

Design and Simulation of a PV System under Different Operating Conditions

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Abstract: Over the past few years, the installed power of wind and photovoltaic power plants in Bulgaria has been significantly increased. The aim of this article is to propose a methodology for the design and construction of a stationary 75kWp photovoltaic power plant, connected to the public grid at the MV level through a CSS (0.4/21 kV). The proposed design methodology is convenient and easy to implement, and the results of practical construction show that the difference between the estimated and the obtained electricity production is less than 5%. It has been found that two main factors have the strongest impact on the electricity production - the pollution of the surface of the modules (i.e. field dust, bird droppings etc.) and the ambient temperature. Reducing their impact can be achieved by using a cleaning and cooling system with temperature feedback, which would lower the operating temperature of the modules from 80-85°C to 47°C /NOCT/. The results of the simulation studies performed show that this would increase electricity production by about 20%, which would compensate for the degradation of the photovoltaic modules.

Keywords: PV systems, power plant, Operating Conditions, MPPP, electricity production.

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1. Introduction

Over the past decade, photovoltaic systems (PV) have entered the energy market and have established themselves as the preferred technology for decentralized power generation in more and more countries and regions due to their modularity and flexibility. The share of solar electricity in the energy resource portfolio has been steadily increasing due to the possibility of free use of the available solar resource, the minimal costs of operation and maintenance of photovoltaic plants, and clean and safe electricity generation [1]. The dynamic growth of the photovoltaic (PV) sector in the United Europe over the past decade has been largely supported by the favorable regulatory framework and incentive mechanisms applied to renewable energy sources. Despite the rapid development of the solar industry in recent years and technological innovations in this area, PV projects are still associated with significant capital investments, and because the results of the investment are realized over a long period of time, the future efficiency of the systems largely depends on the precise assessment of the investment idea and good planning and management of the project initiatives. Regardless of Europe's priority goal of creating a competitive, sustainable, and secure energy supply, economic reasons force the Bulgarian government to frequently change its regulatory framework related to

renewable energy sources and to strive to limit the more expensive energy solutions, including PV, despite their long-term beneficial effect [2]. This circumstance further emphasizes the need for a detailed assessment and quality investment analysis of PV projects, to achieve the investor's goals and achieve the desired economic result in conditions of uncertainty.

Regardless of the relevance and importance of the issues related to the assessment, planning, and management of capital investments in solar power installations, some of their theoretical and practical aspects remain insufficiently studied and investigated, due to the relative novelty of technological solutions for the Bulgarian scientific and applied reality. The features of PV and the trends in solar electricity production, which define this type of solar installation as a specific object of management, have not been systematized and clarified in detail. The main problems related to the assessment and planning of PV projects have not been identified, and there are no specific guidelines for solving them. No scheme has been developed to present the sequence and connections between the activities for organizing the preparation and implementation of the variety of projects for electricity production from PV [3]. The issues related to models for forecasting the amount of electricity produced have not been studied in a sufficiently comprehensive manner. The methods and tools for analyzing and assessing the economic efficiency of capital investments in PV are not sufficiently adapted to practice [4]. At this stage, there are no comprehensive methodological guidelines that would describe the sequence of analytical and evaluation actions



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preceding the implementation of a PV project, which would enable entrepreneurs to improve management and increase the effectiveness of the project initiative.

2. Methodology

In order to achieve maximum electricity production from photovoltaic modules, it is necessary to calculate the optimal installation angle [5]. An algorithm calculated with the MathCAD program is used:

$$J(D) = 360 \cdot \frac{D}{365}, \quad (1)$$

where: D is the day of the year.

Declination of the Sun:

$$\delta_j = (0.3948 - 23.2559 \cos(J + 9.1) - 0.3915 \cos(2J + 5.4) - 0.1764 \cos(3J + 105.2)). \quad (2)$$

Time equality:

$$Zglj = [0.0066 + 7.3525 \cos(J + 85.9) + 9.9359 \cos(2J + 108.9) + 0.3387 \cos(3J + 105.2)]. \quad (3)$$

From the mean European time MEZ and the longitude λ of the location, the mean time of the location is determined:

$$MOZ = MEZ - 4 \cdot (15^\circ - \lambda), \text{ min} \quad (4)$$

where:

MOZ is the mean time of the location [min];

MEZ is the mean European time [min];

$\lambda = 42.18^\circ$ - longitude.

The astronomical time of a place is determined by the:

$$WOZ = MOZ - Zglj \quad (5)$$

$\varphi = 25.13^\circ$ is the latitude.

With the latitude φ of the location and the hour angle ω , given by:

$$\omega = (12 - \frac{WOZ}{60}) \cdot 15 \quad (6)$$

The Sun's altitude γ_s and the solar azimuth α_s are obtained:

$$\gamma_s = \arcsin(\cos \omega \cdot \cos \varphi \cdot \cos \delta + \sin \varphi \cdot \sin \delta),^\circ \quad (7)$$

$$\alpha_{s1} = 180 - \arccos\left(\frac{\sin(\gamma_s) \cdot \sin(\Phi) - \sin(\delta_j)}{\cos(\gamma_s) \cdot \cos(\Phi)}\right) \quad (8)$$

$$\alpha_{s2} = 180 + \arccos\left(\frac{\sin(\gamma_s) \cdot \sin(\Phi) - \sin(\delta_j)}{\cos(\gamma_s) \cdot \cos(\Phi)}\right) \quad (9)$$

Formula (8) gives us the change in the solar azimuth for the time before 12 hours, and formula (9) gives us the change for the time after 12 hours [6]. Using the MathCAD software and the "if" function in it, this calculation is performed automatically according to formula (10):

$$\alpha_s = \text{if}(WOZ < 12, \alpha_{s1}, \alpha_{s2}). \quad (10)$$

There are two angles of tracking the movement of the Sun: θ_{sl1} and θ_{sl2} . θ_{sl1} is determined by the rotation of the Earth around its axis and changes by 15° per hour. θ_{sl2} is determined by the height of the Sun according to the formula:

$$\theta_{sl2} = 90 - \gamma_s, \quad (11)$$

Where γ_s is the altitude of the Sun, determined by (7).

Since the photovoltaic park will be built with fixed panels, we perform optimization based on the height of the Sun γ_s for 12 o'clock, when the intensity of solar radiation reaches its maximum. The photovoltaic modules will be installed with their working surface facing south, and at 12 o'clock the deviation from θ_{sl1} is zero and the panel is perpendicular to the Sun. Fig 1. presents the change in γ_s for each day of the year.

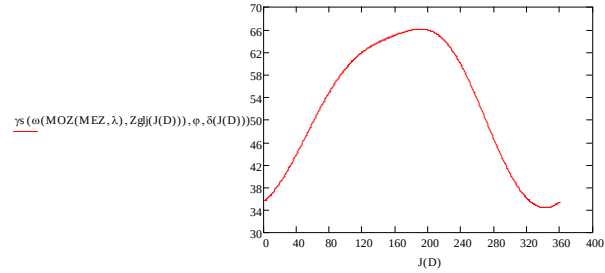


Fig.1. Deviation of γ_s during the year -at 12h.

Based on the data obtained from Fig. 2. we can determine the average angle at which the photovoltaic module should be fixed at 12h for each of the months of the year.

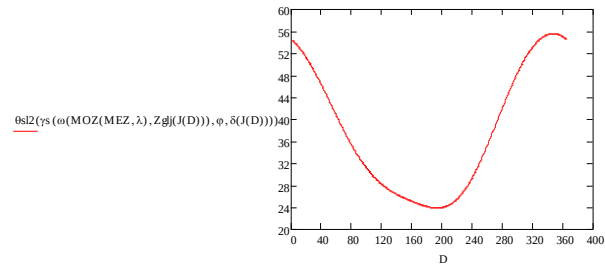


Fig.2. Deviation of θ_{sl2} during the year- at 12h.

This angle is given by the formula:

$$\theta_{sl1n} - \text{av.} = \frac{\sum_{D=1}^m \theta_{sl1}}{\sum_{D=1}^m D} \quad (11)$$

Where:

$\theta_{sl1n-\text{av}}$ is the average angle at which the photovoltaic module should be fixed,

n is the the number of the month of the year, n takes values from 1 to 12;

m is the number of days in the month, m takes values from 1 to 31;

D is the day of the year.

The simulated results are presented in Table 1.

Table 1. Results for $\theta_{sl1n-\text{av}}$ for the months.

Month	$\theta_{sl1n-\text{av}}$	Month	$\theta_{sl1n-\text{av}}$
January	51.76	July	24.13
February	44.63	August	27.13
March	36.68	September	35.03
April	30.24	October	45.13
May	26.69	November	52.94
June	24.75	December	55.29

Table 2 presents meteorological data on direct and diffuse irradiation by month for the area where the photovoltaic park will be built.

Table 2. Direct (Edir) and diffuse (Ediff) irradiation.

Month	Edir (kWh/m ²)	Ediff (kWh/m ²)
January	51	29
February	64	36
March	97	57
April	140	68
May	167	88
June	172	88
July	175	96
August	160	77
September	123	56
October	85	45
November	50	30
December	44	24

Using the data from Table 1. and Table 2, the optimal angle for mounting the modules is determined - $\Theta_{mont.} = 33^\circ$.

2.1. Determining the minimum distance between rows

The distance between the strings is determined using the formula:

$$h = l \sin(\Theta_{mont.}) \quad (12)$$

where:

h is the height between the plane of the lower and upper ends of the module

l is the the length of the photovoltaic module; $l = 1.957\text{m}$.

$\Theta_{mont.} = 33^\circ$ angle at which the panels are mounted.

$$h = 1.957 \cdot \sin(33^\circ) = 1.067 \text{ m}$$

$$h = l1 \cdot \sin(\gamma_s - \alpha_v.) \quad (13)$$

where: $l1$ is the distance from the top of the panel to the end of the shadow that is produced at an angle $\gamma_s - \alpha_v$;

$$l1 = \frac{h}{\sin(\gamma_s - \alpha_v)} \quad (14)$$

Consequently, the minimum distance X between the strings can be determined by the formula:

$$X = l1 \cdot \cos(\gamma_s - \alpha_v.). \quad (15)$$

Thus:

$$X = \frac{h \cdot \cos(\gamma_s - \alpha_v)}{\sin(\gamma_s - \alpha_v)} = h \cdot \cotg(\gamma_s - \alpha_v.) \quad (16)$$

Table 3 presents the values of $\gamma_s - \alpha_v$. For 12h for each of the months, and Table 4 for minimum distance X .

Table 3. Mounty results for $\gamma_s - \alpha_v$.

Month	$\gamma_s - \alpha_v$
January	38.245
February	45.371
March	53.402
April	59.796
May	63.308
June	65.251
July	65.867
August	62.875
September	54.975
October	44.875
November	37.060
December	34.709

Table 4. Mounty results for minimum distance X .

Month	X, m
January	1.354
February	1.053
March	0.792
April	0.621
May	0.5365
June	0.492
July	0.478
August	0.547
September	0.748
October	1.072
November	1.413
December	1.482

Therefore, the minimum row spacing calculated for angle $\gamma_s - \alpha_v$ at 12h is 1.482 m. A spacing of 2.66 m is chosen to allow the use of mechanized equipment between the rows.

2.2. Determination of the annual production from the photovoltaic park

The production of electricity from PV systems depends on a number of factors that must be considered before starting the design: solar radiation, type of modules, operating temperature, V-A characteristic, pollution, optical losses, etc.

The initial approximate analysis in the design of PV systems is based on the peak solar power hours (PSH) indicator [7], which represents the equivalent of one day. This approach is used in the preliminary estimation of the parameters of PV systems that do not have solar concentrators.

The meaning of PSH for one day is equal to the amount of solar radiation accumulated throughout the day relative to the accepted standard value of 1000W/m^2 . This parameter measures time and when expressed in hours it has the same numerical value as the total daily radiation measured in kWh/m^2 [8].

Thus, the approximate annual energy production from the PV system can be forecasted as:

$$X = \frac{h \cdot \cos(\gamma_s - \alpha_v)}{\sin(\gamma_s - \alpha_v)} = h \cdot \cotg(\gamma_s - \alpha_v.) \quad (17)$$

$$EA = \sum_{i=1}^{365} (\text{PSH})_i \cdot P_0 \quad (18)$$

where:

$(\text{PSH})_i$ - the value of the parameter PSH for the i -th day of the year

P_0 - nominal installed power of the system under standard conditions.

For systems operating at the maximum power point MPP, the instantaneous output power relative to the maximum $\frac{P_A}{P_{max}}$ depends on temperature and solar radiation, and therefore equation (18) is only an approximate estimate. A more accurate prediction can be made using a model that takes into account the ambient temperature, the temperature of the modules through the NOCT parameter (normal operating cell temperature) and the temperature coefficient of the modules.

2. Results and analysis

The photovoltaic modules chosen by the investor are CNBM Solar Polycrystalline Series III -260 W. Photovoltaic panels can be connected in parallel or in series depending on the requirements of the device to which they will be connected.

Up to 5 strings can be connected to each inverter. In the inverter, all incoming strings are connected in parallel to common buses – bus “+” and bus “-”, using standard MC-4 type connectors. A mandatory condition for the normal operation of the inverter is that all strings have the same number of photovoltaic modules, that they are of the same type with the same unit nominal power, voltage and current and that they are mounted at the same angle to the ground. If possible, the wires connecting the individual strings to the inverter should have the same parameters.

To protect the wires and photovoltaic modules on the DC side, a string box is installed. One, two or more strings can be combined in the string box, depending on the installed power and the selected configuration. It installs a DC disconnecter, two DC fuses with a fusible silver insert, respectively for “+” and “-”, and a cathode arrester.

Conventional means of automatically shutting down the power supply in emergency mode rely on maximum current protection. Since PV systems are current limited, this makes conventional protections difficult to apply. The short-circuit current is slightly higher than the maximum operating current, so in this case the protection will not work.

Ground leakage can be caused by a number of reasons: damaged insulation, faulty installation, corrosion, etc. In PV systems where the negative is not grounded, a fault will only occur when both conductors leak to ground or the structure on which the modules are mounted. With appropriate placement of the conductors, this type of damage can be minimized.

Significant differences in the voltages of the individual strings at idle, when the inverter is off, can cause equalizing currents to flow. The most common reasons are: shading, partial covering of the modules with snow, damaged module.

Figure 3 shows an example of a ground fault. Three parallel strings connected to common poles “+” and “-” are shown. Under normal operating conditions, the maximum current in each string conductor is equal to the I_{sc} of the modules used.

In this system, which is not grounded by principle, we consider a case when a connection occurs between the negative pole and ground. We assume that this is the first failure and this does not affect the operation of the string. After some time, when a second leakage occurs to ground / in t. x / - which is at a potential different from that of the negative pole, a short-circuit current will flow.

In the diagram shown in Fig. 3, a reverse current flow through some of the PV modules in the damaged string. The magnitude of this current is the same as that of the current flowing through the string cable:

$I_R = (n-1) \cdot I_{sc}$, where n is the number of parallel connected strings.

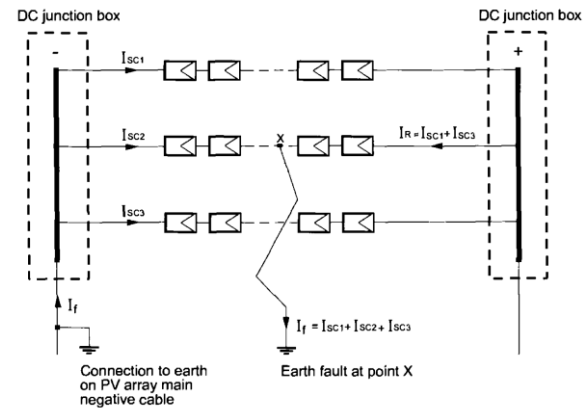


Fig.3. Ground fault.

The reverse current flowing through the modules can cause damage to them and increases the risk of fire. The high temperatures due to the reverse current lead to desoldering and delamination of the individual cells of the PV module.

The estimated yields (Table 4) assumed in the design of the power plant (Fig. 4) are presented in the tables below.



Fig.4. The designed PV system.

Table 5. Mounity estimated yields in the designed PVS.

Month	PSH/h	Electricity produced kWh
January	51	3818.88
February	64	4792.32
March	97	7263.36
April	140	10483.20
May	167	12504.96
June	172	12879.36
July	175	13104.00
August	160	11980.80
September	123	9210.24
October	85	6364.80
November	50	3744.00
December	44	3294.72
Annually		99440.64

Using the SolarLog 500 control and monitoring system, the actual production for the observed period was recorded (Table 6 and Table 7).

Table 6. Actual electricity generation.

Month	Generated energy for the month kWh/kWp	Electricity produced kWh
January	52.07	4165.50
February	83.72	6697.93
March	101.64	8130.87
April	106.31	8504.89
May	143.43	11474.59
June	132.87	10629.75
July	143.89	11511.35
August	147.83	11829.69
September	110.29	8823.24
October	76.25	6099.90
November	43.53	3482.00
December	36.59	2927.22
Annually		94276.93

Table 7. Ratio between achieved and projected results.

Month	Estimated production kWh	Electricity produced kWh	Difference in percentages %
January	3818.88	4165.50	109.08
February	4792.32	6697.93	139.76
March	7263.36	8130.87	111.94
April	10483.20	8504.89	81.13
May	12504.96	11474.59	91.76
June	12879.36	10629.75	82.53
July	13104.00	11511.35	87.85
August	11980.80	11829.69	98.74
September	9210.24	8823.24	95.80
October	6364.80	6099.90	95.84
November	3744.00	3482.00	93.00
December	3294.72	2927.22	88.85
Annually	99440.64	94276.93	94.81

After analyzing the results from above tables, it is seen that despite the large deviations in some months from +39.76 % to -18.87% on an annual basis, the electricity produced is only 5.19% less than previously planned.

The preliminary forecast does not take into account losses in the wires, and the SolarLog 500 system only measures losses in the inverter and the DC network from the photovoltaic modules. In order to get an accurate idea of the real amount of losses in the entire system, a comparison must be made between the readings of the outgoing electricity meter and the data from the SolarLog 500.

3. Conclusions

The comparative analysis of the results shows that:

- The performance of the photovoltaic installation is high when all PV modules are illuminated evenly, with the maximum amount of solar radiation.
- The serial connection of PV modules in a string increases the voltage to the required level for connection to the power grid. On the other hand, optimization of the installed power capacity is possible by changing the

orientation of the modules and the connection between the modules.

- The fluctuation of the generated power by the photovoltaic modules is a major problem affecting the yield of electrical energy.

- The frequent switching of the photovoltaic system due to shading of the PV modules is associated with the operation of the inverter in a nonlinear section of the operating characteristic, giving rise to transient processes. This worsens the electrical parameters of the output voltage and current. Higher harmonics appear in the spectrum of the output indicators and additional reactive components, leading to power loss.

- The operability of the synthesized models is proven by comparing the theoretical and experimental results.

On an annual basis, the difference between the actual and forecasted amounts of electricity is only 5.19%. Future studies should focus on accounting for losses in wires, switching, and protection equipment.

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