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Low-voltage DC-DC off-grid PV system: various irradiance studies

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ABSTRACT

The off-grid photovoltaic (OGPV) system, also referred to as a stand-alone power system, generates electricity from solar energy independently of the main electricity grid. However, photovoltaic (PV) modules face limitations in consistently providing the necessary voltage. Thus, a DC-DC converter is employed to adjust the voltage to match the requirements of the load. This paper proposes a detailed analysis of irradiance patterns resembling in-lab and real-world conditions to address the challenge of selecting the optimal DC-DC OGPV system capable of functioning effectively under standard test condition (STC) and dynamic test condition (DTC), respectively. Three proposed irradiance analyses, tailored to different environmental scenarios, aim to identify output performances for DC-DC OGPV system which are aligning with standards set by the International Electrotechnical Commission (IEC) 61727. The DC-DC OGPV system is simulated using MATLAB Simulink. Furthermore, comparative studies involving different PV module types and several switching techniques (pulse generator and maximum power point tracking or MPPT implementations), where findings are instrumental in advancing the development and projection planning for medium to high-voltage OGPV systems, contributing to the global initiative for accessible and sustainable energy solutions aligned with sustainable development goal (SDG 7).

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1. INTRODUCTION

Solar energy is a renewable source of energy that is sustainable and inexhaustible. Solar energy is the most abundant form of energy available to us where approximately 100,000 TW of solar energy hit on the earth's surface in a day [1]. Therefore, in this modern era, photovoltaic (PV) technology has the most growth prospects for the future, and it is integrated into our lives more than ever before. A PV system can be categorized into three types which are off-grid system, hybrid system and grid-connected system [2]-[4]. This paper focuses on the off-grid photovoltaic (OGPV) system, also known as a stand-alone power system which refers to the system which is not connected to the main electrical grid [3]-[5]. OGPV system can generate power and operate electrical appliances by itself. OGPV system is a green technology because it uses solar energy which decreases the dependency on fossil fuels and produces clean and sustainable energy for consumers [6], [7].

Besides, DC-DC converter is role as the power conversions in the OGPV system. The DC-DC converter is a photovoltaic conversion system that functions as a switching mode regulator, regulating uncontrolled DC voltage and converting it to an appropriate output voltage by increasing or decreasing the DC output voltage value. DC-DC converter may have different topologies to choose from based on the purpose served [8]-[12]. The DC-DC converter's components such as inductor, capacitor, and power switches are located differently based on the circuit requirement and named differently. Due to the nature of solar PV energy that can only generate low DC voltage and vary according to the solar irradiation and ambient temperature, a DC-DC boost converter is applied to convert an unregulated DC supply's input voltage to a stabilized higher output voltage [13], [14]. In addition, to enhance the OGPV system, many studies focus on developing the maximum power point tracking or MPPT algorithm to identify any possibilities to improve power production [15]-[21] or implement soft-switching technique to avoid overlapping between switching current and voltage which aim to reduce switching noise and loss or improving the voltage level by improvised the current topology [8], [9], [11], [14], [22]-[26].

Based on the literature discussed above, to our knowledge, there has been limited discussion on the critical irradiance analysis concerning the output performances for low-voltage DC-DC OGPV systems. Therefore, this paper contributes to the comprehensive analysis of output performances parameters, where efficiency, η is assessed under standard test conditions (STC), while settling time, T_S, minimum irradiance required for power transfer, Irr_{Min}, and peak sun hour (PSH) are evaluated under dynamic test conditions (DTC). Additionally, the comparative analysis involves various types of PV modules and control switching techniques. The efficiency, η, settling time, T_S, and PSH performances align with the testing conditions outlined in IEC 61727 standards. These findings are pivotal in driving advancements in medium to high-voltage OGPV systems, guiding the formulation of development strategies, and future projections. This research significantly contributes to the global target of accessible and environmentally friendly energy solutions, in alignment with the objectives of sustainable development goal (SDG 7).

2. DC-DC OGPV METHODOLOGY

This paper presents a comprehensive methodology for simulating DC-DC OGPV systems using MATLAB Simulink. The irradiance testing conditions focus on assessing the system's performance under varying irradiance levels, while the PV modules section examines the impacts of photovoltaic cells. The control technique strategies are designed to optimize energy transfer and utilization.

2.1. Irradiance testing conditions

Standard test conditions (STC) and dynamic test conditions (DTC) need to be accomplished to obtain the output performance for low-voltage DC-DC OGPV systems. The irradiance setting was first selected based on these three conditions where: i) fixed irradiance to represent STC; ii) abrupt irradiance; and iii) nominal irradiance setting to represent DTC. A constant block is used to represent the fixed irradiance throughout the simulation, whereas a signal editor block is used to represent the abrupt irradiance and nominal irradiance. At this simulation, the temperature is remained constant at 25 °C. Fixed and abrupt irradiance settings can be arranged as Table 1, while the irradiance profile for abrupt and nominal setting can be illustrate as in Figures 1 and 2, respectively. These irradiance setting will be set according to Simulink block diagram as shown in Figure 3, before connecting to the PV module.

2.2. PV modules

There are two PV modules cases that will be testing in this paper. They are Case I and Case II with Tycon Solar TPS-12-15 W and Sealite SL-P020S-12 PV module respectively. Both of these PV modules were chosen to represent low-voltage OGPV system by delivering low-voltage DC inputs of 12 V, therefore will be providing boost output voltage with the aid of DC-DC converter circuit.

Table 1. Fixed and abrupt irradiance setting

Time (s)	Fixed irradiance setting (W/m^2)	Time (s)	Abrupt irradiance setting (W/m^2)
For every 0.0–4.0 sec	100	0.0–1.5 sec	800
	200	1.5–2.5 sec	500
	300	2.5–3.2 sec	1000
	400	3.2–4.0 sec	300
	500		
	600		
	700		
	800		
	900		
	1000		

2.3. Control switching technique strategy

There are two control switching techniques applied in this paper, conventionally used pulse generator method and MPPT-based method using perturb and observe (PNO) technique. Both switching frequency were selected at 30 kHz. The switching technique provides an appropriate duty cycle for the power switch in DC-DC converter circuit. The purpose of conventional control strategy is to provide based-line performance, while the MPPT-based method application is to extract output performance during maximum power tracking. The conventional pulse generator method was provided by a constant 50% duty cycle, while the PNO MPPT method provided with a range of duty cycle depending on the maximum power tracking due to the changing irradiance level. Figure 4 shows the control switching block diagram using conventional pulse generator method and MPPT-based method respectively, while Figure 5 illustrates the flowchart of the maximum power tracking using PNO MPPT-based method.

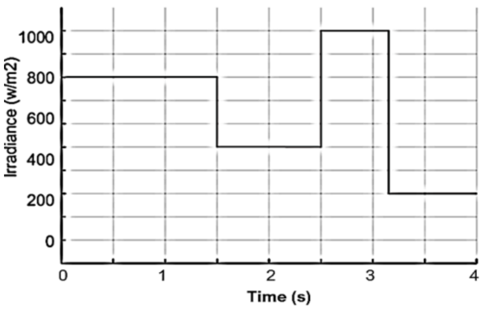

Figure 1. Abrupt irradiance profile

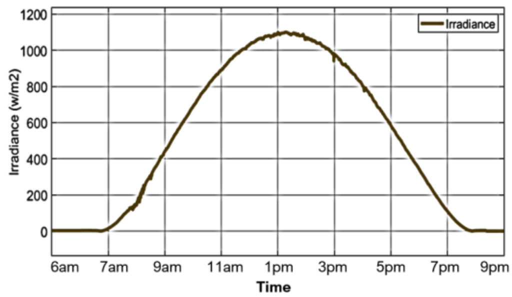

Figure 2. Nominal irradiance profile

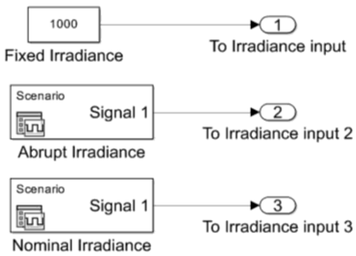

Figure 3. Simulation blocks of irradiance settings

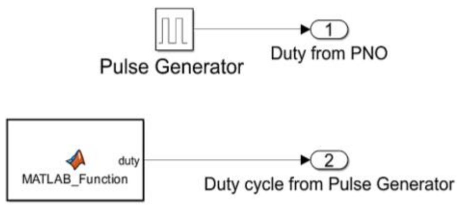

Figure 4. Simulation blocks of control switching technique

2.4. DC-DC converter circuits and load

In this paper, boost DC-DC converter circuits were chosen as the power electronics circuit with a 35 Ω resistor load, extracted from a DC axial fan. Boost circuits including inductor, power switch, diode, and capacitor are arranged as in Figure 6. Based on the figure, diode, Dpv, and capacitor, Cpv are placed after the PV module, aims for protection, and voltage stabilization respectively.

The minimum inductance, L_{min} and the inductor current, I_L for continuous current can be determined from (1) and (2), respectively. In this paper, inductor size is chosen to be 25% larger than L_{min}. Therefore, inductor size is 270µH. The minimum capacitance, C_{min} required to limit the output ripple voltage to a specific percent which can be determined from (3). The selected capacitor, C is 220 µF which needs to be chosen more than the $C_{min.}$ 47.62 µF. Thus, the input power, pin, output power, pout, and efficiency, η can be predicted using (4)-(6) respectively.

$$Lmin = \frac{D(1-D)^2R}{2fs} \tag{1}$$

$$IL = \frac{Vinput}{(1-D)^2R} \tag{2}$$

$$Cmin \geq \frac{D}{R(\frac{\Delta Vo}{Vo})fs} \tag{3}$$

$$Pin = Vinput \times IL \tag{4}$$

$$Pout = \frac{Vo^2}{R} \quad (5)$$

$$\eta = \frac{Pout}{Pin} \times 100\% \quad (6)$$

Table 2 summarizes the simulation parameters setting involve in designing the DC-DC OGPV system. All data were recorded and analyzed to obtain vital parameters for the system.

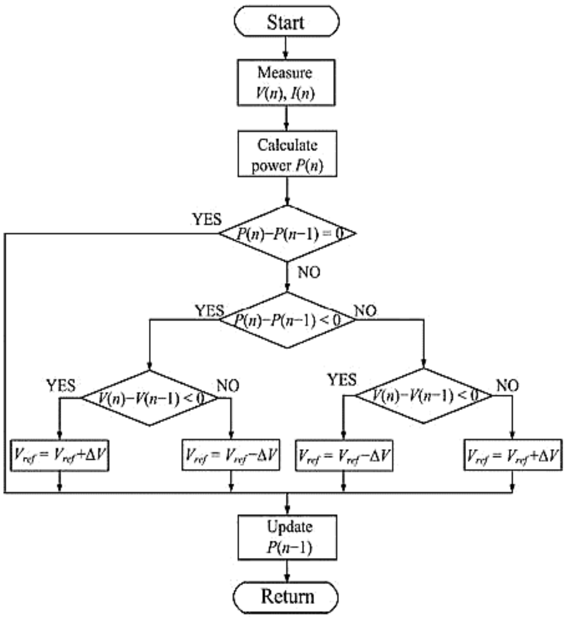

Figure 5. Flowchart of PNO algorithm

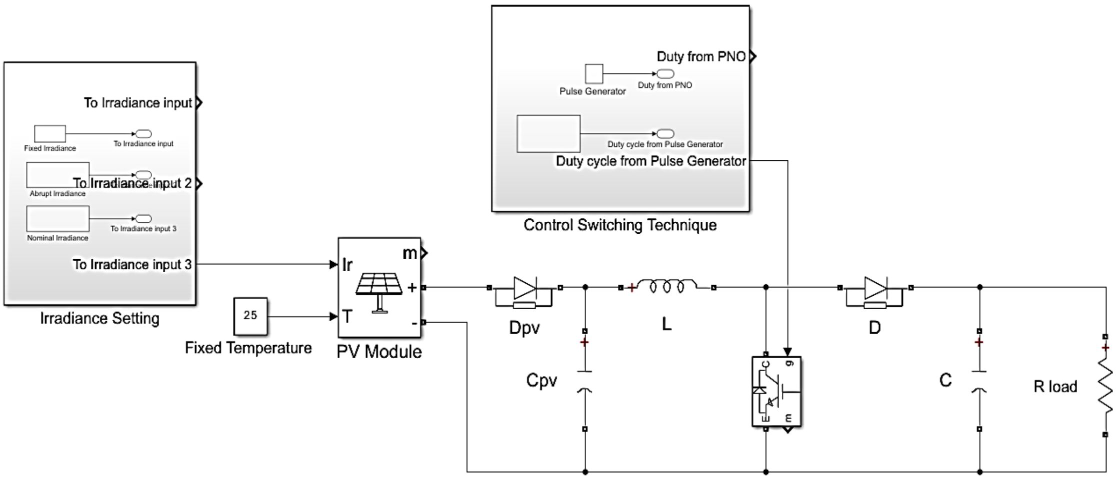

Figure 6. MATLAB Simulink diagram of DC-DC OGPV system for various irradiance settings and control switching technique

Table 2. Simulation parameter settings for DC-DC OGPV system

Parameters	Values
Case I PV module	Tycon Solar TPS-12-15
Case II PV module	Sealite SL-P020S-12
Duty ratio	D = 0.5
Resistor	R = 35 Ω
Switching frequency	f_S = 30 kHz
Inductor	L = 270 μH
Capacitor	C = 220 μF

3. RESULTS AND DISCUSSION

In this section, the output performance of the low-voltage profile of the DC-DC OGPV system toward the different irradiance profiles will be analyzed and discussed in depth. The irradiance in STC and DTC testing conditions will be projected to identify several output performance parameters such as efficiency, η from fixed irradiance analysis, settling time (T_S) from the abrupt irradiance analysis, while the minimum irradiance required for power transfer (Irr_{Min}), and PSH from the nominal irradiance analysis.

3.1. Fixed irradiance

This section covered fixed irradiance analysis occurred at specific simulation period time from 0 to 4 s, aim to obtain the system efficiency,η for the specified irradiance level. The purpose is to establish input and output power at an STC temperature of 25 °C while varying the value of irradiance from 100 W/m^2 to 1000 W/m^2, with conventional control of pulse generator and PNO MPPT-based control strategy. Figure 7 illustrates the efficiency, η trend for DC-DC OGPV system when the irradiance is fixed from 0s until 4s, while the temperature was constant at 25 °C. The required efficiency was selected to be more than 90%, to ensure effective power transferred from PV module to the load. It is clearly seen from Figure 7 that Case II utilizing Sealite PV module for DC-DC OGPV system with PNO MPPT-based control strategy performs a higher efficiency trend compared to others where the efficiency, η>90% efficiency can be achieved when the irradiance as low as 200 W/m^2 is received so that the power could be transferred to the load as soon as possible when receiving minimum irradiance.

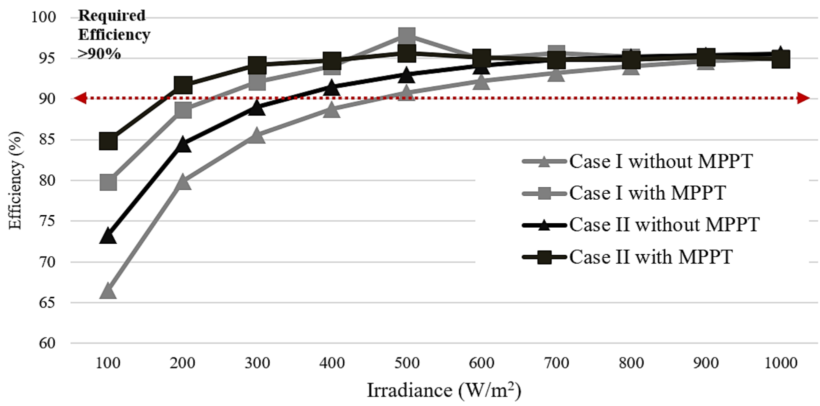

Figure 7. The efficiency, η trend during fixed irradiance analysis

3.2. Abrupt irradiance

This section discusses the DC-DC OGPV system performance when the irradiance changes abruptly during a very short period due to shading effect mimicking the cloud or bird movement, thus the irradiance reaches differently on top of the PV module at any time. This analysis will establish the range of settling time, T_s for the system. Shorter range of settling time was aim for a better stability and lower noise towards the generated output waveform. The settling time, T_S were recorded when the output waveform achieves stability after each of the abrupt changes in irradiance at the setting time mentioned in Table 1.

Figures 8(a)-8(d) illustrates the settling performance of DC-DC OGPV system (with pulse generator and PNO MPPT-based control technique) when irradiance changes abruptly. Case I and Case II demonstrated the output performance of DC-DC OGPV system utilizing Tycon and Sealite PV module, respectively. Therefore, Figures 8(a) and 8(b) employed conventional pulse generator control technique, while Figures 8(c) and 8(d) employed the PNO MPPT-based control technique. From the overview of PV module cases, Figures 8(b) and 8(d) provide a shorter settling time compared to Figures 8(a) and 8(c). However, the control switching technique strategy thus impacted the settling time of the DC-DC OGPV system under abrupt irradiance analysis. Referring to the Figures 8(c) and 8(d) both with PNO MPPT-based control technique performed short range of settling time, TS around 40 ms and 20 ms, respectively.

A shorter settling time, T_S were preferable so that the system could provide stable and maintain output to the load with minimal noise content. However, one issue that emerge from the implementation of MPPT is that the system producing higher ripple indicated by the thicker lines as shown in Figures 8(c) and 8(d), and these affected much higher root mean square or RMS value and at the same time increase the temperature of the components.

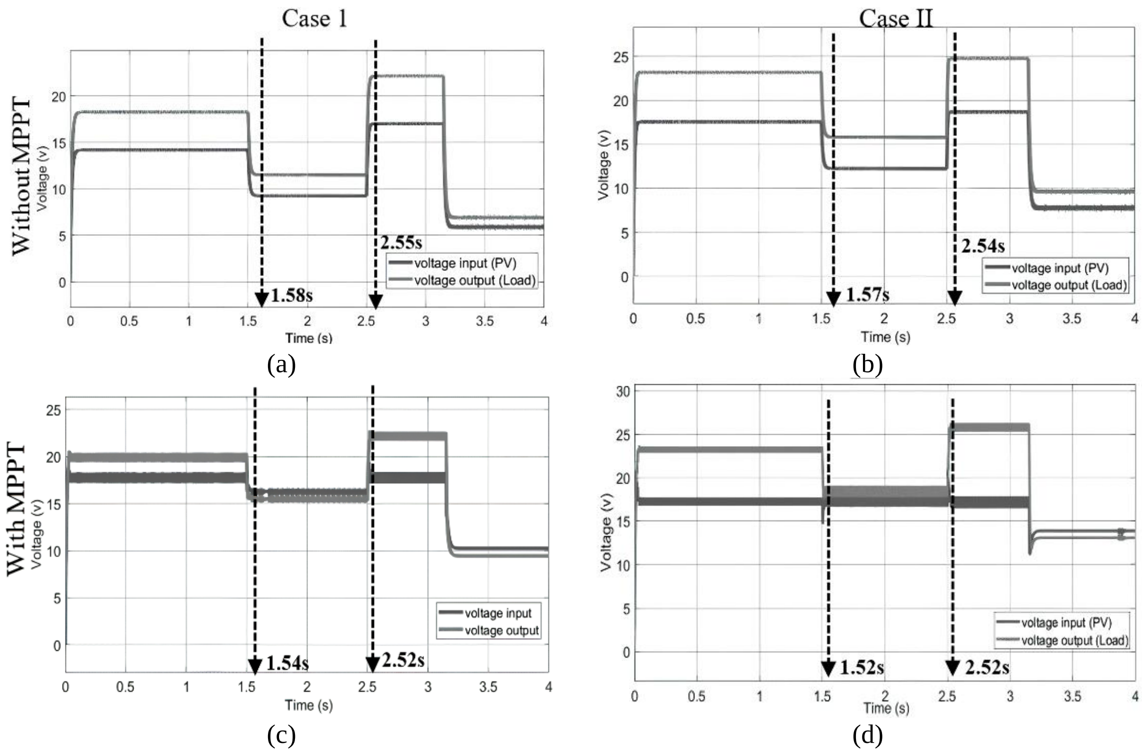

Figure 8. Settling time, T_S performance during abrupt irradiance analysis for (a) Tycon-PV without MPPT, (b) Sealite-PV without MPPT, (c) Tycon-PV with MPPT, and (d) Sealite-PV with MPPT

3.3. Nominal irradiance

This section discussed the DC-DC OGPV system performance when normal irradiance distribution occurred during the day from 6 am until 9 pm. This analysis will reveal whether the DC-DC Converter system able to provide the minimum PSH required in Malaysia which at least PSH = 4. Figure 9 illustrates the output voltage distribution toward nominal irradiance analysis. DC-DC OGPV system able to deliver current toward the load once the system achieves the minimum required output voltage around 21.6 V. From the minimum point of output voltage, therefore the minimum irradiance requirement will be established. There are two consequential points of minimum irradiance requirement that were dotted in the graph, thus imply the PSH contributing from the system.

Figures 9(a)-9(d) illustrates the PSH performance of DC-DC OGPV system (with pulse generator and PNO MPPT- based control technique) during the nominal irradiance analysis. Case I and Case II demonstrated the PSH performance of DC-DC OGPV system utilizing Tycon and Sealite PV module, respectively. Therefore, Figures 9(a) and 9(c) employed conventional pulse generator control technique, while Figures 9(b) and 9(d) employed the PNO MPPT-based control technique.

From the overview of PV module cases, Figures 9(b) and 9(d) both projected with longer PSH around 6 hours, compared to Figures 9(a) and 9(c) both projected with slightly lower PSH around four hours. Referring to Figures 9(b) and 9(d), DC-DC OGPV system utilized the Sealite PV module successfully generates higher power at much lower irradiance which occurred at 707 W/m^2 and 684 W/m^2, while operated using pulse generator technique and PNO MPPT-based technique respectively. This indicate that the design for DC-DC OGPV with Sealite PV module able to convert much more energy to the load with extra two hours (standard PSH = 4), at the same time producing higher efficiency, η as discussed in section 3.1. However, control switching technique strategy provides non-engagement towards the projected PSH of the DC-DC OGPV system, where the power transferred from the PV module to the load occurred only when the irradiance reached 950.5 W/m^2 and 909.8 W/m^2 as shown in Figures 9(a) and 9(c), respectively, regardless of the control switching technique strategy.

3.4. Summary selection

Table 3 tabulates the summary selection for low-voltage DC-DC OGPV system profile for different type of PV modules cases, with conventional pulse generator technique or PNO MPPT-based technique, under various irradiance analysis was studied. Several vital parameters were established by this studied before deciding the optimum selection for DC-DC OGPV system, which are:

- Efficiency, η
- Range of settling time, T_S response to the abrupt changes of irradiance at short interval period
- Minimum irradiance, Irr_{Min} required for transferring power to the load as soon as possible whenever the system meets the minimum output voltage
- PSH establishes for the system

Higher efficiency, η of the system could be determined by running various irradiance analysis study at STC temperature. Shorter time of settling time, T_S was preferable as it becomes an indicator for stability in the system toward abrupt change in irradiance input. Furthermore, nominal irradiance analysis resolved the PSH produced, and the DC-DC converter system should match the minimum PSH requirement (PSH=4). The highlighted parameters were the preferred selection for each category.

DC-DC OGPV system with Sealite PV module under PNO MPPT-based control technique clearly is the optimum selection for low-voltage DC-DC OGPV system, thus require minimum irradiance which enabling power transfer to the load while providing higher values in these parameters: output voltage, V_{OUT}, output power, P_{OUT}, and PSH at the same time. Even though, the efficiency is slightly lower but still acceptable with η>90% of the set efficiency. A bigger heat sink needs to be considered during the hardware setup to absorb excess heat caused by higher temperature in the components due to MPPT implementation.

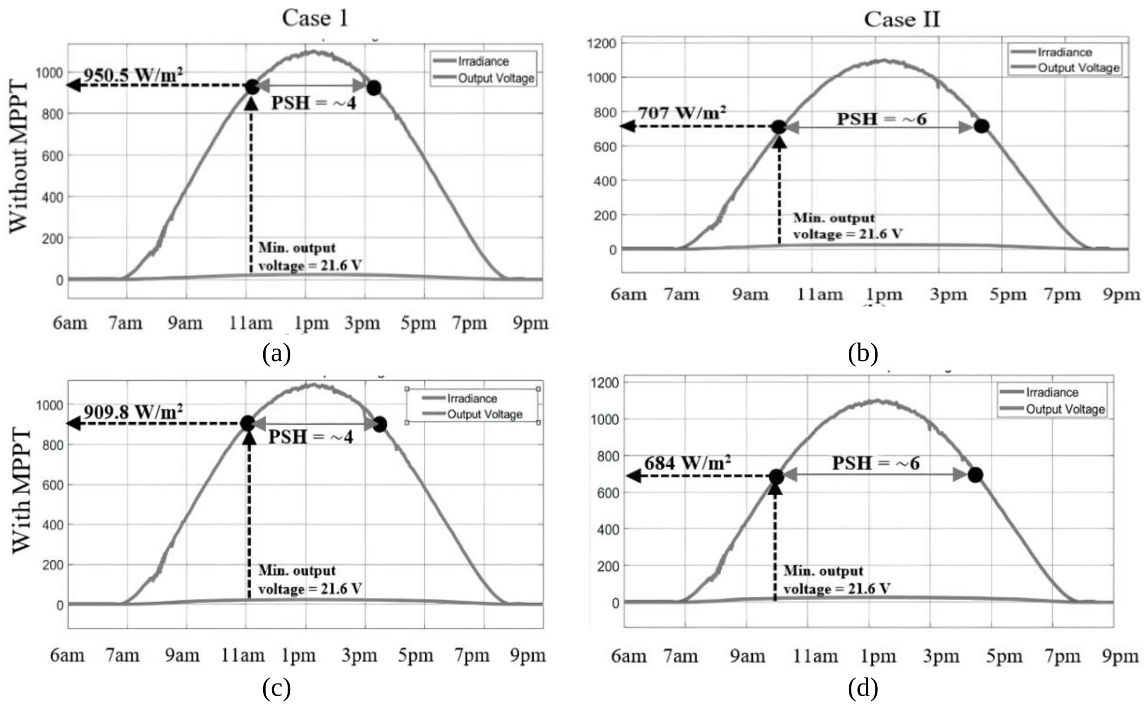

Figure 9. The PSH performance during nominal irradiance analysis for (a) Tycon-PV without MPPT, (b) Sealite-PV without MPPT, (c) Tycon-PV with MPPT, and (d) Sealite-PV with MPPT

Table 3. Summary selection for DC-DC converter system parameters

Type of PV module	MPPT	Output voltage, P_{OUT} (V)	Output power, P_{OUT} (W)	Efficiency, η (%)	Settling time, T_s (s)	Min. irradiance requirement, Irr_{Min} (W/m^2)	Peak sun hour, PSH (hours)
Case I	No	22.17	14.04	95	50 m–80 ms	950	4
(Tycon-PV)	Yes	22.25	14.14	95.1	20 m–40 m	910	4
Case II	No	24.75	17.5	95.5	40 m–70 m	707	6
(Sealite-PV)	Yes	25.76	18.96	95	20 m	684	6

4. CONCLUSION

This paper has presented the low-voltage DC-DC off-grid PV system selection parameters under the influence of several irradiance studies. In this study, three irradiance conditions were being tested: i) Various irradiance when temperature at standard condition of 25 °C; ii) Abrupt irradiance to imitate the shading issue due to cloud or bird movement; and iii) Nominal irradiance throughout the day; provide vital analysis toward the selection of the optimum low-voltage DC-DC for OGPV system performance. Results obtained from the study indicated that the proposed irradiance analysis managed to produce convincing results in terms of achieving a short range of settling time, T_S at the same time transferring power to the load at the earliest occurred irradiance with higher efficiency and longer PSH. Comparative studies with different cases of PV modules and different control switching techniques towards the DC-DC OGPV system significantly impact those parameters. Results obtained from the study can be used for projection planning for medium to high-voltage OGPV system applications.

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