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Development of a mathematical model of the solar panel efficiency factor

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With the tendency of energy and resource saving of primary sources of electric energy there is a necessity to consider and globally implement the use of secondary resources of electric energy. A common trend today is the use of solar panels. But based on the composition of the material used in the creation of solar panels, the type of inverter, the efficiency factor may vary. Also, to accurately determine the parameters of the efficiency factor, it is necessary to develop a mathematical model that would fully describe the operation of the solar panel. This paper discusses a method of describing the operation of a solar panel using a mathematical model.

The composition and design of the solar panel, its elements determine the efficiency of energy production by the finished product. At present, silicon-based solar panels (c-Si, mc-Si and silicon thin-film batteries), cadmium tellurideCdTe, copper-indium (gallium)-selenium compounds Cu(InGa)Se_2, and concentrator batteries based on gallium arsenide (GaAs) are used to generate electrical energy. Brief descriptions of each will be given below.

Silicon-based solar cells (SCs) account for about 85 % of all solar panels produced today. Historically, this is due to the fact that the production of silicon-based SBs used extensive technology and infrastructure of the microelectronics industry, the main ‘workhorse’ of which is also silicon. As a result, many key technologies of the microelectronics industry, such as silicon growth, coating, doping, have been adapted to silicon battery production with minimal changes and investments. In addition, silicon is one of the most abundant elements in the Earth's crust and accounts for 27–29 % by mass according to various data. Thus, there are no physical limitations to producing a significant fraction of the Earth's electricity with the available silicon (Si) reserves [1].

There are two main types of silicon SBs – those based on monocrystalline silicon (crystalline-Si, c Si) and those based on multicrystalline (multicrystalline Si, mc-Si) or polycrystalline. In the first case, high quality (and, consequently, more expensive) silicon grown by the Czochralski method is used, which is the standard method for producing silicon wafers for microprocessor and chip production. The efficiency of SBs made of monocrystalline silicon is usually 19–22 % [2].

In the second case, cheaper silicon produced by the block-cast method, which is specifically designed for the production of SBs, is used for the production of SBs. The resulting silicon wafers consist of many small multidirectional crystallites (typical size 1–10mm) separated by grain boundaries. Such defects in the crystal structure lead to lower efficiency – typical efficiency values of SBs made of mc-Si are 14–18 %. The lower efficiency of these SBs is compensated by their lower price, so that the price per watt of electricity produced is about the same for both c-Si and mc-Si based solar panels [3]. The following figure shows a schematic of the solar panel and possible consumption devices.

And further we consider methods of representing the parameters in the form of a mathematical model

$$q_t = \propto (1-r)G_{hi} - \eta G_{hi}.$$

where q_t – thermal generation per unit area, W/m^2; r– fraction of power reflected in the solar cell, $(m^2 °C)/W$; $\propto$ – fraction of power consumed by the solar cell; G_{hi}– direct global radiation, W/m^2; η – solar panel efficiency, %.

Convective transmission coefficient of the front part of the solar panel h_{cf}, $W/(m\ °C)$:

$$h_{cf} = \left[(2,8-3v_v)^3 + 4,74(t_c - t_a)\right]^{1/3}.$$

The convection transmission coefficient of the rear of the solar panel h_{cp}, $W/(m\ °C)$:

$$h_{cp} = \left[(2,1-2,3v_v)^3 + 3,80(t_c - t_a)\sin(\beta)\right]^{1/3}.$$

Solar panel front panel transmittance h_{rf}, $W/(m\ °C)$:

$$h_{rf} = \in_f \left[6,67 \cdot 10^{-8} t_a^3 \left(1 + (t_c / t_a)\left(1 + (t_c / t_a)\right)^2\right)\right].$$

where t_a is the ambient temperature, °C; t_C is the photocell temperature, °C;

The radiation transmission coefficient of the back of the solar panel h_{rp}, $W/(m\ °C)$:

$$h_{rp} = h_{rf}\left(\in_f / \in_p\right),$$

$$r_f = \sum \left(\frac{x}{k}\right)_i, \quad r_p = \sum \left(\frac{x}{k}\right)_i,$$

$$h_f = h_{cf} + h_{rf}, \quad h_p = h_{cp} + h_{rp},$$

$$a_f = 1 + h_f r_f, \; a_p = 1 + h_p r_p,$$

where k is the conductivity of each encapsulating layer, $W/(m$ °C); v_v is the wind speed (m/s); β is the tilt angle of the PV generator, °C; $\in_f$ is the emissivity of the faceplate surface; $\in_f$ is the emissivity of the faceplate surface; x is the thickness of each layer, m [4]; h_f – is the total conductivity coefficient and frontal thermal radiation, $W/(m$°C); h_p is the global conductivity coefficient and subsequent thermal radiation, $W/(m$°C); r_f is the thermal conductivity resistances of the frontal insulation materials (m^2°C)/W);r_p is the thermal conductivity resistances of the subsequent sealing materials (m^2°C)/W [5].

Dew point temperature t_{pr}: the dew point is the temperature of air at which the vapour contained in it reaches the saturation state and begins to condense into dew [6]:

$$t_{pr} = \frac{243,2 \ln\left[\left(\frac{e^{\left(\ln(6,11) + \frac{17,62 t_a}{243,12 + t_a}\right)} 100}{h_r}\right) - 1559,72\right]}{24,035 - \ln\left(\frac{e^{\left(\ln(6,11) + \frac{17,62 t_a}{243,12 + t_a}\right)} 100}{h_r}\right)},$$

where h_r – relative humidity, %; t_a – ambient temperature, °C.

Equivalent absolute sky temperature given for sky t_s:

$$t_s = t_a \left[0,8 + \frac{t_{pr}}{250}\right]^{0,25}.$$

Thermal radiation coefficients: the emissivity of an object (thermal radiation coefficient) – is the ratio of the emission power of an object at a given temperature to the emission power of a black body (ABB). ABB is defined as the surface that emits the maximum amount of energy at a given temperature.

The emissivity of the ABB is equal to 1,00 [7]:

$$s_f = s_p = \left[0{,}711 + 0{,}56\frac{t_{pr}}{100} + 0{,}73\left(\frac{t_{pr}}{100}\right)^2\right] + 0{,}013\cos\left(2\pi\frac{h}{24}\right) + 1{,}2\cdot 10^{-4}\left(p_a - 1000\right),$$

where s_f– coefficients of thermal radiation into the sky from the front of the solar module; s_p − coefficients of thermal radiation into the sky from the back of the solar module; p_a − atmospheric pressure; h – hours of the day; t_{pr} − dew point temperature.

Thermal radiation coefficients to the ground:

$$w_f = \left(\frac{6{,}67\cdot 10^{-8}\left(\dfrac{1-\cos(\beta)}{2}\right)\in_f}{\dfrac{1-\cos(\beta)}{2}\left(1-\in_f\right)+\in_f}\right)\left(t_f^4 - t_g^4\right)\left(t_f - t_g\right),$$

$$w_p = \left(\frac{6{,}67\cdot 10^{-8}\left(\dfrac{1-\cos(\beta)}{2}\right)\in_p}{\dfrac{1-\cos(\beta)}{2}\left(1-\in_f\right)+\in_p}\right)\left(t_p^4 - t_g^4\right)\left(t_p - t_g\right),$$

where w_f is thermal radiation coefficients to the ground from the front of the solar module; w_p is thermal radiation coefficients to the ground from the rear of the solar module; t_g is equivalent absolute soil temperatures.

The following equations are solved using interactive mathematical methods:

$$t_c = \left[\frac{q_t + \left(\dfrac{w_f}{a_f} + \dfrac{w_p}{a_p}\right)\left(t_g - t_a\right) + \left(\dfrac{s_f}{a_f} + \dfrac{s_p}{a_p}\right)\left(t_s + t_a\right)}{\left(\dfrac{h_f}{a_f} + \dfrac{h_p}{a_p}\right)}\right] - t_a,$$

$$t_f = \left[\frac{\left(t_c - t_a\right) + r_f w_f\left(t_g - t_a\right) + r_f s_f\left(t_s - t_a\right)}{a_f}\right] - t_a,$$

$$t_p = \left[\frac{\left(t_c - t_a\right) + r_p w_p\left(t_g - t_a\right) + r_p s_p\left(t_s - t_a\right)}{a_p}\right] - t_a,$$

where t_f is the absolute temperatures of the front surface of the panel; t_a is the ambient temperature; t_c is the PV cell temperature; t_p is the absolute temperatures of the back surface of the panel [8; 9].

This method is the standard approach, also called the nominal operating temperature of the cell (T_{NOCT}). The cell temperature (T_C) is calculated using the following formula:

$$T_c = T_a + \frac{G_i}{G_{NOCT}}\left(T_{NOCT} - T_{a,NOCT}\right),$$

where T_a is the ambient temperature; G_i is the incident radiation in the panel plane; T_{NOCT} is measured at incident radiation G_{NOCT} = 800 W/m^2, ambient temperature $T_{a,\ NOCT}$ = 20 °C and wind speed 1 m/s. T_{NOCT} is the data provided by the PV panel manufacturer, which depends on the technology by which it was built, but usually around 45ºC [10 –13].

From the Kurtz model, we can calculate the cell temperature using

$$T_c = T_a + Ie^{-3{,}473-0{,}0594 v_{\upsilon}}.$$

The developed mathematical model of a solar panel (fig.) allows estimating the influence of both internal factors (U_{xx}, I_{kz}) and external factors (W, T, α) on the characteristics of solar panels.

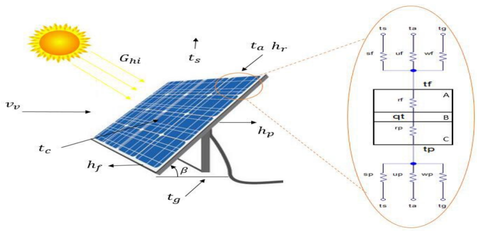

Fig. Solar panel operation diagram and possible consumption devices

The model is intended for designing different kinds of converters and describes all parameters of solar panel operation.

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Photovoltaic direct current power generation system

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The main source of energy for our planet is solar energy. It is the Sun that is the progenitor of all the main energy resources used by mankind – the Sun heats the atmosphere and the surface of the Earth, due to which winds blow, masses of water move, plants develop, organic fuels are formed. And in this regard, the potential of solar energy additionally provides such an opportunity as the use of solar energy to create alternative energy sources, and in this regard, the study of the properties of solar radiation is a particularly urgent task.

In this paper, a multiport dc-dc converter is proposed to be used as a converter. The three port converter contains three so called ports. Two are for solar panel and battery connection and the third one is for load connection.

The structural diagram of the autonomous solar-powered power supply system is shown in Fig. 1.

A multi-port converter has several advantages over stand-alone converters, such as fewer components, some circuit components are common to all ports. As a result, the system has a lighter weight and more compact assembly, which results in a lower cost of the inverter. In addition, there is no need to harmonize converters and transfer information between control systems.