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SCHEMOTECHNICAL TECHNOLOGIES FOR RELIABILITY OF SOLAR ARRAYS

Abstract. Regime factors leading to the failures of photovoltaic units of solar arrays and their components, as well as circuitry methods and means that allow solving the problems of ensuring their reliability are analyzed.
Prospects for improving the efficiency of circuit methods of protection against electrical thermal overloads are pointed out, in particular, based on the use of new elements of protection against current overloads on the basis of carbon-polymer self-resetting fuses.
Keywords: solar arrays, photovoltaic cell

1. Introduction

Solar arrays (SA's) are one of the most promising renewable sources of electricity.

As a rule, SA's are forced to operate in modes with varying inhomogeneous illumination and temperature, with the presence of partial shading effects on the output characteristics of SA and changes in power due to the action of high-energy particles (when used in outer space) and other negative factors [1-4]. This puts forward a number of specific requirements for ensuring high stability and reliability of SA components.

The sources of unreliability of the second group are factors directly related to the features of the regime of the inhomogeneity of illumination and local overheating in photocells due to the so-called nonconformity effects.

In this paper, the regime factors that lead to failures of photodiode components of SA and circuitry methods and means that allow solving to some extent the problems of ensuring the reliability of SA are analyzed.

2. Generalized structure of a solar array and the main sources of its unreliability

As is known, the basis of a solar array is a photovoltaic (solar) cell (PVC), which is a semiconductor p-n-junction, intended for converting electromagnetic solar radiation into electrical energy [5]. When sunlight hits the boundary zone between the n- and p-type layers, an electromotive force arises that creates an electric current in the closed external circuit connected to the PVC contacts. Charge carriers appearing in the cell create a so-called photocurrent, which is determined by the solar radiation level.

Silicon (monocrystalline, polycrystalline, amorphous), cadmium tellurides and (di) selenide of copper (indium) gallium, gallium arsenide, polymers and organics based on carbon fullerenes, copper phthalocyanine, polyphenylene, and others are used to fabricate PVC's [6, 7] .

Structurally, PVC is a plate whose dimensions can not exceed a certain value due to technological features of production.

When connecting such cells to each other in a series, parallel, or combined way, photovoltaic (solar) modules (PVM) are composed, and from them, respectively, a photoelectric system called a solar array. [5, 7, 8].

Modules of the most common crystalline solar cells (Fig. 1) consist of a transparent face surface layer (1), an encapsulator (2), between two layers of which solar cells, electrically interconnected by metal busbars (3), are placed, and a lower (rear) layer (4), which are enclosed in a frame of an aluminum profile (Fig. 1).

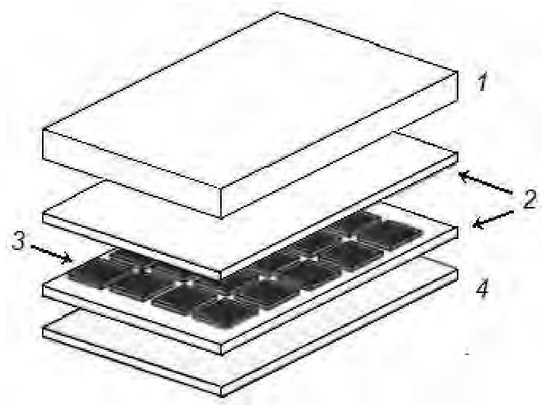

Fig. 1 - Photovoltaic module structure

In most modules, the top layer is made of glass with low iron content. This material has high strength, stability, impermeability to water and gases, good self-cleaning properties, and low cost. The encapsulator is needed to create an intermediate layer between solar cells, the front surface and the rear one of the photoelectric module. It is made from ethyl vinyl acetate (EVA), which is optically transparent and has low thermal resistance. The back layer is made of polyvinyl floride (PVF or Tedlar). The main requirement for it is low thermal resistance, water resistance, and transparency (in double-sided modules). The aluminum frame must not protrude beyond the surface of the module so that water, dust and dirt do not accumulate on it.

The module protects the PVC from weather conditions, and users - from electric shock.

In accordance with the ideas about reliability of electronic and microelectronic devices, to the first group of sources of unreliability of components we must attribute [9-11]:

- PVC degradation (reduction in output power or failure) due to deterioration of contacts or corrosion, metal migration through the p-n junction, deterioration of the antireflection coating;

- short circuits between connecting contacts and PVC, if they are damaged by corrosion, and in the module ("hidden" manufacturing defects or the result of insulation degradation caused by the environment leading to delamination, cracking, and electrochemical corrosion);

- breakage of the electrical circuit of the PVC due to its cracking caused by thermal stress, hail, or manufacturing damage creating "hidden cracks" that can not be revealed during the inspection at the enterprise, but which manifest themselves later;

- breaks in the connecting circuit or in modules (in the bus or junction box) due to fatigue as a result of cyclic thermal stresses and wind action;

- mechanical damage to the glass and encapsulator due to leaching and diffusion (slow exhaustion occurs, and when the concentration falls below the critical level, the encapsulator material rapidly degrades).

Elimination or minimization of the influence of these factors on the operation of solar arrays can be provided by the improvement of their design and manufacturing technology, as well as the use of structural (hardware) backup methods in especially important cases [12-13].

The sources of the second group's unreliability are factors directly related to the features of the regime of changing non-uniform il-

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lumination and local overheating in photocells due to the so-called coupling effects. Current circuitry techniques and means of minimizing the influence of these factors and improving the reliability of components and solar cells themselves are discussed below [9].

3. Connection effects

The term “connection effect” defines the mismatches (inconsistency) of electrical circuits in a module, caused by the use of elements with different properties or operating under different conditions. The inconsistency is a serious problem in photovoltaic modules and arrays under certain conditions, since the output parameters of the module in poor conditions are determined by the characteristics of the solar cell with the lowest output. For example, when a shadow falls on one of the module's elements, the power generated by the other elements can be scattered on the "bad" element and does not reach the payload. This can lead to the scattering of a large amount of electrical power in a small area, as a result of which its temperature and the probability of irreversible damage will increase significantly [9].

3.1. Inconsistency of series-connected elements

Series connection of PVC’s (or PVM’s) with differing parameters may lead to inconsistencies in short-circuit current and idling voltage, which significantly affect the efficiency of such electrical circuits. The currents flowing through two series-connected elements are equal ($I_1 = I_2 = I_S$). The resulting voltage is equal to the sum of the voltages on each element ($U_1 + U_2 = U_S$). Since the current must be the same, the current mismatch means that the total current from the two elements will be equal to the smaller of the currents.

Of the two simplest types of mismatch (mismatches of short-circuit current and no-load voltage), a short-circuit current mismatch occurs more often, since it can occur due to the shading of a part of the module. This type of discrepancy is also the most significant.

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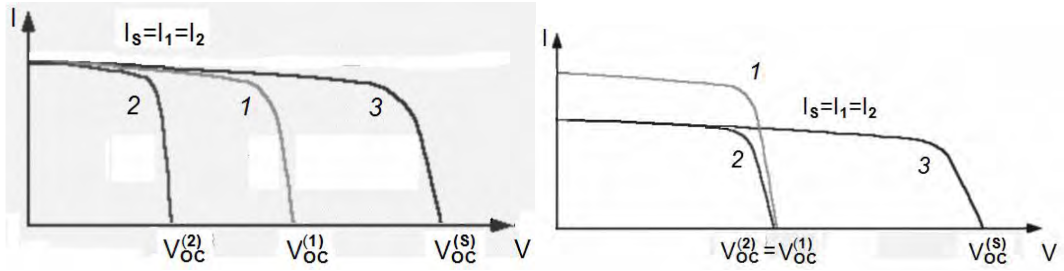

а   б

Fig. 2 - The volt-ampere characteristic (VAC) of a series connection of the photocells (3) of the module (Fig. 1) when their idle (open-circuit) voltages (a) or short-circuit currents (b) do not match each other. Index "1" corresponds to a "good" PVC and "2" – to a “bad” PVC

If the open-circuit voltages do not match each other when cells connected in series, at the short-circuit point the total current of the module remains unchanged, but the module power at the maximum power point decreases because of the lower performance of the "bad" solar cell [9]. Since two elements are connected in series, the same current flows through them, and the resultant voltage can be found by adding the voltages on each of two cells (Fig. 2, a).

The mismatch of the short-circuit currents in series connection case can have a negative effect on the photoelectric device depending on the operating point.

At the no-load voltage point, the effect of short-circuit current reducing is relatively small. The open-circuit voltage decreases only slightly, since it depends logarithmically on the short-circuit current.

However, since the current flowing through the two cells must be the same, the total current cannot exceed the current of the "bad" element. Therefore, the current from the two cells cannot be greater than the short-circuit current of the "bad" cell. At a low voltage at which this condition is fulfilled, the additionally generated current of the "healthy" cell will not be dissipated in each of cells connected in series, but only in the "bad" one. High energy dissipation in a "bad" cell can cause its irreversible damage.

3.2. Local overheating

Overheating in the active section of the series connection of the PVM's (or photocells inside them) takes place when one of them with a low short-circuit current ("bad", for example, a shaded PVM) is connected in series with several elements with a high short-circuit current (Fig. 3).

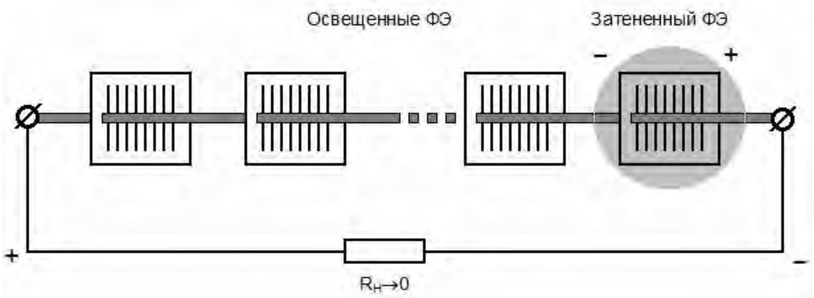

Fig. 3 - One shaded cell in the circuit reduces the current through the illuminated solar cells, as the result they produce a higher voltage that can displace the "bad" element in the opposite direction at a low load resistance RL

If the resulting current of the circuit approaches the short-circuit current of the "bad" cell, then it is limited by this current. The additional current produced by the “good” cells shifts them in the forward direction. If the circuit is closed, a direct bias on “good” cells displaces the "bad" cell in the opposite direction, and it works as a load, and not as a generator. Energy dissipation on such loads leads to an inhomogeneous heating of the module, in particular, to the appearance of local heating regions, which are called "hot spots".

Irregularities of PVM heating are detected and examined by visual inspection, infrared thermography, electroluminescent methods [14-18], etc. Fig. 4 presents the thermogram of the PVM sector given in [7], which illustrates the inhomogeneity of the temperature distribution in photovoltaic modules.

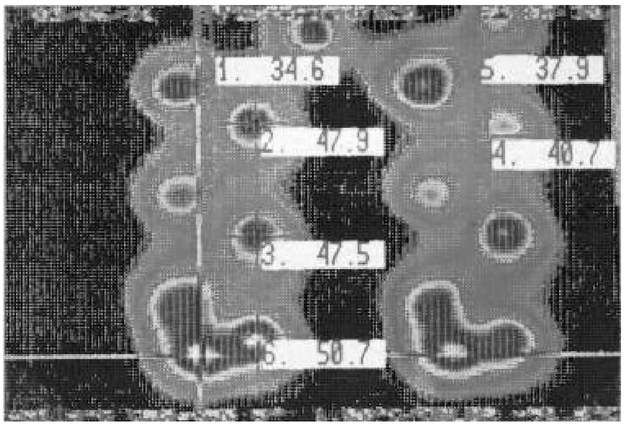

Fig. 4 - Thermographic image of a 16-cell photoelectric module with a single bypass diode at reverse bias, The digits indicate the temperatures of corresponding local areas

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The appearance of "hot spots" and an increase in the PVM temperature lead to a number of undesirable effects [19], in particular:

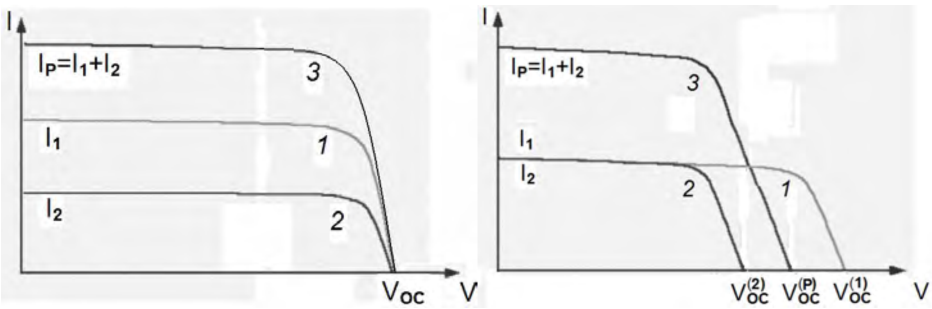
- reduction of its electrical voltage and, consequently, of output power;
- increase in mechanical stresses associated with thermal expansion and various damages (glass cracking, melting of solder, damage to the solar cell itself, etc.);
- increase in the rate of degradation.

It should be noted that another potential cause of hot spots is a defect in the module, for example, a crack, poor soldering of two busbar leads inside the partitions, punctures in the lower fluoroplastic sheet, polarization or dint [16, 18, 20]. This defect becomes a load, so the current also concentrates in this region, using a huge dissipation of power in the damaged cell.

The consequences of the appearance of "hot spots" in most cases lead to accelerated aging of PVM. A "hot spot" caused by a short circuit between the front and rear layers of the PVM partition causes "melting" of its lower layer and can lead to fires.

3.3. Inconsistency of parallel cells

In this case, the voltage in the circuit is always the same, and the resulting current equals to the sum of currents from each cell. In Fig. 5, a the output current of the second ("bad") element is lower than that of the first one. If currents do not match each other, the problem does not arise: the total current is always higher than the current of each cell. If the voltages of two cells connected in parallel do not match, the "bad" element reduces the open-circuit voltage of the "good" element (Fig. 5, b).



а б

Fig. 5 - VAC of parallel connection of cells in the case of inconsistency of short-circuit currents (a) and open-circuit voltages (b). Index "1" corresponds to the "good" PVC and "2" corresponds to the "bad" one

$$V_{OC} = V_{OC}^{(P)} = V_{OC}^{(1)} = V_{OC}^{(2)}$$

4. Circuit technique and means of minimizing the influence of regime factors on the operation of solar array components

4.1. Photovoltaic modules

The destructive effect of local overheating can be leveled with a bypass diode. The bypass diode is connected in parallel with the PVC, so that their polarities are opposite.

Under conditions of short circuit ($R_L \to 0$) and of the open circuit ($R_L \to \infty$) and matched currents, each PVC from their connection in series will be shifted in the forward direction, and the bypass diode – in the reverse, i.e. will be in the idling state (will open the electric circuit).

However, when the "bad" PVC as a result of the mismatch of short-circuit currents between several series-connected cells moves in the opposite direction, the bypass diode will become conductive, allowing the current from the "good" cells to flow in the external circuit without changing the voltage on each "good" cell. The maximum reverse voltage on the "bad" element is reduced by the voltage on each of the diodes, reducing the current and preventing overheating.

The work of the bypass diode and the current-voltage characteristic in the short circuit case with inconsistent currents are shown in Fig. 6. The current from the "good" photocell PVC2 shifts it in the forward direction. The bypass diode of the "good" module D2 is shifted in the reverse direction and does not have any effect. The bypass diode of the shaded cell D1 is shifted in the forward direction from the "good" cell and conducts current. The shaded cell has a reverse bias.

In an open circuit with unmatched currents, the shaded solar cell has a reduced VOC. The bypass diodes are inversely shifted and have no effect.

Due to the fact that in practice using a bypass diode for each photocell is too expensive, they are connected straight to a serial connection of PVC's – from several ones up to the whole module. The voltage on the shaded cell or any other one producing a low current is equal to the forward bias voltage of all the other connected cells plus the voltage on the bypass diode.

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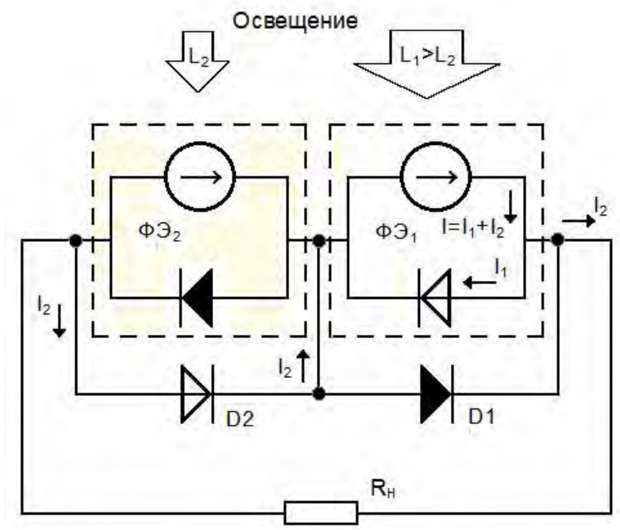

Fig. 6. The principle of the bypass diodes in series-connected solar modules in the case of uncoordinated currents at short circuit. It is assumed that the circuit elements contained in the dashed lines simulate photocells, the first of which is shaded PVC1. The current source is the current I generated by light. Diodes D1 and D2 outside the dashed blue line are bypass

4.2. Solar arrays

In large photovoltaic systems, the modules are connected both in series and in parallel. A successively connected set of cells or modules is called a "row". The combination of serial and parallel connections can lead to some problems in solar panels.

For example, if one row from their parallel connection (which is often called a "block") is opened, the current through the remaining connected rows will be less than the current through the remaining blocks in the array. As a result, this leads to power output loss.

The parallel connection of rows of modules connected in series in combination with the mismatch effect in one of them requires that a bypass diode connected in parallel with the modules can withstand the current of all paralleled array rows. A mismatch in the connected modules will cause current flow through the bypass diode and heating it, which will lead to a decrease in its effective resistance and further increase in the flowing current. As a result, such bypass diodes become even hotter, their resistance is further reduced, increasing current, etc. If the bypass diodes are not designed for such a current, they can burn, which will damage the photovoltaic modules.

In addition to the bypass diodes, a diode, called a blocking diode, is applied to reduce the losses caused by the mismatch [7]. Such blocking diode is also used in stand-alone systems so that at night the current from the chemical batteries does not flow through the solar array. When modules are connected in parallel, each row of modules must have a blocking diode. This not only reduces the load on a single diode, but also does not allow the current from one parallel connected row to flow into a row with a smaller current, which reduces the losses caused by the mismatch when the rows in the array are connected in parallel (Fig. 7).

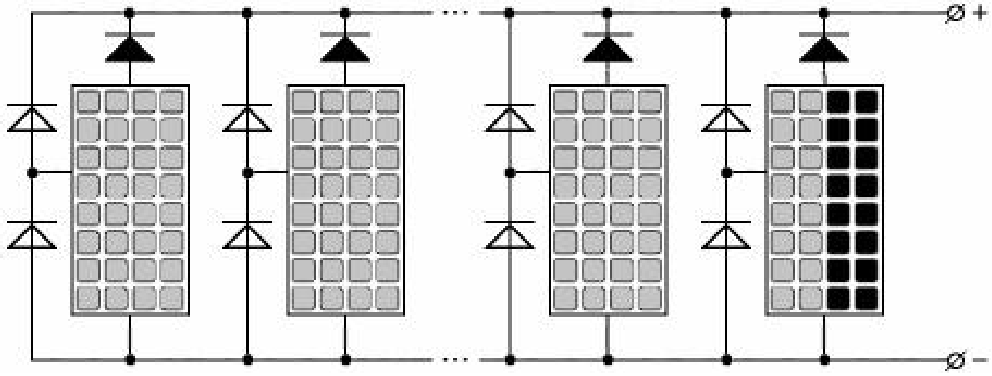

Fig. 7 - Blocking diodes (blackened) at parallel connection of modules: on the shaded module the blocking diode does not allow current flow to this module from the "good" ones connected in parallel

5. Prospects for improving the efficiency of circuit protection methods against electrical thermal overloads

Recently, the problems of research and development of methods and means to improve the reliability of solar arrays and their components are given great importance. There are a number of different approaches to the problem of "hot spots".

One of them is based on the improvement of previously formulated methods and means connected with using bypass diodes. So in [21] a new strategy of shunting for single-crystal and polycrystalline solar panels is presented, which allows to reduce the temperature of the hot spot significantly (up to 24°C maximally), both at partial and full shading. It uses a multiply connected power MOSFET that acting as a voltage divider, subtracts a portion of the reverse voltage from the shaded photocell.

Another direction is based on applying the MPPT (Maximum Power Point Tracking) techniques, which use digital devices that analyze the volt-ampere characteristic of PVM and determine the optimal mode of its operation. The results of simulation and field testing of the

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behavior of "hot spots" in photovoltaic systems with central and distributed MPPT are given in [22]. The latter is recognized to be more effective, since it allowed to avoid "hot spots" under shading conditions up to 50% of one cell (while the central MPPT – only up to 12%).

It is also promising to use self-healing fuses (SHF) of "Polyswith" type [23] as additional blocking devices to isolate temporary short circuits or overcurrent inside photocells and photovoltaic modules. Such SHF's are polymer composites with nanosized carbon fillers. The basic functional property of SHF's is the abrupt increase in electrical resistance by several orders of magnitude when a certain temperature threshold is reached and return to the initial high-conductivity state with temperature decreasing [24, 25].

These elements of electrical and thermal protection have already found application in batteries and galvanic power supplies [25-28]. Their merits include:

- the resistance close to the metal resistance up to the switching temperature and to the insulator resistance above the specified temperature;

- realizability in the form of discrete elements and continuous films – tapes (that is, the possibility of realizing the isolation of a defective local area of a separate photocell);

- a reaction, in the form of a temporary blockage of individual components of the solar array, both to temperature rise and to current density increase.

Conclusions

The sources of unreliability of solar arrays caused by factors directly related to the characteristics of their heterogeneous illumination are described.

The analyzed modern level of circuit technology and methods of protecting solar array components from local overheating and current overload testifies to the need for their improvement. As one of the prospective lines of protection from short circuits and current overloads, it has been proposed to use self-healing fuses made of polymer composites with nanocarbon fillers.

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