Power quality improvement for six pulse diode rectifier front end applications

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Declaration

This dissertation is submitted to The University of Bath in accordance with the requirements of the degree of Master of Science in Electrical Power Systems, in the Department of Electrical and Electronic Engineering. No portion of the work in this document has been submitted in support of an application for any other degree or qualification of this or any other university or institution of learning. Except where specifically acknowledged, it is the work of the author.

Signed .... **Maniea Mohammed Alkhalaiwi**

Date ....09/09/2011...

Abstract

In this project a full study of the common passive harmonic filters for three phase diode rectifier front end applications is presented. The AC line reactors, DC link inductors and tuned shunt filters are considered in the study. Full investigation of the different filtering techniques and related performance analysis is detailed. The main focus of the study is in the tuned shunt filters design for the most dominant current harmonics in the spectrum of the line distorted current. The operating principles of the tuned filter are reviewed and the conventional design method is used.

The study analyses methods to increase the effectiveness of the commonly used tuned shunt filters in reducing the current harmonic distortion levels and improving the line power factor. These ways involve detuning factors considered in the tuned filters design and the AC line reactors with, or without, DC link inductors filters added.

Moreover, a performance comparison of these different passive harmonic filters cases for three-phase 6- pulse diode rectifier front-end applications is provided. The comparison involves the input current total harmonic distortion, input total power factor, rectifier DC link voltage, size and cost. The harmonic resonance risk problem and unbalanced operation performance are investigated. Analysis and computer simulations form the basis of the study.

Key-words: Diode rectifier, harmonic, motor drives, power quality, power factor, passive filters, THD.

List of contents

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List of Abbreviations

AC	Alternative Current
ASD	Adjustable Speed Drives
DC	Direct Current
DPF	Displacement Power Factor
GTOs	Gate-Turn-Off Thyristors
IGBTs	Insulated Gate Bipolar Transistors
IGCTs	Integrated Gate Controlled Thyristors
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
NEMA	National Electrical Manufacturers Association
PCC	Point of Common Coupling
PFC	Power Factor Correction
PWM	Pulse Width Modulation
RMS	Root Mean Square
SCR	Short Circuit Ratio
THD	Total Harmonic Distortion
TDD	Total Demand Distortion
THD_V	Total Harmonic Voltage Distortion

List of Principle Symbols

S	Apparent power
P	Active power
$Q1$	Reactive fundamental power
D	Distortion power
D_f	Detuning factor
I_h	Rms value of the current harmonics
I_1	Rms value of the fundamental current component
I_L	Full-load fundamental current component
I_{sc}	Short circuit current available at the input of the nonlinear load
h	Harmonic order
p	Number of pulses in the DC voltage
X_L	Reactance impedance
f	System frequency
L	Inductance
Z_b	System base impedance
V_r	Rated rms phase voltage
I_r	Rated rms phase current
Ls	AC line inductance
I_d	Load current
u	Current commutation interval between the outgoing diode and the incoming diode
V_{LL}	Line-to-line supply voltage
Q_{filter}	Filter reactive power compensation
Φ_{rect}	Rectifier side displacement power factor angle
Φ_{line}	Line side displacement power factor angle
C_f	Filter capacitance
L_f	Filter reactance
Z	Resonance impedance
f_s	Series resonance frequency
f_p	Parallel resonance frequency
f_h	Harmonic frequency

List of Principle Symbols

Q	Filter quality factor
R	Damping resistance
Ldc	DC link inductor
Lac	AC line reactor
Vdc	DC link output voltage
Vs	Rated phase supply voltage
Hz	Hertiz
Ω	Ohm
H	Henry
F	Farad
kW	Kilo-Watt

1. Introduction

1.1 History and context

The power quality issue in an electrical distribution power system has always been an engineering concern. One of the main power quality problems is the increment of harmonic pollution in the distribution networks. This distortion may occur in the current drawn from the widely used nonlinear loads (mainly the 6-pulse diode rectifier front end applications) and in the supply voltage at the point of common coupling (PCC).

As the nonlinear loads are spread widely in single phase domestic applications and in three phase industry applications, the pollution levels are anticipated to increase while stricter control standards and regulations will be applied. The benefits of using these nonlinear loads are well known and are vital to save more electrical energy consumption and to reduce CO_2 emissions in the air. Therefore, methods and techniques to deal with the problem and reduce these increased levels of harmonic pollution are always under focus and research.

1.2 Motivation

The harmonic mitigation techniques, used to improve the distorted current waveforms drawn by the 6-pulse diode rectifier front end applications, have been always developing. Engineers are usually trying to find efficient, reliable and economical solutions to keep the harmonic distortion values within the defined acceptable levels.

Within these different techniques, the shunt passive filter method is still a commonly used filtering type for the 6-pulse diode rectifier front end applications and are usually combined with the AC line reactors and/or DC link inductors to increase their effectiveness. Full performance investigation of the AC line reactors, the DC link inductors, or a combination of both filters values with the tuned filters, is needed. This will help in choosing the better combination for a specific harmonic level regulation system requirement. Moreover, the effectiveness of the tuned shunt filter in absorbing the harmonic current, and its relation with the designing detuning factor value, needs to be clarified.

1.3 Objective of the project

As stated in the interim report of this project [1] the aim of this project is to investigate the passive harmonic filtering techniques for 6 pulse diode rectifier's front end applications, to reduce the pollution caused by such converters. This will allow the widely used converter topology to meet the harmonic standards limits and meanwhile to improve the line power factor. The project involves a full study of the common passive filtering methods utilized along with a comprehensive comparison assessment. The comparison study will examine the different filters structures performance from no-load to full-load range, under balanced and unbalanced voltage source conditions. The DC-link voltage reduction will be assessed and the reactive power compensation, provided by the filters to improve the line power factor, will be examined. Finally, a possibility of resonance risk with the utility and/or within the filter structure will be looked at.

The most effective combination of the common passive filters will be considered and a detailed analysis will be conducted. And possibilities to improve the topology effectiveness will be the main objective of the study, and subsequent to this, strong practical recommendations will be established.

2 Background

The background section and followed 2.1, 2.2, 2.3, 2.4 sections are taken, updated and summarized from the interim report of this project (literature review submitted last term) [1].

The Power Quality of power systems has a vital impact on all connected to the network electrical and electronic pieces of equipment. It defines the variations in voltage and frequency of the supply system. These deviations can be caused by several types of single phase and three phase loads. Computers, TV monitors and lighting are some single phase loads that may affect the power quality where variable

speed drives in the industrial applications are the major three phase loads causing the same affect [2].

These applications use cost effective power converter circuits (AC/DC and DC/AC) which enhance the overall performance, efficiency, and reliability. However, these utilized converters draw distorted currents rather than pure sinusoidal currents which include a lot of harmonic current components. These harmonics have substantial effects including distorting voltage supplies, interfering with other systems, system reliability reduction, increasing the running costs, temperature rise of the equipments, motor breakdowns, wrong power metering and capacitor collapse.

2.1 Input current harmonics of 6-pulse rectifier system [1]

Over recent decades the six pulse rectifiers have been are commonly used as converters in the power electronic controlled electric equipment [3]. The line AC voltage is rectified with the diodes and smoothed by a DC link capacitor. The DC voltage can be transformed by any defined AC voltage, by means of PWM inverters to drive an AC motor.

Motor drives have been replacing those directly connected to the supply motors. This will allow more flexible motor operation and will save a considerable amount of energy. However, the current drawn by the 6-pulse rectifier converter has a distorted current waveform. Figure 2.1 shows the general topology structure of a 6-pulse rectifier with DC link capacitance, load and main supply with line impedance. The drawn line current waveform and the corresponding harmonic spectrum are shown in Figure 2.2 and Figure 2.3, respectively. Current harmonics generated have 2p±1 order, where p is the number of pulses in the rectifier output DC voltage. For the 6-pulse rectifier case the harmonic spectrum has the first four dominant harmonics (5^{th}, 7^{th}, 11^{th} and 13^{th}) with high percentage value with respect to the fundamental component. As these rectifiers' structures are usually the most widely used power electronic converters to be connected at the point of common coupling (PCC), harmonic currents are injected into the supply systems distorting the supply voltage with extra harmonics.

In general current harmonics in industry can be generated either by AC/DC or DC/AC power converters or usual electromagnetic devices. In modern power systems many applications are contributing a huge amount of harmonics to the power system distribution networks. This may involve semiconductor based power supplies, phase controllers, reactors, etc. In addition arcing furnaces generate a significant amount of current harmonics. In electric power system distribution networks, the main current harmonic sources can be categorized as follows [4].

- Semiconductor based power supply system
- Inverter fed AC drives
- Thyristor controlled reactors
- Phase controllers
- AC regulators
- Magnetization nonlinearities of transformer
- Rotating machines
- Arcing devices

However, among the mentioned harmonic currents sources mentioned the 6 pulse diode converters are widely utilized in industry and are considered to be the most polluted circuits, with current harmonics, that cause power quality problems.

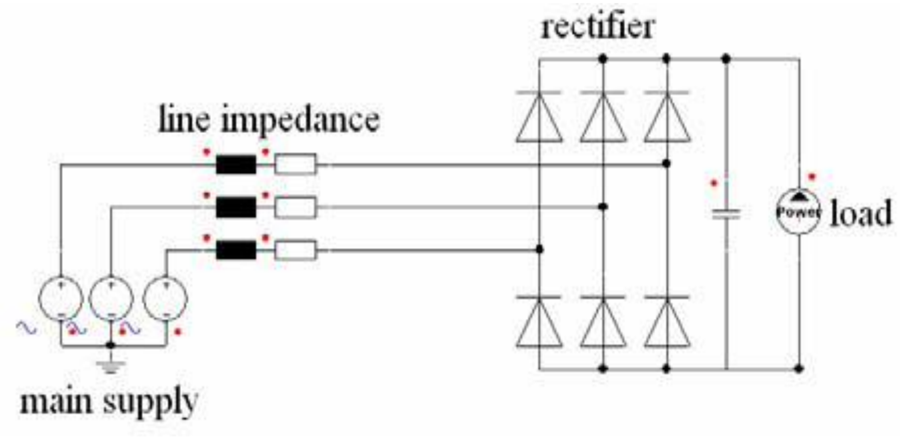


Figure 2.1: Six-pulse diode rectifier structure with DC link Capacitor

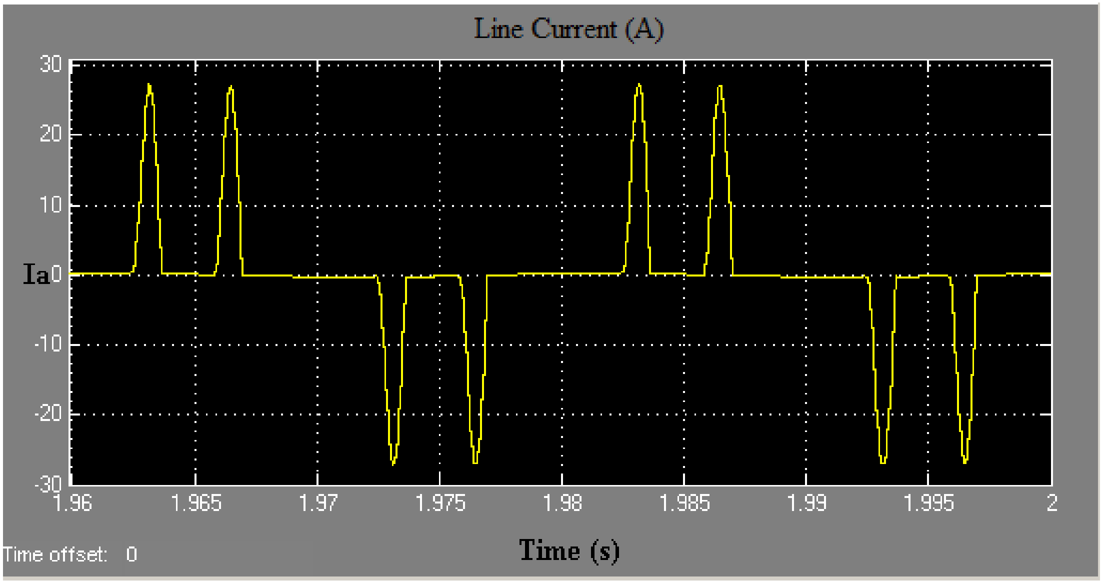


Figure 2.2: Typical line current waveform for 6-pulse diode rectifier using no filters

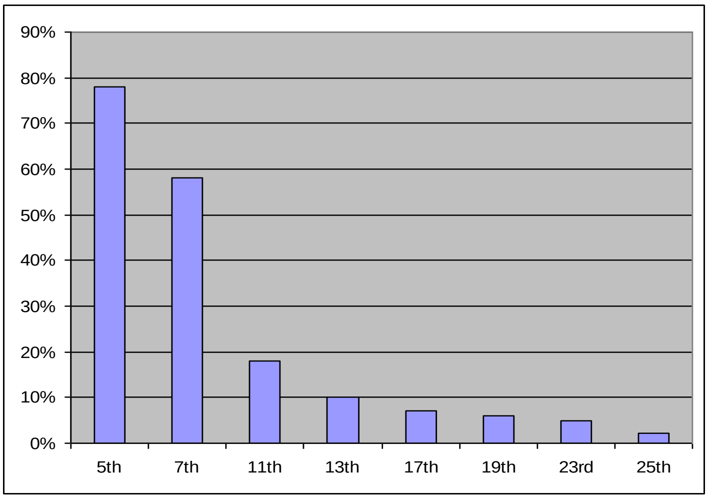


Figure 2.3: Line current harmonic spectrum for 6 pulse diode rectifier using no filters (>80% THD)

2.2 Current harmonics effects in distribution networks [1]

Current harmonics are not desirable and have a negative effect on power system equipment operation in most of the applications in electrical power systems. Harmonics can cause risky overvoltage conditions when resonance in a power system network is created. In addition, it has some bad effects on performance of rotating machines, transformers and transmission networks.

The accuracy of measuring instruments and protective devices may change, due to the existence of unwanted harmonics, causing malfunction. Also reactive power compensation devices, connected to the power system to improve the line power factor operation, may change. Moreover, various consumer sensitive equipment, may suffer from the existence of current harmonics distortion in the power system [5].

Generally, there are two major problems caused by current harmonics to electrical power distribution systems [3]. This involves the increment in the total apparent power demanded (S) by the supply due to the appearance of the extra distortion power component (D). Therefore, the apparent power basic equation will contain a new term presenting the distortion power.

$$S = \sqrt{P^2 + Q_1^2 + D^2} \tag{2.1}$$

where *S* is the apparent power, *P* is the active power, *Q*1 is the reactive fundamental power and *D* is the additional distortion power.

As a result of adding the distortion power (D) term in the equation 2.1, the total demand apparent power to be generated (S) should increase. Consequently, the losses in the networks and the utilized transformers will increase.

In addition to the first problem, a distorted current waveform drawn by the nonlinear load will result in a distorted voltage drop component over the line source impedance. Consequently, this voltage drop will add to the supply voltage and result in a distorted voltage at the point of common coupling (PCC), shown in Figure 2.4. Therefore, other loads, which are connected at the same point of common coupling, will be supplied by a distorted voltage rather than an ideal pure sinusoidal voltage.

Other common harmonics effects may involve noise emissions in transformers and inductors, premature blowing of fuses and the increment of the resonances risk. Furthermore, current harmonics can increase the total current root mean square (rms) values of the neutral line, due to the existence of triple harmonics (3^{rd}, 9^{th} ...etc.) in single phase applications. Also current harmonics can increase the stress over the

power factor correction capacitances connected to the power system distribution networks.

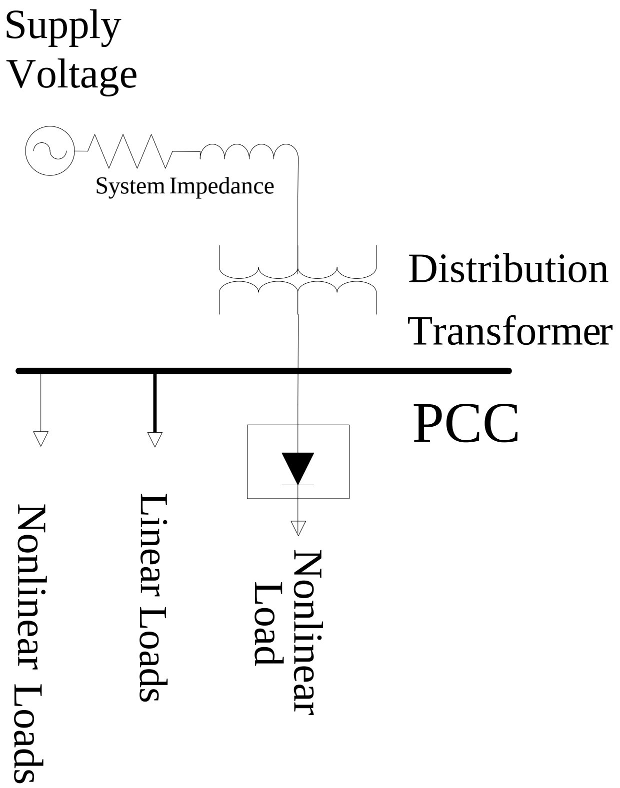


Figure 2.4: Definition of the point of common coupling (PCC)

To ensure a sufficient voltage supply quality, and to reduce the current harmonic effects in the power distribution systems, technical standards and recommendations for power distributors were defined. The IEEE 519 was introduced as a guideline in 1981, and revised in 1992 [6] to define harmonic current limits for the point of common coupling. To keep these limits, further standards like IEC 61000-3-2 or IEC 61000-3-6 with emission limits for electronic equipment have been defined [7], [8], and [9]. For both users and utility ends, the approach set recommended limitations and standards.

For the user end, the standard restricted the level of harmonic current injected at the PCC by any individual end users. Recommended limits are given for both individual current harmonic components and the total distortion indices. Total Harmonic Distortion (THD), given by equation 2.2, is the commonly used indices for

calculating a waveform harmonic content and can be applied to either voltage or current.

$$THD_I = \frac{\sqrt{\sum_{h=2}^{N} I_h^2}}{I_1} \tag{2.2}$$

where the I_h is the rms value of the current harmonics and I_1 is the rms value of the fundamental current component. However, this can be often misleading. For instance, at very light loads (low load current) operation mode for 6-pulse diode rectifier front end applications the input current THD values are usually high. However, practically the magnitude of the harmonic currents components are very low and are not considered as a problem.

Therefore, the IEEE Standard 519-1992 uses the Total Demand Distortion (TDD) additional term, to avoid this uncertainty and misleading. This term is defined as a percent of full-load fundamental load current and not of the fundamental current level at the instant of measurement as in the THD term. This will lead to low TDD values at light load operating conditions which practically accepted. TDD is given by the following equation

$$TDD = \frac{\sqrt{\sum_{h=2}^{N} I_h^2}}{I_L} \tag{2.3}$$

where the I_h is the rms value of the current harmonics and I_L is the rated demand of the fundamental current component.

Therefore, as shown in Table 2.1, the IEEE standard 519-1992 recommended harmonic current limits are expressed in terms of current TDD, rather than current THD. The I_{sc}/I_L ratio is the short circuit ratio at PCC. As I_L is the rated demand of the fundamental current component, I_{sc} is the short circuit current available at the input of the nonlinear load [6].

The ratio is an indication of nonlinear load contribution to the PCC point. In other words, the smaller the I_{sc}/I_L ratio in the system the higher the impact of the nonlinear load connected to the PCC and the less TDD% is allowed to limit the distortion effect. On the contrary, high I_{sc}/I_L ratio in the system means that the nonlinear load connected to the PCC will have a negligible effect on the system, and more flexible TDD% values are permitted by this small nonlinear load.

Table 2.1: IEEE 519 harmonic current limits

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

For the utility end, limiting the voltage distortion at the PCC is the major utility concern. Therefore, the IEEE Standard 519-1992 recommended harmonic voltage THD limits at this point. This harmonic voltage distortion on the utility system arises from the interaction between distorted load currents and the utility system impedance. The standards are given for the maximum harmonic components and for the voltage THD, as shown in Table 2.2, and are expressed as the percentage of the fundamental voltage. For systems below 69 kV, the voltage THD should be < 5% and individual harmonic components < 3% [6].

Table 2.2: IEEE 519 voltage distortion limits

Bus Voltage at PCC	Maximum Individual Harmonic Component %	Maximum THD%
69kV and Below	3.0	5.0
69.001kV Through 161kV	1.5	2.5
161.001kVand Above	1.0	1.5

Accordingly, to comply with these harmonic standards limitations on the voltage supply at PCC and current drawn from the nonlinear loads, application of effective, reliable and economical harmonics mitigating techniques to such nonlinear loads is usually obligatory.

2.3 Harmonic prediction methods [1]

Producers of non-linear 3-phase equipment commonly used in industry utilizing diode/thyristor rectifiers as a front end, such as Adjustable Speed Drives (ASD), is usually forced by the harmonic standards (IEEE 519, IEC 61000 series) to provide detailed harmonic calculation data for a given industrial application. This is due to the increasing focus on the power quality issues in the power system distribution networks.

Typically, up to the 50th harmonic component for harmonic voltage and current spectrum, are demanded. This usually involves the diode rectifier which is the most used front-end topology for 3-phase apparatus. Unfortunately, calculation of the harmonic currents components spectrum of the simple structure of six-pulse diode rectifier is not a simple duty. On the other hand, the calculation of the harmonic voltage distortion is not complicated once the harmonic currents are defined. However, the harmonic currents of the six pulse diode rectifier are deeply depending on the supply voltage distortion and impedance as well as unbalance operating conditions. Generally four stages of modelling the six-pulse diode rectifier and estimating the current harmonics exist [10]. The accuracy level is directly proportional to the amount of system parameters required in each modelling method.

The first stage is the ideal model of the diode rectifier (1/h current source model) requires very few system parameters, however, has a very limited accuracy. It assumes that the rectifier uses an infinity DC link inductor in the DC side and consequently the drawn line current has a quasi square wave shape, shown in Figure 2.5. Using the Fourier series analysis the quasi square current waveform characteristics can be determined, and a simple equation describing the diode

rectifier current fundamental and harmonic components depending on the number of pulses, can be obtained.

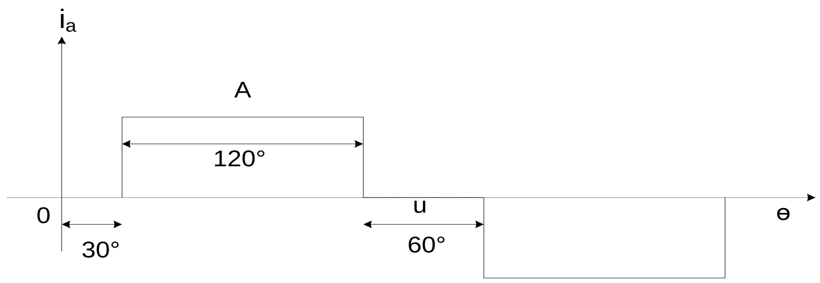


Figure 2.5: Quasi square wave rectifier line current waveform ($L_{dc} \rightarrow \infty$).

Therefore the current harmonics components are given by

$$I_h = I_1 * \frac{1}{h} \tag{2.4}$$

where I_h is the harmonic component and I_1 is the fundamental component. The harmonic order h is given by

$$h = p.K \pm 1 \tag{2.5}$$

where p is the number of pulses in the DC voltage and k = 1, 2, 3.. etc.

A table-based model of diode the rectifier is the second stage model. The method involves measuring or simulating the line current of the diode rectifier under different operating conditions and uses a look-up table process to estimate current harmonics. The method requires the definition of a limited number of parameters on the expenses of accuracy levels obtained by this simple approach which is considered as the major drawback. Practically all system parameters in industrial application are hard to find which make this approach suitable for calculation of the current harmonic distortion and components in an industrial application.

With the table-based method it is possible to estimate the load current waveform data changes due to any system parameters variation. These parameters may involve the

line and source impedance, series ac filter reactance, dc-link inductance and loading conditions. The final results for a set of different practical conditions are stored in a look-up table and then utilized to estimate the actual values for a given application by interpolating the look-up table stored related parameters. However, generating a look-up table with large amounts of data of the line current under a wide range of different conditions by measurements, is a very time consuming process. This is considered as the main drawback of the method. On the contrary, once these look-up tables' data are known, an estimation of the harmonic currents of the 6- pulse diode rectifier can be simple and done in no time.

The third stage of the diode rectifier model used is based on an analytical model. The analytical models can be used provided that more detailed system information is known. The dc-link capacitance, dc-link inductance and load conditions are some of these required parameters. Generally, this method involves highly complex mathematics and is not conventional.

The numerical based circuit simulator presents the fourth stage of the diode rectifier modelling methods. The simple implementation of non-linear system components, such as power diodes, is a preferable advantage. Additionally, unbalanced supply voltages and practical voltage distortion (approx. 3% THD_V) can be easily simulated compared to other methods.

Increasing in computing power and improving the performance of the software products in recent years, numerical methods are becoming widely utilized. The benefits of using more reliable and flexible simulation software for designs make this method very dominant. This also involves using advanced numerical algorithms and the implementation of real devices much closer to practical conditions. However, longer calculation periods and the definition of all system parameters are considered the main drawback of the approach [10]. In this project the numerical method is used and reliable simulation software is utilized.

2.4 Harmonics mitigation techniques for 6-pulse rectifier system [1]

A range of harmonic reduction techniques have been developed to improve the power quality of distribution systems and to comply with the current and voltage harmonic standards (IEEE 519 and IEC 61000 series). In general these techniques can be categorized into five general groups:

a) Passive filters (series ac reactors, tuned series and shunt filters, and DC inductors)
b) Multi-pulse systems (12 pulse and 18 pulse)
c) Active filters (series and shunt)
d) Hybrid filters (passive and active)
e) PWM rectifiers (active rectifiers)

The intent of these different techniques is to improve the distorted input current waveform by controlling harmonics components polluting the current and reducing the overall current THD.

a) Passive Filters:

Passive filters are a well-known method to control harmonics in distribution power networks. They are designed using passive elements, such as reactors and capacitors with different configurations and connection methods.

Series and shunt passive filters connected to the supply side are the main two used types in this filtering technique. The usage of a high series impedance to block harmonics is the concept of the series connected passive filters to prevent the flow of the undesired harmonic currents into the power system. In contrast, the shunt passive filters method uses low impedance shunt trap to redirect the current harmonics through them.

Series filters are connected in series with the supply and will have to carry the full load line current. They can be either simple line reactors to smooth the current waveform and reduce its harmonic contents or a tuned LC series filter that shows

high impedance at specific parallel resonance frequency to prevent the corresponding harmonic component to pass through. Therefore, each dominant harmonic will need a parallel LC filter tuned at the same frequency to block it. The filtering topology structure connected to a 6-pulse diode rectifier front-end application is shown in Figure 2.6.

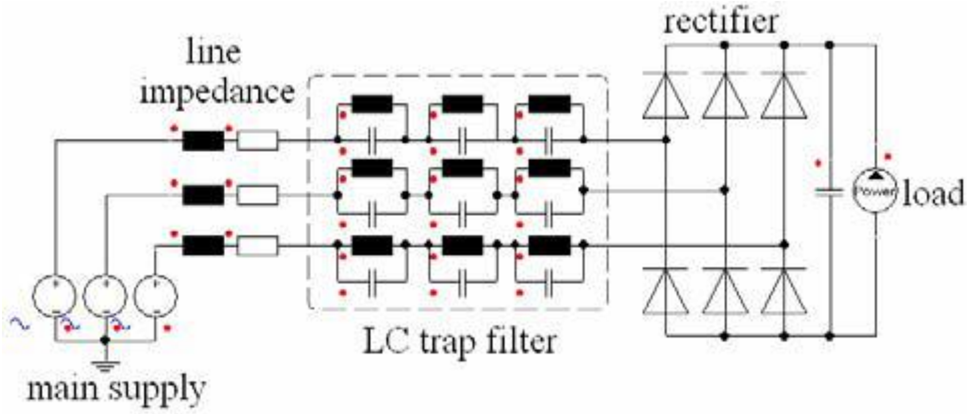


Figure 2.6: Line AC series filters for the dominant harmonics

In general the tuned LC series filters can improve the current waveform and reduce the line current total harmonic distortion. They may also improve the total line power factor and have no parallel resonance risk with the supply impedance. However, the LC series must be designed to carry the full load current at fundamental frequency. This will increase the size and the cost of the filters. Moreover, a high voltage drop occurs on the filters and the DC link voltage is extremely reduced at balanced and unbalanced line voltages [3]. Therefore, this filtering method is usually avoided due to the previous drawbacks and other passive filtering methods maybe preferable. The other series filters (AC line reactors and DC link inductors) are simpler in design and less in size and cost. Therefore, they are commonly used in 6-pulse diode front end applications to improve the current waveform. More details will be provided in section 3.

Shunt tuned filters are the other common type of the passive filtering methods. They can be in different structures combined with the common series filters (AC line reactors and/or DC link inductors). Also they can be designed for a single harmonic or for a multiple current harmonics. Shunt tuned filters are an effective, reliable and economical filtering method and are widely used in practice [11]. The focus of this

project is on the common passive filtering methods and more details will be provided in section 3.

b) Multi-pulse systems

Other than connecting a filter to the conventional 6 pulse rectifiers to decrease the current distortion, the increasing of the number of pulses in the output is a used technique. For instance, 12 – pulse and 18 – pulse converters are possible solutions for reducing the harmonic distortion. In higher pulse rectifier systems the drawn current waveform will contain less harmonic components and will eliminate the first dominant harmonics in the 6- pulse rectifier systems (5^{th} and 7^{th} for 12-pulse).

To get a 12- pulse system, as shown in Figure 2.7, a converter transformer with two output voltages which are phase shifted by 30°, is used. Different transformer connections and phase shift values can be used. Generally, 12- pulse rectifier systems topology can reduce the line current THD, especially at balanced supply voltage conditions. Furthermore, the used transformer may isolate the rectifier system from the supply system and reduce resonant risk possibilities. The cooling of the converter transformer is needed along with the two parallel diode bridge rectifiers [3]. The multi-pulse method usually operates at low efficiency, is large in size, and with different transformers connection topologies the cost may increase [12].

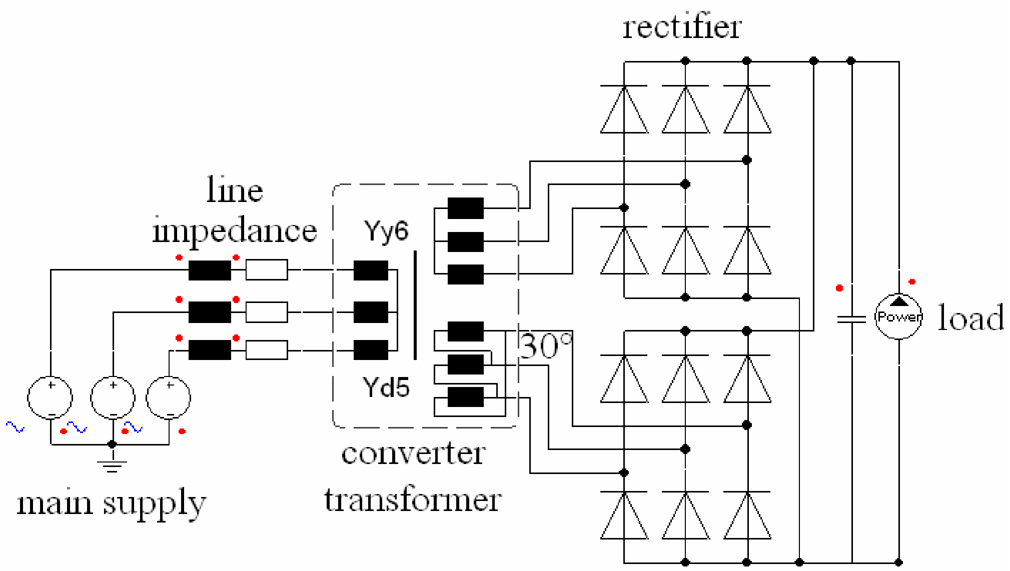


Figure 2.7: Twelve pulse enhancement

c) Active filtering

The active filtering method uses an extra power electronic converter connected to the non-linear loads (e.g. 6-pulse rectifier). The active filter is controlled to generate current harmonics magnitude equal to the load current harmonics magnitudes with 180^o phase shift. The current harmonics, produced by load and injected by the active filter will cancel each others out at the PCC resulting in a very low line current THD. To comply with recent standards, the active filtering method is very effective way to control harmonics. However, its costs are high and it has low reliability and needs complex control methods [13], [14], [15].

In general, pure active filters can be categorized from their circuit configurations into shunt active filters and series active filters, as shown in Figure 2.8 and 2.9, respectively [16]. Typically, shunt active filters are more common than series active filters. Highly rated shunt filters are usually expensive and combined with passive filters to reduce the rating.

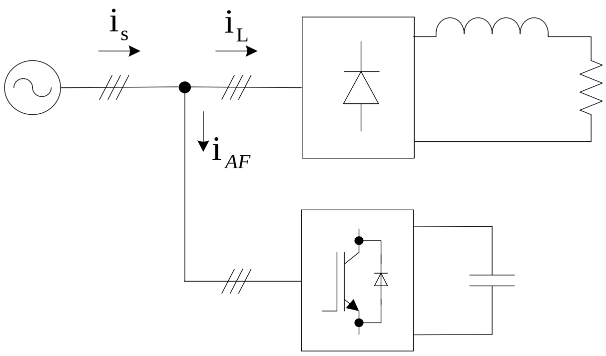


Figure 2.8: Active filter fundamental shunt active filter system configurations

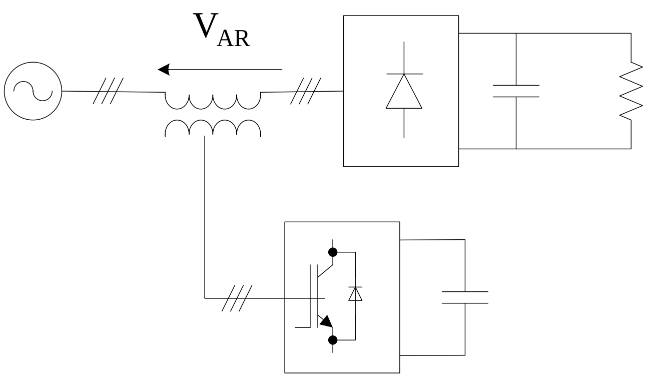


Figure 2.9: Active filter fundamental series active filter system configuration

d) Hybrid filters

To reduce the conventional active stand alone filter cost and to improve efficiency hybrid filters are used. The hybrid filter is a mixture of a passive filter and a small-rated active filter [16]. The initial cost and the operation switching loss of the filter are proportional to the rating of the active filter. The main purpose of hybrid active filters is to decrease initial costs. They enable the use of significantly small rating active filters compared to stand-alone parallel or series active filter solutions [17].

Different structures of passive filters in a hybrid filter have different required ratings of the active part of the hybrid filter. The shunt active filter, with the shunt passive filter, and the series active filter with the shunt passive filter, shown in Figure 2.10 and Figure 2.11, respectively are common filters configuration.

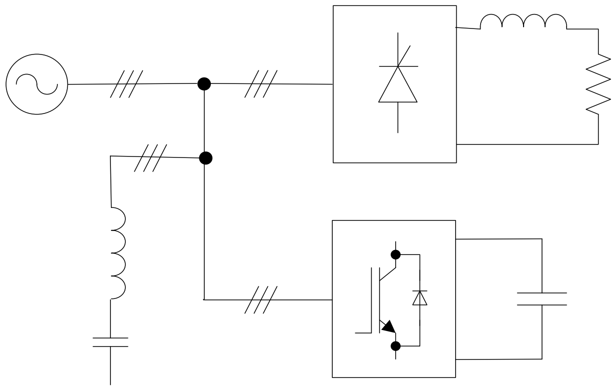


Figure 2.10: Hybrid shunt active filter with shunt passive filter.

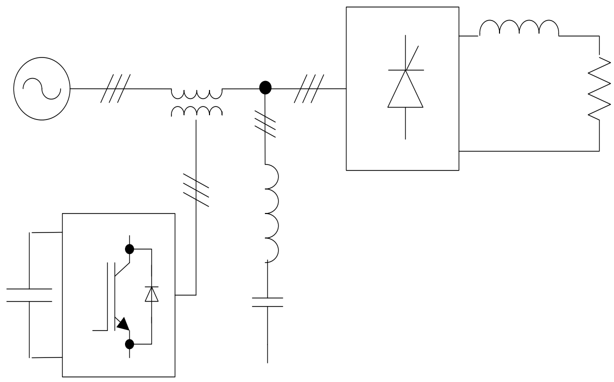


Figure 2.11: Hybrid series active filter with shunt passive filter

The major drawbacks of the active hybrid harmonic filtering technique involve high initial costs and running costs, and complexity. Moreover, the high fundamental component current passing through the series active filter is problematic.

e) PWM rectifiers

The power-factor correction (PFC) method is another technique of harmonics reduction. To change actively the waveform of the input current, simple rectifier diodes are replaced by controlled power switches. These switches can be insulated gate bipolar transistors (IGBTs), gate-turn-off thyristors (GTOs), or integrated gate controlled thyristors (IGCTs). These circuits are able to shape the current waveform reducing its harmonics contents and improving the power factor.

The three-phase (ac-dc) PWM rectifier, shown in Figure 2.12, has superior performance compared to the conventional diode or thyristor bridge rectifiers. It can draw the sinusoidal current at near unity power factor while maintaining a high quality dc output voltage with a small filter capacitor. However, designing a proper controller for it is generally a challenging task [18], [19].

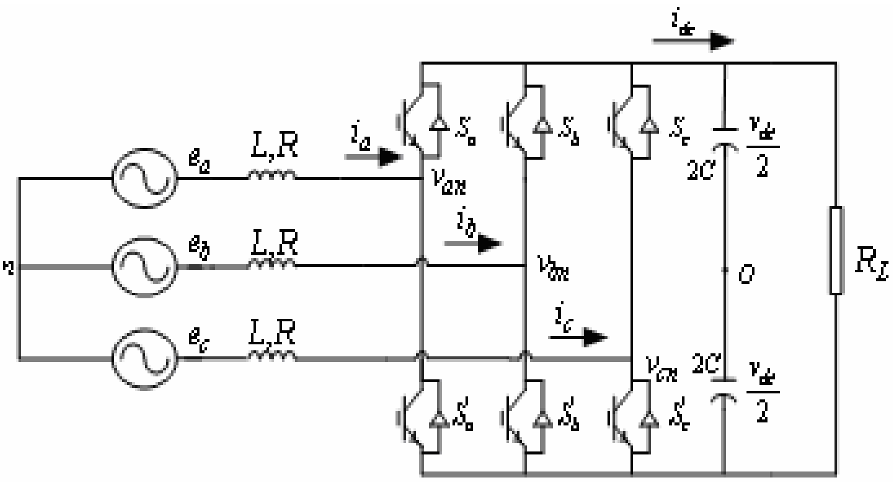


Figure 2.12: Structure of a three phase AC to DC PWM rectifier

In conclusion, most of the stated filtering methods have the common disadvantages of higher costs and complexity compared to passive filtering techniques. As the active harmonic filters remain costly and problematic, passive filtering solutions will continue in the market. Therefore, the passive harmonic filtering systems are still

widely used techniques to reduce the harmonic pollution of 6-pulse front-end diode/thyristor rectifier applications in the utility networks [3], [20], [21], [22].

As a result, high performance passive or hybrid filters must be developed to comply with increasingly strict power quality standards requirements of the present and future technology period. Thus, more focus in passive filter topologies is required to get better performance, smaller size, higher efficiency, reduced noise, and most importantly lower costs. Research in this area is a necessity and has to be developed for better power quality in power systems.

3 Common Passive Harmonic Filters

3.1 AC line reactor and DC link inductor

The most common filter to reduce the harmonic distortion in a 6-pulse diode rectifier front end application is an AC line reactor, DC link inductor filters or a combination of both of them connected to the system [23]. These reactor and inductor impedances control the shape of the line current waveform as they show higher impedance values at higher frequencies of the current harmonic components. The general equation of reactor impedance is given below and the related impedance characteristic is shown in Figure 3.1.

$$jX_L = j(2\pi \times f)L \tag{3.1}$$

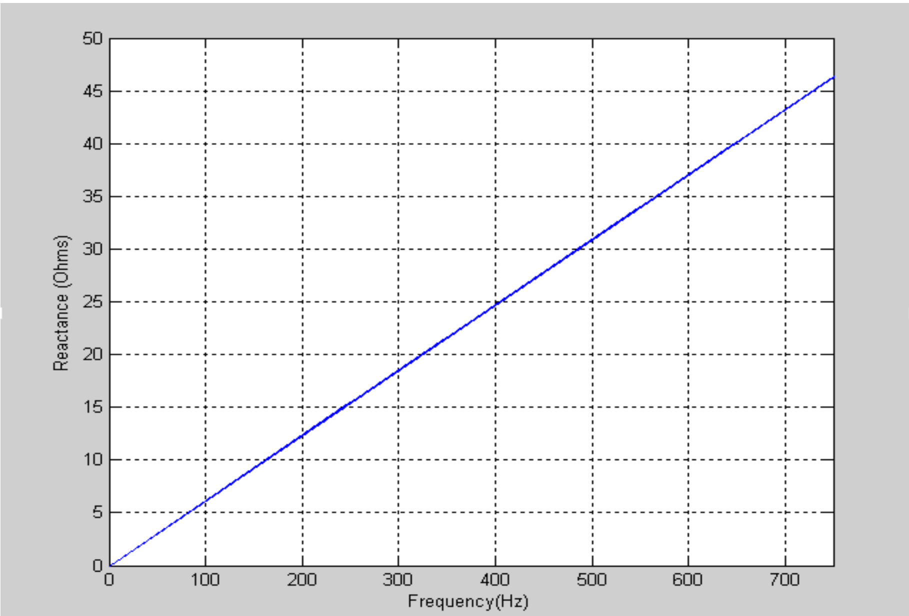


Figure 3.1: Line reactor impedance characteristics

Typically AC reactors and DC inductors are designed typically between 1% to 6% values [24]. The filter impedance is defined as a percentage of the system base impedance Z_b which is given by

$$Z_b = \frac{\mathrm{Vr}}{\mathrm{Ir}} \tag{3.2}$$

where V_r is the rated rms phase voltage and I_r is the rated rms phase current. The filter reactance can be estimated using the following equation

$$\mathrm{F}ilter\,\% = \frac{(2\pi \times f)\mathrm{L}}{\mathrm{Z_b}} \times 100 \tag{3.3}$$

where L is the AC or DC filter reactance in Henries and f is the system frequency in Hz.

The existence of a three phase AC line reactor in the system smoothes the current waveform and reduces its distortion current. Consequently, the DC capacitor current will have fewer ripples. This increases the lifetime of the DC link capacitors at the load side. However, the three phase AC line reactors increase commutation time between the outgoing and incoming diodes causing a voltage drop and the DC link output voltage is decreased. Based on the basic equations for the 6-pulse three-phase diode rectifier, the reduction of the DC link voltage is given by [25]:

$$\Delta \mathrm{V} = \frac{3}{\pi} * \omega L_s * I_d \tag{3.4}$$

Where Ls is the AC line inductance and I_d is the load current. Therefore, from this relation the effect of the AC line reactor in reducing the DC link voltage is directly proportional to the amount of the line reactance.

The general electric circuit structure for a 6-pulse diode rectifier load utilizing a 3-phase AC line reactor filter type connected to the main supply is shown in Figure 3.2. The design of this filter type is simple and at relatively low cost. However, even

though with a DC link inductance it is combined with the AC line reactors. The minimum line current THD value that can be achieved is still high (>30%). Meanwhile the total line power can be improved to maximum 0.90 lagging at full-load. These performances will not comply with the harmonic control standards.

The advantages of this basic filtering technique involve the reduction of line current THD compared to the basic converter topology, the low cost of the filter, and the reduction of unbalance effects and prevention of resonances [3].

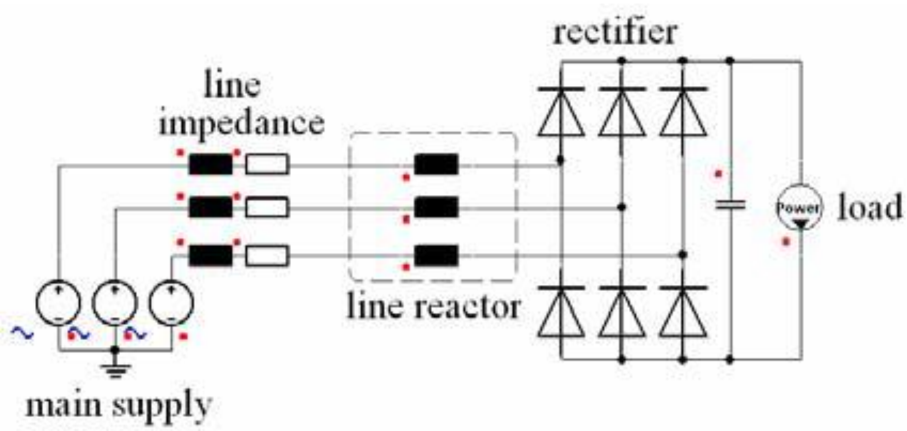


Figure 3.2: Line AC series connected reactor.

3.2 Tuned shunt passive filters

To increase the filtering effect, shunt tuned filters are frequently used and they may have various configurations. The single tuned filters, shown in Figure 3.3, combined with AC line reactors with or without the DC link inductor is the common structure. The single shunt filter is designed to show a very low impedance at the frequency to which it is tuned for, with the respect to the total line impedance existing in the system.

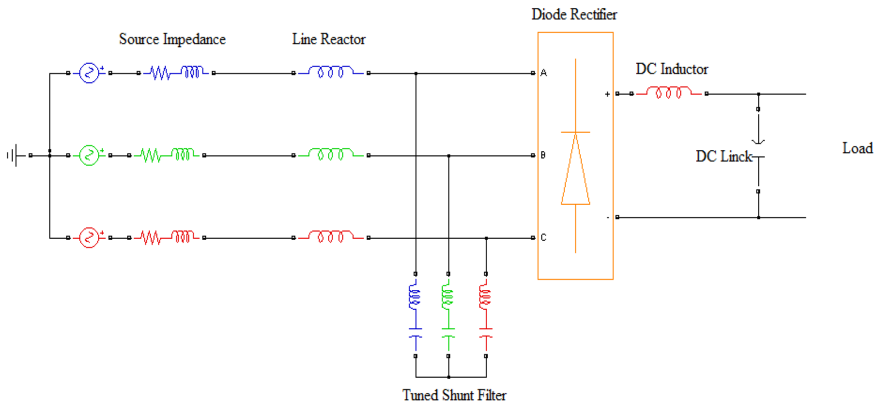


Figure 3.3: Single tuned shunt filter with a line series AC reactor and DC link inductor

In general, multiple shunt tuned LC filters are commonly designed for the most dominant existing harmonics and can provide an excellent filter effect. However, they may be sensitive to voltage unbalances to a certain degree and provide the possibility of resonances with the line impedance and produce capacitive reactive power at no load condition. The total filter cost may vary and depends on the quantity of shunt filters required for the dominant harmonics polluting the system [2], [21], and [22].

3.2.1 Tuned shunt passive filters operating principles

The single tuned shunt filters, shown in Figure 3.4, are probably the most common structure in use. The basic operating principle of this type of filter depends on the series resonance low impedance of the filter. A phenomenon occurs when a reactor is connected in series with a capacitor constructing the circuit. Both passive elements (C_F and L_F) will have equal reactance at specific resonance frequency and the total filter impedance will be very low at such frequency, as shown in Figure 3.5.

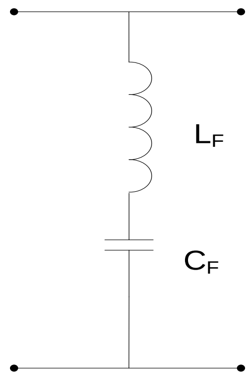


Figure 3.4: The common single shunt filter structure

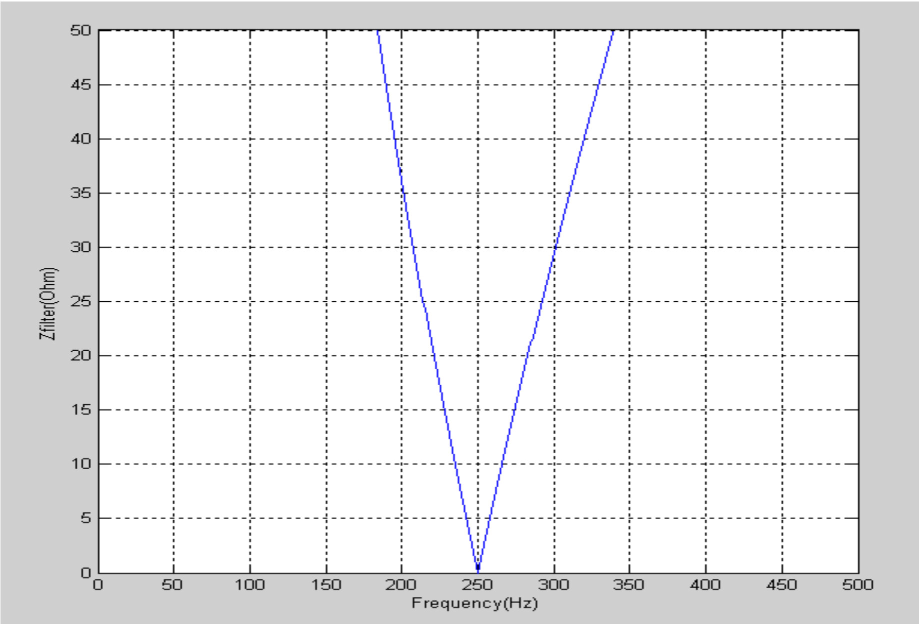


Figure 3.5: The common single shunt filter impedance characteristics

Therefore, the well-designed single shunt filter will show very low impedance at the frequency to which it is tuned with the respect to the line impedance. As a result the low impedance provided will divert the flow of the rectifier harmonic current through its path. For each current harmonic dominant component a single shunt filter will be designed. Harmonic mitigation is achieved provided that the line impedance magnitude is considerably higher than the shunt filter impedance at the harmonic frequency. This is called the filter impedance ratio with respect to the total line impedance in the system. The higher impedance ratio, the more effective filtering effect can be obtained with more harmonic absorption filter capability.

3.2.2 Tuned shunt passive filters design

The tuned passive filter conventional design method is used in this project [26]. Generally the amount of reactive power required for compensation is estimated. This will depend on the displacement power factor (DPF) value estimated at the rectifier side. The rectifier side DPF estimated value is given by the following equation for a diode rectifier case [27].

$$DPF \approx \cos(\frac{u}{2}) \tag{3.5}$$

where u is current commutation interval between the outgoing diode and the incoming diode due to the presence of AC line smoothing reactor. Therefore, the phase shift angle between the line current fundamental component and supply phase voltage is estimated to be half of the commutation interval (u/2). The current commutation interval (u) for a diode rectifier is given by the following equation

$$\cos(u) = 1 - \frac{2\omega \times L_s}{\sqrt{2} \times V_{LL}} \tag{3.6}$$

where L_s is the AC line reactance and V_{LL} is the line-to-line supply voltage. Therefore, for a given total AC line inductance utilized the commutation interval angle can be estimated and consequently the DPF can be calculated.

Knowing the DPF angle (Φ_{rect}) the reactive power compensation required by the tuned filter (Q_{filter}) can be estimated by the following equation

$$Q_{filter} = \tan(\phi_{rect} - \phi_{line}) \tag{3.7}$$

where Φ_{rect} is the rectifier side DPF angle estimated by equation (3.5) and Φ_{line} is the reduced line DPF new angle (nearly zero) by the filter capacitance reactive power supplied at the fundamental frequency to the system. Once the amount of

compensation is calculated the filter capacitor is sized for the amount of reactive power required for each capacitor in the tuned filters. The filter capacitor is estimated using the following equation

$$C_f = \frac{Q_{filter}}{(\omega \times V_{LL}^2)} \tag{3.8}$$

where Q_{filter} is the required compensation and V_{LL} the line-to-line supply voltage.

Practically, multiple single tuned filters are designed to suppress the dominant harmonic components generated by the converter. Therefore, the filters capacitors will share the total required compensation according to their filtering order. Consequently, the filter reactor for each tuned filter can be designed to form a total single filter with very low impedance at the harmonic frequency specified. At this resonance frequency the capacitor and the inductor will have almost the same impedance magnitude with different signs. This will result in a zero resultant impedance value for the filter at this series resonance frequency (f_s). This impedance is given by the following equation

$$Z(@\, f_s) = j \times [\omega L_f - \frac{1}{\omega C_f}] = zero \tag{3.9}$$

Where Z is the resonance impedance at the resonance series frequency (f_s), C_f is the filter capacitance and L_f is the filter reactance. The filter tuned series resonance frequency (f_s) is given by the following equation

$$f_s = \frac{1}{2\pi \times \sqrt{L_f C_f}} \tag{3.10}$$

where f_s is the series resonance frequency, C_f is the filter capacitance and L_f is the filter reactance. On the other hand each tuned filter will be connected in parallel to the line reactor (L_s) in the system and will have parallel resonance impedance at a specific parallel resonance frequency. The parallel resonance frequency (f_p) that

occurs between the single filter components and the total line reactor is given by the following equation

$$f_p = \frac{1}{2\pi \times \sqrt{(L_s + L_f) \times C_f}} \tag{3.11}$$

where f_p is the parallel resonance frequency, L_s is the total line reactance, C_f is the filter capacitance and L_f is the filter reactance. Consequently, very large impedance will be seen by the current harmonics components generated by the converter from the rectifier side due to this parallel resonance. As shown in Figure 3.6, both series and parallel resonance typical impedances are presented. The single tuned filter is showing very low impedance at series resonance frequency f_s (250Hz) and is also resonating with the parallel line impedance at parallel resonance frequency fp slightly less than fs (<250Hz).

Practically, a detuning factor is conventionally used to choose the filter resonance frequency (fs). This detuning factor defines the frequency shift in percentage (%) required when designing and tuning the filter. The detuning factor (D_f) is given by the following equation

$$D_f = \frac{f_h - f_s}{f_h} \tag{3.12}$$

where f_s is the single filter series resonance frequency and f_h is the harmonic frequency to be reduced.

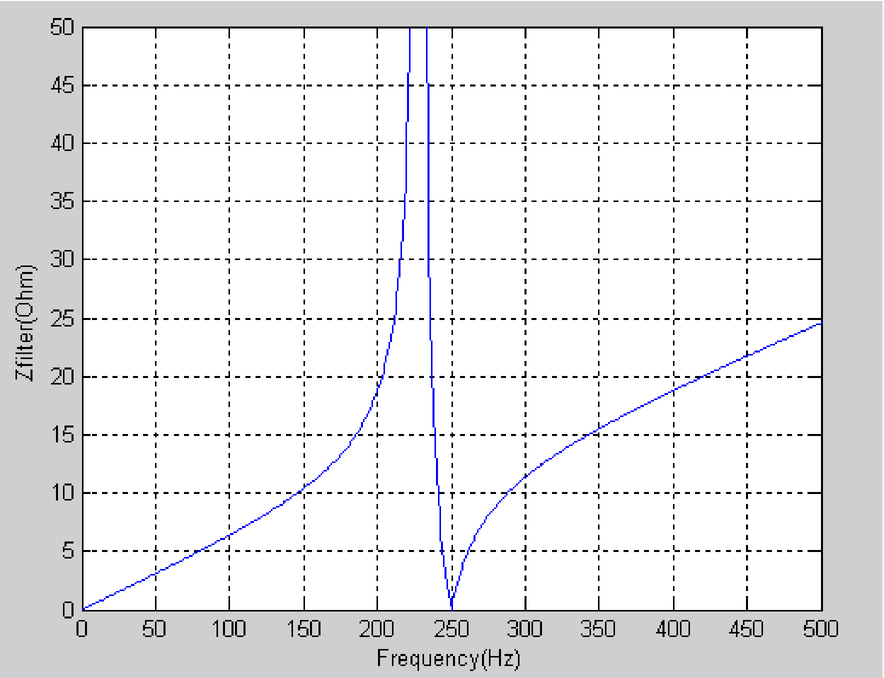


Figure 3.6: Shunt filter and line impedance characteristics

The detuning factor is usually implemented for the following practical reasons:

- Using the series resonance frequency fs for tuning the filter without any shift will attract the dominant harmonics of other nonlinear loads connected at the same PCC and result in an over current problem for the filter.
- Due to operating environment (temperature, humidity, etc.) and the fact that aging the filter components parameters may decrease (mainly the capacitance) and result in increasing the tuned frequency value above the target. This will decrease the filter's effectiveness in suppressing the harmonic it is designed for.
- Shifting the tuned frequency slightly lower than the harmonic frequency will compensate for the slight increase for the resonance frequency due to environmental and aging factors. This will keep the filter effectiveness within an acceptable range.
- To avoid the parallel resonance risk with the line impedance the high impedance and over voltage problems the parallel resonance (fp) should be shifted away from any dominant current harmonic that may coincide with the high impedance.

Therefore, typically a detuning factor is chosen between 3-10% when designing the single tuned shunt filters for the dominant current harmonic components in the system [28]. Consequently, the minimum impedance for the first two dominant harmonic components shunt filters (5^{th} and 7^{th}) will be at an actual frequency slightly less than the harmonic frequency (< 250Hz and <350Hz). This shift amount will be defined by the detuning factor percentage applied.

Another design parameter, which is usually considered, is the filter quality factor (Q). This factor defines the sharpness of the filter and is given by the following equation

$$Q = \frac{\sqrt{L_f / C_f}}{R} \tag{3.13}$$

Where L_f and C_f are the filter designed components and R is the damping resistance. The sharpness of the filter increases by increasing the Q factor. However, this implies increasing the losses in the filter due to the presence of this resistor. Therefore, practically this resistance is not added to the filter and only the internal resistance of the filter component will help in the damping action during transient conditions. This project is not concerned with the transient analysis of the system and is investigating the steady state performance of the 6-pulse diode rectifier front end applications utilizing the common passive filters mentioned above.

Practically, the tuned filters are designed for the most dominant harmonics existing in the system. For 6-pulse diode rectifier front end applications this involves the first four harmonic components (5^{th}, 7^{th}, 11^{th} and 13^{th}). However, designing a single shunt filter for each of the mentioned components will increase the cost of the filtering technique. In low and medium power levels applications (< 500 kW) usually the 5^{th} and 7^{th} harmonic filters are sufficient and other higher order filters are not considered due to the cost constraints. Conventionally, the first two dominant filters are combined with added line AC reactor and/or DC link inductor to increase the effectiveness of the filter.

3.2.3 Tuned shunt passive filters effectiveness

The tuned shunt filters effectiveness measures the ability of the designed filters to absorb the current harmonics generated by the convertor. In ideal conditions all the harmonic current will be diverted to the filter path and will not appear in the line side. On the other hand, the filters should not absorb the fundamental current component and allow all the fundamental current to pass through the line. The impedance ratio between the line impedance and the filters at the harmonic frequencies (250Hz and 350Hz) define this harmonic absorption ability. Meanwhile, the same impedance ratio at the fundamental frequency (50Hz) will avoid the shunt filters from attracting any fraction of the fundamental current component.

In order to increase this effectiveness an extra AC line reactor is usually employed in the system and connected at the supply side to increase the impedance ratio mentioned. On the other hand the effectiveness of the filters is directly affected by the detuning factor value considered in the design. Practically, the selection of this value depends on the amount of harmonic distortion existing at the PCC connecting the loads. For high distortion levels the risk of importing harmonics from other loads connected at the same PCC will be high. This will require a wider safety margin and higher detuning factors will be employed. Consequently, the filter’s effectiveness will decrease and extra line reactors will probably be needed to achieve acceptable system performances.

All these cases are considered in this project and full investigation of the system performance levels is analyzed. This involves the selection of added AC line reactors, DC link inductors and the detuning factors. Finally, adding another AC line reactor at the rectifier side performing the T-shape structure is also considered to increase the effectiveness of the filters especially for high detuning factors conditions. The added rectifier side AC reactor provides an extra smoothing effect on the rectifier current and reduces the stress on the shunt filters components. The line current THD and total power factor values are directly affected by all the previous factors.

Based on the presented design theory and mathematical formulas for a given set of 6-pulse rectifier system parameters, the various considered filtering methods parameters are calculated in MATLAB M-file based computer program that implement the obtained formulas [29]. The various filtering methods involved in the design are in the sequence of the DC link inductor, the AC reactors and the combination of both DC link inductors and AC reactors. Finally, the tuned filters are considered in the design using different detuning factors to get the filters parameters.

4. Computer Simulation and Performance Assessment of the 6-Pulse Rectifier System with Different Passive Filters

In this section, using the design results obtained using the constructed M-file computer code, the steady state performance characteristics will be assessed. Performance will be evaluated at various operating points from no-load to full-load. Operation under balanced and unbalanced utility supply voltage will be considered. Line current THD_I and power factor, DC link voltage will all be evaluated.

The investigation involves a low power and a medium power six-pulse diode rectifier system with 3 kW and 30 kW ratings respectively. This system will be used to define the simple filtering type’s performances (AC reactors, DC link inductors and a combination of both) and the tuned filtering method evaluations as well.

In the computer simulations using SIMULINK the rectifier is modeled with diodes and the utility supply is modeled with the source impedance. A DC link capacitor is selected based on recent studies and the minimum capacitance/kW requirement recommendations [30].   The inverter side of the system is modeled with an equivalent load resistor which is common approximation for ASD systems [31].
The utility supply of 400V line-to-line voltage and 50Hz frequency is considered. The supply source impedance parameters are shown in Table 4.1, for the 3kW and 30kW power ratings considered. These parameters are implemented in the simulation circuit, shown in Figure. 4.1, to evaluate the 6-pulse rectifier system basic performance.

Table 4.1 Six-pulse rectifier diode system parameters for 3kW and 30kW power ratings

Power rating	Source impedance (ohm)	DC Link capacitor (μF)	Load resistance (ohm)
3kW	0.04 + j0.033	300	102.8
30kW	0.004 + j0.0033	30	10.28

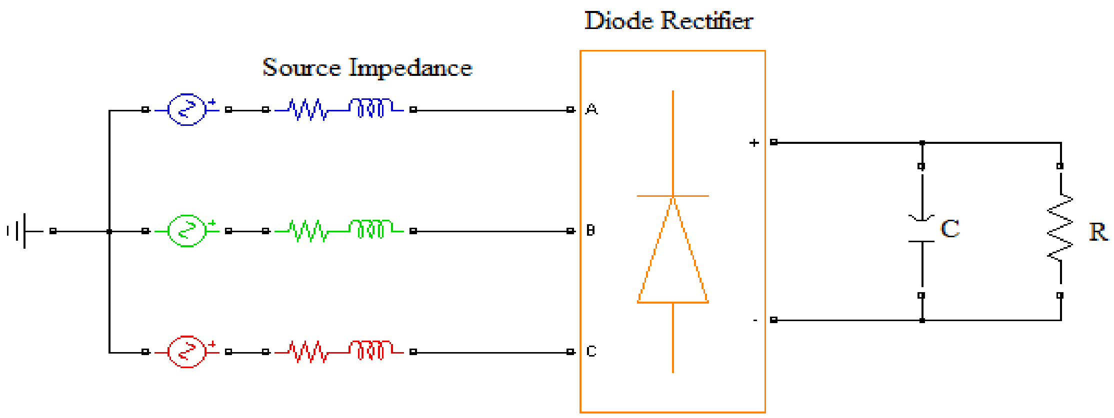


Figure 4.1. Simulation circuit of 6-pulse diode rectifier using no filters

For the 3kW and 30kW rated systems, only the basic simulation waveforms for the 3kW will be presented in this section due to limited space and the large similarity of results. The 30kW case simulation waveforms will be added in the Appendix A1. This will apply for all considered designs in the following sections.

The full-load line current simulation waveform and the corresponding harmonic spectrum for the 3kW 6-pulse rectifier system are shown in Figure 4.2 and Figure 4.3, respectively. The full-load line current and supply voltage simulation waveforms for the 3kW 6-pulse rectifier system are shown in Figure 4.4. The full-load line current has a 166.5% THD_I value with high harmonic components and the line power factor is 0.51 lagging.

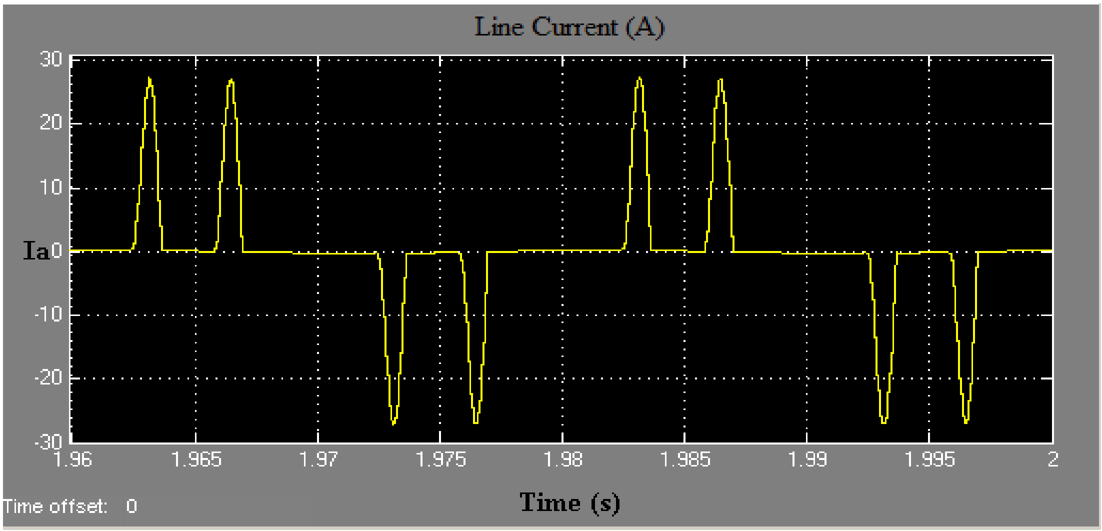


Figure 4.2: Line current simulation waveform for 6-pulse diode rectifier using no harmonic filtering

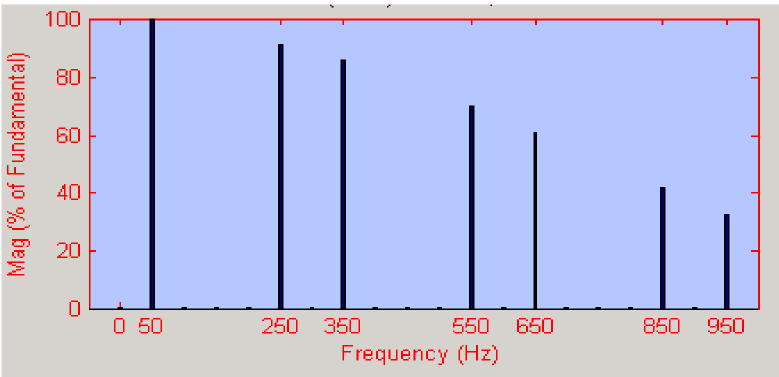


Figure 4.3: Line current harmonic spectrum for 6-pulse diode rectifier using no harmonic filtering

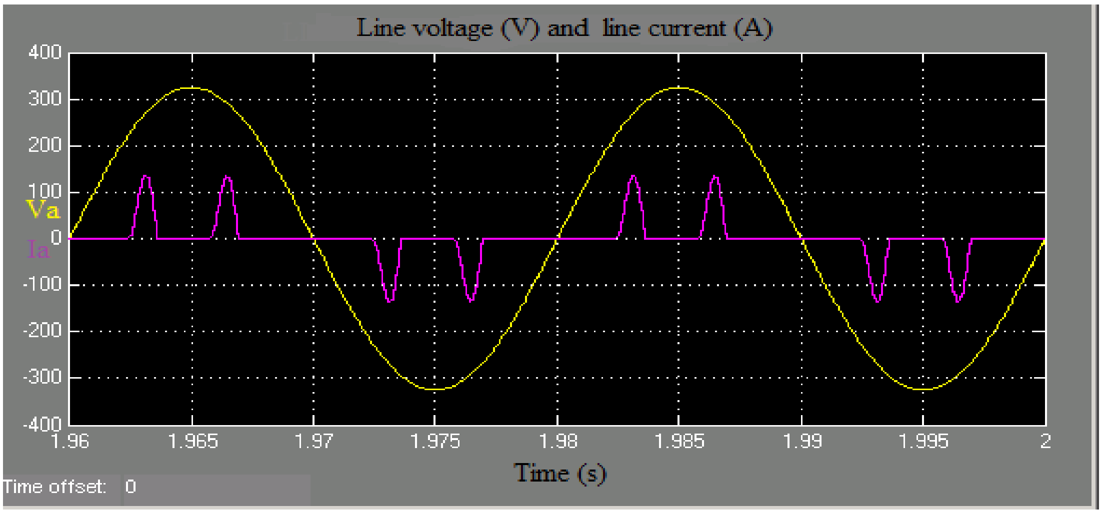


Figure 4.4: Line current and supply voltage simulation waveforms for 6-pulse diode rectifier using no harmonic filtering

Table 4.2 shows the full-load performance results for the selected power ratings of the 6-pulse rectifier system without using any filtering method. The table includes the line current THD, the line power factor and the DC link output voltage values. From the presented simulation waveforms and results a basic 6-pulse rectifier operation commonly used in ASD has very low power quality indices. Therefore, filtering techniques are always introduced for such applications to be able to improve the performance and comply with modern harmonic standards.

Table 4.2: Full-load six-pulse diode rectifier performance witout filtering

Power rating	THD (%)	PF	VDC
3kW	166.5	0.5115	555.2
30kW	168.1	0.5093	554.5

4.1 Six-pulse rectifier system simulations with DC link inductor

The DC link inductor designed using the Matlab code for the 3kW and 30kW rated systems. Table 4.3 shows the DC link inductor conventional range of (1% - 6%) parameters for 3kW and 30kW power ratings. These parameters are implemented in the simulation circuit shown in Figure 4.5 to evaluate the 6-pulse rectifier system basic performance.

Table 4.3: DC link inductor filter parameters for 3kW and 30kW power ratings

P_R (kw)		3	30
DC link inductor percentage	Ldc (1%)	1.62 mH	0.162 mH
	Ldc (2%)	3.24 mH	0.324 mH
	Ldc (3%)	4.85 mH	0.485 mH
	Ldc (4%)	6.47 mH	0.647 mH
	Ldc (5%)	8.09 mH	0.809 mH
	Ldc (6%)	9.71 mH	0.971 mH

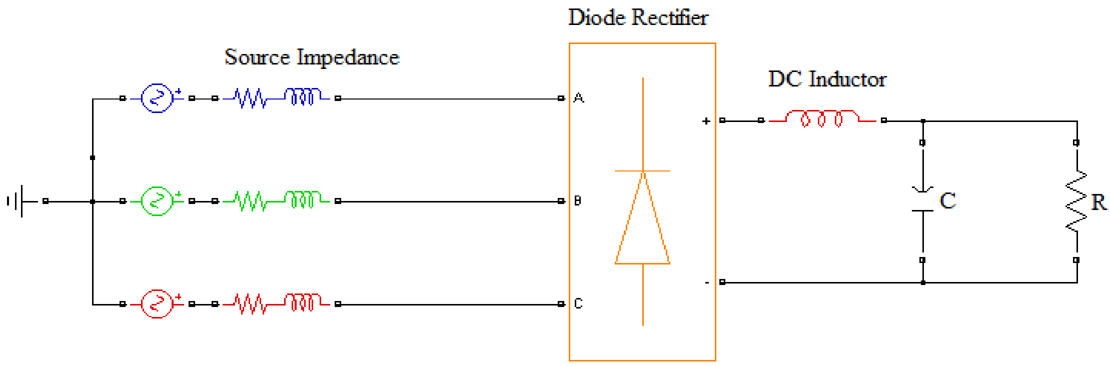
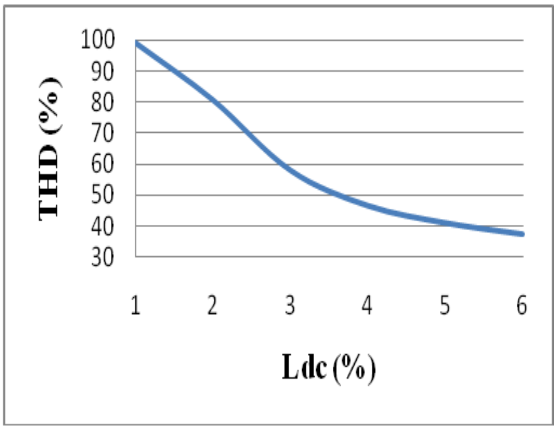


Figure 4.5: Six-pulse diode rectifier system using DC line inductor filter (L_{dc})

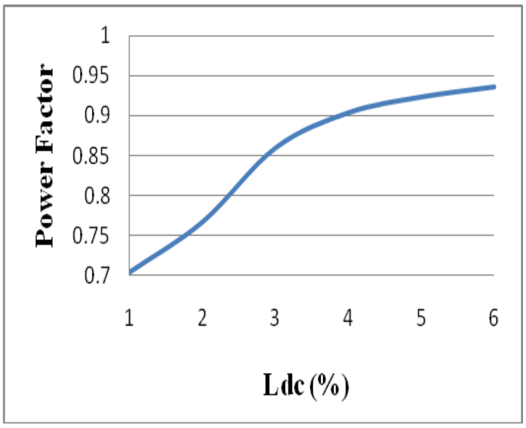
The corresponding system performance (line current THD, line PF and DC voltage) simulation based results for the considered range of DC link iductors are shown in Table 4.4. The considered power quality indices relation with the range of DC link inductors designed, are shown in Figures 4.6. The line THD% values are quite high using the low DC link inductor (99%) and can be reduced to 37% value for 6% of the DC link inductor. Similarly, line power factor values starting points are very low (0.7 lagging) and improves as the DC link inductor utilized increases to achieve (0.94 lagging). Meanwhile, the DC link output voltage is not sensitive for the variation of the filter used and is fixed. Therefore, the overall system performance using the DC link inductors only is not satisfactory. The main advantge for utilizing the DC link inductors is that they do not cause a large voltage drop for the output DC voltage values. However, the considered range of the DC link inductors will not reduce the line current THD to levels that can comply with harmonic standards (IEEE519).

Table 4.4: System performance using different DC line inductor percentage at 3kW

Filter Type		**THD (%)**	**PF**	**Vdc**
DC line inductor	**Ldc (1%)**	**99.32**	**0.7044**	**546.0**
	Ldc (2%)	**80.84**	**0.7673**	**536.6**
	Ldc (3%)	**58.04**	**0.8603**	**534.6**
	Ldc (4%)	**46.57**	**0.9046**	**534.6**
	Ldc (5%)	**40.98**	**0.925**	**534.6**
	Ldc (6%)	**37.32**	**0.9367**	**534.2**



(a)



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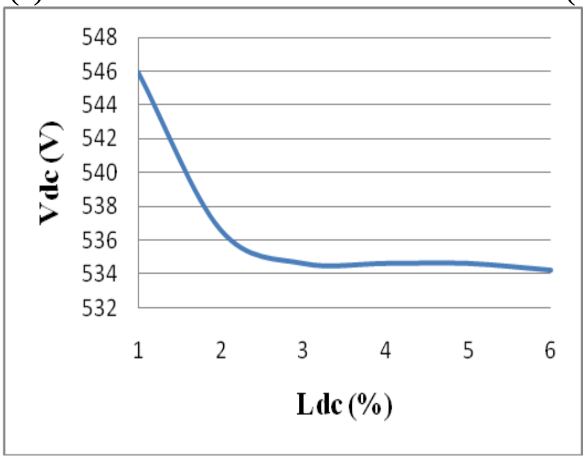


(c)

Figure 4.6: System performance: (a) Line current THD%, (b) Line PF, (c) DC voltage for 3kW 6-pulse rectifier using various DC link inductor values

4.2 Six-pulse rectifier system simulations with AC line reactor

The second filter considered in the design is the AC line reactor to smooth the line current and reduce its distortion. The AC reactor (Lac) is designed in a range of 3% to 6% for the 3kW and 30kW 6-pulse rectifier system. Table 4.5 shows the considered AC reactor filter range parameters for both power ratings considered. These parameters are implemented in the simulation circuit shown in Figure 4.7 to evaluate the 6-pulse rectifier system basic performance.

Table 4.5: AC reactor filter parameters for 3kW and 30kW power ratings

P (kW)		3	30
	Lac (3%)	**4.85 mH**	**0.485 mH**
	Lac (4%)	**6.47 mH**	**0.647 mH**
	Lac (5%)	**8.09 mH**	**0.809 mH**
	Lac (6%)	**9.71 mH**	**0.971 mH**

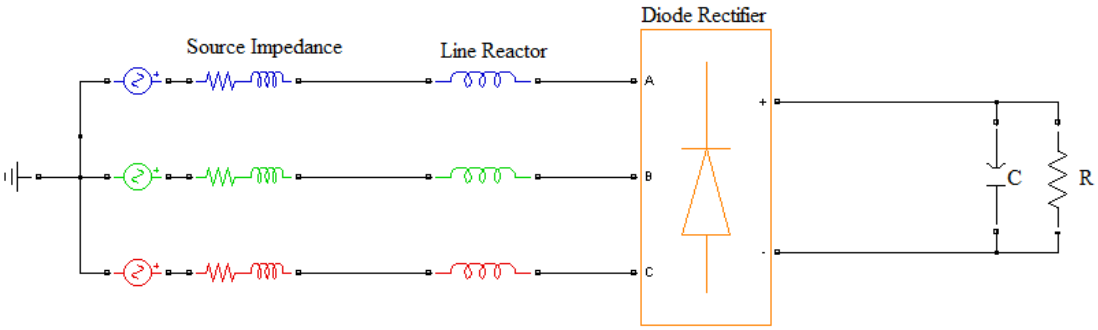


Figure 4.7: Six-pulse diode rectifier system using AC line reactor filter (Lac)

Table 4.6 shows the line current THD, line PF and DC voltage for the considered range of AC reactor based on simulation results. Figures 4.8 shows the assigned power quality indices values and their relation with the range of the AC reactor designed.

The line THD% values have improved combared with the DC link inductor filtering method. The line current THD for 3% Lac is 43% and can be improved to 32% value for 6% AC line reactor (Lac). Meanwhile, the line power factor maximum value which can be achieved is 0.94 lagging.

The DC link output voltage has a considerable reduction as the Lac% filter used increases. This is a major drawback of using the AC reactor connected in series with the supply system. The overall system performance, therefore, using the AC reactors alone may not be preferable. The main advantage for utilizing the AC reactors is that they smooth the line current and can reduce the line current THD values to a range of > 32%. Nevertheless, the achieved line current THD levels can not comply with harmonic standards when applied.

Table 4.6: System performance using different AC line reactor percentage for 3kW

Filter Type		THD (%)	PF	Vdc
	Lac (3%)	43.44	0.9011	525.7
	Lac (4%)	37.82	0.9167	522.5
	Lac (5%)	34.42	0.9328	519.4
	Lac (6%)	32.03	0.9387	516.4

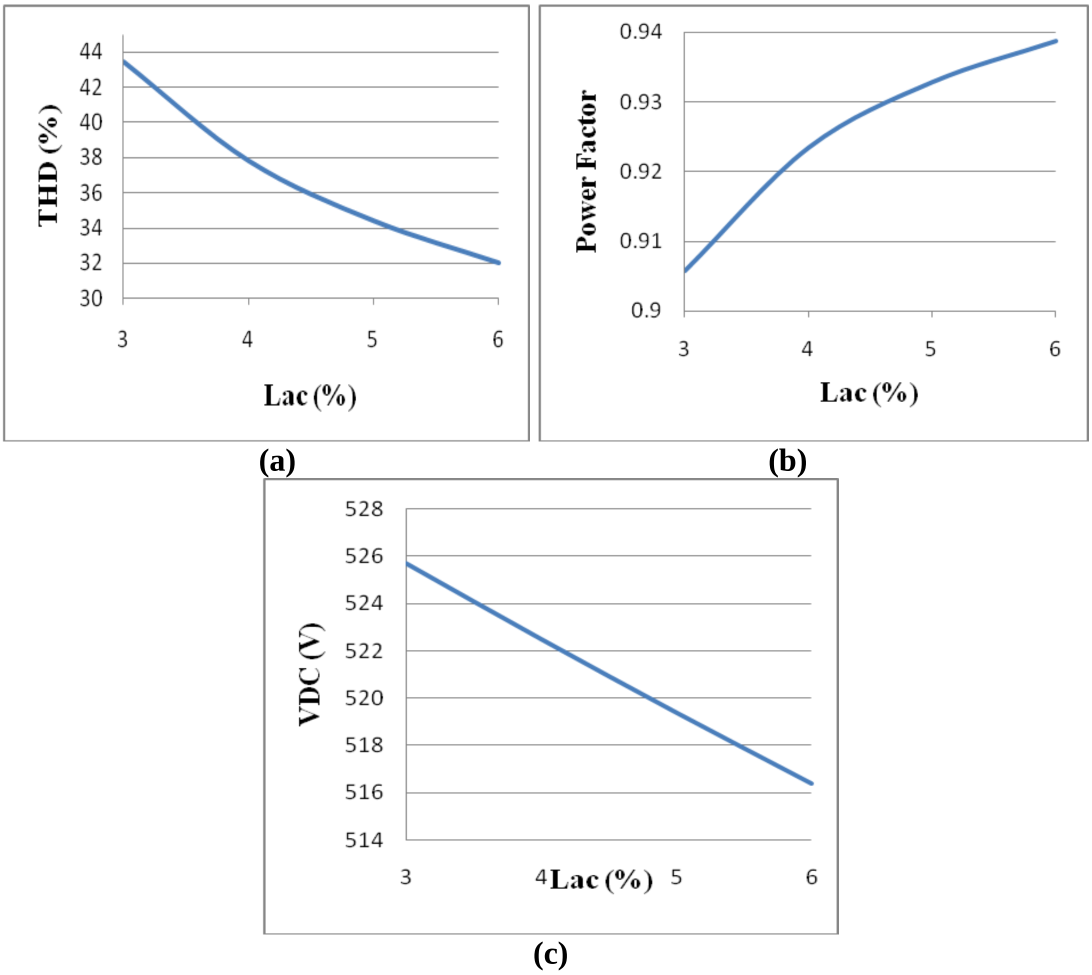


Figure 4.8: System performance: (a) Line current THD%, (b) Line PF, (c) DC voltage for 3kW 6-pulse rectifier using various AC reactor values

4.3 6-pulse rectifier system simulations with combined DC link inductor and AC line reactor

The AC line reactors and DC link inductors are usually combined together and used for the 6-pulse rectifier system. This is considered as a simple and effective solution to a certain limit that can be applied when power quality constraints are more flexible. Using this filtering combination can improve the overall system performance compared with the use of only one filtering technique (DC link inductor or AC line reactor). However, choosing the best combination of both filters is not a straightforward task and a full investigation of the possible filter values needs to be examined. Therefore, all feasible AC line reactors and DC link inductors combination values are considered in the design for 3kW and 30kW power ratings. This is based on the previous sections range of filters already evaluated and the corresponding filter parameters shown in Table 4.3 (DC link inductor) and Table 4.5

(AC reactor). These parameters are implemented in the simulation circuit shown in Figure 4.9 to evaluate the 6-pulse rectifier system basic performance.

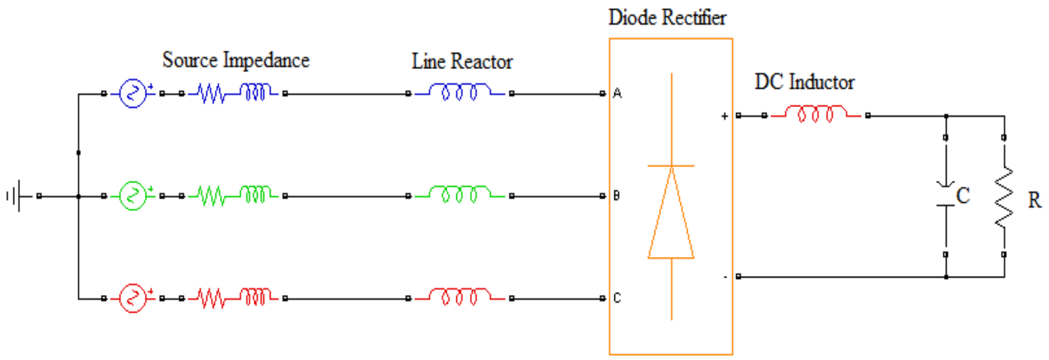


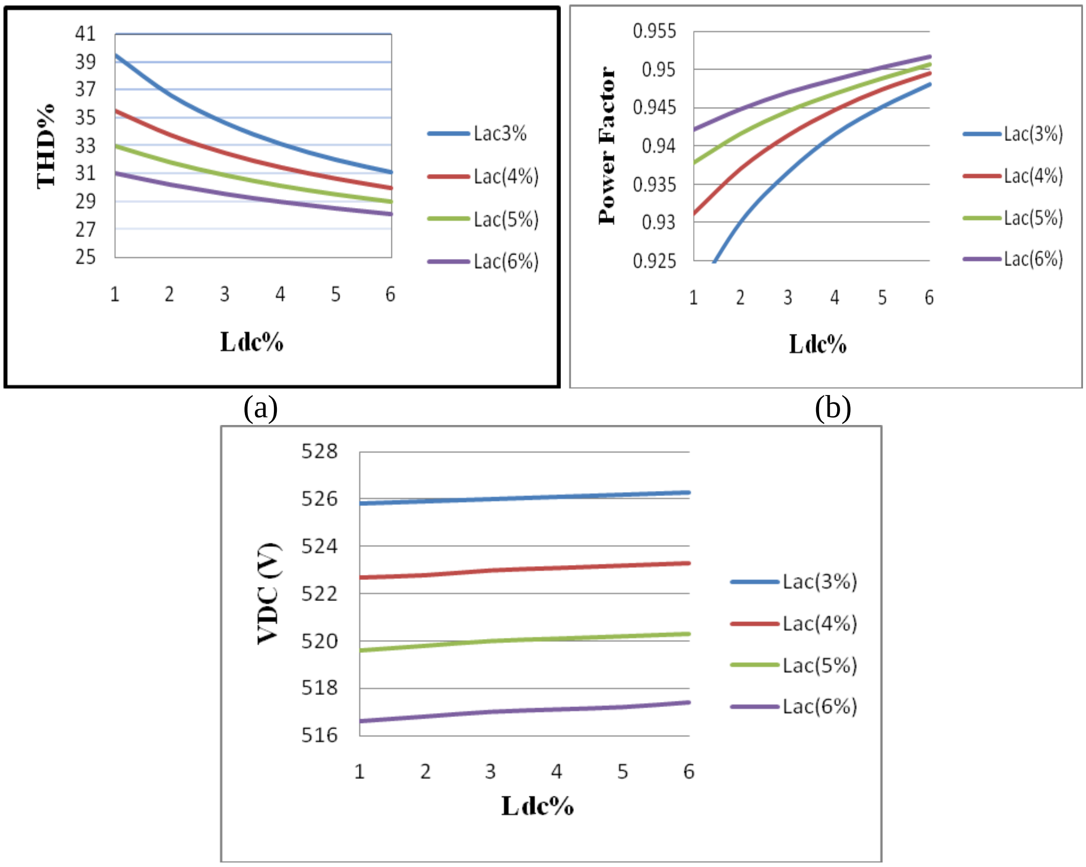
Figure 4.9: Six-pulse diode rectifier system using **AC** line reactor filter (Lac) and DC line inductor (Ldc) filter

Table 4.7 shows the full-load 6-pulse diode rectifier system performance including the line current THD, line PF and the DC output voltage for all possible AC line reactor and DC link inductor filters utilized. Figure 4.10 shows the mentioned system's performance indices relation with the varying Lac% and Ldc% values. The full-load minimum line THD and maximum line power factor that can be achieved is 28% and 0.952 lagging for a 6% Lac and 6% Ldc filters combination. However, the filters used for this case are the largest in size and highest in cost compared to the other combinations. Therefore, a reduction in size and cost of this large combination that may achieve acceptable performance may be required. This may be applied mainly to the DC link inductor value.

As shown in Figure 4.10, the 6% Lac curve for the line THD% and line power factor has the best values and a practical selection of the Ldc% to be combined is required. The line current THD values for this curve improved rapidly (from 31% to 29%) in the first half of the diagram until it reached something like a saturation region and minimum reduction is achieved. Similarly, the line power factor diagram shows a good improvement in the power factor values from 0.942 to 0.947 for combinations including up to 3% Ldc, while this improvement is not significant for the higher Ldc% values. Consequently, the 3% Ldc filter is lower in size and is able to maintain almost the same power quality level in the system when combined with the 6% Lac reactor.

Table 4.7: System performance using combination of AC reactor and DC link inductor filter for 3kW power rating at full-load

Filter Type			THD (%)	PF	Vdc
	Lac (3%)	L_{dc} (1%)	39.43	0.92026	525.8
		L_{dc} (2%)	36.59	0.93009	525.9
		L_{dc} (3%)	34.59	0.9366	526
		L_{dc} (4%)	33.10	0.9416	526.1
		L_{dc} (5%)	31.97	0.9452	526.2
		L_{dc} (6%)	31.08	0.94812	526.3
	Lac (4%)	L_{dc} (1%)	35.52	0.9312	522.7
		L_{dc} (2%)	33.79	0.93707	522.8
		L_{dc} (3%)	32.48	0.9414	523
		L_{dc} (4%)	31.46	0.94474	523.1
		L_{dc} (5%)	30.65	0.9474	523.2
		L_{dc} (6%)	29.97	0.94947	523.3
	Lac (5%)	L_{dc} (1%)	32.93	0.93784	519.6
		L_{dc} (2%)	31.77	0.94166	519.8
		L_{dc} (3%)	30.85	0.9446	520
		L_{dc} (4%)	30.10	0.9469	520.1
		L_{dc} (5%)	29.49	0.9489	520.2
		L_{dc} (6%)	28.97	0.9507	520.3
	Lac (6%)	L_{dc} (1%)	31.01	0.9421	516.6
		L_{dc} (2%)	30.19	0.9448	516.8
		L_{dc} (3%)	<u>29.51</u>	<u>0.9470</u>	<u>517</u>
		L_{dc} (4%)	28.95	0.9487	517.1
		L_{dc} (5%)	28.47	0.9503	517.2
		L_{dc} (6%)	28.06	0.9517	517.4



(c)

Figure 4.10: System performance: (a) Line current THD%, (b) Line PF, (c) DC voltage for 3kW 6-pulse rectifier using various combined AC reactor and DC link inductor values

The full-load line current simulation waveform of the 3kW 6-pulse rectifier system using 6% Lac and 3% Ldc selected combination is shown in Figure 4.11. The full-load line current and supply voltage simulation waveforms for the 3kW 6-pulse rectifier system using the same filters combination is shown in Figure 4.12. The full-load line current has a 29.5% THD and the line power factor is 0.95 lagging. Therefore, the filters combination can improve the power quality of the 6-pulse rectifier system to a higher level than any common individual AC reactor or DC link inductor used. On the other hand, this level of line THD value at full-load operating conditions may not be acceptable according to the recent harmonic standards and it is very common to add shunt tuned filters to the system.

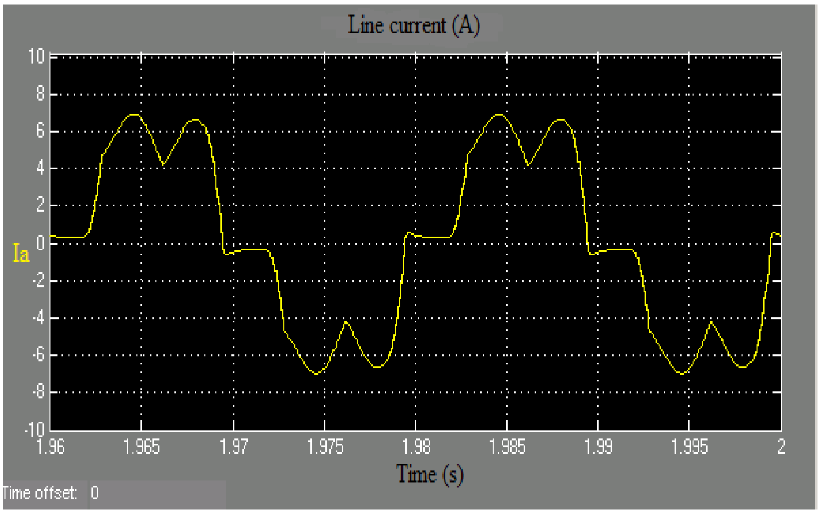


Figure 4.11: Full-load line current simulation waveforms for 3kW 6-pulse diode rectifier system using 6% Lac and 3% Ldc

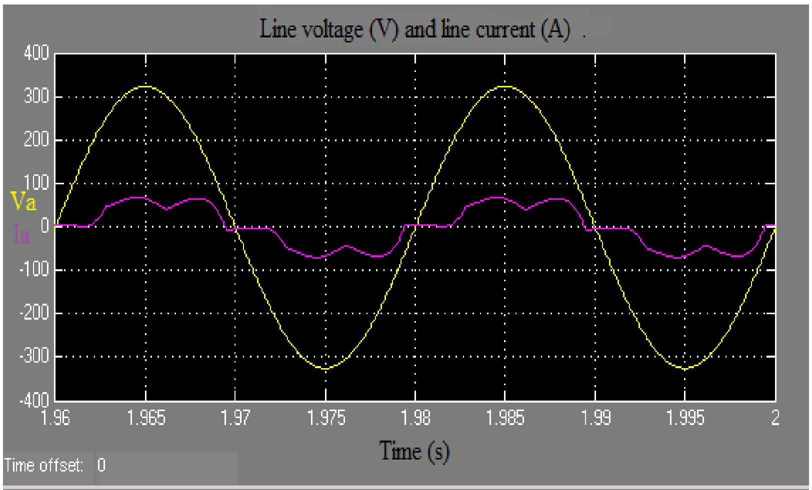


Figure 4.12: Full-load line current and supply voltage simulation waveforms for 3kW 6-pulse diode rectifier system using 6% Lac and 3% Ldc

4.4 Six-pulse rectifier system simulations with Tuned filter combined DC link inductor and AC line reactor

The first two dominant harmonics that polute the line current in the 6-pulse rectifier system is the 5^{th} and 7^{th} components. The two single filters are designed using the Matlab code for the 3kW and 30kW rated systems with 3% detuning factor. This is the minimum conventional detuning factor which can be considered while designing the tuned filters provided that the PCC is not heavily connected with other nonlinear loads.

Table 4.8 shows the 3% Df tuned filters, the 6%Lac reactor and the 3%Ldc inductor parameters for 3kW and 30kW power ratings. These parameters are implemented in the simulation circuit shown in Figure 4.13 to evaluate the 6-pulse rectifier system basic performance.

Table 4.8: Tuned filters (5^{th} & 7^{th}), Lac and Ldc filter parameters for 3kW and 30kW power ratings with 3% detuning factor

P_R (kw)		3	30
5^{th} & 7^{th} tuned filters	Lac (6%)	9.71 mH	0.971 mH
	Ldc (3%)	4.85 mH	0.485 mH
	L_{f5} (mH)	0.0544	0.0054
	C_{f5}(μF)	7.9157	7.9157
	L_{f7} (mH)	0.0833	0.0083
	C_{f7}(μF)	2.6386	2.6386

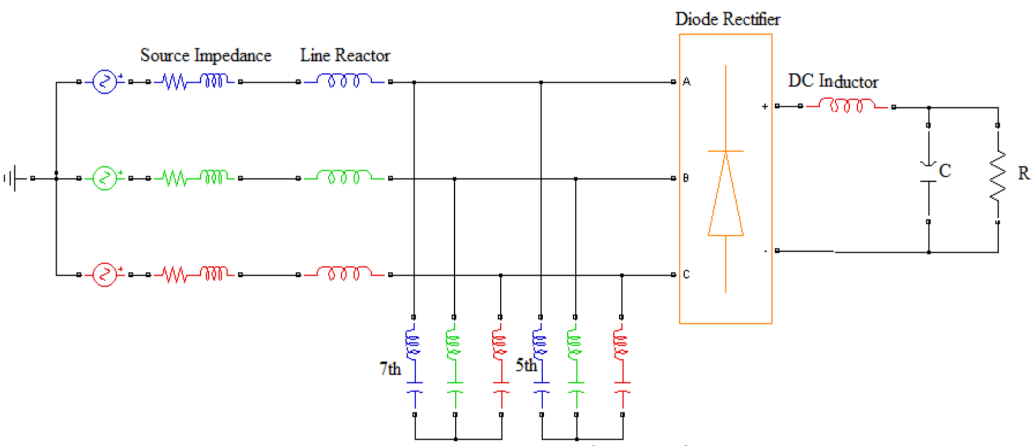


Figure 4.13: Six-pulse diode rectifier using 5^{th} and 7^{th} tuned filters combined with AC and DC line reactors.

a) Simulation results of the 3kW power rated rectifier system

The system performance under balance and 3% unbalance supply voltage simulation results for the considered filtering method are shown in Table 4.9. The unbalance definition applied in the study is the National Electrical Manufacturers Association of USA (NEMA) standard voltage [32]. According to this definition, 3% voltage unbalance is equivalent to 6% voltage value reduction in phase “1”.

The filtering technique using the 5^{th} and 7^{th} shunt (3% Df) tuned filters with the selected 6%Lac and 3% Ldc combination can achieve a low line current THD value of 12.2% and nearly unity line power factor at full-load. However, this rectifier

system is sensitive to the unbalance voltage supply and the line current THD values increases considerably (17.5%) in the 3rd phase. Similarly, the DC output voltage reduced to 515V under the unbalanced case while the line power factor kept the same.

Table 4.9: System performance using the 5th & 7th shunt (3% Df) tuned filters under balanced and 3% unbalance line voltage at 3kW

Filter Type	THD (%)				PF		VDC	
	Balance	Unbalance at phases			Balance	Unbalance	Balance	Unbalance
		1	2	3				
Lac (6%) And Ldc (3%)	12.23	14.23	13.49	17.51	0.99	0.99	530.2	515.1

The full-load line current simulation waveform of the 3kW 6-pulse rectifier system using the 5th & 7th shunt (3% Df) with 6% Lac and 3% Ldc selected combination is shown in Figure 4.14. The full-load line current and supply voltage simulation waveforms for the 3kW 6-pulse rectifier system using the same filters combination is shown in Figure 4.15. The full-load line current has a 12% THD and the line power factor is unity.

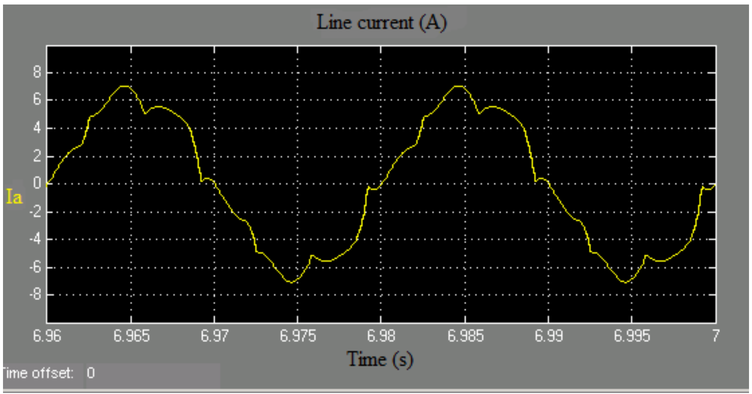


Figure 4.14: Full-load line current simulation waveforms for 3kW 6-pulse diode rectifier system using 5th and 7th (3% D_f) tuned filters with 6% Lac and 3% Ldc

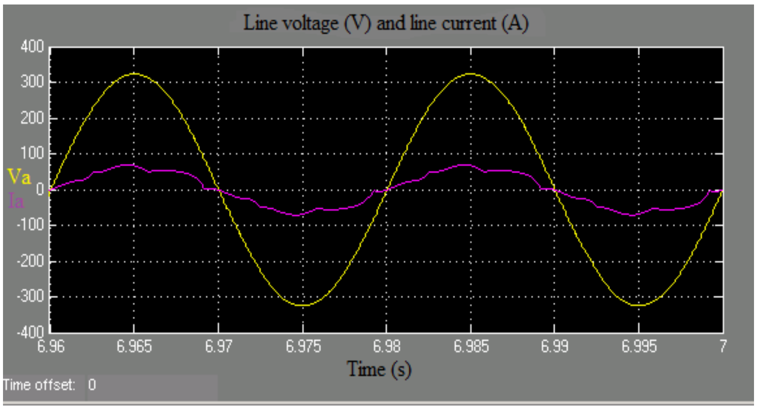


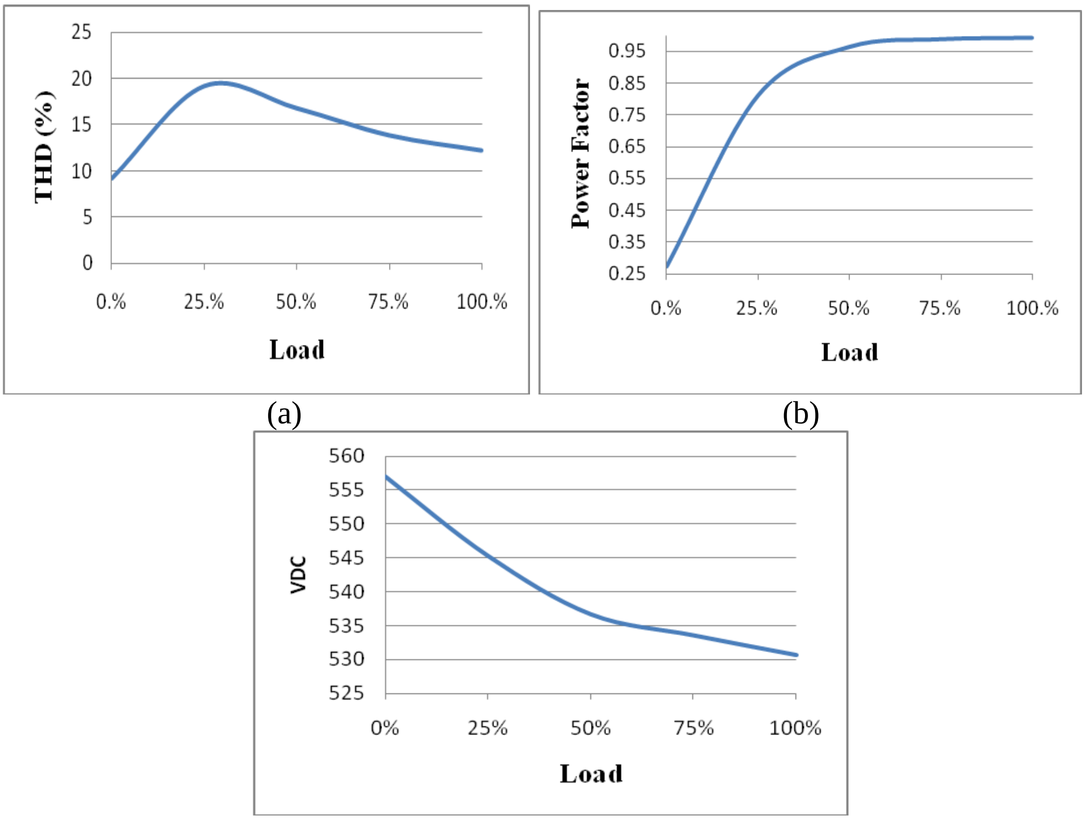
Figure 4.15: Full-load line current and supply voltage simulation waveforms for 3kW 6-pulse diode rectifier system using 5th and 7th (3% Df) tuned filters with 6% Lac and 3% Ldc

The system perfomance load dependency is also investigated using the same simulation method. Table 4.10 shows the main power quality indices considered from no-load to full-load operating conditions. The line current THD, line PF and the DC output voltage power quality indices considered has a load dependency diagrams shown in Figure 4.16. The line current THD for the proposed system has almost the same value from half-load to full-load range while at 25% loading condition the THD value increases to 20% before it goes down again at light load conditions. The line power factor has high values (> 0.95) from half-load to full-load range and decreases at light loading conditions also. On the contrary, the DC output voltage has high values at light load conditions due to the filters boosting capacity and lower values as the loading increases.

In conclusion, the 6-pulse diode rectifier system performance using the 5th & 7th shunt (3% Df) tuned filters with 6% Lac and 3% Ldc% has overall good power quality indices. There is no major effect on the performance for >50% loading conditions, while at light load the effect may be considerable. Moreover, the proposed system and filetring technique senstivity for the unbalance votage supply system is measurable for the line currrent THD and DC output voltage values. On the other hand the line power factor value is kept stable. Therefore, this filtering method is a common way of mitigating current harmonics for 6-pulse diode rectifier front end applications.

Table 4.10: Load dependency system performance using the 5th & 7th shunt (3% Df) tuned filters with 6% Lac and 3% Ldc at 3kW

Load%	THD (%)	PF	VDC
100	12.23	0.9927	530.7
75	13.87	0.9884	533.6
50	16.81	0.9643	536.7
25	19.2	0.8113	545.3
0	9.189	0.2741	557.0



(c)

Figure 4.16: System performance: (a) Line current THD%, (b) Line PF, (c) DC voltage for 3kW 6-pulse rectifier using 5th and 7th (3% Df) tuned filters with 6% Lac and 3% Ldc

The minimum conventional detuning factor (3% Df) considered in the previous section while designing the tuned filters may not be practically acceptable for different conditions. If the PCC is heavily connected with other nonlinear loads the risk of importing current harmonics by the 5th and 7th shunt filters is high. Therefore, the detuning value may be increased to maximum value of 10% at the extreme cases. This requires a full study of the distribution network loading condition before designing the filters [22]. This will negatively affect the filtering effectiveness of the 5th and 7th shunt filters and result in higher line current THD values. However, it

will reduce the risk of stressing the filter components by attracting other current harmonics from the PCC connected to the 6-pulse diode rectifier system.

For the assumed network operating conditions the two single filters are designed using the Matlab code for the 3kW and 30kW rated systems with 10% detuning factor. Table 4.11 shows the 10% Df tuned filters, the 6%Lac reactor and the 3%Ldc inductor parameters for 3kW and 30kW power ratings. These parameters are implemented in the same simulation circuit shown in Figure 4.12 to evaluate the 6-pulse rectifier system basic performance.

Table 4.11: Tuned filters (5^{th} & 7^{th}), Lac and Ldc filter parameters for 3kW and 30kW power ratings with 10% detuning factor

P_R (kw)		3	30
5^{th} & 7^{th} tuned filters	Lac (6%)	9.71 mH	0.971 mH
	Ldc (3%)	4.85 mH	0.485 mH
	L_{f5} (mH)	0.0632	0.0063
	C_{f5}(μF)	7.9157	7.9157
	L_{f7} (mH)	0.0967	0.0097
	C_{f7}(μF)	2.6386	2.6386

The system performance under balance and 3% unbalanced supply voltage simulation results for the considered filtering method are shown in Table 4.12. The filtering technique using the 5^{th} and 7^{th} shunt (10% Df) tuned filters with the selected 6%Lac and 3% Ldc combination has higher line current THD value of 21% and less line power factor value of 0.97 lagging at full-load compared to the 3% Df case study. This is highly expected, as the shunt filters minimum impedance points are shifted away from the harmonic frequency. Furthermore, this designed rectifier system is sensitive to the unbalance voltage supply and the line current THD values increases considerably (25%) in the 3^{rd} phase. Similarly, the DC output voltage reduced to 510V under the unbalanced case while the Line power factor is kept the same.

Table 4.12: System performance using the 5th & 7th shunt (10% Df) tuned filters under balanced and 3% unbalance line voltage at 3kW

Filter Type	THD (%)				PF		VDC	
	Balance	Unbalance at phases			Balance	Unbalance	Balance	Unbalance
		1	2	3				
Lac (6%) And Ldc (3%)	20.73	22.87	18.93	24.69	0.97	0.97	527.3	510.6

The full-load line current simulation waveform of the 3kW 6-pulse rectifier system using the 5th & 7th shunt (10% Df) with 6% Lac and 3% Ldc selected combination is shown in Figure 4.17. The full-load line current and supply voltage simulation waveforms for the 3kW 6-pulse rectifier system using the same filters combination is shown in Figure 4.18. The full-load line current has a 21% THD and the line power factor is 0.97 lagging.

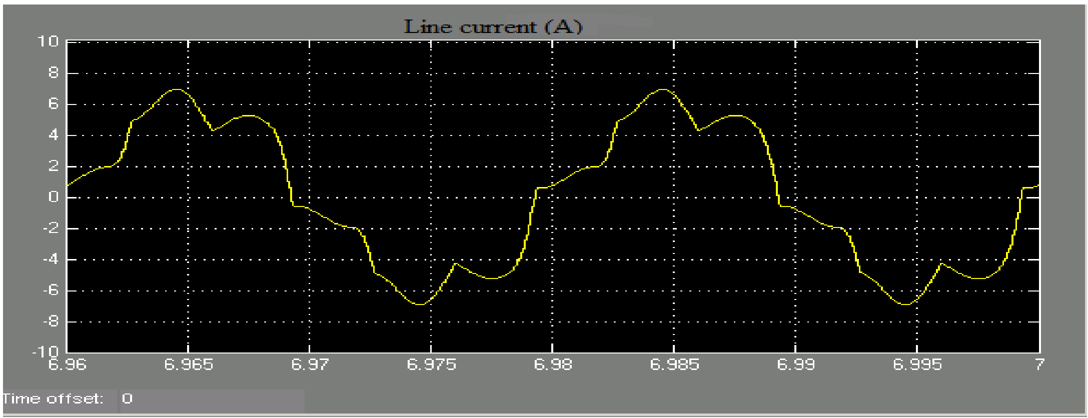


Figure 4.17: Full-load line current simulation waveforms for 3kW 6-pulse diode rectifier system using 5th and 7th (10% D_f) tuned filters with 6% Lac and 3% Ldc

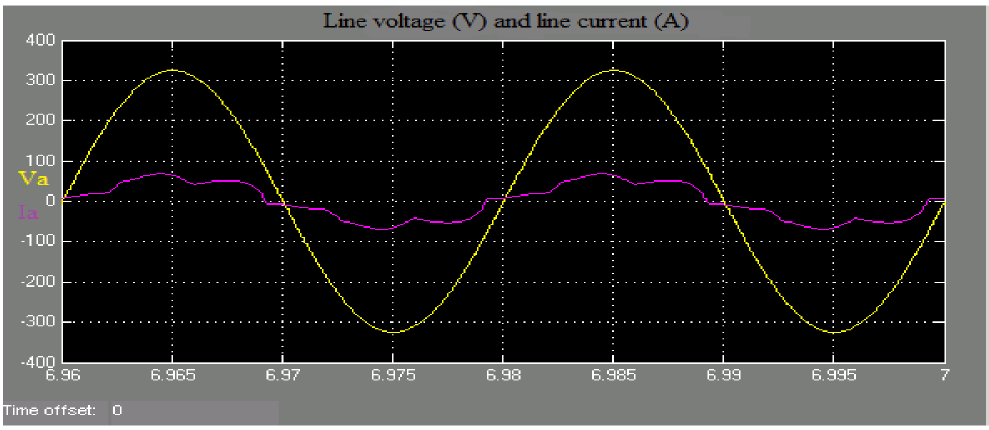


Figure 4.18: Full-load line current and supply voltage simulation waveforms for 3kW 6-pulse diode rectifier system using 5th and 7th (10% D_f) tuned filters with 6% Lac and 3% Ldc

The system perfomance load dependency is also investigated using the same simulation model. Table 4.13 shows the main power quality indices considered from no-load to full-load operating conditions. The line current THD, line PF and the DC output voltage considered has a load dependency diagrams shown in Figure 4.19. The line current THD for the proposed system does not change from half-load to full-load range significantly, while at 25% loading condition the THD value increases to 34% before it declines again at light load conditions (15% at no-load). The line power factor has high values (> 0.94 lagging) for range of >50% loading and decreases at light loading conditions to 0.27 lagging. On the contrary, the DC output voltage has high values at light load conditions (554 V) due to the filters capacitance boosting and has lower values as the loading condition increases.

Table 4.13: Load dependency system performance using the 5^{th} & 7^{th} shunt (10% Df) tuned filters with 6% Lac and 3% Ldc at 3kW

Load%	THD (%)	PF	VDC
100	20.78	0.9791	527.4
75	22.99	0.972	531
50	26.76	0.9396	534.9
25	34.19	0.785	538.8
0	15.41	0.2696	554.8

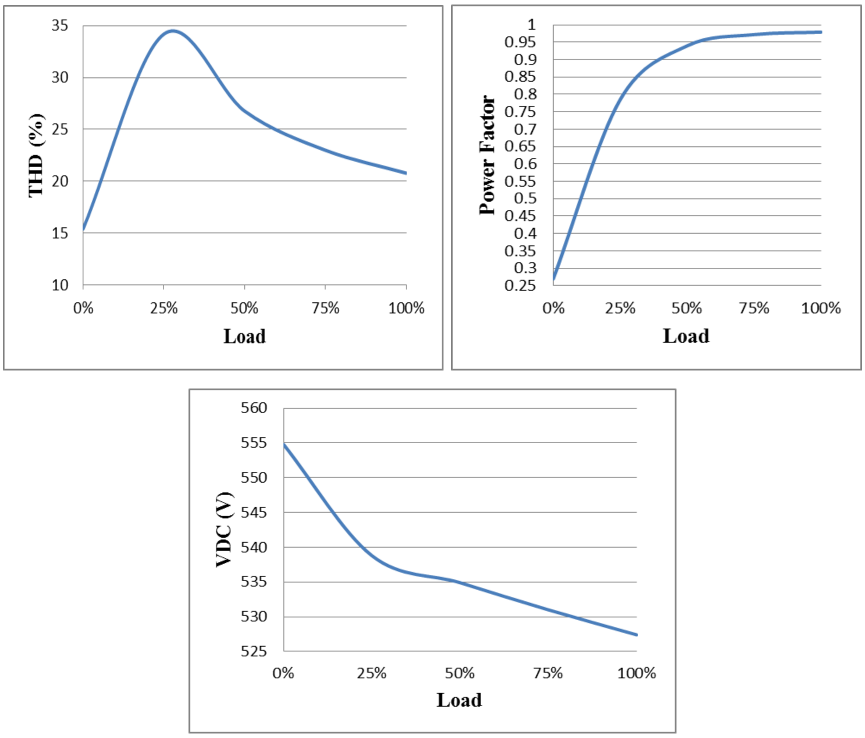
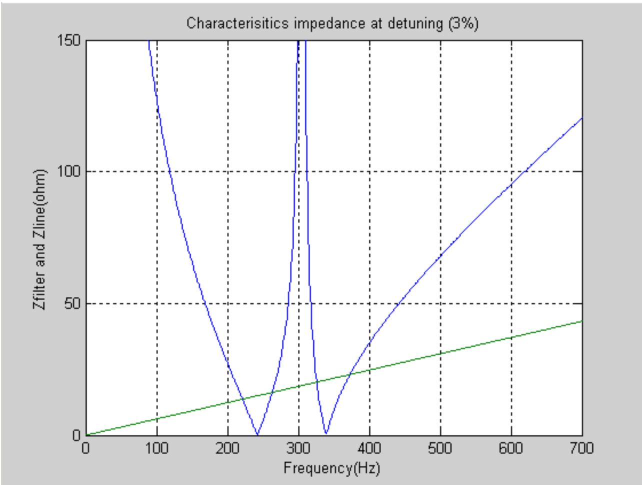
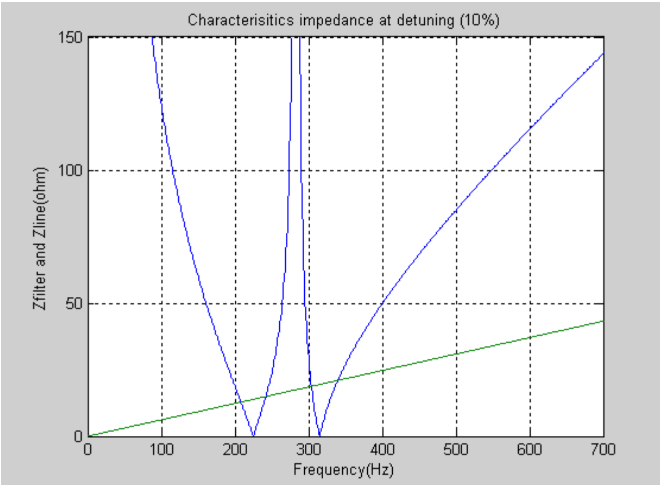


Figure 4.19: System performance: (a) Line current THD%, (b) Line PF, (c) DC voltage for 3kW 6-pulse rectifier using 5^{th} and 7^{th} (10% Df) tuned filters with 6% Lac and 3% Ldc

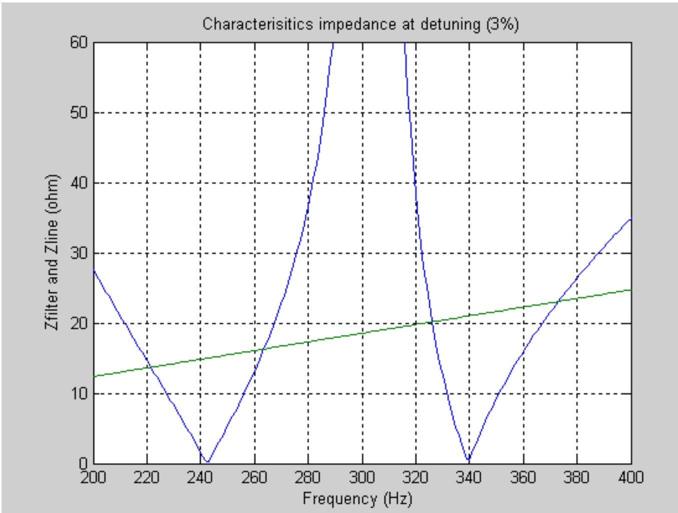
In summary, the 6-pulse diode rectifier system performance using the 5^{th} & 7^{th} shunt (10% Df) tuned filters with 6% Lac and 3% Ldc% has been effected by increasing the detuning factor to maximum value. The Line current THD value increases from 12% to 21% as the detuning factor increases from 3% to 10%. Therefore, the detuning factor is a major designing criteria that might effect the filtering method qulaity. Figure 4.20 shows the impedance characteristics of the line imperdance and the filter impedance as seen from the rectifier side for both detuning factor ends (3% and 10%). The impedance ratio between the line impedance and the filter impedance at the dominant harmonic frequency filters (250Hz and 350Hz) has different values for both detuning factor cases. This explains the filter performance sensitivity for the chosen detuning factor of the single sunt filters used in the system.



(a)



(b)



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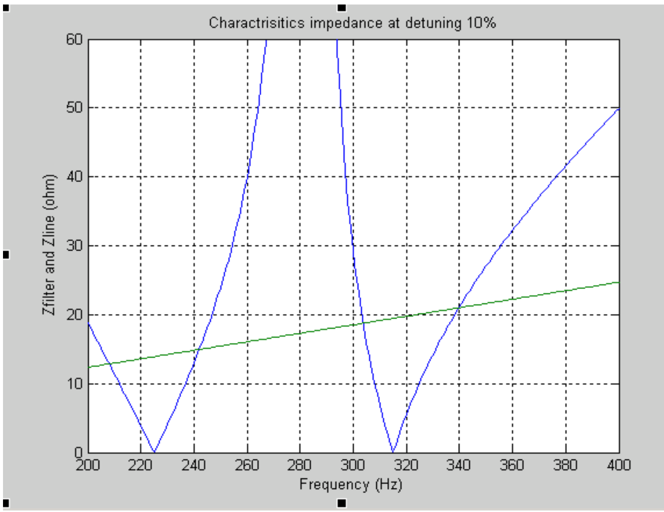


(d)

Figure 4.20: Line and filter impedance characteristics for (a) 3% Df tuning, (b) 10% Df tuning, (c) 3% Df tuning (Zoomed), (d) 10% Df tuning (Zoomed).

Moreover, the proposed system and filtering technique senstivity for the unbalance votage supply system is measurable for the line currrent THD and DC output voltage values. On the other hand the line power factor value is kept stable. Therefore, the design criteria with a high detuning factor for this filtering method may not be a preferable way of mitigating current harmonics for 6-pulse diode rectifier front end applications. An extra enhancement of the filtering method for such a highly polluted PCC condition must be considered. This may involve adding an extra smoothing AC reactor at the reactifier side (Lac2) to reduce the stress on the shunt filters and improve the topology.

b) Simulation results of the 30kW power rated rectifier system

The designed 6-pulse diode rectifier system using the 5^{th} and 7^{th} shunt tuned filters with the selected 6%Lac and 3% Ldc for 30kW power rating has also been tested using the simulation models and similar results obtained. The first case involves the design using the 3% detuned single shunt filter. The system performance under balance and 3% unbalance supply voltage simulation results are shown in Table 4.14.

Similarly to the 3kW power rating designed system, the filtering technique using the 5^{th} and 7^{th} shunt (3% Df) tuned filters with the selected 6%Lac and 3% Ldc combination can achieve low line current THD value of 11.5% and nearly unity line power factor at full-load. Conversely this rectifier system is sensitive to the unbalance voltage supply and the line current THD values increases considerably (17.0%) in the 3^{rd} phase. Similarly, the DC output voltage reduced to 514V under the unbalanced case while the line power factor kept the same. Corresponding simulation waveforms for the 30kW rectifier system will be added in Appendix A1.

Table 4.14: System performance using the 5^{th} & 7^{th} shunt (3% Df) tuned filters under balanced and 3% unbalance line voltage at 30kW

Filter Type	**THD (%)**				**PF**		**VDC**	
	Balance	**Unbalance at phases**			**Balance**	**Unbalance**	**Balance**	**Unbalance**
		1	**2**	**3**				
Lac (6%) And Ldc (3%)	**11.45**	**13.51**	**13.02**	**16.82**	**0.9917**	**0.99**	**529.4**	**513.7**

In the same way, the 6-pulse diode rectifier system perfomance load dependency is investigated using the same simulation technique. Table 4.15 shows the main power quality indices considered for the whole range of loading conditions. Almost all results analysis, observation and conclusions for the 3kW designed rectifier system performance assessment are valid and consistent with the 30kW designed case.

Table 4.15: Load dependency system performance using the 5th & 7th shunt (3% Df) tuned filters with 6% Lac and 3% Ldc at 30kW

Load%	THD (%)	PF	VDC
100	11.45	0.9917	529.4
75	13.13	0.9916	532.4
50	16.30	0.9791	535.5
25	20.07	0.8733	543.5
0	11	0.291	555.6

To validate the other designed case with single shunt (10% Df) 5th and 7th filters, the 30 kW rectifier system is considered and assessed. Table 4.11 shows the used filters parameters for 30kW system that has implemented in the simulation circuit shown in Figure 4.13. The system performance under balance and 3% unbalance supply voltage simulation results for the considered filtering method are shown in Table 4.16. Similarly to the 3kW power rating system case study, the filtering technique using the 5th and 7th shunt (10% Df) tuned filters with the selected 6%Lac and 3% Ldc combination, compared to the 3% Df case study, has at full-load higher line current THD value of 20.3% and lower line power factor value of 0.98 lagging. Furthermore, this designed rectifier system validate the system sensitivity to the unbalance voltage supply and the line current THD values increases considerably in the 3rd phase to be 25%. Similarly, the DC output voltage reduced to 509V under the unbalnce case while the line power factor is fixed.

Table 4.16: System performance using the 5th & 7th shunt (10% Df) tuned filters under balanced and 3% unbalanced line voltage at 30kW

Filter Type	THD (%)				PF		VDC	
	Balance	Unbalance at phases			Balance	Unbalance	Balance	Unbalance
		1	2	3				
Lac (6%) And Ldc (3%)	20.34	22.56	18.62	24.25	0.9777	0.9745	525.7	509

Likewise to the 3kW power rating case study, the system perfomance load dependency is also investigated using the same simulation model. Table 4.17 shows the main power quality indices considered from no-load to full-load operating conditions.

The line current THD for the proposed system has a slight rise from full-load to half-load range and increased to 37 % at 25% loading condition before it decreases again at light load conditions. Similarly to the 3kW rating case study, the line power factor for range of >50% loading has high values (> 0.95 lagging) and decreases at light loading conditions to 0.28 lagging. On the contrary, the DC output voltage has high values at light load conditions (553V) due to the filters boosting capacity and has lower values as the loading condition increases.

Table 4.17: Load dependency system performance using the 5th & 7th shunt (10% Df) tuned filters with 6% Lac and 3% Ldc at 30kW

	THD (%)	**PF**	**VDC**
Full load (%)	**20.34**	**0.9777**	**225.7**
75	**22.79**	**0.9751**	**529.6**
50	**27.2**	**0.9541**	**533.5**
25	**37.03**	**0.836**	**537.4**
No load	**19.08**	**0.2867**	**553.1**

In conclusion, both the 3kW and 30kW case studies considered, have the same performance under different operating conditions for the different detuning factors used in the study. This validates the analysis, design method and simulation results for the considered filtering topology. As mentioned previously, the design criteria with a high detuning factor (10%) for this filtering method is not an effective method of mitigating current harmonics for 6-pulse diode rectifier front end applications.

Therefore, the filtering method for such a highly polluted PCC condition must be modifed to improve its function. The T-shape tuned filtering topology might be a considerable solution to avoid importing current harmonics from the PCC while keeping the power quality performance within the recommended levels. This may involve adding an extra smoothing AC reactor at the reactifier side (Lac2) to reduce the stress on the shunt filters and improve the topology.

4.5 Six-pulse rectifier system simulations with T-shape Tuned filter combined DC link inductor and AC line reactor

The T-shaped tuned filter topology consists of the same conventional structure of the tuned filter adding an extra AC line reactor connected at the rectifier side (Lac2). This added (3% to 6%) AC reactor will help in smoothing the rectifier current waveform drawn by the 6-pulse diode rectifier system and will reduce its harmonic contents. Therefore, the single shunt filter components will have less stress will trapping the current harmonics from the rectifier side and prevent them from appearing in the line side to reduce the line current THD values. The structure of the T-shape filtering topology connected to the 6-pulse diode rectifier is shown in Figure 4.21.

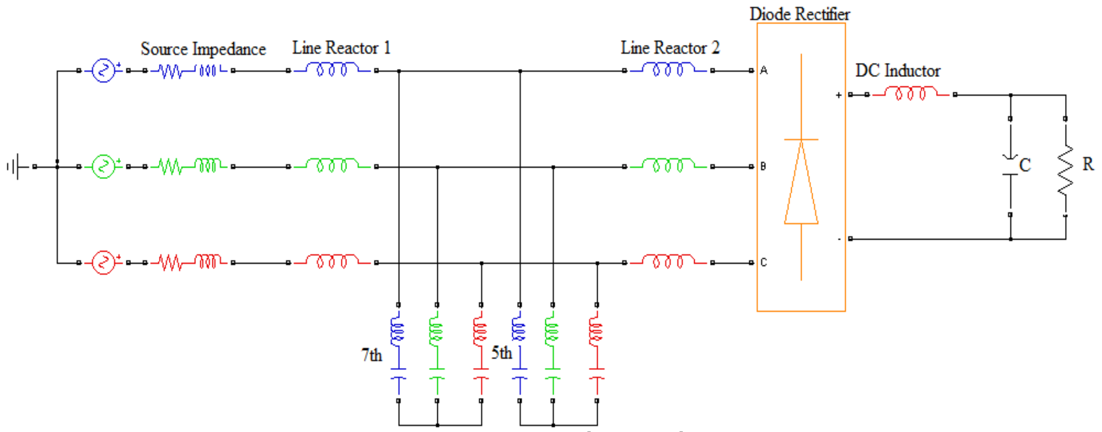


Figure 4.21: Six-pulse diode rectifier using 5th and 7th tuned filter harmonic with two line reactors (T-shape) and DC line inductor

The selection of the second AC line reactor value involves the common range (3% to 6%) designed in section 3.1 and assessed in section 4.2. The T-shape tuned filter will be examined using the same simulation process for the whole range of Lac2 and the results will be evaluated to have the most practical and economical selection. Table 4.18 shows the system performance for the T-shape 5th & 7th shunt (3% Df) tuned filters under balanced and 3% unbalance line voltage at 3kW using the whole range of Lac2 (3%, 4%, 5% and 6%).

The intention in selecting the Lac2% is minimizing its value (less size and cost) while maximizing the improvement in the system performance achieved. Therefore, the 3% Lac2 is the minimum AC line reactor that can be chosen and the

corresponding system performance has almost the same value compared to the higher Lac2 values. For example, the line current THD value has a slight reduction from 8.6% to 6.6% while the Lac2 value is doubled from 3% Lac2 to 6%Lac2. Meanwhile the line PF has unity value for both AC line reactors used. Therefore, an extra AC reactor of 3% is connected to the rectifier side to form the T-shape tuned filtering method.

The new filtering technique using the 5th and 7th shunt (3% Df) tuned filters with the selected 6%Lac1, 3%Lac2 and 3% Ldc combination can achieve lower line current THD value of 8.6% and nearly unity line power factor at full-load. Therefore, adding the 3%Lac2 has contributed in reducing the line THD value from 12.2% (without Lac2) to 8.6% at full-load. This is a significant improvement in the line current THD value that can be achieved with the T-shape tuned filter topology. However, adding this 3% Lac2 to the rectifier system did not reduce its sensitivity to the unbalanced voltage supply. The line current THD values increases to its maximum value in the 3rd phase to 12.8%. Nevertheless, this value is less than 17.5% for the tuned filter designed without adding the 3% Lac2. Similarly, the DC output voltage reduced from 523 to 508V under the unbalance case while the unity line power factor remained constant. As a result, the 3% Lac2 is selected and the new filtering method will be designed using both 3% and 10% detuning factors. System performance is assessed and analysed using the same simulatiom technique.

Table 4.18: System performance using the T-shape 5th & 7th shunt (3% Df) tuned filters under balanced and 3% unbalance line voltage at 3kW

Filter Type		THD (%)				PF		VDC	
		Balance	Unbalance at phases			Balance	Unbalance	Balance	Unbalance
			1	2	3				
Ldc (3%) & Lac1 (6%)	Lac2 (3%)	8.664	10.02	9.937	12.82	0.9962	0.995	523.2	507.8
	Lac2 (4%)	7.94	9.131	9.226	11.89	0.9968	0.9957	520.8	505.3
	Lac2 (5%)	7.44	8.488	8.687	11.19	0.9972	0.996	518.4	502.7
	Lac2 (6%)	6.681	7.897	8.195	10.56	0.9974	0.9964	515	500

a) Simulation results of the 3kW power rated rectifier system

The new T-shape filtering method using the 3% Lac2 is designed and examined using the simulation circuit in Figure 4.21. The full-load line current simulation waveform of the 3kW 6-pulse rectifier system using the T-shape 5^{th} & 7^{th} shunt (3% Df) with 6% Lac1, 3%Lac2 and 3% Ldc selected combination is shown in Figure 4.22. The full-load line current and supply voltage simulation waveforms for the 3kW 6-pulse rectifier system using the T-shape filters combination is shown in Figure 4.23. The full-load line current has 8.6% THD and the line power factor is unity.

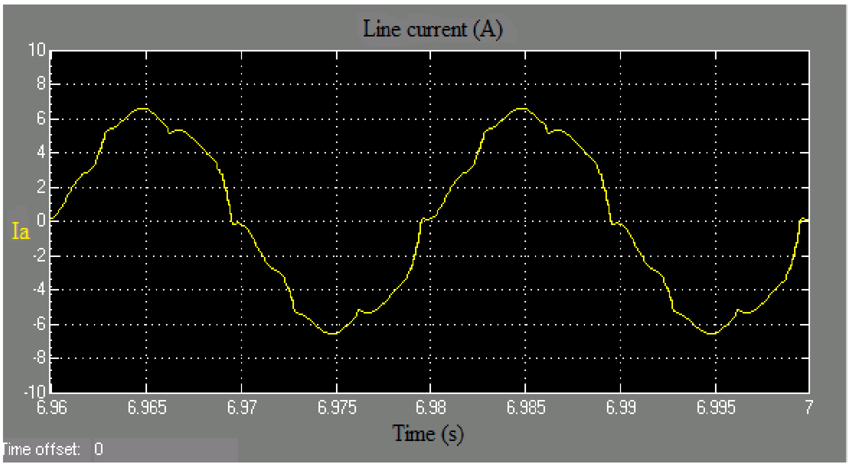


Figure 4.22: Full-load line current simulation waveforms for 3kW 6-pulse diode rectifier system using 5^{th} and 7^{th} (3% D_f) tuned filters with 6% Lac1, 3%Lac2 (T-shape) and 3% Ldc

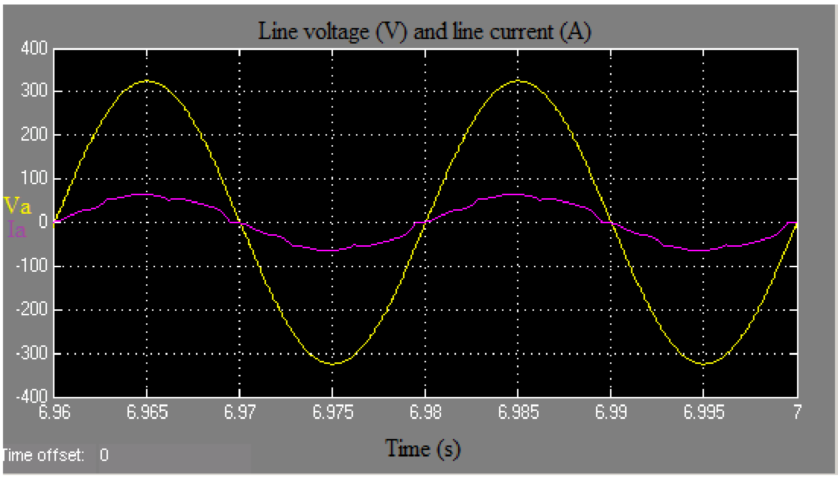


Figure 4.23: Full-load line current and supply voltage simulation waveforms for 3kW 6-pulse diode rectifier system using 5^{th} and 7^{th} (3% D_f) tuned filters with 6% Lac1, 3%Lac2 (T-shape) and 3% Ldc

In the same process, the system perfomance load dependency is also examined using the proposed simulation method. Table 4.19 shows the main power quality indices considered from no-load to full-load operating conditions. From no-load to full-load the line current THD is stable and has a little increment at 25% loading. The line power factor has high values (> 0.95) from half-load to full-load range and decreases at light loading conditions to 0.2 lagging. On the contrary, due to the filters boosting capacity, the DC output voltage has high values at light load conditions and lower values at full-load.

Table 4.19: Load dependency system performance using the 5th & 7th shunt (3% Df) tuned filters with 6% Lac1, 3%Lac2 and 3% Ldc at 3kW

Load %	THD (%)	PF	VDC
100	8.664	0.9962	523.2
75	9.651	0.99	529
50	10.84	0.9501	534.3
25	12.1	0.76	539.7
0	6.022	0.2384	555.5

In conclusion, the 6-pulse diode rectifier system performance using the 5th & 7th shunt (3% Df) tuned filters with 6% Lac1, 3%Lac2 and 3% Ldc has overall good power quality indices. The system performance is showing some improvement compared to the same detuning factor (3%Df) designed filter without using the 3% Lac2. The line current THD value has decreased from 12.23% to 8.6% by adding this new 3% AC reactor at the rectifier side. The achieved line THD value (< 10%) can comply with the most recent harmonic standards in the distribution power networks. This harmonic mitigation method can be a competitive choice for practical 6-pulse diode rectifier front end applications.

The second case involves assessing the designed T-shape 5th and 7th tuned filters with 10% detunnig factor assuming highly polluted PCC. The filter parameters shown in Table 4.11 and Table 4.5 for the 3kW power rating are used. To validate the choice of Lac2 value the same process is used as in the previous section and all the range of Lac2 (3% - 6%) is examined. The related filter parameters are implemented in the simulation circuit shown in Figure 4.21.

The results shown in Table 4.20 agrees with the 3% Lac2 selection method used for the filtering technique. Using the 5th and 7th shunt (10% Df) tuned filters with the selected 6%Lac1, 3%Lac2 and 3% Ldc combination has higher line current THD

value of 16.6% and less line power factor value of 0.97 lagging at full-load compared to the 3% Df case study. This is highly expected as the shunt filters minimum impedance points are shifted away from the harmonic frequency. Sensitivity for the 3% unbalance voltage supply still exists.

Table 4.20: System performance using the T-shape 5th & 7th shunt (10% Df) tuned filters under balanced and 3% unbalance line voltage at 3kW

Filter Type		THD (%)				PF		VDC	
		Balance	Unbalance at phases			Balance	Unbalance	Balance	Unbalance
			1	2	3				
Ldc (3%) & Lac1 (6%)	Lac2 (3%)	16.65	18.1	15.6	19.3	0.986	0.983	520	504.2
	Lac2 (4%)	15.78	17.0	14.85	18.0	0.987	0.985	517.7	501.6
	Lac2 (5%)	14.97	16.0	14.08	16.9	0.988	0.986	515.5	498.8
	Lac2 (6%)	14.15	15.2	13.5	16.2	0.989	0.987	512.5	496.8

The full-load line current simulation waveform of the 3kW 6-pulse rectifier system using the T-shape 5th & 7th shunt (10% Df) with 6% Lac1, 3%Lac2 and 3% Ldc selected combination is shown in Figure 4.24. The full-load line current and supply voltage simulation waveforms for the 3kW 6-pulse rectifier system using the T-shape filters combination is shown in Figure 4.25. The full-load line current has 16.6% THD and the line power factor is 0.98 lagging.

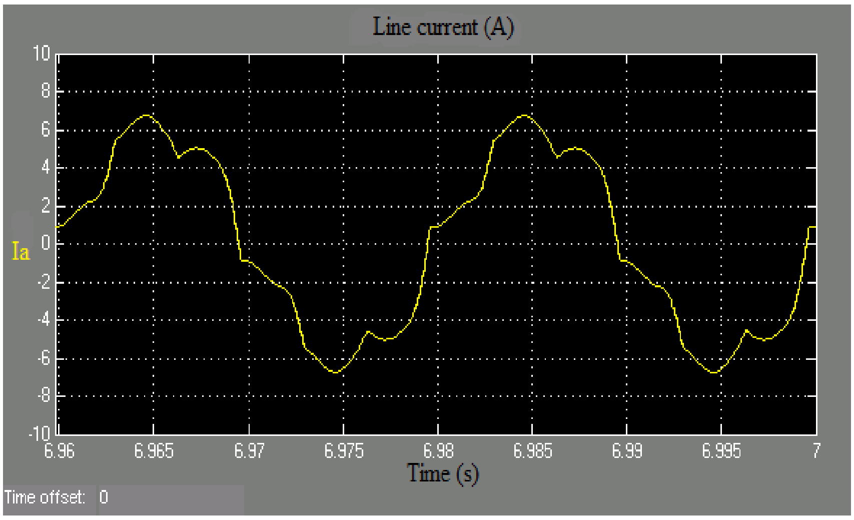


Figure 4.24: Full-load line current simulation waveforms for 3kW 6-pulse diode rectifier system using 5th and 7th (10% D_f) tuned filters with 6% Lac1, 3%Lac2 (T-shape) and 3% Ldc

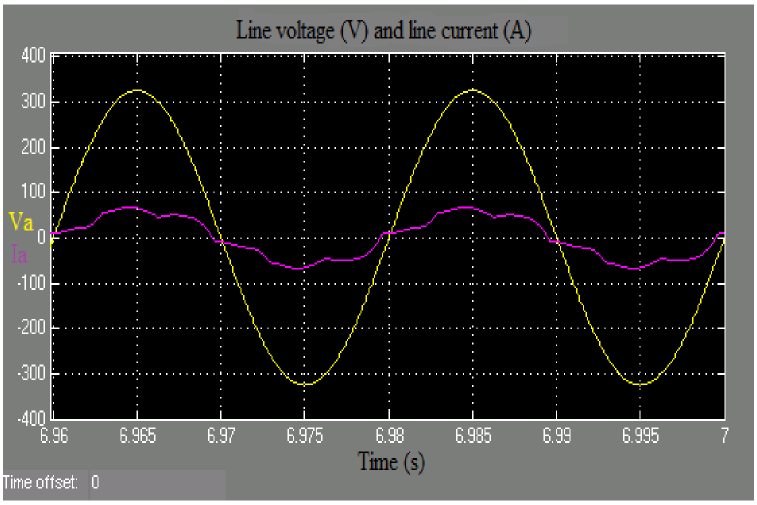


Figure 4.25: Full-load line current and supply voltage simulation waveforms for 3kW 6-pulse diode rectifier system using 5th and 7th (10% D_f) tuned filters with 6% Lac1, 3%Lac2 (T-shape) and 3% Ldc

In the same method, the system perfomance load dependency is also examined for the design. From no-load to full-load operating conditions the main power quality indices considered are shown in Table 4.21. The line current THD is almost fixed and decrease at no-load condition. The line power factor has high values (> 0.94 lagging) from half-load to full-load range and decreases at light loading conditions to 0.2 lagging. In contrast, the DC output voltage has high values at light load conditions due to the filters capacitance boosting.

Table 4.21: Load dependency system performance using the 5th & 7th shunt (10% Df) tuned filters with 6% Lac1, 3%Lac2 and 3% Ldc at 3kW

Load change	THD (%)	PF	VDC
100	16.65	0.9862	520
75	18.28	0.9791	526.4
50	20.32	0.9349	532.6
25	21.99	0.7431	538.7
0	11.17	0.2351	553.6

In conclusion, the 6-pulse diode rectifier using the 5th & 7th shunt (10% Df) tuned filters with 6% Lac1, 3%Lac2 and 3% Ldc has less system performance compared with (3%Df) as expected. Nevertheless, if compared with the same detuning factor considered (10%Df) without using the extra 3%Lac2, the line THD level decreased from 20.3% to 16.6% by adding this new 3% AC reactor at the rectifier side.

(b) Simulation results of the 30kW power rated rectifier system

In order to confirm the obtained results, the designed 6-pulse diode rectifier system using the 5th and 7th shunt tuned filters with the selected 6%Lac1, 3%Lac2 and 3% Ldc for 30kW power rating for both 3% and 10% detuning factor has been tested using the simulation models. The first case involves the design using the 3% detuned single shunt filter. The system performance under balance and 3% unbalance supply voltage simulation results for all Lac2% range are shown in Table 4.22 . The same reasons for selecting the 3% Lac2 are valid for the considered power rating.

Similarly to the 3kW power rating designed system, the filtering technique using the 5th and 7th shunt (3% Df) tuned filters with the T-shape AC reactors combination can achieve low line current THD value of 8.2% and nearly unity line power factor at full-load. Conversely, this rectifier system is sensitive to the unbalance voltage supply and the line current THD values increases considerably (12.5%) in the 3rd phase. Similarly, the DC output voltage reduced from 521V to 505V under the unbalanced case while the line power factor is kept the same. Corresponding simulation waveforms for the 30kW rectifier system will be added in Appendix A1

Table 4.22: System performance using the T-shape 5th & 7th shunt (3% Df) tuned filters under balanced and 3% unbalance line voltage at 30kW

Filter Type		THD %				PF		VDC	
		Balance	Unbalance			Balance	Unbalance	Balance	Unbalance
			phase1	phase2	phase 3				
Ldc (3%) & Lac1 (6%)	Lac2(3%)	8.244	9.61	9.65	12.51	0.994	0.993	521.1	505.6
	Lac2(4%)	8.017	9.20	9.19	11.88	0.994	0.993	518	502.4
	Lac2(5%)	7.533	8.61	8.61	11.09	0.994	0.992	514.9	499.2
	Lac2(6%)	6.51	7.32	7.87	10.2	0.994	0.992	512	496.1

To validate the other designed case with single shunt (10% Df) 5th and 7th filters, the 30 kW rectifier system is considered and assessed. Table 4.11 and Table 4.7 show the used filters parameters for 30kW system that have been implemented in the simulation circuit shown in Figure 4.21. The system performance under balance and

3% unbalance supply voltage simulation results for the considered filtering method are shown in Table 4.23.

Table 4.23: System performance using the T-shape 5th & 7th shunt (10% Df) tuned filters under balanced and 3% unbalance line voltage at 30kW

Filter Type		THD %				PF		VDC	
		Balance	Unbalance			Balance	Unbalance	Balance	Unbalance
			phase1	phase2	phase 3				
Ldc (3%) & Lac1 (6%)	Lac2 (3%)	16.11	17.48	15.1	18.62	0.9844	0.9818	517.9	501.6
	Lac2 (4%)	15.51	16.82	14.57	17.75	0.9846	0.9821	514.6	498.7
	Lac2 (5%)	14.26	15.4	13.54	16.35	0.9862	0.9835	512.1	496
	Lac2 (6%)	13.55	14.59	12.92	15.49	0.9867	0.984	509.2	493.2

4.6 Different Filter Performance Comparison

The final stage of this study involves the comparison of the different passive filtering structures discussed performance for the three-phase –pulse diode rectifier front end applications. The comparison is based on all the results obtained in the previous sections and involves the line current THD value, the line power factor and the DC link output voltage at full load under steady state conditions. Moreover, the comparison includes the line THD rectifier system sensitivity to 3% unbalance supply voltage. Table 4.24 shows the mentioned power quality indices considered for the five different passive filtering methods examined in the study.

As the table indicates, the minimum line current THD that can be achieved (8.6%) is for the T-shape tuned filter with 3%Df while this value is nearly doubled (16.6%) for the same structure using the maximum limit detuning factor of 10%Df. This shows how the filter effectiveness is sensitive to the detuning factor considered. On the other hand the 6%Lac and 3%Ldc filtering combination has 29.5% line current THD. This will not comply with the harmonic standards and recommendations IEEE519 shown in Table 2.1**.** The effect of the detuning factor is also clear in the 5th and 7th tuned filter with only 6%Lac1 added in the line side of the system. The line current

THD value increased from 12% to 21% by shifting the detuning factor from 3%Df to 10%f.

The line power factor value for all 5th and 7th tuned filter structures is high (>0.97 lagging) while the 6%Lac and 3%Ldc filtering combination has a 0.95 lagging power factor. The DC link voltage is affected by the drop in the lines for the AC and DC combination filters in the absence of any capacitance boosting and has higher values for the other filtering design cases. Furthermore, all the evaluated filtering methods have a considerable sensitivity to the 3% voltage supply unbalance. The T-shape tuned filters, although they have more components, they are less sensitive to the voltage imbalance and has better line THD values.

In general, the comparison shows a range of line current THD values and helps engineers to select the most suitable filter structure according to the power quality standard required and distribution network conditions,

Table 4.24 Common passive filters performance comparison for 6-pulse diode rectifier systems

Filter type	6% Lac & 3% Ldc	Tuned filter 3% Df	Tuned filter 10% Df	T-shape Tuned filter 3% Df	T-shape Tuned filter 10% Df
Line THD%	29.5	12.2	20.7	8.6	16.6
Line PF (Lag)	0.95	0.99	0.97	0.99	0.98
DC output voltage	517	530	527	523	520
Max. THD% under 3% unbalance Vs	---	17.5	25	12.8	19.3

5. Conclusion

In this study passive harmonic filtering ways for the 6-pulse diode rectifier front end applications have been investigated. To comply with modern power quality standards passive filtering techniques are utilized to limit the current harmonic of three-phase rectifier converters commonly utilized in industry.

In the first step of the study, general information on the input current harmonics of the 6-pulse rectifier system, current harmonics effects in distribution networks and harmonic prediction methods is provided. Harmonics mitigation techniques for the 6-pulse rectifier system are discussed in this introductory section. This has involved the typical line current waveform for the 6-pulse diode rectifier using no filters and the corresponding line current harmonic spectrum. The line current drawn by the converter is highly distorted with mainly the 5^{th} and 7^{th} dominant harmonic components. The line current THD value can reach a large value of > 80% range. The side effects of these presenting current harmonics in the distribution networks are detailed and the technical harmonic standards and recommendations for power distributors are defined. Finally, the various methods of reducing the current harmonics in such applications are presented. From the presented different methods presented the passive filters are in general less in cost and complexity compared to other filtering methods and therefore, are still widely used.

In the second step of the study the common passive harmonic filters applied for 6-pulse diode rectifier front end applications are investigated. Review of operating principles and design rules for AC line reactors, the DC link inductance and single shunt tuned filters are involved. The single shunt tuned filters combined with the AC and DC reactors are able to reduce the line current THD values to acceptable levels. Therefore, different design cases of the shunt tuned filters are presented considering factors that may affect the filters effectiveness for performance evaluation and comparisons. These factors involve the detuning factor value and adding an extra AC reactor at the rectifier side to perform the T-shape tuned filter structure. The design cases are performed for 3kW and 30kW power ratings, and main filters parameters are calculated using the formulas presented in the section.

The third step of the study has involved assessing the performance of the 6-pulse diode rectifier using the common passive filters considered structures by computer simulations. The focus was on the steady state performance characteristics at a range of different loading conditions, balanced and unbalanced supply voltage. The line current THD, line power factor and DC link output voltage are the main power quality parameters considered. Finally a comparison between the assigned filtering cases is presented.

Table 5.1 shows the performance results comparison of the different passive filtering methods considered for the 6-pulse diode rectifier front end application. Five different passive filters design are considered. This involves the AC line reactor and DC link inductor (6%Lac and 3%Ldc) combination, the dominant 5^{th} and 7^{th} shunt (3%Df) and (10%Df) tuned filters design cases, the T-shape (adding 3%Lac2) 5^{th} and 7^{th} shunt (3%Df) and (10%Df) tuned filters design cases, respectively. The comparison involves the line current THD and PF, the unbalance sensitivity, harmonic resonance risk probability, size, structure complexity and cost features.

Table 5.1 Common passive filters performance comparison for 6-pulse diode rectifier systems at full-load operating condition

Filter type	6% Lac & 3% Ldc	Tuned filter 3% Df	Tuned filter 10% Df	T-shape Tuned filter 3% Df	T-shape Tuned filter 10% Df
Line THD%	V. High	Medium	High	Low	Medium
Line PF (lagging)	Medium	High	High	High	High
V Unbalance sensitivity	-----	High	High	High	High
Resonance Risk	Non	Medium	Low	Medium	Low
Size	Small	Medium	Medium	High	High
Structure Complexity	Simple	Moderate	Moderate	Realistic	Realistic
Cost	V. Low	Low	Low	Moderate	Moderate

The main contribution of this study is investigating the major designing factors that affect the common shunt tuned filters performance. This will help in achieving better selection of the appropriate single tuned filters structure for a given operating conditions and power quality requirements in the network. This selection is based on practical design considerations that can meet the modern harmonic standards and recommendations. Furthermore, a comprehensive and detailed performance comparison at different conditions has been introduced for the most common passive filtering techniques.

References

[1] Maniea, A., Power quality improvement for six pulse diode rectifier front end applications, University of Bath, MSc project literature review, 2011.

[2] Singh, G.K., Power system harmonics research: a survey, European Transaction on Electrical Power 2009, 19: p. 151–172.

[3] Kampen, D., et al. Comparative evaluation of passive harmonic mitigating techniques for six pulse rectifiers in Optimization of Electrical and Electronic Equipment, OPTIM, 11th International Conference, 2008.

[4] S.Chattopadhyay, M. Mitra, S, Sengupta, Electric Power Quality, Springer, 2011, p. 21-22.

[5] S.Chattopadhyay, M. Mitra, S, Sengupta, Electric Power Quality, Springer, 2011, p. 25.

[6] IEEE Recommended Practices and Requirements for Harmonics Control in Electric Power Systems, IEEE Std. 519, 1992.

[7] Power Quality Measurement Methods, IEC 61000-3-2, 2000.

[8] Benachaiba, C. and B. Ferdi, A comparative study of IEC 61000 part 3-2 & 3-4 and IEEE 519-1992 standards in low voltage applications, International Review of Electrical Engineering-IREE, 2007, 2(6): p. 771-776.

[9] McGranaghan, M. and G. Beaulieu. Update on IEC 61000-3-6: Harmonic Emission Limits for Customers Connected to MV, HV, and EHV, In Transmission and Distribution Conference and Exhibition, 2005/2006 IEEE PES. 2006.

[10] Hansen, S., L. Asiminoaei, and F. Blaabjerg. Simple and advanced methods for calculating six-pulse diode rectifier line-side harmonics. In Industry Applications Conference, 2003, 38th IAS Annual Meeting.

[11] Chang, G.W., et al., Passive Harmonic Filter Planning in a Power System With Considering Probabilistic Constraints, Ieee Transactions on Power Delivery, 2009, 24(1): p. 208-218.

[12] Singh, B., et al., Multipulse AC-DC Converters for Improving Power Quality: A Review, IEEE Transactions on Power Electronics, 2008, 23(1): p. 260-281

[13] Lee, K., et al., Input Harmonic Estimation and Control Methods in Active Rectifiers, IEEE Transactions on Power Delivery, 2010. 25(2): p. 953-960

[14] Jamil, M., et al. Harmonics in Adjustable Speed Drives: Causes, Effects, and Solutions in Information and Emerging Technologies, International Conference ICIET 2007.

[15] Akagi, H., Modern active filters and traditional passive filters. Bulletin of the Polish Academy of Sciences: Technical Sciences, 2006. 54(3): p. 255-269.

[16] H. Akagi, "Active and Hybrid Filters for Power Conditioning," IEEE Industrial Electronics Conf. Proc., vol. 1, 2000, pp. TU26-TU36.

[17] Man-Chung, W., L. Chi-Seng, and D. Ning-Yi. Comparison of structure topologies for hybrid filters. in Universities Power Engineering Conference, 43rd International UPEC 2008.

[18] Rodriguez, J.R., et al., PWM regenerative rectifiers: State of the art. IEEE Transactions on Industrial Electronics, 2005, 52(1): p. 5-22.

[19] B. Yin,'' Performance comparison of voltage mode control and current mode control of a three-phase PWM rectifier based on a dual SISO model,'' 32nd Annual Conference of the IEEE-Industrial-Electronics-Society, Nov. 2006, pp. 2220-2226.

[20] Ginn, H.L., 'An optimization based method for selection of resonant harmonic filter branch parameters', IEEE Transactions on Power Delivery, 2006. 21(3): p. 1445.

[21] G. Chang, H. Wang, et al., "Passive Harmonic Filter Planning in a Power System with Considering Probabilistic Constraints." IEEE Transactions on Power Delivery, 2009, vol. 24, no.1, pp. 208-218.

[22] J.C. Das, "Passive Filters – Potentialities and Limitations," IEEE Trans. on Industry Applications, vol. 40, no.1, Jan. /Feb. 2004, pp. 232-241.

[23] F. Wang et al, '' Analysis and Design Optimization of Diode Front-End Rectifier Passive Components for Voltage Source Inverters,'' IEEE Transactions on Power Electronics, 2008, vol. 23, pp. 2278-2289.

[24] A.M. Hava, H. Zubi, "Performance comparison of various passive harmonic filters for adjustable speed drives," PEDS 2005, Malaysia.

[25] Mohan N., Undeland T., Robbins W., Power Electronics, Converters, Applications And Design, John Wiley& Sons, 2003, p. 108.

[26] IEEE Guide for Application and Specification of Harmonic Filters, IEEE Std 1531, 2003.

[27] Mohan N., Undeland T., Robbins W., Power Electronics, Converters, Applications And Design, John Wiley& Sons, 2003, p. 146.

[28] Ginn, H.L., An optimization based method for selection of resonant harmonic filter branch parameters. Ieee Transactions on Power Delivery, 2006. 21(3): p. 1445.

[29] Matlab 7.6. A numerical computation software, Mathworks Inc., 2008.

[30] Wang, F., et al., Analysis and Design Optimization of Diode Front-End Rectifier Passive Components for Voltage Source Inverters. Ieee Transactions on Power Electronics, 2008. 23(5): p. 2278-2289.

[31] Bahrani, B. and R. Grinberg. Investigation of harmonic filtering for the state-of-the-art variable speed drives. in Power Electronics and Applications, 2009. EPE '09. 13th European Conference on. 2009

[32] V. Gosbell, S. Perera, V. Smith, “Voltage Unbalance,” Integral Energy Power Quality & Reliability Centre, Technical Note no.6, Oct. 2002.

Appendix A1

System performance using different DC line inductor percentage at 30kW

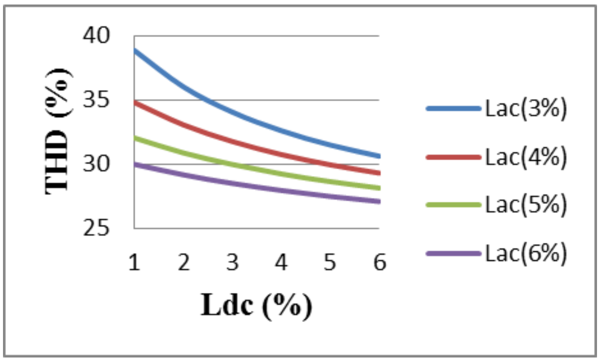
Filter Type		THD (%)	PF	Vdc
Line inductor percentage At DC side	Ldc (1%)	99.38	0.7005	545.9
	Ldc (2%)	81.31	0.7602	536.4
	Ldc (3%)	58.68	0.8538	534.5
	Ldc (4%)	47.33	0.8983	534.6
	Ldc (5%)	42.06	0.9177	534.3
	Ldc (6%)	37.85	0.9326	534.1

System performance using different AC line inductor percentage for 30kW

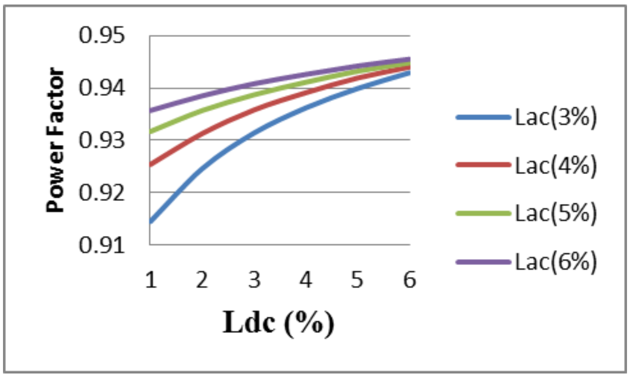
Filter Type		THD (%)	PF	Vdc
	Lac (3%)	42.94	0.8996	524.9
	Lac (4%)	37.14	0.9171	521.5
	Lac (5%)	33.55	0.9264	518.2
	Lac (6%)	31.01	0.9322	514.9

System performance using combination of AC reactor and DC link inductor filter for 30kW power rating at full-load

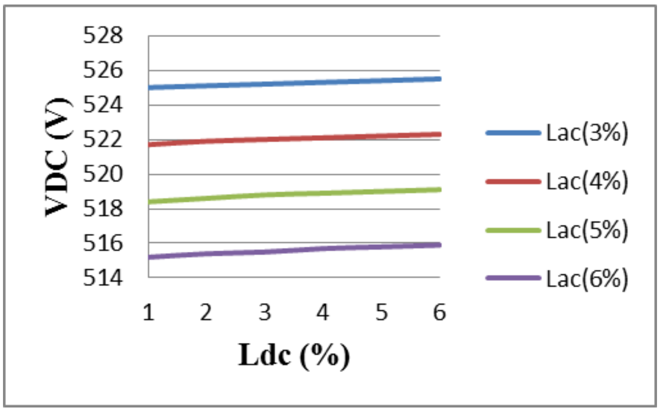
Filter Type			THD (%)	PF	Vdc
	Lac(3%)	L_{dc} (1%)	38.85	0.9145	525
		L_{dc} (2%)	36.01	0.9246	525.1
		L_{dc} (3%)	34.04	0.9314	525.2
		L_{dc} (4%)	32.59	0.9362	525.3
		L_{dc} (5%)	31.47	0.9399	525.4
		L_{dc} (6%)	30.6	0.9429	525.5
	Lac(4%)	L_{dc} (1%)	34.79	0.9254	521.7
		L_{dc} (2%)	33.05	0.9313	521.9
		L_{dc} (3%)	31.75	0.9358	522
		L_{dc} (4%)	30.73	0.9391	522.1
		L_{dc} (5%)	29.93	0.9419	522.2
		L_{dc} (6%)	29.28	0.944	522.3
	Lac(5%)	L_{dc} (1%)	32.03	0.9351	518.4
		L_{dc} (2%)	30.86	0.9383	518.6
		L_{dc} (3%)	29.96	0.941	518.8
		L_{dc} (4%)	29.22	0.9429	518.9
		L_{dc} (5%)	28.62	0.9447	519
		L_{dc} (6%)	28.12	0.946	519.1
	Lac(6%)	L_{dc} (1%)	29.97	0.9385	515.2
		L_{dc} (2%)	29.15	0.9403	515.4
		L_{dc} (3%)	28.48	0.9426	515.5
		L_{dc} (4%)	27.93	0.9442	515.7
		L_{dc} (5%)	27.46	0.9455	515.8
		L_{dc} (6%)	27.07	0.9465	515.9



(a)

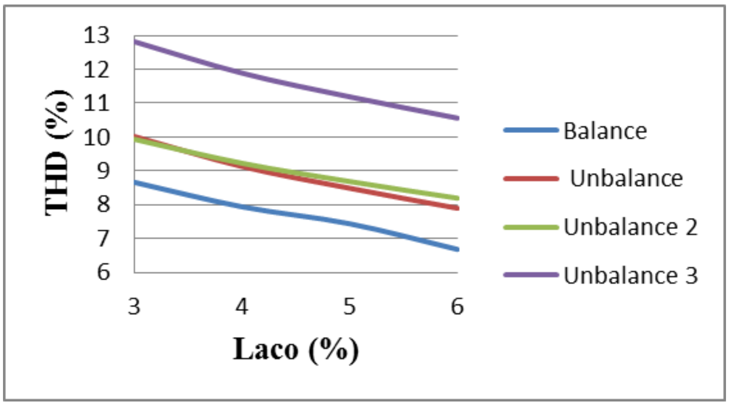


(b)

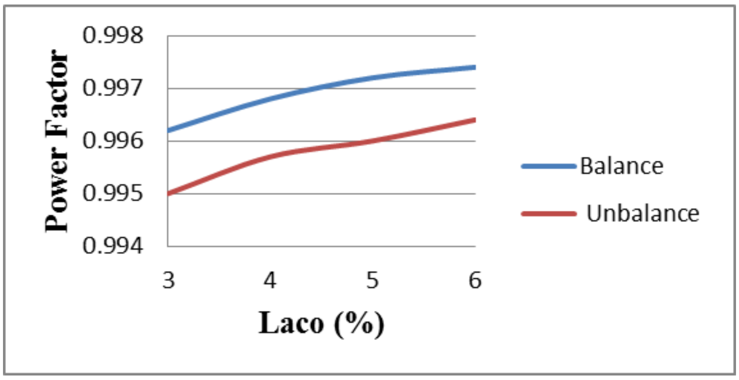


(c)

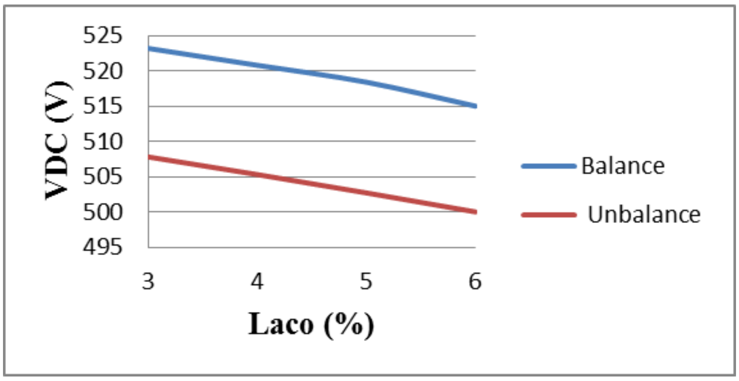
System performance: (a) Line current THD%, (b) Line PF, (c) DC voltage for 30kW 6-pulse rectifier using various combined AC reactor and DC link inductor values



(a)

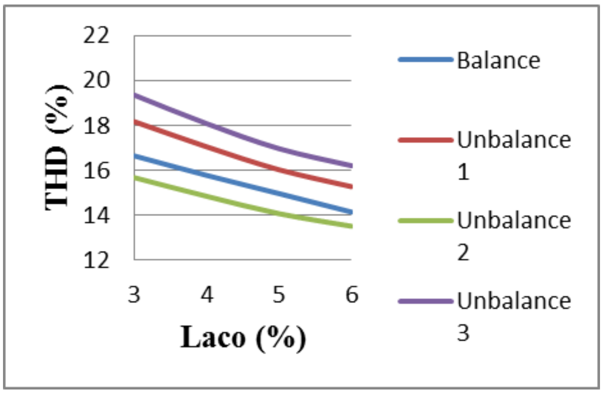


(b)

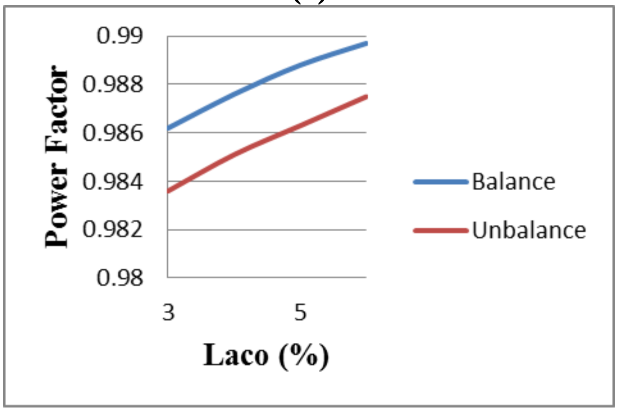


(c)

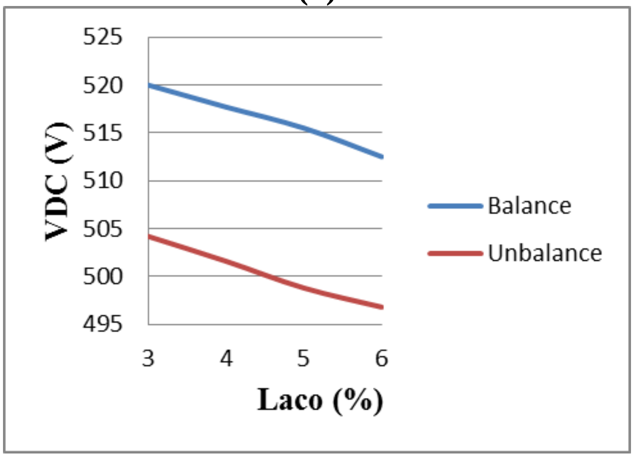
System performance: (a) Line current THD%, (b) Line PF, (c) DC voltage for 3kW 6-pulse rectifier using the T-shape 5^{th} and 7^{th} (3% Df) tuned filters with 6% Lac and 3% Ldc



(a)



(b)



(c)

System performance: (a) Line current THD%, (b) Line PF, (c) DC voltage for 3kW 6-pulse rectifier using the T-shape 5^{th} and 7^{th} (10% Df) tuned filters with 6% Lac and 3% Ldc

Appendix A2

Matlab M-file code

%Single Tuned Shunt Filter Design (July 2011)

```
clc;
%P1=3000;
%P2=30*10^3;
%P3=3e5;
%----------------- Given data -----------
VLL=400;%line to line Voltage
F=50;
P=input('type P(kW)= ');%Load Power
% X=input('type Lac%= ');%Line reactor AC side Percentage
% y=input('type Ldc%= ');%DC side inductor percentage
% I5h=input('type I5%= ');%
% I7h=input('type I7%= ');
% I11h=input('type I11%= ');
% I13h=input('type I13%= ');
%detunning
%-----------------------------------------
Rs=(40e-3)/1.0;%source Line resistor
Ls=(1.05e-4)/1.0;%source line inductor
W=2*pi*F;
%i=sqrt(-1);
Zsource=Rs+i*W*Ls %source impedance
Pkw=P*1000;
Vdc=(3/pi)*sqrt(2)*VLL %DC link capacitor voltage
Idc=Pkw/Vdc %DC current
B=sqrt(2/3);%RMS factor for quasi square line current waveform
Ir=B*Idc%the rms value of the line current
Rdc=Pkw/Vdc
Vr=VLL/sqrt(3);
Zb=Vr/Ir %Z base
Lacper=6
Ldcper=3
Lac=((6/100)*(Zb/W))
Ldc=((3/100)*(Zb/W))
%-----------------------------------------
%-------- design the filter ---------------
u1=1-(2*W*(Lac+Ls)*Idc)/(sqrt(2)*VLL)
u=acos(u1) % it is Radian 180*u/pi
%U=180*u/pi%
phi=u/2 %DPF(displacement power factor angle)
phideg=180*phi/pi%
Q_rectifier=Pkw*tan(phi);
Q_filter=Pkw*(tan(phi)-tan(0);
Q5=Q_filter*0.75; %Composition
Q7=Q_filter*0.25; % Composition
C5th=Q5/(W*VLL^2)
C7th=Q7/(W*VLL^2)
% L5=1/((2*pi*250*0.90)^2*C5th)%at detuning 10%
% L7=1/((2*pi*350*0.90)^2*C7th)%at detuning 10%
L5=1/((2*pi*250*0.97)^2*C5th)%at detuning 3%
L7=1/((2*pi*350*0.97)^2*C7th)%at detuning 3%
  for j=1:1000
Freq(j)=(1.0*j);
W(j)=2.0*pi*Freq(j);
%Z=i*L5*W(j)+1/(i*W*C)
Z5(j)=i*L5*W(j)+(1/(i*W(j)*C5th));
Z7(j)=i*L7*W(j)+(1/(i*W(j)*C7th));
Z57(j)=Z5(j)*Z7(j)/(Z5(j)+Z7(j));
```

```
 ZP(j)=Z57(j);
%the magnitude of the parallel filter impedance:
ZPMAG(j)=abs(ZP(j));
ZLINE(j)=i*(Lac+Ls)*W(j);
Zlineabs(j)=abs(ZLINE(j));
  end
figure(1)
plot(Freq,ZPMAG,'-',Freq,Zlineabs),axis([0 700 0 150.00])
xlabel ('Frequency(Hz)')
ylabel ('Zfilter and Zline(ohm) ')
title ('Characterisitics impedance at detuning (3%)')
grid
figure(2)
plot(Freq,ZPMAG,'-',Freq,Zlineabs),axis([200 400 0 60.00])
xlabel ('Frequency (Hz) ')
ylabel ('Zfilter and Zline (ohm)')
title ('Characterisitics impedance at detuning (3%)')
grid
 %-------- performance estimation ------------
 %now estimate the line current harmonics and the line current THD:
 IRECFUNDP=(2.0*(sqrt(3))/pi)*Idc;%1.1*Idc
 for jk=5:2:13
     FS(jk)=(50.0*jk);
     WS(jk)=2.0*pi*FS(jk);
     %------------------------ Lookup table or FFT ----------------
     IHS(5)=IRECFUNDP*0.2716;
      IHS(7)=IRECFUNDP*0.0863;
       IHS(11)=IRECFUNDP*0.058;
        IHS(13)=IRECFUNDP*0.0382;
%          IHS(17)=IRECFUNDP*0.0184;
%           IHS(19)=IRECFUNDP*0.0174;
%           IHS(23)=IRECFUNDP*0.009;
%           IHS(25)=IRECFUNDP*0.0082;
%           IHS(29)=IRECFUNDP*0.0063;
%           IHS(31)=IRECFUNDP*0.0053;
%           IHS(35)=IRECFUNDP*0.0039;
%           IHS(37)=IRECFUNDP*0.0036;
%           IHS(41)=IRECFUNDP*0.0025;
%           IHS(43)=IRECFUNDP*0.0027;
%           IHS(47)=IRECFUNDP*0.0025;
%           IHS(49)=IRECFUNDP*0.0021;
        %----------------------
     %IHS(jk)=IRECFUNDP*(1/jk);%
     ZLS(jk)=i*(Lac+Ls)*WS(jk);
     Z5S(jk)=i*L5*WS(jk)+1/(i*WS(jk)*C5th);
     Z7S(jk)=i*L7*WS(jk)+1/(i*WS(jk)*C7th);
     Z57S(jk)=Z5S(jk)* Z7S(jk)/(Z5S(jk)+ Z7S(jk));
     ZPS(jk)=Z57S(jk);
     abzps(jk)=abs(ZPS(jk));
     abzls(jk)=abs(ZLS(jk));
     ILH(jk)=(abs(ZPS(jk)))*(IHS(jk))/(abs(ZPS(jk)+ZLS(jk)));
     IFH(jk)=(abs(ZLS(jk)))*(IHS(jk))/(abs(ZPS(jk)+ZLS(jk)));
 end
 THDIREC=sqrt((IHS(5)^2+IHS(7)^2+IHS(11)^2+IHS(13)^2)/(IRECFUNDP^2))
THDILINE=sqrt((ILH(5)^2+ILH(7)^2+ILH(11)^2+ILH(13)^2)/(IRECFUNDP^2))
 figure(3)
 plot(FS,abzps,'o',FS,abzls,'+'),axis([0 700 0 60.00])
 xlabel('Frequency (Hz)')
 ylabel('Zfilter and Zline (ohm)')
 title('ZLINE + and ZFILTER o')
 grid
```