adopted in Fig. 1 the T_{trip} value corresponds to the tripping temperature of the currently most common polymer nanocomposites used in commercial PPTC fuses.

The influence of the amplitude of the constant overvoltage U_0 on the kinetics of changes in the maximum temperature and voltage on the solar cell plate is shown in Fig. 2.

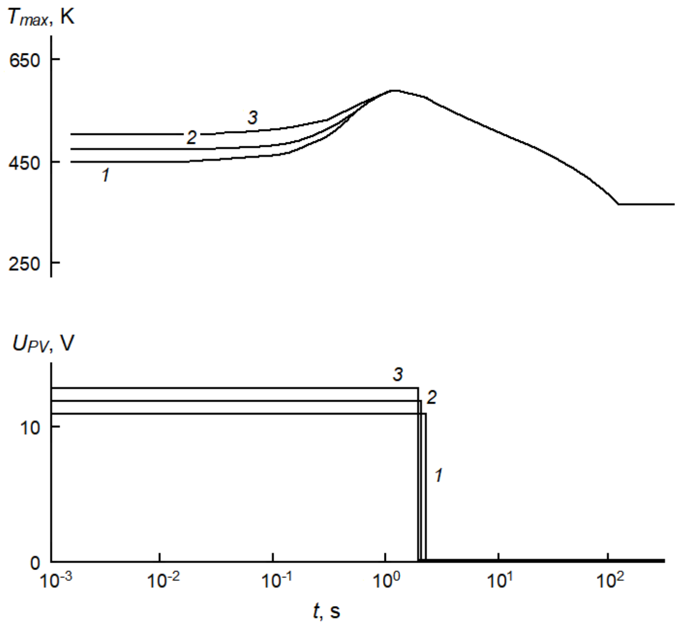

Fig. 2. Time dependences of the maximum temperature T_{max} and the amplitude of the voltage drop for a solar cell plate with a built-in posistor layer when exposed to constant reverse overvoltage U_0, V: *1* – 11; *2* – 12; *3* – 13.

As can be seen, its increase leads to a slight increase in the maximum temperature of the solar cell plate at the initial region of the kinetic dependence. At the same time, the time before the tripping of such overvoltage protection is slightly reduced.

4. Conclusions

Local overheating in structures consisting of a solar cell with an additional polymer nanocomposite PPTC layer, which are in thermal contact, is considered. Within the framework of the concept of a "spreading" heat source arising in the presence of reverse overvoltages, the regions of local heating can expand over time and, as a result, it will spread to the entire plate of the solar cell structure. Within time interval of several seconds, the entire structure can heat up above the phase transition temperature of the PPTC layer. Under these conditions, the PPTC layer will go into a low conductive state and most of the overvoltage will drop across it. The temperature of the structure will decrease to values close to the temperature of the indicated transition.

The process of reaching temperatures sufficient for thermal breakdown of the considered silicon solar cells lasts several tens of seconds [22]. The stay of such photocells for several hours at temperatures below 300 °C does not lead to their significant degradation [23-25]. Thus, the results obtained can be considered as a theoretical substantiation of the prospects of introducing a built-in posistor layer for electrical and thermal protection of solar cells from reverse overvoltages.

References

1. **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.

2. **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.

3. **Oh, W.** Evaluation based on performance and failure of PV system in 10 years field-aged 1 MW PV power plant / W. Oh, H. Choi, K. W. Seo, D. Kim, S. Y. Kim, H. S. Lee, H. Hwang, D. Kim // Microelectronics Reliability. – 2020. – Vol. 114. – Article ID 113763.

4. **Hlushko, O.** Analysis of parameters and characteristics of photovoltaic converters / O. Hlushko, S. Stepenko // Technical Sciences and Technologies. – 2021. – No. 1(23). – P. 249 – 264.

5. **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.

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. **Dhimish, M.** Novel hot spot mitigation technique to enhance photovoltaic solar panels output power performance / M. Dhimish, V. Holmes, P. Mather, M. Sibley // Solar Energy Materials and Solar Cells. – 2018. – Vol. 179. – P. 72 – 79.

8. **Mohammed, H.** Bypass diode effect on temperature distribution in crystalline silicon photovoltaic module under partial shading / H. Mohammed, M. Kumar, R. Gupta, // Solar Energy. – 2020. – Vol. 208. – P. 182 – 194.

9. **Tang, S.** Review and a novel strategy for mitigating hot spot of PV panels / S. Tang, Y. Xing, L. Chen, X. Song, F. Yao // Solar Energy. – 2021. – Vol. 214. – P. 51 – 61.

10. **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.

11. **Tonkoshkur, A. S.** Application of Polymer Posistor Nanocomposites in Systems for Protecting Photovoltaic Components of Solar Arrays from Electrical Overloads. Monograph / A. S. Tonkoshkur, A. V. Ivanchenko, L. V. Nakashydze, A. Yu. Lyashkov, I. V. Gomilko. – USA, Boston: Primedia eLaunch, 2021. – 172 p.

12. **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.

13. **Tonkoshkur, A. S**. Using a layer based on materials with a metal to semiconductor phase transition for electrothermal protection of solar cells / A. S. Tonkoshkur, A. V. Ivanchenko // Tekhnologiya i Konstruirovanie v Elektronnoi Apparature. – 2021. – No. 3–4. – P. 57 – 64.

14. **Gretzke, W.** Use of PolySwitch PPTC protection in automotive applications / W. Gretzke // 42 V-PowerNets / eds. H. Wallentowitz, C. Amsel. – Berlin, Heidelberg : Springer, 2003. – P. 75 – 88.

15. **Cheng, S.** Failure precursors for polymer resettable fuses / S. Cheng, K. Tom, M. Pecht // IEEE Transactions on Device and Materials Reliability. – 2010. – Vol. 10, No. 3. – P. 374 – 380.

16. **Ivanchenko, A. V.** Electrical properties of photogalvanic element with built-in posistor layer based on polymer nanocomposite with carbon filler / A. V. Ivanchenko, A. S. Tonkoshkur // Tekhnologiya i Konstruirovanie v Elektronnoi Apparature. – 2020. – No. 1–2. – P. 30 – 36.

17. **Kuffel, E.** High Voltage Engineering: Fundamentals / E. Kuffel, W. S. Zaengl. – Amsterdam : Elsevier Science, 2013. – 465 p.

18. **Danikas, M. G.** Thermal breakdown in solid dielectrics: A new approach / M. G. Danikas, G. Papaschinopoulos // Journal of the Franklin Institue. – 1998. – Vol. 335, No. 4. – P. 617 – 621.

19. **Virchenko, Yu. P.** Heat localization and formation of heat breakdown structure in semiconductor materials. I. Nonlinear model / Yu. P. Virchenko, A. A. Vodyanitskii // Functional Materials. – 2001. – Vol. 8, No. 3. – P. 428 – 434.

20. **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, No. 1. – P. 77 – 84.

21. **Tonkoshkur, A. S.** Analysis of temperature distribution in a solar element with posistor layer in the presence of local electric heat source / A. S. Tonkoshkur, A. V. Ivanchenko // Journal of Physics and Electronics. – 2020. – Vol. 28, No. 2. – P. 95 – 100.

22. **Ivanchenko, A. V**. Changes in the characteristics of silicon photovoltaic cells of solar arrays after current overloads / A. V. Ivanchenko, A. S. Tonkoshkur // Tekhnologiya i Konstruirovanie v Elektronnoi Apparature. – 2019. – No. 3–4. – P. 19 – 25.

23. **Ivanchenko, A. V**. Investigation into the characteristics of silicon photovoltaic converters of solar batteries in case of overheating / A. V. Ivanchenko, S. V. Mazurik, A. S. Tonkoshkur // Tekhnologiya i Konstruirovanie v Elektronnoi Apparature. – 2018. – No. 4. – P. 14 – 20.

24. **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.

25. **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.