Characteristics of disturbance in frequency 9-150 kHz and harmonic distortion of the on-grid rooftop photovoltaic system for resistive and inductive load

S A Kurniawan and B Sudiarto*

1Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, West Java 16424, Indonesia

*E-mail: budi.sudiarto@ui.ac.id

Abstract. Direct current (DC) electricity generated from photovoltaic (PV) needs to be converted into alternating current (AC) using an inverter so that it could be combined with electricity from the grid. However, the inverter could distort the AC waveform in the form of harmonics and disturbance in the frequency range of 9-150 kHz caused by its switching characteristics which could reduce power quality, disrupt the power line communication (PLC) system, or other electronic equipment connected in the same network. This study investigated the characteristics of the disturbances in the frequency range of 9-150 kHz generated by the on-grid rooftop PV system and observed the correlation with harmonic distortion. There were three types of load used in this study, i.e. pure resistive loads, pure inductive loads, and combination of resistive-inductive loads. The measurements were carried out using an oscilloscope to obtain a time-domain signal, which later processed by Matlab using FFT to see its frequency response, and power quality analyzer to see its harmonic distortion. The results show that each type of load has different relationship characteristics between disturbance and harmonic distortion.

1. Introduction
Energy is an essential need that has increased in use and price. These factors cause the need to use other alternative energy sources that can be renewed in a short time and have a minimal environmental impact. Solar energy is clean energy that is abundant and easy to process into electrical energy. These factors have led to the rapid development of solar power plants in the world, including Indonesia. The potential of solar energy in Indonesia is 207.898 MW, but only 78.5 MW has been utilized [1].

Photovoltaic (PV) systems are one of the most common ways to convert solar energy into electrical energy using the photovoltaic principle. The electricity produced is direct current (DC), it needs to be converted into alternating current (AC) using a device called an inverter so that it can be used on equipment that uses electricity from the utility grid [2]. An inverter is a nonlinear device in which there is a power electronic component that functions as a high-frequency switching component [3],[4]. As a result of its switching characteristics, an inverter can cause disturbances in the form of harmonics, which is sinusoidal voltages or currents that have integer frequency multiples of fundamental frequency (50 or 60 Hz) [5], and supraharmoinics, which are harmonics that occur in the frequency range of 2-150 kHz [6],[7],[8]. Inverters generally have a switching frequency in the range of 9-150 kHz [3],[4]. These disturbances will distort AC waveforms that result in reduced power quality, disrupt the power line communication (PLC) system, and disrupt other electronic equipment.
connected in the same network [9]. Until now, there is no international standard that has been set for emission limits emitted due to supraharmonic disturbances. This study investigates the characteristics of the disturbances in the frequency range of 9-150 kHz caused by an inverter in an on-grid rooftop PV system with several load variations. In addition, the characteristics of harmonic distortion generated will be investigated as well. Both observation results will be compared to see the relationship between them.

2. Fourier Theorem and Research Methodology

Fourier theorem states that an infinite sum of a pure sine or cosine wave having integer frequency multiples of the fundamental frequency, called the harmonic frequency, and different amplitudes can form a function f(x) with the period T [10,11].

\[ f(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} \left( a_n \cos \left( \frac{n \pi x}{T} \right) + b_n \sin \left( \frac{n \pi x}{T} \right) \right) \]  

Where \( a_n \) and \( b_n \) are the coefficients of Fourier series, \( a_0 \) is the first term of \( a_n \) for \( n=0 \).

\[ a_n = \frac{1}{T} \int_{-T}^{T} f(x) \cos \left( \frac{n \pi x}{T} \right) dx, \ 0 \leq n < \infty \]  

\[ b_n = \frac{1}{T} \int_{-T}^{T} f(x) \sin \left( \frac{n \pi x}{T} \right) dx, \ 1 \leq n < \infty \]

This study used pure resistive loads, pure inductive loads, and a combination of inductive and resistive loads. A laptop connected to a picoscope that is connected to a load bus via a high-pass filter is used to observe disturbance in the on-grid rooftop PV system. Data obtained from the picoscope are processed using Matlab with the Fast Fourier Transform (FFT) method to see its frequency response in the frequency range of 9-150 kHz [3]. THDv, THDi, and TDD measurements are carried out at the same time as the disturbance measurement using a power quality analyzer (PQA). The results of the measurement of disturbance that have been processed using Matlab are compared with THDv, THDi, and TDD obtained from PQA to see the relationship between them. The measurement scheme at FTUI's EPES laboratory used in this study is shown in Figure 1.

![Figure 1. Measurement’s scheme.](image)
3. Result of Measurement
Each measurement is done within 5 minutes and produced ±1000 data samples and then randomly selected 5 pieces of data to be processed using Matlab. PQA will record data at the same time as the picoscope at intervals of 1 second and it obtained ±300 data samples. Then 5 THDi, THDv, and TDD data were selected at the same time for 5 data that were processed using Matlab. Data that has been processed using Matlab and data from PQA is averaged to obtain one of the most dominant disturbance voltage value at a particular frequency, THDv, THDi, and TDD.

3.1. Pure Resistive Load
This study used 3 variations of resistance values, i.e. 220Ω, 440Ω, and 880Ω. The measurement results for pure resistive loads are shown in table 1. It can be seen that pure resistive loads have the most dominant disturbance voltage at the frequency of 19.8 kHz and the value decreases with increasing magnitude of the resistance value.

Table 1. Measurement results of disturbances and harmonic distortion for pure resistive loads.

| Load  | Disturbance (mV) | Frequency (kHz) | THDv (%) | THDi (%) | TDDi (%) |
|-------|------------------|-----------------|----------|----------|----------|
| 220Ω  | 776,969          | 19.8            | 1.374    | 3.366    | 3.366    |
| 440Ω  | 776,456          | 19.8            | 1.402    | 5.912    | 2.365    |
| 880Ω  | 776,274          | 19.8            | 1.372    | 12.114   | 2.423    |

The graphs showing the relationship between disturbance voltage with THDv, THDi, and TDD for resistive loads are shown in figure 2.

**Figure 2.** Relationship between (a) disturbance-THDv, (b) disturbance-THDi, (c) disturbance-TDD, for pure resistive loads.

It can be seen directly from figure 2 that THDi increases along with the decrease in disturbance voltage value. Based on the trendline, THDv and TDD decrease as disturbance voltage decreases.
3.2. Pure Inductive Load

This study used 3 variations of the inductance value, i.e. 0.7H, 1.4H, and 2.8H. The measurement results for pure inductive loads are shown in table 2. It can be seen that pure inductive loads have the most dominant disturbance voltage at the frequency of 19.6 kHz and the value decreases with increasing magnitude of the inductance value.

Table 2. Measurement results of disturbances and harmonic distortion for pure inductive loads.

| Load  | Disturbance (mV) | Frequency (kHz) | THDv (%) | THDi (%) | TDDi (%) |
|-------|------------------|-----------------|----------|----------|----------|
| 0.7H  | 790,707          | 19.6            | 1.098    | 2.952    | 2.952    |
| 1.4H  | 747,625          | 19.6            | 1.150    | 5.454    | 2.182    |
| 2.8H  | 739,767          | 19.6            | 1.316    | 13.360   | 2.672    |

The graphs showing the relationship between disturbance voltage with THDv, THDi, and TDD for inductive loads are shown in figure 3.

![Disturbance-THDv on Inductive Load](image1)

![Disturbance-THDi on Inductive Load](image2)

![Disturbance-TDD on Inductive Load](image3)

Figure 3. Relationship between (a) disturbance-THDv, (b) disturbance-THDi, (c) disturbance-TDD, for pure inductive loads.

It can be seen directly from figure 3 that disturbance voltage and THDv as well as disturbance voltage and THDi have the same relationship, which increases with the decrease in the value of the disturbance voltage. Based on the trendline, TDD decreases as disturbance voltage decreases.

3.3. R-L Load

This study used 3 variations of the combination of resistance and inductance values with impedance of 62.21Ω, 77.77Ω, and 103.69Ω. The measurement results for the R-L load are shown in table 3. It can be seen that the R-L load has the most dominant disturbance voltage at a frequency of 19.8 kHz and its value gets smaller as the impedance value increases.
Table 3. Measurement results of disturbances and harmonic distortion for R-L loads.

| Load    | Disturbance (mV) | Frequency (kHz) | THDv (%) | THDi (%) | TDDi (%) |
|---------|-----------------|-----------------|----------|----------|----------|
| 62.21Ω  | 746,308         | 19.8            | 1.366    | 1.692    | 1.692    |
| 77.77Ω  | 744,849         | 19.8            | 1.394    | 1.594    | 1.258    |
| 103.69Ω | 737,115         | 19.8            | 1.386    | 1.950    | 1.129    |

The graphs showing the relationship between disturbance voltage with THDv, THDi, and TDD for R-L loads are shown in Figure 3.

![Figure 3](image)

**Figure 3.** Relationship between (a) disturbance-THDv, (b) disturbance-THDi, (c) disturbance-TDD, for R-L loads.

It can be seen directly from figure 4 that TDD will decrease along with the decrease in disturbance voltage value. Based on the trendline, THDv and THDi increase as disturbance voltage decreases.

**4. Conclusions**

Based on the measurement of disturbance voltage in the frequency range of 9-150 kHz, THDv, THDi, and TDD on the rooftop PV system, the following conclusions can be obtained. The value of the disturbance voltage decreases as the resistance, inductance, and impedance values increase. The most dominant disturbance voltage for pure resistive loads occurs at a frequency of 19.8 kHz. THDv and TDD decrease along with disturbance voltage, but THDi increases when the disturbance voltage decreases. The most dominant disturbance voltage for pure inductive loads occurs at a frequency of 19.6 kHz. THDv and THDi increase when the disturbance voltage decreases, but TDD decreases as disturbance voltage decreases. Furthermore, the most dominant disturbance voltage for R-L loads occurs at a frequency of 19.8 kHz. TDD decreases as disturbance voltage decreases, but THDv and THDi increase when the disturbance voltage decreases.
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