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Assessment of a single-phase single-stage grid-connected photovoltaic system

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ABSTRACT

A grid-connected photovoltaic (GCPV) system plays an important role in the development of green technology. However, generated photovoltaic (PV) power that is injected into the grid causes instability in the grid system. Previous studies have shown that power quality for a three-phase system is thoroughly being discussed, but not for a single-phase system. Single-phase system also contribute to instability in low-voltage grid networks during high power penetration as majority of the single-phase GCPV nowadays are installed on rooftops. Thus, in this study, the power quality of a single-phase single-stage GCPV system is investigated based on the total harmonic distortion (THD), power factor (PF), and the generated active (P) and reactive (Q) power during different solar irradiance and varying loads conditions. A model of the GCPV system was developed in MATLAB/Simulink, so that certain variables can be varied to observe their effect towards the power quality. The results show that the current and voltage of generated PV power are synchronized and having low current THD which is less than 1% for all cases. PF values are also in the acceptable range in compliance to IEC 61727 standard which is 0.9971, and the generated PQ is in accordance to the connected load.

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1. INTRODUCTION

Grid-connected photovoltaic (GCPV) system has gained the attention of researchers in recent years due to the lack of stand-alone photovoltaic (PV) systems that are only operable during day time [1]. Moreover, PV systems with battery storage are more expensive and have shorter lifespan compared to GCPV [2]. However, to inject the generated PV power into the utility grid, there are challenges arise due to the intermittent characteristics of the PV system. Among major problems caused by GCPV system are voltage rise in low-voltage networks under increasing solar penetration levels [3], voltage fluctuation due to rapid changes in the power output of PV system [4], harmonics current introduced by the nonlinear loads [5], active and reactive power control to synchronize with the main grid and the local load [6], and transient and distortions in injected current due to mismatching in the frequency between supply and demand [7].

To investigate the power quality of generated PV power, the GCPV model is developed in a simulation environment so that certain variables can be varied to observe their effect on the power quality [6]. Simulation of GCPV performance under different scenarios would provide useful information to researchers in designing an optimal GCPV system. In previous research, power quality of the injected PV power is being discussed in

[7]. Varying parameters assessed were total harmonic distortion (THD) [8], [9], inverter power factor at different solar irradiance [10], active and reactive power at different solar irradiance [1], [11], direct current (DC) link voltage [10], and synchronisation of grid voltage and current [6], [7]. Meanwhile, Benaissa *et al*. [12] explored on the used of voltage source converter to DC link voltage and grid current components. However, the previous literature focused more on three-phase GCPV system. Despite the fact that a single-phase GCPV system is normally being used in small scale rooftop configuration connecting to low-voltage (LV) distribution network [13], [14], it also contributes towards the instability of grid system especially during high power penetration level.

Performance of the single-phase GCPV system has also been explored by [15]–[18]. Ridzwan *et al*. [15] proposed modified p-q theory control algorithm for a single-phase GCPV based distribution static compensator (DSTATCOM). The modification was based on the p-q theory of a three-phase GCPV system. Diouri *et al*. [16], a GCPV model was proposed using back-stepping control (BSC) in standalone mode. The model was a single-phase double-stage transformer less. The double-stage model needs two separate BSC to control the boost converter and inverter. Muhammad *et al*. [18] applied acceptance ratio (AR) parameter to develop early fault detection and maximize the performance of GCPV system. The actual and calculated AR were then compared and the percentage error between the two values were examined. Zarkov *et al*. [17] compared between simulated and experimental values of current injected to the grid. In their study, a special measurement to compensate the grid voltage distortions was needed to keep the current THD as low as possible. Alhafadhi and Teh [19] reviewed different techniques to reduce THD values in GCPV systems. The causes of harmonics were also investigated in detail. They also suggested the use of adaptive filters for THD reduction [20]. However, the adaptive filter highly depends on the filtering coefficients. Poor selection of filtering coefficients values resulting in high THD values. Furthermore, the THD values obtained from literatures are high, exceed the standard of IEC61727. Khomsi *et al*. [5] proposed the use of proportional - resonant (PR) controller as the current controller to reduce THD introduced by the nonlinear load. Mehrabani and Aalami [21] investigated PV system that was used to feed a single-phase induction motor (SPIM). THD values of input voltage and input current for different solar irradiance were explored. It was found that the THD of SPIM with start-run capacitor is less than SPIM with run capacitor.

In Malaysia, the power quality guidelines are which in accordance to IEC 61727 standard. For low voltage single-phase GCPV system, the nominal voltage is 230 V with steady state voltage limits at +10% and -6%. Voltage fluctuations may occur due to the changing solar irradiance throughout the day. The maximum voltage fluctuation allowed is 6%. Meanwhile, flicker voltage occurrence is due to rapidly changing loads that cause fluctuation in the customer’s voltage. THD parameter is measured at point of common coupling (PCC) and must be less than 5%. Another important parameter is power factor that is the ratio between the active power to the apparent power and must be greater than 0.9. Thus, in this study, a single-stage single-phase GCPV model is developed and performance of the output signal generated by the system is then assessed by observing the PV and grid parameters at different solar irradiance and different loads. Power quality of the injected PV output is also assessed based on the active and reactive power, THD and power factor.

2. METHOD

The developed single-phase single-stage 7.8 kWp GCPV model consists of a PV array, a maximum power point tracking (MPPT), inverter, filter, phase locked loop (PLL), controller, grid and load as shown in Figure 1. The PV array comprises 30 units of 260 Wp PV modules with the specifications as in Table 1. To produce grid voltage, $V_{grid,rms}$=230 V, the minimum solar PV output voltage, V_{pv}, must be greater than or equal to the minimum DC bus voltage, $V_{DC,min}$ in (1). Assuming that the total voltage drop across the filter and inverter is 20% of grid peak voltage, $V_{grid,pk}$ =325 V, which is equal to 65 V, the minimum required voltage of the PV array is $V_{DC,min}$ =390 V. So, from Table 1, these PV modules can be arranged in 2 parallel strings with 15 series-connected modules for each string and connected to solar controller MPPT that regulates the voltage from solar PV to produce a voltage at maximum power point, V_{mpp} =466.5 V.

$$V_{DC,min} = \left(V_{grid,rms} \times \sqrt{2}\right) + V_{drop} \tag{1}$$

MPPT is able to extract maximum power at different solar irradiance. The most popular MPPT algorithms used are perturb and observe (P&O) and incremental conductance (INC). These two methods have been discussed in detail in [22] and INC method is proven to be more accurate compared to P&O method. Thus, this paper developed MPPT model based on INC method. The P-V curve for PV array used in this model shown in Figure 2 at three different solar irradiances. These values can be used to validate the maximum power obtained from simulation model.

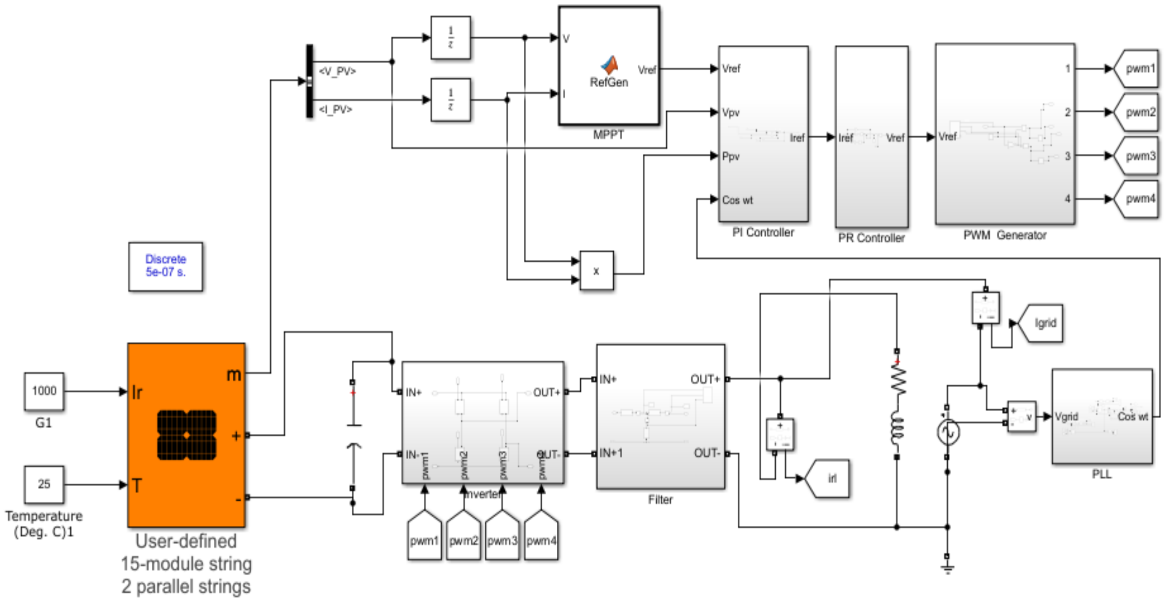


Figure 1. A block diagram of GCPV model in MATLAB/Simulink

Table 1. The specification of PV module

Parameters	Value
Maximum power point voltage, V_{mpp}	31.1V
Maximum power point current, $I_{,mpp}$	8.37A
Short circuit current, I_{sc}	8.98A
Open circuit voltage, V_{oc}	38.1V

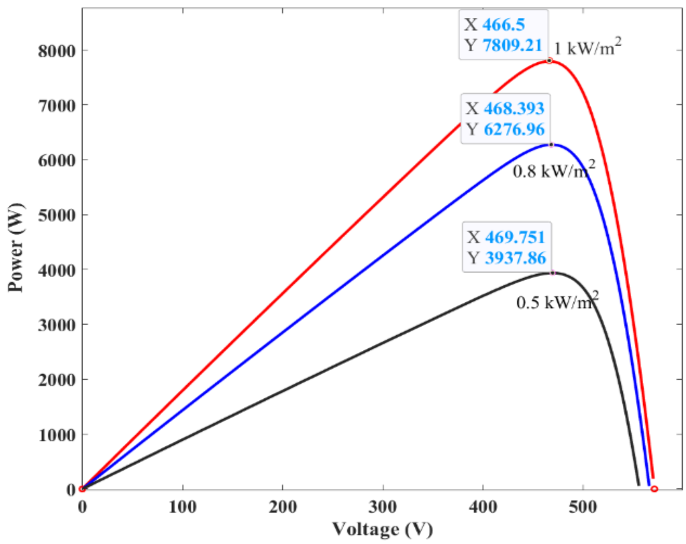


Figure 2. P-V curve for PV array used in the simulation

Single-phase inverter is controlled by four IGBT gate units similar to [23] to convert V_{pv} in DC to AC form. The output of inverter may have some harmonics and must be filtered. In this study, a passive LCL circuit is used for the harmonic's compensation. To determine the value of capacitor and inductors used in the filter, the following equations are used [24]:

$$C = \frac{5\% \times S}{2 \times \pi \times f \times V_{grid,rms}^2} \tag{2}$$

where 5% is the allowable reactive power absorbed at the rated power condition, S=7.8 kVA, and f is grid frequency at 50 Hz. To compute the inductors' value, the following equations are used [24]:

$$L_1 = \frac{V_{mpp}}{4 \times F_{sw} \times \Delta I_{pp,max}} \tag{3}$$

where L_1 is the inductor at the inverter side, F_{sw} is switching frequency that is fixed at 10 kHz, $\Delta I_{pp,max}$ is maximum permissible ripple current which set at 20% of rated current. The rated current, I_{rated} can be calculated from S and $V_{grid,rms}$, then $\Delta I_{pp,max} = \sqrt{2} \times 20\% I_{rated}$. The total inductance is selected based on the maximum voltage drop across the inductor that is limited to 10% of rated voltage [24].

$$L_1 + L_2 = \frac{10\% \times V_{grid,rms}^2}{S \times 2 \times \pi \times f} \tag{4}$$

Using the (2) to (4), the calculated C=23.49 uF, L_1 =1.241 mH and L_2 =0.942 mH were used in the model.

The next component is a phase lock loop (PLL) that is used to synchronise voltage and current injected into the grid. In this model, the grid voltage is taken as input and produced output angle, θ that is always aligned with the grid voltage to be used in generating active current reference signal [24], [25]. The controller consists of voltage controller and current controller. The voltage controller uses PI controller that takes the input parameter V_{ref} produced by the MPPT model. The controller produces I_{ref} which becomes the input to the PR controller that is used as a current controller. The voltage produced by the PR controller will then determine the pulse width modulator (PWM) generator that controls the four IGBT switches in the inverter. The power quality produced by the GCPV model is observed by varying the solar irradiance and the load. Power factor (PF) can be calculated from active power, P (W) and apparent power, S (VA), where Q is reactive power in (VAr).

$$PF = \frac{P}{S} = \frac{P}{\sqrt{P^2+Q^2}} \tag{5}$$

Total harmonic current distortion at PCC is measured at inverter output before the current flows into the load and the grid. This value is obtained using fast fourier transform (FFT) analysis tool provided in MATLAB/Simulink. The THD value is commonly represented by the following equation:

$$THD = \frac{\sqrt{\sum_{n=2}^{k} f_n^2}}{f_1} \tag{6}$$

where f_1 is the fundamental frequency magnitude module, n is harmonic order, k is the last harmonic order and f_n is the quantity module in the harmonic frequency.

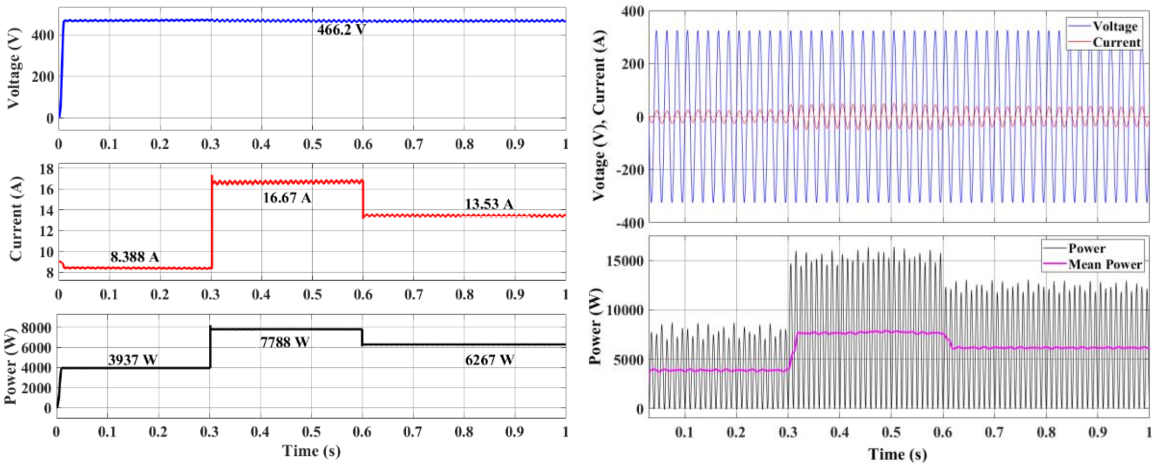
3. RESULTS AND DISCUSSION

This section discusses performance of the developed model. First, the results show the PV and grid parameters without any load connected to the system at different solar irradiance values. Then, the results with resistive, inductive and capacitive loads are discussed at fixed solar irradiance, $G = 1000\ W/m^2$.

3.1. GCPV performance at different solar irradiance

Figure 3 shows three important parameters which are power, voltage and current at input and output of the developed GCPV model. By changing the GCPV input, which is the power generated by PV modules, the GCPV output on the grid will also change, accordingly. At the input side, Figure 3(a) shows the PV output voltage, current and power at $G = \{500{,}1000{,}800\}\ W/m^2$ at $t = \{t < 0.3\ s, 0.3\ s < t < 0.6\ s, t > 0.6\ s\}$, respectively. From the figure, the PV current is highly dependent on the solar irradiance and thus the power. However, the voltage is almost constant at V_{mpp}, with the average of 466.2 V. At $G = 1000\ W/m^2$, the PV power generates almost 7.788 kW. The results were validated using the P-V curve shown in Figure 2, and the model is working satisfactorily at the maximum power point for different solar irradiances.

At the output side, the grid voltage, current and power are plotted as depicted in Figure 3(b). The synchronisation between grid current and voltage is apparent and the mean power injected into the grid at $G = \{500{,}1000{,}800\}\ W/m^2$ were $P_{mean} = \{3.855, 7.679, 6.138\}\ kW$, respectively. Comparing the power values at input and output side of the inverter, a small reduction was anticipated due to the losses in the inverter which has an efficiency of almost 98%. The THD of the output signal during no load produced by the model is 0.92% which is generally low and satisfies the condition as shown in Figure 4.



(a) (b)

Figure 3. Power, voltage and current of (a) PV and (b) grid parameters at different solar irradiance

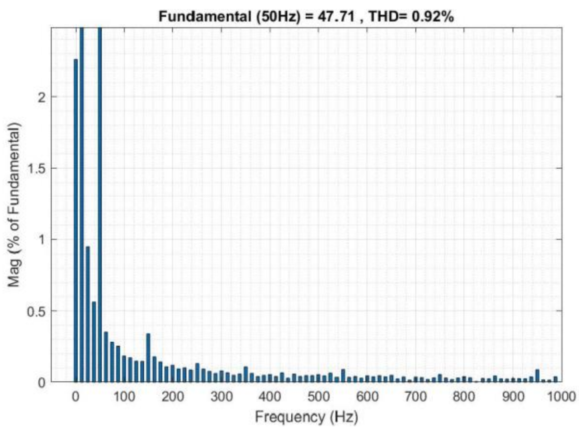


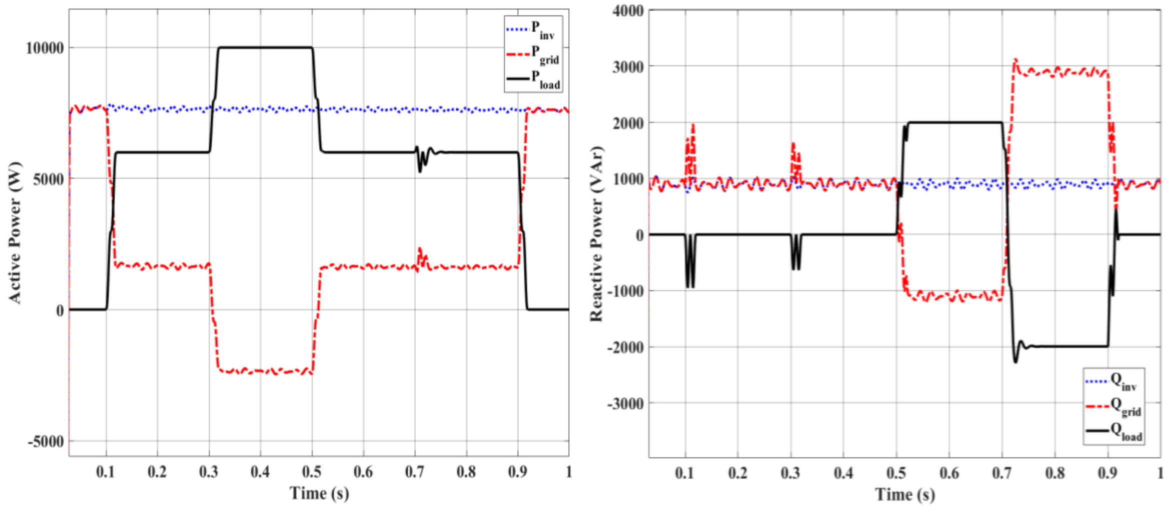
Figure 4. THD value during no load

3.2. GCPV performance at different loads

In this section, different loads consuming different powers are varied at different times shown in Figure 5. At $0 < t \leq 0.1\ s$ the load is zero, at $0.1 < t \leq 0.3\ s$ the load is 6 kW, at $0.3 < t \leq 0.5\ s$ the load is 10 kW, at $0.5 < t \leq 0.7\ s$ the load is 6 kW+2 kVAr, at $0.7 < t \leq 0.9\ s$ the load is 6 kW–2 kVAr, and back to zero load at $t > 0.9\ s$. The active power, reactive power and power factor for these loads are plotted in Figure 5(a), Figure 5(b) and Figure 6, respectively.

From Figure 5(a), it is obvious that during active power load $P_{load} = 0$, the power generated from PV system is injected directly into the grid. When the $P_{load} = 6\ kW$, with or without reactive load, the PV system supplies the power to the load, and the excess power is exported to the grid. When the load consumed more active power than the generated PV power at $0.3 < t \leq 0.5\ s$, both PV and the grid will supply power to the load.

Figure 5(b) shows that during no load and resistive load which means $Q_{load} = 0$, the reactive power produced by inverter is $Q_{inv} \approx 0.8942$ kVAr. This reactive power is generated because of the inductive and capacitive components in the filter. At this state of symmetrical system, the reactive power from GCPV is absorbed by the grid as seen from 0 to 0.5 s in Figure 5(b). Then, at 0.5 s, the load is activated with demand of the reactive power, $Q_{load} = 2$ kVAr in which the load demand is fulfilled by the grid generator at about the same amount. Later, a sudden change of load with a total amount of -4 kVAr occurs which is compensated by the grid at the same amount. When an inductive power load is activated at $Q_{load} = 2$ kVAr, both inverter and the grid will supply reactive power to the load. For a capacitive load $Q_{load} = -2$ kVAr, the grid supplies reactive power of the same amount (2 kVAr) while absorbing another 1 kVAr reactive power from the solar PV.



(a) (b)

Figure 5. Different types of power (a) active power and (b) reactive power at different loads

The power factor for different cases are plotted in Figure 6. The range of PF_{inv} is 0.9909 to 0.9952 in all cases. Meanwhile, PF_{load} shows fluctuation while transitioning from no load to with load and vice versa. PF_{grid} is almost 1 when the grid receives power from PV system, and almost -1 when the grid supplies the power to the load. The worst case of PF_{grid} is at $0.7 < t \leq 0.9\ s$ because the grid supplies more reactive power than active power to the capacitive load.

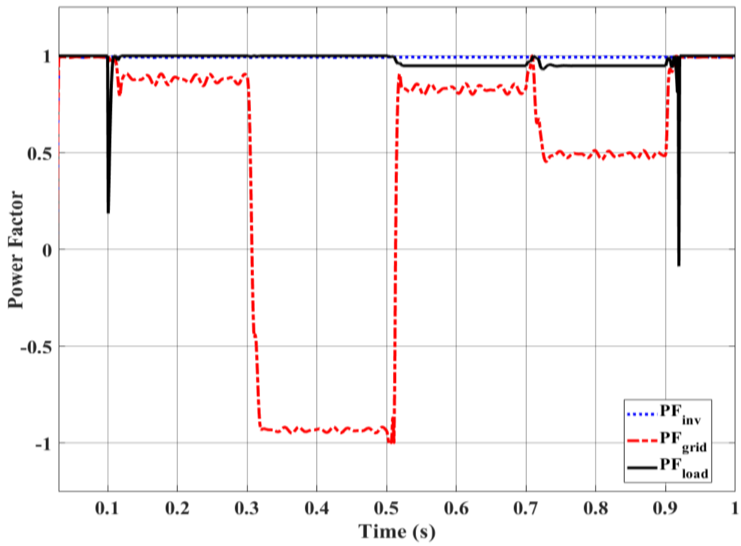


Figure 6. Power factor at different loads

Figures 7 show total harmonic current distortion at PCC during load variations. Figure 7(a) and (b) show THD values for resistive load with low and high-power consumption compared to the rated power, respectively. Meanwhile, Figure 7(c) and (d) illustrate the THD values during inductive and capacitive load. It can be seen that the THD values are varied with different loads, and the values are <5% for all conditions. Thus, THD values satisfying IEC 61727 standard for all conditions.

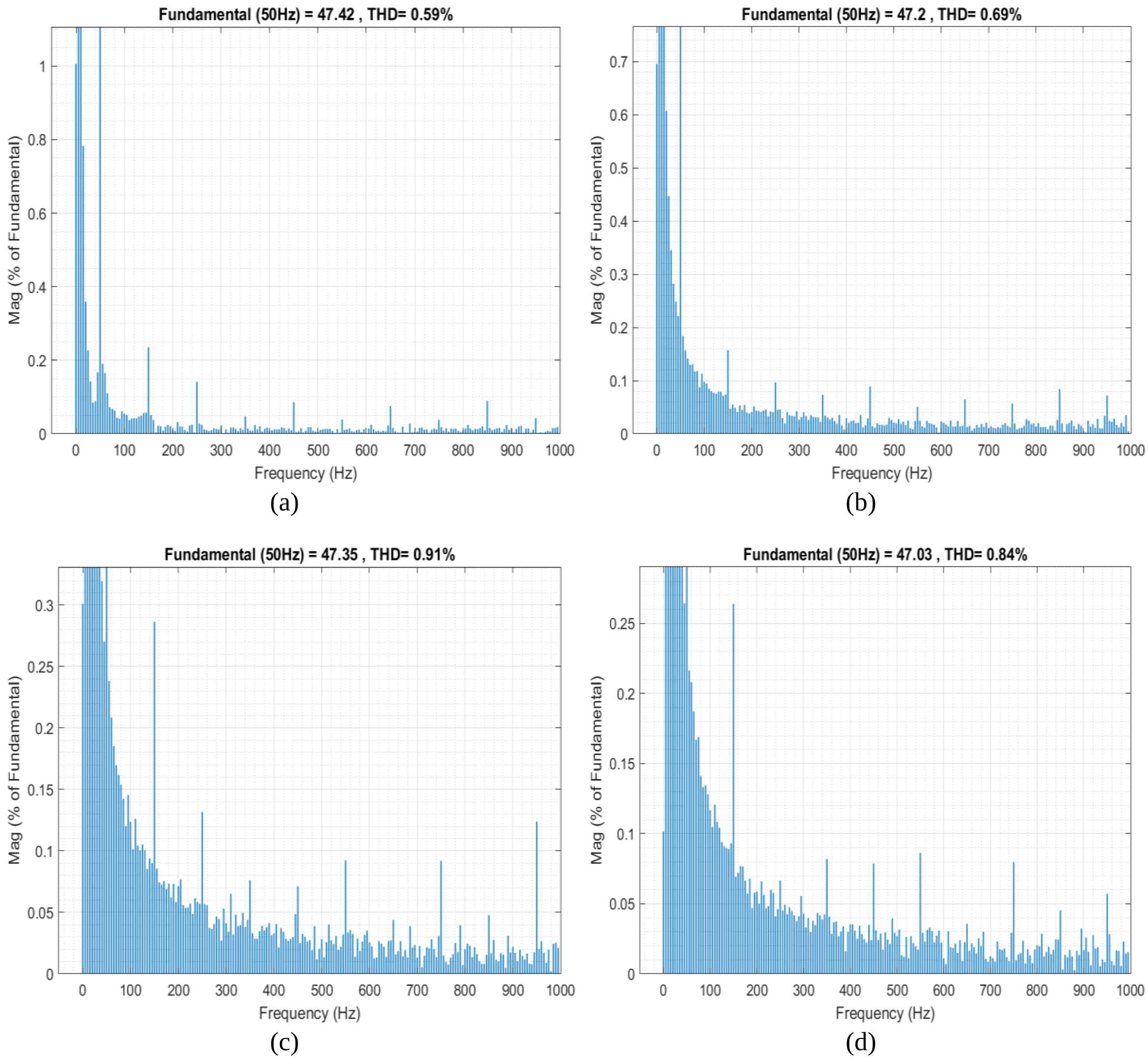


Figure 7. THD values at (a) 0.1 $< t \leq$ 0.3 s for R=6000 Ω (b) 0.3 $< t \leq$ 0.5 s for R=10000 Ω (c) 0.5 $< t \leq$ 0.7 s for R=6000+j2000 Ω and (d) 0.7 $< t \leq$ 0.9 s for R= 6000-j2000Ω

4. CONCLUSION

Performance assessment of a single-phase single-stage GCPV model developed in MATLAB/Simulink was carried out based on a few parameters. From the results of power generated at different solar irradiance, the model generates power at almost theoretical values. The small loss was expected, drawn by the inverter. The synchronisation of AC current and voltage was also observed. THD values were minimal and met the standard for different load conditions. Active and reactive power for different types of loads worked as expected. The power factors were almost unity in most cases.

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