On the Performance of Stationary Grid-Connected Photovoltaic Power Plants

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Abstract— With the increasing number of renewable energy sources being put into operation—particularly stationary, grid-connected photovoltaic (PV) power plants—various technological solutions have been implemented in terms of the tilt angle of the PV panels. This article presents a comparative analysis of the productivity of grid-connected photovoltaic systems. A simulation study is conducted by varying the tilt angle of the panels, and based on the results, an optimal configuration is proposed. Conclusions and recommendations are provided

Keywords— photovoltaic power plant, electricity production, simulation analysis

I. INTRODUCTION

Over the past 5-7 years, there has been a significant increase in the design, construction and commissioning of grid-connected photovoltaic power plants. This growth is driven by several key factors: the relatively low cost of PV panels and inverters, and more favorable conditions for connecting and commissioning new installations. All this is in response to the challenge facing humanity to provide clean, inexhaustible and cheap electrical energy [1–3]. A key advantage of photovoltaic generation systems over other renewable sources—such as wind turbines or hydroelectric power plants—is their ability to directly convert solar radiation into electricity, despite relatively low conversion efficiencies, which typically do not exceed 20%. The performance of photovoltaic systems is commonly evaluated using peak power (Wp) under standard test conditions, with one of the key influencing factors being the Nominal Operating Cell Temperature (NOCT). The most critical parameter affecting the performance of a photovoltaic module—regardless of its type or manufacturing technology—is the angle at which solar radiation strikes its surface. The angle of incidence is determined by the angle of inclination of the surface of the photovoltaic module relative to the horizontal plane and the azimuthal angle of the module orientation.

The azimuth angle represents the module's orientation with respect to the north–south axis. Accurate determination of both the tilt and azimuth angles is essential to maximize the capture of solar radiation and, consequently, the energy output of PV systems [5-10]. Therefore, optimizing the angle between the sun and the PV module surface is crucial for maximizing electricity production by capturing the highest possible amount of solar energy [11-14].

Both the azimuth and tilt angles significantly affect the peak power output of a photovoltaic system, its total energy production, investment return, and relevant factors such as electricity market prices and tariff zones.

II RESEARCH AND ANALIYSIS OF EXISTING SOLUTIONS

In practice, various mathematical models, schematic solutions, and computational algorithms are used to optimize tilt angles at different latitudes, time durations, local positions, regions, etc.

Tracking the sun's trajectory throughout the year or during specific seasons is fundamental for assessing solar activity. This information is crucial for forecasting, simulation, and developing control algorithms for PV system operation.

The theoretical finding of optimal tilt angles is almost always based on work using mathematical models [10-19] . In recent years, both experimental and computational methods or a combination of them have been used. With the rapid development of software technologies, and the accelerated integration of artificial intelligence into scientific and technical fields, including renewable energy—new software tools are being developed for modeling, simulating, and forecasting photovoltaic system performance.

For the purposes of scientific and engineering research, professional commercial software for computational fluid dynamics analysis of the thermal characteristics of photovoltaic panels for different tilt angles are widely used. Among these software solutions, arranged in alphabetical order, are: Homer Pro - Homer Energy, USA ; PV F-Chart-F-Chart software , USA ; pvPlanner - SolarGis , Slovakia; PVsyst - Pvsyst SA, Switzerland ; RETscreen - Natural resources Canada , Canada ; Model on the systemic advisor (SAM) - National laboratory for renewable Energy (NREL), USA ; Solar Pro - Laplace systems , Japan. Last but not least is the EU-approved product - PVGIS which provides information for the sun radiation and work on photovoltaic system for each place in the world, except on The North and the South pole.

At the same time, researchers, designers and scientists, through the application of innovative approaches [19], are increasingly focusing their work on developing new innovative methods and approaches to increase the productivity of photovoltaic panels at an ever lower cost.

There is a massive penetration, use and interest in so-called bifacial photovoltaic panels. The main reasons for this are their greater efficiency compared to conventional photovoltaic panels and their extremely attractive price, which, in order to popularize this type of technology, is in many cases comparable to that of traditional PV panels. Since they capture the sun light from both sides, then they are more suitable mainly for vertical positioning, inverted eastward - west. Thus, in this case, first look simple change in the orientation of the panels, allows displacement on peak electricity production from solar light to the morning and evening ones respectively hours. This leads to relatively uniform production of electricity throughout the day, which also reduces average daily price fluctuations in electricity. [21]

Engineering solutions that deviate from the theoretically optimal tilt angle—depending on specific project requirements or constraints—are also of interest.

For the purposes of the analysis, numerous observations and studies have been conducted on a number of photovoltaic power plants put into operation on the territory of the Republic of Bulgaria over the last 2-3 years. In a large part of them, the tilt angle of the photovoltaic panels is significantly differentiated from the optimal one for the Republic of Bulgaria. Interesting solutions, presented illustratively, are shown in Fig. 1 and Fig. 2, below, as follows:

Fig. 1 Orientation of the panels east-west slope below 30 ^{0}

Fig. 2 Orientation of the panels to the east,
slope below 20 ^{0}

Simulation studies were conducted to determine the estimated amount of annual electricity produced by a grid-connected photovoltaic power plant with a capacity of 300 kWp, located in the vicinity of the city of Sliven. The studies were carried out using the specialized software PVGIS. An analysis was performed on the plant's productivity and losses resulting from changes in the tilt angle of the modules, ranging from 2 to 52 degrees. The data are presented in tabular form as follows:

TABLE I
DEPENDENCE OF THE PERFORMANCE OF THE PV PANELS ON THE ANGLE OF INCLINATION

300 kWp			
Slope [deg]	Annual production on electric energy [kWh]	Annual variation in production [kWh]	Common losses [%]
2	369,714.47	12273.68	-18.93
4	375,898.95	12693.19	-19.45
8	387 176.44	13494	-18.87
10	392,275.49	13874.65	-18.72
15	403,457.33	14759.22	-18.6
20	412,227.81	15545.6	-18.51
25	418,742.44	16227.73	-18.44
30	422 831.91	16802.28	-18.37
32	423 800.25	17001.53	-18.34
34	424 391.06	17183.72	-18.31
36	424 614.04	17349.97	-18.28
38	424 456.23	17501.40	-18.25
40	423 911.39	17632.99	-18.21
42	422 987.12	17744.66	-18.18
44	421 651.82	17837.87	-18.15
46	419 932.18	17909.03	-18.13
48	417 820.97	17963.83	-18.1
50	415 313.41	18001.15	-18.08
52	412 402.16	18015.54	-18.06

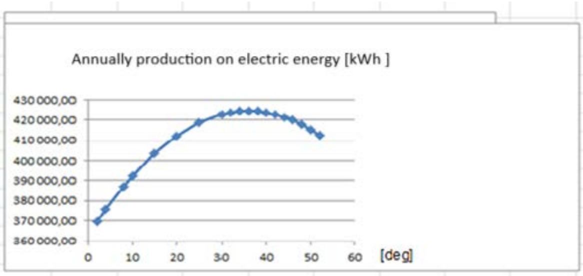

Fig.3 Annually production on electric energy

The calculated values are compared with the Cayley cosine curve shown in Fig. 4, giving the dependence of the relative performance of the photovoltaic cell on the angle of incidence of solar radiation on it.

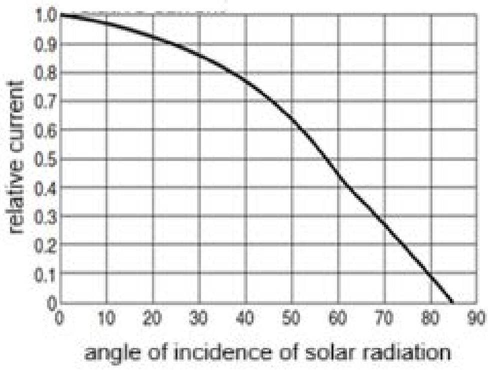

Fig..4 Cayley curve

The increase in the share of electricity produced from renewable energy sources, with a predominant part – photovoltaic power plants, without the presence of storage devices, leads to overproduction and oversaturation of the electricity market during peak production hours. These are the hours with maximum sunlight in the interval between 10:00 and 15:00. During this time interval, the price of electricity traded on the Bulgarian Independent Energy Exchange (IBEX) traditionally reaches its lowest price values (Fig. 5).

Fig. 5 Change in the price of electricity within a day

It can be seen that the average daily price movement changes by over 200%. This is a prerequisite, when performing a technical and economic analysis, for maximum stock market return on investment to seek alternative and at first glance unconventional technical solutions. One such solution is a change in the slope and orientation of the photovoltaic modules, outside the optimal slope angle for the respective region, discussed above. In this way, the lower production of electricity in the hours before 10:00 and after 15:30, is compensated by the significantly higher purchase price of electricity, which increases the economic profitability of the investment.

III CONCLUSIONS

1. A review and analysis of various technological solutions implemented in grid-connected photovoltaic power plants in southeastern Bulgaria was conducted, with a specific focus on the tilt angle of the panels.
2. A comparison was made between software-based electricity production forecasts and established theoretical models.
3. Based on an analysis of fluctuations in electricity prices traded on the Bulgarian Independent Energy Exchange (IBEX), peak daily price intervals were identified.

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