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Investigation of the Usage of Zigzag Transformers to Reduce Harmonics Distortion in Distribution Systems

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Abstract

The increasing use of power electronics in various sectors leads to harmonic distortion in electric power systems, affecting power quality and equipment longevity. While harmonic filters have been used to address this issue, they are limited in effectiveness, particularly in reducing distortion across the entire distribution system. This study aims to reduce harmonic distortion using a zigzag transformer as a more comprehensive solution in mitigating harmonic distortion throughout the entire distribution system. In this research, the zigzag transformer was placed at Point Common Coupling to reduce harmonic distortion in the distribution system as a whole. A zigzag transformer connection was configured by connecting either three windings of a single-phase transformer or one winding of a three-phase transformer. Based on the results of this research, the Total Harmonic Distortion (THD) value has decreased from 25.26% to 2.48% following the implementation of the zigzag transformer. This substantial decrease in THD concludes the zigzag transformer's effectiveness as a solution for improving power quality in electrical distribution systems.

Keywords: zigzag transformer; harmonic distortion; distribution system; non-linear loads.

I. Introduction

Nowadays, renewable energy such as photovoltaics can be integrated into radially connected distribution systems [1]. This renewable energy has power electronic devices that can generate harmonic distortion. The impact of harmonic distortion can cause the stator and rotor coils in electrical machines to heat up quickly during normal use. Previous research that has discussed the stator and rotor in induction motors can be seen in reference [2]. Distribution systems with three phases and four wires are frequently used to provide low voltage to a variety of consumer sectors. A single-phase load or a three-phase load can be connected to a three-phase, four-wire system. Computers, printers, automatic machines, televisions, energy-efficient lighting, variable-speed drives, and other devices are examples of non-linear loads. Current and voltage waveforms generated by non-linear loads are not sinusoidal. Harmonics are brought on by wave distortion, which is caused by this. Harmonics have harmful effects, including raising the neutral current in a three-phase, four-wire system, which increases the risk of overheating and igniting excess heat, shortening the lifespan of transformers due to overheating, deteriorating voltage quality, reducing power factor, and other things.

Using filters, either passive, active, or a combination of passive and active filters, is one way to deal with harmonics. The system impedance has a significant impact on passive filter performance. Active filters, on the other hand, demand a lot of capacity and money. The electromagnetic filter has a simpler circuit design and is more cost-effective. The zigzag transformer used in this study serves as the electromagnetic filter [3]. There is research that has discussed the contribution of zigzag transformers in reducing neutral current in distribution systems connected via Wye with four conductors [4]. For basic knowledge about zigzag transformers can study the reference [5]. Several previous studies have used zigzag transformers with wye connections to reduce triplen harmonics [6]–[8]. However, this research was only carried out on triplen harmonics, not yet carried out on other multiple harmonics. This research will perfect previous research in reducing individual harmonics at other multiple orders.

Each three-phase winding can be split into two parts and connected to a different node to create the zigzag connection. Neutral currents and zero-sequence harmonic currents will be reduced by a zigzag transformer [9]. Previous research has also improved the quality of electrical power in photovoltaics using zigzag and fuzzy transformers [10]. Research conducted by [11] connects the transformer coils in a star-zigzag manner in rural areas to determine the efficiency of the zigzag transformer which is also connected to consumers. Zigzag transformers can also be used to suppress the iron losses and DC magnetization brought on by three-phase rectifiers. Based on these issues, this research was conducted to investigate how zigzag transformers work in the distribution network to reduce harmonics. The purpose of this study is to ascertain whether installing a zigzag transformer has any impact on bringing harmonic levels down to below the predetermined threshold.

Zigzag transformers are applied to balanced loads, according to [12]. In this study, it was discovered that adding an inductor to the load side can increase the load side neutral current's reduction. Harmonic distortion can disrupt the performance of electrical machines, therefore research [13] carried out the installation of zigzag transformers to improve the performance of induction electric machines. Installation of zigzag transformers has also been carried out in railway electrical power systems [14]. The aim is to balance the load on the train's electric power system as well as improve power quality. To obtain a suitable mathematical model for the zigzag transformer under balanced connection conditions, one can refer to Reference [15]. Zigzag transformers have also been used in hybrid AC-DC systems [16]. The aim is to improve the quality of electrical power in the hybrid system which is caused by the large number of inverters in the DC system entering the AC system. Another technique for reducing harmonic distortion is using the Euclidean direction search-based control technique [17]. Zigzag transformers have been used to increase energy efficiency in electric power systems [18]. The research carried out [19], [20] combined a 12-pulse diode bridge rectifier and a 36-pulse AC-DC converter with a zigzag transformer autoconnect to reduce the impact of harmonic distortion from the diode bridge device. Previous research that has discussed the power quality in electrical power systems that are interconnected with renewable energy can be seen in the References [21], [22]. A single-phase rectifier that powers unbalanced non-linear loads and loads with an AC voltage regulator is the load being modeled. The study covered neutral current reduction as well.

Research gap based on previous research [21], [22], shows that harmonic filters, whether passive or active, have shortcomings such as only being able to reduce harmonic distortion in certain areas and are less effective in reducing harmonic distortion in the entire distribution system. The further the distance between the harmonic filter and the non-linear load, the lower the performance of the harmonic filter. Therefore, this journal presents a way to reduce harmonic distortion using a zigzag transformer. The position of the zigzag transformer as a Point of Common Coupling (PCC) can reduce overall harmonic distortion in the distribution system and is more effective than a harmonic filter.

II. Material and methods

A non-linear load is a load that produces a non-sinusoidal output current when operating in a sinusoidal voltage. Non-linear loads are divided into two when viewed in terms of working characteristics. The first type is a transient change which has working characteristics in the form of a momentary increase in current. The second type is a non-linear load which has working characteristics in the form of periodic non-linear current.

In general, non-linear loads are electronic equipment that contains many semiconductor components. In operation, this component works as a switch that is active at every wave cycle from the voltage source. This process causes non-sinusoidal distortion of the current wave. This wave has an erratic shape and can change according to settings in the parameters of the semiconductor components in electronic equipment. The voltage source does not affect the change in wave shape.

Examples of non-linear loads include power electronics applications such as rectifiers and inverters, battery chargers, adjustable speed drives (ASD), silicon-controlled rectifiers (SCR), and others. These loads contribute to the emergence of harmonics which have a negative impact on the electric power system.

A. Harmonic

Harmonics is a phenomenon in electric power systems that can be caused by distortion of current and voltage waves. Therefore it is important to measure harmonics in current transformers and voltage transformers [23]. The cause of this distortion is the formation of waves whose frequencies are integer multiples of the basic frequency [24], [25]. The fundamental wave is distorted by 3rd order harmonic waves. The harmonic waves have a frequency three times the fundamental frequency. This distorted fundamental wave causes the waveform to become non-sinusoidal as shown in Figure 1.

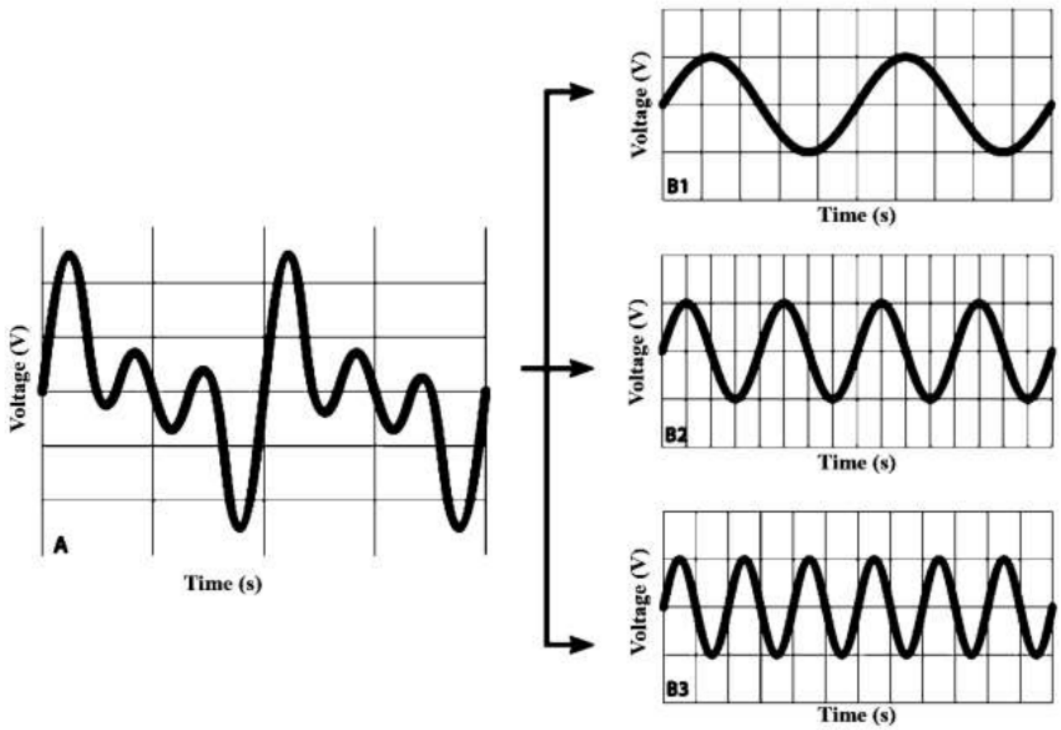

Figure 1. Effect distortion harmonic to sinusoidal waveform

Along with the development of electronic technology in power systems, the use of non-linear loads is increasing. Non-linear loads are loads whose impedance value changes according to changes in voltage, so that the current in the load does not match the voltage [26], [27]. The results of the IEEE standard benchmarking test for the contribution of harmonics to electric power systems [28] show that the causes of harmonics can be written based on the following:

- Power electronic equipment such as rectifiers and converters.
- Equipment that can trigger arcs such as arc furnaces and fluorescent lamps.
- Equipment with ferromagnetic core saturation such as induction motors and transformers.

B. Harmonic Distortion

Harmonics produced by non-linear loads are injected back into the system power source. This harmonic current will have a broad impact and interact with system components such as capacitors, motors, and transformers. Harmonic currents are also the cause of various problems [29], such as induction interference in long-distance communication systems, errors in measuring instruments, excessive heat in circuit breakers so that they can disconnect themselves, and control systems that can lock themselves. This problem can cause cost losses due to maintenance. Harmonics can affect the performance of every equipment component around the distribution system [30], and can even result in power losses in the AC system when sending power through the conductor [31]. This can result in reduced performance and even damage to the equipment.

Normally, a linear load produces load currents per phase that cancel each other out so that the current in the neutral wire will be zero. This is different from single-phase non-linear loads which trigger the emergence of odd harmonics in multiples of three (3rd, 9th, 15th, 21st, and so on) which are zero sequence harmonics.

Harmonics can be analyzed using indices that can be used to determine the impact of these harmonics on the electricity system, namely Individual Harmonic Distortion (IHD) and Total Harmonic Distortion (THD). Individual Harmonic Distortion is the ratio between the Root Mean Square (rms) value of the harmonics of each order and its basic rms value. This IHD applies to both voltage and current. The following is the formula for calculating IHD for harmonics.

$$IHD = \frac{I_n}{I_1} \times 100\ \% \tag{1}$$

where I_n is the nth order harmonic current (A) and I_1 is the fundamental current (A). Based on this definition, IHD_1 will always be 100%. This harmonic calculation method is known as harmonic distortion which refers to its basic value. This calculation is used by the Institute of Electrical and Electronic Engineers (IEEE) in America. Total Harmonic Distortion (THD) is the ratio of the rms value of the total harmonic components to the rms value of the basic components. THD also applies to voltage and current. For example, if the nonlinear voltage has a basic component V_1 and harmonic components V_1, V_2, V_3, up to V_n then the rms value of the voltage harmonics can be calculated using the following equation.

$$V_H = \sqrt{{V_1}^2 + {V_2}^2 + {V_3}^2 + \cdots + {V_n}^2} \tag{2}$$

The THD at voltage can be calculated using the following formula.

$$THD_v = \frac{\sqrt{\sum_{n=2}^{\infty} (V_n)^2}}{V_1} \tag{3}$$

where V_n is the nth order harmonic voltage (V) and V_1 is the fundamental voltage (V). Meanwhile, THD on the current can be calculated using the following formula.

$$THD_i = \frac{\sqrt{\sum_{n=2}^{\infty} (I_n)^2}}{I_1} \tag{4}$$

where I_n is the nth order harmonic current (A) and I_1 is the fundamental current (A)

C. Zigzag Transformer

The transformer is a component that plays an important role in the electricity system. A transformer is an equipment that functions to distribute electrical power to different voltage levels. The voltage can be increased or decreased according to the size of the current flowing through the coil. In principle, a three-phase transformer is a single-phase transformer that is arranged into three phases and has two coils, namely the primary and secondary coils. These coils can be connected in three ways, namely triangular (delta), star or wye, and zigzag connections.

Zigzag transformers are different from transformers in general. This transformer provides a neutral point so it is also called a grounding transformer. This transformer can also equalize the load on a three-phase system. Apart from that, the zigzag transformer is also able to attenuate neutral currents and zero sequence harmonic currents. A transformer with a zigzag connection can be obtained by dividing each wye-connected coil into two equally. This half is connected to the other half of the coil in the opposite way (subtractive polarity) and intersects (zigzag). This subtractive polarity relationship causes the harmonic current to be reduced. The zigzag connection in the transformer is obtained by connecting three single-phase transformers or three-phase transformers in a special way as shown in Figure 2.

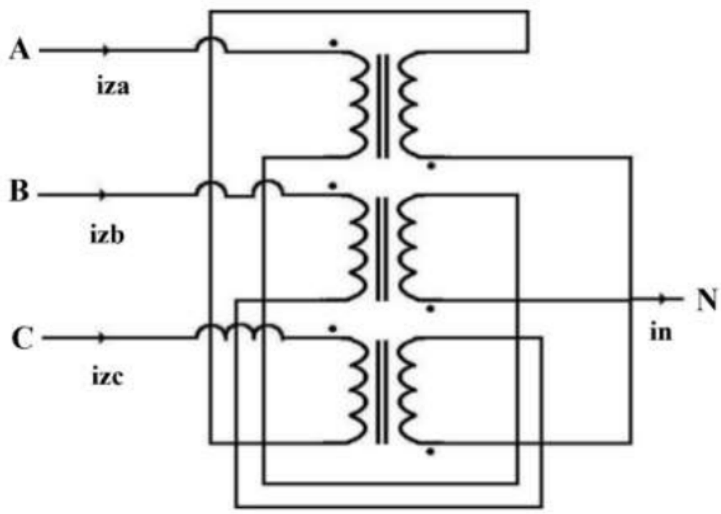

Figure 2. Zigzag transformer connection

In a three-phase four-wire system, the zero sequence three-phase currents $i_{ao}(t)$, $i_{bo}(t)$, and $i_{co}(t)$ have the same amplitude and phase [6], [7], so

$$i_{ao}(t) = i_{bo}(t) = i_{co}(t) \quad (5)$$

The neutral current $i_n(t)$ is the sum of the zero sequence currents which can be written as

$$i_n(t) = 3\, i_{ao}(t) \quad (6)$$

where i_{ao} is the zero sequence A phase current, i_{bo} is the zero sequence B phase current, and i_{co} is the zero sequence C phase current. I_n is neutral current. Because the transformer coils have a ratio of 1:1, the input current flowing to a point on the primary coil will be the same as the output current flowing from a point on the secondary coil, so it can be written as follows.

$$i_{za}(t) = i_{zb}(t) \quad (7)$$

$$i_{zb}(t) = i_{zc}(t) \quad (8)$$

$$i_{zc}(t) = i_{za}(t) \quad (9)$$

Based on Figure 2, the 3 phases voltage analysis on the zigzag transformer used in this research can be represented as the following equations.

$$V_A = V_m \sin(\omega t) \quad (10)$$

$$V_B = V_m \sin\left[\omega t - \frac{2\pi}{3}\right] \quad (11)$$

$$V_C = V_m \sin\left[\omega t + \frac{2\pi}{3}\right] \quad (12)$$

where V_m is the peak value of the voltage in a single phase system in a zigzag transformer. Meanwhile, to analyze the voltage in a 3-phase zigzag transformer system, it can be represented as the following equations.

$$V_{AB} = \sqrt{3}\, V_m \sin\left[\omega t + \frac{\pi}{6}\right] \quad (13)$$

$$V_{BC} = \sqrt{3}\, V_m \sin\left[\omega t - \frac{\pi}{2}\right] \quad (14)$$

$$V_{CA} = \sqrt{3}\, V_m \sin\left[\omega t + \frac{5\pi}{6}\right] \quad (15)$$

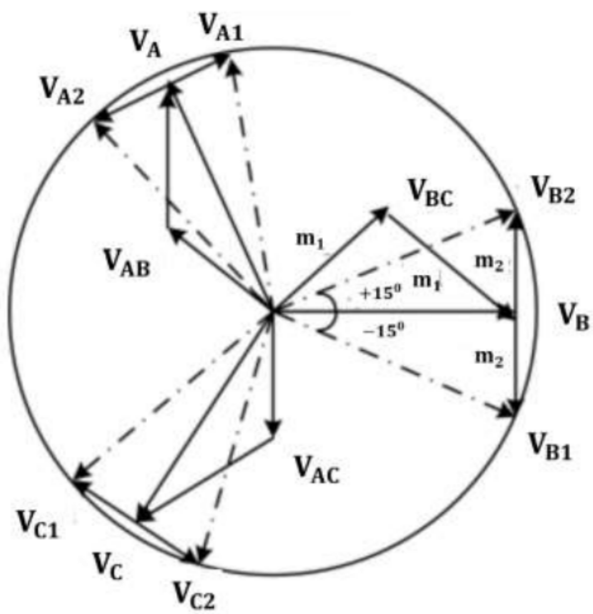

Figure 3. Phasor diagram of zigzag transformer

Figure 3 shows the shape of the phasor diagram of a zigzag transformer. Based on this figure, the shifted voltage values of phases A, B, and C can be calculated using the equation below.

$$V_{A1} = m_1(V_{AB} - V_{AC}) + m_2\, V_{BC} \quad (16)$$

$$V_{A2} = m_1(V_{AB} - V_{AC}) - m_2\, V_{BC} \quad (17)$$

$$V_{B1} = m_1(V_{BC} - V_{AB}) + m_2\, V_{AC} \quad (18)$$

$$V_{B2} = m_1(V_{BC} - V_{AB}) - m_2\, V_{AC} \quad (19)$$

$$V_{C1} = m_1(V_{AC} - V_{BC}) + m_2\, V_{AB} \tag{20}$$

$$V_{C2} = m_1(V_{AC} - V_{BC}) - m_2\, V_{AB} \tag{21}$$

where, V_{AB}, V_{BC}, and V_{AC} are the 3 phase system voltages in the zigzag transformer configuration. Meanwhile, m_1 has a value of 0.5773 and m_2 has a value of 0.2679. The values m_1 and m_2 play a role in determining the number of coils in the zigzag transformer. By substituting the values of m1 and m2 into Equations (16) to (21), the new equations are obtained as follows

$$V_{A1} = (\sqrt{3} - 1)V_m \sin\left[\omega t - \frac{\pi}{12}\right] \tag{22}$$

$$V_{A2} = (\sqrt{3} - 1)V_m \sin\left[\omega t + \frac{\pi}{12}\right] \tag{23}$$

$$V_{B1} = (\sqrt{3} - 1)V_m \sin\left[\omega t - \frac{2\pi}{3} - \frac{\pi}{12}\right] = (\sqrt{3} - 1)V_m \sin\left[\omega t - \frac{3\pi}{4}\right] \tag{24}$$

$$V_{B1} = (\sqrt{3} - 1)V_m \sin\left[\omega t - \frac{2\pi}{3} + \frac{\pi}{12}\right] = (\sqrt{3} - 1)V_m \sin\left[\omega t - \frac{7\pi}{12}\right] \tag{25}$$

$$V_{A1} = (\sqrt{3} - 1)V_m \sin\left[\omega t + \frac{2\pi}{3} - \frac{\pi}{12}\right] = (\sqrt{3} - 1)V_m \sin\left[\omega t + \frac{7\pi}{12}\right] \tag{26}$$

$$V_{A1} = (\sqrt{3} - 1)V_m \sin\left[\omega t + \frac{2\pi}{3} + \frac{\pi}{12}\right] = (\sqrt{3} - 1)V_m \sin\left[\omega t + \frac{3\pi}{4}\right] \tag{27}$$

By applying the voltage equation model, the voltage harmonics in the zigzag transformer can be reduced. Meanwhile, the harmonic current is based on the zigzag transformer configuration as in Figure 4.

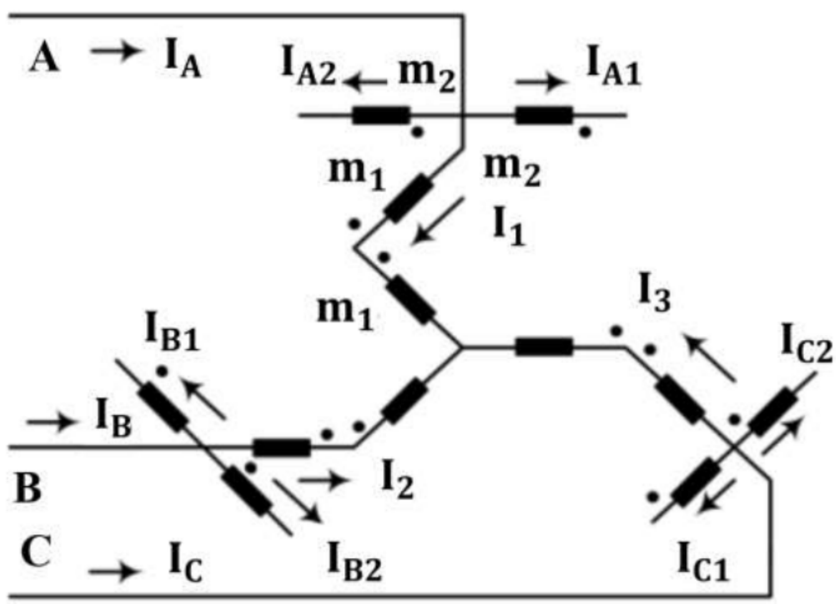

Figure 4. Phasor diagram of zigzag transformer

Based on Figure 4 and by applying Kirchoff's law (KCL), the current input to the zigzag transformer for each phase can be modeled in the following equations.

$$I_A = I_{A1} + I_{A2} + I_1 \tag{28}$$

$$I_B = I_{B1} + I_{B2} + I_2 \quad (29)$$

$$I_C = I_{C1} + I_{C2} + I_3 \quad (30)$$

Meanwhile, in the current coil with the values m_1 and m_2, the current equation for each phase in the zigzag transformer is obtained as follows.

$$m_1\, I_1 = m_2\, (I_{A1} + I_{A2}) \quad (31)$$

$$I_1 = \left(2\sqrt{3} - 3\right)(I_{A1} + I_{A2}) \quad (32)$$

$$I_2 = \left(2\sqrt{3} - 3\right)(I_{B1} + I_{B2}) \quad (33)$$

$$I_3 = \left(2\sqrt{3} - 3\right)(I_{C1} + I_{C2}) \quad (34)$$

By applying the current equation model, the current harmonics contained in the zigzag transformer can be reduced.

D. Method

In the modeling in Figure 5, the system is composed of a three-phase voltage source that serves a non-linear load in the form of a three-phase rectifier. A zigzag transformer is installed between the voltage source and the load. Due to consideration of the impedance factor, the zigzag transformer is connected to a voltage source via a 500 m long conductor and connected to the load via a 20 m long conductor.

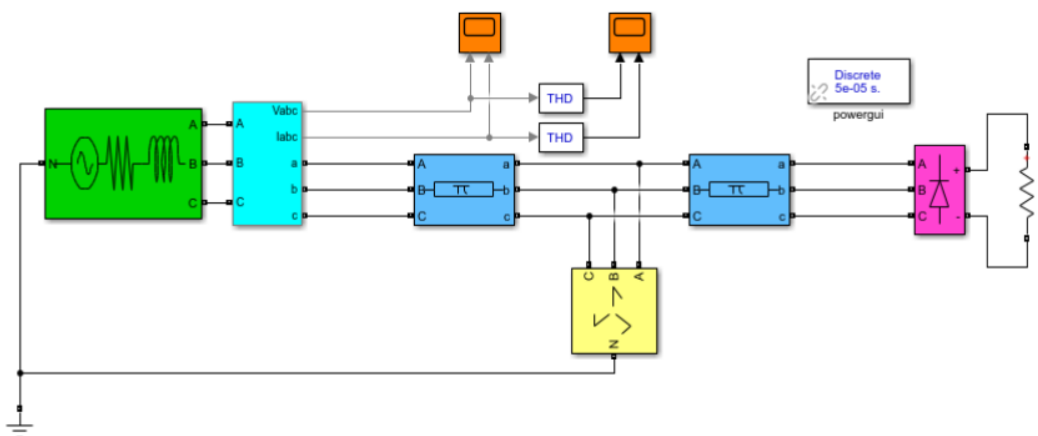

Figure 5. Distribution network model

In Experiment 1, the transformer rating was set at 100 kVA. The zero sequence resistance and reactance are set at 0.025 pu and 0.75 pu, respectively. The magnetization resistance and reactance are set at 0.5 pu and 0.5 pu, respectively. In Experiment 2, the transformer rating value was reduced to 80 kVA. Then in Experiment 3, the zero sequence resistance and reactance values were increased to 0.05 pu and 1 pu, respectively. Then in Experiment 4, the magnetization resistance and reactance values were changed to 1 pu and 1 pu. Meanwhile, the voltage and frequency used were the same for each experiment, namely 220 V and 50 Hz. The simulation is run by collecting data discretely. The simulation was run over a time span of 0.1 s with a sample time of 50 μs. Analysis was carried out with the help of Fast Fourier Transform.

The Fourier transform is a mathematical formula that transforms a function in the time domain into another function in the frequency domain. Apart from time and frequency functions, the Fourier transform is also applicable to other functions. Understanding the Fourier transform will be easier if you use time and frequency parameters. In addition, most uses of the Fourier transform relate to these time and frequency parameters.

The Fourier series is the Fourier transform of a function of time that has periodic properties. A periodic function is a function whose value repeats itself in every certain period for an infinite distance. In general, the parameters related to periodicity are the period T, frequency f, or angular frequency ω. Based on the Fourier transformation, every periodic function x(t) with period T_1 can be decomposed into sine and cosine functions as follows.

$$x(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} [a_n \cos(n\, 2\pi f_1 t) + b_n \sin(n\, 2\pi f_1 t)] \tag{35}$$

$$a_0 = \frac{2}{T_1} \int_{-\frac{T_1}{2}}^{\frac{T_1}{2}} x(t)\, dt \tag{36}$$

$$a_n = \frac{2}{T_1} \int_{-\frac{T_1}{2}}^{\frac{T_1}{2}} x(t) \cos(n\, 2\pi f_1 t)\, dt,\ for\ n = 1, 2, 3, \ldots.. \tag{37}$$

$$b_n = \frac{2}{T_1} \int_{-\frac{T_1}{2}}^{\frac{T_1}{2}} x(t) \sin(n\, 2\pi f_1 t)\, dt,\ for\ n = 1, 2, 3, \ldots. \tag{38}$$

Thus, the decomposition or decomposition of the periodic function x(t) has been defined. These equations represent the Fourier series, namely the Fourier transform for periodic functions. In any periodic function, it is possible to contain a direct component (DC) that has no frequency, a sine or cosine function component with a certain frequency which is the fundamental frequency f_1, and a sine or cosine function component with a frequency that is an integer multiple of the fundamental frequency, namely $2f_1$, $3f_1$, $4f_1$, and so on.

III. Results and Discussions

A. Conditions before the distribution system was installed with a zigzag transformer

In the conditions before the installation of the zigzag transformer, circuit simulations were run to observe the voltage and current waveforms and current harmonic values in each order and as a whole. The voltage and current waveforms before installing the zigzag transformer are shown in Figure 6.

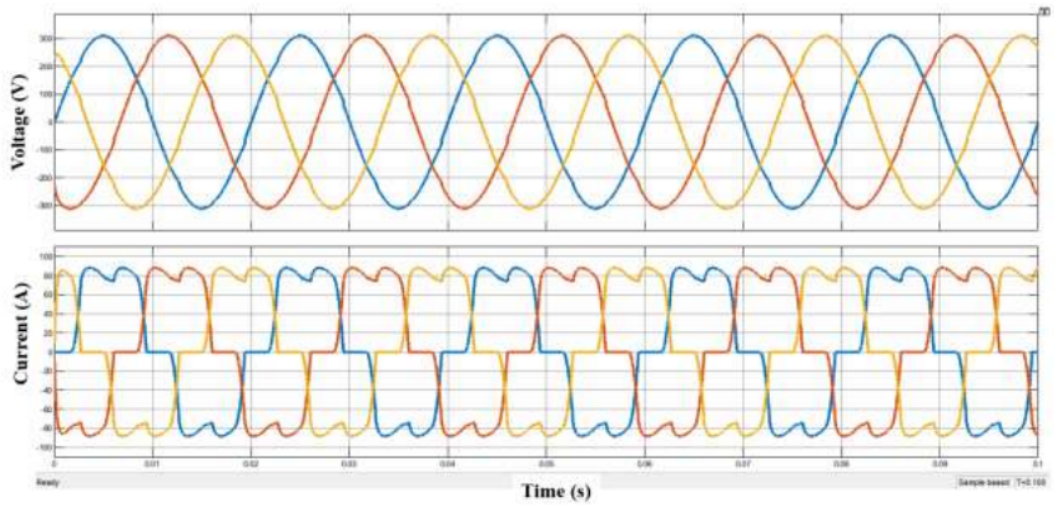

Figure 6. Voltage and current waves before installing the zigzag transformer

Figure 6 shows that the current wave is not sinusoidal. This is due to harmonic distortion caused by non-linear loads. This distortion produces defects in the current wave so that the current wave becomes not sinusoidal. Individual Harmonic Distortion (IHD) values for each order and Total Harmonic Distortion (THD) values for voltage and current are found with the help of the Fast Fourier Transform. The results of the Fast Fourier Transform analysis before installing the zigzag transformer are shown in Figure 7.

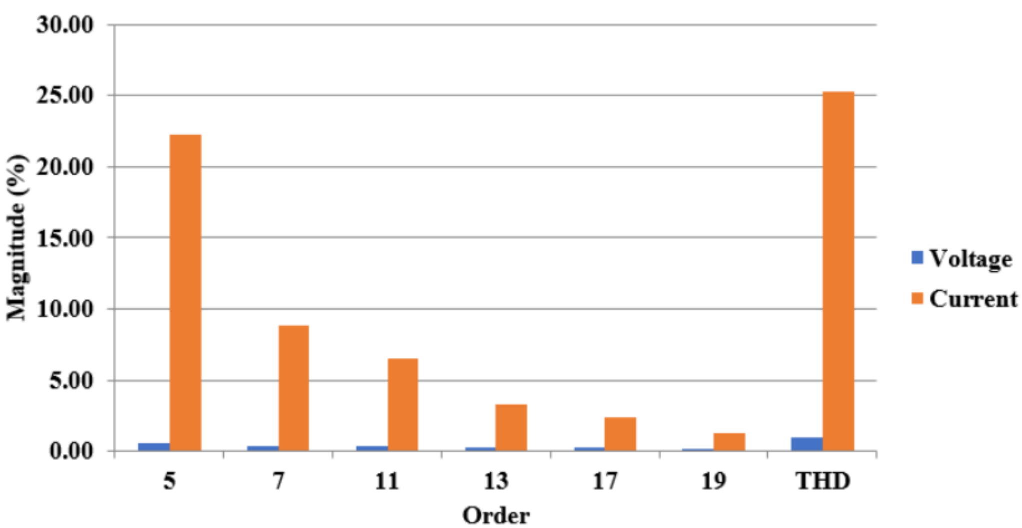

Figure 7. Results of analysis of IHD and THD values before installing the zigzag transformer

Conditions before the installation of the zigzag transformer, the highest voltage harmonics were in the 5th order, namely 1.05%, the 7th order was 0.61%, and the 11th order was 0.67%. Harmonics also appear in the 13th, 17th, and 19th orders at 0.42%, 0.37%, and 0.23%

respectively. Meanwhile, the THD_V value is 1.60%. For current waves, the highest harmonics are in the 5th order, namely 22.27%, the 7th order 8.83%, and the 11th order 6.53%. Harmonics also appear in the 13th, 17th, and 19th orders. Meanwhile, the THD_i value is 25.26%.

B. Experiment 1 after installing the zigzag transformer

In Experiment 1, a zigzag transformer with parameters P_n = 100 kVA, R_0 = 0.025 pu, X_0 = 0.75 pu, R_m = 0.5 pu, X_m = 0.5 pu was installed in the circuit. The voltage and current waveforms in Experimental condition 1 are shown in Figure 8.

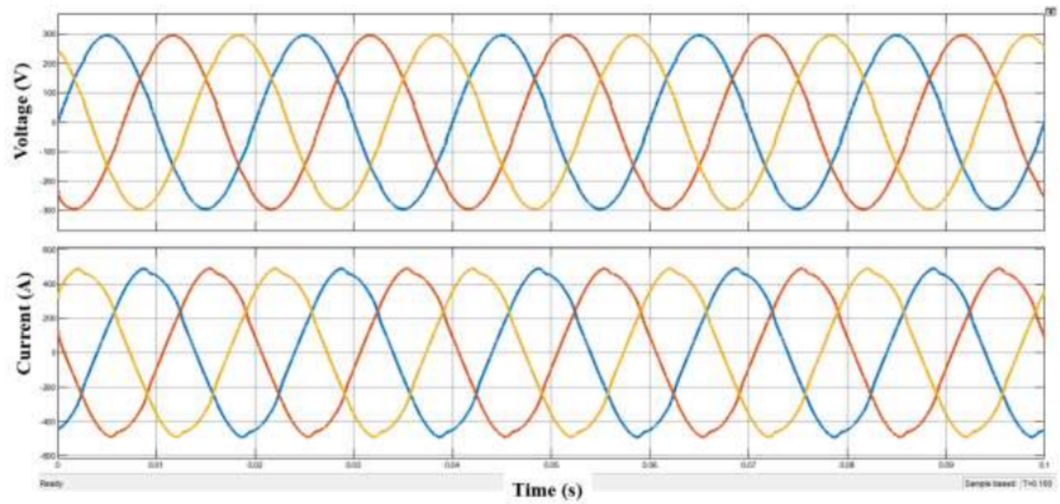

Figure 8. Voltage and current waves in Experiment 1

Figure 8 shows that the current waveform is close to a sinusoidal shape, although not perfect. The imperfection of this sinusoidal shape is caused by harmonic wave distortion that has not completely disappeared. The results of the Fast Fourier Transform analysis after Experiment 1 are shown in Figure 9.

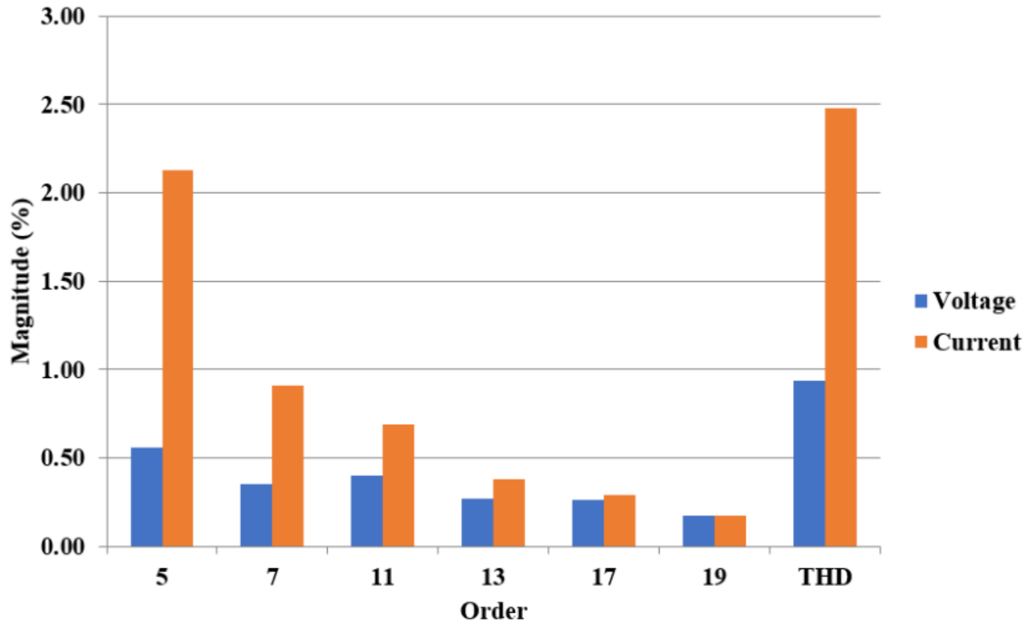

Figure 9. Results of analysis of IHD and THD values in Experiment 1

In Experiment 1, the 5th order voltage harmonics decreased to 0.56%, the 7th order by 0.35%, and the 11th order by 0.40%. The voltage harmonics in the 13th, 17th, and 19th orders also decreased to 0.27%, 0.26%, and 0.17%, respectively. Meanwhile, the THD_v value fell to 0.94%. For current waves, the highest harmonics are in the 5th order, namely 2.13%, 7th order 0.91%, and 11th order 0.69%. Harmonics also appear in the 13th, 17th, and 19th orders, namely 0.38%, 0.29%, and 0.17% respectively. Meanwhile, the THD_i value fell to 2.48%.

C. Experiment 2 after installing the zigzag transformer

In Experiment 2, a zigzag transformer with parameters P_n = 80 kVA, R_0 = 0.025 pu, X_0 = 0.75 pu, R_m = 0.5 pu, X_m = 0.5 pu was installed in the circuit. The voltage and current waveforms after Experiment 2 are shown in Figure 10.

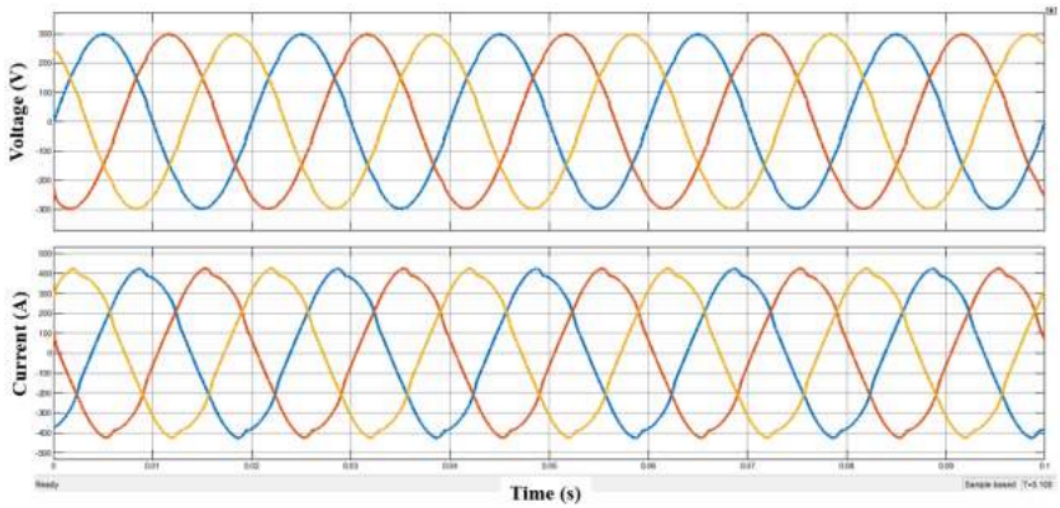

Figure 10. Voltage and current waves in Experiment 2

Figure 10 shows that the current waveform is also close to a sinusoidal shape, although not perfect. The amplitude of the current wave in Experiment 2 decreased slightly when compared to the current wave in Experiment 1. The results of the Fast Fourier Transform analysis after Experiment 2 are shown in Figure 11.

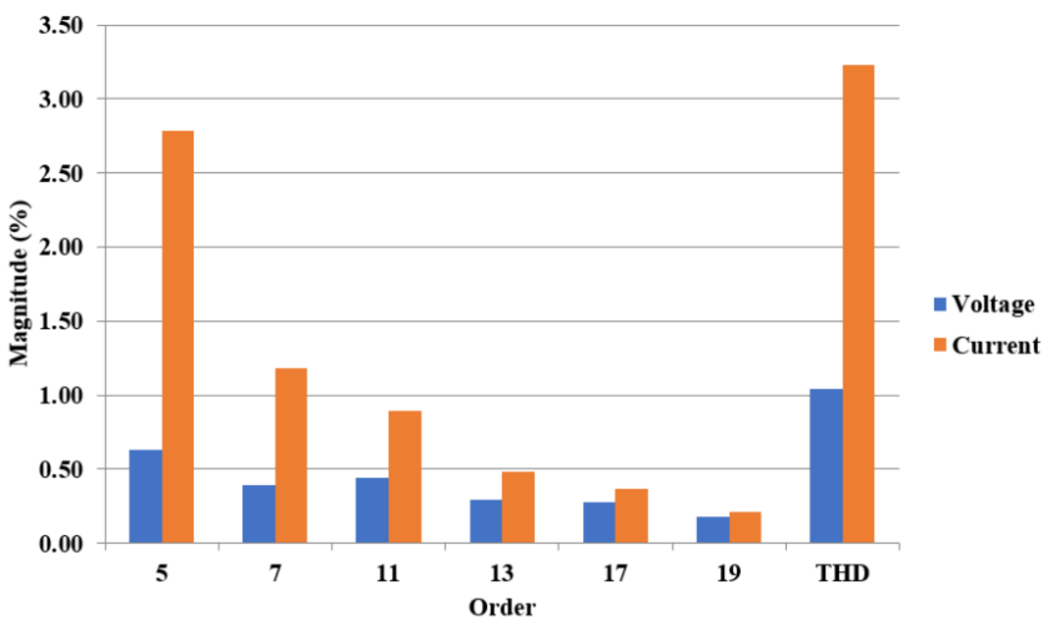

Figure 11. Results of analysis of IHD and THD values in Experiment 2

In Experiment 2, the 5th order voltage harmonics were 0.63%, the 7th order was 0.39%, and the 11th order was 0.44%. Voltage harmonics in the 13th, 17th, and 19th orders are 0.29%, 0.28%, and 0.18%, respectively. Meanwhile, the THD_V value is 1.04%. For current waves, harmonics are found in the 5th order, namely 2.79%, the 7th order is 1.18%, and the 11th order is 0.89%. Harmonics also appear in the 13th, 17th, and 19th orders, namely 0.48%, 0.37%, and 0.21% respectively. Meanwhile, the THD_i value is 3.23%.

D. Experiment 3 after installing the zigzag transformer

In Experiment 3, a zigzag transformer with parameters P_n=100 kVA, R_0 = 0.05 pu, X_0 = 1 pu, R_m = 0.5 pu, X_m = 0.5 pu is installed in the circuit. The voltage and current waveforms in Experiment 3 are shown in Figure 12.

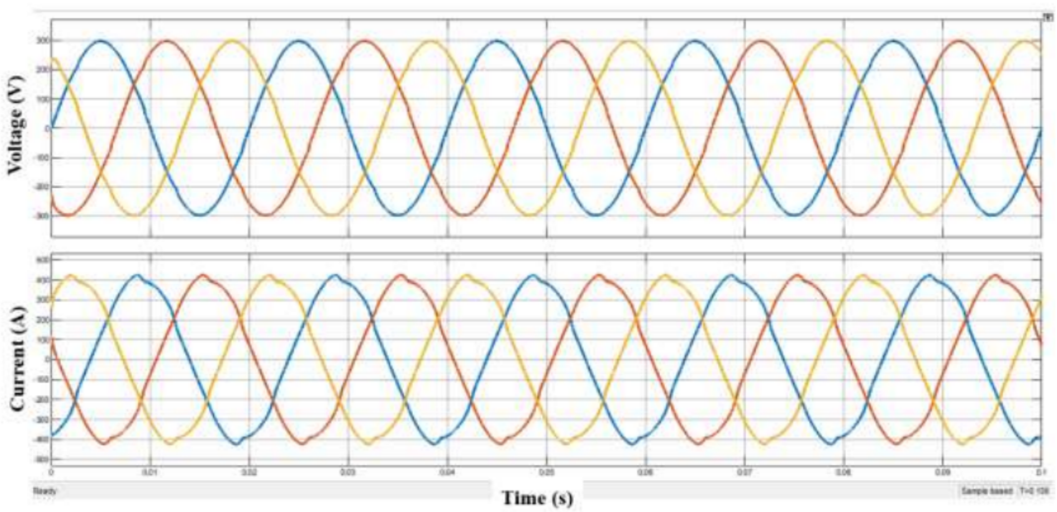

Figure 12. Voltage and current waves in Experiment 3

Figure 12 shows that the current waveform has also approached a sinusoidal shape, although it is not perfect. The amplitude of the current wave in Experiment 3 decreased slightly compared to the current wave in Experiment 1. The wave characteristics were not much different from the wave in Experiment 2. The results of the Fast Fourier Transform analysis after Experiment 3 are shown in Figure 13.

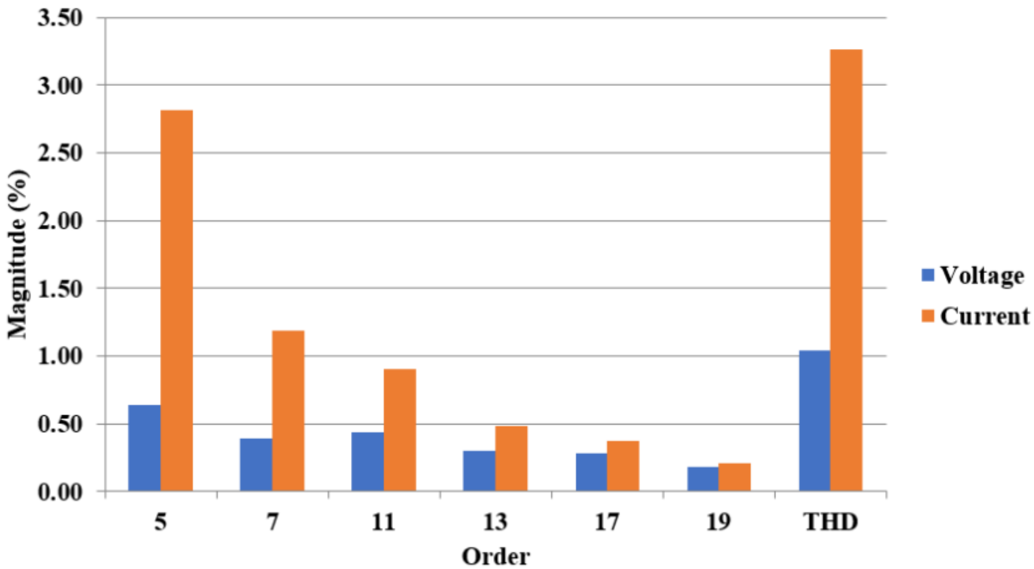

Figure 13. Results of analysis of IHD and THD values in Experiment 3

In Experiment 3, the 5th order voltage harmonics were 0.64%, the 7th order was 0.39%, and the 11th order was 0.44%. Voltage harmonics in the 13th, 17th, and 19th orders are 0.30%, 0.28%, and 0.18%, respectively. Meanwhile, the value of THD_V fell to 1.04%. For current waves, harmonics are found in the 5th order, namely 2.82%, the 7th order is 1.19%, and the 11th order is 0.90%. Harmonics also appear in the 13th, 17th, and 19th orders, namely 0.48%, 0.37%, and 0.21% respectively. Meanwhile, the THD_i value was 3.26%.

E. Experiment 4 after installing the zigzag transformer

In Experiment 4, a zigzag transformer with parameters P_n=100 kVA, R_0 = 0.025 pu, X_0 = 0.75 pu, R_m = 1 pu, X_m = 1 pu is installed in the circuit. The voltage and current waveforms after Experiment 4 are shown in Figure 14.

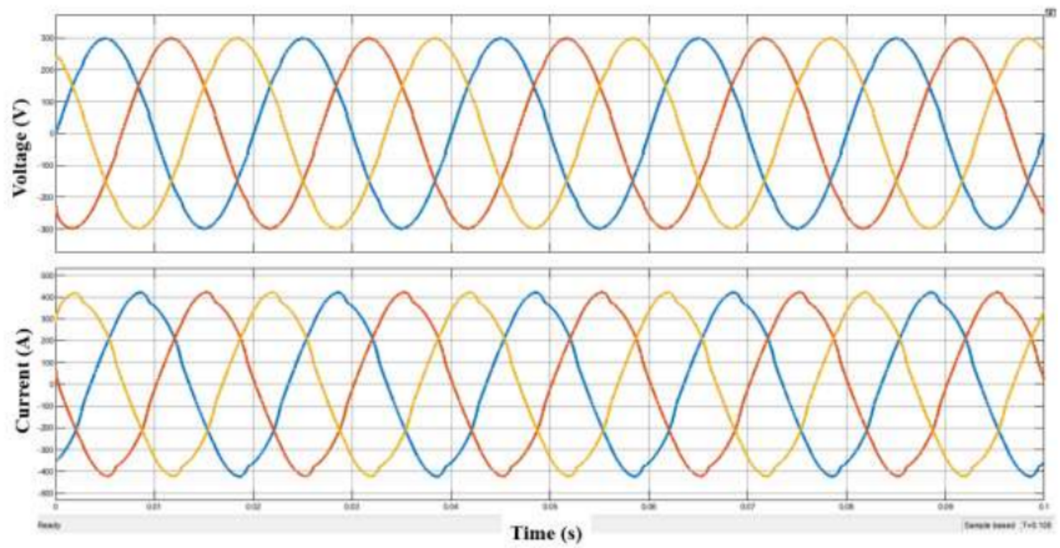

Figure 14. Voltage and current waves in Experiment 4

Figure 14 shows that the current waveform has also approached a sinusoidal shape, although it is not perfect. The amplitude of the current wave in Experiment 4 also decreased slightly compared to the current wave in Experiment 1. The wave characteristics were not much different from the waves in Experiments 2 and 3. The results of the Fast Fourier Transform analysis after Experiment 3 are shown in Figure 15.

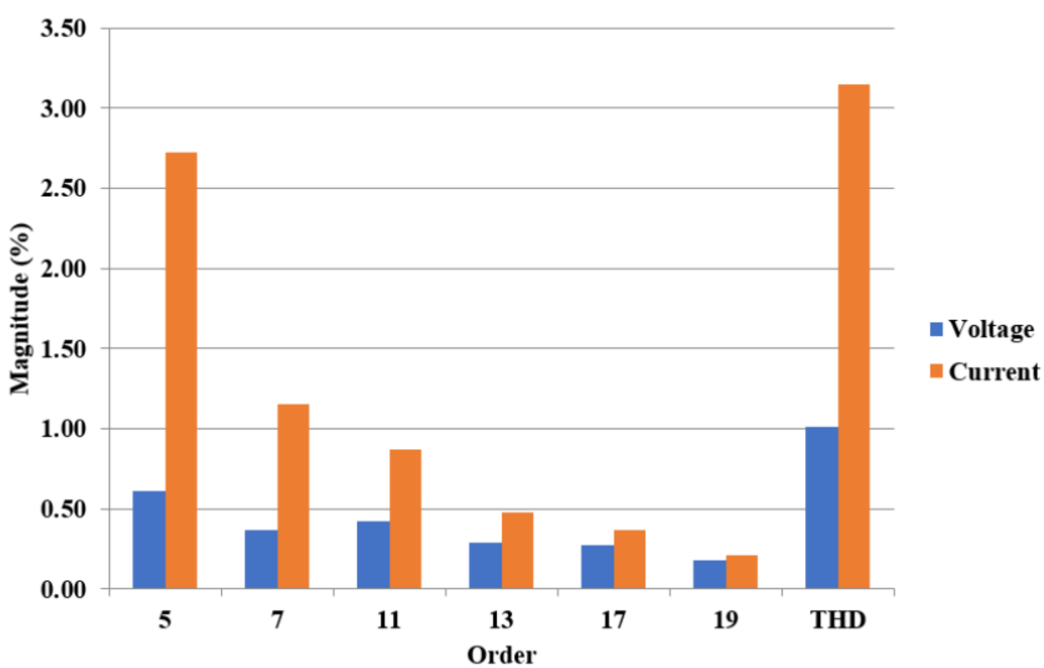

Figure 15. Results of analysis of IHD and THD values in Experiment 4

In Experiment 4, the 5th order voltage harmonics changed to 0.61%, the 7th order to 0.37%, and the 11th order to 0.42%. Voltage harmonics in the 13th, 17th, and 19th orders are 0.29%, 0.27%, and 0.18%, respectively. Meanwhile, the THD_V value fell to 1.01%. For current waves, harmonics are found in the 5th order, namely 2.72%, the 7th order is 1.15%, and the 11th order is 0.87%. Harmonics also appear in the 13th, 17th, and 19th orders, namely 0.48%, 0.37%, and 0.21% respectively. Meanwhile, the THD_i value is 3.15%.

F. Comparison of THD values in each experiment

A comparison of current THD_i values before and after zigzag transformer installation is presented in Figure 16. The changes in voltage THD_V values before and after zigzag transformer installation are presented in Figure 17. Based on the results of this comparison, Experiment 1 gave the best results compared to all other experiments. Experiment 1 was able to reduce the THD_i and THD_V values to the smallest among the other experiments, reaching values of 2.48% for THD_i and 0.94% for THD_V.

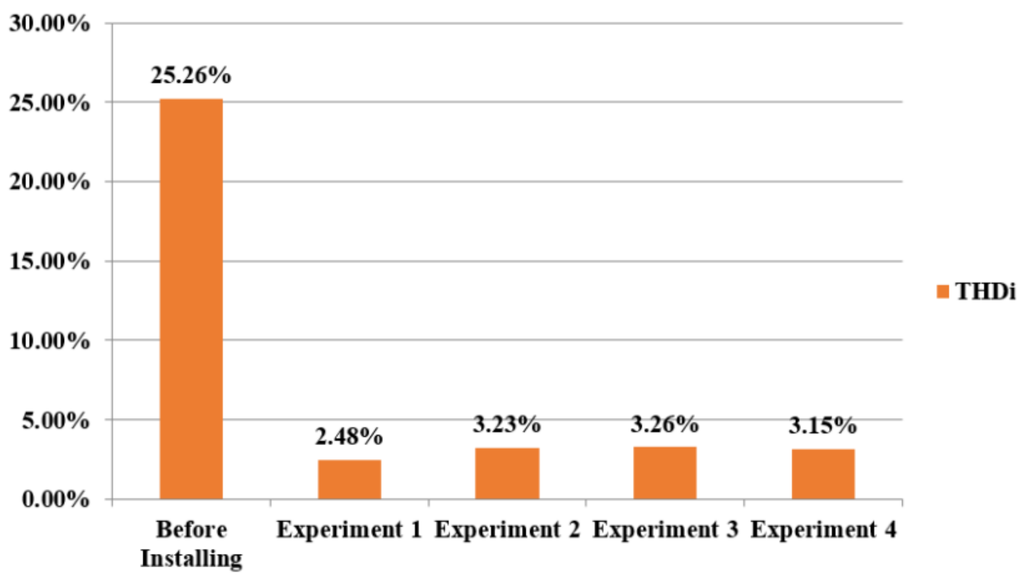

Figure 16. Comparison of THD_i Values in Each Experiment

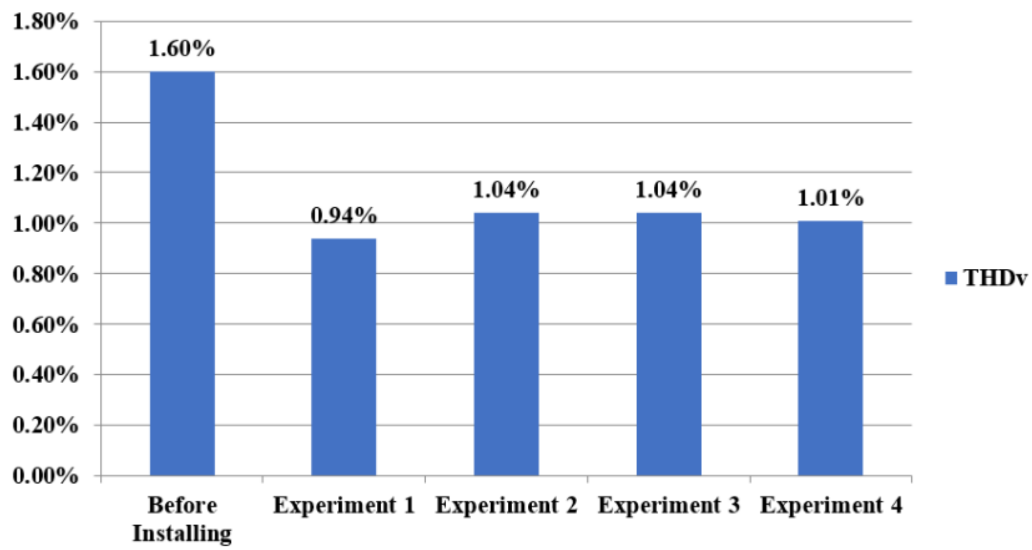

Figure 17. Comparison of THD_V Values in Each Experiment

Based on previous research [21] using a passive shunt harmonic filter and detuned reactor can only reduce voltage harmonics up to 3.07%. Meanwhile, in previous research [22] which used a combination of a C-type harmonic filter with a detuned reactor, it could only reduce THD_i current harmonics by 4.07% and voltage harmonics by 2.71%. This research has better results than previous studies. This research was able to reduce THD_V voltage harmonics by up to 0.94% and THD_I current harmonics by 2.48% in experiment 1. Besides that, previous research was only able to reduce harmonic distorsion in certain areas. Meanwhile, this research can reduce harmonic distortion in the entire distribution network by placing a zigzag transformer on the PCC in the distribution system.

IV. Conclusion

This study has conducted extensive research and experimentation to substantiate that the zigzag transformer is highly efficient at reducing harmonic currents. This efficiency is evident from the transformation of the current waveform, which initially displayed significant distortion-related deformation, but transitioned to an almost sinusoidal shape following the implementation of the zigzag transformer. This study's findings underscore the zigzag transformer's efficiency in reducing harmonic currents, an efficiency that is further supported by the significant reductions observed in both THD_V and THD_i values. Prior to the installation of the zigzag transformer, the THD_V value stood at 1.60%, which subsequently decreased to 0.94% following experiment 1, 1.04% in experiment 2, remained at 1.04% in experiment 3, and slightly reduced to 1.01% in experiment 4. Similarly, the THD_i value, which was initially 25.26% before the installation, notably decreased to 2.48% after trial 1, 3.23% after trial 2, 3.26% after trial 3, and finally 3.15% following trial 4. The extent of reduction in current THD achieved through the deployment of a zigzag transformer is contingent upon several critical parameters including the transformer rating or capacity, zero sequence resistance and reactance, as well as magnetizing resistance and reactance. Based on the results of this comparison, experiment 1 gave the best results compared to all other experiments. Experiment 1 was able to reduce the THD_i and THD_V values to the smallest among the other experiments. The impactful findings of this study, demonstrating the zigzag transformer's significant reduction of THD_i and THD_V values, mark a substantial advancement in improving power quality and system reliability in electrical distribution networks. For future work, investigating the long-term operational effects and cost-efficiency of the zigzag transformer across diverse electrical systems would be highly beneficial.

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