DEVELOPMENT OF A SINGLE PHASE ACTIVE POWER FILTER FOR RECTIFIER LOAD

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ABSTRACT

This project presents the employment of a single-phase active power filter (APF) to compensate harmonics generated by battery charger. The presence of the harmonics leads to various problems and poor power quality. The objectives of this project are to reduce the harmonic distortion of the single-phase system with battery charger load. The operation of APF is verified using the simulations in Matlab/Simulink. Conventional proportional-integral-derivative (PID) control based Shunt APF is being used to regulate the DC bus voltage and hysteresis current controller is employed to generate signal for switching purpose. The process is based on sensing line currents, filter currents and DC side capacitor voltage. The error signal caused by the filter has been computed firstly. Then this error signal has been compensated using the PID controller. The reference filter currents signal then obtained by subtracts the line current with the compensated signal from the controller. This reference current is feed to the hysteresis current controller and compare with the sensed filter currents to obtain the switching signal for active power filter. Simulation results are obtained with the conventional PID. The results are compared and analyzed. The proposed method offers an efficient control method under the varying load and supply conditions. Based on the simulation and experiment results this project verified the ability of proposed method to compensate harmonics generated by the single phase rectifier battery charger. .

ABSTRAK

Projek ini membentangkan satu fasa kuasa aktif penapis (APF) untuk membaiki harmonik yang dihasilkan oleh pengecas bateri. Kehadiran harmonik membawa kepada pelbagai masalah dan kualiti tenaga. Objektif projek ini adalah untuk mengurangkan penyelewengan harmonik sistem satu fasa dengan beban pengecas bateri. Operasi APF disahkan menggunakan simulasi dalam Matlab / Simulink . Konvensional berkadar penting terbitan (PID) kawalan berasaskan hibrid APF adalah digunakan untuk mengawal DC voltan dan arus histerisis digunakan untuk tujuan pensuisan. Proses ini adalah berdasarkan kepada arus talian sensing , arus penapis dan DC voltan kapasitor. Isyarat ralat disebabkan oleh penapis telah dikira. Kemudian isyarat kesilapan ini telah diberi pampasan menggunakan pengawal PID . Arus penapis rujukan isyarat diperolehi dengan menolak arus talian dengan isyarat pampasan dari pengawal. Ini Arus rujukan akan menghasilkan pengawal arus histerisis dan bandingkan dengan arus penapis untuk mendapatkan isyarat pensuisan untuk APF. Keputusan simulasi diperoleh dengan PID konvensional. Keputusan dibandingkan dan dianalisis. Kaedah yang dicadangkan menawarkan kaedah kawalan yang cekap di bawah beban dan bekalan syarat-syarat yang berbeza-beza . Berdasarkan kepada keputusan simulasi dan eksperimen project ini disahkan berkeupayaan untuk menapis harmonik yang dihasilkan oleh satu fasa pengecas bateri.

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURES

LIST OF SYMBOL

APF	- Active Power Filter
PID	- Proportional Integral Derivative
VSI	- Voltage Source Inverter
CSI	- Current Source Inverter
VSAFs	- Voltage Source Active Filter
CSAFs	- Current Source Active Filter
DC	- Direct Current
AC	- Alternative Current
VDC	- Voltage DC
VAC	- Voltage AC
THD	- Total Harmonic Distortion
FFT	- Fast Fourier Transform
PWM	Pulse Width Modulation

CHAPTER 1

INTRODUCTION

1.1 Project Background

In recent years, the wide use of electronic devices such as personal computer, smart phones, tablet, and even electric vehicle leads to employment of battery chargers. Battery charger is a device used to put energy into a battery by forcing current through it. In general, it consists of at least a thyristor to convert AC source to DC source. Thyristor is a non-linear device which generates harmonic in the power system line. The presence of harmonics in the system leads to various problems and poor power quality. These harmonics cause an increase in level of rms supply current, which results an increase of power loss, heating of equipment, voltage sags [1]. The application of passive filter to overcome this problem causes a few problems such as it is large in size and has fixed compensation characteristics and they may fall in series resonance with the source impedance so that voltage distortion produces excessive harmonic currents flowing into the passive filter [1].

For this project, Shunt APF is employing to the system. Generally Shunt APF is designed to eliminate the majority of the harmonic current orders. As is defined in IEEE 519-1992, harmonic voltage is created when harmonic current travels through the impedance of the electrical system toward the lowest impedance point [2]. This study has been focused on improvement of harmonic compensations for single phase system with battery charger as a load. The APF consists of voltage source inverter (VSI) with DC capacitor as an energy storage device. The DC bus capacitor voltage should be controlled to supply the power losses of filter on the system, providing that more effective filtering and reactive power compensation obtained [3]. Hysteresis current control has been used to generate switching signals for the inverter. Hysteresis control technique is used in Shunt APF applications. Hysteresis current control is a method of controlling VSI so that the output current is generated follows the reference current waveform [4]. Trends and prospects in the system are presented and simulation results are carrying out by using MATLAB/Simulink software.

1.2 Problem statement

Nowadays, AC power supply is used as a main supply for operation system. Therefore it will become a problem if the AC supply is not in its original condition due to the harmonic generated by the load especially a device which attached with the power electronic circuits. To solve this problem, harmonic filter is needed in order to remove them from the supply systems.

1.3 Objectives of project.

The main objective in this project is to implement Shunt APF based PID controller in order to reduce harmonic distortions for the system with battery charger load. Other objectives of this project are:

1. To develop a single-phase system with a battery charger load using Matlab/Simulink software.
2. To develop a Shunt APF based PID controller and implemented in Matlab/Simulink software.
3. To implement the circuit APF by applying power electronic devices.
4. To test the APF using TMS320C2800 board controller.

1.4 Scope of study.

The scope of this project is to study the characteristic and effect of the harmonics on non-linear load which is battery charger and to evaluate performance of the Shunt APF based PID controller. Other scopes of this project are:

1. The switching control strategy is hysteresis current controller based on PWM signals.
2. Using Matlab/Simulink software for the software development.
3. Construct the APF circuit in order to reduce the harmonic distortion.
4. Construct the circuits by applying power electronic devices.
5. Interface the APF circuit with Matlab/simulink using TMS320C2800 board.
6. Test the APF circuit.
7. Analysis the result.

1.5 Thesis Outline

The thesis is organized into 5 chapters which are introduction, literature reviews, methodology, simulations and results analysis, conclusion and recommendation.

Chapter I — Discuss the background and general idea of the proposed project. Besides that, the objective and scope of the project are stated in this chapter.

Chapter II — Discuss the reviews of the literature which includes the principles of technique implemented in the active harmonic filters. The brief reviews of the control strategy used in the proposed filters also mentioned in this chapter.

Chapter III — Shows the research methodology of each design stage. The details of the topology are discussed in this chapter with the operations of the system.

Chapter IV — Presents the simulation and experiment results and analyse the compensation performance of the proposed filter subject to a battery charger load. The simulation and experiment results of the systems performance have been observed.

Chapter V States the conclusions and recommendations for future works that can be done to improve the systems.

CHAPTER 2

LITERATURE REVIEW

Mitigation or cancellation of harmonics can be done by using passive or active filters. Passive filters have been used for harmonic mitigation purposes for long time ago. They consist of capacitors, inductors, and resistors. The filter is unable to adapt to the changing system conditions. Passive filters can be divided into four categories which are low pass, band-pass, high-pass, and tuned filters [6]. Nowadays, passive filters are used to cancel the switching frequency of active filters and high frequencies [7, 8].

2.1 Active Filter

This chapter reviews the development of APF technologies. The advantage of the active filtering process over the passive filter is a factor of many researches to be performed on active power filters for power conditioning and their practical applications [9]. By implementing the APF for power conditioning, it provides functions such as reactive power compensations, harmonic compensations, harmonic isolation, harmonic damping, harmonic termination, negative-sequence current or voltage compensation and voltage regulation [10]. The main purpose of the APF installation by individual consumers is to compensate current harmonics or current imbalance as well as power factor improvements of their own harmonic-producing loads. Besides that, the purpose of the

APF installation by the utilities is to compensate for voltage harmonics, voltage imbalance or provide harmonic damping factor to the power distribution systems [10].

The basic principle of APF is to produce specific currents components that cancel the harmonic components draw by the nonlinear load. The APF act as a harmonic source which is same in magnitude but opposite in direction to the harmonic caused by the nonlinear load. Reactive power required by the load also provided by APF and thus improve the power factor of the system. APF consists of an inverter with switching control circuit. The inverter of the APF will generate the desired compensating harmonics based on the switching gates provided by the controller. The crucial parts of this APF are to design the suitable controller and the filters configuration.

2.2 Classifications of Active Power Filter

Based on topology, there are two kinds of active filters which are current source and voltage source active filters. Current source active filters (CSAFs) employ an inductor as the DC energy storage device. In voltage source active filters (VSAFs), a capacitor acts as the energy storage element. VSAFs are less expensive, lighter, and easier to control compared to CSAFs [10].

2.2.1 Voltage Source Active Filters (VSAFs)

The most dominant type of active filter is the voltage source inverter-type active filter, which has been designed, improved, and used for many years and is now in the commercial stage [11,12]. Their losses are less than CSAFs and they can be used in multilevel and multistep configurations [11]. It consists of a DC-bus capacitor as energy storage and power electronic switches to generate harmonics currents according to the signal from controller.

2.3 Connections of Active Power Filter

Active harmonic filter can be connected in several power circuit configurations. In general, they are divided into three main groups which are shunt APF, series APF and Shunt APF.

2.3.1 Shunt Active Power Filter

This connection is most widely used in active filtering applications [3]-[5], [12]. It consists of a voltage or current source configurations. The voltage source inverter (VSI) based shunt APF is the most common type used today due to its well-known topology and straight forward installation procedure [11]-[12].

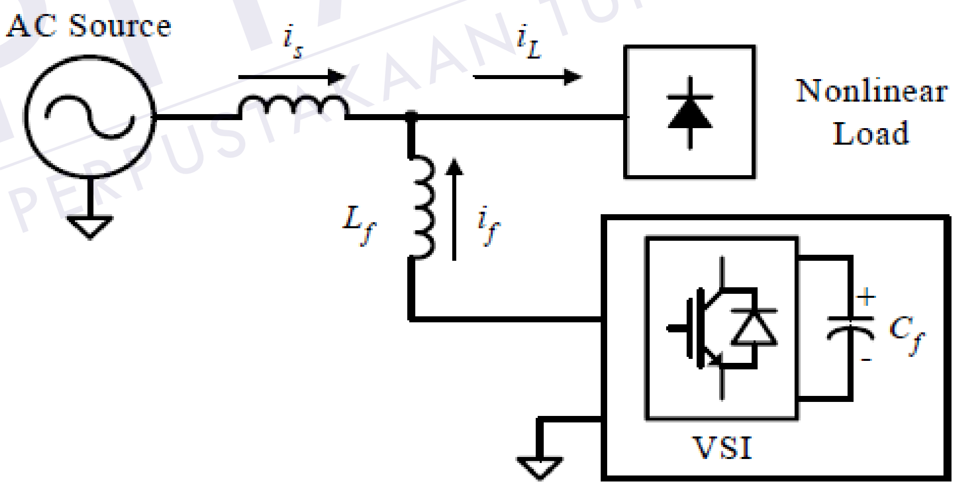

Figure 2.1 Configuration of a VSI based shunt APF

Figure 2.1 show a configuration of a VSI based shunt APF. It consists of a interfacing inductors (L_f) and VSI which is combination of a DC-bus capacitor (C_f) and power electronic switches. Shunt APF acts as a current source, compensating the harmonic currents due to nonlinear loads. The operation of shunt APF is based on injection of compensation current which is equals to the distorted current, thus eliminating the original distorted current. This is achieved by generates the compensation current waveform (i_f), using the VSI switches. The shape of compensation current is obtained by measuring the load current (i_L) and subtracting it from a sinusoidal reference. The aim of shunt APF is to obtain a sinusoidal source current (i_s) using the relationship: $i_s = i_L - i_f$

2.3.2 Series Active Power Filter

The series APF is shown in Figure 2.2. It is connected in series with the distribution line through a matching transformer [13], [14]. VSI is used as the controlled source, thus the principle configuration of series APF is similar to shunt APF, except that the interfacing inductor of shunt APF is replaced with the interfacing transformer.

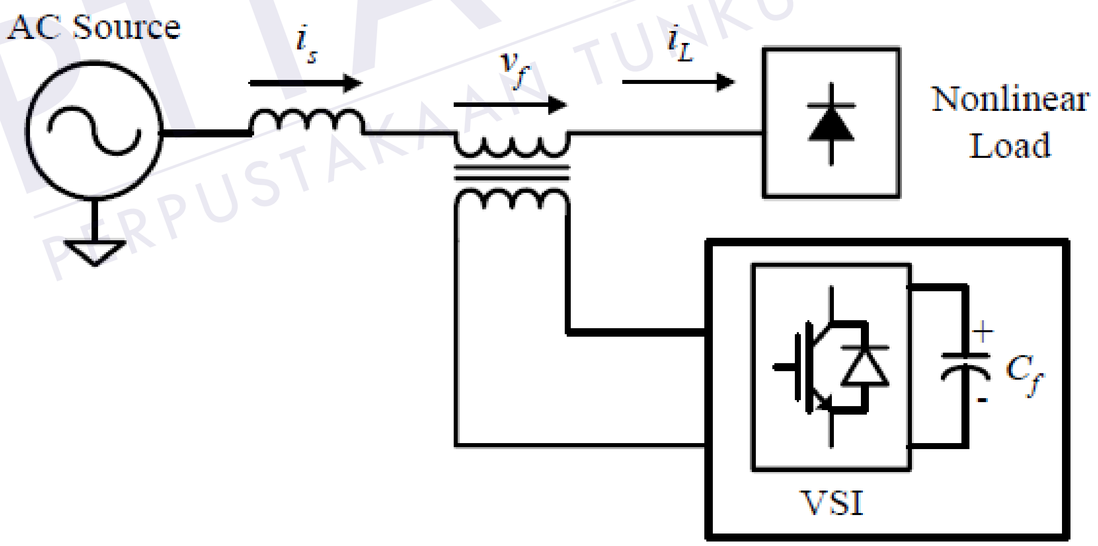

Figure 2.2 Configuration of a VSI based series APF

The operation principle of series APF is based on isolation of the harmonics in between the nonlinear load and the source. This is obtained by the injection of harmonic voltages (v_f) across the interfacing transformer. The injected harmonic voltages are added or subtracted, to or from the source voltage to maintain a pure sinusoidal voltage waveform across the nonlinear load. The series APF can be thought of as a harmonic isolator as shown in Figure 2.3. It is controlled in such a way that it presents zero impedance for the fundamental component, but appears as a resistor with high impedance for harmonic frequencies components. That is, no current harmonics can flow from nonlinear load to source, and vice versa.

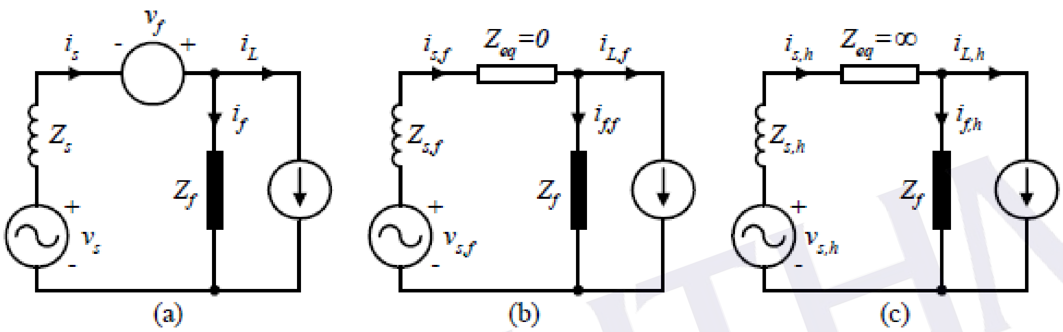

Figure 2.3 Operation principle of series APF: (a) single-phase equivalent of series APF, (b) fundamental equivalent circuit, and (c) harmonic equivalent circuit

Series APFs are less common than the shunt APF. This is because they have to handle high load currents. The resulting high capacity of load currents will increase their current rating compared with shunt APF, especially in the secondary side of the interfacing transformer. This will increase the I^2R losses [14]. However, the main advantage of series APFs over shunt is that they are ideal for voltage harmonics elimination. It provides the load with a pure sinusoidal waveform, which is important for voltage sensitive devices. With this feature, series APF is suitable for improving the quality of the distribution source voltage [12].

2.4 Reference Signal Estimations

Different kinds of control techniques are used to control APF. The reference signal to be processed by the controller is the key component that ensures the correct operation of APF. The reference signal estimation is initiated through the detection of essential voltage or current signals to gather accurate system variables information. The voltage variables to be sensed are AC source voltage and DC-bus voltage of the APF. Typical current variables are load current, AC source current and compensation current of the APF. Based on these system variables feedbacks, reference signals estimation in terms of voltage/current levels are estimated in frequency-domain or time-domain for example [3]-[5], [12],[15] report on the theories related to detection and measurement of the various system variables for reference signals estimation.

2.5 Hysteresis control

Hysteresis current control method is the most commonly proposed control method in time domain. This method provides instantaneous current corrective response, good accuracy, extreme robustness, good stability and allows fast current control [5], [12], [28]. The basic principle of current hysteresis control technique is that the switching signals are derived from the comparison of the current error signal with a fixed width hysteresis band. As long as the error is within the hysteresis band, no switching action is taken. Switching occurs whenever the error hits the hysteresis band. This control scheme is shown in Figure 2.4. The outputs of the comparator are switching gating signals to the inverter.

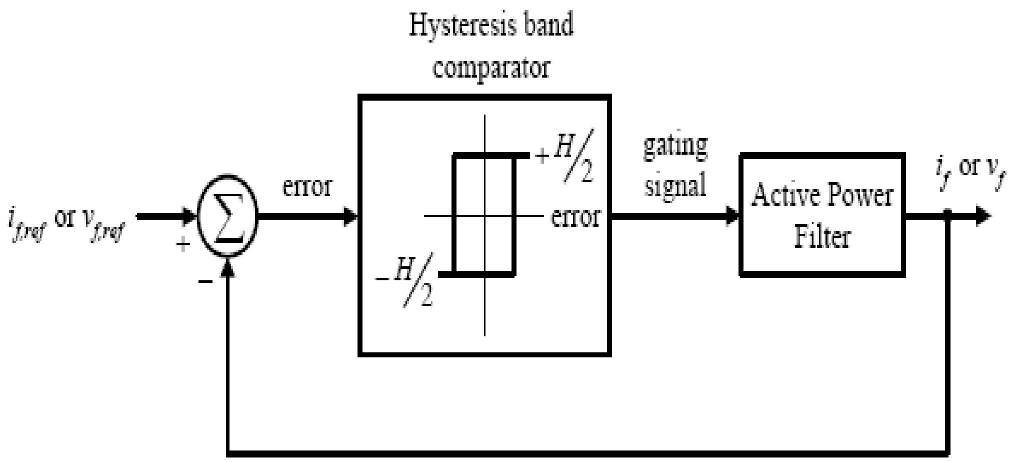

Figure 2.4 Hysteresis control technique

The APF is therefore switched in such a way that the peak-to-peak compensation current/voltage signal is limited to a specified band determined by upper band and lower band as illustrated by Figure 2.5. To obtain a compensation current with switching ripples as small as possible, the value of upper band and lower band can be reduced. However, doing so results in high switching frequency. Thus, increases losses on the switching transistors [12], [28].

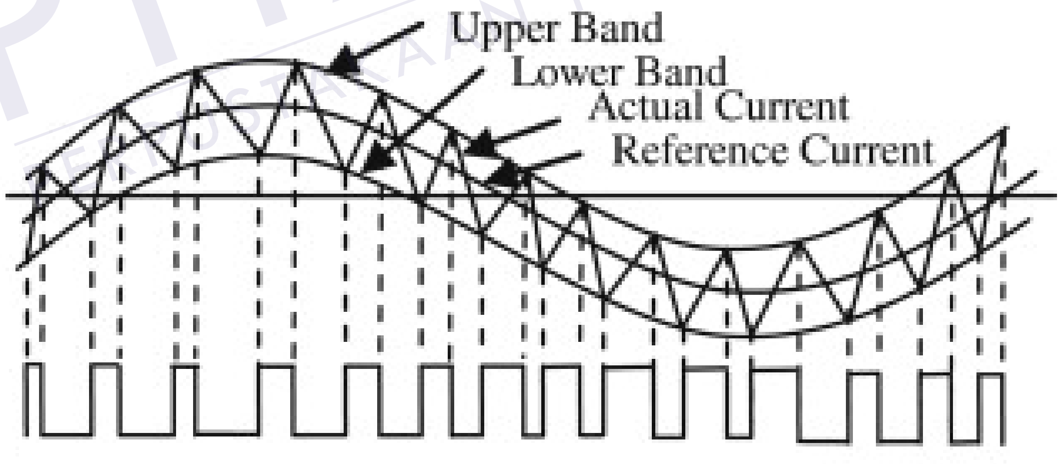

Figure 2.5 Gating signal generation

2.6 DC Voltage Regulation

The DC bus voltage must be regulated in order to set the amplitude of reference current for harmonic and reactive power compensation [28]. Practically, there are switching losses in the APF that increase with the increase in the active power or reactive power demand of the load. These losses are supplied by the capacitor, and its voltage drops. Similarly, the capacitor voltage will increase if the reactive or real power demand of the load decreases. Hence, by monitoring the capacitor voltage, the real power supplied by the APF can be estimated and the amplitude of the fundamental active component of the supply current was estimated indirectly [29].

2.7 Research Comparison

Single-phase Active Power Filter for Harmonic Mitigation in Distribution Power Lines is proposing shunt active power filter by using Fast Fourier Transform (FFT) and Sinusoidal Pulse Width Modulation (SPWM) technique. Fast Fourier Transformer (FIT) algorithm is employed to determine the magnitude and the phase of the harmonic needed to be eliminated. Sinusoidal Pulse Width Modulation (SPWM) technique is introduced to control the phase and magnitude of the inverter output. The essential advantage of this method is injecting certain harmonics with needless to the reference signal, which tremendously reduces the number of filter components and the complexity of the circuit. Then another advantage is less complex circuit, low cost and eliminate low order harmonic. For other disadvantages is not applicable for high order harmonic compensate single harmonic in a time.

Then control strategies analysis of Single-phase Active Power Filter is presented to control Shunt configuration by applying P-Q theory and Hysteresis current controller. P-Q theory is methods proposed to get the harmonic current from line current. Then hysteresis current controller used to give signal to switching the inverter. Advantages this project is feasible current harmonic detection and improves the power current. For disadvantages this control strategies is complicated to design.

Therefore a Shunt Active Harmonic Filter Based on a Voltage Detection Method for Harmonic Voltage Control is applied to control shunt configuration by using voltage detection method and D-Q transformation. A complex control factor, which can be adjusted in both amplitude and phase angle is introduced to achieve optimal operation of the filter under different natures of supply network. Voltage detection method used for suppressing harmonic voltages in a distribution system.

Single-phase Resonant Converter with Active Power Filter is designed to control shunt configuration by using sine multiplication method, PI controller and Hysteresis current control. Advantages of this project is simple, can reduce current harmonic and power factor is improved. For disadvantages is slow response and DC bus voltage unstable.

After that, Design of Single-phase Shunt Active Power Filter Based on ANN is presented to control shunt configuration by using Hysteresis current control and sine multiplication method. From this control strategy shunt active filter can be reduce current harmonic and power factor improvement is achieved. Problem from this project is complex mathematical modeling.

CHAPTER 3

METHODOLOGY

This chapter will describe the method that will be used for this project in order to achieve the desire objectives. This project development is divided into two parts. The first part represented the software development of system based on the PID controller and second part is hardware development. Figure 3.1 compressed the project development.

The project developments shown in Figure 3.1 begin by the development of the single-phase system which consists of source and load. Extensive literature reviews were done on related knowledge to assist in any ways that it may. Such reviews are based on international publications, websites, and engineering books. The system requirement for the active power filter was then determined to proceed on this project.

The next step is followed by planning on the design of the single-phase active power filter system. The PID controllers are responsible to regulate the DC bus voltage of the system and try to obtain the best performance of the system.

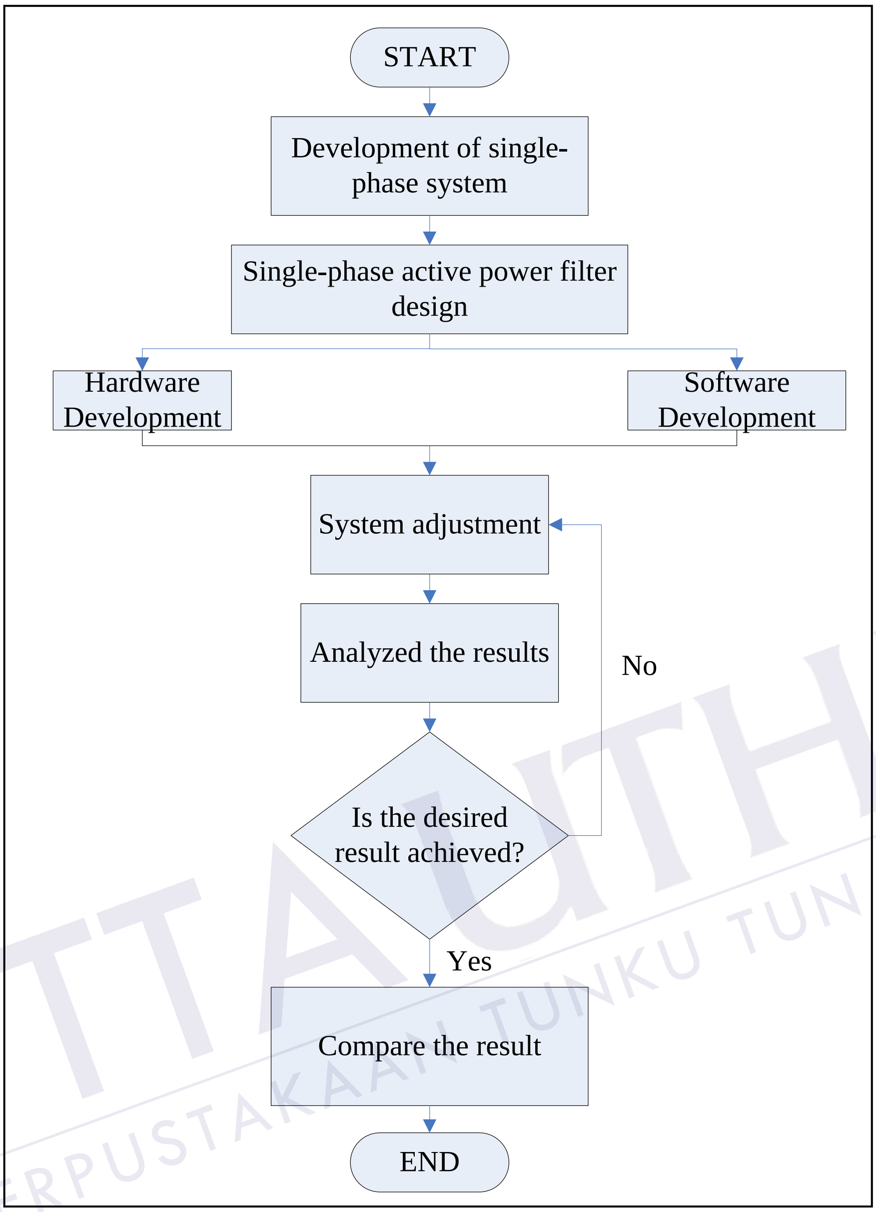

Figure 3.1 Flowchart of project activities.

3.1 System Architecture

Figure 3.2 shows the configuration between the AC source, Shunt APF and battery charger load in single-phase system that will be implemented to this project by using Matlab/Simulink. The APF part is used for compensations of the harmonic generated by the non-linear load and improve the power factor as well. It will provide harmonic signals and inject to the line between the source and the load. These harmonics are same in magnitude but opposite in phase in order to compensate the harmonics from the load. The Shunt APF also maintain the source signal in its original sinusoidal form by providing the reactive power required by the load, thus the source supply only active power to the system.

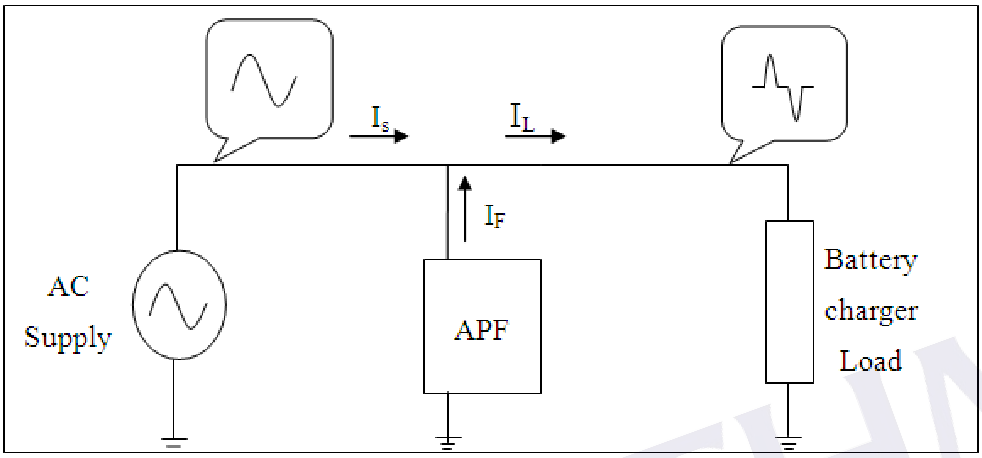

Figure 3.2 System configurations.

3.2 Reference Compensations Current

The performance of an active power filter depends on many factors, but mainly on the selected reference generation scheme [26]. If the voltage of the line supply is a pure sinusoidal waveform, the instantaneous value of the voltage can be represented as in Equation 1.

$$V_{in} = V_s \sin(\omega t) \quad (1)$$

The unit vector for input voltage, *u(t)* is generated as in Equation 2.

$$u(t) = \frac{V_{in}}{V_s} \quad (2)$$

Instantaneous value of total reference active current is obtained by multiplying the peak value of reference supply current i_{dc} with an unity sinusoidal signal, *u(t)* which is obtained from the line supply voltage at the fundamental frequency as in Equation 3.

$$I_s^*(t) = i_{dc} * u(t) \quad (3)$$

Finally, the reference compensation current of the active power filter is calculated by subtracting the instantaneous value of the total active current from the total load current in Equation 4.

$$I_F^*(t) = I_S^*(t) - I_L(t) \tag{4}$$

3.2 PID controller

Classically, PID controller has been used widely for Shunt APF. The PID controller scheme involves regulation of the DC bus capacitor voltage to set the amplitude of reference current for harmonic and reactive power compensation [29]. However, PID controller approach requires precise linear mathematical model which is difficult to obtain. It is also fails to perform satisfactory under parameter variations, non-linearity and load disturbances [15]. Figure 3.3 shows the control algorithm usually used in literature [3], [7], [13], [17], [26].

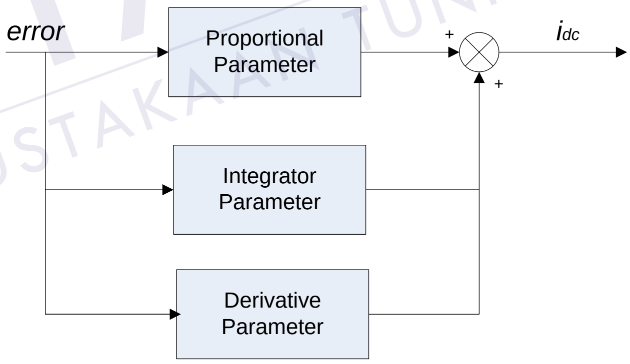

Figure 3.3 PID control algorithm

A PID controller used to control the DC-bus voltage is shown in Figure 3.3. Its transfer function can be represented as:

$$H(S) = K_P + {}^{K_I}/_{S} + K_d s \tag{5}$$

Where K_P is the proportional constant that determines the dynamic response of the DC-bus voltage control, and K_I is the integration constant that determines the settling time. If K_P and K_I are large, the DC-bus voltage regulation is dominant, and the steady-state DC-bus voltage error is low. K_P is derivative constant. The proper selection ofK_P, K_I and K_d is essentially important to satisfy above mentioned two control performances [31].

3.3 Hysteresis Current Controller

The current control strategy plays an important role in fast response current controlled inverters such as the active power filters. There are several types of current controllers such as periodical sampling, PS, hysteresis band, HB controllers and triangular carrier controllers [33]. However, the hysteresis current control method is the most commonly proposed control method in time domain. This method provides instantaneous current corrective response, good accuracy and unconditioned stability to the system. Other than that, hysteresis band current control method is used because implementation of this control is not expensive. Hysteresis current control is a method of controlling a voltage source inverter so that generating appropriate gating signals for the power switches that forces the filter current follow derived reference current.

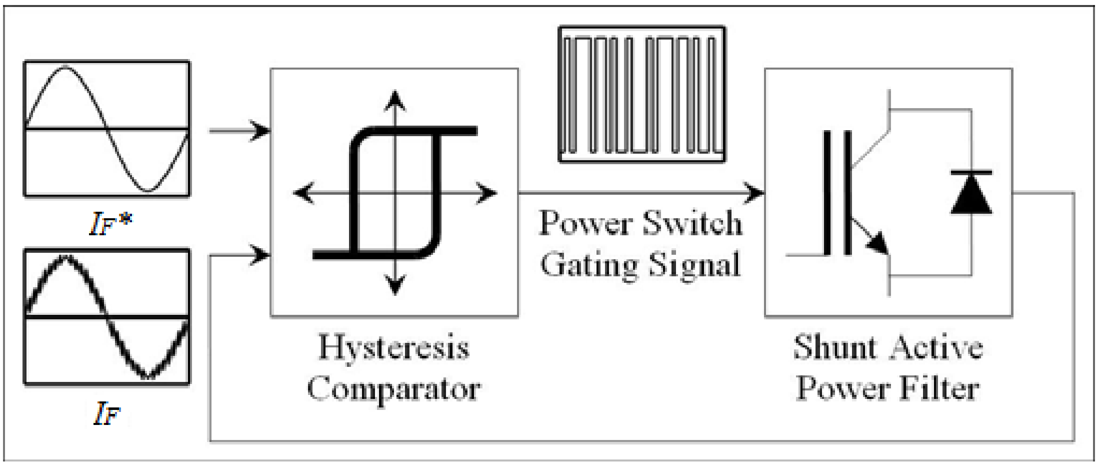

Figure 3.4 Hysteresis control technique

The operating principle of the hysteresis band current controller which is shown in Figure 3.4 depends on comparing of measured APF output current with its reference by the hysteresis comparator. The hysteresis comparator is implemented by presetting the upper and lower tolerance limits which need to be compared to the actual filter signal. The outputs of the comparator are the power switch gating signals. If the measured filter current is bigger (half of the band value) than the reference one, it is necessary to commute the corresponding power switches to decrease the output current, and it goes to the reference. On the other hand, if the measured current is less (half of the band value) than the reference one, the switches commute to increase output current and it goes to the reference. As a result, the output current will be in a band around the reference current. If the measured filter current is within the tolerance band, there will be no switching action for the filter [28].

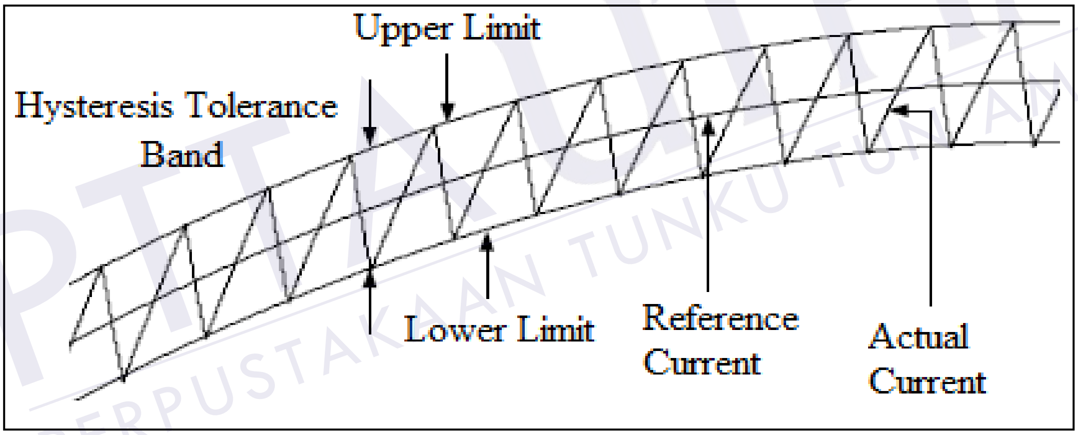

Figure 3.5 Hysteresis current control operation waveform

Figure 3.5 illustrates the ramping of the current between the two limits where the upper hysteresis limit is the sum of the reference current and the hysteresis bandwidth and for the lower hysteresis limit, it is the subtraction of the reference current and the hysteresis bandwidth. The operations of the hysteresis control technique are described below:

If $(i_f > i_f^{*} + H)$: S_1 and S_4 ON, S_2 and S_3 OFF (6)

If $(i_f < i_f^{*} - H)$: S_2 and S_3 ON, S_1 and S_4 OFF (7)

Where S_1, S_2, S_3, and S_4 are the power switching devices of the VSI and H is the hysteresis bandwidth in ampere.

3.4 Inverter Circuit

An inverter operates the inverse process of a rectifier. It converts DC power into AC power at a desired output voltage or current and frequency. The inverter circuit used in the proposed Shunt APF is a full-bridge voltage source inverter (VSI) as shown in Figure 3.6. The inverter consists of four IGBT's as switching devices connected in the form of a bridge.The output of the inverter has square waveform due to the switching pattern. In order to get a smooth signal the filter was used to remove switching frequency [34].

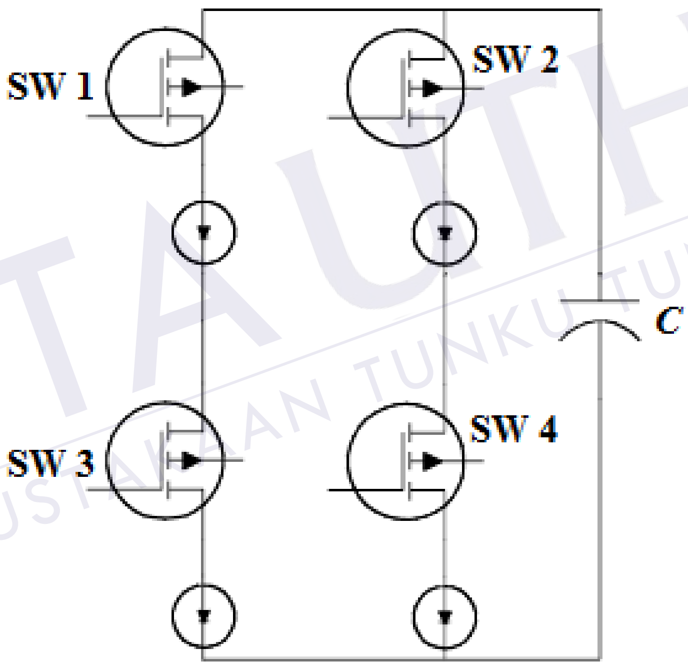

Figure 3.6 Voltage source inverter circuit

For the information, the heart of the APF system is the IGBT based Voltage Source Inverter (VSI) system. This VSI uses a DC-bus capacitor as the supply and switches at high frequency to generate a compensation current that follows the estimated current reference.

3.5 DC Capacitor

The dc side capacitor serves two main purposes: (1) it maintains a dc voltage with a small ripple in steady state, and (2) it serves as an energy storage element to supply the real power difference between load and source during the transient period. In the steady-state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate for the losses in the active filter. Thus, dc capacitor voltage can be maintained at a reference value.

3.6 Controlled Rectifier

Controlled rectifiers are line commutated ac to dc power converters which are used to convert a fixed voltage, fixed frequency ac power supply into variable dc output voltage.

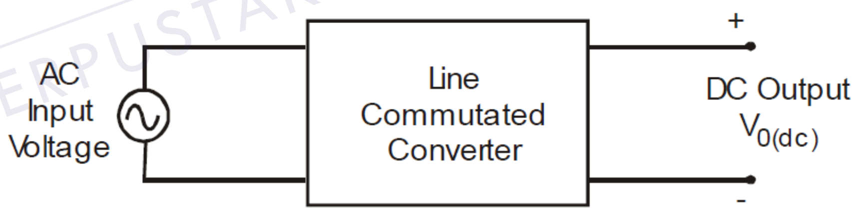

Figure 3.7 Controlled rectifier

The input supply fed to a controlled rectifier is ac supply at a fixed rms voltage and at a fixed frequency. The variable dc output voltage can obtain by using controlled rectifiers. By employing phase controlled thyristors in the controlled rectifier circuits The variable dc output voltage and variable dc (average) output current is obtain by varying the trigger angle (phase angle) at which the thyristors are triggered. The thyristors are forward biased during the positive half cycle of input supply and can be turned ON by applying suitable gate trigger pulses at the thyristor gate leads. The thyristor current and the load current begin to flow once the thyristors are triggered (turned ON) say at $\omega t = \alpha$. The load current flows when the thyristors conduct from $\omega t = \alpha$ to β. The output voltage across the load follows the input supply voltage through the conducting thyristor. At $\omega t = \beta$, when the load current falls to zero, the thyristors turn off due to AC line (natural) commutation.

CHAPTER 4

RESULT AND ANALYSIS

This chapter is dedicated to the Matlab/Simulink simulation verification of the proposed single-phase Shunt active power filter (APF). This chapter also elaborates the results from the simulation and experiments by using PID controller. The results from simulation and experiment are presented step by step. Finally, analysis on the Total Harmonic Distortion (THD) for the Shunt APF is carried out.

4.1 System Modeling

The result data from simulation and experiment are carried out. This data used in control strategy for Shunt APF to reduce the harmonics by using PID controller. When using this data in simulation it will show the THD will reduce and it also proved in experiment. Then it can be conclude the goal or objective this project can be achieved by using this data. The parameters data that are used in this project are listed in Table 4.1.

Table 4.1 Circuit parameter of system

Source voltage	28 V
Source frequency	50 Hz
DC bus capacitor	3290 μf
DC bus reference voltage	48 V
Filter inductance	6 mH
Hysteresis band	0.01A
Load resistor	18 Ω
Load battery capacity	27 VDC

4.2 System Simulation without APF

Figure 4.1 shows a single-phase system without Shunt APF. It consists of a single-phase AC source and nonlinear load which is battery charger. The load is a combination of rectifier circuit, resistive load and battery to be charged.

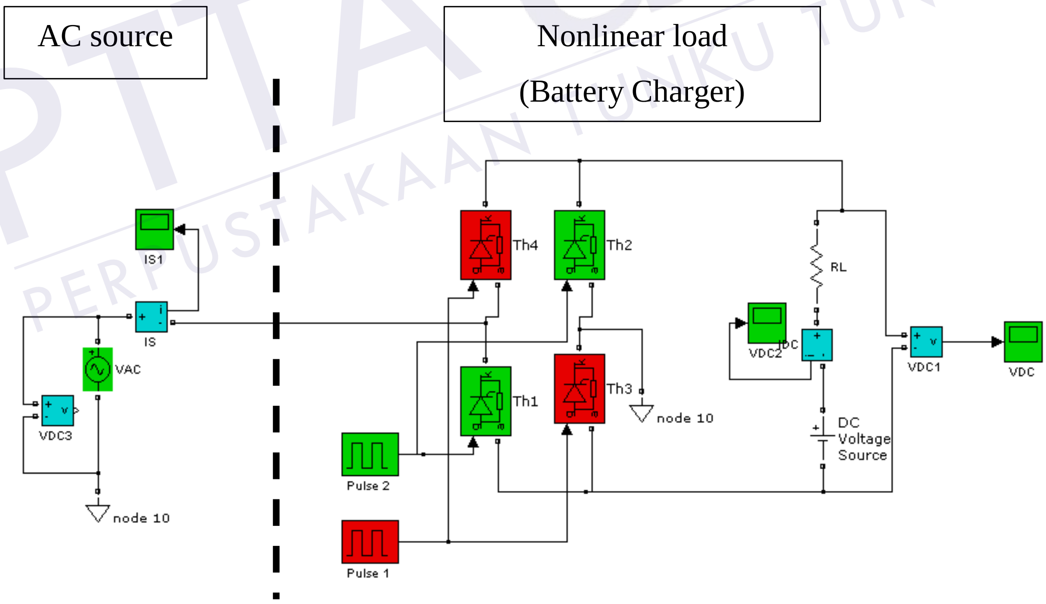

Figure 4.1 Single-phase systems without shunt APF

A single-phase controlled rectifier load is applied to the system in order to obtain the distorted load current. Figure 4.2 shows the simulated load current waveform without any type of compensation. As can be seen, the resulting load current is highly distorted with the harmonic profile of the source current as shown in

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