SHUNT ACTIVE POWER FILTER PERFORMANCE BASED ON SYNCHRONOUS REFERENCE FRAME (SRF) FOR DIFFERENT LOAD CONDITION

TAN ZI HAO

BACHELOR OF ELECTRICAL ENGINEERING WITH HONORS
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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A report submitted
in partial fulfillment of the requirements for the degree of
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2019

DECLARATION

I declare that this thesis entitled "SHUNT ACTIVE POWER FILTER PERFORMANCE BASED ON SYNCHRONOUS REFERENCE FRAME (SRF) FOR DIFFERENT LOAD CONDITION is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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APPROVAL

I hereby declare that I have checked this report entitled “SHUNT ACTIVE POWER FILTER PERFORMANCE BASED ON SYNCHRONOUS REFERENCE FRAME (SRF) FOR DIFFERENT LOAD CONDITION” and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Electrical Engineering with Honours

Signature : ....

Supervisor Name : ....

Date : ....

DEDICATIONS

To my beloved mother and father

ACKNOWLEDGEMENTS

I wish to express my appreciation to my project supervisor, PROF. MADYA. IR. DR. ROSLI BIN OMAR, for his guidance and encouragement. This project would not have been same as presented here, without the continued help and interest from him

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My sincere appreciation also extends to all my friends and others who have aided at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family members

ABSTRACT

The distorted waveforms due to highly uses of the non linear load, especially the current that is considered the main issues need to be addressed seriously. The issues of the distorted waveforms for the current have attracted many researchers to recover them in the electrical system. There are so many electronic devices that have been used in order to protect the waveform of the current from distorted as it is very dangerous and may cause the main supply to shut down or burnt. The main aims of this project is to design and develop a shunt active power filter for the purposes to mitigate the distorted of current waveform produced by the different types of non linear loads using the controller of the SRF. The software MATLAB/SIMULINK will be used to design and develop shunt active power filter and its controller. Finally the performance of the shunt active power filter and its controller at different types of non linear loads will be evaluated through the waveforms of the currents produced by different types of non linear loads and the Total Harmonic Distortion (THD) will be monitored and observed whether meets to the International Electrical Committee (IEC) standard or not.

Keywords: controller, non linear load, harmonics, shunt active power filter, SRF

ABSTRAK

Gelombang elektrik ubah bentuk disebabkan oleh penggunaan beban bukan linear, terutamanya aurs yang dianggap sebagai isu utama perlu ditangani dengan serius. Isu-isu bentuk gelombang yang terganggu untuk masa kini telah menarik ramai penyelidik untuk memulihkannya dalam sistem elektrik. Terdapat banyak alat elektronik yang telah digunakan untuk melindungi bentuk gelombang arus dari menyimpang kerana ia sangat berbahaya dan boleh menyebabkan bekalan utama ditutup atau dibakar. Matlamat utama projek ini adalah untuk merekabentuk dan membangunkan penapis kuasa aktif shunt untuk tujuan mengurangkan ubah bentuk gelombang arus yang dihasilkan oleh pelbagai jenis beban bukan linear menggunakan pengawal SRF. Perisian MATLAB / SIMULINK akan digunakan untuk merekabentuk dan membangunkan penapis kuasa aktif shunt dan pengawalnya. Akhirnya prestasi penuras kuasa aktif shunt dan pengawalnya pada pelbagai jenis beban bukan linear akan dinilai melalui bentuk gelombang arus yang dihasilkan oleh pelbagai jenis beban bukan linear dan Total Distortion Total Harmonic (THD) akan dipantau dan diperhatikan sama ada memenuhi standard Jawatankuasa Elektrik Antarabangsa (IEC) atau tidak.

Kata kunci: pengawal, beban bukan linear, harmonik, penapis kuasa aktif shunt, SRF

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LIST OF SYMBOLS AND ABBREVIATIONS

SAPF	-	Shunt Active Power Filter
SRF	-	Synchronous Reference Frame
THD	-	Total Harmonic Distortion
APF	-	Active Power Filter
SMPS	-	Switch Mode Power Supply

CHAPTER 1

INTRODUCTION

1.1 Introduction

In the modern era, electricity is indispensable to everyone. Human use electronic devices in their daily life. Therefore, power quality is important as it will affect the electronic devices. However, the power quality is not perfect all the time. There are nine common power quality problems which include voltage sag, short interruptions, long interruptions, voltage spike, voltage swell, harmonic distortion, voltage fluctuation, noise, and unbalance voltage. Each of these power quality problems will bring damage to the power system. For harmonic distortion, the consequences are shortening the lifespan of equipment. Harmonic distortion will cause excessive heat and leads to malfunction in electronic devices [1].

In order to prevent the damage lead by harmonic distortion, standards has been set both internationally and nationally. According to IEEE-519, harmonic voltage distortion on power system 69kV and below is limited to 5.0% total harmonic distortion (THD) with each individual harmonic limited to 3%. Another standard set by IEC declared that for 400V power system, the total harmonic distortion is limited to 5%. For 6.6kV, 11kV and 20kV power system, the THD is limited to 4%. In Malaysia, TNB declared that the THD in 400V power system is limited to 5%, 4% for 11kV to 22kV power system, and 3% for 33kV and 132kV power system.

To overcome the power quality problem, passive power filters were introduced. Passive power filter is used to minimize the harmonic distortion in power system. However, there were many disadvantages such as the size of passive power filter is large, it will cause resonance with the power system, and its fixed compensation characteristics [2]. To improve the power quality, active power filters (APF) was introduced to overcome the disadvantages of passive power filters. Active power filters can be classified into shunt active power filter and series active power filter. The function of shunt active power filter and series power filter are different. Shunt active power filter is used to reduce the current harmonics in power system.

1.2 Problem Statement

An important issue in the quality is that the distorted waveform of the current which are produced by the non-linear load. The distorted waveforms of the current is dangerous as it will cause the electrical equipments will damage or malfunction. They are so many electronic devices are used in order to protect the distorted current waveform among the popular device is called an active power filter. Actually the performance of the active power for mitigating the distorted waveform is totally depend on the controllers. As, there exist many controllers which are applied to the active power filtering, still, the SRF technique is widely accepted in the active power filter application. This controller is able to minimize the contains of the harmonics of the current waveform.. This work will concerned with the design and model of the active power filter with its controller using MATLAB/SIMULINK software for the aims of the harmonic minimization of the current waveform

.

1.3 Objective

i) To study the operation of shunt active power filter and the controller applied in shunt active power filter.

ii) To design and model of shunt active power filter and its controller based on synchronous reference frame.

iii) To analyse the performance of shunt active power filter and its controller.

1.4 Scope

The scope of the project is to study, model, and analyse the function of shunt active power filter and its controller based on synchronous reference frame. This project will focus on the distortion of the waveform of the current. The overall system for this project comprises of the supply, loads and the active power filter and its controller. Normally the active power filter is installed between the supply and the load . The distorted current waveforms which are produced by the non-linear loads will be observed The performance of the active power filter with its controller will be analyse.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter included literature review, project background and the theory that needs to be studied related to the shunt active power filter based on synchronous reference frame (SRF) for different load condition.

An overview of this project and project background will be discussed in the first section of this chapter. The theory and working principle of shunt active power filter based on the synchronous reference frame will be presented. A summary of the literature review will be presented in the last section of this chapter.

2.2 Overview of Active Power Filter

In 1970s, active power filter was developed to diminish the harmonic currents in power system. Active power filter produces either harmonic currents or voltages in a way that retains the sinusoidal form of the current and voltage waves in the power system [5]. Without active power filter, harmonic distortion will occur when the power system is connected to non-linear load. Active power filter can be categorised as series active power filter or shunt active power filter based on their function. The function of series active filter is to lessen the voltage harmonics in power system. For shunt active filter, it is used to diminish the current harmonics in power system. Active power filter possess many advantages such as supply reactive currents, do not cause harmful power system resonances. The performance of active power filter is independent of the properties of the power system.

2.3 Shunt Active Power Filter

The function of shunt active power filter is to reduce the current harmonic in power system. To reduce the current harmonic, the shunt active power filter produces a same amplitude but 180° opposite phase current. The current produced by shunt active power filter will cancel out the current harmonic.

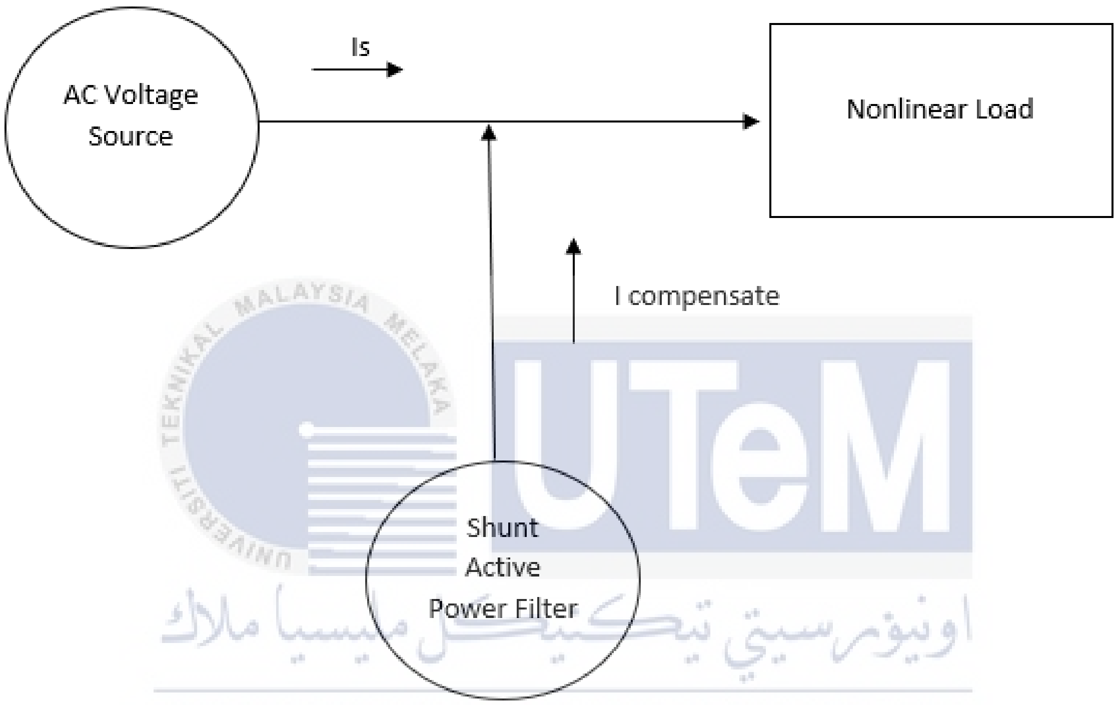

Figure 2-1 Basic scheme of shunt active power filter

Over the years, many control strategies were introduced to control shunt active power filter to generate current that responsible for reducing the current harmonic in power system. The performance of shunt active power filter varies with different control strategy.

2.4 Overview of Control Strategy for Shunt Active Power Filter

In recent year, many controllers is used to improve the performance of shunt active power filter.

In [9], hysteresis current control techniques is employed to control the magnitude and phase angle of the current injected by shunt active power filter. DSP TMS320LF2407 is also implemented to control the shunt active filter. The author claimed that the THD of the source current improves from 11% to 4%. The author also claimed that the input power factor is enhanced from 0.91 to unity.

In the previous study by Arpit Shah and Nirav Vaghela [3], hysteresis current control and instantaneous reactive power theory is used to control the shunt active power filter. The author carried out the study using two different kind of loads which is resistive rectifier load and inductive rectifier load. The author claimed that for resistive rectifier load, THD of source current improved from 27.17% to 1.02%. The author also claimed that THD of source current improved from 25.82% to 2.46% for inductive rectifier load.

From the previous researches by Jarupula Somlal, Venu Gopala Rao.Mannam , Narsimha Rao. Vutlapalli [10], ANN based shunt active power filter is implemented in power system to boost its power quality. The author claimed that the %THD is reduced from 29.71% to 2.27%. Joao Afonso , Mauricio Aredes , Edson Watanabe , Julio Martins [11] had also studied shunt active filter to enhance power quality. The author used digital control in shunt active power filter to enable dynamic power factor correction. The digital control also permit harmonic current compensation and zero-sequence current compensation. The author used instantaneous power theory (p-q theory) to model shunt active power filter. The proposed shunt active power filter were employed using a standard 16 bits microcontroller. Somlal Jarupula et al. [12] has used fuzzy based hybrid active power filter in power systems to boost the power quality. The author claimed that the fuzzy based hybrid active power filter (FHAPF) is able to minimize harmonics and improve the power factor of a power system. In this design, the author used Generalized PI control unit and fuzzy adjustor unit as the controller of FHAPF. The author proposed generalized PI control unit to in order to achieve dividing frequency control. To create better adaptive potential and dynamic response, the author had implemented fuzzy adjustor unit to adjust the parameters of the PI control unit. The author claimed that the power factor has been improved from 0.6 to 0.985 and the %THD is reduced to 0.78% from 21.34%.

C Nalini Kiran et al. [13] had carried out a study using instantaneous power theory for active power filter with PI and hysteresis current controller. The research is carried out under open loop system and closed loop system. The author claimed that the %THD for open loop with nonlinear load is 14.12%, 18.26% for open loop with composite load and 2.75% for closed loop with composite load.

From previous researches by A.Sakthivel et al. [14] , SRF based control algorithm is applied on three phase shunt active power filter. Synchronous Reference Frame (SRF) theory is used to calculate compensating currents. The author constructed a three-phase source that is feeding a highly non-linear load. The author claimed that the %THD in the source current is reduced to 2.58%.

From the previous researches by R.Sheba Rani et al. [15] ,PSPWM based Five-Level Shunt Active Filter is employed to power system network to enhance power quality. The author used Phase-Shifted carrier PWM technique to produce the gate drive signals of the inverter. The author claimed that the %THD in source current is maintained within nominal values of 3.27% with the balanced non-linear type of load. From the previous researches by Sanvog Dubey et al.[16], a three-phase four wire neutral clamped active power filter is employed to minimise the harmonics and reactive power created by non-linear balanced and unbalanced low power loads in steady state and in transients. From the previous researches by Niklesh Das et al. [17], a shunt active power filter is implemented to enhance the power quality of three phase system. The proposed shunt active power filter is based on the instantaneous active and reactive current component (Id-Iq) method. The author also studied the synchronous detection method. A PI controller for the (Id-Iq) control strategies for different voltage condition is implemented.

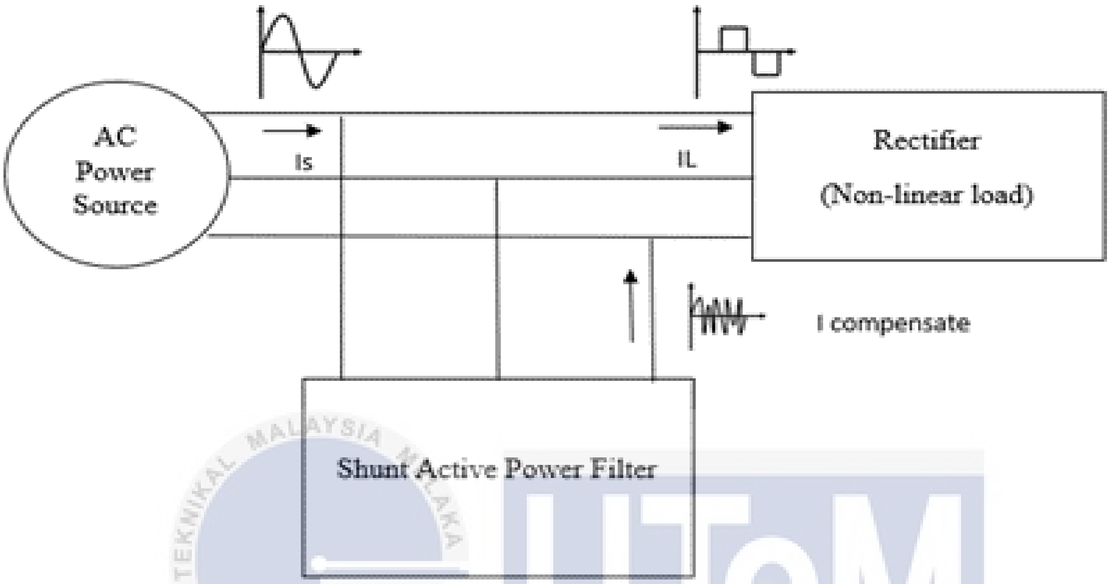

Figure 2-2 Basic scheme of three-phase shunt active power filter with distribution network

In [18], a fuzzy logic controller based three-phase shunt active power filter is used to mitigate harmonics and reactive power under unbalanced mains voltages. The author used instantaneous reactive power (p-q) theory to calculate the reference current of the shunt active power filter. The author applied the system based on PLL (Phase Locked Loop) in order to control the shunt active power filter under unbalanced mains voltage. The author also used hysteresis controller to generate switching signals of the voltage source inverter. The author claimed that the current THD is reduced from 20.18% to 1.89%. In [19], PI, fuzzy logic controlled shunt active power filter is applied on three-phase four-wire systems with balanced, unbalanced and variable loads to mitigate harmonic distortion. The author used Fast Fourier Transform method to calculate the reference compensation current. The author claimed that the %THD for balanced, unbalanced and variable load is below 5% for both PI controlled SAPF and fuzzy logic controlled SAPF.

In [20], hierarchical neuro-fuzzy current control scheme is proposed to improve the performance of a single fuzzy controller. An ANFIS based neuro-fuzzy controller is connected hierarchically to a single fuzzy controller. In [21], synchronous reference frame PI based controller with anti-windup scheme is applied to shunt active power filter to enhance the harmonic filtering. The author claimed that this method can compensate the winding up phenomenon caused by the integral term of the PI controller. The author claimed that the %THD decreased from 12.45% to 3.87%. From the previous research by K. Sreenubabu and Mr. B. Ranganaik [22], a novel fuzzy logic controller based shunt active power filter is proposed to reduce the harmonic in power system. The author used PI controller based and fuzzy logic controlled three-phase shunt active power filter to mitigate harmonics and reactive power by nonlinear load. The author claimed that fuzzy control does not require a mathematical model of the system. The author claimed that the source current THD is reduced from 27.88% to 2% for PI controller and 2.89% for fuzzy controller. In [23], the author studied PI, fuzzy and ANFIS control of three-phase shunt active power filter in power quality improvement and harmonic mitigation. The author used hysteresis control to control the current in PWM inverter. The author claimed that the %THD is reduced to 3.89% for PI controller, 2.24% for fuzzy controller and 2.10% for ANFIS controller.

From the previous study by B. Mazari and F. Mekri [24], fuzzy hysteresis control is used to enhance the parameters of shunt active power filter. The author implemented fuzzy hysteresis band techniques in this design to derive the switching signals. This technique also used to select the best value of the decoupling inductance. To optimize the energy storage, a DC voltage controller is used. The author claimed that the %THD under fuzzy hysteresis current controller decreased from 29.5% to 2%. In [25], fuzzy logic controller is used to control the shunt active power filter to eliminate the harmonics in the power system. The author claimed that the %THD decreased from 27.28% to 2.29%. In [26], a fuzzy logic controlled shunt active power filter is used to mitigate harmonic and improve power quality. To extract compensated reference harmonic current, the author employed Instantaneous Reactive Power Algorithm to the design. The author improved the active filter dynamic by apply Hysteresis Band Current (HBC) to balance the DC capacitor voltage of shunt active power filter. . The author claimed that the %THD is maintained within the limit of the harmonic standard recommendation of IEEE 519-1992 on harmonics level.

In [27], a fuzzy logic controlled shunt active filter is also studied to improve the power quality. The author proposed a novel control strategy. The author incorporate the inverter with active power filter functionality to transform the inverter to multifunction device. The author claimed that the %THD is reduced to 2.49%.

2.5 Harmonics

Harmonics are undesired AC voltages and currents in a power system that contain non-linear loads. The frequency of harmonics are integer multiples of the fundamental frequency of normal AC voltages and currents. The power conversion method employed to non-linear load caused the existence of harmonics. The basic calculation of harmonics in power system is depends on the fundamental frequency of the distribution system. For example, the 2^{nd} harmonic in a 50Hz system can be calculate by 50 times 2 which is 100Hz. However, for a 60Hz power system, the 2^{nd} harmonic will be 120Hz which is 60 times 2. In a three-phase power system, there is only odd-order harmonics (3^{rd}, 5^{th}, 7^{th}, 9^{th}) but no even-order harmonics is presented. Electronics equipment with non-linear load such as computer are consuming current in abrupt short pulses. The short pulses created will misshape the fundamental sinusoidal wave of the AC power system. The non-sinusoidal wave which is harmonic will flow back into the power system source and flow to other parts of the power system. Harmonic distortion is more common in a power system that connected to many electronic devices such as computer, fluorescent light and variable speed drives [30].

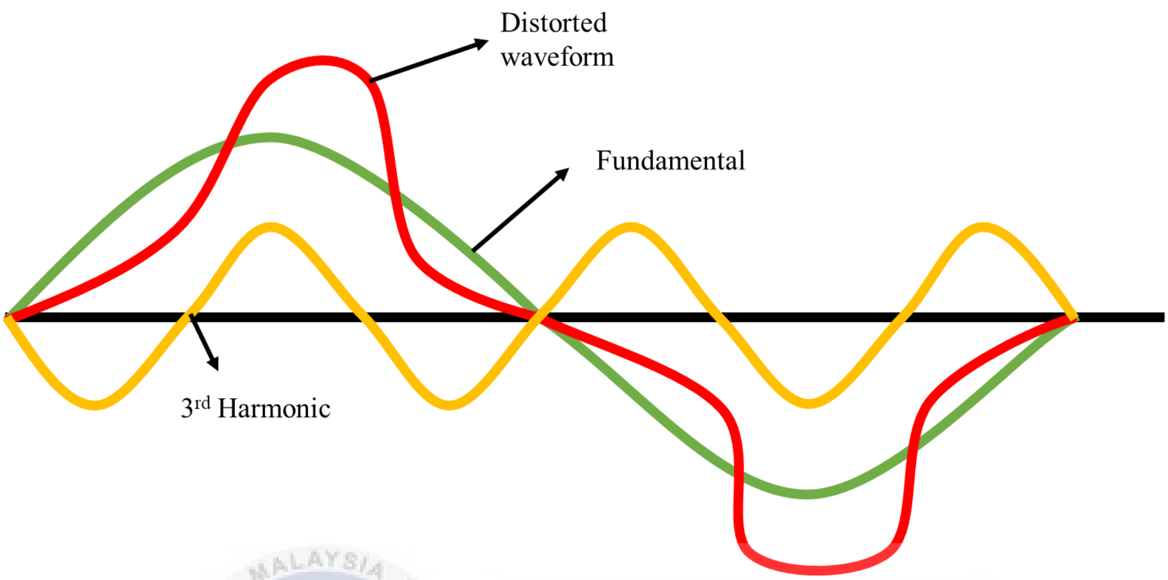

Figure 2-3 Waveform of harmonics [29]

2.5.1 Total Harmonic Distortion

Total harmonic distortion (THD) is a measure of the effective value of the distorted sinusoidal waveform's harmonic components. Normally, total harmonic distortion is used to relate with voltage harmonic distortion. However, total harmonic distortion is also used to calculate current harmonic distortion in a power system. The following equation is used to measure and calculate THD in a power system:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} M_h^2}}{M_1} \tag{2.1}$$

Where,

Mh = individual harmonic component

M1 = fundamental component

M can be either voltage or current

In Matlab/Simulink, THD can be calculated using FFT analysis function.

2.6 Synchronous Reference Frame Theory

Synchronous reference frame theory also called d-q theory. This theory needs only simple calculation and only algebraic calculation is involved. Therefore synchronous reference frame theory is applied extensively in shunt active power filter [33]. This theory is developed in time domain based reference current generation. The basic concept of synchronous reference frame is it transform load current to the d-q synchronous reference coordinate. Only d and q is considered in this theory. In SRF, a high pass filter is needed. A SRF based controller do not required voltage info. However, the SRF based filtering is not going to work when the load is imbalanced.

The Park Transform method is used to transform the load current. The following equation shows Park Transform:

$$\begin{bmatrix} id \\ iq \\ i0 \end{bmatrix} = \frac{2}{3} \times \mathrm{K} \times \begin{bmatrix} iLa \\ iLb \\ iLc \end{bmatrix} \quad (2.2)$$

Where,

$$\mathrm{K} = \begin{bmatrix} \cos(wt) & \cos(wt - \frac{2\pi}{3}) & \cos(wt + \frac{2\pi}{3}) \\ -\sin(wt) & -\sin(wt - \frac{2\pi}{3}) & -\sin(wt + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (2.3)$$

Inverse Park Transform is performed to calculate the current source reference in three-phase system. The following equation shows inverse Park Transform:

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = K_{inv} \times \begin{bmatrix} id \\ iq \\ i0 \end{bmatrix} \quad (2.4)$$

Where,

$$K_{inv} = \begin{bmatrix} \cos(wt) & -\sin(wt) & 1 \\ \cos(wt - \frac{2\pi}{3}) & -\sin(wt - \frac{2\pi}{3}) & 1 \\ \cos(wt + \frac{2\pi}{3}) & -\sin(wt + \frac{2\pi}{3}) & 1 \end{bmatrix} \tag{2.5}$$

2.7 Non-linear Load

Non-linear load is a load that changes its impedance according to applied voltage. The current drawn by non-linear load is not sinusoidal even when the voltage source is a sinusoidal source. The non-sinusoidal currents is called harmonic currents. Harmonic currents will cause voltage distortion in a power system. The voltage distortion will affect the power system and others load that is connected to it. The introduction of Switch-mode Power Supply (SMPS) causes wide spread of non-linear load. SMPS is implemented on almost every power electronic devices that are widely use today [34].

CHAPTER 3

METHODOLOGY

3.1 Introduction

The methodology of this project can be divided by five stages as follows;

In stage 1, the previous works on shunt APF, regarding topologies, control scheme, and applications will be reviewed. Investigation on the different techniques of the cotrollers used in shunt APF especially for SRF is necessary in order to develop a simple formulation of control strategy.

In stage 2, a formulation of SRF method will be applied for shunt APF topology.

In stage 3, once the formulation of the control strategy is developed, the MATLAB/SIMULINK simulation package will be used for this purpose. In particular, new formulation will be formed that have not been previously reported in the literature for shunt APF configuration.

In stage 4, the proposed control strategy based on SRF will be applied to the three phase shunt APF. In this work, the complete switching solutions will reduced the total harmonic distortion in power system.

In stage 5, the proposed model of the shunt APF will be modelled using MATLAB/SIMULINK and the control strategy based on SRF, the complete modelling and its controller will be running in order to obtain the simulation. The results of the simulations with different types of non linear load will be monitored and analysed based on its THD values. The obtained THD values then will be compared with IEC standard.

The methodology of this project can be summarized by using a flow as illustrated below;

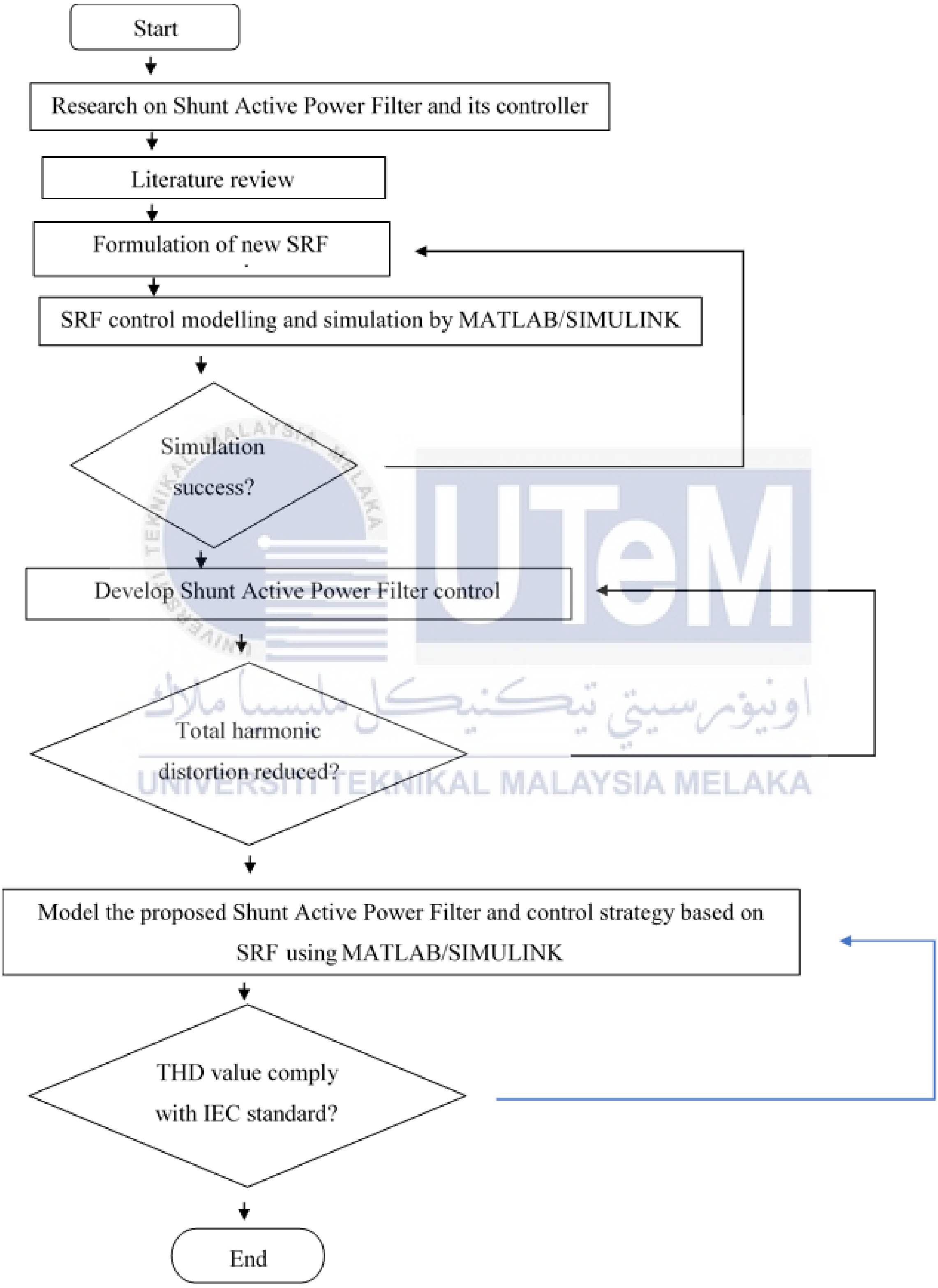

Figure 3-1 Project flow

3.2 Sample Model of Shunt Active Power Filter

Figure 3.2 and Figure 3.3 shows the Simulink model of three-phase power system that is used in this project. The model consists of AC voltage source, ground, inductor, current measurement block, ammeter, powergui block, three-phase VI measurement block, and bridge diode harmonic source block and series RLC branch block.

Figure 3.4 to Figure 3.12 displayed similar Simulink model as in Figure 3.2 and Figure 3.3. However, the Simulink model from Figure 3.4 to Figure 3.12 consist of passive filter and SRF based Shunt Active Power Filter.

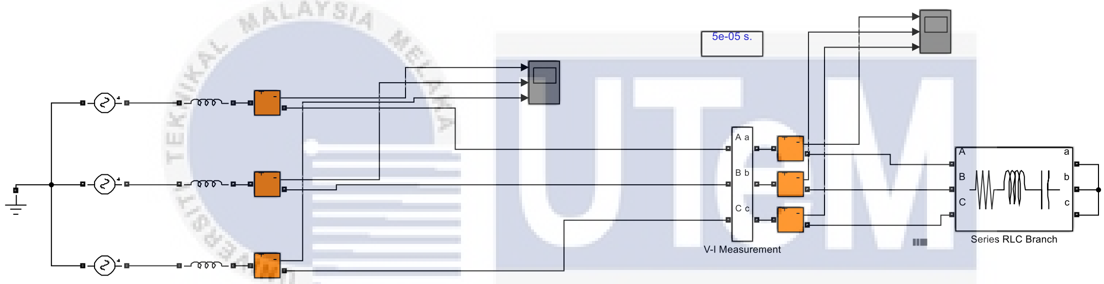

Figure 3-2 Simulink model of three phase power system with linear RLC load

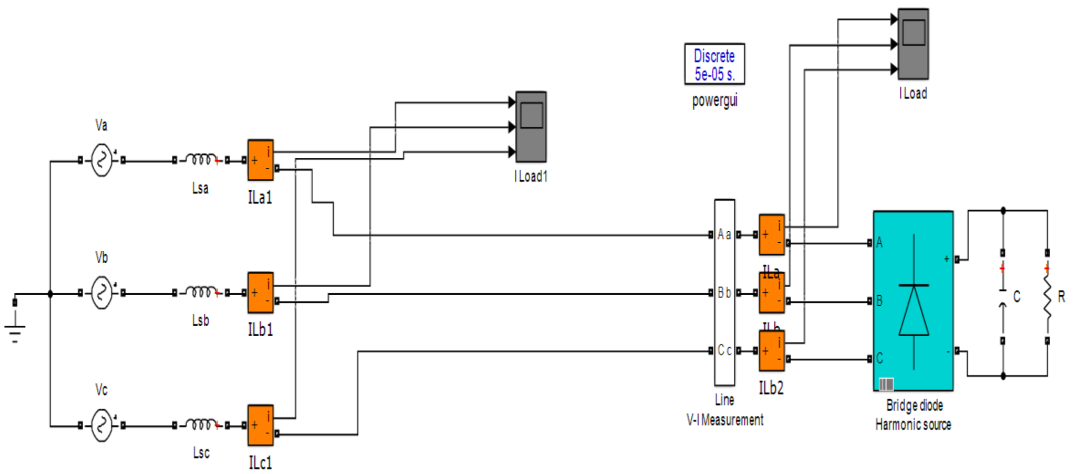

Figure 3-3 Simulink model of three phase power system with diode rectifier

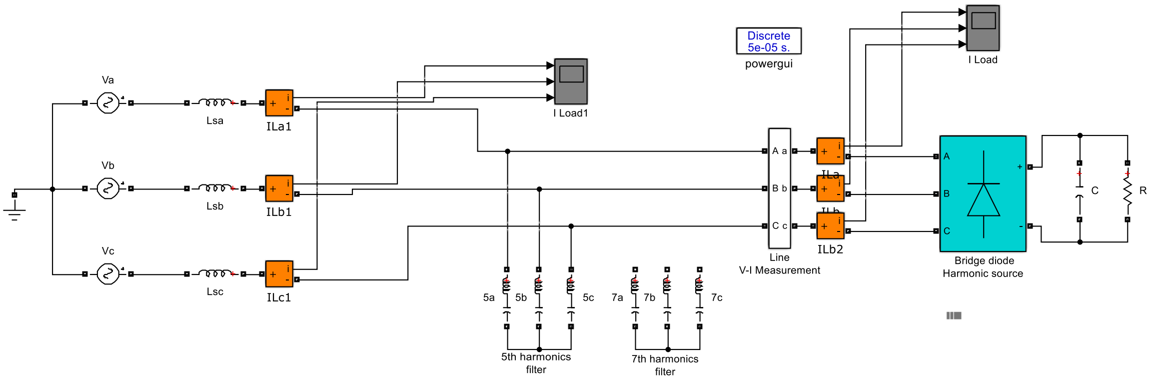

Figure 3-4 Three phase power system with diode rectifier and 5th harmonic filter

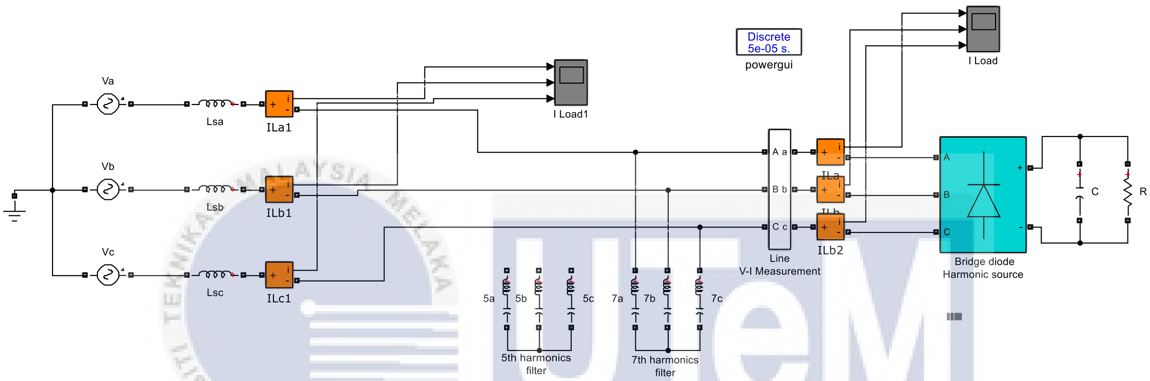

Figure 3-5 Three phase power system with diode rectifier and 7th harmonic filter

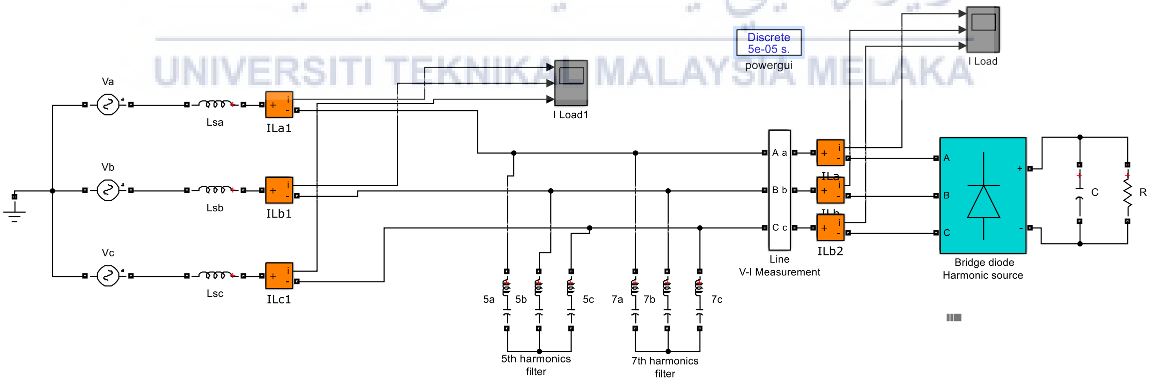

Figure 3-6 Three phase power system with diode rectifier and 5th and 7th harmonic filter

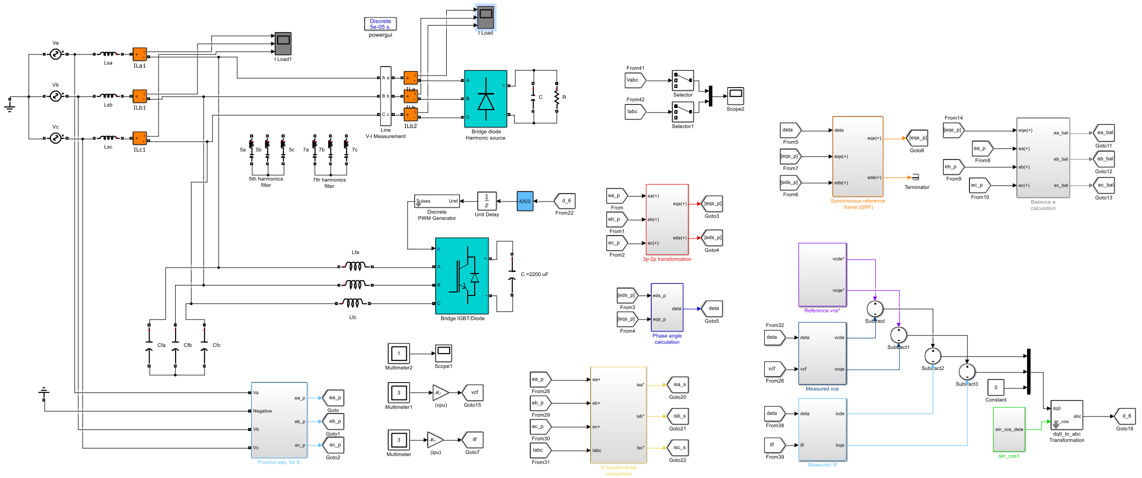

Figure 3-7 Three phase power system with diode rectifier and SRF based SAPF

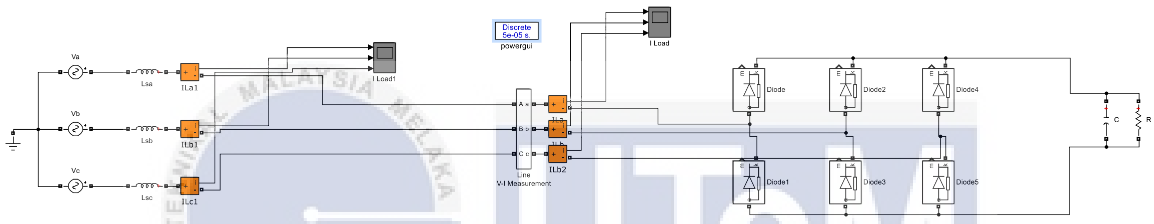

Figure 3-8 Three phase power system with 6 pulse rectifier

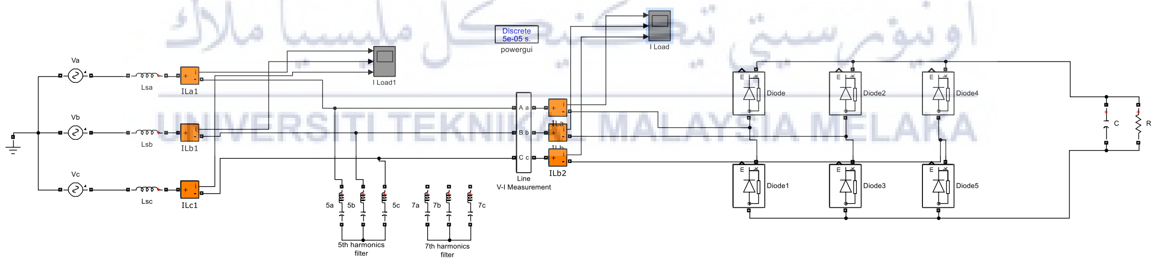

Figure 3-9 Three phase power system with 6 pulse rectifier and 5th harmonic filter

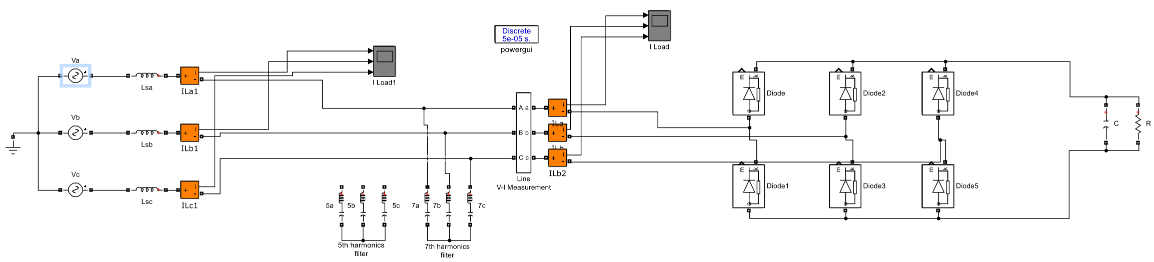

Figure 3-10 Three phase power system with 6 pulse rectifier and 7th harmonic filter

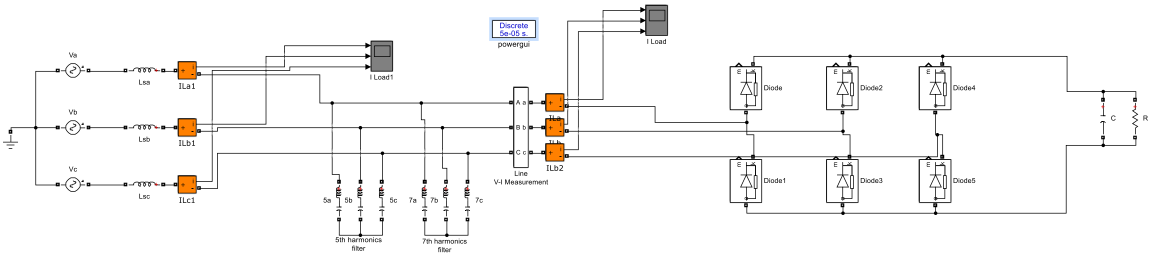

Figure 3-11 Three phase power system with 6 pulse rectifier and 5th and 7th harmonic filter

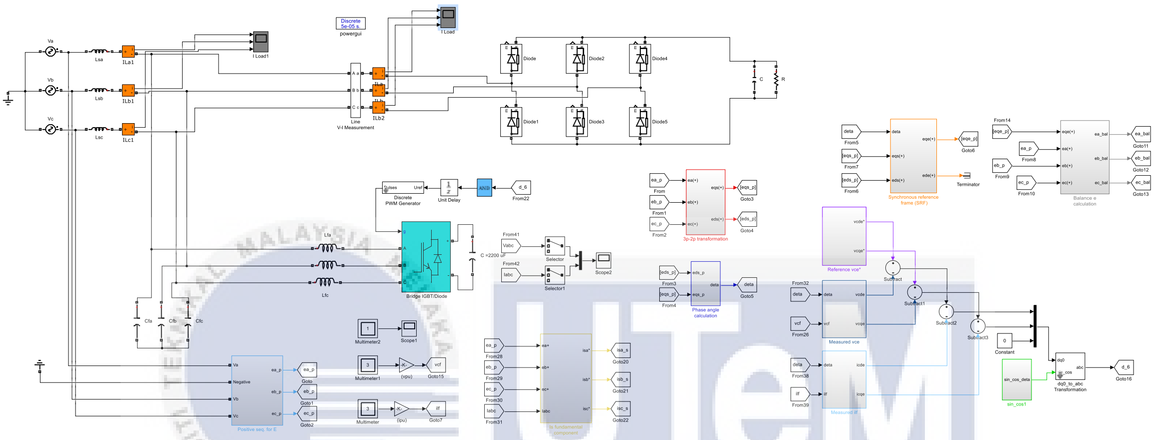

Figure 3-12 Three phase power system with 6 pulse rectifier and SRF based SAPF

3.2.1 AC Voltage Source

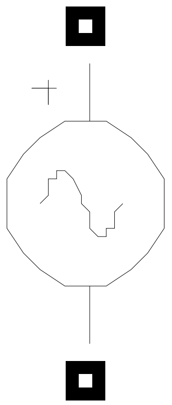

Figure 3-13 Simulink AC Voltage Source block

Figure 3.13 shows the AC voltage source block in Simulink. The function of this block is to implements an ideal AC voltage. Three AC voltage source blocks is used to construct a three-phase voltage source. The peak amplitude is set as 339.463V and the frequency is set as 50Hz for all three blocks. The three blocks have different parameter for phase which is 0, 120, and -120.

3.2.2 Diode Rectifier

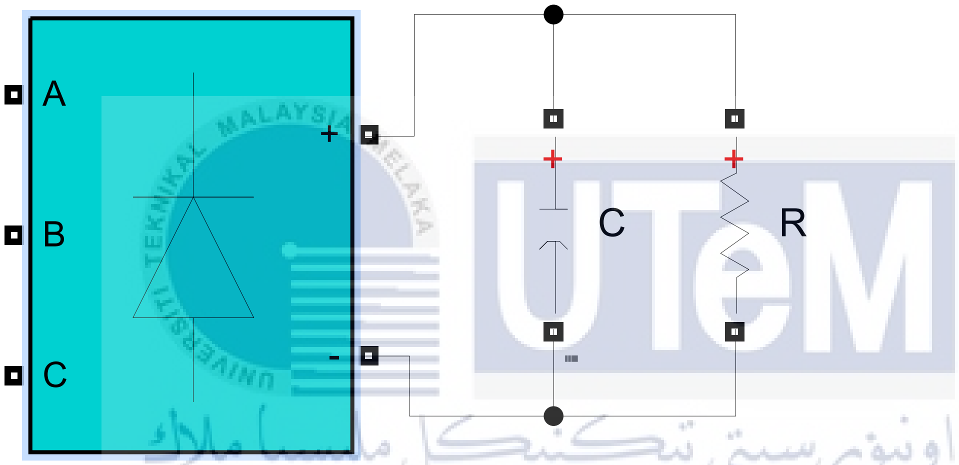

Figure 3-14 Simulink model of diode rectifier

Figure 3.13 shows universal bridge in Simulink. The function of universal bridge is to implement universal power converter with selectable topologies and power electronic devices. In the designed power system, the universal bridge is connected with RC load to construct a diode rectifier which is a non-linear load that produce current harmonic. In this project, the parameter of the number of bridge arms is set to 3 to get a three-phase converter connected in Graetz bridge configuration (six switching devices).

Table 3-1 Parameters of diode rectifier

Rs	10Ω
Cs	1e-9 F
Ron	6.5e-3 Ω
Lon	0 H
Vf	1.26 V
R	10Ω
C	100e-6 F

3.2.3 Three-Phase Series RLC Branch

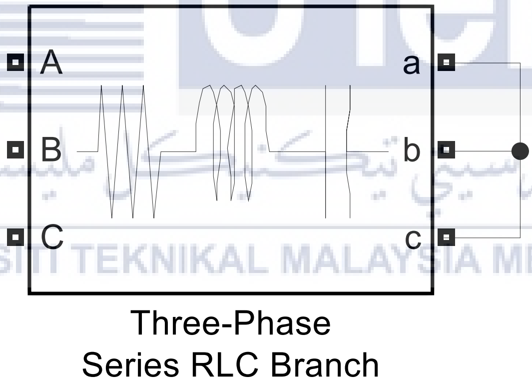

Figure 3-15 Simulink model of Three-Phase RLC Branch

Figure 3.14 shows Three-Phase Series RLC branch simulink block. The Three-Phase Series RLC Branch block implements three balanced branches consisting each of a resistor, an inductor, or a capacitor or a series combination of these. In this project, the RLC branch is used as non-linear load. The parameters of the RLC branch is shown in Table 3.2.

Table 3-2 Parameters of Three-Phase Series RLC Branch

R	100 Ω
L	10e-3 H
C	1000e-6 F

3.2.4 Passive Filter

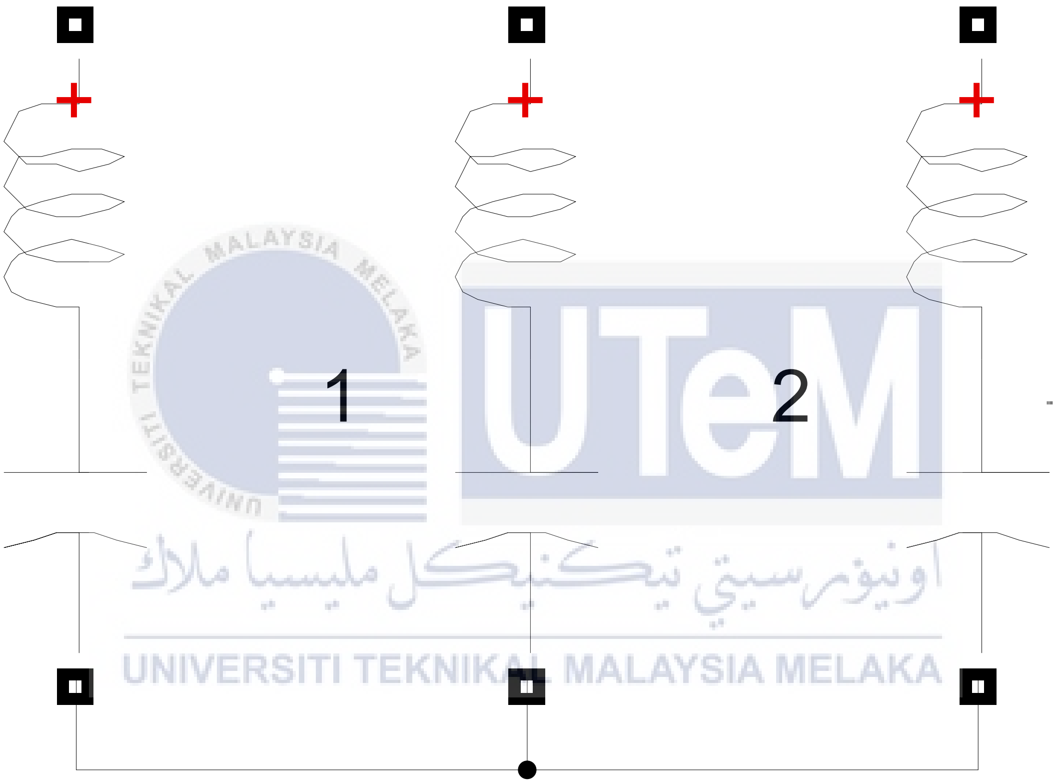

Figure 3-16 Simulink model of three-phase LC filter

Figure 3.15 shows three series LC branch Simulink block. Each branch consists of a capacitor and an inductor. The branches are connected in parallel to form a three-phase LC filter which is a passive filter. The LC filter are tuned at 5^{th} and 7^{th} harmonics order by varying the parameter of the capacitors and inductors. The parameter of 5^{th} harmonic filter and 7^{th} harmonic filter is presented in Table 3.3 and Table 3.4.

Table 3-3 Parameters of 5th harmonic filter

L	2.02e-3 H
C	200e-6 F

Table 3-4 Parameters of 7th harmonic filter

L	2.07e-3 H
C	100e-6 F

3.2.5 6 pulse rectifier

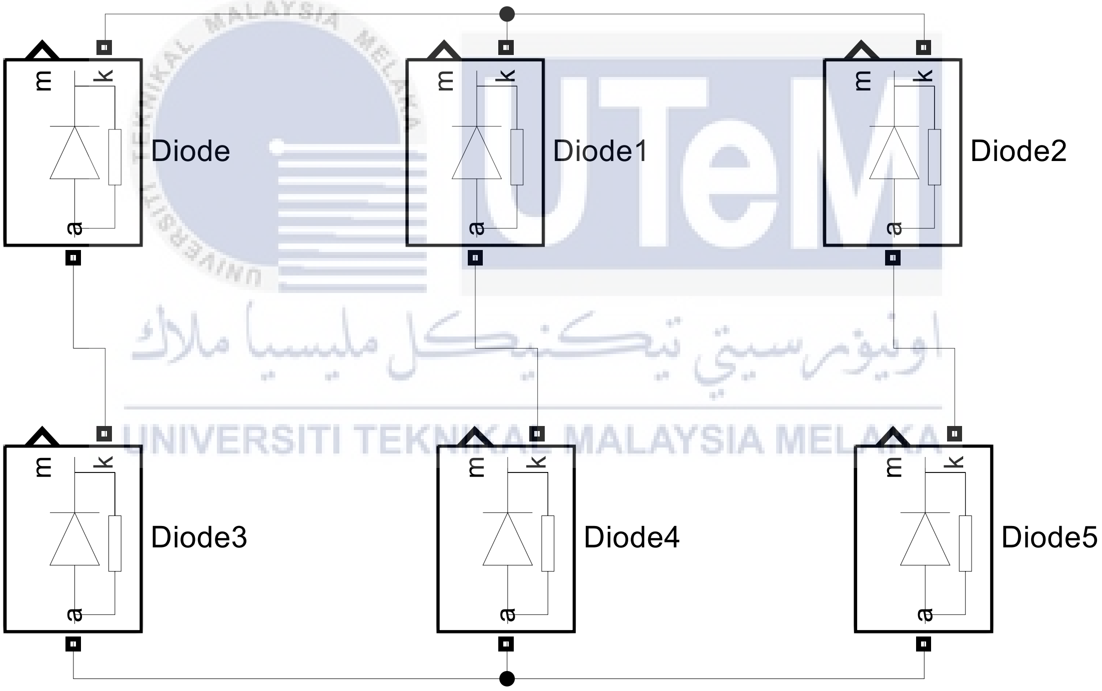

Figure 3-17 Simulink model of 6 pulse rectifier

The simulink model of 6 pulse rectifier is shown in Figure 3.16. The 6 pulse rectifier consists of 6 diodes, which consists of three parallel branch where each branch are made up of two series connected diode. Six pulse rectifier is a non-linear load often used in variable frequency drive. The parameters of the diode in six pulse rectifier is displayed in Table 3.5.

Table 3-5 Parameters of six pulse rectifier

Rs	10Ω
Cs	1e-9 F
Ron	6.5e-3 Ω
Lon	0 H
Vf	1.26 V

3.2.6 Vabc to Vdq Transformation

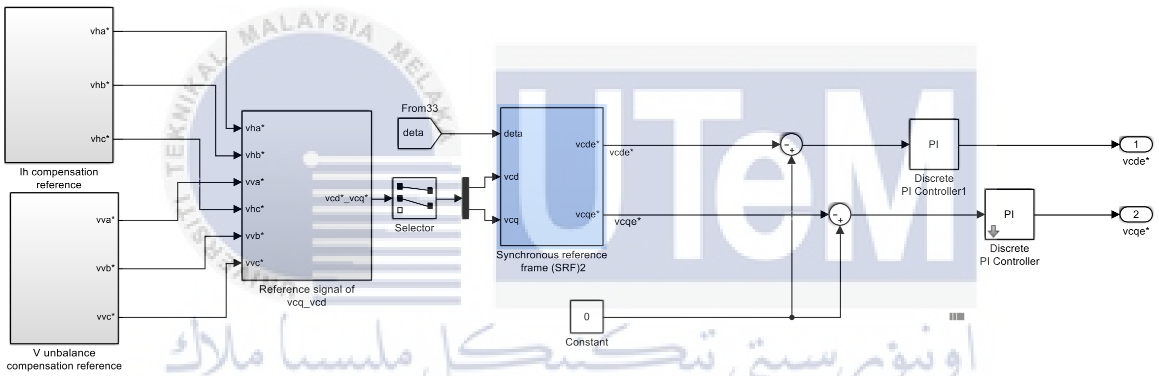

Figure 3-18 Simulink model of Vabc to Vdq transformation

The load voltage in three-phase abc frame Vlabc is transformed into its corresponding two-phase dq frame Vldq to isolate harmonic components from its fundamental component. The transformation process is summarized as:

$Vd= 2/3\ (Va*\sin\omega t + Vb*\sin(\omega t-2\pi/3) + Vc*\sin(\omega t+2\pi/3)$

$Vq= 2/3\ (Va*\cos\omega t + Vb*\cos(\omega t-2\pi/3) + Vc*\cos(\omega t+2\pi/3)$

$V0= 1/3(Va + Vb + Vc)$

3.2.7 Synchronous Reference Frame 2

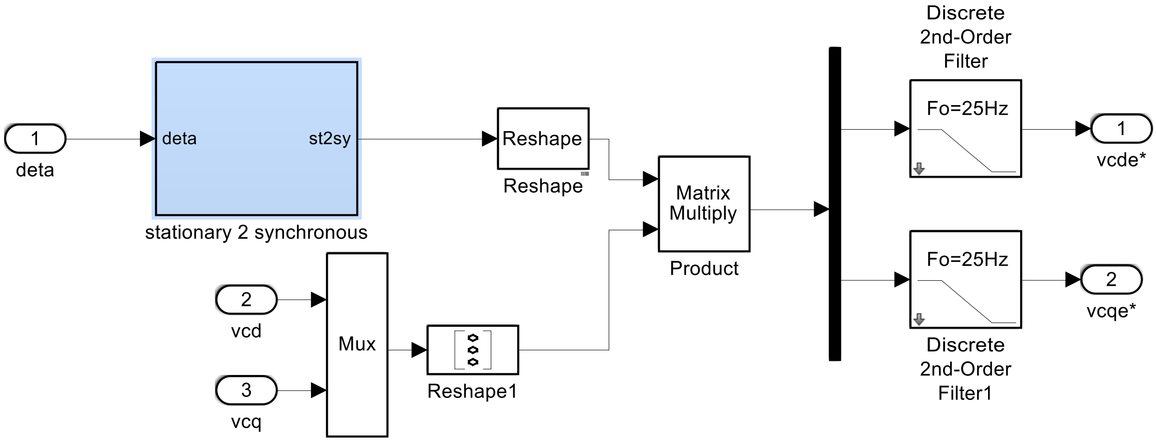

Figure 3-19 Simulink model of synchronous reference frame 2

Synchronous reference frame (SRF)2 block further process Vcd and Vcq. Two discrete 2nd-order low pass filter with a cutting frequency of 25Hz are used to detect the dc component of the Vcq and Vcd.

3.2.8 Vdq to Vabc Transformation

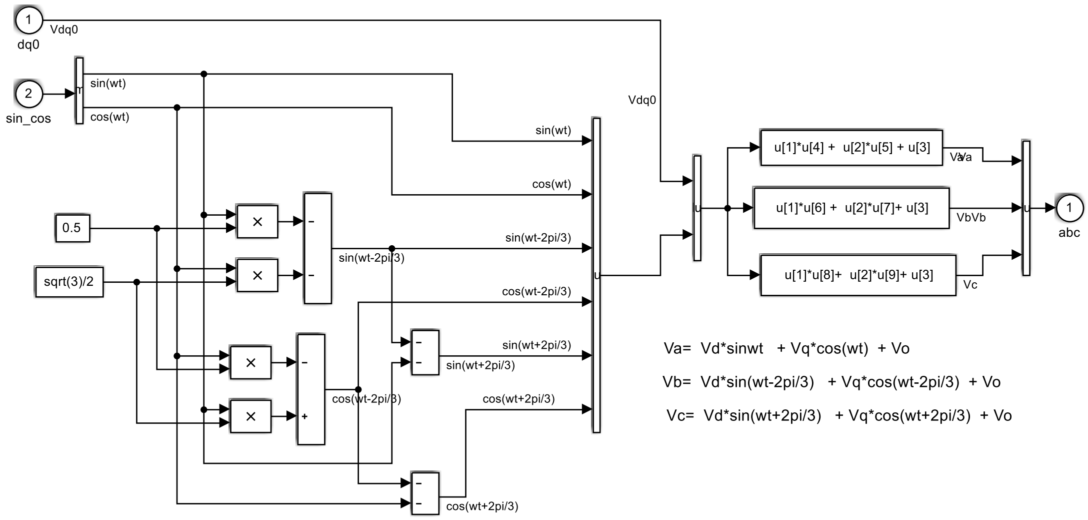

Figure 3-20 Vdq to Vabc transformation

The two-phase dq frame Vldq is transformed back to three-phase Vabc. The transformation process is summarized as:

Va= Vd*sinωt + Vq*cos(ωt) + Vo

Vb= Vd*sin(ωt - 2π/3) + Vq*cos(ωt-2π/3) + Vo

Vc= Vd*sin(ωt + 2π/3) + Vq*cos(ωt + 2π/3) + Vo

3.2.9 Iabc to Idq Transformation

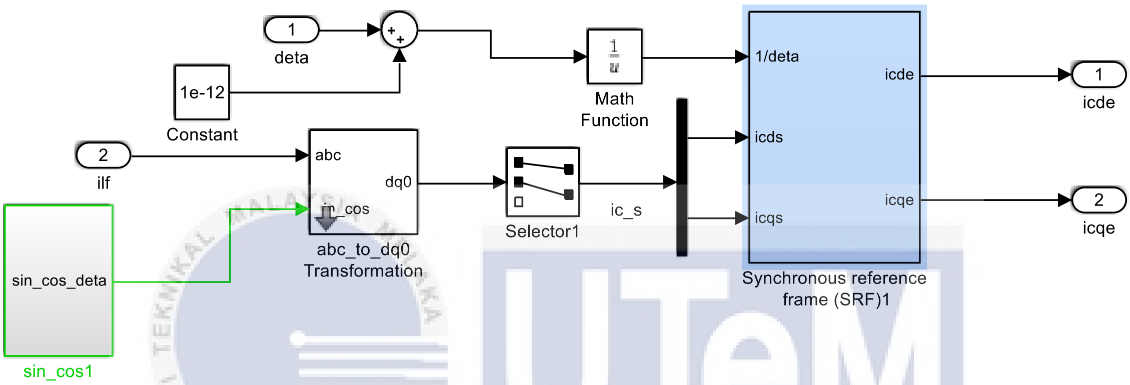

Figure 3-21 Simulink block of Iabc to Idq transformation

The inductor current of Lfa, Lfb, and Lfc are taken and processed to obtain ilf which is load current. Three-phase abc frame ilabc is transformed into its corresponding two-phase dq frame ildq to isolate harmonic components from its fundamental component. The transformation process is summarized as:

Id= 2/3 (Ia*sinωt + Ib*sin(ωt-2π/3) + Ic*sin(ωt+2π/3)

Iq= 2/3 (Ia*cosωt + Ib*cos(ωt-2π/3) + Ic*cos(ωt+2π/3)

I0= 1/3(Ia + Ib + Ic)

3.2.10 Phase Angle Calculation

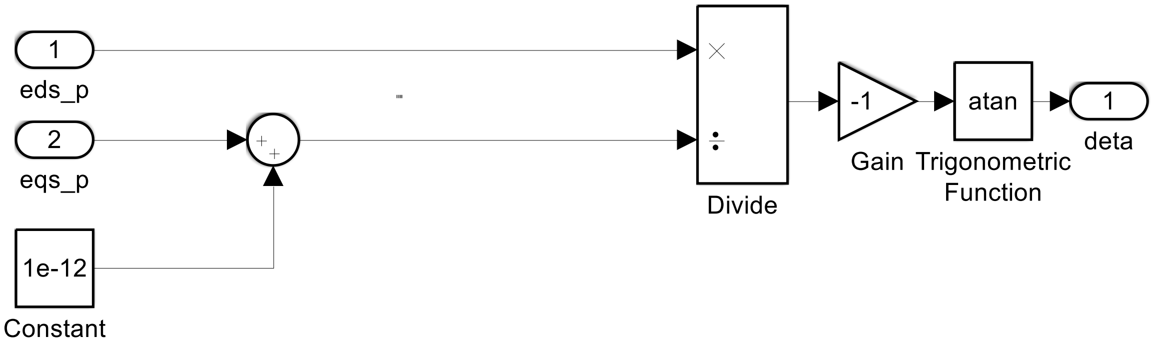

Figure 3-22 Simulink model of phase angle calculation

The simulink model of phase angle calculation is used to calculate the phase angle for the synchronous frame calculation.

3.2.11 Voltage Source Inverter

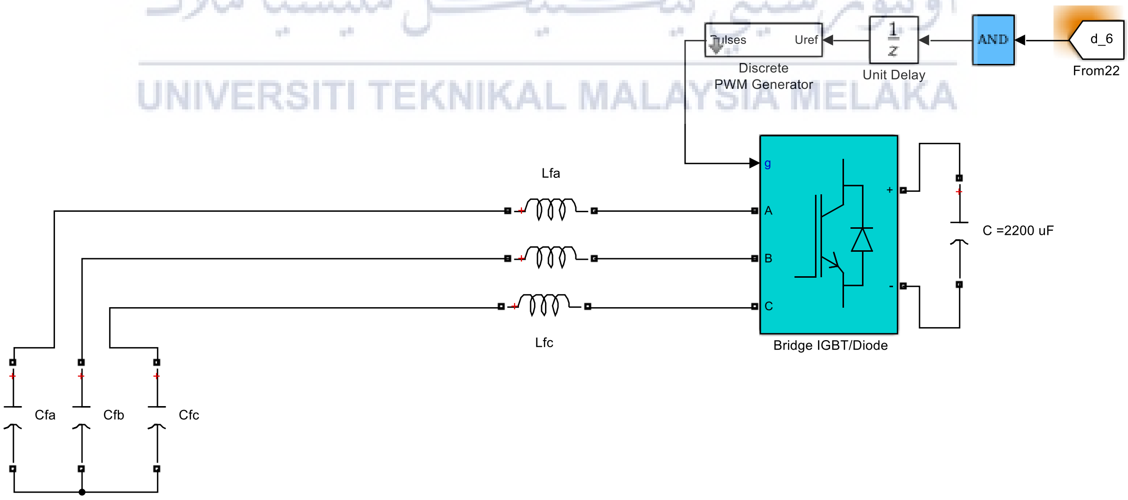

Figure 3-23 Simulink model of voltage source inverter

The voltage source inverter is used to provide controlled current. The voltage source inverter supply compensation current to the system. The parameters of the voltage source inverter is shown in Table 3.6. PWM generator is used to create swtiching signals for the voltage source inverter to generate compensating current to the system. The carrier frequency of the PWM generator is set to 20kHz.

Table 3-6 Parameters of voltage source inverter

Rs	10 Ω
Cs	1e-9 F
Ron	1e-3 Ω
Forward voltages	0
Lfabc	1e-3 H
Cfabc	2.5e-6 F

3.3 Summary

This chapter presented the flow of this project and explained the tools and parameters used in this project. Matlab/Simulink is used to model and also simulate the power system.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presented simulation results of proposed system that is connected passive filter and SRF based Shunt Active Power Filter under different load condition, which is linear load and non-linear load. A summary of the simulation results will be presented at the end of this chapter.

4.2 Linear Load

Figure 3.2 shows the proposed system consists of three phase power supply. The output of the system is connected to linear load which is RLC load. In this case, no filter is connected to the system. The waveform of the current measured at the load side is perfect sinusoidal or without any distortion. In short, it can be concluded that the waveform of the current at the load side is almost the same with the waveform of the current at the source side as shown in the Figure 4.1 and Figure 4.2. Meanwhile the THD value for the load and source sides are equal 0% as illustrated in Figure 4.3 and Figure 4.4 because the linear load will not cause harmonic distortion in the system.

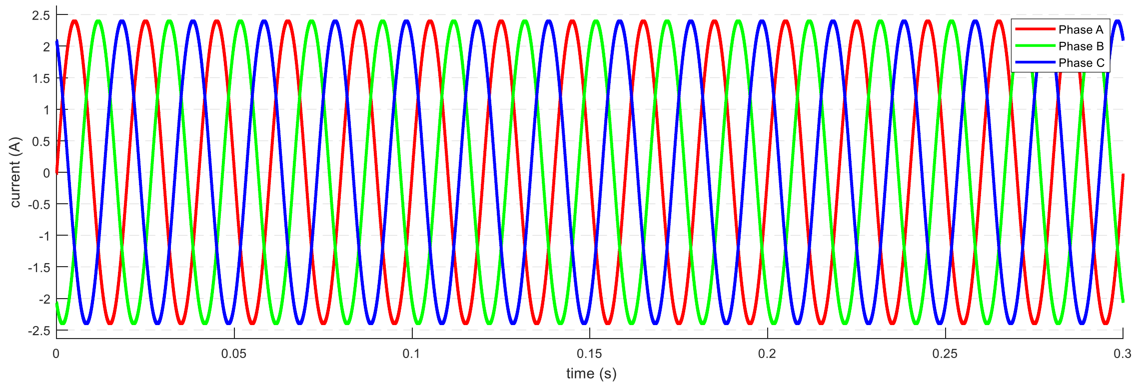

Figure 4-1 RLC load current waveform

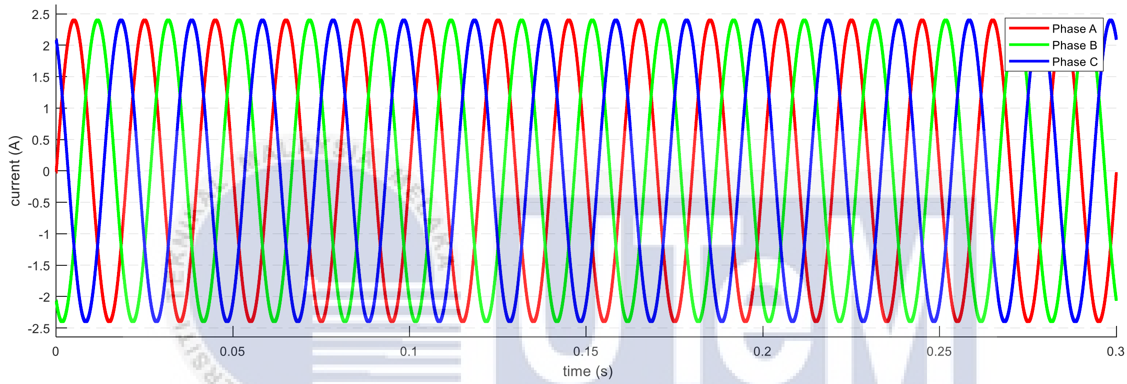

Figure 4-2 Source current waveform with RLC load

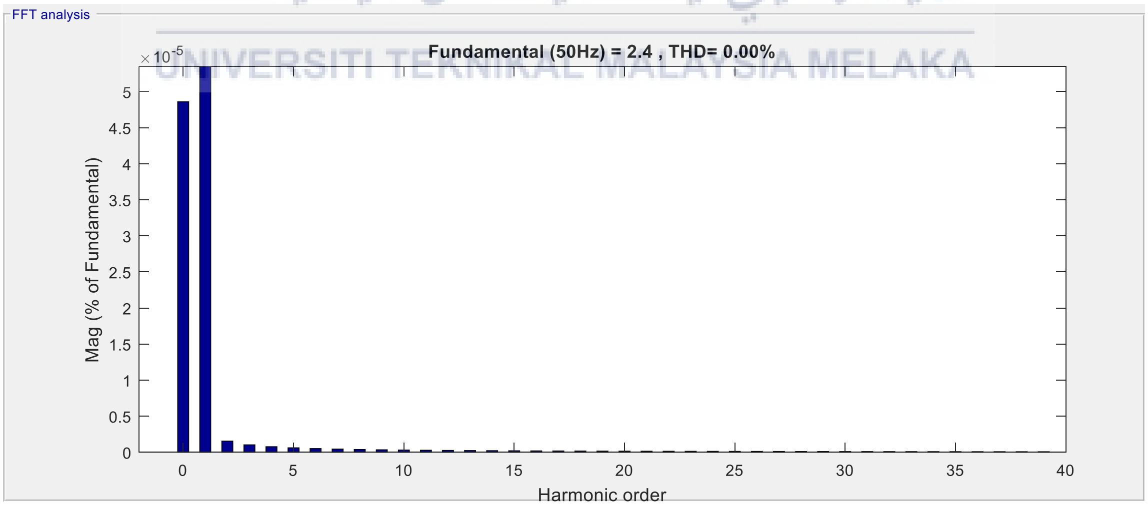

Figure 4-3 THD value of RLC load current

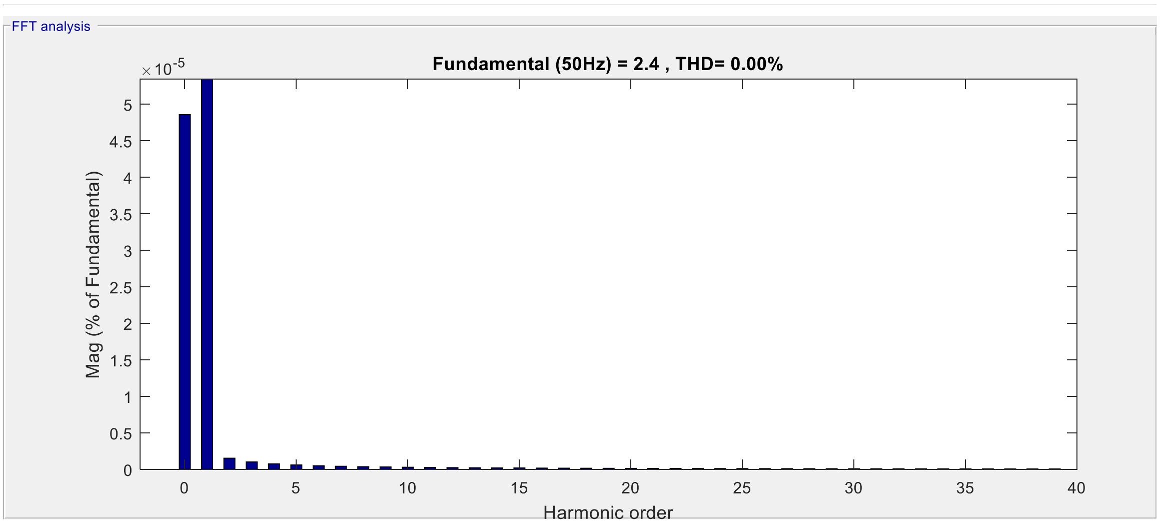

Figure 4-4 THD value of source current with RLC load

4.3 Non-linear Load

4.3.1 Diode Rectifier

For the next simulation, the proposed system consists of three phase power supply is connected to a diode rectifier which is a type of non-linear load as presented in Figure 3.3. The waveform of the current is measured at the both sides of the load and the source of the proposed system. The waveforms of the current at the load and source sides as shown in Figure 4.5 and Figure 4.6 and can be observed that the waveforms are distorted and their THD value for the current of source and load side are considerably high at around 24.9% as displayed in Figure 4.7 and Figure 4.8.

Filtering scheme is used to minimize the highly content of harmonic in the system. The three phases of the proposed system are installed with a passive filter in parallel which can be seen in Figure 3.4, Figure 3.5 and Figure 3.6. The passive filter is tuned at 5^{th} and 7^{th} harmonic order as exhibited in Table 3.3 and Table 3.4.

The measured load and source current waveform of the proposed system that consists of three phase voltage supply and diode rectifier as load and connect parallel with 5^{th}

harmonic filter as shown in Figure 3.4 are displayed in Figure 4.9 and Figure 4.10. It is noted that the load current waveform is highly distorted in Figure 4.9 and the THD value of load current is 30.48% as presented in Figure 4.11. The waveform of the source current as shown in Figure 4.10 is less distorted after the system connected with 5th harmonic filter and the THD value of the source current is reduced to 5.93%. However, the THD value of the system is still exceed the limit set by IEC which is 5%.

Figure 4.13 and Figure 4.14 show the load and source current waveform of the proposed system comprising three phase voltage supply and diode rectifier as load and connected parallel with 7th harmonic filter in Figure 3.5. The load current waveform is extremely distorted as observed in Figure 4.13 and its THD value is 29.7% as shown in Figure 4.15. To mitigate the harmonic in the system, each phase of the system is connected to 7th harmonic filter. From Figure 4.14, the waveform of the source current is less distorted and the THD value of the source current is lessen to 18.82%. The THD value in the power system is still higher than the maximum THD value set by IEC.

In the next simulation, the proposed system is connected parallel to both 5th and 7th harmonic filter at each phase of the system as displayed in Figure 3.6. The current waveform for load side and source side is obtained and shown in Figure 4.17 and Figure 4.18. It can be observed that the current waveform is greatly distorted in Figure 4.17 because of the diode rectifier load and the THD value of the current waveform is 31.1% as displayed in Figure 4.19. The waveform of the source current is clearly less distorted as observed in Figure 4.18 and the THD value of the source current is 6.58% as presented in Figure 4.20. It can be concluded that the 5th and 7th harmonic filter can lower the THD value in the system but unable to comply with the IEC standard which is 5%.

The proposed system is connected with SRF based Shunt Active Power Filter in the next simulation as shown in Figure 3.7. The source current and load current waveform are obtained. It can be observed that the load current waveform is hugely distorted as displayed in Figure 4.21 and the THD value of the load current is 33.39% as shown in Figure 4.23. Meanwhile, the source current waveform is clearly less distorted and very close to sine wave as presented in Figure 4.22 and the THD value of the source current is 0.49% as presented in Figure 4.24. The parameters of RC load of the diode rectifier in Figure 3.7 are changed to 10kΩ and 10μF. The current waveform os source side and load side are obtained. The load current waveform is heavily distorted as shown in Figure 4.25 and the THD value of the load current is 257.73% as displayed in Figure 4.27. The source current waveform is close to perfect sine wave and the THD value of the source waveform is 0.13% as shown in Figure 4.26 and Figure 4.28. The THD value of the proposed system fulfil the IEC standard which the THD value in the system must not more than 5%. Therefore, we can conclude that the SRF based Shunt Active Power Filter can mitigate the harmonic in the power system.

The simulation results are summarised as shown in Table 4.1.

Table 4-1 THD value of load and source current with diode rectifier load and different filter

Load	Filter	%THD of load	%THD of source
Diode rectifier	-	24.92	24.92
Diode rectifier	5^{th} harmonic	30.48	5.93
Diode rectifier	7^{th} harmonic	29.7	18.82
Diode rectifier	5^{th} & 7^{th} harmonic	31.1	6.58
Diode rectifier	SRF based SAPF	33.39	0.49
Diode rectifier	SRF based SAPF	257.73	0.13

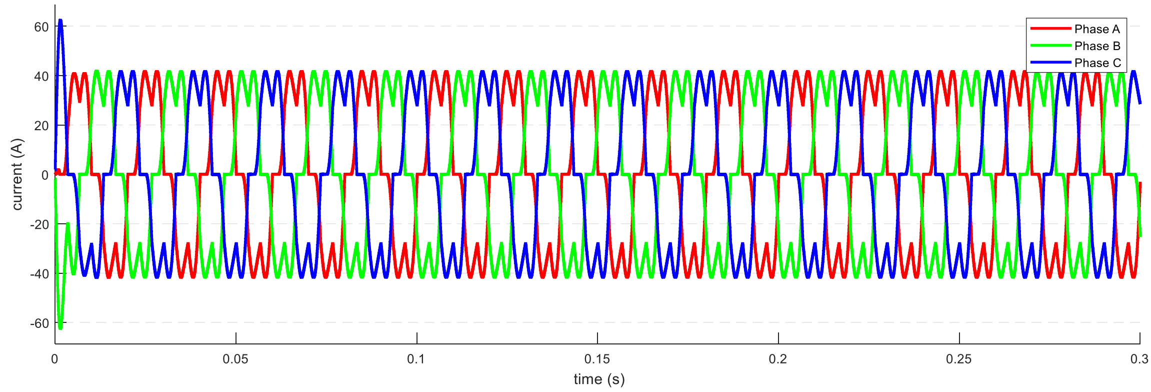

Figure 4-5 Diode rectifier load current waveform

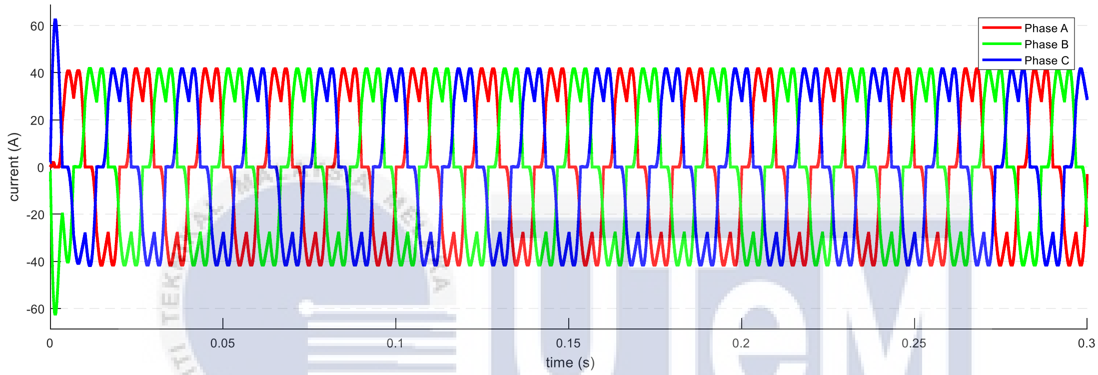

Figure 4-6 Source current waveform with diode rectifier load

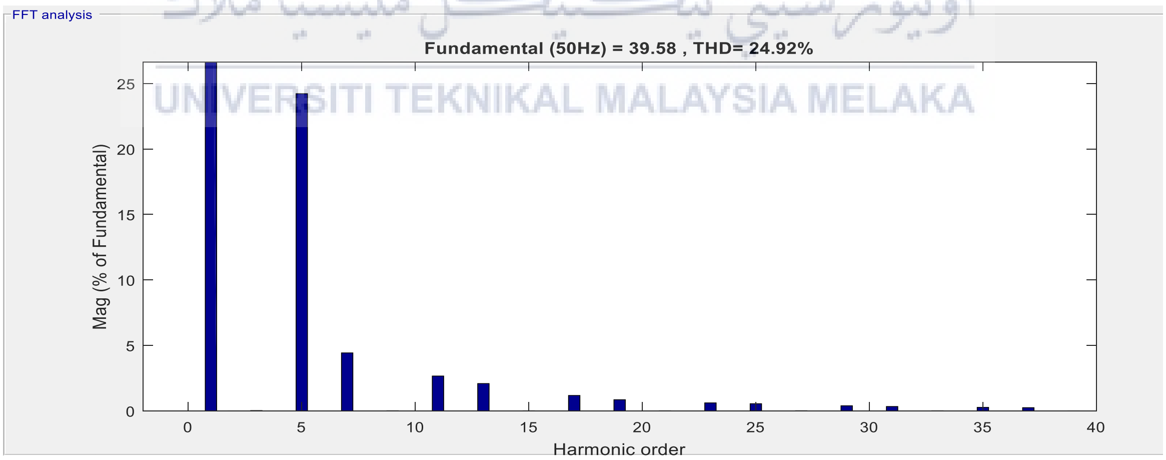

Figure 4-7 THD value of diode rectifier load current

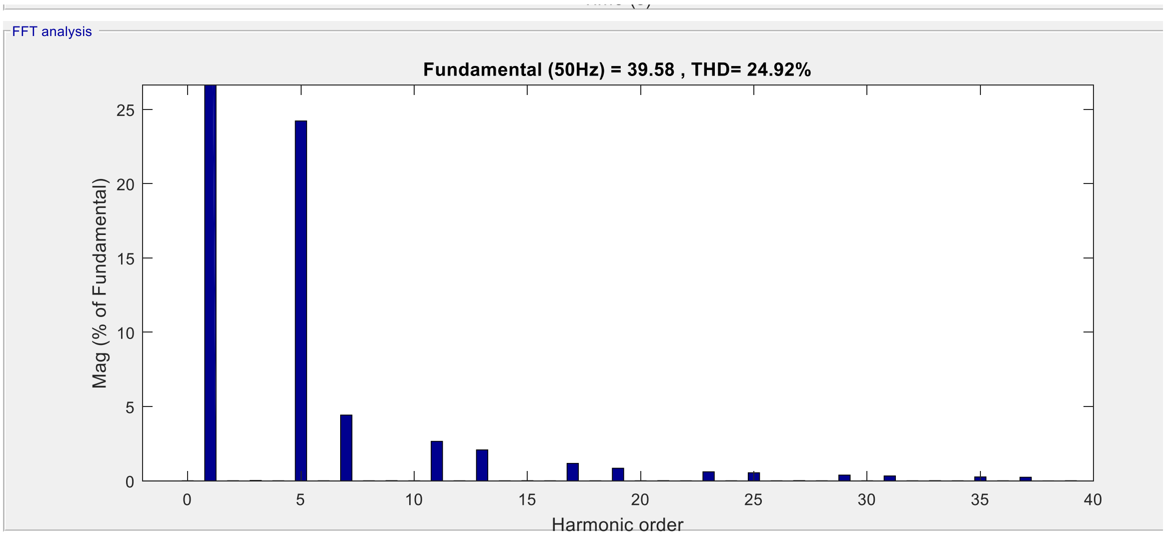

Figure 4-8 THD value of source current with diode rectifier load

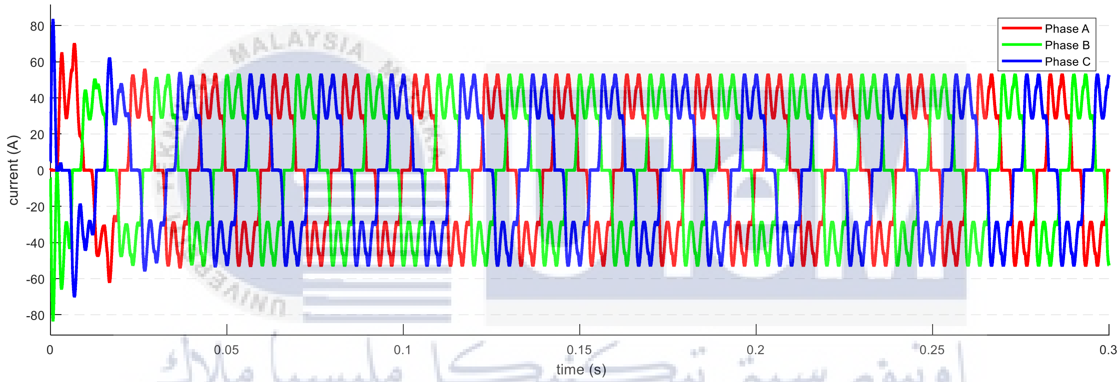

Figure 4-9 Load current waveform of diode rectifier load and 5th harmonic filter

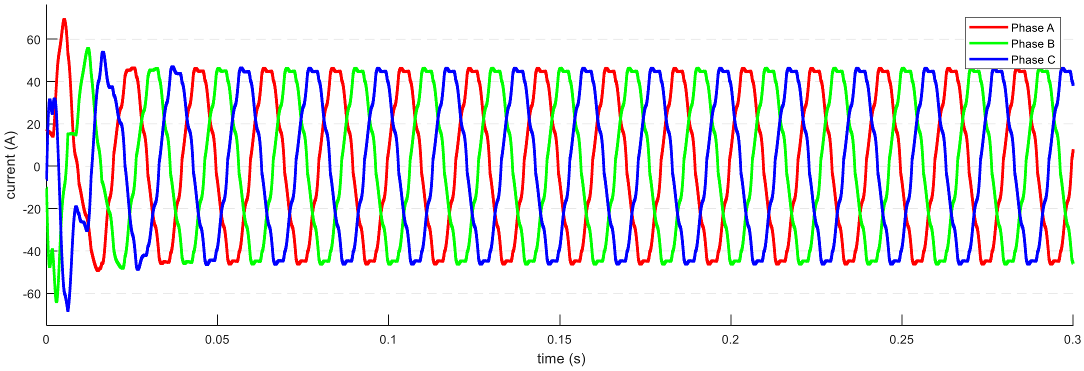

Figure 4-10 Source current waveform of diode rectifier load with 5th harmonic filter

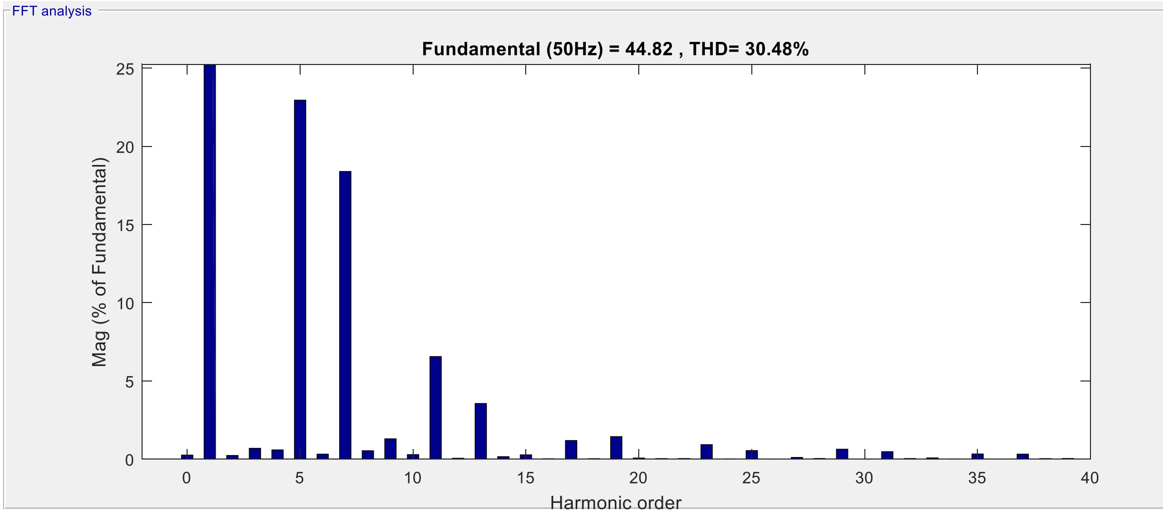

Figure 4-11 THD value of load current of diode rectifier load with 5th harmonic filter

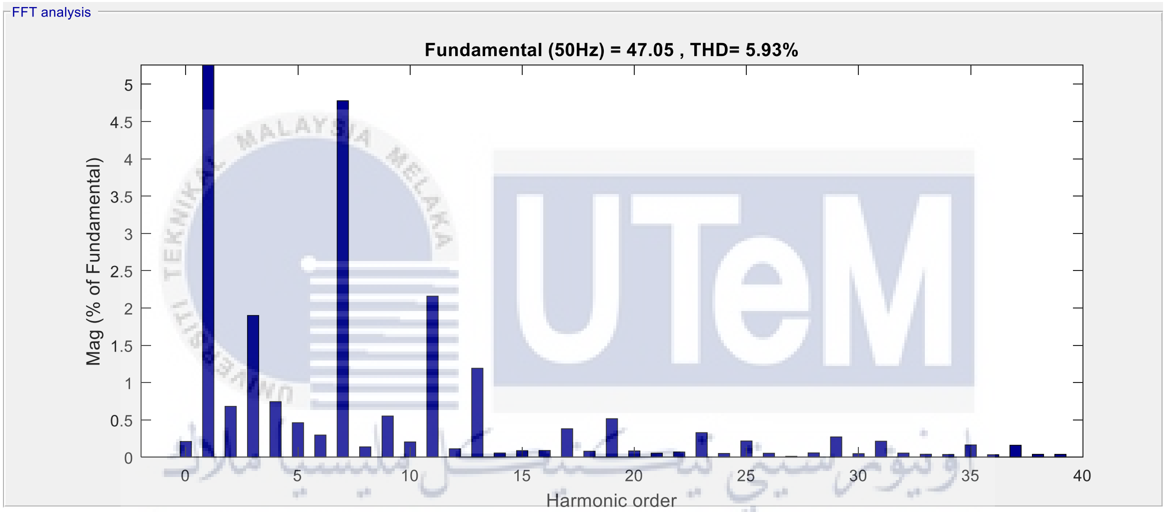

Figure 4-12 THD value of source current of diode rectifier load with 5th harmonic filter

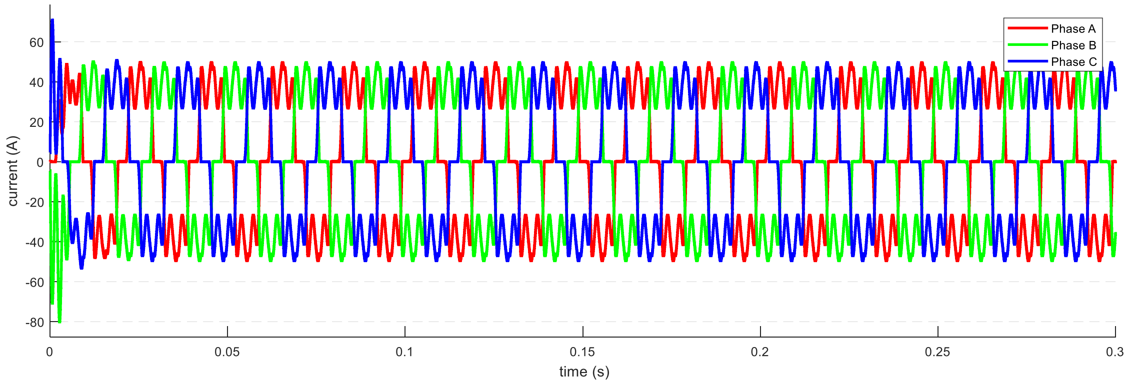

Figure 4-13 Load current waveform of diode rectifier load with 7th harmonic filter

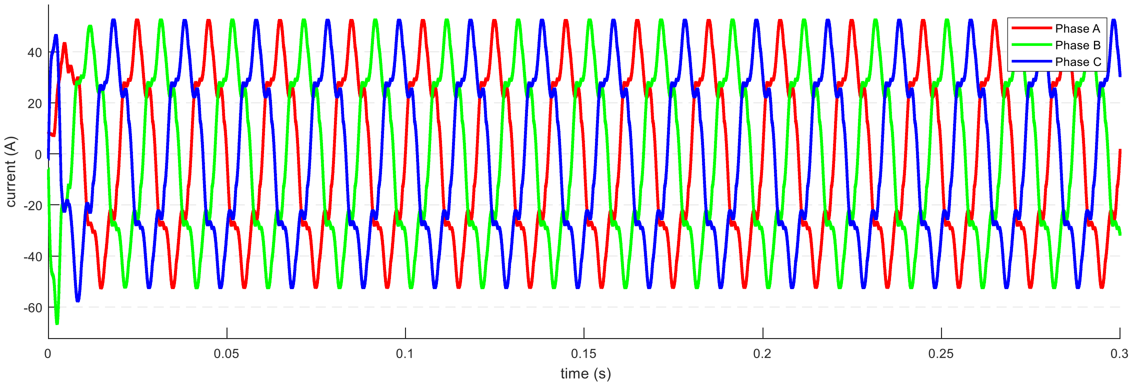

Figure 4-14 Source current waveform of diode rectifier load with 7th harmonic filter

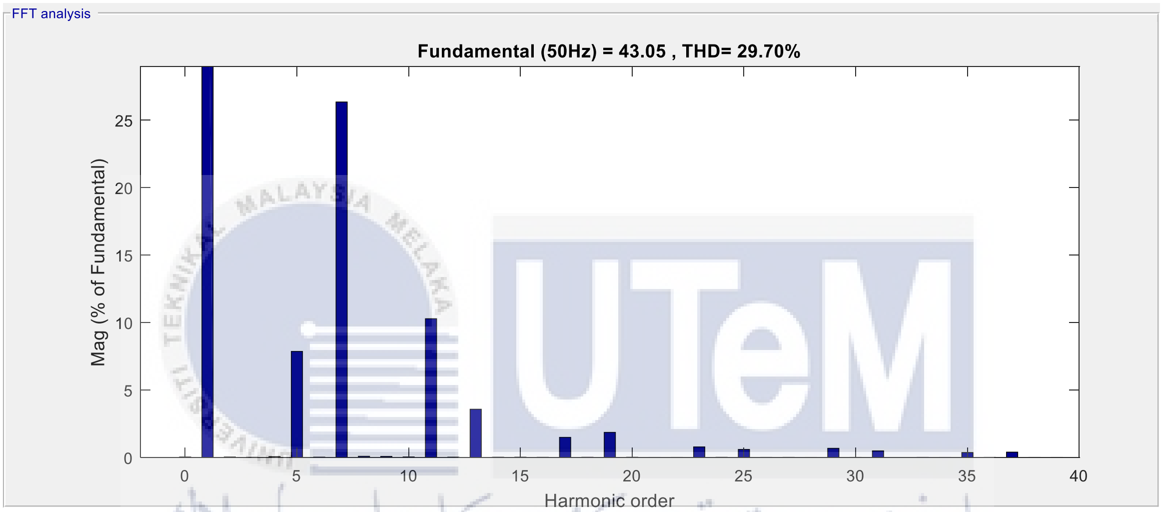

Figure 4-15 THD value of load current for diode rectifier load with 7th harmonic filter

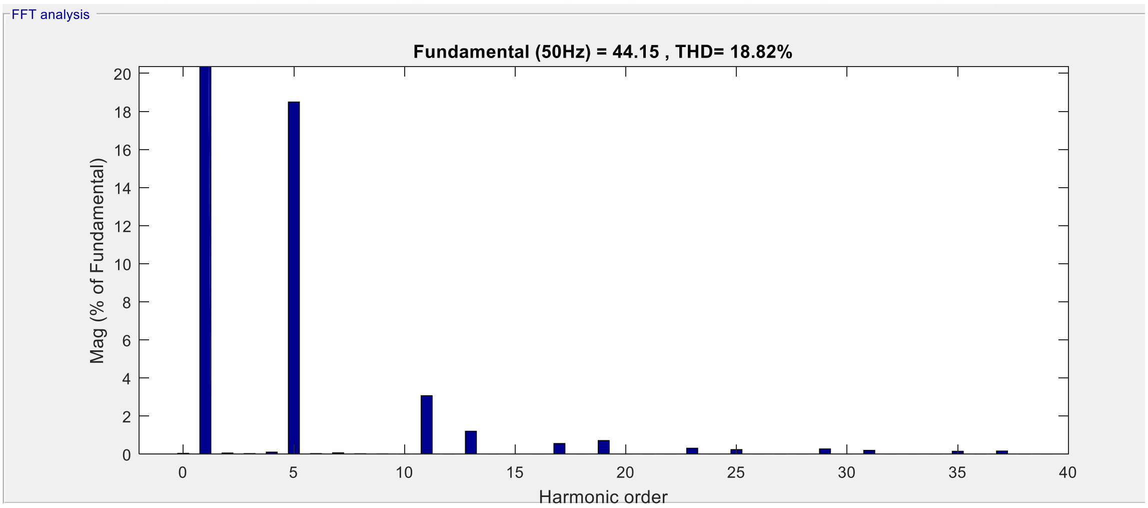

Figure 4-16 THD value of source current for diode rectifier with 7th harmonic filter

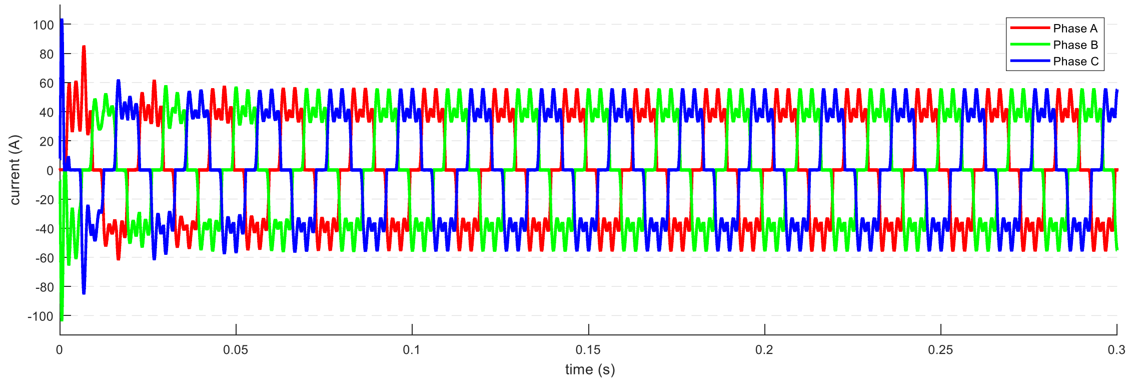

Figure 4-17 Load current waveform of diode rectifier load with 5th and 7th harmonic filter

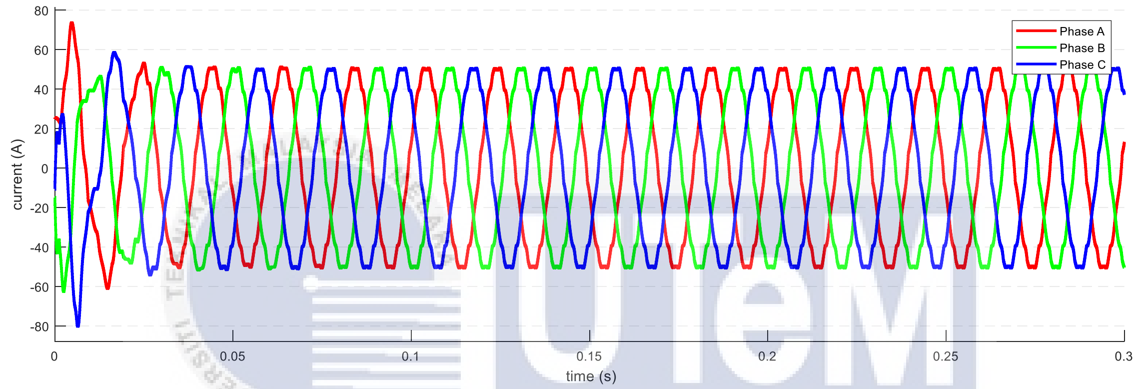

Figure 4-18 Source current waveform of diode rectifier load with 5th and 7th harmonic filter

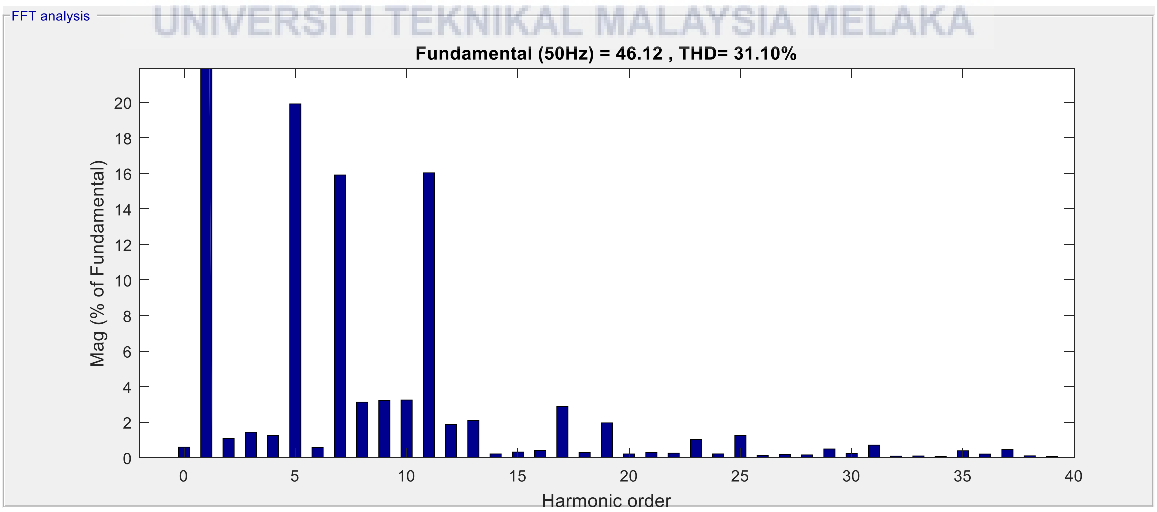

Figure 4-19 THD value of load current for diode rectifier load with 5th and 7th harmonic filter

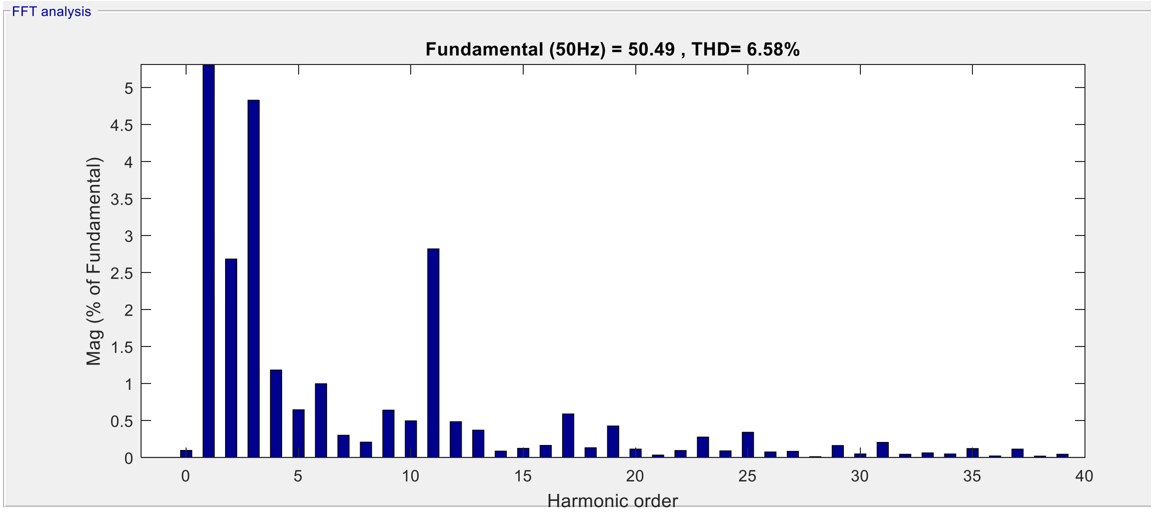

Figure 4-20 THD value of source current for diode rectifier with 5th and 7th harmonic filter

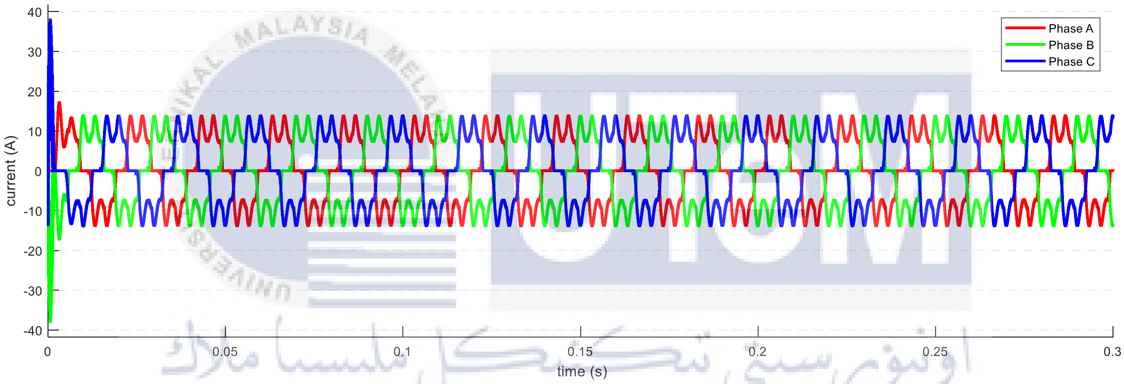

Figure 4-21 Load current waveform of diode rectifier load with SRF based SAPF

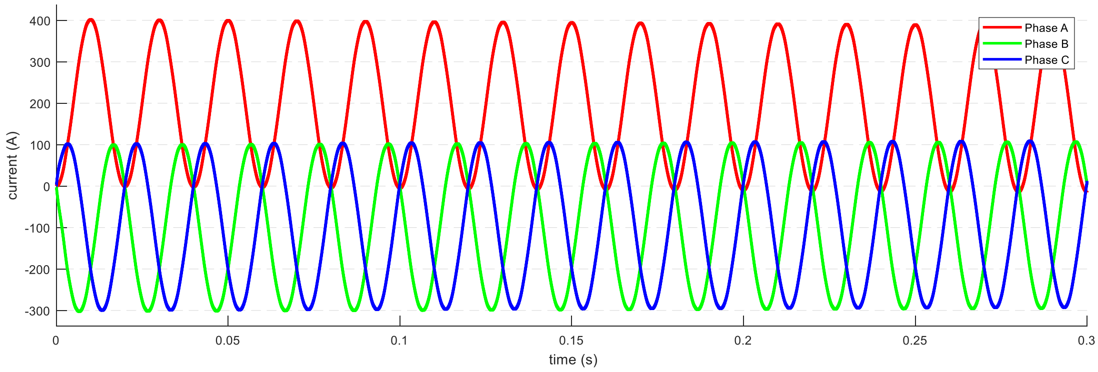

Figure 4-22 Source current waveform of diode rectifier load with SRF based SAPF

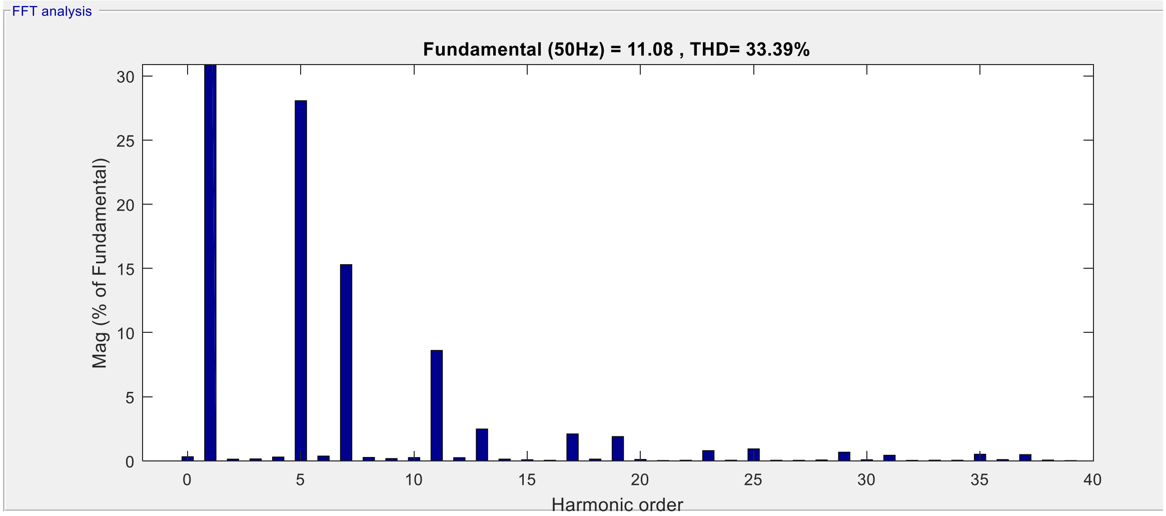

Figure 4-23 THD value of load current for diode rectifier load with SRF based SAPF

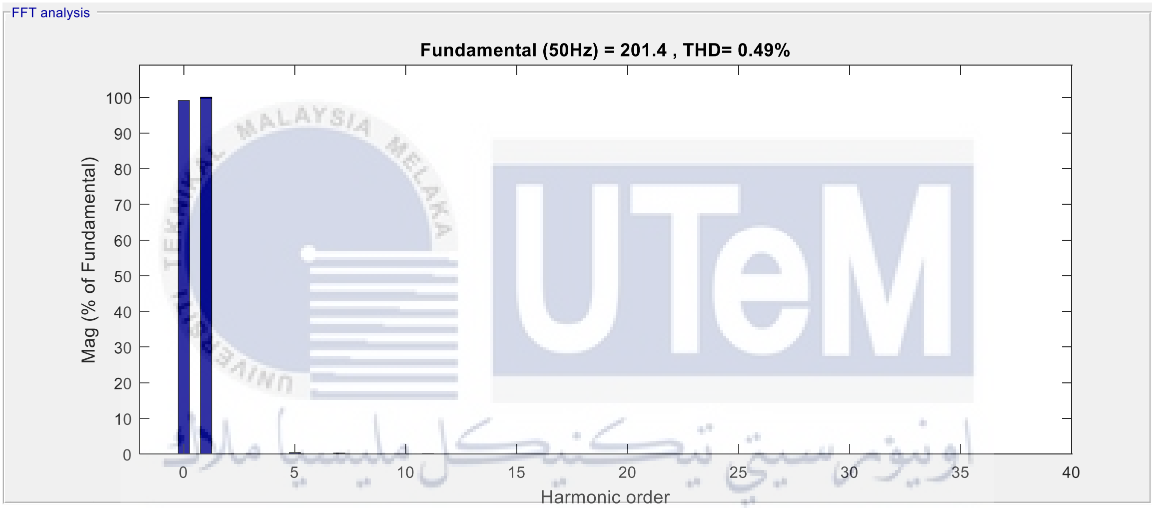

Figure 4-24 THD value of source current for diode rectifier with SRF based SAPF

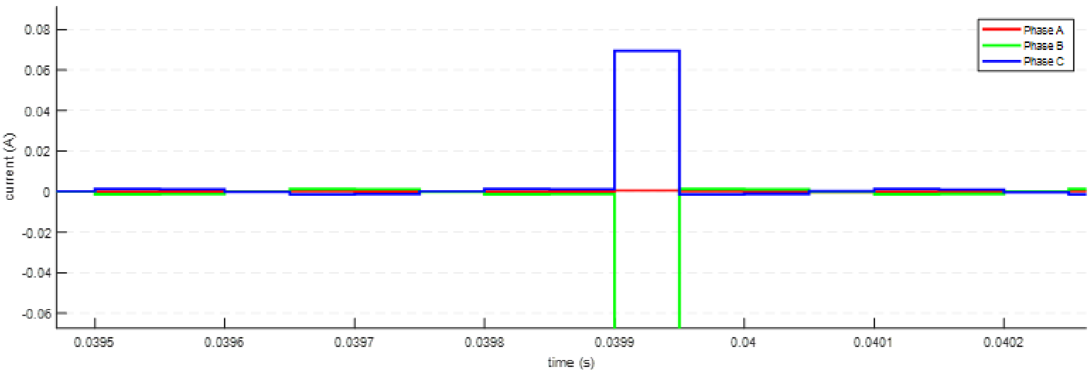

Figure 4-25 Load current waveform of diode rectifier load with SRF based SAPF

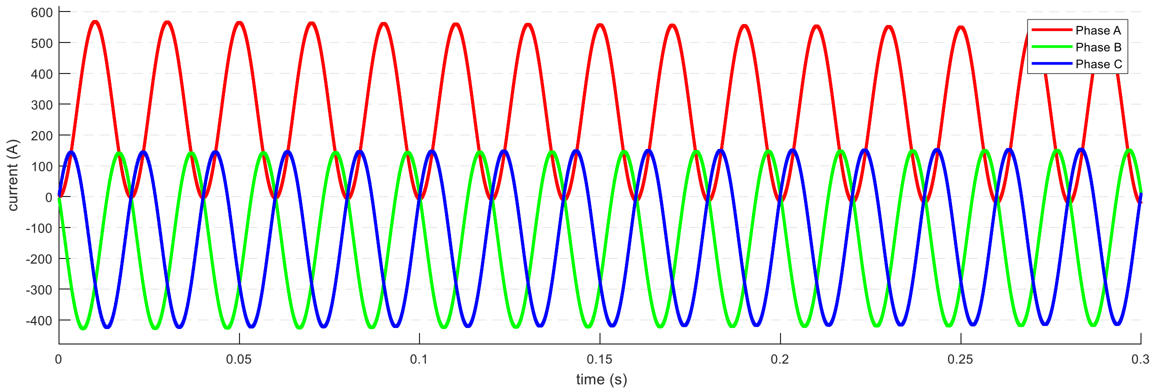

Figure 4-26 Source current waveform of diode rectifier load with SRF based SAPF

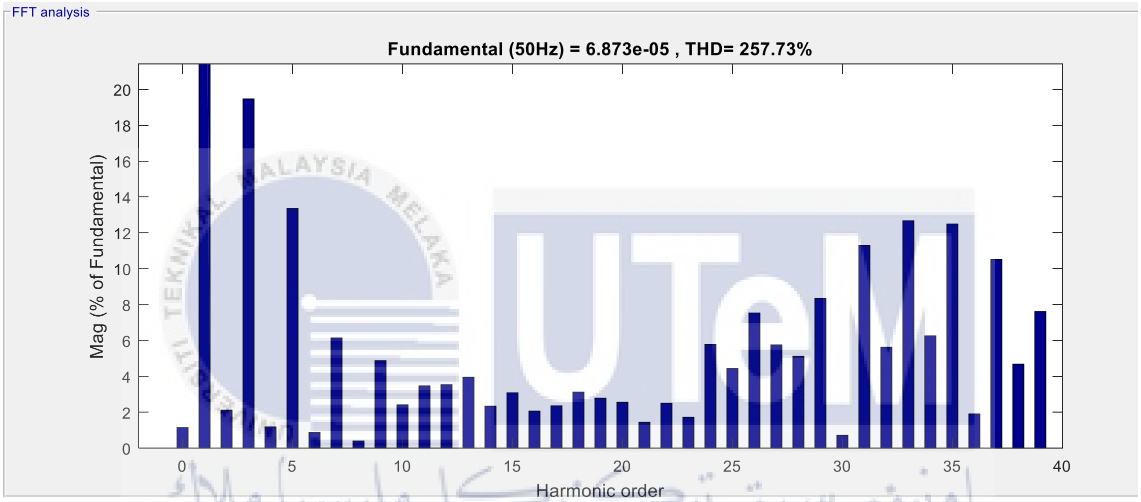

Figure 4-27 THD value of load current for diode rectifier load with SRF based SAPF

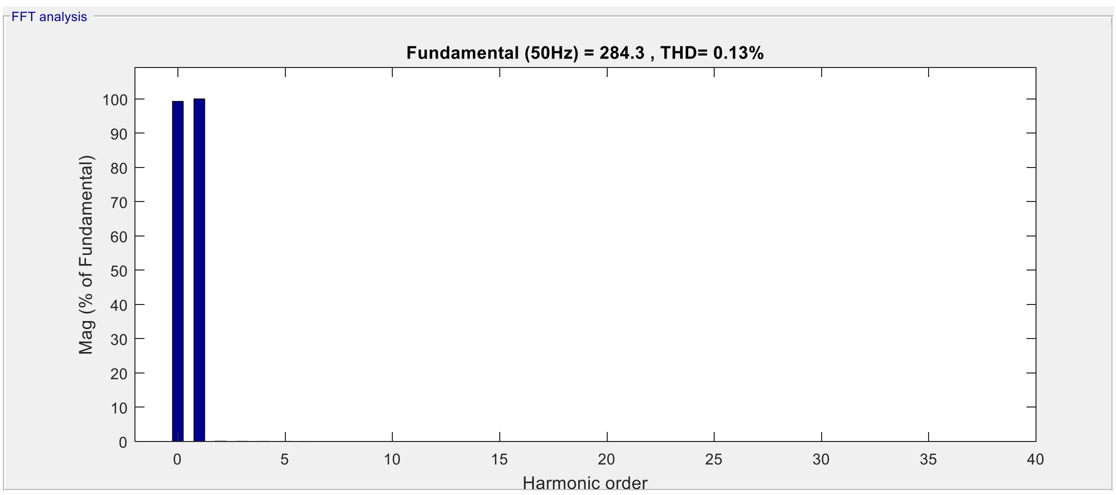

Figure 4-28 THD value of source current for diode rectifier with SRF based SAPF

4.3.2 6 Pulse Rectifier

The proposed system consists of three phase voltage supply and six pulse rectifier as load is connected to six pulse rectifier which is a type of non-linear load as presented in Figure 3.8 for the next simulation. The proposed system is simulated and the current waveform at the load side and current side are measured. Figure 4.29 and Figure 4.30 show the load current waveform and source current waveform and it can be observed that the waveforms are distorted and the THD value for the load current and source current are very high at around 25.01% as shown in Figure 4.31 and Figure 4.32.

To mitigate the harmonic content in system, filtering scheme is used. Figure 3.9, Figure 3.10 and Figure 3.11 show that the three phases of the system are connected to passive filter in parallel manner. Table 3.3 and Table 3.4 show the parameters of tuned passive filter.

The load current waveform and source current waveform of the proposed system comprising three phase voltage supply and six pulse rectifier as load as shown in Figure 3.9 are displayed in Figure 4.33 and Figure 4.34. The load current waveform is extremely distorted in Figure 4.33 and the THD value of load current is 30.6% as exhibited in Figure 4.35. The waveform of the source current is less distorted after the system is connected with 5th harmonic filter as shown in Figure 4.34 and the THD value of the source current is reduced to 5.93% as displayed in Figure 4.36. However, the THD value of the system is still exceed the limit set by IEC which is 5% in a power system.

The current waveform for load and source side of the proposed system as shown in Figure 3.10 is measured and displayed in Figure 4.37 and Figure 4.38. The waveform of the load current is greatly distorted as observed in Figure 4.37 and its THD value is 29.76% as shown in Figure 4.39. To reduce the harmonic content in the system, each phase of the system is connected to 7th harmonic filter. From Figure 4.38, the source current waveform is less distorted and the THD value of the source current is lowered to 18.74% as in Figure 4.40. The THD value in the system is still greater than the IEC standard.

The proposed system is connected to both 5th and 7th harmonic filter in parallel at each phase of the system as displayed in Figure 3.11 in the next simulation. The source current waveform and load current waveform is obtained and displayed in Figure 4.41 and Figure 4.42. The current waveform is highly distorted in Figure 4.41 because of the six pulse rectifier load and the THD value of the current waveform is 31.17% as displayed in Figure 4.43. The source current waveform is distinctly less distorted as observed in Figure 4.42 and the THD value of the source current is 6.59% as presented in Figure 4.44. In short, it can conclude that the 5th and 7th harmonic filter can reduce the harmonic content in the system but unable to fulfil the IEC standard which is 5%.

In the next simulation, the proposed system is connected with SRF based Shunt Active Power Filter as displayed in Figure 3.12. The current waveform of both source side and load side are obtained. It can be observed that the load current waveform is greatly distorted as shown in Figure 4.45 and the THD value of the load current is 33.54% as shown in Figure 4.47. The current waveform of source side is less distorted, and the shape of the source current waveform is very similar to sine wave as presented in Figure 4.46 and the THD value of the source current is 0.49% as exhibited in Figure 4.48. The THD value of the proposed system is comply with the IEC standard which the THD value in the system must be less than or equal to 5%. In short, we can conclude that the SRF based Shunt Active Power Filter can mitigate the harmonic content in the system that is connected with non-linear load.

The simulation results are summarised as shown in Table 4.2

Table 4-2 THD value of load and source current with 6 pulse rectifier load and different filter

Types of load	Filter	%THD of load	%THD of source
6 pulse rectifier	-	25.01	25.01
6 pulse rectifier	5th harmonic filter	30.6	5.93
6 pulse rectifier	7th harmonic filter	29.76	18.74
6 pulse rectifier	5th & 7th harmonic filter	31.17	6.59
6 pulse rectifier	SRF based shunt active power filter	33.54	0.49

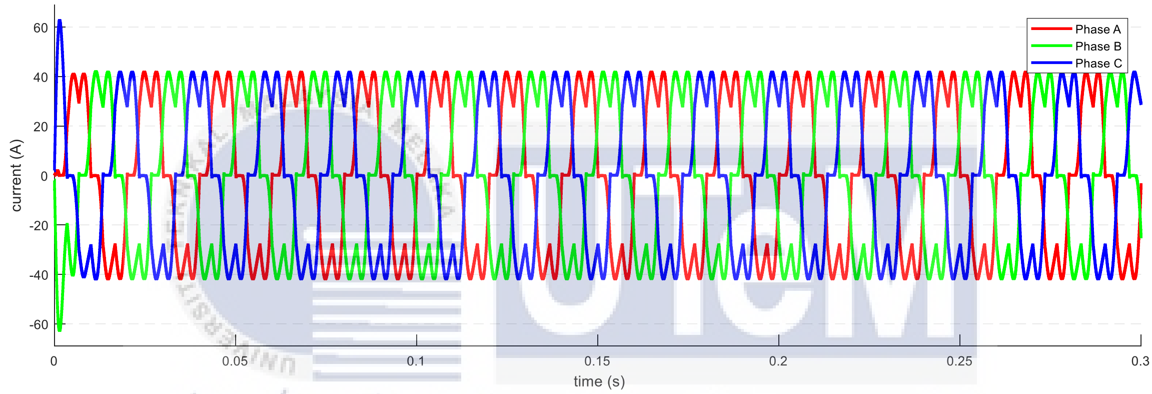

Figure 4-29 Six pulse rectifier load current waveform

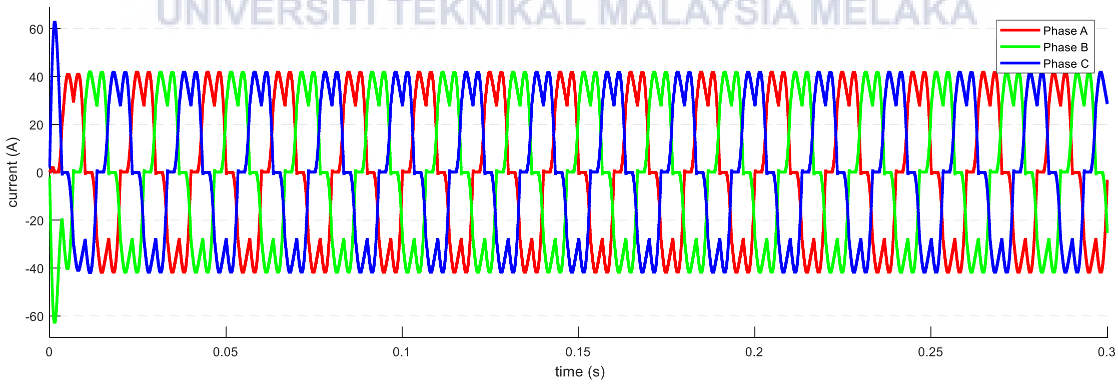

Figure 4-30 Source current waveform with six pulse rectifier load

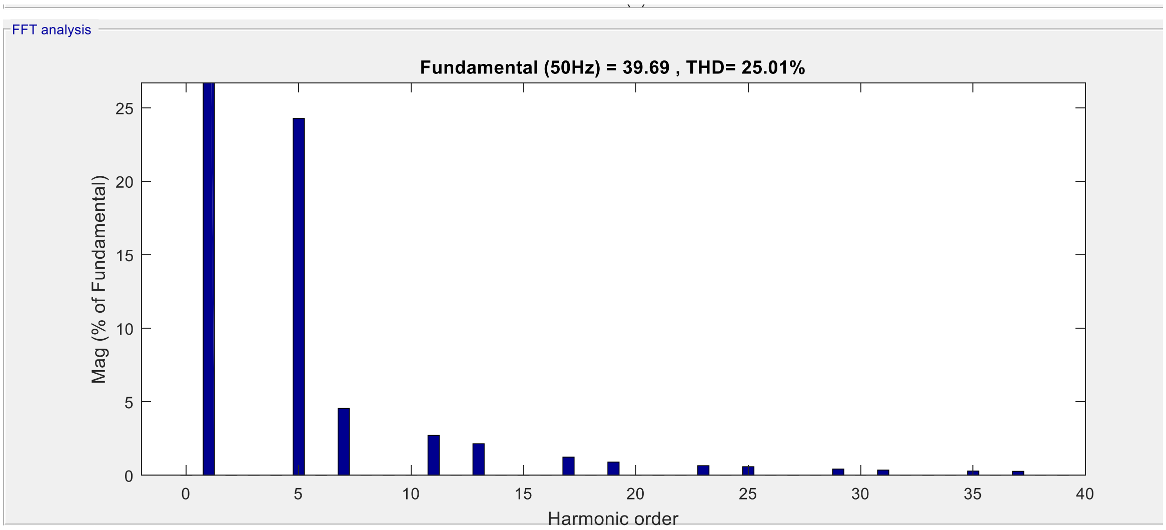

Figure 4-31 THD value of six pulse rectifier load current

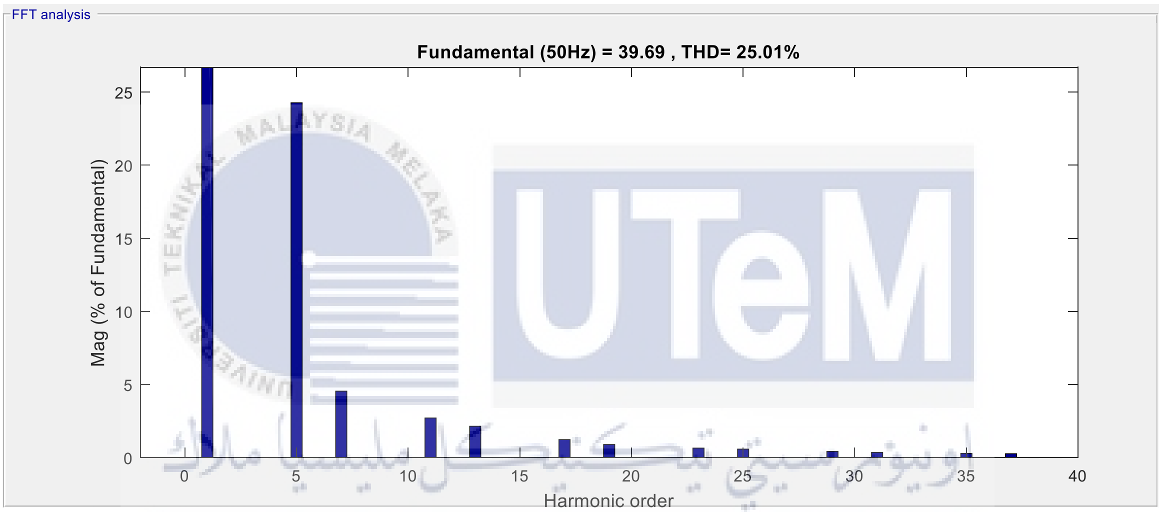

Figure 4-32 THD value of source current with six pulse rectifier load

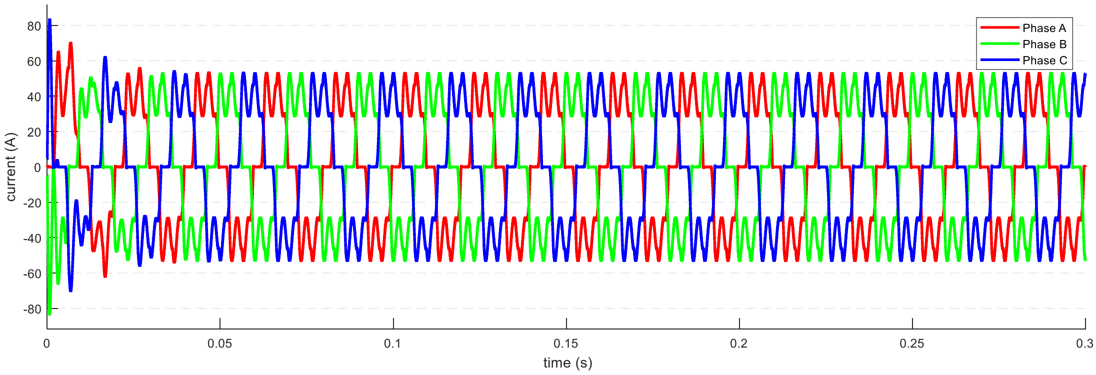

Figure 4-33 Load current waveform of six pulse rectifier load with 5th harmonic filter

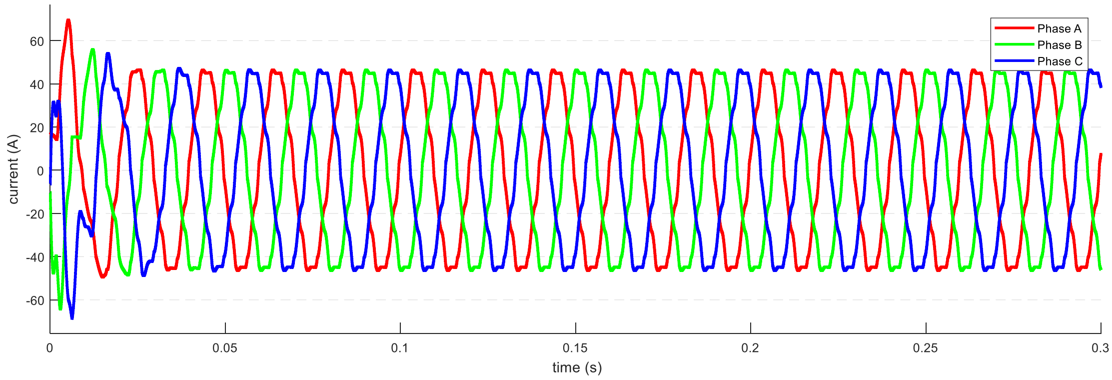

Figure 4-34 Source current waveform of six pulse rectifier load with 5th harmonic filter

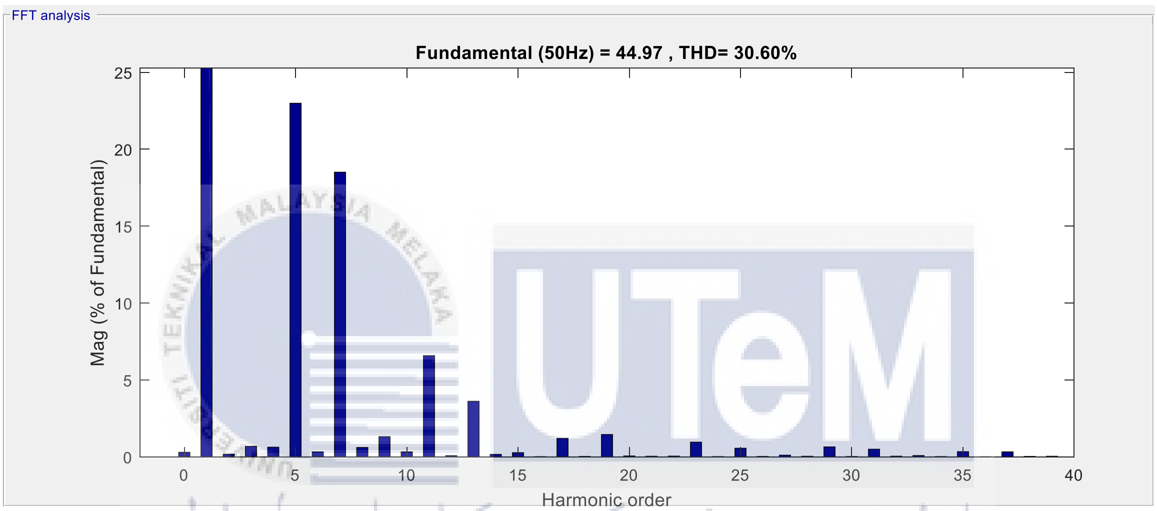

Figure 4-35 THD value of load current of six pulse rectifier load with 5th harmonic filter

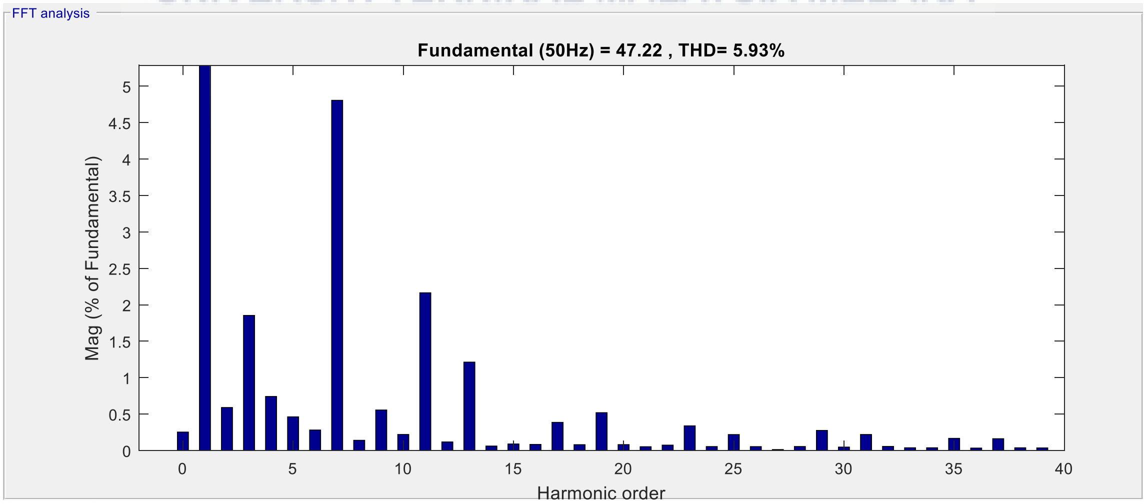

Figure 4-36 THD value of source current of six pulse rectifier load with 5th harmonic filter

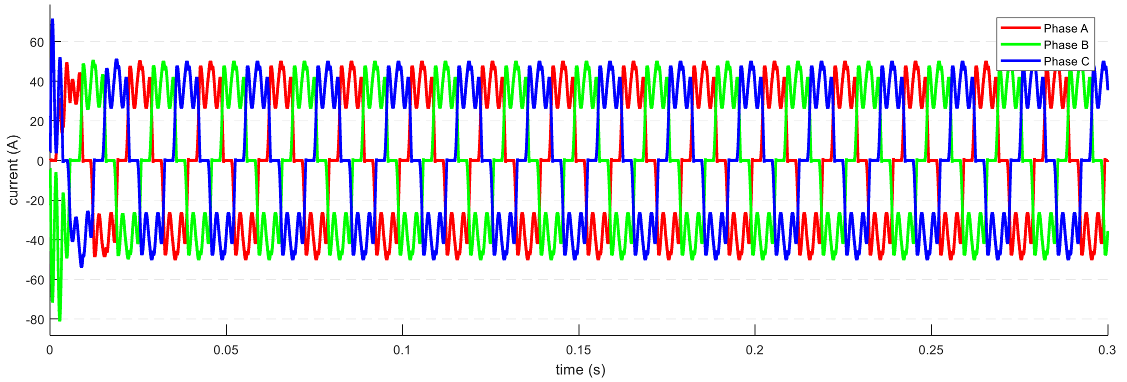

Figure 4-37 Load current waveform of six pulse rectifier load with 7th harmonic filter

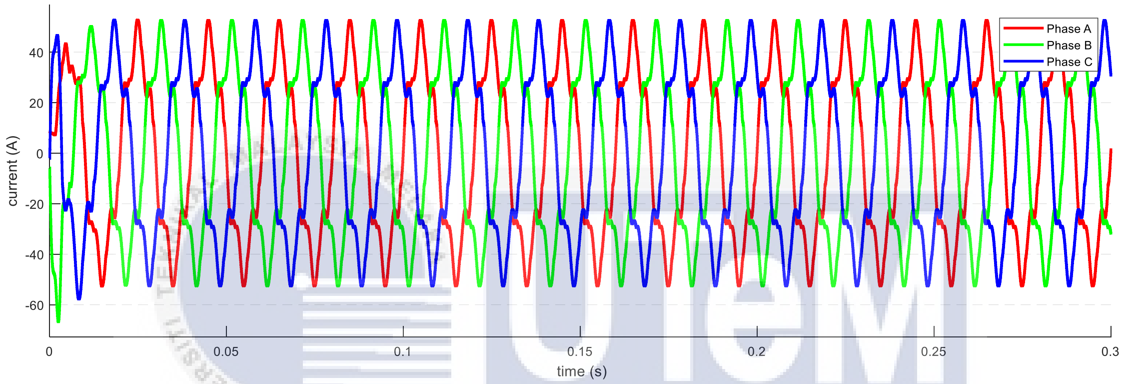

Figure 4-38 Source current waveform of six pulse rectifier load with 7th harmonic filter

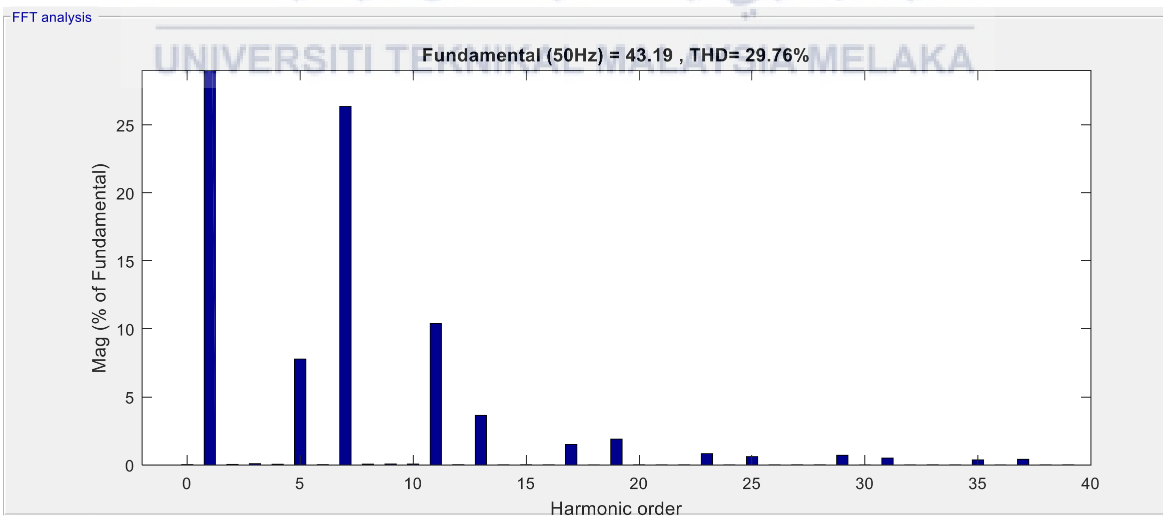

Figure 4-39 THD value of load current of six pulse rectifier load with 7th harmonic filter

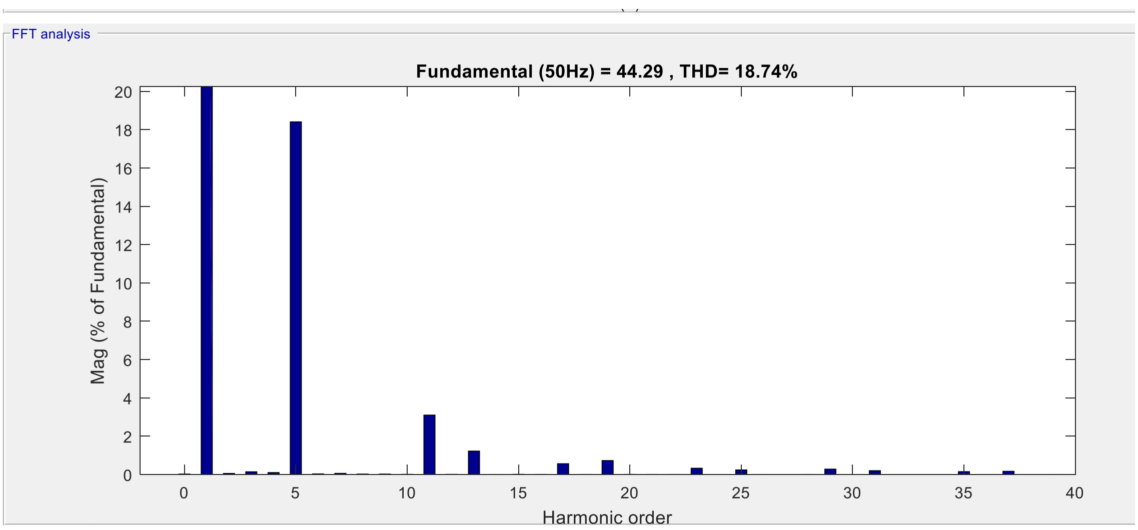

Figure 4-40 THD value of source current of six pulse rectifier load with 7th harmonic filter

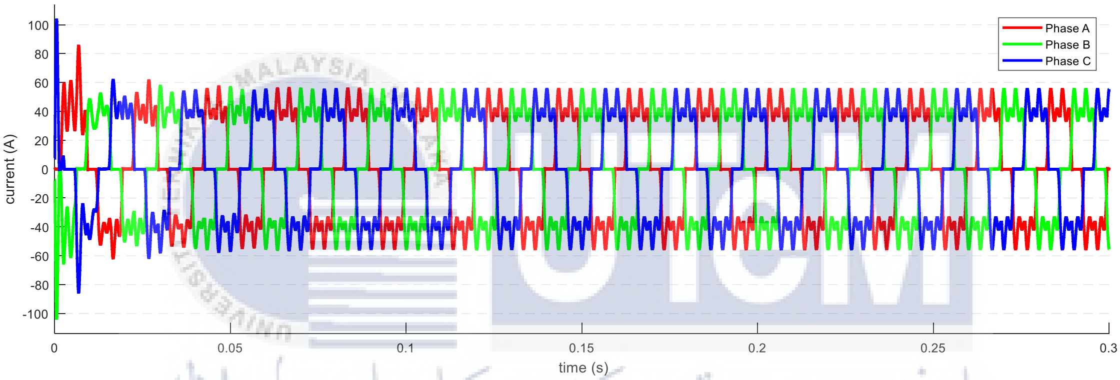

Figure 4-41 Load current waveform of six pulse rectifier load with 5th and 7th harmonic filter

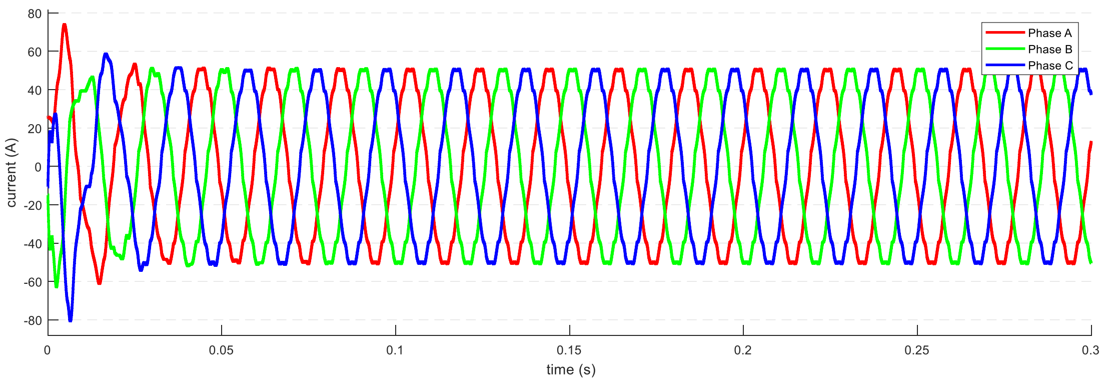

Figure 4-42 Source current waveform of six pulse rectifier load with 5th and 7th harmonic filter

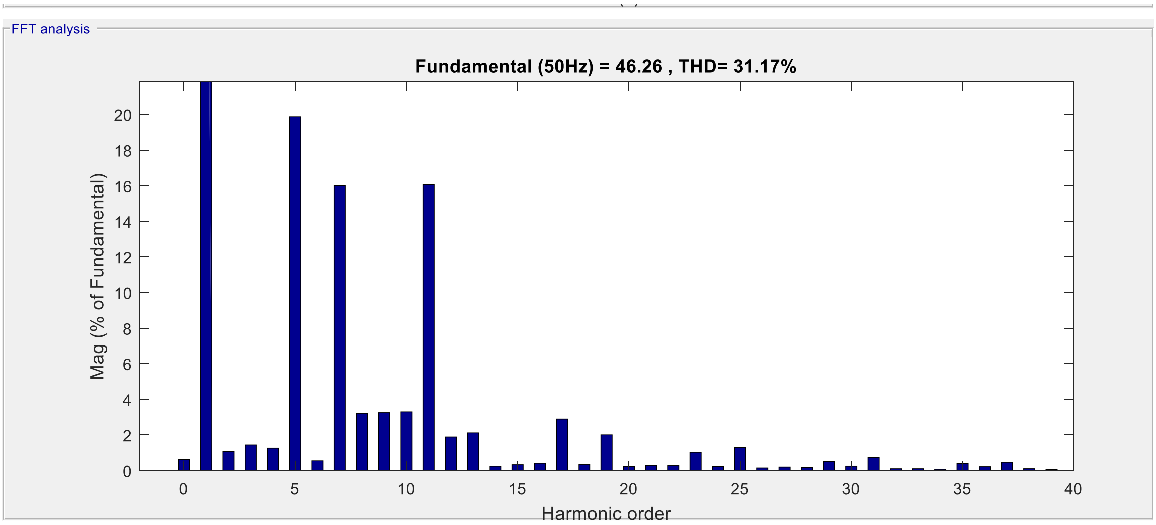

Figure 4-43 THD value of load current of six pulse rectifier load with 5th and 7th harmonic filter

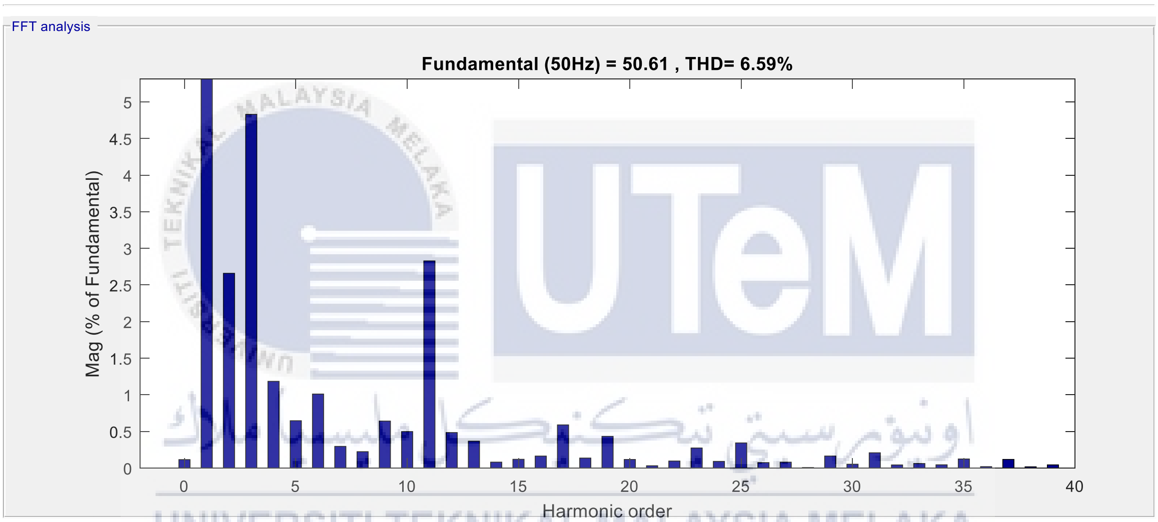

Figure 4-44 THD value of source current of six pulse rectifier load with 5th and 7th harmonic filter

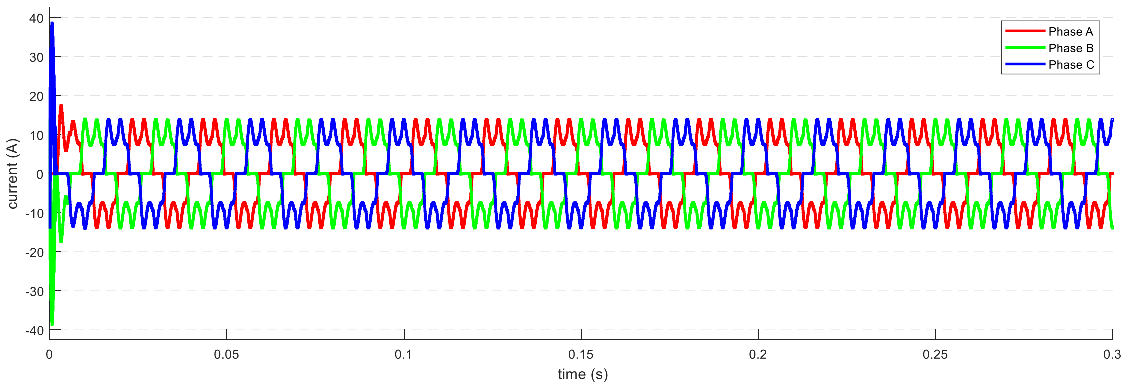

Figure 4-45 Load current waveform of six pulse rectifier load with SRF based SAPF

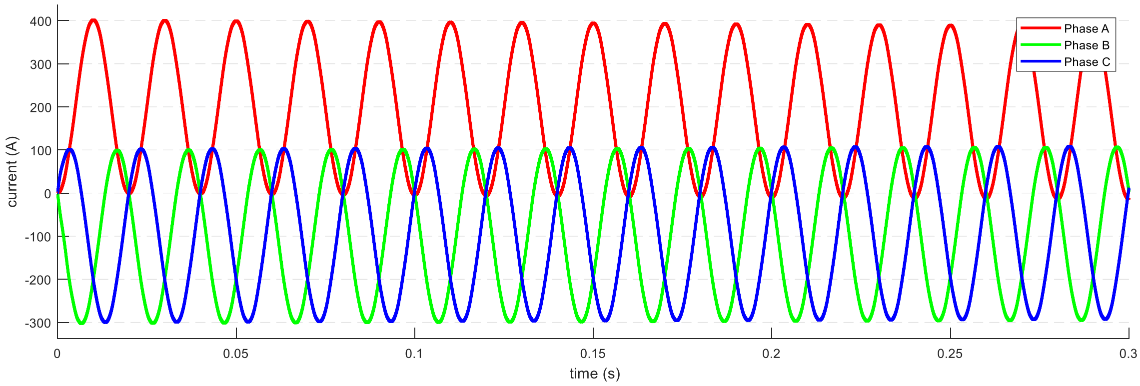

Figure 4-46 Source current waveform of six pulse rectifier load with SRF based SAPF

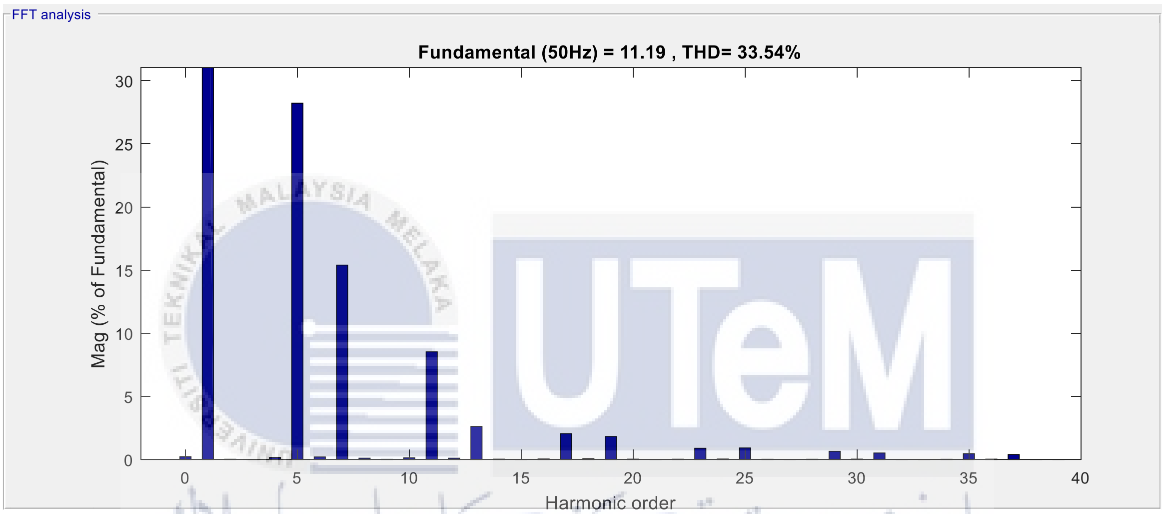

Figure 4-47 THD value of load current of six pulse rectifier load with SRF based SAPF

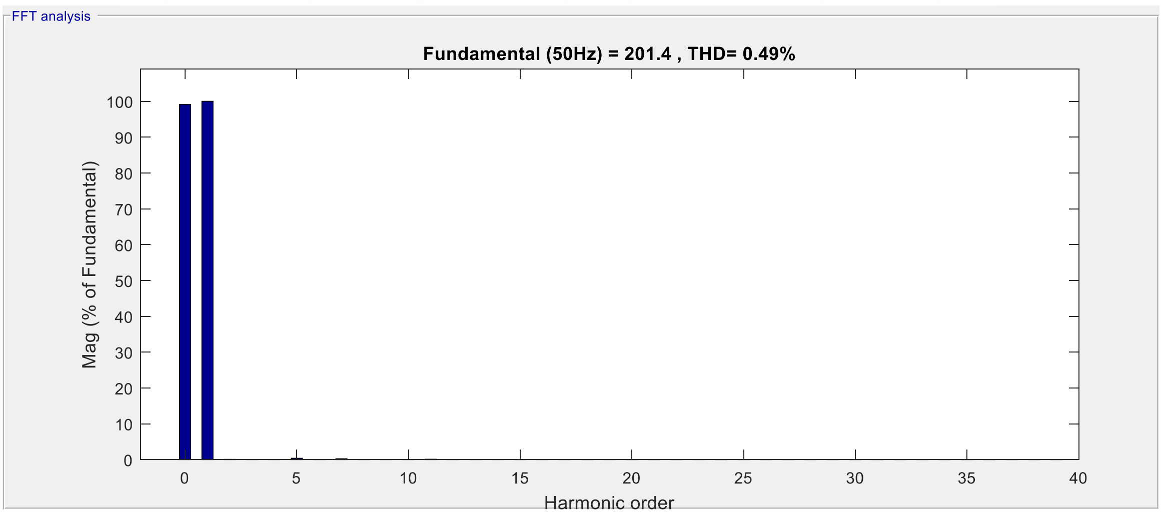

Figure 4-48 THD value of source current of six pulse rectifier load with SRF based SAPF

4.4 Limitation

The SRF based Shunt Active Power Filter is designed to correct the distorted waveform cause by non linear load to sine wave. The proposed SRF based Shunt Active Power Filter is unable to correct other waveform such as triangular wave.

4.5 Summary

From the simulation result acquired, the best filter is SRF based shunt active power filter. The shunt active power filter decrease the total harmonic distortion of source current to 0.13% which satisfy the IEC standard. The 5th and 7th harmonic filter can lessen the total harmonic distortion of source current. However, the outcome did not satisfy the IEC standard which is 5% maximum. The 5th harmonic filter can just lessen the total harmonic distortion to around 5.93%, which is 0.93% higher than IEC standard. The 7th harmonic filter can just lower the total harmonic distortion to around 18.74 % which did not fulfill the IEC standard.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

In conclusion the objectives of this project are achieved where an SRF based shunt active power filter is successfully modelled and the performance of the SRF based shunt active power filter is analyzed and compared with IEC standard. Based on the simulation results, the SRF based shunt active power filter is able to reduce the harmonics distortion in the proposed system to a THD value of 0.49%. The performance of the proposed SRF based shunt active power filter satisfied the IEC standard which the THD value in a system must be not more than 5%. The simulation results also showed the performance of the SRF based shunt active power filter under different type of load is almost the same.

5.2 FUTURE WORK

For future work, the performance of the SRF based shunt active power filter can be compare with shunt active power filter under different control method such as instantaneous active and reactive power theory. The performance of SRF based Shunt Active Power Filter can be test on Switch Mode Power Supply (SMPS) system and on variable frequency drive (VFD) load.

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