Cape Peninsula
University of Technology

DESIGN AND DEVELOPMENT OF MEDIUM VOLTAGE OPEN RACK HARMONIC FILTERS FOR DISTRIBUTION NETWORKS

by

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Thesis submitted in fulfilment of the requirements for the degree

Master of Technology: Electrical Engineering

in the Faculty of Engineering

at the Cape Peninsula University of Technology

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Cape Town

August 2013

DECLARATION

I, Alan Henry Micheni Meru, declare that the contents of this thesis/dissertation represent my own unaided work, and that the thesis/dissertation has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed **Date**

ACKNOWLEDGEMENTS

I would like to thank Almighty God for giving me the strength and ability to do all that was required to complete this thesis.

I acknowledge with gratitude the following people, companies and institutions for their valuable contributions towards this study:

First and foremost I wish to express my sincere gratitude to my erudite supervisor, Prof Gary Atkinson-Hope for his unwavering commitment, enthusiasm, encouragement and tireless academic assistance.

Willem Christofel Stemmet, my late colleague and friend, for the support and assistance given during the research.

My parents deserve special mention for their inseparable support and prayers. I am deeply and forever indebted for their love, encouragement and understanding throughout my entire life. I am also grateful to my brothers and sister.

Mr Jeremy Wood and Mr Kyle Lass of RWW Engineering, Mr Kelvin Talbot of formerly HVT, Mr Bryan Jones of Redwing Technologies, Mr Chris De Kock of ABB, Mr Johan Redelinghuys of Westingcorp Capacitors and lastly Mr Bernhard Cronje and Chris Terleblance of DRA. All firms are in Johannesburg where the interviews were conducted.

Mr Jeremy Wood and Mr Kyle Lass of RWW Engineering and Mr Berhard Cronje of DRA for the photos of harmonic filters used in this work and pamphlets on filter installation.

Mr Garreth Rose and the staff of the Heavy Current Lab at the Department of Electrical Engineering, CPUT, for their support and willingness to assist in some of the experiments. My colleagues at work for providing a conducive atmosphere throughout the research.

My friends Prof. Mugendi M'Rithaa, Dr Patrick Ndakidemi, Allan Omari, Ng`ang`a Kibandi for their friendship, motivation and assistance towards this study.

The financial assistance of the Seed funding (CPUT Research funds) towards this research is acknowledged. Opinions expressed in this thesis and the conclusions arrived at, are those of the author, and are not necessarily to be attributed to the CPUT Research Funds.

DEDICATION

The late Willem Christofel Stemmet, a good friend and colleague. Gone too soon.

ABSTRACT

Harmonic voltages and currents in distribution networks are on the increase in recent times due to the introduction of a proliferation of electronic controlled devices such as variable speed drives. These non-linear devices improve efficiency but distort the supply waveforms. To address the harmonic issues, harmonic filters are used to mitigate distortion levels and prevent damage. These harmonic filters are commonly found at medium voltage levels in power systems. The problem is that knowledge from the design to commissioning stages of these medium voltage harmonic filters are neither well developed nor adequately documented. The aim of this research is to investigate and expound upon the process whilst taking into account all the factors involved throughout the process from bringing such a filter into operation in the real world.

Medium voltage harmonic filters are usually the open rack type found in outdoor installations. Capacitors and reactors are the main components used in the construction of such harmonic filters and in some instances resistors are also used. The physical size and spacing of such components determines the construction layout area and how this is done in practice warrants being researched and explained in this thesis.

In order to make these factors explicit, a methodology is developed from design, to installation and commissioning and is applied to two networks which are used to prove that the developed methodology is applicable for the different types of harmonic filters designed. The network voltage levels are also different, thus implying that the components will have different design factors. The final arrangements of the harmonic filters are later drawn and shown in three-dimension (3D) as per dimensions. The 3D figures are a further contribution as the design is taken from theory and is ultimately implemented into an installation and construction layout for erection at site.

Interviews and surveys are conducted with specialists in industry dealing with harmonic filter applications and the results are analysed as part of implementation of the developed methodology.

The design, installation and construction phases are documented and shown to be effective in application and the work disclosed in this thesis will help newcomers to this specialised field and is recommended for use in industry.

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GLOSSARY

A	**Amp, Unit of current**
ASD	**Adjustable speed drive**
C	**Capacitance**
C_1	**Capacitance at fundamental frequency**
f_1	**Fundamental frequency**
f_r	**Resonant frequency**
h_1	**Harmonic at fundamental frequency**
HD_V	**Individual voltage distortion**
HD_I	**Individual current distortion**
Hz	**Hertz, Unit of frequency**
L	**Inductance**
L_1	**Inductance at fundamental frequency**
P	**Active power absorbed by loads**
PCC	**Point of common coupling**
PF_{TRUE}	**True power factor**
PF_{DPF}	**Displacement power factor**
Q_1	**Reactive power at fundamental frequency**
Q_f	**Quality factor**
R	**Resistance**
R_1	**Resistance at fundamental frequency**
THD	**Total harmonic distortion**
THD_V	**Total harmonic voltage distortion**
THD_I	**Total harmonic current distortion**
V	**Volt, Unit of voltage**
VA	**Volt Ampere**
Var	**Volt Ampere Reactive**
V_1	**Voltage at fundamental frequency**
Vr	**Rated voltage**

VSD	**Variable speed drive**
W	**Watts**
X_C	**Capacitive Reactance**
X_L	**Inductive Reactance**

CHAPTER ONE: INTRODUCTION TO THE STUDY

1.1 Introduction

This thesis addresses the challenges of design, installation and commissioning of harmonic filters. Whereas adequate literature address the theoretical issues related to the aforementioned, very little literature exists on actual construction of real life harmonic filters. Additionally even less literature is available for analysing the effectiveness of existing harmonic filters in general. This first chapter presents a background and research considerations for the design, installation and commissioning of open rack medium voltage harmonic filters.

1.2 Background

Advances in technology have led to new types of electrical equipment being used in power networks. The applications of these new types of equipment has been growing at a tremendous rate in the last decade and are typically electronic controlled devices (non-linear loads) such as inter alia, variable speed drives, personal computers, uninterruptible power supplies, and battery chargers. These electronic controlled devices cause harmonics to penetrate distribution networks. With the increase of such devices some drawbacks arise in power networks. The currents drawn by such loads are no longer sinusoidal and become distorted. These distorted waveforms can be decomposed into harmonic components and are known as harmonics.

Capacitors in networks are used for reactive power compensation and/or power factor correction. When a capacitor is present harmonic resonance can occur which causes amplification of voltages and currents and this can get to unacceptable levels and cause damage to network components (Atkinson-Hope & Folly, 2004:1393).

The use of the passive harmonic filter is one of the most common techniques used to mitigate unacceptable levels of harmonic distortions (Babrzadeh et al. 2011:973, Pragale et al., 2011:1201).

1.3 Problem Statement

Harmonic mitigation is a technique applied in networks to reduce unacceptable distortion levels to acceptable values. The theoretical method for designing harmonic filters is well known. What is not commonly known is how to take a design through the various stages of installation and commissioning process, especially medium voltage open rack type outdoor harmonic filters commonly found at large mines and factories

Cooper et al., 2013:1043). This process knowledge is not well documented and is in the hands of some specialists and this shortcoming is what this work wishes to overcome and in so doing help demystify this specialised field and provide a platform that can be applied in industry

1.4 Need for Research

There is thus a need to investigate and document the design, installation and commissioning process and in so doing bring forth the important factors that need to be taken into account when taking this process from theory to a fully installed and commissioned medium voltage harmonic filter in the field. Design of existing and non-existent networks needs to be considered in terms of data to be used in the design. The use of measurements for existing plants and simulations for non-existent plants is emphasised (Allenbaugh et al., 2013:1161; Cooper et al., 2013:1043). The work includes investigating types of capacitors, reactors and resistors used in the filters. The physical sizes of the components are explored. Details of how these are determined for real world applications are obtained from manufacturers. Their sizes and layout when arranged for construction are determined by the site space available. There is also a further need to investigate all the other factors that contribute to the open rack type harmonic filter process and this needs to be shown to be effective by applying this process to different networks.

1.5 Research boundaries

In this research, open rack harmonic filters will be designed and the installation and commissioning process explained for such filters. Open rack harmonic filters are outdoor installation filters consisting of capacitor banks in stacks with air core reactors and in some cases resistors are included. Simulations and calculations will be used to verify the developed methodologies in three scenarios. Networks will be modelled in frequency and harmonic domain and results analysed. The harmonic filter parameters will be calculated and manufacturer inputs are considered. The factors that need to be considered for the installation and commissioning of such filters are looked at in detail. The medium voltage levels considered in this work are in the range of 4.16 kV to 12 kV. Electrical protection of the harmonic filters will be discussed but only in broad detail.

1.6 Main contributions of the thesis

In this investigation open rack type harmonic filters are designed, taking into account specifications provided by manufacturers and/or suppliers of filter components. Power networks will be modelled using simulation software and load flows will be conducted. Harmonic penetration and resonance is analysed in case studies. Next, all factors needed for installation and commissioning of such filters are considered and elaborated in detail. A methodology is developed and demonstrated taking into account all factors needed for the design, installation and commissioning process and in particular three dimensional (3D) site layout drawings which are an essential requirement needed to make this work relevant to industry is included.

1.7 Outline of Thesis

The outline of this thesis is per chapter:
Chapter 2 is literature review of what is known in the field of harmonic filters, the significance and the need for this research to be conducted in the field.

Chapter 3 provides a background addressing concepts and theory relating to harmonics.

In Chapter 4, the contribution of the thesis is explained and includes a flow chart of the whole process on design of filters. 3D figures of final filter products are shown. The methods and formulas used in design of harmonic filters and data required for such design are looked at. The components used for the filters are elaborated with details of what is sent to manufacturers.

Chapter 5 looks at the aspects involved in the installation of harmonic filters looking at the component sizes and connections. The steps followed in commissioning of harmonic filters including tests done before hand over of filters to clients are elaborated. A flow chart on installation and commissioning is included in the chapter.

In Chapter 6, two different networks are investigated and harmonic analysis is conducted with each scenario explained. Software packages are used to analyse load flows, harmonic injections and impedance graphs of the networks with and without harmonic filters.

In Chapter 7, the results obtained from three scenarios in chapter 6 and interviews conducted with specialist engineers in industry dealing with harmonic filters are analysed and findings made.

In Chapter 8, conclusions are made from the work conducted in the thesis and explained. Finally ideas on any future research related to the topic are detailed for future purposes.

1.8 Summary

This chapter looks at sources of harmonics and mitigation of harmonics employing harmonic filters. The lack of information on harmonic filter design, installation and commissioning is elaborated and the need for the knowledge to be available is the main objective of this investigation. The thesis layout is also part of this chapter.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

This chapter presents an overview and critical analysis of available literature with respect to the field of harmonic filters. As will be discussed subsequently, very little information is available on the design of real life or practical harmonic filters. Notwithstanding, the installation and commissioning of harmonic filters is deemed feasible through the application of theoretical principles.

2.2 Background

Lemieux (1990:483-488) used a case study to investigate harmonic distortion and used a passive filter as a corrective measure to reduce effects of harmonic resonance. The work disclosed the calculation procedure for designing a filter making use of a power factor correction capacitor.

Similarly, Makram et al. (1993:1176-1183) also studied the design of shunt harmonic filters. The work disclosed a methodology for filter design. A shunt filter typically comprising of a capacitor (C_1) and non ideal reactor (L_1) having a resistance (R_1) is designed where C_1, L_1 and R_1 are parameters at fundamental frequency (f_1). A single tuned filter is designed to reduce the impact of a specific harmonic (h). The filter does this by tuning, which is making the inductive reactance at “h” equal to the capacitive reactance at “h”.

Syed and Cascadden (1995:841-847) addressed basic concerns on the need for harmonic filters and their influence on displacement power factor (PF_{DPF}, Power factor at f_1) with variable speed drives (VSDs). Harmonic currents drawn by VSDs were used for harmonic analysis. The harmonics were related to the pulse number using the equation:

$$h = (pn) \pm 1 \qquad (2.1)$$

Where

h is the harmonic number

p is the pulse number of the VSD

n is an integer having values of 1, 2, 3…..

They investigated cases where multiple VSDs are present in a network and proposed steps to be used when designing a harmonic filter with VSDs present. They proposed the idea that manufacturer specifications for harmonic currents for VSDs should be used for filter design. They also proposed that filters should be tuned slightly lower than the nominal resonant frequency for the reason that resonance changes due to temperature and age.

McGranaghan and Muller (1999:312-318) investigated the voltage and current harmonic limits and their applications to typical industries employing *adjustable speed drives* (ASDs) in relation to IEEE-519-1992 standard. They demonstrated harmonic filter design procedures to handle harmonics produced by ASDs and their main contribution is an example of how a 4.7^{th} tuned filter is designed.

In 2001, Nokian capacitors came up with the instructions for installation, operation and maintenance of high voltage capacitors and capacitor banks with voltages over '1000V'. The manual discussed the construction of the capacitor unit and capacitor bank. Factors such as ambient temperature, overvoltage, over current and harmonics are addressed in the manual. Issues of switching current transients in single and multiple banks together are addressed and transient voltages when switching on are discussed. The main factors for selecting circuit breakers in capacitor banks are well explained. The installation method for capacitor banks is explained. Before banks are commissioned, the manual also gives some of the factors to be checked.

In 2002, Nokian capacitors published instructions for installation, operation and maintenance of air core reactors. The manual had instructions on safety while working on reactors. Steps to consider before working on or near reactors are given. Issues of electromagnetic compatibility explaining why large metal structures should not be in the vicinity of the reactors are part of the manual. Packaging, transportation and handling of reactors are clearly explained and also unpacking the reactor. Different ways of mounting reactors is explained i.e. coils either in rows or stacks. The electrical and earth connections of the reactors and final inspection of the reactors as per tightness of joints is explained. The maintenance of the reactors is explained taking into account the environmental factors.

General Electric (n.d.) published instructions for stacking racks in high voltage capacitor equipment for power factor improvements. The guide covers practices in receiving, handling, installation, fusing, field testing and disposal of capacitor units. Protection against electrical shocks is done by grounding banks via internal discharge resistors. The construction and arrangement of the banks in racks is detailed and considers devices such as breakers, switches and controls. Electrical connection of capacitor racks is also disclosed. Spacing of reactors and other structures or fences is clearly stipulated. GE shows ways of connecting capacitors i.e., ungrounded wye, grounded wye, delta or double wye neutral are differentiated. This is done having a number of capacitor groups in series and parallel. Protection from lightning using line type arrestors is explained. Switching of banks in relation to transient currents and voltages are looked into as well as ambient temperature when the banks operate.

(Das, 2004:232-242) covers the limitations and constraints in harmonic filter design, such as filters not being effective under changing system conditions.

Atkinson-Hope and Folly (2004:1393-1399) developed a three stage process for making harmonic resonance mitigation in networks. The first stage was to decide whether resonance levels are extreme. The second stage was to determine the severity of the resonance and decide on different sizes of capacitors as to which size is the most desirable. The final stage was to decide if mitigation was needed in such a network. The load profile was looked at in deciding the capacitor values. The load was categorised in three levels i.e. minimum (s_1), mean (s_2) and full load (s_3) where each level had its own capacitor bank. Existing plants data is obtained using measurements over duration of time (say 7 days). Non-existent plants used a method of “relative heights” to predict the data of such a network. A network was investigated in the case study and it was found that mitigation was not necessary. At the end, it was found that the developed decision theory was effective in application.

Nassif et al. (2009:1710-1718) investigated the different harmonic topologies and the processes and procedures followed in determining the final filter design. It was noted that in some filter applications, different filter combinations could be used to achieve the required filtering goals. Emphasis is on the filter design considered, the filter performance, cost, component stress level and electrical losses. The filters at the same time were used for reactive power compensation. A methodology was derived with a flow chart on filter selection. A network was investigated and different filter configurations were considered and elimination was done to find the most suitable filter combination for harmonic mitigation.

Badrzadeh et al. (2011) conducted harmonic analysis and harmonic filter design for an aluminium smelting plant at 132 kV factoring in any scenarios that can affect the filters such as temperatures up to 45^{o}C. The design considered all the factors involved in harmonic filters starting with providing reactive power compensation with minimal costs. Power System Analysis software purchased was used for the harmonic penetration analysis and filter design. The design considered the tuning harmonic order, filter type i.e. tuned or damped, filter size (in Mega Vars), filter quality factor Q and number of filter branches. The two most commonly used filters i.e. single tuned and second order were designed using formulas shown. Different filter configurations and combinations were derived and the most effective was selected. The selection also considered cost since more filters mean higher costs. To minimise filter maintenance costs, all filters components were of the same rating. Three damped filters tuned at the 6.8^{th}, 10.8^{th} and 16.7^{th} frequencies were used with a single tuned filter tuned at the 4.8^{th} frequency. To verify the filter selections, harmonic impedance sensitivity plots of the filters were produced. Filter component rating i.e. capacitors, reactors and resistors was done considering factors such as peak current, rms voltage, peak voltage and reactive power. The capacitors were rated at 145kV to allow for system over voltages with circuit breakers rated at 170kV.

Later, Pragale et al. (2011) designed harmonic filters for a bleach production facility that consisted of three rectifiers. Each rectifier had a 5 stage harmonic filter i.e. 5^{th} (4.8), 7^{th} (6.8), 11^{th} (10.8), 13^{th} (12.8) and 17^{th} (16.8) designed. The plant was exposed to various loading situations and capacitor combinations and the response investigated. Each filter had a rating of 1950 kVar. The authors developed tables with the specifications of each of the five harmonic filters. Each table showed the currents through the filters for each harmonic till the 25^{th}. The filter capacitors were rated at 39490 V unlike the system 34500 V to cater for voltage rises at switch on. Over current protection was set at 135% of rated current and the capacitors at 180% of rated current. For cheaper maintenance, standard capacitors of 100 and 150 kVar were used. Unbalance protection was connected on wye capacitors so as to set the alarm in case of loss of a capacitor can and tripping the filter bank in case of loss of two or more capacitor cans.

In 2013, Allenbaugh et al. (2013) conducted harmonic analysis of a new rectifier and designed a multi stage harmonic filter to mitigate harmonic and support voltage. At the same time, analysis of possible interaction of the harmonic filter with a nearby reactive compensator was looked at. On-site measurements and network modelling were used for the study. The measurements were conducted by installing power quality analysers in the electrical distribution system to determine power and harmonics at each substation. The measurements were conducted on existing loads on the network before the rectifier was installed. With this information, the expected operating scenarios of the rectifier and multi stage harmonic filter were considered. The results were able to identify any existing problems that needed to be looked into and the necessary solution of a 5^{th} harmonic filter and any modifications to the network were brought in. One of the main recommendations of this paper was that measurements are necessary to verify filter performance. These measurements are taken over a certain period of time as they consider different load conditions. Lastly, it was advised that designers need to spend time to perform power studies before specifying mitigation solution equipment.

Cooper et al. (2013) proposed a systematic approach for power factor correction for Medium voltage networks. This was done by conducting measurements to consider the loads and harmonic content. The measurements were conducted for 12 months as this was adequate to verify kVar needed. Computer simulations on the systems harmonic content were considered in terms of filtering and resonance mitigation. Harmonic analysis on the network was evaluated on the basis of IEEE Std. 519-1992 limits. The studies were done in three scenarios i.e. existing system without capacitor, with a capacitor bank for power correction and with designed filter in the network. It was concluded that a systematic approach is needed in MV PF design as if not done well unexpected consequences can come up in such a network. Load flows, harmonic measurements and harmonic analysis were conducted to determine reactive compensation using capacitors and filters to be used in the network.

Post Glover (n.d.) published a document that gives a description of harmonic filter resistors. The site discusses all the factors that are considered in the manufacturing of harmonic filter resistors that are discussed. These include power dissipation, resistance value, voltage/insulation class and current rating. At the same site, a specification for the data that harmonic filter resistors need to feed in when requesting for harmonic filter resistors. In specifications, issues of environment conditions, connection, accessories, enclosures and enclosure finish are given.

2.3 Typical harmonic filters

Figures 2.1 and 2.2 show typical harmonic filters found in industry. The most commonly used filters are the series tuned and second order.

Figure 2.1: Series tuned harmonic filter at site

Figure 2.2: Second order harmonic filters at site

2.4 Short comings of previous work

From literature reviewed very little is documented about MV open rack harmonic filters. The IEEE Std. 1623-2004 defines medium voltage as a range of (1kV <kV < 35kV). This qualifies the work done in this thesis to be placed in the medium voltage range as will be seen in the case studies.

Different approaches to filter design have been reviewed and the literature discloses work on harmonic filter design. Virtually no references are found on the overall installation and commissioning of harmonic filters, nor on open rack harmonic filters. What however is found is separate literature about capacitors and reactors from specific manufacturers. However, knowledge on how to combine these components into an MV rack type filter is restricted and known to only a few specialists. There is thus a need to research and establish the knowledge that is known to demystify this important topic by encapsulating the whole process into a single document that is easily readable and make a contribution to this field and in so doing fulfilling a need desperately needed.

2.5 Summary

This chapter reviews the work done by authors on harmonic filter design and the factors to be considered are established. Manufacturers of filter components have developed manuals for the installation of their individual components. Incidentally these manuals are only available to clients when the components are delivered. This shows that very little information is in the public domain on the installation and commissioning of harmonic filters. This shows the lack of information on such topics and the need for this contribution, which will be the first of its kind on this topic.

CHAPTER THREE: HARMONIC FILTER THEORY

3.1 Introduction

This chapter explores the developments and scope of applications of several theories relating to harmonic filter design. A number of commentators acknowledge the fact that there are a number of practical challenges associated with real world applications of these theories. Consequently a number of theories from related domains are interrogated for their appropriateness and practicality in terms of harmonic filter design and implementation.

3.2 Basic concepts

3.2.1 Harmonic voltages and currents

Harmonics are currents and voltages that are integer multiples of the fundamental frequency. For instance a waveform having a frequency of 250Hz in a 50Hz supply network will have the 5th harmonic. Other typical harmonic values are the 7^{th} (350Hz), 11^{th} (550Hz), and so on.

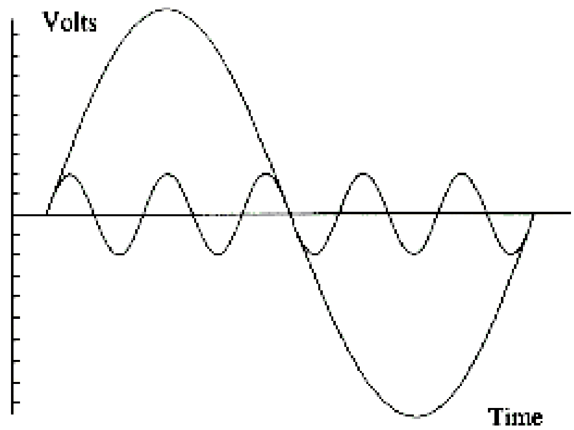


Figure 3.1: Fundamental and 5^{th} harmonic waveforms

In Figure 3.1, we see only two waveforms, a fundamental frequency waveform together with a 5^{th} harmonic curve. These two waveforms can be synthesised into the complex wave ($\nu_{complex}$) shown in Figure 3.2, using:

$$\upsilon_{complex} = V_1 Sin\omega t + V_5 \sin 5\omega t \quad (3.1)$$

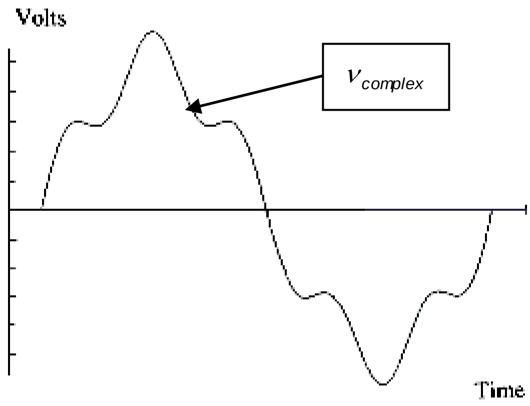


Figure 3.2: Resultant complex voltage for fundamental and 5th harmonics waveforms

Generally, complex waves contain many harmonics.

3.3 Resonance

For a given L and C circuit, inductive reactance (X_L) elements increase with increasing frequency while capacitive reactance (X_C) decreases with increasing frequency. When (X_C) equals the inductive reactance (X_L), resonance occurs. This frequency is called the resonant frequency (ω_r). It can be denoted that resonance occurs when:

$$X_{Lr} = \omega_r L = X_{Cr} = \frac{1}{\omega_r C} \qquad (3.2)$$

Implying that at resonant frequency

$$\omega_r = \frac{1}{\sqrt{LC}} rads/\sec \qquad (3.3)$$

Where

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (3.4)$$

There are two types of resonance: i.e. series and parallel (Arrillaga, J. 1988:110-113), (Wakileh, 2001:26-28).

3.3.1 Series Resonance

Figure 3.3 shows a series RLC circuit supplied from an ac voltage with a variable frequency (Wakileh, 2001:27-28).

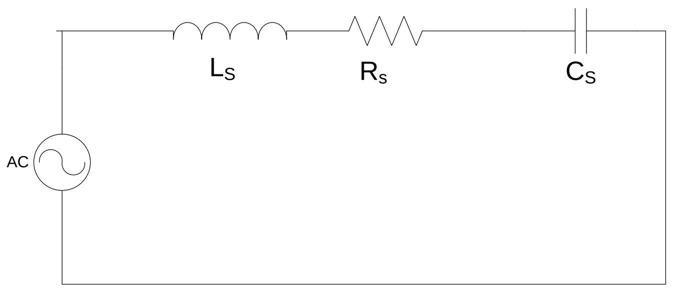


Figure 3.3: Series resonant circuit

As the frequency of the voltage source is varied both X_L and X_C vary. At the resonance frequency (f_r),

$$X_L = X_C \tag{3.5}$$

Figure 3.4 shows that the impedance (Z_S) of the circuit becomes a minimum, such that $Z_S = R_S$. The current in the circuit will be a maximum causing the voltage across each of the elements to be a maximum. Resonance can thus cause the elements to be damaged due to this rise in voltage and increase in current.

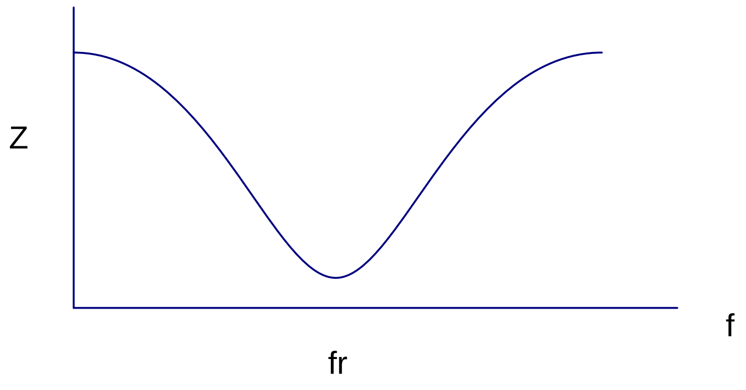


Figure 3.4: Impedance vs frequency for series resonant circuit

The value of R_S plays a very important role in the circuit. The greater the value of R_S, the smaller is the maximum current and voltages in the circuit and vice versa. This role is quantified by the index Quality factor (Q), where by:

$$Q = \frac{X_L}{R_s} = \frac{X_C}{R_s} \tag{3.6}$$

Thus at f_r ,

$$Q_r = \frac{X_L(f_r)}{R_s} = \frac{X_C(f_r)}{R_s} \tag{3.7}$$

A high Q_S value indicates that the circuit damping (value of R_S) is low and vice versa. When designing circuits that can be subjected to resonance, the selection of Q_r value to affect damping levels is essential.

At instances not f_r, the equivalent impedance of the circuit, say when $X_L > X_C$, is:

$$Z = R_s + j(X_L - X_C) \quad (3.8)$$

When a complex voltage is applied to the circuit, then for every harmonic (h) the impedance becomes:

$$Z(h) = R_s + j(hX_L - \frac{X_C}{h}) \quad (3.9)$$

And when, $hX_L = \frac{X_C}{h}$, harmonic resonance occurs and $Z(h_r) = R_s$.

Ignoring skin effect of R_S, the current flowing becomes:

$$I(h_r) = \frac{V(h_r)}{Z(h_r)} = \frac{V(h_r)}{R_s} \quad (3.10)$$

The current $I(h_r)$ will then be a maximum. The quality factor Q (h_r) is given by

$$Q(h_r) = \frac{X_r}{R_s} \quad (3.11)$$

Where X_r = either the inductive or capacitive reactance at h_r (Wakileh, 2001:28).

3.3.2 Parallel Resonance

Figure 3.5 shows a parallel circuit supplied from an ac voltage with a variable frequency.

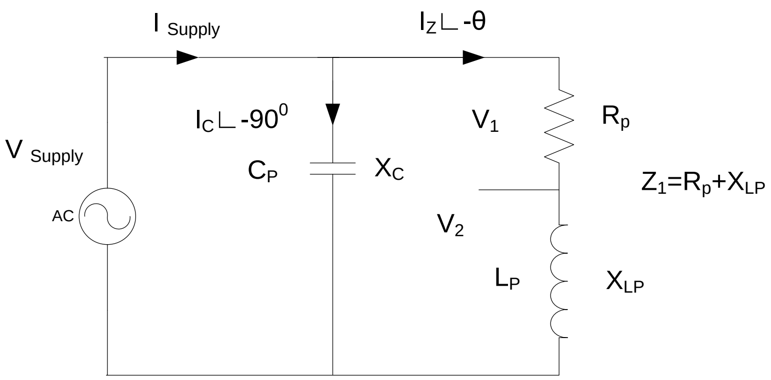


Figure 3.5: Parallel resonant circuit

The current through the inductive branch is

$$I_Z = \frac{V}{\sqrt{\{R^2 + (2\pi fL)^2\}}} \quad (3.12)$$

And the phase angle between I_1 and V is;

$$\phi = \tan^{-1} \frac{2\pi fL}{R} \quad (3.13)$$

R is taken to be very small in respect to $2\pi fL$, therefore ϕ is close to 90^o . The current through the capacitor $I_C = 2\pi fCV$, is leading V_{supply} by 90^o .

In a situation where the resultant of I_C and I_Z , I_{Supply} is in phase with V_{supply} the network is said to be in resonance. At resonance (f_r), $I_C = I_Z Sin\phi$. Incidentally,

$$Sin\phi = \frac{2\pi f_r L}{\sqrt{\{R^2 + (2\pi f_r L)^2\}}} \tag{3.14}$$

Substituting for I_C , I_Z and $\sin\phi$ in the above equation the resultant becomes

$$2\pi f_r CV = \frac{2\pi f_r LV}{R^2 + (2\pi f_r L)^2} \tag{3.15}$$

There by resulting in

$$f_r = \frac{1}{2\pi}\sqrt{\left(\frac{1}{LC} - \frac{R^2}{L^2}\right)} \tag{3.16}$$

At resonance, the current through L and C can be many times greater than the resultant current. The supply current is thus greatly magnified such that,

$$\frac{I_C}{I_{supply}} = \frac{I_Z \sin\phi}{I_{supply}} = \frac{\sin\phi}{\cos\phi} = \tan\phi = \frac{2\pi f_r L}{R} = \text{Q factor of circuit} \tag{3.17}$$

In this case, Q factor is used for current magnification. The resultant supply current is in phase with the supply voltage with network impedance given as:

$$\frac{V}{I} = \frac{V}{I_C}\tan\phi = \frac{1}{2\pi fC}.\frac{2\pi f_r L}{R} \tag{3.18}$$

Therefore:

$$Z_r = \frac{L}{CR} \tag{3.19}$$

A resonant parallel network is equivalent to a non-reactive resistor of *L/(CR)* ohms where Z_r is termed as dynamic impedance of the circuit. (Hughes, 2012:319-320).

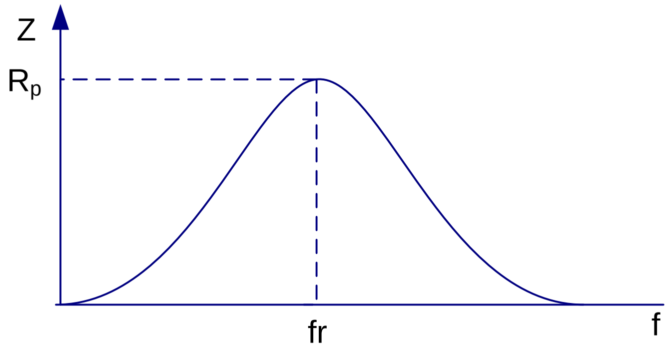


Figure 3.6: Impedance vs frequency for parallel circuit

Figure 3.6 shows that the impedance (Z_r) of the circuit at resonance becomes a maximum when $Z_r = R_P$. Likewise the current in the circuit becomes a minimum causing the voltage across the elements each also to be a minimum but the currents flowing in the capacitor and inductor become very high and can cause damage.

3.4 Power Factor Correction

3.4.1 Displacement Power Factor (PF_{DPF})

Most common loads on electrical systems are inductive and are typically induction motors, reactors and transformers. All the inductive loads require two kinds of power to function properly i.e. active power (W) – needed to perform the work and reactive power (Var) – to sustain electromagnetic field and allow the loads to operate. The resultant of the two is the apparent power demand (VA). Power factor is the ratio of (active) power to apparent power and determines how effective a load utilises current from an AC power system. Utility suppliers offer incentives to large consumers to increase their PF_{DPF} close to unity as this improves overall power supply effectiveness. When the only waveform present in a system is the fundamental f_1, Displacement Power Factor (DPF) is denoted by PF_{DPF} (Acha & Manuel, 2001:46; Wakileh, 2001:20).

$$DPF = \cos\theta = \frac{ActivePower}{ApparentPower} = \frac{P_1}{S_1} \qquad (3.20)$$

Where:

P_1 = Active power (Watts) at f_1

S_1 = Apparent power (Volt Amperes) at f_1

Power capacitors are used for power factor correction as they supply reactive power (Var).

3.4.2 Power Triangle

Capacitors are rated in electrical units called “Vars”. Each unit of capacitor Var decreases the inductive reactive power that is needed to be supplied. This effectively means lower resultant apparent power demand (VA).

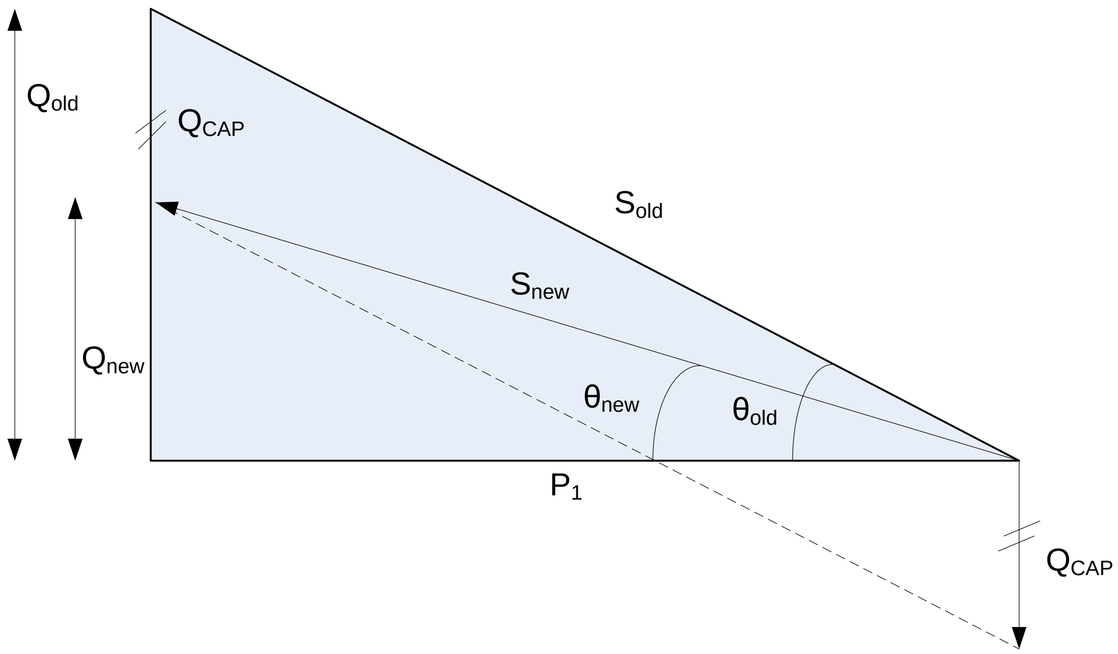


Figure 3.7: DPF triangle

Where:

P_1 is the total real power delivered by system (W)

Q_{OLD} is the reactive power (Vars) drawn by the load at specific loading conditions

S_{OLD} is the apparent power (VAs) drawn by the load at specific loading conditions

Q_{NEW} is the resultant system reactive power with capacitor connected

S_{NEW} is the resultant system apparent power with capacitor connected

θ_{OLD} is the original power factor angle at the specific loading condition

θ_{NEW} is the angle improved after power factor capacitor (Q_{CAP}) connection

Q_{CAP} is the reactive power delivered by capacitor bank i.e. (Q_{OLD} - Q_{NEW}) to improve θ_{OLD} to θ_{NEW}

With power factor correction using a capacitor, P_1 stays constant only the reactive power is altered through compensation.

The line current in a 3 phase network at f_1 is given by:

$$I_L = \frac{P_{3\Phi}}{\sqrt{3}V_L Cos\theta} \quad (3.21)$$

Where

$P_{3\theta}$ = 3 phase real power in Watts

$V_L =$ Line voltage in Volts

As VA is decreased, the maximum demand tariff payable is reduced. Most utilities recommend that customers have a DPF of 0.9 lagging and above. Tariffs vary per season of year such as winter season tariffs can be different from summer. According to (Kyle 2009), tariffs such as Mega flex recommend a DPF of 0.96 while KVA Night recommends a DPF 0.99. Depending on what type of load a consumer has, the utility supplier will implement a certain tariff. Customer improved DPF values mean lots of economic saving.

3.4.3 Sizing of capacitor bank

The size of the capacitor to be used for power factor correction is done mathematically working with the power triangle discussed above. This can be done for either a star connection or delta connection.

Step 1: Determine the PF_{DPF} of network.

Firstly determine the values of the real (P_1) and apparent power (S) at a specific loading, and voltage. Example is a 3 phase network operating at 11kV (line voltage) with real and apparent powers of 12kW and 16kVA. In this case, the Displacement power factor will be found as:

$$PF_{DPF} = \cos\theta = \frac{P_1}{S_1} = \frac{12}{16} = 0.75 \quad (3.22)$$

This means that the reactive power will be 10.58 kVar.

Step 2: Determine Q_{NEW} when PF_{DPF} is improved to 0.95.

The new value of apparent power (S_{NEW}) is determined by.

$$S_{NEW} = \frac{P_1}{PF_{DPFNEW}} = \frac{12}{0.95} = 12.63kVA \quad (3.23)$$

The new value of the (Q_{NEW}) is determined by using:

$$Q_{NEW} = \sqrt{\left(S^2 - P^2\right)} = \sqrt{(12.63^2 - 12^2)} = 3.939kVar \quad (3.24)$$

Step 3: Determine Q_{CAP} to improve PF_{DPF} to 0.95.

The value of capacitance to be used will be:

$$Q_{CAP} = Q_{OLD} - Q_{NEW} = (10.58 - 3.94) = 6.64kVar \quad (3.25)$$

Step 4: Determine new current in network.

The new current flowing in the capacitor will be:

$$I = \frac{Q_{CAP}}{\sqrt{3}V_L} = \frac{6.64K\,\text{var}}{\sqrt{3} \times 11kV} = 0.349A \quad (3.26)$$

Step 5: Determine capacitance per phase.

The capacitive reactance per phase will be:

$$X_C = \frac{\frac{V_L}{\sqrt{3}}}{I} = \frac{\frac{11kV}{\sqrt{3}}}{0.349A} = \frac{6351V}{0.349A} = 18.2k\Omega \quad (3.27)$$

Step 6: Determine capacitance per phase:

This can be done for the star connection at fundamental frequency of 50Hz as:

$$C_{STAR} = \frac{1}{2\pi \times f_r \times X_C} = \frac{1}{2\pi \times 50 \times 18.2 \times 10^3} = 0.175\mu F \quad (3.28)$$

For a Delta connection, the capacitance at fundamental frequency of 50Hz would be:

$$C_{DELTA} = \frac{0.175 \times 10^{-6}}{3} = 0.058\mu F \quad (3.29)$$

In this case a 0.175 μ F capacitor per phase in star or 0.058 μ F capacitor per phase in delta would be used to improve the power factor from 0.75 to 0.95 operating at 11kV.

3.5 True Power Factor

In situations where harmonics are present, the ratio of real power to apparent power is called true power factor and is denoted by True Power Factor (PF_{TRUE}) and calculated by the equation 3.30. This considers the power at each harmonic frequency (Acha & Manuel, 2001:46; Wakileh, 2001:20).

$$PF_{TRUE} = \frac{V_1 I_1 \cos\theta_1 + V_3 I_3 \cos\theta_3 + V_5 I_5 \cos\theta_5 + ...}{V_{rms} I_{rms}} \quad (3.30)$$

Where: $V_{rms} = \sqrt{\left(V_1^2 + V_3^2 + V_5^2 + V_7^2 + ...\right)}$ (3.31)

$$I_{rms} = \sqrt{\left(I_1^2 + I_3^2 + I_5^2 + I_7^2 + ...\right)} \quad (3.32)$$

When harmonics are not present in a network, $PF_{DPF} = PF_{TRUE}$.

3.6 Harmonic filters

The principles for designing the two most commonly used harmonic filters i.e. series tuned and second order are reviewed. These designs assume 100% loading of network where the filter will be installed.

3.6.1 Series tuned filter

Series tuned filters are used to mitigate the distortion effects of harmonic resonance dominated at a specific harmonic frequency. For a series tuned filter shown in Figure 3.8, the following steps show the methodologies for basic filter design (Wakileh, 2001:116-117).

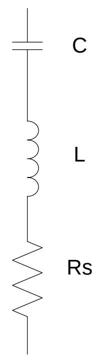


Figure 3.8: Series tuned harmonic filter

STEP 1:

The capacitor bank size (Q_C) for a 3 phase installation is first established. It is then used to determine its X_C value.

$$X_C = \frac{V_L{}^2(kV)}{Q_C(Var)} \tag{3.33}$$

Where

X_C is the capacitive reactance, allowing "c" to be determined

Q_C is the capacitor size in Vars used for power factor correction

V_L is the line to line voltage of the network

STEP 2:

To mitigate the harmonic (h_{tuned}), the reactor size can be calculated as:

$$X_L = \frac{X_C}{h^2{}_{tuned}} \tag{3.34}$$

Where

h_{tuned} is the harmonic to which the filter is to be tuned.

X_L is reactor size from which "L" can be determined.

STEP 3:

The reactors resistance (R_S) is found using equation 3.35. To determine R_S , a quality factor(Q_f) is chosen from the (30 < Q_f < 100) range - (Wakileh, 2001:116).

$$R_s = \frac{X_r}{Q_f}\Omega \qquad (3.35)$$

STEP 4:

The characteristic reactance X_r is found using:

$$X_r = \sqrt{X_C X_L} = \sqrt{\frac{L}{C}} \qquad (3.36)$$

Where

X_r = characteristic reactance

$L = \frac{X_L}{2\pi f_r}$ is the inductance henries

$C = \frac{1}{2\pi f_r X_C}$ is the capacitance in farads

STEP 5:

The filter size in Vars is thus:

$$Q_f = \frac{V^2(kV)}{(X_C - X_L)(\Omega)} \qquad (3.37)$$

Where

V = phase voltage

STEP 6:

The impedance of the filter at a value of $h \neq h_{tuned}$ is:

$$Z(h) = R + j(hX_L - \frac{X_C}{h}) \qquad (3.38)$$

When

$$hX_L > \frac{X_C}{h}$$

Or

$$Z(h) = R + j(\frac{X_C}{h} - hX_L) \tag{3.39}$$

When

$$hX_L < \frac{X_C}{h}$$

3.6.2 Second order harmonic filter

Second order harmonic filters are used to mitigate the distortion of a range of offending harmonics as opposed to series tuned filters that mitigate against a single harmonic. For a second order filter shown in Figure 3.9, the following steps show the principles for basic filter design (Wakileh, 2001:121).

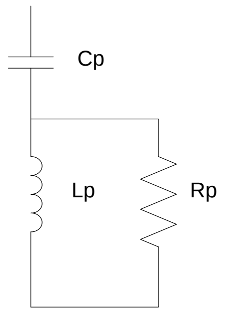


Figure 3.9: Secord order harmonic filter

STEP 1:

The capacitor bank size (Q_C) for a 3 phase installation is given as first established. It is then used to determine its X_C value.

$$X_C = \frac{V_L^{\,2}(kV)}{Q_C(Var)} \tag{3.40}$$

Where

X_C is the capacitive reactance, allowing "C" to be determined

Q_C is the capacitor size in Vars used for power correction

V_L is the line to line voltage of the network

STEP 2:

To mitigate the harmonic (h_{tuned}), the reactor size can be calculated as:

$$X_L = \frac{X_C}{h^2{}_{tuned}} \tag{3.41}$$

Where

h_{tuned} is the harmonic to which the filter is to be tuned.

X_L is reactor size from which "L" can be determined.

STEP 3:

The resistance (R_p) is found using equation 3.42. To determine R_p, a quality factor(Q_f) is chosen from the (0.5 < Q_f < 5) range.

$$R_p = X_r . Q_f \tag{3.42}$$

STEP 4:

The characteristic reactance X_r is found using:

$$X_r = \sqrt{X_C X_L} = \sqrt{\frac{L_p}{C_p}} \tag{3.43}$$

Where

X_r = characteristic reactance

$L_p = \dfrac{X_L}{2\pi f_r}$ is the inductance henries

$C_p = \dfrac{1}{2\pi f_r X_C}$ is the capacitance in farads

STEP 5:

The filter size in Vars is thus:

$$Q_f = \frac{V^2 (kV)}{(X_C - X_L)(\Omega)} \tag{3.44}$$

Where

V = phase voltage

STEP 6:

The impedance of the filter at a value of $h \neq h_{tuned}$ is:

$$Z(h) = \frac{jRhX_L}{R + jX_L} - j\frac{X_C}{h} \tag{3.45}$$

The current in the reactor and resistor are shown below respectively:

$$I_{L(h)} = \frac{R_P}{\sqrt{R_P{}^2 + X_{Lh}{}^2}} . I_{Fh} \tag{3.46}$$

$$I_{R(h)} = \frac{X_{Lh}}{\sqrt{R_P{}^2 + X_{Lh}{}^2}} . I_{Fh} \quad (3.47)$$

Where

I_{Fh} = total filter current

3.7 Harmonic Indices

3.7.1 Total Harmonic Distortion (THD)

The total harmonic distortion (THD), of a complex waveform is expressed as a ratio (Stemmet & Atkinson-Hope, 2006:34):

$$M_{THD} = \frac{\sqrt{\sum_{h=2} (M_h)^2}}{M_1} \times 100\% \quad (3.48)$$

Where *M* = voltage (V) or current (I)

M_h = Root mean square value of voltage or current at harmonic frequency “h”

M_1 = Root mean square value of voltage or current at f_1

h = harmonic frequency

If the waveform is for current I_{THD} is used and for voltage V_{THD} is used.

3.7.2 Individual Harmonic Distortion (HD)

The individual harmonic distortion (HD), of a waveform can either be in current (I_{HD}) or voltage (V_{HD}), respectively, for example.

$$I_{HD} = \frac{I_h}{I_1} \times 100\% \quad (3.49)$$

3.8 Harmonic Analysis Software

For the study of industrial networks, software packages have been developed to assist in analysis. For the work done in this thesis, ERACS - Electrical Power Systems Analysis Software, Version 3.7.2 is chosen. This package can be used to conduct simulations from a model that is developed for a network and do studies at fundamental frequency and in harmonic domain.

3.8.1 Load flow

Once a software model of a network has been built, it is normal practice to conduct a load flow at f_1. Load flow option calculates the steady state results. Voltage, current, PF_{DPF}, real and reactive power results are obtained. These results are then analysed to determine if all the components are adequately rated and that the voltages are within acceptable range (± 6%) of nominal voltage and that the powers delivered to the load is what customers need and also to check if the supply is suitable to meet the demand (Eracs Technical Manual, 2005: 4.3).

3.8.2 Harmonic Studies

ERACS, can also be used to conduct simulation studies in the harmonic domain. Harmonic sources (e.g. VSD`s) draw non-sinusoidal currents from a sinusoidal voltage source. (Eracs Technical Manual, 2005:4.37; 4.56) These harmonics are injected into the network and their penetration causes harmonic voltages. ERACS, besides harmonic penetration studies can also be used for harmonic resonance studies, whereby a frequency scan is generated from which it can be seen at which frequency it will occur.

The two simulation tools also enable THD and HD to be calculated for the network. Using penetration studies, the level of harmonic indices can be assessed likewise these indices can be also obtained at resonant frequency. These index results are then checked against a standard (IEEE 519) and if the limits are exceeded then mitigation in the form of a filter needs to be considered.

The harmonic source (VSD) is usually modelled using harmonic currents specified by their magnitudes together with their phase angles relative to the reference angle at the injection point. The software results can be used to generate the complex waveforms.

3.9 IEEE Std 519 - 1992

Tables 3.1 and 3.2 show the current and voltage harmonic limits as per IEEE Std 519-1992. The current values are determined from the ratio of the short circuit current to the load current at the PCC. For example, if the I_{SC} / I_L ratio is less than 20, any harmonic equal to or less than the 11^{th} should not have a harmonic current distortion (I_{HD}) greater than 4%. In terms of voltage range, voltages below and equal to 69kV should not have a voltage distortion (V_{HD}) values greater than 3% and the complex wave should not have a total harmonic distortion (V_{THD}) greater than 5%.

Table 3.1: Current Distortion Limits (I_{HD}) for General Distribution Systems (120V through 69,000V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd harmonics)						
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

Where:

I_{sc} is the short circuit current at the point of common coupling (PCC)

I_L is the maximum current the load is carrying at the PCC

Table 3.2: IEEE 519-1992 Recommended Voltage Distortion Limits

Bus voltage at PCC	**Individual Voltage Distortion (%)**	**Total Voltage Distortion THD (%)**
69 kV and below	3.0	5.0
69,001 kV through 161 kV	1.5	2.5
161,001 kV and above	1.0	1.5

This recommended guide is applicable to industrial systems when converters are used and is specified when problems relating to reactive power compensation and harmonic control are involved.

3.10 Filter Components

The main components used in harmonic filters are discussed below.

3.10.1 Capacitors

Each capacitor bank is constructed from a number of individual capacitors called elements. The elements are constructed of aluminium foil electrodes and dielectric of polypropylene film. To achieve the required voltage, the elements are connected in series and for power rating elements are connected in parallel. The capacitors used in open rack harmonic filters are available as internally fused, externally fused or fuseless. (http://www.hv-eng.com/2011CEDCapacitors.pdf, http://www.geindustrial.com/publibrary/checkout/Shunt%20Capacitor?TNR=White%20Papers|Shunt%20Capacitor|generic).

3.10.1.1 Internally fused capacitors

Figure 3.10 shows a diagram of an internally fused capacitor bank typically used in open rack type filters. The main components are insulators, capacitors and internal fuses. The fuse is a wire connected in series with each element in a capacitor bank. A fuse limits the current flowing in a capacitor element as it will fuse if its rated current is exceeded.

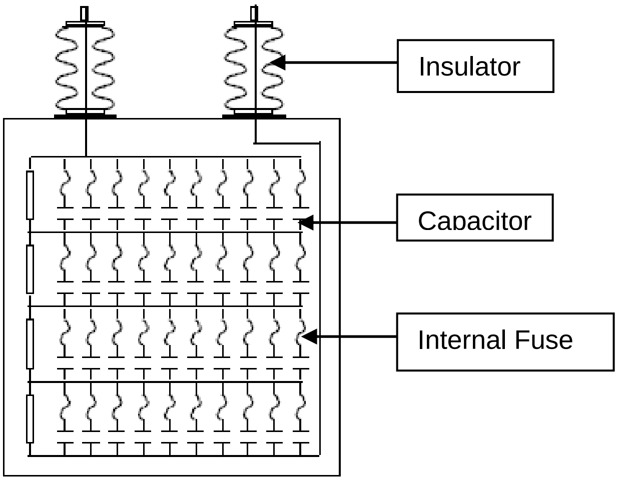


Figure 3.10: Internally fused capacitor bank

This type of bank has more series elements than parallel elements. Their design is such that if one element fails, the others can still operate but the voltage across the remaining elements increases. When 2 or 3 elements fail, the voltage across the bank will increase above an acceptable level and an unbalance relay will then trip the bank.

3.10.1.2 Externally fused capacitors

Externally fused also known as expulsion or current limiting capacitor banks have an external fuse connected to the supply. Figure 3.11 shows an externally fused capacitor bank showing the connection of the external fuse with the bushing. Failure of one element raises the voltage across the remaining elements. After 2 or 3 elements fail, the external fuse blows. They are used in small kVar size units and are easy to identify by blown fuses.

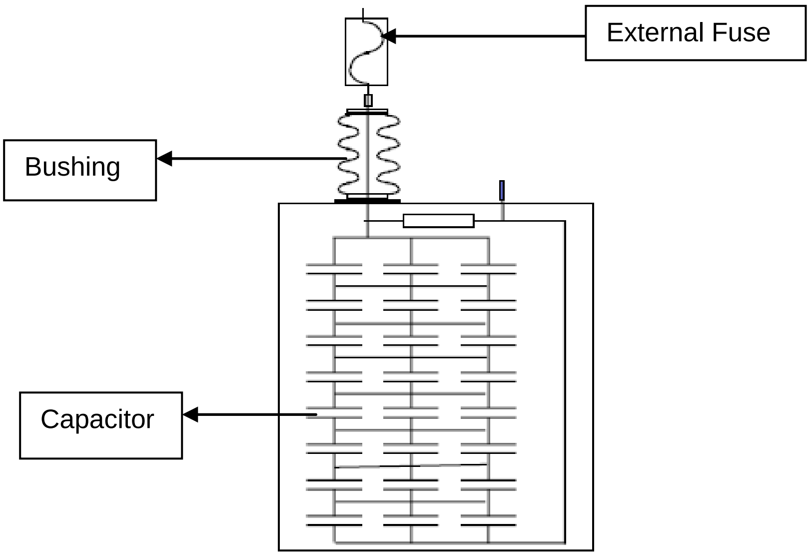


Figure 3.11: Externally fused capacitor bank

3.10.1.3 Fuseless capacitors

Fuseless capacitors have less than 10 elements in series thus the bank is not removed from service when one element fails due to volt drop. The fuseless capacitor banks (Figure 3.12) are used in banks where the rated voltages are above 35kV. Unbalance relays are used for protection. The advantage in using this type of bank is that they occupy limited space due to their design and easier installation due to fewer parts. There is no maintenance as no fuses need to be replaced and no nuisance tripping occurs due to faults induced by animals and birds.

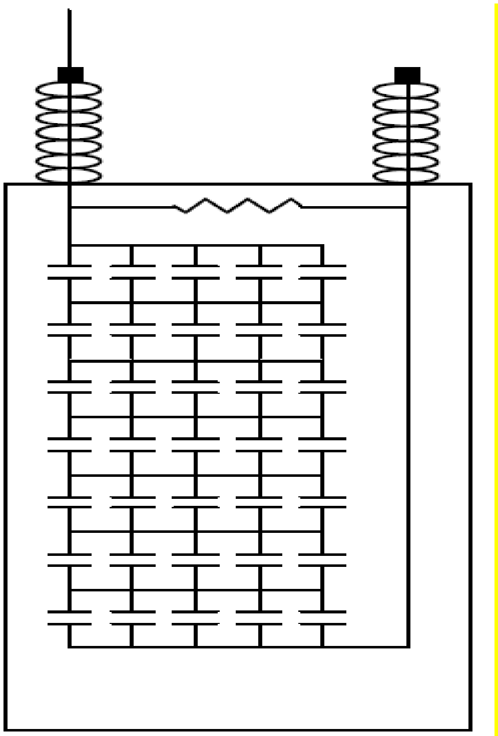


Figure 3.12: Fuseless capacitor bank

3.10.2 Reactors

Air core reactors (Figure 3.13) are used in harmonic filters and can cater for a wide range of currents and frequencies. They have accurate inductance values and are thus used in medium voltage applications due to the currents flowing in the filter. Due to the design parameters, they also have resistance which can be calculated by the designer. The reactor rating depends on:

i) Voltage

ii) Inductance value

iii) Power rating in Vars

iv) Current rating

v) Issues such as atmospheric pressure, corrosive environment, attitude, and seismic zone.

The windings are made from aluminium and wound in layers to achieve the rated values. Depending on available space at the installation site the reactors can be stacked horizontally or vertically. Insulators are put between the reactor phases.

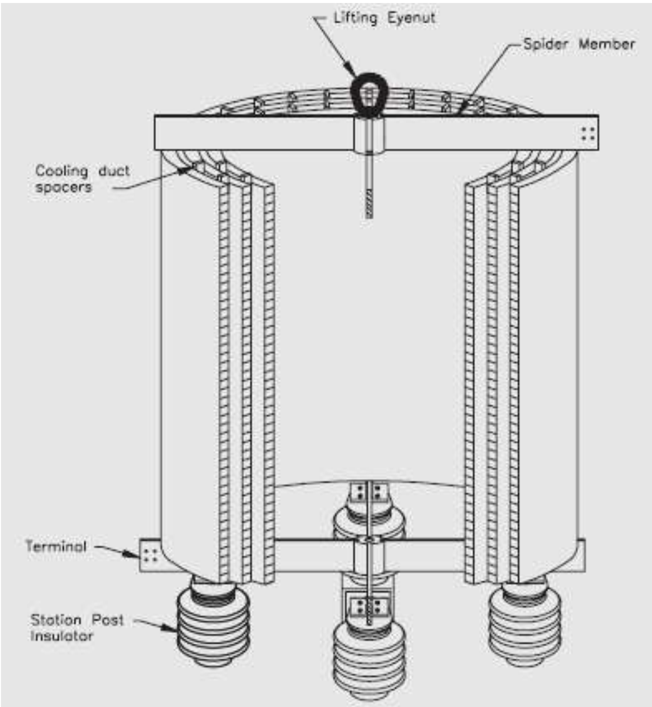


Figure 3.13: Air Core reactor (Source: Trenchgroup.com)

3.10.3 Resistors

A resistor bank is used in harmonic filters shown in Figure 3.14 to help to mitigate harmonic distortion. In such banks, the currents through them are dissipated as heat and lost in the system. The resistor material used is manufactured from nickel chromium stainless steel as they have high resistance to corrosion and oxidation plus can withstand high temperatures. Resistor rating is dependent on the values such as voltage, resistance value, power rating in watts, current rating and issues such as atmospheric pressure, corrosive environment, attitude, and seismic zone.

Resistors are used in 2nd order harmonic filters for damping and increasing the quality factor. Increased bandwidth increases the response of tuning frequency in order to increase immunity to frequency variation and component tolerances due to manufacturing and temperature. These resistors have a high positive thermal coefficient of resistivity.

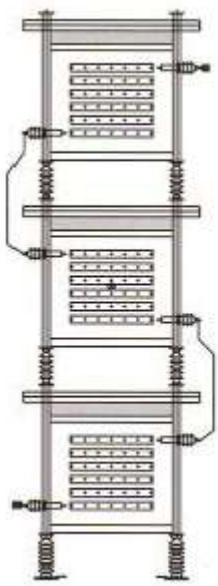


Figure 3.14: Resistor bank

The resistor banks are delivered assembled ready for installation since they are custom-built to each client`s individual needs.

3.11 IEEE Std. 1531-2003

This guide is used for the specification of components, protection and control of harmonic filters. The filters are based on either 50 or 60 Hz for all voltage levels, low, medium and high voltage. Factors affecting the design of harmonic filters such as the reactive power requirements, harmonic limitations, normal system and normal harmonic filter conditions are considered. Capacitors used for reactive power compensation together with reactors and in some cases resistors are included in harmonic filters. Capacitor banks may be switched in depending on load variation.

Normal system conditions include the loading conditions, voltage variations, voltage unbalance, frequency variation and the type of harmonics present. Normal harmonic filter conditions depend on component tolerances, temperature conditions and capacitor failure.

Some contingency conditions like harmonic filter switching, having filters of same frequency, system frequency variations are considered. The different filter configurations and filter locations are taken into account in the guide. It is noted that the normal existing capacitors banks are not used in harmonic filters unless they are over-rated initially.

The effects on the capacitor banks and reactors in the filter are considered in this guide for low, medium and high voltage applications. These effects also include operating temperatures that lead to dielectric damage and corrosion of parts exposed to air. Voltage stress levels also affect capacitor dielectric. Overheated fuses bring about nuisance tripping while eddy currents will cause high resistance at higher harmonics in harmonic filters.

Harmonic filters should be designed to operate above normal conditions. This means that such designs cater for any other harmonics drawn from the system which could potentially lead to overloading.

3.11.1 Component specification

In this section of the guide, the filter components (including capacitors, reactors and resistors) are specified. These include the component ratings in detail where current through a component and voltage across a component is determined. The operating temperatures, type of installation and environmental conditions like altitude, ice loading, ambient temperature and wind velocity are major factors in filter operation and must be taken into account.

With reactors, manufacturers specify the radius clearance to avoid magnetic flux in surrounding magnetic materials as this can cause overheating which can affect filter tuning. The reactor inductance and tolerance, Q at tuned frequency, preferred coil dimensions and mounting arrangement, noise limits, duty cycle are major concerns. Transient currents occur at switching on of the filter and contribute in the eddy current losses. Resistor banks are used for damping purposes in filters where more than one harmonic need to be mitigated.

3.11.2 Harmonic Filter Protection

The guide also provides for filter protection. Harmonic filters are protected in cases where faults occur by using relays connected to alarms to notify personnel. Concern is on over-current, over-voltage, unbalance and harmonic overloading. The main protection devices used are types of relays applied for over-current and over-voltage protection. Filter over-load and phase unbalance is also considered to be relevant in capacitor bank protection. These aspects are not discussed in this work but are mentioned here for completeness.

3.11.3 Harmonic Filter Design Procedure

The guide discusses the factors that are considered in harmonic filter design. In the procedure for filter design, an example is used to show how the filter values were derived. Calculations are used in every step to determine the values of the components used in the filter. The values of the filter components are worked out as follows.

Step1: Determine reactive size if filter

The value of the capacitor bank for reactive power compensation is worked out as in Section 3.43. This value is denoted as Q_{eff} .

Step 2: Select filter tuning

Filters are tuned approximately between 3% and 15% of tuning frequency. Typical example is a 5th filter at 60Hz tuned at the 4.7th harmonic. Using the value of Q_{eff} , the effective impedance of the filter is calculated as

$$X_{eff} = \frac{V_L^{\ 2}(kV)}{Q_{eff}\,(M\ \mathrm{var})} \qquad (3.50)$$

Where

V_L is the system line voltage

Q_{eff} is the reactive power of the harmonic filter

X_{eff} is the reactance of the harmonic filter after reactive power compensation

Using the selected tuning frequency e.g. 4.7th harmonic,

$$X_C = \left(\frac{h^2}{h^2 - 1}\right).X_{eff} \qquad (3.51)$$

$$X_L = \frac{X_C}{h^2}\Omega \qquad (3.52)$$

Where

X_C is the capacitive reactance at fundamental frequency

X_L is the inductive reactance at fundamental frequency

h^2 is the harmonic number the filter is tuned to.

Step 3: Determine component rating

The voltage across the filter capacitor is calculated as

$$V_C = \sum_{h=1}^{\infty} I(h) X_C(h) \qquad (3.53)$$

This value considers the fundamental and harmonic voltages across the capacitor. The fundamental current is calculated as

$$I_{f1} = \frac{V_p}{(X_C - X_L)} \qquad (3.54)$$

Where

V_P is the phase to neutral voltage

X_C is the capacitive reactance at fundamental frequency

X_L is the inductive reactance at fundamental frequency

The harmonic voltages are calculated using the total rms current

$$I_{rms} = (I_{f1}^2 + I_{f5}^2 + I_{f7}^2 + I_{f11}^2 + ...)^{1/2} \qquad (3.55)$$

The capacitor voltage at fundamental frequency is

$$V_{C1} = I_{f1} X_C \text{ V} \qquad (3.56)$$

The harmonic voltage $V_C(h)$ is given as

$$V_C(h) = \sum_h I_f(h)\left(\frac{X_c}{h}\right) \text{V} \qquad (3.57)$$

The capacitor voltage is thus going to be

$$V_C = \left[V_{C1} + V_C(h)\right] \text{ V} \qquad (3.58)$$

It is noted that the capacitor voltage is greater than for the capacitor that was used for reactive power compensation. From the above voltage it is shown that the filter capacitor rating is given as

$$Q_F = \frac{\left(\sqrt{3}V_C\right)^2}{X_C} \qquad (3.59)$$

Where

Q_F is the three phase rating of capacitor bank (MVar)

X_C is the reactance of the capacitor bank per phase (Ω)

The filter current in the capacitor on rated voltage and kVar is

$$I_{filter} = \frac{Q_F\,(kVar)}{\sqrt{3}V_C\,(kV)} \tag{3.60}$$

The nominal current value is calculated to be similar to the rms value.

3.12 Summary

This chapter reviews the basic concepts and standards used in this thesis. It includes an introduction to harmonics and resonance and indices for the evaluation of their effects in networks. The effects are reviewed by explaining the IEEE 519 standard, as well as the IEEE standard that applies when harmonic filters need to be designed. Power factor correction is reviewed as it is commonly found that the compensating capacitors are often used as part of harmonic filter designs to reduce their cost. The ERACS software tools applied in this thesis is also introduced.

CHAPTER FOUR: INDUSTRIAL DESIGN PROCESS OF MV OPEN RACK HARMONIC FILTERS

4.1 Introduction

This chapter presents the main contribution of this thesis in the form of guidelines employed in the decision making process to determine whether or not harmonic mitigation is required in a specific network. The chapter also offers practical steps in the form of a logical flow chart to inform decision making in the design of optimal harmonic filters.

4.2 Industrial Design

The design process for harmonic filters for the real applications differs from ideal designs discussed in Chapter 3. The process introduced here focuses on open rack type filters for the two most commonly used configurations found in industry at medium voltage level (MV), namely series tuned and 2nd order harmonic filters.

The design of filters for industrial application needs to take into account certain additional factors, amongst these, are temperature, altitude of installation and available space for installation. In this chapter a detailed process is developed for designing an industrial harmonic filter and takes into consideration factors not traditionally considered. In general, when evaluating if a harmonic filter is required or not there are two scenarios that need to be considered. The whole process is described in two interlinked flow charts, A and B as follows:

Flow Chart A explains the initial process to be followed as the first steps towards making a mitigation decision or not. If a new plant is to be designed then stages 1a to 7a are followed. If a decision is needed on an existing plant then steps 1b to 4b are followed. If the IEEE std. 519 limits are not exceeded then no mitigation is needed, if they are exceeded then mitigation is needed.

When the limits are exceeded, the resonance plots are used to determine the dominant frequency/harmonic. The data is then used to determine the type of filter to be designed between the series tuned and second order filters. The type of capacitors to be used in the filter will then be decided depending on customer needs. The filter component values will then be determined using the methodologies discussed previously in Section 3.11.1 of this thesis. The determined filter components are then modelled into the network and harmonic analysis is done.

The effectiveness of the filter is compared to Section 3.9. If the filter is not effective, the filter is re-designed and components modelled to network again till the filter becomes effective. If design is effective, component values are filled in the designed manufacturer's templates and sent for supply.

4.3 New Plants

When designing a filter for a new plant, the parameters for the equipment need to be firstly determined. In this method some assumptions are needed. Two common assumptions made are that the loads usually operate at 80% of the full load rating as experience has proven this to be the most successful value (Kyle, 2009). The second assumption is that most loads in the new plant are inductive, such as induction motors, etc. With induction motors operating at 80% full load, the PF_{DPF} is usually 0.8 lagging (Kyle, 2009). Both assumptions are used when calculating the reactive power compensation to be added into the plant.

4.3.1 New Plants Data Collection

a) *Draw a one line diagram of the plant*

b) *Develop a fundamental frequency software model of the plant network based on full load specifications of all equipment to be used. Where applicable use 0.8 DPF.*

c) *Run at f_1 a load flow and see if the model gives acceptable results, that is, the loads receive their powers, volt drops and DPF, are correctly modelled. Improve DPF to 0.96 by adding capacitor bank and generate results.*

d) *Set the variable loads (e.g. VSDs) to 80% of full load, 0.96 DPF. Run at f_1 a load flow and record the data required in Table 4.1.*

e) *Model the VSD(s) as harmonic current sources and develop harmonic domain model and then conduct harmonic penetration and resonance studies. Check THD and HD indices against limits on the IEEE standard. If exceeded then filter is needed to mitigate the unacceptable distortion level.*

f) *If a filter is needed, then Table 4.1 data is needed to commence the filter design.*

Then obtain data results from the study needed to complete Table 4.1 for the point in the network where filter is to be added.

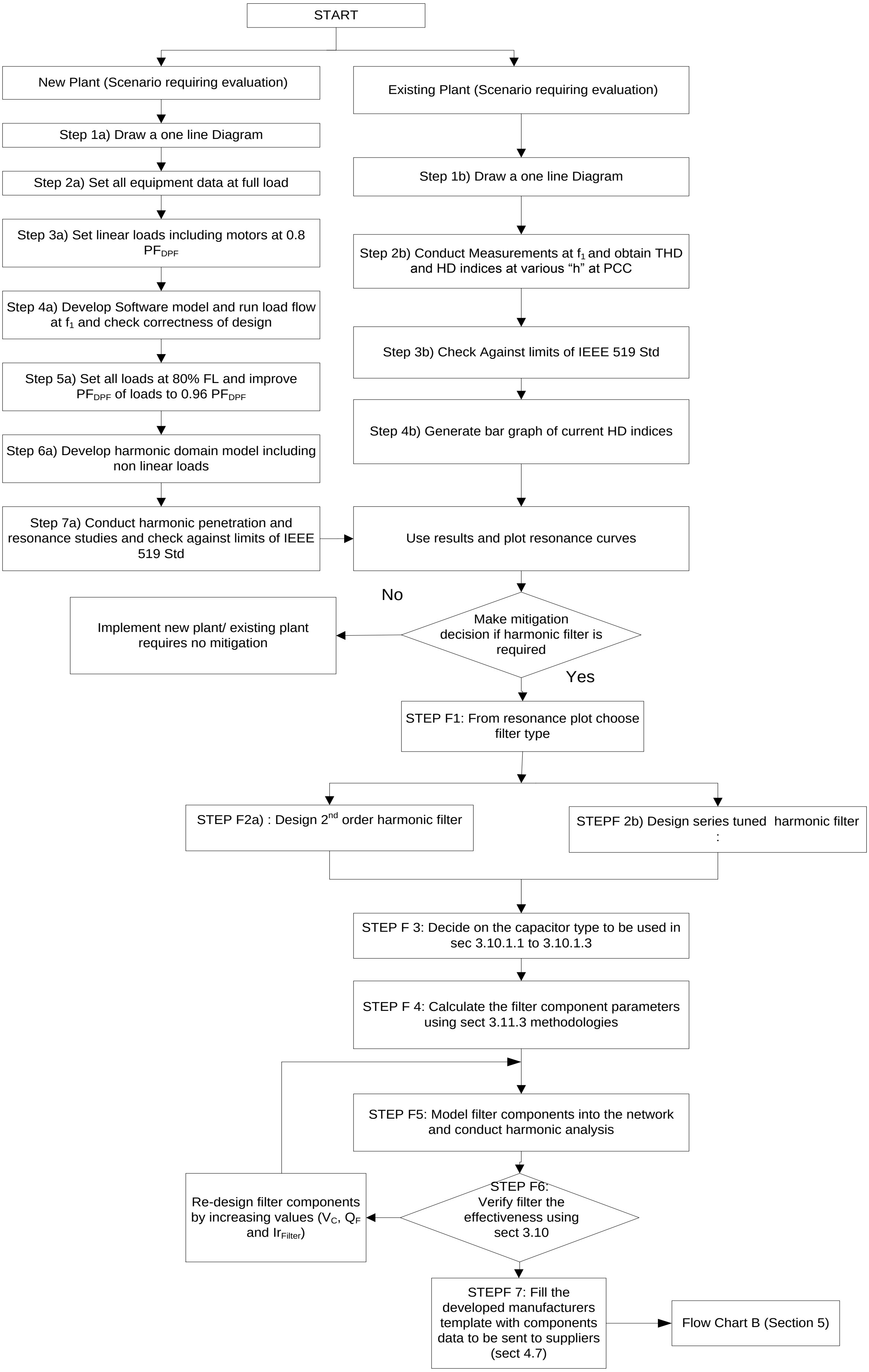


Figure 4.1: Decision and design of harmonic filter flow chart (A)

4.4 Existing Plant Methodology

A power quality analyser is used for measurements such as power, voltage, power factor, current and voltage THD%. The readings taken by the power quality analyser are taken over a period of time which depends on the network load profile. The analyser has leads that can measure line or phase voltage values depending on connections. For current, each phase is measured by a current transformer (CT). An appropriate CT needs to be chosen and calibrated to measure currents at the desired level. Figure 4.2 shows an example of a Fluke 435 3 phase power analyser (Fluke Brands, n.d.).

Figure 4.2: Fluke 435 power quality analyser with flex clamps (source: Fluke Brands, n.d.)

The measurements values obtained from an analyser are used to compare them against limits at the PCC (Allenbaugh et al., 2013:1161, Cooper et al., 2013:1043). If exceeded, the results are used in the design as it is essential to evaluate the load profile since it can vary with time of day or season. The maximum, average and minimum values of the load are taken into consideration in the design process (Atkinson-Hope & Folly, 2004:1394). A filter can be designed to have some of its components switched on or off at certain loading situations. Typical readings that can be taken in Fluke 435 power analyser and used in the network studies including harmonic filter design are shown in Appendix 1.

4.4.1 Existing Plant Data Collection

a) *Check THD and HD readings against IEEE standard limits at PCC and if exceeded. These results are shown for each harmonic such as shown in figures 7 and 8 in Appendix 1.*

b) *Check loading level for data at point in network where a new filter is to be installed using a power analyser. Figure A1.2 in Appendix 1 shows typical power readings at the PCC in the network.*

c) *Use the power data, work out PF_{DPF} of 0.8 ($\cos^{-1}$ 36.87º) and adjust S (up or down) to 80% loading assuming linear load.*

d) *Then calculate new P and Q for this 80% loading.*

e) *Table 4.1 data is completed at 80% loading and 0.8 $PF_{DPF.}$*

f) *Use this data to start the design process for the industrial filter.*

Table 4.1: Plant data at 80% load at 0.96 PF_{DPF} (PF_{DPF} to 0.96 recommended)

Value	Symbol
Voltage	V
Real Power	W
Reactive Power	Var
PF_{DPF}	CosΦ

The above table data is used in the design of both the new plants and existing plants.

4.5 Design Procedures

Design process for harmonic filters is given in the flow chart in Figure 4.1. The design procedure is developed for use by filter design practitioners – the process is an improvement over the theoretical approach given in Section 3.6.

4.5.1 Step 1 Choose filter type

From the resonance plots of the network, a decision will be made on the type of filter that will be used for the mitigation between series tuned or second order filters.

4.5.2.1 Step 2(a) Series tuned harmonic filters

Series tuned harmonic filters seen in (Figure 3.8) are the most commonly used filters and are applied to trap a specific harmonic and mitigate the effects of an aggravating resonance. The design procedure of this type of filter is done as explained in Section 3.11.3 with equations 3.50 to 3.60. The only information that has to be added in the design is from Section 3.7.1 to calculate the value of resistance in the reactor using equation 3.35. Figure 4.3 shows a 3 dimensional diagram of a typical series tuned filter as it would exist in an actual network.

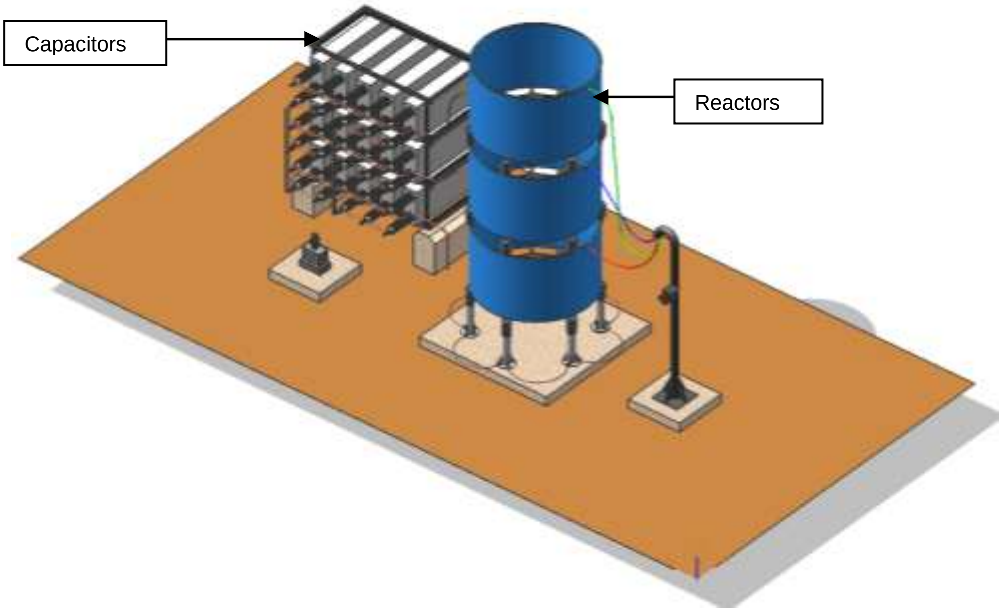


Figure 4.3: "3" Dimensional series tuned harmonic filter

4.5.2.2 Step 2(b) Second order harmonic filters

Such filters are shown in Figure 3.9, and are used to mitigate a range of harmonics as opposed to a series filter. The range usually starts from the 13^{th} harmonic upwards. They consist of a capacitor used for reactive power compensation in series with a reactor and resistor connected in parallel. The resistor is used for damping by reducing the current. A typical 3 dimensional figure of a second order filter is shown in Figure 4.4.

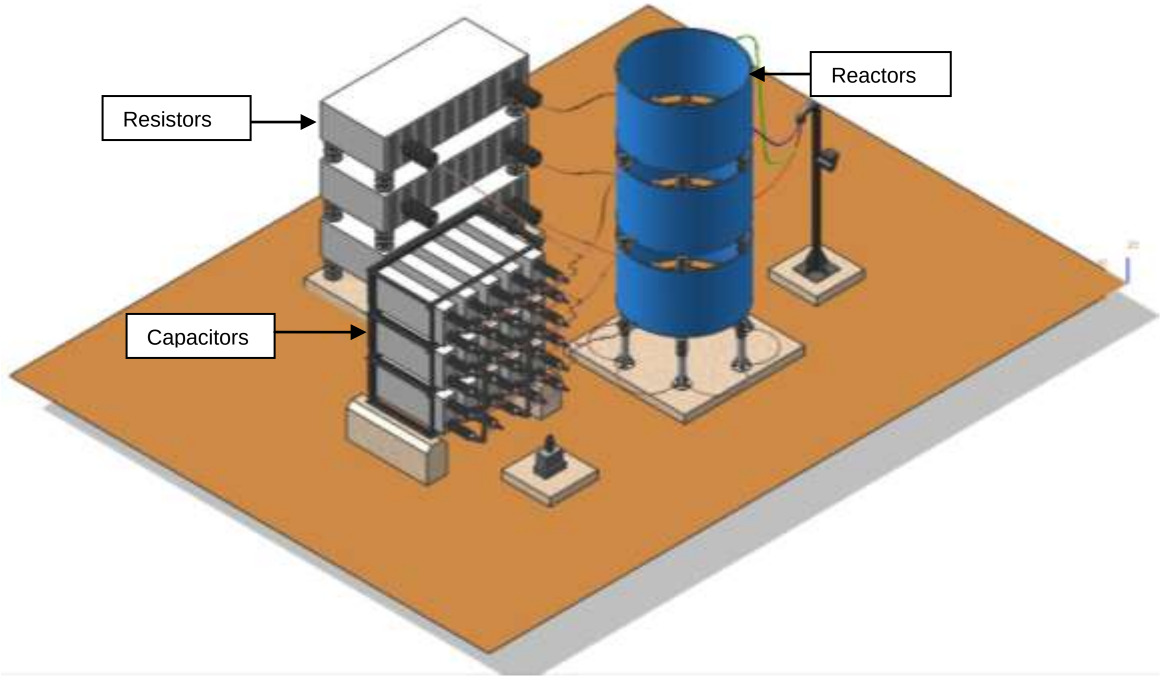


Figure 4.4: "3" Dimensional second order harmonic filter

The design procedure is the same as the one used for the series tuned filters used in Section 3.10.3 with equations 3.50 to 3.60. The only information that has to be added in the design is from Section 3.6.2 to calculate the resistor value in parallel with the reactor using equation 3.42.

4.5.3 Select type of capacitor

Using the capacitors explained in Sections 3.10.1.1 to 3.10.1.3, the designer chooses one from the internally fused, externally fused or fuseless. These are determined considering the type of protection the clients wants for the filter.

4.5.4 Calculate filter components

The filter components values are determined using the methodologies developed in Section 3.11.3.

4.5.5 Model filter components into network

With the derived filter components values found, they are modelled in the network and harmonic analysis is conducted.

4.5.6 Verify filter effectiveness

Harmonic analysis is conducted in the network and the results are verified against known standards. If the results are effective, move to 4.4.7. If not effective, the filter components are re-designed and then modelled into the network as in 4.4.5. This process can be repeated till the filter is found to be effective.

4.5.7 Manufacturers Specification Templates

Once the filter design has been verified (step 6), is complete, the designer will need to specify the rating of the components to manufacturers (step 7). The components that will be ordered will have to consider all the factors that will make the filter operate at an optimum level. This is an important step in the process. Manufacturer templates have been developed showing the information that designers send to manufacturers. These templates take into consideration the factors affecting the filter components for the installation engineers. The factors include the environmental factors where the filter will be installed. Some of the information used in the manufacturers' template has to be supplied by the client.

For the three filter components (R, L, C), templates are developed and each aspect is explained detailing all the information required. Templates 4.1, 4.2 and 4.3 show the developed manufacturing templates that are given for the manufacture of capacitor banks, reactors and resistors, respectively.

The common information in the three component templates is the name of the client, their contact details entailing the phone and fax numbers and email address. The person who made the order for component is also included in the template for communication purposes. Considering most filter projects have time considered for the filter to be in operation, the due date for components to be delivered is also added into the template.

4.5.7.1 Capacitor Specification Template

The voltage can be denoted either in phase or line values as this depends on the connection of capacitors. The connection can either be in star or delta. The capacitor`s voltage is rated is 1.25 more than the system voltage as that can absorb the harmonic voltages of the system.

The power frequency denotes the supply frequency of the network used while the tuning frequency shows the frequency the filter is designed for. This frequency could be for the 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, 19^{th} etc., harmonic. The current is rated 1.2 times than the calculated current as this caters for any unseen currents that can occur through the capacitor. Capacitor power is the power rating in Vars.

The capacitor connection is dependent on the capacitor configurations which can either be star grounded, star ungrounded or delta. Fusing is determined by the type of capacitors used (Section 3.10.1). Unbalance determines if a relay is used for protection of the bank. This depends on the client’s needs.

The mounting of the capacitor banks will either be vertical or horizontal. This factor depends on the available space for installation, horizontal when space is plenty and vertical when space is limited. The mounting also has an effect on the elevation height of the bank from the ground that has to be specified.

Bushing creepage determines the shortest path between the two conductive parts measured along the surface of bushing insulation. The value depends on altitude of installation and atmospheric conditions. In high altitudes, values of 20kV/mm are used while in low altitudes next to the sea where fog and humidity is prone, values of 31kV/mm are used.

The temperature range shows the possible variation the capacitor bank is going to be exposed to at any time of the year. This assists the manufacturer in supplying capacitor banks that can operate satisfactory at the temperatures it will be exposed to without being damaged.

Table 4.2: Capacitor specification template

Client Name	Alan Meru
Phone	021-4603085
Fax	021-4603705
Email	MeruA@cput.ac.za
Due Date	Aug - 13
Quote requested by	Alan Meru
Bank Voltage (1.25 $\times$ system V_L)	KV
Power frequency (f)	Hz
Tuning Frequency	Hz
Current (1.2 $\times$ system I)	A
Capacitor Reactance (X_C)	Ω
Capacitance	F
Capacitor Power	Var
Connection	Grounded or ungrounded
Fusing	Fuseless/Internal/External
Unbalance	Yes/No
Mounting	Vertical or horizontal
Elevating structure height	Mm
Bushing creepage	kV/mm
Temp range (min to max)	Degrees

4.5.7.2 Reactor Specification Template

The system voltage with reactors is either a phase or line value depending on the filter connection. The power frequency shows the supply frequency of the network while the tuning frequency shows the frequency which the filter`s reactor is designed for. In this case, the tuning frequency can be for the 5^{th}, 7^{th} or 11^{th} harmonic.

The current is rated 1.2 times as this caters for any unseen currents that can occur through the reactor. The reactor is rated in Henries. The reactance is calculated at the tuned frequency and given in ohms.

The Q factor of the reactor is decided by the designer of the filter components. This value is used to determine the resistance in the reactor.

The mounting of the reactors is either in the vertical or horizontal configuration. This factor depends on the available space for installation where horizontal when space is plenty and vertical when space is limited. The dimensional limitations are used to give the available space due to the magnetic fields produced. The magnetic fields are limited to certain radii. Depending on reactor rating, the number of units to be delivered is stipulated as this can vary between single phase and three phase networks.

Table 4.3: Reactor specification template

Client Name	Alan Meru
Phone	021-4603085
Fax	021-4603705
Email	MeruA@cput.ac.za
Due Date	Aug – 13
Quote requested by	Alan Meru
System voltage	V
Power frequency (f)	Hz
Tuning Frequency	Hz
Current (1.2 × system I)	A
Reactance (X_L)	Ω
Reactor Rating	H
Q factor of Reactor	
Resistance	Ω
Mounting	Vertical/horizontal
Dimensional limitations	m^2
No of units	

4.5.7.3 Resistor Specification Template

For the resistors, the voltage shows the system voltage and can either be phase or line values depending on the connection. The power frequency denotes the supply frequency of the network used while the tuning frequency shows the frequency to which the filter is designed. The tuning frequency can be for the 17th, 19th, 23rdor 25th harmonic as they are used for higher order harmonic filters. The current is given by the value that goes through the resistor bank. The resistance is given in ohms.

The mounting of the resistors can be in either the vertical or horizontal configuration. This factor depends on the available space for installation where horizontal is used when space is readily available while vertical is when space is limited.

The dimensional limitations are used to give the available space due to the heat the resistor banks produce. Depending on the resistor rating, the number of units to be delivered is stipulated as this can vary between single phase and three phase networks.

The ambient temperature gives the range of temperatures the resistor will be exposed to. Such information assists the manufacturer in producing resistor banks that can operate as expected in the given temperatures. Creepage is the length of the bushes used in the resistor and varies in length depending on the same factors as for the capacitors.

Table 4.4: Resistor specification template

Client Name	Alan Meru
Phone	021-4603085
Fax	021-4603705
Email	MeruA@cput.ac.za
Due Date	Aug – 13
Quote requested by	Alan Meru
Power system frequency (f)	Hz
System voltage	kV
System current	A
Resistance	Ω
Mounting	Vertical/Horizontal
Dimensional limitations	m^2
No of units	
Ambient temperature	Degrees
Creepage	kV/mm
Seismic zone	
Elevating stand height	Mm
Finish	Galvanised/Steel

Depending on the zones in which the resistors are installed, the seismic zones need to be considered as they affect the resistor performance. Elevation shows how high the resistor is installed from ground. The finishing of the casing for the resistor is determined by the altitude of the installation and also that some environments are conductive to corrosion than others.

4.6 Summary

The industrial design process for series and second order harmonic filter steps is explained in this chapter by use of calculations and formulas. A flow chart is developed and shows the steps followed in the process. The values of the components are calculated showing all the factors the designer considers. The components used in the filters are explained in terms of their functions and factors considered in selecting them.

Manufacturer templates have been developed for the components used in filters. The templates show all the factors the components will be exposed to when installation is done. Such factors play a big part in having a long life and optimum operation of the components.

CHAPTER FIVE: INSTALLATION AND COMMISSIONING OF HARMONIC FILTERS

5.1 Introduction

This chapter deals with the installation and commissioning of harmonic filters. Additionally it addresses issues relating to site construction and practical aspects of harmonic filter deployment. The chapter builds up on the flow chart presented in Chapter Four by elaborating on the steps and tests conducted in the commissioning of the harmonic filters.

5.1.1 Installation

Installation is the assembly of electric equipment in a given location, designed for coordinated operation, and properly erected and wired (Kruesi, et al., 1978:337). It can be taken as the process of placing in position all the equipment required to fill up an apparatus like a harmonic filter and then connecting all parts of the apparatus together to make it ready for use. This involves interconnecting the components and then connecting the apparatus in readiness to be energised from the supply network.

5.1.2 Commissioning

Once an installation is complete, the next stage is to commission the apparatus. Commissioning is the process of ensuring that all the electrical systems are checked, tested and perform interactively as expected from the design documentation. Commissioning tests are applied to a machine and site under normal service conditions to show that the machine is erected and connected in the right manner and is able to work satisfactorily (ibid).

This process entails verification that the system will function technically properly as required in its system operations. The individual functions such as instruments and components are verified as well as the checking of each piece of apparatus involved.
Commissioning requires the use of testing instrumentation. It is also the process of integrating the installed apparatus into the day-to-day operation of the system to which it is to be connected. This enables testing that the new and existing equipment is acceptable. Commissioning includes the final hand over of apparatus to the owners. Open rack harmonic filters, as complete apparatus need to be installed and commissioned before being put into an electrical network to provide the required mitigation.

5.2 Installation Drawing

Before doing an installation, drawings are prepared and they show the physical placement of the filter components on a site, clearly indicating the dimensions of the components (their size) and their relationship to each other and the site boundaries.

Appendix 2, (Figures A 2.1 to A 2.4) show typical drawings of a 4.5 MVar 11kV, 5th harmonic filter (courtesy of RWW Engineering (PTY) LTD, South Africa).

Figure A 2.1 of Appendix 2 shows a top view of the filter site indicating the positions of the capacitor and reactor plinths and where the supply cables will be laid. The plinths are constructed to handle the reactor weight of 600kg and capacitors weight of 1200kg. In the same figure, the dimensions of the site including gate entrance are shown.

Figure A 2.2 of Appendix 2 shows that the filter is connected in star with an unbalance relay between the two branches of the filter. Each of the three phases will have 3.8mH reactors rated at 300 amps in series with 413kVar capacitors at phase voltages 7.62kV. The filter will have 15 capacitors in total per phase which will have 2 branches with one branch having 9 capacitors and the other 6. This means that one branch will have 3 parallel connections with 3 capacitors in series while the other branch will have 2 parallel branches with 3 capacitors in series.

Figure A 2.3 of Appendix 2 gives the side view of the filter installation. This shows the capacitor foundation will be at a height and depth of 400 mm respectively. Each of the three capacitor racks will have a length of 475 mm thus the total height of the capacitors from ground will be 1875 mm. The reactors length from ground will vary from 2600 mm to 3100 mm depending on manufacturer. The site is then fenced with a height of 2000 mm using a strand barbed wire.

Figure A 2.4 of Appendix 2 shows the layout of the installed filter from the top view. Trenches for the supply cables are dug with a depth of 300 mm. The radius of the reactor will be 1210 mm thus having a foundation of 1500 mm by 1500 mm with a depth of 400 mm. The reactor foundation will have no metallic reinforcement to avoid any magnetic effects when the filter is operating. The magnetic clearance of the reactor is given as 1250 mm radius.

5.3 Site construction

The choice of site where one or more harmonic filters are to be installed depends on certain factors. Such factors can be from the number of filters, types of filters, proximity of the filter to power supply, data from component manufacturers and the space available. At such a site, the ground has to be level and gravel is spread all over the floor of the site. Gravel is a good insulator and caters for water logging at the site and is also used for covering the earth conductors connected to the earth mat.

Concrete plinths are constructed at the site for the filter components. The reactors` position should not be near any metallic parts as there may be magnetic coupling. Since there are magnetic fields generated by the reactors, the concrete plinths are constructed without any metallic reinforcements. The reactors are mounted on stands with insulators to lift them above ground level.

Figure 5.1 shows concrete plinths built for the installation of the reactors and capacitor banks. The area occupied by each filter component has to adhere to the specifications supplied by the manufacturer. This also depends on the space limitations.

Figure 5.1: Site constructed for reactor and capacitor installation

5.4 Site Preparation and Grounding Connections

Grounding connection is the connection used to establish a ground and consists of a grounding conductor, or a grounding electrode, and the earth that surrounds the electrode or some conductive body that serves instead of the earth (Kruesi, et al., 1978:294). Grounding is a method of protection in which faults to ground within the protected equipment are detected irrespective of system phase conditions (Kruesi, et al., 1978:337). Grounding is used to divert excess and leakage currents to ground. The benefits of grounding are to protect equipment and provide safety for human and animals. Leakage currents are the currents that flow through or across a surface of insulation and defy the insulation resistance at the specified direct current potential (Kruesi, et al., 1978:367). The leakage currents could be due to lightning or power transients during switching on.

A common ground is the point at site where all ground points meet with continuity to ground. The common ground is connected to the ground mat. The ground mat is a system of bare conductors, on or below the surface of the earth, connected to the ground or ground grid to provide protection from dangerous touch voltages. Plates and gratings of suitable area are common forms of grounded mats (Kruesi et al., 1978:294).

Figure 5.2 shows a filter site where the earth mat has been laid on the ground and gravel is then put on the surface of the site that is then levelled. Earth cables connected to the common points protrude from earth so as to connect to the apparatus to be installed at site.

Figure 5.2: Earth wires at harmonic filter site

The earth cables are joined together at common earth points in the site as shown in Figure 5.3 below for the continuity.

Figure 5.3: Common earth point at harmonic filter site

All points at the site that are conductive are connected to the earth wires as shown in Figure 5.4 with a steel structure earthed.

Figure 5.4: Earth points connection at harmonic filter site

5.5 Site Fence

The site where the filter is installed must be fenced and is usually at a place without trees around. The fence prevents access into the site by human beings and animals that need to be kept away.

Figure 5.5: Site fencing for harmonic filter installation

The fence for the filter site is positioned adequately away far away (about 2m) from the reactor positions so that magnetic coupling does not occur. Figure 5.5 shows that the rubble has been laid, the concrete plinths built and the fence installed for a filter site. Warning signs are placed on the fence to deter entry by people into the site due to the voltage levels and capacitor bank charges present (see Figure 5.6).

Figure 5.6: Warning sign at the fence of harmonic filter site

5.6 Filter Installation

5.6.1 Capacitors

Capacitor banks are delivered from manufacturers either in pallets, open or closed crates or in containers. The client is required to verify the name plate (see Figure 5.10) on the capacitors upon delivery. Bushings (see Figure 5.10) are to be inspected for cracks as damage may occur in transportation.

A capacitor rack (shown in Figure 5.8) consists of a specific number of capacitors connected in series and parallel to obtain the desired voltage and Var size. The number of capacitors for a filter is given by manufacturers as per the design template specifications. The capacitors are connected in series and parallel in a rack. In such a rack, the capacitor elements will have bushings and interconnecting busbar (see Figure 5.10).

The frame of the rack is usually made from aluminium and can have as many capacitors per row depending on size. A typical fabricated capacitor rack is shown in Figure 5.7 where the capacitors are to be installed. Such racks are manufactured according to the capacitor sizes and configuration layout.

Figure 5.7: Fabricated capacitor rack frame

Each capacitor rack is insulated from the others and the earth point for each rack is connected individually so that if a fault occurs in any bank the fault goes to the earth. This also eliminates chances of other banks failing since a fault in one bank could affect the others. The capacitor banks can be connected in star or delta depending on design and voltage levels.

Base insulators are used for the capacitor rack platforms. The assembly of parts is done according to the field assembly drawings supplied by the capacitor manufacturer in their instruction manual.

When moving the capacitor banks, lifting lugs (see Figures 5.8 and 5.9) should be used for each rack. The lifting lags are connected to each stack to make it balanced and have good lifting points to avoid sliding or skidding. It is insisted that no lifting should be done via bushings since they can easily be damaged.

Some elevating structures can be employed if necessary and should be requested depending on capacitor rack size that can be supplied by manufacturers. In most cases the capacitor banks are delivered unassembled. The plinths are built so that the bases are not subjected to unnecessary physical stresses. A plinth is a concrete foundation of correct size and weight absorbing capability on which racks can be mounted.

Figure 5.8 shows an already assembled capacitor rack being off loaded from a truck at an installation site using a crane. The lifting lugs are connected to the rack for easy connection to the crane. In such a case the capacitor rack was assembled before being delivered to the installation site.

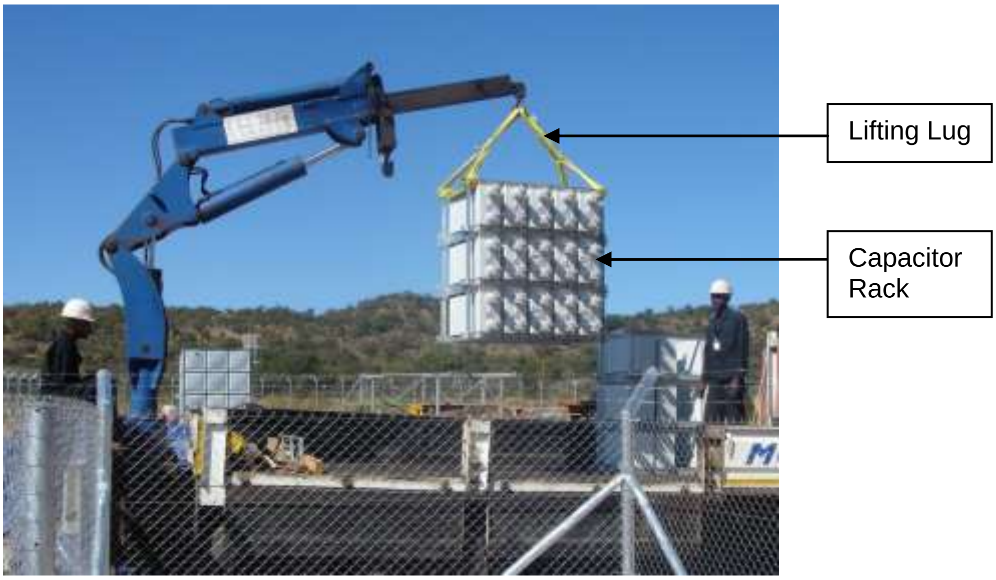


Figure 5.8: Crane removing capacitor rack from truck

Figure 5.9 below shows a capacitor rack being off loaded and positioned and laid on the already prepared plinth for installation using the crane. A lot of care is taken not to damage the racks.

Figure 5.9: Crane downloading capacitor rack to plinth

Once the capacitor rack is connected to the plinth, the capacitors are then connected to the supply bus as shown on Figure 5.10 below.

Figure 5.10: Connecting capacitors to busbar

The connection of the banks to the supply busbar is done with specifications given by manufacturers. Spring washers are used with unit nuts to tighten capacitor units to a busbar and are done according to torque strengths provided by the manufacturer.

Figure 5.11: Tightening capacitors as per recommended torque levels to bus bar

Nokian capacitors have the recommended torques and wrenches for the capacitors used shown in Table 5.1 below.

Table 5.1: Recommended tightening torques for capacitor bushes

Wrench	Tightening torque Nm
M12	15-18
M14	30-34
M16	40-50

The torque of the electrical connections should be checked 24 hours after installation to avoid any loose connections.

Surge arrestors (seen in Figure 5.12) can be placed between the supply and capacitor banks close to capacitor banks as much as possible to limit lightning and switching surges.

An unbalance relay (seen in Figure 5.12) is used for protection of capacitor banks in case one of the phases has a fault. Unbalance relaying considers factors such as unbalances due to manufacturing of capacitors, system voltages unbalances in the network and over current unbalance due to one or more series elements failing.

The surge arrestors can also be connected at the capacitor banks on the earth points to discharge any leakage currents. Unbalance relays and surge arrestors are auxiliaries in the capacitor banks and are supplied depending on client specifications. As part of the work limitations the surge arrestors and the unbalance relays are not mentioned in detail in this work.

Figure 5.12: Unbalance relay and surge arrestor connected to capacitor banks

5.6.2 Reactors

The reactors are usually delivered in crates without insulators and bushings as they could be damaged during transportation. The manufacturer supplies drawings for the assembly of a reactor rack. The reactor specifications should be verified upon delivery to verify the reactor ordered. A typical harmonic filter reactors nameplate is shown in Figure 5.13.

Figure 5.13: Reactor Nameplate

For open rack assemblies, stacks are used. Figure 5.14 shows a reactor being assembled with its insulators in between before being erected as a vertical stack.

Figure 5.14: Reactors being assembled at site

Terminals are used for electrical connections to the coils while the insulators are used for insulation with the reactor stacks. Insulators separate the coils from each other as they are vertically mounted but there must be a way in which connections are made to the electrical system. Each phase has an electrical input and output terminal made of Copper Aluminium (CuAl) plates that are used for the electrical connections as seen in Figure 5.15.

Figure 5.15: Reactors electrical input and output connections

Alternatively, vertical stack reactors can be assembled by the manufacturer and then delivered to the site. A stack has three sections mounted on each other to make up a three-phase bank. Each section makes a phase of a bank. Between the phases of the reactors, insulators are installed and their rating is according to the voltage level, typically rated for MV applications.

Figure 5.16: Assembled reactors being delivered at site

When reactors are delivered by the manufacturers to the client, a technical sheet is supplied. The sheet will have data on the environmental conditions for installation, electrical data, construction data and support system.

When installing reactors the magnetic clearance to metallic parts and between reactor coils is specified by the manufacturers. This clearance is defined in a way that no magnetism is induced in any metallic structure when the reactor is in operation. Metallic materials in the vicinity can affect the filter operation. In human beings, hearing devices are some of the components that are affected by magnetic fields of the reactors.

In some cases extension brackets are supplied to maintain the necessary magnetic clearance below the reactor.

Suppliers usually also supply information on:

i) Magnetic field distribution for foundations, fences and adjacent structures.

ii) Force on adjacent installations, bus and cable connections.

iii) Analysis of entire reactor assemblies.

The terminals should be at the right position by placing the middle coil and tightening the bolts. The top reactor is mounted on the middle reactor just as the middle one is done on the bottom one.

After the installation, the terminals of the reactors are cleaned and layers of grease are applied to prevent corrosion. The engineers also make sure terminals are tightened using right tightening torques not to damage the reactor terminals which are made from Aluminium. Nokian capacitors have the recommended torques for the reactors seen in Table 5.2 with right wrench to be used.

Table 5.2: Recommended tightening torques for reactors

Joint	Screw/nut Material	Wrench	Tightening torque Nm
Insulators	AISI	M12	45-50
		M16	95-105
Others	AISI	M10	40-45
		M12	70-75
		M16	110-130

The reactors have to be earthed at the base points with continuity to earth points in the site as seen below.

Figure 5.17: Reactor supports earthed

5.6.3 Resistors

Resistors are usually connected in parallel with the reactors for the 2nd order harmonic filters. Resistor banks are in most instances constructed before delivery to site. They come assembled with insulators and internal connections ready for installation.

For transportation purposes the resistor banks are mounted on wooden pallets and fastened with bolts to avoid any damage while on the move. Lifting lugs are supplied for loading and unloading. The client is requested to inspect the banks on arrival to check if any damages occurred in transportation. Inspection includes verifying that all insulators are intact, all internal connections and bolts are tight after transportation and the insulators are clean and unpolluted. Since resistor banks are heavy, they are handled carefully using either cranes or forklifts (http://www.msresistances.com/2-DA/Operation%20Manual%20%20(DA).pdf).

Resistor banks are placed on prepared concrete foundations depending on their weight loading. This foundation is designed to withstand stresses during operation, such as wind, ice load, vibrations etc. The foundation must be of adequate distance away to give the required clearance from the reactor and capacitor banks respectively. Data of harmonic filter resistors on the electrical part, enclosure arrangement and design should be adhered to as per the recommendations (http://www.msresistances.com/pdf/brochure_damping.pdf, (http://www.fortressresistors.com/wp-content/uploads/R10_00_FILTER_RESISTORS.pdf)

Figure 5.18: Harmonic filter resistor assembled ready for installation

During installation, the bushings on the resistor banks should be mounted and tightened. Lifting lugs are used to erect and place the resistor banks on its foundation.

They are stacked units and porcelain is installed on the bottom of the metallic structure or steel bottom plate with the right bolts. The middle and top units are installed in the same manner. The banks have to be properly grounded and the input and output connections are tightened.

5.7 Control Panel

The harmonic filter will have its operations controlled from a control panel. There are cables laid to connect the filters from the control panel. At the control panel display readings of current, voltage, power factor are displayed at the front. Inside the control panel components such as relays, circuit breakers, power factor controllers, fuses, timers, contactors, and display lights, will be found. The components in a control panel depend on the filter clients needs and available finances. Not much is to be said about the control panel in this work. Figure 5.19 shows a typical control panel for a harmonic filter with the three phases of current displays.

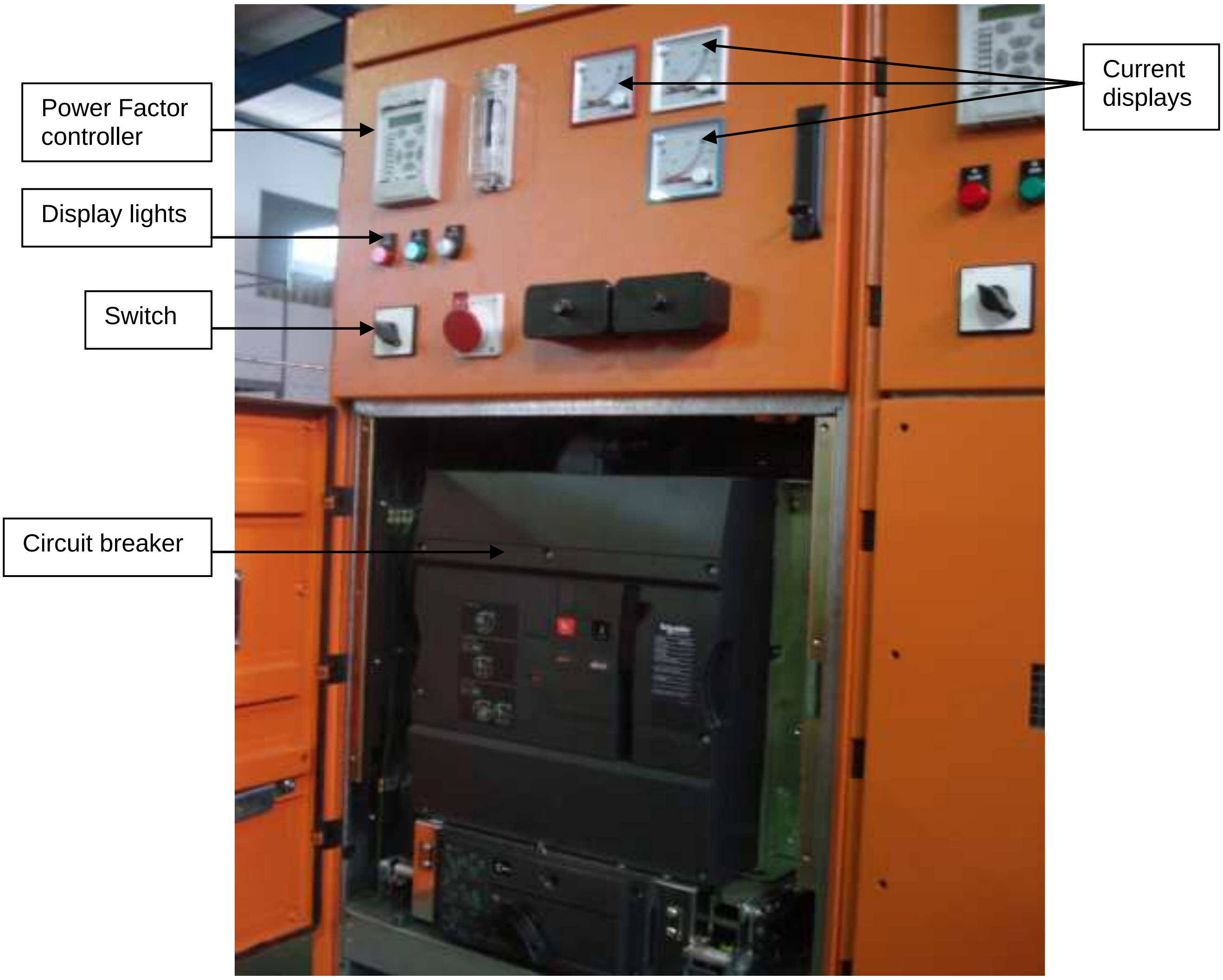


Figure 5.19: Harmonic filter control panel

5.8 Filter Commissioning

Commissioning of a harmonic filter follows a process with some tests done which includes verifying that all the filter components operate as expected.

5.8.1 Capacitors

With capacitors the tests and procedures below are conducted or followed depending on size of bank.

a) The capacitance of capacitor banks is measured using capacitor meters. The readings are used to verify that the values are correct and the phases are balanced. If the values are not balanced, then each capacitor element is measured to note the one that is not operating as expected.

b) Verifying that the capacitors are installed according to manufacturer diagrams. This could either be star or delta connection. In such situations measuring the voltage across the phases can give the correct readings.

c) In some instances current transformers are used to measure current supplied to the capacitor banks. These current transformers are found in the control panels. Where current transformers are included, the continuity of such transformers is measured as some transformers may have defects of manufacture.

d) In the control panels of some filters, some control programmes are designed for the operation. These are dependent on the client`s needs, so they are optional. They could be for alarms in case of over current, power factor controllers etc. These are verified by injecting currents in the control circuits where the current transformers measuring harmonic switch on the relays. The relays will switch off the circuits and ignite the alarms in cases where the harmonic content exceeds expected values.

e) Tests can be done on the capacitor switches and control panel lights to make sure they operate as expected. This can be done by supplying the control panel with power and then switching on and off the panel. Protection devices such as circuit breakers are also part of such switches.

f) The cables supplying the filters are checked to make sure that they conform to the rated values. Such values are shown on the cables sheath and when switched on, checks are made to make sure the cables are not overheating or producing any “hissing” noises.

g) Checks are conducted of bushings of the capacitor banks for any chips or cracks that might have occurred during transportation or installation. If any irregularities are found, the components are replaced immediately.

h) The voltage and current in each phase is verified using multi meters to make sure they are balanced and within the ratings of equipment.

i) 24hrs after commissioning of the banks, visual checks should be conducted to note if there is any occurrence of overheating of electrical joints in the banks. This could also include verifying that the banks are still balanced.

5.8.2 Reactors

Before commissioning the reactors, all joints are checked referring to the manufacturers specified torque values. Visual checks on the surfaces of the reactor are conducted. The value of reactance is measured using reluctance meters. The continuity of all ground points is checked using meggers or resistance meters. Lastly, it is important to verify that no loose objects such as tools and bolts are left on the reactors or between cylinders or near the reactors as they can induce some magnetism when the filter is switched on.

5.8.3 Resistors

With resistor banks, the resistance is measured at cold temperature and insulation resistance of resistor mid-point and resistor frame ensuring the value should be over 500 Mega ohms under 500V DC. The values should take into consideration the ambient temperatures of the site for installation and compared with the suppliers readings. Other tests done in the commissioning of resistor banks are shown by Microelettrica Scientifica (M.S.) (http://www.msresistances.com/2-DA/ITP%20(Draft).pdf) and include insulation and applied dielectric tests.

5.9 Flow Chart of Installation and Commissioning of Harmonic Filter

The steps followed in the installation and commissioning of harmonic filters are shown in Figure 5.20.

5.9.1 Step 1

The filter components are verified according to design parameters that were ordered and supplied.

5.9.2 Step 2

a) Capacitor racks are fabricated according to capacitor sizes and connections.

b) *The plinths for the filter components are built.*

5.9.3 Step 3

Capacitor banks assembled in the racks and connected.

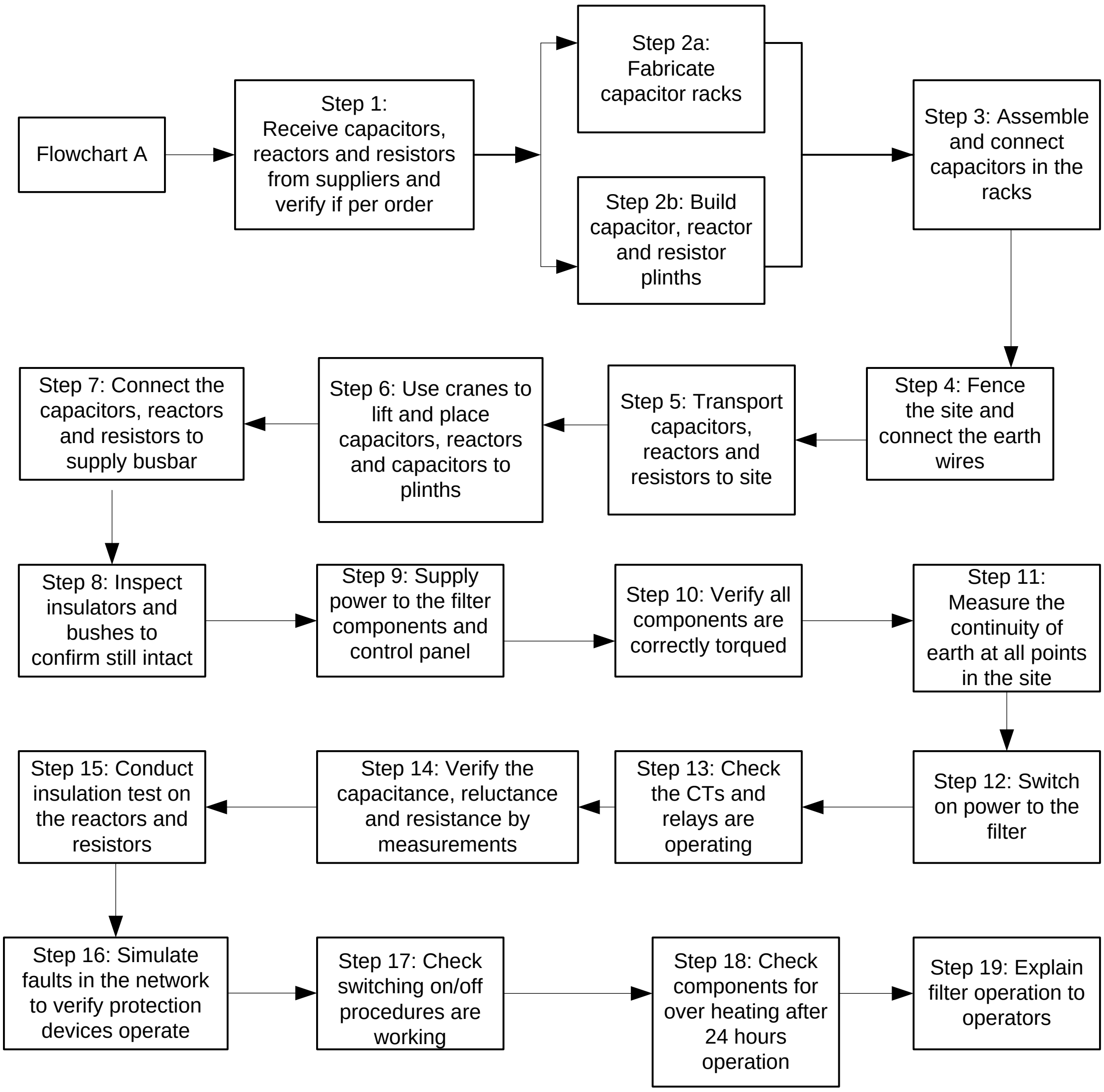


Figure 5.20: Flow chart B on installation and commissioning of harmonic filter

5.9.4 Step 4

Fence the filter site to deter humans and animals with fences of heights of 2 metres.

5.9.5 Step 5

The capacitors, reactors and resistors are transported to the filter site.

5.9.6 Step 6

Cranes are used to lift the capacitor banks, reactors and resistors to the plinths.

5.9.7 Step 7

Connect the capacitor banks, reactors and resistors to the power supply via busbars

5.9.8 Step 8

Inspect bushings and insulators to verify they are still intact after the transportation and installation.

5.9.9 Step 9

Supply power to the filter components and control panel.

5.9.10 Step 10

Verify that the filter components are connected using the correct torque.

5.9.11 Step 11

Measure the earth continuity in the grounding of the site as shown in Figure 5.21.

Figure 5.21: Earth continuity test using digital earth tester

5.9.12 Step 12

Switch on power to the filter.

5.9.13 Step 13

Check that all the monitoring devices such as relays and CTs operate as expected.

5.9.14 Step 14

Verify the capacitance, reluctance and resistance values by conducting measurements.

5.9.15 Step 15

Conduct insulation tests on the resistors and reactors to make sure they are still intact.

5.9.16 Step 16

Simulate faults in the filter to verify the protection devices operate as expected.

5.9.17 Step 17

Check that the switching on and off procedures work as expected.

5.9.18 Step 18

Check the filter components for loose connections and overheating after 24 hours operation.

5.9.19 Step 19

Explain to the filter operators the operation and fault finding of filters.

5.10 Summary

The chapter discusses all the steps that take place for a harmonic filter to be installed. This starts with the site for the installation where foundations have to be built and site fenced. The foundations will be of certain heights and built in a certain way to cater for magnetic fields of reactors. No metallic components will be used in the foundations of the reactors.

The site for the installation will have earth points all over for safety purposes. This will be connected to the earth mat laid below the rubble at the site. The earth points will be easily connected to the filter components of a harmonic filter.

The control of the filter will be done from a control panel. The panel will be close to the main supply and will have all the monitoring devices in it. All filter components will be assembled and installed and ready for commissioning.

A typical 5^{th} harmonic filter can be seen in Appendix 2. Diagrams of the side view plan, top view side plan, area plan and filter connection are shown. Details of the diagrams are clearly explained.

This chapter discusses all the tests that are conducted on the filter components at the commissioning stage. Each component has its own steps that need to be checked and verified. A flow chart is designed showing all the steps in the commissioning of the harmonic filters and the control panels of the filters.

CHAPTER SIX: CASE STUDIES AND APPLICATION OF METHODOLOGIES

6.1 Introduction

In this chapter, two scenarios (case studies) are demonstrated applying the developed methodology (Figure 4.1). The methodology is applied in a step-by-step manner to show its effectiveness. The first application of the methodology is to the scenario where a “new plant” is under consideration. The application of the methodology will also be applied to an existing plant. In both scenarios, the process of open rack harmonic filter design and installation will be demonstrated.

6.2 New plant (4.16kV Network)

This case study involves a simple radial power system. This is a system to be built in future. The distribution network will supply an end user plant having only one harmonic source (HSOURCE1). The network is supplied using a 44 kV/4.16 kV transformer rated at 10 MVA with an X/R ratio of 5. At the PCC (bus 1AB), a linear load of 4.5 MVA, 0.8 DPF (load1) and a 6 pulse drive of 2.574 MVA which is the harmonic source are connected. A capacitor bank is to be added to the system to improve the power factor (PF_{DPF}).

6.2.1 Decision

6.2.1.1 Step 1(a)

Draw a one line diagram of the network as shown in Figure 6.1 with the capacitor modelled.

6.2.1.2 Step 2(a)

Set the equipment at full load. This is done by using the data in Appendix 3 then modelling it using software program (ERACS).

6.2.1.3 Step 3(a)

Set the linear loads to 0.8 PF_{DPF}. In this particular case, the linear load already has a PF_{DPF} of 0.8 from the specifications.

6.2.1.4 Step 4(a)

Develop software model, run load flow at f_1 (Figure 6.2) and check correctness of design.

6.2.1.5 Step 5(a)

Set all loads at 80% FL and improve PF_{DPF} of loads to 0.96 PF_{DPF}. In this case, the loads whose values are set to 80% are the linear load and the 6 pulse drive. Figure 6.3 shows the load flow of the network with the 80% loading.

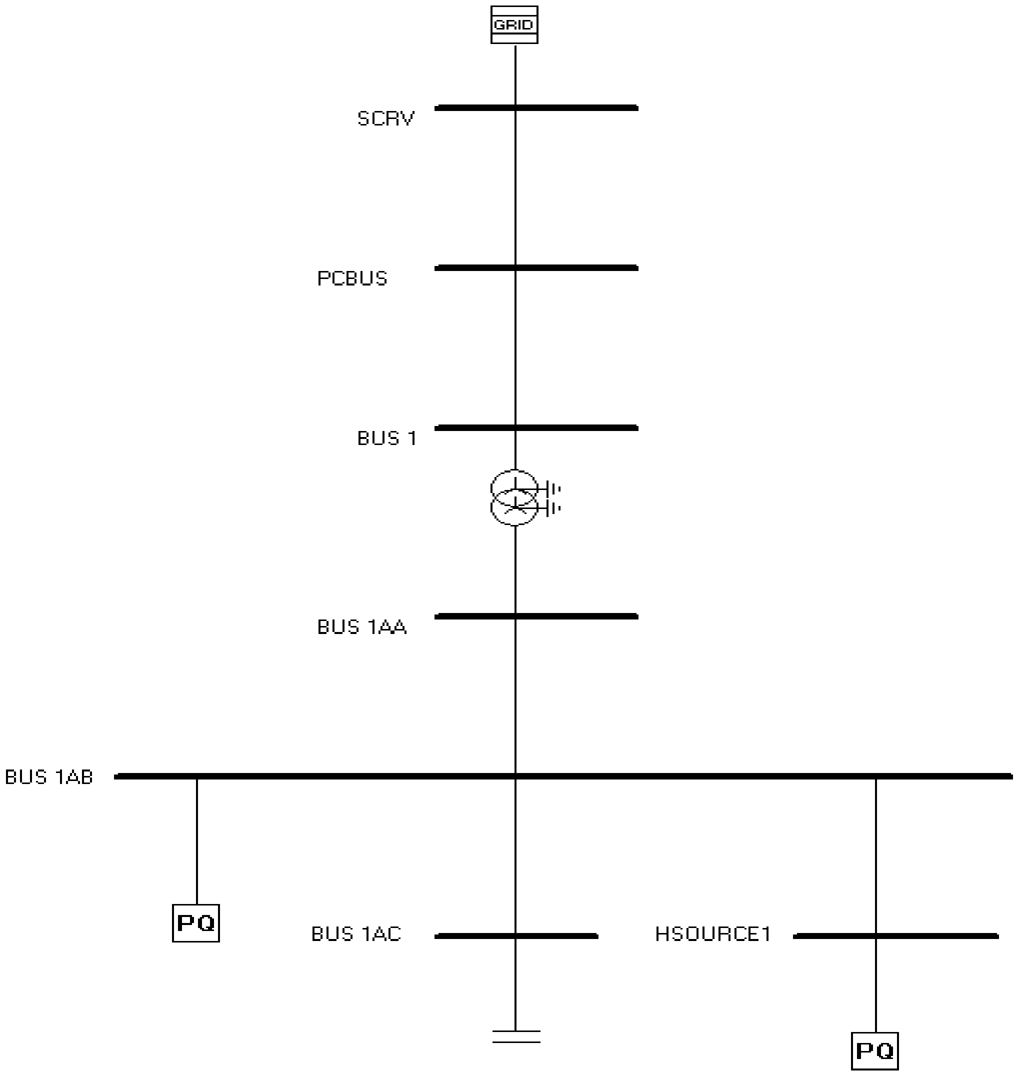


Figure 6.1: One line diagram of network

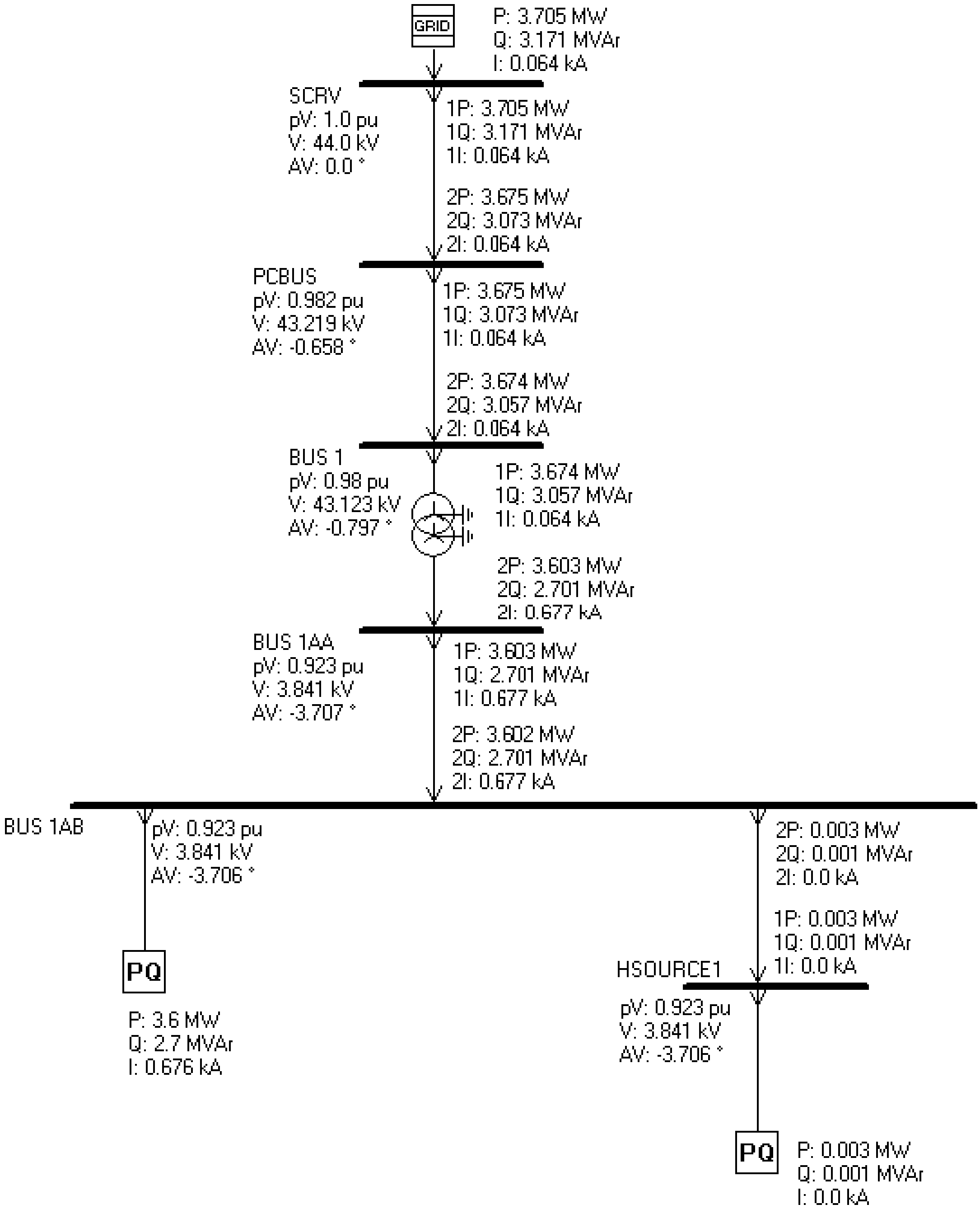


Figure 6.2: Load flow at f_1

The linear load connected from bus 1AB will now be 3.6 MVA at PF_{DPF} of 0.8. The 6 pulse drive connected at bus HSOURCE1 will then be 2.0592 MVA.

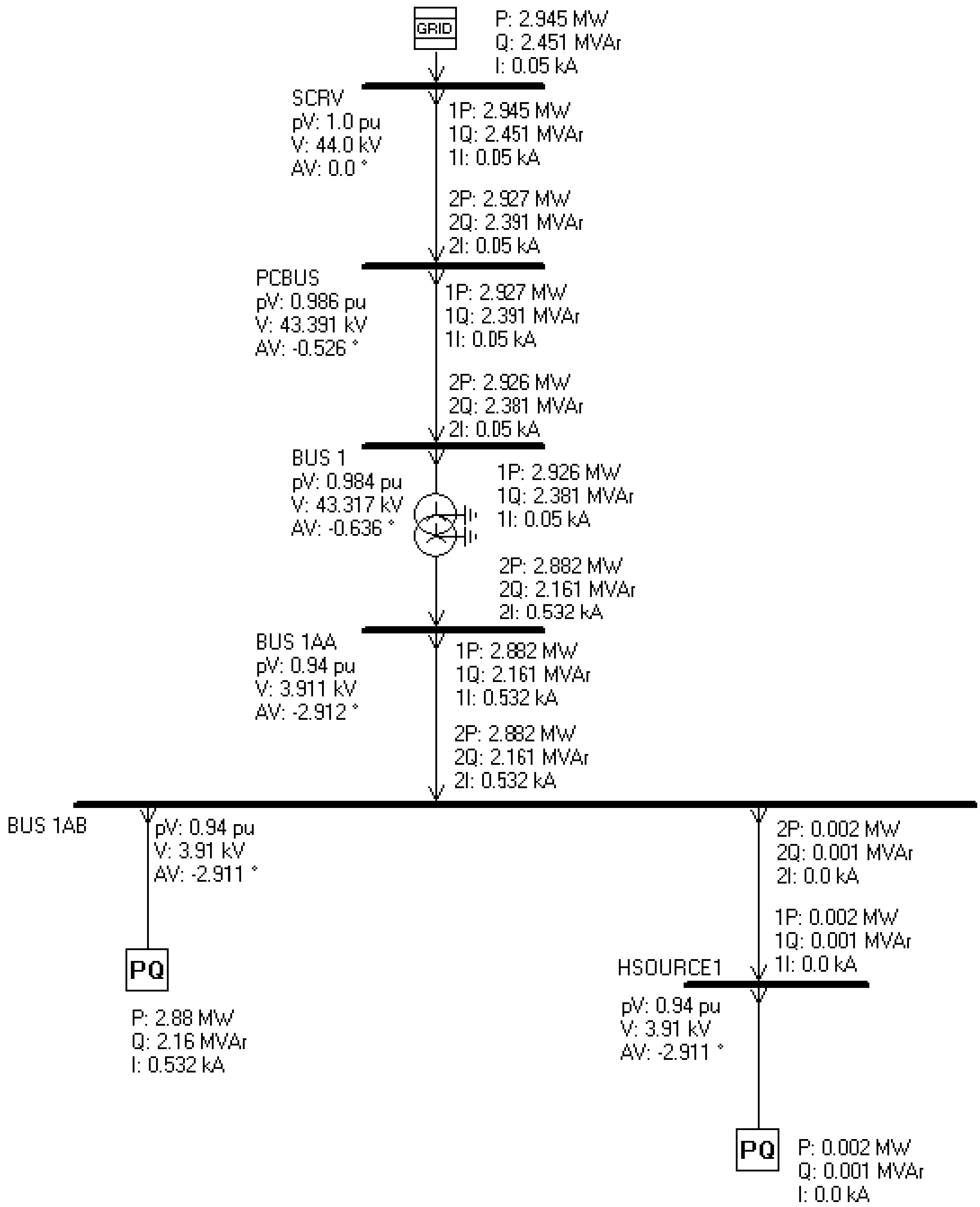


Figure 6.3: Load flow at f_1 with 80% load

To improve the PF_{DPF} at bus 1AB to 0.96, the following calculations will be done.

$$S = \frac{2.882}{0.96} = 3.002 MVA$$

$$Q = \sqrt{S^2 - P^2} = \sqrt{3.002^2 - 2.882^2} = 0.84 MVar$$

Where

$$Q_{New} = 2.161 - 0.84 = 1.321 MVar$$

A capacitor of 1.321 MVar is modelled at bus 1AC to get a PF_{DPF} of 0.96. A load flow (Figure 6.4) is conducted to verify the design correctness.

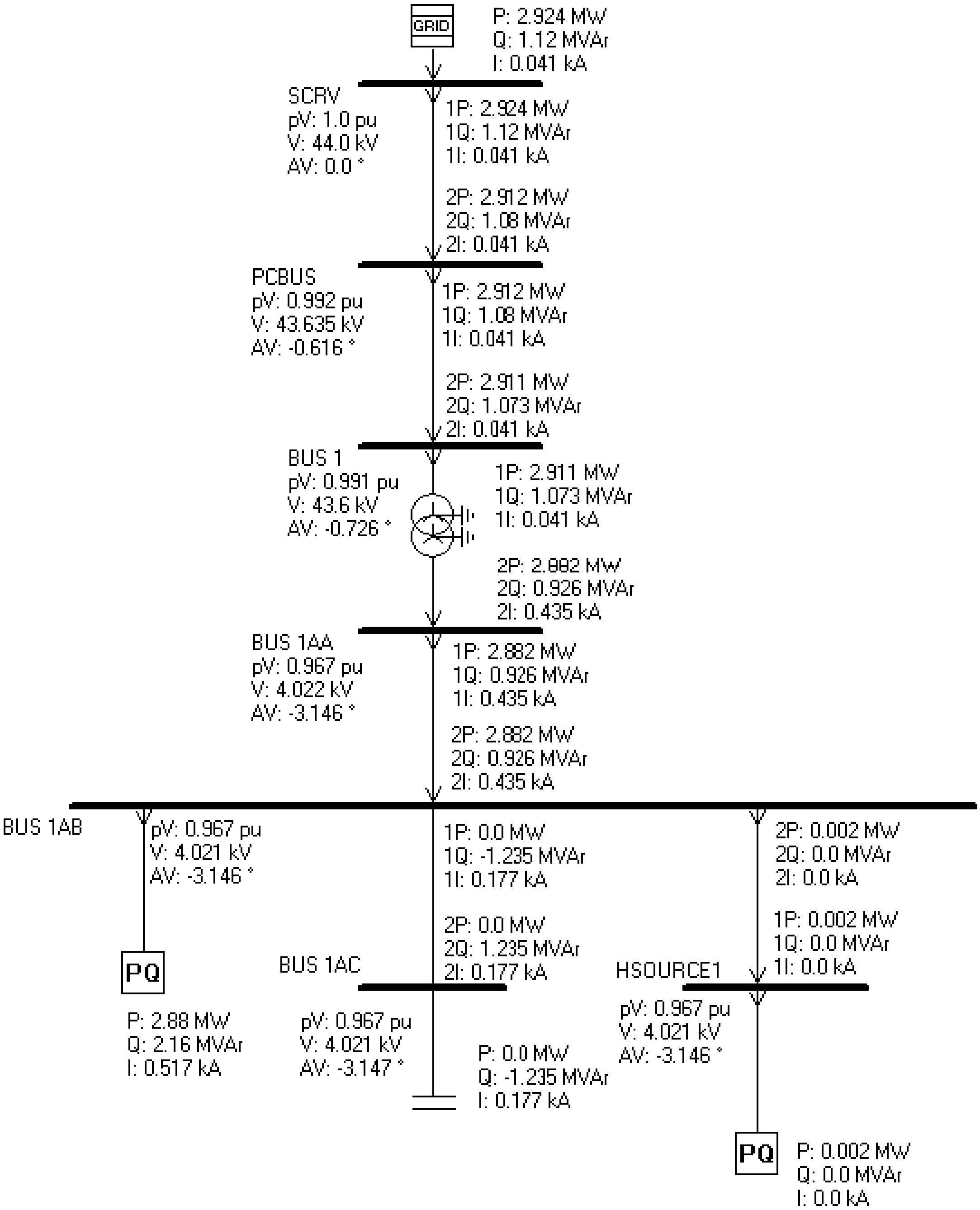


Figure 6.4: Load flow at f_1 with 80% load and PF_{DPF} correction to 0.96

6.2.1.6 Step 6(a)

Develop harmonic domain model that includes the non linear load.

6.2.1.7 Step 7(a)

Conduct harmonic penetration and resonance studies and check against limits of IEEE 519 Standard. In this case the harmonic penetration is limited to the 5^{th}, 7^{th}, 11^{th}, 13th, 17th and 19th characteristics harmonics. The 5th harmonic penetration is shown in Figure 6.5. Similarly for the other harmonics, results can be found the same way.

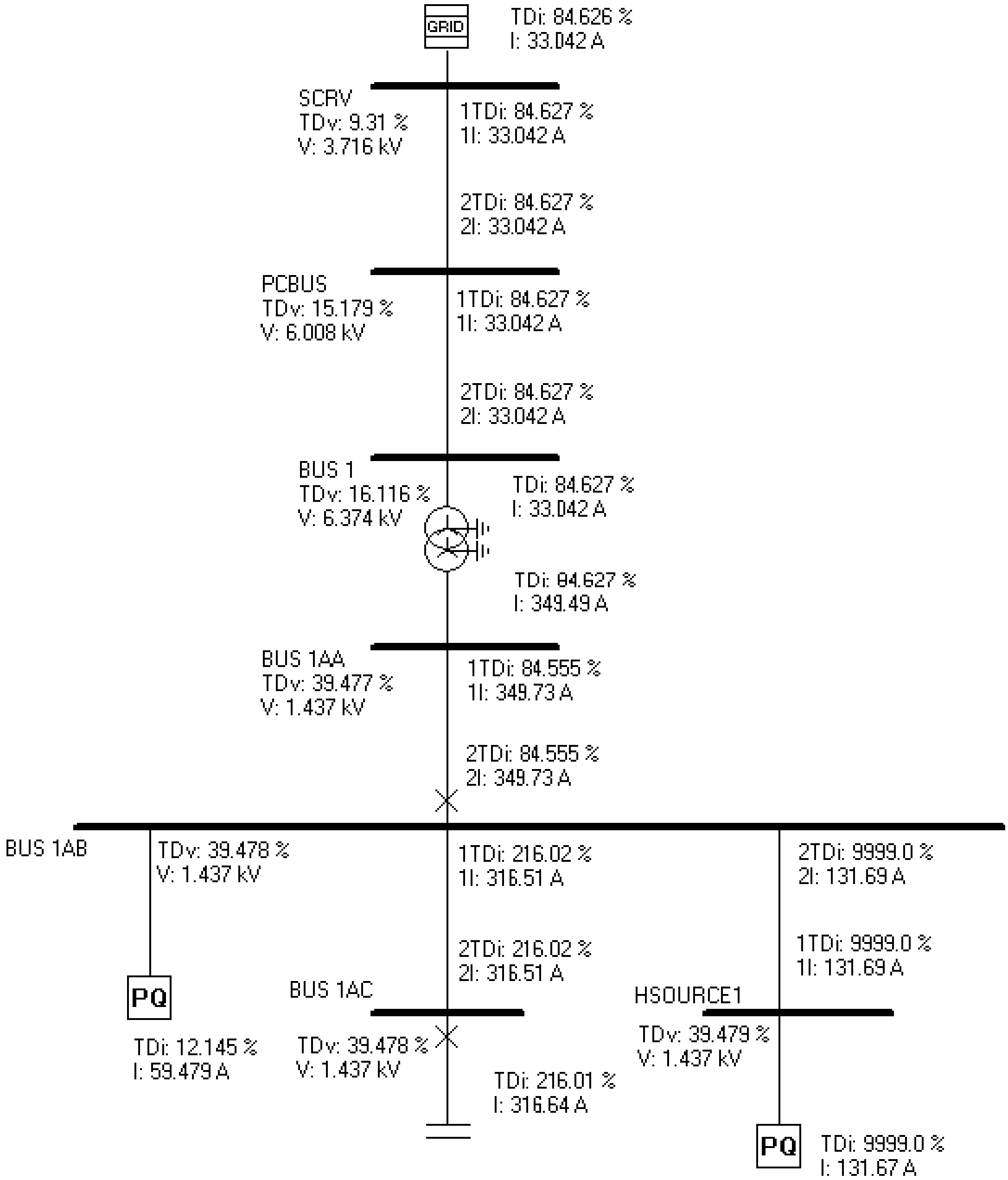


Figure 6.5: Harmonic penetration of the 5th harmonic

The harmonic graph (harmonic number versus impedance) of bus 1AB is shown in Figure 6.6. The graph shows that a parallel resonance point occurs at the 5.5th frequency with an impedance of 49.6 ohms. The harmonic injection of this study is at bus HSOURCE1.

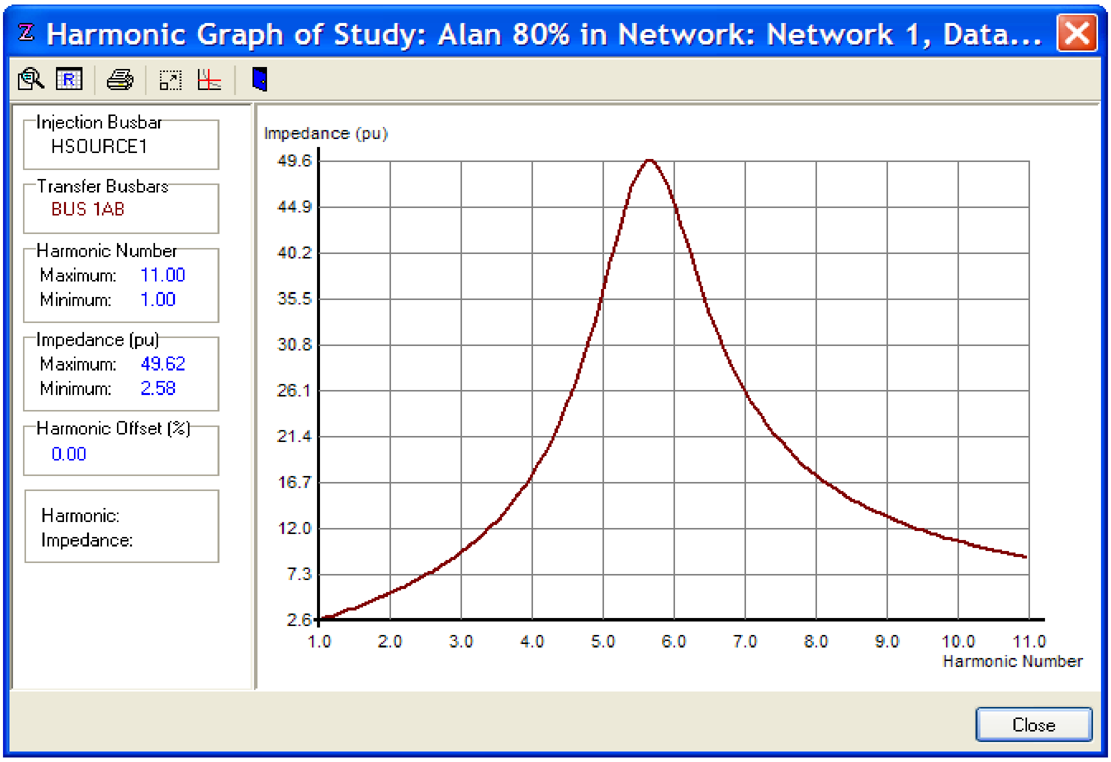


Figure 6.6: Harmonic graph of the 4.16 kV network at bus 1AB

6.2.1.8: Record Results

The harmonic profiles for the voltage at bus 1AB and current at the branch between bus 1AB and the linear load are shown in Figures 6.7 and 6.8, respectively.

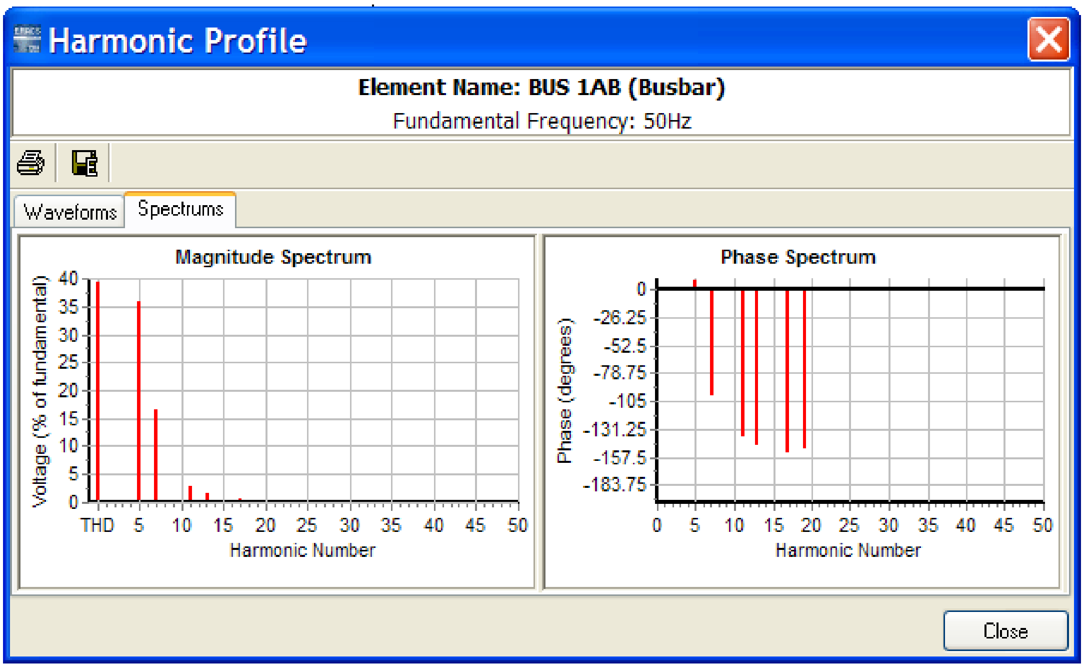


Figure 6.7: THD_V at PCC (BUS 1AB)

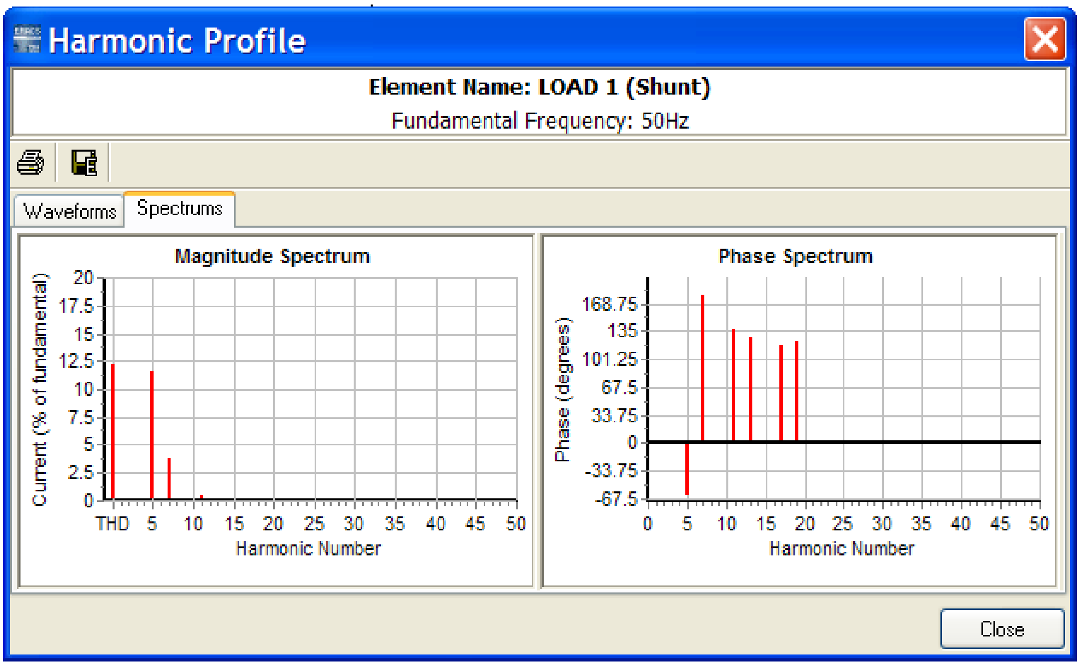


Figure 6.8: THD_I at linear load at bus 1AB

6.2.1.9: Decision

Using the above information and results, a decision will be made as to whether a harmonic filter is required in the network. According to the values derived from table 3.2 of the IEEE Standard 519, the harmonic profile results for the voltage at Figure 6.7 are above the recommended limits. This makes it necessary to conduct harmonic mitigation using a 5th harmonic series filter. Traditional filter design (as discussed in Sections 3.6.1 and 3.6.2) based on text books theory will be denoted as the "Designed Filter" in this work while the filter that is developed from the methodology in Chapter 4 (as shown in Figure 4.1) will be termed as the "Rated Filter".

6.2.2 Designed Filter

6.2.2.1 Step F1: Choose filter type

From the current and voltage magnitude spectrums in Figures 6.7 and 6.8, the 5th harmonic is the most dominant. A 5th harmonic series filter will be designed for the network as resonance in the harmonic graph is close to 5th harmonic.

6.2.2.2 Step F2: Design 5th harmonic series tuned filter

The filter is designed using the formulas and calculations below.

$$X_{eff} = \frac{V_{LL}(kV)}{Q_{eff}(MVar)} = \frac{4.16^2}{1.321} = 13.1\Omega$$

Using a tuning frequency of 4.8

$$X_C = \left(\frac{h^2}{h^2 - 1}\right) = \left(\frac{4.8^2}{4.8^2 - 1}\right) 13.1 = 13.69\Omega \Rightarrow C = 232.5\mu F$$

The inductive reactance becomes:

$$X_L = \frac{X_C}{h^2} = \frac{13.69}{4.8^2} = 0.594\Omega \Rightarrow 1.89mH$$

Using equation (3.35) to find the resistance, a Q value of 100 is chosen since it is the highest values from the range of 30 to 100 thus becoming:

$$R = \frac{f_r.X_L}{Q} = \frac{240 \times 0.594}{100} = 1.4256\Omega$$

6.2.2.3 Step F3: Decide on capacitor type to be used

Depending on the client's protection needs and finances, the type of capacitors used in the banks will be chosen. The capacitor banks will be decided between the internally fused, externally fused and fuseless capacitors (as discussed in Sections 3.10.1.1 to 3.10.1.3).

6.2.2.4 Step F4: Calculate the filter component parameters

Using sec 3.10.3, the filter components will be calculated. The designed component values are then modelled into the network. A load flow (shown in Figure 6.9) is conducted on the network which derives the fundamental current. Harmonic penetration is then conducted on the network and the harmonic currents across each of the filter components are found. The 5th harmonic penetration is shown in Figure 6.10. Similarly for other harmonics i.e. 7th, 11th, 13th, 17th and 19th and the currents are shown in Table 6.1 below.

Table 6.1: Harmonic currents through the filter (BUS 1AC)

Harmonic	Current (Amps)
1st	185
5th	87.255
7th	43.624
11th	18.593
13th	12.754
17th	6.083
19th	4.37

The rms current using all the harmonics flowing through the filter components is calculated as:

$$I_{rms} = \sqrt{\left(185^2 + 87.255^2 + 43.624^2 + 18.593^2 + 12.754^2 + 6.083^2 + 4.37^2\right)} = 210.49A$$

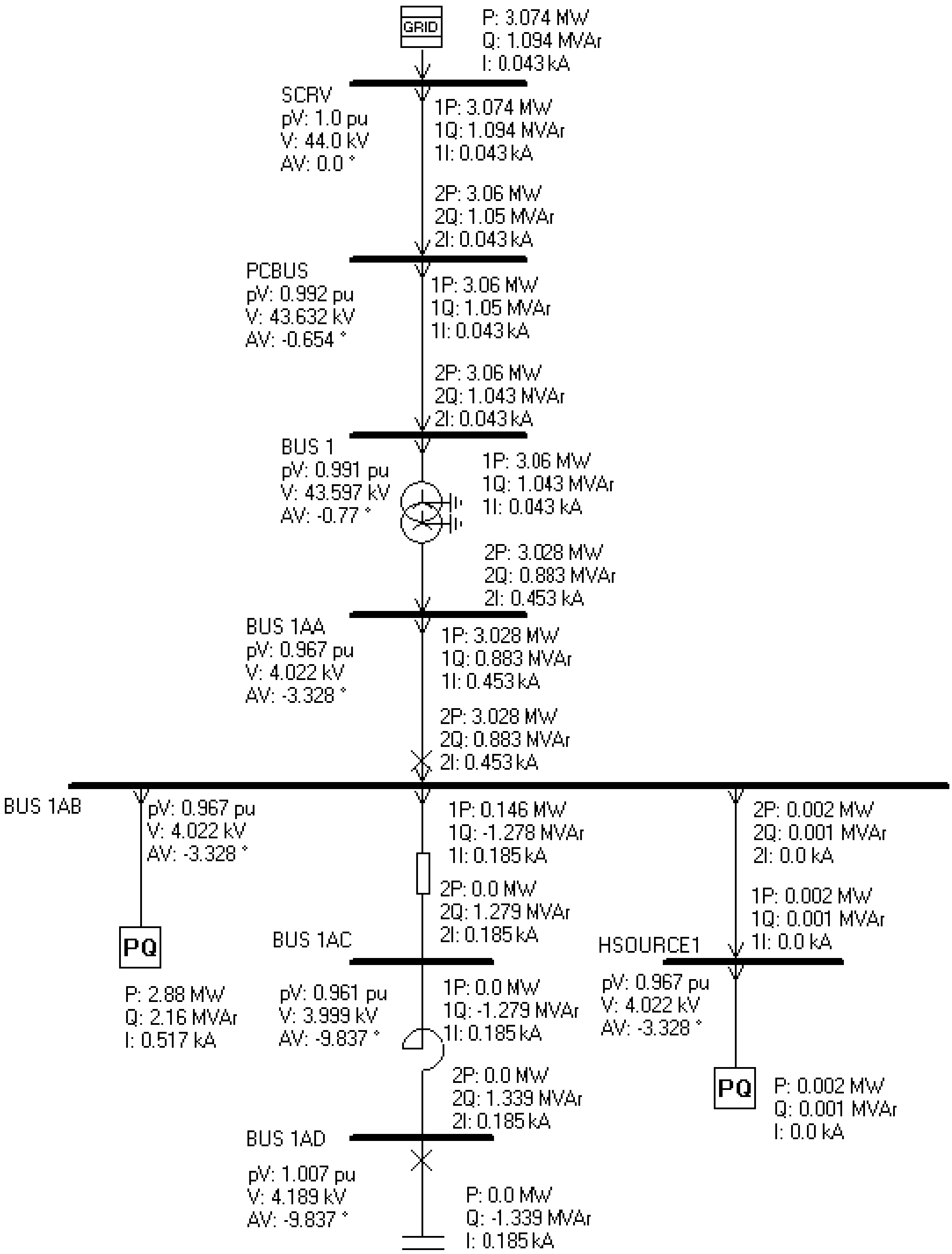


Figure 6.9: Load flow with Designed Filter

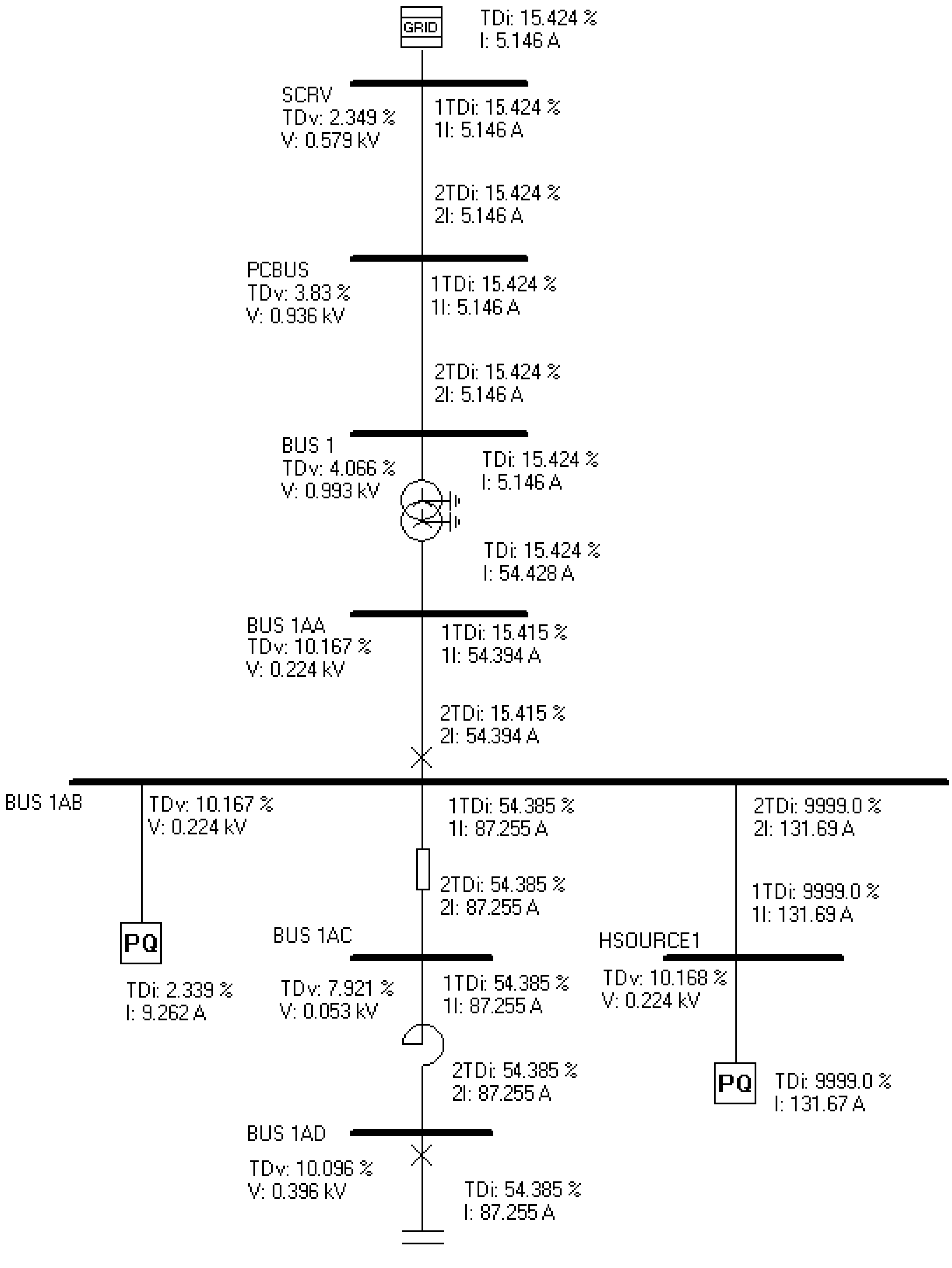


Figure 6.10: 5th harmonic penetration with Designed Filter

The magnitude spectrums in percentage values are obtained at bus 1AB and branch between bus 1AB and linear load PQ, respectively. These are shown in Figures 6.11 and 6.12.

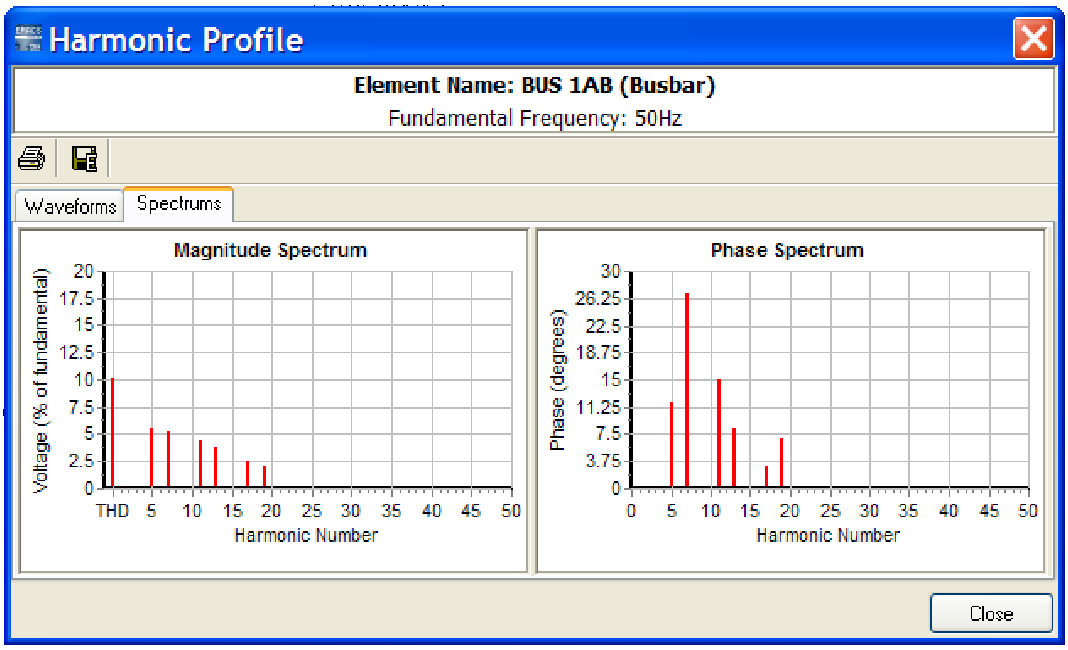


Figure 6.11: THD_V at PCC (BUS 1AB) with Designed Filter

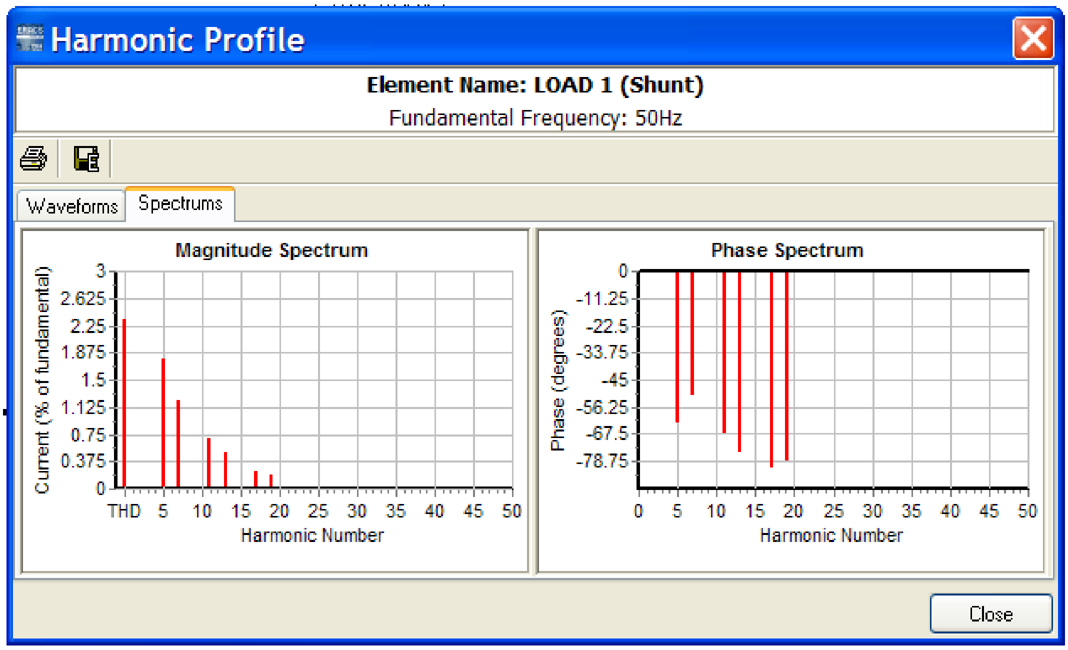


Figure 6.12: THD_I at linear load at PCC (BUS 1AB) with Designed Filter

The harmonic graph (harmonic number vs impedance) at bus 1AB with the Designed Filter is shown in Figure 6.13.

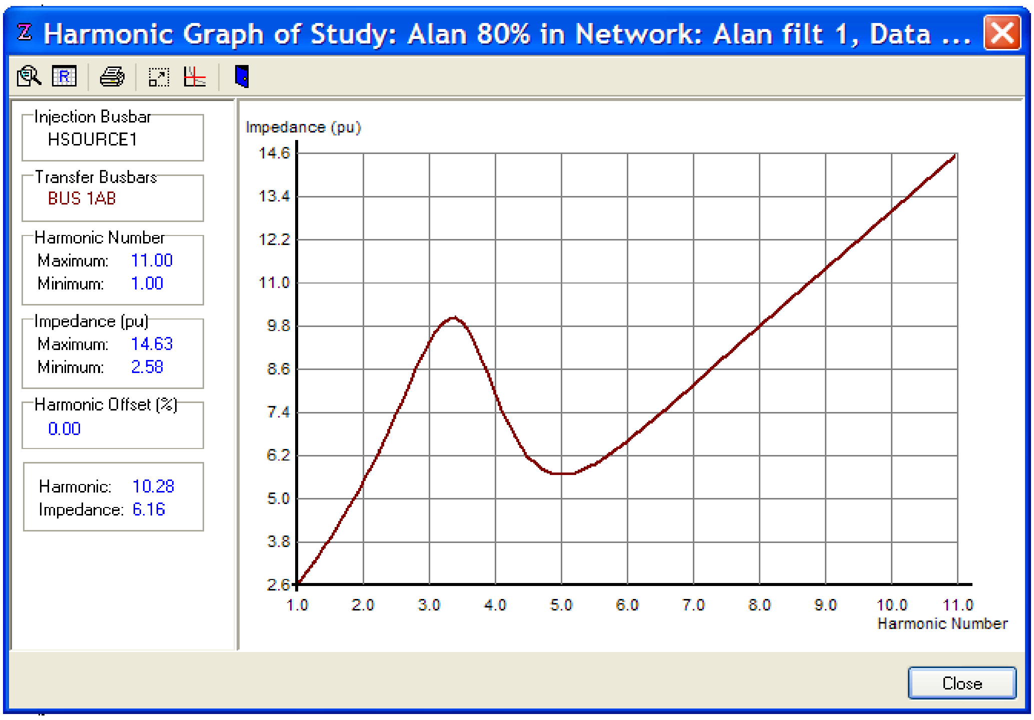


Figure 6.13: Harmonic graph with Designed Filter at bus 1AB

The voltage across each of the filter components is then calculated.

Capacitor:

The fundamental voltage across the capacitor is found using:

$$V_C(1) = I_f(1).X_c$$

$$V_C(1) = 13.1 \times 185 = 2423.5V$$

The harmonic voltage across the capacitor is found using:

$$V_C(h) = \sum I_f(h)\left(\frac{X_c}{h}\right)$$

$$V_C(h) = (87.255 \times \frac{13.1}{5}) + (43.624 \times \frac{13.1}{7}) + (18.593 \times \frac{13.1}{11})$$

$$+ (12.754 \times \frac{13.1}{13}) + (6.083 \times \frac{13.1}{17}) + (4.37 \times \frac{13.1}{19}) = 352.942V$$

The peak voltage across each capacitor unit (V_C) will be V_C (1) + V_C (h) to be 2423.5 + 352.942 = 2776.442V and this is called the rated voltage, and is an rms value, see section 3.11.3.

The actual capacitor reactive power will be (rated 3 phase value):

$$Q_C = \frac{\left(\sqrt{3}V_C\right)^2}{X_c} = \frac{\left(\sqrt{3} \times 2.776\right)^2}{13.1} = 1.765MVar$$

The capacitor to be used in the harmonic filter will have a rating of 1.765 MVar which is higher than the one used for reactive power compensation of 1.321 MVar.

The nominal capacitor current that flows in the harmonic filter is calculated to be (see section 3.11.3):

$$I_C = \frac{Q_C(kVar)}{\sqrt{3}V_C(kV)} = \frac{1.765 \times 1000}{\sqrt{3} \times \sqrt{3} \times 2.776} = 211.936A$$

Where V_C is the rms phase voltage.

Reactor:

The total voltage across the reactor is calculated using the formula below:

$$V_L(h) = \sum I_f(h)(X_L.h)$$

$$V_L(h) = (185 \times 0.594 \times 1) + (87.255 \times 0.594 \times 5) + (43.624 \times 0.594 \times 7) +$$
$$(18.593 \times 0.594 \times 11) + (12.754 \times 0.594 \times 13) + (6.083 \times 0.594 \times 17) +$$
$$(4.37 \times 0.594 \times 19) = 881.144V$$

The total voltage through the reactor will be 881.144V. The actual reactor reactive power will be:

$$Q_L = \frac{\left(\sqrt{3}V_L\right)^2}{X_L} = \frac{\left(\sqrt{3} \times 0.881\right)^2}{0.594} = 3.92MVar$$

Resistor:

The voltage across the resistance of the reactor will be calculated using the formula below:

$$V_R(h) = \sum I_T(h)(R.h)$$

$$V_R(h) = (185 \times 1.426) + (87.255 \times 1.426) + (43.624 \times 1.426) + (18.593 \times 1.426) +$$
$$+ (12.754 \times 1.426) + (6.083 \times 1.426) + (4.37 \times 1.426) = 510.048V$$

Using the above voltage, the resistors real power rating will be:

$$P = \frac{\left(\sqrt{3}V_R\right)^2}{R} = \frac{\left(\sqrt{3} \times 0.510\right)^2}{1.426} = 0.547MW$$

6.2.2.5 Step F5: Model filter components

Model the filter components into the network and conduct harmonic analysis. This will include load flow, harmonic penetration and voltage and current magnitude spectrums. The harmonic graph of the network is also simulated.

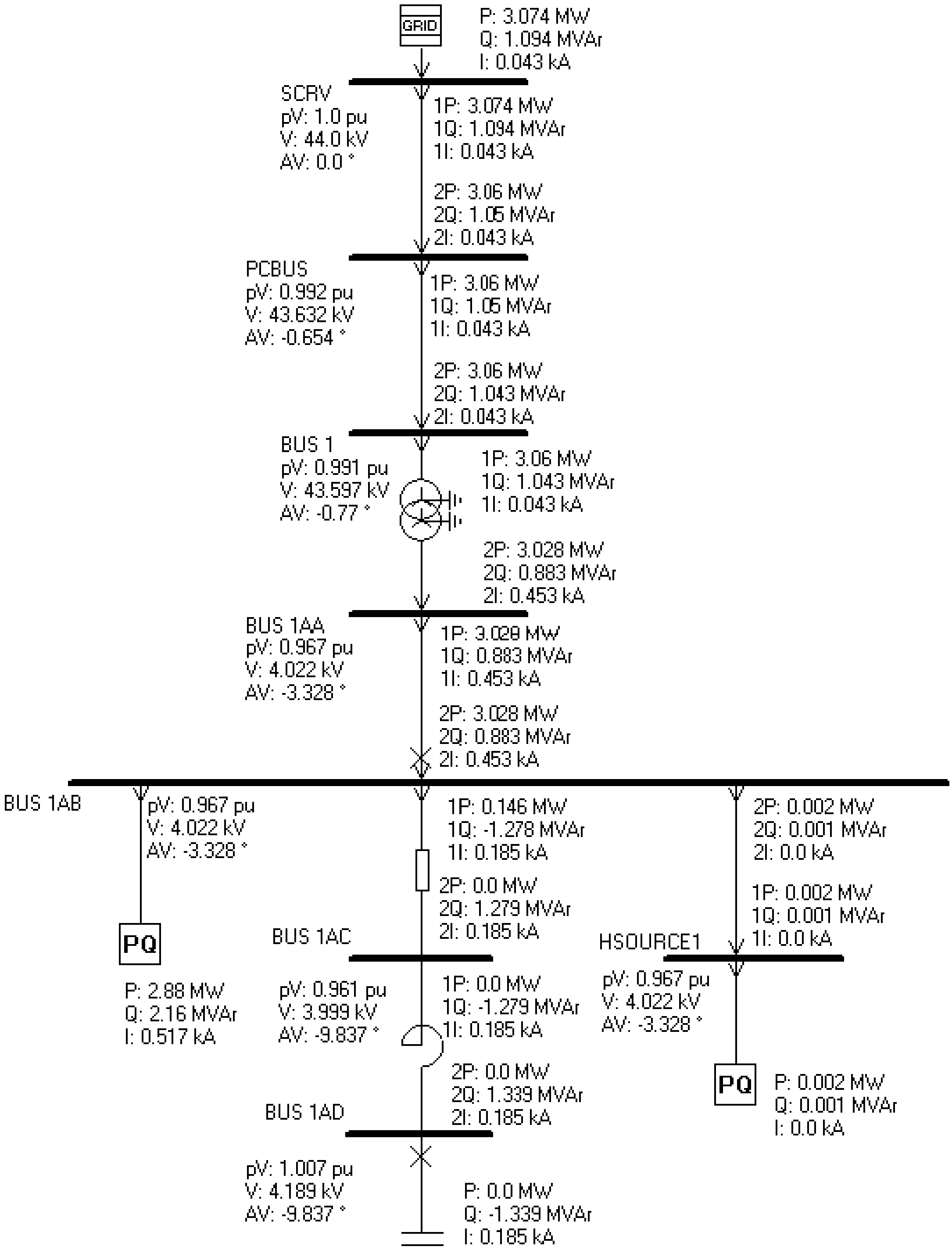


Figure 6.14: Load flow with Rated Filter

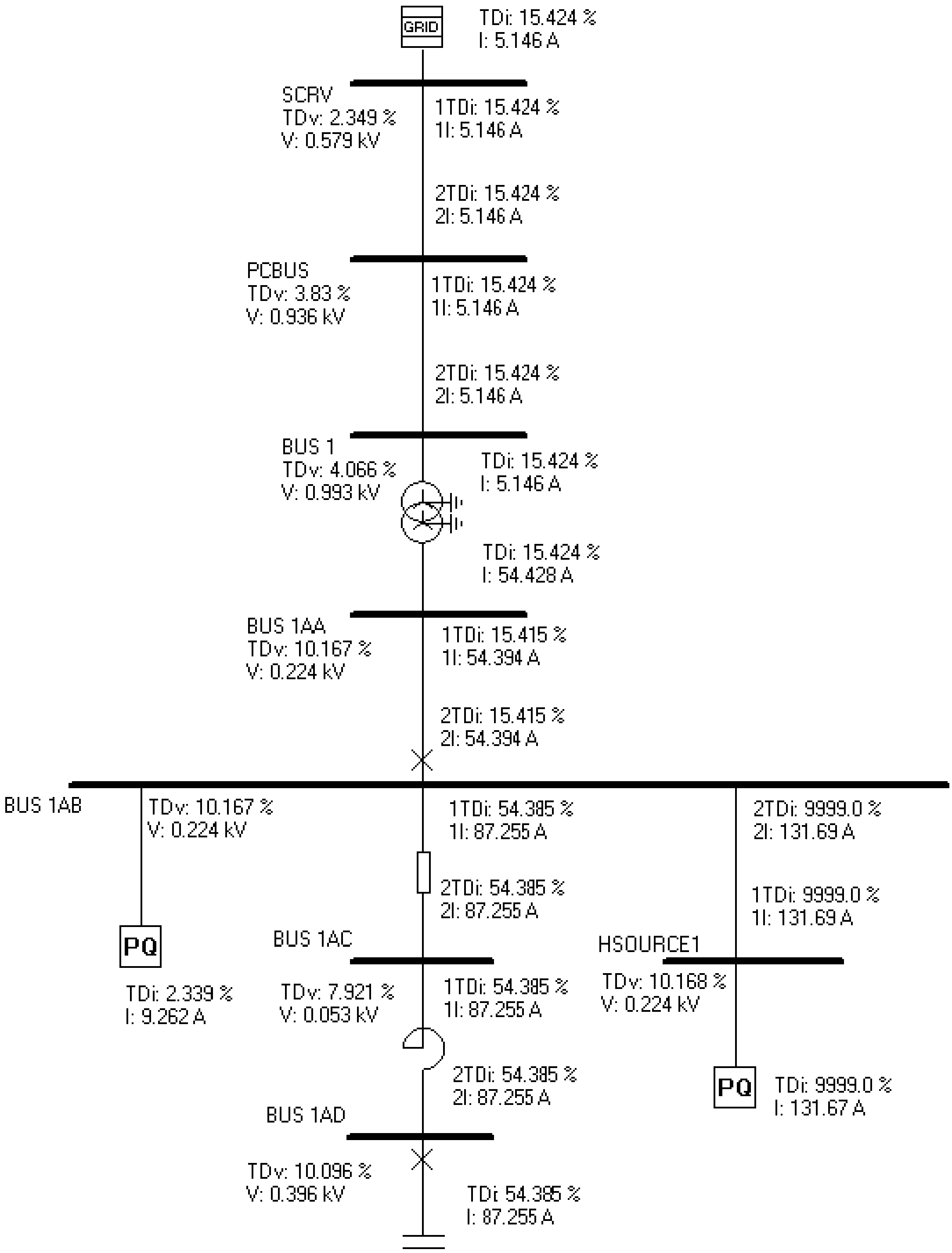


Figure 6.15: 5th harmonic penetration with Rated Filter

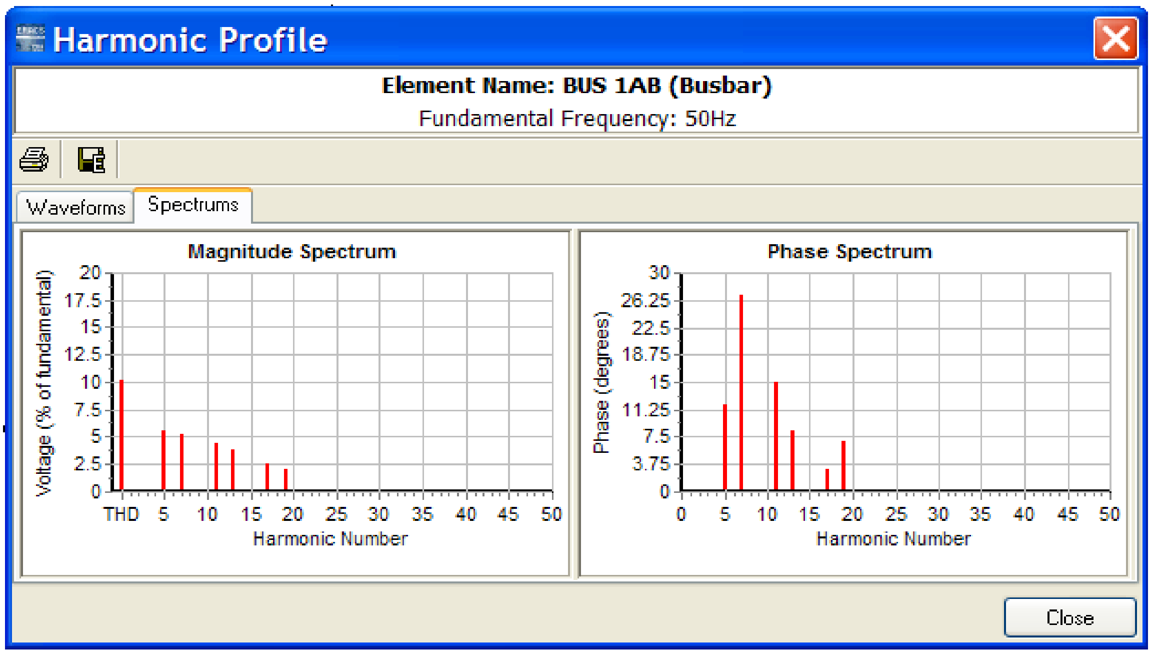


Figure 6.16: THD_V at PCC (BUS 1AB) with Rated Filter

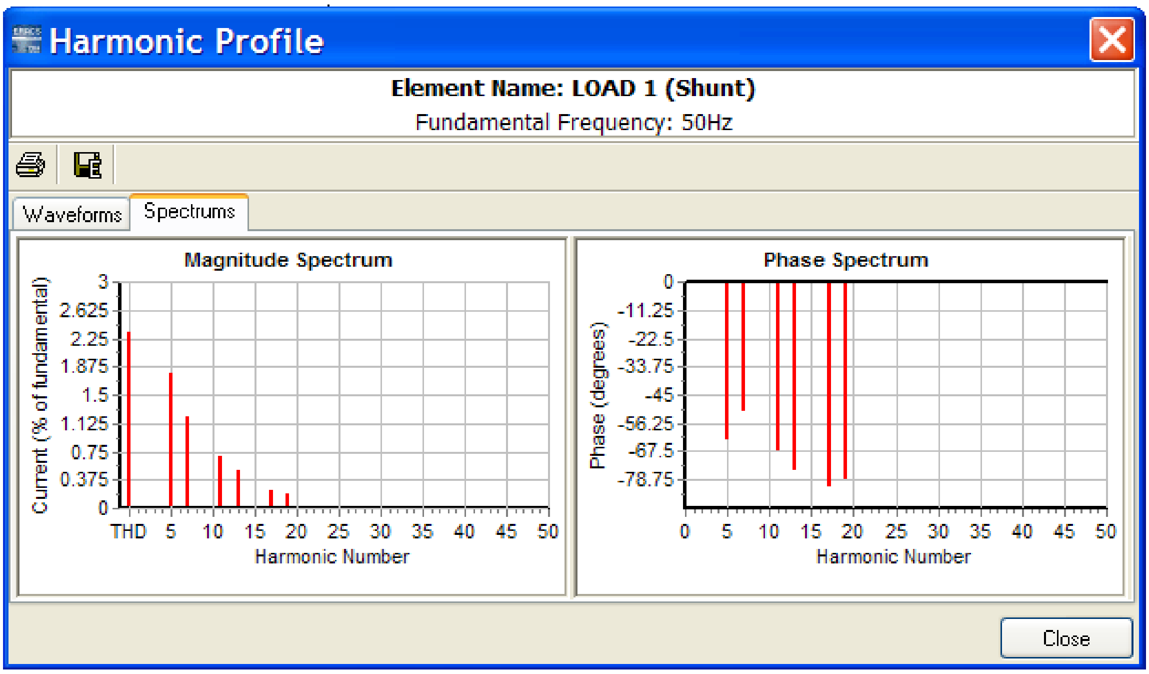


Figure 6.17: THD_I at Linear Load at PCC (BUS 1AB) with Rated Filter

The harmonic graph (harmonic number vs impedance) of bus 1AB is shown in Figure 6.18 below.

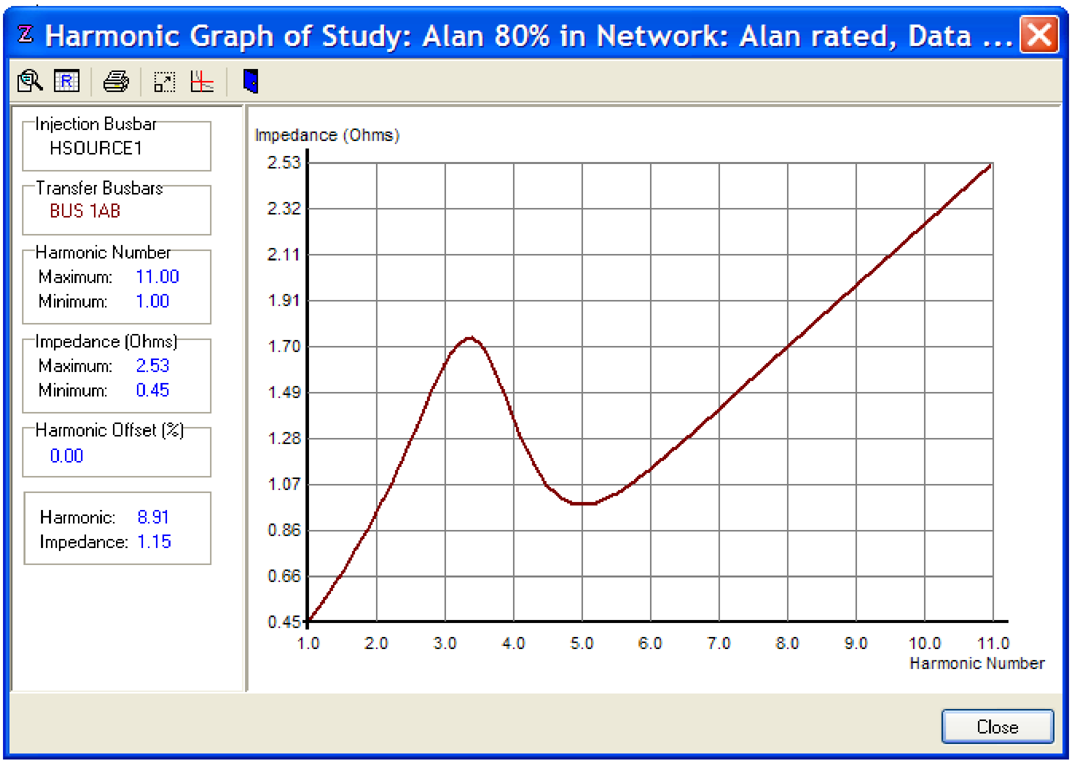


Figure 6.18: Harmonic graph with Rated Filter at bus 1A

6.2.2.6 Step F6: Verify filter effectiveness

From the results it is noted that the Designed Filter alters the parallel resonance point of the network. With power factor correction, the resonance point is at the 5.5^{th} frequency with 8.59 ohms. With the Designed and Rated Filters modelled into the network, the parallel resonating points move to the 3.5^{th} frequency at 1.70 ohms. THD_V decreased to 10.17% with both the Designed and Rated Filters from 20.11% when only the PF_{DPF} capacitor was in the network. This shows that the Rated Filter is effective.

6.2.2.7 Step F7: Fill the manufacturer's template

Once the filters performance is designed to give acceptable values, the next step is to fill in the manufacturer's template. The templates are to be sent to the filter component manufacturers. The templates give all the details and rating of the components considering the space available for installation and environmental factors of the area. Tables 6.2 and 6.3 show the filter templates that would be used to get the filter components manufactured.

Table 6.2: Series tuned filter capacitor data for manufacturer

Client Name	Alan Meru
Phone	021-4603085
Fax	021-4603705
Email	MeruA@cput.ac.za
Due Date	Aug - 13
Quote requested by	Alan Meru
Bank Voltage (1.25 $\times$ system V_L)	5.2 KV
Power frequency (f)	50 Hz
Tuning Frequency	240 Hz
Current (1.2 $\times$ system I)	232 A
Capacitor Reactance (X_C)	13.1 Ω
Capacitor Power	1.764 MVar
Connection	Grounded
Fuses	Fuseless
Unbalance Relay	Yes
Mounting	Vertical
Elevating structure height	X mm
Bushing creepage	X kV/mm
Temp range (min to max)	X Degrees

Table 6.3: Series tuned filter reactor data for manufacturer

Client Name	Alan Meru
Phone	021-4603085
Fax	021-4603705
Email	MeruA@cput.ac.za
Due Date	Aug – 13
Quote requested by	Alan Meru
System voltage	4.16 kV
Power frequency (f)	50 Hz
Tuning Frequency	240 Hz
Current (1.2 $\times$ system I)	232 A
Reactance (X_L)	0.594 Ω
Reactor Rating	1.89 mH
Q factor of Reactor	100
Resistance	1.426 Ω
Mounting	Vertical
Dimensional limitations	32 m^2
No of units	3

The next step is to implement flow chart B Figure (5.20). For the installation of the filter, the methodology developed in chapter 5 is followed and implemented. Typically such a filter would be installed and it is expected that an area of 4000mm by 8000mm would be sufficient for the Rated Filter. The above values are derived from Figures A2.3 and A2.4 in Appendix 2. The layout of the filter would be similar to the one in Figure 6.19.

Figure 6.19: Series tuned harmonic filter at site

6.3 Existing Network (12 kV Network)

The second study was done using (Figure 6.20), which is a 40kV network having two radial distribution networks (Thunberg & Soder, 1999:272). Capacitor banks are connected at buses 6BA and 4A for power factor correction for the loads connected on bus 6B and whole network, respectively. Two loads at buses 5A and 5B are connected to bus 5 via transformers of different voltage ratios. Two harmonic sources (6 pulse drives) are connected at buses 6AA and 6AB, operating at different voltage levels i.e. 6kV and 0.4kV, respectively. 6 pulse drives typically inject characteristic harmonics of 6k±1, where k =1, 2, 3, etc., which are typically the 5^{th}, 7^{th}, 11^{th}, 13th, 17^{th} and 19^{th}. All the data of the components in the network can be seen in Appendix 4 that includes the harmonics induced by the two speed drives.

As an existing network, the methodology in Chapter 4 (Figure 4.1) is used for harmonic analysis. The end user at bus 5A wants to improve the low PF_{DPF} of 0.5 and is also aware of other capacitors in the network and the two drives at bus 6. At the same time, the end-user is concerned that his new capacitor could be damaged by resonance and that there may be a need for mitigation. He is also aware that the power drawn by his plant has an impact on the severity of harmonic resonance in the network. The end user will need to decide on the size of capacitor to be installed and make a mitigation decision (Atkinson-Hope, 2003).

6.3.1 Methodology

6.3.1.1 Step 1(b)

Draw a one line diagram (Figure 6.20) of the network to be investigated as to whether or not a harmonic filter is needed.

6.3.1.2 Step 2(b)

The first thing is to determine the value of capacitor that would be used at bus 5A to improve the PF_{DPF} from 0.5 to 0.96. The value is determined as follows:

$$S = \frac{P}{PF_{NEW}} = \frac{2.0}{0.96} = 2.083MVA$$

$$Q_{NEW} = \sqrt{S^2 - P^2} = \sqrt{2.083^2 - 2.0^2} = 0.583MVar$$

Where

$$Q_{CAP} = Q_{OLD} - Q_{NEW} = 3.464 - 0.583 = 2.881MVar$$

Using the calculated capacitance value, model the capacitor into the network. Then conduct measurements at f_1 (load flow) as shown in Figure 6.21. Obtain THD and HD indices at various “h” at PCC and load at bus 5A. This is achieved by conducting harmonic penetration studies. Figure 6.22 shows the 5^{th} harmonic results.

6.3.1.3 Step 3(b)

Check results against IEEE 519 Standards using voltage and current magnitude spectrums.

6.3.1.4 Step 4(b)

Generate bar graph of voltage and current HD indices. The voltage spectrums at buses 3 and 5A are shown in Figures 6.23 and 6.24, respectively. The current spectrum at load 5A (current from bus 5A to load) is shown at Figure 6.25.

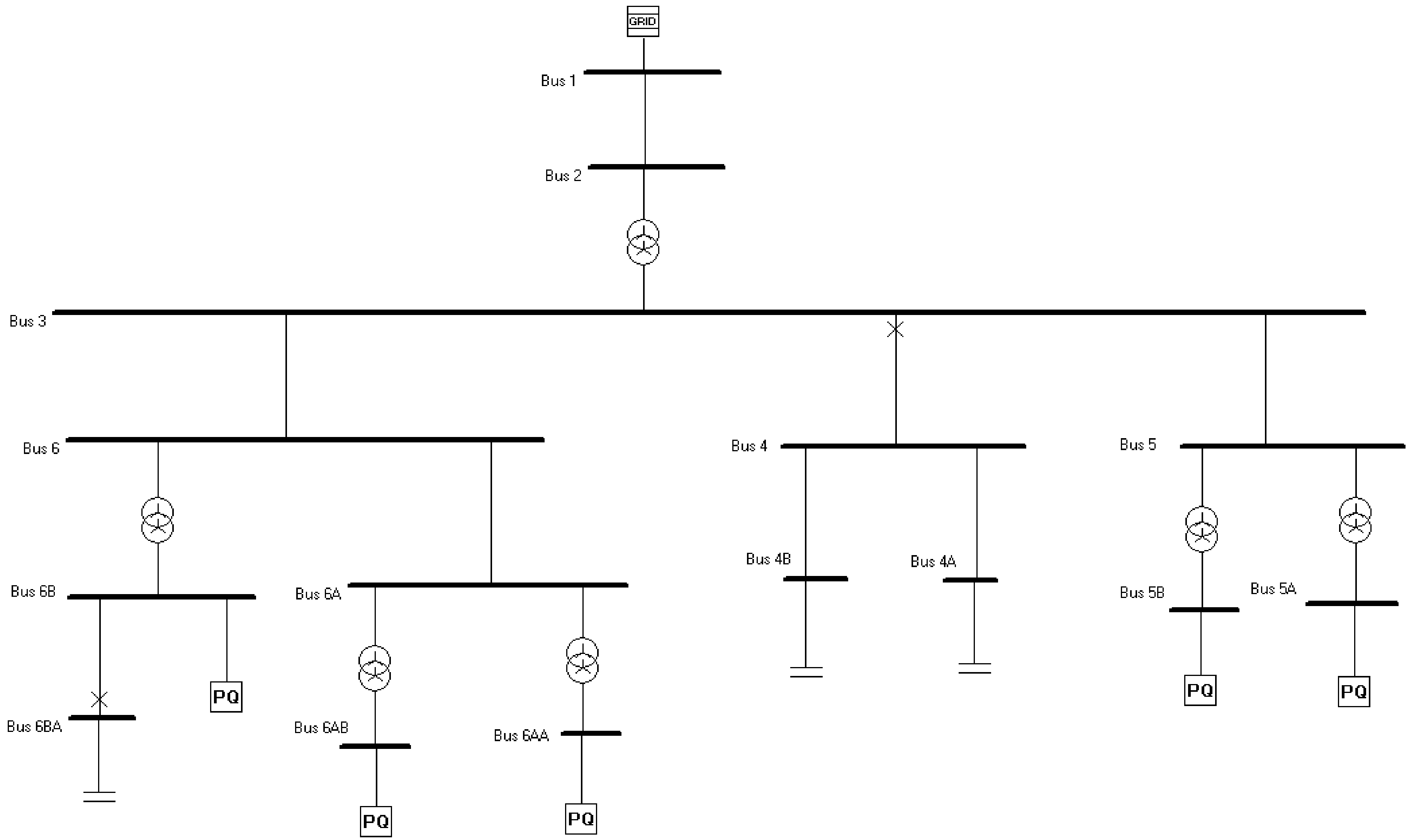


Figure 6.20: One line diagram of 40 kV supply with two radial distribution networks

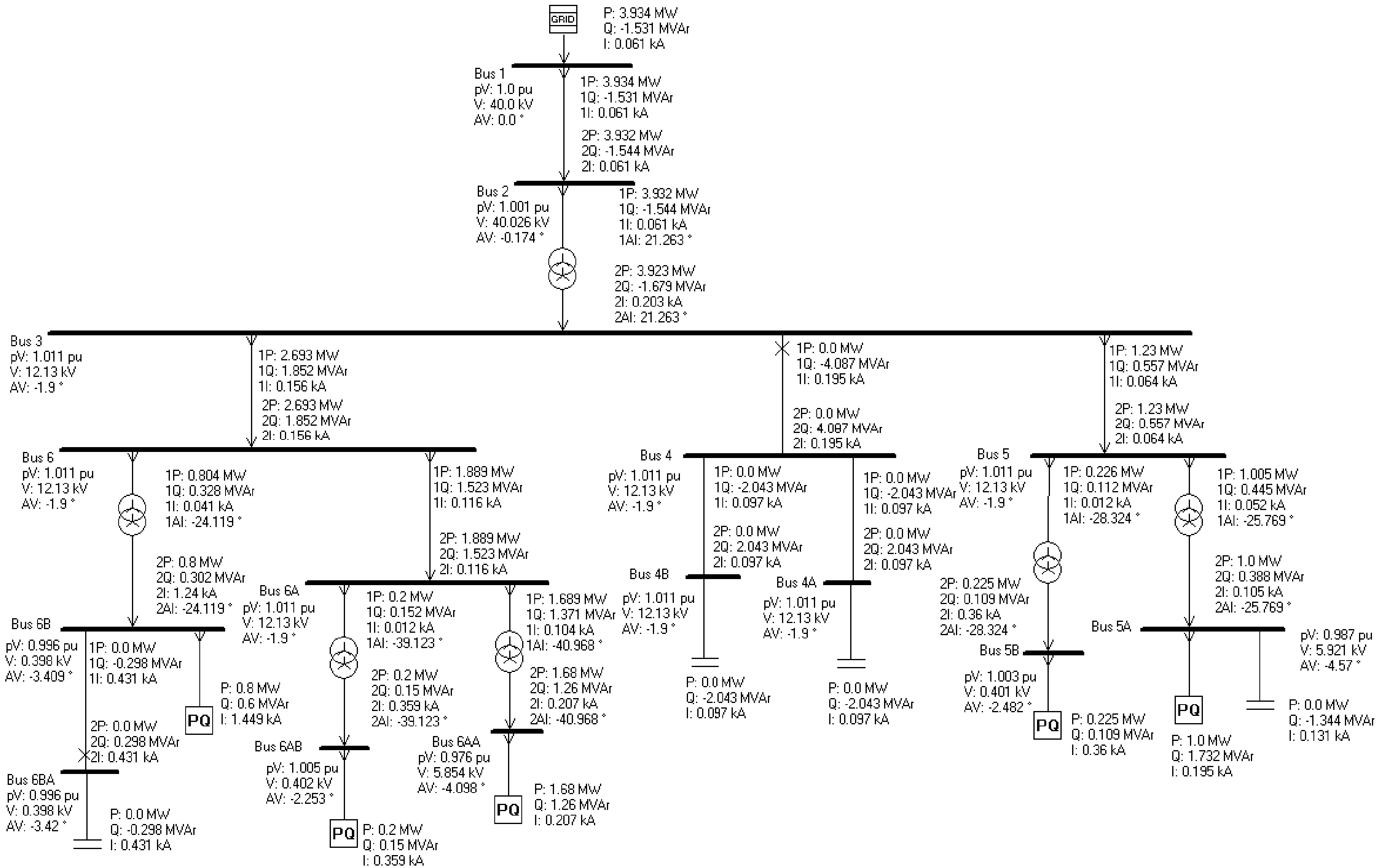


Figure 6.21: Load flow with PF_{DPF} capacitor at bus 5A

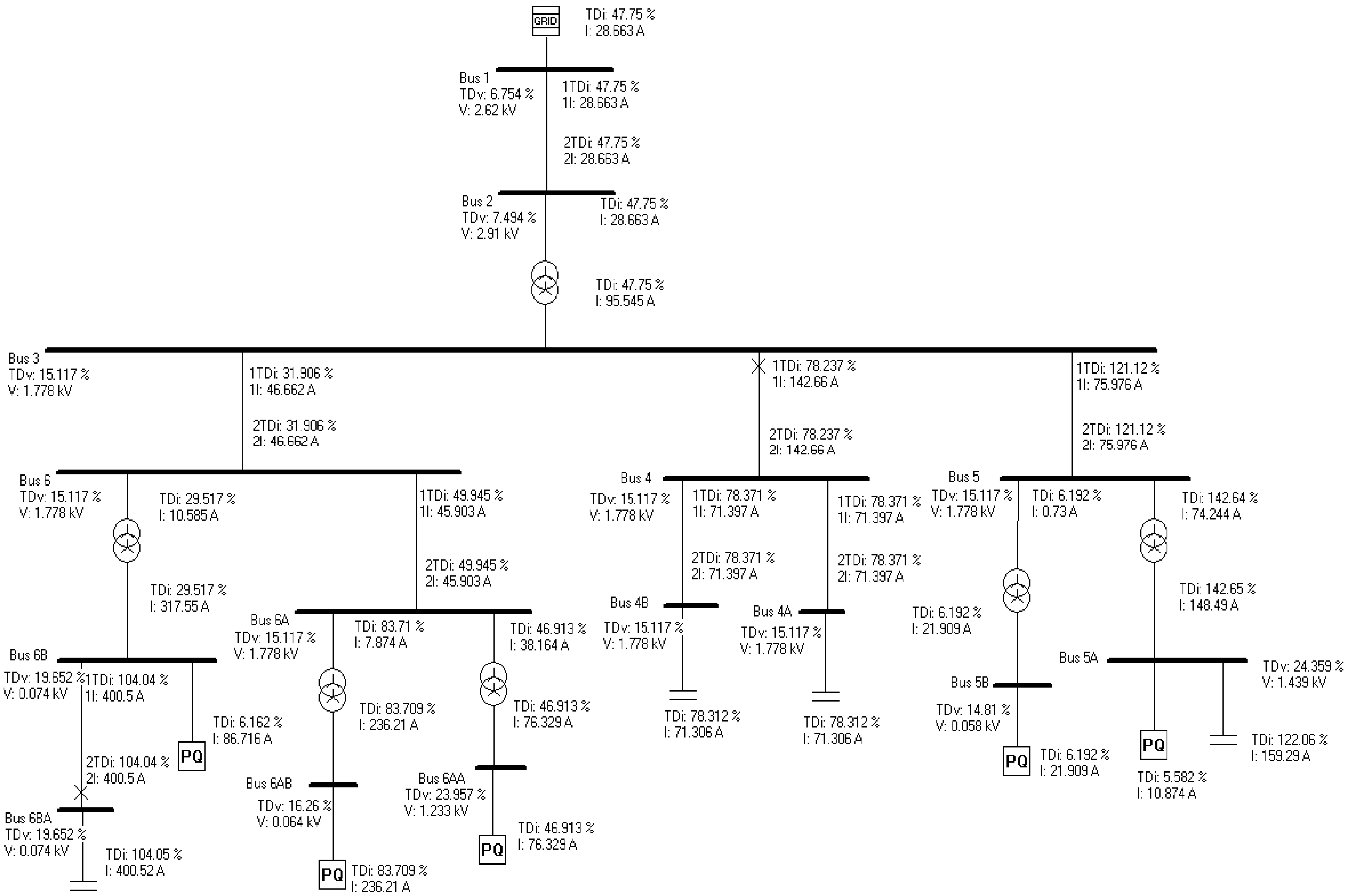


Figure 6.22: 5th harmonic penetration results with PF_{DPF} capacitor at bus 5A.

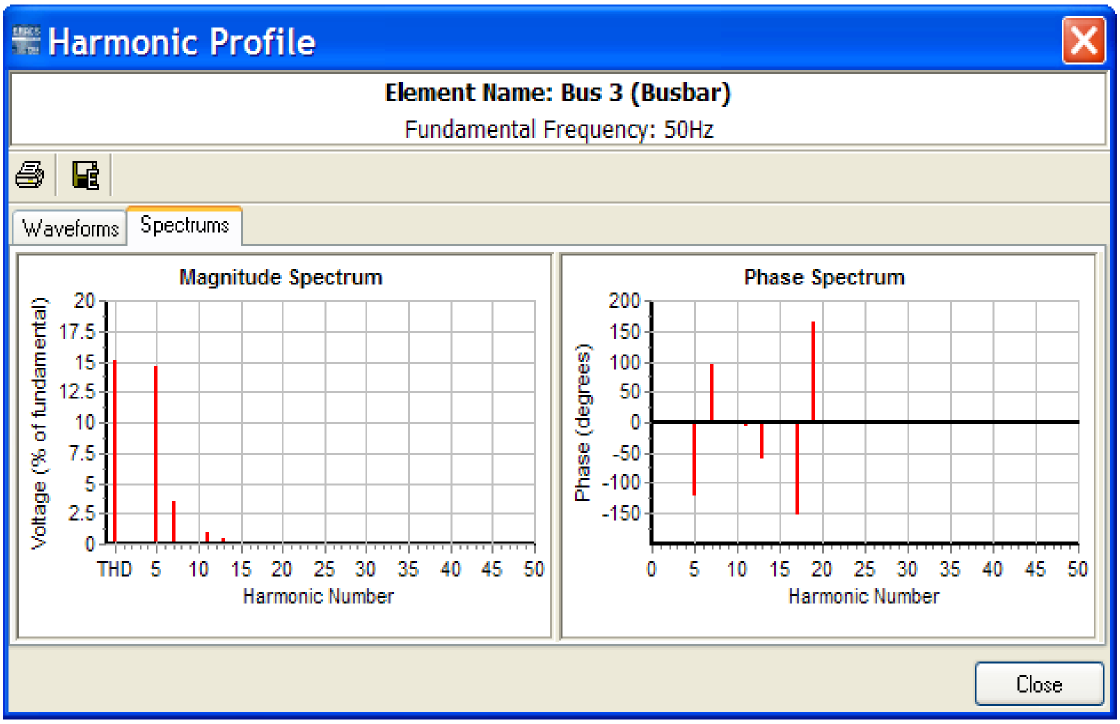


Figure 6.23: THD_V at bus 3 with PF_{DPF} capacitor at bus 5A

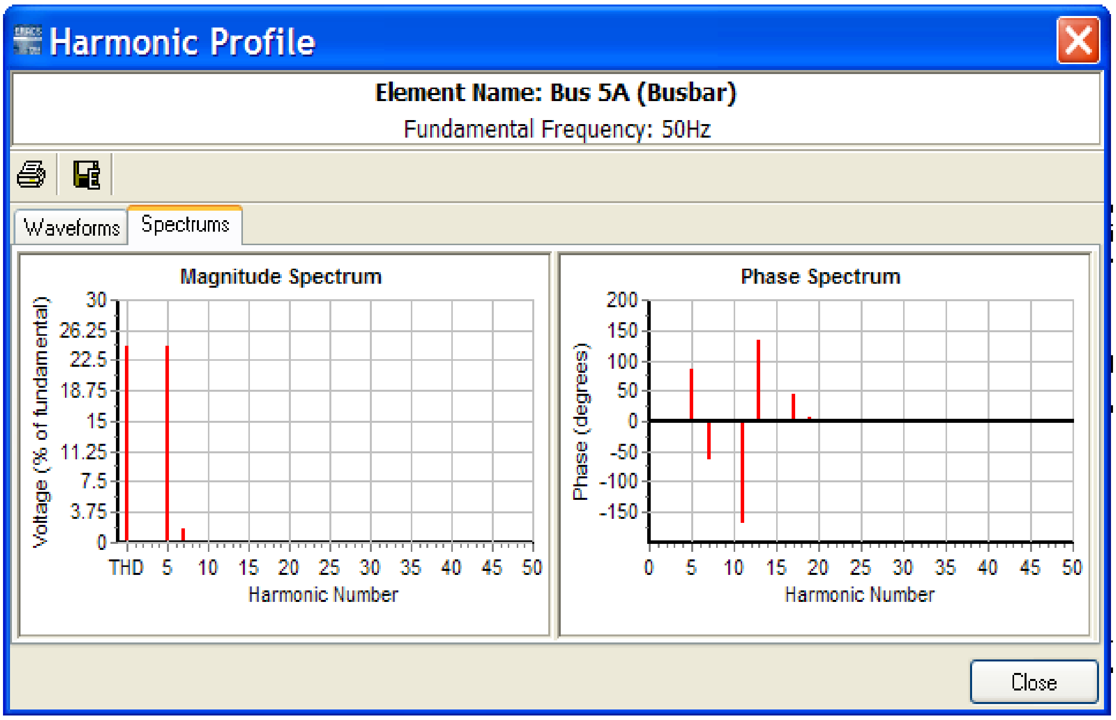


Figure 6.24: THD_V at bus 5A with PF_{DPF} capacitor at bus 5A

The current spectrums of the current to the load from bus 5A are shown in Figure 6.25 below.

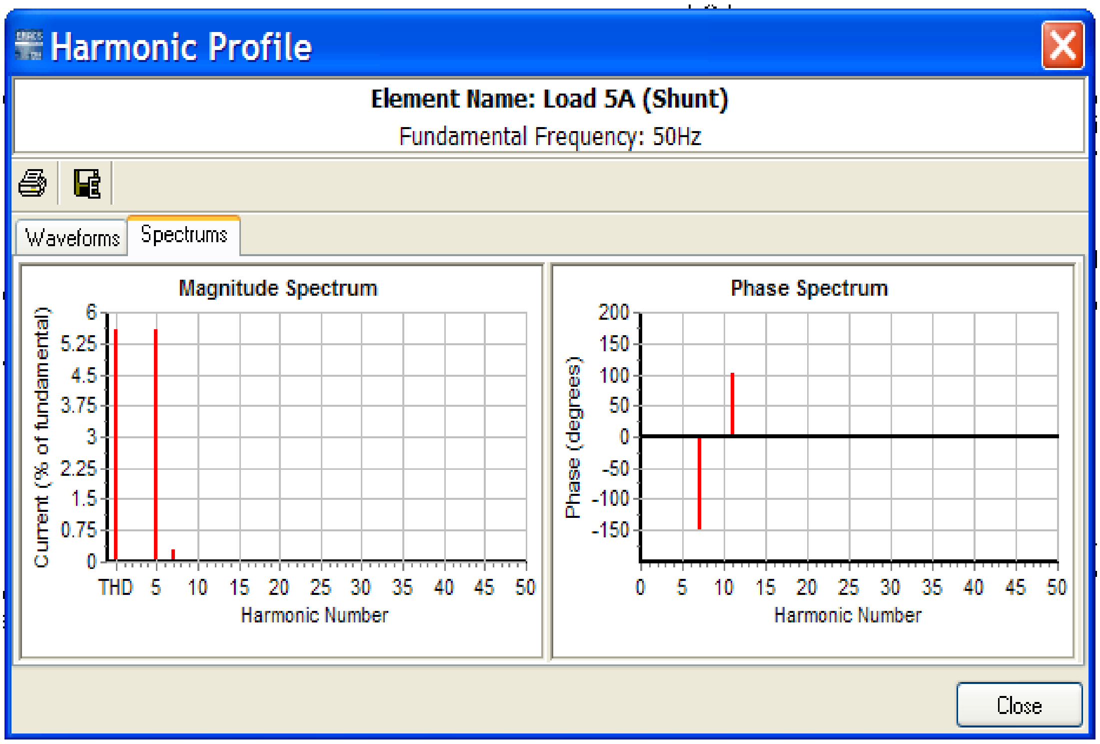


Figure 6.25: THD_I at load at bus 5A with PF_{DPF} capacitor at bus 5A

6.3.1.5: Record Results

The harmonic graph (harmonic number versus impedance) of buses 3 and 5A are shown in Figure 6.26.

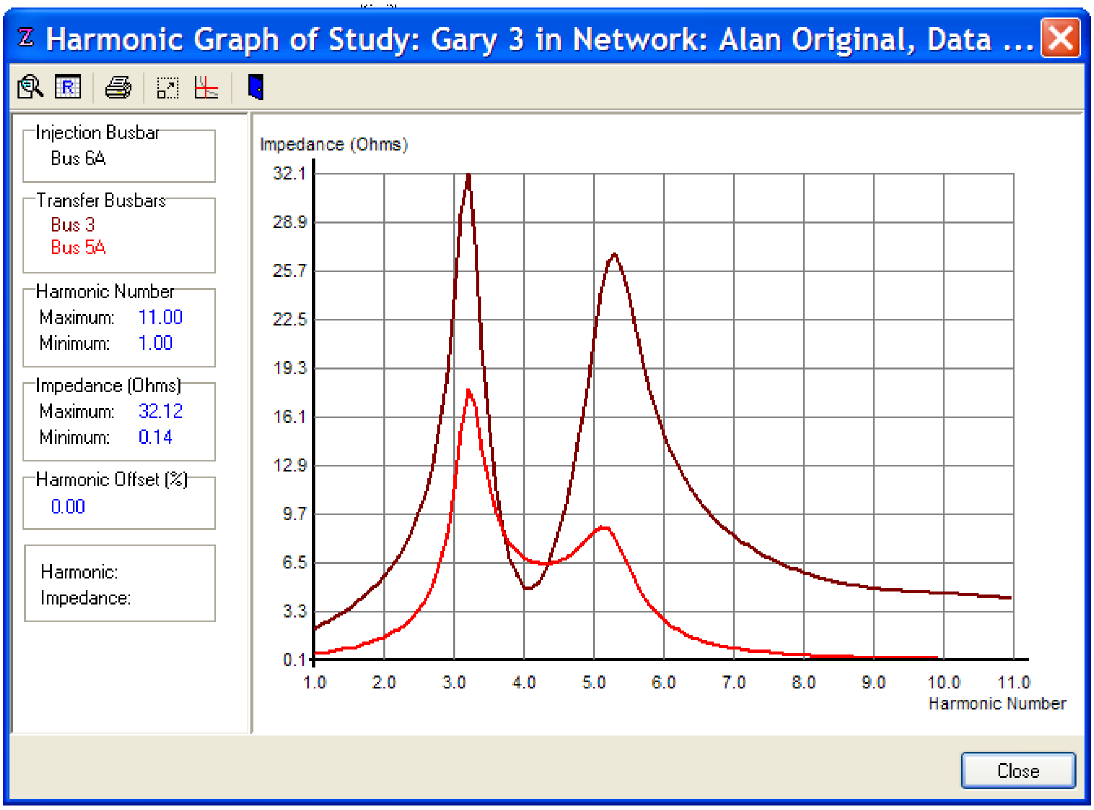


Figure 6.26: Harmonic graph at buses 3 and 5A.

The results show that bus 3 has two resonance points at the 3.23rd and 5.28th frequency with respective, impedances of 31.28 and 26.68 ohms. Bus 5A also has two resonance points at the 3.19th and 5.16th frequency with respective, impedances of 17.63 and 8.89 ohms.

6.3.1.6: Decision

Using the above information and results, a decision will be made as to whether a harmonic filter is required in the network. According to the values derived from Table 3.2 of the IEEE std. 519, the harmonic profile results for the voltage at Figure 6.23 are above the recommended limits. The results thus necessitate harmonic mitigation using a harmonic filter. From the harmonic graph in Figure 6.26, two different types of harmonic filter will be designed. The performance of each of the two filters will be evaluated to find which of the two is more effective.

6.3.2 Design

6.3.2.1a) Step F1 a: Choose filter type

Two options of filters present themselves for this network. The first option is a second order filter at bus 3 and is the responsibility of the utility. The second option is a 5th harmonic series tuned filter at bus 5A that will be the responsibility of the end user at bus 5A. Before a decision is made as to which filter is to be installed, both these options need to be investigated. We can start with the 2nd order harmonic filter.

6.3.2.1b) Step F2 a: Design a 12 kV second order harmonic filter

Capacitors CAP 4A and CAP 4B will be used for the filter design with a tuning frequency of h ≥ 10.8. The total capacitive power of the two capacitors connected in parallel is 4 MVar and make up the capacitor for the filter. A new busbar 4C will be introduced to replace busbars 4A and 4B where both capacitors are connected.

The capacitive reactance will thus be:

$$X_{eff} = \frac{V_{LL}(kV)}{Q_{eff}(MVar)} = \frac{12^2}{4} = 36\Omega$$, and the capacitance C = 88.419µF

The inductive reactance will then be:

$$X_L = \frac{X_{eff}}{h^2} = \frac{36}{10.8^2}\Omega = 0.3086\Omega$$, and the inductance L = 982.44 mH

The characteristic impedance, X_r becomes:

$$X_r = \sqrt{(X_L X_C)} = \sqrt{(0.3086.36)} = 3.333\Omega$$

As the values *Q* ranges between 0.5 and 5, “1” is chosen giving a resistance in the filter to be:

$$R = Q.X_r = 1.3333 = 3.333\Omega$$

The three independent filter elements are thus modelled using the software and harmonic analysis done thereafter. The filter design model is shown in Figure 6.27.

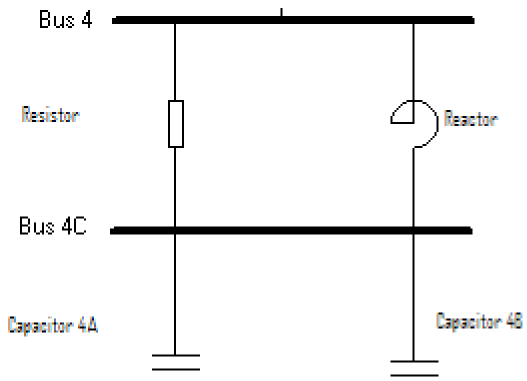


Figure 6.27: Second order harmonic filter model

6.3.2.1c) Step F3 a: Decide on the capacitor type

Depending on the client`s protection needs and finances, the type of capacitors used in the banks will be chosen. The capacitor banks will be decided between the internally fused, externally fused and fuseless capacitors (see Sections 3.10.1.1 to 3.10.1.3).

6.3.2.1d) Step F4 a: Calculate filter component parameters

Using sec 3.10.3, the filter components will be calculated. The component values are then modelled to the network. A load flow (Figure A5.1) is conducted on the network that derives the fundamental current. Harmonic penetration showing the 5^{th} harmonic penetration (Figure A5.2) is also done on the network and the currents at filter component at each harmonic i.e. 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th} and 19^{th} are shown in Table 6.4.

Table 6.4: Harmonic currents through filter components

Harmonic	Capacitor (4A)	Capacitor (4B)	Reactor	Resistor
1	98	98	195	18
5	60.473	60.473	108.87	50.396
7	19.795	19.795	32.842	21.281
11	7.783	7.783	10.717	10.91
13	5.093	5.093	6.388	7.683
17	2.465	2.465	2.585	4.064
19	1.22	1.22	1.178	2.069

To obtain parameters for the “Rated Filter”, the current values through the “Designed Filter” are used. The rating of the filter components is done individually as below.

Capacitor:

The total rms currents for each capacitor of the filter will be:

$$I_{rms} = \sqrt{(98^2 + 60.473^2 + 19.795^2 + 7.783^2 + 5.097^2 + 2.465^2 + 1.22^2)} = 117.24A$$

The fundamental voltage across the capacitor banks is calculated as shown below:

$$V_C(1) = I_f(1).X_c$$

$$V_C(1) = 98 \times 72 = 7056V$$

The voltages for the 5th, 7th, 11th, 13th, 17th and 19th harmonics will be given by:

$$V_C(h) = \sum I_f(h)\left(\frac{X_C}{h}\right)$$

$$V_C(h) = (60.473 \times \frac{72}{5}) + (19.795 \times \frac{72}{7}) + (7.783 \times \frac{72}{11}) + (5.097 \times \frac{72}{13}) +$$

$$(2.465 \times \frac{72}{17}) + (1.22 \times \frac{72}{19}) = 1168.652V$$

The total voltage across each capacitor unit (V_C) will be V_C (1) + V_C (h) given as 7056 + 1168.652 = 8224.652 V and this is called the rated voltage, and is an rms value, see section 3.11.3.

The actual capacitor reactive power will be (rated 3 phase value):

$$Q_C = \frac{\left(\sqrt{3}V_C\right)^2}{X_c} = \frac{\left(\sqrt{3} \times 8.224\right)^2}{72} = 2.818MVar$$

Each of the two capacitor banks used for a 2nd order harmonic filter will thus have the rating increased to 2.818 MVar from 2.0 MVar. The nominal capacitor current that flows in the harmonic filter is calculated to be (see section 3.11.3):

$$I_C = \frac{Q_C(kVar)}{\sqrt{3}V_C(kV)} = \frac{2.818 \times 1000}{\sqrt{3} \times \sqrt{3} \times 8.224} = 114.22A$$

Where V_C is the rms phase voltage

Reactor:

The total voltage across the reactor is calculated using the formula below:

$$V_L(h) = \sum I_f(h)(X_L.h)$$

$$V_L(h) = (195\times0.3086\times1)+(108.87\times0.3086\times5)+(32.842\times0.3086\times7)+$$
$$(10.717\times0.3086\times11)+(6.388\times0.3086\times13)+(2.585\times0.3086\times17)+$$
$$(1.178\times0.3086\times19)=381.583\,V$$

The reactor rated reactive power will be:

$$Q_L = \frac{\left(\sqrt{3}V_L\right)^2}{X_L} = \frac{\left(\sqrt{3}\times0.381\right)^2}{0.3086} = 1.411MVar$$

The manufacturer of the reactor will determine the real power loss in the reactor windings. The Q factor given by the designer in the manufacturer`s template can be used as guideline.

Resistor:

The voltage across the resistor will be calculated using the formula:

$$V_R(h) = \sum I_T(h)(R.h)$$

$$V_R(h) = (18\times3.333)+(50.396\times3.333)+(21.281\times3.333)+(10.91\times.333)+$$
$$+(7.683\times3.333)+(4.064\times3.333)+(2.069\times3.333)=381.282\,V$$

The rated resistance power will be:

$$P = \frac{\left(\sqrt{3}V_R\right)^2}{R} = \frac{\left(\sqrt{3}\times0.381\right)^2}{3.333} = 0.131MW$$

6.3.2.1e) Step F5a: Model filter components

Model the filter components into the network (Figure 6.26) and conduct harmonic analysis. Then a load flow shown in Appendix 5 (Figure A5.7) and harmonic penetration for the 5th harmonic (Figure A5.8) are produced. The percentage voltage distortion at bus 3 and bus 5A are shown in Figures A5.9 and A5.10, respectively. The current percentage distortion is shown in Figure A5.11 and the harmonic graph in Figure A5.12.

6.3.2.1f) Step F6a: Verify filter effectiveness

The results show that the filter design alters the parallel resonance points of the network. With the power factor correction capacitor at bus 5A, THD_V at bus 3 and 5A is 15.12% and 24.36%, respectively. THD_I to the load at bus 5A is 5.58%. With the rated filter, THD_V at buses 3 and 5A goes down to 4.91% and 9.08%, respectively. THD_I to the load at bus 5A decreases to 2.08%. The results show that the filter is effective in mitigating harmonics.

6.3.2.1g) Step F7a: Fill the manufacturer's template

Once the filters performance is of acceptable values, the next step is to fill in the manufacturer's template. The templates are to be sent to the filter component manufacturers. The templates give all the details and rating of the components considering the space available for installation and environmental factors of the area. Tables 6.5, 6.6 and 6.7 show the filter templates that would have the values for the "Rated Filter" which are sent to manufacturers.

Table 6.5: Second order filter capacitor data for manufacturer

Client Name	Alan Meru
Phone	021-4603085
Fax	021-4603705
Email	MeruA@cput.ac.za
Due Date	Aug - 13
Quote requested by	Alan Meru
Bank Voltage (1.25 $\times$ system V_L)	15 KV
Power frequency (f)	50 Hz
Tuning Frequency	540 Hz
Current (1.2 $\times$ system I)	130 A
Capacitor Reactance (X_C)	72 Ω
Capacitance	44.21 μF
Capacitor Power	2.6176 MVar
Connection	Grounded
Fusing	Fuseless
Unbalance Relay	Yes
Mounting	Vertical/Horizontal
Elevating structure height	X mm
Bushing creepage	X kV/mm
Temp range (min to max)	X Degrees

Table 6.6: Second order filter reactor data for manufacturer

Client Name	Alan Meru
Phone	021-4603085
Fax	021-4603705
Email	MeruA@cput.ac.za
Due Date	Aug – 13
Quote requested by	Alan Meru
System voltage	12 kV
Power frequency (f)	50 Hz
Tuning Frequency	540 Hz
Current (1.2 $\times$ system I)	253 A
Reactance (X_L)	0.3086 Ω
Reactor Rating	982 mH
Q factor of Reactor	1
Mounting	Vertical/horizontal
Dimensional limitations	X m^2
No of units	3

Table 6.7: Second order filter resistor data for manufacturer

Client Name	Alan Meru
Phone	021-4603085
Fax	021-4603705
Email	MeruA@cput.ac.za
Due Date	Aug – 13
Quote requested by	Alan Meru
Power system frequency (f)	50 Hz
System voltage	12 kV
System current	50 A
Resistance	3.333 Ω
Mounting	Vertical/Horizontal
Dimensional limitations	X m^2
No of units	3
Ambient temperature	X Degrees
Creepage	X kV/mm
Seismic zone	X
Elevating stand height	X mm
Finish	Galvanised/Steel

The next step is to implement flow chart B, Figure (5.20). For the installation of the filter, the methodology developed in Chapter 5 is the next step. Typically such a filter would be installed and it is expected that an area of 6000mm by 8000mm would be sufficient for the Rated Filter. The values are derived from Figures A2.3 and A2.4 in Appendix 2. The extra area recommended for this filter differs from Figures A2.3 and A2.4 as the resistor bank in this filter is now incorporated in the site. This considers that the filter components are installed in a vertical layout. The layout of the filter would be similar to Figure 6.28.

Figure 6.28: Second order harmonic layout after installation.

6.3.2.2a) Step F2 b: Design 6 kV 5th harmonic filter

This second option is designing a series 5th harmonic filter at user bus 5A. The costs will be catered for by the end user at his bus 5A. The filter will be designed using the PF_{DPF} capacitor modelled at bus 5A. The design procedure is as follows:

The effective value of the capacitive reactance will be calculated as below:

$$X_{eff} = \frac{V^2{}_{LL}(kV)}{Q_{eff}\,(M\,\mathrm{var})} = \frac{6^2}{2.881} = 12.5\Omega$$

The value of the capacitive reactance (using a tuning of 4.8th) will be:

$$X_C = \left(\frac{h^2}{h^2-1}\right).X_{eff} = \left(\frac{4.8^2}{4.8^2-1}\right)12.5 = 13.067\Omega$$, and the capacitance

C = 243.6µF.

The reactor used for the filter values will be calculated as below:

$$X_L = \frac{X_C}{h^2} = \frac{13.067}{4.8^2} = 0.567\Omega$$, and the reactance L = 1.805mH.

Using Q as a value of 100 for the reactor, the reactor resistance will be:

$$R = \frac{f_r.X_L}{Q} = \frac{240\times.0.567}{100} = 1.3608\Omega$$

The calculated values are then modelled into the network and results collated.

6.3.2.2b) Step F3 b: Decide on the capacitor type

Depending on the client`s protection needs and finances, the type of capacitors used in the banks will be chosen. The capacitor banks will be decided between the internally fused, externally fused and fuseless capacitors (Sections 3.9.1.1 to 3.9.1.3).

6.3.2.2c) Step F4 b: Calculate filter component parameters

Using sec 3.10.3, the filter components will be calculated. The component values are then modelled into the network. A load flow (Figure A6.1) is conducted on the network which derives the fundamental current. Harmonic penetration showing the 5th harmonic (Figure A6.2) is also done on the network and the currents at filter components at each harmonic i.e. 7th, 11th, 13th, 17th and 19th are shown in Table 6.8. THD_V at bus 3 and 5A are seen in figures A6.3 and A6.4, respectively. THD_I at the load at bus 5A and harmonic graph of the network with the Designed Filter are shown in Figures A6.5 and A6.6 (Appendix 6).

Table 6.8: Harmonic currents through the Designed Filter

Harmonic	Current (Amps)
1	128
5	59.156
7	6.397
11	0.986
13	0.436
17	0.114
19	0.044

Now, to obtain parameters for the “Rated Filter”, the current values through the Designed Filter are used.

The rms current across the Designed Filter components is calculated as:

$$I_{rms} = \sqrt{\left(128^2 + 59.156^2 + 6.397^2 + 0.986^2 + 0.436^2 + 0.114^2 + 0.044^2\right)} = 141.158A$$

Capacitor:

The fundamental voltage across the capacitor is found using:

$$V_C(1) = I_f(1).X_c$$

$$V_C(1) = 13.067 \times 128 = 1672.576V$$

The harmonic voltage across the capacitor is found using:

$$V_C(h) = \sum I_f(h)\left(\frac{X_c}{h}\right)$$

$$V_C(h) = (59.156 \times \frac{13.067}{5}) + (6.397 \times \frac{13.067}{7}) + (0.986 \times \frac{13.067}{11})$$

$$+ (0.436 \times \frac{13.067}{13}) + (0.114 \times \frac{13.067}{17}) + (0.044 \times \frac{13.067}{19}) = 168.266V$$

The peak voltage across each capacitor unit (V_C) will be V_C (1) + V_C (h) to be 1672.576 + 168.266 = 1840.842V and this is called the rated voltage, and is an rms value, see section 3.11.3.

The actual capacitor reactive power will be (rated 3 phase value):

$$Q_C = \frac{\left(\sqrt{3}V_C\right)^2}{X_c} = \frac{\left(\sqrt{3} \times 1.840\right)^2}{13.067} = 0.777MVar$$

The capacitor to be used in the harmonic filter will have a rating of 0.777 MVar which is lower than the one used for reactive compensation of 2.881 MVar. The nominal capacitor current that flows in the harmonic filter is calculated to be (see section 3.11.3):

$$I_C = \frac{Q_C(kVar)}{\sqrt{3}V_C(kV)} = \frac{0.777 \times 1000}{\sqrt{3} \times \sqrt{3} \times 1.839} = 140.76A$$

Where V_C is the rms phase voltage

Reactor:

The total voltage across the reactor is calculated using the formula below:

$$V_L(h) = \sum I_f(h)(X_L.h)$$

$$V_L(h) = (136 \times 1.1319 \times 1) + (57.463 \times 1.1319 \times 5) + (6.315 \times 1.1319 \times 7) +$$
$$(0.982 \times 1.1319 \times 11) + (0.435 \times 1.1319 \times 13) + (0.114 \times 1.1319 \times 17) +$$
$$(0.044 \times 1.1319 \times 19) = 550.952V$$

The total voltage across the reactor will be 550.952V. The actual reactor reactive power will be:

$$Q_L = \frac{\left(\sqrt{3}V_L\right)^2}{X_L} = \frac{\left(\sqrt{3} \times 0.550\right)^2}{1.1319} = 0.802MVar$$

Resistor:

The voltage across the resistance of the reactor will be calculated using the formula below:

$$V_R(h) = \sum I_T(h)(R.h)$$

$$V_R(h) = (136 \times 2.717) + (57.463 \times 2.717) + (6.315 \times 2.717) + (0.982 \times 2.717) +$$
$$+ (0.435 \times 2.717) + (0.114 \times 2.717) + (0.044 \times 2.717) = 547.095V$$

Using the above voltage, the reactors real power rating will be:

$$P = \frac{\left(\sqrt{3}V_R\right)^2}{R} = \frac{\left(\sqrt{3} \times 0.547\right)^2}{2.717} = 0.330MW$$

6.3.2.2d) Step F5 b: Model filter component

Model the Rated Filter components into the network and conduct load flow (Figure A6.7) and harmonic graph (Figure A6.8). THD_V at bus 3 and 5A are seen in Figures A6.9 and A6.10, respectively. THD_I at the load at bus 5A and harmonic graph of the network with the Designed Filter are shown in Figures A6.11 and A6.12.

6.3.2.2e) Step F6 b: Verify filter effectiveness

The results show that the Designed Filter alters the parallel resonance points of the network. With the Designed Filter, THD_V at buses 3 and 5A is 8.05% and 3.62%, respectively. When the Rated Filter is modelled, THD_V at the same buses increases to 19.07% and 8.78%, respectively. THD_I for the load at bus 5A increases to 2.03% with the Rated Filter from 0.83% compared to the Designed Filter. The results show that the Rated Filter is not effective in reducing THD_V at the point of common coupling bus 3. The 2nd order Rated Filter is thus the chosen filter.

6.3.2.2f) Step F7 b: Fill the manufacturer's template

In this case, since the filter is not viable, it is not necessary to fill in a manufacturer's template. This means no installation of a 5th harmonic filter will take place. The second order Rated Filter is thus the chosen filter.

6.4 Summary

In this chapter, two networks were investigated where harmonic analysis and mitigation was conducted. The first network was taken as a new plant to be designed in future. All the steps developed in the methodology (Figure 4.1) were followed in this network analysis.

The second network was taken as an existing plant and measurement based results were used in the analysis. From the resonance curves derived from the network, two different types of filters were designed. A second order and series tuned harmonic filter were evaluated. From the results it was observed that only the second order harmonic filter was effective.

From the three filters designed in this chapter only two were viable. Courtesy of RWW Engineering (PTY) LTD, two typical reactor and capacitor specifications can be seen in Appendix 7. The diagrams in Appendix 7 show the details which come with the reactors and capacitors when they are delivered to the client by the manufacturers.

CHAPTER SEVEN: ANALYSIS OF DEVELOPED METHODOLOGY

7.1 Introduction

In this chapter, the results of the two scenarios in Chapter Six are analysed with reference to the developed methodology (Figure 4.1). In the process of applying the methodology, the Designed Filter (3.6.1 and 3.6.2) is compared with the design based on needs for real life filters (3.11.3). In this analysis this filter is called Rated Filter.

7.2 New Network: 4.16kV 5th Harmonic Filter

The network being a new network has some assumptions that have to been taken into consideration in the harmonic analysis. These involve assuming that the loads operate at 80% full load and the PF_{DPF} will be 0.8 lagging. The capacitor bank used for power factor correction is used for the Designed Filter. Table 7.1 shows the current values of each harmonic with the PF_{DPF} capacitor, Designed Filter and Rated Filter after being modelled in the network.

Table 7.1: Harmonic currents through capacitor and filter components from bus 1AB

Harmonic	Capacitor current (A)	Designed Filter current (A)	Rated Filter current (A)
1	**177**	**186**	**186**
5	**316.79**	**87.25**	**87.25**
7	**204.36**	**43.624**	**43.624**
11	**54.503**	**18.593**	**18.593**
13	**34.876**	**12.754**	**12.754**
17	**15.455**	**6.083**	**6.083**
19	**10.856**	**4.37**	**4.37**

Firstly, Table 7.1 compares the currents flowing in the capacitor branch (bus 1AC) to ground (Figure 6.4 for the fundamental, Figure 6.5 for the 5th harmonic and likewise for other harmonics i.e. 7th to 19th Harmonic). The next one is when a Designed Filter is used (Figures 6.9 and 6.10). Then in the last column is when the filter is the Rated Filter (Figures 6.14 and 6.15).

The above results show that the harmonic currents decreased with the Designed and Rated filters modelled in the network. Only the fundamental current was higher in the filters. The currents through the Designed and Rated Filters were the same as the currents flowing in the loads i.e. 6 pulse drive (harmonic source) and linear load did not change from the supply with both filters modelled.

Table 7.2 shows the voltage values at each harmonic at bus 1AB with power factor capacitor, Designed and Rated Filter, respectively. The filter voltages were the same as the load currents with both filters modelled were the same as the currents in Table 7.1.

Table 7.2: Results of HD_V and THD_V at bus 1AB

Element Name: BUS 1AB (Busbar)						
	PF Capacitor		Designed Filter		Rated Filter	
Harmonic Number	Voltage (V)	Voltage (% of fundamental)	Voltage (V)	Voltage (% of fundamental)	Voltage (V)	Voltage (% of fundamental)
5	**459.61**	**11.75%**	**223.77**	**5.56%**	**223.77**	**5.56%**
7	**418.02**	**10.69%**	**208.11**	**5.17%**	**208.11**	**5.17%**
11	**326.9**	**8.36%**	**181.51**	**4.51%**	**181.51**	**4.51%**
13	**272.99**	**6.98%**	**154.44**	**3.84%**	**154.44**	**3.84%**
17	**175.86**	**4.50%**	**101.18**	**2.52%**	**101.18**	**2.52%**
19	**175.86**	**3.65%**	**82.35**	**2.05%**	**82.35**	**2.05%**
THD	**20.11%**		**10.17%**		**10.17%**	

The results of the HD_V and (THD_V) at bus 1AB are given in Table 7.2. Figure 7.1 is an analysis of these results, from which HD_V per harmonic and THD_V are compared. It was found out that THD_V decreases with the Designed and Rated Filter, respectively and did not change as the voltages values were the same with both filters modelled.

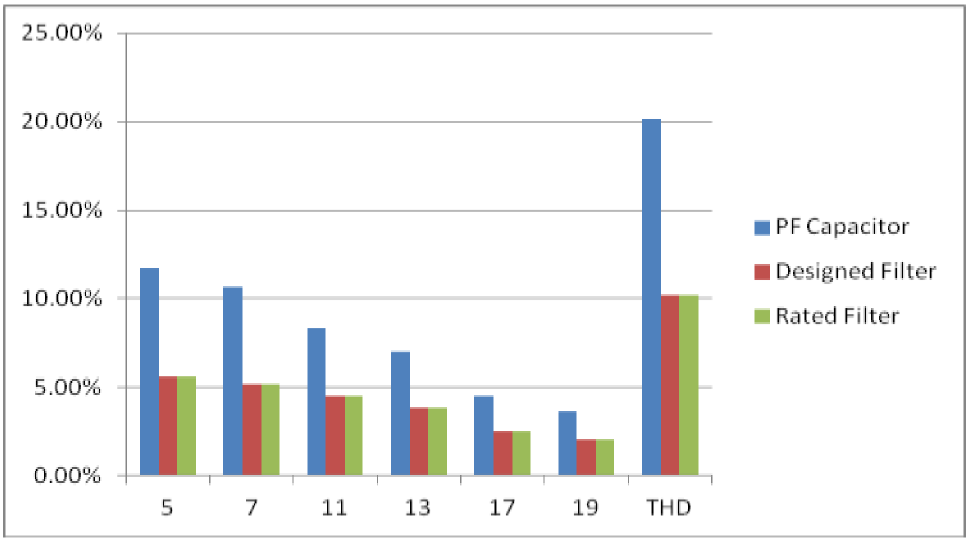


Figure 7.1: HD_V and THD_V at bus 1AB

Table 7.3 shows the actual current values flowing from bus 1AB to the load connected to bus 1AB. These values compared between when the capacitor was modelled at bus 1AC and the Designed Filter and Rated Filter were modelled at bus 1AD. Incidentally the currents through the shunt load with both the Designed and Rated filter values were the same as the load was still the same and the supply current remained the same.

Table 7.3: HD_I and THD_I results at shunt load from 1AB

Element Name: LOAD 1 (Shunt)						
	PF Capacitor		Designed Filter		Rated Filter	
Harmonic Number	Current (% of fundamental)	Current (A)	Current (% of fundamental)	Current (A)	Current (% of fundamental)	Current (A)
5	**3.79%**	**20.12**	**1.79%**	**9.26**	**1.79%**	**9.26**
7	**2.50%**	**13.29**	**1.21%**	**6.25**	**1.21%**	**6.25**
11	**1.26%**	**6.68**	**0.68%**	**3.51**	**0.68%**	**3.51**
13	**0.89%**	**4.73**	**0.49%**	**2.53**	**0.49%**	**2.53**
17	**0.44%**	**2.34**	**0.25%**	**1.27**	**0.25%**	**1.27**
19	**0.32%**	**1.70**	**0.18%**	**0.93**	**0.18%**	**0.93**
THD	**4.82%**		**2.34%**		**2.34%**	

Figure 7.2 is an analysis of these results, from which it is found that HD_I decreases with both the Designed and Rated filters. The values remained the same with the two filters modelled, respectively.

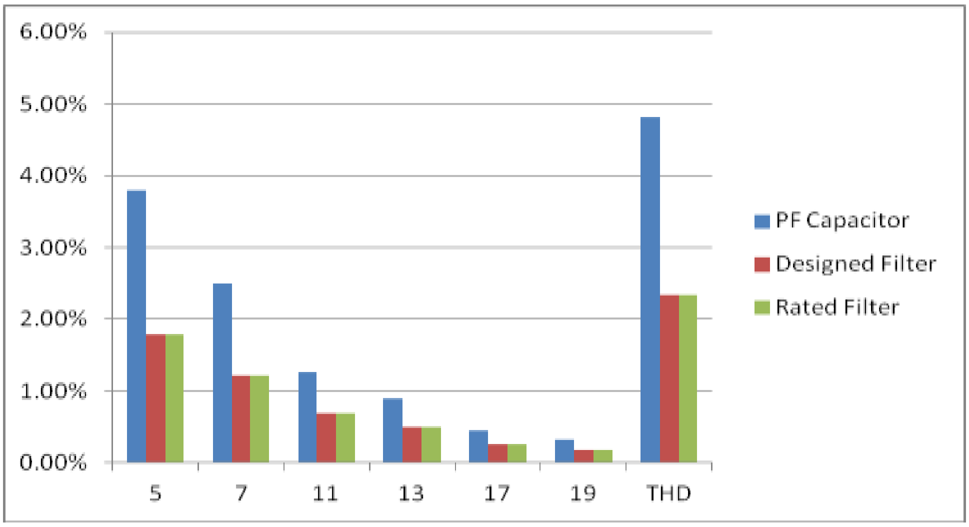


Figure 7.2: HD_I and THD_I flowing from bus 1AB to Capacitor, Designed and Rated Filter

Table 7.4 shows that the PF_{DPF} capacitor and Designed Filter have the same voltage and Var rating. This is because they are designed for fundamental voltage and current only. The Rated Filter has a higher voltage and Var rating as this considers all the harmonic currents flowing in the filter components. The only factor similar in the Designed and Rated filter is the PF_{DPF} value. The results show that the PF_{DPF} values improve with both the Designed and Rated Filters in the network.

Table 7.4: Voltage, Var and PF_{DPF} results of Capacitor, Designed and Rated Filter

	Capacitor	Designed Filter	Rated Filter
V	**2.4kV**	**2.4kV**	**2.776kV**
Vars	**1.321MVar**	**1.321MVar**	**1.764MVar**
PD_{DPF}	**0.8 lagging**	**0.96 lagging**	**0.96 lagging**

7.3 Existing Network: 12kV Network

In this network two possible harmonic filter designs were considered. Each design was investigated and its impact on the whole network was considered. A 2nd order and a series tuned 5th harmonic filter were designed. Table A8.1 shows THDv at bus 3 and 5A is 15.12% and 24.36%, respectively. THD_I for the current that was flowing to the load from bus 5A was 5.58%. These results are when the PF_{DPF} capacitor was modelled at bus 5A. Using the results from Table A8.1, (Appendix 8) Figure 7.3 was produced to show the THDv and THD_I values.

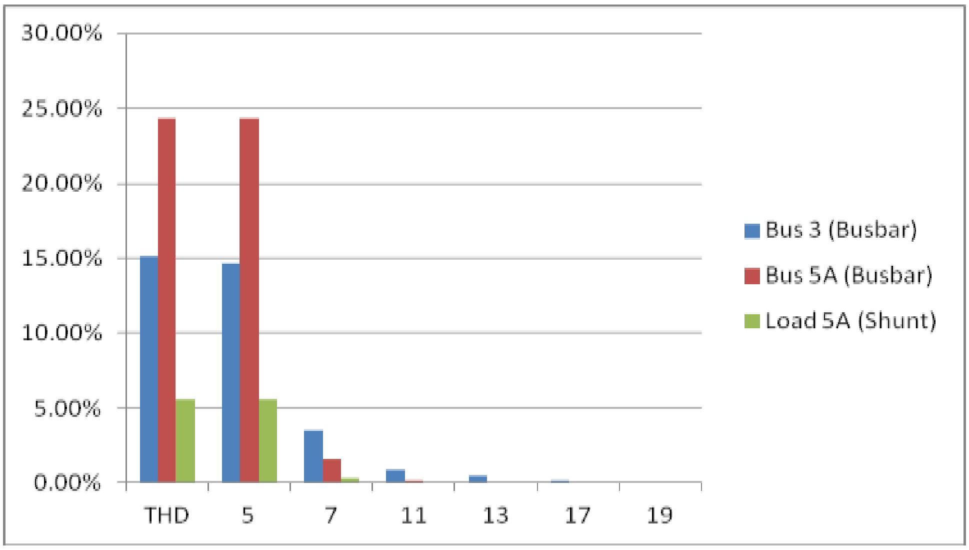


Figure 7.3: THDv at buses 3 and 5A and THD_I at load at bus 5A

THDv at bus 3 and THD_I flowing to load at bus 5A values are found to be above the IEEE Standard 519 limits. The results in Table A8.1 and Figure 7.3 were thus the base in deciding mitigation in this network.

7.3.1 Design 1 Option: 12kV second order harmonic filter

The existing capacitors (Cap 4A and 4B) in the network were used for the design of this filter. The Designed and Rated Filters were compared with the currents flowing through the components. Table 7.5 shows the currents through each of the capacitors at bus 4 after the power factor capacitor was modelled at bus 5A.

The values in Table 7.5 were derived so as to compare current on existing capacitors when used for PF_{DPF} and as part of the harmonic filter.

Table 7.5: Harmonic currents through each capacitor at buses 4A and 4B

Harmonic	Cap 4A	Cap 4B
1	**97**	**97**
5	**71.306**	**71.306**
7	**24.047**	**24.047**
11	**9.638**	**9.638**
13	**6.07**	**6.07**
17	**2.767**	**2.767**
19	**1.345**	**1.345**

After the 2nd order filter was designed, the filter components were modelled into the network and the currents through the filter components are compared in Table 7.6.

Table 7.6: Harmonic currents through the Designed Filter components

Harmonic	Cap 4A	Cap 4A	Reactor	Resistor
1	**98**	**98**	**195**	**18**
5	**61.08**	**61.08**	**109.96**	**50.902**
7	**19.79**	**19.79**	**32.834**	**21.276**
11	**7.783**	**7.783**	**10.717**	**10.91**
13	**5.097**	**5.097**	**6.388**	**7.683**
17	**2.465**	**2.465**	**2.585**	**4.063**
19	**1.22**	**1.22**	**1.178**	**2.069**

Using the above current values, the Rated Filter was designed and modelled into the network. The Rated Filter component currents were found as in Table 7.7.

Table 7.7: Harmonic currents through the Rated Filter components

Harmonic	Cap 4A	Cap 4A	Reactor	Resistor
1	**141**	**141**	**280**	**26**
5	**43.359**	**43.359**	**78.778**	**36.467**
7	**17.502**	**17.502**	**29.038**	**18.817**
11	**7.355**	**7.355**	**10.128**	**10.309**
13	**4.874**	**4.874**	**6.109**	**7.347**
17	**2.405**	**2.405**	**2.522**	**3.965**
19	**1.197**	**1.197**	**1.156**	**2.03**

It was denoted that the capacitor currents did not change with the Designed Filter. When the Rated Filter was modelled on the network, the fundamental current increased as the other harmonic currents decreased. The actual values at bus 3 with the Designed and Rated Filter are shown in Table A8.2. From Table A8.2, Figure 7.4 was produced.

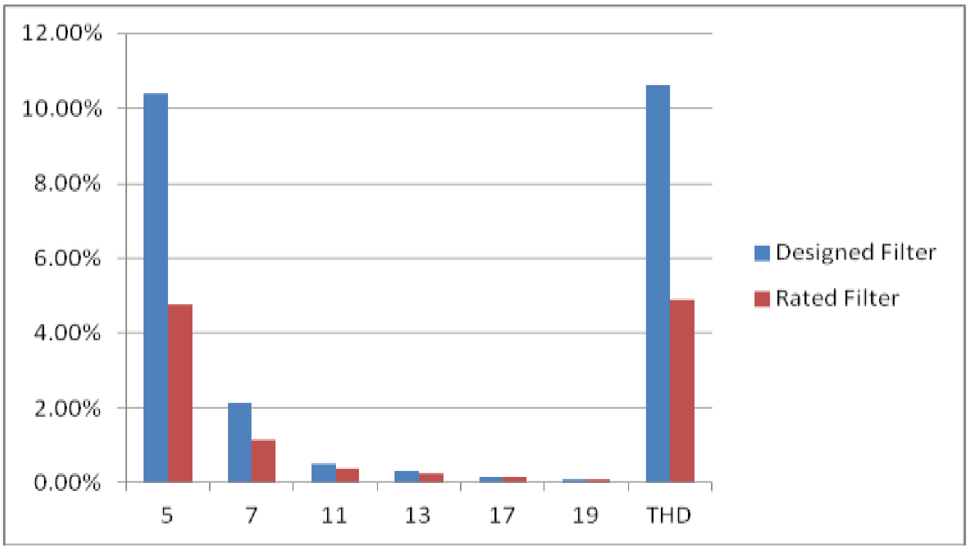


Figure 7.4: HDv and THDv at bus 3

The results show that THDv at bus 3 decreased to 4.91% with the Rated Filter from 10.64% of the Designed Filter. Similarly Table A8.3 shows the HDv and THDv values at bus 5A. Figure 7.5 shows that THDv at bus 5A decreased to 9.08% with the Rated Filter compared to 16.91% with the Designed Filter.

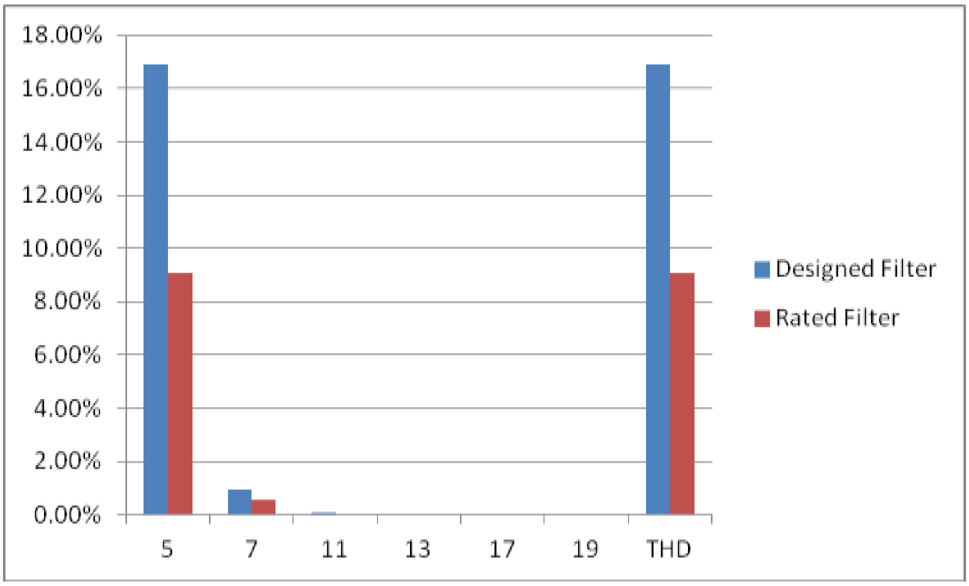


Figure 7.5: HDv and THDv at bus 5A

The HD_I values flowing to the load connected to bus 5A compared with the Designed and Rated Filter modelled in the network as shown in Table A8.4. Figure 7.6 was produced from the results in Table A8.4. It was found that the THD_I flowing to the load at bus 5A decreased from 3.88% to 2.08% with the Rated Filter.

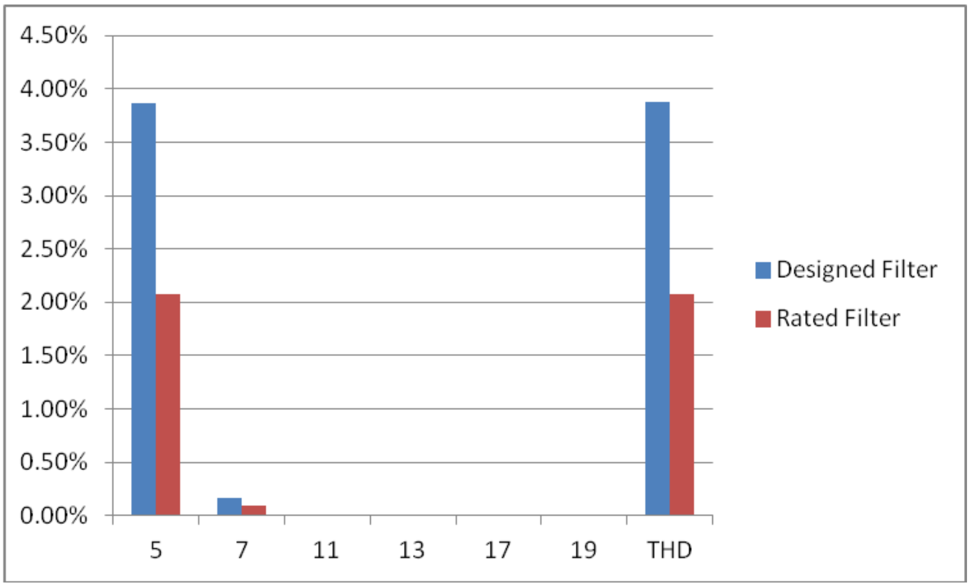


Figure 7.6: HD_I and THD_I to the load connected at bus 5A

Table 7.8 compares the capacitors used for PF_{DPF} and filter design. The results show that the PF_{DPF} capacitor and Designed Filter have the same voltage and Var rating. This is because they are designed for fundamental voltage and currents only. The Rated Filter has a higher voltage and Var rating as this considers all the harmonic currents flowing in the filter components. The PF_{DPF} value at bus 3 decreased slightly to 0.926 lagging with the Designed Filter from 0.933 leading when the PF_{DPF} capacitor was at bus 5A. Incidentally the PF_{DPF} value at bus 3 deteriorated to 0.7522 lagging with the Rated Filter.

Table 7.8: Voltage, Var and PF_{DPF} results at Bus 3

	Capacitor	Designed Filter	Rated Filter
V	**12 kV**	**12 kV**	**15 kV**
Vars	**2 MVar**	**2 MVar**	**2.818 MVar**
PD_{DPF}	**0.933 leading**	**0.926 lagging**	**0.7522 lagging**

7.3.2 Design 2 Option: 6kV 5th harmonic filter

A load flow and harmonic penetration was conducted on the network and currents in Table 7.9 were flowing through the PF_{DPF} capacitor at bus 5A. Using the PF_{DPF} capacitor bank, a 5th harmonic filter was designed and simulations performed. The filter components were then redesigned and remodelled into the network and the current values obtained as shown in Table 7.10.

Table 7.9: Harmonic currents through capacitor at bus 5A

Harmonic	Bus 5A (A)
1	**131**
5	**159.29**
7	**14.812**
11	**1.839**
13	**0.789**
17	**0.199**
19	**1.345**

Table 7.10 shows that the current values decreased with the Designed Filter compared to when only the PF_{DPF} capacitor is applied. The Rated Filter increases the current values slightly further except for the fundamental that decreased compared with the Rated Filter.

Table 7.10: Harmonic currents through filters at bus 5A

Harmonic	Designed Filter (A)	Rated Filter (A)
1	**136**	**53**
5	**57.463**	**66.324**
7	**6.315**	**7.479**
11	**0.982**	**0.958**
13	**0.435**	**0.412**
17	**0.114**	**0.105**
19	**0.44**	**0.04**

HDv and THDv results at bus 3 with the Designed and Rated Filters are shown in Table A8.5.

The results in Table A8.5 given in Figure 7.7 show that the THDv increased at bus 3 when the Rated Filter was applied.

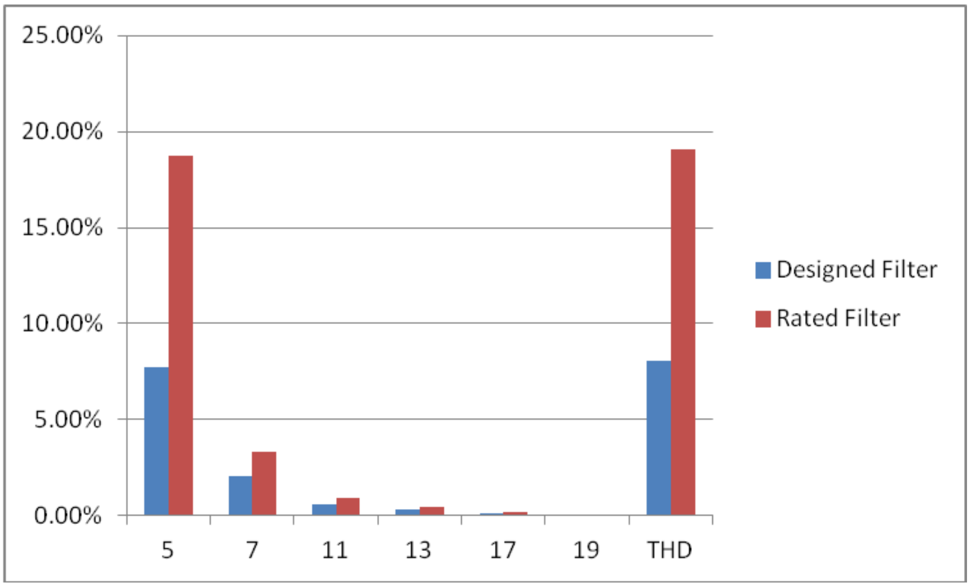


Figure 7.7: THDv at bus 3

Bus 5A where the filter was to be installed was also investigated. HDv and THDv results are shown in Table A8.6.

The results produced the bar graph in Figure 7.8, which shows that the THDv at bus 5A increased with the Rated Filter.

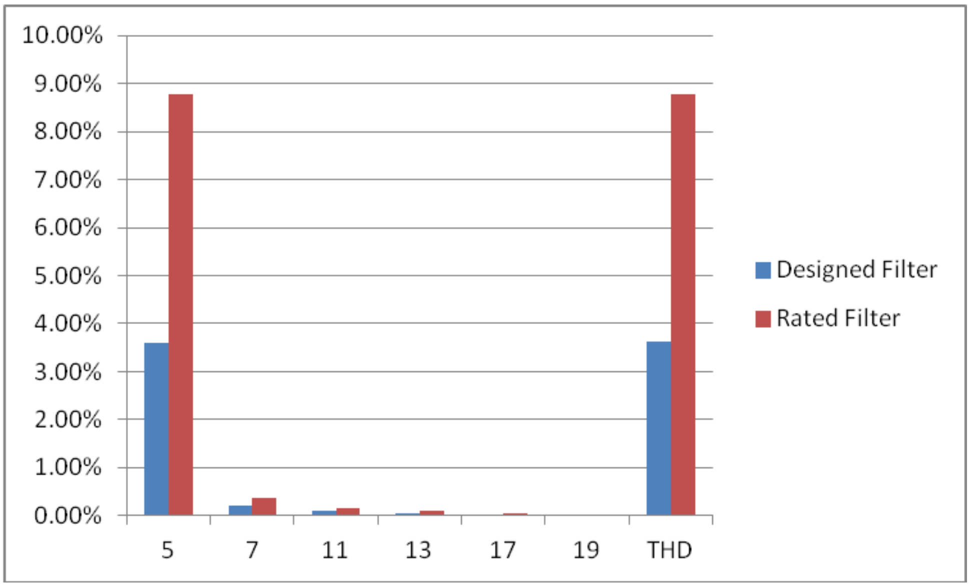


Figure 7.8: THDv at bus 5A

HD_I and THD_I for the current flowing to the load at bus 5A is shown in table A8.7. THD_I values increased slightly with the Rated Filter as shown in Figure 7.9.

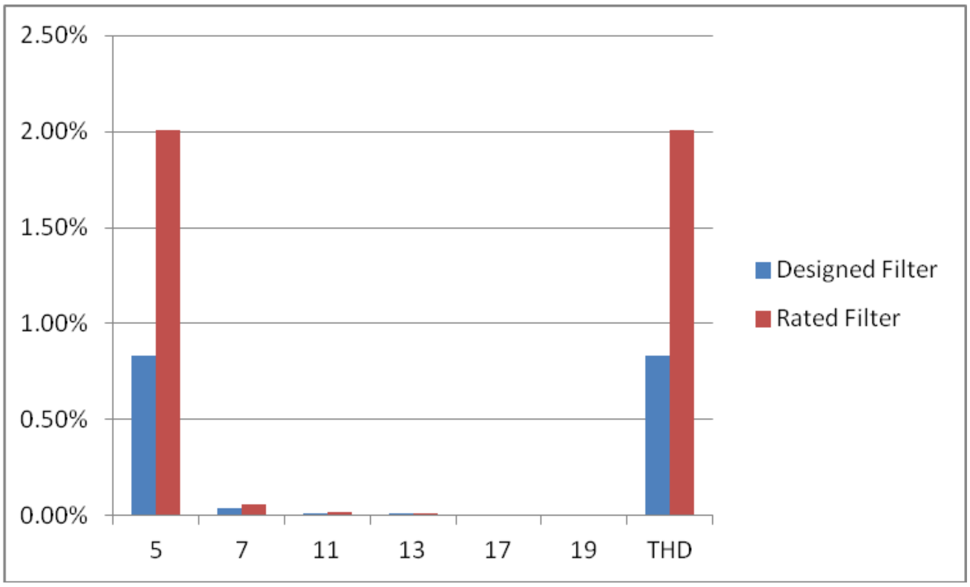


Figure 7.9: THD_I to load connected at bus 5A

Table 7.11 shows the voltage across the capacitor of PF_{DPF}, Designed and Rated Filter. The Var values show that the Rated Filter values are lower than the PF_{DPF} capacitor and Designed Filter. This values show that the PF_{DPF} values at bus 5A reduces to 0.64 lagging with the Rated Filter. These results mean that the Rated Filter decreases the PF_{DPF} value at bus 5A. The PF_{DPF} reading at bus 3 has a leading value of 0.92 at both instances when the PF_{DPF} capacitor is only used and when the Designed Filter was modelled. With the Rated Filter the PF_{DPF} value goes to 0.985 leading at bus 3.

Table 7.11: Voltage, Var and PF_{DPF} readings (Buses 3 and 5A)

	Capacitor	Designed Filter	Rated Filter
V	**6 kV**	**6 kV**	**7.5 kV**
Vars	**2.881 MVar**	**2.881 MVar**	**0.776 MVar**
PD_{DPF} at bus 3	**0.9214 leading**	**0.9217 leading**	**0.985 leading**
PD_{DPF} at bus 5A	**0.96 lagging**	**0.96 lagging**	**0.64 lagging**

Figure 7.8 results prove that the 5^{th} series tuned harmonic filter at bus 5A is not viable. The PF_{DPF} value at bus 5A decreases with the Rated Filter modelled. The results make it clear that having such a filter at bus 5A would create more problems in the network and then cannot considered being modelled in the network at all.

7.4 Interviews

The interviews reported in Appendix 9 were conducted with four harmonic filter specialists in industry. The interviews entailed questions on harmonic filter design, installation and commissioning.

7.4.1 Design

When it came to design it was found that the load profile greatly determines the filter components. The load variation and harmonic content play a vital role in determining the size of the filter bank. It was found that internally fused banks are usually used in low voltage installations below 6.6kV to 11kV. Externally fused banks are used for medium voltage banks of up to 22kV and anything above 33kV, fuseless banks are used. The choice of the banks depends on the protection equipment that can be incorporated into the filter at the different voltage levels.

It was also found that in design of filters the same concept was used in new plants just as existing plants. The main difference between them was that of getting data for existing plants and this involves conducting measurements using power quality analysers over duration of time. In new plants a lot of assumptions are taken and data used is the one specified by manufactures sheets. Simulations are used in both instances to give an idea of the response of such a network. Depending on the software used, the response should be similar with other software only that the modelling of components could be different. It is also accepted that with measurements done, simulations are used to confirm that results are similar.

The filter designer specifies the components to be used for an installation and this is determined by the space available for the actual application. In such an instance, the available space for the filter determines the manufacturing and size of components. Altitude data helps to decide the type of insulation used for capacitors. Coastal areas have more salt, mist and frost leading to filter banks having longer insulators just as in areas of high pollution. In higher temperature regions, components need to be de-rated. Also areas with high lightning occurrences will mean that components will need appropriate protection.

7.4.2: Installation

The installation engineer needs to assemble the components as per the manufacturers drawing and designer specifications. This is considering that the reactors and capacitors are delivered unassembled. Resistors used for second order harmonic filters are delivered assembled and are usually custom built. Protection of the filter components is a major concern for the installation engineer. A wide variety of protection devices is available and depends on the client`s needs and capital available and require a separate study on its own. Capacitor switches, contactors, line fuses, voltage and current transformers and circuit breakers are some of the protection devices found in filter banks. The availability of the components is also a major concern as delivery time affects a harmonic filter projects completion time. For the protection of the harmonic filter ground earth mats are used and are usually connected to specific parts of each of the filter components (e.g. reactor bases, and capacitor surge arrestors).

The position of the harmonic filter should be close to the main sub or load so as to minimise cable length. The capacitor banks are also located close to the mains supply as the metering devices are next to the power supply. Relays, PLCs and power factor controllers are used to monitor the load profiles and switch the banks in the harmonic filters if switching is part of the requirements.

Depending on the size of filter bank, the installation engineer will need equipment and labour. Equipment such as cranes is needed for lifting the capacitor banks, reactors and resistors. In terms of labour, civil and electrical engineers are needed to set up the installation site and install the filter controls. Installation of reactors emphasises that no adjacent magnetic components should be located nearby so as not to induce magnetic fields. The distance between the reactors and fence is specified by manufacturers and has to be adhered to.

The position of the filter site should consider of wind loading. This determines the support structure for the filter components. In some locations, the noise produced by the filter reactors is a concerning factor and is not acceptable. Animals and birds and their droppings need to be considered in locating a filter site as they can cause corrosion. The capacitor banks are also to be monitored as electrolyte spillages can cause fires in extreme cases.

7.4.3: Commissioning

Before the harmonic filter is handed over to the client, a commissioning phase is implemented and a number of procedures need to be conducted. This will include checking that the capacitor banks have the required Var rating and installed capacitors are up to the manufacturer`s drawings. The programs in the control of the bank are checked to confirm if they operate properly.

For protection purposes, faults can be simulated by injecting currents into the CTs to ensure that the relays trip. The cables for communicating with the relays are checked if well connected. The rating of the cables and switchgear should also be verified. Switching of capacitors and operation of the control panel and its lights is also checked.

7.5 Summary

This chapter looks at the results from the three filters designed using the methodology developed for the two networks in Chapter 6. Each filter is considered individually. The behaviour of how the harmonic graphs vary in the original network and with the Designed and Rated Filter is looked at. Also compared are the variations of PF_{DPF} and the effect of the filter design on the network in general at the PCC.

The relationship between the Designed (text book) Filter and Rated (filter using developed methodology) Filter is compared and evaluated.

The questionnaires included as part of the research are analysed in terms of design installation and commissioning. The various factors the filter specialists consider important were ascertained and their importance as part of the overall methodology. These include labour and equipment in the installation phase. The developed methodology is demonstrated and its effectiveness is shown.

CHAPTER EIGHT: CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

This final chapter reviews the research objections and presents conclusions drawn from this study. Further the chapter attempts a justification of the study in terms of its contribution to knowledge in the field of harmonic filters. Though every effort has been made to address as many issues relating to harmonic filters, no single study can adequately claim to address all questions arising from the research process. Consequently, limitations of the study and implications for further research are presented for consideration

8.2 Conclusions

From the case studies and interviews conducted, a number of issues were found. It was found from the work done in this thesis that harmonic filter design for the real world is a specialised topic. On paper it seems simple but in real life it is complex. Most networks will contain harmonic sources and some mitigation will need to be done and it was found out that many factors have to be considered.

At the same the effects of a filter being installed in a network can be detrimental to other loads in the network. This means all consumers in network can be affected by a filter being installed. Manufacturers of the filter components will deliver filter components in different sizes and configurations depending on designer`s specifications. The specifications could be related to the altitude of installation area, space for filter to be installed, humidity in the air, pollution, dust, and wind loading. Coastal areas are more humid thus higher rating insulators are needed. Strong winds will need stronger structures to support the filter structures.

It was found that industrial harmonic filter design is quite a complicated issue. Most documents discuss design of filters but rarely, are the issues of component rating for filters ever discussed. It was found out that capacitors used for PF_{DPF} correction capacitors cannot operate sufficiently as harmonic filter capacitors. This is because they are usually designed for linear loads which only take the fundamental current into consideration. When it comes to harmonic filters, the capacitors will have to cater for both fundamental and harmonic currents flowing through. In this case the capacitor bank for the harmonic filter will have to have a higher rating in terms of Vars hence either the current or voltage or both ratings will need to be increased.

In terms of filter design other factors need to be considered too. This will include the load profile of the network. In some instances the load varies with the time of day or season in the year. This variation could have maximum, average or minimum load, etc. In such situations, the filter banks will need switching steps. Such steps are specified to the manufacturers thus making manufacturing more complicated and costly. When it comes to design of new plants, it becomes very tricky as some information is not available and assumptions are needed. The only information the designer can use is the one from the network components from the manufacturers. Assumptions are also made in such instances they are based on experience that the designer has in this field. Typical assumptions are that the loads will operate at 80% full load and that the PF_{DPF} will be 0.8 lagging.

Another consideration in design of filter is future expansions of a plant. In this case the filter designed should look at factors that will cater for further expansion. This could include issues of space for installation, switchgear, cables used, etc. All these factors will cause increased cost implications.

Typically simulations for design assume the loading to be 100% full load. In most plants 100% loading is not practical. Experienced designers use loadings of 80% which are practical. The assumptions made depend on each network individually. The labour needed for filter installations is typically electrical and civil. Machinery such as cranes are used to lift capacitor banks. This can either be supplied by installation engineers or hired.

Every harmonic filter project is unique on its own. The capital available for the project determines other factors in project. This factors include fencing of the installation area, type of protection used for the filter etc. The more capital available the better and more sophisticated protection devices will be used in a filter. Availability and time duration to delivery of components is also a big influence. Filter components i.e. capacitors, reactors and resistors are manufactured to clients specifications and this takes time.

A harmonic filter installed by a consumer in a network influences other consumers in a network and in some cases it is positive and others negative. The filter will be to improve the PF_{DPF} of the consumer and mitigate harmonics. Incidentally by having capacitor banks in the filters, resonance may occur at other points in the network.

8.3 Recommendations and future work

From the studies done in this thesis it is advisable to conduct studies on the effects of a harmonic filter to other consumer in the same network. It would be very necessary to investigate the effects of one harmonic filter on other consumers in a network.

For future research a network can be investigated where certain loading variations occur when a filter is installed. The client in this case would want to increase the load at a later date with a certain value of power. The issue to be looked at is the power factor of the current loading and the extra loading to be added. The designer would look at the different types of filters that can be designed in such a project. The different designs would have cost implications and analysis of the different costs compared.

Certain aspects can also be investigated such as the effects of switching of harmonic filter capacitors. These would be broadened by looking at the transients.

Another issue that can be investigated are the effects of harmonic filters in unbalanced networks as in most cases; assumptions take networks to be balanced. Control aspects of filters can also be looked into. Lastly the costs of harmonic filters can be compared on all the aspects from design to commissioning.

The main recommendation is that harmonic filters need to be designed, installed and commissioned by specialists. Also the methodology developed for this thesis will help to extend the knowledge on this topic that is largely unknown. It is recommended that the methodology developed be implemented.

REFERENCES

Acha, E & Manuel, M. 2001. *Power Systems harmonics: Computer Modelling and Analysis*. John Wiley & Sons.

Almonte, R.L. & Ashley, A.W. 1995. *Harmonics at the Utility Industrial Interface: A Real World Example*, IEEE Transactions on Industry Applications, 31(6):1419-1426, November/December.

Allenbaugh L.M., Dionise J.T. & Natali J.T. 2013, *Harmonic Analysis and Filter Bank Design for a New Rectifier for a Cold Roll Mill*, IEEE Transactions on Industry Applications, 49(3), May/June.

Arrillaga, J. 1988. *Power System Harmonics*. Great Britain: John Wiley & Sons.

Atkinson-Hope, G. 2003, Decision theory process for a mitigation decision on harmonic resonance in power systems. Unpublished Phd Thesis. University of Cape Town.

Atkinson-Hope, G. & Folly, K. A. 2004, *Decision theory process for a mitigation decision on harmonic resonance*, IEEE Transactions on Power Delivery Applications, 19(3), July.

Badrzadeh, B., Smith, K.S. & Wilson, R.C. 2011, *Designing Passive Harmonic filters for an Aluminium Smelting plant*, IEEE Transactions on Industry Applications, 47(2), March/April.

Capacitors. n.d. http://www.hv-eng.com/2011CEDCapacitors.pdf [21 September 2012]

Cooper, L.C., Pragale, O.R. & Dionise, J.T. 2013. *A Systematic Approach for Medium Voltage Power Factor Correction Design*, IEEE Transactions on Industry Applications, 49(3), May/June.

Das, J.C., 2004, Passive Filters - Potentialities and Limitations, *IEEE Transactions on Industry Applications*, 40(1), January/February

ERA Technology ltd, ERACS Technical Manual, 8th edition, Chapter 4, pp 4.3, 4.37 & 4.56, April 2005, Ref No 66/4957/9024/008.

Filter Resistor Data Sheet Ref. R10. n.d., http://www.fortressresistors.com/wp-content/uploads/R10_00_FILTER_RESISTORS.pdf [18 July 2012].

Fluke Brands. n.d. http://www.fluke.com/fluke/m2en/Power-Quality-Tools/Logging-Power-Meters/Fluke-435-Series-II.htm?PID=73939 [24 August 2011].

General Electric. n.d. (http://www.geindustrial.com/publibrary/checkout/Installation%20and%20Instruction%7CGEH-2710F%7CPDF) [20 July 2012].

Harmonic Filter damping Resistors, http://www.msresistances.com/pdf/brochure_damping.pdf [18 July 2012].

Harmonic Filter Resistors, http://www.postglover.com/Literature/HF105-07_Hrm_Fltr_Te_Sht.pdf [19 July 2012].

Hughes, E. 2012. *Electrical and Electronic Technology*. England: Pearson Education Limited.

Microelettrica Scientifica (M.S.) Resistances. 2008. *Inspection & Test Plan (ITP)*, http://www.msresistances.com/2-DA/ITP%20(Draft).pdf [20 July 2012].

Installation & Maintenance Manual Damping Resistors, http://www.msresistances.com/2-DA/Operation%20Manual%20%20(DA).pdf [20 July 2012].

IEEE Power Engineering Society. 2003. 1531 Guide for Application and Specification of Harmonic Filters. New York. 24 November.

IEEE Std. 519-1992. 1993. IEEE Recommended practices for requirements for harmonic control in electrical power systems. *IEEE*. 12 April.

Kruesi, W.R. et al 1978. IEEE Std. 100-1977. IEEE Standard dictionary of Electrical and Electronics terms, second edition, 22 May 1978.

Kyle, L. 2009. Semi-structured interview with author at the RWW Engineering (PTY) Ltd offices. Robertsham, Johannesburg: 11 June 2009. [Notes, voice recording and transcribed responses in possession of author].

Lemieux, G. 1990. *Power System Harmonic Resonance - A Documented Case*, IEEE Transactions on Industry Applications, 26(3):483-488, May/June.

Makram, E.B., Subramaniam, E.V., Girgis, A.A., & Catoe, R. 1993. *Harmonic Filter Design using Actual Recorded Data.* IEEE Transactions on Industry Applications, 29(6):1176-1183, November/December.

Mc-Granaghan, M.F. & Mueller, D. 1999. *Designing harmonic filters for adjustable speed drives to comply with IEEE-519 Harmonic limits.* IEEE Transactions on Industry Applications, 35(2):312-318, March/April.

Nassif, A.B, Xu, W. & Freitas, W. 2009. *An investigation on the selection of filter toplogies for passive filter applications*. IEEE Transactions on Power Delivery, 24(3):1710-1718, July.

Nokian Capacitors brochure, "High voltage capacitors and capacitor bank (U>1000V, Instructions for installation, operation and maintenance", Version O/MHe, pp. 10-17, 8th June 2001

Nokian Capacitors brochure, "Air core reactors, Instructions for installation, use and maintenance", Version 1.2KJy, pp. 5-9, 11th November 2002.

Peeran, S.M. & Cascadden, C.W.P. 1995. *Application, Design, and Specification of Harmonic Filters for Variable Frequency Drives,* IEEE Transactions on Industry Applications, 31(4):841-847, July/August.

Post Glover. n.d. http://www.postglover.com/Literature/HF105-07_Hrm_Fltr_Te_Sht.pdf, [22 July 2012].

Pragale, R., Dionise, J.T. & Shipp, D.D. 2011. *Harmonic Analysis and Multistage Filter Design for a Large Bleach Production Facility*, IEEE Transactions on Industry Applications, 47(3), May/June.

Shunt Capacitor Bank Fundamentals and Protection, http://www.geindustrial.com/publibrary/checkout/Shunt%20Capacitor?TNR=White%20Papers|Shunt%20Capacitor|generic [21 September 2012]

Stack Rack High Voltage Capacitor Equipment for power factor improvement instructions: http://www.geindustrial.com/publibrary/checkout/Installation%20and%20Instruction%7CGEH-2710F%7CPDF [20 September 2012]

Stemmet, W.C & Atkinson-Hope, G. 2006, *Risk Evaluation of Results when Utilizing Software Simulations to Identify a Harmonic Offender in a Power System*, Electrical Power Quality and Utilization Magazine, 2(2): 33-41.

Thunberg, E & Soder, L. 1999, *Norton Approach to distribution network modelling for harmonic studies*, IEEE Transactions on Power Delivery, 14(1), January.

Wakileh, G. J. 2001, Power System Harmonics: Fundamentals, Analysis and Filter Design, Berlin: Springer.

APPENDIX 1

The Fluke 435 three phase power quality Analyser is used to take a number of readings in a network. The figures in Appendix 1 show some of the screen readings taken by the power analyser. Figure A1.1 shows the voltages and current in the three phases.

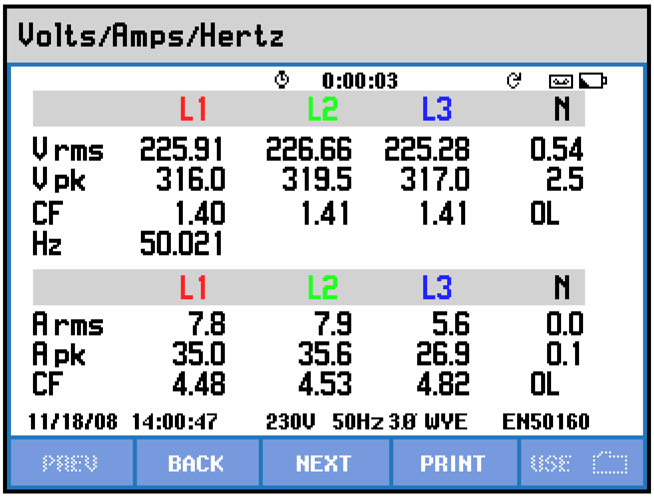


Fig A1.1: Fluke 435 Volts/Amps/Hertz screen

Figure A1.2 shows the power readings for the three phases. The PF and cos Φ values of each phase are also shown. The VAR readings show whether the phase is capacitive or inductive at any instant.

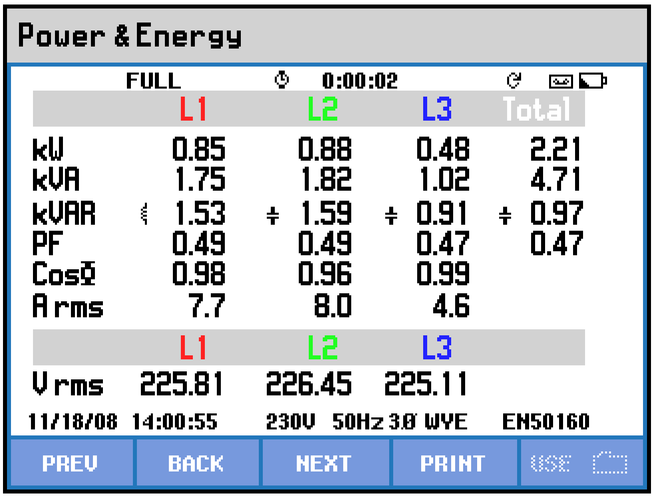


Fig A1.2: Power and energy screen

Figures, A1.3 and A1.4 show the voltage and current waveforms at any instant in the network and the values.

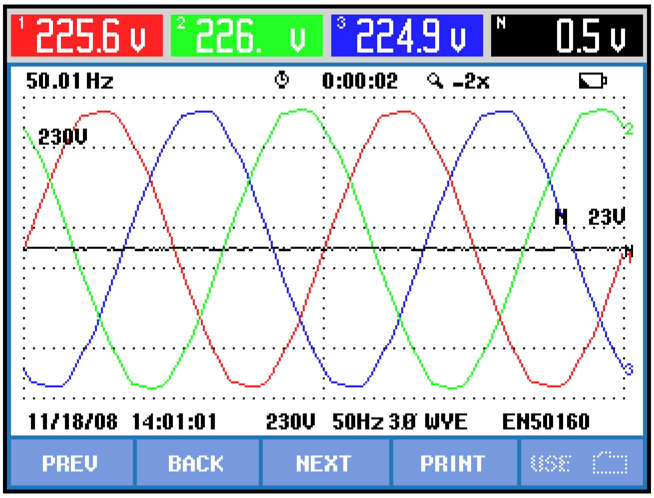


Fig A1.3: 3-phase voltage values and waveforms

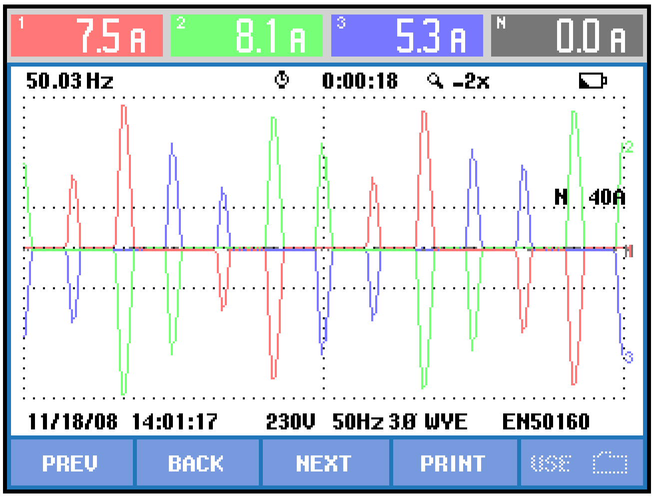


Fig A1.4: 3-phase current values and waveforms

Figures, A1.5 and A1.6 show the voltage and current phasor sequence diagrams and angles with respect to the reference angles at the network and the magnitudes.

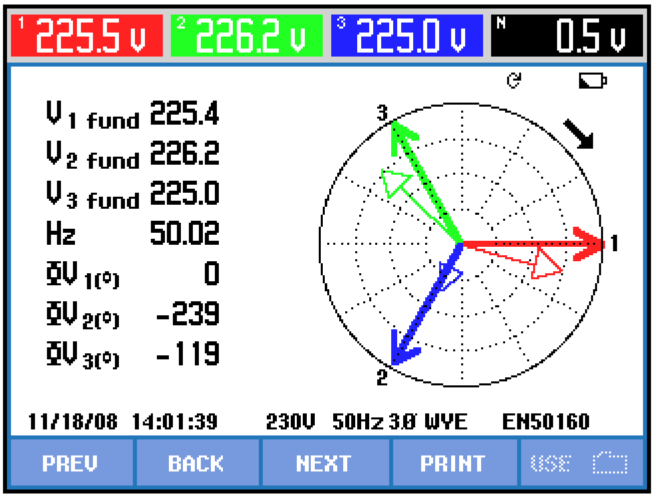


Fig A1.5: 3-phase voltage phase sequences and angles

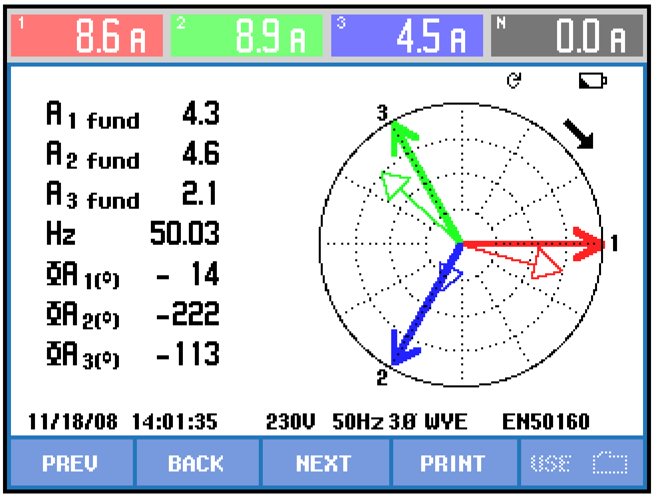


Fig A1.6: 3-phase current phase sequences and angles

Figures, A1.7 and A1.8 show the 5th harmonic red phase voltage and current spectrums. These screens also show the frequency, harmonic distortion, angle and magnitudes of the voltage and current.

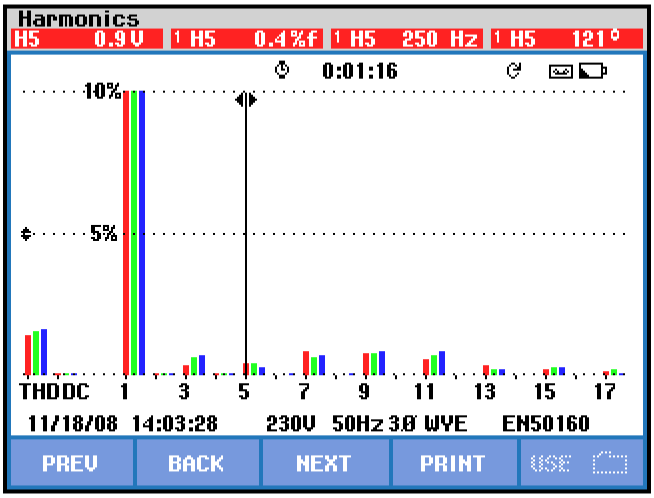


Fig A1.7: Red phase 5th harmonic voltage spectrum readings

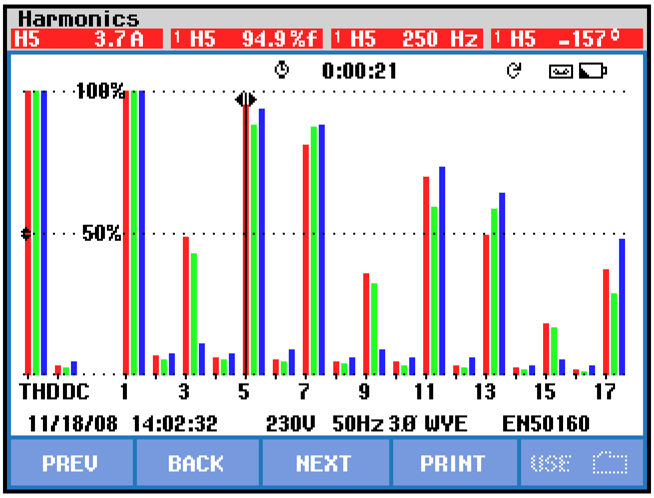


Fig A1.8: Red phase 5th harmonic current spectrum readings

APPENDIX 2

The installation of the harmonic filter is done once the components have been delivered. Typical diagrams for installation of an 11kV 4.5 MVAR 5th harmonic filter are as follows.

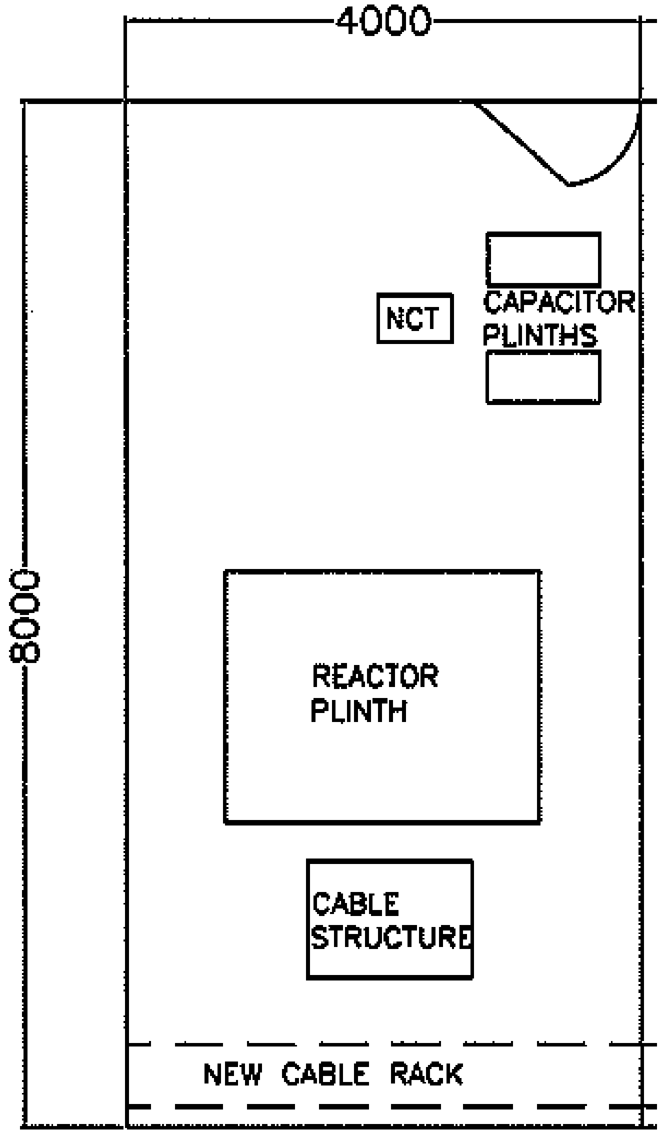


Fig A2.1: Top Plan view of harmonic filter site with dimensions (Courtesy of RWW Engineering, South Africa)

The capacitor banks are in some cases assembled in workshops and then transported to the sites or assembled at site. Due to the size of the racks, cranes are used for lifting the capacitors and reactors to the foundations with a lot of care not to damage the insulators attached. A 4.5 MVAR filter reactor will weight 600kg while the capacitors weight is 1200kg.

The capacitors and reactors are then connected to the power supply from the control panels are typically star connected.

The capacitor foundation will be at a height and depth of 400 mm respectively. The capacitor racks for each phase will be 475mm thus having a height of 1875mm for the three phases of the capacitors from ground level.

The reactors length from ground will vary from 2600 mm to 3100 mm depending on manufacturer. The radius of the rector will be 1210mm thus having a foundation of 1500mm by 1500mm with a depth of 400mm. The reactor foundation will have no metallic reinforcement to avoid any magnetic effects when the filter is operating. The magnetic clearance of the reactor is given as 1250mm radius.

Trenches for the supply cables are dug with a depth of 300mm. The site is then fenced with a height of 2000mm using stranded barbed wire. All the earth points form a grid with squares of 500mm by 500mm which are laid on the foundation at a depth of 500mm. Gravel which acts as an insulator is poured above the earth conductors as it helps to avoid damp situations when it rains.

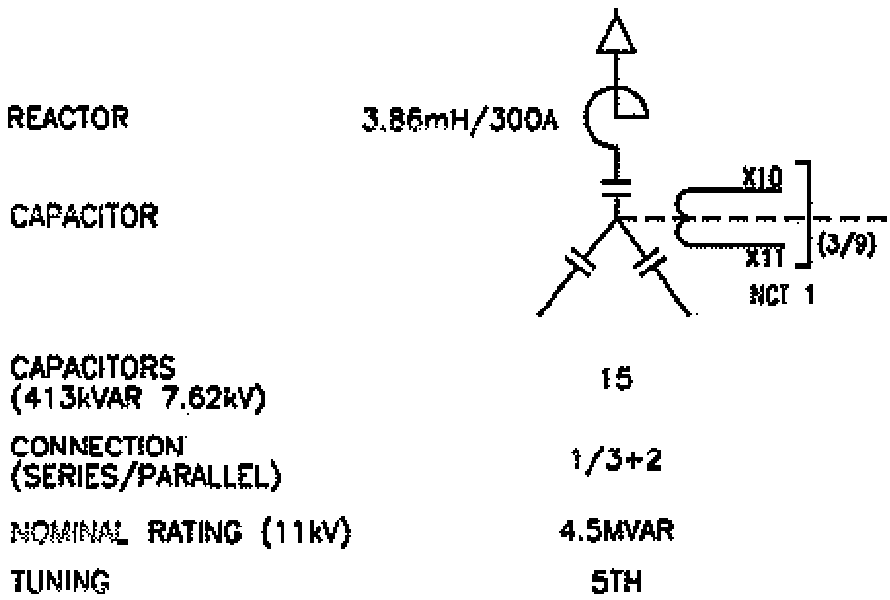


Fig A2.2: Filter components connection (Courtesy of RWW Engineering, South Africa)

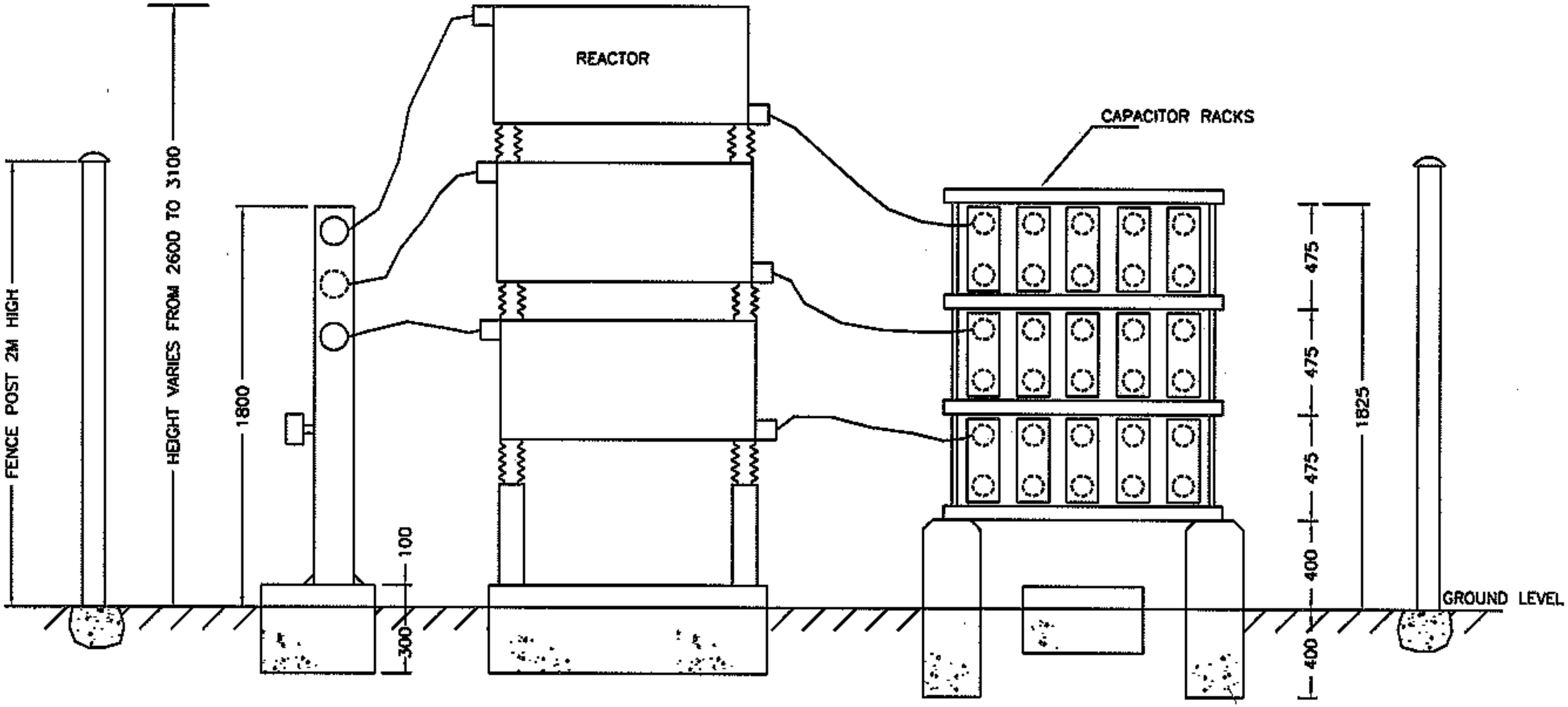


Fig A2.3: Side Plan view of harmonic filter site (Courtesy of RWW Engineering, South Africa)

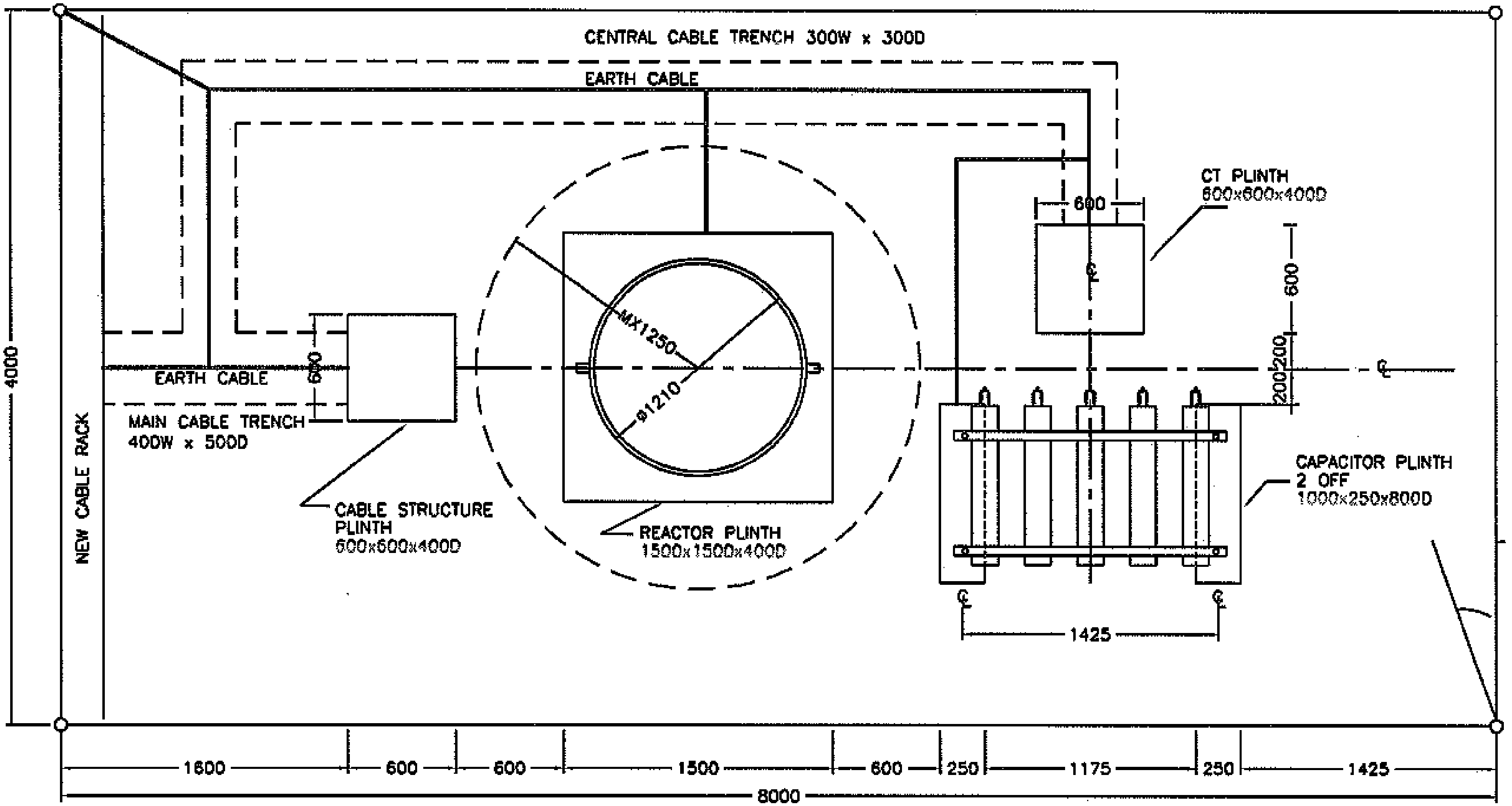


Fig A2.4: Top Plan view of harmonic filter site (Courtesy of RWW Engineering, South Africa)

APPENDIX 3

Network 1 Data

VSOURCE NAME = VSRC BUS = BUSSRCV MAG =25403

BRANCH NAME = equiv from SCRV to PCCBUS R=2.46, X=8.00

CONSUMER 1

44kV Distribution Line

BRANCH NAME **LINE 1** FROM PCCBUS to BUS 1 R=0.0581, X=1.2778

Transformer at entrance to End-User

TRANSFRORMER	**NAME=T1**	MVA=10
H.1 = BUS 1	X.1=BUS1AA	
Kvh=44.00	kVX=4.16	
%R.HX=3.0	%X.HX=15%	

Transformer connection to End-User

BRANCH NAME = **Con 1** from BUS 1AA to BUS 1AB R=0.0001, X=0.0

Linear Load = 100% Three phase motor

LINEAR LOAD NAME = **LOAD1** FROM= BUS 1AB KVA=4500 KV=4.16 PF=0.8

Capacitor connection to consumer bus

BRANCH NAME = R1 FROM BUS 1AB TO BUS AC R=0.0001, X=0.0

Capacitor Bank

CAPACITOR NAME = **CAP 1** FROM BUS 1AC R=0.0KV KV=4.16 MVA=2.025

HARMONIC CURRENT SOURCE

Metering element in series with 6 pulse drive

Branch Name – **rect1** from BUS 1AB to HSOURCE R=0.0001, X=0.0

Three Phase Harmonic Source

2.5745 MVA Drive, 6 pulse, 4.16 kV, 6% commutation reactance

NON LINEAR LOAD NAME=**DRIVE 1** BUS= HSOURCE1 KVA=858.156 KV=2.4018 PF=0.97107
TABLE

1,	202.07259,	166.19
5,	36.3706,	110.51
7,	24.2487	82.08
11,	12.1243	22.63
13,	8.0829	-9.39
17,	4.0414	-82.42
19,	2.0207	-125.51

End of Input File

APPENDIX 4

Network 2 Data

VSOURCE NAME = VSRC BUS = BUS 1 MAG =23094

BRACH NAME **- LINE 1** FROM BUS 1 TO BUS 2 R=0.1872, X=1.1644

Transformer at SOURCE

TRANSFRORMER	**NAME = TS**	MVA=20
H.1 = BUS 2	X.1=BUS3	
kVH=40.00	kVX= 12.00	
%R.HX=1.0	%X.HX=15.10	

PF CAPACITORS AT BUS 3

BRANCH NAME=**BRANCHA** FROM BUS 3 TO BUS 4 R=0.0001, X=0.0

PF Capacitor Bank 4A connection

BRANCH NAME=**BRANCHAA** FROM BUS 4 TO BUS 4A R=0.0001, X=0.0

CAPACITOR NAME=**CAP4A** FROM BUS 4B KV=12.0 MVA=2.0

PF Capacitor Bank 4B connection

BRANCH NAME=**BRANCHAB** FROM BUS 4 TO BUS 4B R=0.0001, X=0.0

CAPACITOR NAME = **CAP4B** FROM BUS 4B KV=12.0 MVA=2.0

DISTRIBUTION NETWORK 1
12Kv Distribution line

BRANCH NAME=**LINE2** FROM BUS 3 TO BUS 5 R=0.0001, X=0.0

CONSUMER 1

Transformer at entrance to Consumer 1

TRANSFRORMER	**NAME = T1**	MVA=5
H.1 = BUS 5	X.1 = BUS5A	
kV.H =12.00	kV.X = 6.00	
%R.H.X = 0.9885	%X.HX = 12.0%	

Linear load=100% Three phase motor load

LINEAR LOAD NAME= **LOAD 5A** FROM BUS 5A= BUS 5A KVA=2000 KV=6.00 PF=0.5

CONSUMER 2

Transformer at entrance to Consumer 2

TRANSFRORMER T2 MVA = 1.0

H.1 = BUS 5	X.1 = BUS5B
KV.H = 12.00	KV.X = 0.40
%R.HX = 0.8635	%X.HX = 5.0%

Linear load=100% Three phase motor load

LINEAR LOAD NAME= **LOAD 5B** FROM BUS 5B KVA=250 KV=0.40 PF=0.90

DISTRIBUTION NETWORK
12kV Distribution Line

BRANCH NAME = **LINE 3** FROM BUS3 TO BUS 6A R=0.000001, X=0.000001

CONSUMER 3
Metering element for monitoring injected harmonics from drives 1 and 2

BRANCH NAME = **LINE 4** FROM BUS6 TO BUS 6A R=0.000001, X=0.000001

TRANSFRORMER	**NAME=T3A**	MVA=5.0
H.1 = BUS 6A	X.1 = BUS6AA	
kVH = 12.00	kVX = 6.0	
%R.HX = 0.9885	%X.HX = 12.0%	

Metering element in series with drive 1

BRANCH NAME=**BRANCHB** FROM BUS 6AA TO HSOURSE1 R=0.0001, X=0.0

Three phase harmonic source 1

2.10 MVA Drive, 6 Pulse 6.0kV

NON LINEAR LOAD NAME=**DRIVE 1** BUS= HSOURCE2 KVA=700 KV=3.4641 PF=0.80
TABLE =

1,	202.07259,	166.19
5,	36.3706,	110.51
7,	24.2487	82.08
11,	12.1243	22.63
13,	8.0829	-9.39
17,	4.0414	-82.42
19,	2.0207	-125.51

Transformer feeding Drive 2 in consumer 3

TRANSFORMER	**NAME=T3B**	MVA=2.0
H.1 = BUS 6A	X.1 = BUS6AB	
kVH=12.00	kVX = 0.4	
%R.HX = 0.9861	%X.HX = 7.0%	

Metering element in series with drive 2

BRANCH NAME= **BRANCHC** FROM BUS 6AB TO HSOURSE2 R=0.0001, X=0.0

Three phase harmonic source 2

0.25 MVA Drive, 6 Pulse 0.4 kV

NON LINEAR LOAD NAME=**DRIVE 2** BUS= HSOURCE2 KVA=83.333 KV=0.23094 PF=0.80
TABLE=

1,	360.8428,	166.19
5,	64.9516	110.51
7,	43.3011	82.08
11,	21.6505	22.63
13,	14.4337	-9.39
17,	7.2168	-82.42
19,	3.6084	-125.51

Transformer feeding pf corrected load in consumer 3

TRANSFORMER	**NAME=T3C**	MVA=2.0
H.1 = BUS 6	X.1 = BUS6B	
kVH=12.00	kVX = 0.4	
%R.HX=0.9861	%X.HX = 7.0	

Linear load=100% Three phase motor in consumer 3

LINEAR LOAD NAME= **LOAD 6A** FROM BUS 6B KVA=1000 KV=0.40 PF=0.80

PF capacitor in consumer 3

Metering element in series with capacitor

BRANCH NAME=**BRANCHD** FROM BUS 6B TO BUS6BA R=0.0001, X=0.0

CAPACITOR NAME=**CAP 6BA** FROM BUS6BA KV=0.40 MVA=0.3

End of Input file

APPENDIX 5

RESULTS: 12kV 2nd order harmonic filter

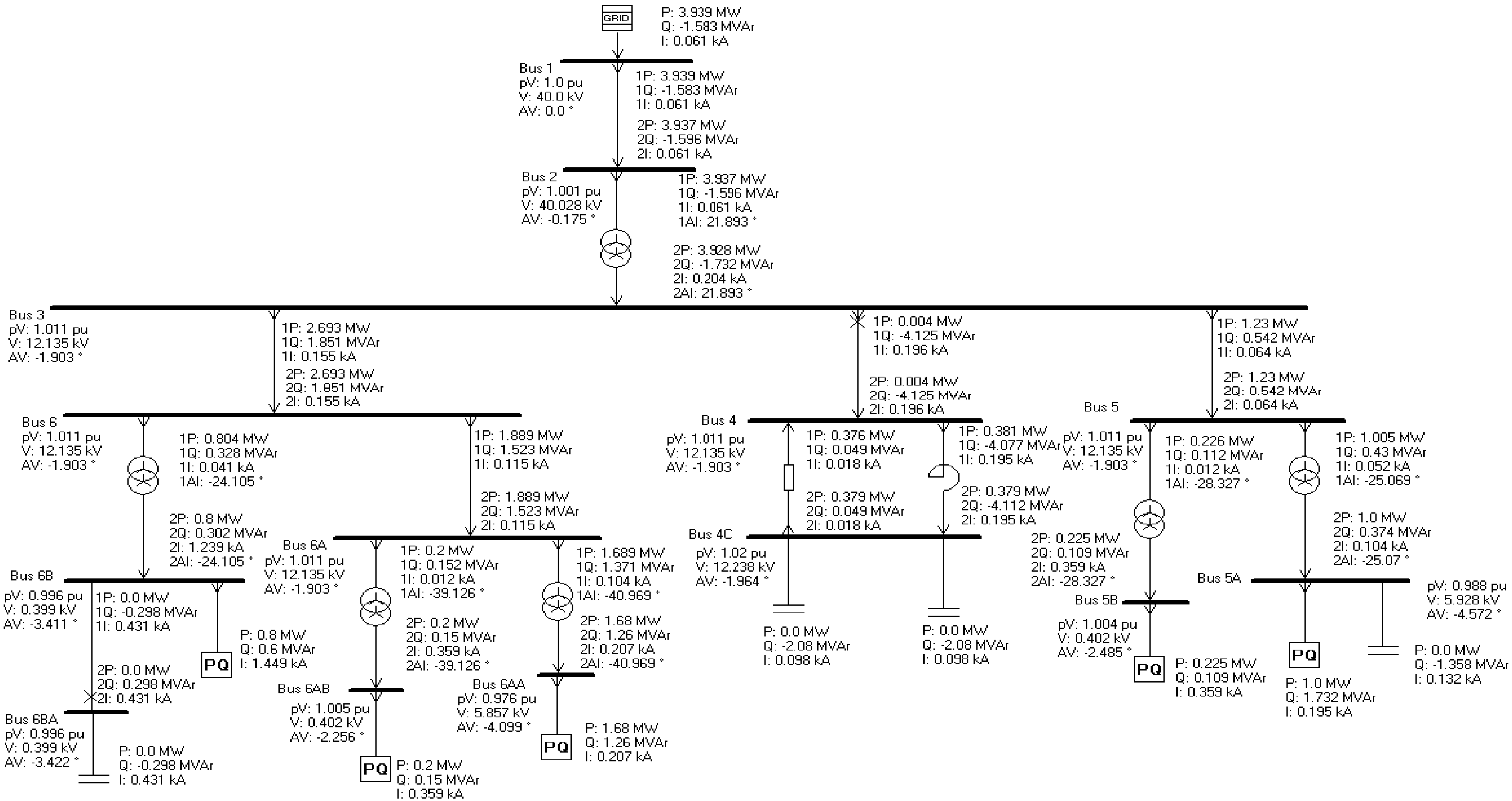


Figure A5.1: Load flow with second order Designed Filter

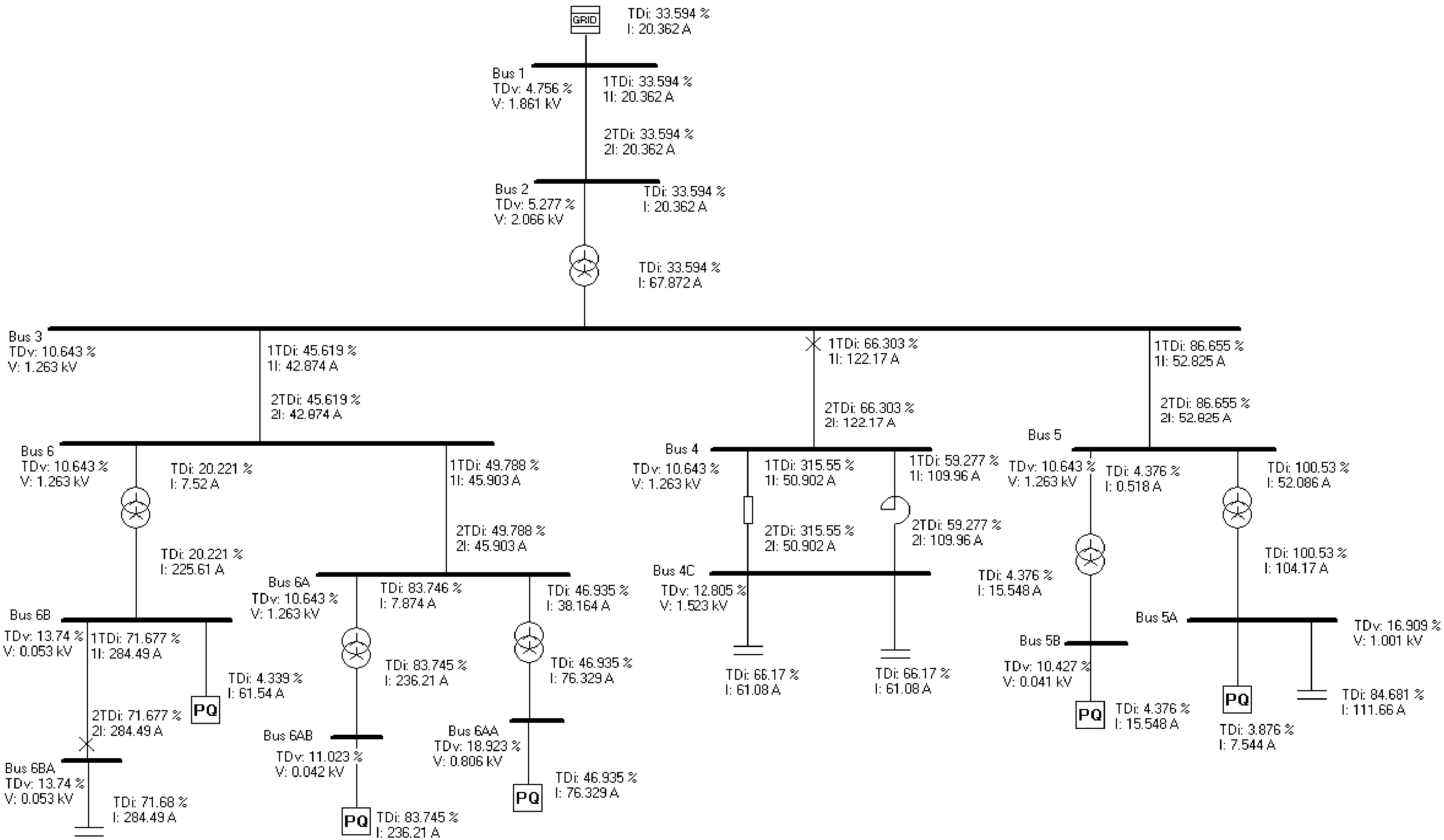


Figure A5.2: 5th harmonic penetration with second order Designed Filter

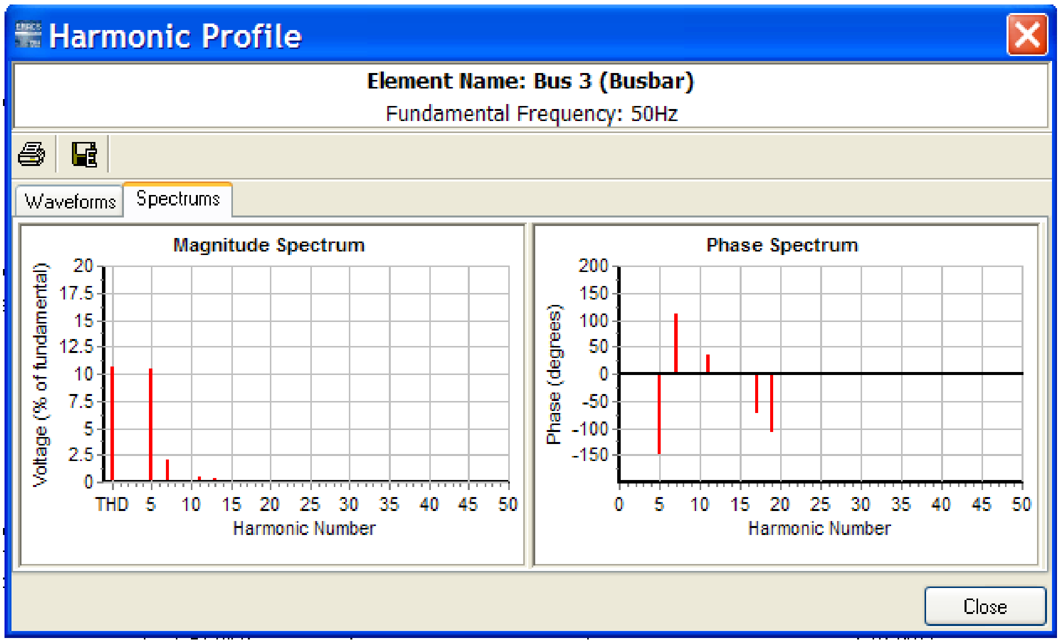


Figure A5.3: THD_V at Bus 3 with second order Designed Filter at Bus 5A

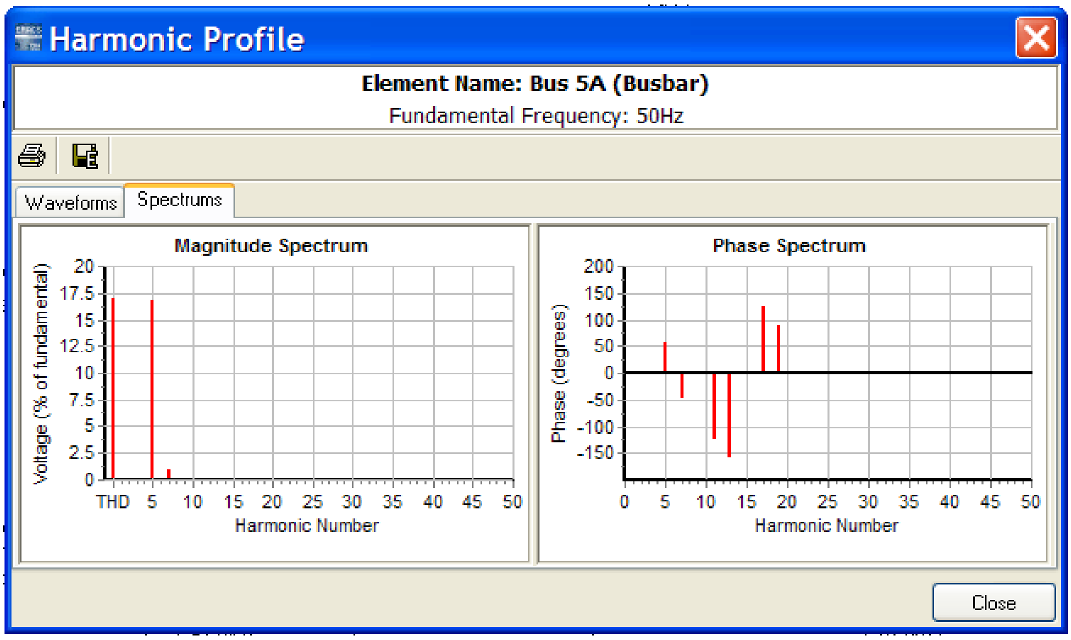


Figure A5.4: THD_V at Bus 5A with second order Designed Filter at Bus 5A

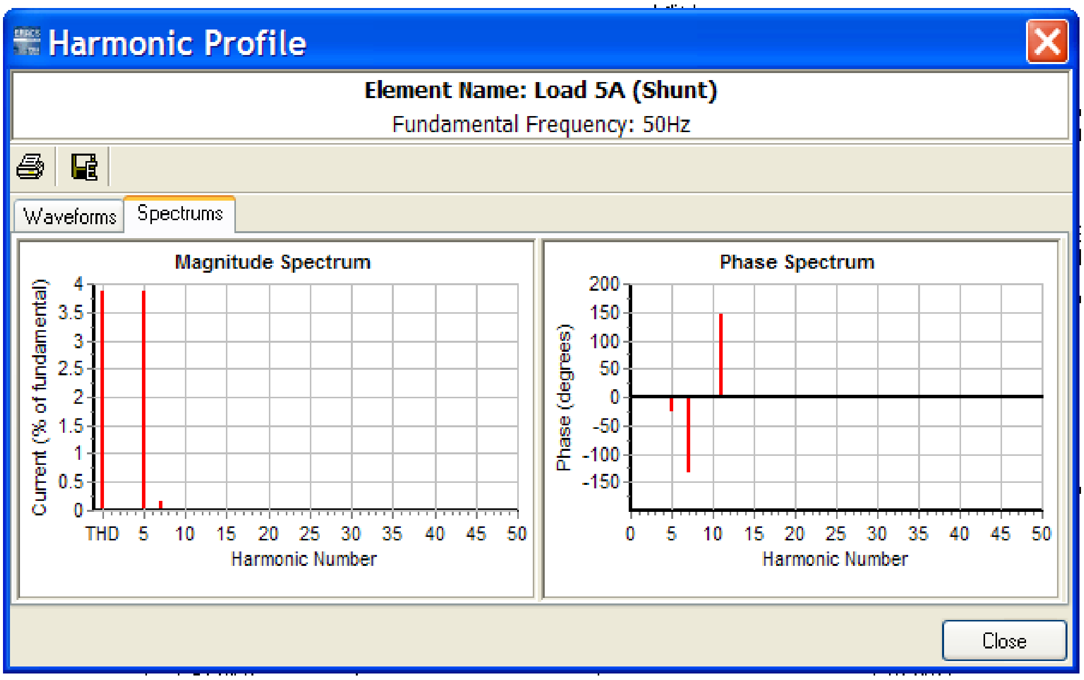


Figure A5.5: THD_I at Load 5A with second order Designed Filter at Bus 5A

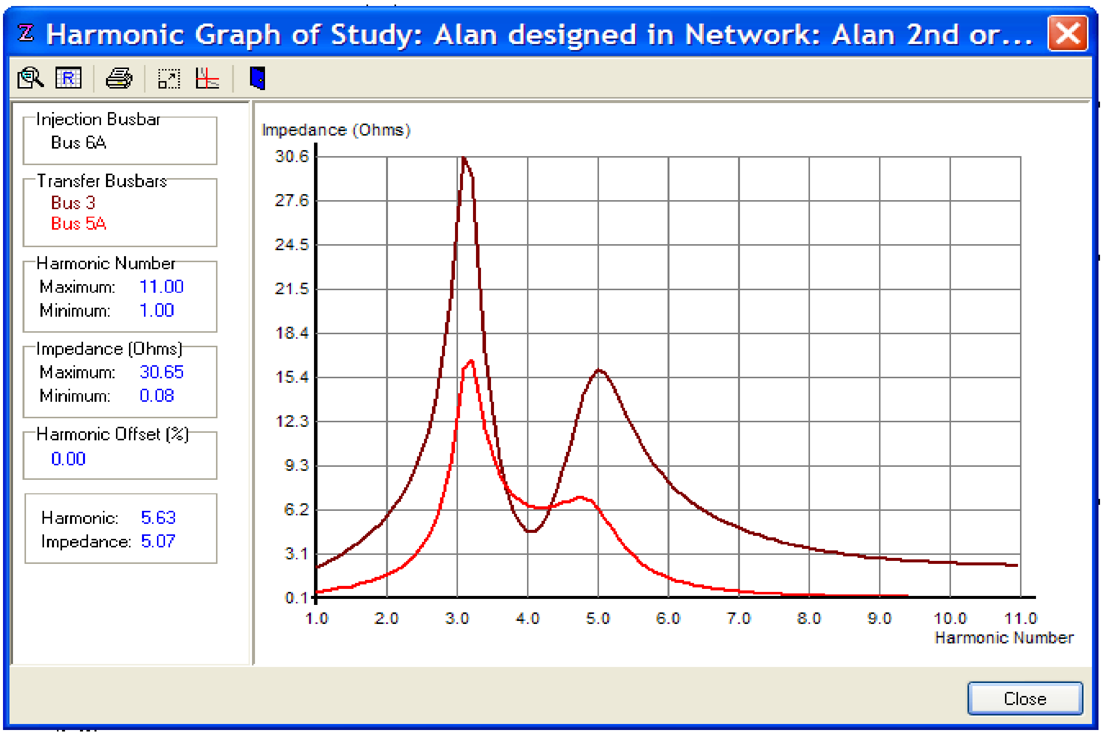


Figure A5.6: Harmonic graph of network with second order Designed Filter at Bus 5A

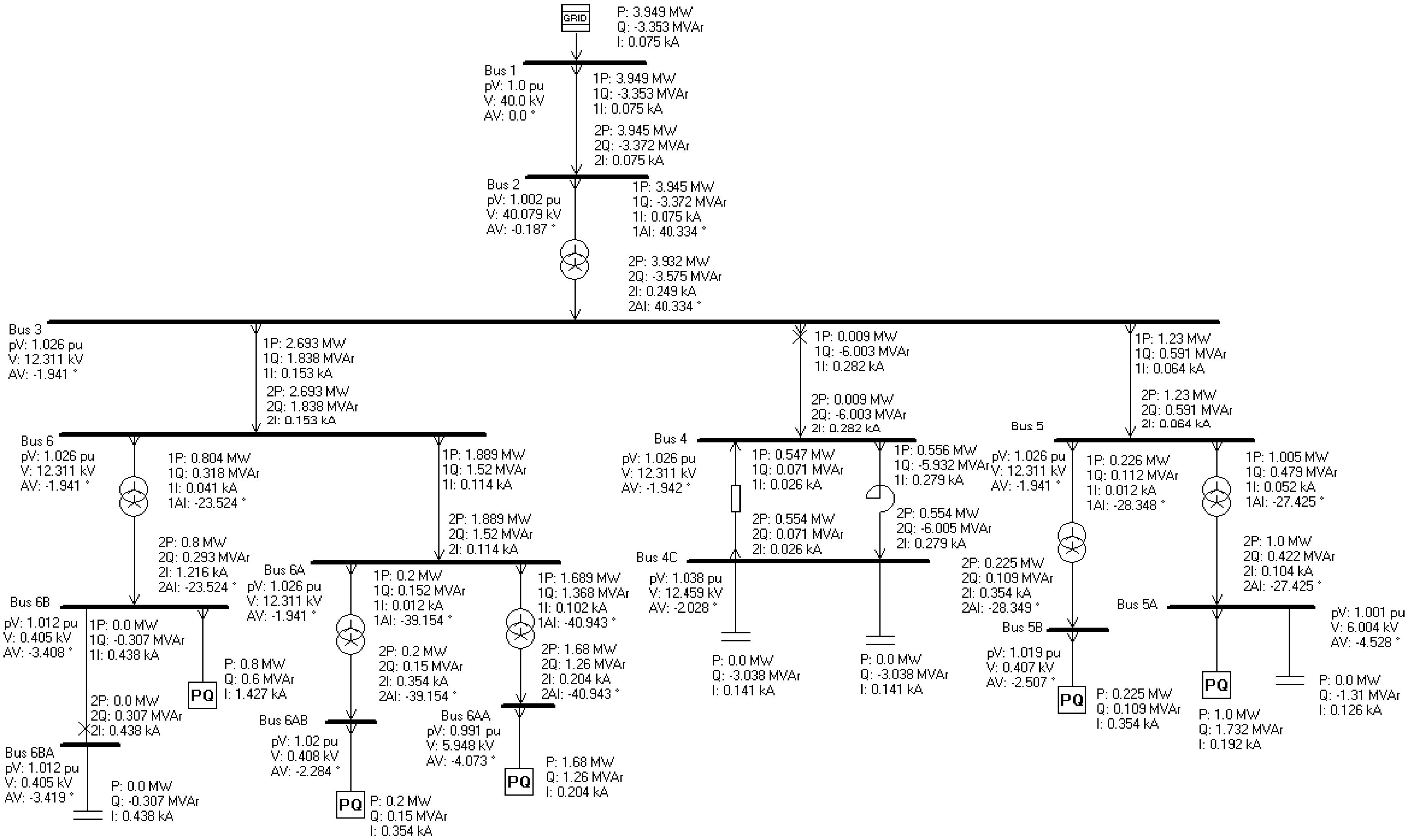


Figure A5.7: Load flow with second order Rated Filter

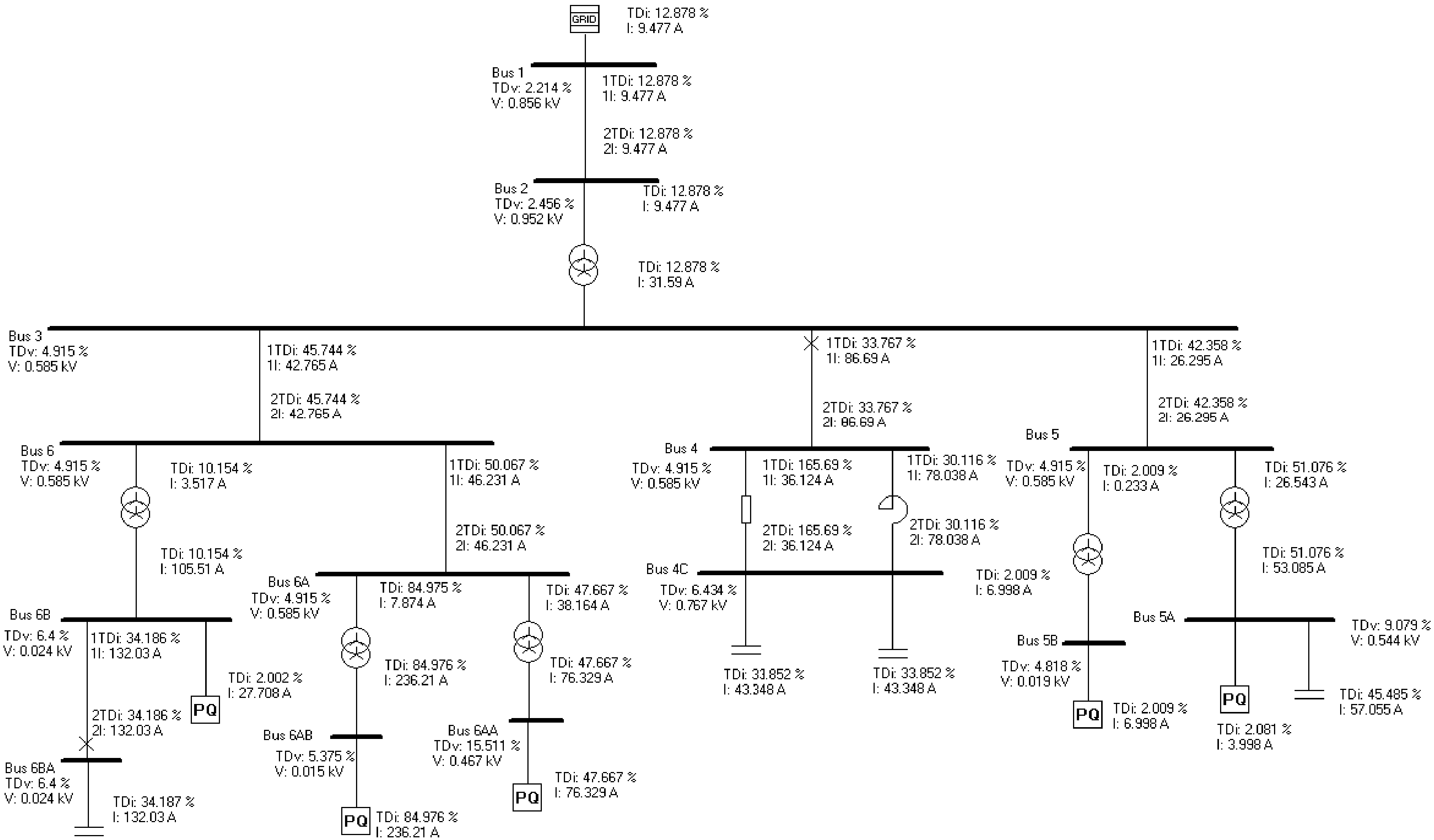


Figure A5.8: 5th harmonic penetration with second order Rated Filter

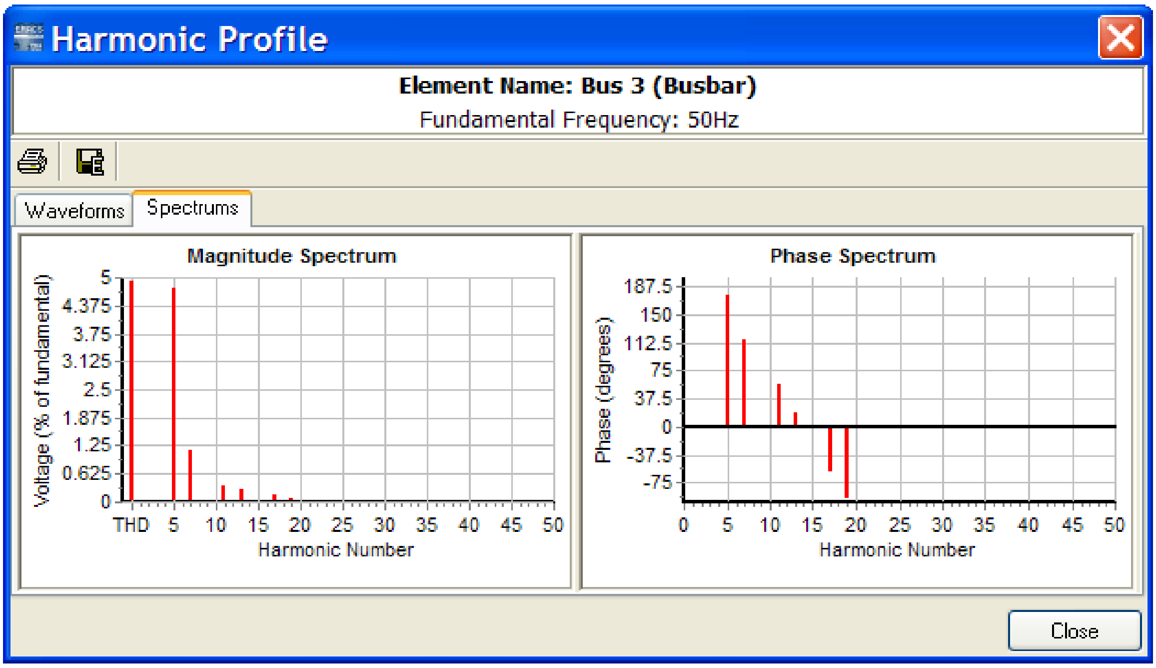


Figure A5.9: THD_V at Bus 3 with second order Rated Filter at Bus 5A

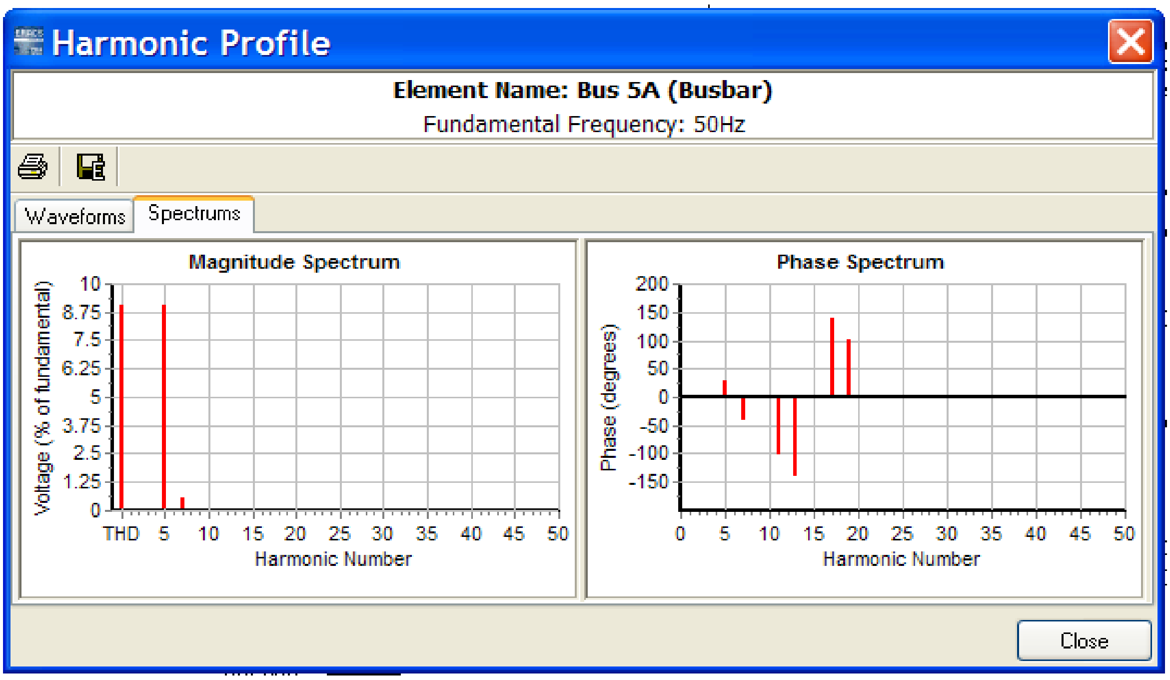


Figure A5.10: THD_V at Bus 5A with second order Rated Filter at Bus 5A

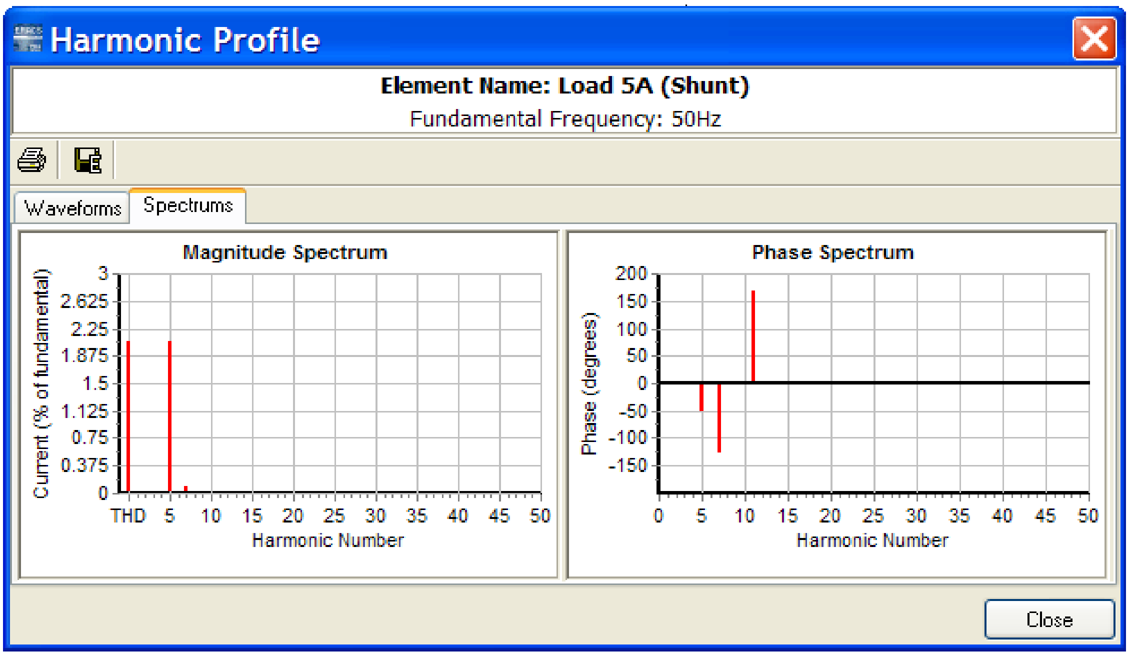


Figure A5.11: THD$_I$ at Load 5A with second order Rated Filter at Bus 5A

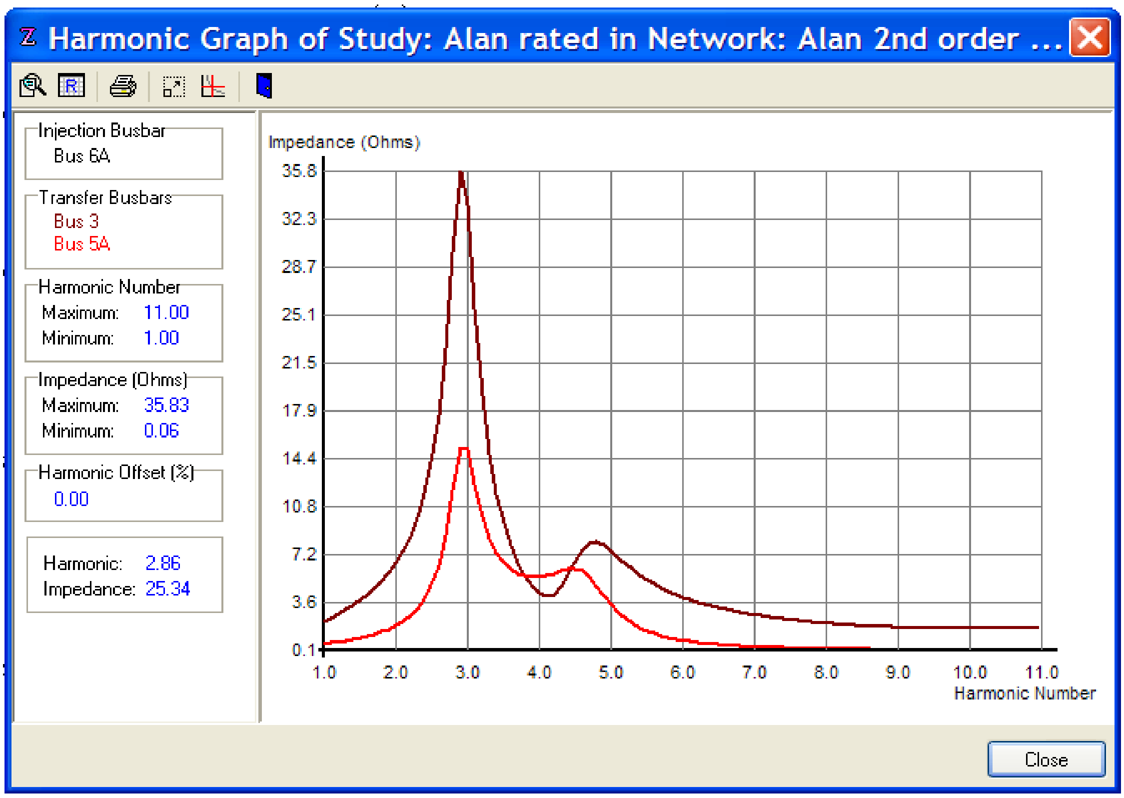


Figure A5.12: Harmonic graph of network with second order Rated Filter at Bus 5A

APPENDIX 6: 6Kv 5th series tuned harmonic Filter

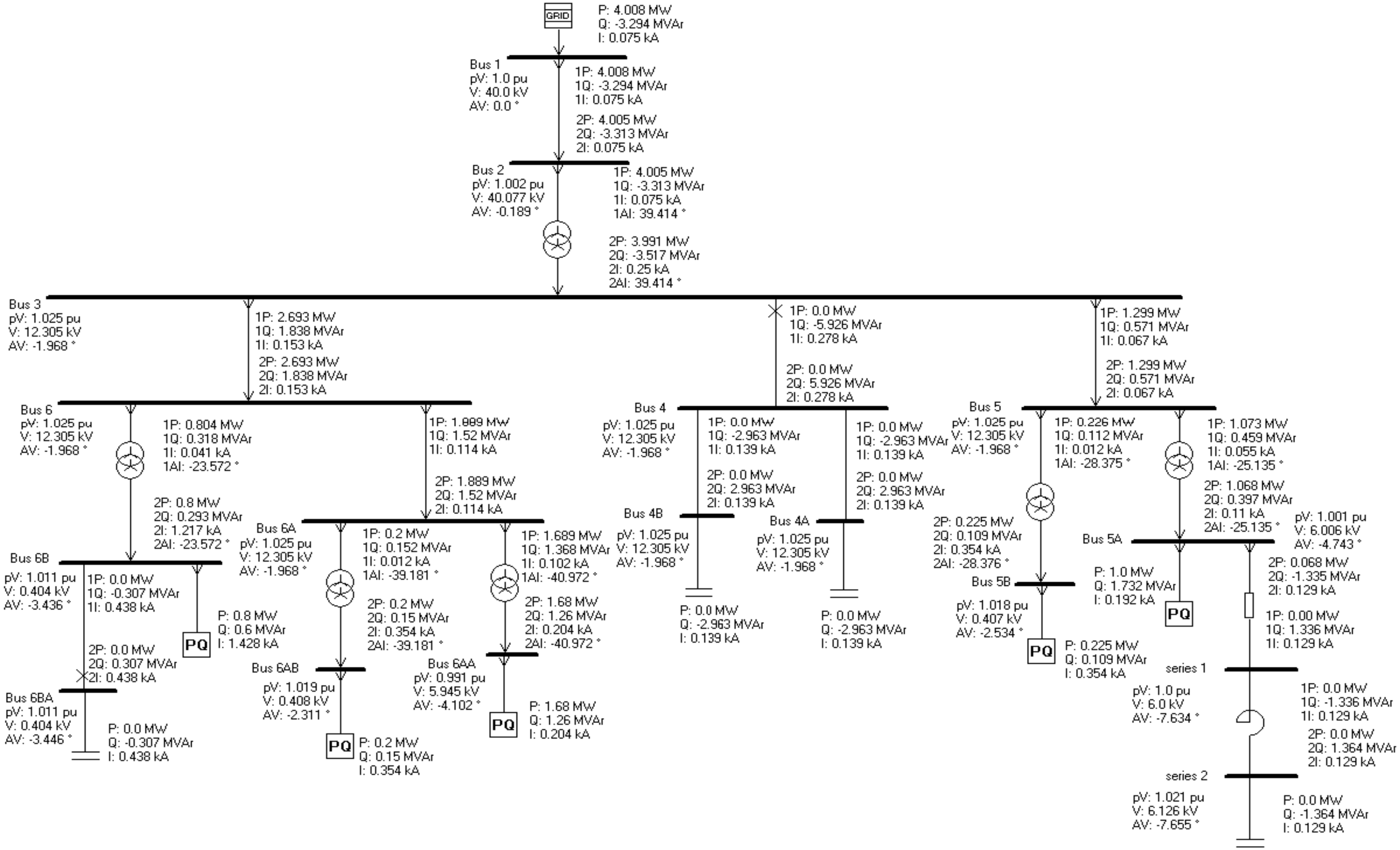


Figure A6.1: Load flow with series tuned Designed Filter at Bus 5A

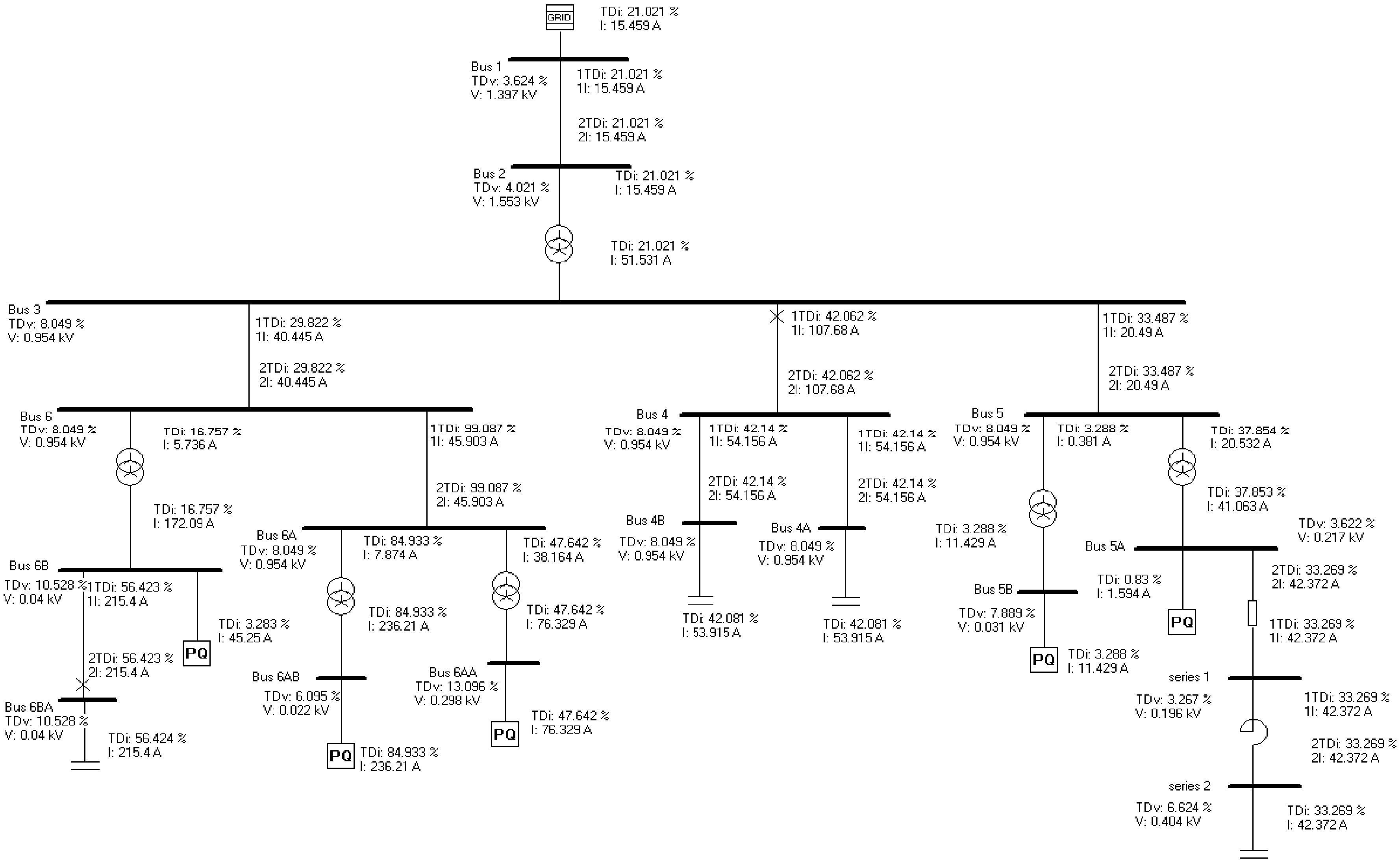


Figure A6.2: 5th harmonic penetration with series tuned Designed Filter at Bus 5A

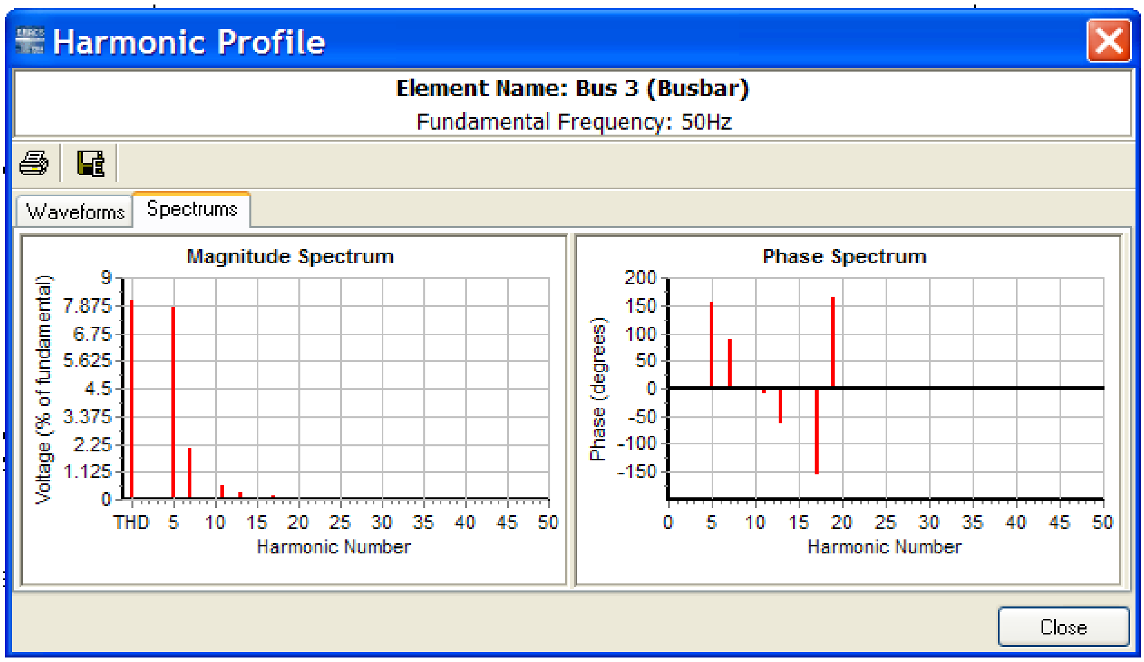


Figure A6.3: THD$_V$ at Bus 3 with series tuned Designed Filter at Bus 5A

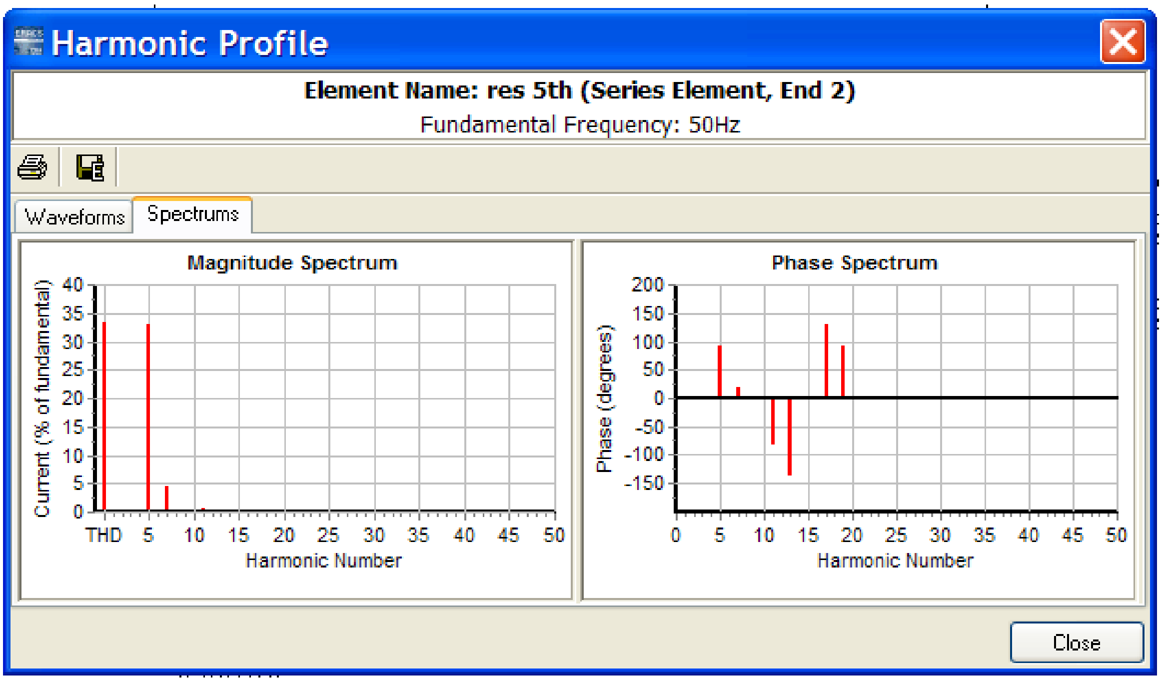


Figure A6.4: THD$_V$ at Bus 5A with series tuned Designed Filter at Bus 5A

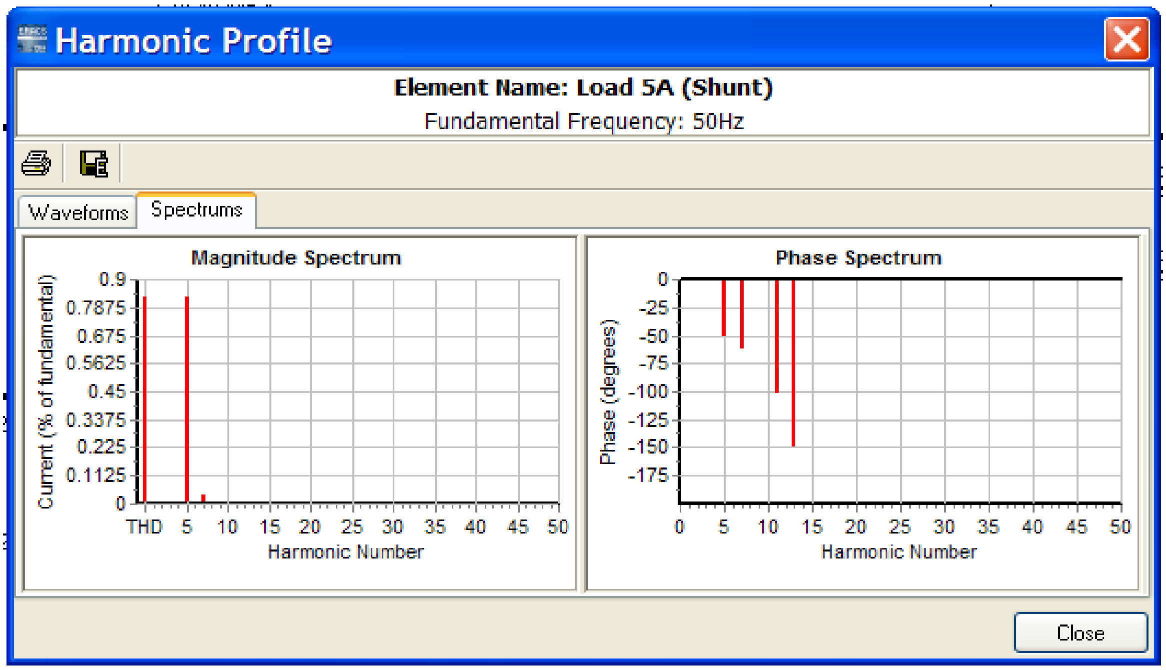


Figure A6.5: THD$_I$ at Load 5A with series tuned Designed Filter at Bus 5A

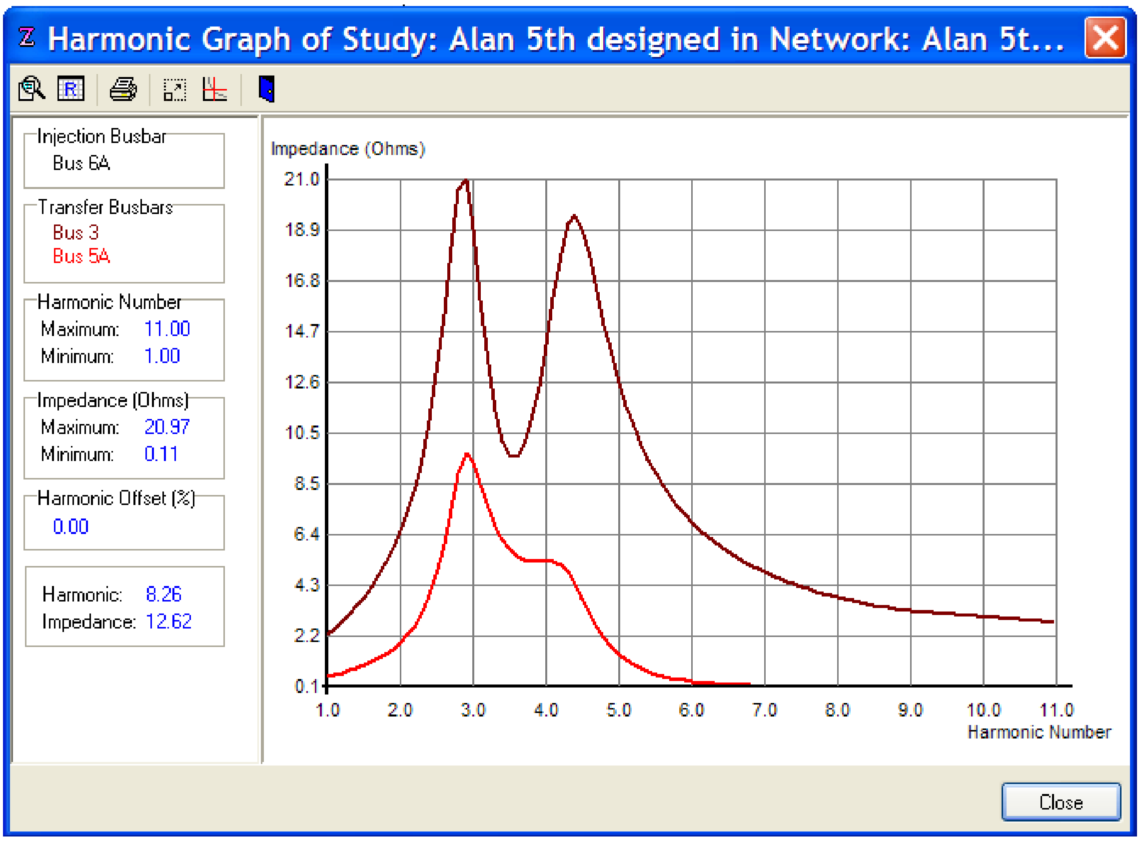


Figure A6.6: Harmonic graph of network with series tuned Designed Filter at Bus 5A

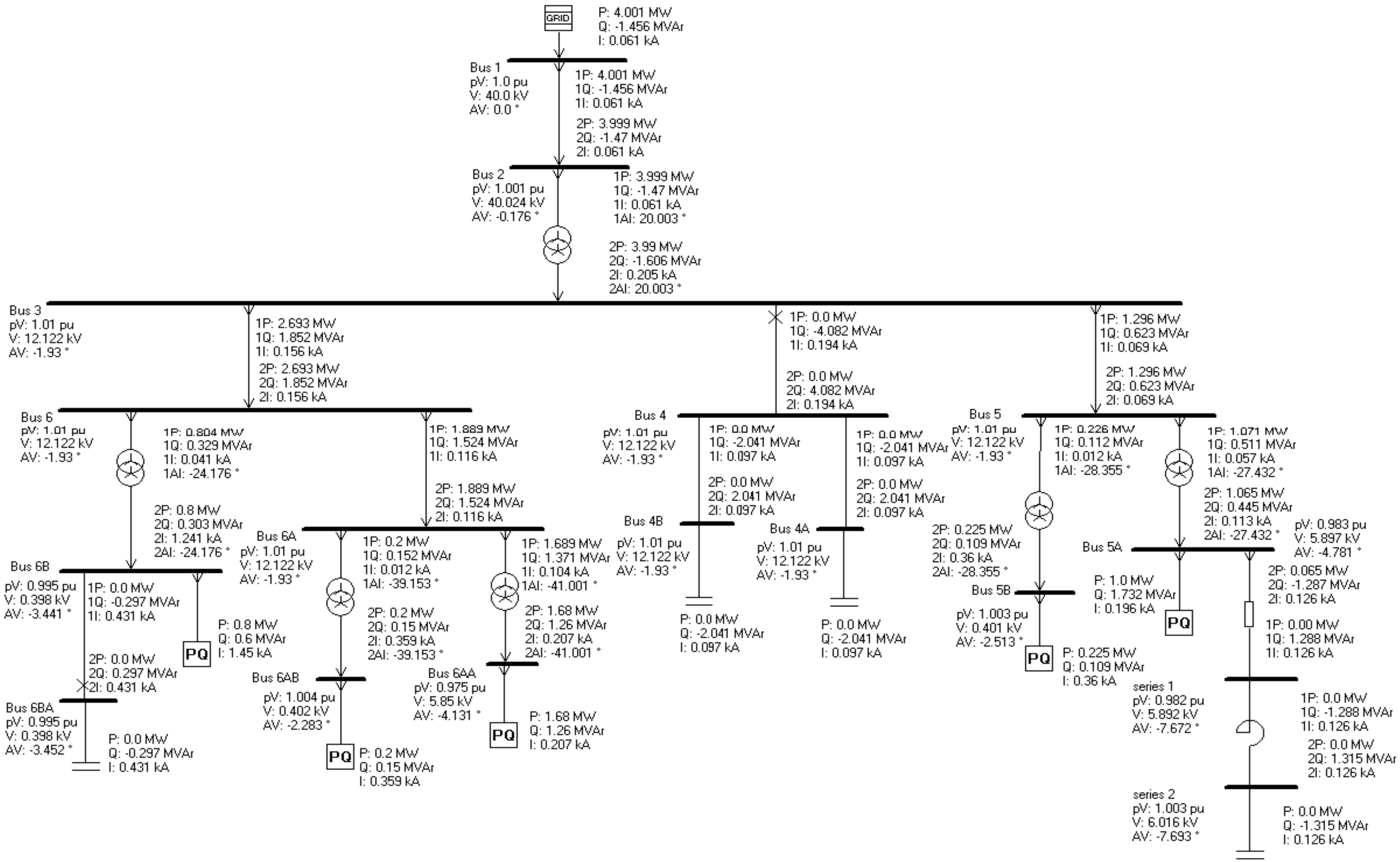


Figure A6.7: Load flow with series tuned Rated Filter at Bus 5A

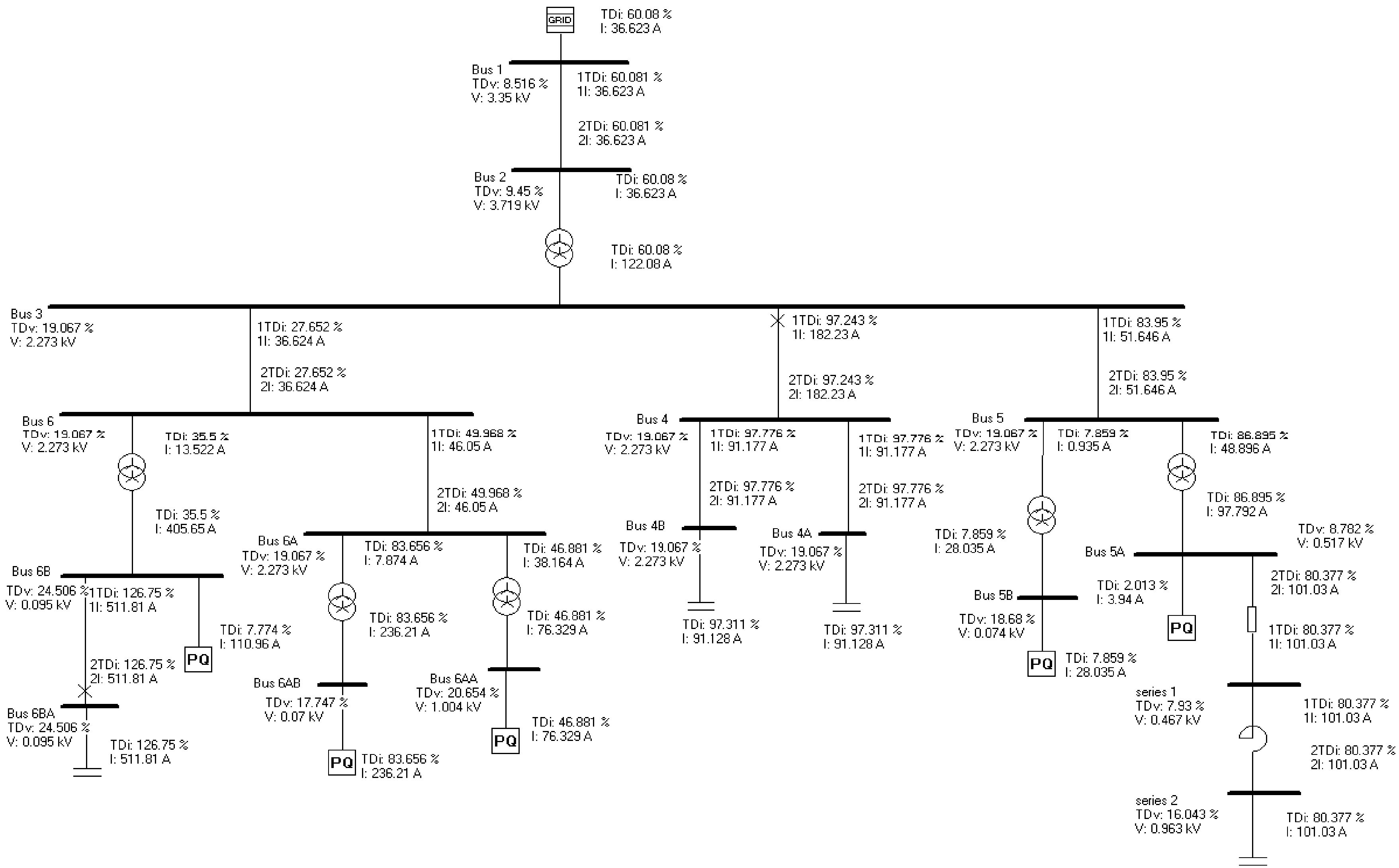


Figure A6.8: 5th harmonic penetration with series tuned Rated Filter at Bus 5A

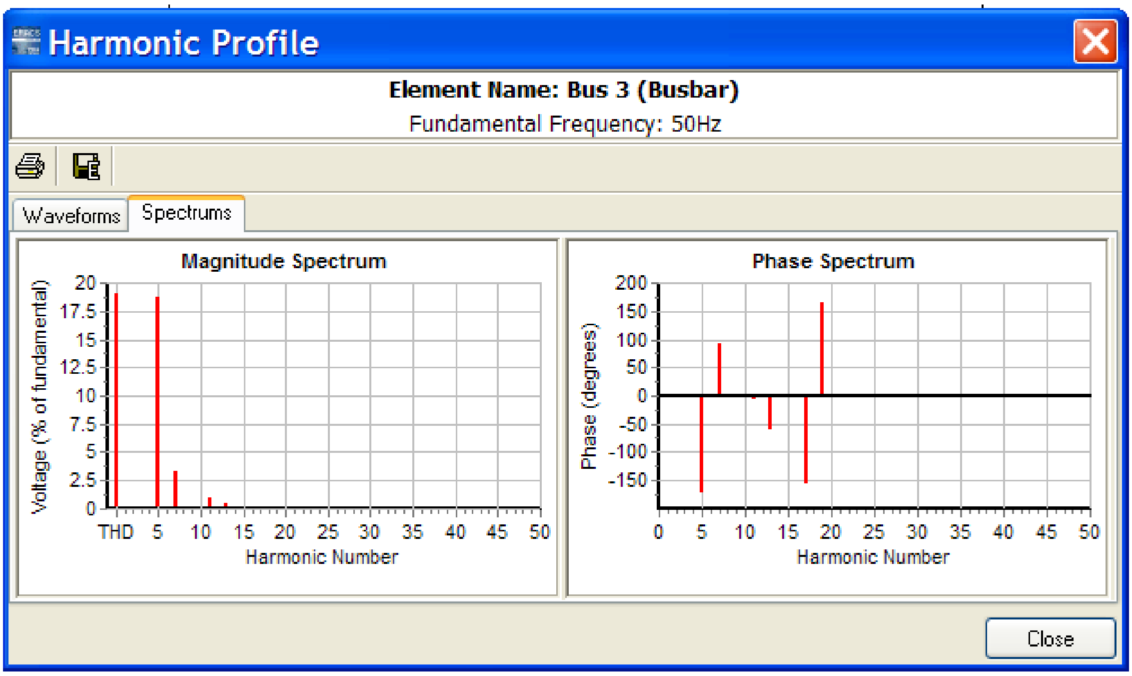


Figure A6.9: THD_V at Bus 3 with series tuned Rated Filter at Bus 5A

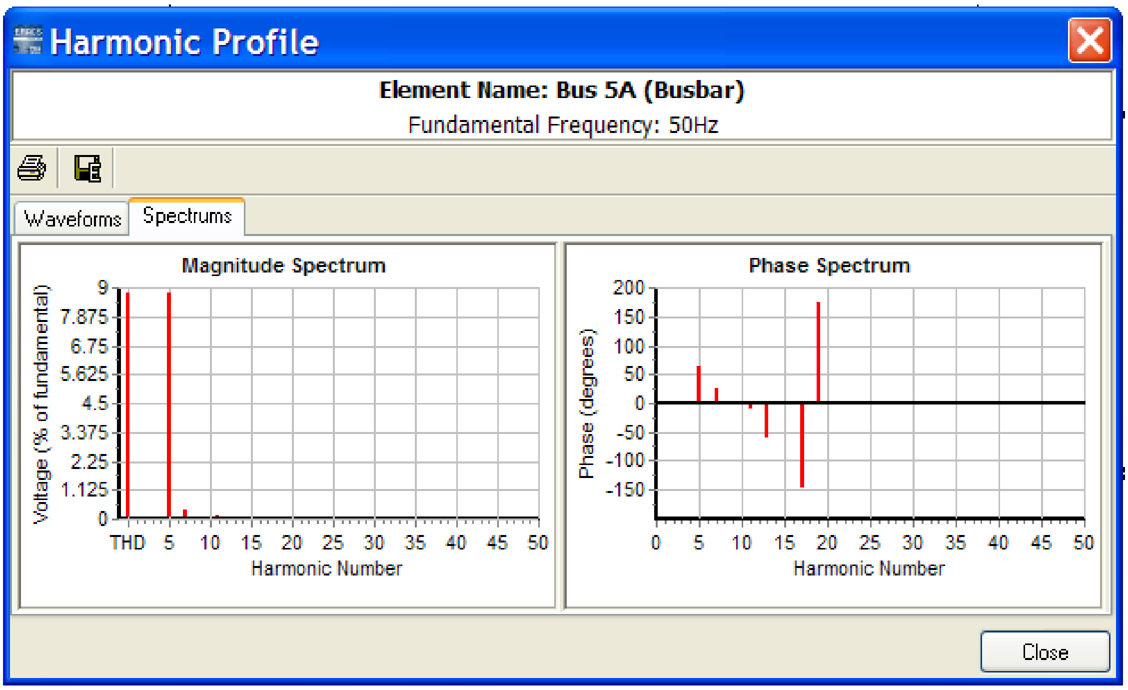


Figure A6.10: THD_V at Bus 5A with series tuned Rated Filter at Bus 5A

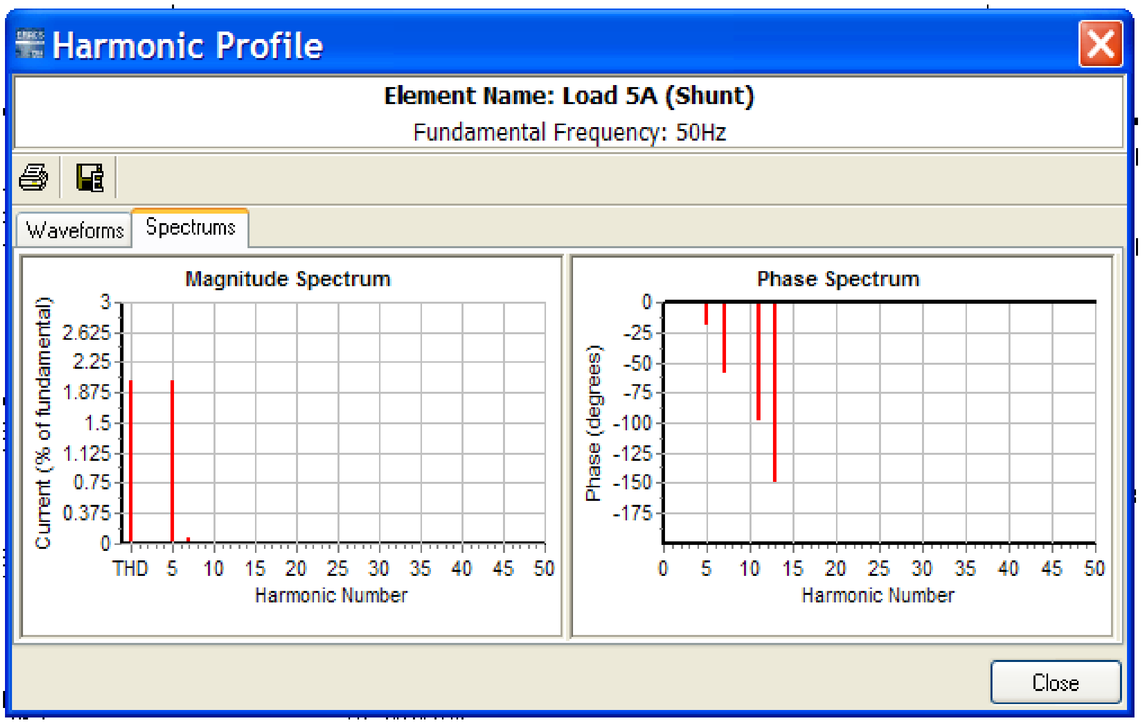


Figure A6.11: THD_I at Load 5A with series tuned Rated Filter at Bus 5A

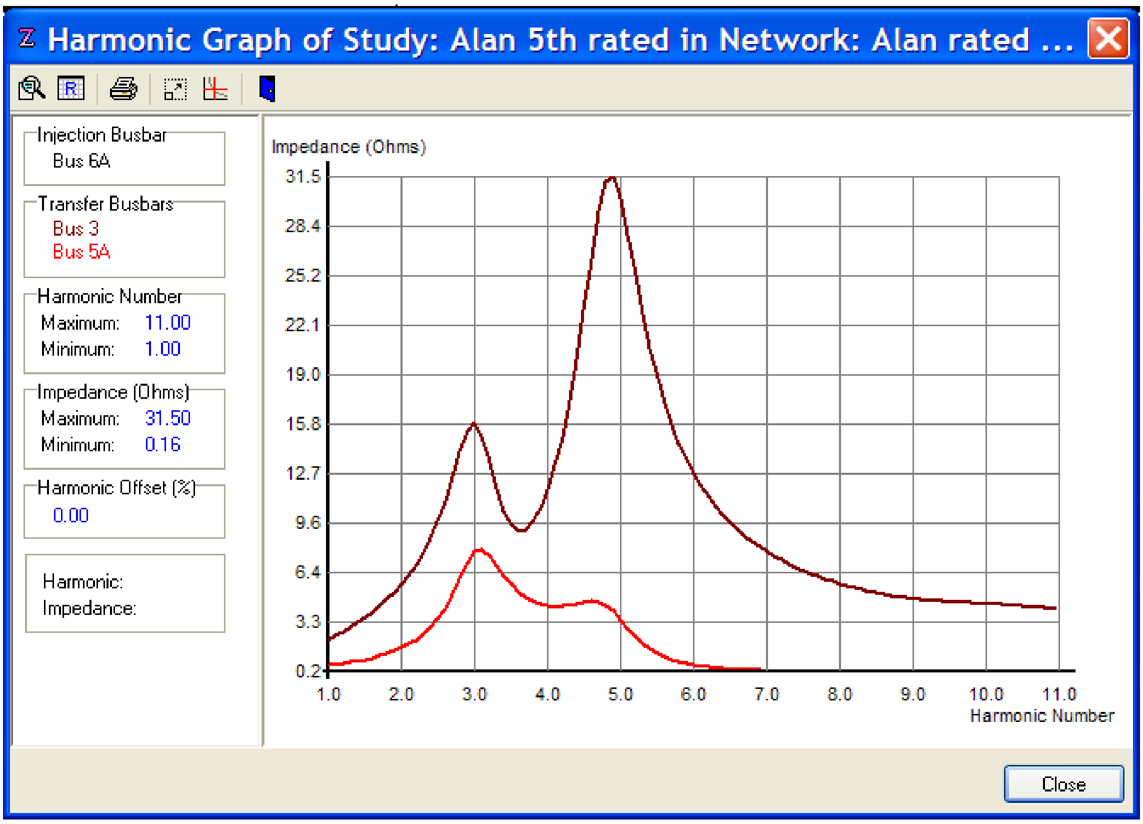


Figure A6.12: Harmonic graph of network with series tuned Rated Filter at Bus 5A

APPENDIX 7:
Harmonic Filter Reactor 1

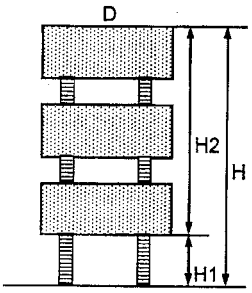
NOKIAN CAPACITORS

Customer
Offer No. /
Date

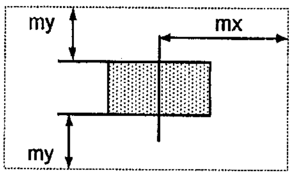
SPECIFICATION OF REACTOR

Type designation				XKKP		3,8 mH /	286	A
Rated voltage							11	kV
Rated current	285	10	10	10	10	10	8	A
Rated frequency	50	150	250	350	450	550	650	Hz
Rated inductance		3,8 mH,			tol.	+3	/ -3	%
Off-load tappings								%
3-phase losses at rated current	(+75 °C)	50 Hz		12,4 kW		total	12,6	kW
Insulation level						28	/ 95	kV
Temperature class of the reactor								F
Ambient temperature range						+40	/ -40	°C
Thermal short circuit current rating (Amps and duration time)					4,83 kA		1	s
Dynamic short circuit current rating (peak)							12,32	kA
Cooling : natural air circulation								AN
Weight							500	kg

Dimension



Minimum magnetic clearance to metallic parts not forming closed loops



D	920 mm
H1	395 mm
H2	2235 mm
H	2630 mm
mx	850 mm
my	400 mm

Drawing No

Standards: IEC Publication 60289, Reactors, 1988

Phase coils of insulated Al-conductor

Outdoor mounting

Notes :

PRELIMINARY!

Figure A7.1: 11kV, 3.8mH, 286A Air core reactor

Harmonic Filter Reactor 2

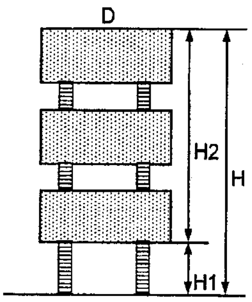
NOKIAN CAPACITORS

Customer
Offer No. /
Date

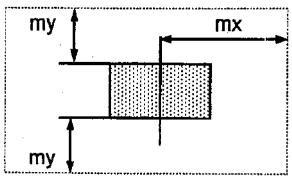
SPECIFICATION OF REACTOR

Type designation			XKKP		7,6 mH /	143	A
Rated voltage						11	kV
Rated current		143	4	4	6	2	A
Rated frequency		50	150	250	350	450	Hz
Rated inductance		7,6 mH,		tol.	+3	/ -3	%
Off-load tappings							%
3-phase losses at rated current	(+75 °C)	50 Hz	9,7 kW		total	9,8	kW
Insulation level					28	/ 95	kV
Temperature class of the reactor							F
Ambient temperature range					+40	/ -40	°C
Thermal short circuit current rating (Amps and duration time)				2,53 kA		1	s
Dynamic short circuit current rating (peak)						6,46	kA
Cooling : natural air circulation							AN
Weight						390	kg

Dimension



Minimum magnetic clearance to metallic parts not forming closed loops



D	940 mm
H1	315 mm
H2	2625 mm
H	2940 mm
mx	750 mm
my	250 mm

Drawing No

Standards: IEC Publication 60289, Reactors, 1988

Phase coils of insulated Al-conductor

Outdoor mounting

Notes :

PRELIMINARY!

Figure A7.2: 11kV, 7.6mH, 143A Air core reactor

Harmonic Filter Capacitor 1

NOKIAN CAPACITORS

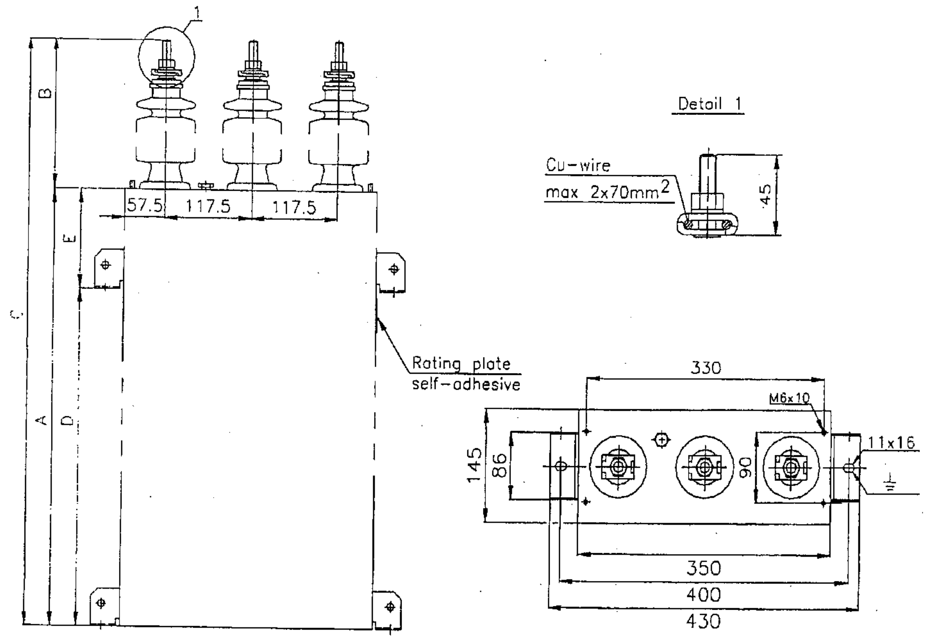
SPECIFICATION OF CAPACITOR UNIT

Type designation		QYLP
Rated power		207 kvar
Rated voltage		8000 V
Rated current		14.9 A
Rated frequency		50 Hz
Rated capacitance		5.1 µF
Tolerance of capacitance		-5/+5 %
Temperature category		-40/C °C
Number of elements	in series	2
	in parallel	4
Number of bushings		3
Internal connection of unit		3-Phase
Dielectric		pp-film
Impregnation liquid		non-pcb
		9 kg
Test voltage between terminals	ac 19.9kV	or dc 39.7kV
Insulation level between terminals and container:		20/60 kV
Built-in discharge resistance	3 *	9000 kΩ
Discharging time to 75 V		480 s
Fuses		internal
Average losses in steady state at rated voltage and frequency at 20°C ambient temperature		0.13 W/kvar
Main dimensions of the container		145x350x520 mm
Bushing:	-Type porcelain	M16
	-B.I.L	125 kV
	-Creep	380 mm
	-Length	220 mm
Mounting		outdoor
Weight of unit		43 kg
Standards		IEC 60871-1
Container:	Stainless steel AISI 409	
Painting:	Epoxy paint, primer+finish, thickness 80-120um Colour, light grey, RAL 7035	

Note

NOKIAN CAPACITORS

QYLP 207kvar 8000V 50Hz



A 520 mm

B 220 mm

C 740 mm

D 420 mm

E 100 mm

Weight 43 kg

Terminal nut M16

Torque 38-42 Nm

Figure A7.3: 8kV, 207kVar, 5.1μF, 14.9A Capacitor

Harmonic Filter Capacitor 2

NOKIAN CAPACITORS

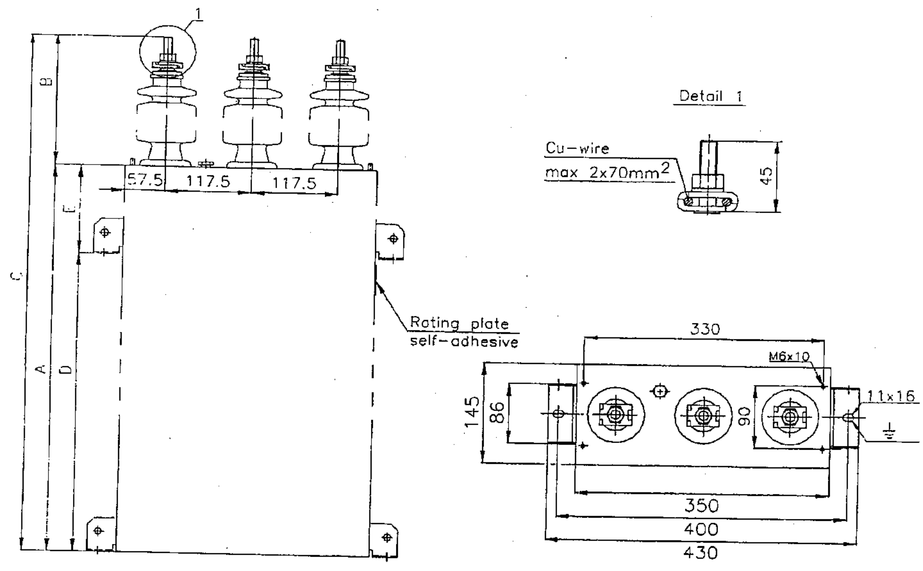
SPECIFICATION OF CAPACITOR UNIT

Type designation		QYLP
Rated power		345 kvar
Rated voltage		8000 V
Rated current		24.9 A
Rated frequency		50 Hz
Rated capacitance		8.6 µF
Tolerance of capacitance		-5/+5 %
Temperature category		-40/C °C
Number of elements	in series	2
	in parallel	7
Number of bushings		3
Internal connection of unit		3-Phase
Dielectric		pp-film
Impregnation liquid		non-pcb
		14 kg
Test voltage between terminals		ac 18.5kV or dc 37.0kV
Insulation level between terminals and container:		20/60 kV
Built-in discharge resistance		3 * 5720 kΩ
Discharging time to 75 V		510 s
Fuses		internal
Average losses in steady state at rated voltage and frequency at 20°C ambient temperature		0.13 W/kvar
Main dimensions of the container		145x350x820 mm
Bushing:	-Type	porcelain M16
	-B.I.L	125 kV
	-Creep	380 mm
	-Length	220 mm
Mounting		outdoor
Weight of unit		63 kg
Standards		IEC 60871-1
Container:	Stainless steel AISI 409	
Painting:	Epoxy paint, primer+finish, thickness 80-120um Colour, light grey, RAL 7035	

Note

NOKIAN CAPACITORS

QYLP 345kvar 8000V 50Hz



A 820 mm

B 220 mm

C 1040 mm

D 720 mm

E 100 mm

Weight 63 kg

Terminal nut M16

Torque 38-42 Nm

Figure A7.4: 8kV, 345kVar, 8.6μF, 24.9A Capacitor

APPENDIX 8: Results Tables

Table A8.1: HD_V and THD_V values with PF Capacitor at Bus 5A

Element Name	Bus 3 (Busbar)		Bus 5A (Busbar)		Load 5A (Shunt)	
Harmonic Number	Voltage (% of fundamental)	Voltage (V_h)	Voltage (% of fundamental)	Voltage (V_h)	Current (% of fundamental)	Current (I_h)
5	**14.66%**	**1778.47**	**24.31%**	**1439.11**	**5.58%**	**10.87**
7	**3.53%**	**428.41**	**1.61%**	**95.59**	**0.27%**	**0.52**
11	**0.90%**	**109.26**	**0.13%**	**7.55**	**0.01%**	**0.03**
13	**0.48%**	**58.16**	**0.05%**	**2.74**	**0.00%**	**0.01**
17	**0.17%**	**20.29**	**0.01%**	**0.53**	**0.00%**	**0.00**
19	**0.07%**	**8.83**	**0.00%**	**0.18**	**0.00%**	**0.00**
THD	**15.12%**		**24.36%**		**5.58%**	

Table A8.2: HD_V and THD_V values at Bus 3 with second order filter

Element Name: Bus 3 (Busbar)				
	Designed Filter		Rated Filter	
Harmonic Number	Voltage (% of fundamental)	Voltage (V_h)	Voltage (% of fundamental)	Voltage (V_h)
5	**10.41%**	**1263.19**	**4.75%**	**584.96**
7	**2.13%**	**257.98**	**1.16%**	**142.73**
11	**0.51%**	**61.99**	**0.37%**	**45.08**
13	**0.32%**	**38.9**	**0.26%**	**32.48**
17	**0.16%**	**19.94**	**0.15%**	**18.90**
19	**0.08%**	**10.27**	**0.08%**	**9.97**
THD	**10.64%**		**4.91%**	

Table A8.3: HD_V and THD_V values at Bus 5A with second order filter

Element Name: Bus 5A (Busbar)				
	Designed Filter		Rated Filter	
Harmonic Number	Voltage (% of fundamental)	Voltage (V_h)	Voltage (% of fundamental)	Voltage (V_h)
5	**16.88%**	**1000.73**	**9.06%**	**543.97**
7	**0.96%**	**56.87**	**0.57%**	**34.46**
11	**0.07%**	**4.25**	**0.06%**	**3.31**
13	**0.03%**	**1.82**	**0.03%**	**1.62**
17	**0.01%**	**0.52**	**0.01%**	**0.52**
19	**0.00%**	**0.21**	**0.00%**	**0.22**
THD	**16.91%**		**9.08%**	

Table A8.4: HD_I and THD_I values to load at Bus 5A with second order filter

Element Name: Load 5A (Shunt)				
	Designed Filter		Rated Filter	
Harmonic Number	Current (% of fundamental)	Current (I_h)	Current (% of fundamental)	Current (I_h)
5	**3.87%**	**7.54**	**2.08%**	**4.00**
7	**0.16%**	**0.31**	**0.09%**	**0.18**
11	**0.01%**	**0.01**	**0.01%**	**0.01**
13	**0.00%**	**0.01**	**0.00%**	**0.00**
17	**0.00%**	**0**	**0.00%**	**0.00**
19	**0.00%**	**0**	**0.00%**	**0.00**
THD	**3.88%**		**2.08%**	

Table A8.5: HD_V and THD_V values at Bus 3 with series tuned filter

Element Name: Bus 3 (Busbar)				
	Designed Filter		Rated Filter	
Harmonic Number	Voltage (% of fundamental)	Voltage (V_h)	Voltage (% of fundamental)	Voltage (V_h)
5	**7.76%**	**954.38**	**18.75%**	**2272.88**
7	**2.04%**	**251.28**	**3.31%**	**401.02**
11	**0.58%**	**71.64**	**0.89%**	**107.79**
13	**0.32%**	**38.86**	**0.48%**	**57.66**
17	**0.11%**	**13.96**	**0.17%**	**20.21**
19	**0.05%**	**6.12**	**0.07%**	**8.81**
THD	**8.05%**		**19.07%**	

Table A8.6: HD_V and THD_V values at Bus 5A with series tuned filter

Element Name: Bus 5A (Busbar)				
	Designed Filter		Rated Filter	
Harmonic Number	Voltage (% of fundamental)	Voltage (V_h)	Voltage (% of fundamental)	Voltage (V_h)
5	**3.61%**	**216.98**	**8.77%**	**517.35**
7	**0.22%**	**13.41**	**0.36%**	**21.39**
11	**0.10%**	**6.04**	**0.15%**	**9.07**
13	**0.06%**	**3.65**	**0.09%**	**5.40**
17	**0.02%**	**1.44**	**0.04%**	**2.09**
19	**0.01%**	**0.65**	**0.02%**	**0.93**
THD	**3.62%**		**8.78%**	

Table A8.7: HD_I and THD_I values at load at Bus 5A with series tuned filter

Element Name: Load 5A (Shunt)				
	Designed		Rated	
Harmonic Number	Current (% of fundamental)	Current (I_h)	Current (% of fundamental)	Current (I_h)
5	**0.83%**	**1.59**	**2.01%**	**3.94**
7	**0.04%**	**0.07**	**0.06%**	**0.12**
11	**0.01%**	**0.02**	**0.02%**	**0.03**
13	**0.01%**	**0.01**	**0.01%**	**0.02**
17	**0.00%**	**0.00**	**0.00%**	**0.00**
19	**0.00%**	**0.00**	**0.00%**	**0.00**
THD	**0.83%**		**2.01%**	

APPENDIX 9:
Interview A: BERNAND CRONJE FORMERLY OF DRA INTERNATIONAL

1. Do the capacitor banks come assembled or does the installation engineer do the assembling?
- Installation engineer.

2. Do the reactors come assembled or does the installation engineer do the assembling?
- Installation engineer.

3. How does load profile affect the filter components in design?
- Greatly. A fluctuating load requires more steps. The harmonic content determines the type of filter required.

4. What switch gear does one consider in a harmonic filter and availability?
- Switches rated to switch capacitors - IEC 60056. I don't know about the present availability

5. Is there switch gear for the reactors separate from the capacitors?
- No – One switch for the caps and reactors together.

6. In capacitor banks, what are commonly used i.e. internally fused, externally fused or fuseless? What are the factors that make one decide on one type over the other? N/A

7. Where does one position the harmonic filter in the site? i.e. proximity to factory etc
- As close as possible to the main sub or the main load – to keep cable lengths short.

8. Where does one position the harmonic filter switch gear? i.e. proximity to harmonic filter etc
- In the main sub or near the reactors

9. In what instances are the following used in harmonic filters? Circuit breakers, current transformers, voltage transformer, fuses?
- On large filters - Almost always. (Except for the VT's).

10. Are Automatic power factor controllers, relays, PLCs common in harmonic filters?
- Yes – you need to control the switching of the banks.
-

11. Design of harmonic filters comes in two phases

a) New plants- using data given by manufacturers of equipment to be installed in plant, harmonics produced, possibilities of plant extensions.

b) Existing plants- Use of power analysers to measure power readings over duration of time i.e. 2 weeks and consider possibilities of plant extensions.

How do the two different set up differ?
- On new plants you work with estimated data – manufacturers data sheets. But in principle, it should be the same.

11. In installation of a harmonic filter how are the following considered?

a) SITE construction- floor (no metal bars, fencing etc)

b) Control construction- i.e. Panels

c) Personnel - Electrical, civil, control (to set the PLCs and relays)

d) Equipment - Cranes, capacitor connections etc

- Speak to filter installation people…

12. The electromagnetic compatiblity (EMC) of the reactors is a factor in positioning of the harmonic. How is it measured?

- Magnetic fields induced may become a problem. You have a magnetic clearance – keep the reactors away from metal objects. E.g. No reinforcing in the concrete plinths.

13. The electrostatic fields from the capacitors is a factor in positioning the harmonic filter. How are they measured?

- Not an issue.

14. Before commissioning a harmonic filter what tests are done?

- Refer to commissioning procedures of installation people.
- Do a Post Commission harmonic test
- Check the logic works
- Make sure switching procedure in/out works
- Simulate faults
- Check breakers
- Simulate and check Vars

15. In open stack filter (out door) what environmental factors does one take into consideration in harmonic filter installation? N/A

16. Are filters installed in inlands different in specifications that the ones installed in coastal areas?

- Yes. Altitude and pollution determines the degree of insulation required. If it is salty or high pollution area, you need longer insulators.

17. For high pass filters resistors are used. Are this special types of resistors? Do they come in standard sizes or custom built? N/A

18. Who determines the Q value in a filter as there is a given range of $0.5<x<5$ for high pass filters and $30<x<100$ for LC filters? N/A

19. How is the floor of a harmonic filter grounded?

Read NRS060 and IEC 71-1 for electrical clearances

Interview B: JEREMY WOODS AND KYLE LASS OF RWW Engineering (PTY) LTD

1. Do the capacitor banks come assembled or does the installation engineer do the assembling?
   - Individual capacitors arrive in crates – local installation team assembles into steel frames.

2. Do the reactors come assembled or does the installation engineer do the assembling?
   - Individual reactors arrive in crates
   - Erecting and installation done by site crew
   - Installations done by the Engineer.

3. How does load profile affect the filter components in design?
   - Amount of Vars
   - Load variation

4. What switch gear does one consider in a harmonic filter and availability?
   - MV- ratings according to the harmonics present
   - High switching operations >150 000
   - Rated for capacitor switching
   - 11kV and below usually use contactors with line fuses
   - 22kV and above use circuit breakers
   - Circuit breaker panels usually 22 weeks delivery
   - Contactor panels 18 weeks delivery

5. Is there switch gear for the reactors separate from the capacitors?
   - No

6. In capacitor banks, what are commonly used i.e. internally fused, externally fused or fuseless? What are the factors that make one decide on one type over the other?

   - Internally fused on medium voltage

7. Where does one position the harmonic filter in the site? i.e. proximity to factory etc
   - Filters closer to load to absorb harmonics
   - Capacitor banks close to main supply for metering – kVA savings

8. Where does one position the harmonic filter switch gear? i.e. proximity to harmonic filter etc
   - Medium voltage switchgear normally in main substation to reduce cost – (Distributed switchgear is much more expensive)

9. Are Automatic power factor controllers, relays, PLCs common in harmonic filters?
   - PLCs in more complex filters. (More than 1 incomer). More often use harmonic controllers such as Nokain NC12 controller.

10. Design of harmonic filters comes in two phases

a) New plants- using data given by manufacturers of equipment to be installed in plant, harmonics produced, possibilities of plant extensions.

b) Existing plants- Use of power analysers to measure power readings over duration of time i.e. 2 weeks and consider possibilities of plant extensions.

How do the two different set up differ?

- On new plants, the load is modelled and simulations are done while n existing plants measurements are taken using power analysers.

11. In installation of a harmonic filter how are the following considered?

a) SITE construction- floor (no metal bars, fencing etc)

- Cable length
- Clearances per IEC Standards
- Safety of not having steel reinforcing and capacitors next to switches
- Lightning area
- Earthing system
- Civil space required

b) Control construction- i.e. Panels

- Accessibility to site
- Building plus switching and personnel
- Cable entry position
- Control cable lengths

c) Personnel - Electrical, civil, control (to set the PLCs and relays)

- Electrical available while civil is contracted.

d) Equipment - Cranes, capacitor connections etc

- This are hired out for jobs.

12. The electromagnetic compatibility (EMC) of the reactors is a factor in positioning of the harmonic. How is it measured?

- The reactor manufacturer will give you the necessary information when supplying reactor

13. The electrostatic fields from the capacitors is a factor in positioning the harmonic filter. How are they measured?

- Electrostatic fields from reactors are more important – the magnetic clearance of the reactor needs to be clear of all closed metal loops

14. Before commissioning a harmonic filter what tests are done?

- Current injection in the CTS to ensure relays trip
- Capacitance farads to ensure banks are balance
- Functional test to switch capacitors and lights
- Cable rating and switch gear
- LF testing of cables
- Testing of all communications cables
- Testing of control signals

15. In open stack filter (out door) what environmental factors does one take into consideration in harmonic filter installation?

- Altitude
- Lightning impulse levels as theis are higher in in coastal areas
- Dust in iron ores. (Chrome mines need 95-120kV/mm bushes)
- Temperature as some components need to be derated for higher temperatures
- Animals, birds

16. Are filters installed in inlands different in specifications that the ones installed in coastal areas different?

- In land- more insulation.

- Coastal- Fog, mist and salt.

17. For high pass filters resistors are used. Are this special types of resistors? Do they come in standard sizes or custom built?

- They are custom built, metallically built using stainless steel enclosures to absorb higher order harmonics

18. Who determines the Q value in a filter as there is a given range of $0.5<x<5$ for high pass filters and $30<x<100$ for LC filters?

- Use natural Q of reactor.

19. How is the floor of a harmonic filter grounded?

- Grounded at the base of insulator using $70mm^2$ wire around the reactor.

Interview C: KELVIN TALBOT FORMERLY OF (High Voltage Technology) HVT

1. Do the capacitor banks come assembled or does the installation engineer do the assembling?

- They come preassembled.

2. Do the reactors come assembled or does the installation engineer do the assembling?

- They come preassembled.

3. How does load profile affect the filter components in design?

- Significantly as this determines the size of the bank.

4. What switch gear does one consider in a harmonic filter and availability?

- 6.6 to 11kV use vacuum circuit breakers and contactors
- Above 11kV use of SF6 Circuit breakers as contactors are extremely expensive at 33kV and above

5. Is there switch gear for the reactors separate from the capacitors?

- No – One switch for the caps and reactors together.

6. In capacitor banks, what are commonly used i.e. internally fused, externally fused or fuseless? What are the factors that make one decide on one type over the other?

- Above 33kV fuseless capacitor banks
- 22kV use externally fused
- Below 6.6kV and 11kV depends on the application i.e. externally fused or internally fused

7. Where does one position the harmonic filter in the site? i.e. proximity to factory etc

- Close to the load in industry.

8. In what instances are the following used in harmonic filters? Circuit breakers, current transformers, voltage transformer, fuses?

- CTs
- VTs for power to the auxilliary

9. Are Automatic power factor controllers, relays, PLCs common in harmonic filters?

- Yes

10. Design of harmonic filters comes in two phases

a) New plants- using data given by manufacturers of equipment to be installed in plant, harmonics produced, possibilities of plant extensions.

b) Existing plants- Use of power analysers to measure power readings over duration of time i.e. 2 weeks and consider possibilities of plant extensions.

How do the two different set up differ?

- On new plants you work with estimated data and simulations using ERACS.
- On existing plants one can do measurements.

11. In installation of a harmonic filter how are the following considered?

a) SITE construction- floor (no metal bars, fencing etc)

- Reactors do not need reinforcing thus there are physical constraints to install them.

b) Control construction- i.e. Panels

- Depends on incoming supply and faults

c) Personnel - Electrical, civil, control (to set the PLCs and relays)

- The company has readily available staff

d) Equipment - Cranes, capacitor connections etc

- Cranes are readily available

12. The electromagnetic compatiblity (EMC) of the reactors is a factor in positioning of the harmonic. How is it measured?

- The reactor manufacturer will give you the necessary information when supplying reactor

13. The electrostatic fields from the capacitors is a factor in positioning the harmonic filter. How are they measured?

- Measure corona rings before installation.

14. Before commissioning a harmonic filter what tests are done?

- Measure capacitance on capacitors
- Make sure capacitor is designed to drawings
- Check continuity of current transformers
- Check programmes and do injections at the workshop

15. In open stack filter (outdoor) what environmental factors does one take into consideration in harmonic filter installation?

- Wind loading
- Distance between one bank and the other

16. Are filters installed in inlands different in specifications that the ones installed in coastal areas?

- The capacitor creepage in inland is recommended as 21kv/mm or 25kV/mm while in coastal areas its 31kV/mm.

17. For high pass filters resistors are used. Are this special types of resistors? Do they come in standard sizes or custom built?

- Depends on BIL, application and are custom built.

18. Who determines the Q value in a filter as there is a given range of $0.5<x<5$ for high pass filters and $30<x<100$ for LC filters?

- The designer.

19. How is the floor of a harmonic filter grounded?

- Using an earth mat and earthed twice.

Interview D: CHRIS DE KOCK OF ABB

1. Do the capacitor banks come assembled or does the installation engineer do the assembling?
   - You get a company to make the capacitor racks.

2. Do the reactors come assembled or does the installation engineer do the assembling?
   - They are assembled.

3. How does load profile affect the filter components in design?
   - The Var requirements
   - The harmonic content.

4. What switch gear does one consider in a harmonic filter and availability?
   - Circuit breakers for voltage to avoid restrike as open cb when cap is fully charged will have double voltage on the capacitor.

5. In capacitor banks, what are commonly used i.e. internally fused, externally fused or fuseless? What are the factors that make one decide on one type over the other?
   - Fuses are used for breaker coordination
   - Internally fused (opinion) but depends on voltage

6. Where does one position the harmonic filter in the site? i.e. proximity to factory etc
   - Source of harmonic not practical in some instances hence use NRS48
   - Power factor capacitors close to ESKOM meters
   - Depends on many factors.

7. Where does one position the harmonic filter switch gear? i.e. proximity to harmonic filter etc
   - Close to supply using technical and logical reasons

8. In what instances are the following used in harmonic filters? Circuit breakers, current transformers, voltage transformer, fuses?
   - Depends on filtering requirements and customer needs. There is no standard.

9. Are Automatic power factor controllers, relays, PLCs common in harmonic filters?
   - Depends on costs

10. Design of harmonic filters comes in two phases

a) New plants- using data given by manufacturers of equipment to be installed in plant, harmonics produced, possibilities of plant extensions.

b) Existing plants- Use of power analysers to measure power readings over duration of time i.e. 2 weeks and consider possibilities of plant extensions.

How do the two different set up differ?

- Measurements are used to confirm simulations
- Basically they are the same
- Depends on software to analyse network to confirm the model of network
- On new plants you work with estimated data and simulations using ERACS.
- On existing plants one can do measurements.

11. In installation of a harmonic filter how are the following considered?

a) SITE construction- floor (no metal bars, fencing etc)

- Reactors do not need reinforcing thus there are physical constraints to install them.

b) Control construction- i.e. Panels
- Depends on incoming supply and faults

c) Personnel - Electrical, civil, control (to set the PLCs and relays)
- The company has readily available staff

d) Equipment - Cranes, capacitor connections etc
- Cranes are readily available

12. The electromagnetic compatiblity (EMC) of the reactors is a factor in positioning of the harmonic. How is it measured?
- By reactor manufacturer.

13. The electrostatic fields from the capacitors is a factor in positioning the harmonic filter. How are they measured?
- Capacitor design.

14. Before commissioning a harmonic filter what tests are done?
- Make sure fundamentals of design are correct and if the new design is correct
- Protection relays to measure harmonic content
- Protection of capacitors, reactors or resistor banks.

15. In open stack filter (outdoor) what environmental factors does one take into consideration in harmonic filter installation?

- Noise requirement
- Oil in the capacitor in case of fire and spillage.

16. Are filters installed in inlands different in specifications that the ones installed in coastal areas?
- ICC specs for BIL (derating factors in capacitor banks)
- Salt and fog on insulation in coastal areas.

17. For high pass filters resistors are used. Are this special types of resistors? Do they come in standard sizes or custom built?
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18. Who determines the Q value in a filter as there is a given range of $0.5<x<5$ for high pass filters and $30<x<100$ for LC filters?

- Designer

19. How is the floor of a harmonic filter grounded?

- Using a floor mat that is connected to 2 points of the harmonic filter.

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