International Journal on Advanced Science Engineering Information Technology

Vol.13 (2023) No. 1
ISSN: 2088-5334

Effect of Combination Shunt Passive Filter Harmonic and Detuned Reactor on the K-Factor Changes of Transformer

Langlang Gumilar [a,*], Arif Nur Afandi [a], Aripriharta [a], Muhammad Afnan Habibi [a], Arya Kusumawardana [a]

[a] *Department of Electrical Engineering, Universitas Negeri Malang, Jalan Semarang Number 5, Malang, 65145, Indonesia*
*Corresponding author: *langlang.gumilar.ft@um.ac.id*

***Abstract*—This paper describes the impact of changes in harmonic distortion on the value of the transformer K-Factor. The transformer has a capacity of 1.5 MVA and a K-Factor value of 1 under normal conditions. Techniques were installed to reduce harmonic distortion, shunt passive filter, and detuned reactor. Several condition scenarios were created to compare changes in harmonic distortion's value to the K-factors value. Scenario 1, the transformer works in harmonic conditions. The K-factor value of the transformer becomes 3.947101, and the new capacity of the transformer that can serve the load becomes 1.27 MVA. Scenario 2, a passive shunt filter was installed in the transformer circuit. Shunt passive filter can reduce IHD-V and THD-V values on PCC but increase IHD-I and THD-I values on the load side. The k-factor value fell to 1.5775, and the new capacity of the transformer increased to 1.44 MVA. The novelty of this paper is in scenario 3, a combination of a passive shunt filter and a detuned reactor was installed in the transformer circuit. The detuned reactor can limit the harmonic current that enters the harmonic filter. As a result, all values, including IHD-V, THD-V, IHD-I, and THD-I fell below the maximum harmonic distortion limit. The k-factor value fell to 1.0361, and the new capacity of the transformer increased to 1.49 MVA. The existence of a detuned reactor has been able to increase the performance of the passive shunt filter. The impact of the detuned reactor for future research is that it can be used to protect important equipment in the electric power system.**

***Keywords*— Harmonic distortion; shunt passive filter harmonic; detuned reactor; transformer; K-Factor.**

Manuscript received 15 Aug. 2021; revised 16 Sep. 2021; accepted 13 Dec. 2021. Date of publication 28 Feb. 2023.

I. INTRODUCTION

Power quality is an important part of electricity distribution from producers to consumers. Large-scale power systems often experience a decrease in power quality. The cause of this decrease is the large number of nonlinear loads scattered in the electric power system. The type of linear load does not have a disruptive impact on the electric power system, and Nonlinear load components that cause the current to increase are not proportional to the increase in voltage. Large amounts of nonlinear loads eventually cause harmonics [1]-[4]. Examples of nonlinear loads that are often used in industry are inverters, variable speed drives for motor control, and rectifiers. These nonlinear loads are better known as power electronic devices [5]-[8].

A sign of an electrical power system experiencing harmonic disturbances is the breakdown of voltage and current sinusoidal waves [9],[10]. Disturbances with the high harmonic distortion cannot be allowed to continue in the power system, and high harmonic distortion can cause damage to equipment in the vicinity of the electric power system. The permissible limits of tolerance for harmonic distortion do not exceed the IEEE 519-1992 standards for current and voltage parameters [11]. Apart from THD, there are other parameters in harmonic measurement, namely Individual Harmonic Distortion (IHD). This IHD also consists of IHD-I for current and IHD-V for voltage.

Equipment that is often damaged or burned due to harmonics is the transformer. Harmonics can affect the ability of the transformer to serve loads [12]. This capability is often referred to as the K-factor transformer. Normally, the K factor value without harmonics is 1. If the K factor value is more than 1, it can be concluded that the transformer performance has been affected by harmonics [13],[14]. The higher the K factor value, the faster the transformer will heat up when serving the load. In other words, to serve the same load size, a transformer with a high K factor will experience a faster heat gain than a transformer with a K-factor value of 1.

Active and passive filters have their respective challenges and are most often used to reduce harmonic distortion [15]. An active harmonic filter can reduce THD and IHD in changing dominant order, and meanwhile, passive harmonic filters can only reduce THD and IHD in dominant order fixes. Previous studies that have discussed the ability of active filters can be seen in the following references [16]-[18]. Likewise, a discussion of passive filter capabilities can be seen in the following references [19]-[21].

Active filters and passive filters are becoming less effective at reducing THD at very high dominant orders [22]. When the harmonic filter is installed in the PCC, the THD-V and IHD-V values decrease. Besides that, the THD-I and IHD-I values increase on the load side. In addition, harmonic filters are also affected by nonlinear load harmonics. The harmonic filter gets THD-I and IHD-I values. The novelty of this paper is to reduce harmonic distortion in this problem and improve the performance of harmonic filters. The method to overcome this problem combines a passive harmonic shunt filter with a detuned reactor. The detuned reactor can improve the performance of the passive harmonic shunt filter. Previous studies that have discussed the ability of detuned reactors in the case of power quality improvement can be seen in the following references [23]-[25].

The impact of combining passive harmonic filters and detuned reactors should also be observed on changes in the K factor value of the transformer. This impact can support the novelty of this paper. The amount of THD value influences changes in the value of the K-factor, and it should decrease the value of THD can also reduce the value of the K-factor of the transformer. Several scenarios are created in the method section to find out how much influence the presence of a combination of passive harmonic filters and detuned reactors has and changes in the THD value on the K factor value.

II. Material and Method

A. Harmonic

The currents and voltages on the Alternating Current (AC) grid are described as sinusoidal waves at the fundamental frequency of 50 Hz in Indonesia. Power electronic devices whose working principle is like switching can cause harmonic currents of different frequencies. These currents have a frequency of multiples of the order. Usually, harmonics use odd number orders. Even number order harmonics are entered into the Fourier series and then cancel each other out, or the spectrum value is 0. The harmonic spectrum can be calculated using the Fourier series equation [26].

$$Y\ (t) = Y_0 + \sum_{n=1}^{n=\sim} Y_n \sqrt{2}\ Sin\ (n\, 2\pi f t -\ \varphi_n) \qquad (1)$$

Where Y (t) is the amplitude of DC component, usually in distribution network zero. Y_n is the rms value of the n component harmonic. f is the fundamental frequency. φ_n is the phase angle of the n component. Whereas n is harmonic order. An example collection of several sinusoidal waves with different frequencies becoming a harmonic wave is shown in Fig. 1.

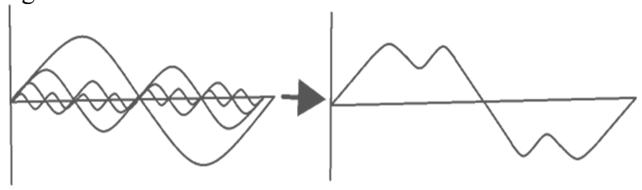

Fig. 1 Wave of Harmonic.

In the voltage parameters, there are IHD-V and THD-V. These two parameters are used to determine the amounts of harmonics in the electric power system in units of a percent (%). IHD-V is the ratio of the rms voltage value in the nth harmonic to the fundamental or first-order rms voltage value. THD-V is the ratio of the total rms voltage value on all harmonic components to the fundamental rms voltage value. The IHD-V and THD-V equations can be written as follows.

$$IHD\_V_n = \sqrt{\left(\frac{V_n}{V_1}\right)^2} \times 100\% \qquad (2)$$

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100\% \qquad (3)$$

Where V_n is the value of the n^{th} order rms voltage. V_1 is the fundamental or first-order rms voltage value. n is the harmonic order. While the explanation for the IHD-I and THD-I parameters is the same as for the previous voltage parameters. IHD-I and THD-I refer to harmonic currents. The IHD-I and THD-I equations are written as follows.

$$IHD\_I_n = \sqrt{\left(\frac{I_n}{I_1}\right)^2} \times 100\% \qquad (4)$$

$$THD\_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100\% \qquad (5)$$

Harmonic distortion levels that exceed the standard tolerance limits can cause an abnormal heat increase in the equipment, and in the worst conditions, it can cause hanging up and permanent damage to some electrical equipment. Tables I and II show the limits for harmonic distortion according to the IEEE 519-1992 standard [11].

TABLE I
STANDARD OF IEEE 519-1992 FOR VOLTAGE HARMONIC DISTORTION

Voltage Harmonic Distortion in % Fundamental Value			
Voltage System	**< 69 kV**	**69<V≤ 161kV**	**>161 kV**
THD (%)	5.0	2.5	1.5
Individual (%)	3.0	1.5	1.0

TABLE II
LIMIT OF CURRENT HARMONIC DISTORTION FOR DISTRIBUTION SYSTEM 120 V – 69 KV

Current Maximum Harmonic Distortion in % I_L						
	Individual Harmonic Order					
I_L	**<11**	**11≤n≤17**	**17≤n≤23**	**23≤n ≤25**	**n≥35**	**THD (%)**
<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

B. Shunt Passive Filter Harmonic and Detuned Reactor

The ability of a harmonic filter to minimize harmonic distortion depends on its components. The passive filter consists of a resistor, inductor, and capacitor components. The passive filter used is a type of shunt passive filter harmonic. This filter is connected in series with the detuned reactor. In comparison, the load is connected in parallel with the overall harmonic filter. There is a transformer that lowers the voltage from the voltage source to the load. Installed loads are nonlinear loads. The circuit image of the components can be seen in Fig. 2.

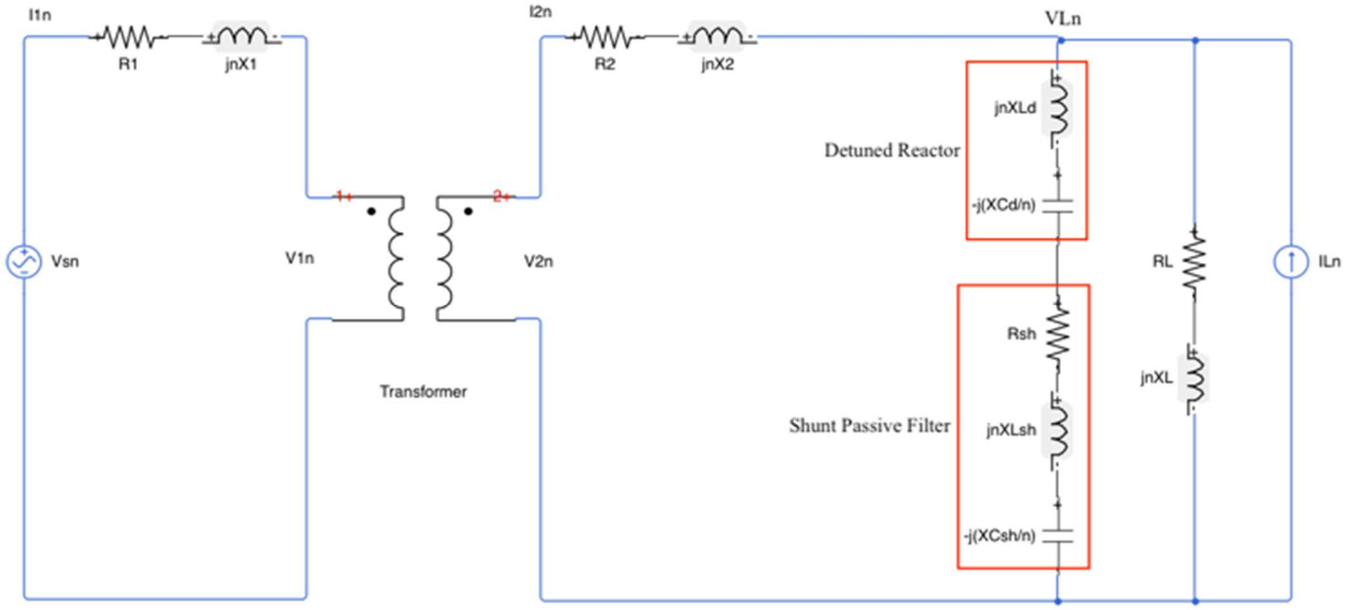

Fig. 2 System under study configuration.

The passive shunt filter consists of a shunt resistor (R_{sh}), a shunt inductor (X_{Lsh}), and a shunt capacitor (X_{Csh}). While the symbol n represents the harmonic order. Overall, the shunt passive filter impedance (Z_{shn}) can be calculated using the equation below.

$$Z_{shn} = R_{sh} + j\left(nX_{Lsh} - \frac{X_{Csh}}{n}\right) \quad (6)$$

The detuned reactor is placed in series with the passive shunt filter. The detuned reactor is connected in parallel to the load and voltage source. X_{Ld} as an inductor and X_{Cd} as a capacitor contained in the detuned reactor. The detuned reactor (Z_{dn}) impedance can be calculated using the equation below.

$$X_{dn} = j\left(nX_{Ld} - \frac{X_{Cd}}{n}\right) \quad (7)$$

V_{sn} as a voltage source, supplies primary current (I_{1n}) to the transformer primary winding. The primary winding side of the transformer consists of a primary resistor (R_1) and a primary reactor (X_1). The primary voltage of the transformer is written as V1n. The secondary voltage of the transformer is written as V2n, and a secondary current (I2n) comes from the secondary winding. The secondary winding side consists of a secondary resistor (R_2) and a secondary reactor (X_2). The two components' transformer impedance (ZTn) can be calculated using the following equation.

$$Z_{Tn} = R_2 + jnX_2 \quad (8)$$

The nonlinear load is written as consisting of a load resistor component (R_L) and a load reactor (X_L). This nonlinear load impedance (Z_{Ln}) is calculated using the following equation.

$$Z_{Ln} = R_L + jnX_L \quad (9)$$

The transformer secondary current (I_{2n}) flows into the detuned reactor and the passive shunt filter. The current also supplies nonlinear loads, and Nonlinear loads provide harmonic current (I_{Ln}), contributing to the transformer. I_{2n} can be written into the following equation.

$$I_{2n} = \frac{[A_1]+j[A_2]}{[B_1]+j[B_2]} \quad (10)$$

The voltage on nonlinear loads is written into the following equation.

$$V_{Ln} = \frac{[C_1]+j[C_2]}{[B_1]+j[B_2]} \quad (11)$$

Where the components of the variables A_1, A_2, B_1, B_2, C_1, and C_2 are written more clearly in the equations below.

$$A_1 = V_{2n}(R_{sh} + R_L) + I_{Ln}.D_3 \quad (12)$$

$$A_2 = V_{2n}(D_1 + nX_L) + I_{Ln}.D_2 \quad (13)$$

$$B_1 = \left(D_5 + R_{sh}(R_2 + R_L)\right) - (D_1.X_{TL}) - (D_1 + nX_L) \quad (14)$$

$$B_2 = (D_4 + R_{sh}.X_{TL}) + \left(D_1.(R_2 + R_L)\right) + (R_L + R_{sh}) \quad (15)$$

$$C_1 = V_{2n}.D_3 - I_{Ln}(D_5.R_{sh} - D_4.D_1 - D_2 \quad (16)$$

$$C_2 = V_{2n}.D_2 - I_{Ln}(D_5.D_1) + D_4.R_{sh} + D_3 \quad (17)$$

The components of the variables D_1, D_2, D_3, D_4, and D_5 are written more clearly in the equations below.

$$D_1 = nX_{Lsh} + nX_{Ld} - \frac{X_{Csh}}{n} - \frac{X_{Cd}}{n} \quad (18)$$

$$D_2 = R_{sh}.nX_L + D_1.R_L \quad (19)$$

$$D_3 = R_{sh}.R_L - D_1.nX_L \quad (20)$$

$$D_4 = R_2.nX_L + R_L.nX_2 \quad (21)$$

$$D_5 = R_2.R_L - n^2.X_2.X_L \quad (22)$$

$$X_{TL} = n(X_2 + X_L) \quad (23)$$

C. *K-Factor*

The transformer has a K-factor value. This K-factor shows the amount of heat generated by the transformer when serving the load. In conditions without harmonics, the k-factor value of the transformer is 1. When overheating occurs due to harmonics, the K-factor value is higher than 1. The K-factor can be calculated using the following equation.

$$K = \frac{\sum I_n^2.n^2}{\sum I_n^2} \quad (24)$$

Based on the K-factor value obtained from the equation, the transformer's capacity to serve loads under various levels of nonlinear load current can also be seen.

$$\%Capacity = \sqrt{\frac{1+P_{ECR}}{1+(K.P_{ECR})}}.Rate\,Transformer \quad (25)$$

Where P_{ECR} is the eddy current loss factor. P_{ECR} values can be referred to in tables III and IV [27]. Table III shows the P_{ECR} values for dry transformers, and Table IV for oil-filled transformers.

TABLE III
P_{ECR} VALUE OF DRY TRANSFORMERS

Dry Transformers	P_{ECR} (%)
≤1000 kVA	3-8
≥1500 kVA, 5 KV, HV	12-20
≤1500 kVA, 15 kV, HV	9-15

TABLE IV
P_{ECR} VALUE OF OIL FILLED TRANSFORMERS

Oil Filled Transformers	P_{ECR} (%)
≤2500 kVA, 480V, LV	1
>1500 kVA ≤ 5000 kVA, 480 V, LV	1-5
> 5000 kVA, 480 V, LV	9-15

III. Result and Discussion

In this section, several scenarios are created to determine the changes in the transformer's IHD, THD, K-factor, and the performance of the combination of passive shunt filter harmonic and detuned reactor. Each scenario gave different results, and each scenario had IHD-V, IHD-I, THD-V, THD-I results, and K factor values. In addition, there is also a change in the sinusoidal wave figure for voltage and current in each scenario. The transformer specifications used in Figure 2 have a primary voltage of 75 kV, a secondary voltage of 15 kV, and a transformer capacity of 1.5 MVA.

A. Scenario 1

In this scenario 1, the system is under the harmonic condition without a harmonic filter and detuned reactor. Fig. 3 shows the IHD-V at the PCC or V_{Ln} point. The 7^{th} harmonic order is the dominant order in this IHD-V. Table I becomes a reference for the harmonic tolerance limits in this paper so that the 5^{th}, 7^{th}, 11^{th}, and 13^{th} orders are outside the limits of harmonic tolerance in individual harmonic systems. The 17^{th} and 19^{th} harmonic orders are below 3% or below the individual harmonic tolerance limits. The THD-V value in this condition is 22.21%. The fundamental voltage at V_{Ln} is 15 kV.

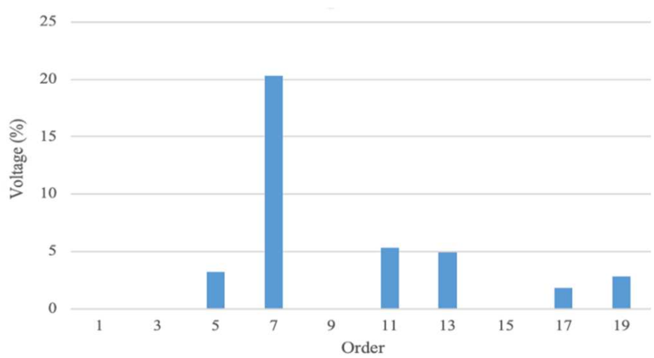

Fig. 3 Spectrum IHD-V in Scenario 1.

Fig. 4 shows a sinusoidal waveform voltage at harmonic conditions measured at point V_{Ln}. It looks like the waveform is broken, unlike a pure sinusoidal wave.

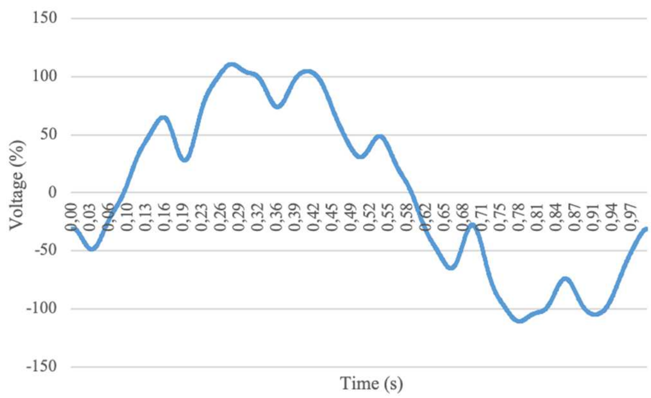

Fig. 4 Voltage Harmonic Wave in Scenario 1.

Measurement of harmonic currents on the load side is written in IHD-I, as shown in Fig. 5. The 7^{th} harmonic order becomes the dominant order in this IHD-I. Based on the reference table II with the fundamental load current of 1391.47 A, only the 7th order is outside the maximum limit of harmonic currents. The THD-I value in this condition is 24.54%, which means that the value is also outside the THD-I tolerance limit in Table II. Fig. 6 shows the load current sinusoidal waveform which is influenced by the harmonics.

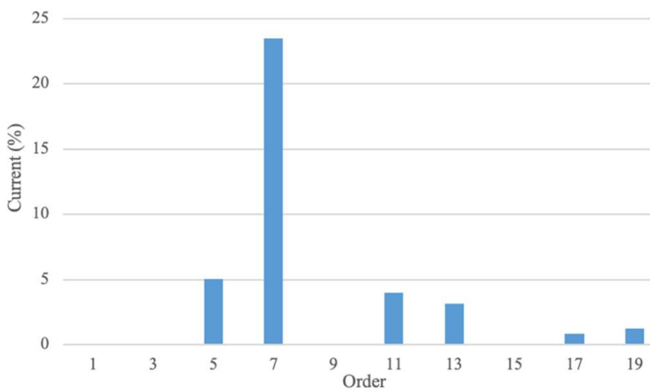

Fig. 5 Spectrum IHD-I in Scenario 1.

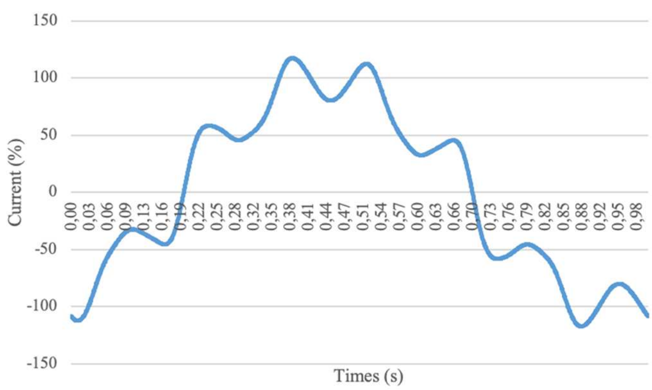

Fig. 6 Current Harmonic Wave in Scenario 1.

The transformer is also affected by harmonic currents from nonlinear loads. The measured IHD-I on the transformer is shown in Fig. 7. The dominant order of harmonics is also in the 7^{th} order. Based on the reference in Table II with the fundamental current of the transformer 185.53 A, only the 7th order has exceeded the maximum limit of harmonic currents.

The THD-I value on the transformer is 24.54%. The THD-I value is also outside the limit of harmonic tolerance.

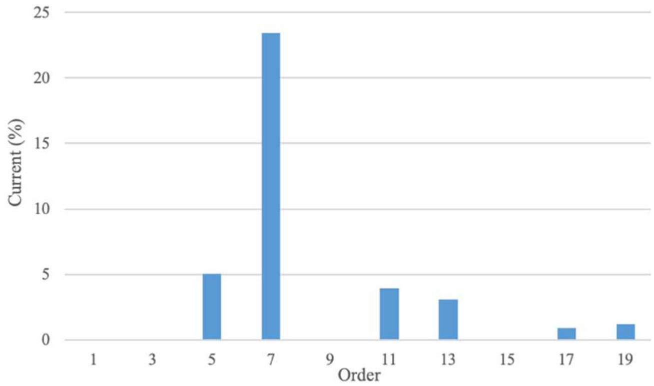

Fig. 7 Spectrum IHD-I Transformer in Scenario 1.

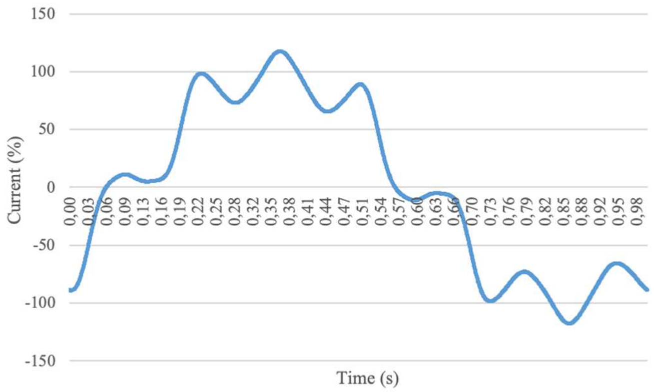

Fig. 8 Current Harmonic Wave Transformator in Scenario 1.

Fig. 8 shows the load current sinusoidal waveform which is influenced by the harmonics. Harmonic distortion affects the K-factor value of the transformer. Table V shows the breakdown of the transformer current in odd-order harmonics based on the data in Figure 7. To find the K-factor value, you can use equation 24, so that the K-factor value of the transformer in scenario 1 is 3.947101. Furthermore, this value can determine the performance of the transformer capacity, which can be used in harmonic conditions. This means that there is a change in the capacity of the transformer rating from normal conditions.

TABLE V
CURRENT OF TRANSFORMERS IN SCENARIO 1

n	I	I (p.u)	I^2	$I^2.n^2$
1	185.53	1	1	1
3	0	0	0	0
5	9.3450162	0.050369	0.002537	0.063427
7	43.486191	0.234389	0.054938	2.691972
9	0	0	0	0
11	7.3509769	0.039622	0.00157	0.189953
13	5.7762168	0.031134	0.000969	0.163812
15	0	0	0	0
17	1.6283133	0.008777	$7.7x10^{-5}$	0.022261
19	2.2574734	0.012168	0.000148	0.053447
		Total	**1.06024**	**4.184872**

The calculation of the new capacity of the transformer can use equation 25. The transformer specifications used in this paper are 1.5 MVA, and the voltage is 15 kV. This transformer is included in the dry transformers group, so the maximum value of the PECR is 15% based on table III. Based on equation 25, the % capacity for the transformer is 0.849901, and the transformer new capacity in this scenario 1 harmonic condition is 1.27 MVA.

B. Scenario 2

In scenario 2, a shunt passive filter harmonic is used to reduce IHD, and THD. Only the harmonic filter, without a detuned reactor. Installation of parallel harmonic filters against nonlinear loads. The values for the harmonic filter components are the resistor 5.3 Ω, capacitor 263.85 µF, and inductor 3.29 mH. IHD-V measurements at the PCC or V_{Ln} point are shown in Fig. 9.

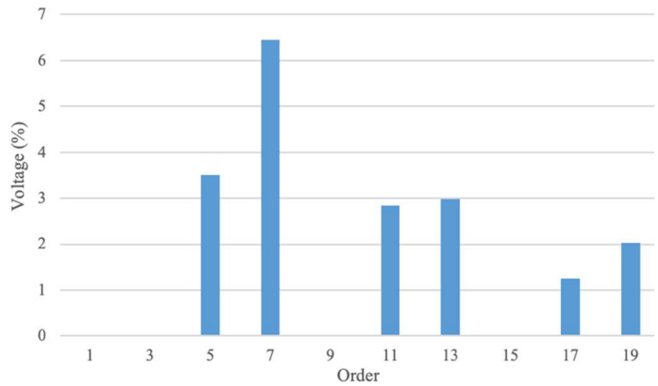

Fig. 9 Spectrum IHD-V in Scenario 2.

All IHD-V values are lower than in scenario 1. The 3rd and 7th order harmonics are still outside the maximum value of the harmonic limit, while the other orders are below the maximum limit. After a decrease in all IHD-V values, it is followed by a decrease in THD-V values also to 8.8% at a fundamental voltage of 15 kV. Furthermore, this sinusoidal voltage waveform is also better than scenario 1, as shown in Fig. 10.

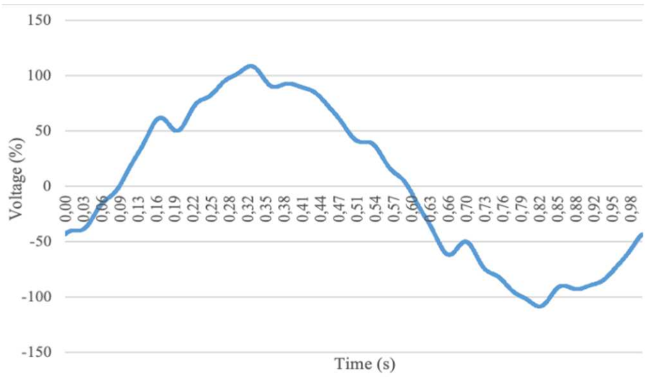

Fig. 10 Voltage Harmonic Wave in Scenario 2.

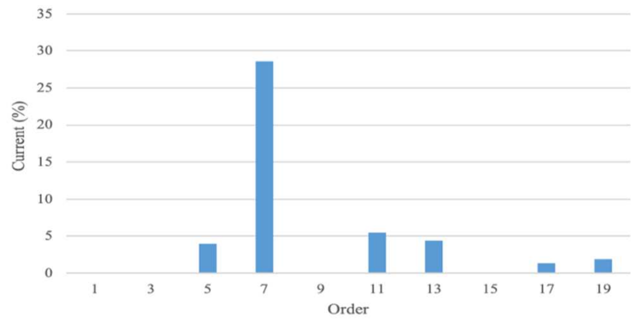

Fig. 11 Spectrum IHD-I in Scenario 2.

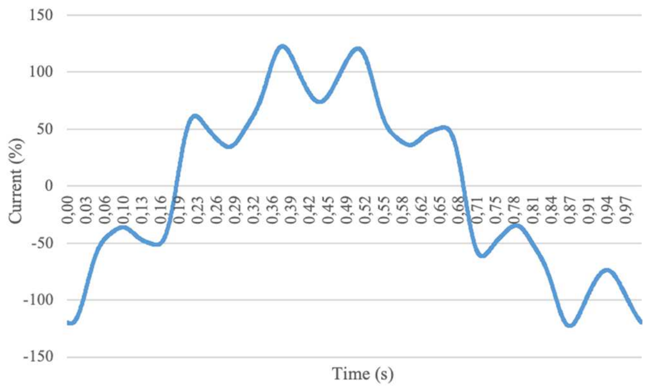

Fig. 12 Current Harmonic Wave in Scenario 2.

The measurement of harmonic currents in the IHD-I on the load side is shown in Fig. 11. The installation of a shunt passive filter harmonic makes the IHD-I values higher than in the previous scenario. A significant increase in IHD-I occurred in the 7th order to reach 28.62%. This change in IHD-I values increased the THD-I value to 29.83%. This is a drawback of this paper's shunt passive harmonic filter. The change in the current sinusoidal waveform is shown in Fig. 12.

IHD-I measurements were also carried out on a shunt passive filter harmonic. There is a harmonic current coming into the harmonic filter. The IHD-I measurement results are shown in Fig. 13. The dominant IHD-I value reached 155.83% in the 7th harmonic order. In comparison, the THD-I value on this harmonic filter reaches 161.4%. All these harmonic distortion values are very high and can damage the harmonic filter components. The fundamental current that enters the filter is 231.18 A. Fig. 14 shows the harmonic waveform of the current entering the harmonic filter.

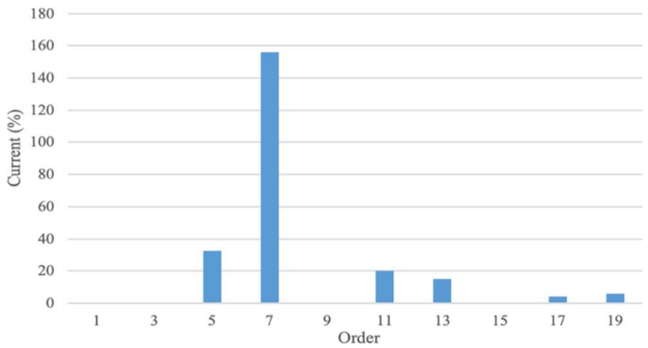

Fig. 13 Spectrum IHD-I of Shunt Passive Filter Harmonic in Scenario 2.

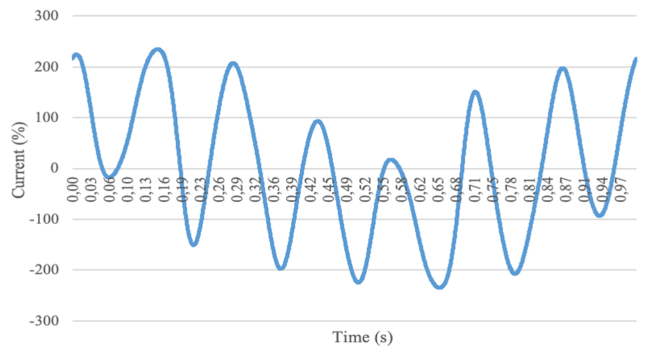

Fig. 14 Current Harmonic Wave of Shunt Passive Filter Harmonic in Scenario 2.

The IHD-I conditions on the transformer are shown in Fig. 15. IHD-I values in the 7th, 11th, 13th, 17th, and 19th orders have decreased for all harmonic orders. In contrast to the 5th harmonic order, which has increased. The change in IHD-I values causes the THD-I value of the transformer to drop to 10.61%, this value is lower than in scenario 1. Referring to the IEEE 519-1991 standard, all IHD-I and THD-I values of the transformer in this scenario is below the maximum limit of harmonic currents. Fig. 16 shows the current waveform in the transformer. The current wave is better than scenario 1.

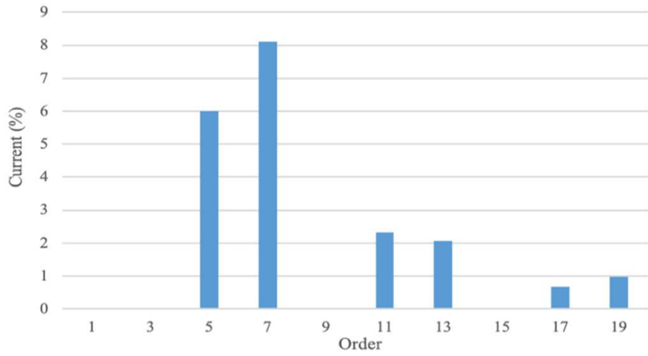

Fig. 15 Spectrum IHD-I Transformer in Scenario 2.

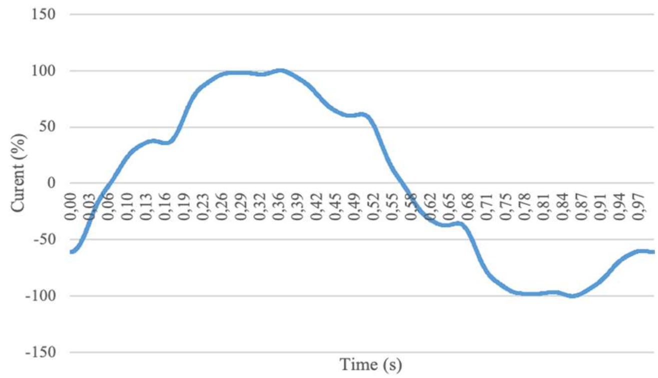

Fig. 16 Current Harmonic Wave Transformator in Scenario 2.

A decrease in the IHD-I value of the transformer can cause a decrease in the K-factor of the transformer. Table VI displays the details of the harmonic currents of each odd order which are used to find the K-factor value. From the results of the calculations in the table, the K-factor value of the transformer in this condition is 1.5775. This value is lower than the value in the previous scenario. This means that the lower the K-factor value, the better the transformer's ability to serve the load. At the same load for the transformer in scenarios 1 and 2, the heat generated by the scenario 2 transformer is lower than in scenario 1.

TABLE VI
CURRENT OF TRANSFORMERS IN SCENARIO 2

n	I	I (p.u)	I^2	$I^2.n^2$
1	170.42	1	1	1
3	0	0	0	0
5	10.21002	0.059911	0.003589	0.089733
7	13.81029	0.081037	0.006567	0.321781
9	0	0	0	0
11	3.953966	0.023201	0.000538	0.065134
13	3.522667	0.020671	0.000427	0.072209
15	0	0	0	0
17	1.137191	0.006673	$4.45x10^{-5}$	0.012868
19	1.644459	0.009649	$9.31x10^{-5}$	0.033613
		Total	**1.011259**	**1.595339**

In addition to heat in the transformer, the decrease in the value of this K-factor can also increase the new capacity of the transformer in harmonic conditions. The calculation method is the same as scenario 1, so the value for %capacity for this transformer is 0.9643. Meanwhile, the new capacity of the transformer, which is affected by harmonics in scenario 2 is 1.44 MVA. The %capacity value and the new capacity of the transformer are better than scenario 1.

C. Scenario 3

In scenario 3, a passive shunt filter harmonic and detuned reactor was used to reduce the values of IHD and THD. In scenario 2, IHD-I and THD-I values still exceed the maximum harmonic current. The existence of a detuned reactor can solve these problems. The parameter size for the passive filter in this scenario is the same as in the previous scenario. While the values of the detuned reactor components are capacitor 796.17 µF and inductor 3.18 mH. Measurement of IHD-V at the PCC point is shown in Fig. 17. All IHD-V values fall below the harmonic tolerance value for the individual harmonic scale. Furthermore, a decrease was also followed for the THD-V value to 2.56%. The IHD-V and THD-V values in this scenario were the best compared to those in all other scenarios. Fig. 18 shows the change in the voltage wave at PCC after experiencing a decrease in the THD-V value. The voltage wave returns to a sinusoidal form as under normal conditions.

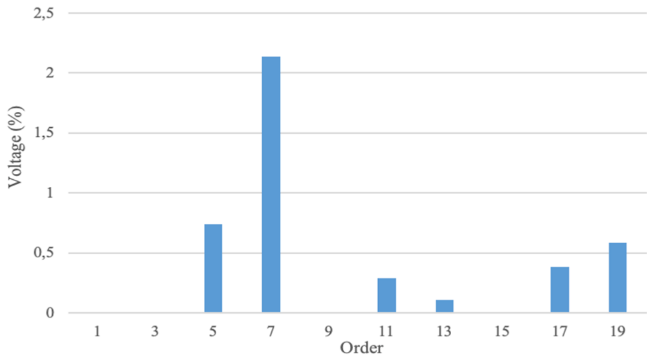

Fig. 17 Spectrum IHD-V in Scenario 3.

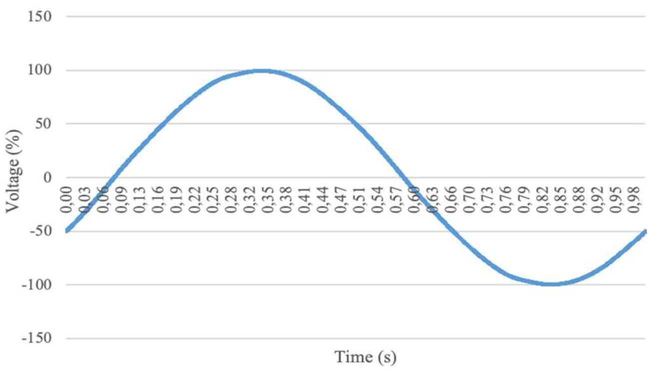

Fig. 18 Voltage Harmonic Wave in Scenario 3.

The mitigation technique in scenario 3 effectively reduces all IHD-I values on the load side. IHD-I values are displayed in a graph, as shown in Figure 19. Based on this graph, all IHD-I values are below the maximum limit of harmonic currents. A decrease followed this in the value of THD-I, which reached 3.28%. After comparing with all previous scenarios, the mitigation technique in scenario 3 was able to reduce the IHD-I and THD-I values until they reached the lowest values. Figure 20 shows the current waveform after experiencing a decrease in harmonic distortion.

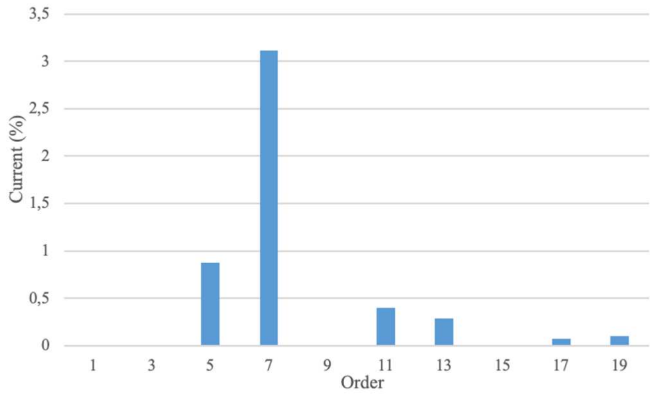

Fig. 19 Spectrum IHD-I in Scenario 3.

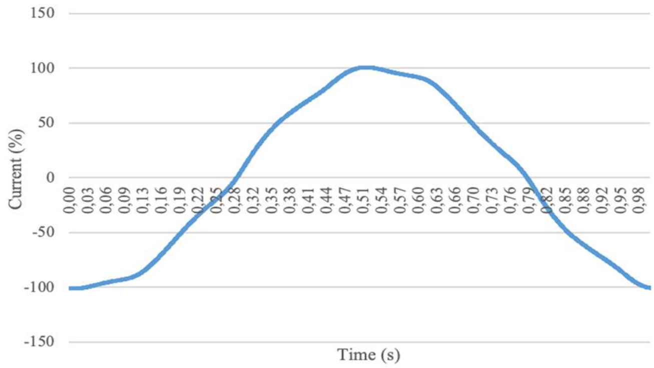

Fig. 20 Current Harmonic Wave in Scenario 3.

The detuned reactor can limit the harmonic current that enters the shunt passive filter harmonic. The harmonic currents in the IHD-I are displayed in graphical form, as shown in Fig. 21. Based on the graph, all IHD-I values are below the maximum limit for harmonic currents. A decrease also followed this decrease in IHD-I in the THD-I value of up to 3.95%. The change in the waveform of the harmonic current entering the filter is shown in Fig. 22.

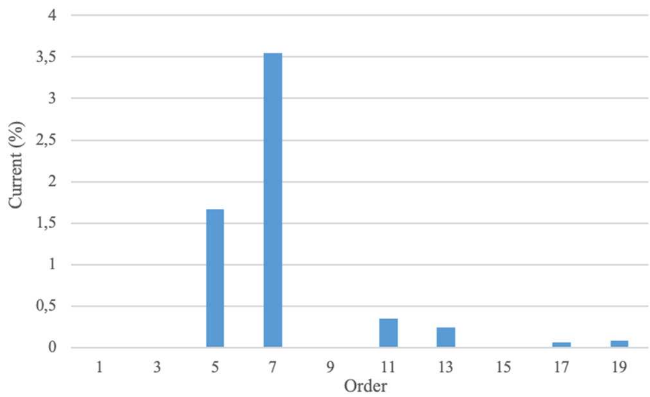

Fig. 21 Spectrum IHD-I of Shunt Passive Filter Harmonic in Scenario 3.

The harmonic current entering the transformer also changes in this scenario 3. The decrease in IHD-I values for the transformer is presented in a graph as shown in Fig. 23. All IHD-I values are below the maximum limit of harmonic currents. Likewise, the THD-I value decreased to 2.66%. The

IHD-I and THD-I values on this transformer are the best values compared to all other scenarios. The form of sinusoidal harmonic currents after experiencing a decrease in harmonic distortion can be seen in Fig. 24.

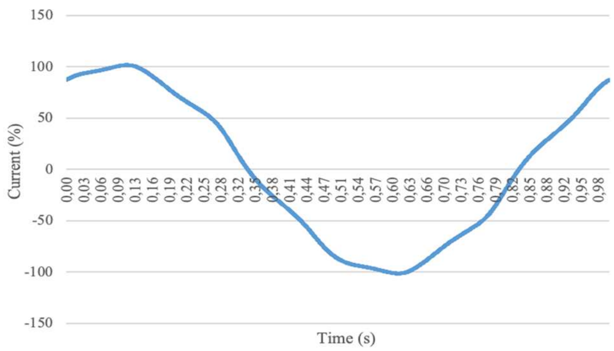

Fig. 22 Current Harmonic Wave of Shunt Passive Filter Harmonic in Scenario 3.

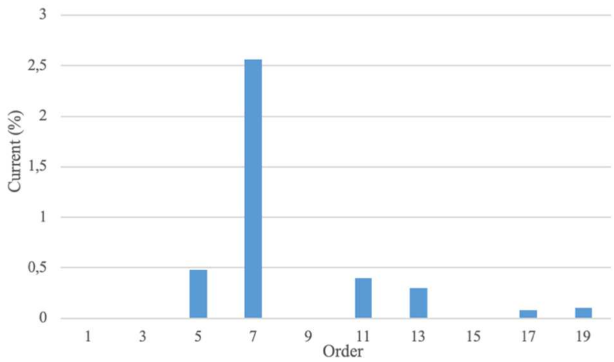

Fig. 23 Spectrum IHD-I Transformer in Scenario 3.

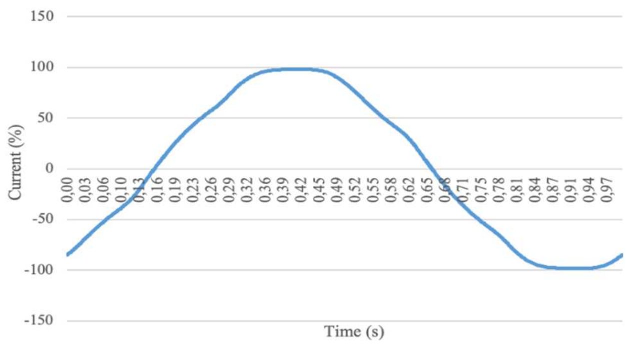

Fig. 24 Current Harmonic Wave Transformator in Scenario 3.

A passive shunt filter and a detuned reactor mitigate the next changes in the transformer's K-factor value after harmonic distortion. A decrease in the IHD-I value should make the K-factor value also decrease. Table VII shows the harmonic current calculation to get the K-factor value.

TABLE VII
CURRENT OF TRANSFORMERS IN SCENARIO 3

n	I	I (p.u)	I^2	$I^2.n^2$
1	163.74	1	1	1
3	0	0	0	0
5	0.78652673	0.004804	$2.31x10^{-5}$	0.000577
7	4.20212512	0.025663	0.000659	0.032272
9	0	0	0	0
11	0.65611109	0.004007	$1.61x10^{-5}$	0.001943
13	0.48937301	0.002989	8.9310^{-6}	0.00151
15	0	0	0	0
17	0.128	0.000782	$6.12x10^{-7}$	0.000177
19	0.17311739	0.001057	$1.12x10^{-6}$	0.000404
		Total	**1.000708**	**1.036882**

Furthermore, the K-factor value of the transformer in scenario 3 is 1.0361. This K-factor value is the best compared to all other scenarios because it is close to number 1 or it is close to the transformer without harmonics. This means that in terms of performance, scenario 3's condition can make the transformer able to serve the highest load with the lowest heat increase compared to transformers in other scenarios.

The decrease in the K-factor value further affects the transformer's new capacity to serve the load. The calculation of the value of %capacity and the new capacity of the transformer uses the same method as in the previous scenario. The value of %capacity transformer in scenario 3 can be 0.9976, so the value of this transformer's new capacity is 1.49 MVA. The %capacity value and the new capacity of the transformer are the best values compared to all other scenarios.

IV. CONCLUSION

This paper uses high artificial harmonics for a case study to determine the performance of a combination of shunt passive filter harmonics and a detuned reactor. High harmonic distortion is shown in scenario 1. All THD and some IHD values for the current and voltage parameters are above the tolerance limits for harmonic distortion according to the IEEE 519-1991 standard. The effect of the harmonic distortion causes the K-factor value of the transformer to be 3.947101 and the new capacity of the transformer that can serve the load to be 1.27 MVA.

In scenario 2 which only uses a shunt passive harmonic filter to reduce harmonic distortion. The harmonic filter can reduce some IHD and THD values, even though these values are still above the maximum harmonic distortion limit. A unique problem occurs in the measurement of IHD-I and THD-I on the load side. There is an increase in IHD-I and THD-I values in scenario 2 after being installed with a harmonic filter. On the other hand, it turns out that the harmonic filter also gets a high contribution of harmonic distortion. The decrease in some IHD and THD values caused the K-factor of the transformer to drop to 1.5775 and the new capacity of the transformer to increase to 1.44 MVA.

In scenario 3, the addition of a detuned reactor can improve the performance of the harmonic filter. All IHD and THD values fell below the maximum limit of harmonic distortion. The detuned reactor can limit the contribution of harmonic currents that enter the harmonic filter so that the harmonic currents in the harmonic filter are smaller than before. Likewise, the IHD-I and THD-I values on the load side are reduced. The decrease in IHD and THD values in scenario 3 causes the transformer's K-factor value to decrease until it reaches 1.0361, and the new capacity of the transformer increases to 1.49 MVA. The K-factor value of the transformer is getting closer to 1. Then the transformer gets closer to performance under normal conditions. Scenario 3 has the best result compared to all other scenarios.

The impact of this paper for further research is to provide an overview of the ability of a detuned reactor. Detuned reactors can be further researched to protect other electrical equipment, and it not only protects the harmonic filter from harmonic currents and other equipment from other disturbances. Therefore, further research is recommended to use detuned reactors to protect other electrical equipment in short circuits, overcurrent, and overvoltage conditions. That electrical equipment will have a longer life.

Acknowledgment

The authors thank the University of Malang for funding this research through the PNBP program. We are grateful to the electrical engineering department for supporting this study.

References

[1] M. Bajaj and A. K. Singh, "Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques," *International Journal of Energy Research*, vol. 44, no. 1. 2020, doi: 10.1002/er.4847.

[2] F. Nejabatkhah, Y. W. Li, and H. Tian, "Power quality control of smart hybrid AC/DC microgrids: An overview," *IEEE Access*, vol. 7. 2019, doi: 10.1109/ACCESS.2019.2912376.

[3] J. Barros, M. de Apráiz, and R. I. Diego, "Power quality in DC distribution networks †," *Energies*, vol. 12, no. 5, 2019, doi: 10.3390/en12050848.

[4] O. Lennerhag and M. Bollen, Power Quality, *Springer Handbooks*, 2021.

[5] T. J. C. Sousa, V. Monteiro, J. G. Pinto, and J. L. Afonso, "Performance comparison of a typical nonlinear load supplied by ac and dc voltages," *EAI Endorsed Trans. Pervasive Heal. Technol.*, vol. 7, no. 25, 2020, doi: 10.4108/eai.13-7--2018.161748.

[6] U. Borup, F. Blaabjerg, and P. N. Enjeti, "Sharing of nonlinear load in parallel-connected three-phase converters," *IEEE Trans. Ind. Appl.*, vol. 37, no. 6, 2001, doi: 10.1109/28.968196.

[7] L. Li, J. Li, Y. Wang, and W. Gong, "Analysis of nonlinear load-displacement behaviour of pile groups in clay considering installation effects," *Soils Found.*, vol. 60, no. 4, 2020, doi: 10.1016/j.sandf.2020.04.008.

[8] R. Senra, W. C. Boaventura, and E. M. A. M. Mendes, "Assessment of the harmonic currents generated by single-phase nonlinear loads," *Electr. Power Syst. Res.*, vol. 147, 2017, doi: 10.1016/j.epsr.2017.02.028.

[9] F. C. Alegria, "Precision of the sinefitting-based total harmonic distortion estimator," *Metrol. Meas. Syst.*, vol. 23, no. 1, 2016, doi: 10.1515/mms-2016-0003.

[10] I. Alhamrouni, W. Wahab, M. Salem, N. H. A. Rahman, and L. Awalin, "Modeling of micro-grid with the consideration of total harmonic distortion analysis," *Indones. J. Electr. Eng. Comput. Sci.*, vol. 15, no. 2, 2019, doi: 10.11591/ijeecs.v15.i2.pp581-592.

[11] T. M. Blooming and D. J. Carnovale, "Application of IEEE STD 519-1992 harmonic limits," 2006, doi: 10.1109/papcon.2006.1673767.

[12] V. Sousa, H. H. Herrera, E. C. Quispe, P. R. Viego, and J. R. Gómez, "Harmonic distortion evaluation generated by PWM motor drives in electrical industrial systems," *Int. J. Electr. Comput. Eng.*, vol. 7, no. 6, 2017, doi: 10.11591/ijece.v7i6.pp3207-3216.

[13] A. Gómez, J. Miguel, A. Córdova, R. Alfonso, and I. Salinas, "K factor estimation in distribution transformers using linear regression models," *Tecnura*, vol. 20, no. 48, 2016.

[14] M. A. Taher, S. Kamel, and Z. M. Ali, "K-Factor and transformer losses calculations under harmonics," 2017, doi: 10.1109/MEPCON.2016.7836978.

[15] L. Motta and N. Faúndes, "Active / passive harmonic filters: Applications, challenges & trends," in *Proceedings of International Conference on Harmonics and Quality of Power, ICHQP*, 2016, vol. 2016-December, doi: 10.1109/ICHQP.2016.7783319.

[16] S. Musa and M. A. M. Radzi, "Synchronous reference frame fundamental method in shunt active power filter for mitigation of current harmonics," *Pertanika J. Sci. Technol.*, vol. 25, no. S, 2017.

[17] Y. Hoon, M. A. M. Radzi, M. A. A. M. Zainuri, and M. A. M. Zawawi, "Shunt active power filter: A review on phase synchronization control techniques," *Electronics (Switzerland)*, vol. 8, no. 7. 2019, doi: 10.3390/electronics8070791.

[18] X. Shen, H. C. Shu, and M. Cao, "Research on harmonic suppression ability of active power filter," in *IOP Conference Series: Materials Science and Engineering*, 2019, vol. 658, no. 1, doi: 10.1088/1757-899X/658/1/012013.

[19] Y. Y. Hong and W. J. Liao, "Optimal passive filter planning considering probabilistic parameters using cumulant and adaptive dynamic clone selection algorithm," *Int. J. Electr. Power Energy Syst.*, vol. 45, no. 1, 2013, doi: 10.1016/j.ijepes.2012.08.061.

[20] J. Fang, X. Li, and Y. Tang, "A review of passive power filters for voltage-source converters," 2017, doi: 10.1109/ACEPT.2016.7811547.

[21] S. Z. M. Noor, N. Rosmizi, N. Aminudin, and A. H. Faranadia, "Investigation of passive filter performance on three phase DC to AC converter," *Int. J. Power Electron. Drive Syst.*, vol. 9, no. 3, 2018, doi: 10.11591/ijpeds.v9n3.pp1016-1028.

[22] L. Gumilar, A. Kusumawardana, M. A. Habibi, S. Norma Mustika, and W. S. Nugroho, "Current and Voltage Harmonic Distortion Minimization in Nonlinear Loads," 2020, doi: 10.1109/ICOVET50258.2020.9230217.

[23] P. Agraekar and P. M. Joshi, "Industrial Practices for Power Factor Improvement and Harmonic Control," 2020, doi: 10.1109/INOCON50539.2020.9298216.

[24] I. Hadzhiev, D. Malamov, I. Balabozov, and I. Yatchev, "Study of operational parameters of a capacitor bank with detuned reactor for power factor correction in a low voltage network," 2020, doi: 10.1109/SIELA49118.2020.9167141.

[25] R. N. Shulga, Y. A. Ivanova, N. G. Lozinova, and M. I. Mazurov, "Choice of line reactors for HVDC lines and back-to-back links," *Russ. Electr. Eng.*, vol. 82, no. 9, 2011, doi: 10.3103/S1068371211090112.

[26] N. T. Quach, S. H. Chae, M. H. Kang, D. W. Kim, S. H. Ko, and E. H. Kim, "Application of double fourier series for analyzing harmonics of a modular multilevel converter," *Renew. Energy Power Qual. J.*, vol. 1, no. 15, 2017, doi: 10.24084/repqj15.289.

[27] M. F. M. H. W. B. R. C. Dugan, *Electic Power System Quality*. 2004.