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DETERMINATION OF CLOUD COVER PARAMETERS

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Abstract: A methodology for determining the virtual density of clouds, which takes into account both the values of direct and reflected solar radiation, using the method of reverse transformation is given. Beer's law presented in the paper describes a decrease in the total radiation intensity, calculated per unit of the surface area perpendicular to the direction of radiation distribution. The article considers three cases of a ratio between the linear velocity of clouds and the velocity of the Sun, which is determined by its angular displacement. Each case is supported by an algorithm for the calculation of virtual cloud density, formulas for the computation of solar intensity, cloud projections onto solar panels, and a linear absorption coefficient, whose values are correlated with the cloud density. Using the example of cumulus clouds, two of the set of physical parameters that characterize the state of cloud cover are evaluated. A formula for the calculation of fractal dimension is given. In order to determine whether a solar panel cell is shaded with the presence of haze, an S-curve is used. The two-dimensional discrete Vilenkin-Krestenson transformation with a finite argument is proposed to determine the virtual cloud density. Formulas for direct and reverse Vilenkin-Krestenson transformation are given. Basic functions for symmetric transformation on finite intervals are presented. It is shown that knowing the virtual cloud density and fractal dimension of a cloud cover projection onto the areas of a solar power station allows sections with self-similar properties to be found.

1. Introduction

In recent decades, power plants with renewable energy sources are widely used in Smart Grids in the world in general and in Ukraine in particular [1]. For example, in 2016, the installed peak power of solar power plants in Ukraine exceeded 450 MW [2].

According to Heisenberg's uncertainty principle, for the efficiency of solar power plant operation to be improved, it is necessary that two-channel control be implemented. The first channel is to provide control on the basic interval to ensure the required level of energy for charging the storage. The second channel is to provide control on a minimum duration of the observation interval to ensure the maximum level of the possible energy of solar panels [3].

The necessary step in solar power plants control is describing the parameters of the environment, for example, intensity of solar radiation, pressure, air temperature, humidity, etc.

The level of solar power plant energy is determined by the total area of the solar panels, the efficiency factor, and the average monthly solar radiation intensity. The intensity, in turn, depends on the geographical position, climate conditions, time of day, atmosphere transparency, clouds presence, nature of underlying surface, etc. [4, 5].

There are several methods for the estimation of solar panels energy level, including: 1) use of light sensors; 2) position fixation; 3) use of algorithms for maximum power point finding. When considering the current at the solar panels output as a final result of the passage of solar radiation through the external environment over the solar panels, it is advisable to evaluate the effect of this medium on the magnitude of the generation energy.

In addition, clouds may be accompanied by haze, fog or other physical phenomena. A complex of clouds and the accompanying haze is called cloud cover. To evaluate the impact of the external environment on the amount of energy at the output of a solar power plant, we consider the method of determining two of the set of physical parameters that characterize the state of the cloud cover – fractal dimension and density of clouds.

The aim of this paper is to develop a method for the calculation of virtual cloud cover density and fractal dimension, and to show numerical results.

2. Virtual Cloud Density

When considering large power plants such as the Ivanpah Solar Electric Generating System [6] consisting of 300.000 solar panels of 14 m^2 each, given that the area of the cloud projection (for example, bulky) reaches an average of 100.000 m^2, a continuous calculation model can be used.

Since the transverse dimensions of a Sun's beam are much smaller than the longitudinal ones, the beam is characterized by the intensity $I(z)$ in each specific point. When quanta of solar radiation pass through a cloud, the total radiation intensity, calculated per unit of surface area, perpendicular to the direction of the radiation distribution, decreases in accordance with Beer's law [7]:

$$I(z) = I_0 e^{-\int_0^z m(\vec{z})dz}, \qquad (1)$$

where z is the coordinate of a point on the line along which the radiation is distributed; I_0 is the initial value of intensity, or the intensity of radiation emitted into the Earth's atmosphere; $m(\vec{z})$ is the linear absorption coefficient, which is a function of three spatial coordinates (x, y, z) that form a radius vector $\vec{z}$. Values of the coefficient $m(\vec{z})$ are calculated in points on a straight line, parallel to the axis Oz and correlate with the values of the cloud density in the points of the vector $\vec{z}$. The magnitude of the intensity of the solar radiation passing through the cloud is inversely proportional to the density of the cloud.

The logarithm of the ratio of the intensity of radiation emitted to the solar panel, to the initial intensity, will be called the projection of the cloud along the line of radiation distribution $p(z) = -\ln\frac{I(z)}{I_0}$, or $p(z) = \int_0^z m(\vec{z})dx$. To find the density of a cloud, a set of its projections for all possible cloud positions in the coordinates x, y, z is needed.

Connecting a power converter (in general case, a pulse regulator) to each elementary cell of the solar power plant (a separate solar panel is called an elementary cell) provides the implementation of methods for the estimation of a solar panels output energy level with further summation of the energy in the common node [8, 9].

Depending on the ratio between the linear velocity of the cloud motion and the velocity of the Sun, which is determined by its angular displacement, the following cases are possible:

1. the linear velocity of the cloud is significantly greater than that of the Sun: $V_{cloud} >> V_{sun}$. Then at a certain observation interval (for example, 1 hour), the position of the Sun is considered fictitious (Fig. 1, a). Lines of the rays *A – A*, *A' – A'*, *A'' – A''* retain their colliarity while the projection of the cloud passes the distance h;
2. the linear velocity of the cloud is significantly less than that of the Sun: $V_{cloud} << V_{sun}$. Then the lines of the rays vary from *A – A* to *B – B* with the Sun displacement angle θ. It varies in the certain limits $q_{\min} < q < q_{\max}$ (Fig. 1, b);
3. the linear velocity of the cloud and the velocity of the Sun have the same order of magnitudes: $V_{cloud} \approx V_{sun}$. This case combines the features of two previous cases.

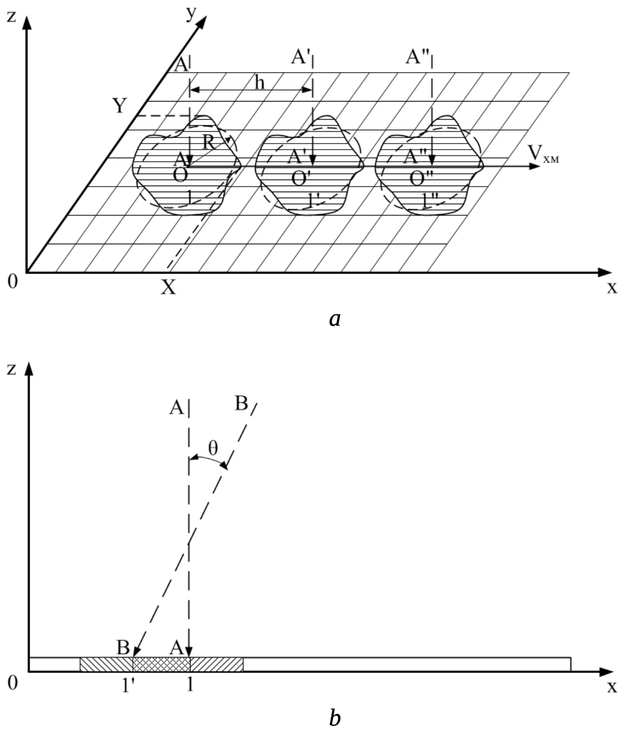

Fig. 1. Clouds projections onto a solar panel: a – provided that $V_{cloud} >> V_{sun}$; b– provided that $V_{cloud} << V_{sun}$.

Although the definition of the shape of a cloud projection is an important task, in this article to simplify the calculations, the shape of the cloud projection is approximated by circle of a certain radius R with a center in the point O.

Since the total intensity of the Sun's radiation is determined by: 1) a direct solar radiation flow through the cloud; 2) an absorbed radiation flow; 3) a radiation flow reflected by the surface of the Earth; 4) a radiation flow reverted from the surface of the cloud; 5) an inducted flow from other objects on the surface [10], to simplify the calculations, we shall use some equivalent virtual cloud density. This will take into account both the magnitude of the direct and the reflected radiation. In addition, for clarity, we shall calculate the density of one cloud. Though a dozen clouds of different sizes, shapes and densities pass through a solar power station overnight, the calculation method for each of the clouds will remain the same. There are several methods for determining the virtual density, one of which is the method of inverse transformation, which allows determining the density of an object based on a set of its projections onto a certain plane [11].

Assuming that the velocity of the cloud is significantly greater than the velocity of the Sun, the calculation method for virtual cloud density that is based on the inverse transformation is described as follows.

On the solar panel we select the original Cartesian coordinate system *Oxyz* with the center *O*. The solar radiation is distributed along the axis *Oz*. With $z = 0$, initial cloud projection 1 is situated on the plane *Oxy*. The center of the plane coincides with the projection center (Fig. 2, a). Since the position of the Sun is fixed, we investigate a number of collinear beams, the Sun displacement angle $\theta = 0$. The next cloud projection 1’ is calculated in the coordinate system Ocg . The center is transferred to the point *O’* with the coordinates (*a*, *b*); the axis Oc direction coincides with that of the axis *Ox*; the axis *Og* direction coincides with that of the axis *Oy*. The position of the new coordinate system relative to the initial one is determined by the following equations:

$$\begin{cases} c = x - a \\ g = y - b \end{cases}.$$

According to equation (1), the solar radiation intensity on the plane of a solar panel is determined as follows:

$$I(x,y) = I_0 e^{-\int_0^x\int_0^y m(x-c,y-g)\,dc\,dg}. \quad (2)$$

For further calculations we assume that outside the cloud $\mu = 0$, and the integral in equation (2) is calculated solely on the segment that is located inside the circle area.

Let us rewrite an equation for the cloud projection onto a solar panel as follows:

$$p(x,y) = \int_0^x\int_0^y m(x-c,y-g)\,dc\,dg .$$

Given that the change in the function $\mu(x, y, z)$ per unit of distance along the axis *Oz* is determined by the operator $p_z = \frac{d}{dz}$, and applying the inverse transformation [12], we obtain the following expression for the clouds linear absorption coefficient:

$$m(x,y,z) = \int_0^\infty p(x,y)e^{j(p_z x + p_z y)}dp_z ,$$

which determines its density.

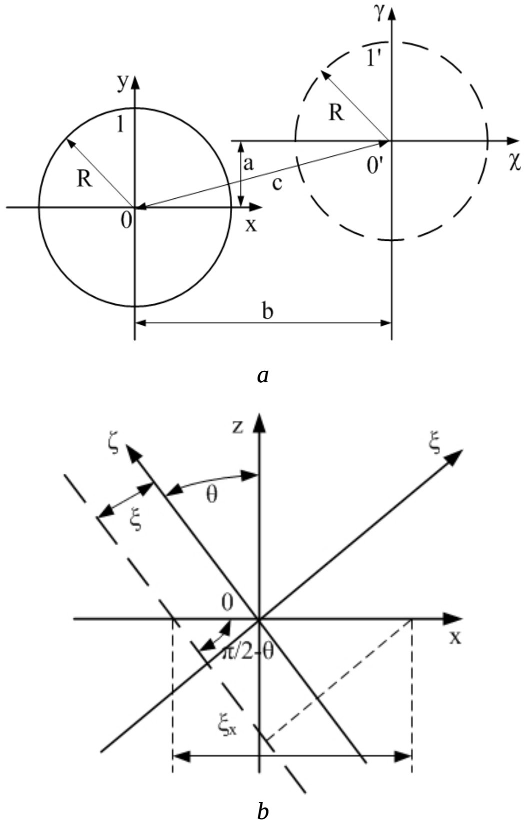

Fig. 2. The scheme of coordinate system location:
a – provided that $V_{cloud} >> V_{sun}$; b – provided that $V_{cloud} << V_{sun}$.

When the linear velocity of the cloud is significally less than the velocity of the Sun, we assume that the displacement of the Sun along the axis *Oy* is negligible. Then, relative to the stationary coordinate system *Oxz*, we introduce a moving system with the axis directed as shown in Fig. 2, b. The position of the moving system relative to the fixed one is determined by the angle θ:

$$\begin{cases} z = z\cos q + x\sin q \\ x = -z\sin q + x\cos q \end{cases}.$$

The intensity of solar radiation for a certain value of the cloud projection coordinate y is determined by the angle θ of the current beam displacement relative to the initial one:

$$I(x,y,q) = I_0 \exp\left(-\int_0^Z m(x,y,z)dV\right),$$

where *Z* is the upper boundary of the cloud.

The set of cloud projections on the axis *Ox* is determined as follows:

$$p(x,y,q) = \int_0^Z m(x,y,z)dV .$$

Considering that the axis Ox is rotated relative to the axis *Ox* with the angle $\frac{p}{2}-q$, the equation of the projection x_x of the axis Ox onto the axis *Ox* is written as $x_x = -z + x\text{ctg}q$.

Then, denoting the set of cloud projections through $p(x_x, y, q)$ and taking into account that $\frac{dq}{dx} = w_x$ is the change in the angle of rotation of the coordinate system per distance unit on the axis *Ox*, we obtain the following equation for calculating the linear absorption coefficient:

$$m(x,y,z) = \int_0^{\infty} p(x_x, y, q) e^{jw_x x_x} dw_x \,,$$

which, as in the previous case, determines the virtual cloud density.

In the case when the linear velocity of the cloud and the velocity of the Sun have the same order of magnitudes, it is necessary that the features, mentioned in the previous two cases be taken into account. If the Sun's displacement along the axis *Oy* is negligible, similar calculations can be performed in a new coordinate system:

$$\begin{cases} z = z\cos q + x\sin q \\ x = -z\sin q + x\cos q \\ g = y - b \end{cases},$$

using the operators $\frac{d}{dz}$ and $\frac{d}{dx}$.

3. Cloud cover fractal dimension

The boundary between individual bulk cloud projections in mist is defined as the average value of the distance between the neighboring cloud projections. In the limits obtained, part of the solar panels generates more energy, and part of the panels generates less. This indicates the possibility of using the notion of fractal dimension [13] of the projection of a cloud cover area on separate parts of the solar power plant:

$$D_0 = \frac{\ln N}{\ln n}, \qquad (3)$$

where n is the number of elementary cells of the solar panel, shaded by a cloud; N is the total number of elementary cells of a solar panel in each of the isolated sections of the solar power plant.

In the case when there are no clouds over the solar power plant surface, the fractal dimension of the area is $D_0 = 2$. When the surface area of the solar power plant is completely covered with clouds, $D_0 = \lim\limits_{n\to 0} \frac{\ln N}{\ln n} = 0$. In all other cases $D_0 < 2$. The areas of the solar power plant for which the value of fractal dimension is similar will be considered self-similar.

To determine whether the solar panel cell is shaded, we use the membership function or the S-shaped curve [14]. It allows determining the collision state depending on the magnitude of the solar radiation intensity. It is calculated as follows:

$$f_s(I^*) = \frac{1}{1 + e^{-\left(I^* + I^*_{threshold}\right)}},$$

where $I^* = I/I_0$ is the relative solar radiation intensity, $I^* \in 0...I_{\max}$; I and I_0 are the intensities of radiation that enters the solar panel and in the Earth's atmosphere; $I^*_{threshold}$ is the threshold value of intensity; $I_{\max}$ is the maximum value of intensity on the solar panel surface.

For example, let us consider a solar power plant with 100 solar panels (10×10). The values of solar radiance varies randomly from 150 to 500 W/m^2 on each cell. We calculated the maximum and minimum values of a solar-induced current: I_{phmax} = 3,67 A, I_{phmin} = 1,47 A. If the current value is less than I_{phmin} the cell is considered to be shaded. A Simulink model of current measurement for each solar cell in shown in Fig. 3.

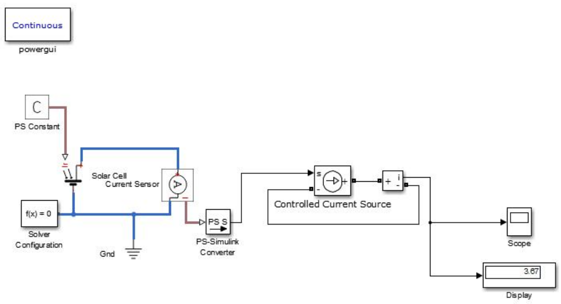

Fig. 3. Simulink model of current measurement for each solar cell.

The current have been measured, we find that 47 of the 100 cells are shaded. Taking into account equation (3), we then calculate the fractal dimension of a cloud cover projection: $D_0 = \frac{\ln 100}{\ln 47} = \frac{4,605}{3,85} = 1,196 \approx 1,2$.

4. Determination of cloud transfer and weight functions

A cloud transfer function is determined by the ratio of the solar radiation intensity at the cloud output to the solar radiation intensity at the input. The values of the solar radiation intensity at the output and the input of the cloud are the functions of spatial coordinates (x, y) and time. The time of measurement of input and output radiation intensity is selected from the following conditions:

$$\begin{cases} \Delta t \cdot V_{cloud} << X \\ \Delta t \cdot V_{cloud} << Y \end{cases},$$

where $\Delta t << T_x$, $\Delta t << T_y$. T_x and T_y is the time during which the projection of the cloud passes distances X and Y. These distances are determined by the maximum size of a solar power plant. The minimum linear dimensions of the cloud projection onto the plane of the solar panel are determined by the Kotelnikov theorem with steps T_x / N_x, T_y / N_y along the axes *Ox* and *Oy*. N_x and N_y are the numbers of elementary cells of the solar panel along the axes.

Since the solar radiation intensity at the input and the output of the cloud for a minor interval throughout the plane is uniform and constant, the transfer function of the cloud in the image area is determined by the following equation:

$$W(p_x, p_y) = \frac{I(p_x, p_y)}{I_0(p_x, p_y)},$$

where $I(p_x, p_y, p)$ and $I_0(p_x, p_y, p)$ are the values of solar radiation intensity at the cloud output and input.

The weight function is considered as a system response to the input influence. In order to find it in the coordinates (x, y), we apply the inverse transformation to the transfer function:

$$w(x, y) = L^{-1}\{W(p_x, p_y)\} =$$
$$= \frac{1}{X}\frac{1}{Y}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} W(p_x, p_y) e^{p_x x + p_y y} dp_x dp_y.$$

Since to find the cloud transfer function, it is necessary that a two-dimensional data array of solar radiation intensity be processed, we consider a two-dimensional Vilenkin-Krestenson transformation for the function of two variables n_x and n_y, defined on the intervals $N_x \cong m_1^{n_1}$ and $N_y \cong m_2^{n_2}$ where m_1, n_1, m_2, n_2 are some integers. The application of this transformation reduces the amount of computations required for the transition from the original to the image and vice versa.

The direct and inverse Vilenkin-Krestenson transformations on the interval $N = N_x N_y$ are described by the following equations:

$$W(n_x, n_y) = \frac{1}{N}\sum_{n_x=0}^{N_x-1} \cdot \sum_{n_y=0}^{N_y-1} w(n_x, n_y) \times f_W(n_x, n_y, n_x, n_y),$$

$$w(n_x, n_y) = \sum_{n_x=0}^{N_x-1} \cdot \sum_{n_y=0}^{N_x-1} W(n_x, n_y) \times f_W^{*}(n_x, n_y, n_x, n_y),$$

where $w(n_x, n_y)$ and $W(n_x, n_y)$ are the discrete values of the original and the image of the cloud transfer function; $f_W(n_x, n_y, n_x, n_y)$ and $f_W^{*}(n_x, n_y, n_x, n_y)$ are the basic and complex-conjugate functions; the values n_x and n_y can be interpreted as the number of revolutions, which the vector of discrete exponential functions will perform on the intervals N_x and N_y [15].

The complex nature of the Vilenkin-Krestenson transformation functions and the unequal appearance of direct and inverse transformations complicate the application of this method. This method retains information about the phase, i.e. the direction of cloud motion. If this information is not important, it is advisable to use a symmetric transformation on finite intervals [16]. The basic functions for this transformation in the case of two variables are described by the following equation:

$$j(n_x, n_y, n_x, n_y) =$$
$$= \text{cas}\left(\frac{2p}{m_1}\sum_{s=1}^{n_1} n_x^{(s)} n_x^{(s)}\right) \mathbf{o}\, \text{cas}\left(\frac{2p}{m_2}\sum_{s=1}^{n_2} n_y^{(s)} n_y^{(s)}\right),$$

where $\mathbf{o}$ is the sign of the “main action” operation.

5. Conclusion

The described method allows two main parameters of the cloud cover to be determined: the fractal dimension of a cloud cover projection onto the area of a solar power station, and the coefficient of linear absorption or the virtual cloud density. The determination of these parameters makes it possible to identify the areas with self-similar properties. It is the basis for the development of identical control algorithms. The example of calculating fractal dimensions shows the results that verify the theoretical data.

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ВИЗНАЧЕННЯ ПАРАМЕТРІВ ХМАРНОГО ПОКРИВУ

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Наведено методику визначення віртуальної щільності хмар з використанням методу зворотного перетворення. Розглянуто три випадки співвідношення лінійної швидкості руху хмар та швидкості Сонця, яка визначається його кутовим переміщенням. Для кожного випадку наведено схему для обчислення віртуальної щільності, формули для розрахунку інтенсивності сонячного випромінювання, проекції хмари на площину сонячних панелей та коефіцієнта лінійного поглинання. Наведено оцінку двох фізичних параметрів, що характеризують стан хмарного покриву на прикладі купчастих хмар. Представлена формула для розрахунку фрактальної розмірності. Для визначення віртуальної щільності хмар запропоновано використовувати двовимірне дискретне перетворення Віленкіна–Крестенсона з кінцевим аргументом. Показано, що знання віртуальної щільності хмар та фрактальної розмірності проекції хмарного покриву на окремі ділянки сонячної електростанції дає моєливість знаходити ділянки із самоподібними властивостями.

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