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ESTIMATING PHOTOVOLTAIC SYSTEM OUTPUT

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Photovoltaic power system output depends on major factors such as the local latitude, the ground reflectivity and meteorological conditions. Due to the fact that the intensity of the light on a surface varies throughout a day, as well as day to day and month to month, the actual output of a solar power system can vary substantial. In this paper, the performance of photovoltaic systems is analyzed and also a method for calculation of the electrical output of PV systems is given.

Keywords: renewable energy source, photovoltaic system, module, efficiency.

1. Introduction

Renewable energy sources are considered as viable alternatives to conventional supply systems, in the provision of electricity to isolated communities, especially in the rural areas. The solar energy systems are suitable for supplying small loads operating independently or individual households in areas far away from the electricity grid. Solar electric panels can generate electricity that is free from pollution, fuelled by the natural resource of the sun. Presently, several photovoltaic (PV) power plants are connected to electricity grids in USA, ASIA and Europe.

2. The performance of photovoltaic systems

The basic unit of photovoltaic conversion is a semiconductor device called the solar cell. Photovoltaic or solar cells generate electricity when the sun shines and not at night. Photovoltaic cells are thin layers of a semiconductor, usually crystalline silicon, that convert sunlight directly to d.c. electricity, and then an inverter converts the d.c. to standard a.c. power for connection to utility systems. These solar cells are built up into panels with power ratings ranging from a few watts to about 100 W. Many individual solar cells can be interconnected into a PV module. These PV modules are interconnected using combinations of parallel and series connections to form a PV array. The panels are modular and can be

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configured into larger arrays to match almost any load requirement. A single PV array is considered to be a single direct current (DC) power supply unit. A PV array may consist of a single PV module, a single PV string or several parallel-connected strings, or several parallel-connected PV sub-arrays and their associated electrical components. In fig. 1 are given the typical PV system components.

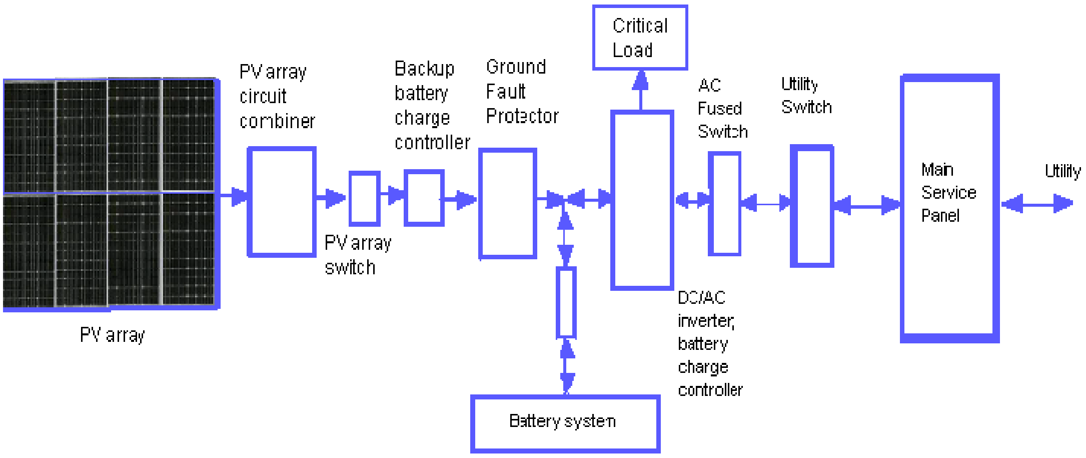

Fig.1. Typical PV system components

Batteries are used in PV systems for the purpose of storing energy produced by the PV array during the day, and to supply it to electrical loads as needed – during the night and periods of cloudy weather. Moreover, in most cases, a battery charge controller is used in these systems to protect the battery from overcharge and over-discharge [4].

Photovoltaic modules can be placed on almost any building surface which receives sunshine for most of the day. Roofs are the usual location for PV systems on houses but photovoltaic modules can also be placed on facades or as a shade structure. These shade systems can support small to large PV systems. The photovoltaic module supplies direct current, which needs to be converted into alternating current using an inverter, a type of electronic box. The a.c. current can then be fed into the electricity distribution grid. One categorization of PV systems is as follows [7]:

- small PV system – up to 10 kW;
- medium PV system – 10 kW to 200 kW;
- large PV system – above 200 kW.

The PV power systems produce electricity in proportion to the intensity of sunlight striking the solar array surface. PV power systems can be stand alone or connected to the power grid [1, 2]. In fig. 2 is shown a schematic PV system having the possibility to be connected to the power grid. PV array is installed on the roof of home.

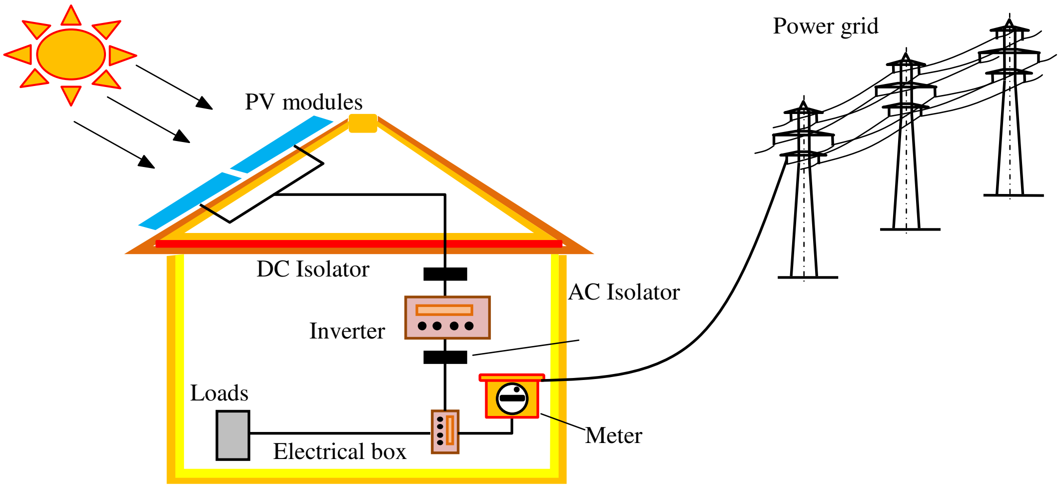

Fig.2. A schematic interconnected PV system.

The performance of PV modules (arrays) are generally rated according to their maximum d.c. power output under Standard Test Conditions (STC), that are defined by a module (cell) operating temperature of 25 ºC, an incident solar irradiance level of 1000 W/m² and a light spectrum corresponding to an atmospheric mass of 1.5 (called and spectrum 1.5 AM) [2, 3, 7]. The solar spectrum at 1.5 AM is based on ERDA/NASA (1977) data [5]: the energy available is only 49,5% to a silicon photovoltaic cell due to the fact that the photons with wavelength longer than 1,11μm don't have enough energy to excite electrons (20,2%) of the incoming solar energy and those with shorter wavelengths can't use all of their energy (30,2%).

A simple evaluation regarding PV system output can be obtained on basis of manufacturer's data. A manufacturer may rate a particular solar module output at 100 Watts of power under STC, and the product is considered a "100-watt solar module". This module will often have a production tolerance of +/-5% of the rating, which means that the module can produce 95 W. A PV array's performance may be affected by many factors, such as: shading, temperature rise, voltage drop in cables, pollution of the surface of the array. Nearby trees and buildings may cause shadows to fall on the PV array during some part of the day. Output can be reduced by shade or non-optimal orientations or tilt angles [3].

Module output power reduces as module temperature increases. When operating on a roof, a solar module will heat up substantially, reaching inner temperatures of 50-75ºC. For crystalline modules, a typical temperature reduction factor is about 89%. So a ”100-watt” module will typically operate at about 85 Watts W (95 Watts*0,89=85 Watts) under full sunlight conditions [2]. Dirt and dust can accumulate on the solar module surface, blocking some of the sunlight and reducing output. The dirt and dust should be cleaned off during every rainy season, but is more realistic to estimate system output taking into account the reduction due to dust. A typical annual dust reduction factor to use is 93%.

All PV arrays should have similar rated electrical characteristics including short circuit current, open circuit voltage, maximum power current, and maximum power voltage and rated power, all being at STC. The maximum power output of the total PV array is always less than the sum of the maximum output of the individual modules. The difference is a result of slight inconsistencies in performance from one module to the next and this is called module mismatch and amounts to at least a 2% loss in system power. Power is also lost to resistance in the system wiring. These losses should be kept to a minimum but it is difficult to keep these losses below 3% for the system. A reasonable reduction factor for these losses is 95% [2]. The d.c. power generated by the solar module must be converted into a.c. power using an inverter. Some power is lost in the conversion process, and there are additional losses in the wires from the rooftop array down to the inverter and out to the house panel. Modern inverters commonly used in residential PV power systems have peak efficiencies of 92-94% indicated by their manufacturers. The overall d.c.-a.c. conversion efficiencies may be about 88-92%. Finally can be calculated the “100-watt module” output, reduced by production tolerance, heat, dust, wiring, ac conversion, and other losses will translate into about 67 Watts of a.c. power delivered to the house panel during the middle of a clear day: 100 Watts × 0,95 ×0,89 × 0,93 ×0,95×0,90 = 67 Watts.

Other factors, such as sun angle and house orientation, can influence the system energy output. During the course of a day, the angle of sunlight striking the solar module will change, which will affect the power output. The pitch of the roof may affect the sun angle on the module surface, as will the East-West orientation of the roof [3]. The output from the “100-watt module” will rise from zero gradually during dawn hours, and increase with the sun angle to its peak output at midday, and then gradually decrease into afternoon and back down to zero at night. For example, in Europe a system with a PV array tilted towards the south would generate approximately 750/1500kWh/year per kWp installed [4]. So a typical 2 kWp system - around 20 square metre of multicrystalline modules, would generate around 1500/3000 kWh per year [2].

3. Method for calculation of the electrical output of a PV system

A method for estimation of the average daily output *E* of a photovoltaic panel, based on the insolation summed over a month, can be approximated by:

$$E = \frac{A\sum \eta_i I_i}{N} \tag{1}$$

where: the value of *E* (kWh) is the averaged daily energy output for the period (for one month); A (m²) is the panel area; η_i is the average hourly panel efficiency; I_i (kW/m²) is the integrated insolation for the hour; *N* is the number of days in the integration period and the sum is hourly (corresponding to the daylight hours) for the month. Although weather can change from day to day in many locations, this method assumes an average for the month [6]. Hourly cell efficiency η_i is a function of cell and array design, cell temperature and isolation intensity. It can be characterized by the following equation:

$$\eta_i = \eta_r\left[1-\beta\left(T_{ci}-T_r\right)+\gamma\log_{10}(I_i)\right] \tag{2}$$

where η_r is the rated efficiency, β is the temperature coefficient of efficiency (C^{-1}), T_{ci} is the cell average temperature for the hour, T_r is the temperature at which the cell efficiency was rated, and γ is the insolation flux density coefficient of cell efficiency. All temperatures are in Celsius. The averaged daily energy output *E* can be also calculated from the equations:

$$E = \left(\frac{n_r A}{N}\right)\left[\sum I_i - \beta\sum\left(T_{ci}-T_{ai}\right)I_i - \beta\sum\left(T_{ai}-T_M\right)I_i - \beta\sum\left(T_M-T_r\right)I_i + \gamma\sum I_i\log_{10}(I_i)\right] \tag{3}$$

where:

T_{ai} is defined as the average ambient air temperature for the hour and T_M is defined as the mean air temperature for the month. The monthly average efficiency η is used in preference to hourly values, and *E* can be obtained from:

$$E = \frac{\eta A}{N}\sum\left(I_i\right) \tag{4}$$

$$\eta = \eta_r\left[1-\beta\left(T_c-T_a\right)-\beta\left(T_a-T_M\right)-\beta\left(T_M-T_r\right)+\gamma\log_{10}(I_i)\right] \tag{5}$$

For example, in USA the difference $(T_a - T_M)$ was found to be typically within the range 3+/-2K and the difference $(T_M - T_r)$ can be found from weather data and the manufacturer's data for the rating test cell temperature T_r.

The sum of the electrical output and thermal loss is given by:

$$\alpha\tau I_i = \alpha\tau\eta_i I_i + U_L(T_{ci} - T_{ai}) \tag{6}$$

where U_L is the unit area thermal loss coefficient (or thermal conductance based on panel area, kW/m²·K); α and τ are the PV cell surface absorbance and array protective covering transmittance for insolation. On the assumption that the electrical generation is small relative to the heat generation will result:

$$T_{ci} - T_{ai} \approx \frac{\alpha\tau I_i}{\sum I_i} \tag{7}$$

For the local site of interest:

$$\frac{U_L(T_c - T_a)}{\alpha\tau} = \frac{\sum I_i^2}{\sum I_i} = 0{,}219 + 0{,}832 K_r \tag{8}$$

The equation (8) was based on the assumption that PV panel is at the optimum tilt angle for each month, which changes from month to month. A tilt correction factor C_f for $(T_c - T_a)$ was determined by computer analysis and simulation to be approximated by [6]:

$$C_f = 1.0 - 0.000117(S_M - S)^2 \tag{9}$$

$$\log(I) = \frac{\sum I_i \log(I_i)}{\sum I_i}\ ; \qquad \log(I) = 0{,}640 - 0{,}0732 K_r. \tag{10}$$

The optimum tilt angle depends on the local latitude and month of the year and grand reflectivity, unless the panels are installed horizontally on a flat roof. Additional computer simulations suggested optimum tilt, expressed in degrees. The tilt correction factor C_f shall be calculated on the month-by-month basis, taken into account the local latitude L and data given in table 1, [6].

Table 1

The optimum tilt for each month of the year

Month	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**
Optimum tilt	L+29	L+18	L+3	L-10	L-22	L-25
Month	**Jul.**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Optimum tilt	L-24	L-10	L-2	L+10	L+23	L+30

All of the above has lead to a group of equations that permit monthly estimates of the electrical output of a PV system, as follow:

Example

For a PV array tilted at 45° to the south at a location where the latitude is 45° north, shall be determined the total output from the array, corresponding to June [kWh], on basis of the following parameter values:

$$U_L = 0{,}02 kW \cdot m^{-2} \cdot K^{-1};$$
$$\alpha = 0{,}88; \quad \mathrm{t} = 0{,}95; \quad \eta_\mathrm{r} = 0{,}15; T_r = 20°C;$$
$$\beta = 0{,}0045°C^{-1}; \qquad \mathrm{K_r} = 0{,}502$$
$$\overline{H}_c = 4{,}97 kWhm^{-2} / day \quad \text{and } \mathrm{T_M} = 15{,}3°C$$

Solution: from the equation (8) will result

$$\frac{U_L(T_c - T_a)}{\alpha\tau} = 0{,}219 + 0{,}832 \times 0{,}502 = 0{,}637\ kW \cdot m^{-2}$$

From (9) and table 1, corresponding to June: $S_M = 45 - 25 = 20°$ and

$$C_f = 1{,}0 - 0{,}000117(20 - 45)^2 = 0{,}927$$

$$(T_c - T_a) = \frac{(0{,}927 \times 0{,}637) \times 0{,}88 \times 0{,}95}{0{,}02} = 24{,}7 K.$$

On the assumption that $(T_c - T_M) = 3$ K

and $(T_M - T_r) = 15{,}3 - 20 = -4{,}7K$

The average cell efficiency for the month is calculated from equation (5):

$$\eta = \eta_r[1 - \beta(T_c - T_a) - \beta(T_a - T_M) - \beta(T_M - T_r) + \gamma\log_{10}(I_i)] =$$
$$0{,}15[1 - 0{,}0045(24{,}7 + 3 - 4{,}7)] = 13{,}4\%$$

The daily average insolation integral is 4,97 kWh/m² and June has 30 days, thus E=0,134*30*4,97=19,98 kWh/m².

Extending this solution to an entire year can be obtained data for a year, using a spreadsheet or programming language such as Matlab.

6. Conclusions

This paper should be helpful to easier estimation of the electrical output of a PV systems and also to find of the adequate site, giving a higher efficiency, because is here some simplified evaluation mentioned with references to specific literature.

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