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# Harmonics Analysis of Input Current of 3-Phase PWM Rectifier

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## ABSTRACT

Rectifier is a non-linier load that causes harmonic distortion in the power system. Pulse-width modulation (PWM) method is an effective method in pressing the magnitude of harmonics in a rectifier application, it provides an almost sinusoidal input current. However, the variation of loads that supplied by a rectifier cause the harmonics that arise can still beyond the applicable standard. The amount of harmonics in the operating range of a rectifier need to be identified to determine the filter on the input side. In this research article, 3-phase PWM rectifier was designed with hysteresis current control technique using PSCAD software simulation. Harmonic compensation was carried out by applying an active filter based on P-Q theory to reduce the harmonic distortion that occurs in the input current, thus giving a low total harmonic distortion (THD) value. Based on the simulation, 3-phase PWM rectifier operation starting at a power level of 150 kW, giving a THD value above 5-10% by the increasing the amount of load supplied by the rectifier. The application of active filter based on the P-Q theory is able to compensate harmonics in the input current wave with a THD value below 5% in the rectifier operating range.

## INTRODUCTION

The use and utilization of large electrical energy such as electrical load equipment that continues to develop from time to time is also followed by problems in terms of power quality, one of the problems in power quality is harmonics. Harmonics are power quality phenomena that occur due to distortion of current and voltage waves due to the use of non-linear loads. Some examples of non-linear loads are static power converters, arc discharge devices, saturated magnetic devices, and rotating machines [1].

Rectifier is one of the power converter applications which is a non-linear load. The use of rectifier can reduce the quality of electrical power, which results in harmonics. In improving the power quality that has decreased due to harmonics, a device that can mitigate harmonics is used, which is called harmonic filter [2]. There are 3 types of harmonic filters that can be used, namely passive filter, active filter, and hybrid filter [2]. An active filter is a filter consisting of active components, such as transistor or thyristor. Active filter is a power converter that consists of a power circuit and a control circuit, which is one of the best solutions to overcome harmonics [3-8]. In this research article, active filter will be used as a harmonic filter to reduce harmonics that arise.

In some literatures, the effect of loading on power converter which is a non-linier load can increase the amount of harmonics that arise in the system so that it worsen the power quality [9-10]. In suppressing the magnitude of harmonics in a rectifier application, effective control techniques are used, one of the effective control is PWM (Pulse-Width Modulation) method in the rectifier circuit. PWM rectifier application can reduce harmonic distortion in electrical network because it consumes almost sinusoidal input current, so that the supply network is maintained [11-15]. However, with the variations of load supplied by a rectifier, the resulting harmonics can still get through the applicable standard. The amount of harmonics in this variation range needs to be known and identified for its characteristics to determine the need to apply an input filter and to design the size of the input filter that must be placed.

### *Harmonics*

Harmonics are one of the power quality phenomena that cause distortion in current and voltage waves. Harmonics are the formation of waves with different frequencies which are multiples of the frequency of the fundamental wave. Figure 1 shows a distorted fundamental frequency wave due to the addition of a harmonic wave so that it is no longer sinusoidal.

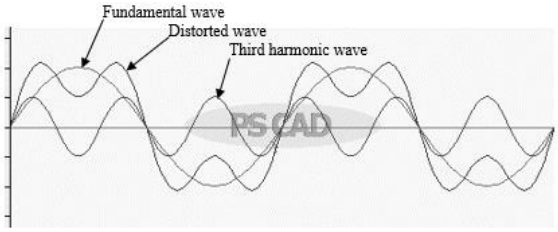


Figure 1. Wave Distorted by Harmonics

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Distorted waves can be broken down into several waves that have a frequency multiple of the fundamental wave frequency [16]. If the fundamental frequency is 50 Hz, then the second harmonic frequency is 100 Hz, and the third harmonic frequency is 150 Hz, and so on for the next harmonic wave. These harmonic waves attach to the fundamental wave, so that the fundamental wave with a frequency of 50 Hz will be distorted and no longer sinusoidal.

### *Active Filter*

In power quality, harmonics can be reduced by using filter. The filter will limit the rising harmonic waves in the fundamental wave. Therefore, harmonics will not propagate throughout the power grid which will have a bad impact. There are several advantages in applying an active filter, namely eliminating harmonics, blocking resonances, reactive power management capabilities, easy and accurate tuning, and overcoming varying harmonic components [2].

Active filter consists of active components that uses power electronics principle in the form of pulse-width modulation which is designed to reduce harmonics. This filter will inject current to compensate for harmonic current generated by non-linear loads. The basic principle of an active filter uses power electronics technology to produce specific current components that aim to thwart the harmonic current components that arise due to non-linear loads [17].

### *Pulse-Width Modulation Rectifier*

At present, current harmonics and reactive power generated by power converters especially rectifier are a problem in electrical power systems [18]. Pulse-Width Modulation (PWM) rectifier appears as a solution to power quality problems in power systems for rectifier applications. The circuit topology for the PWM rectifier is a controlled rectifier built using a semiconductor with gate turn-off capability [18]. A converter with a semiconductor that have this capability will allow it to be fully controlled as it can be switched on and off at any time [18]. There are several advantages of this circuit, namely that the current and voltage can be modulated (pulse width modulation or PWM), produces less harmonic contamination, and the power factor can be controlled [18].

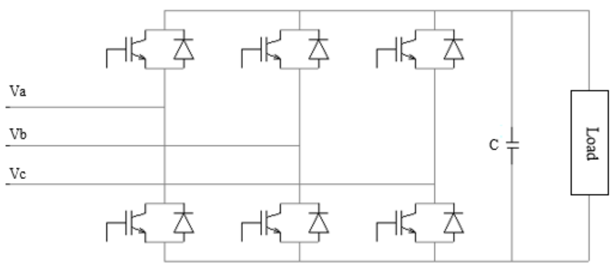



Figure 2. 3-Phase PWM Rectifier Topology

Figure 2 shows the 3-phase PWM rectifier circuit topology. This topology which is the most popular topology is the universal topology that has advantage of using a low-cost rectifier module with two-way energy flow capability and can provide a unity power factor [19]. The output of the PWM rectifier converter is a constant dc voltage, so it can be used under various load conditions. To obtain constant dc voltage, capacitor and control loops were used [18]. The principle operation of the PWM rectifier can be seen in Figure 3. The rectifier maintains a constant dc output voltage which is done by output voltage feedback, where the capacitor's dc voltage will be compared with the set reference voltage [20].

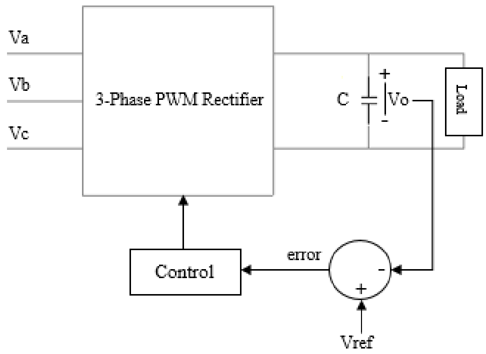
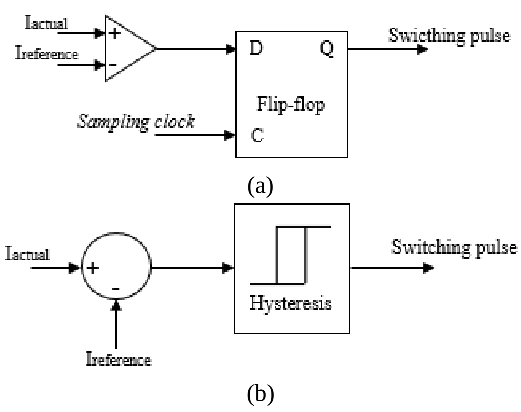



Figure 3. Principle Operation of PWM Rectifier

The comparator will compare the DC output voltage measured on the capacitor with the reference voltage, so that the error value (e) will be obtained. Switch on and off for all the power switches in the converter are set based on the error values [18]. Power can flow or return back to the source side according to the dc voltage output requirements [18]. To obtain a certain pattern form that will be used as a PWM pattern as an on and off switch based on the voltage error value on the dc side, the rectifier is controlled. The rectifier can be controlled in two ways, namely control of the input current of the rectifier and control of the value and phase of the modulation voltage [18]. The control which is carried out on the rectifier is to get a reference value that will be modulated to generate a PWM pattern and will be passed to each power switch.

There are many modulation methods that can be used, but there are three of the most widely used methods, namely periodical sampling, hysteresis band, and triangular carrier [18]. Figure 4 shows the block diagram of the modulation method for the three most widely used methods. The periodical sampling control method requires a comparator and type D flip-flop, the hysteresis band method requires a hysteresis control block, and the triangular carrier method requires a PI controller and a comparator to modulate the reference value to generate PWM pattern.

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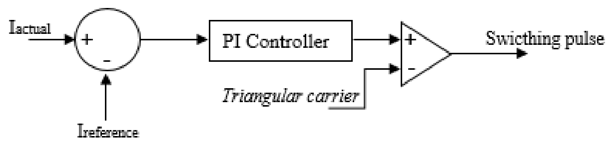



(c)

Figure 4. Modulation Methods, (a) Periodical Sampling, (b) Hysteresis Band, (c) Triangular Carrier

### Application of P-Q Theory to Harmonic Filter

P-Q theory was first published in 1982 by Akagi and his colleagues. This theory is based on a set of instantaneous power defined in the time domain [10]. P-Q theory changes the voltage and current from the abc coordinate ($V_a$, $V_b$, $V_c$ and $I_a$, $I_b$, $I_c$) to the αβ0 coordinate ($V_\alpha$, $V_\beta$, $V_0$ and $I_\alpha$, $I_\beta$, $I_0$) using clarke transformation, after that the value of instantaneous power component is determined at this coordinate. The clarke transformation of the voltage and current in a three-phase system are expressed in equation (1) and equation (2) [21].

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2}$$

The instantaneous power components, namely real power ($p$), reactive power ($q$) and zero sequence power ($p_0$) are determined based on equation (3) through the results of voltage and current calculation in αβ0 coordinate in the previous equation [21]. The power components consist of the average power ($\bar{p}$, $\bar{q}$, and $\overline{p_0}$) and the oscillating power ($\tilde{p}$, $\tilde{q}$, and $\widetilde{p_0}$). In the application of the harmonic filter, the power that will be compensated is the oscillating power, and it can be obtained by using a high pass filter on the instantaneous power component [3-4].

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} V_0 & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} \tag{3}$$

Furthermore, the compensation reference current calculation at the αβ0 coordinate is carried out based on the compensation power component. The compensation reference current in the αβ0 coordinate ($I_{c\alpha}$, $I_{c\beta}$, $I_{c0}$) is transformed back into 3-phase coordinate ($I_{ca}$, $I_{cb}$, $I_{cc}$) as the harmonic compensation reference current. The compensation reference current calculation and its transformation back into the 3-phase coordinate are determined based on equation (4) and (5) [21].

$$\begin{bmatrix} I_{c0} \\ I_{c\alpha} \\ I_{c\beta} \end{bmatrix} = \frac{1}{V_\alpha{}^2 + V_\beta{}^2} \begin{bmatrix} V_0 & 0 & 0 \\ 0 & V_\alpha & V_\beta \\ 0 & V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} \widetilde{p_0} \\ \tilde{p} \\ -\tilde{q} \end{bmatrix} \tag{4}$$

$$\begin{bmatrix} I_{ca} \\ I_{cb} \\ I_{cc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & 0 & 0 \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_0 \\ I_{c\alpha} \\ I_{c\beta} \end{bmatrix} \tag{5}$$

## METHOD

### Single Line Diagram Design of Distorted System

The harmonic distorted system is configured into a single line diagram as shown in Figure 5. Non-linear loads connected to the power source will cause harmonic distortion on the input side of the system. This harmonic distortion will propagate to the power grid and cause a bad impact on the system. Therefore, a harmonic filter is needed on the input side of the non-linear load, so that harmonic distortion can be suppressed and does not propagate to the power grid.

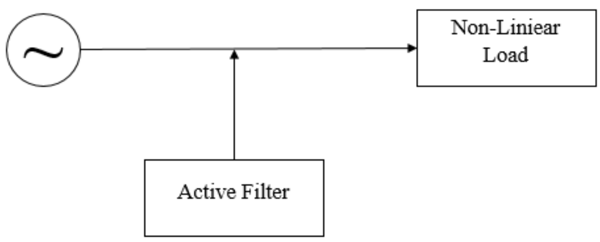



Figure 5. Single Line Diagram of Distorted System

### Block Diagram Design of Distorted System

This non-linear load block diagram modeling shows the equivalent circuit of system condition that distorted by harmonics. In this system, the non-linear load is a power converter in the form of a 3-phase PWM rectifier which is designed using PSCAD software simulation. Non-linear load that connected to a power source will cause harmonic distortion on the input side of the system. The 3-phase PWM rectifier circuit topology is a fully controlled rectifier using 3 pairs of diodes and IGBTs as the power switch as shown in Figure 6, where this topology is a universal and the most widely used topology, with low production costs of rectifier circuits [19].

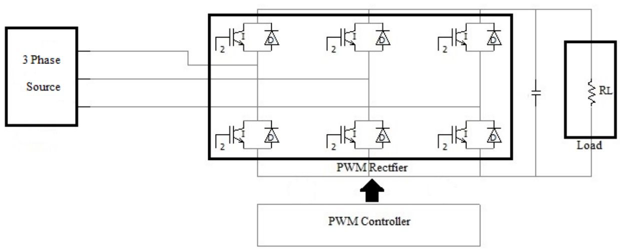



Figure 6. Block Diagram of Distorted System

### *Harmonic Reduction Cicrcuit Design with Active Filter*

Active filter generally consists of PWM converter and active filter controller. Active filter controller functions is to calculate harmonics compensation reference current continuously. This compensation reference current will be generated through PWM converter as a harmonic compensation current to reduce the harmonics that arise in distorted system. The controlling technique for the active filter controller to calculate the reference current is based on the P-Q theory.

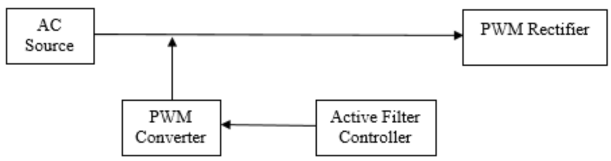



Figure 7. Active Filter Modelling in the System

The converter topology that is used as a PWM converter on an active filter is an inverter equipped with a dc capacitor as a voltage source [5-7]. Active filter is arranged in parallel in the circuit to overcome the harmonic currents that arise. Figure 7 shows a parallel active filter configuration in a system that distorted by harmonics due to non-linear load. Active filter for harmonic compensation designed using PSCAD software simulation.

### *Control Technique of 3-Phase PWM Rectifier*

The control technique used to produce PWM patterns in this system is current controlling technique. This method is used to make the measured instantaneous input current follow a given reference current pattern, so that the distorted current on the input side due to non-linear load can become almost sinusoidal and reduce the percent of harmonic distortion on the input current side. The process of producing reference current pattern in this method can be seen in Figure 8. To get the maximum value of the reference current is processed through a controller such as proportional integral (PI), fuzzy, and other controllers that are used to obtain system stability in the voltage loop control feedback [18]. In this research article, PI controller is used with the output of the controller is the maximum value for the reference current.

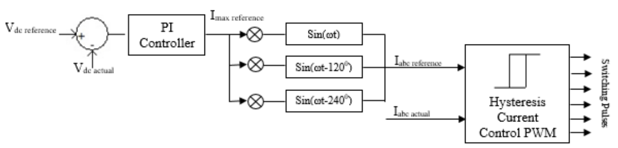



Figure 8. Control Technique of 3-Phase PWM Rectifier

Furthermore, the maximum value of the reference current is synchronized with the actual instantaneous current for the three phases. The maximum value of the reference current is multiplied by the sine function according to the system frequency and the phase angle based on the angle value for each phase, so that the reference current values for the three-phase system are generated. The modulation method used to generate PWM pattern in this system is hysteresis current control method. This technique is widely used in controlling current because it is not complicated in its implementation [22-27].

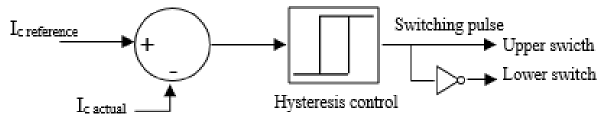



Figure 9. Hysteresis Current Controlling Method in PWM Rectifier

The reference current generated for the three phases and the actual instantaneous current for the three phases become the input in the hysteresis current control block to generate switching pulses. The hysteresis current controlling method for one of the phase in the PWM hysteresis current control block is shown in Figure 9. The reference current will be compared with the actual instantaneous current so that the error value is obtained. The error value resulting from the comparison will be given a range of hysteresis limits, namely the upper and lower limits that refer to the reference current value.

### *Harmonic Compensation Algorithm Based on P-Q Theory*

Active filter control used in this research article is based on the instantaneous power theory or P-Q theory. This theory is very efficient to use in controller design for power conditioning using power electronic devices [16]. Block diagram for active harmonic filter control based on P-Q theory is shown in Figure 10.

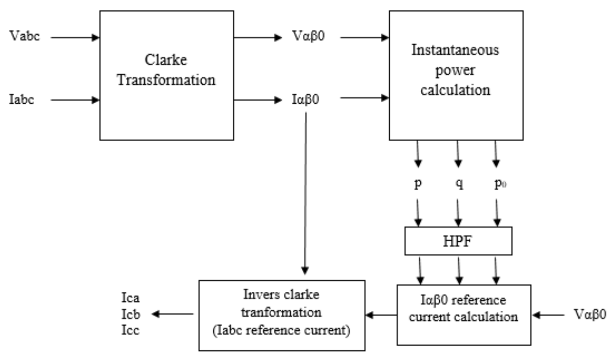



Figure 10. Block Diagram for Active Harmonic Filter Control Based on P-Q theory

This control is used to generate compensation current to reduce harmonic currents that arise in the system due to non-linear load. Voltage and current in 3-phase system or in abc coordinate are transformed into αβ0 coordinate using clarke transformation with equations (1) and (2). Then the calculation of the instantaneous power component with equation (3) and the compensation reference current in αβ0 coordinate with equation (4). The compensation reference current in the αβ0 coordinate is transformed again by inverse of transformation clarke with equation (5) as the reference current in abc coordinate or in three-phase system.

Furthermore, after obtaining the result of the compensation reference current, a modulation technique is needed to generate a PWM signal which will be forwarded to the switch gate on the PWM converter. The modulation method used is the hysteresis current control method. The compensation reference current is as input to the hysteresis current control block along with the actual instantaneous current on the input side of the PWM converter for the three phases. Figure 11 shows the hysteresis current controlling method for one of the phase in the active filter.

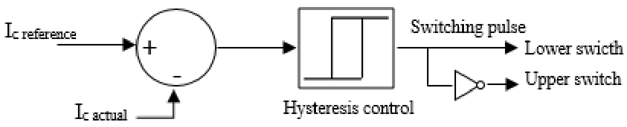



Figure 11. Hysteresis Current Controlling Method in Active Filter

## RESULTS AND DISCUSSION

The system designed in this research article is a 3-phase PWM rectifier with a voltage source ($V_{LL}$) of 380 V and a system frequency (*f*) of 50 Hz. Figure 12 shows the 3-phase PWM rectifier converter circuit. The 3-phase PWM rectifier circuit and the active filter designed using PSCAD software simulation.

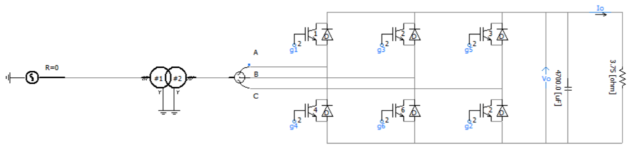


Figure 12. 3-Phase PWM Rectifier Circuit

The output of the 3-phase PWM rectifier is a controlled dc voltage based on the dc voltage reference value set on the converter. The dc output voltage can still refers to the voltage reference value for load variations. Figure 13 shows the 3-phase PWM rectifier output waveform at a power level of 70 kW.

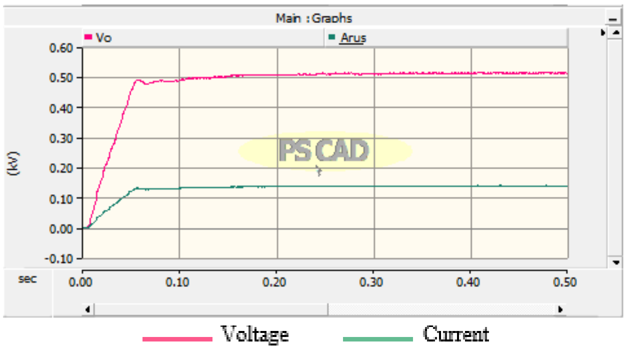



Figure 13. 3-Phase PWM Rectifier Output Waveform

The control method used to generate PWM pattern for converter switching is hysteresis current control. Through this method, the distorted current due to the power converter which is a non-linear load will be directed to be like the specified sinusoidal reference current and to reduce the harmonic currents that arise. Figure 14 shows the control circuit of the hysteresis current control method in 3-Phase PWM rectifier. Figure 15 shows the rectifier input current waveform based on PWM control for the three phases at a power level of 70 kW.

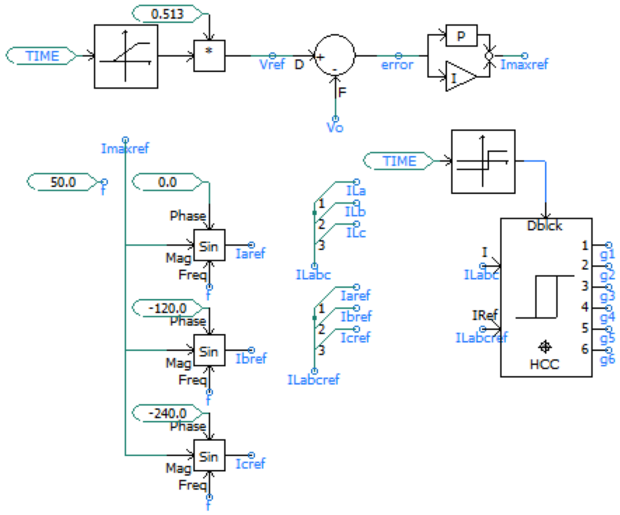



Figure 14. Hysteresis Current Control Circuit in 3-Phase PWM Rectifier

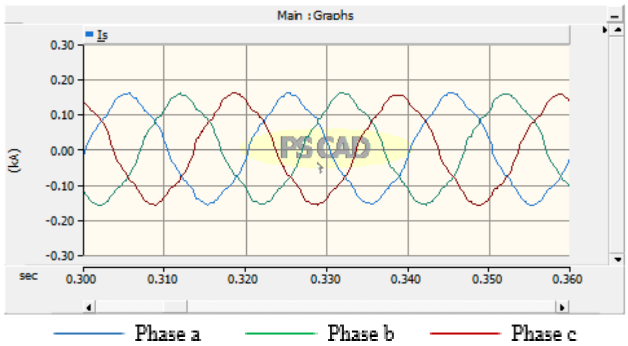



Figure 15. 3-Phase PWM Rectifier Input Current Waveform

In pressing the magnitude of harmonic currents that arise, the PWM method is an effective method to reduce harmonic current distortion. The PWM rectifier can keep the current on the input side nearly sinusoidal. However, the variation of load supplied by the rectifier will affect the amount of harmonic currents that arise on the input side, so that the harmonic current distortion can still get through the applicable standard. The harmonic currents standard in the system designed in this research article refers to the standards set by IEEE 512-1992, at the standard of 5% [1]. Table 1 shows the variation values of total harmonic current distortion ($THD_i$) in the 3-phase PWM rectifier operating range. The harmonic variations of the current is measured on the input current side of the system. Based on the table below, it can be seen that with varying the amount of load supplied by 3-phase PWM rectifier affect the harmonic current distortion value, which harmonic current distortion that arises can still be of high value. Figure 16 shows the input current waveform of the 3-phase PWM rectifier at power level 150 kW, 70 kW, and 16 kW.

Table 1. $THD_i$ Variations on the Input Current Side of the 3-Phase PWM Rectifier Operating Range

| ***R*** **(Ω)** | ***P*** **(kW)** | **Total Harmonic Distortion ($THD_i$) (%)** | | |
|---|---|---|---|---|
| | | $I_a$ | $I_b$ | $I_c$ |
| 16.5 | 16 | 9.921 | 9.756 | 10.443 |
| 13.15 | 20 | 7.824 | 8.060 | 8.078 |
| 8.74 | 30 | 6.236 | 6.230 | 6.062 |
| 6.57 | 40 | 5.809 | 5.748 | 5.662 |
| 5.25 | 50 | 5.788 | 5.777 | 5.811 |
| 4.38 | 60 | 5.677 | 5.736 | 5.698 |
| 3.75 | 70 | 5.834 | 5.611 | 5.903 |
| 3.29 | 80 | 5.896 | 6.033 | 5.766 |
| 2.92 | 90 | 6.202 | 6.245 | 6.380 |
| 2.62 | 100 | 6.170 | 6.404 | 6.351 |
| 2.38 | 110 | 6.211 | 6.295 | 6.204 |
| 2.19 | 120 | 5.914 | 6.035 | 5.875 |
| 2.02 | 130 | 5.878 | 5.918 | 5.944 |
| 1.87 | 140 | 5.692 | 5.619 | 5.665 |
| 1.75 | 150 | 5.463 | 5.464 | 5.470 |
| 1.64 | 160 | 5.007 | 5.006 | 5.011 |
| 1.55 | 170 | 4.616 | 4.608 | 4.605 |
| 1.46 | 180 | 4.136 | 4.134 | 4.142 |
| 1.4 | 188 | 3.666 | 3.663 | 3.667 |

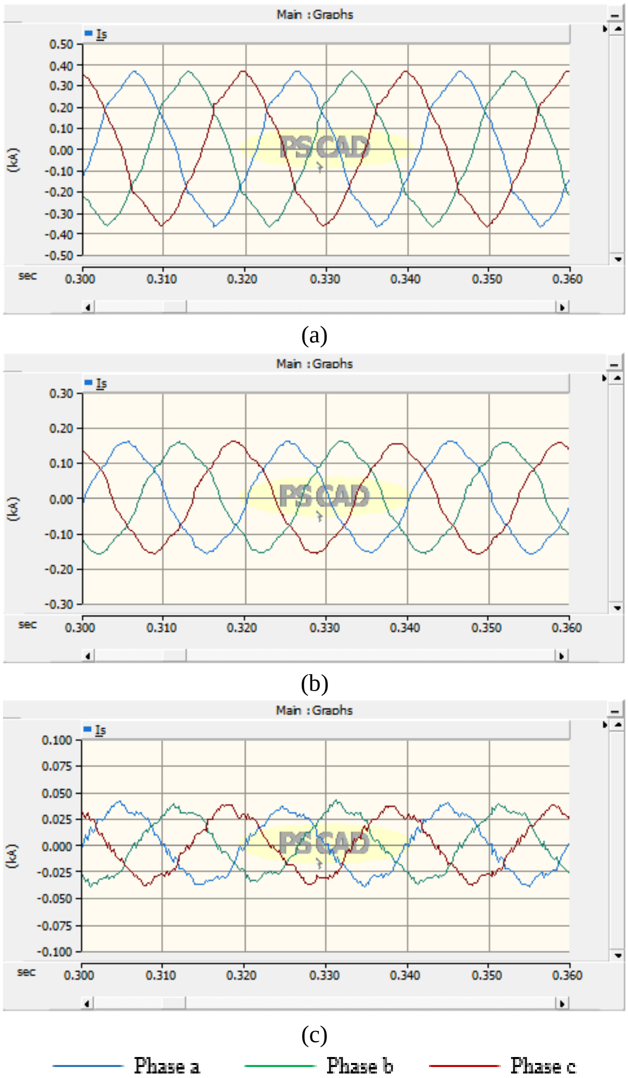



Figure 16. The Input Current of the 3-Phase PWM Rectifier at Power Level, (a) 150 kW, (b) 70 kW, and (c) 16 kW

In the data obtained based on the operating range of the rectifier for power level of 160-188 kW, the harmonic distortion that occurs on the input current side is not too large and can still be tolerated because it does not get distorted more than 5%. In the operating range for power level of 30-150 kW, the harmonic distortion that occurs is quite large and almost constant, where the current at the input side of the system is distorted about 5-6%. In the operating range for power level of 16-20 kW, the harmonic distortion is large, because the harmonic current distortion on the input side of the system is 7-10%. Figure 17 shows the graph of $THD_i$ relationship to output power ($P$) of the rectifier in the rectifier operating range for the three phases.

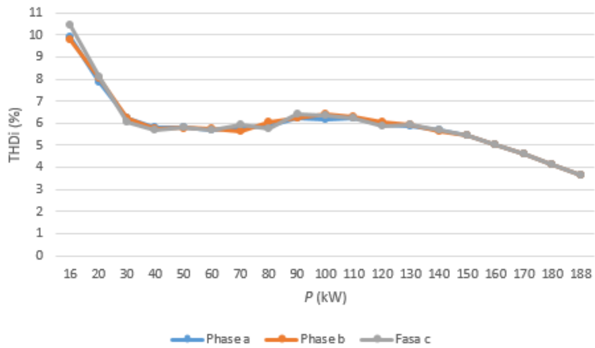



Figure 17. Graph of $THD_i$ Relationship to the Output Power ($P$)

Based on the rectifier rating in this research article, the variation of harmonic currents that appear in the 3-phase PWM rectifier operating range can be determined that the operation starts at a power level of 150 kW and so on with the increase in the amount of load supplied by the converter, starts to require a harmonic filter on the input current side of the system. When handling a varying harmonic values, active filter is the right choice to use as harmonic filter. In this research article, active filter is designed based on the P-Q theory to produce harmonic compensation current. Figure 18 shows the 3-phase PWM rectifier circuit with active filter.

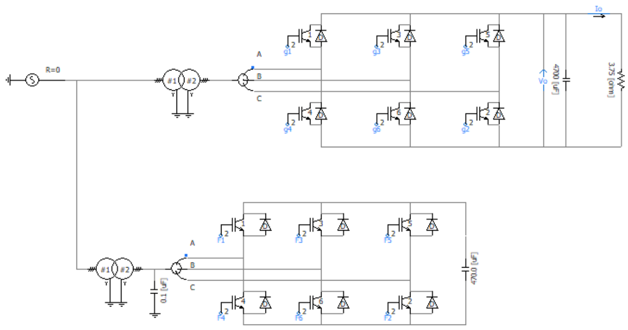


Figure 18. 3-Phase PWM Rectifier Circuit with Active Filter

The active filter is designed based on the P-Q theory through the equations of the instantaneous power component in the theory. Active filter controller works to get the value of the compensation reference current which will be calculated continuously. The value of the compensation reference current will be generated through the PWM converter as a compensation current and will be forwarded to the distorted input system side to reduce the harmonic currents that arise. Figure 19 shows the active filter control circuit based on P-Q theory to calculate the compensation current. Figure 20 shows the compensation current waveform generated by the active filter based on PQ-Theory.

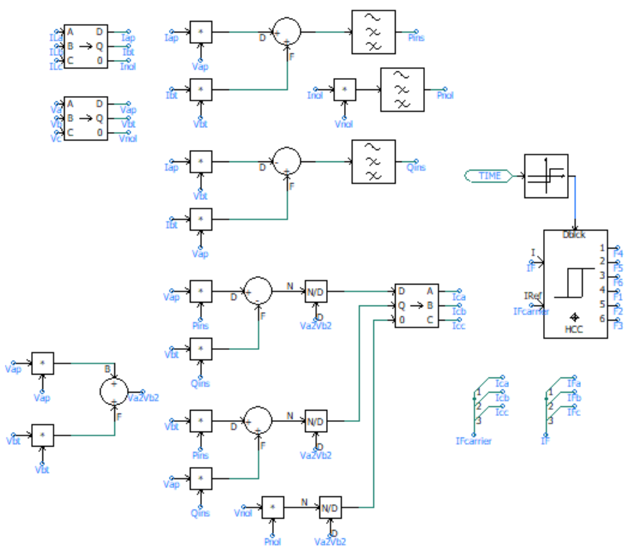
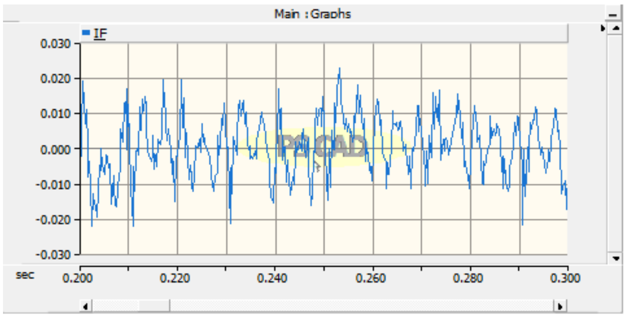
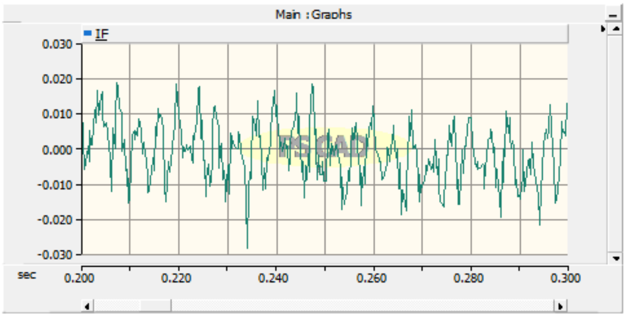


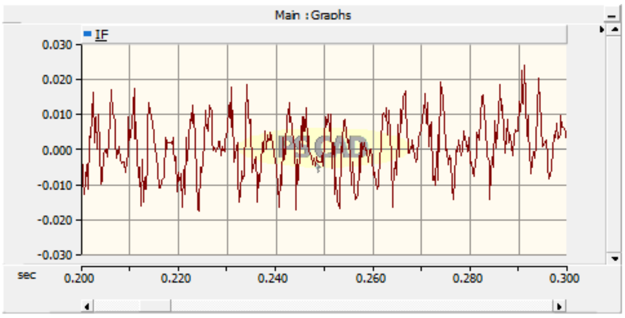
Figure 19. Active Filter Control Circuit Based on P-Q Theory




Phase a

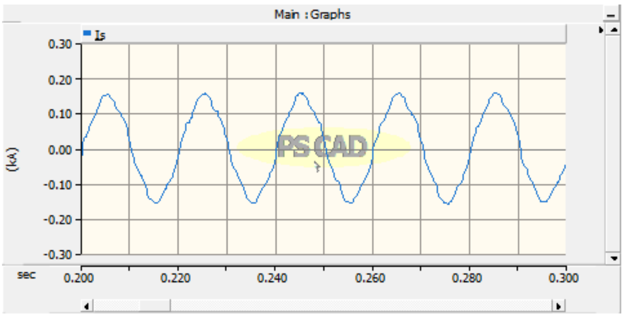



Phase b

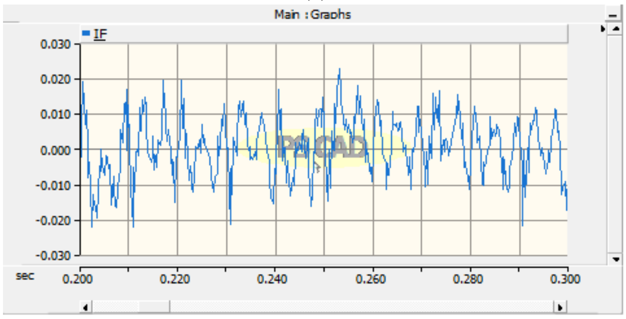



Phase c

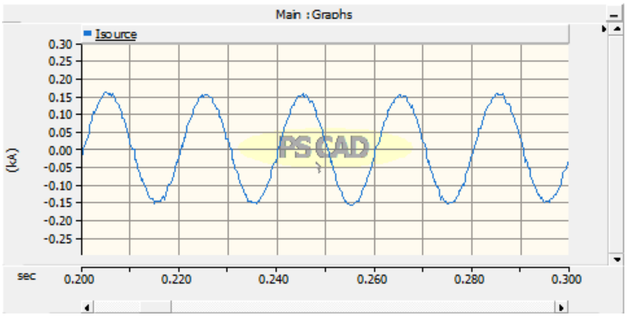
Figure 20. The Compensation Current Waveform for the Three Phases




(a)




(b)




(c)

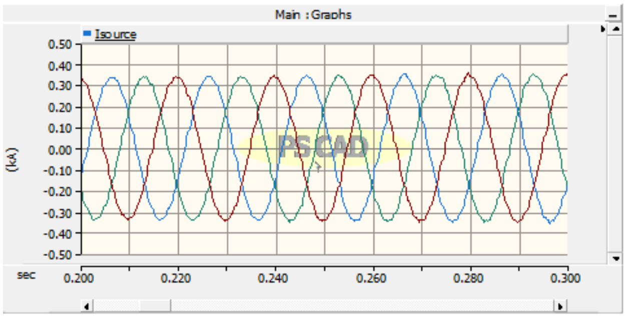
Figure 21. Process of Harmonic Reduction on the Input Current Wave at a Power Level of 70 kW, (a) Input Current Wave Without Active Filter, (b) Harmonics Compensation Current, and (c) Input Current Wave with Active Filter

Table 2. THD$_i$ Variations on the Input Current Side of the 3-Phase PWM Rectifier Operating Range with Active Filter

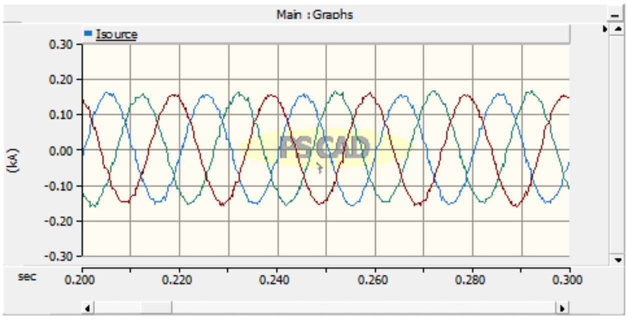
| ***R*** **(Ω)** | ***P*** **(kW)** | **Total Harmonic Distortion (THD$_i$) (%)** | | |
|---|---|---|---|---|
| | | $I_a$ | $I_b$ | $I_c$ |
| 16.5 | 16 | 4.762 | 4.693 | 4.948 |
| 13.15 | 20 | 4.739 | 4.387 | 4.399 |
| 8.74 | 30 | 3.296 | 2.841 | 3.300 |
| 6.57 | 40 | 2.400 | 2.340 | 2.499 |
| 5.25 | 50 | 1.771 | 1.952 | 1.891 |
| 4.38 | 60 | 1.510 | 1.540 | 1.604 |
| 3.75 | 70 | 1.420 | 1.464 | 1.452 |
| 3.29 | 80 | 1.409 | 1.408 | 1.519 |
| 2.92 | 90 | 1.312 | 1.307 | 1.296 |
| 2.62 | 100 | 1.081 | 0.880 | 0.942 |
| 2.38 | 110 | 0.910 | 1.238 | 1.346 |
| 2.19 | 120 | 0.999 | 0.828 | 0.970 |
| 2.02 | 130 | 0.742 | 0.674 | 0.708 |
| 1.87 | 140 | 0.668 | 0.740 | 0.762 |
| 1.75 | 150 | 0.773 | 0.753 | 0.788 |
| 1.64 | 160 | 0.554 | 0.571 | 0.574 |
| 1.55 | 170 | 0.535 | 0.596 | 0.506 |
| 1.46 | 180 | 0.510 | 0.486 | 0.509 |
| 1.4 | 188 | 0.433 | 0.413 | 0.393 |

The current generated by the PWM converter in the active filter will reduce the harmonic currents that arise on the distorted input system side. This current is generated based on the calculation of P-Q theory for the three phases. With harmonic compensation through this active filter, it can return the current form on the input side to a pure sinusoidal form. Figure 21 shows the process of harmonic reduction on the input current wave of the 3-phase PWM rectifier at a power level of 70 kW in phase a.

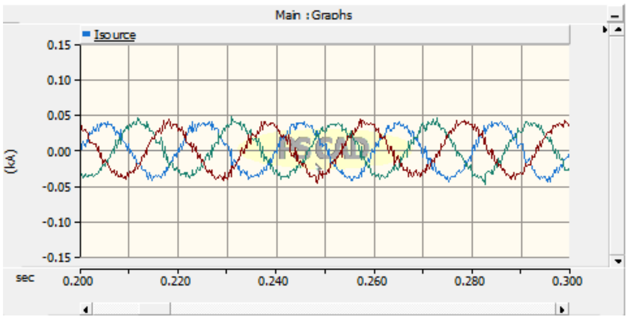
The active filter which has been designed based on the P-Q theory is able to generate harmonic compensation current for all three phases. The compensation current is injected into the current on the distorted input system side. The current on the input side can be returned back to the sinusoidal form and has a low THD value. Table 2 shows the variation values of $THD_i$ in the 3-phase PWM rectifier operating range with active filter. Figure 22 shows the input current waveform of the 3-phase PWM rectifier at power level 150 kW, 70 kW, and 16 kW after the application of the active filter




(a)




(b)




(c)

Figure 22. The Input Current of the 3-Phase PWM Rectifier with Active Filter at Power Level, (a) 150 kW, (b) 70 kW, and (c) 16 kW

The active filter is able to reduce high value harmonic currents at the input side of the 3-phase PWM rectifier. Active filters can substantially reduce up to 3-5% harmonic distortion on the input current of the system. Figure 23 shows the graph of $THD_i$ relationship to output power (*P*) of the rectifier in the rectifier operating range before and after the application of the active filter for the three phases.

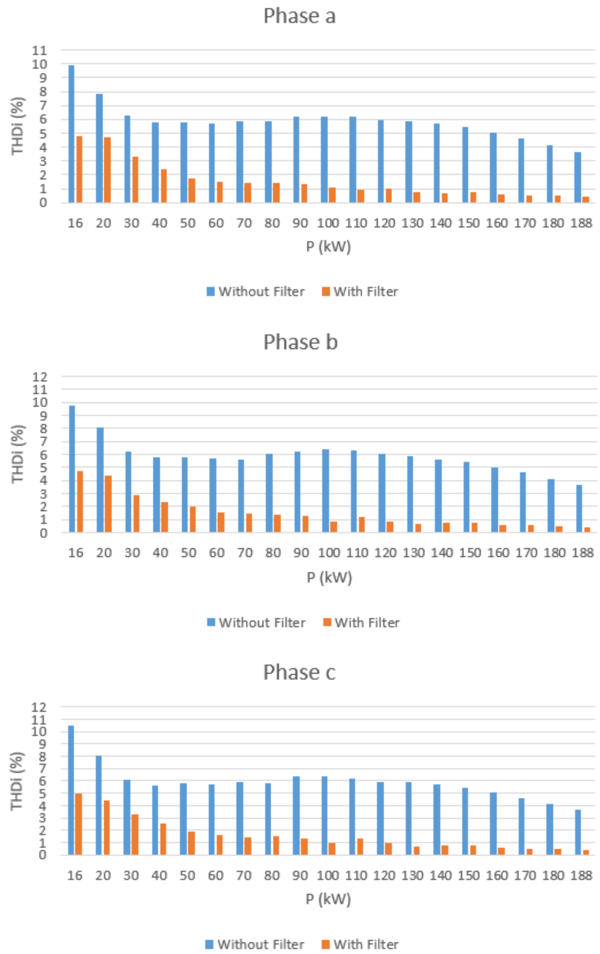



Figure 21. Graph of $THD_i$ Relationship to the Output Power (*P*) Before and After the Application of the Active Filter

Based on Tabel 2 and Figure 21, the active filter that applied to the input side of the 3-phase PWM rectifier can reduce the harmonic currents. The harmonic compensation current generated by the active filter based on the P-Q theory is able to give a low THD value on the input current with an almost sinusoidal waveform. All harmonics in the 3-phase PWM rectifier operating range are below 5%. The variations in the amount of harmonics in the 3-phase PWM rectifier operating range with the application of active filter can fulfill the applicable standard.

## CONCLUSIONS

Based on the rectifier rating, the 3-phase PWM rectifier operation has the highest THDi value at a power level of 16 kW and the lowest THDi value at a power level of 188 kW, and a THDi value at a power level of 30-150 kW has a nearly constant value. The operation based on the rating of the rectifier, starting at a power level of 150 kW and so on with the increase in the amount of load supplied by the rectifier causes harmonic current distortion on the input side of the rectifier has passed the applicable standard, so it is necessary to apply a harmonic filter on the input side of the rectifier. Operation of the 3-phase PWM rectifier after the application of the active filter on the input side has a THDi value

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below 5% for each load variation supplied by the rectifier. The application of active filter on the input side of the 3-phase PWM rectifier based on the P-Q theory can reduce the amount of harmonics in the rectifier input current, with a decrease in the THDi value by an average of 4.4%, thus giving an almost sinusoidal input current waveform.

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## NOMENCLATURE

| | |
|---|---|
| $V_a$ | phase a voltage |
| $V_b$ | phase b voltage |
| $V_c$ | phase c voltage |
| $I_a$ | line a current |
| $I_b$ | line b current |
| $I_c$ | line c current |
| $V_\alpha$ | α-axes voltage |
| $V_\beta$ | β-axes voltage |
| $V_0$ | zero-sequence voltage |
| $I_\alpha$ | α-axes current |
| $I_\beta$ | β-axes current |
| $I_0$ | zero-sequence current |
| p | real power |
| q | reactive power |
| $p_0$ | zero-sequence power |
| $I_{c\alpha}$ | α-axes compensation reference current |
| $I_{c\beta}$ | β-axes compensation reference current |
| $I_{c0}$ | zero-sequences compensation reference current |
| $I_{ca}$ | phase a compensation reference current |
| $I_{cb}$ | phase b compensation reference current |
| $I_{cc}$ | phase c compensation reference current |
| $V_{LL}$ | line to line voltage |
| f | frequency |
| R | load |
| P | output power |

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