INFLUENCE OF THE SUN POSITION AND SOLAR IRRADIATION OVER PHOTOVOLTAIC POWER PRODUCTION

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Abstract: In this paper we present a mathematical algorithm used to determine the photovoltaic power depending of position of the sun and the solar irradiation. The algorithm can be used to simulate the sun position, the solar irradiation and the electrical power production of an particular photovoltaic cell panel.

Keywords: sun, solar irradiation, photovoltaic panel,

1. INTRODUCTION

1.1. Solar Radiation

The solar constant, which is defined as the average energy flux incident on a unit area perpendicular to the solar beam outside the Earth's atmosphere has been measured to be S = 1.367 kW/m^2.
The solar radiation incident on a collector on the Earth's surface is affected by a number of mechanisms, as shown in Figure 1. Part of the incident energy is removed by scattering or absorption by air molecules, clouds and other particles in the atmosphere. The radiation that is not reflected or scattered and reaches the surface directly is called beam radiation. The scattered radiation which reaches the ground is called diffuse radiation. Some of the radiation is reflected from the ground onto the receiver; this is called albedo radiation. The total radiation consisting of these three components is called global radiation. Although it varies significantly, a solar irradiance value of 1 kW/m^2 has been accepted as the standard for the Earth's surface. The spectral distribution of this standard radiation is called Global AM 1.5 solar spectrum, where AM stands for Air Mass and AM 1.5 indicates that the direct beam path of the sun's rays travels through 1.5 times the thickness of the atmosphere in a typical situation.

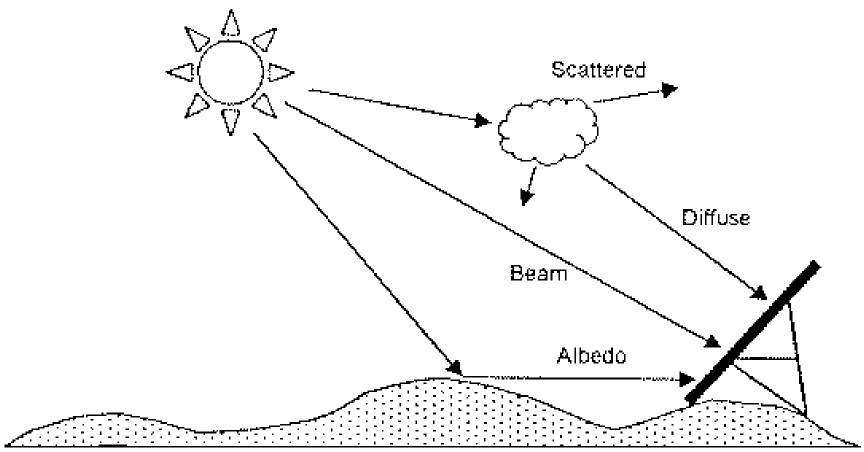

Fig. 1 - Solar radiation in the atmosphere.

1.2. Experimental Data

Calculation of the incident radiation for a particular site from theoretical methods is extremely difficult as it is highly dependent on variables such as local weather conditions, the composition of the atmosphere above the site, and the reflectivity of surrounding land. For this reason, the design of a photovoltaic system relies on the input of experimental data measured as close as possible to the site of the installation. This data is generally given in the form of global irradiation on a horizontal surface for each day at a particular location, or for a representative day of every month. Since solar panels are usually tilted, a manipulation of the experimental data is necessary.

1.3. Daily Irradiation

Solar irradiance integrated over a period of time is called solar irradiation. Of particular significance in solar panel design is the irradiation over a day. The process of determining the total irradiation incident on a tilted plane over one day consists of calculating the equivalent radiation outside of the atmosphere, comparing this with experimental data measured on a horizontal surface at the site to determine the relative components of beam and diffuse, then adjusting them for the panel angle and including the albedo radiation.

The daily irradiation received by a unit horizontal surface above the Earth's atmosphere consists only of the beam component, B0 and is calculated in equation 1:

$$B0 = \frac{24}{\pi} \cdot S \cdot \left(1 + 0.033\cos\left(\frac{2 \cdot \pi \cdot d_n}{365}\right)\right) \cdot \left(\cos\varphi \cdot \cos\omega_S + \omega_S \cdot \sin\varphi \cdot \sin\delta\right) \quad \left[\frac{kWh}{m^2}\right] \quad (1)$$

where

- S = solar constant = 1.367 kW/m2
- d_n = day number of the year from 1 to 365
- φ = latitude
- δ = solar declination
- ω_S = sunset hour angle.

To determine an average value for a particular month, a day towards the middle of the month is chosen as the basis for calculations.

A clearness index, KT, can be defined to describe the attenuation of solar radiation by the atmosphere at a given site during a given month, and is calculated from the proportion of the available radiation that reaches the ground, eq.2:

$$KT = G / B0 \quad (2)$$

where G is the global irradiation received on a horizontal plane at the site, which is usually determined experimentally as described above.

The diffuse irradiation can be approximated as, eq. 3:

$$D = G\,(1 - 1.13 * KT) \quad (kWh/m^2) \quad (3)$$

and the beam irradiation by eq. 4:

$$B = G - D \quad (kWh/m^2) \quad (4)$$

Note that it is assumed that no albedo radiation reaches the horizontal surface, as would be expected from consideration of the physical situation.

Adjustment for Tilted Plane.

For a panel facing due north in the southern hemisphere, or due south in the northern hemisphere, and tilted at an angle beta to the horizontal, the calculations for beam irradiation B, diffuse irradiation D and albedo radiation R are as follows:

$$B(\beta) = \frac{B\left(\cos(\varphi - \beta) \cdot (\sin \omega_{S1} - \omega_{S1} \cdot \cos \omega_{S1})\right)}{\sin \omega_S - \omega_S \cos \omega_S} \left[\frac{\mathrm{kWh}}{\mathrm{m}^2}\right] \quad (5)$$

$$D(\beta) = 0.5 \cdot (1 + \cos \beta) + D \left[\frac{kWh}{m^2}\right] \quad (6)$$

$$R(\beta) = 0.5 \cdot (1 - \cos \beta) \cdot \rho \cdot D \left[\frac{kWh}{m^2}\right] \quad (7)$$

where

- ω_{S1} = the sunset hour angle adjusted for a tilted plane to allow for the effect of the sun rising and setting behind the panel, using the formula (8):

$$\omega_{S1} = -\arccos\left(-\arctan(\varphi - \beta) \cdot \tan \delta\right) \quad (8)$$

- ρ = reflectivity of the surrounding area. Typical reflectivity values are 0.2 for dry bare ground, 0.3 for grassland and 0.6 for snow.

The total irradiation received by a tilted plane over one day is then found by summing the calculated values of the beam, diffuse and albedo irradiations.

2. DETERMINATION OF THE SUN'S POSITION

The position of the Sun in the sky varies throughout the day and season due to the spin of the earth around its axis and to its orbiting around the Sun. Knowledge of spherical and plane trigonometry as well as some elementary notions of astronomy are required in order to understand, and not just apply, the formulas for the computation of the times and directions of the direct incoming radiation on any locality of a planet.
In order to determine the position of the celestial bodis in the sky, they are assumed to lie on a single sphere, the Celestial sphere (Clelestial Vault). The center is depending on the different conventions, the centre of our Celestial Vault coincides with the position of the observer (horizontal system) that is indicated by the pyramid in the centre of the picture.

The apparent daily rotation of the celestial sphere about the earth's axis may be expressed in terms of the hour angle: the angular distance between the hour circle and the observer's meridian. One hour is equivalent to 360°/24 = 15° of the rotation of the celestial vault. All the values of time in solar energy computations are expressed in terms of apparent solar time (this is also known as true solar time). But in certain casses, it may be necessary to express the successive positions of the Sun relative to a fixed point on the earth's surface in term of local clock time that differs from the apparent solar day. This program is based on the apparent solar time.

The basic terms and formulas used in the SunPath applet
Latitude (φ) = the latitude of a place on the surface of the Earth is its angular displacement above or below the Equator, measured from the centre of the Earth. It is given between 0 ° and 90 ° N or 90 ° S.

Solar Time (T) = the solar time is defined as the number of hours before or after noon. Noon is defined as the time when the Sun is highest in the sky.

Hour angle (ω) = for mathematical analysis the solar time is converted to an angle in degrees of radians. This is known as the hour angle and is the angular displacement of the sun from its noon position.

Solar Declination (δ) = the declination is the angular displacement of the Sun from the plane of the Earth's equator. The value of the declination will vary throughout the year between +23.45° and -23.45° because the axis of the Earth is tilted at a constant angle of its rotation about the Sun.

During a single day the declination delta can be assumed constant and equal to its value at midday. The solar declination for the Northern Hemisphere is calculated by equation 9:

$$\delta = 23.45 \cdot \sin\left[\frac{(day\_number - 81) \cdot 2 \cdot \pi}{365}\right] [\deg] \quad (9)$$

where day_number is the day number of the year, starting from 1 on the 1th of January.

Sunrise hour angle (ω_S) = the sunrise hour angle is the hour angle at sunrise:

$$\omega_S = \arccos(\tan\varphi \cdot \tan\delta)\,[rad] \quad (10)$$

The sunset hour angle is equal at $-\omega_S$.

Solar Altitude (α) = the solar altitude is the angle a direct ray from the Sun makes with the horizontal at a particular place on the surface of the Earth. The Sun will be at its highest above the horizon at noon each day. The altitude of the Sun at any time of the day is determined by: equation 11:

$$\alpha = \arcsin(\sin\delta \cdot \sin\varphi + \cos\delta \cdot \cos\varphi \cdot \cos\omega)\,[rad] \quad (11)$$

Solar Azimuth (ξ) = the solar azimuth angle is defined as the angle a horizontal projection of a direct ray from the Sun makes with the true north-south axis. This is usually given as an angular displacement through 360° from true north, but for the purposes of SunPath it is express in a set of (-180°, +180°).
The azimuth of the Sun at any time of the day is given by equation 12:

$$\xi = \pi - \arccos\left[\frac{(\cos\varphi \cdot \sin\delta - \cos\delta \cdot \sin\varphi \cdot \cos\omega)}{\cos\alpha}\right] [rad] \quad (12)$$

3. PHOTOVOLTAIC SYSTEM

Photovoltaic is the art of converting sunlight directly into electricity using solar cells.

Solar cells are manufactured from semiconductor material, that is, material which acts as an insulator at low temperatures, but as a conductor when energy or heat is available. At present most solar cells are silicon based, since this is the most mature technology. A silicon solar cell is a diode formed by joining p-type (typically boron doped) and n-type (typically phosphorous doped) silicon. Light shining on such a cell can behave in a number of ways as illustrated in figure 2. To maximize the power rating of a solar cell, it must be designed so as to maximize desired absorption (3) and absorption after reflection (5).

A typical representation of an IV curve for a photovoltaic cell, showing short circuit current (Isc) and open circuit voltage (Voc) points, as well as the maximum power (Vmp Imp) is shown in Fig. 3.

The two limiting parameters used to characterize the output of solar cells for given irradiance, operating temperature and area are:

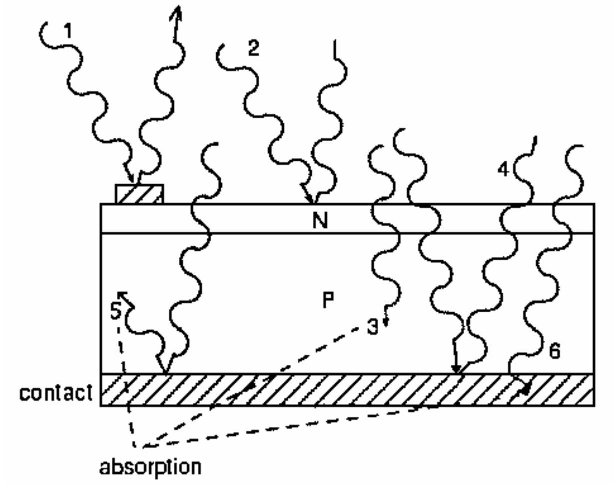

Fig. 2. Behaviour of light shining on solar cell:
1. Reflection and absorption at top contact;
2. Reflection at cell surface;
3. Desired absorption;
4. Reflection from rear out of cell-weakly absorbed light only;
5. Absorption after reflection;
6. Absorption in rear contact.

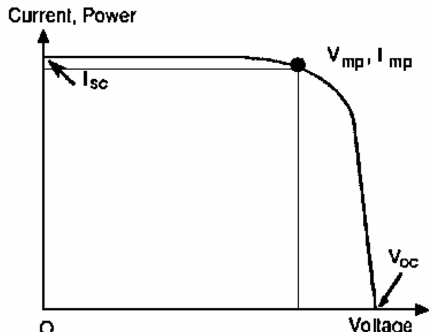

Fig. 3. IV curve.

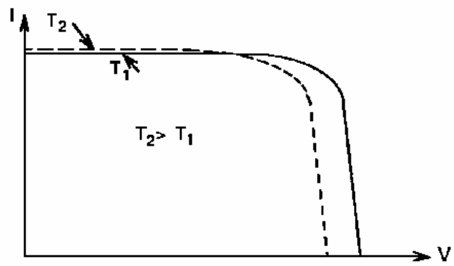

Fig. 4. The effect of temperature on the IV characteristics of a solar cell.

Short-circuit current, Isc, the maximum current, at zero voltage. Note that Isc is directly proportional to the available sunlight.

Open-circuit voltage, Voc, the maximum voltage at zero current. Voc increases logarithmically with increased sunlight. This characteristic makes solar cells ideally suited to battery charging.

For each point on the IV curve, the product of the current and voltage represents the power output for that operating condition. A solar cell can also be characterized by its maximum power point, when the product Vmp Imp is at its maximum value. The maximum power output of a cell is graphically given by the largest rectangle that can be filled under the IV curve.

3.1. Effect of temperature

The operating temperature of solar cells is determined by the ambient air temperature, by the characteristics of the module in which it is encapsulated, by the intensity of sunlight falling on the module, and by other variables such as wind velocity.
The main effect of increasing temperature for silicon solar cells is a reduction in Voc and hence the cell output as shown in figure 4.

3.2. PV cell interconnection and module design

Solar cells are rarely used individually. Rather, cells with similar characteristics are connected and encapsulated to form modules (arrays) which, in turn, are the basic building blocks of solar arrays.

As maximum voltage from a single silicon cell is only about 600 mV, cells are connected in series to obtain the desired voltage. Usually about 36 cells are used for a nominal 12 V charging system.

Under peak sunlight (1 W/m^2) the maximum current delivered by a cell is approximately 30 mA/cm^2. Cells are therefore paralleled to obtain the desired current.

A typical 36 cell module based on screen printed silicon cell technology has the cells series connected to suit the charging of 12 volt battery.

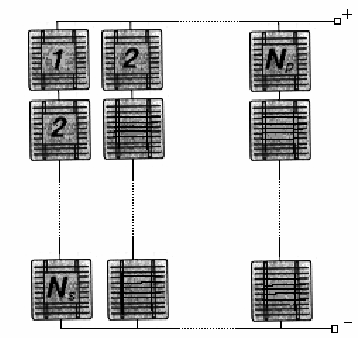

Fig. 5. Cells in series and in parallel.

The typical characteristics for each cell would be:

- Voc = 600 mV (25 C)
- Isc = 3.0 Amps
- Vmp = 500 mV (25 C)
- Area = 100 cm^2

Therefore 36 cells in series give:

- Voc = 21.6 Volts (25 C)
- Isc = 3.0 Amps
- Vmp = 18 Volts (25 C)
- Imp = 2.7 Amps

The modules and the solar array must therefore take full advantage of radiative, conductive and convective cooling and absorb the minimum of unused radiation.
Different encapsulation types, giving vastly different thermal properties, have been utilized by manufacturers to meet different market needs.

Equation to calculate the output power
To calculate the output power generated by a photovoltaic panel the program uses the equation 13:

P = n_modules_series * (Vmp - Vtc * (working_temp - standard_temp)) * n_modules_parallel * Imp * irrad;

where:

- n_modules_series is the number of modules in series;
- Vmp is the voltage at maximum power point (Volts);
- Vtc is the voltage temperature coefficient (Volts/ deg C);
- working_temp is the working temperature (deg C);
- standard_temp is the standard temperature (deg C);
- n_modules_parallel is the number of modules in parallel;
- Imp is the current at maximum power point (Amps);
- irrad is the normalized irradiations, it means that if the irradiations are measured in Watth/m^2 you have to divide that one per 1.000 Watth/m^2, istead if it is measured in kWatth/m^2day you have to divide that one per 1 kWatth/m^2day.

4. REFERENCES

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