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Tracking Photovoltaic Systems at Mountain Heights

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Abstract. The expansion of the use of solar energy in most cases depends on the energy capabilities of each specific country. In Tajikistan, where 93% of the territory is mountains, it is necessary to build solar power plants high in the mountains. At mountain heights, the performance of panels increases in winter, in addition, the snow cover that reflects the sun's rays also contributes to an increase in the efficiency of solar panels. Experts note that solar panels receive less radiation in valleys, as clouds and fogs often prevent the passage of sunlight. At the heights of the mountains, there is no air pollution and, as a result, a longer operating time of the solar power plant. In the conditions of Tajikistan, one more drawback of solar stations in the valleys should be added - this is the rapid pollution of the panels due to dust storms in the summer-autumn period. The Chinese company Sun Tech Power Holdings will build a 10 MW power plant in Tibet at an altitude of 4000 meters above sea level.

Keywords: Fuzzy Analysis, Maximum Power Point, Tracking, Eastern Pamir

1. Introduction

In recent years, much attention has been paid to (PV) systems because of their ability to efficiently convert solar energy into electricity. In addition, these systems do not pollute the environment and are environmentally attractive. Photovoltaic systems in regions with high solar radiation can have higher power. However, such regions are characterized by high temperatures, which adversely affect the performance of the system.

The first part of the article will focus on the use of solar energy in Tajikistan, where there is high solar radiation both in the low-lying semi-desert zone and in the mountains at high altitudes. The influence of the cold high-altitude climate on the power of the photovoltaic system is investigated. Measurement data are offered at two different sites, one in the city of Dushanbe, at an altitude of 800 meters, and the other in the Eastern Pamirs on the shores of Lake Karakul at an altitude of 4000 meters. In the city of Dushanbe, the efficiency of the photovoltaic system is affected by the high temperature in the summer (about $40℃$) and severe air pollution due to dust storms. On the contrary, in the high-mountain Eastern Pamirs, a cold climate and transparent air are observed all year round. The method of tracking the point of the maximum power of the photovoltaic panel at

different angles of azimuth and height is applied. For this purpose, the Arduino system is used to measure and record the parameters of the photovoltaic system using fuzzy controllers.
The second part of the article is devoted to the analysis of fuzzy trackers of the point of maximum power and location of the Sun. It is shown that the point of the maximum power of the PV can be found by adjusting the working cycle of the converter with a reverse stroke. Fuzzy controllers are proposed for tracking the Sun in horizontal and vertical directions. To localize the position of the Sun, solar sensors are used based on fuzzy data. The fuzzy analysis method has advantages over other methods in the sense that they demonstrate a more stable and faster response. The basics of fuzzy analysis were developed by L. Zadeh in his work [1] back in 1965. A fuzzy analysis is widely used in various areas of science and technology. Research related to the subject of the article was carried out by scientists from different countries. In particular, we used some ideas and specific developments outlined in the works [2-8]. These are, first of all, developments on fuzzy analysis of PV systems with trackers by Iranian specialists [2-4], Indian scientists [5,6], specialists from Austria [7] and Switzerland [8]. Recently, publications have appeared on the economic, environmental, and energy problems of Eastern Pamirs [9]. In the work [10] several scenarios are proposed. Similar issues were also considered in the works [10, 11].

2. Physical-geographical and economic-legal aspects

2.1. Influence of solar irradiation

The generation of electricity on PV systems depends on weather conditions affecting solar irradiation. The amount of irradiation in a particular meteorological and geographical area depends on weather data such as sundials, relative humidity, maximum and minimum temperature, and cloudiness.
Solar radiation travels a long way to reach the Earth's surface. An important task is to simulate solar radiation and the movement of atmospheric particles. Radiation is that either reflected or scattered through molecules in the atmosphere and reaches the Earth's surface is directly, called direct radiation. The part of the radiation that is scattered from all directions, except the solar disk known as diffuse radiation. Sunlight that hits the surface after reflected off the ground and reaches an inclined plane called radiation reflected off the ground. The sum of the three types of radiation [10] known as global radiation (see Figure 1.).

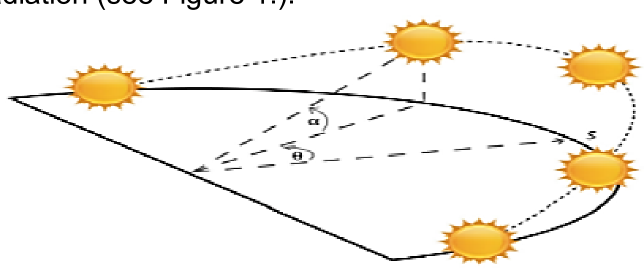

Figure 1. Solar angles

Global horizontal irradiation (GHI) is a reference parameter for calculating solar radiation on sloping surfaces and for comparing climatic zones. Figure 2. shows a map of Tajikistan's global horizontal exposure.
The duration of sunshine is the most useful parameter for estimating global solar radiation. It can be considered a climatological indicator, and it is usually expressed in annual averages. It is defined as the duration of sunshine over a given period (day or year) for a specific region on Earth.

In Figure 2. shows a map of solar irradiation, which gives the average annual amount of concentrated solar power.

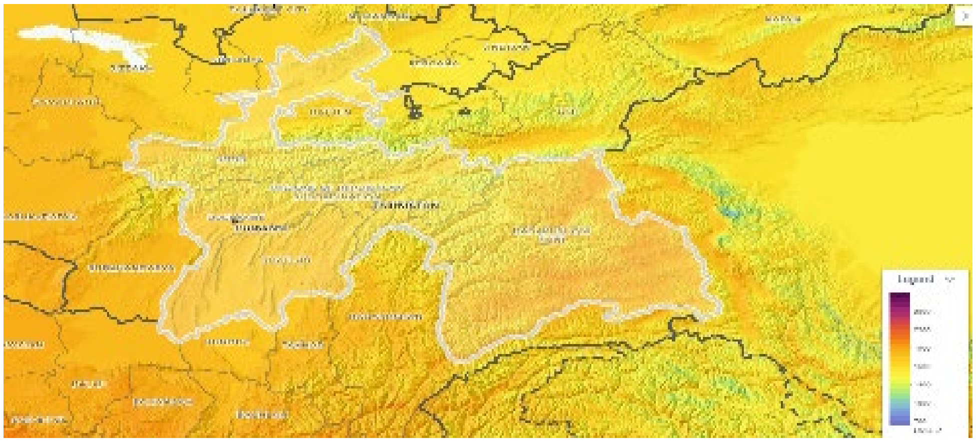

Figure 2. Global Solar irradiation map, Tajikistan

Such maps visually represent solar resources and often used to assess the possibility of generating solar energy in a particular region. Comparing the map of Tajikistan's global horizontal irradiation with the country topographic map (see Figure 3.), we will see a correlation between mountainous areas and high global horizontal irradiation.

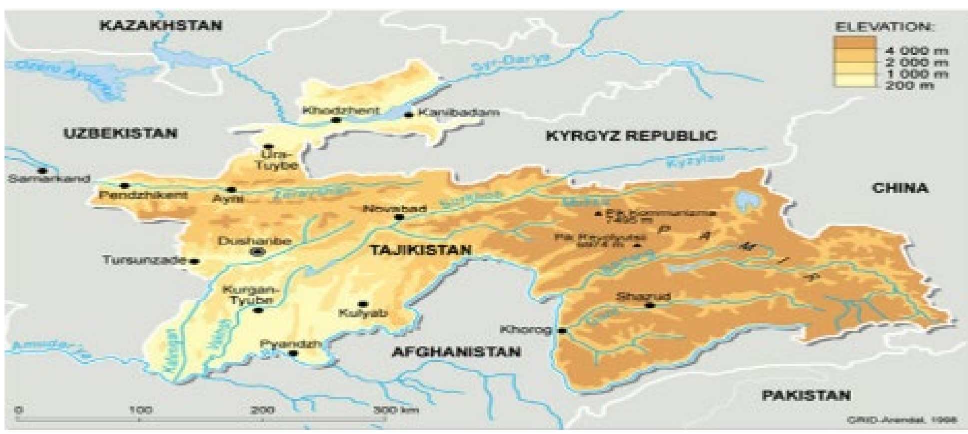

Figure 3. Topological map, Tajikistan

The highest mountains of Tajikistan are located in the Pamir region. The Pamir highlands, or Eastern Pamirs, make up 38% of the country's territory. As the solar radiation map and the topographic map of Tajikistan show, this region has a large potential for solar radiation. This once again proves that as the slope increases, more irradiation (direct radiation) and less diffusion are obtained.

2.2. Influence of temperature

Like all semiconductor devices, solar cells are very sensitive to temperature. As the temperature rises, the energy of the electrons in the material also increases, which in turn reduces the band gap of the semiconductor. Oscillations in the electronic generate a slightly larger current, but a smaller voltage. As a result, the potential difference (voltage) affects the no-load voltage (V_{oc}), as well as at the point of maximum power, which leads to a decrease in total power. This effect of temperature on V_{oc} shown in Figure 4 (a, b).

a) I-V characteristics

b) P-V characteristics

Figure 4. I-V and P-V characteristics of a solar module under varied temperature [3]

Voltage characteristics I-V and P-V are in the range from zero current at idle voltage V_{oc} up to short circuit current (I_{SC}) at zero voltage. The increase in current with increasing temperature is not significant and can be neglected. However, the dependence of voltage on temperature is significant. As shown in Figure 4. there is a linear relationship between voltage and temperature before $25°\text{C}$, but after that, the voltage begins to decrease with a further increase in temperature. In the mountains, the ambient temperature usually decreases with altitude. Although temperature inversion effects are possible at higher altitudes as well, they are thought to have less of an impact on solar energy, as such effects usually occur during the winter season and at night.

2.3. Economic and environmental aspects

A remote mountainous area, such as the Eastern Pamirs, is an example of a natural environment with an acute shortage of electrical energy, but with a large potential for renewable energy [9]. A detailed and high-scientific-level analysis of the potential of renewable sources in Eastern Pamirs proposed in the work [8]. It is emphasized that the possibilities of using solar energy for the generation of solar energy should be considered taking into account natural and socio-economic factors. In [9] a map of the magnitude of monthly solar radiation for the Eastern Pamirs compiled, and the slopes of the mountains that allow obtaining the maximum annual solar radiation are determined. Realistic scenarios for the use of solar energy based on technological requirements and financial conditions for the design of solar power plants in large settlements based on the available amount of energy have also been developed. An assessment of the potential environmental benefits of replacing biomass energy with solar energy is given. It should be noted that after the publication of the article [8], a few years later in 2020, the largest PV station in Tajikistan in Murghab was put into operation in the district center of Murghab - a district center with a capacity of 200 kW (Figure 5.).

Figure 5. PV Plant in Murgab

The Eastern Pamirs is a high-altitude plateau in eastern Tajikistan with an altitude of 3500 to 5500 meters above sea level an area of more than 36000 km^2 and a population of just over 15000 people. The climate is cold and dry, with an average temperature $-1℃$ and an average precipitation of 100 mm in the valleys.

Natural conditions have led to the absence of forests and trees. The only native woody vegetation is the dwarf shrub (Krascheninnikova ceratoid). To estimate the amount of solar radiation in the village of Murgab and its environments (20 km2), four automatic weather stations cited and installed (Figure 6.).

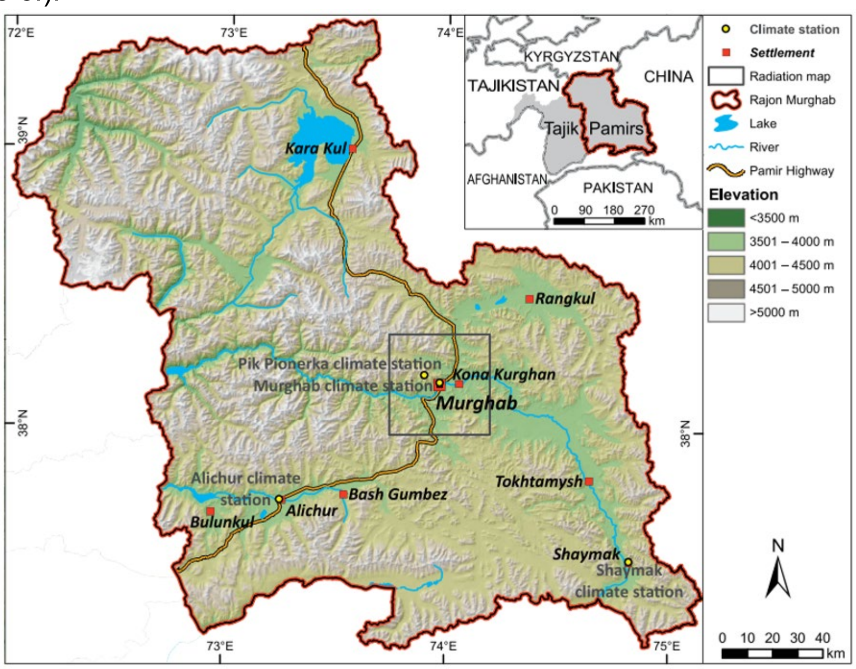

Figure 6. Map of Eastern of Pamirs, climate stations

At these stations, such climatic parameters as altitude above sea level, valley exposures and their orientation from north to south and from east to west, a compass of directions, etc. are recorded on them at half-hour intervals, global radiation, wind speed, and direction, relative humidity and temperature are measured.

3. Fuzzy trackers of the maximum power point and position of the Sun

This section provides a detailed discussion of the process of tracking the maximum power point of the PV module and the position of the Sun based on fuzzy analysis L. Zadeh [1].

3.1. Tracking the maximum power point of the PV module based on fuzzy logic

The maximum power point can be found by adjusting the transducer's duty cycle with feedback. Note that the fuzzy logic method demonstrates a more stable and faster response compare to other methods of tracking the maximum power point of the PV module.

In this method, the input variables of the fuzzy controller are the function $\frac{dp}{dI}$ and its variations $\Delta\left(\frac{dp}{dI}\right)$.

The fuzzy controller allows for calculating values $E = \frac{dp}{dI}(k)$ and $dE(k)$ using the input measurable power of the solar panel and the amperage based on the following ratios:

$$E = \frac{dp}{dI}(k) = \frac{P(k) - P(k-1)}{I(k) - I(k-1)}, \qquad (3.1)$$

$$dE(k) = E(k) - E(k-1). \qquad (3.2)$$

The input and output of a fuzzy controller are expressed in five linguistic variables: PB (positive large), PS (positive small), ZO (zero), NS (negative small), and NB (negative large). The controller's membership functions are shown in Figures 7(a), 7(b), and 7(c). The triangular membership function of fuzzy subsets is selected and expressions for the boundaries of this function are found.

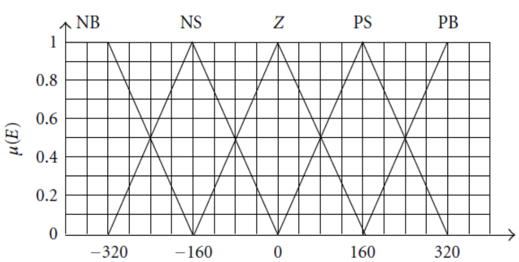

Figure 7(a). Membership function plots of E

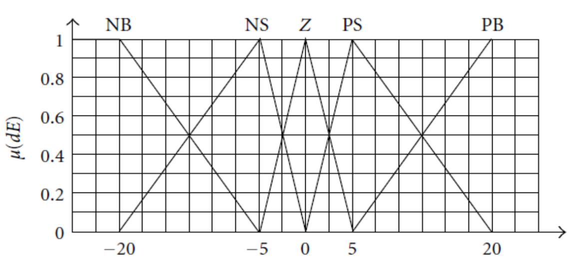

Figure 7(b). Membership function plots of dE

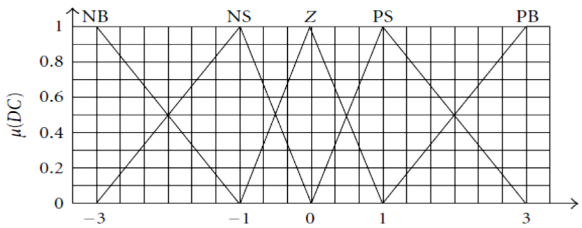

Figure 7(c). Membership function plots of converter duty cycle

Figure 8. shows a comparison of the power curve and current curve of a solar panel and the three operating points on them.

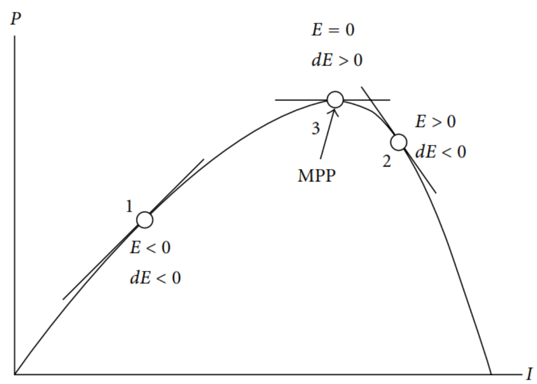

Figure 8. Power versus current curve of a solar panel

The scope of the accessory function values is determined especially based on the panel specification, the ratios (3.1), (3.2), and the empirical experiment. By the experiment, the membership function, together with the value domain, is modified so that it is different for E and dE. Moreover, the output membership functions computed by the fuzzy center and empirical experiments in data defuzzification.

3.2. Tracking the Sun based on fuzzy analysis

As noted in [4] there are various solar tracking systems. Some of them are based on complete one-year solar trajectories. Some others, generally speaking, use a solar sensor for tracking and can be implemented based on estimating the no-load voltage, short-circuit current, solar illumination, instantaneous output power, or maximum output solar panel.

To track the Sun at high altitudes (about 4000 m above sea level) in the horizontal and vertical directions, we propose the use of two similar fuzzy controllers. Two DC motors control the orientation of the solar panel through a developed board driven by motors.

Figure 9. ([4]) shows a supposed solar sensor to localize the position of the Sun. As shown in Figure 3, four silicon solar cells are located on the four sides of the cubic box (J1, J2, J3, J4).

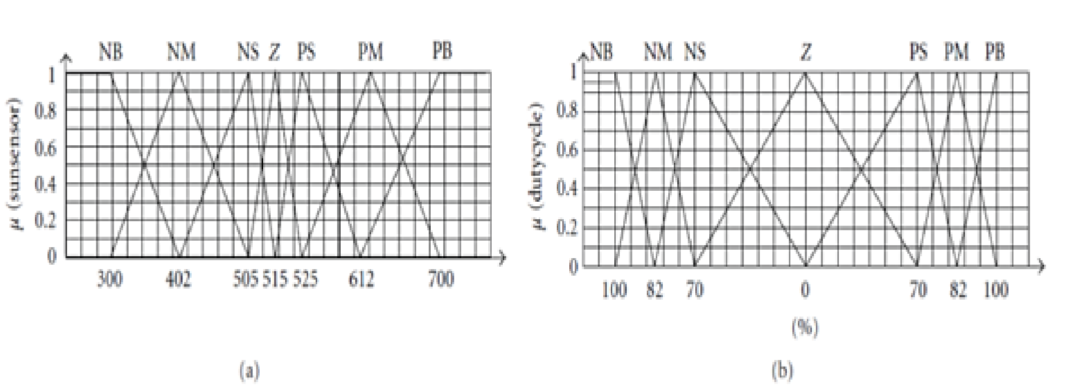

Figure 9. (a), (b). Membership function of sun-tracking subsets

Voltages on opposite sides are calculated using the following formulas:

$$Sun\ 1 = V(J1) - V(J2), Sun\ 2 = V(J3) - V(J4), \qquad (3.3)$$

Where is $Sun\ 1$ and $Sun\ 2$ are used as input controllers to track the Sun. If the levels of solar radiation on the solar cells are the same, then the values $Sun\ 1$ and $Sun\ 2\ will$ be zero. This means that the Sun falls on the solar panels vertically. Fig. 4 shows the values of the membership function of fuzzy Sun-tracking controllers. Table 2 shows seven fuzzy logic rules used in the two controllers [4]. Calibration of the sensors listed here (Table 1) is necessary to accurately monitor the position of the Sun. The proposed controlled backlight system and the four solar cells are also subject to calibration. Light falls on each cell and values $Sun\ 1$ and $Sun\ 2$ are subject to measurement. This procedure is performed four times for all solar cells, respectively, for J1, J2, J3, and J4 from (3.3). The microcontroller system reads the voltage of the cells $Sun\ 1$ and $Sun\ 2$ at each calibration step.

Table 1. Maximum power point tracking fuzzy rule base

	dE				
E	NB	NS	Z	PS	PB
NB	NB	NB	NB	Z	Z
NS	NS	NS	NS	Z	Z
Z	NS	Z	Z	Z	Z
PS	Z	Z	PS	PS	PS
PB	Z	Z	PB	PB	PB

Finally, the sensors used can be calibrated and included in a fuzzy algorithm for tracking the Sun.

Table 2. Sun tracking fuzzy rule base

Sun sensor	NB	NM	NS	Z	PS	PM	PB
Duty cycle	NB	NM	MS	Z	PS	PM	PB

The values of the input and output membership functions in a fuzzy solar tracker are calculated based on (3.3).

Data availability statement

The data that support the finding of this study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare no competing interests

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