Faculty of Electrical Engineering

REDUCTION OF HARMONIC USING SINGLE PHASE SHUNT ACTIVE FILTER BASED ON P-Q THEORY METHOD FOR PWM CASCADED MULTILEVEL INVERTER

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DECLARATION

“ I hereby declared that this report is a result of my own work except for the experts thst have been cited clearly in the references”

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DECLARATION

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Signature :____________________________

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Date : ___/___/2016

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ABSTACT

In recent years the extreme used of power electronic converters and other non-linear loads in industry deteriorates the power systems voltage and current waveforms. The use of nonlinear loads and power electronic circuit in power systems are grow rapidly. Examples are thyristor controlled inductors, converters for High Voltage Direct Current (HVDC) transmission and large adjustable speed drives. All of these loads created unwanted currents into the power system. The impact of harmonic caused more power losses, shorten device life time, and undermine the accuracy of protection and instrumentation device on the system. For higher power applications, multilevel inverter (MLI) structures have the particular advantages of operation at high DC bus voltages which can be achieved by using series connection of switching devices. However, conjunction in designing inverter, it is better to install active power filter such a way to mitigate the harmonic generated by other nonlinear load in the system. For this project, active power filter (APF) helps to enhance the quality of the distorted current waveform produced by the nonlinear load. The performance of APF based on instantaneous power theory control strategies is used and combined with MLI. The detailed analysis and evaluate the performance of APF with p-q theory is based on mathematical method p-q theory equation to generating reference current of shunt APF .The system is validated through extensive MATLAB-SIMULINK Tool Box to analyze the output waveform in term of total harmonic distortion (THD) of current and voltage. Based on result from simulation, by injecting current from APF to the line the THD is decreased in range 4% to 98%.

ABSTRAK

Dalam tahun kebelakangan ini, penggunaan penukar elektronik dan beban bukan linear yang melampau dalam industri mengakibatkan kerosotangelombang kuasa sistem voltan dan arus semasa. Penggunaan beban tidak linear dan kuasa litar elektronik di dalam sistem kuasa sedang berkembang pesat. Contohnya adalah thyristor mengawal pengaruh, penukar untuk penghantaran kuassa tinggi dan pemacu kelajuan boleh laras. Kesemua beban ini mencipta arus yang tidak diingini ke dalam sistem kuasa. Kesan harmonik menyebabkan lebih kerugian lebih kuasa, memendekkan jangka hayat peranti, dan melemahkan ketepatan perlindungan dan alat peranti pada sistem. Bagi applikasi kuasa yang lebih tinggi, inverter bertingkat (MLI) struktur ini mempunyai kelebihan tertentu seperti operasinya pada voltan bas DC yang boleh dicapai dengan menggunakan sambungan siri peranti pensuisan. Walau bagaimanapun, dengan adanya reka bentuk inverter, ia adalah lebih baik untuk memasang kuasa penapis aktif dengan cara ini ia dapat mengurangkan harmonik yang dihasilkan oleh beban tidak linear dalam sistem. Untuk projek ini, penapis kuasa aktif (APF) membantu meningkatkan kualiti bentuk gelombang yang dihasilkan oleh beban tidak linear. Prestasi APF berdasarkan strategi kawalan teori kuasa serta-merta dan digabungkan dengan MLI. Analisis terperinci dan menilai prestasi APF dengan teori pq adalah berdasarkan kaedah matematik dan persamaan teori pq untuk menjana arus rujukan untuk sistem pirau APF . Sistem ini disahkan melalui penggunaan MATLAB SIMULINK-Tool Box untuk menganalisis gelombang keluaran dari segi jumlah herotan harmonik (THD) arus dan voltan. Berdasarkan hasil dari simulasi, dengan menyuntik arus dari APF ke laluan arus jumlah THD itu menurun dalam julat 4% sehingga 98%.

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CHAPTER 1

INTRODUCTION

1.1 Overview

In a modern electrical distribution system, there are extensive of used nonlinear electronic load such as power supplies, rectifier equipment, domestic application, adjustable speed drive, etc. One of the most problems associated with nonlinear electronic load is a nonlinear characteristic. These nonlinear loads produce non-sinusoidal current and voltage called harmonic distortion. The present of harmonic distortion can cause many problems such as transmission power losses, conductor overheating, over loading of capacitor bank, low power factor and etc [1]. This problem will make suffered in payment of electricity bills because of power quality issues. Over a last few years, there was many effort have been made in improving the harmonic distortion in power system distribution. A traditional method to improve harmonic distortion is by using passive filter (PPF). PPF is able to mitigate the harmonic component and improve power quality of electrical power system. However, the performance of passive filter is not satisfied although the cost is acceptable. This is because passive filter has many disadvantages due to capable to eliminated higher frequency harmonic, resonance problem, mistuning of passive element and instability in operation [2].

Therefore, a dynamic, versatile and viable solution to mitigate the non-sinusoidal current produce by nonlinear load is active power filter (APF). The use of APF is a trend of harmonic improvement in distribution power system because of its excellent characteristic. APF divided in two categories which is series and shunt filter. Generally, series APF used to generate harmonic voltage to compensate load harmonic voltage, while shunt APF effective in generate harmonic current to compensate harmonic current. Researchers have been developed and determine that shunt APF as a feasible solution to the problem created by nonlinear load. Shunt APF will operate at relative high switching frequency for generating the desired injection current that used to mitigate lower frequency harmonic order. Most of the techniques have their own difficulty level. In this project the instantaneous reactive power theory are selected as a method to implement in shunt active power filter.

In designing of inverter the most concern is to develop the harmonic less inverter. A lot of technique and topologies is developing to improve the harmonic of inverter. It is one of the popular devices used in high power medium- voltage (MV) drives. The MLI has an advantage of operation at high direct current (DC). The most significant advantage of MLI can generate output voltage with very low harmonic distortion. MLI also can solve the problem of high harmonic distortion that produced by the conventional inverter that have been used in energy conversion. The total harmonic distortion (THD) can cause the additional losses, overheating and overloading that can reduce the power quality of electrical system. There are various topologies of MLI but, the most common multilevel inverter topologies are Cascaded H-Bridge (CHB) inverter. In this project, the CHB is used to model and analyze the performance of MLI and tested with several of load. The used of CHB in this project is because the cascade MLI easy to control compare to other topologies such as Neutral Project Clamped (NPC) and Flying capacitor (FC).

1.2 Problem statement

Due to extensive of used power converter and nonlinear load, power distribution systems suffer with the power quality issue. One of the power quality issues is harmonic. In Malaysia the development of solar system become highly demand with introduction of fit in tariff (FIT). In solar system, the most important part that need to be develop is inverter and to produce the harmonic less inverter will contribute to costly and complexity of the inverter.
To overcome these situations, the harmonic less MLI have been developed. Traditional method in designing the harmonic less inverter used PPF to mitigate harmonic, but PPF only eliminate at high frequency and it creates series/parallel resonance. Moreover, there is no effect in eliminated harmonic if nonlinear load connected to electrical system. If the inverter is connected to fixed load, it give good result in mitigates the harmonic. Unfortunately, the growth of dynamic load by the consumers bring the presents of harmonic. To overcome that issue the implementation of APF will cater the generation of harmonic.

1.3 Objective

The objectives of this project are:

1. To model a single phase shunt active power filter based on instantaneous reactive power theory.
2. To analyze the performance of single phase shunt active power filter connected with multilevel inverter.
3. To validate the design in reduce the harmonic for PWM cascaded multilevel inverter

1.4 Scope

The scope of this study is to conduct the simulation on single phase shunt APF that combine with MLI. The CHB topologies used as MLI and operate by trinary, bipolar and unipolar switching method. The filter used control technology by using time domain technique. The method of obtain reference current is use the instantaneous reactive power theory. The simulation will conducted using MATLAB/Simulink software. The simulation block will be developed based on mathematical equation of p-q theory. The purpose of this simulation is to reduce the present of harmonic. Moreover, DC supply that used as source for MLI is assumed from photovoltaic solar as renewable energy system to determined performance of CHB-MLI with the effect of harmonic. Lastly, the different of load is tested which are fixed and dynamic load. It consists of R, RL and RC for fixed load while R, RL, and RC combine with rectifier consider as dynamic load. This variable load is used to determine the several change of THD that occur in the system.

1.5 Project Organization

This thesis contains of five chapters, starting with the introduction of research project which is about the effect of harmonic and implementation to mitigate the problem using shunt active power filter.

Chapter 2 covers the literature review of this project and details about power quality, harmonic distortion and the effect, the harmonic problem method to overcome, type of MLI and the method to operate

Chapter 3 discuss about on the switching technique to operate the cascaded multilevel inverter (MLI). There are many type of switching that use for MLI. For this chapter the trinary, bipolar and unipolar techniques are explaining more detail including the appropriate design to generate the switching waveform. Moreover, the main purpose of this project is to develop the single phase of active filter (APF). The power instantaneous technique that been used also discussed in this chapter. Moreover, the combination between MLI and APF also explain in general.

Chapter 4 examined the simulation of cascaded multilevel inverter that combined with shunt APF. From the multiple type of switching method of CHB-MLI and instantaneous reactive power theory method for APF, the system is tested with different type of load. The result will shows the different of line current and load current before and after the connected of shunt APF.

Chapter 5 is a discussion about the overall result of the simulation and prove the performance of shunt APF in order to improve the total harmonic distortion.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is discussing about the literature review of previous research. From the review will get more information that can be made to complete this project. All the new information taken from journals, papers, books and any academic articles that are related to this project will cite according to it belongs.

2.2 Power Quality

A latest innovative idea to make the life easy is by using the technology depends on the application of power electronics. Power quality (PQ) problem issues most concern nowadays. PQ problems can usually be traced from things like the starting and stopping of refrigeration compressors or air-conditioner motors, circuit overloads, harmonic currents created by electronic equipment, or grounding and wiring problems. Moreover, the increasing of non-linear load in electrical systems produces major causers of power quality problems [3]. With increasing of non-linearity, all these load cause disturbance in the voltage waveform.

The degree of purity of power element can defined a power quality. It can classify that the performance of electrical system will work properly without any losses or the system is fully function form any interruption for the customer used [4]. Power supply, there are two type of frequency that has been used which is 50 Hz and 60 Hz. It also knows as fundamental frequency. If the presence of non-linear load in electrical system the frequency of voltage and current will be change. This is because the process multiplies of fundamental frequency with voltage or current frequency. It is also categorize as pollution to electrical system also know as harmonic distortion.

2.2.1 Harmonic in Electrical System

Harmonic is defined as a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency [5]. In power system there are always had a present of harmonic. In early of 1890's harmonic were related on current and voltage waveform shape on transmission system. This shows that, it did not effect in industrial or commercial building due to the equipment was less sophisticated. Nowadays, the rapid increase number of electronic device has brought subject up-front. Due to this phenomenon, the harmonic creating devices also increase.

Since 1965, the harmonic creating devices that low cost, high efficiency semiconductor has increased in electronic power converters. Most of industry is use it in form of variable speed drive to control most of type of machinery. After the oil embargo and associates rapid increase in energy cost in 1973, the use of electronic power converter on larges system was essential. This is one of contributor on harmonic in power systems.

The presence of harmonic in electrical system is because present of non-linear load. Uninterruptible power supplies (UPS) system, solid state variable speed motor drives, rectifiers and personal computer are examples of non-linear load. Non-linear load occur when the impedance is not constant and the current produce is not proportional as voltage waveform. The current drawn from this load is not sinusoidal although it periodic. Typically, non-linear load from electronic switch power supplies and some device that involve in energy conversion. From this load, the consumer pays more in unused energy due to voltage and current distortion. If compare to linear load, the impedance is constant and the current is proportional to voltage because linear element in power system. Besides that, for linear load the consumers pay for unused energy from voltage distortion.

In a simple word harmonic is a summation of mathematical model of sinusoidal waveform that have been distorted. From the Fourier series equation of current and voltage represent in Equation 2.1 and Equation 2.2 , it is represent the additional of sinusoidal wave of various frequency that have been integer multiples of fundamental frequency.

$$i(t) = I_{0} + \sum_{n=1}^{\infty} I_n \cos(nw_0 t + \emptyset_{I_n}) \tag{2.1}$$

$$v(t) = V_{0} + \sum_{n=1}^{\infty} V_n \cos(nw_0 t + \emptyset_{V_n}) \tag{2.2}$$

Where,

$$\omega_0 = \frac{2\pi}{f}$$

To analyze the harmonic in power system, the present of distortion in waveform is important to determined. The Equation 2.3 and Equation 2.4 represent the total harmonic distortion (THD). The value of V_1 and I_1 are the fundamental voltage and current while V_n and I_n are the harmonic voltage and current.

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty}(V_{n,rms})^2}}{V_{1,rms}} x100\% \quad (2.3)$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty}(I_{n,rms})^2}}{I_{1,rms}} x100\% \quad (2.4)$$

2.2.2 Effect of harmonics

The increasing use of non-linear load devices will introduced a power quality issue in the form of harmonic distortion. The magnitude of this harmonic distortion varies with the nonlinear load distribution at various level of voltage in a system. The effect of generating harmonic that came from nonlinear load are facing a serious problem in the power system such as low power factor, increases losses, reduces the efficiency and increase the total harmonic distortion [6].

Harmonic distortion can cause poor power factor. Power factor problem will affect the overall power distribution system. The low of power factor may cause consumer to get heavy fines when the facility given is affecting the ability of efficiently the supply power. Due to distribution equipment overheating, random breaker tripping, or even sensitive equipment failure, it will produce increases of power losses [7].

Creating additional heating in power system components will reduce the expectancy of lifespan. Moreover, the false tripping or sensitive failure may result the equipment easy damage or blow for a no accepting reasons. In the long term, the problem due harmonic will break down an electrical system. All the electrical appliance or distribution equipment need to extra maintenance or change for a new. This particular will affect increasing of costs since harmonics affected in all power system equipment and high of electric bill [8].

2.2.3 Harmonic Standard

The cause of excessive heating, pulsating and reduced torque in motor or generator, increasing heating, voltage stress in capacitor, missed operation in electrical switch gear makes the harmonics are concern. In order to minimize the problems, it is useful to measure and limit the harmonics in electrical system by follow the standard. Moreover, the lifetime of equipment may reduced if a system is design without consider the harmonic rated [7]. For the action of this issues the following standard and guidelines have been establish that specify limit on the magnitudes of harmonic current and voltage distortion at various harmonic frequencies [8].

2.2.3.1 IEC Harmonic Standard 555-2

International Electrotechnical Commission (IEC) has prepared this standard and have been accepted by National Committees which are Australia, Austria, Belgium, Canada, Egypt, Finland, France, Germany, Hungary, Ireland, Japan, Korea, Netherlands, Norway, Poland, Romania, South Africa, Switzerland, Turkey and United Kingdom.

For the public distribution system of 50 Hz or 60 Hz frequency and having an input current that more than 16 A, the IEC 555-2 have provides harmonic current limit for all electrical and electronic equipment. It divided into two categories which are single phase and three phases. The single phase is cover on 220 to 240V and three phase in between 380 to 415V. It also has several classes from class A until D. Class A for balanced three phase equipment and anything else that does not fit into others group, Class B for any portable equipment, Class C for lighting equipment and Class D having an input current with a special wave shape.

The harmonic limits are defined in absolute values, irrespective of the equipment power rating. Table 2.1 gives the maximum permissible harmonic current in amperes in these four groups according to the IEC 555-2.

Table 2.1: IEC 555-2 Harmonic Current Content Limits

	Odd harmonic							Even Harmonic			
Harmonic Order (n)	3	5	7	9	11	13	15<n<39	2	4	6	8<n<40
Max. Permissible Harmonic Current (A)	2.3	1.14	0.77	0.40	0.33	0.21	0.15x15/n	1.08	0.43	0.30	0.23x8/n

2.2.3.2 IEEE Standard 519-1992

Harmonic voltage distortion on power systems 69 kV and below is limited to 5.0% total harmonic distortion (THD) with each individual harmonic limited to 3% based on the IEEE 519. Based on the short circuit strength of the system that are being injected the current harmonic limits is vary. Overall, if more allowed current inject for customer, the system more able to handle harmonic currents.

Table 2.2 shows the IEEE 519 harmonic voltage limits mean while Table 2.3 shows the harmonic current limits. The customer can injecting current into the utility system based on the maximum amount of harmonic current that have been specify. The customer can avoid be accused if the customer meets the harmonic current limits because the utility have their own responsible to provide low distortion of voltage [9].

The purpose of IEE 519 recommended this standard is because to make a practice among users so that each of users did not degrade the serving of voltage from utilities by applying the nonlinear current to utilities. Furthermore, this will make sure the utilities provide to the users with purely sine wave of voltage and current [9].

Table 2.2: IEEE Standard 519-1992 Harmonic Voltage Limit

Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5
NOTE: High-voltage system can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time is tapped for a user		

Table 2.3: IEEE Standard 519-1992 Harmonic Current Limit

Current Distortion Limits

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonic)						
I_{sc}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
Even harmonic are limited to 25% of the odd harmonic limit above.						
Current distortions that result in DC offset, e.g half-wave converters are not allowed.						
*All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L						
Where I_{sc} = max short-circuit current at PCC I_L = max demand load current (fundamental frequency component) at PCC TDD =Total demand distortion (RSS), harmonic current distortion in % of max demand load current (15 or 30 min demand) PCC = Point of common coupling						

2.3 Harmonics mitigation

Currently, the elimination of harmonic for improve the power quality is a great issue. To overcome this problem, there are two approaches than can be done which are by knowing the load condition and by installing of line filter to suppress the power system disturbance [10]. The second approach is widely used and divided into two methods which are passive power filter (PPF) and active power filter (APF).

2.3.1 Passive Power Filter

Passive power filter (PPF) is a conventional method and most commonly used to reduce percentages of total harmonic distortion in power distribution system. It is simple and used for long time but the performance of PPF is limited. To reduce certain harmonic frequency it need separated filter. There are several type of passive filter that contained the combination of passive element namely low-pass filter, high-pass filter, band-pass filter and tune filter.

All type of filter is illustrated on Figure 2.1. The low-pass filter used to remove the high frequency while the high-pass filters to attenuate the low frequency. Band-pass filter is used to allow the band of frequency to pass by rejecting the others frequency and lastly tuned filter used for cancel the specific frequency [11].

They have some advantages and disadvantages using PPF. The advantages of PPF are the simplicity of design, reliability and it no need external source to operate. It is also suitable because of no limitation due to range of frequency. However, this filter required large numbers of component, it is shows that so bulky in natural and can produce resonance in power system [12].

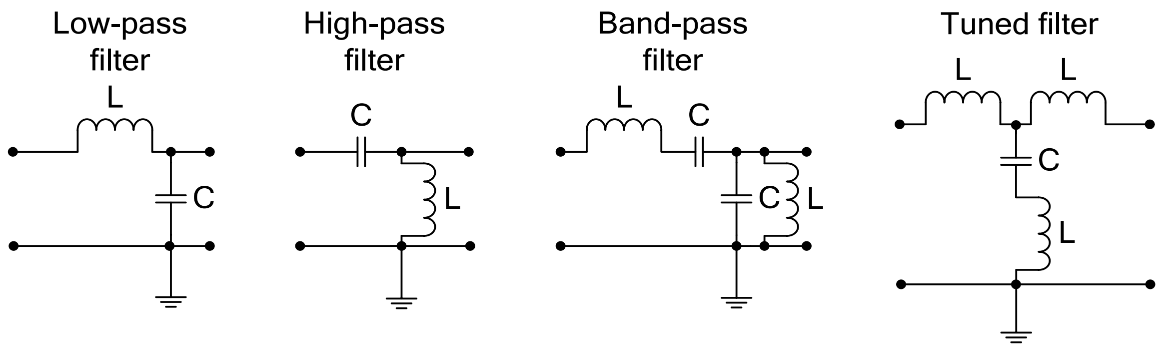


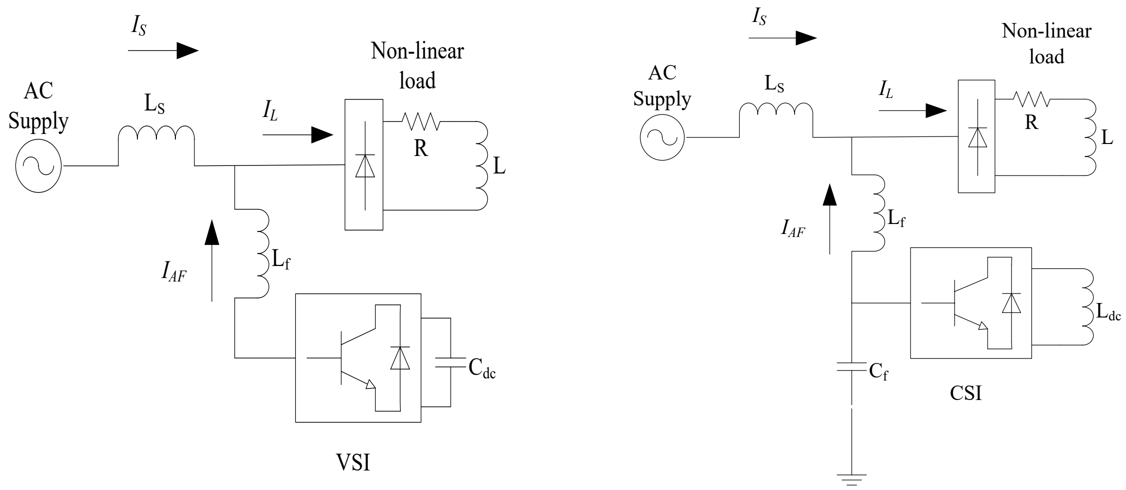
Figure 2.1: Type of passive power filter

2.3.2 Active Power Filter

There a two classification of active power filter that usually used in power system which are based on voltage source and current source. In other words it knows as voltage source active power filter (VSAPF) and current source active power filter (CSAPF).

The supply and PWM bridge of VSAPF need to connect with filter either first or third order to control the current while CSAPF need to connect with second order filter to filter carrier frequency components from the PWM. The DC link of VSAPF is connected with electrolyte capacitor that acts as energy storage. However, the capacitor has disadvantages because of the limited lifetime. For CSAPF the DC link is connected with inductor as the storage component. Because of the bulky and heavy component used the lifetime of the DC coil is not limited as was that of the electrolytic capacitor in the VSAPF [13].

To utilize the performance of CSAPF, the DC link current need to higher that peak of the filter current while to enhance the VSAPF, the DC bus voltage need to higher that peak of line voltage. So that the DC link current can depend on nonlinear load characteristic or same to the rated power while DC link of bus voltage depend only on rated voltage of active power filter. The circuit using the two methods is illustrated in Figure 2.2.



(a) (b)

Figure 2.2: Single phase of (a) VSAPF and (b) CSAPF

2.3.2.1 Type of Active Power Filter

Active power filter (APF) generally to compensate current and voltage harmonic. There is several topology based on classification APF which are the series active power filter, shunt active power filter, unified power quality conditioner (UPQC) combination of shunt and series active power filter and hybrid active power filter the combination of shunt or series active filter and passive filter.

The series active filter work act as a voltage source and shunt active filter acts as a current source. The series filter is suitable to balance capacitive or voltage source load and eliminate voltage harmonic while shunt filter is suitable to compensate inductive or current source load and mitigate current harmonic. The UPQC is response to eliminate the voltage and current harmonics and load voltage regulation and balancing the current. Hybrid active power filter or combination active filter and passive filter are suited to compensate both voltages and currents simultaneously [13].

2.3.2.2 Shunt Active Power Filter

The widest use of APF is shunt active power filter. Generally, the load is connected parallel with filter and the filter act as harmonic current generator. This is because to compensate the harmonic and reactive current at a certain position in power system [14]. The purpose of this filter is to inject current that used to mitigate low order current harmonic by operate at high switching frequency [15]. However, the supply current which is return to electrical system is merely fully sinusoidal although the load current remains distorted [16].

The Figure 2.3 shows the block diagram of shunt active power filter. This block diagram contains voltage supply, filter that connects in parallel and the nonlinear load. The mission of this filter is to inject current inverter controlled by pulse width modulation (PWM) signal. According to the Kirchhoff's current law, the relationship between the load current, filter current and supply current are represent in Equation 2.5.

$$I_L = I_s + I_F \tag{2.5}$$

If the nonlinear load has a purely resistive, the output waveform will produce sinusoidal equivalent to supply current. Based on Figure 2.4 the waveform is illustrated as the load current, the desired filter or injection current and the supply or resultant current.

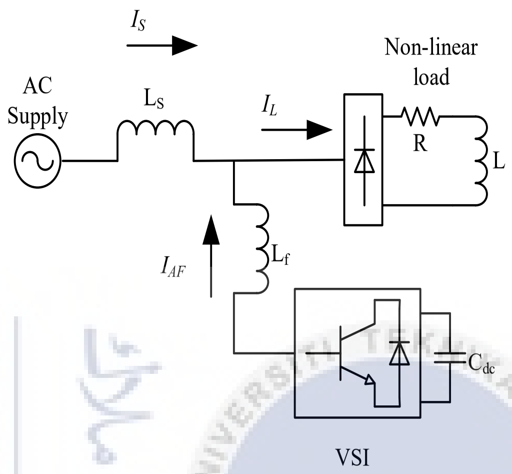


Figure 2.3: Block diagram shunt active power filter

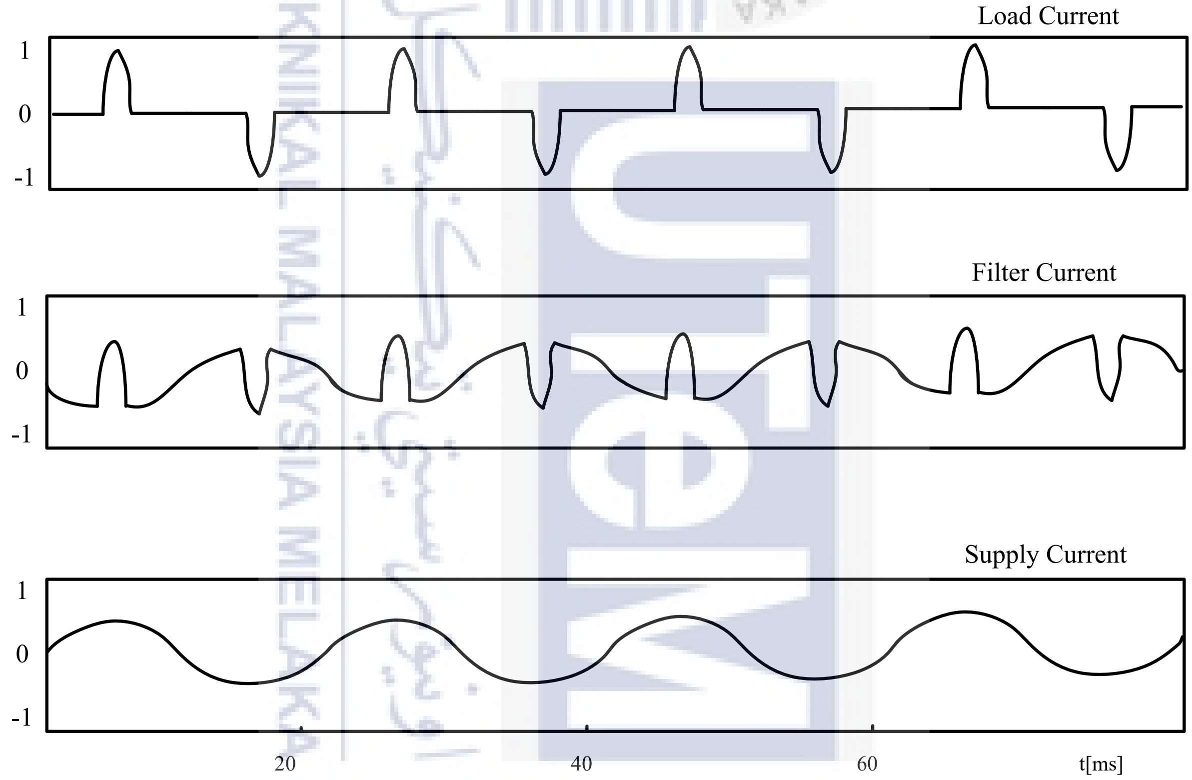


Figure 2.4: Waveform of conventional active power filter

2.3.2.3 Series Active power Filter

Other control strategy to mitigate the harmonic is series APF. The cost effective of series active power filter make it easy to implement [17]. The configuration of series APF is by using transformer to isolate harmonic between source and non-linear load. The Figure 2.5 shows the block diagram of series APF.

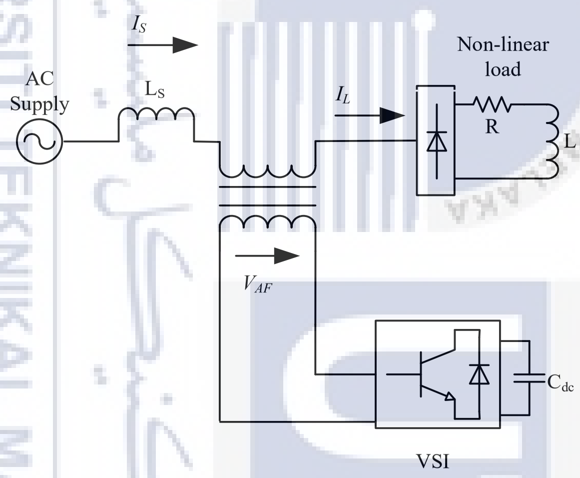


Figure 2.5: Block diagram series active power filter

The operation of series APF is by adding the compensation voltage to network to harmonic component of nonlinear voltage. The purpose of compensating voltage is to suppress the harmonic distortion. The voltage and current is makes as input to generate the compensation voltage and fed to network using transformer. The advantages of series APF is it able to compensation for varying loads, resonance free, does not affect power factor and can be combined with passive filter network. However, it has to handle high power losses makes the increases of current rating [18].

2.3.2.4 Hybrid Active Power Filter

There are lots of techniques to limiting the distortion current in electrical system. Some of the technique has own capability and limitation. Hybrid APF is a combination between two filters which is APF and PPF. It can connect in series or parallel. It intention to overcome the disadvantages of APF and PPF while maintain both advantages [17]. PPF can endure high voltage and capacity whereas APF can filter harmonic effectively, so hybrid APF is very practical and economical. APF work as to filter out higher order of harmonic while PPF tuned at particular frequency to filter lower order of harmonic in hybrid APF. So the cost and size of hybrid APF is reduce [18]. Generally there are three topologies that able in power system to mitigate harmonic distortion which is hybrid APF connect in shunt APF and shunt PPF, connect in series APF and shunt PPF and series connection between APF and PPF.

The reasonable of design and control hybrid APF can reduce the disturbance of source voltage and harmonic current in power system. So it is suitable with load that easy to effect by source voltage and can cancelled the harmonic disturbance. However the producing of equal high impedance refers to harmonic current of load will happen if the output of series APF controlled. Therefore, the shunt PPF branches will have harmonic current flow through it. As well knows, the PPF always can compensate harmonic current with fixed frequency. These create high impedance in PPF and the harmonic current will yield harmonic voltage on this impedance, the situation will worsen the waveform of load voltage [19].

2.3.2.5 Unified Power Quality Conditioner

In 1998 Hirofumi Akagi was proposed a unified power quality conditioner (UPQC). UPQC can improve voltage quality and current quality at the same time by combining shunt APF and series APF by haring a DC capacitance. To compensate voltage flicker/imbalance, reactive power, negative sequence current, and harmonics is the main purpose of a UPQC [20].

If installed on power distribution systems or industrial power systems UPQC has the capability of improving power quality. Cause of large capacity loads sensitive to supply voltage flicker or imbalance, the UPQC provide most powerful solutions. Series APF can eliminates supply voltage flicker or imbalance from the load terminal voltage, capability of voltage flicker or imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer point of common coupling (PCC). Shunt APF will absorb all the current harmonics produced by a nonlinear load and compensate for reactive power and negative-sequence current, and regulate the DC-link voltage between both APF [20].

Overall, the most flexible approach for filtering the supply voltage and the load current is UPQC. UPQC protects critical loads against voltage disturbance and compensates the current of these protected loads. This is because to ensure the sinusoidal and balanced current drained from the network. Although, UPQC can well solve the problems but the shunt APF capacity UPQC needed is very large as capacity, high installation investment and low efficiency [21]-[22].

2.3.3 Control Technique

Frequency domain technique and time domain techniques can be categories as technique in control reference for active power. Figure 2.6 shows the type of control technique used to control the APF. For the frequency domain its only contains single technique while time domain has lots of technique used. Several techniques for time domain are stated in Figure 2.6.

Variants of the active power filter controlled method have been proposed and some of the control produced different control technique but there are mostly similar objectives. From the power system and APF circuit the information of variable voltage and current will manipulated by the control technique. AC source voltage, DC bus voltage and transformer voltage are sensed by voltage variable while AC source current, APF current and DC link current are sensed by current variable.

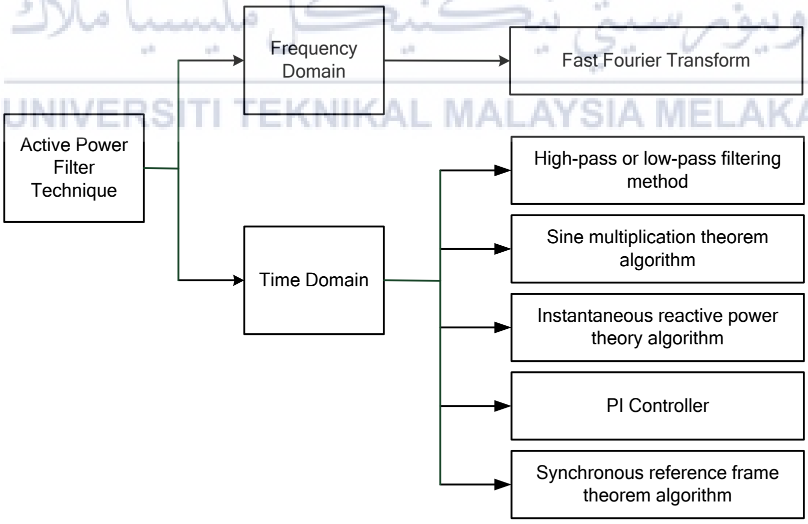


Figure 2.6: Categorize of control technique of APF

2.3.3.1 PQ theory

In 1983 Hirofumi Akagi introduced p-q theory. The harmonic power optimally in balanced or unbalanced and sinusoidal supply voltage systems is compensates. This theory is based on instantaneous power defined in time domain. It is valid for both transient and steady state. Clarke transformation transforms voltages and currents from *a-b-c* coordinates to mutually perpendicular set of *α-β-0* axis. Based on this transformation, transformed voltages and currents are given Equation 2.6and Equation 2.7.

$$i_{\alpha\beta0} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} i_{abc} \tag{2.6}$$

$$\mathrm{v}_{\alpha\beta0} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} v_{abc} \tag{2.7}$$

$$p = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 \tag{2.8}$$

$$q = v_\alpha i_\alpha - v_\beta i_\beta \tag{2.9}$$

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix}\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{2.10}$$

$$p = \bar{p} + \tilde{p} \tag{2.11}$$

$$q = \bar{q} + \tilde{q} \tag{2.12}$$

The equation of instantaneous real power p and instantaneous imaginary power q can be expressed as Equation 2.11 and Equation 2.12 where $\bar{p}$ mean value of instantaneous real power, $\tilde{p}$ alternating value of instantaneous real power $\bar{q}$ mean value of instantaneous imaginary power $\tilde{q}$ alternating value of instantaneous imaginary power The alternating value of the instantaneous real power is $\tilde{p} = p - \bar{p}$. The compensating currents in *α-β-0* coordinate expressed in Equation 2.13. After inverse Clarke transformation, the compensating currents in *a-b-c* plane expressed in Equation 2.14.

$$i_{\alpha\beta} *= \frac{1}{{v_\alpha}^2 + {v_\beta}^2} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{2.13}$$

$$i_{abc} *= \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{\sqrt{2}} & \frac{\sqrt{3}}{2} \\ -\frac{1}{\sqrt{2}} & -\frac{\sqrt{3}}{2} \end{bmatrix} i_{\alpha\beta} \tag{2.14}$$

2.3.3.2 Fast Fourier Transform

The harmonic current can be reconstructed by eliminating the fundamental component from the transformed current signal. Then the inverse transform is applied to obtain a time-domain signal is fast Fourier transforms technique [23]. The simplest way to identify harmonics and generate the harmonic current is to use discrete Fourier transformation (DFT) of fast Fourier transformation (FFT). Although it has wide applications, the DFT or FFT has certain limitations in harmonic analysis. The main disadvantage of this system is the accompanying time delay. This technique needs to take samples of one complete cycle to generate the Fourier coefficients and it is therefore suitable for slowly varying load conditions

2.3.3.3 Hysteresis band

In general, shunt APFs is current controlled voltage source inverters (VSI) which are proposed to inject a compensating current into the supply system to mitigate the harmonics and reactive power and improve power quality indices [24]. The APF is designed in such a way that it is capable of compensating the complex and randomly varying load current harmonics with high control accuracy.

There are two key segments in APF. The first segment is current estimation circuit that estimates the compensating current to be injected at point of common coupling (PCC) and the essential active component of the current to be absorbed, which is necessary to retain the DC bus voltage. The second key segment of an APF is a current controlled voltage source inverter (VSI). Among the existing current control techniques, Hysteresis Current Control HCC technique is considered by its simplicity of implementation with high precision and dynamic response.

HCC technique is used for single phase system because of its simplicity. The HCC is operated by comparing a current error. It compares the difference between the reference and the actual current. Figure 2.7 illustrates the hysteresis modulation. When the current tracking error crosses the upper hysteresis band (HB), the VSI output is switched low, and when the current error crosses the lower HB, the inverter output switches high. Therefore each inverter phase leg output is the replica of the other [24]. However, utilization of HCC is restricted due to large variations in switching frequency and its related effects. To make sure safety and efficiency of APF operation, the switching frequency of current controlled VSI and the DC link voltage should minimum.

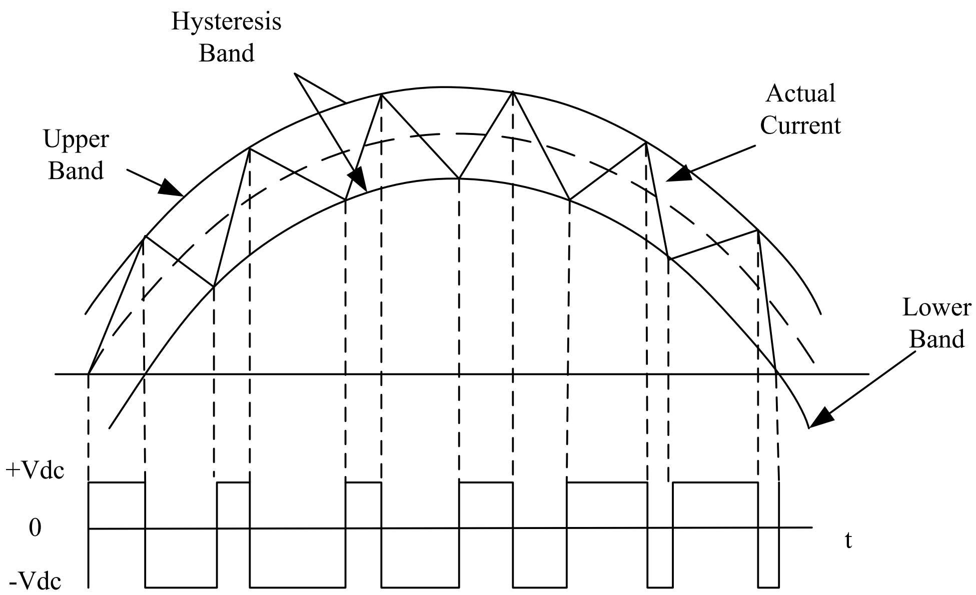


Figure 2.7: Hysteresis modulation

2.4 Multilevel Inverter

Multilevel converters (or inverters) have been used for rectifier, cycloconverter, inverter, and chopper power conversion in high-power applications such as utility and large motor drive applications. Multilevel inverter (MLI) provides more than two voltage levels. A desired output voltage waveform can be synthesized from the multiple voltage levels with less distortion, less switching frequency, higher efficiency, and lower voltage devices. There are three major multilevel topologies cascaded, diode clamped, and capacitor clamped [25].

2.4.1 General Topologies of Multilevel Inverter

From last few decades, industry eager for higher power equipment, which now reaches megawatt level. Power electronic inverters are becoming popular for various industrial drives applications. MLI are best suited for medium to high voltage ratings. Hence, MLI has arisen for working with higher voltage levels. The most attractive features of MLI are generated output is of low distortion and lower dv/dt, they draw input current with very low distortion, common-mode voltage is low, hence reducing stress in motor bearings, operating frequency is reduced, good power quality, good electromagnetic compatibility and high voltage compatibility [26]. The MLI topologies can be classified into three types namely diode clamped MLI (DCMLI), flying capacitor MLI (FCMLI) and cascaded H-Bridge MLI (CHMLI) [27].

2.4.2 Neutral Point Clamped Multilevel Inverter (NPMLI)

Neutral point clamped multilevel inverter (NPMLI) is knows in 80 century and for improvement of NPMLI the diode clamped multilevel is introduced (DCMLI). The DCMLI used clamping diode and cascaded DC capacitors to produce AC voltage waveform with multiple levels. The diode is used as clamping device to clamp the DC bus voltage. So it can achieve steps in the output voltage. Thus, the main concept of this inverter is to use diodes to limit the power devices voltage stress. The DCMLI also used to smooth the switching frequency ripple voltage. However, it has small capacity to fulfill the requirement for each clamping capacitor. To overcome this problem DCMLI need to increase the number of level. If increased the number of level thermal designing, low-inductance designing, as well as insulation designing of the system will become critical [28].

2.4.3 Flying Capacitor Multilevel Inverter (FCMLI)

The structure of Flying Capacitor Multilevel Inverter (FCMLI) is similar to the diode clamped inverter but FCMLI using clamping capacitor. The flying capacitor involves series connection of capacitor clamped switching cells. This topology has a ladder structure of DC side capacitors, where the voltage on each capacitor differs from other capacitor. The voltage increment between two adjacent capacitor legs gives the size of the voltage steps in the output waveform. The voltage levels and the arrangements of the flying capacitors in the FCMLI structure convince that the voltage stress across each main device is same [29].

The most important advantages of FCMLI topology are preventing the filter demand and controlling the active and reactive power flow besides phase redundancies. However, the increment of level will restrain the accurate charging and discharging control of capacitors. The cost of inverter will increase due to the large number of bulky capacitors and it inhibits the industrial use of this topology [30].

2.4.4 Cascaded H-bridge Multilevel Inverter (CHB-MLI)

The concept of this inverter is based on connecting H-bridge inverters in series with separate DC sources. The source used may be from batteries or fuel cells to get a sinusoidal voltage output. The output voltage is the sum of the voltage that is generated by each cell. By increase the H-bridges in a phase, the synthesized output waveform adds more steps, producing a staircase wave which approaches the sinusoidal wave with minimum harmonic distortion. One of the advantages of this type of multilevel inverter is that it needs less number of components comparative to the diode clamped or the flying capacitor, so the price and the weight of the inverter is less than that of the two types [29].

2.4.5 Multilevel Inverter Modulation Control Schemes

Switching losses and harmonic can deducted by applied the modulation strategies. It is used to control the inverter and will affect the efficiency parameters of a multilevel inverter. In addition to these topologies, the modulation control schemes for the multilevel inverter can be divided into two categories which are fundamental switching frequency and high switching frequency PWM [31]. Figure 2.8 shows the multilevel converter modulation methods.

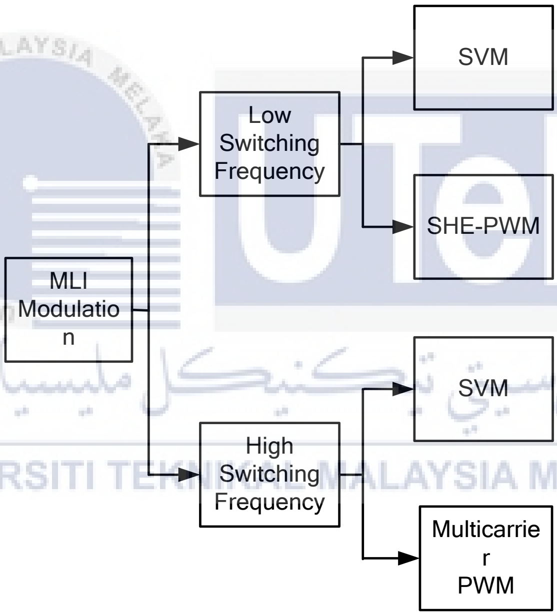


Figure 2.8: Multilevel converter modulation methods

The most commonly used control schemes for the control of multilevel inverters is by using sinusoidal PWM (PWM). It provided many advantages such as easy implementation lower harmonic output and low switching loss [30]. A reference signal or modulating signal which is sinusoidal and a carrier signal which is a triangular is used for sinusoidal PWM output to control of the switches. The two types of PWM control schemes are bipolar and unipolar switching schemes [32].

2.4.5.1 PWM with Bipolar Switching

The comparison between the control signal, V_r and the triangular signal, V_c will produce the switching pulses or PWM to turn ON and OFF the switching devices. The output waveform is as Figure 2.9. By comparing between reference waveform and triangular waveform in sinusoidal PWM with bipolar voltage switching, the output waveform is positive V_{DC} when sinusoidal waveform more than carrier waveform and will negative V_{DC} if reference waveform below than triangular waveform.

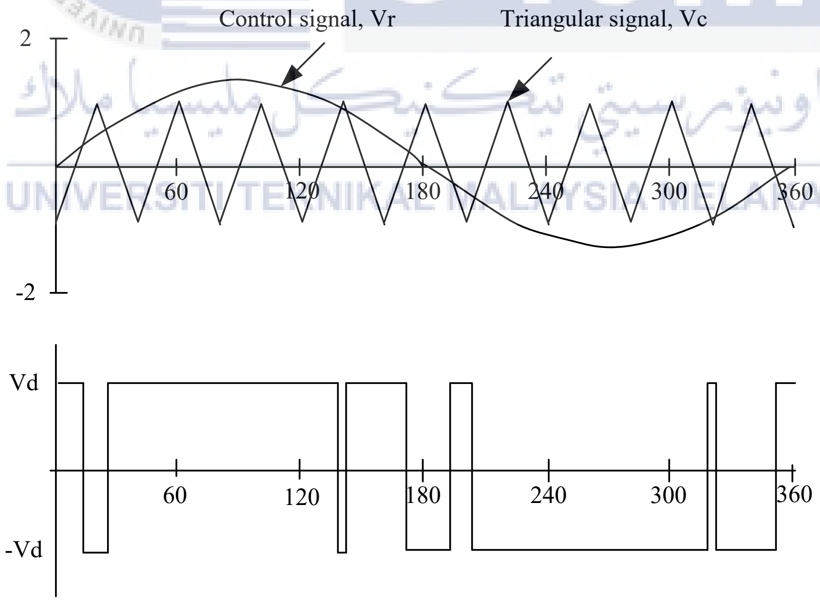


Figure 2.9: (a) Switching pattern (b) Output waveform

2.4.5.2 SPWM with Unipolar Switching

Another switching scheme beside bipolar is unipolar. In unipolar switching scheme are from two reference signals that shifted by 180° and compare with triangular signal. The output is switched either from high to zero or from low to zero, rather than high and low as in bipolar switching [32]. Note that switch pairs (S_1,S_4) and (S_2,S_3) are complementary. One pair of switches are operating at the carrier frequency while the other pair operates at the reference frequency, thus having two high-frequency switches and two low-frequency switches [32].

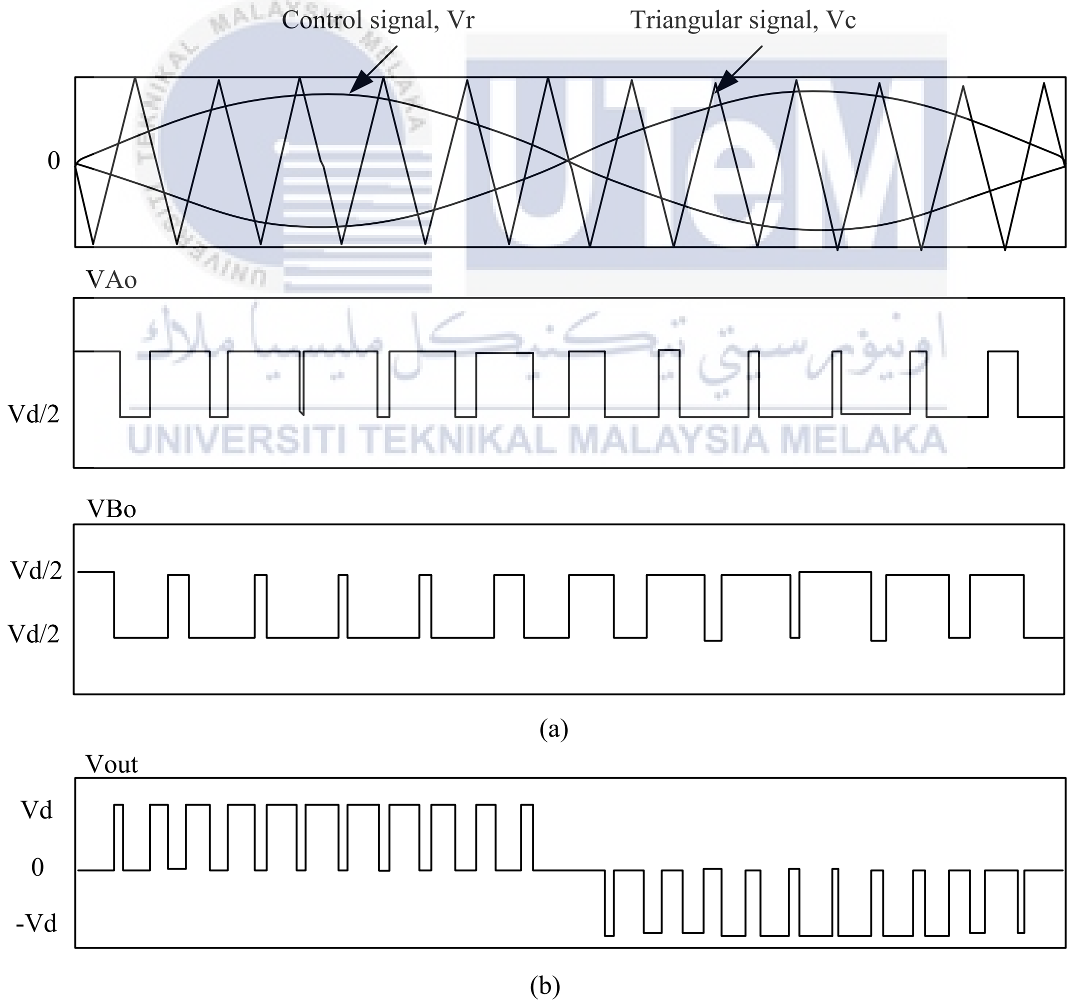


Figure 2.10: (a) Switching pattern (b) Output Waveform

Figure 2.10 (a) show the comparison between reference waveform, V_r and triangular waveform, V_c produce voltage switching and Figure 2.10 (b) show the output waveform where positive V_{DC} when reference waveform more than triangular waveform and negative V_{DC} when reference waveform below than triangular waveform.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discussed about the methodology fo this project. It consist flow of process and explanation about this research. The method used for implement the multilevel inverter and shunt active power filter also explain details in this chapter.

3.2 Research Methodology

This project divided into five stages. The first stage is making a survey and several literature reviews about multilevel inverter and active power filter. The second stage is modeling simulation of single phase multilevel inverter. The third stages are modeling and simulated the single phase multilevel inverter connected with shunt active power filter. The fourth stage is analyzed the data obtained and compare the results before and after the implement of filter.

3.3 Flowchart

Figure 3.1 show the flow chart of activities conducted to achieved the objective of this project. The flow chart, start with doing literature review that cover multilevel inverter (MLI) and active power filter (APF) in mitigate the harmonic. From a review, all the information that related to the project will grouped and discussed. The content of the review sre discussed in Chapter 2.

After grouped the information, the designed and simulated the conventional single phase of MLI was conducted. It aims to know the behavior of output and the pattern of waveform. The simulation was conducted using software called MATLAB/Simulink tools. Each of multilevel has their own switching schema. For this project, there are three type of switching used to operate the multilevel inverter which are trinary, bipolar and unipolar. The different type of switching will produce different value percentage of harmonic distortion.

Next the design of MLI with appropriate switching is simulated in the multilevel inverter to confirm the algorithm. The data is capture and analyze for next action. In order to improve the data capture based on previous step, the modeling of MLI connected with shunt APF is performed.

APF has a lot of types, methods, topologies and techniques to solve the problem faced. For this project the voltage source APF with instantaneous power theory is used to mitigate the harmonic load. Although the design of MLI is good enough to eliminate harmonic distortion, the presence of harmonic will occur if connected to nonlinear load. So that the next action need to take by implement the shunt APF. After modeling and simulated the combination of APF and MLI, the result is validating to fulfill the requirement standard.

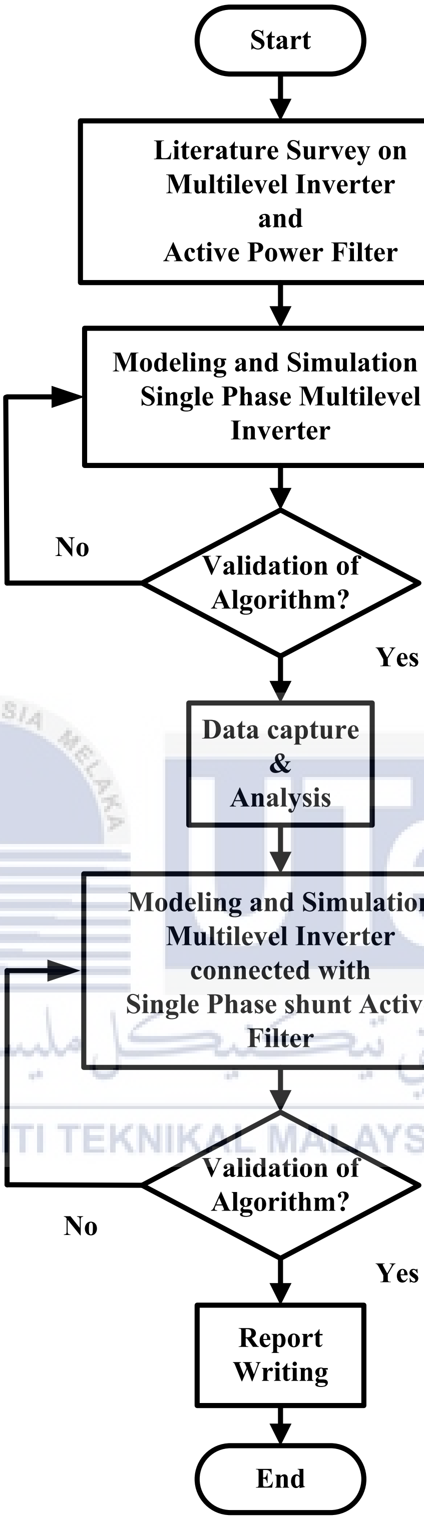


Figure 3.1: Flowchart of Research Methodology

3.4 Milestone

A five milestone in this project is to fulfill the objective. The first milestones are to make a survey and several literature reviews about multilevel inverter and active power filter. The type, method, topology, technique are study for strong the fundamental.

The second milestones are modeling and make simulation the single phase multilevel inverter. The technique switching used are trinary, bipolar and unipolar. It tests with various type of load to determine the percentage of total harmonic distortion and output waveform.

The third milestones are modeling and simulated the single phase multilevel inverter connected with shunt active power filter. For the filter selected it used the p-q theory technique in order to improve the distortion create from nonlinear load.

The fourth milestone are analyzed the data obtained. Comparison results before and after the implement of filter is discussed.

For last milestone the producing report for discussed the result found.

3.5 Gantt chart

Table 3.1: Gantt chart of Research Methodology

Milestone	Year	2015				2016				
	Week	**9**	**10**	**11**	**12**	**1**	**2**	**3**	**4**	**5**
1	Research on MLI and APF									
2	Simulation of Single Phase Multilevel Inverter									
3	Simulation of Single Phase Multilevel Inverter connected with shunt Active Power Filter.									
4	Analyzed the data obtained									
5	Report writing									

Table 3.1 show that the activities that was conducted to accomplish this project. This table is referring on activities that plan in 2015 and 2016. For the first three month to study and survey about the title given. The research consists of multilevel inverter, the switching schema, the filter and the effect of harmonic. While make a review, three month provided for design and implement the model of multilevel inverter for variant of load. The inverter is actually for learning process to know the effect of harmonic. All the activities are done in 2015. For 2016 focus on design and simulated the shunt active filter. The filter will connect to improve the result than obtained in inverter simulation. From the result of simulation it takes four month to analyze the data and validate the information. The information are group together to differentiate before and after the implement the filter. The report writing is done along the project conducted.

3.6 Trinary DC Source Switching Technique

Studies found that trinary characteristic of output voltage can synthesize high quality output voltage near to sinusoidal waveform. This shows that trinary technique is good to achieve output voltage with less of harmonic effect. This technique is simple and easy to control. For this project, the five level of trinary is selected. If the level of trinary increase it can produce output voltage that close to sinusoidal waveform. The topology and operational of cascaded H-Bridge multilevel inverter using trinary DC source is illustrated in Figure 3.2. From the circuit above, pulse width modulation (PWM) are used to trigger the switching device show in Table 3.2. The main of PWM are to control the inverter output voltage and to reduce the harmonic content in the output voltage.

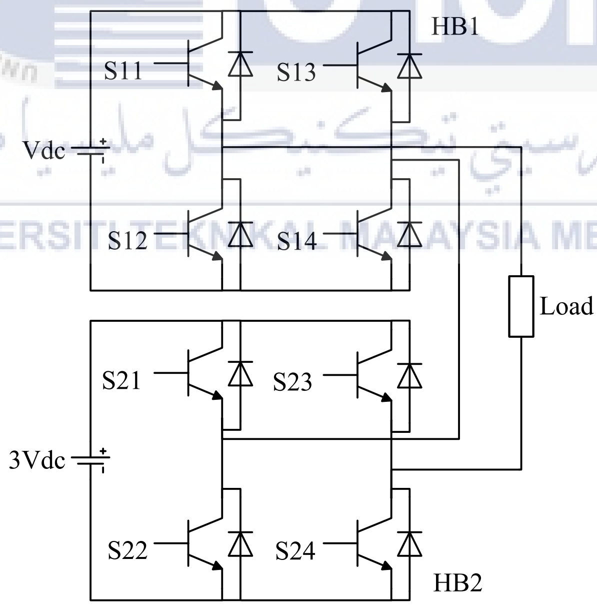


Figure 3.2: Trinary DC Source MLI

Table 3.2: Switching sequences of Trinary MLI

H-Bridge \ V_{ou}	0	V_{DC}	$2V_{DC}$	V_{DC}	0	$-V_{DC}$	$-2V_{DC}$	$-V_{DC}$	0
S_{11}	0	1	0	1	0	0	1	0	0
S_{12}	1	1	0	1	1	0	1	0	1
S_{13}	0	0	1	0	0	1	0	1	0
S_{14}	1	0	1	0	1	1	0	1	1
S_{21}	0	0	1	0	0	0	0	0	0
S_{22}	1	1	1	1	1	1	0	1	1
S_{23}	0	0	0	0	0	0	1	0	0
S_{24}	1	1	0	1	1	1	1	1	1

The simulations are implemented using MATLAB/Simulink to determine the percentage of total harmonic distortion for voltage and current (THD_v & THD_i). The value of THD is changes according to variation of load. The loads that have been used are R, RL, RC and passive element with rectifier. Value for the load selected is constant for every simulation and it stated as Table 3.3.

Table 3.3: Value of each load

Load	Value
Resistor (R)	10 Ω
Inductor (L)	2 H
Capacitor (C)	1 uF

A trinary DC source is to obtain a large number of output voltage levels with minimum devices. The use of inverter can synthesize high quality output voltage near to sinusoidal waves. By using this technique the system can eliminates the complexity of components and generating gate signals. As summary this technique is economical circuit configuration, easy to increase of the output voltage levels and output power and little transition loss of switches due to low switching frequency and it is suitable for high voltage applications.

3.7 PWM Switching Technique

The pulse width modulation switching (PWM) can be divided into two switching scheme which are PWM with Bipolar voltage switching and PWM with Unipolar voltage switching. Pulse width modulation is the mostly used method in motor control and inverter application. It is widely used in power electronics to give supply so that a voltage pulses can be generated by the on and off of the power switches. It also provides way to decrease the total harmonic distortion. To generate the PWM it required reference or modulating signal which is in sinusoidal form and carrier signal which in triangular form.

3.7.1 Bipolar multilevel inverter switching technique

To generate the bipolar switching, it compared the sinusoidal waveform, V_r with the triangular carrier waveform, V_C. From the comparison with two type of waveform, then produce the switching pattern for each of switching device. The switching pattern will generated according to two conditions. If sine wave is larger than the triangular wave it will produce positive value of direct current $+V_{DC}$, while modulating signal is less than carrier the output in negative of direct current $-V_{DC}$. Figure 3.3 shows the carrier and sinusoidal wave compare each other to produce the output that uses to generate the multilevel inverter.

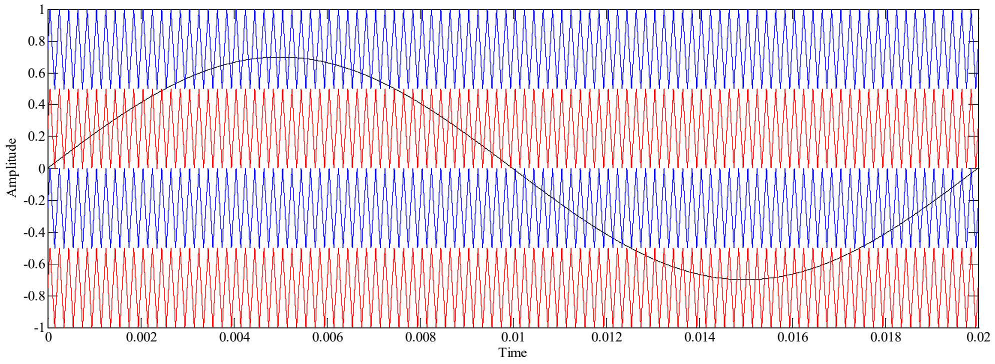


Figure 3.3: Sinusoidal Pulse Width Modulation

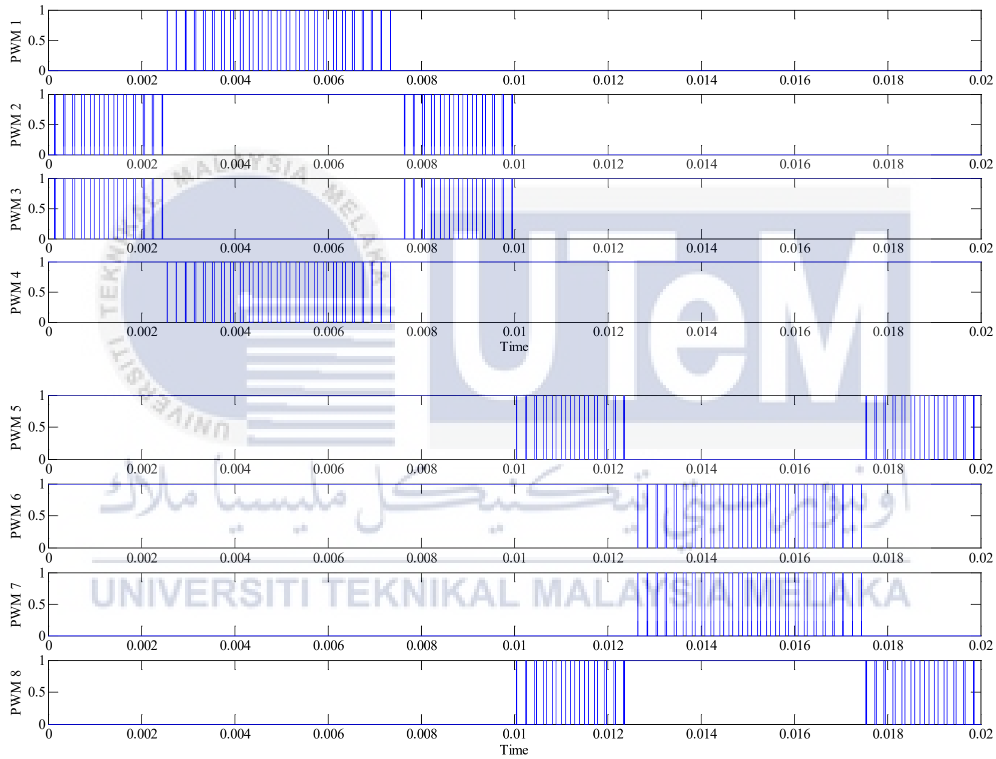


Figure 3.4: Bipolar Switching

From the comparison between two signals it produces eight PWM. The PWM 1 until 4 will operate in H-Bridge 1 and other will operate for H-Bridge 2. In generated the PWM, there is need some consideration to be done which are the frequency modulation ratio m_f, amplitude modulation ratio m_a, switches and reference voltage. For this project the consideration is stated in Table 3.4.

Table 3.4: Bipolar PWM Parameter

Parameter	Value
Triangular frequency	5kHz
Sine frequency	50Hz
Freq. modulation ratio, m_f	100
Triangular amplitude	1
Sine amplitude	0.7
Amplitude modulation ratio, m_a	0.7
V_{DC1}	100
V_{DC2}	100

3.7.2 Unipolar multilevel inverter switching technique

To generate the unipolar switching, it compared two sinusoidal shift by 180° waveform, V_r with the triangular carrier waveform, V_C. From the comparison with two type of waveform, then produce the switching pattern for each of switching device. The switching pattern will generated the output voltage changes between positive and zero, or between zero and negative voltage levels.

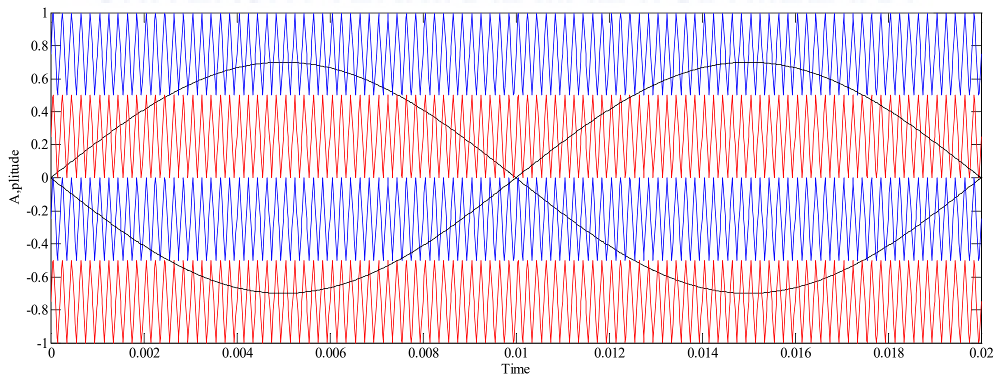


Figure 3.5: Sinusoidal Pulse Width Modulation

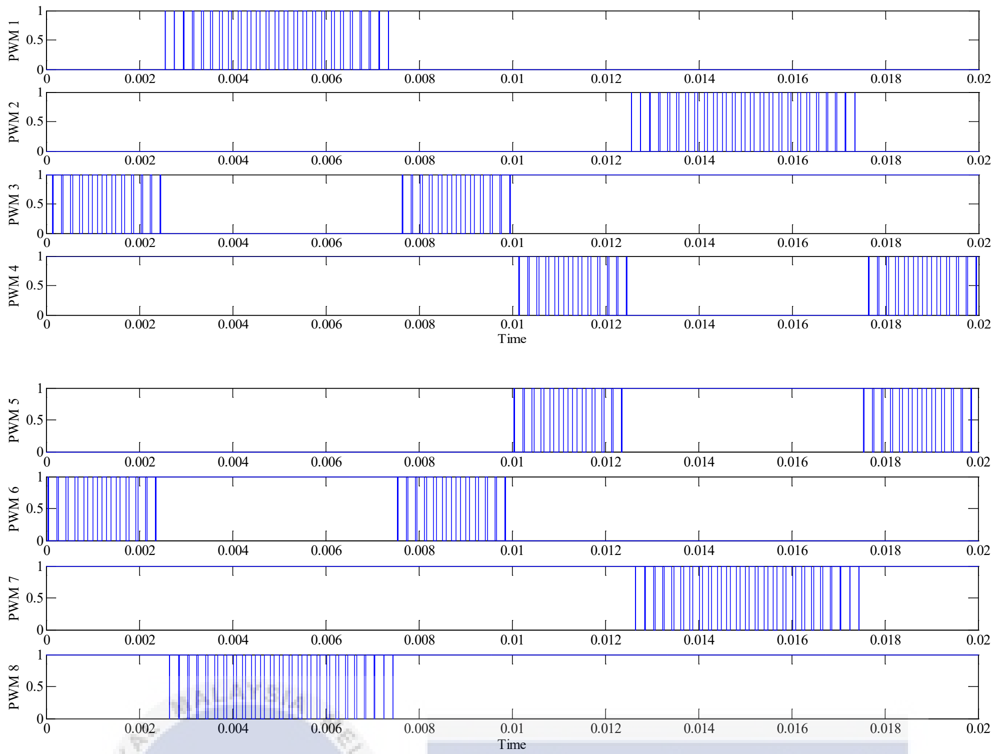


Figure 3.6: Unipolar Switching

The bipolar switching has been widely used in the digitally controlled H-bridge inverter system because of its simple implementation. However, unipolar switching have advantage of the filter elements needed are much less. Therefore, the unipolar has better output waveforms.

3.8 Active Power Filter

For the past decades, APF is familiar in designed, improve and commercialized. The purpose of active power filter is to compensate the current-based distortion and voltage-based distortion. The distortion come from current or voltage harmonic, reactive power and neutral current, voltage flickers, voltage sags and swell and voltage imbalances [17]. The APF can be categories in two connections which are single phase and three phase. The single phase load normally will create the power quality problem, so the single phase APF used to compensate the problem. The high power nonlinear load such as adjustable speed drive will handle by three phase APF [33].

In order to generate the APF, there are two method used which is current source (CSAPF) and voltage source (VSAPF). The different between these method is the used of energy storage device. For CSAPF it used inductor while VSAPF used capacitor. VSAPF mostly implement because of easy to control although it is more expensive than CSAPF. Beside that APF has several type of connection which is in series, shunt or hybrid [33]. Figure 3.7 illustrated the topologies of APF.

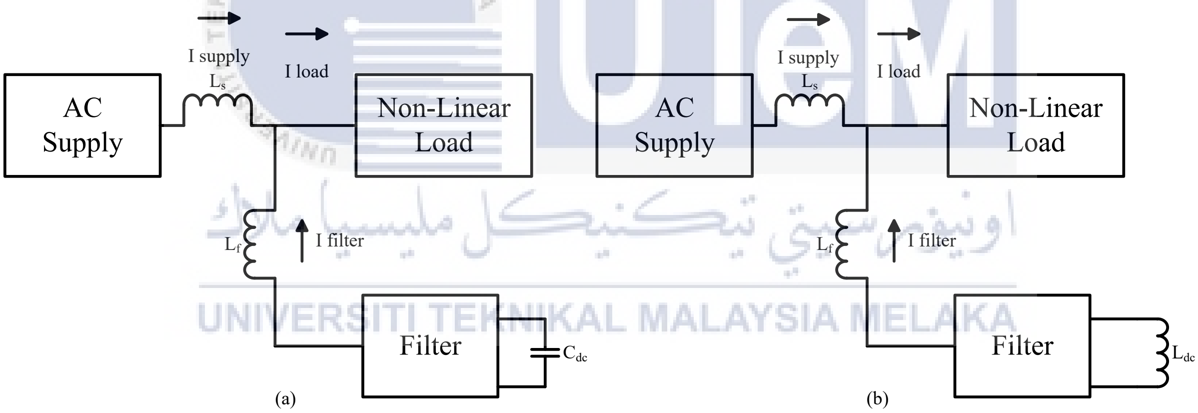


Figure 3.7: Block diagram of (a) VSAPF and (b) CSAPF

3.8.1.1 Instantaneous Power Theory

The method to control of APF was developed by *Akagi et al* in 1983 is the p-q theory also knows as instantaneous power theory. Generally, it was developed only for three phase systems without neutral wire, but this controller can be implementing for single phase by duplicating two more current and voltage signal with 120° angle shifting. The proposed Instantaneous reactive power (p-q) theory is based on *α-β* transformation which is done by Clarke transformation [35]. The main advantage of this technique is simpler. It convert three phase voltages and currents in *a-b-c* coordinates to *α-β-0* coordinates, followed by calculations of instantaneous power components and inverse back to reference current signal for control the APF. Figure 3.8 shows the sequences in develop the technique.

To develop the instantaneous power and reactive power the voltage and current is transform by using Equation 3.1 an Equation 3.2

$$i_{\alpha\beta 0} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} i_{abc} \tag{3.1}$$

$$v_{\alpha\beta 0} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} v_{abc} \tag{3.2}$$

After the voltage and current had transform, the active and reactive power refer to p-q theory is written as Equation 3.3 and Equation 3.4. Active and reactive power can distinguish to two parts which is DC and AC part.

$$p = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 \tag{3.3}$$

$$q = v_\alpha i_\alpha - v_\beta i_\beta \tag{3.4}$$

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{3.5}$$

$$p = \bar{p} + \tilde{p} \tag{3.6}$$

$$q = \bar{q} + \tilde{q} \tag{3.7}$$

The DC part can determine by using low pass filter that remove the high frequency and give the fundamental component or called DC part. From the active and reactive power the α-β references current is produce as shows in Equation 3.8. Then transform again as Equation 3.9 to determine the three phase reference current for active filter. The current will compare with load current for the PWM signal to active filter. The process of this technique is illustrated using block diagram as Figure 3.8.

$$i_{\alpha\beta} *= \frac{1}{{v_\alpha}^2 + {v_\beta}^2} \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{3.8}$$

$$i_{abc} *= \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{\sqrt{2}} & \frac{\sqrt{3}}{2} \\ -\frac{1}{\sqrt{2}} & -\frac{\sqrt{3}}{2} \end{bmatrix} i_{\alpha\beta} \tag{3.9}$$

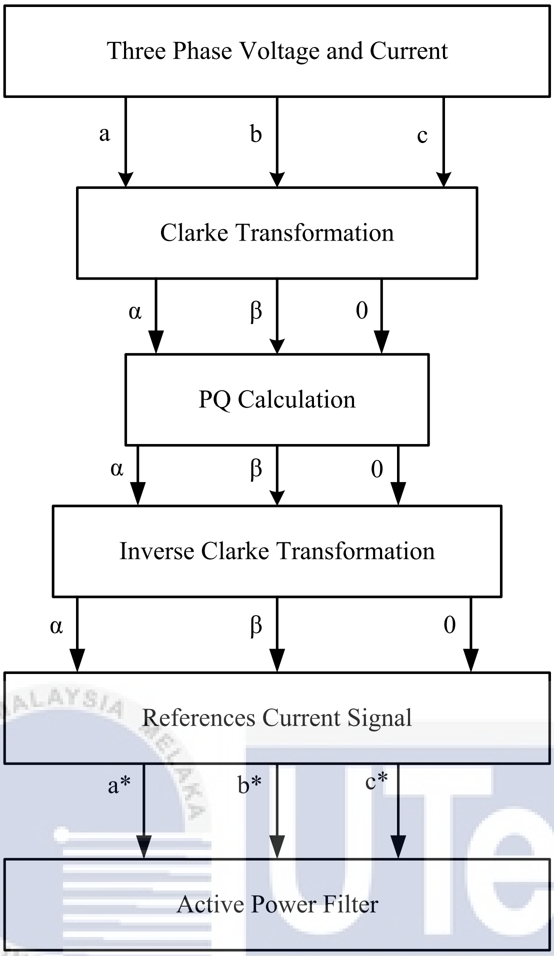


Figure 3.8: Flow chart represents the p-q theory

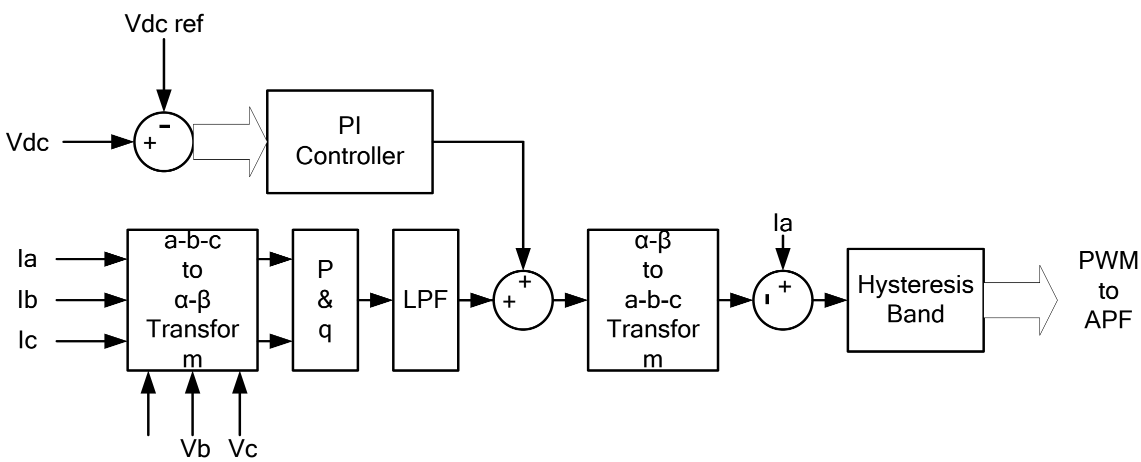


Figure 3.9: Block diagram of p-q theory

3.9 Combination of multilevel inverter and shunt active power filter

Extensive used of nonlinear applications such as power electronic devices have affected power quality of electrical power system. To minimize the effect of harmonic distortion in electrical system MLI is introduced. However, the present of nonlinear load will produce the harmonic distortion in electrical system. In order to improve the power quality in electrical system the current is injected by using shunt APF. This combination of shunt APF with MLI is to mitigate the current and voltage harmonic distortion.

The MLI is design based on multiple of inverter that connected in series. The MLI is trigger by connected with design PWM. To improve the performance of MLI in mitigate the harmonic distortion, the shunt APF is connected. The APF is design based on mathematical equation based on instantaneous power theory. The Figure 3.10 shows the block diagram of combination system.

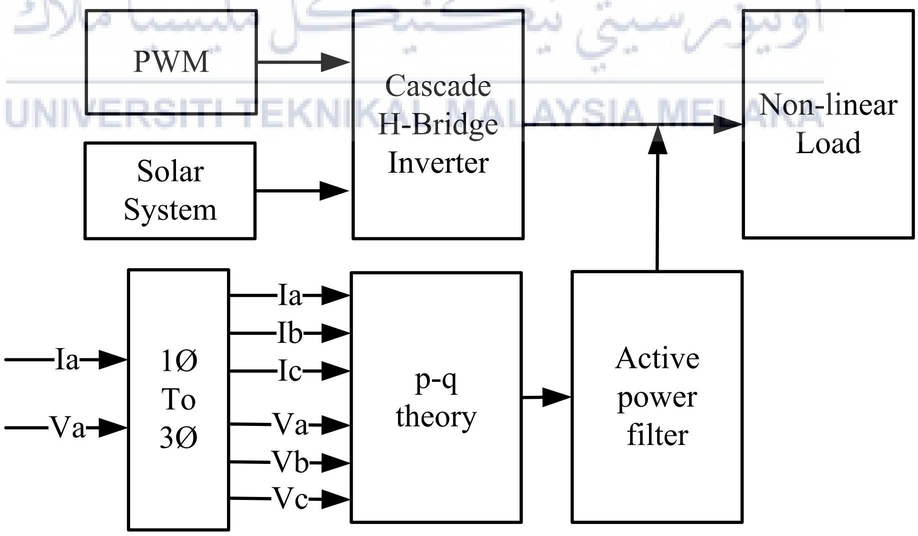


Figure 3.10: Block diagram of combination process

3.10 Simulation Block

For this project, it is focus on simulation using MATLAB software to mitigate the harmonic. The harmonic is actually different according to variation of load. Harmonic create in the system based on usage of electronic equipment such as inverter. On this matter, the switching technique selections are discussed in order to operate the multilevel inverter with appropriate parameter selected. The switching technique for the multilevel inverter is trinary, bipolar and unipolar. For this project Cascade H-Bridge Multilevel Inverter is used to make a simulation. In order to fulfill the problem statement, the simulation on multilevel inverter is conducted to analyze the performance in reduce the harmonic. The result of the simulation is discussed on Chapter 4.

3.10.1 Simulink block of multilevel inverter

The simulation of single phase MLI for this project is by using PWM and SPWM switching method. The simulation conducted using MATLAB/Simulink simulation tools. The MLI structures are constructed using several subsystem blocks represent the element selected.

3.10.1.1 Multilevel inverter using Pulse Width Modulation

Figure 3.11 shows the simulation of MLI using PWM. This method produces low switching to MLI. In general, the purpose of PWM is to control power delivery, especially to inertial electrical devices. So, this technique is used to power up the IGBT in H-Bridge configuration. By controlled the modulating waveform, the amplitude of output voltage can be controlled in PWM. The two distinct advantages of PWM are it can decreased harmonic and control of output voltage amplitude by reduced the filter requirement. However it have drawback which are, more complex controlled circuit for switches and increased losses due to more frequent switching. The block diagram consists of switching signal, H-bridge, voltage source and load system. Low switching signal is used to generate desired signal to turn on the set of IGBTs form of cascaded H-Bridge.

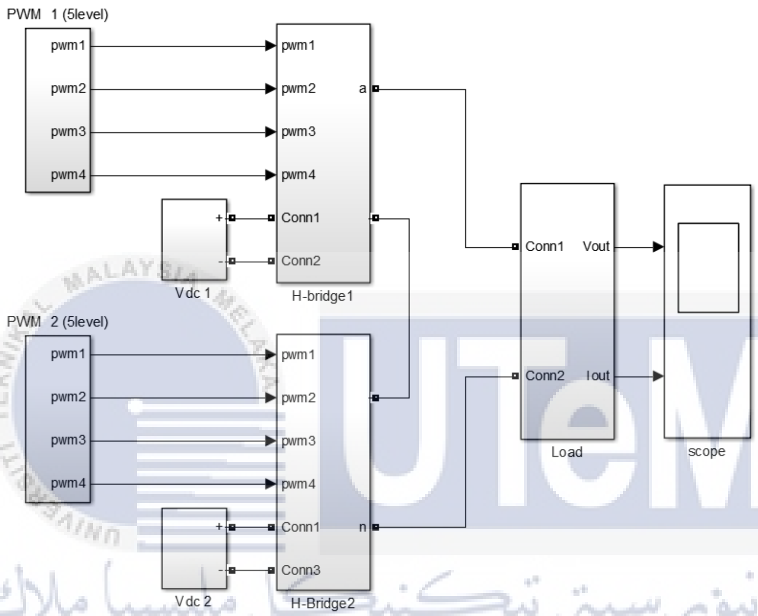


Figure 3.11: Single Phase Trinary Source MLI Simulation Block

To power up the H-Bridge, Vdc1 is 100V and Vdc2 is 300V are connected. The load subsystem consists of combination of passive element. The scope is used to measure the output from MLI and Figure 3.12 shows the result when load used is the combination of resistor and inductor.

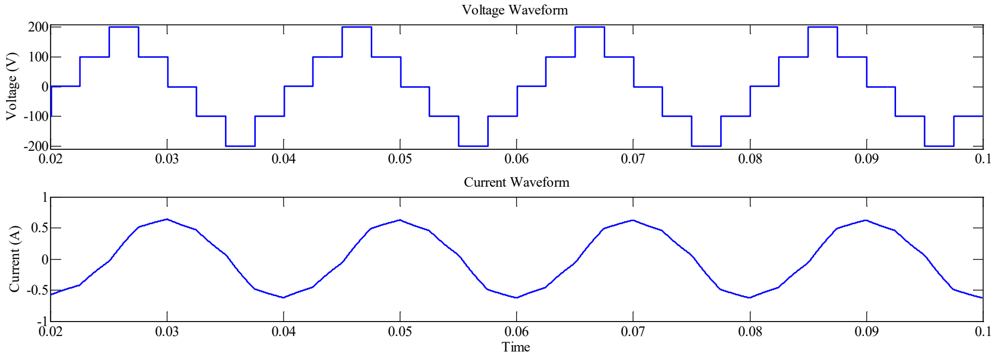


Figure 3.12: Single Phase Trinary Switching Generation

3.10.1.2 Multilevel inverter using Sinusoidal Pulse Width Modulation

Figure 3.13 shows the simulation of MLI using SPWM. This method produces high switching to MLI. As Figure 2.10 illustrated the SPWM, it shows several pulses are produced per half cycle. The pulses near the edges of the half cycle are always narrower than the pulses near the center of the half cycle such that the pulse widths are proportional to the corresponding amplitude of a sine wave at that portion of the cycle. To change the effective output voltage, the widths of all pulses are increased or decreased while maintaining the sinusoidal proportionality. So, this method generated high frequency to on and off switching device.

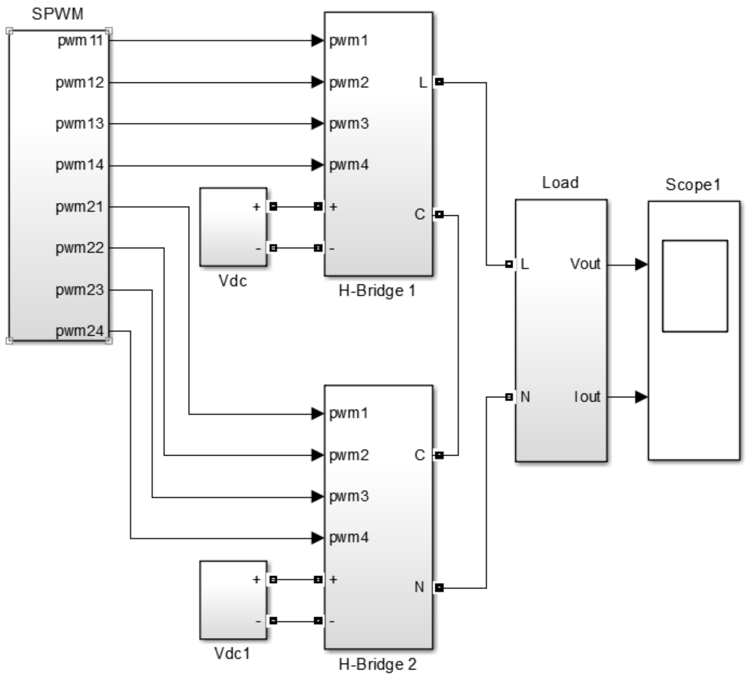


Figure 3.13: Single Phase Trinary Source MLI Simulation Block

To power up the H-Bridge, both are connected with DC voltage source of 100V. The load subsystem consists of combination of passive element. The scope is used to measure the output from MLI and Figure 3.14 shows the result when load used is the combination of resistor and inductor by using bipolar SPWM.

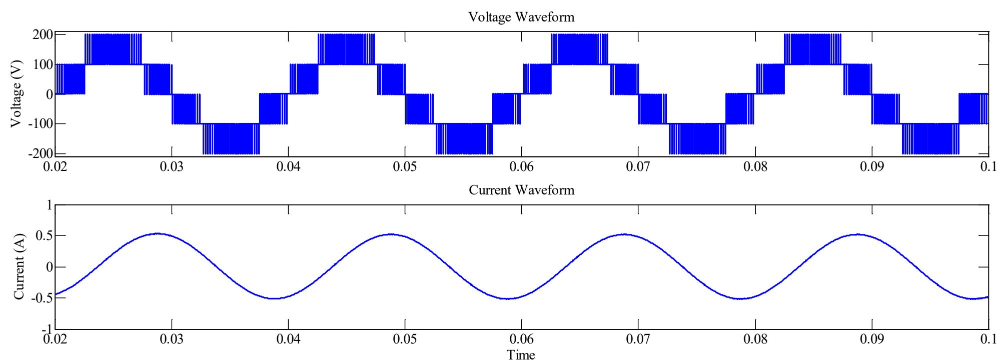


Figure 3.14: Single Phase Bipolar Switching Generation

3.10.2 Type of Load

In order to simulated the simulation block. The blocks need to connect to desired value of load. The loads selected are R-load, RL-load and RC-load. All these loads are connected with rectifier to perform nonlinear load characteristic. The purpose using several of load for this project are to study the effect of load current under nonlinear load condition in real system.

3.10.2.1 First Load: Single-Phase Uncontrolled Rectifier Supplying an R-Load

Single phase uncontrolled rectifier is connected with resistor shows in Figure 3.15. The purpose using several type of load is to study the effect of load current under nonlinear load condition in real system and the effect percentages of THD. For the first load the resistor value is 100 Ω. The used of rectifier is same act as tyristor which is to convert AC power supply to DC power supply and supplies the DC power to the R-Load.

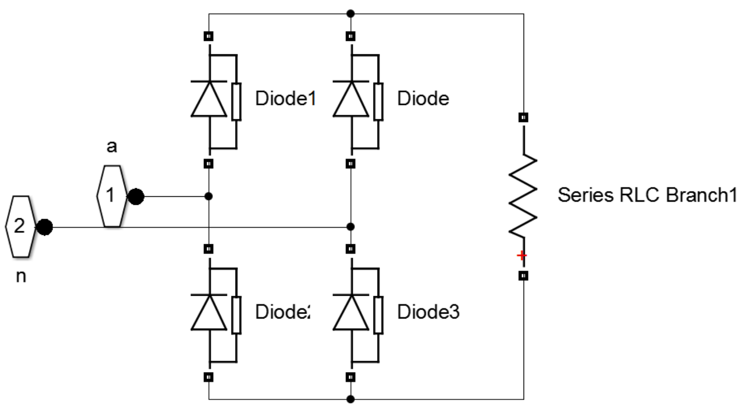


Figure 3.15: Simulation diagram for single phase rectifier connected to R-Load

3.10.2.2 Second Load: Single-Phase Uncontrolled Rectifier Supplying an RL-Load

Single phase uncontrolled rectifier is connected with resistor shows in Figure 3.16. The purpose using several type of load is to study the effect of load current under nonlinear load condition in real system and the effect percentages of THD. For the second load the resistor value is 100 Ω and 2 H of inductor.

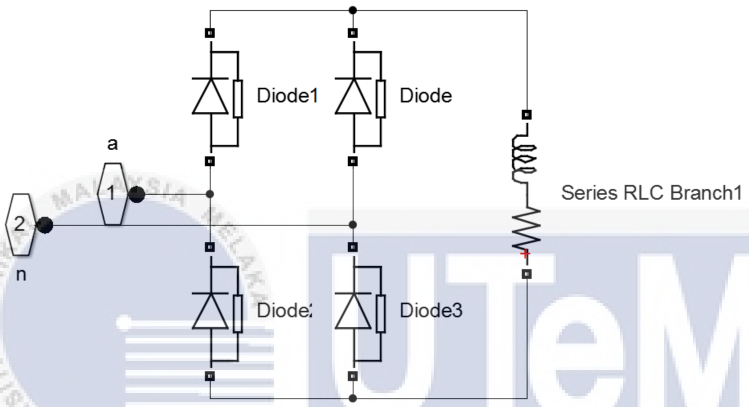


Figure 3.16: Simulation diagram for single phase rectifier connected to RL-Load

3.10.2.3 Third Load: Single-Phase Uncontrolled Rectifier Supplying an RC-Load

Single phase uncontrolled rectifier is connected with resistor shows in Figure 3.17. The purpose using several type of load is to study the effect of load current under nonlinear load condition in real system and the effect percentages of THD. For the third load the resistor value is 100 Ω and 1uF of capacitor.

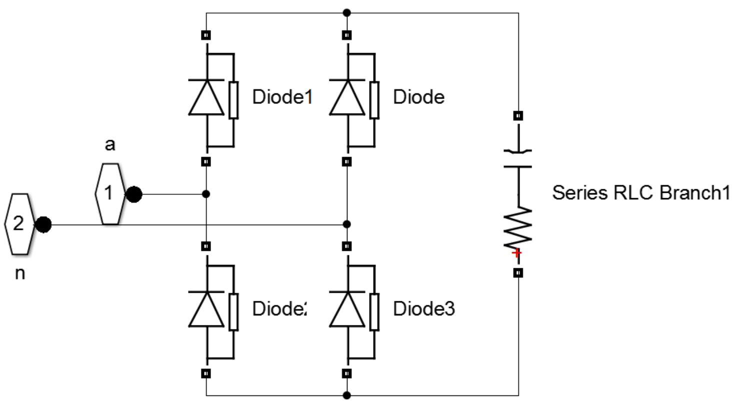


Figure 3.17: Simulation diagram for single phase rectifier connected to RC -Load

3.10.3 Simulation of Active Power Filter combining with Multilevel Inverter

In order to predict the actual behavior of the system, the simulation is used to simulate a real system or environment with the actual data. The selected of right software need to consider in order to have the capability to simulate the single phase shunt active filter. The selected software is MATLAB 2015b. It is the advanced software that can be used for modeling, simulation and analysis dynamic response of a system with little effort. The little effort means the selected of component to simulated is more easy compare to hardware implementation. This software makes the user easy to construct a block diagram to simulate the system. Figure 3.18 shows the block diagram of MLI and APF that constructed using Simulink/MATLAB. The simulation consists of MLI, APF and nonlinear load.

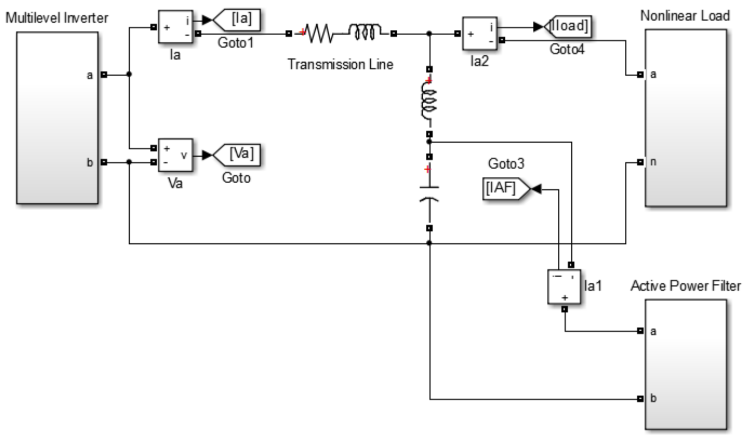


Figure 3.18: Simulation of Active Power Filter combining with Multilevel Inverter

3.10.3.1 Active Power Filter

Active power filter complete model is shows in Figure 3.19. The model consists of supply from MLI, single phase rectifier, controller, nonlinear load and single phase APF that connect in parallel.

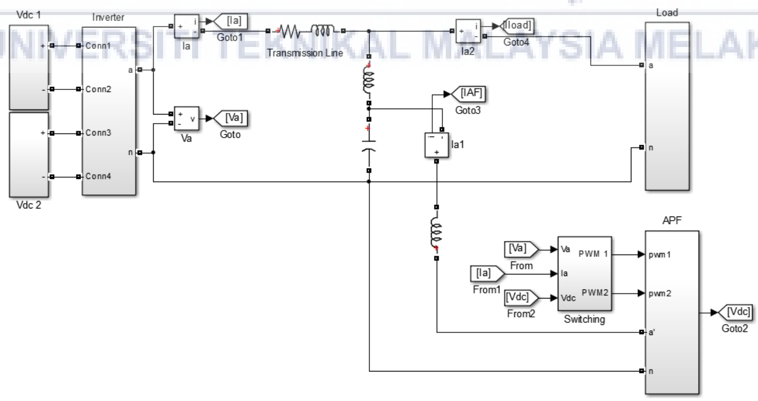


Figure 3.19: Complete simulation diagram for single phase shunt APF

In order to control the APF, it needs controller. Figure 3.20 shows the block diagram of controller which is p-q technique. The p-q technique consists of algebraic transformation of two-phase to three-phase, three-phase to two-phase, power losses calculation and hysteresis band.

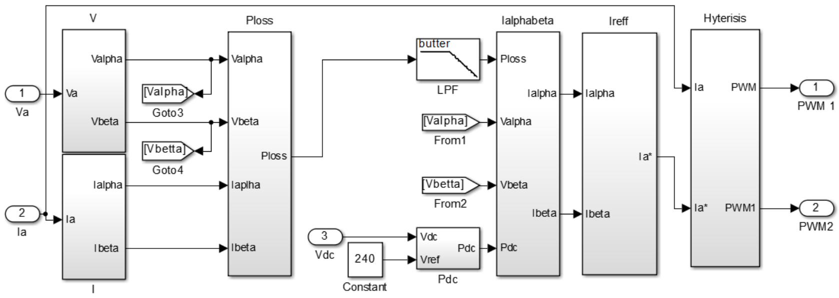


Figure 3.20: The p-q controller

3.10.3.2 Single phase Power Supply

The AC source for this simulation is from the MLI which energy conversion from DC to AC. The single phase is generated by the MLI block diagram. Before connected to the load the internal resistor needs to consider as transmission line. The AC source resistor and inductor is connected series with the output of MLI. The value of transmission line is 0.5Ω and 0.2 H.

3.10.3.3 Clark Transformation

This technique actually for three phase system, but it can implemented in single phase system by duplicating two more current and voltage signal with 120̊ angle shifting. From the duplicated current and voltage, this technique need to determine α and β reference current by using Clarke transformation. From the alpha and beta signal the active and reactive power is generated as stated in Equation 2.8 and Equation 2.9. Basically, from power generated it consists of two part which are mean part and oscillating part. The two part of power also knows as AC part and DC part. The DC part can be calculated by using low-pass filter which is removing the high frequency and only maintain the fundamental component. To generated the PWM as signal for APF. The hysteresis band in conducted.

3.10.3.4 Hysteresis Band Current Controller

Generated PWM process is from the comparison of actual current of MLI and inverse of Clark transformation. Hysteresis band will produce six PWM signal and for single phase active filter it is only used two as input of hysteresis band. Figure 3.21 shows the simulation diagram of controller. The simulation diagram consists of "subtract", "NOT" and "relay" block set. All the individual simulation set can be found at "Simulink/Math Operation" library.

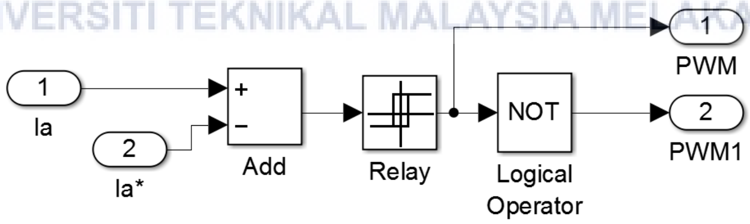


Figure 3.21: Simulation diagram for hysteresis current controller.

CHAPTER 4

RESULT

4.1 Introduction

This section will continue discussing the simulation result of single phase active power filter. This project is consists of the multilevel inverter MLI and the shunt active power filter APF to mitigate the total harmonic distortion THD. The discussion will focus on the effects of THD on single phase shunt APF.

4.1.1 Simulation Result using R-Load

The cascaded MLI is operates in three switching method which are, trinary, bipolar and unipolar. The MLI is to convert single phase DC power supply to AC power supply that connected to R load. The value THD of current is different based on type of switching method while value THD of voltage is remaining same. Figure 4.1 shows the current and voltage waveform of MLI when connected to R load.

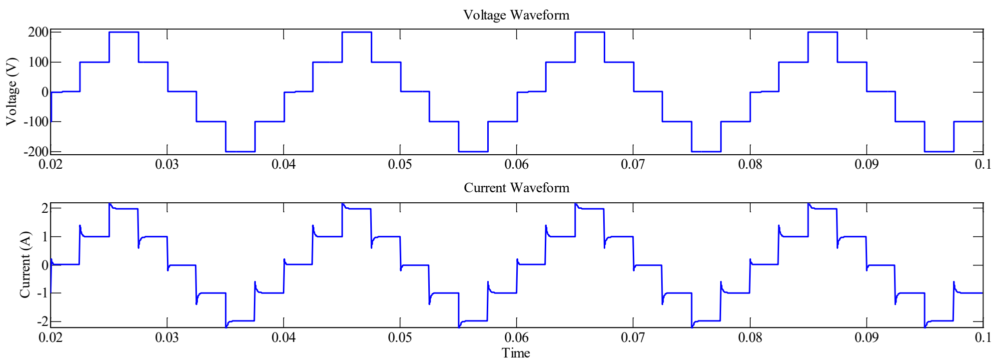


Figure 4.1: Single Phase Five Level Trinary DC Source MLI with R Load Output

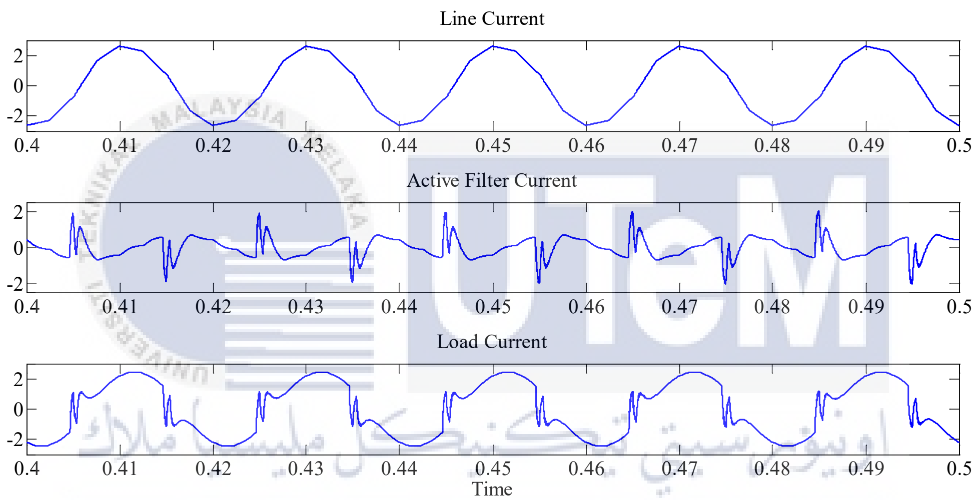


Figure 4.2: Single Phase Five Level Trinary MLI connected shunt APF with R Load Output

By injecting the current compensated from shunt APF the system can improve the current waveform at line that almost in sine wave form. Figure 4.2 shows that the current waveform that consists of line current, APF current and load current. By implement the shunt APF to MLI, the THD of current also can be reduced around 14% to 83%. Figure 4.3, 4.4, 4.5 shows the THD for line current for trinary, bipolar and unipolar switching method.

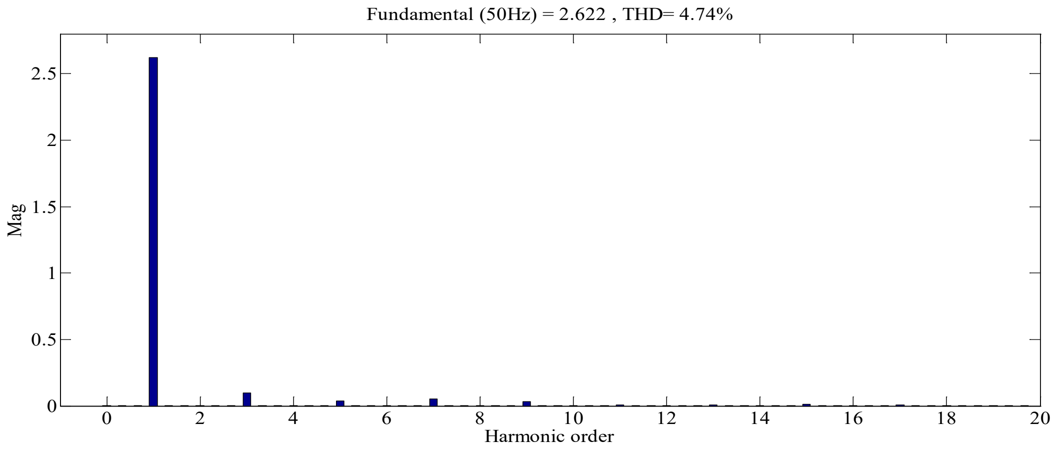


Figure 4.3: Single Phase Trinary MLI connected shunt APF with R Load Harmonic Spectrum

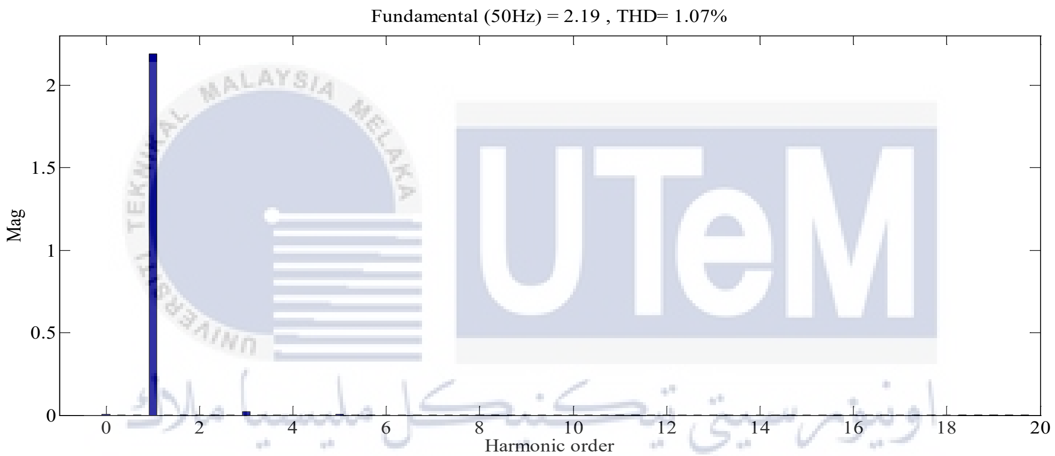


Figure 4.4: Single Phase Bipolar MLI connected shunt APF with R Load Harmonic Spectrum

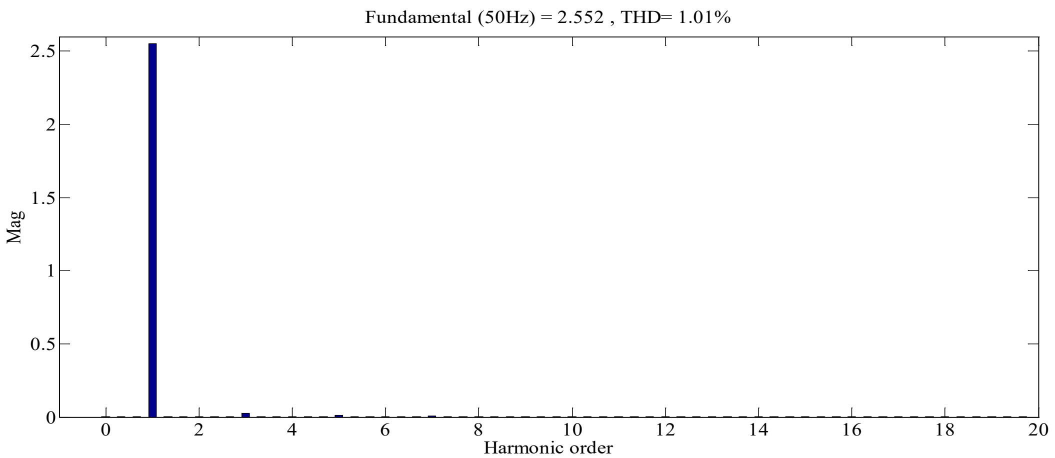


Figure 4.5: Single Phase Uniplar MLI connected shunt APF with R Load Harmonic Spectrum

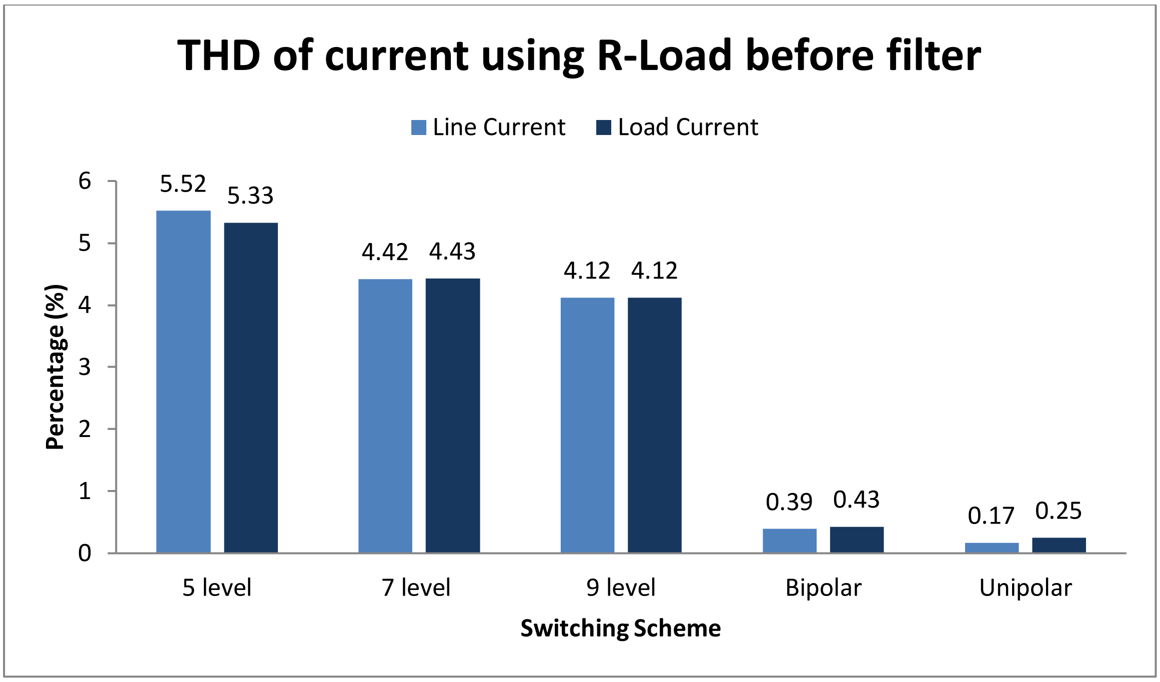


Figure 4.6: Percentage THD of Current connect with R-Load before filter

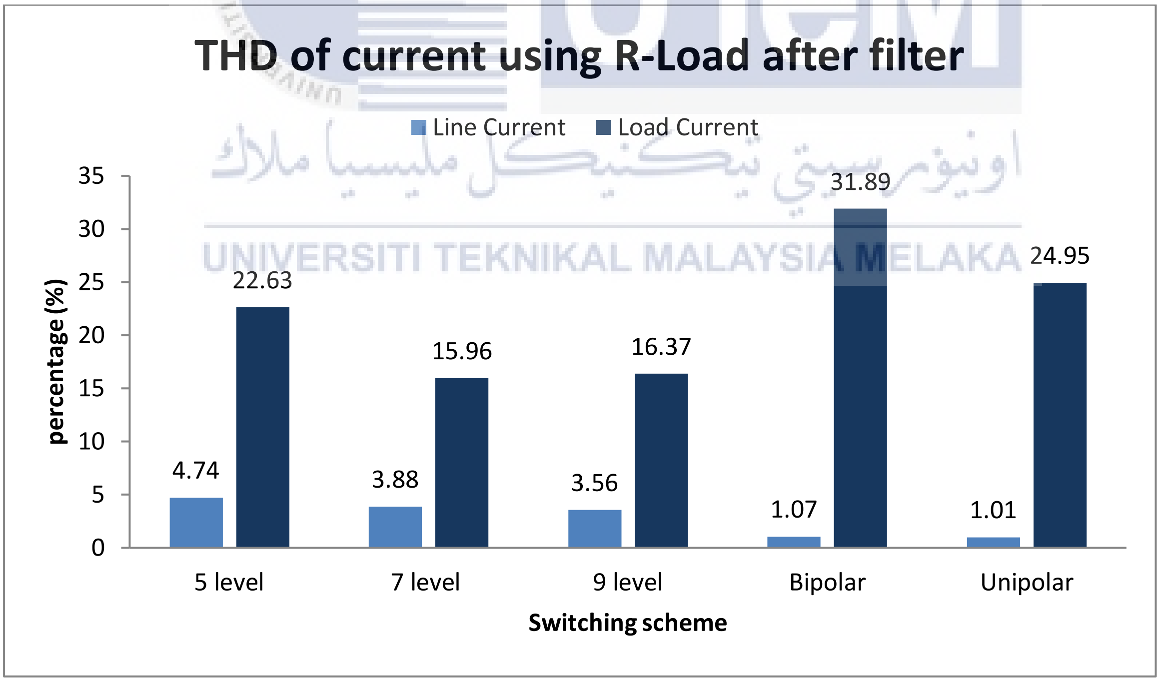


Figure 4.7: Percentage THD of Current connect with R-Load after filter

From Figure 4.6 it shows when system is not filter the percentage of THD between line current and load current is almost same. After connected with shunt APF the percentage of line current is reduced while the percentage of load current is increased as shows in Figure 4.7. This is because the load current is added by filter current to reduce distortion in line. From the result also shows the unipolar provide lowest percentage of THD because of the high efficiency due to reduced losses.

4.1.2 Simulation Result using RL-Load

The cascaded MLI is operates in three switching method which are, trinary, bipolar and unipolar. The MLI is to convert single phase DC power supply to AC power supply that connected to RL load. The value THD of current is different based on type of switching method while value THD of voltage is remaining same. Figure 4.8 shows the current and voltage waveform of MLI when connected to RL load.

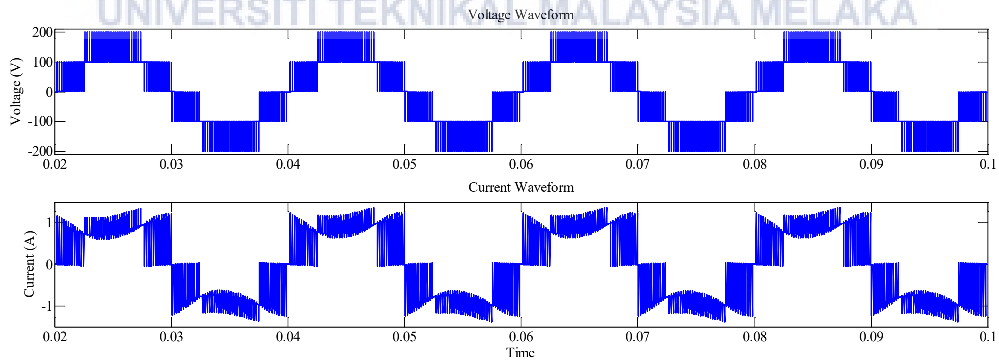


Figure 4.8: Single Phase Bipolar DC Source MLI with RL Load Output

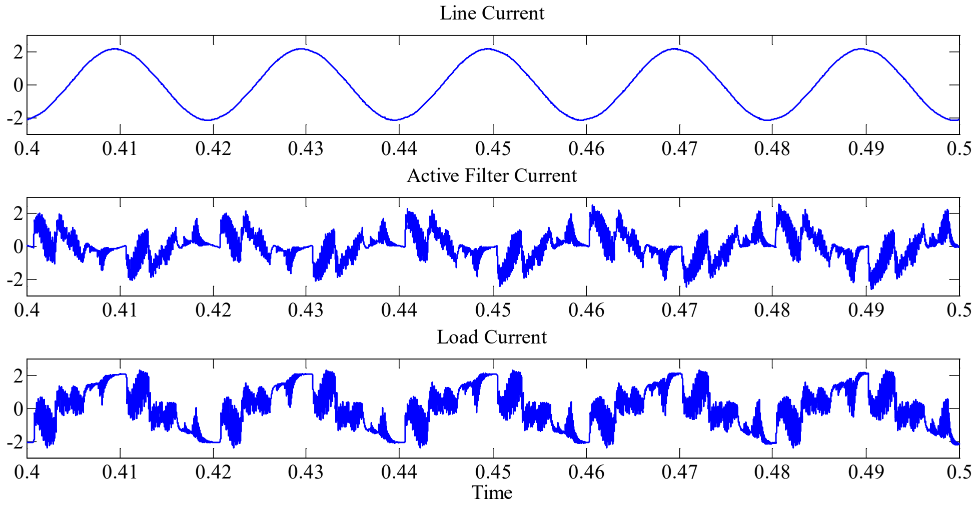


Figure 4.9: Single Phase Bipolar MLI connected shunt APF with RL Load Output

By injecting the current compensated from shunt APF the system can improve the current waveform at line that almost in sine wave form. Figure 4.9 shows that the current waveform that consists of line current, APF current and load current. By implement the shunt APF to MLI, the THD of current also can be reduced around 70 % to 84 %. Figure 4.10, 4.11, 4.12 shows the THD for line current for trinary, bipolar and unipolar switching method.

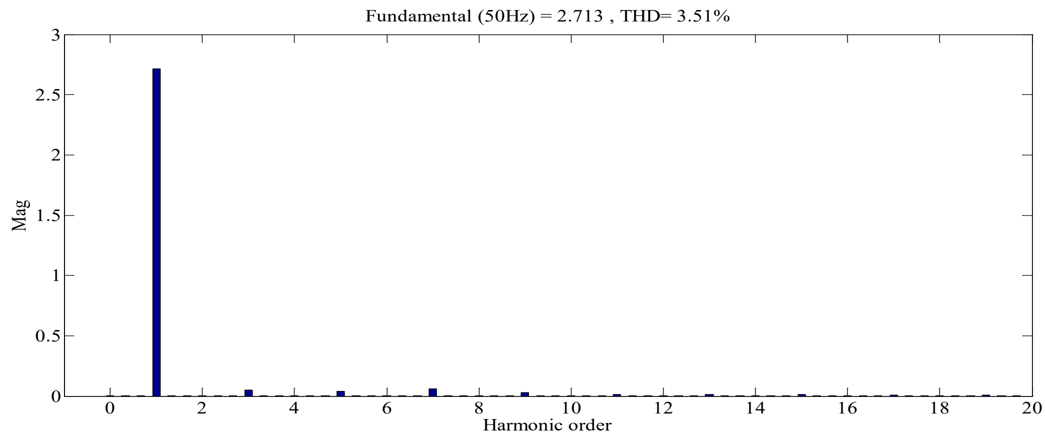


Figure 4.10: Single Phase Trinary MLI connected shunt APF with RL Load Harmonic Spectrum

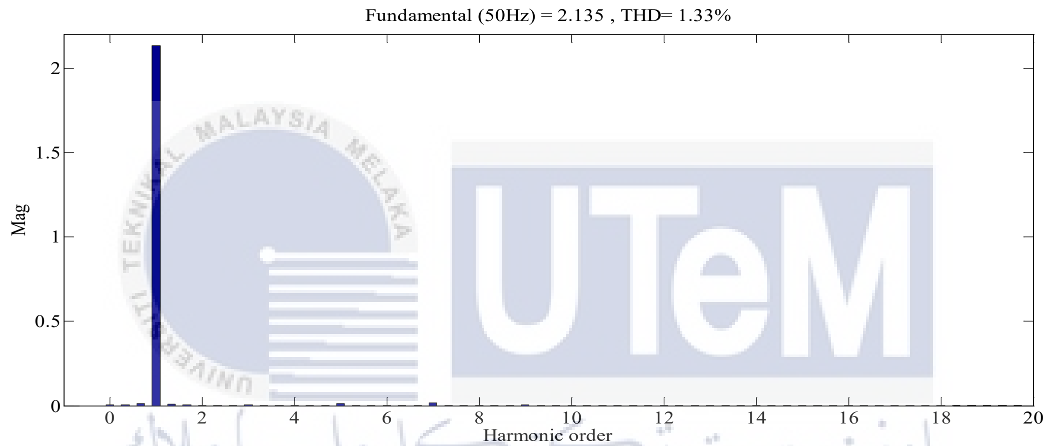


Figure 4.11: Single Phase Bipolar MLI connected shunt APF with RL Load Harmonic Spectrum

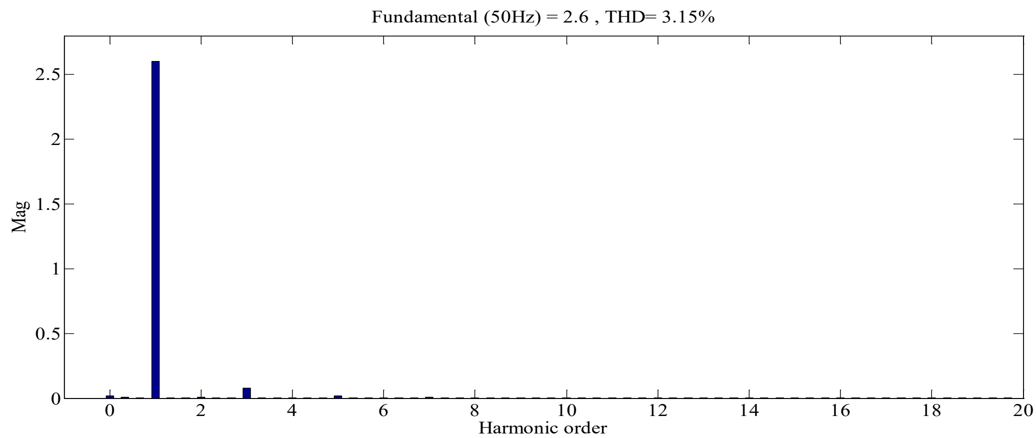


Figure 4.12: Single Phase Unipolar MLI connected shunt APF with RL Load Harmonic Spectrum

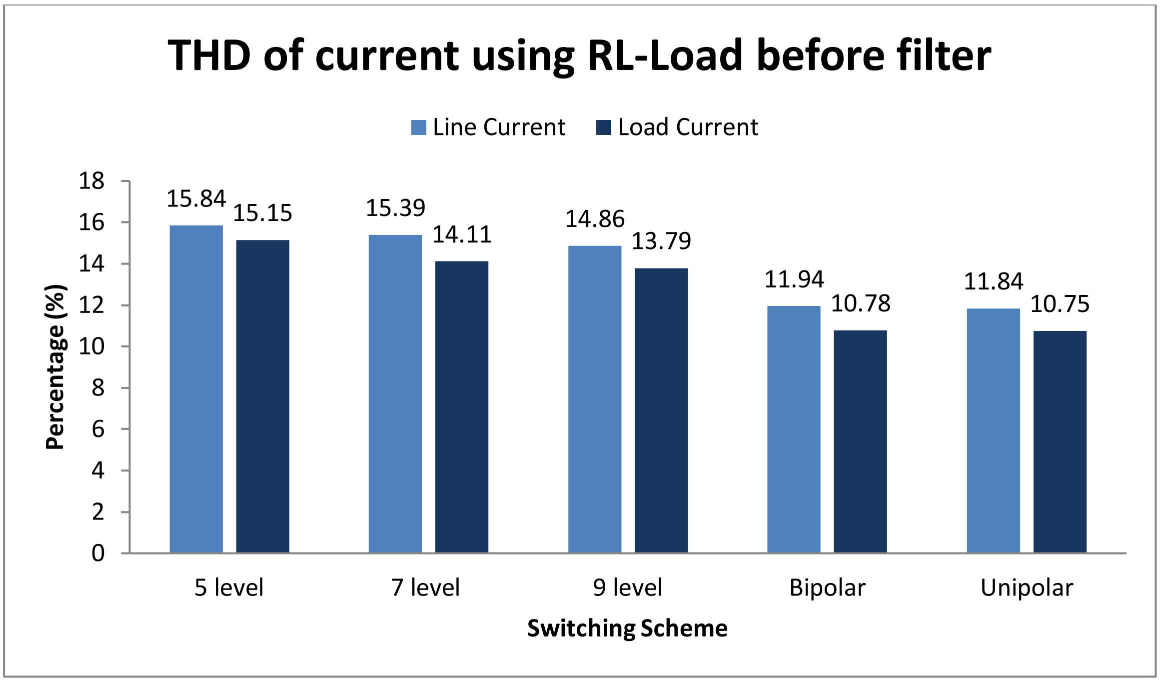


Figure 4.13: Percentage THD of Current connect with RL-Load before filter

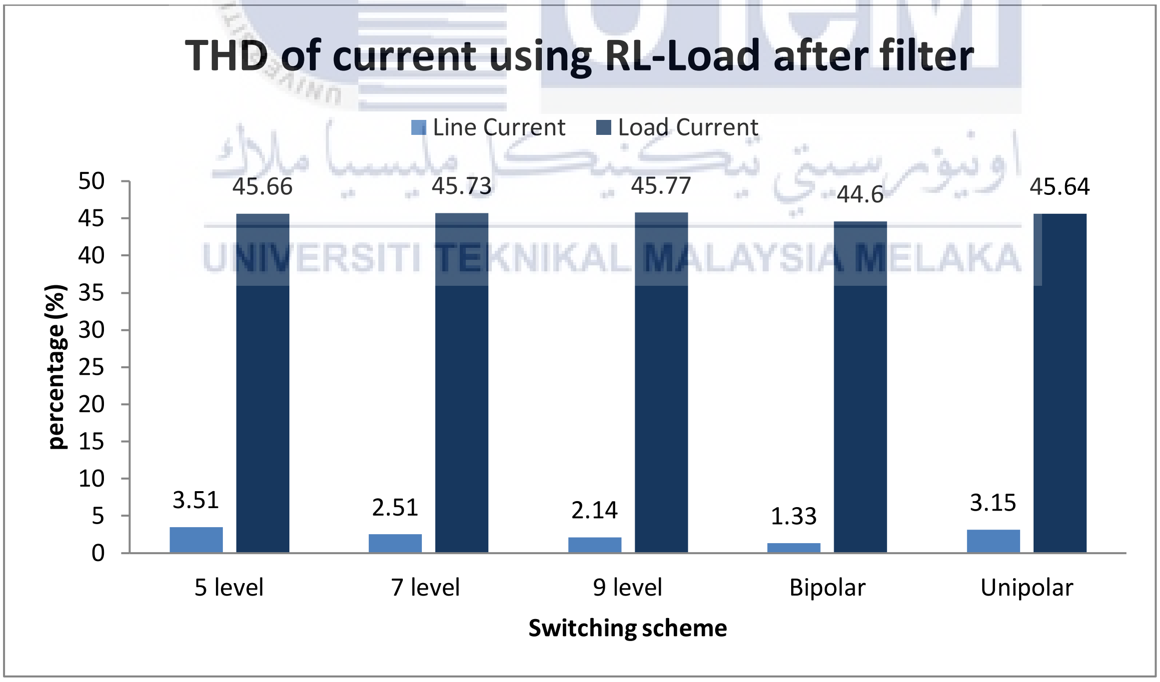


Figure 4.14: Percentage THD of Current connect with RL-Load after filter

From Figure 4.13 and 4.14 it shows when system is not filter the percentage of THD between line current and load current is almost same while after connected with shunt APF the percentage of line current is reduced and the percentage of load current is almost same. These occur because the present of combination of resistive and inductive load. It indicated that in real situation the load used is almost in resistive and inductive. However, the result after MLI connect with APF shows that the percentage of THD of line current is below that 5%. The results have achieved and follow the IEC Harmonic Standard 519-1992. In addition, from the graph of percentage it notes that the bipolar switching method is better that trinary and unipolar. This is because bipolar has switching pattern that covers between positive and negative V_{DC} during generation of PWM, it also can reduce low frequency when power output is low.

4.1.3 Simulation Result using RC-Load

The cascaded MLI is operates in three switching method which are, trinary, bipolar and unipolar. The MLI is to convert single phase DC power supply to AC power supply that connected to RC load. The value THD of current is different based on type of switching method while value THD of voltage is remaining same. Figure 4.15 shows the current and voltage waveform of MLI when connected to RC load.

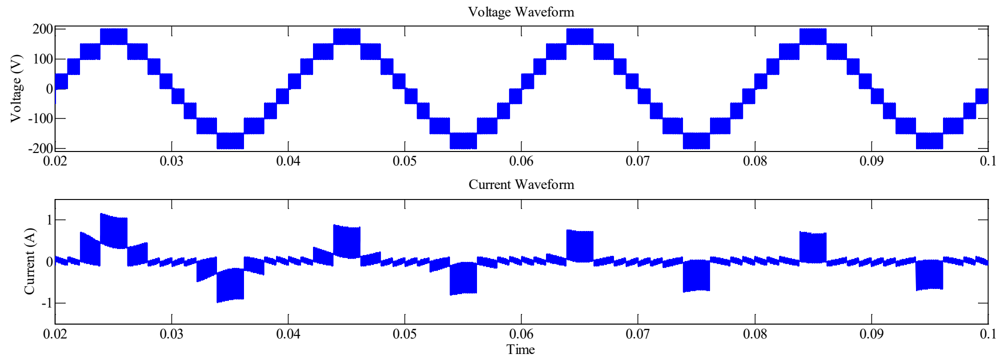


Figure 4.15: Single Phase Unipolar DC Source MLI with RC Load Output

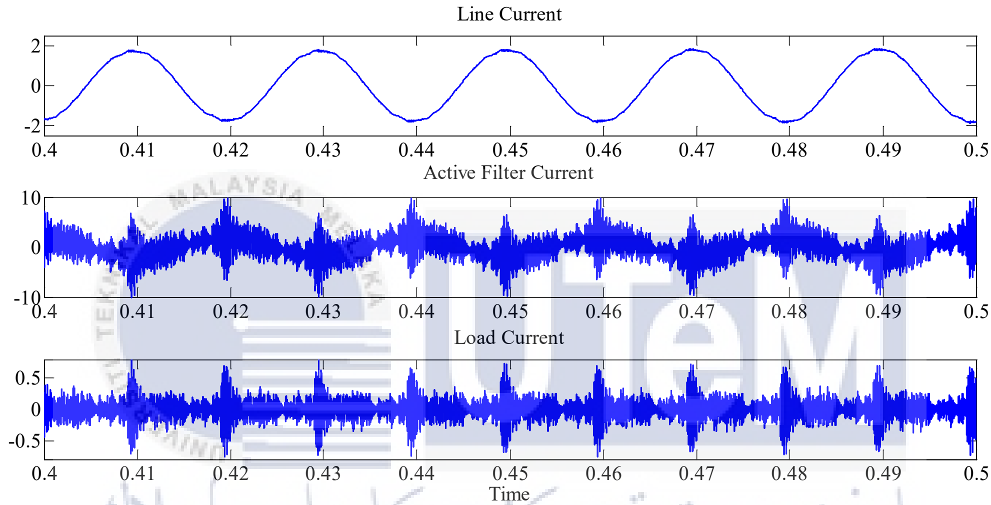


Figure 4.16: Single Phase Unipolar MLI connected shunt APF with RC Load Output

By injecting the current compensated from shunt APF the system can improve the current waveform at line that almost in sine wave form. Figure 4.16 shows that the current waveform that consists of line current, APF current and load current. By implement the shunt APF to MLI, the THD of current also can be reduced around 39 % to 98 %. Figure 4.15, 4.16, 4.17 shows the THD for line current for trinary, bipolar and unipolar switching method.

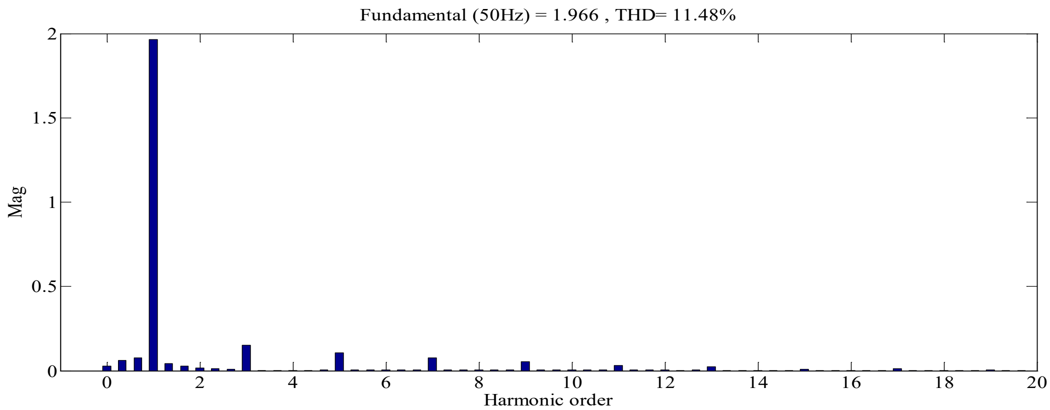


Figure 4.17: Single Phase Trinary MLI connected shunt APF with RC Load Harmonic Spectrum

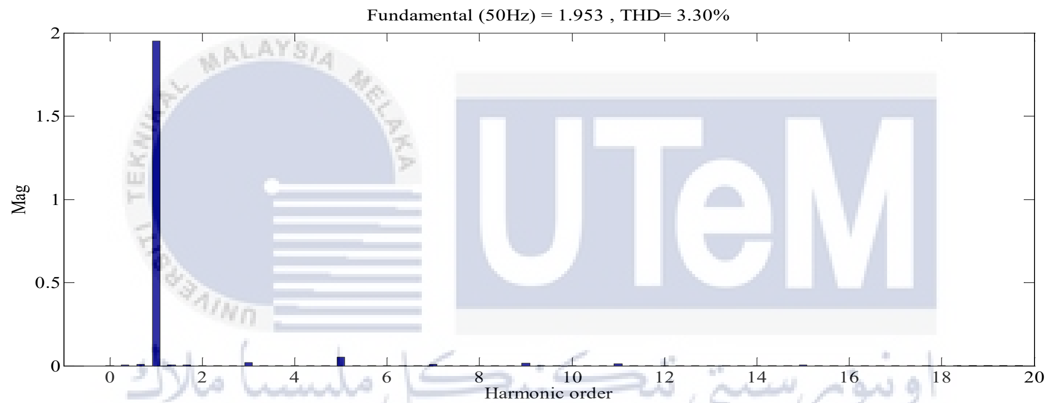


Figure 4.18: Single Phase Bipolar MLI connected shunt APF with RC Load Harmonic Spectrum

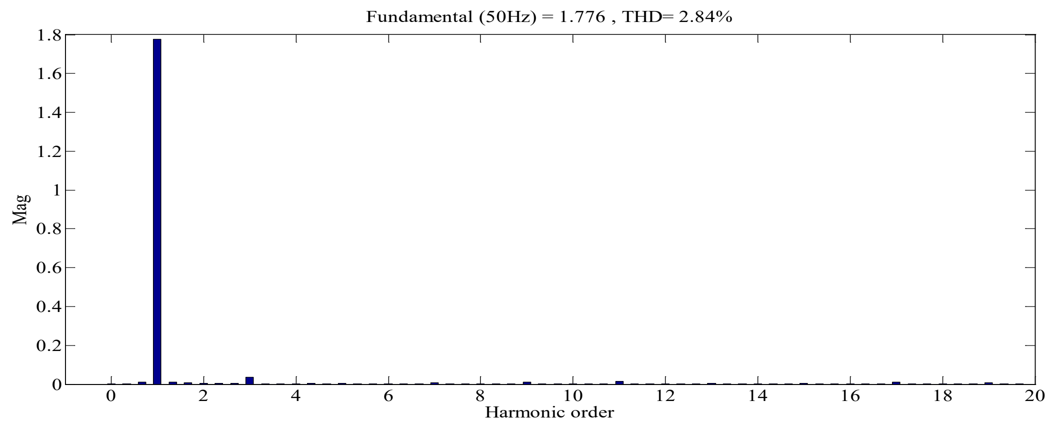


Figure 4.19: Single Phase Uniplar MLI connected shunt APF with RC Load Harmonic Spectrum

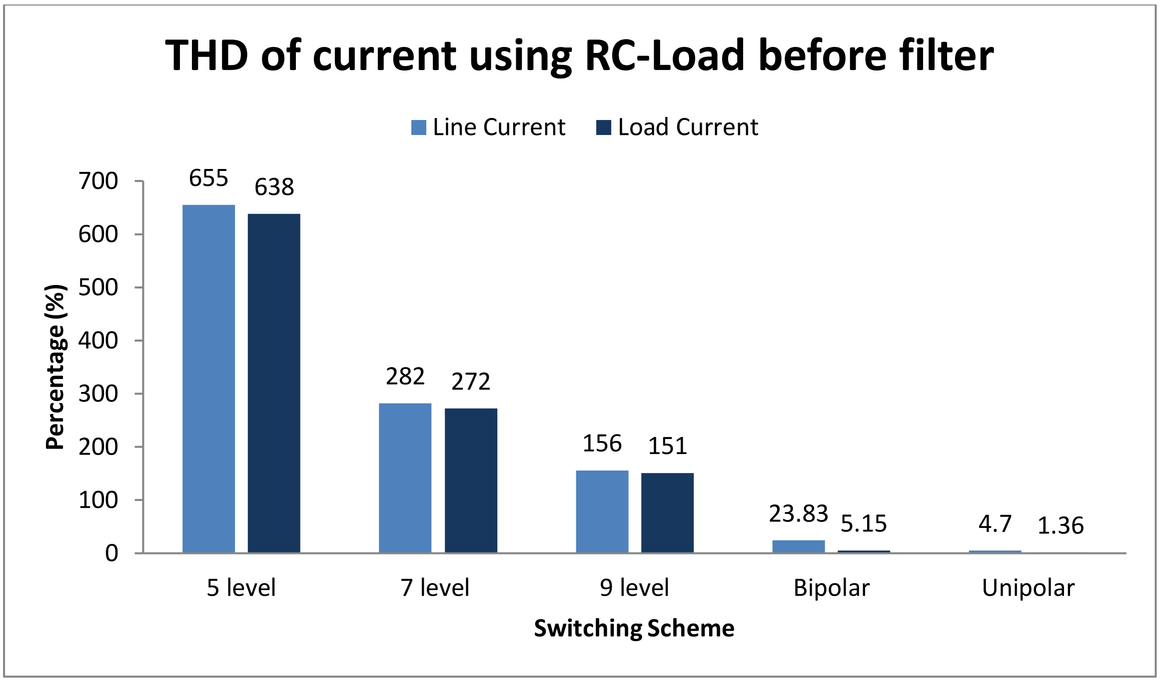


Figure 4.20: Percentage THD of Current connect with RC-Load before filter

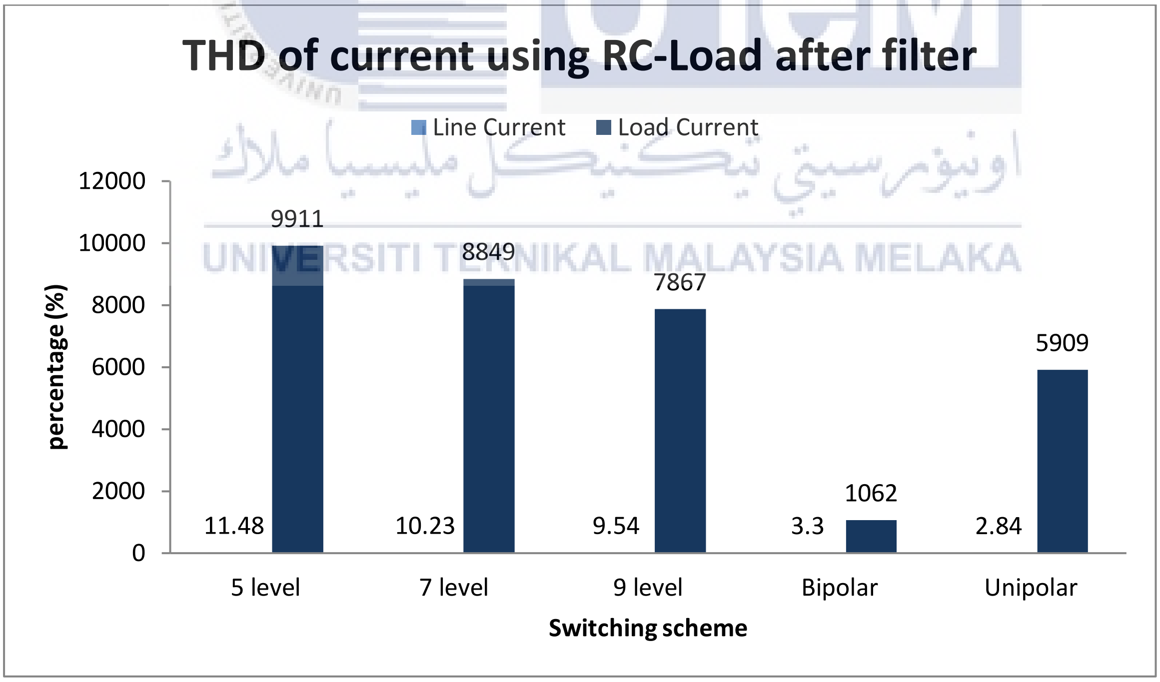
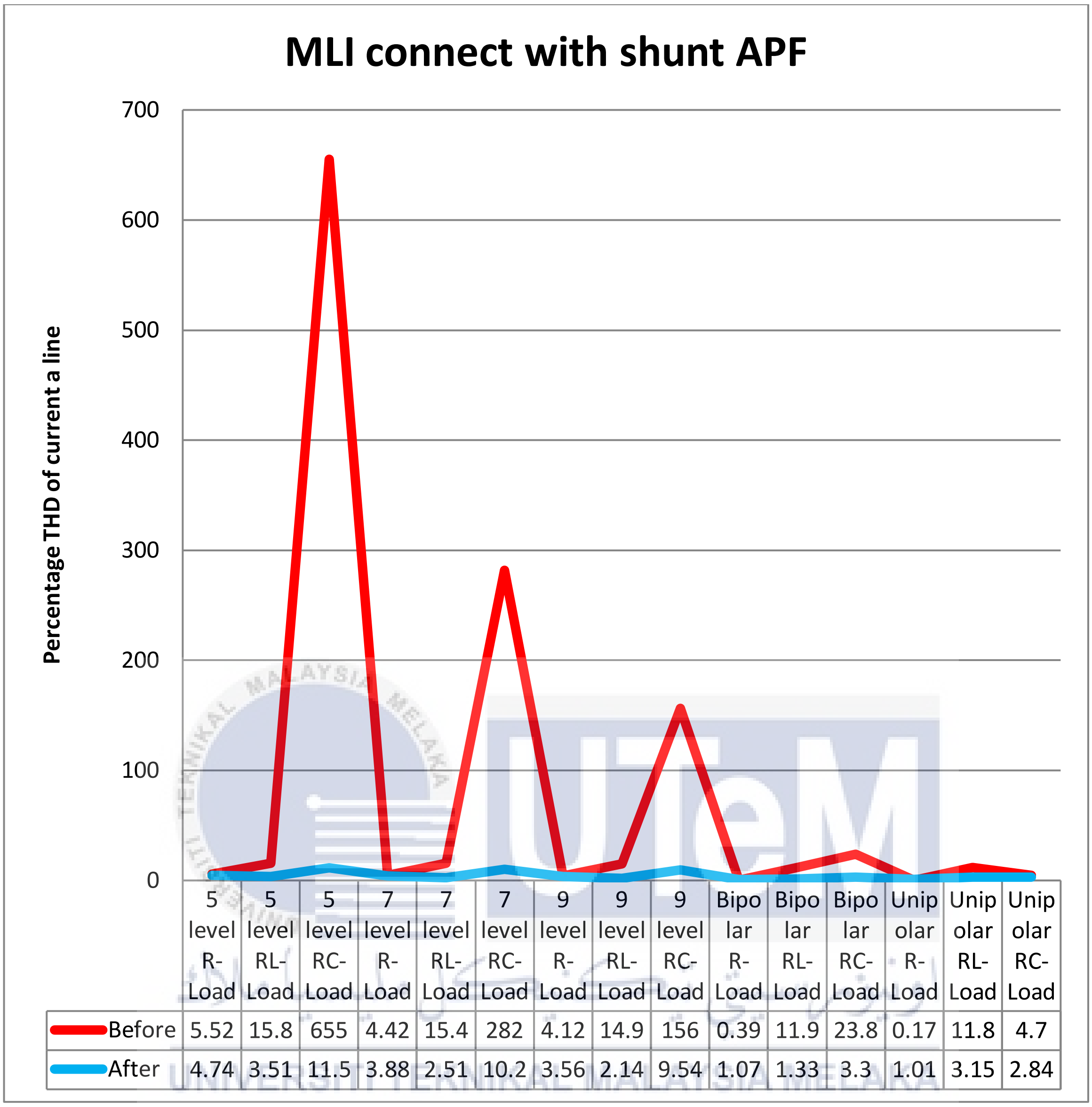


Figure 4.21: Percentage THD of Current connect with RC-Load after filter

From Figure 4.20 and 4.21 it shows when system is not filter the percentage of THD between line current and load current is almost same while after connected with shunt APF the percentage of line current is reduced and the percentage of load current is almost same. These occur because the present of combination of resistive and capacitive load.. However, the result after MLI connect with APF shows that the percentage of THD of line current is below that 5%. The results have achieved and follow the IEC Harmonic Standard 519-1992. From the result also shows the unipolar provide lowest percentage of THD because of the high efficiency due to reduced losses.

4.2 Summary of Simulation

As a conclusion for this simulation process, it shows that by implementing the shunt APF the harmonic distortion can be mitigate. Recalled back the previous result when the present of fixed load, the THD of voltage is produced mostly same while THD of current will have a little bit change. The change in THD of line current is because the variety of load. It will give effect of current when load is pure in resistive or have the combination of inductive and capacitive. However, when the load is in dynamic form such as DC motor or present of rectifier the value of THD will increase. To mitigate or reduce the percentage of THD, the responsibility was taken by shunt APF from injecting filter current. Moreover, by implementing the shunt APF also the output waveform of line current is mostly in sine waveform. Indirectly, the percentage of THD follows the IEC Harmonic Standard. Figure 4.22 shows the summary of percentage of THD of current before and after the implementation of shunt APF more clearly.



	5 level R-Load	5 level RL-Load	5 level RC-Load	7 level R-Load	7 level RL-Load	7 level RC-Load	9 level R-Load	9 level RL-Load	9 level RC-Load	Bipolar R-Load	Bipolar RL-Load	Bipolar RC-Load	Unipolar R-Load	Unipolar RL-Load	Unipolar RC-Load
Before	5.52	15.8	655	4.42	15.4	282	4.12	14.9	156	0.39	11.9	23.8	0.17	11.8	4.7
After	4.74	3.51	11.5	3.88	2.51	10.2	3.56	2.14	9.54	1.07	1.33	3.3	1.01	3.15	2.84

Figure 4.22: Summary of Percentage of Total Harmonic Distortion of Line Current before and after the implementation of shunt APF.

CHAPTER 5

CONCLUSION

The extreme developments in power electronic switches create output current and voltage waveform distortion in power supply. This phenomenon will create the harmonic distortion in electrical system. In order to minimize the effect of harmonic, the design of MLI is implemented. MLI knows that can generate output voltage with very low harmonic distortion. MLI also can solve the problem of high harmonic distortion that produced by the conventional inverter that have been widely used in energy conversion. However, the implementation of MLI is not good enough to mitigate the harmonic distortion if the system is connected with nonlinear load. By connect the APF in shunt the problem in harmonic distortion can be reduced. This situation is proved by the simulation that shows when the MLI connected with shunt APF the harmonic distortion is decreased even the load is in dynamic form. The result also shows when used the best design of MLI the percentage of THD is follow the IEC Harmonic Standard. This is because of implementation the SPWM schemes to control inverter switches. The SPWM carrier signals thus generated are compared with sinusoidal signals for production of switching. By have the good design of MLI and suitable method control of shunt APF the THD of current is reduced by 4% to 98%.

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