Disturbance Characteristics of the Off-Grid Photovoltaic System in the Frequency Range from 9 - 150 kHz with Changing Solar Irradiance and Shading Area

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Abstract. A solar power plant converts light into electricity using photovoltaics. It uses an inverter to convert DC to AC current to be connected to an AC load. Increasing use of solar panels in household application results in an increase in the use of inverters, in which some might due to the fact that inverters can produce disturbances at a frequency between 9-150 kHz. This study is focused on observing the disturbance characteristics of an off-grid photovoltaic system due to variations of irradiation and shading in the frequency range from 9 - 150 kHz. It is expected that the output of this observation can provide a reference for research in determining the effects on electric power system. This observation provided a shading effect of 0%, 25%, 50%, 75%, and 100% of the photovoltaic area and then conducted observation based on two solar irradiation conditions. Based on the observations, it is identified that in general there are 3 frequency ranges of dominant disturbances, they are: 20-25 kHz, 72-73 kHz, and 144-146 kHz. Their voltage disturbance will decrease with increasing shading area, where at shading conditions of 25% and 50% they will have a value voltage disturbance that tends to be the same as that in the 3 dominant frequency ranges.

1. Introduction
The high demand for electricity encourages the development in the use of non-fossil energy sources, such as renewable energy. This is useful to reduce the level of dependence on limited fossil energy sources. Solar energy is one of the renewable energy sources that is commonly used to generate electricity that is available through the planet [1]. A photovoltaic (PV) converts solar energy into electricity. It produces direct current (DC) which can be converted into alternating current (AC) using an inverter, thus it can be connected to an AC load. High frequency switching of inverters can reduce the low order harmonic distortion, but it shifts emissions into higher frequencies (> 2 kHz) [2]. The switching process and the use of power electronic components in an inverter can generate disturbances in the output voltage [3]. In the frequency range between 9 kHz and 150 kHz it is reported by some researchers that inverter technology is predicted on generating a disturbance [3],[4].

The main parameters that affect the photovoltaic output are shadow, temperature, cloudy weather [5],[6] and beam angle [7],[8]. Among all these parameters, problems are generally found in shadows [9]. Shadows can make the PV surface partially or completely shaded. It is caused by dirt, animals, buildings, etc. This causes a very significant decrease in PVs’ output power [7],[10]. The decreasing amount of such output is also influenced by the electrical configuration of the array [11]. Based on the
foregoing, this study focused on observing the disturbance characteristics of PVs’ output with variations in the vertical shading effect and with a frequency range of 9-150 kHz.

2. Fourier Transform

The observation was conducted by measuring the electrical signal properties. The time domain signal was taken in this research and then Fourier Transform principle was used to convert it into the frequency domain signal. Based on the Fourier theorem, the infinite sum of the pure sine or cosine waveform is expressed as a periodic waveform of different amplitudes where the frequency of each sinusoid is an integer multiple of the fundamental frequency called a harmonic frequency.

\[
V_{rms} = \sqrt{\sum_{h=1}^{h_{\text{max}}} \left(\frac{1}{\sqrt{2}} V_h \right)^2} = \frac{1}{\sqrt{2}} \sqrt{V_1^2 + V_2^2 + V_3^2 + \cdots + V_{h_{\text{max}}}^2} \quad (1)
\]

\[
l_{rms} = \sqrt{\sum_{h=1}^{h_{\text{max}}} \left(\frac{1}{\sqrt{2}} I_h \right)^2} = \frac{1}{\sqrt{2}} \sqrt{l_1^2 + l_2^2 + l_3^2 + \cdots + l_{h_{\text{max}}}^2} \quad (2)
\]

The square root of the sum of RMS squares of all individual components computes the RMS values of the waveforms. Where \(V_h\) and \(I_h\) are the amplitude of a waveform at the harmonic component \(h\). \(V_h\) and \(I_h\) are all zero in the pure sinusoidal condition and only \(v_1\) and \(i_1\) remains. In this research, fast fourier transformation was used to analyze the waveform and determine the amplitude of frequency disturbance.

3. Testing and Measurement Scheme

The study was conducted by observing the disturbance in a photovoltaic system operating by connecting it to a picoscope connected to a laptop. A side of the load output which is the output of the inverter was connected to the picoscope through a high pass filter to get an observation of disturbances. The photovoltaic surface was subject to different shading effects. The shading effect covered the surface of photovoltaics under five different conditions. The shading effect on the surface of photovoltaics varied, i.e. at 0%, 25%, 50%, 75%, and 100% as illustrated in Figure 1. The load observed in this observation was resistive load. Disturbances were measured at the same time as measurement of solar radiation. Once measurement results had been obtained, data processing was carried out, which was seen only from the voltage side to determine the characteristics of the voltage disturbance from the generating source working towards its contribution to the disturbances given to the system.

Figure 1 (a) explains the process/steps needed in order that the research can be carried out in structured and systematic manners. This flow chart becomes the author’s reference in carrying out this research so that the work of the study runs effectively and efficiently.

Figure 1 (b) explains the research configuration needed in order to describe a study in structured and systematic manners. This flow chart becomes a description of the system employed in the study.

Based on Figure 1 (c), it is revealed that the disturbance voltage at a frequency range of 9-150 kHz can be recorded using a high pass filter principle. The high pass filter will be connected to a picoscope to help gather voltage disturbance data. Then, the voltage disturbance can be recorded and transferred into a laptop. The voltage disturbance will be calculated in time domain signal for 20 ms time with frequency sampling of 3.2 \(\mu\)s and the time domain signal will be converted into the frequency domain in bandwith group of 200 Hz. Each part of the measurement conditions will take a hundred data.

4. Result and Analysis

In order to observe the effect of shading effect on the voltage disturbance for a photovoltaic off-grid system, we prepared two types of initial measurement. The first one was solar irradiation measurement at a range of ±200 W/m² and the second one solar irradiation measurement at a range of ±500 W/m². Figure 2, describe the graph obtained when solar radiation is ±200 W/m² while Figure 3, show the graph obtained at solar radiation of ±500 W/m². By looking at Figures 2-3, it can be seen that
there are three dominant frequencies which have a considerable disturbance voltage, namely frequency ranges of 20-25 kHz, 72-73 kHz, and 144-146 kHz.

![Research flow chart](image1)
![Solar Panel Shade](image2)

**Figure 1.** (a) Research flow chart, (b) Solar Panel Shade: A) 0% shading effect, B) 25% shading effect, C) 50% shading effect, D) 75% shading effect, E) 100% shading effect, (c) Configuration observation system

Based on Table 1, it can be seen that in the absence of a shading effect on the PV system, the resulting disturbance voltage value at the frequency range of 72-73 kHz with a radiation value of ±200 W/m² amounts to 92.6 mV and 95.1 mV at a radiation value of ±500 W/m². It shows that in the frequency range from 72-73 kHz an increase in solar radiation is directly proportional to the increase in disturbance voltage, but this doesn’t apply in other frequency ranges. Otherwise, when the PV system is given a shading effect of 25% and 50%, an increase in solar radiation causes an increase in the disturbance voltage value. The increase in solar radiation is directly proportional to the increase in disturbance voltage when a shading effect of 25% and 50% is used, but there was no direct comparison for shading effects at 0%, 75%, and 100%.

Based on Table 1, it can be concluded that the highest voltage is generated at the frequency range of 72-73 kHz. In this frequency range, the voltage drop pattern is linear with an increase in the shading.
effect given to the photovoltaic system, but this does not apply to other frequency ranges. The decrease in disturbance voltage is very significant as well in the frequency range of 72-73 kHz.

The resulting disturbance voltage for shading effects at 25% and 50% is the same, as illustrated in Figure 4 on the equivalent circuit. On the D1 series circuit shading effects of 25% and 50% will have an output voltage that is almost the same, because current cannot pass the PV cell that is exposed to the shadow, thus PV cells work only on the D2.

![Figure 2](image)

**Figure 2.** a) 0% Shading Effect at ±200 W/m² irradiation, b) 25% Shading Effect at ±200 W/m² irradiation, c) 50% Shading Effect at ±200 W/m² irradiation, d) 75% Shading Effect at ±200 W/m² irradiation, and e) 100% Shading Effect at ±200 W/m² irradiation

5. **Conclusion**

It can be concluded that the largest disturbance voltage is generated in the frequency range of 72-73 kHz. In this frequency range, the voltage drop pattern is linear with an increase in the shading effect given to a photovoltaic system, but it does not apply to other frequency ranges. The decrease in disturbance voltage is very significant as well in the frequency range of 72-73 kHz. It was found that the increase in solar radiation is directly proportional to the increase in disturbance voltage when it gives the effect of shadings of 25% and 50%, but there was no direct comparison of 0%, 75%, and 100% shading effect.
Figure 3. a) 0% Shading Effect at ±500 W/m² irradiation, b) 25% Shading Effect at ±500 W/m² irradiation, c) 50% Shading Effect at ±500 W/m² irradiation, d) 75% Shading Effect at ±500 W/m² irradiation, and e) 100% Shading Effect at ±500 W/m² irradiation

Figure 4. Equivalent Circuit of Photovoltaics
Table 1. Disturbance Voltage at 3 Dominant Frequencies

| Shading Effect (%) | Description | Irradiance ±200 W/m² | Irradiance ±500 W/m² |
|--------------------|-------------|-----------------------|----------------------|
|                    |             | Range Frequency (kHz) | Range Frequency (kHz) |
|                    |             | 20-25                 | 72-73                |
|                    |             | 143-146               | 143-146              |
| 0                  | Frequency (kHz) | 20.8 | 72.8 | 145.8 | 24 | 72.2 | 144.8 |
|                    | V_{peak} (mV) | 67.2 | 92.6 | 73.4 | 53.2 | 95.1 | 56.5 |
| 25                 | Frequency (kHz) | 24.6 | 72.2 | 143.8 | 22 | 72.4 | 145.2 |
|                    | V_{peak} (mV) | 43.3 | 67.2 | 53.2 | 50.7 | 76.5 | 57.3 |
| 50                 | Frequency (kHz) | 23.2 | 72.4 | 145 | 20.8 | 72.8 | 145.8 |
|                    | V_{peak} (mV) | 47.4 | 64.3 | 52.3 | 50.3 | 73.1 | 57.4 |
| 75                 | Frequency (kHz) | 23.2 | 72.4 | 145.2 | 20.6 | 72.8 | 145.8 |
|                    | V_{peak} (mV) | 14.05 | 20.2 | 9.77 | 8.74 | 17.70 | 8.59 |
| 100                | Frequency (kHz) | 23.2 | 72.2 | 145.6 | 21.0 | 73.0 | 146.0 |
|                    | V_{peak} (mV) | 17.64 | 3.95 | 4.24 | 17.25 | 5.90 | 8.00 |

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