Harmonics Analysis of Inverter Circuits on Smart Grid System

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Abstract. Smart Grid System has Harmonics Distortions. Caused when switching inverters convert DC current into AC that lowers power quality and affects power generation system. Interference occurs in sinusoidal wavelengths of voltage or system currents that have frequency multiples of fundamental frequencies. Therefore, analysis is required based on IEEE Std 519-2014 standard which is for 20kV Bus voltage has a limit value of 3% for $V_{IHD}$ and 5% for $V_{THD}$, using ETAP software was conducted simulating the condition of the non-grid bus system has a $V_{THD}$ value of 4.9%, while the on-grid system conditions that have inverters for buses have a $V_{THD}$ value of 5.81%, and simulations before passive filters are installed in the 5th order ($f = 250$ Hz) with a $V_{THD}$ value of 6.33%; $V_{IHD}$ 4.82% after installing passive filter $V_{THD}$ value 1.88 %; $V_{IHD}$ 0.00 %, while in the 7th order ($f=350$ Hz) the $V_{THD}$ value is 6.33%; $V_{IHD}$3.33 % after installing passive filter $V_{THD}$ value 1.88%; $V_{IHD}$ 0.00%. The passive filter used is a single tuned passive filter. Change the PF (Power Factor) value before filtering is installed on the distribution bus = 82.9%, after the passive filter installed is 88.1%.

Key words: Smart Grid, Harmonic Distortions, Power factor, ETAP, passive filter

1. Introduction

The distribution system is part of the electrical power transmission system which has different parameters and characteristics with the transmission system. This is because the distribution system is directly connected to the load, the type of load itself there are two kinds of linear electricity load and nonlinear electrical load will but the non-linear load is the cause of the current distortion in the electrical system that Power and malfunction of the equipment[1]. In some studies the quality of this power is less than perfect due to the harmonics generated by the inverter used. This inverter generates a distortion wave due to the process of changing the DC current to AC current, the disturbance occurs in the voltage and current sinusoidal waves which have a frequency multiple of the fundamental frequency.

Several experimental results regarding power quality problems associated with photovoltaic systems have been presented. Presentation of the results of analysis and testing of passive filters to reduce total harmonization distortion at the output of the single-phase inverter. Testing and analysis of filters with dynamic loads to see the ability of the filter to reduce harmonics, maintain voltage and inverter operating power. With the model used, the filter is proven to reduce harmonics in the range of 39.82%, down to 0.035% with the average voltage and power changing according to the resistive load. In the analysis of the two transformers studied on a 20kV distribution network feeder, GIN 6. It is shown that all the values of the Total Harmonic Distortion current ($I_{THD}$) and Total Harmonic
Distortion voltage ($V_{THD}$) on the transformer have exceeded the IEEE 519-192 standard values. The simulation of harmonic disturbances was carried out using ETAP software. Based on the literature review, which is used as a reference, in this final project journal entitled "Harmonics Analysis of Inverter Circuits on a Smart Grid System", the analysis of harmonic disturbances is carried out based on simulations carried out on ETAP software. With some parameter data taken from several references. This final project journal aims to determine the passive filter as a damper for harmonic disturbances [2].

2. Methodology

2.1 Harmonics

Harmonics are one of the things that can cause distortion in the fundamental waveform of voltage and current. This phenomenon arises due to the influence of the non-linear load characteristic which is modeled as a current source that injects harmonic currents into the electric power system, shown in Figure 1.

If the frequency component is twice the fundamental frequency, it is called the 2nd harmonic. If in the electric power system the fundamental frequency is 50 Hz / 60 Hz but in the application its use is based on the load used the current and voltage frequencies can be abnormal or be a multiple of the normal frequency of 50/60 Hz then this is what is called harmonization [3].

![Figure 1. Wave combination between harmonic waves with normal sinusoidal waves.][4]

So in a 50 Hz power system, the harmonic component, $h$, which is sinusoidal has a frequency:

$$h = n \times 50 \text{ Hz}$$

where:

- $n$ = Integer as shown in Figure 1
- $h$ = Harmonic Components

[4]
Figure 2. Several basic waves and harmonic waves, represented in the frequency region. [4]

Figure 2 shows the first harmonic or fundamental waves, the 5th, 7th harmonic waves and the total or distorted waves formed by the fundamental waves, 5th, 7th, and 11th harmonic waves.

2.2 Total Harmonics Distortion (THD)

THD or what is called the Total Harmonic Distortion Value is the value of the sum of the harmonic distortions of currents and voltages which results in disturbances in the electrical system. Harmonics are basically a symptom of the formation of sinusoidal waves caused by multiplying an integer with the fundamental frequency, at a different frequency. The amplitude of each harmonic can be described in a curve called the harmonic spectrum. In general, the harmonic distortion spectrum is presented without showing the fundamental components as shown in Figure 3. The Total Harmonic Distortion (THD) value is the ratio between the RMS value of all harmonic components to the RMS value of the fundamentals. THD is usually expressed as a percentage (% THD). The percentage of the results will be used to measure the amount of deviation from the periodic waveform containing the harmonics of the pure sinusoidal wave. In a perfect sinusoidal wave the THD value is 0%, while to calculate the THD of the distorted current and voltage is to use the equation 2 and 3.

\[ V_{THD} = \sqrt{\frac{\sum_{n=2}^{\infty} V_n^2}{V_1^2}} \times 100\% \]  \hspace{1cm} (2)

where:
- \( V_n \) : Harmonic voltage value (V)
- \( V_1 \) : Fundamental voltage value (V)
- \( n \) : The observed maximum harmonic component

\[ I_{THD} = \sqrt{\frac{\sum_{n=2}^{\infty} I_n^2}{I_1^2}} \times 100\% \]  \hspace{1cm} (3)

where:
- \( I_n \) : Harmonic current values (A)
- \( I_1 \) : Fundamental current values (A)
- \( n \) : The observed harmonic component
The sum of the sinusoidal waves in Figure 1 into non-sinusoidal waves can be analyzed using the Fourier series concept, which can be defined by the following equation.

\[ Y(t) = Y_0 + \sum_{n=1}^{\infty} Y_n \sqrt{2} \sin (n2\pi ft - \varphi_n) \]  

where:

- \( Y_0 \): The amplitude of a normally deep DC component
- \( Y_n \): The rms value of the nth harmonic component
- \( f \): Basic frequency (50Hz)
- \( \varphi_n \): The phase angle of the nth harmonic component

Determining the needs of the inverter, and the inverter is supposed to supply a full system until 7

\[ V_{in\text{dc}} = \sqrt{2} x V_{inv} \]  

\[ I_{in\text{dc}} = \frac{V_{inv} x I_{load}}{V_{in\text{dc}}} \]  

\[ I_{in\text{battery}} = \frac{V_{battery \text{dc}} x I_{battery}}{V_{in\text{battery}}} \]

where:

- \( V_{in\text{dc}} \): Value of inverter voltage dc (V)
- \( I_{in\text{dc}} \): Value of inverter current dc (A)
- \( I_{in\text{battery}} \): Value of Battery current dc (A)
- \( V_{in\text{battery}} \): Value of Battery voltage dc (V)

All processes to be performed in this research, the stages of design or design work in software (software) with the results of his research. Figure 4 shows a flow chart of the stages of work to be carried out.
Input data parameters: battery, dc-dc Converter, inverter bus, power grid, transformer, cable, load, harmonic source (Details on 3.2.2 Grid System Planning)

Load flow & harmonic analysis running on ETAP 12.6

Load flow & harmonic Distortion (THD) on smart grid system

Harmonic interference analysis on smart grid systems

Figure 4. Block diagram of the work plan

The DC source diagram with a Power Grid Synchronization inverter by the ETAP application. In this process the parameters are calculated by calculating the harmonic analysis in the described ETAP application. This harmonic analysis of the inverter circuit on a smart grid system is the development of several review journals. In the circuit above, it is a battery as a source and is flowed through the inverter and synchronized to the grid and a filter will be installed if the harmonic level is high. Figure 5 shows the flowchart of the harmonic analysis simulation process of the smart grid system.
3. Result and discussion
In the system to be built, there are 2 sources of electricity to supply the entire load, where the 1st source is a 2.057 kV battery with a capacity of 1,800 Ah connected in parallel with 8 units, while the second source is electricity from PLN as a backup source or supply half of the total load. So that the power supplied from the 2 sources is expected to be the same. The following is the system planning table that will be made.

**Table 1. Load Power Bendul Merisi [10]**

| Load  | P (kW) | S (kVAR) | Q (kVAR) | V (kV) | I (A) | PF (%) |
|-------|--------|----------|----------|--------|-------|--------|
| Load 1 | 245    | 288      | 152      | 20     | 8,31  | 85     |
| Load 2 | 655    | 771      | 406      | 20     | 22,26 | 85     |
| Load 3 | 463    | 545      | 287      | 20     | 15,73 | 85     |
| Load 4 | 463    | 545      | 287      | 20     | 15,73 | 85     |
| Load 5 | 324    | 381      | 201      | 20     | 11,00 | 85     |
| Load 6 | 306    | 360      | 190      | 20     | 10,39 | 85     |
| Load 7 | 592    | 790      | 523      | 20     | 22,81 | 75     |
| Load 8 | 483    | 568      | 299      | 20     | 16,40 | 85     |
| Load 9 | 426    | 568      | 376      | 20     | 16,40 | 75     |
| Load 10| 394    | 463      | 244      | 20     | 13,37 | 85     |
Table 1 shows the power load that will be entered in the designed system, where the power will be seen for changes before and after the filter is installed, especially focusing on reactive power (Q). It is known that passive filters can generate reactive power because of the capacitor component in the passive filter, so that it will reduce the absorption of reactive power at PLN to reduce fines due to high reactive power absorption where PLN has a standard that is fixed on a low PF. The total load design power required can be calculated as follows.

Based on the data that has been designed, the next step is to enter the data into the ETAP software, Table 2 is the load flow result of the system that has been designed.

Table 2. Loadflow results before installing a passive filter.

| BUS       | V   | VA  | % PF  | Current (A) |
|-----------|-----|-----|-------|-------------|
| Bus 1     | 20.000 | 5.212 | 82.8  | 150.7       |
| Bus 2     | 20.000 | 0.287 | 85.0  | 8.3         |
| Bus 3     | 20.000 | 4.152 | 82.2  | 120.2       |
| Bus 4     | 20.000 | 3.596 | 81.7  | 104.6       |
| Bus 5     | 20.000 | 3.055 | 81.0  | 89.0        |
| Bus 6     | 20.000 | 0.773 | 75.0  | 22.6        |
| Bus 7     | 20.000 | 1.905 | 82.4  | 55.7        |
| Bus 8     | 20.000 | 1.553 | 81.7  | 45.4        |
| Bus 9     | 20.000 | 1.000 | 79.8  | 29.3        |
| Bus 10    | 20.000 | 0.450 | 85.0  | 13.2        |
| Distribution Bus | 20.000 | 5.219 | 82.9  | 150.7       |
| Inverter Bus | 20.000 | 2.575 | 81.5  | 74.3        |
| PLN Bus   | 500.000 | 2.796 | 80.3  | 3.2         |
| Trafo Bus | 20.000 | 2.647 | 84.1  | 76.4        |

Table 3. Loadflow results before the on-grid system

| BUS       | Voltage (kV) | S (MVA) | % PF  | Current (A) |
|-----------|-------------|--------|-------|-------------|
| Bus 1     | 20.000      | 4.780  | 82.8  | 144.3       |
| Bus 2     | 20.000      | 0.263  | 85.0  | 7.9         |
| Bus 3     | 20.000      | 3.808  | 82.2  | 155.1       |
| Bus 4     | 20.000      | 3.298  | 81.7  | 100.1       |
| Bus 5     | 20.000      | 2.801  | 81.0  | 85.2        |
| Bus 6     | 20.000      | 0.709  | 75.0  | 21.6        |
| Bus 7     | 20.000      | 1.747  | 82.4  | 53.3        |
| Bus 8     | 20.000      | 1.424  | 81.7  | 43.5        |
| Bus 9     | 20.000      | 0.917  | 79.8  | 28.0        |
| Bus 10    | 20.000      | 0.413  | 85.0  | 12.6        |
| Distribution Bus | 20.000      | 4.787  | 82.9  | 144.3       |
| PLN Bus   | 500.000     | 5.375  | 75.2  | 6.2         |
| Trafo Bus | 20.000      | 4.790  | 82.9  | 144.3       |

Based on the data in Table 3, when the system is still not on-grid, it can be seen that the PF value on each bus has not changed significantly. The total load is borne by 1 source, namely the PLN power grid. However, the most significant difference in value is in apparent power (S). Compared to the data distribution bus, when the system was not on-grid, the apparent power (S) was 4,787 MVA; PF 82.9%; and current 144.3 A, while when the on-grid system conditions the apparent power (S) is 5,219 MVA;
PF 82.9%; and the current 150.7 A. The PF value itself does not change. So based on this data, when the system has become a grid, the inverter installation can put more burden on the system.

The source of the harmonics used above is the design in ETAP. The harmonics are in the form of a voltage harmonic source which has been designed in such a way that it has data such as Table 4, where the largest magnitude is in the 5th and 7th order. This final project will reduce the 5th Order and 7th Order, in which the harmonic source is applied to Load 7 on Bus 6 and Load 10 on Bus 10.

Table 4. Source data of harmonics at load 6 and load 9

| n th orde | Frequency | Mag |
|-----------|-----------|-----|
|           | Hz        | %   |
| 1.00      | 50.00     | 100.00 |
| 5.00      | 250.00    | 53.50 |
| 7.00      | 350.00    | 35.00 |
| 11.00     | 550.00    | 10.00 |
| 13.00     | 650.00    | 2.00  |
| 17.00     | 850.00    | 1.00  |
| 19.00     | 950.00    | 0.10  |

The source of harmonic disturbances designed in the library menu which is then included in the inverter rating data and the load that has been selected, the magnitude shown in Table 4 is filled randomly or is not determined in theory or so, harmonics are designed to have the largest magnitude in the Order to -5 and 7th Order. Figure 6 shows the waveform and spectrum of harmonic sources used in inverters and loads.

![Waveform and Spectrum](image)

Figure 6. Wave and spectrum of harmonic sources on the inverter, load 7 and load 9.

Table 5. Passive filter parameters

| Connected Bus | Capacitor C1 | Inductor L1 | R |
|---------------|--------------|-------------|---|
| ID            | kVar         | Xl          | Q Fact. | Ohm |
| Bus 6         | 173.0        | 47,1991     | 40.00  | 0.0003 |
| Bus 6         | 173.0        | 92,51030    | 40.00  | 0.0006 |
| Bus 9         | 123.8        | 65,96500    | 40.00  | 0.0006 |
| Bus 9         | 123.8        | 129,2914    | 40.00  | 0.0010 |

The simulation results after installing the passive filter on Bus 6 as shown in Figure 6 show the harmonic spectrum after the simulation of the installation of 2 passive filters is carried out. Table 5 shows the overall passive filter data used on Bus 6 and Bus 9.
In Figure 7 it can be seen that the harmonic disturbances in the 5th and 7th orders have a small value, namely 0.4% for the 5th order and 0.5 for the 7th order. Where without using a passive filter for harmonics with the 5th order it has a value of 4.8% and the 7th order has a value of 3.3%. This indicates that the filter that has been planned in the calculation is successful in reducing the disruption of the system to the harmonics that appear in the 5th and 7th orders. As for the results of the voltage wave after the filter is installed, it can be seen in Figure 8.

Figure 8 is the result of repair of sinusoidal waves due to disruption of the system to the appearance of harmonics in the 5th and 7th orders. When compared with the sinusoidal and pre-filter installation, it can be seen that the voltage / sinusoidal waves have significantly improved significantly, indicating that in addition to improving the spectrum analyzer this filter also improves the voltage / sinusoidal side of the wave which is almost close to pure sinusoidal. Figure 9 shows the harmonic spectrum after a simulation of the installation of 2 passive filters on Bus 9.
Figure 10 is the result of repair of sinusoidal waves due to disruption of the system to the appearance of harmonics in the 5th order, namely the frequency of 250 Hz and the 7th order, the frequency of 350 Hz. The results of the simulation show that the waves are taken in 1 alternating wave cycle. When compared with the sinusoidal waves before the filter installation, it can be seen that the voltage / sinusoidal waves have significantly improved significantly, indicating that in addition to improving the spectrum analyzer this filter also improves the voltage / sinusoidal side waves which are almost close to pure sinusoidal.

Table 6. Bendul Merisi load flow [10]

| Bus          | MW  | MVAR | Amp | % PF | % Tap |
|--------------|-----|------|-----|------|------|
| Distribution Bus | -4,314 | -2,323 | 141.7 | 88.0 |
| Bus 2       | 0.244 | 0.151 | 8.3   | 85.0 |
| Bus 3       | 3,417 | 1,767 | 111.2 | 88.8 |
| Bus 1       | -0.244 | -0.151 | 8.3   | 85.0 |
| Bus 1       | -3.412 | -1.766 | 111.2 | 88.8 |
| Bus 4       | 2.951 | 1.480 | 95.6   | 89.4 |
| Bus 3       | -2.937 | -1.477 | 95.6   | 89.3 |
| Bus 5       | 2.480 | 1.194 | 80.0   | 90.1 |
| Bus 4       | -2.476 | -1.193 | 80.0   | 90.1 |
| Bus 6       | 0.582 | 0.163 | 17.6   | 96.3 |
| Bus 7       | 1.576 | 0.833 | 51.9   | 88.4 |
| Bus 5       | -0.581 | -0.162 | 17.6   | 96.3 |
| Bus 5       | -1.570 | -0.832 | 51.9   | 88.4 |
| Bus 8       | 1.271 | 0.647 | 41.7   | 89.1 |
| Bus 7       | -1.270 | -0.647 | 41.7   | 89.1 |
| Bus 9       | 0.799 | 0.355 | 25.6   | 91.4 |
| Bus 8       | -0.799 | -0.355 | 25.6   | 91.4 |
| Bus 10      | 0.383 | 0.237 | 13.2   | 85.0 |
| Bus 9       | -0.383 | -0.237 | 13.2   | 85.0 |
| Inverter Bus | -2.099 | -0.892 | 65.9   | 92.0 |
| Trafo Bus   | -2.221 | -1.432 | 76.3   | 84.0 |
| Bus 1       | 4.320 | 2.325 | 141.7 | 88.1 |
| Distribution Bus | 2.100 | 0.893 | 65.9   | 92.0 |
| Trafo Bus   | 2.241 | 1.665 | 3.2   | 80.3 |
| Distribution Bus | 2.222 | 1.432 | 76.3   | 84.0 |
| PLN Bus     | -2.222 | -1.432 | 76.3   | 84.0 | 5,625 |
Based on Table 6, the data shows that in this research, the bus distribution is divided into 2 branches from the direction of the grid. The data above only shows the change in the PF value after the installation of the passive filter at each bus branch.

**Table 7. Load flow results after filter installation**

| Bus       | kV  | MVA | % PF | Amp |
|-----------|-----|-----|------|-----|
| Bus 1     | 20.00 | 4,900 | 88.0 | 141.7 |
| Bus 2     | 20.00 | 0,287 | 85.0 | 8.3  |
| Bus 3     | 20.00 | 3,841 | 88.8 | 111.2 |
| Bus 4     | 20.00 | 3,288 | 89.3 | 95.6  |
| Bus 5     | 20.00 | 2,748 | 90.1 | 80.0  |
| Bus 6     | 20.00 | 0,774 | 75.0 | 22.6  |
| Bus 7     | 20.00 | 1,777 | 88.4 | 51.9  |
| Bus 8     | 20.00 | 1,426 | 89.1 | 41.7  |
| Bus 9     | 20.00 | 1,001 | 79.8 | 29.3  |
| Bus 10    | 20.00 | 0,451 | 85.0 | 13.2  |
| Distribution Bus | 20.00 | 4,906 | 88.1 | 141.7 |
| Inverter Bus | 20.00 | 2,282 | 92.0 | 65.9  |
| PLN Bus   | 500.00 | 2,792 | 80.3 | 3.2   |
| Trafo Bus | 20.00 | 2,643 | 84.0 | 76.3  |

Table 7 shows that some of the data taken for comparison with the data before installing the passive filter, it is known that on bus 6 before the filter is installed it gets 790 kVA of apparent power and after the filter is installed the apparent power becomes 774 kVA, then pay attention to the PF where before the passive filter is installed the value is 75% while after installing the filter it becomes PF 96.3%, which can be seen in the ETAP, as well as the current becomes smaller where before the filter is installed the current is 22.81 A then after the filter is installed it becomes 22.6 A. occurs in the system bus, namely the distribution bus which is useful for dividing power to all existing loads. The PF value before installing the filter on the distribution bus was 82.9%, while after the passive filter was installed it became 88.1%, proving that the passive filter at certain loads has an effect on changes in the PF value of the entire system.

**Table 8. The result of PF reduction from before the filter is installed and after the filter is installed**

| BUS            | Before filter | After filter | PF |
|----------------|---------------|--------------|----|
| Bus 1          | 0.75          | 0.88         | 0.13 |
| Bus 2          | 0.85          | 0.85         | 0.00 |
| Bus 3          | 0.85          | 0.888        | 0.038 |
| Bus 4          | 0.85          | 0.893        | 0.043 |
| Bus 5          | 0.85          | 0.901        | 0.051 |
| Bus 6          | 0.75          | 0.75         | 0.00 |
| Bus 7          | 0.85          | 0.884        | 0.034 |
| Bus 8          | 0.85          | 0.891        | 0.041 |
| Bus 9          | 0.85          | 0.798        | 0.052 |
| Bus 10         | 0.85          | 0.85         | 0.00 |
| Distribution Bus | 0.84          | 0.881        | 0.041 |

Table 8 shows the change in PF before and after the installation of passive filters, where in addition to improving harmonics in the passive filter system, it can also improve PF which is quite bad, to avoid fines imposed by PLN with existing references. Significant changes can be seen in the distribution bus, where this bus is the main bus of several buses, before the PF filter was installed at 0.84, while after the filter it became PF 0.881, where this PF value was already in a safe situation.
against fines from PLN. Figure 11 shows the harmonic waves of all buses after the on-grid system is installed.

![Harmonic waves of all buses after the on-grid system is installed.](image)

**Figure 11.** Harmonic waves of all buses after the on-grid system is installed.

4. Conclusion

From the planning and manufacturing of the system then conducted such testing, some analysis and methods used can be concluded:

In an on-grid system, a DC source using an inverter as an AC voltage converter which has a harmonic source can cause harmonic disturbances in the distribution system to the load. Installation of passive filters affects changes in sinusoidal waves, harmonic spectrum, PF, reactive power values, and system apparent power. Installation of passive filters has significant changes in some data, namely before the passive filter is installed in the 5th order (f = 250 Hz) with a $V_{THD}$ value of 6.33%; $V_{IHD}$ 4.82% after installing a passive filter, the $V_{THD}$ value is 1.88%; $V_{IHD}$ 0.00%, while in the 7th order (f = 350 Hz) the $V_{THD}$ value is 6.33%; $V_{IHD}$ 3.33% after installing a passive filter, the $V_{THD}$ value is 1.88%; $V_{IHD}$ 0.00%; where the value of these parameters fixes the system. The change in PF value before installing the filter on the distribution bus = 82.9%, while after the passive filter is installed it becomes 88.1%, proving that the passive filter at certain loads has an effect on changes in the PF value of the entire system. Based on the comparison between the condition of the non-grid system bus 6 has a $V_{THD}$ value of 4.9%, while the condition of a grid system that has an inverter for bus 6 has a $V_{THD}$ value of 5.81%, where the $V_{THD}$ limit value is 5%.

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