Design and analysis of hybrid filters for harmonic reduction in three-phase nonlinear rectifier loads

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ABSTRACT

Rectifiers are included in the non-linear load category and can create resonance in a distribution network, which can be called harmonics. In a distribution network, rectifiers (non-linear loads) distort voltage and current harmonics, resulting in power losses and reduced power quality in the network. Harmonics in the distribution power grid cannot be eliminated, but can be reduced to values that can still be tolerated and evaluated until they are by the IEEE 519-2014 Standard. This research discusses reducing harmonic values in distribution networks designed in a simulation to implement a combination (hybrid) of series active and passive filters of the high pass and high pass type-C types. The results of research using the installation of high pass filters, type C filters, series active filters, hybrid-1 filters, and hybrid-2 filters, respectively, for each current total harmonic distortion (THD) value are 15.93%, 16.15%, 8.51%, 0.27%, and 0.25% where the current THD value when using the two hybrid filters is below the specified standard limit, namely 5%. By installing a hybrid filter, the harmonic value in each feeder is much better than installing a single series active filter, a high pass filter, and a type-C filter.

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1. INTRODUCTION

Damage that often occurs in electrical power system equipment, which is used to distribute good quality power, is caused by non-linear loads. In a distribution network, non-linear loads give rise to non-sinusoidal currents or non-sinusoidal voltages, also called harmonics. Non-linear loads can affect the system by generating current and voltage harmonics [1]–[4]. Harmonic currents and voltages can also cause excessive power loss and damage to system installation components. High-order frequencies are very difficult to repair using protective relays and can cause the relay to fail or even be damaged. Loads with non-linear characteristics can cause the harmonic injection current to become non-sinusoidal when starting the operation. Harmonic reduction can be done by installing a component called a filter.

The increase in the number of users of computers, televisions, and electrical loads based on the switching process causes harmonic distortion in the distribution network. The increase in harmonic distortion causes disturbances that can have fatal consequences, such as overheating of transformers, overheating of conductor wires, damage to capacitor banks, disruption of communication systems, and malfunctions in electrical equipment [5]. Losses caused by network impedance will also be greater if there is harmonic distortion. This will cause damage to parallel loads and system imbalance. Therefore, solutions to improve the electrical power quality in the network caused by harmonic distortion are increasing in the electricity industry. Harmonic distortion has a negative impact in the form of increasing the cost of using the load used by customers. In the last ten years, power electronic components have become widely used in the industrial era. This can be considered to have a more efficient impact on power consumption and a more space-saving construction [6]–[8].

One of them is the variable frequency drive, which regulates the speed of electric motors. This variable frequency drive is often found in industries that use pumps, conveyors, fans, compressors, water mixers, and others to obtain varying speeds [6]. This variable frequency drive was chosen because it offers more efficient power consumption compared to the previous method, which utilizes a variable resistor. However, the variable frequency drive has a disadvantage, namely that it produces harmonic interference caused by the power electronic components contained in it. Harmonic disturbances have parameter units to determine the magnitude of harmonic values, including total harmonic distortion (THD) and individual harmonic distortion (IHD) [9]–[11]. These two things are a value in the form of the percentage of components that experience harmonic interference from both voltage and current waves to their fundamental components. Important problems and issues in the electric power system are closely related to the quality of the electric power produced. In overcoming this problem, passive power filters have been widely used to suppress several current harmonics and compensate for reactive power in distribution systems. Passive filters require relatively low cost, simple structure, and high-efficiency characteristics. However, passive filters also have the disadvantages of low dynamic performance and resonance problems, and their filtering characteristics are easily affected by small changes in system parameters. Since the alternating active power filter was invented in 1976, several research studies say that active power filters in current quality compensation have gained more attention. Passive filters installed in parallel and passive filters installed in series differ in reducing harmonics [12], [13]. Passive filters installed in parallel are widely used and usually combined (hybrid).

This research has some knowledge gaps, such as research regarding the analysis of harmonics using hybrid filters [14]. Industrial loads used and directly connected to the distribution network are nonlinear loads in the form of SCR, resistive loads, RL loads, and inductive loads. Filters to reduce harmonics in this research use a mixed filter hybrid power filter (HPF) where an active filter is installed in series on the transmission per phase and then paired in parallel with a high-pass damped passive filter, where the results of the analysis show that the largest contribution to harmonic reduction in the distribution transmission is the hybrid power filter (HPF) type with a THDv value of 4.20% and IHDv of 1.71%.

Furthermore, previous research has been conducted regarding harmonics in the load of DC shunt motor self-excited AC-DC converters, reduced by using passive filters [15]. This research provides results in the form of a distorted 3-phase current input, and a THD value of 49.02% is found, where this figure does not comply with IEEE 519-1992 Standards. The next experiment was to install a passive filter as a single-tuned 3-phase, which had previously found 3rd-order harmonics of 23.45% at a frequency of 50Hz. After installing a single-tuned filter focused on 3rd-order harmonics, it was found that the harmonics had been reduced with a THD value of 0.14% from 49.02% per IEEE 519-1992 Standards. This research found that the single-tuned passive filter is suitable for reducing harmonics in this network.

Harmonics are difficult to eliminate in distribution transmissions. However, we can reduce harmonics by improving the waves using filter components. The use of filters is carried out for improvements whose working principle is to reduce the amplitude of certain frequencies of a voltage and current wave that occurs until it is by the IEEE 519-2014 Standard value [16]. Passive filters consist mainly of passive components, including resistors, capacitors, and inductors. An HPF is the installation of two mixed filters, including an active filter in series with a parallel passive filter, either one or four passive filters in parallel. Both filters are designed and installed precisely to reduce harmonics maximally [14], [17], [18].

Based on the previous research, similarities between this research and previous research are using non-linear loads and hybrid filters from passive and active filters; meanwhile, the differences are in this research, which adds high-pass and high-pass type-C types and loads using three-phase rectifier diodes and RL loads [11], [19]. Furthermore, in Islam [9], the similarities are using passive filters and harmonic results based on IEEE 519-2014 Standards. Meanwhile, the difference is that previous research uses AC-DC converters based on self-excited DC shunt motors.

Therefore, this research models and simulates an 11 kV distribution transmission network, which has been designed and adapted to the components and specifications in the MATLAB Simulink software. The novelty in our research is reducing harmonic values in distribution networks designed in a simulation to implement a combination design (hybrid) of series active and passive filters of the high pass and high pass type-C types within thresholds that are still accepted according to the IEEE 519-2014 Standard.

2. METHOD
2.1. Harmonic

In the electric power system in Indonesia, the normal working frequency is 50 Hz. But when a load is installed on the system, the voltage and current frequencies become abnormal or multiples of the normal frequency, namely 50 Hz. This is what is called harmonic distortion, specifically, the existence of frequencies in a device's output that are multiples of input signal components and absent from the input signal. If f1 is the fundamental frequency of a system, then the h-order frequency (2,3,4,...h) is fh, which is an integer multiple of the fundamental frequency, so that a frequency of 50 Hz produces a disturbance wave of (100 Hz, 150 Hz, 200 Hz,…n) [4], [20].

This interference wave, or not sinusoidal, will give the result of adding the fundamental wave with its harmonic waves. Figure 1 shows the shape of the fundamental wave, the fundamental wave +3rd harmonic (distorted fundamental wave), and 3rd harmonic wave (harmonic component). If more harmonic orders are displayed, the curve will move more towards a square shape, or the wave will be far from a sinusoidal shape [3], [21]. Meanwhile, the short circuit current (I_{HS}) value at the consumer connection point and the maximum load current (I_L) at the fundamental frequency can be calculated using (1) and (2), where I_{HS} is the short circuit current (A), P_{TF} is the apparent power of power transformer (MVA), V_{l-l} is the line-to-line voltage at PCC (kV), I_L is the load current (A), PF is the power factor on the system (%), I_{DC} the magnitude of the rectifier output DC current (A), V_{DC} the DC voltage output of the rectifier (A), V_{l-l}phase-to-phase rms voltage (V), R Resistance. Next, after the value of the short circuit current (I_{HS}) and load current (I_L) is obtained, the value of the short circuit ratio (SC_{ratio}) is obtained by dividing the value of the short circuit current (I_{HS}) by the load current (I_L), as in (3). Meanwhile, the value of the DC output current and voltage can be calculated as in (4) and (5). Then, the rms current value at the output voltage can be determined in (6) and (7), and the calculation of active power and apparent power can be defined in (8) and (9) [22]–[24]:

$$I_{HS} = \frac{P_{TF} \, . \, 1000}{\sqrt{3}\ V_{l-l}} \tag{1}$$

$$I_L = \frac{P}{\sqrt{3}(V_{\emptyset-\emptyset})\ PF} \tag{2}$$

$$SC_{ratio} = \frac{\mathrm{I_{HS}}}{\mathrm{I_L}} \tag{3}$$

$$V_{DC} = V_{l-l}\frac{3}{\pi} \tag{4}$$

$$I_{DC} = \frac{V_{DC}}{R} \tag{5}$$

$$I_{s,rms} = I_{DC}\sqrt{\frac{2}{3}} \tag{6}$$

$$I_{D,rms} = \frac{I_{DC}}{\sqrt{3}} \tag{7}$$

$$P = I_{s,rms}^2 \, . \, R \tag{8}$$

$$S = \sqrt{3}\ (V_{l-l})(I_{s,rms}) \tag{9}$$

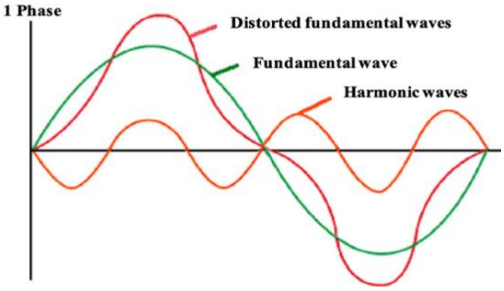

Figure 1. Fundamental, distorted, and harmonic waves

2.2. Harmonic filter

In an electric power distribution system, harmonics can increase when distributing power to non-linear loads. Several ways can be done to reduce distortions in the distribution system. One way is to install a circuit called a filter. Adding a harmonic filter to an electric power system can reduce harmonic value. Two types of filters are known to reduce harmonics, namely active and passive. This filter has various ways of application and can also be combined. The following is an explanation of the use of active and passive filters [18], [25].

2.2.1. Passive filters

A passive filter is an arrangement of inductance, capacitance, and resistance, which is arranged in such a way that it acts as a filter/frequency differentiator. For example, a passive filter provides a low impedance path for harmonic components, or it can be interpreted as a filter that allows for passing some frequencies and blocking/blocking others. Therefore, passive filters can be connected to multiple passive filters in both series and/or parallel (shunt) configurations [26], [27]. The capacitor in the passive filter functions to pass high-frequency signals and block low-frequency signals. The inductor in a passive filter is the opposite of the inductor [28]. Passive filters are designed for certain harmonics, and proper study is needed to achieve perfection in reducing/reducing harmonics. Therefore, several types of passive filters work according to the order number of their harmonics. The advantages of passive filters can also be found in improving power quality and reducing harmonic frequencies. Passive components in the form of capacitors play an important role in improving the power quality of passive filters. Another advantage of using a passive filter is that installation costs are relatively cheaper, and there is not too much noise due to the lack of reinforcement. In general, passive filters are divided into four types in reducing harmonics, as seen in Figure 2, namely: i) single tuned filter [29], [30], ii) double tuned filter [31], [32], iii) high pass filter [33]–[35], and iv) C-type high pass filter [36], [37].

2.2.2. Active filters

Active filters work based on the working principle of power electronics, where the constituent materials are types of active components (op. amplifiers, diodes, and transistors). Active filters are made of pulse width modulation (PWM), which produces analogue signals from digital devices. Active filters are a more complex design than passive filter types in terms of performance in reducing harmonics. Therefore, active filters are more expensive than passive filters in terms of installation to reduce harmonics. Active filters also have a certain bandwidth, making them useless for higher frequencies [38].

Active filters can be connected in series or parallel. If the active filter is connected in series, it overcomes high load currents, which results in copper losses, but it is very suitable in cases of reducing voltage harmonics. The series active filter is installed before the non-linear load is connected in series using a transformer. However, if the active filter is connected in parallel (shunt type), the current entered into the point of common coupling (PCC) on the consumer side can reduce current harmonics and reactive power compensation, but cannot reduce voltage harmonics properly. The shunt-type active filter is installed in the same way as the series active filter type; the only difference is that it is installed without a transformer. Figure 3 shows a schematic of an active filter type [39], [40].

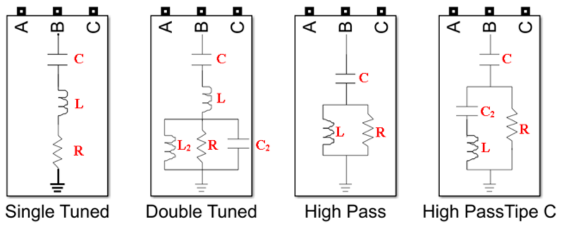

Figure 2. Passive filter circuit

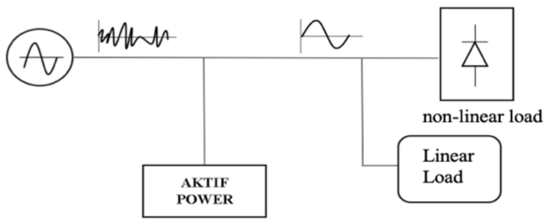

Figure 3. Active filter scheme

2.2.3. Harmonic value limits according to IEEE 519-2014 Standard

The harmonic value contained in power quality already has limitations in its licensing provisions, which are by international standards, where these standards refer to the IEEE 519-2014 Standard [41], [42]. This harmonic standard contains guidelines, practical recommendations, and designs for electrical systems installed on non-linear loads and harmonic limits so that the existing electrical system does not experience things that could be detrimental. This standard regulates voltage harmonic distortion limits for different system voltage levels, as shown in Table 1.

Table 1. Voltage harmonic distortion limits

Bus voltage V at PCC	Individual harmonics (%)	THD (%)
V≤1.0 kV	5.0	8.0
1 kV<V≤69 kV	3.0	5.0
69 kV<V≤161 kV	1.5	2.5
161 kV<V	1.0	2.25

Table 1 shows that the greater the voltage in the electrical power system conductor, the smaller the harmonic limit and THD. This is because high and extra high voltage air ducts have long conductors and power losses, one of which is caused by changes in temperature and harmonics, which are one of the causes of heat. High voltage lines also have a more complex protection system, so the harmonic value must be suppressed to prevent damage to the existing protection system. This standard also regulates the value limits for current harmonics, which are shown in Table 2.

Table 2. Current harmonic distortion limits (in percent IL)

I_{HS}/I_L	Individual harmonic order "h" odd harmonics					Total demand distortion
	3≤h<11 (%)	11≤h<17 (%)	17≤h≤23 (%)	23≤h<35 (%)	35≤h≤50 (%)	
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20-50	7.0	3.5	2.5	1.0	0.5	8.0
50-100	10.0	4.5	4.0	1.5	0.7	12.0
100-1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

3. RESULTS AND DISCUSSION

3.1. Simulation results before adding filters

Calculations of power flow simulation results in Simulink software are completed using the Newton-Raphson algorithm. Figure 4 shows an 11 kV circuit before adding a filter, which must be simulated first to determine the number of harmonics to reduce. The data results from the fundamental circuit diagram simulation are shown in Table 3.

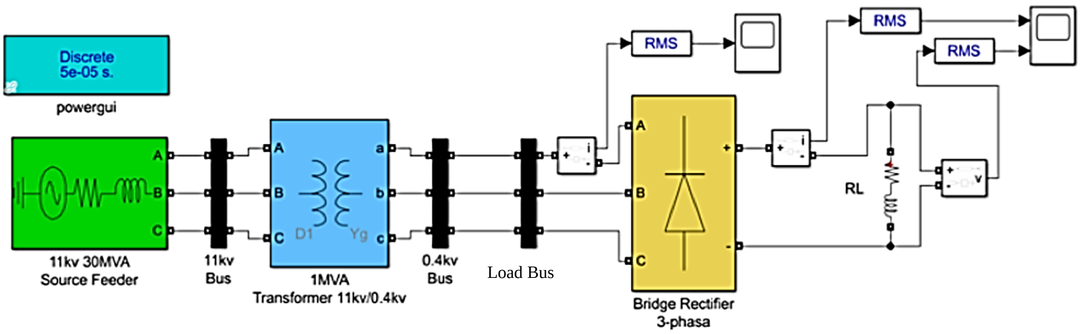

Figure 4. Circuit diagram before adding a filter

Table 3. Current harmonic distortion limits

Load	Parameter			
	P (kW)	Qc (kVAR)	Irms (A)	PF
Rectifier bridge 3-phase	7.744	7.971	17.6	0.63

In the simulated system, the load modeling component used in the harmonic simulation is a three-phase full wave (6 pulse) rectifier diode with a DC load, namely an RL circuit connected in series. The harmonic spectrum graph is shown in Figure 5. As can be seen in Figure 5, the largest harmonic values when using a three-phase rectifier diode load type occur in the 5th, 7th, 11th, and 13th orders. The type of load used will influence the respective values of the current and voltage harmonics in each order. The higher the harmonic order, the lower the harmonic value.

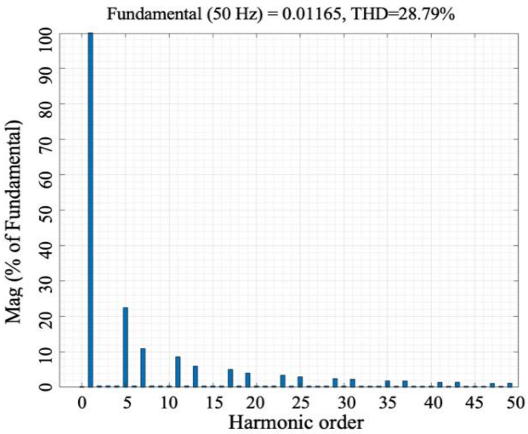

Figure 5. Simulation graph of the harmonic spectrum

3.2. Passive filter design to reduce harmonics

Passive filter design aims to reduce harmonic orders due to non-linear loads in the distribution network. Apart from being able to reduce harmonics, passive filters can also improve the power factor caused by the presence of capacitor components in the filter. Harmonics can occur when a source supplies current to a load, which produces harmonics. Therefore, loads that produce these harmonics produce undesirable harmonic currents. Installing a passive filter causes the load current to produce harmonics that flow towards the filter so that the frequency can be reduced by the harmonic filter, and the desired frequency flows back towards the distribution source, resulting in the harmonic current disappearing.

In this research, the harmonic filters used are high pass and high pass type-C filters. The harmonics identified in the order of harmonics that will be eliminated are in the 5th, 7th, 11th, and 13th orders, which have the greatest distortion. After that, passive filters will be designed and installed in turn on the 11 kV distribution network loaded with three-phase rectifier diodes to see the performance of each passive filter.

3.2.1. Design of high-pass filter

After entering all the data from components such as capacitor, inductor, and resistor values required from the high-pass filter for the order whose harmonics will be reduced, a simulation can be run to get the current harmonic values after the filter has been installed. The filter is installed at the point common coupling (PCC) point, which is the closest distance to the source that causes harmonics, where later, the harmonic index value for each order reduced by the filter will be visible in the FFT analysis module. Figures 6 and 7 show the simulation results of using a high-pass filter in an 11 kV distribution network with a three-phase rectifier diode load with reduction orders 5, 7, 11, and 13. Meanwhile, Table 4 describes a high-pass harmonic filter.

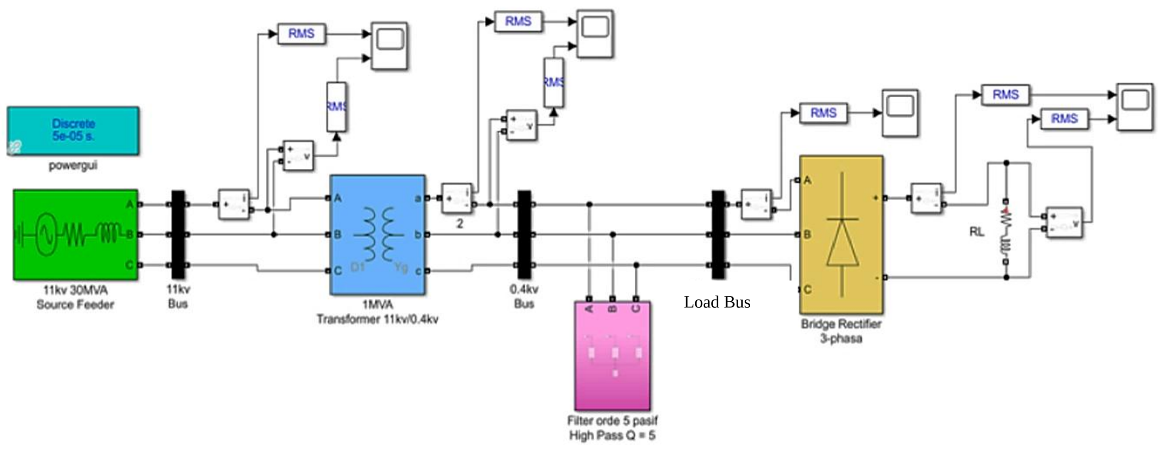

Figure 6. Circuit diagram after installing the high pass filter

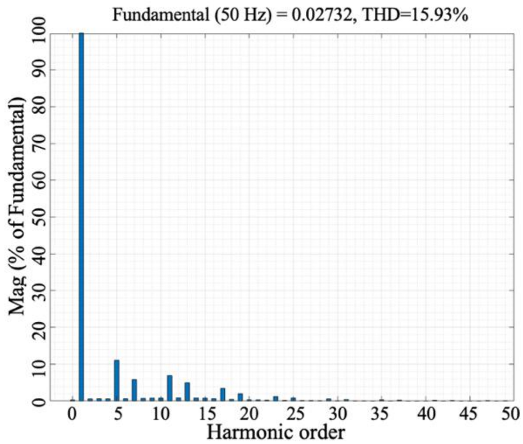

Figure 7. Simulation spectrum graph after installing a high-pass filter

Table 4. High-pass harmonic filter specifications

Load filter	Harmonic order	IHDI%	Limitations IHDI%	THDI%	Limitations THDI%	Exceeds the limit (Y/N)
High pass	5	11.10	10	15.93	12	Yes
	7	5.82	10		12	Yes
	11	6.91	4.5		12	Yes
	13	4.97	4.5		12	Yes

The simulation results show that the harmonic values in the 5th, 7th, 11th, and 13th orders after installing the high pass filter have decreased. However, considering the IEEE 519-2014 Standard, the resulting IHD and THD values still do not meet the maximum limits that have been determined. This happens because the filter design is carried out for fifth-order values so that the filter can only reduce orders close to the fifth order, such as the seventh order. However, even though it does not meet the standards, what can be done next is to combine it with a series active filter for maximum results. This also shows that the High Pass Filter can effectively reduce harmonics, considering that the previous fifth order IHD was 22.50%. In comparison, the result after the reduction was 11.10%, and it can be concluded that the reduction was approximately 11.40%. The THD value has decreased from 28.79% to 15.93%, resulting in a decrease of approximately 12.86%. All of the above is influenced by the adjustments made, where the filter is designed as a 5th-order high pass type.

The component characteristics of the type C filter are almost the same as those of the high-pass filter. The difference is that the type C filter has two capacitor components, which, in theory, can improve the power factor and suppress any loss of power frequency, which causes sinusoidal wave distortion in the current. Because the high pass and type C filters have the same component characteristics, the calculations carried out on the R, L, and C components in the type C filter are the same. In this research, the value settings for the capacitors C1 and C2 used in the type C filter are the same values as shown in Table 5.

Table 5. Specifications of type C harmonic filter

Filter	C1 & C2 (F)	Inductor (H)	Resistor (Ω)
High pass type C	48.01×10^{-5}	0.844×10^{-3}	0.265

After entering all the data from the components needed for the type C filter for the order whose harmonics will be reduced, a simulation is run to get the harmonic values after installing the filter. The working principle of the type C filter is that the capacitor C1 functions to supply the reactive power required at the fundamental frequency. Meanwhile, capacitor C2 and inductor L are designed to be at the PCC point, which is the closest distance to the source of harmonics in the 11 kV distribution network loaded with a three-phase rectifier diode with reduction orders 5, 7, 11, and 13 shown in Figures 8 and 9.

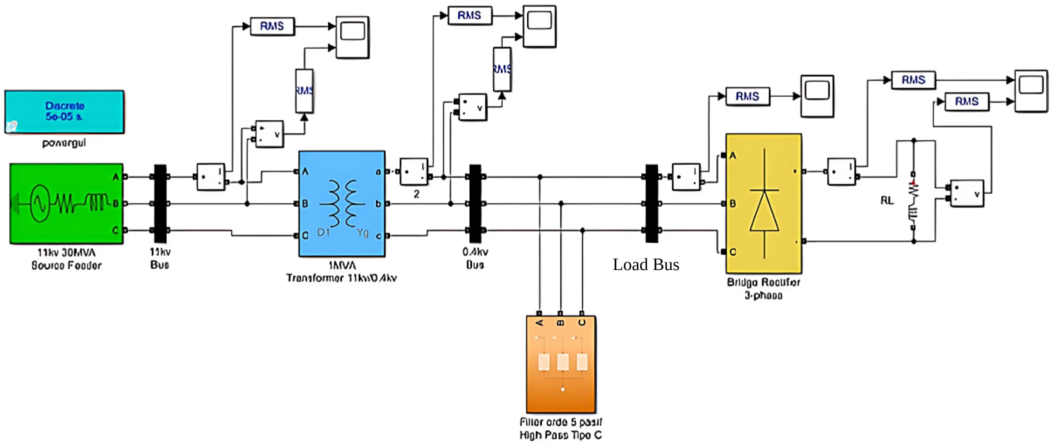

Figure 8. Circuit diagram after installing type C high pass filter

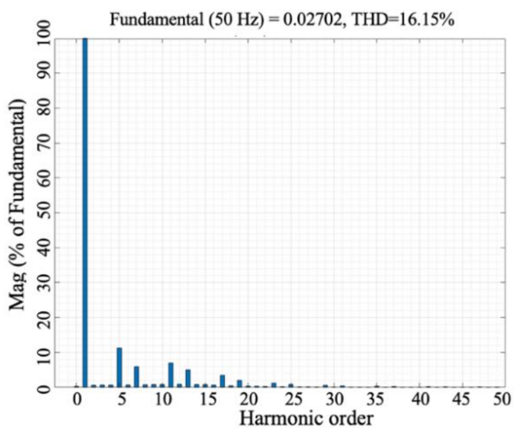

Figure 9. Simulation spectrum graph after installation of type C filter

The simulation results of harmonic values after installing the type C filter in Simulink above are then compared with the IEEE 519-2014 Standard limits to see the effect of filter design in reducing harmonics in the distribution network. Table 6 shows the results of the harmonic simulation after installing the high pass filter. The simulation results show that the harmonic values in the 5th, 7th, 11th, and 13th orders after installing the high pass filter have decreased. However, considering the IEEE 519-2014 Standard, the resulting IHD and THD values still do not meet the maximum limits that have been determined. However, even though it does not meet the standards, what can be done next is to combine it with a Series active filter for maximum results. This also shows that the high pass filter can effectively reduce harmonics, considering that the previous fifth order IHD was 22.50%. In comparison, the result after the reduction was 11.24%, and it can be concluded that the reduction was approximately 11.26%. The THD value has decreased from 28.79% to 16.15%, where the efficiency reduction is approximately 12.64%. The harmonic value after installing the type C filter, compared to the high pass filter experienced a slight increase in harmonics due to the influence of the arrangement of the L-C components, which are arranged in the type C Filter because it is more complex and has two capacitors in it. All of the above is, of course, also influenced by the adjustments made; the characteristics and values of the filter's passive components also influence the harmonic values' results.

Table 6. Current harmonics based on IEEE 519-2014 Standard

Load filter	Harmonic order	IHDI%	Limitations IHDI%	THDI%	Limitations THDI%	Exceeds the limit (Y/N)
High pass	5	11.24	10	16.15	12	Yes
type C	7	5.94	10		12	Yes
	11	7.01	4.5		12	Yes
	13	5.02	4.5		12	Yes

3.2.2. Design of series active filters

The active filter used in this simulation already has parameters adjusted to the circuit and passed through various experiments before starting this research. The active filter comprises several components: inverter (IGBT), capacitor, inductor, PLL, PWM, and single-phase linear transformer. This active filter is designed in series with the 11 kV distribution circuit and installed at the PCC point, the closest distance to the source of harmonics in the 11 kV distribution network loaded with three-phase diode rectifiers. The PLL and PWM in this active filter circuit are useful for providing a signal or triggering a reference voltage to process the repair frequency, which can later be injected into the circuit as a repair voltage or current so that a better sinusoidal wave is produced to improve the power factor in the circuit. The reference voltage is converted into a signal to control the inverter (IGBT). The linear transformer connects the active filter series with the source and load. Active filter parameters are shown in Table 7. After entering all the data from the components needed for the active filter to reduce harmonics, a simulation is run to get the harmonic values after installing the filter. The simulation results are shown in Figures 10 and 11.

Table 7. Active harmonic filter parameters

Filter	C (F)	Inductor (H)
Series active filters	10	10

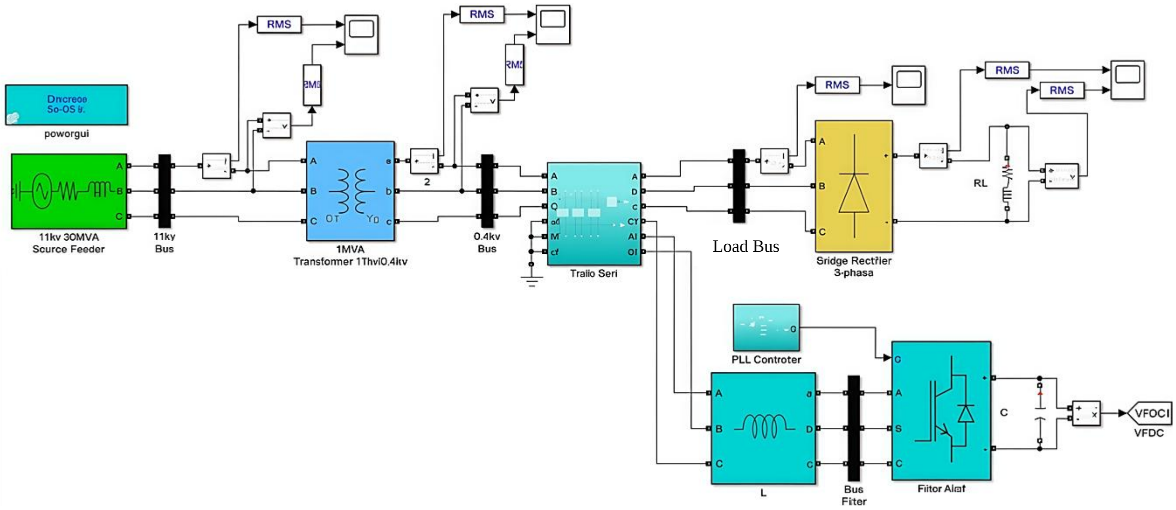

Figure 10. Circuit diagram after installation of active filter

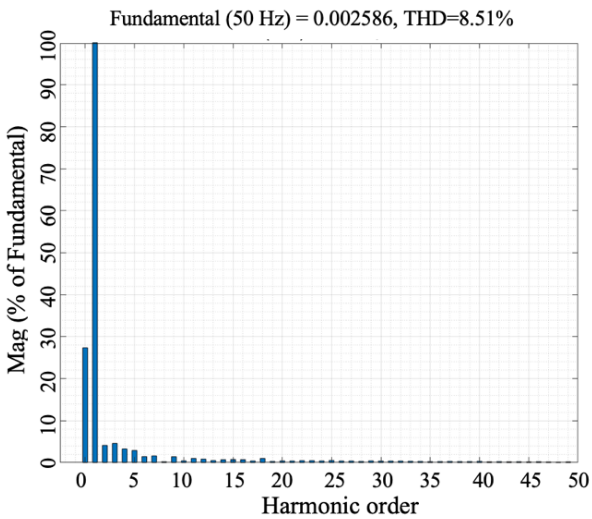

Figure 11. Simulation spectrum graph after installation of active filter

The simulation results of harmonic values after installing the series active filter type in Simulink above are then compared with the IEEE 519-2014 Standard limits to see the effect of filter design in reducing harmonics in the distribution network. Table 8 shows the results of the harmonic simulation after installing the high pass filter. The simulation results show that the harmonic values in the 5th, 7th, 11th, and 13th orders after installing the high pass filter have decreased. However, considering the existence of the IEEE 519-2014 Standard, the resulting IHD values for orders 5, 7, 11, and 13 are already below the established standards. However, even though it meets the standards, the resulting THD value is still above the standards that have been set. This occurs due to increased harmonics in the 2nd, 3rd, and 4th orders, resulting in the THD value remaining above standard. This series of active filters has shown that it can effectively reduce the IHD value, considering that the previous 5th-order IHD value was 22.50%. In comparison, the result after the reduction was 2.92%, and it can be concluded that the reduction was approximately 19.58%. The THD value has decreased from 28.79% to 8.51%, where the efficiency reduction is approximately 16.15%. The harmonic value after installing the series active filter compared to the type C high pass and high pass filters experienced a better decrease in harmonics due to the influence of the arrangement of the IGBT, which is given a corrective signal from the process of changing the reference voltage into a corrected signal frequency by the PLL and PWN and injected into the IGBT which processes it. The output signal returns to harmonic improvements, although it is also influenced by the amount of inductance and capacitance used

Table 8. Current harmonic simulation results based on IEEE 519-2014 Standard

Load filter	Harmonic order	IHDI%	Limitations IHDI%	THDI%	Limitations THDI%	Exceeds the limit (Y/N)
Active series	5	2.92	10	8.51	12	No
	7	1.62	10		12	No
	11	1.01	4.5		12	No
	13	0.52	4.5		12	No

3.2.3. Hybrid filter design–1 (active series+high pass)

In this design, a combination of the use of active filters in series and 5th-order passive high-pass filters in parallel is carried out, which is expected to reduce harmonics better than the single use of active or passive filters. The active and passive filter parameters are the same, with no changes. After entering and assembling all the data from the components needed for the active and passive filters to reduce harmonics, a simulation is run to get the harmonic values after installing the filter. The simulation results are shown in Figures 12 and 13. Figure 13 shows the results of the spectrum after installing the hybrid-1 filter at the 5th, 7th, 11th, and 13th orders have experienced a better decrease than before (such as high pass filters, C-type high pass filters, and series active filters), and the THD value has decreased by 0.27%.

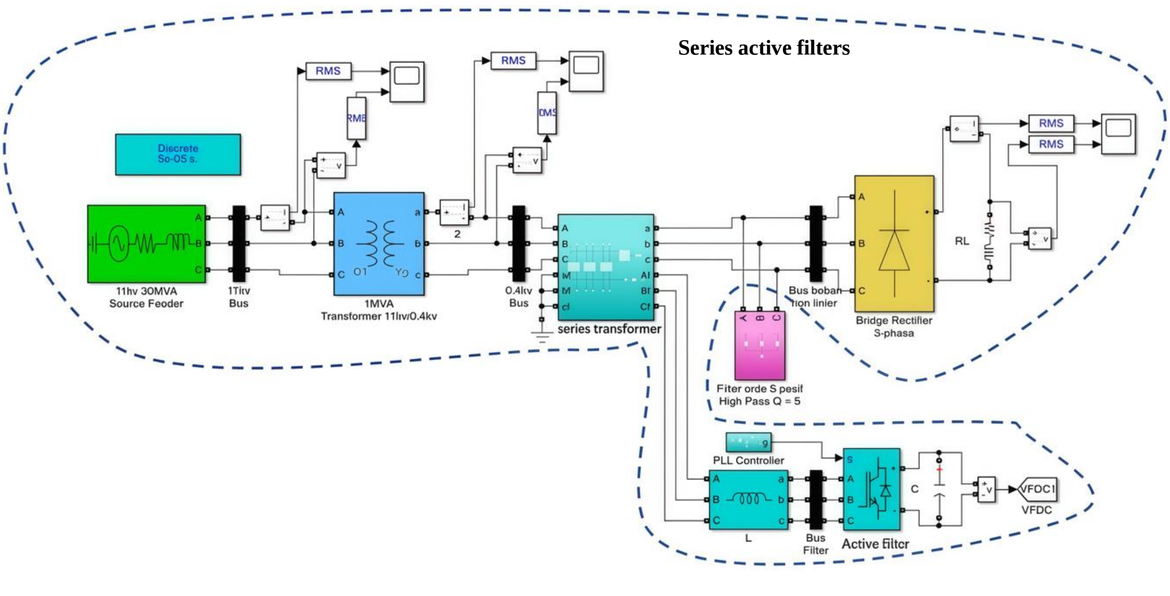

Figure 12. Circuit diagram after installation of hybrid-1 filter

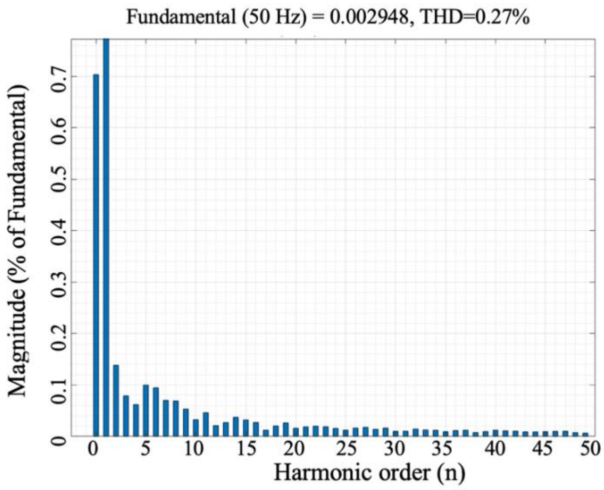

Figure 13. Simulation spectrum graph after installation of the hybrid-1 filter

3.2.4. Hybrid filter design–2 (active series+high pass type C)

In this design, a combination of active filters in series and 5th-order type C high-pass passive filters in parallel is carried out, which is expected to reduce harmonics better than the single use of active or passive filters. The active and passive filter parameters are the same, with no changes. After entering and assembling all the data from the components needed for the active and passive filters to reduce harmonics, a simulation is run to get the harmonic values after installing the filter. The simulation results are shown in Figures 14 and 15. Figure 15 shows the results of the spectrum after installing the hybrid-2 filter at the 5th, 7th, 11th, and 13th orders have experienced a better decrease than the others (such as hybrid filter design1, high pass filters, C-type high pass filters, and series active filters), and the THD value has decreased by 0.25%. The simulation results of harmonic values after installing the hybrid-1 and hybrid-2 filter types in Simulink above are then compared with the IEEE 519-2014 Standard limits to see the effect of filter design in reducing harmonics in the distribution network. Table 9 shows the harmonic simulation results after installing the hybrid-1 and hybrid-2 filters.

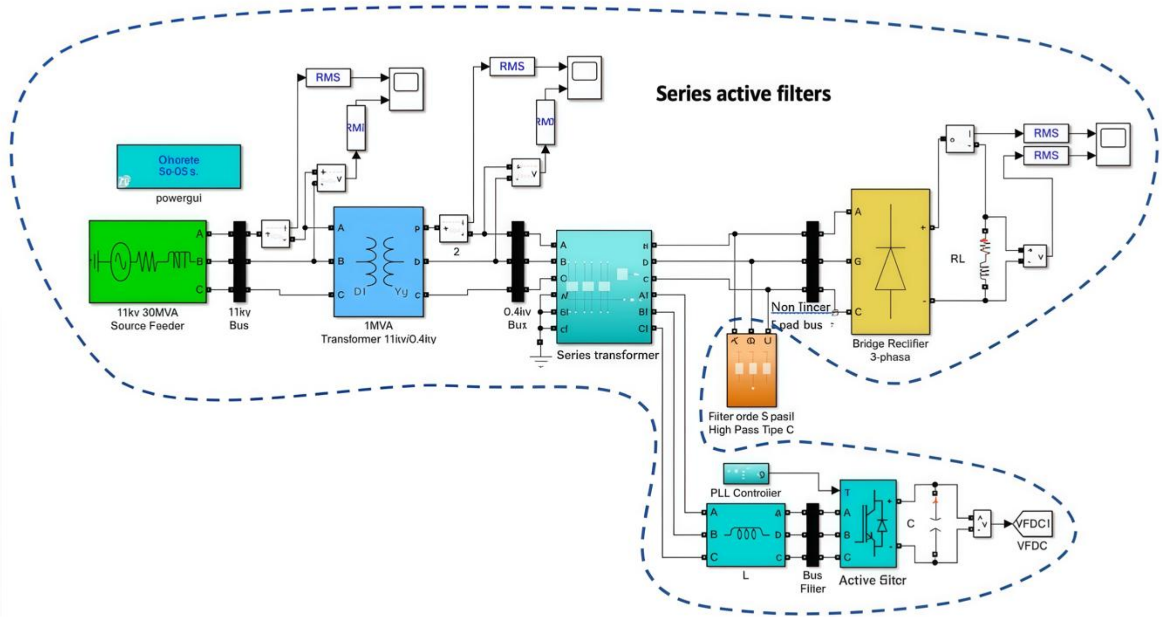

Figure 14. Circuit diagram after installation of hybrid-2 filter

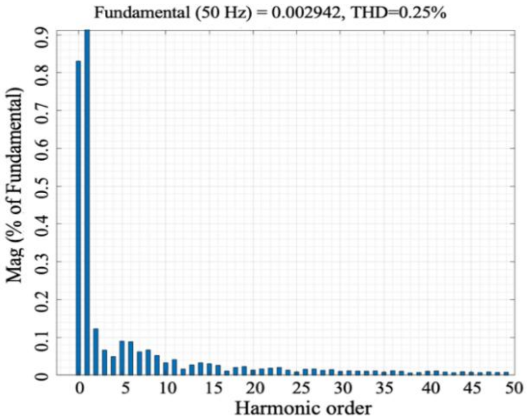

Figure 15. Simulation spectrum graph after installation of the hybrid-2 filter

Table 9. Current harmonic simulation results based on IEEE 519-2014 Standard

Load filter	Harmonic order	IHDI%	Limitation IHDI%	THDI%	Limitation THDI%	Exceeds the limit (Y/N)
Hybrid–1	5	0.10	10	0.27	12	No
	7	0.07	10		12	No
	11	0.05	4.5		12	No
	13	0.03	4.5		12	No
Hybrid–2	5	0.09	10	0.25	12	No
	7	0.06	10		12	No
	11	0.04	4.5		12	No
	13	0.03	4.5		12	No

The simulation results show that the harmonic values in the 5th, 7th, 11th, and 13th orders after installing the hybrid-1 and hybrid-2 filters experience very large reductions in harmonics with little difference between them. However, considering the existence of IEEE 519-2014 Standard, the IHD values for the 5th, 7th, 11th, and 13th orders produced are already below the set standards, and the resulting THD values also meet the set standard limits. Apart from this, this hybrid filter has shown that it can effectively contribute to reducing the IHD and THD values, considering that the previous 5th-order IHD value was 22.50%. In comparison, the results after reduction were 0.10% (high pass) and 0.09% (type C). The THD value itself has decreased from a value of 28.79% to 0.27% and 0.25%.

3.2.5. Simulation comparison results with spectrum graphs and tables

In this section, we show a comparison of the use of active, passive, and hybrid filters, which are simulated to display the THD and IHD quantities to reduce harmonics with limits adjusted to the IEEE 519-2014 Standard for three-phase non-linear rectifier bridge loads. The results of the series active filter, high pass, high pass type-c, hybrid-1, and hybrid-2, as shown in Figure 16 and Table 10.

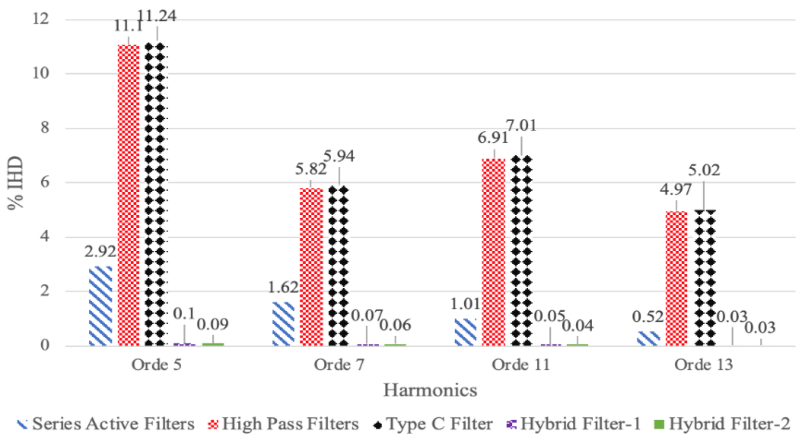

Figure 16. IHD comparison of filter use

Table 10. The series active filter, high pass, high pass type-c, hybrid-1, and hybrid-2

Harmonics	Series active filters	High pass filters	Type C filter	Hybrid filter-1	Hybrid filter-2
Order 5	2.92	11.10	11.24	0.10	0.09
Order 7	1.62	5.82	5.94	0.07	0.06
Order 11	1.01	6.91	7.01	0.05	0.04
Order 13	0.52	4.97	5.02	0.03	0.03
THDI%	8.51	15.93	16.15	0.27	0.25

After carrying out the simulation, the simulation results were obtained as shown in graph Figure 14 and data in Table 10, where it was concluded that the use of a hybrid filter is highly recommended for harmonic reduction in the 11 kV network in contrast to three-phase diode bridge rectifiers. The comparison of the use of active and passive filters is very prominent in the reduction section, where the active filter uses active components whose working principle is to inject rectifying waves into the main network using DC components, which are controlled using PLL and PWM, so the results have the side effect of the emergence of order 0 harmonics which are generated by the use of components. Excessive DC and unsymmetrical load phasors and the results obtained by the reducer result in a decrease in the IHD and THD values, which are already below the IEEE 519-2014 Standard. The use of passive filters can certainly be reduced. However, it can only reduce close to the IEEE 519-2014 Standard limit value because high pass and type C filters must be adjusted accordingly and are usually combined with other passive filters to achieve maximum results. Overcoming the shortcomings of each active and passive filter, a hybrid filter was created, which is expected to reduce harmonics to tolerable limits and improve power quality as well as reduce electrical losses with simulation results as in Table 10 that the value of harmonics in the highest order is already below 1% due to a combination of active and passive filters that complement each other. A hybrid 2 (active series+high pass type C) filter greatly lowers signal losses at the fundamental frequency, making it superior to a normal hybrid 1 (active series+high pass filter). A more intricate design that incorporates an extra capacitor and inductor that are adjusted to the fundamental frequency is used to accomplish this.

4. CONCLUSION

The simulation results show that the type of load used influences the levels of voltage and current harmonics. This simulation uses harmonic load modelling of the three-phase full-wave (6 Pulse) rectifier diode type. The IHD and THD values of this feeder current show the highest orders at 5, 7, 11, and 13, with the current THD already exceeding the IEEE 519-2014 Standard limit. The harmonic values after installing five types of filters, namely series active filters, 5th order high pass passive filters, fifth order type C high pass passive filters, hybrid-1 filters, and hybrid-2 filters, have differences in the harmonic values reduced by the load three-phase rectifier diode. The current THD values after installing a series active filter, a fifth-order high-pass passive filter, a fifth-order type C high-pass passive filter, hybrid filter-1, and hybrid filter-2, respectively, are 8.51%, 15.93%, 16.15%, 0.27%, and 0.25%. Only hybrid-1 and hybrid-2 filters have been proven to reduce harmonics to below the IEEE 519-2014 Standard limit. The current IHD value on the three-phase rectifier diode feeder for orders 5, 7, 11, and 13 after installing hybrid-1, hybrid-2, and series active filters is below the IEEE 519-2014 Standard limit; however, not for high-pass and type C filters. Combining active and passive filters has been proven to reduce harmonic values in a distribution network where the circuit and value of the passive components in the filter can support the effectiveness of using active filters when combined to reduce harmonic values, because active filters have a certain frequency bandwidth and cannot be used for high frequencies. In contrast, passive filters can reduce the desired harmonic order. Then, future research will discuss the cost, scalability, or maintenance of the proposed hybrid filter designs and dynamic non-linear loads

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
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D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author [Yulianta Siregar] on request.

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