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Original scientific paper

Effects of Dynamic Shading on Thermal Exergy and Exergy Efficiency of a Photovoltaic Array

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Abstract: In this study, the effects of dynamic shading caused by an incorrectly positioned transformer building in a Photovoltaic array were investigated regarding the exergy efficiency and thermal exergy for a year. Experimental and theoretical results show that the thermal exergy is affected by the surface temperature of solar panels depending on their shading ratio. In addition, as the shading ratio increases, the electrical exergy and power conversion efficiency decrease. It is also seen that the thermal exergy and exergy efficiency of the PV power system is negatively affected by the increasing solar cell temperature. The average shading ratio of 3.11% during a year causes an increase of about 23.32% of the thermal exergy, and loss in power conversion efficiency of about 4.88% and loss in exergy efficiency of about 13.72% over a year. Overall, it can be concluded that the long-term shading will significantly adversely affect the PV array performance in terms of electrical exergy and thermal exergy.

Keywords: dynamic shading; electrical exerg; exergy efficiency; photovoltaic array; thermal exergy

1 INTRODUCTION

Solar panel devices are one of the fastest developing technologies that collect solar radiation and convert it into usable electricity [1]. When converting solar radiation into electricity some are lost, main of these is released as a significant amount of heat and is wasted. The operating temperature of the photovoltaic (PV) panel during electricity generation is affected by many environmental parameters such as partial or full shading, dust, paint, reflection, etc. [2]. Shading effect caused by various environmental factors that will affect the operation of PV panels is one of the basic problems. As known the shaded cells of the PV Modules absorb the electrical power produced by the unaffected cells, which causes hot spots and can cause irreversible damages [3]. In other words, the shading effects on the PV panels increase the cell temperature due to the formation of hot spots on the surface of the PV modules and cause the PV systems to heat up, and heat loss. So it is important to investigate these losses in order to improve PV system performance.

The performance analysis of the PV panels is discussed according to the laws of thermodynamics. Although the first law of thermodynamics discusses the energy analysis of the PV systems, it does not discuss the contribution of energy types of the operating sources and it does not distinguish irreversibility [4]. The second law of thermodynamics, namely exergy, can be defined as the maximum work that can be theoretically obtained from a thermodynamic system [5].

Thermal exergy, which can be expressed as the heat loss from the PV panel surface during the production of electricity from the sun, is one of the key parameters in the investigation of exergy and exergy efficiency, the performance analysis of PV systems.

Here a brief literature review has been made on the effects of shading on the efficiency of photovoltaic power systems, mainly on lost thermal exergy. In recent years, many energy and exergy analyses have been made to examine the effects of shading on PV performance; Alonso et al. (2006) simulated shading effects on photovoltaic arrays. In their study, the effects of shading ratio, the type of reverse characteristic of the cell, the length of the array and the number of shaded cells were analysed [6]. Martinez-Moreno et al. (2010) proposed a mathematical model to reduce the shading losses in PV modules [7]. Alsayid et al. (2013) simulated the states of photovoltaic panels in different shading conditions using the Matlab program [8]. Sener Parlak (2014) proposed a new maximum power point tracking (MPPT) method for a PV array system operating under partially shaded conditions [9]. Khaing et al. (2014) investigated the effects of partial shading on the operating characteristics of four different types of solar PV panels, including amorphous thin film, polycrystalline, CdTe thin film and CIGS thin film PV panels [10]. Sathyanarayana et al. (2015) analysed the effect of uniform and non-uniform shading on the performance of the PV panel [11]. Vijayalekshmy et al. (2016) proposed a new Zig-Zag array scheme for total cross-connected interconnection of PV modules to reduce the partial shading losses [12]. Bayrak et al. (2017) designed an experimental setup to investigate different parameters such as shading rate and the shading positions on the PV panels. They concluded that shading has a significant effect on the energy and exergy efficiency of the PV system and the most important effect occurs in the case of horizontal shading [13]. Madhanmohan et al. (2020) proposed a new PV module configuration system to achieve maximum performance under partial shading conditions known as diagonally dispersed Total Cross Tied (D-TCT) [14]. Bayrak et al. (2020) investigated the effects of static and dynamic shading on the thermodynamic and electrical performance of photovoltaic panels [15]. Tarabsheh et al. (2021) studied the energy efficiency of partially shaded photovoltaic panels by applying two single-pole double-throw (SPDT) switches [16].

Several researchers have done the investigation of thermal effects on PV performance; Iakovidis et al. (2014) conducted wind tunnel experiments to determine the effect of turbulence intensity on local and average heat transfer coefficients [17]. Vasel et al. (2017) analysed the effect of wind direction on the PV array performance. They concluded that the arrangement of the PV array rows can significantly affect the turbulence intensity and thermal losses [18]. Jaffery et al. (2018) proposed a method to characterize the operating temperature of the PV panel under outdoor conditions using thermal imaging [19]. Wu et al. (2018) performed wind tunnel experiments and computational fluid dynamics (CFD) simulations to investigate the temperature distribution on a PV panel, and the results of this study were used by Ghabuzyan et al. (2020) [20, 21]. Al-Waeli et al. (2019) discussed the existing evaluation criteria for PV/T, suggested four novel methods, and outdoor experiments were done in Bangi-Malaysia. Dhimish (2020) comprehensively discussed the performance ratio (PR) of 8000 PV panels distributed across three regions in England by detailed experiments of three different PV modules [23]. Ghabuzyan et al. (2021) investigated the thermal effects on photovoltaic array performance. In their studies, the relationships between ambient temperature, wind speed, and wind direction on PV electrical output were analysed [24].

In this study, a controlled experimental investigation of thermal exergy phenomenon was carried out due to the misallocated transformer building creating a shading effect of a PV array. It is known that the performance of the PV panel is significantly affected by the shading effect. The thermal exergy and PV performance analysis have been made using the real environmental parameters conditions such as wind speed, cell temperature, ambient temperature and the PV surface area.

2 MATERIALS AND METHOD

2.1 PV Array

The PV array consists of 240 poly-crystalline panels each with a maximum output of 260 W controlled by 2 inverters of 15 kW.

This PV array was installed with the support of the European Union project. Fig. 1 illustrates an image of the mounted PV array.

Figure 1 Image of the PV array

2.2 Methods

This case study started in June 2019 and continued for 12 consecutive months until May 2020. Technical and scientific data in sunny and clear sky conditions were taken on different days. The shading effect occurred dynamically due to the variation of the sun's height, azimuth and zenith angles on different months and daily time zones. To perform the controlled experiment, two arrays of PV panels (120 panels each) were selected. One array was affected by shading and the other was unaffected, which were controlled by two inverters. Solar panels are mounted on south-facing steel legs with an inclination angle of 23° in order to benefit from sunlight at the highest level in different seasons to reduce the installation costs. One array, which is affected by shading, was named Shaded-Array (Sh-Array), while the other not affected was named Unshaded-Array (USh-Array). The measurements of the shaded area for each month were started with the sunrise in clear weather, continued until the shade disappeared on the panels at local time. Each measurement was taken once every quarter of an hour. Output electrical power generation (P) data was taken from the inverters. Kipp & Zonen Pyranometer was used to measure the total solar radiation on the surface of the modules (I_s). Wind speed (v) was measured with Wellhise HT-380 digital anemometers. Shaded and total array area were measured to find the ratio of shaded area (R).

3 THEORETICAL ANALYSIS OF THE PV SYSTEM

The performance and thermal exergy analysis of PV systems can be made on the basis of the first and the second laws of thermodynamics. As known, the first law of thermodynamics is not enough to define the system performance, but the second law of thermodynamics by considering environmental parameters gives results that are more realistic.

3.1 Energy Efficiency Analysis

The first law of thermodynamics discusses the energy analysis of the PV system. Solar irradiation (I_s) is the sun's radiant energy incident on a surface of unit area (A), expressed in units of W/m^2. Incident solar power is given as:

$$P_{\text{sun}} = I_s \times A \tag{1}$$

By reaching solar radiation on the surfaces of panels, PV device converts it into usable electricity.

Maximum electrical output power of the PV panel is given by:

$$P = V_m I_m \tag{2}$$

PV power conversion efficiency is the percentage of incident solar energy that is converted into electricity:

$$\eta_{pce} = \frac{V_m I_m}{I_s A} \times 100 \tag{3}$$

where (I_m), (V_m) and (A) represent maximum current, the maximum voltage and the photovoltaic panel area, respectively. In this study, total PV array (120 panels) surface is 196 m^2 (the area of each panel is 1.633 m^2).

As seen in Eq. (3), the calculation of the power conversion efficiency is based on electrical energy, which is generated by PV, solar radiation and the surface area of the module. Other environmental parameters such as ambient temperature, cell temperature and wind speed are not taken into account.

In energy analysis of PV array only the electrical energy generated by the system is calculated or simply read from the inverter, but on the other hand the exergy analysis by considering environmental parameters, gives more realistic information about the optimization and performance of PV systems.

As with any efficiency calculations, the exergy efficiency (Ψ_{PV}) of a system is expressed as the ratio of output exergy $\left(\dot{E}x_{\text{out}}\right)$ to input exergy $\left(\dot{E}x_{\text{in}}\right)$ [13, 15]:

$$\Psi_{PV} = \frac{\dot{E}x_{\text{out}}}{\dot{E}x_{\text{in}}} \times 100 \tag{4}$$

The Sun is the energy source of the PV systems, so it is considered as the input energy/exergy. Differently from the solar energy, the solar radiation exergy simply is performed by considering the ambient and the sun surface temperature, which was proposed by Petela [25].

$$\dot{E}x_{\text{in}} = AI_s\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] \tag{5}$$

where T_s is the temperature of the Sun 5778 °K.

The exergy output $\left(\dot{E}x_{\text{out}}\right)$ of the photovoltaic systems can be expressed as follows:

$$\dot{E}x_{\text{out}} = \dot{E}x_{\text{electrical}} - \dot{E}x_{\text{thermal}} \tag{6}$$

where $\dot{E}x_{\text{electrical}}$ shows electrical exergy, $\dot{E}x_{\text{thermal}}$ gives thermal exergy.

Electrical exergy of a PV system is given by:

$$\dot{E}x_{\text{electrical}} = I_m V_m \tag{7}$$

Thermal exergy, the heat loss from the PV surface to the environment, can be express as [16]:

$$\dot{E}x_{\text{thermal}} = \dot{Q}\left[1 - \left(\frac{T_a}{T_{cell}}\right)\right] \tag{8}$$

where:

$$\dot{Q} = h_{ca} A\left(T_{cell} - T_a\right) \tag{9}$$

$$h_{ca} = 5.7 + 3.8v \tag{10}$$

where T_{cell} is the temperature of the cell, h_{ca} is the heat transfer coefficient, v is the wind velocity.

By using Eq. (9) and Eq. (10) in Eq. (8) the thermal exergy of the PV system is given as:

$$\dot{E}x_{\text{thermal}} = \dot{Q}\left[1 - \left(\frac{T_a}{T_{cell}}\right)\right] h_{ca} A\left(T_{cell} - T_a\right) \tag{11}$$

As seen in Eq. (11), the thermal exergy depends on the environmental parameters factors such as wind speed and cell temperature.

By putting Eq. (7) and Eq. (11) in Eq. (6), the output exergy is arranged as:

$$\dot{E}x_{\text{out}} = I_m V_m - \left[1 - \left(\frac{T_a}{T_{cell}}\right)\right] h_{ca} A\left(T_{cell} - T_a\right) \tag{12}$$

By using Eq. (5) and Eq. (12) in Eq. (4), the exergy efficiency is written as:

$$\Psi_{PV} = \frac{I_m V_m - \left[1 - \left(\frac{T_a}{T_{cell}}\right)\right] h_{ca} A\left(T_{cell} - T_a\right)}{AI_s\left[1 - \frac{4}{3}\left(\frac{T_a}{T_s}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right]} \tag{13}$$

From these equations, thermal exergy as a heat loss, which is related to environmental condition, is one of the important parameters in the performance analysis of PV systems. It is important to minimize the heat loss of PV systems to prevent damage of the solar module.

4 RESULTS AND DISCUSSIONS

This study was performed to analyse the shading effect by a misallocated transformer building on the electrical exergy and lost thermal exergy of a PV array depending on the dynamic shading ratio for a realistic view to the industrial and scientific community.

The data: the intensity of sunlight (I_S), wind velocity (v), ambient temperature (T_a), solar cell temperature (T_{cell}), electrical power output (P), power conversion efficiency (η_{pce}) and exergy efficiency (ψ) for each month were analysed. Variations of cells temperature, electrical exergy, thermal exergy, power conversion efficiency and exergy efficiency of Ush-Array and Sh-Array with different shading ratios are given in Tab. 1.

Table 1 Variation of cells temperature, electrical exergy, thermal exergy, power conversion efficiency and exergy efficiency of Ush-Array and Sh-Array with different shading ratio

Months		USh-Array						Sh-Array			
	T_{cell} / °K	Ex_{elec} / W	Ex_{thermal} / W	η_{pce} / %	ψ_{PV} / %	T_{cell} / °K	Ex_{elec} / W	Ex_{thermal} / W	η_{pce} / %	ψ_{PV} / %	*Shading Ratio* / %
June. 19	305.16	6116	1226	9.12	7.82	306.72	5895	1600	8.79	6.87	2.84
July. 19	306.86	5333	1253	8.09	6.64	308.2	5022	1587	7.62	5.59	3.57
Agu. 19	307.97	4984	1190	7.75	6.33	309.45	4650	1552	7.23	5.17	4.94
Sep. 19	302.31	4531	915	7.60	6.50	304.06	4165	1275	6.99	5.20	5.05
Oct. 19	297.04	3366	585	7.12	6.30	298.78	3196	881	6.76	5.25	3.25
Nov. 19	292.91	3042	593	6.66	5.74	293.58	2981	705	6.52	5.33	1.56
Dec. 19	289.89	2918	616	6.50	5.48	290.35	2850	696	6.34	5.13	1.31
Jan. 20	288.12	2822	630	6.42	5.33	288.97	2746	789	6.25	4.76	1.69
Feb. 20	288.18	2669	546	6.33	5.38	289.11	2589	704	6.14	4.78	1.91
Mar. 20	290.37	3232	676	6.87	5.81	291.86	3042	941	6.46	4.94	3.55
Apr. 20	293.69	4148	748	7.80	6.85	295.34	3880	999	7.30	5.80	3.82
May. 20	297.39	4309	734	7.85	6.97	298.91	4009	1006	7.34	5.86	3.9

In order to observe the shading effect, controlled experimental method was done, Ush-array and Sh-Array at different shading ratios were analysed under the same environmental conditions. In the shading affected "Sh-Array" it was found that the shading ratio varied between about 1.31% and 3.9% depending on the angle of incidence of the sunlight during the 12 months a year.

As seen in Tab. 1, the maximum electrical exergy, power conversion efficiency and exergy efficiency for Ush-Array and Sh-Array were observed on June 2019. For USh-Array, the minimum electrical exergy, power conversion efficiency and exergy efficiency were seen on February 2020. The minimum electrical exergy, power conversion efficiency for Sh-Array were observed on February 2020 and the lowest exergy efficiency for this case was on June 2019. While the exergy efficiency for USh-Array varied between 546 W to 1253W during a year, for Sh-Array it changed from 696 W to 1600 W.

4.1 Measurement of Weather Parameters

The weather conditions of the installation place play an important role in the exergy evaluation of PV system. Fig. 2 illustrates the intensity of solar radiation, which is received to the installation area for 12 months of the year. The amount of solar radiation absorbed by any surface is simply the product of how much solar energy is incident to that surface. The incident solar radiation is found to vary between 215 w/m^2 to 342 w/m^2 during a year. The maximum value of solar radiation is on June 2019 and the minimum is on February 2020. Wind speed is another effective parameter for analysing the convective coefficient heat loss that is used to calculate the thermal exergy of a PV module. The average wind speeds for the installation place vary between 2.22 m/s and 3.77 m/s during a year and this is represented in Fig. 3.

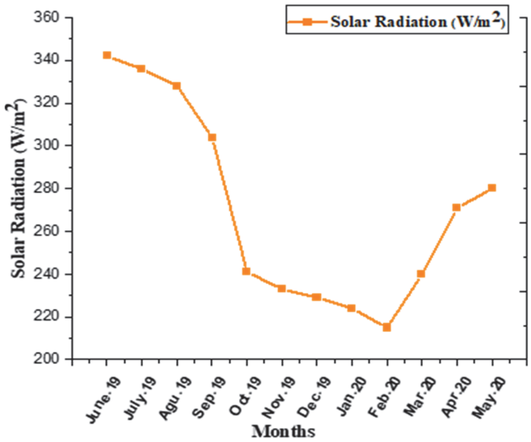

Figure 2 The intensity of solar radiation during a year

In the exergy analysis of the PV module, the influence of ambient temperature, and cell temperature is very important. Increasing in PV cell temperature causes higher thermal losses in the PV systems. In this study, the comparison of the cells temperature of USh-Array and Sh-Array at outdoor temperature is illustrated in Fig. 4.

As seen is Fig. 4, temperature of the Sh-Array is higher than that of the USh-Array. This is due to the formation of hot spot which occurred in the shading areas. The highest cell temperature for USh-Array is 307.96 °K and for Sh-Array it is 309.45 °K on August 2019. The lowest cell temperature for USh-Array is 288.12 °K and for Sh-Array it is 288.97 °K on February 2020.

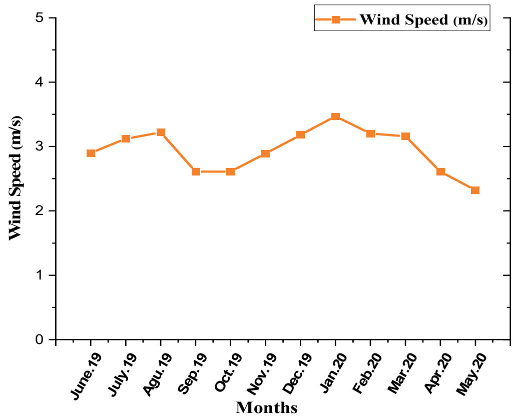

Figure 3 Wind speed for the installation place during a year

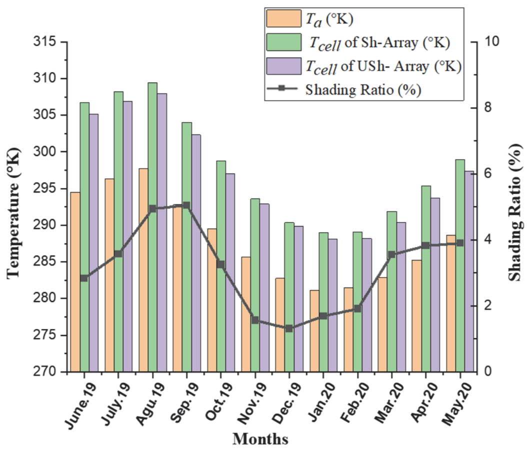

Figure 4 Variation of temperature of USh- Array and Sh-Array with different shading condition over a year

4.2 PV Performance Analysis and Comparison

Variation of electrical exergy of USh- Array and Sh-Array with different shading condition over a year is shown in Fig. 5.

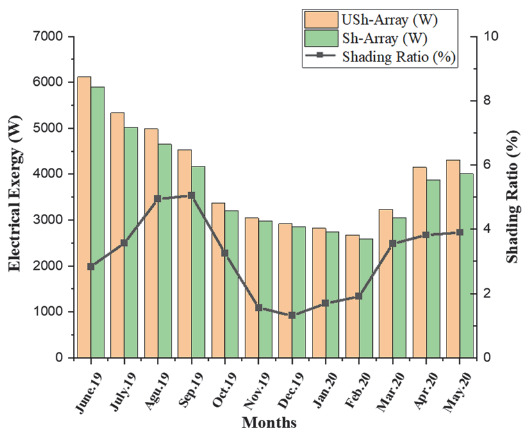

Figure 5 Variation of electrical exergy at Sh-Array and USh-Array over a year

As seen in Fig. 5, typically the electrical exergy of the Sh-Array is lower than the USh-Array. Due to the increased shading rate on the PV panel, the loss rate of electrical exergy increased from June to September. From September to November, the loss electrical exergy decreased. From December to June 2020, the rate of loss electrical exergy increased again as the shading rate increased.

The highest electrical exergy for USh-Array is 6116 W and for Sh-Array it is 5895 W on June 2019. In addition, the lowest electrical exergy for USh-Array is 2669 W and for Sh-Array it is 2588 W on February 2020.

The variation of thermal exergy of USh- Array and Sh-Array with different shading ratio over a year is given in Fig. 6.

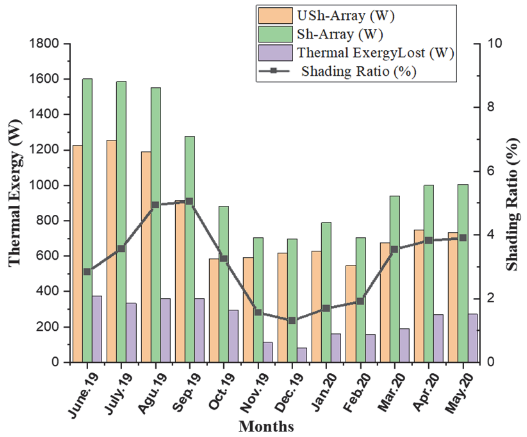

Figure 6 Thermal exergy of USh- Array and Sh-Array with different shading condition over a year

In Fig. 6, the thermal exergy varied depending on the shading ratio. In addition, thermal exergy of the Sh-Array is higher than the USh-Array. The highest thermal exergy for USh-Array is 1253 W on July 2019 and for Sh-Array it is 1600 W on June 2019. In addition, the lowest thermal exergy for USh-Array is 546 W and for Sh-Array it is 704 W on February 2020. As a result, the maximum thermal exergy loss is 374 W on June 2019 and minimum thermal exergy loss is 158 W on February 2020. Average 3.11% shading ratio causes 23.32% increase in thermal exergy over a year.

The efficiencies (power conversion and exergy) ratio and loss efficiencies ratio graphs of PV panels for Sh-Array and USh-Array conditions are shown in Fig. 7 and Fig. 8 for different months.

As seen in Fig. 7, power conversion efficiency and exergy efficiency in the Sh-Array are lower than the USh-Array. In addition, exergy efficiency is lower than the power conversion efficiency for all conditions. The highest value of power conversion efficiency for USh-Array is 9.12% and for Sh-Array is 8.79% on June 2019. The lowest value of power conversion efficiency for USh-Array is 6.33% and for Sh-Array is 6.14% on February 2020. While the value of exergy efficiency for USh-Array varies between 7.82% on June 2019 to 5.38% on February 2020, the value of exergy efficiency for Sh-Array varies between 6.87% on June 2019 to 4.76% on January 2020. These results are in good agreement with the reported results by Kumar et al. (2020) [26].

Fig. 8 shows that the loss power conversion efficiency and loss exergy efficiency varied depending on the shading ratio. The highest loss power conversion efficiency ratio is 8.07% on September 2019 and the lowest loss power conversion efficiency ratio is 2.01% on November 2019. As a result, the maximum loss exergy efficiency is 20.08% on September 2019 and minimum loss exergy efficiency ratio is 7.08% on December 2019. Average 3.11% shading ratio during a year causes 4.88% and 13.72% losses in power conversion and exergy efficiency respectively over a year.

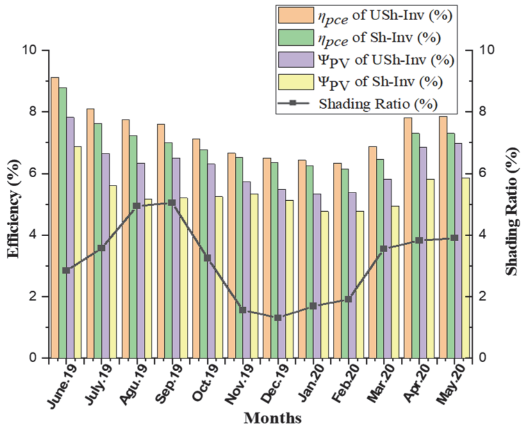

Figure 7 Variation of power conversion and exergy efficiency of USh-Array and Sh-Array

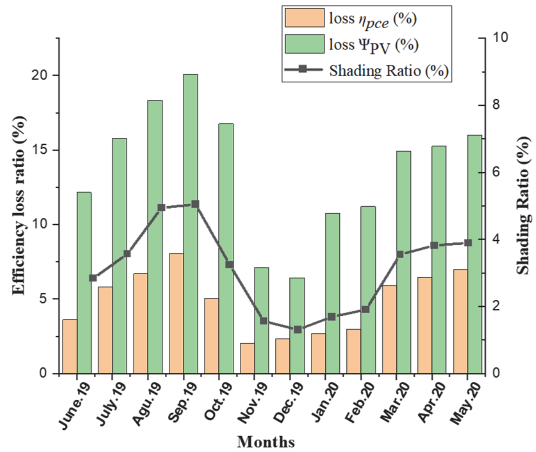

Figure 8 The loss power conversion and exergy efficiencies ratio of Sh-Array and USh-Array over a year.

5 CONCLUSION

The thermal exergy phenomenon created by the shading of an incorrectly positioned transformer building on the electricity generation of a PV array has been analysed and discussed on energy and exergy efficiency for one year and 12 months.

The main results of this study are summarized as below:

- Environmental factors such as the solar irradiation and wind speed are effective parameters on the performance of the PV systems.
- The temperature of the cells forming the solar panel changes depending on the ratio of the shaded area falling on it. It can be concluded that the reverse current caused by partial shading causes high temperature on the module.
- The output electrical power of the PV array decreases as the shading ratio increases.
- The exergy efficiency and thermal exergy of the PV power system are inversely affected by the PV cell temperature.
- The thermal exergy increases as the shading ratio increases.

- Environmental parameters (wind speed, ambient temperature, cells temperature etc) have a notable impact on the exergy efficiency of the PV power system.
- Exergy efficiency is lower than the power conversion efficiency for all conditions because the exergy efficiency by considering environmental parameters gives results that are more realistic.
- Shading ratio of about 3.11% during a year causes an increase of about 23.32% in thermal exergy, about 4.88% loss in power conversion efficiency and 13.72% loss in exergy efficiency over a year.

According to the results, it can be concluded that the shading caused by an incorrectly positioned transformer building will significantly affect the performance of the PV array, in other words, the operation of the panels. In addition, due to shading the temperature of the cells forming the panels can be risky to damage the solar module. As a recommendation, it is important to construct the transformer building in the right place to avoid shading effects and thermal losses in the PV array.

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