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IoT-based monitoring, analysis and supervisory control of voltage harmonics in a three-phase system using four singles tuned lowpass filter

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Abstract

Total Harmonic Distortion is a vital part of communications, power distribution, and audio. In power distribution, it must be kept as low as possible. Voltage pollution occurs at the point of common coupling, which leads to a higher THD. Higher THD ensues thermal stress to the system where issues in the power system arise. Odd harmonic frequencies, specifically, the 5th, 7th, 11th, and 13th are the primary cause of the increase in THD. Several ways to reduce harmonics are the use of reactors, passive filters, and active front end solutions. This study is focused on minimizing the voltage harmonics by monitoring the voltage coming from a three-phase system by using four single-tuned filters that will tune out the unwanted harmful frequencies. The data will send through the IoT analytics platform which can then be viewed from ThingView, and the filters can be controlled through Arest.io. The system was compared to an oscilloscope then used Root-Mean-Square Error for system reliability test and yielded 0.097696 for data without filter and 0.048485 for data with a filter. Lastly, the system effectively decreased the THD by 32% compared to an unfiltered source.

Keywords: Total Harmonic Distortion; Passive Filter; Fast-Fourier Transform; Internet-of-Things

1. Introduction

In general, power is distributed as a sinusoidal voltage waveform. In comparison with a generator, a sinusoidal waveform is produced when a field winding rotates around a stator winding. As the rotor or field winding turns, voltage is generated in a sinusoidal manner. According to Steve Koehler of Yaskawa America, Inc., three-phase system is the most widely used in alternating current power generation. The output of a three-phase system in the Philippines is ideally a sinusoidal voltage of about 220 - 240 Vrms with a frequency of 60 Hz. However, this signal can be distorted when non-linear loads are attached to the system. A load is said to be non-linear if it draws a non-sinusoidal current from a sinusoidal voltage source that is available in residential buildings and offices. These distortions produced by non-linear loads are called harmonics. Harmonics is a general term used to depict distortion of a sinusoidal voltage or current waveforms, as in Fig.1. Meanwhile, the harmonics present in a three-phase system are in the form of multiples of fundamental frequency [3]. The effect of these harmonics is related to the power absorbed by the load. From Ohm's Law and Power Formula, with an excess or distortion in an ideal sinusoidal waveform, this may induce thermal stress to the system.

According to Bingham, triplen harmonics in a three-phase wye system are additive in the neutral. This is because the harmonic number multiplied by the 120-degree phase shift between phases is an integer multiple of 360 degrees [3]. These often result in overheated neutrals, and thus a great loss of power is dissipated through heat. These harmonics that periodically occur in a facility can cause equipment malfunction, data distortion, transformer and motor insulation failure, overheating of neutral buses, and solid-state component breakdown [12]. Moreover, according to article [11], this harmonic distortion leads to failure of electrical or electronic components, transformer heating, failure of power factor correction capacitors, and losses in power generation and transmission. In Akagi's study, he showed the minimum and

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maximum values for the Total Harmonic Distortion (THD) in a typical three-phase power system in Japan with a rating of 6.6kV in power distribution system [1]. For residential structures, the maximum THD was measured to be 3.5% while commercial infrastructures' THD was measured to be 4.6%. An almost the same value can be observed when it comes to the corresponding 5th harmonic voltage with an average rating of 3.4% and 4.3% respectively. However, the maximum value in specific locations specifically the downtown area, may exceed up to 7% under light-load conditions [1]. Here in the Philippines, as per ERC Resolution No. 9 Series of 2012, Grid Users are required to monitor and submit their Power Quality (PQ) as part of compliance to the Philippine Grid Code (PGC) policy on PQ. The PGC Performance Standards for Transmission (PST) states that "the THD of the voltage and Total Demand Distortion (TDD) of the current shall not exceed the limits of 3% and 5%, respectively" [10]. This standard is specifically for an establishment which has a 69kV capacity. For the individual odd harmonic frequency, THD and must not exceed 3%.

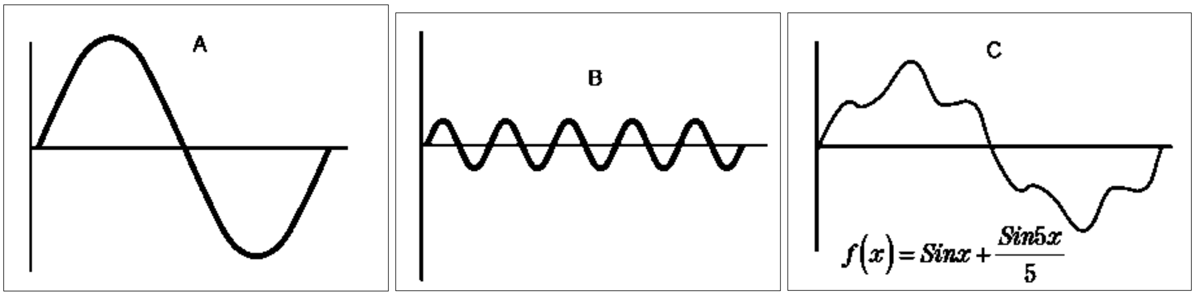

Figure 1 Output Waveforms of: (a) Fundamental Frequency. (b) 5th Harmonic Frequency (c) Sum of Harmonics in a System

Harmonics in the power system are reprimanded for the decrease in the quality of power accessible to non-linear loads [11]. To suppress the effects of power system harmonics, harmonic filters are used. Harmonic filters generally consist of one or more tuned series inductor-capacitor (LC) legs which fend off specific harmonic currents away from the power system. Under the IEEE 519-1992 standard entitled "Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," the THD level must not exceed five percent [5]. Based on this standard, power engineers do not look at the current amplitude, but at the voltage amplitude. THD in terms of current can be misleading; a small current may have a high THD but not a significant threat to a system. Power system harmonics can be monitored wirelessly utilizing a microprocessor system for constructing the bridge linking to the server and I/O interface, and GUI package using Fast Fourier Transform (FFT) [7].

In the research conducted by Rajkumar [11], NI-DAQ card for USB was used to acquire and capture the voltage and current waveforms. The system essentially requires two channels of analog input—one for the line voltage and one for the line current. Based on a comparison of passive and active filters conducted by Aswal et. al [2], the active filter proves to be more successful in suppressing harmonic frequencies. However, the implementation of an active filter cannot be implemented directly like passive filters. With these problems to address, the researchers will develop a single-tuned passive filter specifically for the 5th, 7th, 11th, and 13th harmonic frequencies. According to Bingham [3], the harmonics present in a three-phase system are the 5th, 7th, 11th, 13th, 17th, 19th and so on. However, the magnitude of these harmonics decreases as its nth-order increases, and as the harmonic frequencies goes higher than 13th-order is negligible. In the proposed device, 220 V/60 Hz source will also be stepped down to 1 V to be interfaced into an Arduino microcontroller. The researchers will be using the FFT algorithm in analyzing the frequency response of the system. The main objective of this study is to develop a monitoring system, analyze, and control the harmonics present in the three-phase system. A Fast Fourier Transform (FFT) can be used to compute for the THD and then send the data into the IoT platform via the internet [7]. The control part is responsible for the detected harmonics utilizing four single-tuned passive filters to attenuate the 5th, 7th, 11th, and 13th harmonic frequencies [4]. The systems will send the THD into the IoT platform with a delay of 20 seconds per data and can be seen and control the harmonics present in the system using the GUI in smartphone.

This study will provide a better three-phase system harmonic mitigation and analysis as well as a real-time monitoring system to lessen the excessive power loss due to non-linear loads. Facilities with heavy and plant machinery, motors, pumps, and even air-conditioning systems, are a few examples that require the use of a three-phase source. This study will provide a monitoring system for the harmonic filtering which will be helpful to discern which equipment draws more power. The user can control the device remotely and by reducing the THD.

It focused on analyzing harmonic frequencies so that its effect can be monitored and controlled. The researchers will be using a passive single-tuned filter to focus on eliminating the harmful harmonics, which are the 5th, 7th, 11th, 13th order for a three-phase system. The load that was used in this study will be a light dimmer circuit to resemble a non-linear load. This load was chosen because upon the conclusion of Di Mauro et al. [9] shows that the harmonics introduced by these dimmer circuits greatly exceeds the values dictated by the standard IEC 61000-3-2. The voltage will also be stepped down into 230 V/60 Hz to 1 V/60 Hz so that it will be easily fed into an Arduino MCU which gathers the time domain data and computes for the THD. Lastly, the data will be uploaded into the IoT platform to visualize the magnitude of THD. For easy monitoring, the graphs displayed in the IoT platform will be accessed by a smartphone. A power factor of 0.8 is chosen because according to article [8], most generator sets are rated kVA at 0.8 lagging power factor. Operating a generator at lagging power factor does not require additional power from the prime mover (North East Power Systems, Inc, 1999). The kind of filter is a passive filter tuned to the 5th, 7th, 11th, and 13th harmonic frequency. Even harmonics are either not present or usually low in magnitude compared to odd harmonics. This research will focus voltage harmonics that power engineers look at the voltage amplitude rather than the current distortion. A small current may have a high THD, but it does not propose a threat to the whole system [6], [11]. The 230 V/60 Hz needs to be stepped down to 1 V/60 Hz as this microcontroller has a voltage limitation of 5 Vpp thus, tapping the system into the line will not be directly implemented. The effect of this transformer as an inductive load in the whole system will also not be included. The IoT platform that will be used is ThingSpeak and is a MATLAB supported platform. The load used in this study were limited to a function generator and VARIAC only.

2. Material and methods

2.1. System Block Diagram

Figure 2 depict on how the system will development. A three-phase system was used and values for the parameters were set as follows: S = 478.05 kVA, f = 60 Hz, V = 230 Vrms and PF = 0.8. The input system voltage was stepped down to 1 Vrms by a transformer to be able for the Arduino MCU to receive the data. Since there are three single-phase sources in a three-phase system and only one analog input for the MCU, a multiplexer is used. The data gathered by the MCU will then be processed using the Fast Fourier Transform (FFT) to determine the magnitude of THD. The data is sent simultaneously to the IoT platform. If the user chooses to turn on the filter, the signal will be filtered by four single-tuned filters to attenuate the 5th, 7th, 11th, and 13th harmonic frequencies. Lastly, by using an application, the user can access the data through a smartphone.

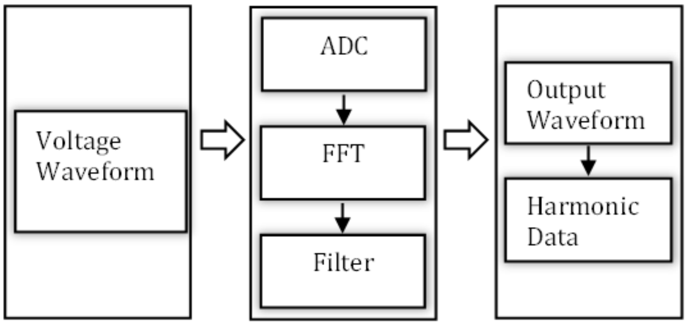

Figure 2 General Block Diagram of the System

2.1.1. Input

The voltage waveforms of a three-phase system will first be stepped down from 230 Vrms to 1 Vrms. These stepped down values will then be gathered and received by an Arduino Microcontroller Unit. It requires only one channel of analog input since the microcontroller has a limitation of one analog input, a multiplexer is implemented. The three-phase system has the following parameters namely apparent power of the system (Q) equal to 478.05 kVA, system frequency (f) equivalent to 60 Hz, system voltage (V) corresponding to 230 Vrms and power factor (PF) equal to 0.8.

2.1.2. Process

The analog signal generated by the three-phase source generator is then fed to Arduino's ADC or Analog-to-Digital Converter which will convert the analog signal to a digital signal. The digital data is then processed by the same microcontroller unit performing Fast Fourier Transform to recognize the existence of harmonics and the magnitude of THD present in the system. With the implementation of a relay, filters can be remotely turned on or off. The harmonics present in the system will then be filtered by a single-tuned filter adjusted to a specific harmonic order namely 5th, 7th, 11th, and 13th. Fast Fourier Transform will be used to convert the time domain results to frequency response so that the harmonics can be visualized, and the removal of the bad harmonics can be seen. With the implementation of a relay, filters can be remotely turned on or off.

2.1.3. Output

In the three-phase system, the non-linear load implemented was a light dimmer circuit. Upon connecting the four-parallel single-tuned filter designed to mitigate the 5th, 7th, 11th, and 13th harmonic frequencies, the magnitude of the THD should be reduced. From the FFT analysis from NI Multisim, it can be observed that these bad harmonics that were present were eliminated. This data will then be stored in the IoT platform and using a mobile application this data can be viewed in a smartphone.

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2.1.4. Monitoring and Data Acquisition

To investigate the harmonics, present in a three-phase system with a light dimmer circuit, the monitoring system must be isolated. The materials needed for this part include a step-down transformer from 230 Vrms to 1 Vrms and a WiFi-based Arduino MCU. The 230 Vrms/1 Vrms transformer has a bobbin cross-sectional area of 25 mm x 25 mm. The primary winding is 1750 turns of AWG 36 or 11, and the secondary winding is 38 turns of AWG 18. The method of isolation is required because the Arduino MCU will only have the capacity of 5 V in its ADC; therefore, a step-down transformer is needed to comply with the MCU's range of input voltage as well as not to damage it. After stepping the voltage down, the measurement must have a DC offset of 2.5 Vpeak. This is because the AC signal will deviate from positive 2.5 V to negative 2.5 V which resembles a 2.5 Vpeak. For safety purposes, an offset of 1.5 was chosen to give a marginal error for voltage spikes so as not to damage the MCU. Measuring this with Arduino's ADC, we can calculate the RMS value at any given time. Performing FFT, we can now see the equivalent samples in the frequency domain and the magnitude of the THD. After gathering the data, it is then saved as a packet.

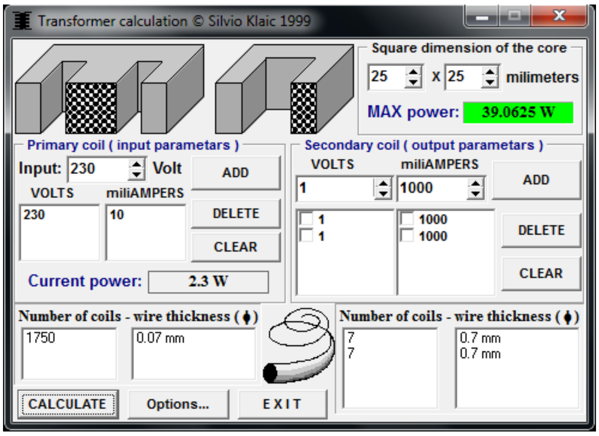

Figure 3 Transformer Specification Calculation Tool

The transformer will have the following specifications: a ratio of 1:77, because the primary voltage is 230V and the secondary voltage is 1V. The primary winding will have 1750 turns of AWG 37 while the secondary winding will have seven turns of AWG 18. An offset of 1.5V was chosen to give allowance for voltage spikes so as not to damage the MCU. Computation of the transformer parameters can be done using a software called "Transformer Calculation© Silvio Klaic 1999" as shown in Fig. 3.

Figure 4 depicts the FFT analysis using the NI Multisim. It can be observed that 5th, 7th, 11th, and 13th harmonic order possess the most harmonic magnitude relative to the percent fundamental which is 286.6. Moreover, the computed Total Harmonic Distortion (THD) is at 5.44% which is high compared to the < 5% set by the IEEE 519-1992 Standard. High THD can cause severe damage to the equipment which can lead to malfunction.

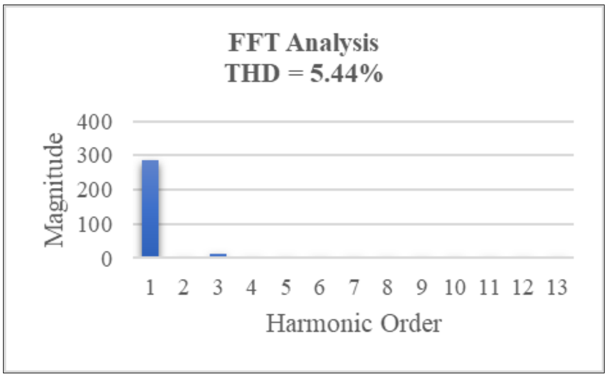

Figure 4 Simulation of FFT Analysis Before Filtering

2.1.5. Controller and Single-Tuned Passive Filter

To control the harmonics, present in the system and lessen the overall THD, four-single-tuned passive RLC filters must be designed. Passive components like resistor, inductor, and capacitor will be used in designing the filters. The input parameters from the three phases system are f = 60 Hz, V = 230 Vrms, S = 478.05kVA, PF = 0.8. From the constant parameters given by this system, the reactive power Q needed by the system can be calculated using:

$$PF = \frac{P_{(W)}}{|S_{(VA)}|} \quad \textbf{(1)}$$

$$S = \sqrt[2]{P^2 + Q^2} \quad \textbf{(2)}$$

where:

PF = power factor
$P_{(W)}$ = P = Real Power
$S_{(VA)}$ = S = Apparent power
Q = Reactive Power of the system

Shown in Fig. 5 is the configuration of the three-phase system with monitoring, filter, and load blocks. The filter will be directly tapped into the line voltage which reads 230 Vrms. The filters are four-parallel single-tuned filters designed to

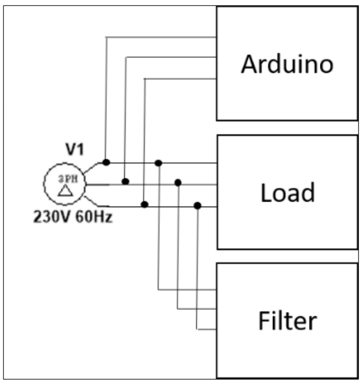

Figure 5 Schematic block diagram

attenuate the 5th, 7th, 11th, and 13th harmonic frequencies. The reactive power of the filter is assumed to be equal for each filter, therefore, dividing the reactive power of the system by n-number of multi-section filters.

To realize actual values, the following formulas are needed:

$$C = \frac{Q_C}{2\pi f V^2} \quad \textbf{(3)}$$

$$X = \frac{1}{2\pi f h C} = \sqrt{\frac{L}{C}} \quad \textbf{(4)}$$

$$L = \frac{X}{2hf} \quad \textbf{(5)}$$

$$Q = \frac{2\pi f L}{R} \quad \textbf{(6)}$$

$$R = \frac{1}{2\pi f C} \quad \textbf{(7)}$$

$$f_n = \frac{1}{2\pi\sqrt{L_n/C_n}} \quad \textbf{(8)}$$

Where:

H = tuning point of the filter
Q_C = reactive power of the filter (kVAR)
Q = Quality factor
F = System frequency
V = System voltage
X = reactance of the capacitor or inductor tuned at a specific frequency
f_n = series resonant frequencies for multi section filters

To test for the filter effectivity, the researchers replicated the effect of the 5th, 7th, 11th, and 13th harmonic frequencies by connecting function generators in series. The frequencies' corresponding magnitude are tabulated in Table 1. This represented a polluted voltage source, and the filter was made to be connected in parallel. THD before and after filtering was recorded.

Table 1 Frequency and Their Corresponding Magnitude

Frequency, Hz	Magnitude, Volts
60	0.856
300	0.454
420	0.329
660	0.235
780	0.111

In Fig. 6, 5th, 7th, 9th, 11th, and 13th harmonic order was reduced after passing through the single-tuned filter based on the measured harmonic magnitude relative to the percent fundamental. Also, the THD level was decreased from 5.44% to 5.03%.

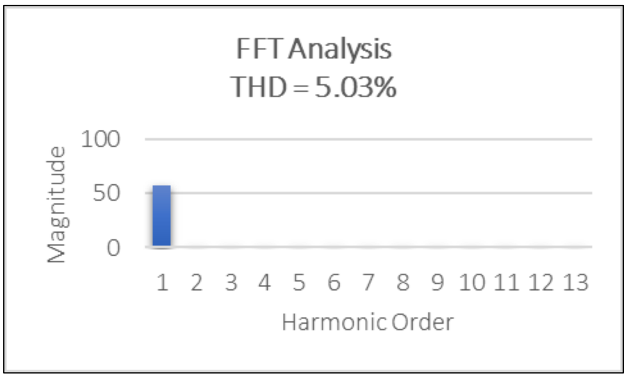

Figure 6 FFT Analysis After Filtering

2.1.6. Output Display

After getting the time domain data and harmonics are visualized using FFT, the THD is calculated, and this data will then be transferred and stored to the cloud via Wi-Fi connection. The IoT platform, ThingSpeak, will display the computed magnitude of THD of the system. ThingSpeak is an open-source internet of things platform service that allows the user to aggregate, visualize, and analyze data streams in the cloud. The user can send data to ThingSpeak from their devices and create instant visualizations of these data. With MATLAB analytics inside ThingSpeak, the user can write and execute MATLAB codes to perform pre-processing, visualizations, and analyses. ThingSpeak enables engineers and scientists to prototype and builds IoT systems without setting up servers or developing web software. To view the graphs even without access to a PC display, an Android application ThingView developed by Cinetica will be used. The sending of data has a delay of 20 seconds.

Figure 7 Sample ThingSpeak Display in Smartphone via ThingView Application

To use the ThingSpeak IoT platform, a MathWorks account must be created. Upon successful creation and verification of the account, a channel can be made to visualize data in whichever plot the user intends to show. A unique Application Programming Interface will be provided for every channel created, and this will be included in the Arduino code to transfer data to the channel. Fig. 7 is the display for the three channels in a three-phase source displaying harmonics using ThingSpeak. This platform will enable the researchers to transfer and monitor the harmonics present in a three-phase system on a real-time basis.

3. Results and discussion

Customized housing was made to position the components and materials produced in this research, as shown in Fig. 8. The housing was composed of two levels. The four single-tuned lowpass filters were condensed in the second level. Meanwhile, the three step-down transformers were situated at the first level of the housing. The 4-channel relay and the ESPDuino were likewise located on the first level. A function generator was also used in this research to simulate the frequency of the harmonics. Similarly, an oscilloscope was also included to view the voltage waveform before and after using the filter. A light dimmer circuit is also present in the figure that resembles the non-linear load utilized in this study.

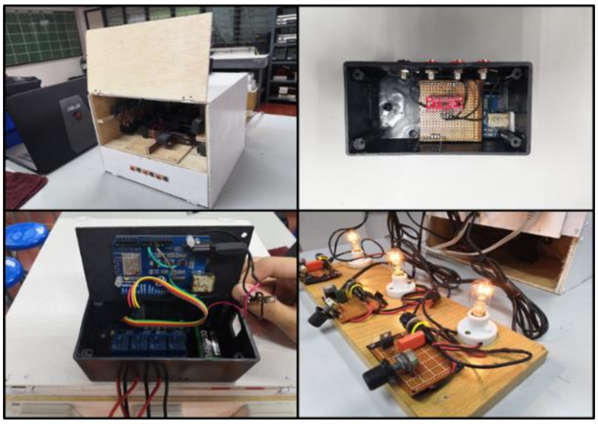

Figure 8 Proposed System Device

Figure 9 shows the total harmonic distortion for Line A having different loads. The figure reveals that the function generator produces a higher THD compared to variable AC and without load. Moreover, the harmonic distortion obtained from variable AC and without load results to closer values. This indicates that variable AC does not produce a substantial amount of harmonic distortion.

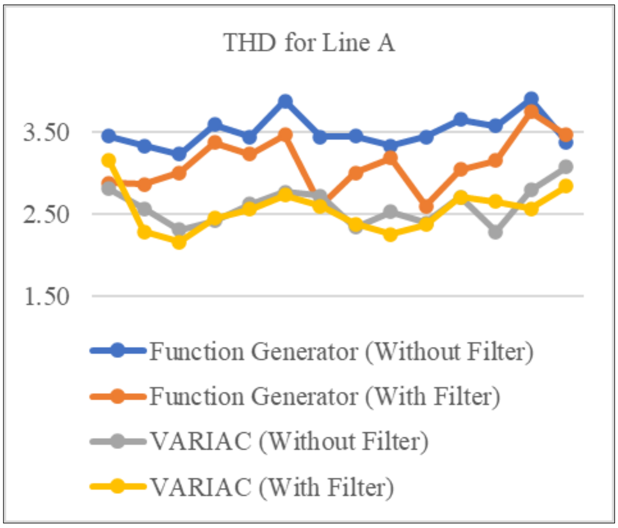

Figure 9 Total Harmonic Distortion for Line A with Different Loads

Figure 10 illustrates the total harmonic distortion for Line B. Relating the results obtained from Line A; the function generator still draws a higher THD compared to VARIAC. The distortion of the function generator peaks at 3.09 against the 3.01 of the variable AC. The harmonics detected was below the standard set by IEEE 519-1992 and Philippine Grid Code because of the load used.

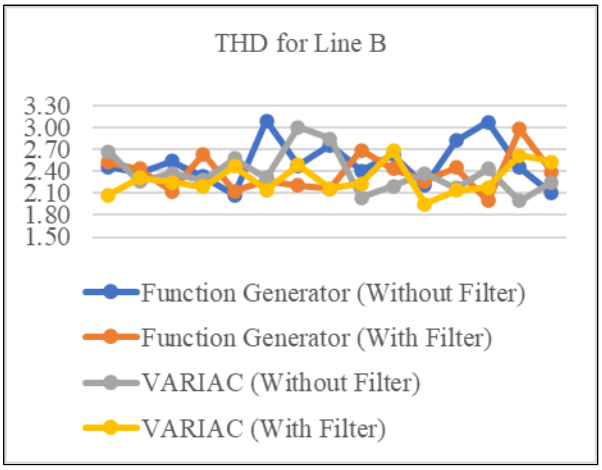

Figure 10 Total Harmonic Distortion for Line B with Different Loads

Whereas in Fig. 11, it presents the total harmonic distortion for Line C. The THD for the function generator tops at 3.32 compared to 3.35 of the VARIAC. However, with the use of the filter, the total harmonic distortion was reduced to 2.62 and 2.31 respectively. Overall, the function generator draws a higher total harmonic distortion compared to VARIAC. Function generator's harmonic distortion peaked at 3.95 compared to VARIAC's 3.35. Implementing a much higher non-linear load will undoubtedly increase the THD of the system. Also, among the three lines, Line A recorded a greater harmonic distortion compared to two other lines.

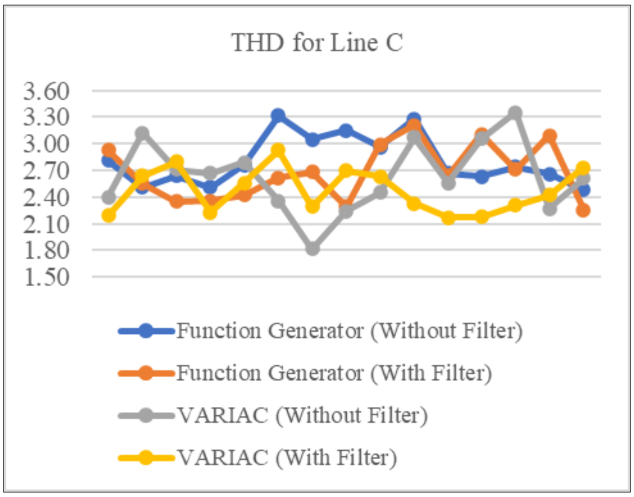

Figure 11 Total Harmonic Distortion for Line C with Different Loads

4. Conclusion

The researchers were able to reduce the Total Harmonic Distortion in Line A from 1.7470 to 1.1359, in Line B from 2.0563 to 1.2630 and in Line C from 2.1290 to 1.6622 through the model. With the proper tuning of the four filters that were used and incorporated in the design which regulated the voltages that were coming in and out of the prototype, THD was reduced by an average of 32% in all three lines. After several tests with different loads, the prototype still produces a more refined THD compared to the unfiltered THD, averaging a 30% reduction in the THD which is a significant amount especially when using machines and components that draws more power.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to disclosed.

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