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Online Monitoring System for Harmonics with Passive Filter on A 110 KW Three-Phase Inverter

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ABSTRACT

Mardha Haryono Putro. Master's Program in Applied Electrical Engineering. Online Monitoring System for Harmonic Filters in a Three-Phase Inverter with a Capacity of 110 kW. This study aims to design and implement an Internet of Things (IoT)-based electrical power quality monitoring system and to design a single-tuned passive harmonic filter to reduce the fifth-order individual harmonic distortion (iHD-5) in a 110 kW three-phase inverter system. The monitoring system was developed using a GAE MG50 power meter and an ESP8266 microcontroller, integrated with Google Sheets and the Blynk app for real-time monitoring. Data was collected over 7 days before and after filter installation. Measurement results showed an initial THDi value of 67.35% and a fifth-order iHD value of 47.8%, exceeding the 12% threshold according to IEEE Std 519-1992. The passive filter was designed with a capacitance of 155.2 µF and an inductance of 2.89 mH. After installation, THDi decreased to 38%, iHD-5 to 9.96%, neutral current dropped from 18 A to 9 A, and power factor improved from 0.76 to 0.91. Energy savings are estimated at ± 2,484 kWh per month, equivalent to ± Rp 2,571,391 at an industrial electricity rate of Rp 1,035.78/kWh. The research results indicate that integrating an IoT monitoring system with a passive harmonic filter can improve energy efficiency, reduce harmonic distortion, and enhance power quality in industrial electrical systems.

KEYWORDS *Harmonisa, Filter Pasif, Inverter, ESP8266, THD, Power Factor, IEEE 519-1992, IoT*

INTRODUCTION

The interaction between sinusoidal waves in an electrical power system and other wave components that have frequencies that are integer multiples of the fundamental component causes wave distortion known as harmonics. One of the main problems in power quality is harmonics (Al et al., 2021).

The presence of harmonics can interfere with the performance of electrical power systems and potentially cause damage. This is due to the widespread use of variable speed drives (VSDs), which consist of power electronic components. If harmonic currents exceed standard limits, they can have a negative impact on electrical power distribution systems, such as increased power losses in cable conductors, increased transformer temperatures, and reduced operational efficiency (Amir & Firdaus, 2017), (Ishaya et al., 2023), (Cho & Cha, 2011).

The use of Variable Speed Drive (VSD) as a three-phase induction motor drive is one of the main factors causing harmonics (Al et al., 2021), (Amir & Firdaus, 2017), (Ishaya et al., 2023), (Cho & Cha, 2011). To overcome the effects of harmonic currents, several methods can be applied, such as the use of single-phase isolation transformers and the implementation of active and passive harmonic filters. All of these methods aim to limit current harmonic distortion (Total Harmonic Distortion of Current or THDi) and voltage harmonic distortion (Total Harmonic Distortion of Voltage or THDv) in accordance with IEEE and SPLN standards (Atmam et al., 2018), (Amir & Firdaus, 2017), (Ishaya et al., 2023)

Preliminary data shows that in a 110 kW Variable Speed Drive (VSD) system, the 5th order THDi value reaches 67.35%, which can cause increased power loss in the network and impact the reliability of the electrical power system. By implementing a passive harmonic filter (Single Tuned), the THDi value can be reduced to < 12%, enabling the system to operate more stably and in compliance with applicable standards. Additionally, this harmonic reduction helps reduce excessive heat in electrical equipment, thereby improving system efficiency and extending the lifespan of the equipment (Artiyasa et al., 2020).

In previous research, Marchtindra Al, Atmam, and Elvira Zondra in a study titled Application of Passive Filters as Harmonic Reducers in Three-Phase Inverters did not implement a real-time monitoring system, so the harmonic characteristics of the inverters used could not be measured continuously and optimally. Therefore, the research results did not provide a comprehensive picture of the harmonic characteristics produced, especially in the use of Variable Speed Drives (VSDs). Another study conducted by Bambang Yan Ardianto in his research titled "Harmonic Current Protection in Three-Phase Inverter Installations with Nonlinear Loads"(Atmam et al., 2018), (Amir & Firdaus, 2017), (Ishaya et al., 2023)[5], (Cho & Cha, 2011) also indicates the need for development in the aspect of real-time harmonic monitoring.

However, the scope of this research is still limited to three-phase inverters with a capacity of 37 kW, whereas in this study, a three-phase passive harmonic filter (Single Tuned) will be designed and applied to a 110 kW Variable Speed Drive (VSD) for controlling the speed of an induction motor. Additionally, this research design will be equipped with a real-time monitoring system, enabling harmonic characteristics to be monitored at all times and analyzed with greater accuracy (Ishaya et al., 2023), (Cho & Cha, 2011), (Gupta et al., 2021).

In this study, an Internet of Things (IoT)-based monitoring system integrated with an ESP8266 microcontroller will be developed to improve energy monitoring efficiency. With accurate and up-to-date data available, the system can quickly respond to changes in power quality and proactively take corrective action. The implementation of this IoT-based energy monitoring system with the ESP8266 microcontroller enables faster and more responsive data transmission, as well as supporting a more efficient I/O switching system for high-order harmonic filter settings (Zlatanov, 2016). This opens up opportunities for smarter and more integrated solutions in electrical power quality management (Akintade et al., 2019), (Rif'an, 2019).

The implementation of this design in industrial environments is expected to improve the reliability of electrical power systems, reduce potential equipment malfunctions, and ensure compliance with power quality standards. With real-time monitoring, the system can detect harmonic changes immediately and make automatic adjustments to maintain voltage and current stability. This not only supports energy efficiency but also enables industries to manage operational risks more effectively (Sulistyorini et al., 2022), (Putra et al., 2023).

It is hoped that the results of this study will produce a passive harmonic filter design (Single Tuned) that can improve power quality and be applied to industrial-scale electrical network installations to reduce the impact of harmonics on industrial electrical equipment (Hailan et al., 2023), (Shrestha et al., 2025).

Research Problem Formulation and Research Questions

The research questions in this study focus on three main aspects, namely fifth-order individual harmonics, power factor improvement, and energy efficiency. The research questions asked are as follows:

1. What are the characteristics of the fifth-order harmonic current (iHD-5) generated by the use of a three-phase Variable Speed Drive (VSD) on a 110 kW induction motor, and its impact on the efficiency of the electrical power system?
2. How to design and implement a single-tuned passive harmonic filter in accordance with the standards IEEE Std 1531-2003, IEEE Std 519-1992, and IEEE Std 519-2014, to reduce the 5th-order iHD value below the specified threshold?
3. How can an Internet of Things (IoT)-based monitoring system with a GAE MG50 power meter and ESP8266 microcontroller be used to monitor power quality parameters in real-time and support the technical validation process for the designed filter?
4. To what extent can the installation of passive harmonic filters improve the power factor and reduce active power consumption, thereby contributing to energy savings and industrial electricity costs?

Research Objectives

This study aims to:

1. Analyzing the individual characteristics of fifth-order harmonic currents (iHD-5) caused by non-linear loads in the form of three-phase Variable Speed Drives (VSD) on 110 kW induction motors, and evaluating the extent to which harmonic distortion affects the performance of electrical power systems, particularly in terms of neutral current, power factor, and energy efficiency.
2. Designing and implementing a single-tuned passive harmonic filter specifically aimed at reducing fifth-order harmonics based on the following references:
   - IEEE Std 1531-2003: as a technical guideline in the design and installation of single-tuned passive harmonic filters.
   - IEEE Std 519-1992: as a reference standard for maximum individual harmonic distortion limits in electrical systems.
   - IEEE Std 519-2014: as an update to the previous standard, it provides guidance on power quality management in low-voltage industrial systems, particularly the Total Harmonic Distortion of Current (THDi) parameter.
3. Evaluating the limited influence of harmonics on power factor parameters and energy losses, as well as their impact on the performance of the electrical distribution system. This study does not discuss harmonics in all orders or all system components in detail (such as transformers or cables), but focuses on the influence of 5th order iHD on system efficiency.

Developing an Internet of Things (IoT)-based monitoring system consisting of a GAE MG50 Power Meter and an ESP8266 microcontroller, as a medium for real-time acquisition and recording of electrical parameters, particularly current, active power, power factor, and THDi.

a. Conducting limited experimental validation of the passive harmonic filter design with controlled measurement scenarios. Although not validated with a Power Quality Analyzer (PQA), the system uses the GAE MG50, which has been proven accurate in industrial practice and is used in annual energy audits by independent technical agencies. The validation focus is directed at observing changes in the 5th-order iHD value, power factor improvement, and practical energy savings.

RESEARCH METHOD

Scope of Research

This research was conducted by collecting data from a Schneider ATV610 Variable Speed Drive (VSD) with a capacity of 110 kilowatts (kW) installed at PT Lami Packaging

Indonesia – Cikande, Banten. The inverter is used to regulate the speed of the induction motor that functions as the main drive for the cold water pump in the chiller system.
The inverter panel has the following main specifications:

a. Input voltage: 3-phase, 380–415 V, 50/60 Hz
b. Output voltage: 3-phase, 0–415 V variable
c. Motor capacity: 110 kW
d. Panel protection: 250A MCB, MCCB, surge arrester
e. Main panel components: ATV610 VSD, contactor, overload relay, control MCB, terminal block, and cooling fan
f. Panel cooling: Forced ventilation (fan and top ventilation holes)

The electrical connection diagram for this system is as follows:

a. The power source comes from the main distribution panel (MDP), then enters the inverter panel.
b. From the inverter, variable AC current is sent to a 110 kW induction motor that drives the water pump in the chiller.
c. For power quality monitoring, the system is equipped with a power meter installed on the inverter output to the load.
d. data such as voltage, current, THD, and power factor are read by the Modbus RTU microcontroller, then transmitted to the user interface in real time.

Figure 1. Photo of Schneider ATV610 110kW Inverter Panel

Figure 2. Photo of 110 kW Induction Motor Nameplate

The method used in this study is as shown in Figure 3 below :

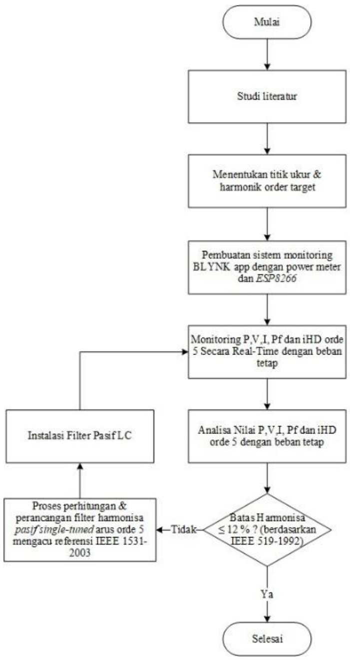


Figure 3. Research flow

Data collection was carried out by measuring the electrical parameters of the induction motor load using a real-time monitoring system, in which the microcontroller acted as the main control unit for data acquisition and processing (Mubarok et al., 2024), (Widagdo et al., 2023).

RESULTS AND DISCUSSION

Monitoring System Architecture

In this study, an electrical power quality monitoring system was designed using a combination of microcontrollers and communication modules, consisting of:

a. Arduino Uno / Raspberry Pi as the main control unit tasked with reading data from Modbus RTU-based power meters.
b. ESP8266 functions as a Wi-Fi communication module to send data to the cloud platform in real time.
c. The Modbus RTU communication protocol is used to access data from power meters serially (RS485), which is then processed and sent via ESP8266.

This architecture was chosen because it is flexible, low cost, and compatible with various IoT-based monitoring systems. Figure 4 below shows the connection between the ESP 8266 and the power meter.

Figure 4. Wiring Diagram of MICROCONTROLLER Integration of Power Meter and User Interface

Programming and Integrating Data Loggers into Google Sheets

Data from electrical parameter readings (current, voltage, THD, power factor, etc.) is automatically recorded in Google Sheets using the following approach:

a. The ESP8266 is programmed using Arduino IDE with HTTP/HTTPS library and Google Apps Script as the receiving endpoint.

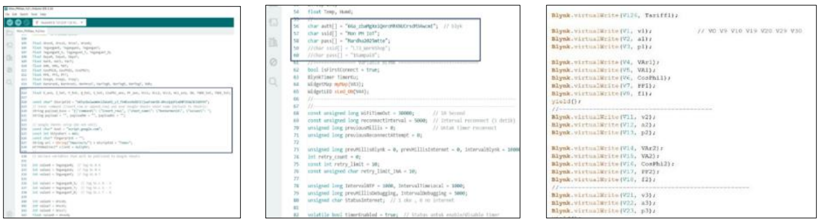


Figure 5. ESP8266 program on Arduino IDE

a. All data read from the power meter is sent to Google Sheets via webhook. Figure 6 below shows the apps script on Google Sheets.

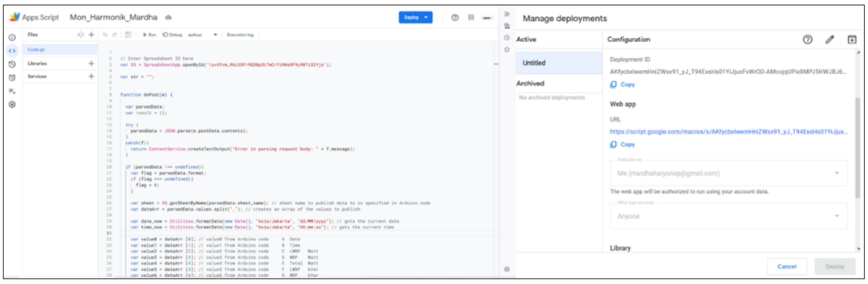
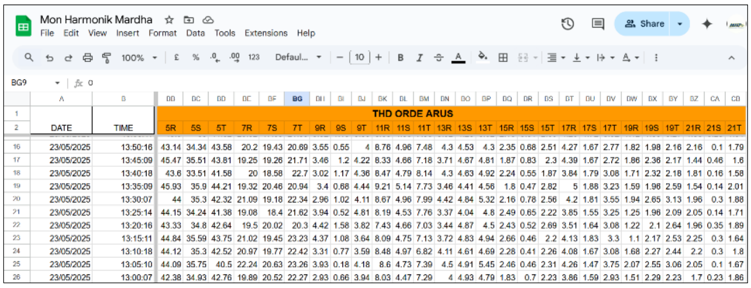


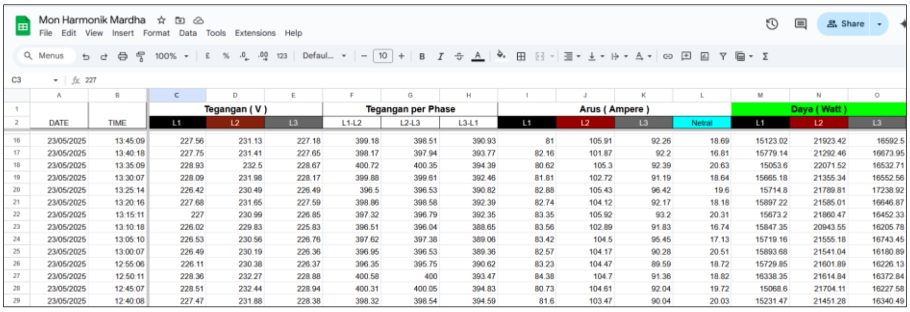
Figure 6. App script program on Google Sheets

b. Google Sheets functions as a historical data logger, enabling long-term trend analysis of electrical parameters. Electrical parameter data is automatically collected from May 20 to 27, 2025. Figures 7 and 8 show the historical data logger on Google Sheets.



		THD ORDE ARUS																										
DATE	TIME	5R	5S	5T	7R	7S	7T	9R	9S	9T	11R	11S	11T	13R	13S	13T	15R	15S	15T	17R	17S	17T	19R	19S	19T	21R	21S	21T
23/05/2025	13:50:16	43.14	34.34	43.58	20.2	19.43	20.69	3.55	0.55	4	8.76	4.96	7.48	4.3	4.53	4.3	2.35	0.68	2.51	4.27	1.67	2.77	1.82	1.98	2.16	2.16	0.1	1.79
23/05/2025	13:45:09	45.47	35.51	43.81	19.25	19.26	21.71	3.46	1.2	4.22	8.33	4.66	7.18	3.71	4.67	4.81	1.87	0.83	2.3	4.39	1.67	2.72	1.86	2.36	2.17	1.44	0.46	1.6
23/05/2025	13:40:18	43.6	33.51	41.58	20	18.58	22.7	3.02	1.17	4.36	8.47	4.79	8.14	4.3	4.63	4.92	2.24	0.55	1.87	3.84	1.79	3.08	1.71	2.32	2.18	1.81	0.16	1.58
23/05/2025	13:35:09	45.93	35.9	44.21	19.32	20.46	20.94	3.4	0.68	4.44	9.21	5.14	7.73	3.46	4.41	4.56	1.8	0.47	2.82	5	1.88	3.23	1.59	1.96	2.59	1.54	0.14	2.01
23/05/2025	13:30:07	44	35.3	42.32	21.09	19.18	22.34	2.96	1.02	4.11	8.67	4.96	7.99	4.42	4.84	5.32	2.16	0.78	2.56	4.2	1.81	3.55	1.94	2.65	3.13	1.96	0.3	1.88
23/05/2025	13:25:14	44.15	34.24	41.38	19.08	18.4	21.62	3.94	0.52	4.81	8.19	4.53	7.76	3.37	4.04	4.8	2.49	0.65	2.22	3.85	1.55	3.25	1.25	1.96	2.09	2.05	0.14	1.71
23/05/2025	13:20:16	43.33	34.8	42.64	19.5	20.02	20.3	4.42	1.58	3.82	7.43	4.66	7.03	3.44	4.87	4.5	2.43	0.52	2.69	3.51	1.64	3.08	1.22	2.1	2.64	1.96	0.35	1.89
23/05/2025	13:15:11	44.84	35.59	43.75	21.02	19.45	23.23	4.37	1.08	3.64	8.09	4.75	7.13	3.72	4.83	4.94	2.66	0.46	2.2	4.13	1.83	3.3	1.1	2.17	2.53	2.25	0.3	1.64
23/05/2025	13:10:18	44.12	35.3	42.52	20.97	19.77	22.42	3.31	0.77	3.59	8.48	4.97	6.82	4.11	4.61	4.69	2.28	0.41	2.26	4.08	1.67	3.08	1.68	2.27	2.44	2.2	0.3	1.8
23/05/2025	13:05:10	44.09	35.75	40.5	22.24	20.63	23.26	3.93	0.18	4.18	8.6	4.73	7.39	4.5	4.91	5.45	2.46	0.46	2.31	4.26	1.47	3.75	2.07	2.55	3.06	2.05	0.1	1.67
23/05/2025	13:00:07	42.38	34.93	42.76	19.89	20.52	22.27	2.93	0.66	3.94	8.03	4.47	7.29	4	4.93	4.79	1.83	0.7	2.23	3.86	1.59	2.93	1.51	2.29	2.23	1.7	0.23	1.86

Figure 7. Historical THD logger for Google Sheets current order



		Tegangan (V)			Tegangan per Phase			Arus (Ampere)				Daya (Watt)		
DATE	TIME	L1	L2	L3	L1-L2	L2-L3	L3-L1	L1	L2	L3	Netral	L1	L2	L3
23/05/2025	13:45:09	227.56	231.13	227.18	399.18	398.51	390.93	81	105.91	92.26	18.69	15123.02	21923.42	16592.5
23/05/2025	13:40:18	227.75	231.41	227.65	398.17	397.94	393.77	82.16	101.87	92.2	16.81	15779.14	21292.46	16673.95
23/05/2025	13:35:09	228.93	232.5	228.67	400.72	400.35	394.39	80.62	105.3	92.39	20.63	15053.6	22071.52	16532.71
23/05/2025	13:30:07	228.09	231.98	228.17	399.88	399.61	392.46	81.81	102.72	91.19	18.64	15665.18	21355.34	16552.56
23/05/2025	13:25:14	226.42	230.49	226.49	396.5	396.53	390.82	82.88	105.43	96.42	19.6	15714.8	21789.81	17238.92
23/05/2025	13:20:16	227.68	231.65	227.59	398.86	398.58	392.39	82.74	104.12	92.17	18.18	15897.22	21585.01	16646.87
23/05/2025	13:15:11	227	230.99	226.85	397.32	396.79	392.35	83.35	105.92	93.2	20.31	15673.2	21860.47	16452.33
23/05/2025	13:10:18	226.02	229.83	225.83	396.51	396.04	388.65	83.56	102.89	91.83	16.74	15847.35	20943.55	16205.78
23/05/2025	13:05:10	226.53	230.56	226.76	397.62	397.38	389.06	83.42	104.5	95.45	17.13	15719.16	21555.18	16743.45
23/05/2025	13:00:07	226.49	230.19	226.36	396.95	396.53	389.36	82.57	104.17	90.28	20.51	15893.68	21541.04	16180.89
23/05/2025	12:55:06	226.11	230.38	226.37	396.35	395.75	390.62	83.23	104.47	89.59	18.72	15729.85	21601.89	16226.13
23/05/2025	12:50:11	228.36	232.27	228.88	400.58	400	393.47	84.38	104.7	91.36	18.82	16338.35	21614.84	16372.84
23/05/2025	12:45:07	228.51	232.44	228.94	400.31	400.05	394.83	80.73	104.61	92.04	19.72	15068.6	21704.11	16227.58
23/05/2025	12:40:08	227.47	231.88	228.38	398.32	398.54	394.59	81.6	103.47	90.04	20.03	15231.47	21451.28	16340.49

Figure 8. Historical voltage, power, and current logger Google Sheets

Live Monitoring Visualization with Blynk

For real-time monitoring, this system is connected to the Blynk app:

a. Blynk receives data via a Wi-Fi connection from ESP8266. Electrical parameters such as current, voltage, and THD are displayed in real time in the form of graphs and numerical values.
b. The Blynk application for remote monitoring is run on Android/iOS devices.

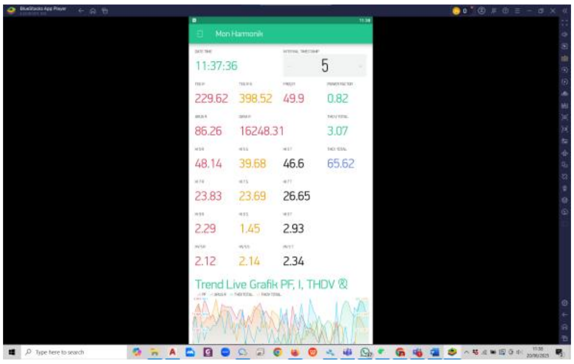


Figure 9. Visualization of Live Monitoring in BLYNK application

Figure 9 shows the results of real-time visualization of the IoT-based power quality monitoring system through the Blynk application accessed on an Android device. The data was obtained before the installation of the harmonic filter, with data collection on May 20, 2025 at 11:37:36.

Important parameters such as interphase voltage (Vph), current (A), power factor (PF), frequency, and current Total Harmonic Distortion (THDi) values are displayed numerically and graphically. The THDi value is observed to be quite high in all three phases, reaching 65.62%, with the dominance of 5th-order harmonics (H5R of 48.14%, H5S of 39.68%, and H5T of 46.6%). The nominal current was also observed to be quite large, at 86.26 A, indicating the presence of inefficient power quality due to harmonic interference.

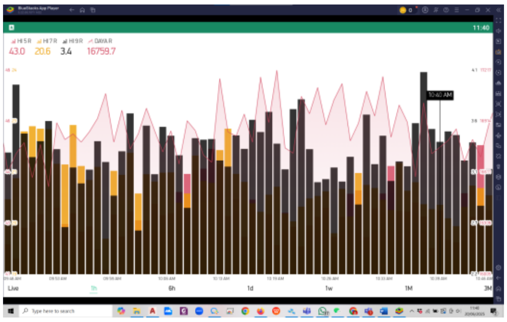
This visualization becomes the basis for analyzing the need for passive harmonic filter installation and power factor improvement. Through the integration of the ESP8266 microcontroller, data is sent directly to the Blynk app, allowing users to monitor power quality flexibly and in real-time from any location.

Figure 10. Trend graph of electrical parameters before filter installation

Figure 10 displays a real-time trend graph taken from the Blynk application prior to the installation of the passive harmonic filter. The visualized parameters include power factor (Power Factor), phase R load current (ARUS.R), total harmonic distortion of current (THDi), and total harmonic distortion of voltage (THDv), with a monitoring time range from 10:15 am to 11:37 am.

It is clear that:
- Power Factor values (red line) are in the low range, averaging 0.80, indicating the dominance of the reactive power component.
- The THDi value (yellow line) is very high, averaging 62.9%, which far exceeds the IEEE 519-2014 standard limit of 8%, indicating severe harmonic dominance from non-linear loads.
- The THDv value (green line) stands at 2.9%, still within a reasonable threshold below the 5% limit.
- The R phase load current (light blue line) varies fluctuatingly to exceed 86 A, indicating an unstable load pattern.

This data is automatically acquired and transmitted by the ESP8266 microcontroller via communication protocol to the Blynk app. This trend visualization feature allows users to evaluate power quality conditions directly and historically, thus supporting the decision-making process in harmonic mitigation planning.



Ficture 11. Live monitoring quality energy Blynk Apps

Figure 11 shows the trend graph of individual harmonic 5th order, 7th distortion (iHD) and active power (R power) in phase R before the installation of passive harmonic filter. This data is collected and visualized in real-time through the Blynk application connected to the ESP8266 microcontroller-based monitoring system.

The graphical display shows some important parameters:
- 5th-order harmonics (H5R) dominate with an average of about 43%, which far exceeds the maximum limit of 12% based on the IEEE 519-1992 standard for systems with ISC/IL ratios between 100 and 1000.
- The 7th-order harmonic (H7R) is also quite significant, standing at 20.6%, while the 3rd-order (H3R) is relatively small at 3.4%.
- The red line shows the active power fluctuation of phase R, with the highest value recorded at 16,759.7 Watts, indicating that the dominant harmonic currents contribute to energy waste and reduce system efficiency.

This graph provides a comprehensive visual depiction of the dominance of harmonics occurring on the R phase side. Under these conditions, it is clearly necessary to implement harmonic mitigation through a 5th-order passive filter to suppress distortion and improve power quality.

Determination of Harmonic Filter Design at Distribution Voltage (400 V)

The harmonic filter design on the low voltage side of the transformer is determined based on the IEEE Std 1531-2003 standard reference. The calculation steps begin with determining the capacity of the harmonic filter, which is focused on handling 5th-order harmonics, given the large contribution of this order to the total harmonic distortion in the system.

The filter design is carried out by considering the target of improving the power factor (cos φ) to 0.95 as well as the non-linear load characteristics identified from the monitoring results. The capacitance and reactance values of the filter are calculated to produce an LC filter circuit that effectively reduces individual current harmonics at the 5th frequency, while providing the required reactive power compensation.

This approach aims to maintain the quality of electrical power in the internal distribution system to remain within the limits of the IEEE 519-1992 standard, as well as improve the operational efficiency of electrical equipment connected to the network. The process of calculating and designing a single-tuned passive harmonic filter follows the following steps:
Determine the initial power factor (pf0) and desired power factor (pf1) of the non-linear load.
Initial power factor (pf_0) = 0,76
Desired power factor (pf_1) = 0,95
Apparent power (S) = 24,02 kVA
Active power (P) = 19,21 kW
Reactive power (Q) = 14,41 kVar

1. Determine the effective reactive power capacity of the filter based on the equation:
$$Q_{eff} = S \times [\sin(cos^{-1}pf_0) - \sin(cos^{-1}pf_1)]$$
Calculations:
Q_{eff} = S × [sin(cos⁻¹(pf_0)) - sin(cos⁻¹(pf_1))]
Q_{eff} = 24,02 × [sin(0,722) - sin(0,318)]
Q_{eff} = 24,02 × 0,344 = 8,11 kVar
2. Determining the filter tuning frequency
According to IEEE 1531-2003, the frequency of the single-tuned Harmonics filter is determined to be 3% - 15% below the specified frequency as a safety factor.
ftuning = 0,95 × 250 Hz = 237,5 Hz
Determining the effective impedance of the filter.
$$X_{eff} = \frac{V_{LLsys}^2}{Q_{eff}}$$
Calculations :
$X_{eff} = V_{LLsys}^2 / Q_{eff}$
X_{eff} = 400^2 / 8110 = 19,7 Ohm
3. Determine the capacitive reactance and inductive reactance at the fundamental frequency.
$$X_c(1) = \left(\frac{h^2}{h^2 - 1}\right) X_{eff}$$
$$X_L(1) = \left(\frac{X_c(1)}{h^2}\right)$$
Calculations :
$X_c(1)$ = (h^2 / (h^2 - 1)) × Xeff = (25 / 24) × 19,7 = 20,5 Ohm
$X_L(1)$ = XC(1) / h^2 = 20,5 / 25 = 0,82 Ohm
h = the harmonic order targeted by the filter
4. Determining the RMS current of the filter
$$I_f(1) = \left(\frac{V_S}{X_c(1) - X_L(1)}\right)$$
Calculations:
Vph = 400 / √3 = 230,94 V
$I_f(1)$ = Vph / ($X_c(1)$ - $X_L(1)$)
= 230,94 / (20,5 – 0,82)

= 11,7 A

5. Determine the capacitor's reactive power capacity rating.

$$Q_{C\_rated} = P \times [\tan(cos^{-1}pf_0) - \tan(cos^{-1}pf_1)]$$

Calculations:

Q_{C_rated} = P × [tan(cos^{-1}(pf$_0$)) - tan(cos^{-1}(pf$_1$))]

Q_{C_rated} = 19,21 × [tan(40.54) - tan(18,19)]

Q_{C_rated} = 19,21 × 0,5266 = 10,11 kVar

6. Determine the nominal current of a capacitor.

$$I_{nom} = \frac{Q_{C_{rated}}}{\sqrt{3}\,.\,V_{C_{peak}}}$$

Calculations :

I_{nom} = QC_rated / (√3 × 400)

I_{nom} = 10,11 / 0,6928

I_{nom} = 14,6 A

With reference to the calculation steps 1 to 7 above, if given a power factor with a value of 0.95, the following data is obtained:

- Calculation for capacitance and inductance:
- Initial power factor, pf_0 = 0.76
- Final target power factor, pf_1 = 0.95
- Reactive power required, Q_eff = 8.11 kVar
- Reactive power available Q_(C_rated) = 10.11 kVar
- Reactive current of capacitor, Inom QC = 14.6 A
- Capacitive reactance XC = 20.5 Ohms
- Inductive reactance XL = 0.82 Ohms
- System voltage (3 phase), V_{ll} = 400 V
- System frequency, f = 50 Hz
- Tuning frequency, ft = 0.95 × 250 Hz = 237.5 Hz

1. Calculating Capacitance (C)
   Formula:
   $C = 1 / (2\pi f X_C)$
   Calculations:
   C = 1 / (2 × π × 50 × 20,5)
   C = 1 / 6442,85 = 155,2 µF
2. Calculating Inductance (L)
   Formula:
   $L = 1 / ((2\pi ft)^2 \times C)$
   Calculations:
   L = 1 / ((2 × π × 237,5)^2 × 155,2 × 10^{-6})
   L = 1 / (1495,3^2 × 155,2 × 10^{-6})
   L = 1 / (2236672,09 × 155,3 × 10^{-6}) = 1 / 347,41
   L = 0,002289 H
   L = 2,89 mH

Figure 30 shows the measurement results of inductance (L) and capacitance (C) for the single tuned filter to be installed.

Figure 12: Making a Passive Filter Circuit

Table 1. Table of calculation results of QCrated, Inom, L and C with a power factor of 0.95

pf_0 (Initial)	pf_1 (Target akhir)	Q_C_rated (kVAR)	I_{nom} Q_C_rated (A)	Induktor (L)	Kapasitor (C)
0,76	0,95	10,11	14,6	2,89 mH	155,2 µF

Empirically and practically, the decrease in harmonics (especially iHD) is directly proportional to the increase in power factor. Then the PF ratio approach can be used to calculate the decrease in iHD as follows:
Initial power factor, pf_0 = 0,76
Final power factor, pf_1 = 0,95
iHDawal = 47,8%

1. Final iHD calculation

$$iHD_{end} = iHD_{Initial} \times \frac{1 - pf1}{1 - pf0}$$
$$iHD_{end} = 47{,}8\% \times \frac{1 - 0{,}95}{1 - 0{,}76}$$
$$iHD_{end} = 9{,}96\%$$

2. Calculation of iHD reduction

$$\text{Decline iHD\%} = \frac{iHD_{end} - iHD_{Initial}}{iHD_{Initial}} \text{ x } 100\%$$
$$\text{Decline iHD\%} = \frac{47{,}8\% - 9{,}96\%}{47.8\%} \text{ x } 100\%$$
$$\text{Decline iHD\%} = 79{,}15\%$$

Table 2. Table of results of the 5th order harmonic IHD calculation with a power factor of 0.95

pf_0 (Initial)	IHD H-5 Initial (%)	pf_1 (Final target)	IHD H-5 end (%)	Decline IHD (%)
0,76	47,8	0,95	9,96	79,15

Manufacturing and Installation Testing of Harmonic Filters

From the calculation results, a single tuned passive filter design of a series Inductor (L) & Capacitor (C) circuit was obtained, as shown in Figure 22 below:
L = 2,89 mH , C = 155,2 µF

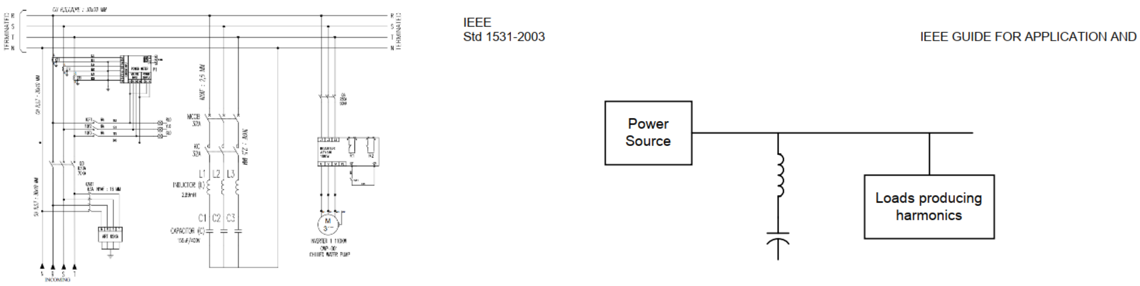


Figure 13. Wiring diagram of a fifth-order single tuned LC passive filter

To meet these values, a simple filter assembly was constructed for testing by purchasing materials available on the market. Figure 13 shows the assembly of a single tuned L and C passive filter to reduce harmonic iHD.

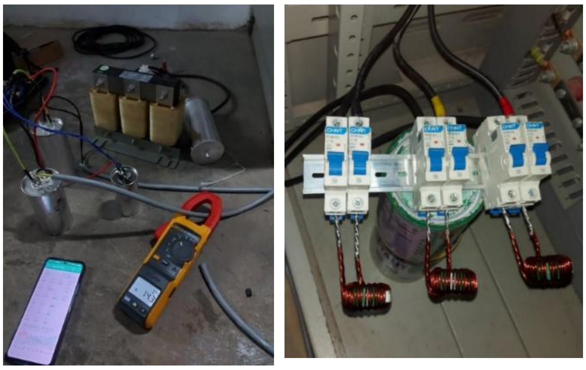


Figure 14. Fifth-order single tuned LC passive filter assembly

Based on the calculation results, a single-tuned passive filter design was obtained with a series configuration between the inductor (L) and capacitor (C). The purpose of installing this filter is to suppress the dominant 5th order harmonics that arise due to the use of non-linear loads in the electrical distribution system.

The values of the components used are Inductor: L = 2.89 mH and capacitor C = 155.2 µF / 400 V.

To implement this design, a simple filter assembly was constructed. The assembly process was carried out in accordance with the wiring diagram shown in Figure 32, which represents a 3-phase system in which each phase (R, S, T) is fitted with an LC circuit connected to the neutral point.

Figure 14 shows documentation of the filter installation process on June 20–24, 2025, and the physical assembly of the filter, including the installation of MCBs for phase protection and inductors and capacitors assembled according to calculations. Measuring instruments such as multimeters and LCR meters were also used to validate the initial performance of the system. With this configuration, the filter can operate optimally in absorbing harmonic currents at the specified tuning frequency, thereby improving the quality of the electrical power system.

The Effectiveness of IoT Monitoring Systems in Power Quality Analysis After Filter Installation

The Internet of Things (IoT)-based monitoring system developed in this study has been proven effective in:

1. Measure power quality parameters in real time, including voltage, current, active power, power factor, Total Harmonic Distortion (THD), and iHD per harmonic order.

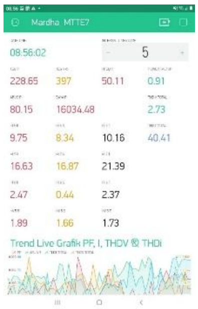


Figure 15. Blynk Monitoring Display After Installing the Harmonic Filter

Figure 15 shows the results of real-time monitoring of the electrical system through the Blynk application after installing a single-tuned passive harmonic filter. The data was collected at 08:56:02 WIB with a reading interval of every 5 minutes.

Based on the numerical display:

- The power factor value increased to 0.91, indicating a significant improvement from the initial condition (0.76).
- The total THDi was successfully reduced to 40.41%, a significant decrease from the initial value of 67.35%. Although it has not yet reached the IEEE 519-2014 standard (<8%), this downward trend indicates the system's success in effectively reducing current harmonics.
- The Individual Harmonic Distortion (iHD) of the 5th order (H5R, H5S, H5T) has dropped drastically to 9.75%, 8.34%, and 10.16% — all of which are below the maximum limit of 12% according to the IEEE 519-1992 standard, meaning they meet the individual harmonic regulation requirements.
- The iHD values for the 7th order (H7R, H7S, H7T) have also decreased to the range of 16–21%, down from the previous 27–29%.
- Phase R current was monitored at 80.15 A, with active power of 16,034.48 W, indicating an improvement in system efficiency, although there is still room for further optimization.

The graph trend in Figure 19 shows the stability of power quality parameters (THDv, THDi, current, and power factor) under operating conditions after the filter is installed. This data confirms that the integration of an ESP8266-based IoT monitoring system with a passive filter is not only capable of displaying real-time data, but also serves as the basis for quick and accurate technical decision-making.

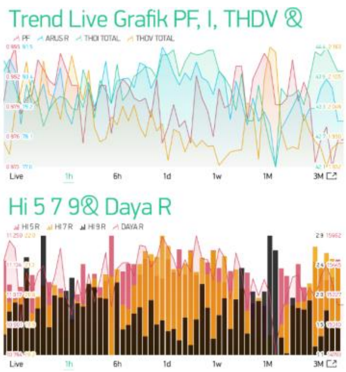


Figure 16. Live monitoring quality after filter installation

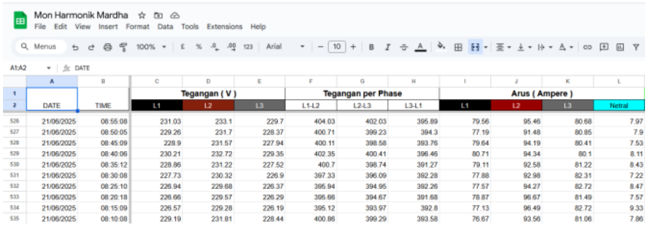
Figure 16 above shows live monitoring displaying graphs of THDi, Current, Power Factor, and Individual Harmonics trends after filter installation. This figure shows the results of real-time monitoring of power quality trends using the Blynk application after installing a single-tuned passive harmonic filter. The graph is divided into two parts:

a. Trend Graph of PF, Current, THDi, THDv Parameters:
   - The blue color indicates that the Total THDi value is stable below 45%, a significant decrease from the initial value before the filter of 67.35%.
   - The pink color indicates that the Power Factor has increased to the range of 0.9–0.92, from the previous range of 0.76–0.80, indicating an improvement in system efficiency.
   - The current on phase R also shows stability, without the extreme fluctuations observed before the filter was installed.
   - The Total THDv value (orange color) remains within the range of 2.7–3%, indicating that voltage distortion is maintained within safe limits.

a. Bottom Graph – 5th, 7th, 9th Order Individual Harmonics and Active Power of Phase R:
   - The bar chart shows a significant decrease in individual harmonics:
     - The H5R (5th order) decreased to 9–11%, meeting the maximum limit of 12% as per IEEE 519-1992.
     - The H7R (7th order) decreased to 16–18%, from nearly 29% previously.
     - The 9th (H9R) and 11th (H11R) order harmonics also showed small values (<3%), indicating their insignificance to the overall THDi.
   - The red line shows the active power (R Power) fluctuation which remains in the range of 15,000–16,500 W, indicating that the system is more stable in terms of energy consumption after installing the filter.

Overall, this trend confirms that the implementation of passive harmonic filters and IoT monitoring systems has had a positive impact in reducing current harmonics, improving power factor, and stabilizing active power consumption — in accordance with the design objectives and the referenced IEEE standards.

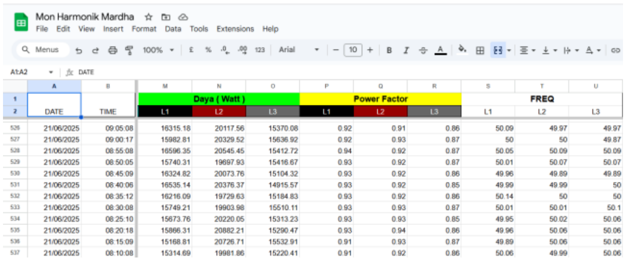
1. Automatically send data to Google Sheets and the Blynk application, so that monitoring can be done at any time without the need for manual measurements.



Mon Harmonik Mardha

	DATE	TIME	Tegangan (V) L1	Tegangan (V) L2	Tegangan (V) L3	Tegangan per Phase L1-L2	Tegangan per Phase L2-L3	Tegangan per Phase L3-L1	Arus (Ampere) L1	Arus (Ampere) L2	Arus (Ampere) L3	Arus (Ampere) Netral
526	21/06/2025	08:55:08	231.03	233.1	229.7	404.03	402.03	395.89	79.56	95.46	80.68	7.97
527	21/06/2025	08:50:05	229.26	231.7	228.37	400.71	399.23	394.3	77.19	91.48	80.85	7.9
528	21/06/2025	08:45:09	228.9	231.57	227.94	400.11	398.58	393.76	79.64	94.19	80.41	7.53
529	21/06/2025	08:40:06	230.21	232.72	229.35	402.35	400.41	396.46	80.71	94.34	80.1	8.11
530	21/06/2025	08:35:12	228.86	231.22	227.52	400.7	398.74	391.27	79.11	92.58	81.22	8.43
531	21/06/2025	08:30:08	227.73	230.32	226.9	397.33	396.09	392.28	77.88	92.98	82.31	7.22
532	21/06/2025	08:25:10	226.94	229.68	226.37	395.94	394.95	392.26	77.57	94.27	82.72	8.47
533	21/06/2025	08:20:18	226.66	229.57	226.29	395.66	394.67	391.68	78.87	96.67	81.49	7.57
534	21/06/2025	08:15:09	226.57	229.28	226.19	395.12	393.97	392.8	77.13	96.49	82.72	9.33
535	21/06/2025	08:10:08	229.19	231.81	228.44	400.86	399.29	393.58	76.67	93.56	81.06	7.86

Figure 17. Google Sheets Voltage and Current Measurement Results After Filter Installation



Mon Harmonik Mardha

	DATE	TIME	Daya (Watt) L1	Daya (Watt) L2	Daya (Watt) L3	Power Factor L1	Power Factor L2	Power Factor L3	FREQ L1	FREQ L2	FREQ L3
526	21/06/2025	09:05:08	16315.18	20117.56	15370.08	0.92	0.91	0.86	50.09	49.97	49.97
527	21/06/2025	09:00:17	15982.81	20329.52	15636.92	0.92	0.93	0.87	50	50	49.87
528	21/06/2025	08:55:08	16596.35	20545.45	15412.72	0.94	0.92	0.87	50.05	50.09	50.09
529	21/06/2025	08:50:05	15740.31	19697.93	15416.67	0.93	0.92	0.87	50.01	50.07	50.07
530	21/06/2025	08:45:09	16324.82	20073.76	15104.32	0.93	0.92	0.86	49.96	49.89	49.89
531	21/06/2025	08:40:06	16535.14	20376.37	14915.57	0.93	0.92	0.85	49.99	49.99	50
532	21/06/2025	08:35:12	16216.09	19729.63	15184.83	0.93	0.92	0.86	50.14	50	50
533	21/06/2025	08:30:08	15749.21	19903.98	15510.11	0.93	0.93	0.87	50.01	50.01	50.1
534	21/06/2025	08:25:10	15673.76	20220.05	15313.23	0.93	0.93	0.85	49.95	50.02	50.06
535	21/06/2025	08:20:18	15866.31	20882.21	15290.47	0.93	0.94	0.86	49.96	50.06	50.06
536	21/06/2025	08:15:09	15168.81	20726.71	15532.91	0.91	0.93	0.87	49.89	50.06	50.06
537	21/06/2025	08:10:08	15314.69	19981.86	15220.41	0.91	0.92	0.86	50.06	49.99	50.06

Figure 18. Results of Power, Power Factor and Frequency measurements on Google Sheets after filter installation

	DATE	TIME	THD Tegangan L1	THD Tegangan L2	THD Tegangan L3	THD Tegangan TOTAL	THD Arus L1	THD Arus L2	THD Arus L3	THD Arus TOTAL
530	21/06/2025	08:50:05	2.82	2.82	3.24	2.95	36.65	31.66	40.45	36.83
531	21/06/2025	08:45:09	2.91	2.64	3.19	2.95	35.75	32.78	41.44	37.71
532	21/06/2025	08:40:06	2.78	2.75	3.17	2.81	36.41	31.47	43	39.59
533	21/06/2025	08:35:12	2.94	2.81	3.05	2.86	35.77	32.52	42.09	37.06
534	21/06/2025	08:30:08	3.09	2.77	3.22	3.02	36.75	31.88	40.99	36.7
535	21/06/2025	08:25:10	3.07	2.85	3.33	3.1	36.58	31.26	39.9	36.99
536	21/06/2025	08:20:18	2.97	2.76	3.23	2.99	37.03	30.39	41.22	36.8
537	21/06/2025	08:15:09	3.12	2.93	3.41	3.12	39.51	30.63	40.34	37.67
538	21/06/2025	08:10:08	2.73	2.69	3.09	2.81	39.41	33.16	42.23	38.81
539	21/06/2025	08:05:11	2.81	2.68	2.97	2.78	37.9	30.75	40.18	37.87
540	21/06/2025	08:00:07	2.67	2.6	3.06	2.76	40.74	32.98	40.49	39.07
541	21/06/2025	07:55:28	2.76	2.75	3.21	2.9	40.7	33.81	40.91	39.26

Figure 19. Results of THD Voltage and THD Current Measurements on Google Sheets After Filter Installation

	DATE	TIME	3R	3S	3T	5R	5S	5T	7R	7S	7T	9R	9S	9T	11R	11S	11T	13R	13S
			iHD ORDE ARUS																
530	21/06/2025	08:50:05	7.65	4.35	7.25	9.33	8.19	10.08	16.52	17.49	18.61	2.84	1.11	2.37	7.88	5.2	7.14	4.04	4.86
531	21/06/2025	08:45:09	9.44	4.8	8.5	9.36	8.33	10.61	16.97	18.55	19.11	4.58	0.25	3.01	7.18	4.49	7.19	4.11	5.15
532	21/06/2025	08:40:06	9.35	5.05	9.3	9.28	8.09	10.59	16.35	17.06	18.91	4.01	1	4.29	7.42	4.88	7.48	3.75	4.64
533	21/06/2025	08:35:12	7.86	3.8	8.87	9.4	8.54	10.31	16.48	17.01	20.25	2.95	1.82	1.7	7.2	5.09	7.84	4.09	5.42
534	21/06/2025	08:30:08	7.39	3.84	7.71	9.63	8.32	10.32	16.69	17.25	19.33	3.11	0.57	3.2	8.02	5.12	7.17	4.76	5.56
535	21/06/2025	08:25:10	8.56	5.18	7.7	9.54	8.07	10.09	16.13	16.98	19.44	3.6	1	1.68	7.97	4.75	7.07	4.75	5.11
536	21/06/2025	08:20:18	7.98	4.73	8.26	9.37	7.88	10.23	17.29	16.53	20.06	4.24	1.05	2.7	7.29	5.01	6.85	4.47	5.01
537	21/06/2025	08:15:09	10.29	5.43	8.93	9.68	7.94	9.99	16.93	16.43	19.2	3.4	0.1	3.83	7.65	4.58	7.02	4.16	4.58
538	21/06/2025	08:10:08	8.6	4.32	8.79	9.72	8.62	10.01	18.48	17.72	20.39	4.35	0.68	3.27	6.66	4.61	7.36	4.65	5.21
539	21/06/2025	08:05:11	7.72	4.95	8.57	9.82	8.39	9.76	17.72	16.39	20.65	3.18	0.25	2.72	7.12	4.46	6.94	4.58	4.35
540	21/06/2025	08:00:07	7.19	4.46	8.68	10.36	8.56	10.4	19.32	17.69	20.89	2.83	0.48	3.15	7.27	4.35	6.23	4.1	4.97
541	21/06/2025	07:55:28	7.65	4.98	9.75	10.39	8.71	9.86	18.4	17.91	20.17	3.11	1.27	2.67	6.81	4.05	6.37	4.06	5.09

Figure 20. Results of iHD measurements of Google Sheets Current order after filter installation

1. Monitor load patterns during operating hours (24 hours), and detect significant sources of non-linear harmonics, especially those of the 5th order.
2. Support technical analysis and decision-making processes, such as determining appropriate harmonic filter designs based on actual data.

   With ease of integration and relatively low cost, this system is very suitable for application in industrial environments.

Evaluation of 5th Order Harmonic Limits Based on IEEE Standard 519-1992

To determine whether the individual harmonic distortion (iHD) value at the 5th order is still within the limits permitted by the IEEE 519-2014 standard, a calculation is made based on the ratio between the system short circuit current ISC and the maximum load current IL.

Calculation:

Given:

Transformer capacity = 2500 kVA

System voltage = 400 V

Maximum nonlinear load current = 90 A

Transformer impedance assumed = 7%

Calculation steps:

Transformer nominal current:

$$I_{FL} = \frac{S}{\sqrt{3} \times \mathrm{V}} = \frac{2.500.000}{\sqrt{3} \times 400} = 3.608A$$

System short circuit current:

$$I_{SC} = \frac{I_{FL}}{\mathrm{Z}} = \frac{3.606}{0{,}07} = 51.543A$$

The ratio between short circuit current and load current:

$$\frac{I_{SC}}{I_{FL}} = \frac{51.543}{3.608} = 572{,}7$$

Reference to IEEE 519-1992 (refer to table 1):

Based on IEEE 519-1992 standard, for ratio 100<I_SC/I_FL <1000, the maximum limit of individual harmonic current distortion (iHD) for the 5th harmonic order (category h<11h<11) is 12% of the load current / nominal. If the actual value of the 5th order iHD exceeds 12%, then the system is declared not to meet the standard and appropriate harmonic filtering needs to be applied.

Comparative evaluation of power quality performance before and after filter installation

Tables 3 and 4 compare power quality performance before and after filter installation. Graphs 21 and 22 compare power quality parameters before and after filter installation.

Table 3. Power quality performance before filter installation

Tegangan (V)	Tegangan per Phase	Arus (Ampere)		Daya (Watt)	Power Factor	FREQ	THD Tegangan		THD Arus		iHD ORDE ARUS %								
L1	L1-L2	L1	Netral	L1	L1	L1	L1	TOTAL	L1	TOTAL	3R	3S	3T	5R	5S	5T	7R	7S	7T
228	400	87	18	15.856	0,8	50	2,1	2,1	73	68	11	12	18	51	43	47	27	29	28
227	397	84	22	15.241	0,8	50	2,1	2,0	73	69	12	11	18	50	42	49	27	24	27
228	398	84	20	15.401	0,81	50	2,2	2,1	71	68	11	12	21	49	43	46	26	27	26
228	399	85	21	15.392	0,80	50	2,1	2,0	73	68	11	10	17	50	42	50	27	26	28
228	400	83	20	15.145	0,80	50	2,2	2,2	74	68	11	12	18	50	42	48	27	26	27

Table 4. Power quality performance after filter installation

Tegangan (V)	Tegangan per Phase	Arus (Ampere)		Daya (Watt)	Power Factor	FREQ	THD Tegangan		THD Arus		iHD ORDE ARUS %								
L1	L1-L2	L1	Netral	L1	L1	L1	L1	TOTAL	L1	TOTAL	3R	3S	3T	5R	5S	5T	7R	7S	7T
229	400	77	9	15.114	0,9	50	3	3	41	39	7	6	9	10	9	10	20	19	20
229	400	78	9	15.457	0,9	50	3	3	41	38	6	5	9	11	9	10	19	19	22
228	399	76	9	14.838	0,9	50	3	3	42	39	7	6	10	11	8	9	19	18	21
229	399	77	8	15.180	0,89	50	3	3	41	39	5	5	10	11	9	10	19	18	20
230	400	76	10	14.995	0,89	50	3	3	42	41	7	5	9	11	9	10	20	18	22

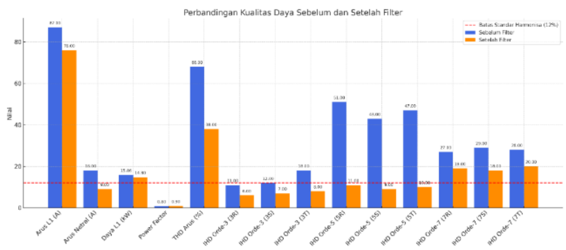


Chart 21. Power quality parameters and IHD before and after filter installation

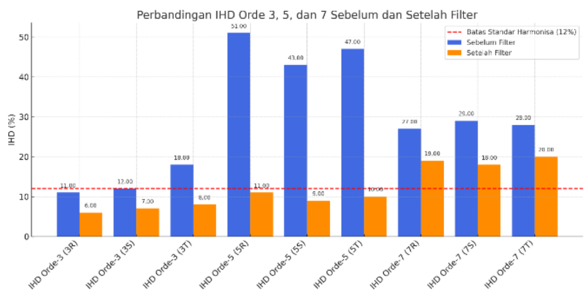


Chart 22. IHD parameters before and after filter installation

Table 5. Harmonic filter performance evaluation table

No	Parameter	Nilai Awal	Nilai Akhir	% Penurunan	Deskripsi hasil
1	Ampere Netral	18	9	50%	Filter menyerap harmonisa triplen yang mengalir di netral
2	iHD Orde-3 (3R, 3S, 3T)	11 | 12 | 18	6 | 7 | 8	-	Penurunan harmonisa orde ke-3, indikasi redaman triplen
3	iHD Orde-5 (5R, 5S, 5T)	51 | 43 | 47	11 | 9 | 10	78%	Reduksi signifikan harmonisa orde ke-5
4	iHD Orde-7 (7R, 7S, 7T)	27 | 29 | 28	19 | 18 | 20	30%	Reduksi harmonisa orde ke-7 dalam batas moderat
5	Arus Listrik per Fasa (Irms)	87	76	12.6%	Sedikit penurunan arus karena penurunan THDi
6	Power Factor (L1 L2 L3)	0,8	0,9	+12.5%	Peningkatan faktor daya mendekati target
7	Daya Aktif (Watt) (L1 L2 L3)	15,86	14,8	-6.7%	Penurunan daya akibat efisiensi sistem harmonik
8	THDi L1	70	42	40%	Penurunan THDi signifikan pada fasa L1
9	THDi L2	56	35	37.5%	Penurunan THDi signifikan pada fasa L2
10	THDi L3	69	41	40.6%	Penurunan THDi signifikan pada fasa L3
11	THDi Total (avg)	65	39,3	39.5%	THDi total turun hampir 40%

Based on graphs 21, 22 and table 5 of the results of measurements and analysis of electrical power quality before and after the installation of a single-tuned harmonic filter, it can be concluded that the designed system provides significant improvements to harmonic parameters and power efficiency.

The main focus of the evaluation is on the 5th order Individual Harmonic Distortion (iHD) value, which according to the IEEE 519-1992 standard, the maximum limit for systems with an ISC/IL ratio between 100–1000 is 12% of the load current.

1. Before the filter is installed:
   a. The fifth-order iHD values are very high: 51% (L1), 43% (L2), and 47% (L3).
   b. After installing a single-tuned passive filter, the fifth-order iHD was successfully reduced to 11% (L1), 9% (L2), and 10% (L3).
   c. All of these values meet the 12% threshold of IEEE 519-1992, demonstrating the filter's effectiveness in attenuating dominant harmonics.
2. In addition, the power factor also improved:
   a. Before installation, the PF value was only 0.76, indicating reactive power dominance.
   b. After installation, the PF value increased to 0.91, closer to the ideal value (1.0), indicating the system is operating at greater efficiency.
3. From the Total Harmonic Distortion current (THDi) side:
   a. The THDi value before installation was very high: 67.35%, far exceeding the 8% tolerance limit for non-linear load currents based on IEEE 519-2014 for distribution categories <69 kV.
   b. After installation, the THDi was successfully reduced to 38%, although not meeting the 8% limit, but a reduction of more than 40% from the original value.
4. Other parameters that also prove the improvement of system performance:
   a. The neutral current decreased from 18 A to 9 A, indicating a drastic reduction in triplen harmonics.
   b. The L1 phase load current decreased from 87 A to 76 A.
   c. The L1 active power also decreased from 18.00 kW to 14.80 kW, indicating more efficient use of electrical power.
5. Energy Efficiency Estimation:
   a. A power reduction of 3.45 kW over 24 hours and 30 days results in: 3.45 kW × 24 hours × 30 days = 2,484 kWh/month.
   b. With the Indonesian industrial tariff of Rp1,035.78/kWh, the estimated monthly savings are: Rp2,572,877 per month.

CONCLUSION

Based on the results of measurements, analysis, and implementation of passive harmonic filters in electrical systems with non-linear loads (110 kW inverter), the following conclusions can be drawn: Effectiveness of the IoT Monitoring System: An Internet of Things (IoT)-based monitoring system using an ESP8266 microcontroller integrated with a Modbus RTU-based power meter, Google Sheets, and the Blynk application successfully recorded electrical parameters in real time. This system was effective in detecting changes in power quality and enabled remote monitoring and analysis of historical harmonic data. Reduction of 5th-Order Current and THD: The installation of a single-tuned passive harmonic filter significantly reduced harmonic distortion. The measurement results showed:

a. The THDi value of the current decreased from 67.35% to 38% (a decrease of 43.6%).
b. The Individual Harmonic Distortion (iHD) current for the 5th order decreased from 47.8% to 9.96% (a decrease of 79.15%).
c. The 5th-order iHD value after the filter is below the maximum limit of 12% as stipulated by the IEEE 519-1992 standard for systems with an ISC/IL ratio between 100 and 1000.
d. The THDi value of 38% still does not meet the ideal THDi limit of <5% for low-voltage distribution systems (<69 kV) according to IEEE 519-2014, but it has shown significant improvement from the initial condition.

3. Power Factor Improvement and Energy Efficiency
   a. The power factor increased from 0.76 to 0.91, approaching the industry ideal of at least 0.95.
   b. The neutral current decreased from 18 A to 9 A, indicating a reduction in unbalance due to harmonics.
   c. The active power per phase decreased from 18.25 kW to 14.8 kW, with the load current decreasing from 90 A to 76 A.
   d. Overall, the system experienced an increase in energy efficiency of approximately 18.9%.
   e. Passive Harmonic Filter Design Parameters The designed single-tuned filter has the following characteristics:
      -Capacitance: 155.2 µF
      -Inductance: 2.89 mH
      -Tuning frequency: 237.5 Hz
      -Capacitor reactive power (QCrated): 10.11 kVar
      -Capacitor nominal current: 14.6 A
4. Financial Impact – Energy Savings by reducing active power consumption and increasing system efficiency, resulting in energy savings that directly impact operational costs. Referring to the electricity tariff for industrial class I3 in Indonesia of Rp 1,035.78/kWh, then:
   a. A reduction in active power of (18.25 – 14.8) kW = 3.45 kW
   b. In one month of operation (30 days × 24 hours), the resulting energy savings are: 3.45 kW × 720 hours = 2,484 kWh
   c. Estimated monthly electricity cost savings: 2,484 kWh × Rp 1,035.78 = ± Rp 2,572,877 per month
5. Thus, the installation of harmonic filters not only improves power quality and system efficiency, but also directly contributes to significant and sustainable industrial energy cost savings. The combination of a single-tuned passive harmonic filter and an IoT monitoring system has been proven to significantly improve power quality. This system also enables more responsive and efficient monitoring for industrial applications, and supports data-driven decision-making in harmonic mitigation planning.

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