# Analysis of total harmonic distortion in single-phase single-stage grid-connected photovoltaic system

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**ABSTRACT**

This study presents the power quality issue mainly focus the effect of total harmonic distortion (THD) on a grid-connected PV system. Firstly, a grid-connected PV system with a single-phase single-stage has been developed to monitor the output values of voltage and current and also its harmonic distortion behaviours. Maximum power point tracking (MPPT) was implemented since it is proven as the first step for THD reduction because MPPT will extract maximum output power, voltage, and current of the PV system without fluctuation which leads to a low THD level. Furthermore, the employment of a good filter also reduces the THD level in a PV system. Thus, this study will focus on the THD analysis to resolve the power quality problems in the grid-connected PV system. The result shows that the THD value for current, $I_{THD}$ analysis is more significant than the THD value for voltage, $V_{THD}$ analysis in the case of grid-connected PV systems operating under different solar irradiances. In a conclusion, the increase in solar irradiance will increase the rated values of generated power and current thus, increasing the performance of THD values.



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## 1. INTRODUCTION

The increase in demand for clean energy and the awareness about global warming has been growing with alternative sources, especially on the use of renewable energy (RE). Renewable energy usage recorded that installed power capacity expand more than 200 gigawatts (GW) in 2019, and solar photovoltaics (PV) was the highest implementation as compared to the other RE sources. However, the emergence and speedy spread of COVID-19 that started in late 2019 had become a worldwide pandemic by early 2020. As a result, this pandemic had caused health issues and economic crises all over the world [1]. Furthermore, the energy sector including RE also affected due to this crisis. The conventional non-renewable sources will give effects on the environment such as carbon dioxide, carbon monoxide, sulphur dioxide, and many more [2]. Thus, the installation of renewable energy systems on medium and low-voltage distribution networks is gaining popularity [3]. The use of PV systems, which are safe, clean, highly reliable, and abundantly available from the sun's source of energy, has rapidly grown across the globe [4]–[6]. Referring to World Energy Outlook, 2020 reports [7], the generation of photovoltaic power will increase gradually until 2040, thus results in the highest renewable energy usage as compared to the other forms of energy.

In grid-connected PV systems, single-stage, double-stage, and multi-level are commonly applied in solar PV systems [8]–[11]. Typically, the PV system interface from the DC source to the load, then to the grid comprises of a double-stage converter that involves DC/DC converter and the DC/AC converter, which is also known as an inverter. Nevertheless, the common solution with a double-stage inverter requires several additional devices which cause high implementation cost, sluggish transient response, and also conduction losses. Hence, previous researches discover that single-stage inverters have high efficiency, a lower price, and are easy to implement [12]. However, the moving innovation of PV in distribution systems causes issues on the power quality system [13]–[15]. To solve the problems, there were many different connection topologies and connection strategies presented by previous researchers to solve THD generated by the converters and inverters of the PV system [16], [17]. As a summary, power quality issues such as total harmonic distortion (THD) is important to analyse in order to monitor the performances of the electric network in the grid-connected PV system.

The importance of THD and different ways to reduce THD at different stages in PV system has been discussed thoroughly in [18] and the references therein. A new method of THD reduction using adaptive filter also has been proposed recently in [19]. The percentage of reduction before and after using the proposed filter in [19] was high, more than 70%, however, the adaptive filter highly depends on the filtering coefficients. Poor selection of filtering coefficients values resulting in high THD values. Furthermore, the most important point to be taken into account in THD analysis is the THD value must comply to the utility grid standard which is less than 5% [5], [20].

In this particular study, solar irradiance was varied in order to examine the performances of the PV system under THD analysis. Hence, a PV system model has been developed to monitor the values of current and voltage, and also its harmonic distortion behaviours. Based on the literature, previous researches proved that PV system output power results in proportional relationship to the different solar irradiance [21]–[23]. Firstly, incremental conductance (IC) algorithm was developed in maximum power point tracking (MPPT), then the maximum value was used as inverter input. MPPT techniques are proven as the first step for THD reduction because MPPT will extract maximum output power, voltage, and current from the PV system without fluctuation which leads to low THD level [18], [23]. Next, the selection of power electronic components of single-stage single phase inverter was chosen before connected to a low pass LCL filter. Many literatures agreed that the use of the filter demonstrates less THD than before filtering [2], [6], [17].

## 2. METHOD

In this topic, the simulation of the PV model, the development of MPPT and implementation of single-phase inverter with LCL filter will be discussed and illustrated in detail. The specifications of the PV module at standard test conditions (STC), was measured at the fixed solar irradiance of 1000 W/m$^2$ and ambient temperature of 25 °C is shown in Table 1.

Table 1. PV module characteristics for a module

| PV module | Specifications |
|---|---|
| Type of cells | Polycrystalline |
| STC power rating | 260.307 Wp |
| Peak efficiency | 15.89% |
| Number of cells | 60 |
| Maximum point voltage, $V_{mp}$ | 31.1 V |
| Short circuit current, $I_{sc}$ | 8.98 A |
| Maximum point current, $I_{mp}$ | 8.37 A |
| Open circuit voltage, $V_{oc}$ | 38.1 V |
| Temperature coefficient of $P_{max}$ | -0.40%/ °C |
| Module dimension | 1650 × 992 mm$^2$ |
| Lifetime | 21-25 years |

### 2.1. Grid-connected PV system

In grid-connected PV system, the simulation of the PV array was done using MATLAB/Simulink software based on the specification of the research project. This study applied single phase single-stage grid-connected PV system where it comprised of PV array of double parallel strings, each consist of 15 modules which connected in series. Figure 1 illustrates the schematic diagram of the grid-connected PV system implemented in this study. Referring to Figure 1, there were several parts involved which includes PV array, MPPT, single phase inverter which include inverter control, LCL filter, and lastly, distribution grid. In this study, the system applied MPPT directly to the inverter, without DC boost converter. This part is important to extract the maximum available power from the PV array. Then, DC link capacitor was connected between the output of the PV array and the input of the inverter. In addition, the LCL filter used in the study was connected to the output of the inverter hence, the measurement of voltage, current and power will be observed in the distribution grid. The MPPT was implemented with a simple control algorithm, which is IC method so that the maximum values are taken directly from the PV current and PV voltage [12], [24]. This step was applied to maintain the stability and robustness of the system. The output of the MPPT controller, $V_{DC} = V_{PV}$, is extracted to the DC bus controller to regulate the appropriate voltage for MPPT, which known as $V_{ref}$. After that, the research study was continued with the development of an inverter where single phase with a single-stage inverter was developed. At this point, $V_{ref}$ obtained from MPPT was injected to single phase inverter, together with voltage across DC link capacitor of 5000 µF. Then, a low pass LCL filter was employed in order to eliminate harmonic distortion in the output waveform. Note that, a phase-locked loop (PLL) was applied in the controller for the harmonization between the grid current with the grid voltage. After the filtering process, all models were combined, and the results should be obtained with a better sinusoidal output waveform that was similar to the grid output. To make it clearer, the diagram of simulation system was shown in Figure 2.

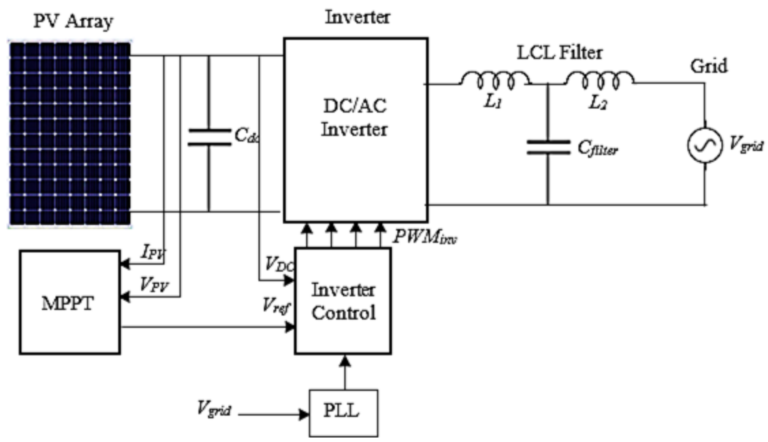



Figure 1. Schematic diagram of single-phase single-stage PV system

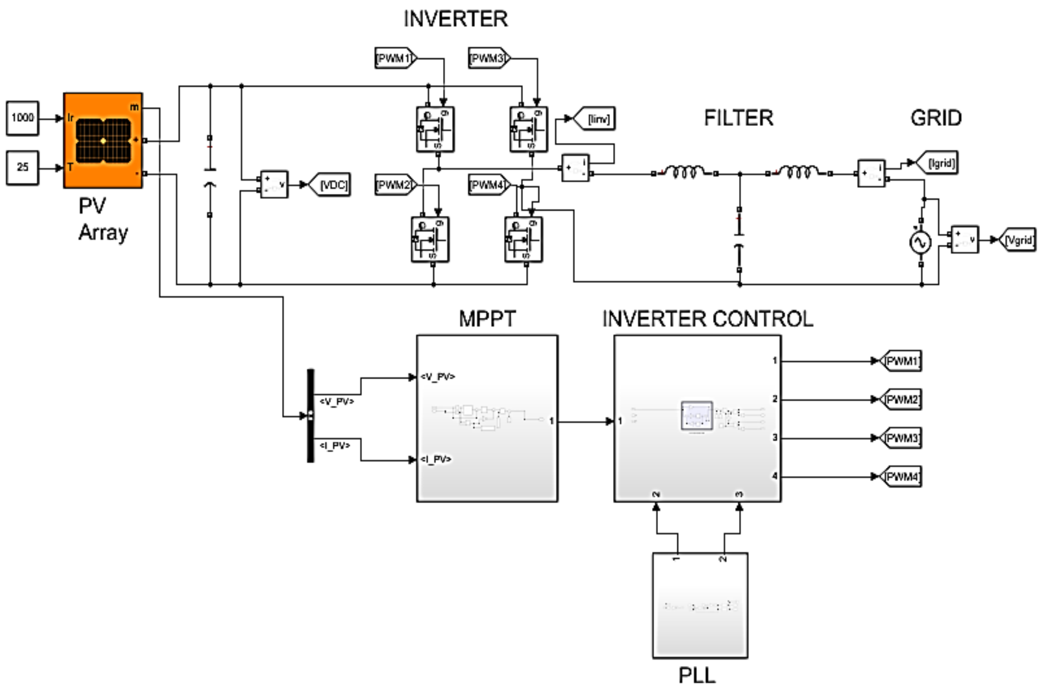



Figure 2. Simulation diagram of single-phase single-stage PV system

### 2.2. Harmonic distortion

Harmonic distortion is a major power quality issue in an electrical power system. It is defined by a distortion of a regular current and voltage waveform that is subsequently corrected back to its actual shape or properties. Harmonic distortion is most commonly induced by intrinsic effects from nonlinear loads, rectifiers, transformers, power converters, and rotating machines [25]. Meanwhile, extrinsic effect such as weak and distorted connection to electrical grid also give impact to the harmonic behaviours. Moreover, the fluctuation of solar irradiance and temperature also affected the harmonic distortion in PV system.

As stated by many research before, PV systems are made up of many power-electronic components that cause distortion, and inverters, which are the most important component in grid-connected PV systems, are no exception. The efficiency and quality of the energy supply are two of the most essential qualities of the grid-connected PV systems. As a result, the distortion occurs in current and voltage waveforms can be used to investigate the quality behaviours of the power supply. Total harmonic distortion (THD) is important in order to measure the harmonics in the power system. The THD for current and voltage observed in a waveform indicate the harmonic distortion of the system. THD is referred as the ratio of the equivalent root mean square (RMS) voltage or current of all the harmonic frequencies over the RMS voltage or current of the fundamental frequency. The equation were expressed as (1) [26].

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{k} h_n^2}}{h_1} \quad (1)$$

Where the effective value of the harmonic orders *1, 2, 3, …, k* was represented by $h_2$, $h_3$, …, $h_n$. Meanwhile, fundamental component was denoted by $h_1$. The $n$ in the equation refers to the harmonic order whereas, $k$ be the last harmonic series. In addition, overall harmonic distortion is 0 which represents perfect sinusoidal wave. Furthermore, more specific metrics for quantitative examination of the components, such as current and voltage distortion in percentage using the equations follows, respectively [26]:

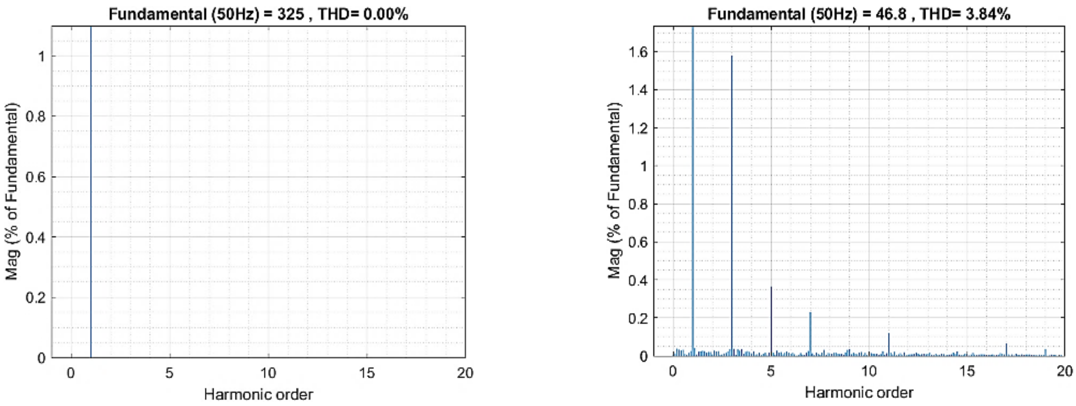
$$V_{THD}\% = \frac{\sqrt{|V_2|^2 + |V_3|^2 + |V_4|^2 + \ldots}}{|V_1|} \times 100\% \quad (2)$$

$$I_{THD}\% = \frac{\sqrt{|I_2|^2 + |I_3|^2 + |I_4|^2 + \ldots}}{|I_1|} \times 100\% \quad (3)$$

Normally, in grid-connected PV system, the output voltage and grid voltage signal should be harmonized, also the waveform of the current measurement should be as perfect sinusoidal waveform, as possible. As a result, the grid integration of PV systems must adhere to specific standards in order to limit the effects of THD on the utility grid [20], [27], [28]. From the abovementioned standards, inverters should have a $I_{THD}$ not exceed 5%, which focusing on the Malaysian grid. Furthermore, grid-connected PV system with output voltage at 400 V and less, a THD should not more than 5% [5], [20]. Hence, these percentage benchmark will be considered as the reference in the study analysis.

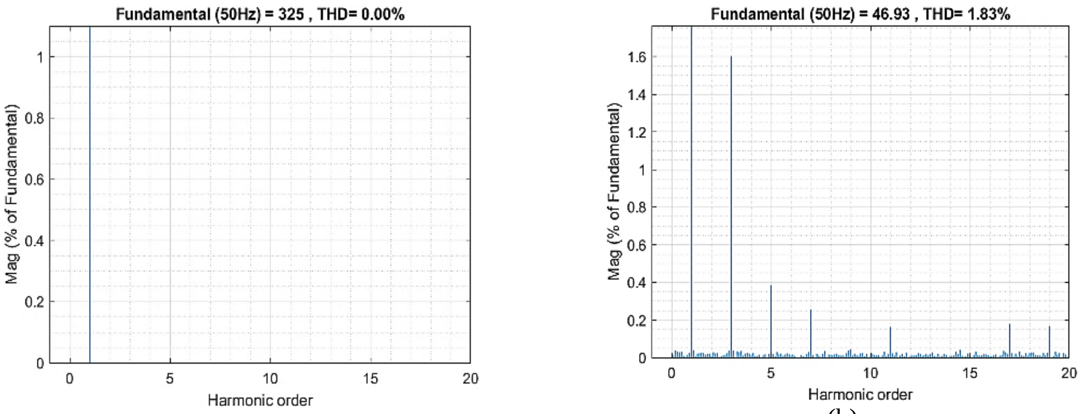
## 3. RESULTS AND DISCUSSION

In this section, the results of the THD level will be discussed in detail. To ensure that other equipment connected to the grid is not affected, the PV system's output measurements should have as minimum THD values, as possible either for current or voltage. In this study, the Fast Fourier Transform (FFT) tool found in MATLAB/Simulink was used to capture the THD for both output current and voltage waveform. In the system, fundamental frequency used is 50 Hz. Furthermore, the results were analyzed with and without LCL filter. Figures 2(a) and 2(b) shows the plot of THD for voltage and current without LCL filter, respectively. The measurement of THD was taken during G=1000 W/m$^2$ and T=25 °C. From Figure 2(a), it can be seen that THD for voltage, $V_{THD}$ was 0% whereas, in Figure 2(b) THD for current, $I_{THD}$ was oscillating around 3.84%. $V_{THD}$ and $I_{THD}$ obtained were not exceed 5% which follows the standards for Malaysian grid. However, as per agreed in literature [2], [5], [18], implementing relevant filters can improve the performance of THD. Hence, this study will be implementing a filter to observe the effect on the THD level. In this case, L1 = 1.214 mH, L2 = 9.423×10e$^{-4}$ H, and Cfilter = 23.49 µF were applied in LCL filter. Hence, Figures 3(a) and 3(b) shows the results obtained after implementing low pass LCL filter. From the results, $V_{THD}$ was maintained at 0% and $I_{THD}$ observed was 1.83%, which is much lower than the previous results. The results indicate that PV system operates at low THD values with the presence of LCL filter into the system.




(a) (b)

Figure 2. THD level at STC without LCL filter (a) voltage waveform and (b) current waveform




(a) (b)

Figure 3. THD level at STC with LCL filter (a) voltage waveform and (b) current waveform

Furthermore, by comparing the plot of Figure 4, results shows that there was distortion occurred in the current waveform before using filtering and the shape of the current waveform is smoother after implementing filter to the PV system. Although there was only a small change, the results obtained proved that THD values can be improved by using a proper LCL filter to the PV system.

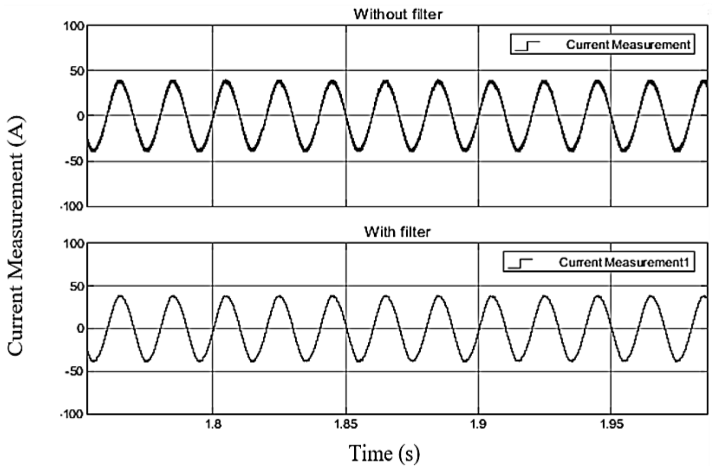
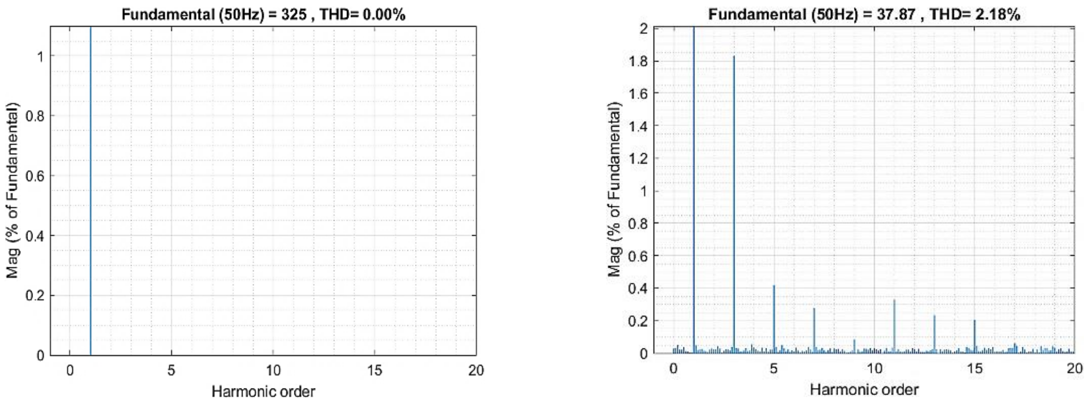



Figure 4. Current waveform without and with LCL filter

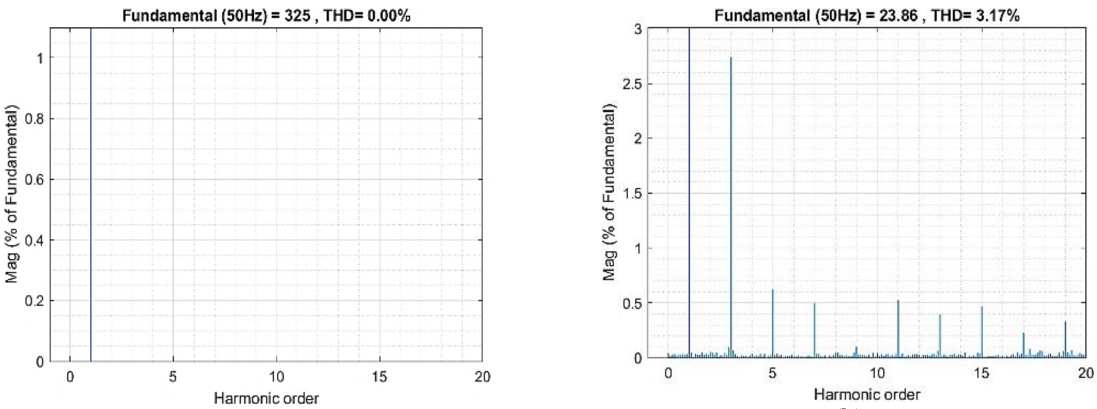
Next, PV system with filter proves that power quality issues such as THD can be resolved for better system performances. Considering about the weather condition might have fluctuated, further study was continued with the variation of solar irradiance between 800, 500, and 100 W/m$^2$ in order to validate the system and test the system's robustness. The results of $V_{THD}$ and $I_{THD}$ under different solar irradiance were illustrated in Figures 5, 6, and 7 for 800, 500 and 100 W/m$^2$, respectively. From the results, $V_{THD}$ for both 800, 500, and 100 W/m$^2$ were 0%. Meanwhile, $I_{THD}$ for 800 W/m$^2$ was 2.18%, $I_{THD}$ for 500 W/m$^2$ was 3.17%, and $I_{THD}$ for 100 W/m$^2$ was 4.72%. It can be seen that $I_{THD}$ values were increasing when the solar irradiance was decreased to 100 W/m$^2$, but still below 5% which follows Malaysian grid standards.

In summary, the lower the THD values, the better the performance of the system. On the other hand, $V_{THD}$ was constant at 0% for all values of solar irradiance. Therefore, it can be concluded that this study was focusing more on $I_{THD}$ analysis than the $V_{THD}$ analysis in the scope of grid-connected PV systems under different solar irradiances. In addition, it is noticeable that when the solar irradiance is at low, grid-connected PV system needs more current harmonics into the utility grid, as compared to high solar irradiance [6]. Moreover, the generated power and current were lower than the rated value when solar irradiance was 800, 500, and 100 W/m$^2$, as compared to 1000 W/m$^2$. Meanwhile, the generated voltage was almost maintained despite the difference in solar irradiance. Table 2 summarizes the results of generated power, voltage and current, and also THD values under different solar irradiances.




(a) (b)

Figure 5. THD level at 800 W/m$^2$ solar irradiance (a) voltage waveform and (b) current waveform




(a) (b)

Figure 6. THD level at 500 W/m$^2$ solar irradiance (a) voltage waveform and (b) current waveform

On top of that, current waveform under different solar irradiances was plotted with and without using filter in order to observe the distortion in the waveform. As mentioned earlier, overall THD level is 0% which represents a perfect sinusoidal waveform, that was happened in voltage waveform. Hence, this study was focusing more on the current waveform in order to distinguish between distortion occurred with and without using filter. Figure 8 shows the results of current waveform for 800, 500 and 100 W/m$^2$ with and without using filter. It was noticeable that the system needed more time at the beginning to reach steady state, that is the reason why the simulation took longer time under 800 W/m$^2$. From the results, it can be spotted that the distortion occurred in the current waveform without using filter was clearer than with filtering. It was shown with the 'thicker' waveform, as compared to smoother waveform obtained from system with filter. The distortion happened concluded that the system operates under low power quality. Table 2 represents the summary of all output under different solar irradiances. From the results, it can be concluded that the THD percentages for current under different solar irradiance still produces less than 5% which follows Malaysian grid standards [5], [20]. Thus, this analysis is very important in order to monitor and resolve the power quality problems in the system.

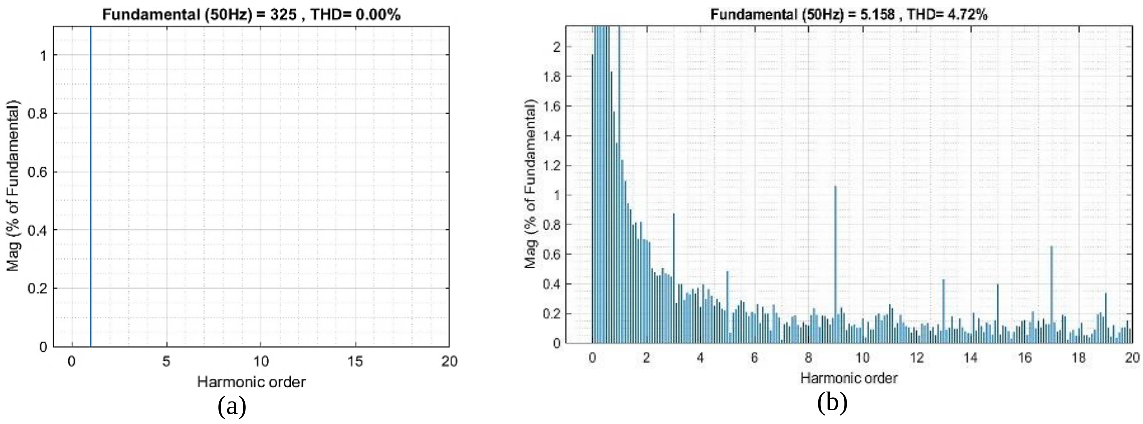



Figure 7. THD level at 100 W/m$^2$ solar irradiance (a) voltage waveform and (b) current waveform

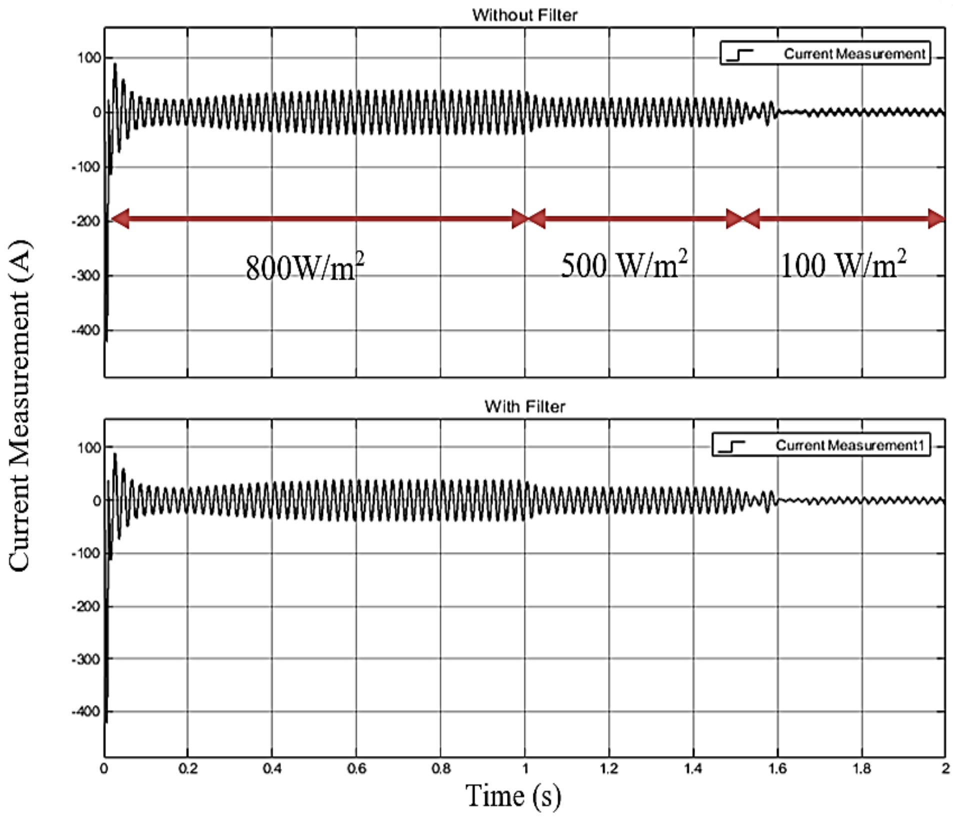



Figure 8. Current waveform under different solar irradiance without and with LCL filter

Table 2. Summary of the output under different solar irradiance

| Solar irradiance ($W/m^2$) | Power (W) | Voltage, $V_{rms}$ (V) | Current, $I_{rms}$ (A) | THD level of Voltage (%) | THD level of Current (%) |
|---|---|---|---|---|---|
| 1000 | 7742 | 229 | 33.44 | 0 | 1.83 |
| 800 | 6060 | 228 | 26.59 | 0 | 2.18 |
| 500 | 3929 | 231 | 17.02 | 0 | 3.17 |
| 100 | 767 | 231 | 4.06 | 0 | 4.72 |

## 4. CONCLUSION

As a conclusion, THD analysis is important in order to generate better performances of the PV system. Besides, THD analysis can solve power quality issue that usually happen in the system. From the results obtained, THD values show an inverse relationship to the solar irradiance. The increase in solar irradiance will increase the rated values of generated power and current thus, increasing the performance of THD. To conclude, power quality problems such as THD can be resolved with single phase single-stage inverter with proper use of LCL filter into the PV system.

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