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Voltage stability and PQ analysis of a PV solar grid-connected system under varying weather conditions in Oman

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ABSTRACT

This paper studies the voltage stability and power quality (PQ) of a 128 kW grid-connected photovoltaic (PV) system installed at a school in Al-Hamra, Oman, by using a MATLAB/Simulink model. An incremental conductance maximum power point tracking (MPPT) algorithm is used to control the duty cycle of a DC/DC boost converter and to keep the DC-link voltage almost constant at about 498 V for different solar irradiance levels. A rotating d-q control strategy is applied to the voltage source converter (VSC) to generate balanced three-phase currents with a high power factor while the PV system partly supplies an average 400 kW school load and the remaining power is taken from the local distribution network. Steady-state and transient simulations with real irradiance and temperature data are carried out to examine the system performance during sudden changes in irradiance, load, and grid conditions such as voltage sags. The results show that the proposed control scheme keeps the DC-link voltage stable, reduces overshoot during disturbances, and achieves good power quality at the point of common coupling, with THDi of about 1.45%. Although this work is based only on simulations, it confirms that the controller can operate robustly under different weather and operating conditions and can help the integration of solar PV into the Omani distribution network.

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1. INTRODUCTION

With the global expansion of solar grid-connected systems, such systems are becoming increasingly common in most countries [1], [2]. However, the rapid rate of global installation of different renewable energy sources poses distinct challenges for power networks that are effectively incorporating intermittent generation [3], [4]. In addition, power quality issues in PV systems become a major challenge [5]-[7]. In general, power quality (PQ) problems related to renewable energy sources can be grouped into: low power factor [8], [9], harmonic distortion [10], [11], frequency fluctuations [12], [13], transients, and electromagnetic interference [14], [15]. Power inverters are utilized to establish a connection between renewable energy sources and the power system. However, in many cases, the utilization of power inverters introduces harmonics into the system [16]-[18]. The presence of harmonics in a power system can lead to the distortion of the source voltage, resulting in the occurrence of additional losses caused by the undesired flow of current in the source, which may disturb the operation of relays, main switches, and other control devices. Other PQ challenges in the grid-connected PV system include reverse power flow, islanding, synchronization issues, and intermittent power flow. The negative impacts of these disturbances on the voltage regulation systems, protection, and storage devices are addressed in [19].

Besides that, the presence of wind and PV power systems at a high level of penetration amplifies the levels of fluctuation and causes uncertainty in the net load, as claimed in [20]. Also, in cases where the uncertainty of the power generation is present, it is typically necessary to have reserve capacity. To mitigate this uncertainty, system operators should ensure that there is an appropriate reserve capacity [21], [22]. These uncertainties have the potential to result in unsatisfactory levels of variability and increases in the total cost.

The Sultanate of Oman provides a favourable investment environment for the promotion of renewable energy projects, particularly in the field of solar and wind energy applications [23], [24]. Oman Electricity Transmission Company (OETC) and Nama Power and Water Procurement Companies (NPWP) experience enhanced efficiency through the execution of a comprehensive strategy to support the national target of 30% (3,840 MW) of the energy mix by 2030 [25]. The details of the selected locations and types of renewable energy resources and capacity are presented in Table 1.

Table 1. Oman's planned renewable energy projects (2023-2029)

Project	2023	2024	2025	2026	2027	2028	2029
Manah I solar IPP	-	-	500	500	500	500	500
Manah II solar IPP	-	-	500	500	500	500	500
Ibri III solar IPP	-	-	-	-	500	500	500
JBB wind IPP	-	-	-	-	100	100	100
Duqm wind IPP	-	-	-	-	200	200	200
Ras madrakah wnd IPP	-	-	-	-	200	200	200
MIS solar IPP 2027	-	-	-	-	500	500	500
Barka WTE IPP	-	-	-	-	-	140	140
Solar PV IPPs 2029	-	-	-	-	-	-	1000
Wind IPP 2029	-	-	-	-	-	-	200
Total planned capacity (MW)	-	-	1000	1000	2500	2640	3840

In the case of Oman, generally, less work has been done to study and examine the impacts of solar and wind grid-connected systems in Oman, and more research work is needed to investigate the future impacts of more penetration of solar and wind grid-connected systems on the transmission and distribution networks. A study [26] addressed three internal dynamic failures- dust accumulation, inverter malfunction, and faulty protection schemes at a 6 MW solar station. It was found that the plant performance dropped sharply, with power generation down by 43.5%. The advantages, disadvantages, and a detailed review of topological advancements in PV grid-connected inverters are presented in [27]. The harmonic impacts were analysed using an electrical transient analyser program to uncover the effect of irradiance on the inverters' power quality running at 85% and 100% power factors [28]. The voltage unbalance, flicker, and harmonics of the 50 MW wind system in Dhofar-Oman has been discussed in [29]. The fluctuation of wind power generation has been minimized by using a shunt active filter to reduce the harmonic distortion to the permitted limit. The impacts of an 8.852 MWp solar station on the local distribution network under different weather conditions were investigated [30]. The voltage unbalance and total harmonic distortion (THD) levels were within the limits stated by the Omani and international distribution codes. However, the voltage flickers showed some violations of the limits specified by the distribution code, requiring closer system monitoring. The readiness of the Omani Electricity Network for Solar Energy Integration was discussed in [31]. The Al Bashir primary substation load distribution in Oman [32] was used to study the impacts of solar penetration on the grid-connected load. Results reflect that up to 80% of the minimum load can be decreased if the solar station is synchronized properly. Other PQ issues were discussed in [33]. Generally, the power quality issues of the solar and wind systems and the impacts in the network in Oman are limited, and more work must be done.

This research work aims to examine the performance of a 128 kW solar grid-connected distribution network in Al-Hamra, Oman. The focus will be to study and analyse the voltage stability and the power quality of the injected power to the local distribution network under different conditions of solar irradiance. Real data of the weather conditions and technical details of the selected site will be used as input entries to the MATLAB/Simulink model of the 128 kW solar grid-connected system. The Maximum power point tracking (MPPT) of the control system will be examined at transient conditions of weather variations and unexpected load variations.

2. SYSTEM DESCRIPTION

The selected study site is the 128 kW solar grid-connected system at Abu Said Al-Kadami School in Al-Hamra town, located at 23°07′N 57°17′E and 197 km from Muscat. Figure 1 shows a photo of the 128 kW solar station and the inverter system. The solar system consists of 318 panels of type PVM-405 W with V_{OC} = 33.2 V and I_{SC} = 13.3 A. Every 15 panels are connected in series to the same string. Six strings are connected to the same inverter to generate a total of 36 kW.

The solar irradiances and the generated power on November 11th, 2023 (Sunny Day) are presented in Figure 2. The maximum solar irradiance was 840 W/m^{2,} and the generated power was 84.73 kW. The average monthly solar production from the solar system and the solar irradiances for one year are shown in Figure 3. Rainy seasons have impacted the production of the solar system in March, June, and September 2023.

Figure 1. Photos of the 128 kW solar system and the inverter system

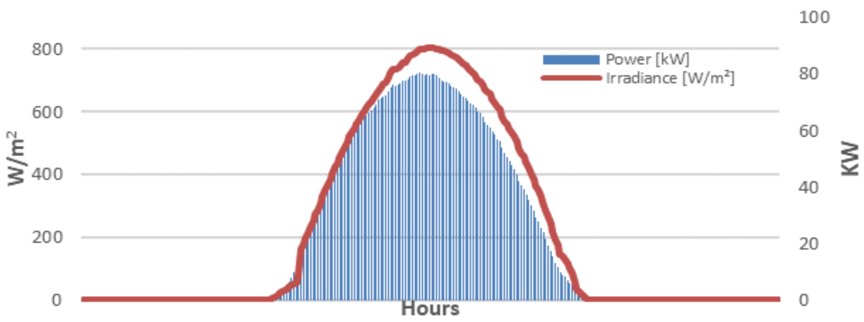

Figure 2. Solar irradiances and the generated power on 11th Nov, 2023

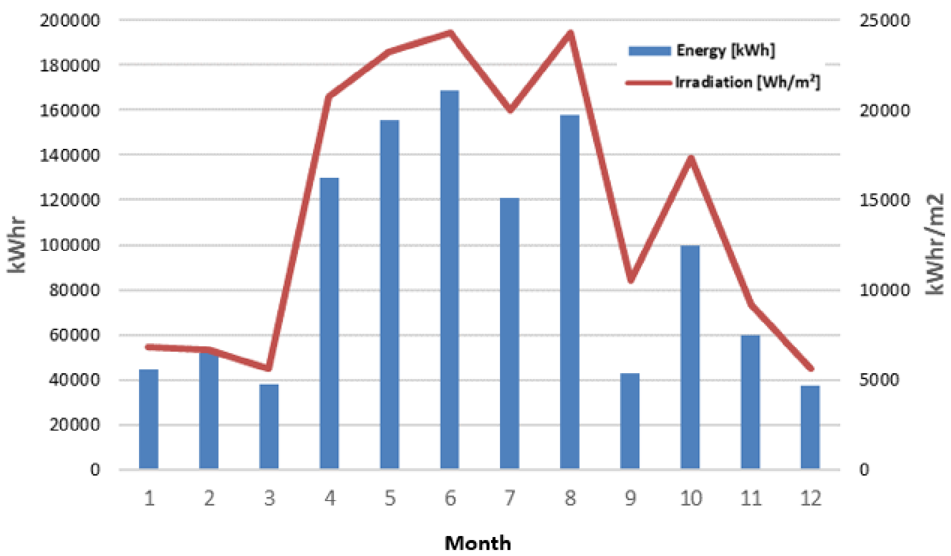

Figure 3. The average monthly energy production and the average monthly solar irradiance

3. MODELING AND SIMULATION

The MATLAB/Simulink model of the 128 kW solar grid-connected system is shown in Figure 4. The 128 kW solar system is connected to four DC/DC boost converter and then to the DC/AC inverter to produce the required three-phase AC system. The 400 kW school average load is fed by the solar system and the distribution network via the 150 kVAR transformer. The V-I and P-V characteristics of the solar system at different temperature levels and constant solar irradiances at 1 kW/m^2 are shown in Figure 5. The maximum power production of the solar system is at point A at voltage and current values of 270 V and 389 A, respectively.

The same figure shows clearly that the output generated power is reduced when the temperature increases. Figure 6 shows the I-V and P-V characteristics of the PV system under different solar irradiance and constant temperature. Generally, both figures show that the PV solar system has nonlinear characteristics due to the changeable behavior of the semiconductor materials with the temperature levels. The performance of the PV is affected by the weather conditions and the output of the solar system is varied accordingly [34] and the maximum power point is changed [35].

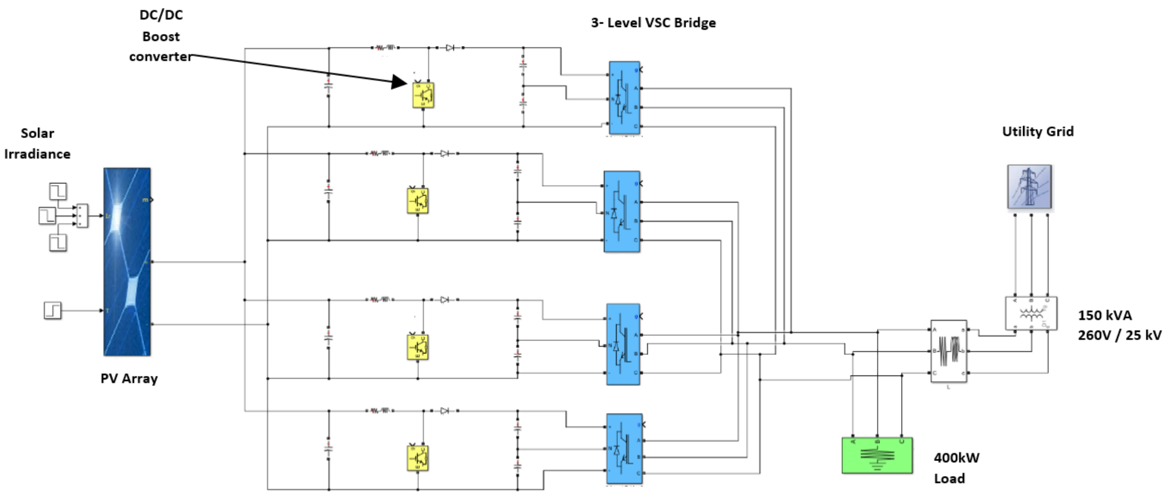

Figure 4. MATLAB/Simulink model of the 128 kW solar grid connected system

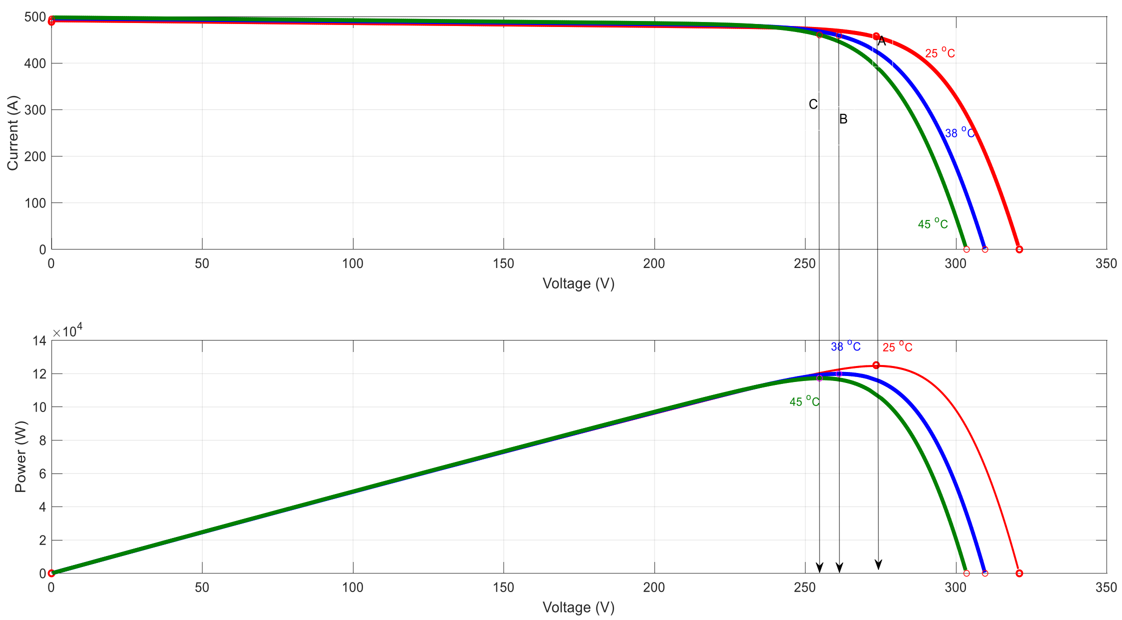

Figure 5. The V-I and P-V characteristics at different temperature levels

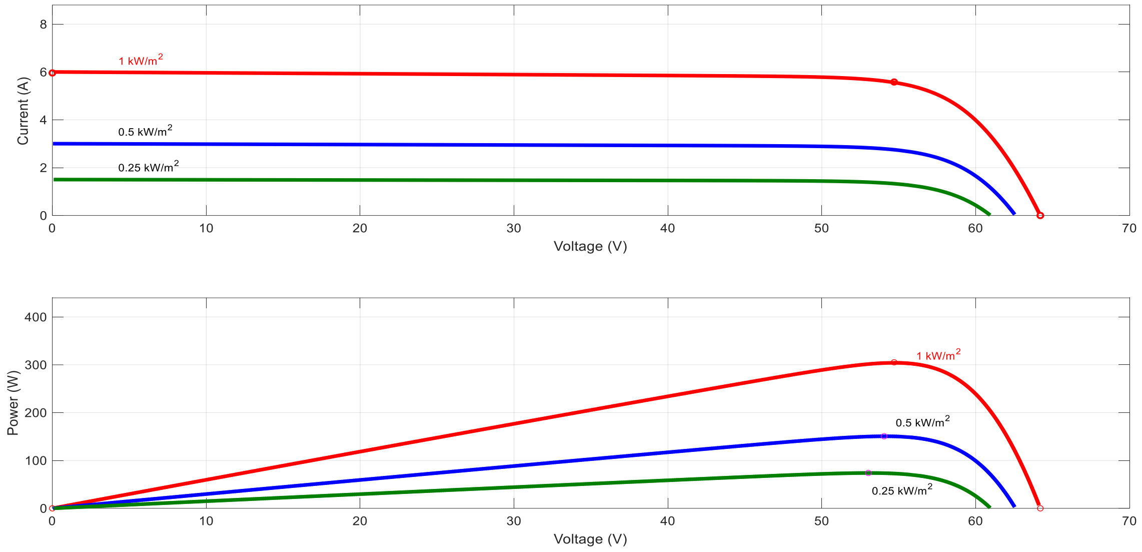

Figure 6. The V-I and P-V characteristics at different solar irradiance

In such a case, a maximum power point tracker must be implemented to adjust the voltage level of the PV array and so to match the impedance of the PV panels with the load impedance of DC/DC boost converters [36]. Many MPPTs were introduced in solar applications such as fractional short circuit current, fuzzy control, perturb and observe (P&O), fractional open circuit voltage, incremental conductance, and neural network control [37], [38]. More description is presented in Figure 7. In comparison between the different MPP techniques, the conventional P&O are suitable under full sunshine conditions but not at partial shading [39], [40]. Furthermore, it has been verified from different literature that intelligent and hybrid techniques are more efficient compared to conventional methods [41]. However, they have more complex design, control and more expensive than the conventional methods [42], [43]. Also, they have slower response in terms of the tracking speed and stability. It can be concluded that conventional MPP techniques such as the P&O are most widely used in the industry [44]-[46].

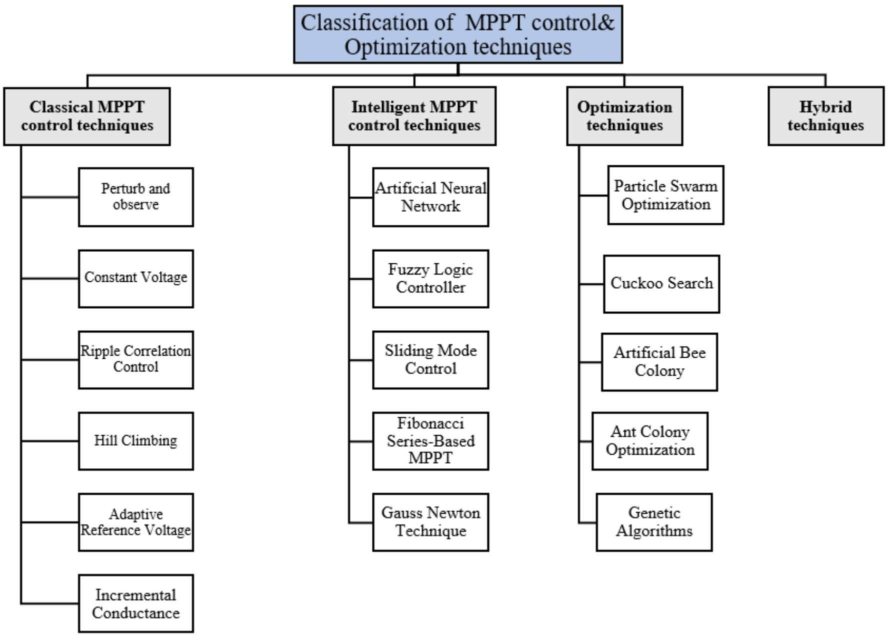

Figure 7. Classification of MPPT techniques

In this model, the incremental conductance technique is implemented. This technique aims to maintain the maximum power point by tracing the slope of the P–V curve of the solar panel. The incremental conductance method reads the slope of the voltage and current values of the PV array on both left- and right-hand sides of the P-V curve and works to bring it back to the maximum power point. Three possible cases are expected as mentioned by (1)-(3).

$$\frac{\Delta I}{\Delta V}+\frac{I}{V}=Zero, \text{(At maximum power point)} \tag{1}$$

$$\frac{\Delta I}{\Delta V}+\frac{I}{V}>Zero, \text{(At left side of maximum power point)} \tag{2}$$

$$\frac{\Delta I}{\Delta V}+\frac{I}{V}<Zero, \text{(At right side of maximum power point)} \tag{3}$$

According to (1)-(3), the voltage level on the left maximum power point must be increased; or decreased on the right-hand side, otherwise it must be kept constant at a slope value equal to zero [47]. Figure 8 shows the flow chart of the incremental conductance MPP technique.

The outcomes of this process produce the required gate pulses of the DC/DC boost converter [48]. After that, the DC/AC voltage source converter works to match the output of the PV panels through the DC/DC boost converter, and the AC grid generates neutral three-phase voltage commands for a balanced three-phase load. The rotating d-q technique is used to control the DC/AC voltage source converter (VSC) and to produce the pure three phases' currents at a high-power factor. The AC side of the variable speed converter (VSC) is connected to an average 400 kW load and then to the 150 kVA (260 V/25 kV) transformer. The transformer is connected to the grid system via a long utility feeder and M_{VAR} load. The next section discusses the performance of the MATLAB simulation model and the results at steady state and transient status.

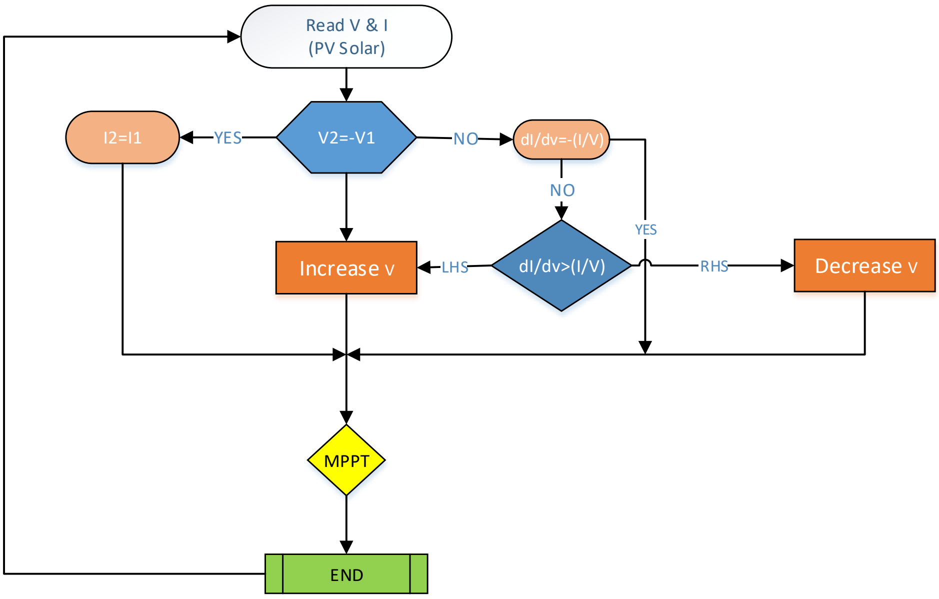

Figure 8. Flowchart of the incremental conductance MPPT

4. RESULTS AND DISCUSSIONS

4.1. Steady state analysis

The steady-state operation of the simulation model was examined at four different levels of solar irradiances at a fixed temperature of 46 °C. In case 1, the 128 kW solar panels were tested at a solar irradiance of 1000 W/m^2, case 2 at 800 W/m^2, case 3 at 600 W/m^2, and case 4 at zero solar irradiances which represents fully cloudy day or night-time. Variation of the solar irradiance is presented in Figure 9(a). It can be noticed that the average DC voltage level of the solar system is kept at an average of 260 V, as shown in Figure 9(b). This is due to the effectiveness of the MPPT system. The output current and the output power from the solar system are presented in Figure 9(c) and Figure 9(d), respectively. The output power generated is reduced by decreasing the level of the solar irradiances and the output power is equal to zero at zero solar irradiance.

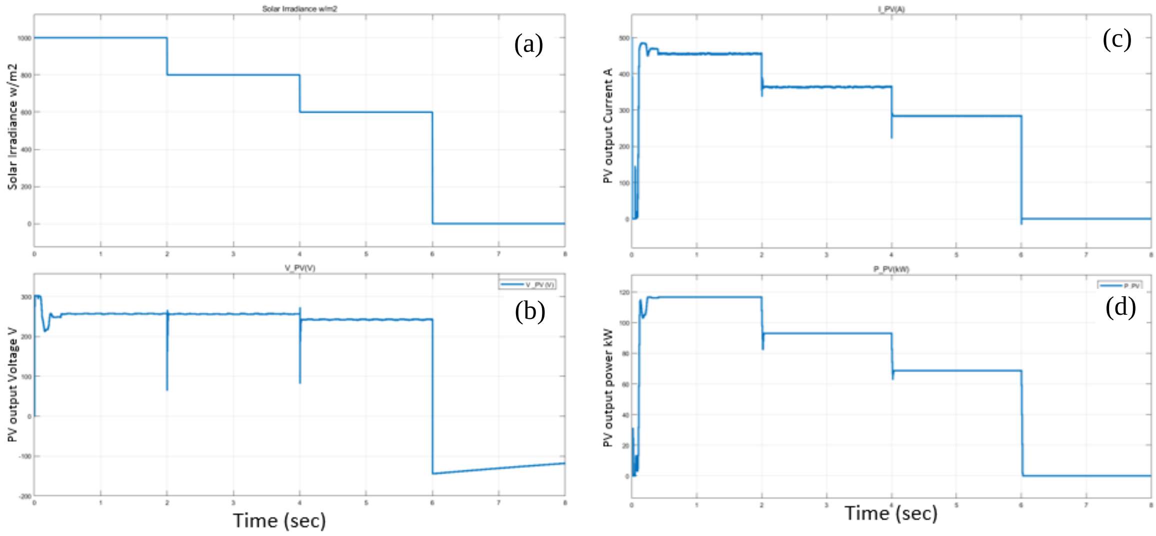

Figure 9. Performance of the solar system at different levels of solar irradiance: (a) solar irradiance, (b) PV output DC voltage, (c) PV output DC current, and (d) PV output power

Figure 10 presents the performance of the DC/DC converter against the variation of the solar irradiance. The input DC voltage from solar panels is presented in Figure 10(a), the output voltage of the DC/DC boost converter is presented in Figure 10(b), the output power of the solar system is presented in Figure 10(c) and the variation of the duty cycle (D) is presented in Figure 10(d). The voltage levels of the PV panels and the DC/DC boost converter are kept constant. The average output DC voltage of the boost converter is kept constant at 498.1 V. This value can be calculated using the basic (4).

$$\frac{v_0}{v_S} = \frac{1}{1-D} \tag{4}$$

Where Vo is the average output voltage of the DC/DC boost converter. Vs is the average input voltage from the solar system and D is the duty cycle. As the solar irradiance changed, the output voltage of the DC/DC converter must be kept constant at $V_{DC/DC}$ = 498 V, as illustrated in Figure 10(b). Hence the duty cycle is adjusted. D is small at high input PV voltage, and is smaller at higher PV output voltage, as shown in Figure 10(d). An example is presented ay time = 2s, Vs = 263 V, D = 0.472, and the calculated average output voltage equals to 498.1 V.

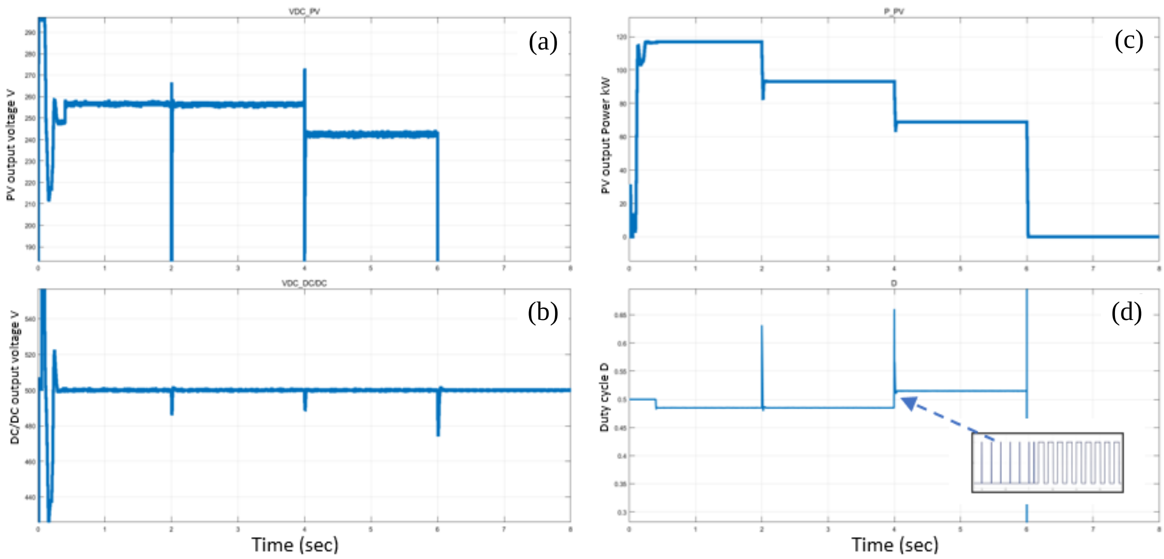

Figure10. System performance of the DC/DC boost converter: (a) PV output voltage, (b) DC/DC output voltage, (c) PV output power, and (d) duty cycle

4.2. Transient conditions and sensitivity analysis

Real data was used to study the performance of the grid-connected solar system at transient conditions due to a sudden drop of the solar irradiances. The solar irradiances sharply dropped from 740 to 337.4 W/m^2. Consequently, the generated output power decreased from 65.53 to 32 kW, as shown in Figure 11. This drop can lead to power quality issues in the grid-connected system, as discussed in [49]. However, in this system, minimum impacts were noticed due to the high capacity in the local network which was able to instantaneously cover the power drop. As a result, the system was recovered quickly. Figure 12 presents the FFT analysis, and the THD_i was found equal to 1.45% which is within the acceptable range of the IEEE standard. This proves the ability of the 128 kW solar gird connected system to provide power to the gird at high quality and no need for filtration requirements.

Under the variations of the weather condition, the sensitivity analysis must be addressed to the examine the robustness of the converter system to uncertainties and disturbances in the weather conditions [50], [51]. This will help to design an optimal system and predict efficient performance [52]. In this research work, the sensitivity analysis of the MPPT system is evaluated by considering the variations in environmental conditions and in the sudden load change as explained below. To investigate the voltage sagging, the performance of the solar system was examined under sudden drop of the solar irradiances from 900 to 300 W/m^2. Figure 13(a) presents the ac voltages and currents waveforms. The voltage waveform was not affected which presents stable operation of the system. However, the current waveform was dropped by almost 50%. This has no impacts on the network as explained before. On the other hand, the sensitivity analysis is also discussed at sudden load change, as shown in Figure 13. The solar irradiance is maintained at a constant level of 950 W/m^2. At constant solar irradiances, the fluctuation noticed in the lower graphs are due to the grid disturbances or load change. The dynamic behavior can be addressed by checking the stability of the voltage waveform, as shown in Figure 13(b). The voltage amplitude is around 20 kV. However, the voltage waveform effected slightly at time 0.75 s before returning to stability. We can conclude that the sensitivity analysis of the MPPT control system managed to respond to the transitions from low power to high power efficiently without substantial overshoot. However, the system is more sensitive to load change at 0.7 second, where we can see heavy current mess up and the controller suffers to clear the fault for less than one second and then it was able to reset the stability.

The incremental conductance MPPT algorithm maintains a stable DC-bus voltage (498.1 V) across wide irradiance variations from 1000 W/m² to 300 W/m², outperforming conventional P&O methods, which suffer oscillations under dynamic conditions. The d–q VSC control achieves THDi = 1.45%, eliminating the need for auxiliary filtering, unlike the 50 MW Dhofar wind farm, which required shunt active filters. Compared with prior Oman studies, the 128 kW system demonstrates superior control resilience with voltage stability during transients, whereas a 6 MW installation experienced 43.5% performance losses due to internal failures. The sensitivity analysis confirms that properly tuned classical MPPT combined with d–q VSC provides a practical balance between performance and implementation simplicity, making it suitable for distribution-level PV deployment in Oman's renewable energy roadmap.

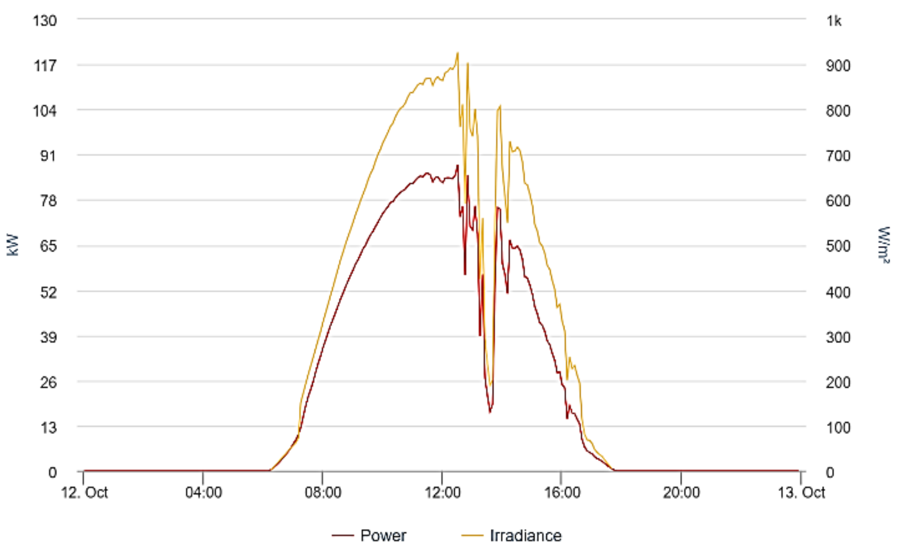

Figure 11. Impact of the sudden drop in solar irradiances on the generated power from solar system

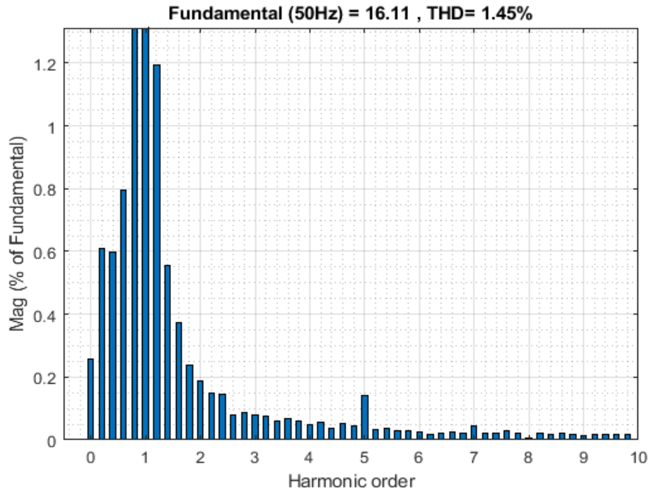

Figure 12. FFT Analysis of the THD of the grid injected current

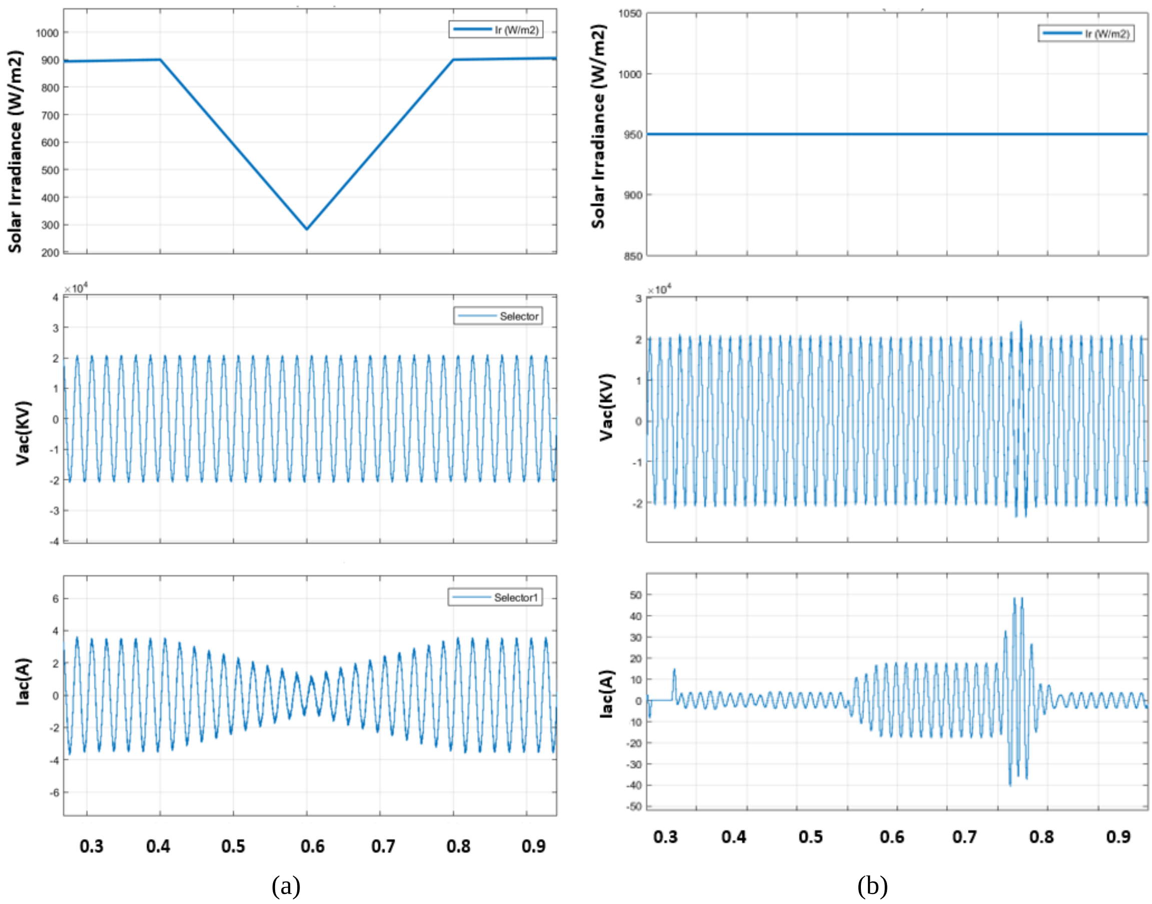

Figure 13. Performance of the solar system at (a) voltage sagging and (b) sudden load change

5. CONCLUSION

In this paper, a MATLAB/Simulink model was developed to examine the voltage stability and power quality of the power injected from a 128 kW solar grid-connected system into a local distribution network in Oman. The PV system is interfaced through four DC/DC boost converters controlled by an incremental-conductance-based MPPT algorithm, which successfully maintains a stable DC-link voltage over a wide range of solar irradiance conditions. The model was also evaluated under transient conditions associated with sudden weather changes, and the results confirm the effectiveness of the d–q control technique in injecting high-quality power into the grid.

The grid code requirements were satisfied, as the THDi of the injected current was limited to 1.45%, indicating that no additional filtering is required. Although the present work is purely simulation-based and does not include field measurements, it provides power quality insights that support Oman's renewable energy roadmap targeting a 30% contribution from renewables by 2030. Advanced mitigation techniques for PQ issues, such as those considered here, can enable reliable and efficient integration of solar and other renewable resources into the main interconnected system (MIS), enhancing overall system efficiency, reducing losses, and supporting the national economy. Future work may focus on extending the study with hardware-in-the-loop or field validation, as well as integrating artificial intelligence–based control strategies and energy storage systems for smarter grid interaction. In addition, the outcomes of such studies can inform the development of updated national policies and inverter standards aligned with international frameworks such as the IEEE 1547 series and IEEE 2800, while fostering local expertise and attracting further international investment in the Omani renewable energy sector.

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AUTHOR CONTRIBUTIONS STATEMENT

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Rashid Al-Abri	✓						✓			✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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