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Analysis of Hybrid Energy Modelling Using Grid Following Inverter for the Integration of Renewable Energy Generation

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***Abstract*— The energy dependency of the grid will cause its own problems because the energy generated comes from fossil fuels. On the other hand, centralized electrification using renewable energy has a high risk on frequency and voltage stability. Renewable energy depends entirely on climate conditions and has no inertia to maintain stability. Hybrid energy between grids and Inverter Based Resources (IBRs) are alternative solutions used. The research applies an inverter control scheme to IBRs to be penetrated the grid. The research will apply a zero-export load with electricity requirements to be charged to renewable power plants using grid distribution networks. The inertia less properties of renewable energy will cause interference when combined with the power grid (synchronous generator). It will also be analyzed on this study by applying the following inverter scheme by paying attention to the phase angle and synchronization against the voltage, current and frequency variables of the grid. The results obtained in this study; renewable energy can contribute 90% to the load. This is due to the Losses factor and efficiency system in the plant. Renewable energy generators feed active power to the grid as well as support grids with a Total Harmonic Distortion (THD) indicator of <10%. In the design of this hybrid power system, it is done on MATLAB software with installation configuration in accordance with IEEE standards so that it can be a reference for the installation of real-condition renewable energies with grid.**

***Keywords*—Renewable Energy, Grid Following, Green Electricity, Hybrid Energy**

I. INTRODUCTION

Power plants have been a vital component of a country's sustainable development. However, power plants in Indonesia are still dependent on fossil fuels. This dependency has a significant negative impact on carbon emissions from the combustion process at the plant. Aprilianto, R.A., & Ariefianto, M.R. (2021).

Renewable energy is the best alternative to reducing carbon emissions because renewables convert unlimited amounts of natural energy (solar) into electricity. On the one hand, the use of renewable energies as primary energy is still unable to be done because the energy sources are unstable.

It's caused by climate change and the fluctuating intensity of sunlight every second. Suhadi, S., & Princess, J. K., (2024). The integration of renewable energy with the grid is one of the most effective solutions to solving the energy filling problem. Renewable energy is expected to be able to supply power through the grid to consumers. However, it still has obstacles. This integration has its own challenge, which is the characteristic difference between the two plants. Renewable power plants are inertialess or have no inertia. Thus, in this study, the Grid Following Inverter (GFLI) control scheme was applied. A GFLI-based energy resource is a type of inverter that absorbs existing active and reactive power and generates current that tracks the angle and magnitude of the network to inject or absorb active and reactive power in order to generate a stable network frequency and voltage through the synchronization process.

In the study S. Prakash, et al (2023), control GFLI in uneven network conditions. In the results, the study explains the quality and stability of power output in the presence of system network interference. As a result, the proposed IARC method enjoys the advantages of a conventional IARC scheme and also has the advantage of other schemes by producing positive and negative sinusoidal sequence current components in unbalanced conditions. Another highlighted advantage is the relatively low cost, no battery use, and environmentally friendly generation of more quality energy, as demonstrated through Chapter 3. Thus, the integration of renewable energy with GFLI can optimize the stability of the frequency and voltage of the network generated.

II. LITERATURE REVIEW

A. *Grid Following Inverter*

Grid following inverters, also known as grid-tied inverters, are devices that convert direct current (DC) electricity from renewable energy sources into alternating current (AC) electricity, synchronized with the utility grid. Zarei, S. F., et al. (2019). These inverters play a crucial role in integrating renewable energy into the power grid, ensuring stability and efficiency. The operation of grid following inverters is based on several key theories, including the Phase-Locked Loop (PLL), which is a control system that synchronizes the inverter's output with the grid frequency and phase, and the Voltage Source Inverter (VSI), a type of inverter that controls the output voltage and is commonly used in grid-following applications. L. Wang, C. -S. Lam and M. -C. Wong (2018). Additionally, theories

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related to maintaining the quality and stability of the power output in the presence of grid disturbances are fundamental to understanding their operation.

The conceptual framework of grid following inverter is based on understanding the interaction between grid following inverters and the power grid. This involves examining synchronization mechanisms, such as how inverters align their output with grid parameters, control strategies used to maintain stability and efficiency in real-time operation, and the impact of inverters on overall grid performance and reliability.

B. Hybrid System

Hybrid systems in embedded control are systems where digital controllers, computers, and subsystems modelled as finite-state machines are integrated with controllers and plants that are described by partial or ordinary differential equations or difference equations. Subramaniam U., et al (2020). These hybrid systems emerge in scenarios where logical decision-making processes are combined with the generation of continuous-valued control laws. Essentially, hybrid systems represent a blend of discrete and continuous dynamics, which necessitates the coordination of both types of systems to achieve desired control objectives. The discrete components, typically represented by finite-state machines, handle logical operations and decision-making tasks.

The principal work of hybrid systems is to integrate discrete decision-making processes with continuous control dynamics. This involves synchronizing digital controllers or finite-state machines with systems governed by differential or difference equations. Nishant Jha., (2022). By doing so, hybrid systems enable complex and precise control in applications such as automotive systems, aerospace, robotics, and industrial automation, where both logical decisions and continuous control laws are crucial.

C. Grid System

The PLTS grid system is a network configuration system between PLTS and the main power plant network. PLTS configuration network system can be divided into several types based on its function. Generally, the PLTS system is divided in three types: PLTS on-grid PV system, PLTS offline PV system and PLTS hybridly connected to the general power grid, the power system generated by solar panels can be combined with the electricity system produced by the solar panel. On- grid solar power generation system (PLTS) is connected directly to the main grid or grid. They can regulate the power supply to the public grid with the help of inverter electrical devices. If the solar panel system on the grid can't produce enough energy, such as during bad weather or at night, the electric grid is usually used as a reserve source of energy. In this PLTS on grid system, the energy generated by solar panels will be used directly to meet the electricity needs of a house or building. Kamil, I., & aripriharta. (2023).

Unlike on-grid solar power plants, off-grids use solar energy as their only resource. They are usually used as a backup and supported by generators or batteries to store energy. Due to its autonomous and battery-dependent characteristics, the system is ideal for buildings that are difficult to access by PLN networks. Households using off-grid PLTS systems will not be affected in power outages. Vember Restu Kossi (2020)

The PLTS Hybrid Grid System is a combination of On-Grid and Off-Grid systems that are connected to the general power grid but also have battery storage for energy saving so that it can operate independently when needed. The solar panels in the PLTS Hybrid system generate energy from the sun, and the system can use the energy reserve from the stored battery in case of power shortage. The system combines the advantages of the On-Grid and Off-Grid systems, so that users can maximize flexibility and energy efficiency. WANDIRA, B. R. (2022).

D. PV System

What a solar power generation systems work using photovoltaic solar cell panels connected to the network for residential purposes: The solar cell module generates solar energy into a DC electric current. This current is then delivered through an inverter, or power regulator, which then converts it into an AC electric current, which is then distributed through an indoor distribution panel, which automatically controls the entire system. Watt-hour meters will be used to find out how much and how much electricity the house uses. Kementrian Energi dan Sumber Mineral. 2010. Pembangkit Listrik Tenaga Surya (05 Desember 2014).

A solar cell module, also known as a photovoltaic cell, is a device that can convert solar radiation into electrical energy. Basically, a solar cell is made of semiconductor material that is processed in such a way that it can produce direct current (DC) electricity. When used, the solar cells are connected to each other, parallel or serial, to generate power with the desired combination of voltage and current. Alamendah. 2014. Pembangkit Listrik Tenaga Surya, (05 Desember 2014).

III. METODOLOGY

A. PV on-Grid Instalation

The sizing of the PV system will be carried out by considering Zero Export, or all the power supply to the load will be provided by the PV and BESS. The generator will supply a daily load of 50 kW. The following is the configuration for the PV sizing.

$$PV\ Power = \frac{Daily\ consumption\ x\ oversizing\ factor}{PSH} \tag{1}$$

Oversizing is a planning parameter to prevent maximum load, uncertainty, and losses in the power system. In this planning, the oversizing value is 1.5. Meanwhile, PSH or Peak Sun Hour is the amount of effective irradiation received by the PV. Based on the research by 1, the PSH value in Indonesia is 4.5 hours.

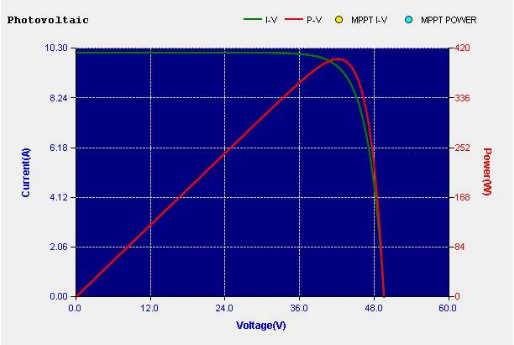

Figure 1. PV and IV Curve of PV modul used (source: SAS ITECH)

The PV module used has a capacity of 400 Wp with PV and IV curves shown in figure 1 (SAS ITECH simulation). The number of modules needed in the system is obtained by dividing the total PV capacity by the capacity per module as shown in equation 2.

$$num\ of\ modul = \frac{Pv\ power}{C\ modul\ PV} \tag{2}$$

After determining the number of modules used, the next step is to configure the PV system, including series and parallel arrangements, considering the area obtained from the SAS ITECH simulation, which is 3251 m².

$$nb\ of\ string = \frac{num\ of\ moduls}{num\ of\ moduls\ per\ string} \tag{3}$$

B. BESS Capacity

BESS works as a backup energy system designed to provide 1 MW of backup power when PV cannot supply power. The equation for calculating BESS sizing is shown by equation 4.

$$BESS\ Sizing = \frac{Daily\ Consumption\ x\ DoA}{DOD\ x\ System\ Voltage\ x\ Inv\ efficiency\ x\ batt\ derating} \tag{4}$$

$$Total\ capacity = BESS\ sizing\ x\ system\ voltage \tag{5}$$

$$num\ of\ batt = \frac{total\ capacity}{batt\ power} \tag{6}$$

$$num\ of\ batteries\ in\ string = \frac{\max \text{voltage}\ input\ of\ inv}{batt\ volt} \tag{7}$$

Where DoA is the Daily Autonomy, which represents the number of days of backup planned. Then, DoD is the Depth of Discharge, which is a measure of how much battery capacity is used relative to its total capacity. System voltage is the output voltage of the battery per module, and battery derating is the reduction in battery lifespan due to varying usage.

C. Inverter Capacity

The inverter will be set as a multi-string inverter. The inverter will use a capacity of 60 kW, which is determined based on the PV configuration. Thus, the number of inverters to be used for the PV system follows equation 8.

$$nb\ of\ Inverter = \frac{PV\ Power}{inverter\ Capacity} \tag{8}$$

$$num\ of\ inverter = \frac{load}{inv\ capacity} \tag{9}$$

D. LCL Filter

The LCL filter is a crucial component for reducing Total Harmonic Distortion (THD). Therefore, the selection of L and C filter parameters needs to be done accurately. The following equations are used to determine the filter.

$$L \geq \frac{\sqrt{3}\,Vdc}{12\ f_{sw}\ \delta\ I_{rate}} \tag{10}$$

$$L2 = rL1 \tag{11}$$

$$Cf\ = \alpha C_b \tag{12}$$

$$C_b = \frac{1}{\omega gZb} \tag{13}$$

Where the parameters for determining L1 include Vdc, which is the input voltage of the inverter, fsw, the switching frequency, δ, the attenuation factor, and Irate, the AC current of the inverter. L2 is 50% of L1, where r represents the ratio of L1 to L2, which is 50%. Cf is the filter capacitance, calculated as α times Cb. α is a factor x, valued at 5% of the base capacitor (Cb). Cb is derived from the grid frequency variable (wg) and the base impedance (Zb).

PV system		BESS		Inverter		LCL Filter
Total Capacity	50kWp	Total Capacity	AH	Switching frequency (Fsw)	10 kHz	Inductor (L1)
Capacity per modul	400 Wp	Capacity per battery	200 AH	Inv capacit unit	60 kW	Inductor (L2)
Voc	49,4	System voltage	48 V	Vin (DC)	600 V	Capacitor (Cf)
Isc	46,9	DOD	30%	Vout (AC)	380 V	δ
Num of string		Num of string		Irate		Zb
		DOA	1 day			
		Battery deratting	5%			

IV. DISCUSSIONS

Photovoltaic (PV) systems operate based on two main sources: irradiation and temperature. The energy generated by the PV panels is first directed to a boost converter. The main function of the boost converter is to increase the current to a suitable level for further processing. After the boost converter, the energy moves to a switching mechanism, which serves as a control interface between the PV system and the electrical grid. This switch ensures that the current and voltage from the PV system are synchronized with those in the grid, allowing for smooth energy transfer.

Next, the energy passes through an inverter, which converts the direct current (DC) generated by the PV panels into alternating current (AC) suitable for use in the grid. The inverter must store and manage the current and voltage, ensuring that they are not activated simultaneously to prevent overloading the system. After the inverter, the energy flows through capacitors and inductors. These components have two functions: filtering the current to eliminate interference and smoothing it to ensure a stable and consistent flow.

Finally, the processed energy is connected to the electrical grid, where it can be used efficiently. The combination of these components—from the initial boost converter to the final connection to the grid—ensures that the energy generated by the PV system is optimized, stable, and compatible with the existing electrical infrastructure. Providing innovative sustainable solution in the form of research paper and poster.

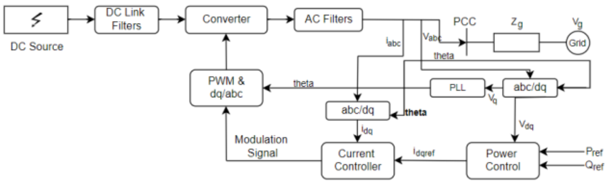

Figure 2. Grid-following control architecture

The image above is a block diagram depicting the signal flow in a control system. The diagram begins with four main input signals: VR, VB, IR, and IB, which represent the voltage (V) and current (I) in phases R and B, respectively. The first step in the diagram is the coordinate transformation block, which uses the Park transformation to convert three-phase signals (abc) into two-axis signals (dq) and a zero-axis signal (0). The first block transforms the voltage signals VR and VB into Vd and Vq, while the second block transforms the current signals IR and IB into Id and Iq.

After the transformation, these signals pass through the combining and subtraction stage. The Vd and Vq signals from the voltage path are added to the signals generated from the other path. In the lower path, the Vd and Vq signals are fed into PI (Proportional-Integral) controllers, which regulate the Id and Iq signals. There are two PI controllers in this diagram, one for each of the d and q components.

After passing through the PI controllers, these signals then go through several additional blocks that may include filters and other components to smooth the current and voltage. Finally, the processed signals are connected to the grid, ensuring that the generated energy is compatible and stable for use in the existing electrical network. This diagram shows the signal processing flow from the initial input to the final output that is ready to be delivered to the electrical grid.

A. Power Factor

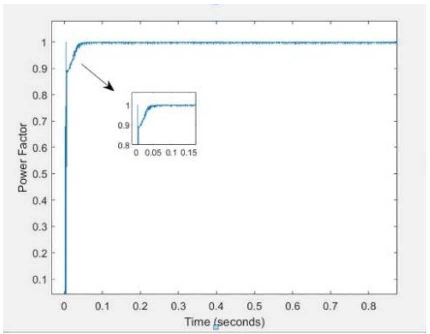

Figure 3. Power Factor

The power factor is a critical measure in electrical engineering, indicating the efficiency with which electrical power is being used. Essentially, it is the ratio of real power, which performs the actual work, to apparent power, which is the product of the current and voltage supplied to the circuit.

In the provided graph, the x-axis represents time or operational cycles, ranging from 0 to 1. This likely corresponds to a specific time interval, possibly in seconds, or a fraction of the system's full operational cycle. On the other hand, the y-axis represents the output of power factor generated by the point of common coupling already indicates that the result is good.

The graph shows a rapid rise in the power factor at the beginning, which quickly stabilizes at a value of 1. This suggests that the system starts up and reaches optimal efficiency almost immediately, maintaining this efficiency throughout the observed peri/od. The initial spike indicates the system overcoming initial inefficiencies or inrush currents, after which it operates steadily at maximum efficiency. This behavior is typically desirable in electrical systems, as a consistent power factor close to 1 ensures minimal energy losses and optimal performance.

B. Active Power

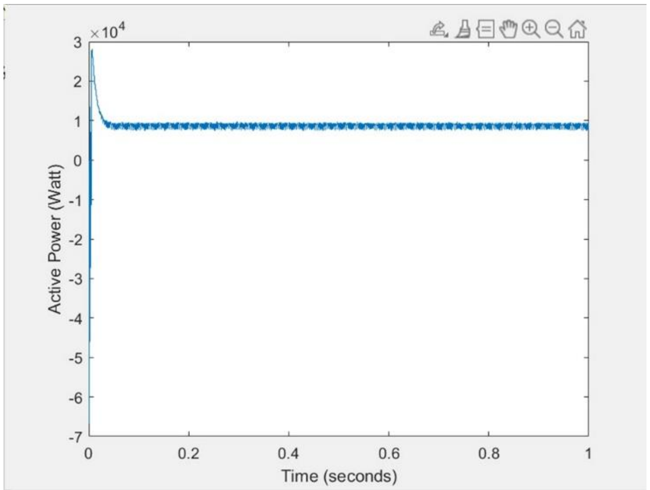

Figure 4. Active Power

Active power, also known as real power, is the portion of power that performs work in the system, such as turning motors or lighting lamps. It is measured in watts (W) and represents the actual energy consumed by the load.

The x-axis represents time or operational cycles, indicating the progression of the system over a specific interval. The y-axis represents active power, which is scaled by a factor of 10^4, meaning the values on the y-axis should be multiplied by 10,000 to get the actual power values in watts.

At the beginning of the graph, there is a significant spike in active power, which then quickly diminishes and stabilizes at a consistent level. This initial spike indicates a high inrush current or initial surge in power as the system starts up, which is a common occurrence in electrical systems when they are first powered on.

C. Reactive Power

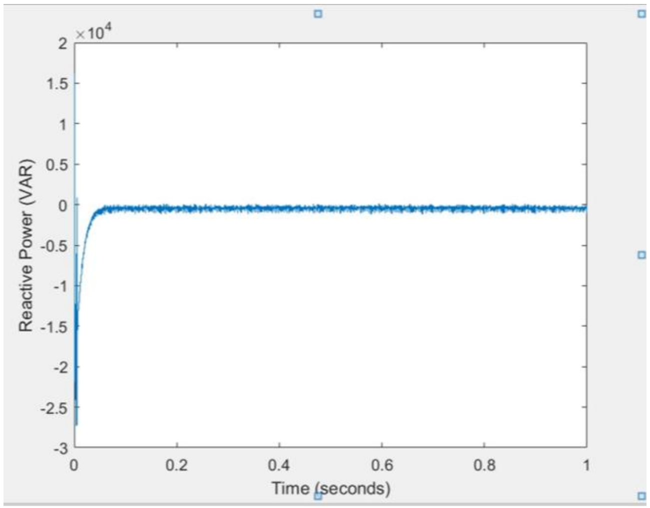

Figure 5. Reactive Power

Reactive power is the portion of power that oscillates between the source and the load, not performing any real work but necessary for maintaining the voltage levels that allow the system to function effectively. It is measured in volt-amperes reactive (VAR).

The x-axis represents time or operational cycles, which likely range from 0 to 1, indicating a specific time interval or fraction of an operational cycle. The y-axis represents reactive power, scaled by a factor of 10^4. This means the values on the y-axis need to be multiplied by 10,000 to get the actual reactive power values in VAR.

The graph shows an initial negative spike in reactive power, which then quickly rises and stabilizes around zero with a slight positive value. This initial negative spike indicates the system's reactive power requirements at startup, followed by stabilization, suggesting that the system reaches a steady-state operation where the reactive power is relatively minimal but necessary for maintaining system voltage.

D. Voltage at Point Common Coupling

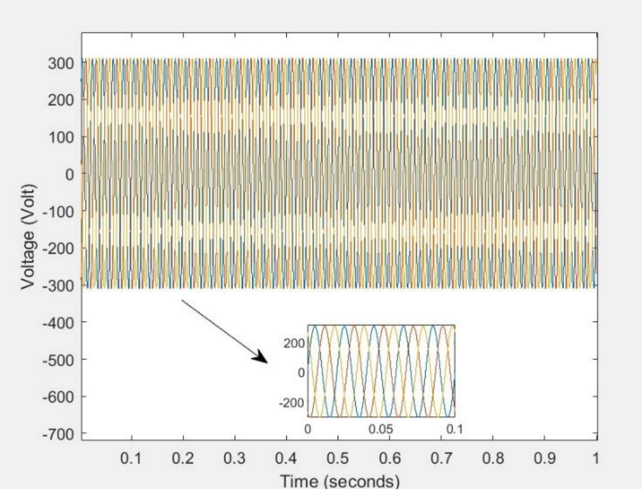

Figure 6. Voltage at Point Common Coupling

The image shows to be a plot of three-phase voltage waveforms typically observed in a three-phase electrical system. Each phase, denoted as Phase A, Phase B, and Phase C, is represented by different colored lines (likely yellow, blue, and red). These waveforms are sinusoidal and are shifted by 120 degrees relative to each other, which is a characteristic of balanced three-phase systems.

In a balanced three-phase system, the voltages are equally spaced in time, ensuring that the power delivered is constant and efficient. The voltages in this plot oscillate between positive and negative values, with peak values around 300 volts, indicative of the maximum amplitude of the sinusoidal waveforms. The zero-crossings of each phase are evenly distributed, confirming the 120-degree phase shift. This type of waveform is essential in many industrial applications because it provides a steady and reliable power supply.

The plot's consistency and uniformity suggest that the system is operating correctly, without significant disturbances or anomalies. Any deviations from this regular pattern could indicate issues such as voltage imbalances, harmonic distortions, or faults in the system.

E. Current at Point Common Coupling

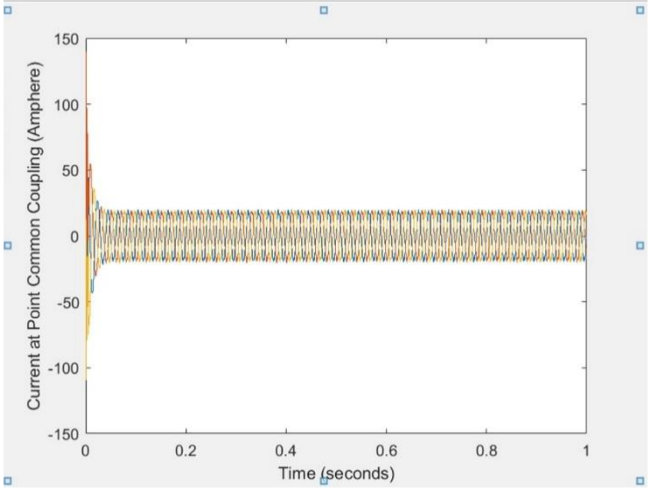

Figure 7. Current at Point Common Coupling

The image displays a plot of three-phase current waveforms over time, labeled as Current Phase A, Current Phase B, and Current Phase C, each represented by different colored lines. At the beginning of the plot, there is a noticeable transient response where the current values fluctuate significantly before stabilizing. This transient behavior is common when a system is first energized or experiences a sudden change in load, resulting in a brief period of instability. After this initial transient period, the currents in all three phases settle into a regular sinusoidal pattern, oscillating symmetrically around the zero current level. Around time zero, the current waveforms exhibit noticeable instability, characterized by rapid fluctuations in magnitude.

This indicates a balanced three-phase system where the currents in each phase are equal in magnitude and 120 degrees out of phase with each other. The current waveforms oscillate between approximately +50 and -50 units, likely amperes, indicating the peak current values during steady-state operation. The consistent phase shift of 120 degrees between the waveforms of each phase ensures balanced loading and efficient operation of the three-phase system, minimizing potential issues like excessive neutral current or overheating.

The initial high amplitude and rapid oscillations suggest that the system experienced a surge or inrush current, typical when large inductive loads, like motors, are switched on. The steady-state sinusoidal currents confirm that the system is operating correctly after this initial surge, which is expected in three-phase systems used in industrial settings to ensure continuous and reliable operation.

F. Total Harmonic Distortion

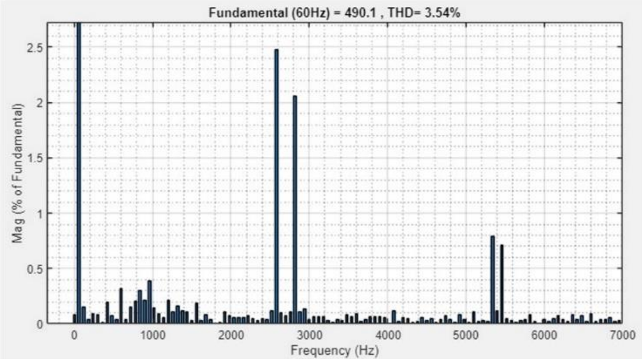

Figure 8. Total Harmonic Distortion

The provided image illustrates a frequency spectrum analysis of an electrical signal, focusing on its harmonic components. The analysis identifies the fundamental frequency at 60 Hz, a standard value in many power systems. This fundamental frequency is measured with a magnitude of 490.1. The graph also highlights the Total Harmonic Distortion (THD) of the signal, calculated at 3.54%. THD is a critical metric in assessing the quality of electrical signals, as it quantifies the level of distortion present by comparing the power of all harmonic frequencies to that of the fundamental frequency.

The x-axis of the graph represents the frequency range, extending up to approximately 7000 Hz, while the y-axis denotes the magnitude of each harmonic component as a percentage of the fundamental frequency. The graph reveals the presence of several significant harmonic frequencies, notably around 1800 Hz and 4800 Hz, which are visualized as peaks in the spectrum.

The relatively low THD value of 3.54% suggests that the signal maintains a level of purity that may be considered acceptable, depending on the specific requirements of the application. According to (Siahaan, F. J., et. al (2020), a value below 5% indicates that the AC power source is of good quality and does not have much distortion. However, the presence of harmonic components indicates that there is some distortion in the signal, which could potentially impact the performance of electrical equipment if not properly managed. Overall, this frequency spectrum analysis provides a clear insight into the harmonic content of the signal, offering valuable information for evaluating and optimizing electrical system performance.

V. CONCLUSION

The integration of renewable energy sources into the power grid using Grid Following Inverters (GFLIs) represents a promising approach to enhancing the stability and efficiency of hybrid energy systems. GFLIs play a crucial role in managing the interaction between renewable energy sources and the power grid by maintaining frequency and voltage stability, as well as minimizing total harmonic distortion (THD). This enables smoother energy transfer and makes the power system more resilient.

The system shows efficient and stable performance, seen from important values such as power factor, active power, reactive power, voltage at the joint connection point (PCC), and current at the PCC. The power factor shown in the graph reaches a value near to 1.0 quickly after the initial leap, indicating that the system operates at maximum efficiency by using all the power supplied effectively without wasting. The active power, which is shown in the chart as a significant boost at first, then stable at a lower value. This indicates the presence of an inrush current when the system was first turned on, which was a common phenomenon, followed by a stable operation.

The reactive power initially shows a negative boost, then stable approaches zero with little positive value. This indicates that the system requires reactive energy to maintain the voltage, but after the initial phase, this need decreases and the system achieves stability. The voltage in the PCC shows a consistent sinusoidal pattern with a peak of about 300 volts per phase, indicating that the voltage system operates in balanced conditions without major interference. Currents in PCC also indicate stability after the initial transitional phases, with peaks of about ±50 amps per Phase, showing a uniform load distribution and no significant imbalance. And also the total harmonic distortion (THD) calculated at 3,54% which shows that the AC power source is of good quality and does not have much distortion. Overall, the system operates with high efficiency and stability, ensuring optimal and reliable performance in industrial applications.

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