Characteristics of harmonic distortion and disturbance in frequency 9-150 kHz of the grid-connected rooftop photovoltaic system for various types non-linear household loads

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Abstract. The usage of Photovoltaic (PV) energy system as a solar power plant has been growing rapidly in the world, because it is clean without emitting greenhouse gasses. The rapid development of power electronics technology has an impact in the development of PV system and the usage of non-linear household appliances that use inverter technology. In PV system, an inverter is used to convert direct current (DC) power from sunlight to alternating current (AC). Inverters usually have a switching rate higher than 1 kHz, which may cause waveform distortions and disturbances in AC power output, such as harmonics and disturbance in the frequency range 9-150 kHz. These disturbances may affect the performance of equipment, as well as neighbor equipment connected to the same network. This research is focused on analyzing the effect of current flowing in the non-linear household loads (induction cooker and compact fluorescent lamp) to the harmonics distortion (THDi, TDDi and harmonic voltage distortion) and disturbance in frequency 9-150 kHz on the Grid-connected Rooftop PV System by conducting laboratory measurement using a computer-based oscilloscope and power quality analyzer. The results show that the variation of current flowing in the equipment affects the harmonics distortion and disturbance in frequency 9-150 kHz.

1. Introduction

As an effort towards sustainable development in Indonesia, one of the targets that must be achieved is the availability of a sustainable energy system that is through increasing the contribution of renewable energy to the energy mix and increasing energy efficiency [1]. With the increasing demand for sustainable energy systems, this has an impact not only on increasing the number of power generation from renewable energy sources such as wind and solar, but also on reducing the consumption of electric power for existing applications [2]. On the other side, the rapid development of power electronics technology has an impact on several pieces of equipment that are using inverter technology, where one of the advantages is to make energy consumption more efficient [3].

Utilization of solar energy using photovoltaic (PV) cells is currently growing rapidly in Indonesia since the existence of government regulations at the end of 2018 that allow consumers of the state-owned company of electricity utilization (PT. PLN (Persero)/PLN) transferred electrical energy from their Rooftop PV system to the distribution network of PLN [4]. In PV systems, sunlight is converted into electrical energy using solar cells or PV cells. The electric power produced by PV cells is direct
current (DC) power, by using power inverter this DC power is converted into alternating current (AC) power which is widely used in electrical equipment and used on the PLN’s electricity network.

Current characteristics generated in PV systems and several household appliances are non-linear due to the use of inverters and other power electronic components. A non-linear device is a device in which the current is not proportional to the applied voltage [5]. Inverters usually use switching frequency in the range 9-150 kHz, that may cause waveform distortions and disturbances in the AC power output [3],[6]. This disturbance can be in the form of harmonics and/or supraharmomics [7]. Harmonics is distortion in the low frequency range (50 Hz – 2/2.5 kHz) and supraharmomics is disturbance in the high frequency range (9 kHz – 150 kHz) [7]. Both disturbances may have a negative impact on the performance of the equipment itself, as well as other equipment connected to the shared network. [8],[9]. However, the international standard has not covered enough how much emission limit in the frequency range 9-150 kHz [10].

This research is focused on analyzing the effect of induction cooker and Compact Fluorescent Lamps (CFLs) as a non-linear appliance to the harmonics distortion and disturbance in frequency 9-150 kHz on the Grid-connected Rooftop PV System. The characteristic of harmonic distortion and voltage disturbance in frequency 9-150 kHz will be observed by varying the power consumption level of induction cooker and by varying the number of CFLs in parallel. The result of this research is expected can provide a reference in finding a solution to minimize the undesired impact of the PV system and non-linear equipment on the electric power system.

2. Measurement Methodology

In this research, the experiment was carried out on the grid-connected Rooftop PV system with a 1280 Wp PV module and 1200 W grid-tied inverter. The grid-tied inverter is a special type of inverter that could feed electric power into the utility grid which can only operate when the inverter connects to the utility grid [11]. The measurement system diagram is shown in Figure 1.

![Figure 1. Measurement system diagram.](image)

Equipment under test (EUT) used in this measurement are induction cooker and CFLs. The study will observe behavior of voltage disturbance in frequency 9-150 kHz and harmonic indices by varying the power consumption level of the induction cooker and by varying the number of CFLs in parallel.

Power Quality Analyzer (PQA) is used to measure current, harmonic voltage, harmonic current, and harmonic indices. Harmonic content measurements usually use the two most common harmonic indices, the total harmonic distortion (THD) and the total demand distortion (TDD) [5]. This study
focuses on the current THD (THDi) and current TDD (TDDi) which is measured on the load side of PV system as shown in Figure 2. THDi and TDDi definitions are presented in equation (1) and (2). [5]

\[
\text{THD}_i = \sqrt{\frac{\sum_{n=2}^{\infty} I_i^n}{I_1}}
\]

(1)

\[
\text{TDD}_i = \sqrt{\frac{\sum_{n=2}^{\infty} I_i^n}{I_L}}
\]

(2)

where \(I_i\) is the RMS current of the \(i^{th}\) harmonic, \(I_1\) is the RMS value of fundamental current and \(I_L\) is the peak or maximum load current at the fundamental frequency.

At the same time as harmonic measurement by PQA, the voltage disturbance was measured by Picoscope, a computer-based oscilloscope with a differential USB oscilloscope device that can be connected to a computer. The Picoscope was connected to the load side of the system through a high pass filter (HPF) using 22 kΩ resistor and 1 nF capacitor to obtain voltage disturbance in high-frequency band as shown in Figure 2. After the measurement results were recorded in the computer, the data was processed in Matlab software by using the Fast Fourier Transform method to get the voltage frequency spectrum for the range of 9 kHz up to 150 kHz (at 200 Hz interval).

![Figure 2. Equivalent Circuit of Grid connected PV system measurement.](image)

3. Measurement Results and Analysis

3.1. Waveform characteristic for each EUT

As a non-linear load, the current flow in each EUT is not proportional to the applied voltage. Figure 3 shows the current flow in the induction cooker and CFLs is not purely sinusoidal like a voltage waveform.

![Figure 3. Voltage and current waveform of (a) Induction cooker (b) CFLs.](image)

3.2. Harmonic and disturbance characteristic when induction cooker as a load of the PV system

The measurement on the induction cooker is conducted in 6 levels of power consumption which are 100 W, 400 W, 1000 W, 1400 W, 1800 W, and 2100 W. Figure 4 shows the relationship between the
current flow in the induction cooker, THDi, TDDi and voltage disturbance generated by the induction cooker.

![Figure 4](image_url)

**Figure 4.** Measurement result when the load is an induction cooker (a) voltage disturbance in the frequency range 19 – 22 kHz (b) harmonic current distortion (1st to 50th order harmonic).

The voltage disturbance, THDi and TDDi trend in Figure 4 is an average of 5 (five) measurement results at each power level. At each level, the dominant frequency and harmonic order are selected which produces the highest voltage disturbance and harmonic voltage distortion as shown in Table 1.

**Table 1.** Maximum disturbance and harmonic distortion when the load is an induction cooker.

| Power level (W) | Load current flowing (A) | Maximum disturbance | Maximum harmonic distortion |
|----------------|--------------------------|---------------------|---------------------------|
|                |                          | Frequency (kHz)     | Voltage (mV)              | Order/Frequency          | Voltage (mV)   |
| 100            | 3.4                      | 19.8                | 1489                      | 5th/250 Hz               | 2681          |
| 400            | 3.9                      | 19.8                | 1577                      | 5th/250 Hz               | 2653          |
| 1000           | 3.9                      | 19.8                | 1623                      | 5th/250 Hz               | 2620          |
| 1400           | 5.9                      | 22.6                | 5230                      | 5th/250 Hz               | 2634          |
| 1800           | 7.5                      | 21.4                | 8427                      | 5th/250 Hz               | 2553          |
| 2100           | 8.3                      | 21.0                | 8994                      | 5th/250 Hz               | 2502          |

Figure 4 (a) and Table 1 shows that voltage disturbance in the power level 100 W, 400 W, and 1000 W relatively the same due to the similar value of current flowing (3.4 - 3.9 A). Voltage disturbance increases significantly due to the power level 1000 W to 2100 W due to the significant increase of current flowing. When the induction cooker operates in power level 1400 W to 2100 W, as the voltage disturbance increase then the dominant frequency shift to the smaller frequency. This frequency range arises as the result of the operating characteristics of the induction cooker.

Figure 4 (b) shows that the TDDi generated by the induction cooker is proportional to the amount of current flowing. As the current flowing in the induction cooker increases, the TDDi also increases. However, the TDDi relatively the same in the power level 100 W, 400 W, and 1000 W due to the similar value of current flowing. From the trend in Figure 4 (b), it can be noticed that the value of THDi is also affected by changes in current flowing, but the value is not directly proportional to the amount of current flowing. Table 1 shows that maximum harmonic voltage distortion in the PV system occurred in the 5th harmonic order. Besides the 1000 W power level, voltage distortion in the 5th harmonic order is decreased when the current flowing in the induction cooker increases.

Based on voltage disturbance and harmonic distortion characteristic related to the variation of induction cooker’s power level represented by the current flowing in the induction cooker, the relationship between voltage disturbance to the TDDi and the 5th order of harmonic voltage is obtained. The higher the TDDi, the voltage disturbance will also be high, however as the disturbance voltage increase then the 5th order of harmonic voltage is decreased.
3.3. Harmonic and disturbance characteristic when CFLs as a load of the PV system

The measurement on the CFLs is conducted by varying the number of CFLs arranged in parallel. Thus, the measured current represents the total current flowing in all CFLs. The number of CFLs that will be tested is 2 lamps, 4 lamps, 6 lamps, and 8 lamps respectively which each lamp has a power consumption of 45 W. Figure 5 shows the trend between the total current flow in CFLs, THDi, TDDi, and voltage disturbance generated by CFLs.

![Figure 5](image)

**Figure 5.** Measurement result when the load is CFLs (a) voltage disturbance in the frequency 19.8 kHz (b) harmonic current distortion (1\textsuperscript{st} to 50\textsuperscript{th} order harmonic).

Just like measurement in the induction cooker, the voltage disturbance, THDi and TDDi trend in CFLs as shown in Figure 5 is an average of 5 (five) measurement results at each number of CFLs arranged in parallel. At each combination of CFLs, the dominant frequency and harmonic order are selected which produces the highest voltage disturbance and harmonic voltage distortion as shown in Table 2.

| Number of CFLs parallel | Load current flowing | Maximum disturbance | Maximum harmonic distortion |
|-------------------------|----------------------|---------------------|---------------------------|
|                         | Frequency            | Voltage             | Order/Frequency           | Voltage                   |
| 2 pcs                   | 0.6 A                | 19.8 kHz            | 5\textsuperscript{th}/ 250 Hz | 2637 mV                   |
| 4 pcs                   | 1.1 A                | 19.8 kHz            | 5\textsuperscript{th}/ 250 Hz | 2449 mV                   |
| 6 pcs                   | 1.7 A                | 19.8 kHz            | 5\textsuperscript{th}/ 250 Hz | 2647 mV                   |
| 8 pcs                   | 2.3 A                | 19.8 kHz            | 5\textsuperscript{th}/ 250 Hz | 1998 mV                   |

Figure 5 (a) and Table 2 show the voltage disturbance tends to be higher as the number of CFLs increases, but the voltage disturbance changes relatively small. The dominant frequency is 19.8 kHz, where this frequency as the interaction result with the PV system because the inverter of the PV system has a switching frequency around 20 kHz.

Almost same as the voltage disturbance measurement result, Figure 5 (b) shows that THDi change is also relatively small along with the increasing number of CFLs. The different thing is found in TDDi. TDDi increases significantly along with the increase of current flowing in measurement point due to the increasing number of CFLs arranged in parallel. Characteristic of this TDDi value is obtained due to the formula in equation (2) using maximum load current at the fundamental frequency when the number of CFLs arranged in parallel is 8 lamps. Table 2 shows that maximum harmonic voltage distortion in the PV system occurred in the 5\textsuperscript{th} harmonic order.

Based on voltage disturbance and harmonic distortion characteristic related to the variation of the number of CFLs arranged in parallel, the relationship between voltage disturbance and TDDi is obtained, the higher the TDDi, the voltage disturbance will also be high.
4. Conclusions

The voltage disturbance and harmonics distortion in the grid-connected rooftop PV system is affected by current flowing in the non-linear equipment. The measurement results give two characteristics of voltage disturbance in frequency 9-150 kHz and harmonic distortion. The first is the relationship between the current flowing in the measurement point to the voltage disturbance and harmonic distortion (THDi, TDDi, and individual harmonic voltage). As current flowing in the measurement point increases, the voltage disturbance and TDDi also increase. In the induction cooker, THDi is not directly proportional to the amount of current flowing, but in the CFLs, as current flowing increases, THDi also increases although the change is relatively small. When the load is an induction cooker, the maximum voltage distortion of the PV system in the 5th harmonic order is decreased when the current flowing in the induction cooker increases. The second is the characteristic between voltage disturbance and harmonic distortion. From the measurement result, the higher the TDDi, the voltage disturbance will also be high. However, when the load is an induction cooker, as the disturbance voltage of the PV system increase then the 5th order of harmonic voltage is decreased. For further study, it is important to determine the internal impedance behavior of the PV system and non-linear equipment to validating the measurement results by performing the simulation.

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