Advance Sustainable Science, Engineering and Technology (ASSET)
Vol. 7, No.4, October 2025, pp. 0250403-01 ~ 0250403-011
ISSN: 2715-4211 DOI: https://doi.org/10.26877/asset.v7i4.1981

Comparison of Conventional and Adaptive Hysteresis Current Control Methods for Power Quality Improvement using Active Filters

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Abstract. Hysteresis is widely applied in converter control techniques because of its simplicity and stability. This paper discusses hysteresis current control applied to single-phase active filters. Active filters are designed for harmonic mitigation and reactive power compensation. Simulation and comparison of conventional hysteresis control (constant hysteresis band - variable frequency) and adaptive hysteresis (variable hysteresis band - constant frequency) on active filters were carried out. Simulations were carried out using MATLAB Simulink. The simulation results show that the active filter can work well when using conventional or adaptive hysteresis current control. This is indicated by a decrease in the THD_I of the source current and an increase in the power factor on the source side. From the simulations carried out, with a maximum source current THD_I target of 5% according to the IEEE 519 standard, the hysteresis band required for conventional hysteresis control is 0.5 A, and the switching frequency required for adaptive hysteresis control is 120 kHz. By increasing the power factor to unity, it results in a reduction in reactive losses in the system. These findings are significant in advancing more efficient power quality control strategies, reducing harmonic distortion and improving power factor in electrical systems. Such improvements contribute directly to the development of more sustainable and resilient electrical infrastructures.

Keywords: harmonics, active filter, hysteresis, voltage source inverter (VSI), power quality

(Received 2025-05-16, Revised 2025-07-02, Accepted 2025-07-08, Available Online by 2025-08-22)

1. Introduction

The quality of electrical power is important in the operation of the power system. Various kinds of loads such as computers, energy-saving lights, and inverters are often installed in the electric power system. Many industries also use power electronics-based equipment such as switch mode power supply (SMPS), uninterruptible power supply (UPS), and others [1]. The use of these loads can cause harmonics that will cause distortions in voltage and current [2]. The consequences that can be caused by the harmonic content of current include excessive vibration in the motor, interference with sensitive electronic equipment, and overheating of the transformer [3]. While the low power factor can cause overload on the line.

Several methods can be used to overcome this power quality issue, one of which is filters. Filters can be grouped into two, namely passive filters and active filters. The use of passive filters can be used to increase the power factor and lower harmonics [4]. Passive filters produce low impedance at the selected harmonic frequencies. This passive filter is popular because it is simple, reliable, efficient, and inexpensive [5]. However, passive filters also have disadvantages, namely resonance problems, aging, and large size. The use of active filters can solve the problems that exist with these passive filters. Active filters can be used for harmonic filters, isolation, power factor repair, voltage regulation, flicker voltage minimization, and others [6]. In addition, active filters have good accuracy and speed [7]. The use of an active filter can lower harmonics well but there is a problem of switching loss that reduces efficiency.

The main component of an active filter is a voltage source inverter. In renewable energy applications such as solar energy, this inverter is often used to send power [8, 9]. In addition to power transfer, this inverter can have additional features, namely active filters, so that inverters in renewable energy sources can also be used to reduce harmonics and improve power factors [10].

In conventional hysteresis control, a constant hysteresis band (HB) is used which causes the switching frequency to be variable. This can lead to increased losses to the equipment. To overcome this, the hysteresis bandwidth is adjusted so that the switching frequency remains constant. Some examples of the use of hysteresis control include conventional hysteresis for three-phase active filters [7], adaptive hysteresis for three-phase active filters to improve electrical power quality [6,11], and comparison of several types of hysteresis control on grid-connected inverters [12].

Therefore, several current control techniques are used to overcome these switching losses, including PWM techniques, delta modulation, and hysteresis current control [11,13,14]. Hysteresis current control is widely used in power electronics applications due to its simple implementation. Hysteresis-based current control with constant switching frequency can provide good performance in active filter systems, especially to reduce switching losses and improve efficiency [15]. Meanwhile, [16] in their study of BLDC motors found that hysteresis control techniques provide fast dynamic response and simplicity of implementation, making them suitable for application in power electronics-based systems including active filters [22,23].

This research simulated and compared conventional and adaptive hysteresis control applied to a single-phase active filter to reduce the harmonics distortion of the source current and increase the power factor. This research aims to simulate and analyze a comparison between conventional hysteresis current control (with constant hysteresis bandwidths and variable switching frequencies) and adaptive hysteresis current control (with variable bandwidth and constant switching frequency) applied to single-phase active filters. A Shunt Active Power Filter (SAPF) for a single-phase system is designed and simulated to reduce harmonics that arise due to the use of single-phase non-linear loads that are often used in households. The main objective of this research is to evaluate the effectiveness of each method in reducing source current harmonics (THDI) and increasing the power factor, in order to support the improvement of the power quality that contributes to an efficient and sustainable electrical system.

2. Methods

Figure 1 shows the installation of an active filter which is a voltage source inverter. This figure shows a parallel (shunt) single-phase active filter installation scheme to improve power quality. The main function of this filter is to inject the compensating current into the point of common coupling (PCC).

The inverter in a single-phase active filter consists of a capacitor as a DC voltage source and four power electronics components. In this study, the power electronics component used is IGBT. The load model as harmonic source consists of a single-phase full-wave rectifier and RLC components. In Figure 1, Rs and Ls are the resistance and inductance of the source, Lf is the filter inductance, and Cdc is the capacitor.

The control circuits used to control the active filter consist of DC capacitor voltage control and output current control. DC capacitor voltage control uses PI control while output current control uses hysteresis current control. To make the source current phase with the source voltage (unity power factor), a Phase Lock Loop (PLL) is used to detect the phase voltage (θ).

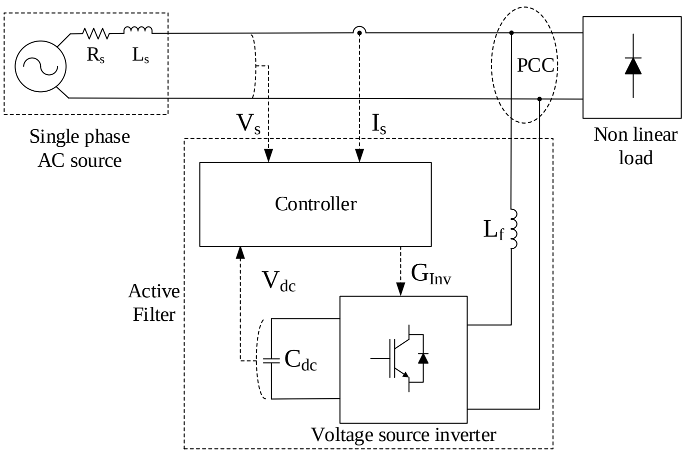

Figure 1. Active Filter for Power Quality Improvement

Figure 2 shows the chart block for the active filter control. There are 4 (four) components, namely DC voltage regulator, PLL, reference current calculation, and hysteresis current controller.

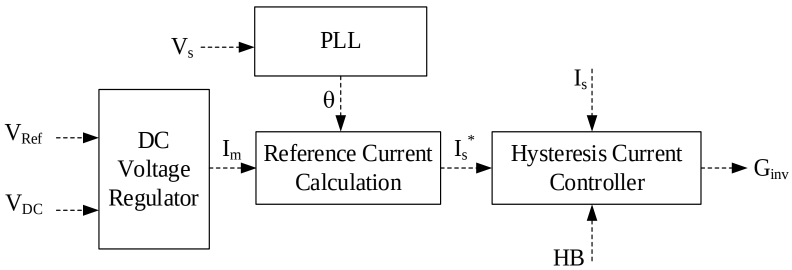

Figure 2. Active Filter Control Scheme

2.1. DC Voltage Regulator

This regulator is used to set the voltage value of a DC capacitor constant according to the predetermined reference voltage value. Proportional Integral (PI) control is used for this DC voltage regulator. The output of this regulator is the peak current current (I_m) flowing at a single-phase source. Figure 3 shows a block diagram of the DC voltage regulator.

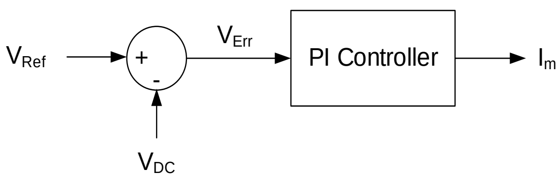

Figure 3. DC Voltage Regulator Block Diagram

The inputs of these regulators are the reference voltage (V_{Ref}) and the capacitor voltage (V_{DC}). The reference voltage value used for the simulation is 400 V. The voltage error on the capacitor is obtained by the equation:

$$V_{Err} = V_{Ref} - V_{DC} \quad (1)$$

This voltage error becomes the input for the PI block and the output is the peak value of the current flowing at the single-phase source (I_m). The current of this block (I_m) and the phase angle (θ) generated by the PLL are used to generate a sinusoidal reference current at a single-phase source.

2.2. Phase locked loop (PLL)

Phase Locked Loop (PLL) is a technique commonly used to obtain phase angle and frequency information [17]. In this paper, the PLL output (phase angle) is used to regulate the source current so that it is phase with the source voltage.

2.3. Reference Current Calculation

The instantaneous value of the source reference current is calculated by

$$I_s^* = I_m cos\ \theta \quad (2)$$

The peak current (I_m) is obtained from the DC voltage regulator and the angle θ is obtained from the PLL. The current is sinusoidal and becomes a reference for the source current. This current I_s^* is phase with the voltage at the PCC.

2.4. Hysteresis Current Control

Hysteresis current control is already recognized as a good method for active filters, motor driving, and semiconductor converters [15,16,18]. Conventional hysteresis current control has a variable switching frequency depending on the load and/or reference current [19]. This method has a good transient response and high accuracy. In addition, the current ripple can be set by specifying the upper and lower limits of the hysteresis band [20, 21].

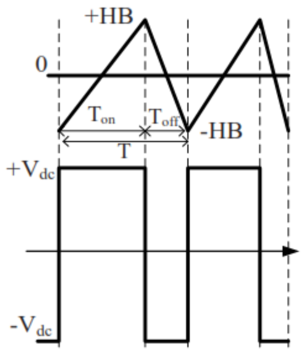

Figure 4. Hysteresis Current Control

Figure 4 shows the principle of hysteresis current control. In this research, hysteresis was used in the control of the current control to control the compensation current. The advantage of this control is its simplicity and fast dynamic response. When injecting filter current through the coupling inductor, the inverter switch will work based on this hysteresis control [24, 25]. The control strategy for single-phase bridge inverter used on active filters is as follows:

S (switch condition) = 0 if $i_s(t) > i_s(t)^* + HB$ → The top switch is off and the bottom switch is on
S = 1 if $i_s(t) < i_s(t)^* - HB$ → The top switch is on and the bottom switch is off.

With this control, the compensation current will be within the hysteresis band.

In this paper, active filter current control is performed using conventional hysteresis (constant hysteresis band – variable frequency) and adaptive hysteresis (variable hysteresis band – constant frequency). For conventional hysteresis, the hysteresis band has a constant value i.e:

$$HB_{Konvesional} = C \tag{3}$$

Meanwhile, for adaptive hysteresis, the input is the switching frequency. The hysteresis band is calculated by the following equation [12]:

$$HB_{Adaptif} = \frac{V_{dc}}{4Lf_{sw}} - \frac{L}{4f_{swV_{dc}}}\left(\frac{V_g}{L} + \frac{di^*}{dt}\right)^2 \tag{4}$$

In conventional hysteresis control, the hysteresis band used is constant which causes the switching frequency to be variable and causes increased losses in the equipment. While in adaptive hysteresis, the switching frequency is set to remain constant. In a sustainable system, losses in this equipment are one of the things that need to be considered.

2.5. Matlab Simulink Simulation Model

This research was conducted with Matlab simulink simulation without hardware implementation. In order for the simulation results obtained to be valid and acceptable, the size of the components used needs to be considered based on the value of the existing components.
Table 1 shows the circuit specifications used for simulation with Matlab Simulink.

Table 1. Circuit Specifications

Parameters	Value
Single-phase source voltage (rms)	V_s = 220 V; f = 50 Hz
Source impedance	R = 0.1 Ω; L = 1 μH
Reference DC voltage	V_{Ref} = 400 V
Filter inductor	L_f = 1 mH
DC Capacitors	C_{dc} = 1 mF
Smoothing capacitor	C = 1 mF
Smoothing inductor	L = 1 mH
Load resistance	R = 10 Ω

Simulink's Matlab model in Figure 5 shows the rectifier connected to a single-phase voltage source. Active filters are connected parallel to nonlinear loads. The parallel active filter is a voltage source inverter using IGBT connected to the PCC via a coupling inductor. A capacitor is installed on the VSI input. The inputs for PI controller are the DC voltage and the reference voltage. After the reference current calculation is performed, hysteresis control is used to generate the firing pulse. This pulse is fed to the VSI input. In the hysteresis current control model, the reference current is compared to the source current.

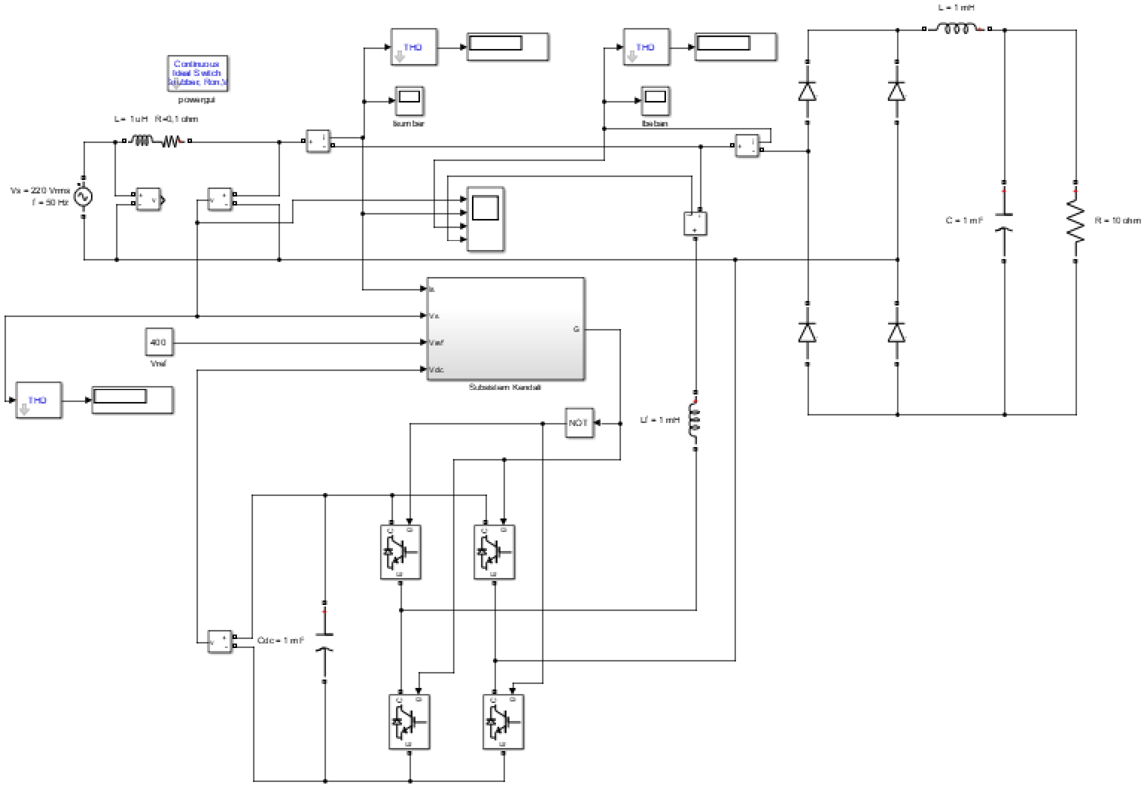

Figure 5. Active Filter Simulation with Matlab Simulink

3. Results and Discussion

Before connecting the parallel active power filter, observations are made on the source voltage and current, the Total Harmonic Distortion (THD) of the source current and the load current. The simulation is carried out for 2 seconds and the simulation results are displayed between 1.9 – 2 seconds.

3.1. Without Active Filters

Figure 6 shows the simulation results when the active filter is not installed. The source voltage wave (V_s) is sinusoidal. The source current (I_s) and the load current (I_b) have the same waveform and are not sinusoidal. The THD of the source current is equal to the load current, which is 112.6%. This THD value exceeds the IEEE 519 standard, which is a maximum of 5%. Whereas the filter current I_{filter} = 0 A because the filter is not yet connected. In this unfiltered condition, the power factor (pf) is 0.6617.

3.2. Conventional Hysteresis Active Filter

Figure 7 shows the simulation results when the active filter with conventional hysteresis control installed. The hysteresis band used is 1 A. After the active filter is connected in parallel with the load, then the source current THD drops to 7.09% from the original value of 112.6%. It can be seen in Figure 7 that the source voltage (V_s) and the source current (I_s) are in phase with a power factor of 0.9971.

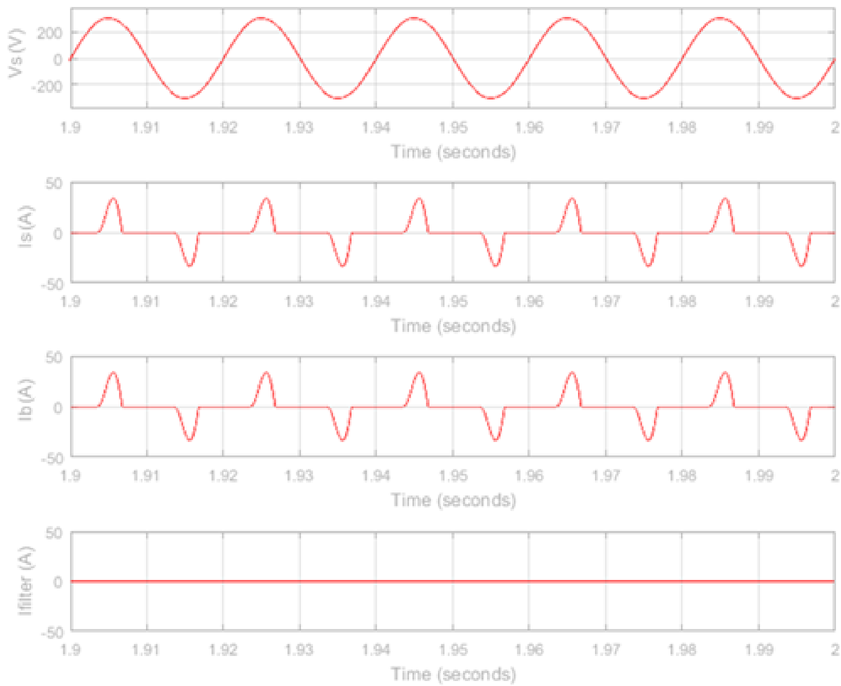

Figure 6. Simulation Results when Active Filter is not Installed

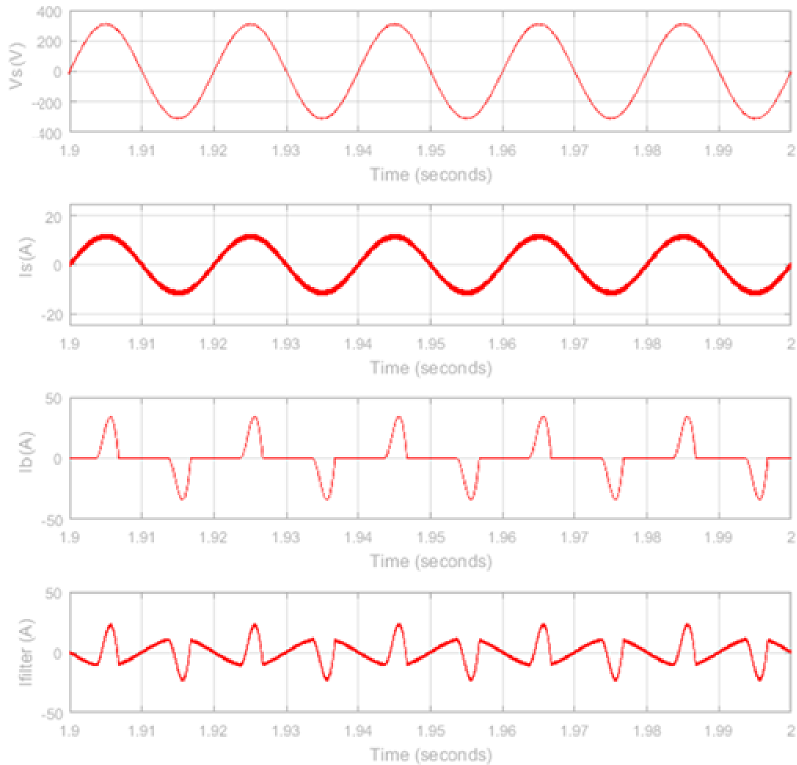

Figure 7. Simulation Results with Conventional Hysteresis Active Filter Installed (HB=1A)

Figure 8 shows the switching frequency and hysteresis bandwidth versus time. The hysteresis band used is 1 A and it can be seen from the results of the simulation that the width of HB fluctuates around 1 A. For HB = 1 A, the switching frequency varies between 35 – 100 kHz.

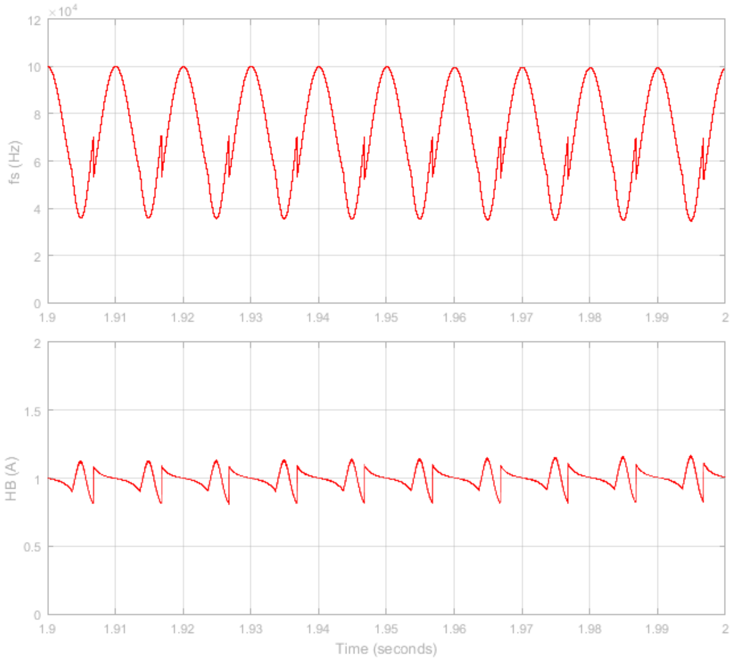

Figure 8. Switching Frequency (f_s) and Hysteresis Bandwidth (HB) in Conventional Hysteresis Control

Table 2 and Figure 9 show the simulation results of the switching frequency as a function of the hysteresis bandwidth between 0.5 – 3 A. It can be seen that the wider the hysteresis band, the lower the switching frequency and the greater the current THD. The relationship between bandwidth and THD_I is close to linear. THD_I values that do not exceed the IEEE 519 standard (maximum 5%) occur when HB = 0.5 A.

Table 2. Simulation Results of Frequency and Current THD vs Hysteresis Bandwidth (HB)

No	Hysteresis Bandwidth (A)	Switching Frequency (kHz)	Power Factor	THD_I (%)
1	0.5	70 - 200	0.9993	3.60
2	1	35 - 100	0.9971	7.09
3	1.5	23 – 66.7	0.9925	10.65
4	2	17.5 - 50	0.9890	14.42
5	2.5	14 - 40	0.9801	17.74
6	3	12 – 33.3	0.9725	21.13

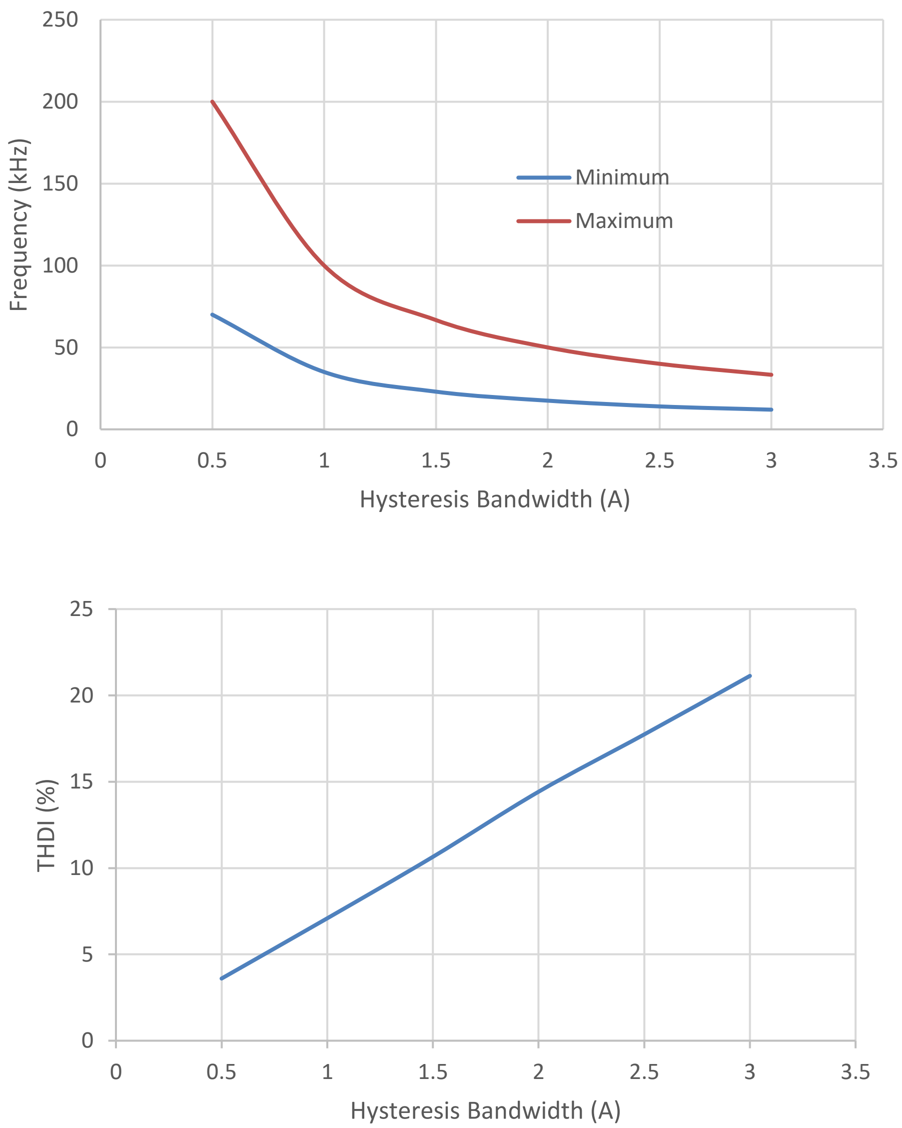

Figure 9. Frequency and THD_I versus HB in Conventional Hysteresis Control

3.3. Adaptive Hysteresis Active Filter

Figure 10 shows the simulation results when the filter is active with adaptive hysteresis control installed. The switching frequency is set to a constant of 100 kHz. Once the active filter is connected in parallel with the load, the THD of the source current drops to 5.06%. It can be seen in Figure 10 that the source voltage and the source current are in phase with a power factor of 0.9985.

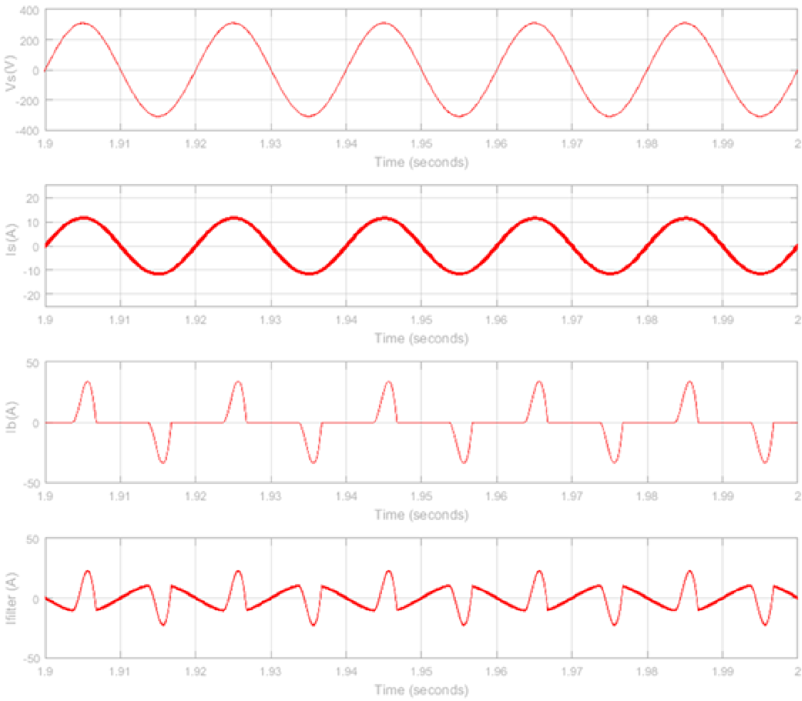

Figure 10. Simulation Results with Adaptive Hysteresis Active Filter Installed (f_s=100 kHz)

Figure 11 shows the switching frequency and the hysteresis bandwidth. The switching frequency is set at 100 kHz and from the simulation results it is obtained that the frequency value fluctuates around 100 kHz.

With a constant switching frequency of 100 kHz, the hysteresis bandwidth fluctuates (adaptively) in the range of 0.4 – 1 A. The minimum hysteresis bandwidth occurs when the highest voltage in the PCC is 310 volts. At the time of this 310 volt voltage, $\frac{di^*}{dt} = 0$ due to the reference current is at the peak position of the sinusoidal wave. Using equation (4), the minimum hysteresis bandwidth is:

$$HB = \frac{V_{dc}}{4Lf_{sw}} - \frac{L}{4f_{sw}v_{dc}}\left(\frac{V_g}{L} + \frac{di^*}{dt}\right)^2 = \frac{400}{4.10^{-3}.10^5} - \frac{10^{-3}}{4.10^5.400}\left(\frac{310}{10^{-3}} + 0\right)^2 = 0.4\ A$$

Meanwhile, the maximum hysteresis bandwidth that occurs when Vg = 0 volts cannot be calculated because $\frac{di^*}{dt}$ is unknown.

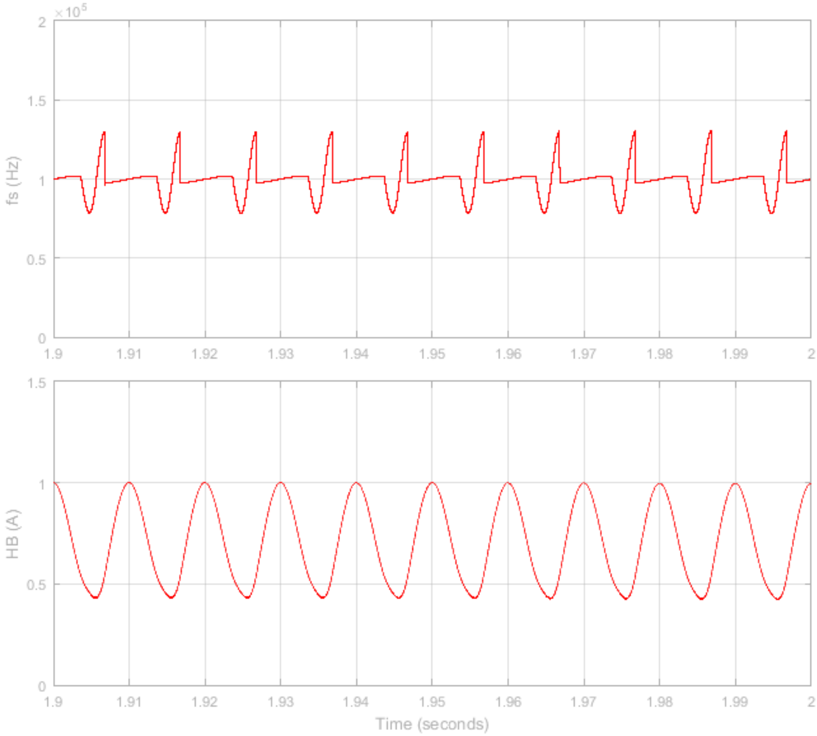

Figure 11. Switching Frequency (f_s) and Hysteresis Bandwidth (HB) on Adaptive Hysteresis Control (f_s=100 kHz)

Table 3 shows a recapitulation of the results of adaptive hysteresis control simulation for the switching frequency of 20 - 120 kHz. THD_I values that do not exceed the IEEE 519 standard (maximum 5%) occur at a switching frequency of 120 kHz.

Table 3. Hysteresis Bandwidth and Frequency THD Simulation Results

No	Switching Frequency (kHz)	Hysteresis Bandwidth (A)	Power Factor	THD_I (%)
1	20	2 - 5	0.9651	26.10
2	40	1 – 2.5	0.9900	12.93
3	60	0.67 – 1.67	0.9954	8.69
4	80	0.5 - 1.25	0.9975	6.51
5	100	0.4 - 1	0.9985	5.32
6	120	0.33 – 0.83	0.9991	4.37

Figure 12 shows the curve of the hysteresis bandwidth and THD_I as a function of the switching frequency. It can be seen that the higher the switching frequency, the smaller the HB and THD of the current. In this control it was seen that the hysteresis bandwidth were variable (adaptive) to maintain a constant switching frequency.

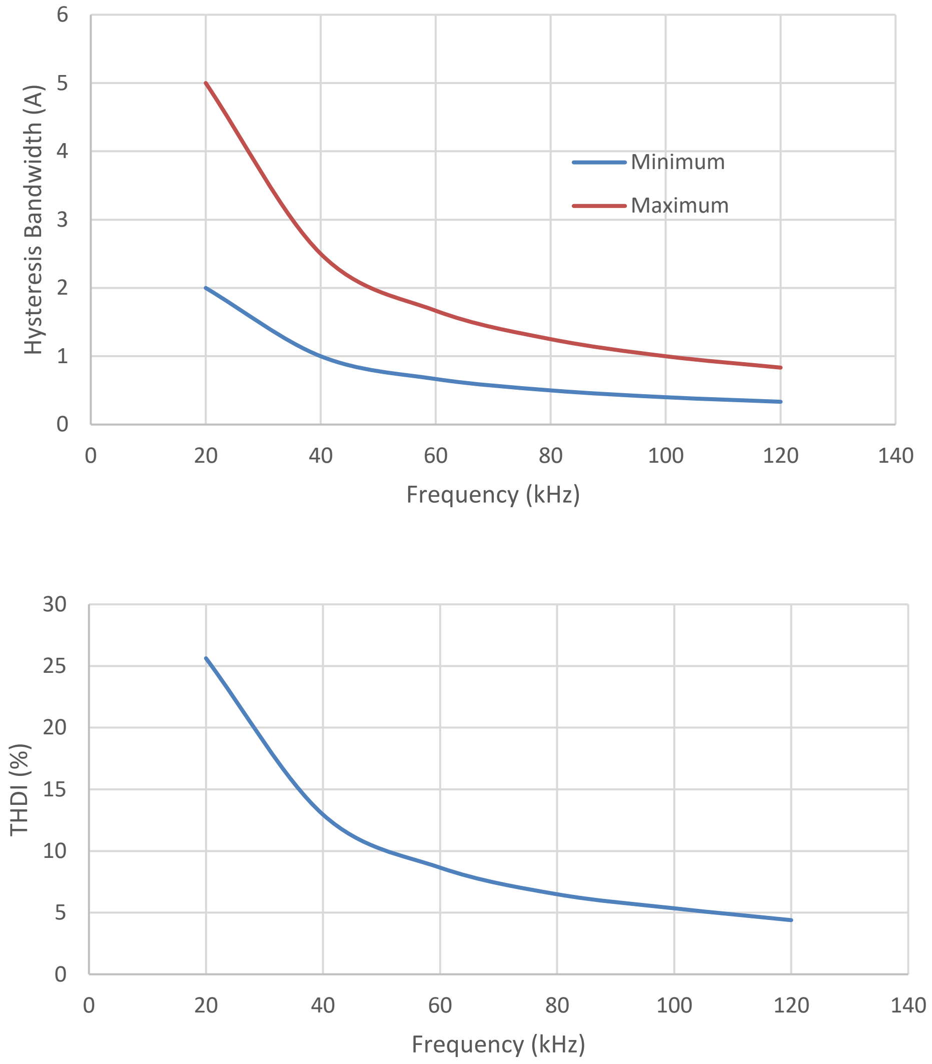

Figure 12. Hysteresis Bandwidth and THD_I vs Frequency in Adaptive Hysteresis Control

From the simulations carried out, namely without filters, with conventional hysteresis filters, and with adaptive hysteresis filter, it can be seen that the two active filters succeeded in lowering the THD of the source current and increasing the power factor. In the condition without a filter, the THDI value was 112.6% and after the filter was installed, the THDI decreased.

After installing a filter with conventional or adaptive hysteresis current control, this THDI is affected by the width of the hysteresis bandwidth. The wider the hysteresis band, the greater the THDI. The difference lies in the inputs used, namely the of the hysteresis bandwidth for conventional hysteresis and the switching frequency (fs) for adaptive hysteresis. The wider the hysteresis band, the lower the switching frequency. For conventional hysteresis control, with a constant hysteresis bandwidth input, a variable switching frequency is obtained. And conversely, for adaptive hysteresis control, with constant switching frequency input, a variable hysteresis band width is obtained.

High harmonics in the power system can disrupt sensitive equipment such as data centers and manufacturing facilities. Therefore, even the slightest change in power quality can cause very high disturbances in the operation of these sensitive loads. From the discussion that has been done, the use of conventional and adaptive hysteresis methods in active filters in the electric power system has been proven to improve the quality of electric power, namely reducing harmonics. Harmonics can be reduced so that they comply with the IEEE 519 Standard. In addition to reducing harmonics, active filters can also increase the power factor. This means that active filters function to compensate for reactive power in the system which results in reduced loading on the line. With smaller loading, losses in the power system become smaller and cause the use of electrical energy to be more efficient.

This active filter is also very useful in renewable energy systems, which operate on intermittent sources such as wind and solar and have power quality problems. The use of active filters in renewable energy solutions can reduce carbon emissions. And this makes active filters very important in providing sustainable energy solutions.

One of the problems often faced related to the use of this active filter is the price of the active filter which is still expensive. The price also depends on the product brand. There are also requirements from the utility regarding the quality of power that needs to be met, including the permitted power factor. This requires further consideration to decide the need to install an active filter.

4. Conclusion

The simulation results showed that the active filter using conventional and adaptive hysteresis control succeeded in improving the quality of electrical power. With an initial THD_I value of 112.6% (before the filter is installed) and a maximum THD_I target of 5% according to the IEEE 519 standard, the required bandwidth is 0.5 A for conventional hysteresis control and a switching frequency of 120 kHz for adaptive hysteresis control. The power factor also increases from 0.6617 to 1 (unity power factor). This shows that the active filter can work well to lower the harmonics and increase the power factor.

Furthermore, comparison of these two control methods can be implemented in hardware for future work. This active filter can also be integrated with renewable energy sources such as solar energy that uses voltage source inverters so that it contributes directly to the development of more sustainable and resilient electrical infrastructures. This inverter is not only used for power transfer but also used to improve power quality.

Acknowledgements
Authors gratefully acknowledge the financial support from Diponegoro University through the RPP research scheme.

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