A COMPARATIVE STUDY INTO THE APPLICATION OF THE NRS 048, IEEE 519-1992 AND IEC 61000-3-2 ON HARMONIC APPORTIONING IN A DISCRIMITIVE TARIFF

SL BEZUIDENHOUT B.Ing.,N.H.D.

Dissertation submitted in partial fulfilment of the requirements for the degree Magister in Engineering in Electrical Engineering of the Potchefstroomse Universiteit vir Christelike Hoër Onderwys

Supervisor: Mr. A.P.J. Rens

May 2003

Potchefstroom

Acknowledgments

I would like to thank the following people, because without them this thesis would not have been possible:

- GOD, without WHOM nothing is possible.
- Mr. Johan Rens for his guidance and support, making my studies a worthwhile experience.
- Robert Koch, who initiated this project and Eskom for their financial support through TESP.
- My parents, my wife (Faith), my brothers (Deon, Karel, Johan) and sister (Wilma) for there continue support and help.

Synopsis

Development in power electronics enabled sophisticated energy conversion. These new solid-state energy conversion processes are energy-effective, but are inherently non-linear which means that the load current is typically non-sinusoidal in shape although fed by a sinusoidal voltage source.

Although the utility strives to guarantee a pure sinusoidally shaped voltage waveform at every Point of Common Coupling (PCC), harmonic currents deteriorate the overall power quality in the power system. Various undesirable effects of nonsinusoidal conditions in a power system are, possible resonance at power factor capacitors, metering errors, increased reactive power, increased motor losses, increased transformer losses, increased line losses and additional heat in cables and equipment.

Harmonic distortion on the power system and within customer facilities is a growing concern due to the growth in non-linear loads, which manifests as higher distortion levels throughout the entire power network. This phenomenon has reached a magnitude where several international bodies have proposed harmonic apportioning standards (IEEE 519-1992 (America), IEC 61000-3-2(Europe) and NRS 048 (South Africa)). These standards provide the Electricity industry with guidelines in apportioning a predetermined level of harmonic emission per customer connected at the PCC. The harmonic apportioning standards had the result that users and suppliers must be partners in an effort to maintain the quality of supply whilst the network expands.

The impact that harmonics can have on the network and other equipment operating from it can range from a minor annoyance to a system malfunction and disruption in operation. Harmonics directly influence the effectiveness of the operation of the utility and it's revenue. Customers will not only experience continuous energy losses, but also major production losses when the supply to a plant is disrupted. The harmonic load currents force the utility to have a higher real energy input then the actual real power needed to maintain a plant's production at a certain level. The utility carries the extra transmission losses due to the extra I^2R losses caused by the harmonic currents. Installed power system capacity will be higher then necessary for pure linear loads.

Traditional energy rates fails to accounts for these effects. A fair tariff structure thus have to be design, which may allocate the cost of waveform distortion according to the relative contribution of loads connected to the PCC, and which will require the utility to supply a

minimum distorted voltage signal at the PCC. Such a tariff structure should also recognize the installation of equipment by customers which decrease the Total Harmonic Distortion (THD) observed at the PCC, or when they implement new technology, which withdraw sinusoidal load currents.

Sinopsis

Nuwe ontwikkelinge in drywingselektronika het bygedra tot verbeterde energie omskakelings prossese. Hierdie verbeterde energie omskakelings prossese is baie meer energie-effetief maar is nie-linieêr wat beteken dat die lasstroom is nie-linieêr alhoewel die bron spanning sinusvormig is.

Die elektrisiteits verskaffer poog om 'n sinusvormige spanning te lewer by elke punt van gemene koppeling maar harmoniese strome verswak die algehele drywingskwaliteit van die kragstelsel. Nie-sinusvormige toestande in 'n kragstelsel kan verskeie probleme veroorsaak soos resonansie by arbeidsfaktor verbetering kapasitore, 'n toename in reaktiewe drywing , 'n toename in transformator verliese, toename in lyn verliese en ekstra hitte in kabels en toerusting.

Harmoniese distorsie op die kragstelsel is aan die toeneem en verskeie internationale liggame het harmoniese standaarde (IEEE 519-1992 (Amerika), IEC 61000-3-2 (Europa) en NRS 048 (Suid Afrika)) voorgestel om die probleem aan te spreek. Hierdie standaarde is riglyne vir die elektrisiteits industrie .

Die impak wat harmonieke op 'n kragstelsel het , kan varieer vanaf 'n steurnis tot algehele krag onderbreking. Harmonieke veroorsaak dat klante 'n kontinue energie verlies het en die elektrisiteits verskaffer is genoodsaak om 'n hoër energie energie inset te lewer, as wat vereis word.

Tradisionele energie tariewe neem nie hierdie ekstra effekte in ag nie en 'n tarief stelsel sal moet ontwerp word om die koste van harmoniese distorsie te allokeer.

Table of Content

Table of Figures

List of tables

Abbreviations and symbols

rms	-	root mean square
PCC	-	point of common coupling
Hz	-	hertz
AC	-	alternating current
DC	-	direct current
SVC	-	static var compensator]
HVDC	-	high voltage direct current
UPS	-	uninterruptible power supply
MW	-	megawatt
PFC	-	power factor correction
kV	-	kilovolts
QoS	-	quality of supply
MVA	-	mega volts amps
LV	-	low voltage
HV	-	high voltage
EHV	-	extra high voltage
SCR	-	silicone controlled rectifier
THD	-	total harmonic distortion
ITHD	-	total current harmonic distortion
VTHD	-	total voltage harmonic distortion
PCC	-	point of common coupling
FFT	-	fast fourier transform

Chapter 1

INTRODUCTION

1.1 Overview of study

The aim of this study is to give possible suggestions on tariff strategies that can be used to penalize harmonic producing loads. A study of how harmonic penetrate the power system will be done and different harmonic apportioning standards will be compared. Different power theories, definitions and indexes for non-sinusoidal conditions will be discussed and the suggestions that are made will be evaluated using measurements. The utility's customer supply contract and their current billing structure will be investigate to see if it will be possible to implement new tariff strategies.

1.2 Aim of chapter

The aim of this chapter is to give an introduction into the harmonic problem and how it is currently addressed.

1.3 Harmonic problem

Harmonic distortion in the power system and within customer facilities is a growing concern due to the increasing non-linear loading of the power system, which is the cause of harmonics in the power system. These higher distortion levels in the power network have impacts that can range from a minor annoyance to a system malfunction, which could cause a disruption in operation.

The electrical power quality deteriorated as development in power electronics enabled more sophistication in energy conversion. These solid-state energy conversion processes, are inherently non-linear, implicating a non-sinusoidal (fundamental plus harmonics) load current being drawn from the network. The problem has reached a magnitude where several countries (Europe, USA including South Africa) have proposed harmonic apportioning standards (IEEE 519-1992 (USA), IEC 61000-3-2 (Europe), NRS 048 (South Africa)).

This standards provides the Electricity Supply industry with a basis for apportioning a predetermined level of harmonic emission allowed per customer. The users and suppliers must now be partners in an effort to maintain the quality of supply as the network is expanding to allow electrification to proceed effectively and economically.

The quality of supply requirements are stipulated in a supply contract between the supplier (Eskom) and customers, but customers does not always adhere to these requirements. There is currently not a tariff system that can be used to punish non-linear customers when they exceed their allowable levels of harmonic pollution. Methods must also be devised to determine such contribution to the degradation of the power quality by a non-linear customer.

A non-linear customer consumes load current that is typically non-sinusoidal in shape although fed by a sinusoidal voltage source. A non-sinusoidal current is typically represented in the frequency domain as an infinite sum of discrete frequencies that is an integer multiple of a fundamental frequency quantity, thus referring to such waveform as containing harmonic components. Figure 1.1 gives a graphical representation of the third and fifth harmonic in relation to the fundamental frequency waveform.

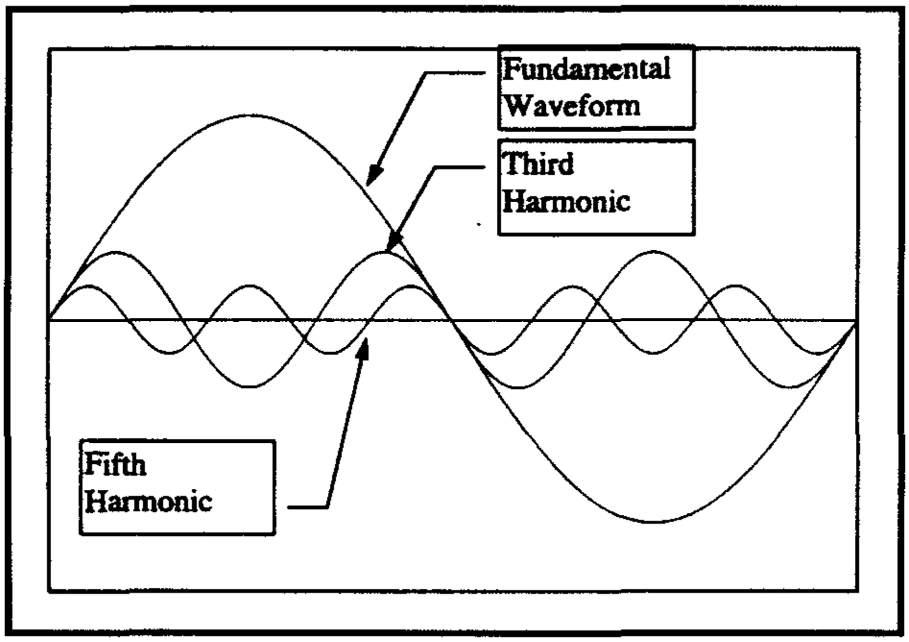


Figure 1.1 Graphical representation of harmonic waveforms in relation to the fundamental frequency waveform.

Harmonic distortion can bring about overheating and maloperation of equipment, capacitor failure, necessitate derating of transformers, telephone interference.

1.4 Conclusion

Harmonic producing loads have the potential to affect the utility and customer's revenue and costs and therefore customers that have non-linear loads should be penalise for the potential damage that they can cause.

Chapter 2

HARMONICS IN POWER SYSTEMS

2.1 Aim of chapter

The aim of this chapter is to discuss different types of loads that produce harmonics and how harmonics penetrate the power system. The effects that harmonics can have on equipment will be briefly studied as well as possible mitigation techniques that can be used to solve the harmonic problem.

2.2 Harmonic sources

There are two main sources of harmonics in conventional power system [1]:

1. Devices involving electronic switching: Static power converters are a typical example of such devices. The switching process is generally synchronised to 50 Hz and causes distortion on the switched voltage waveform. This distortion can be quantatively studied by the Fourier series method.

2. Devices with non-linear voltage and current relationships: Iron-core reactors are a typical example of such devices. When excited with a periodic voltage input, the non-linear *v-i* relationship leads to the production of harmonic currents. Devices such as arc-furnaces also fall into this category.

Both voltage and current waveforms may appear non-sinusoidal at a given location. It is not usually possible to separate the contributions to or identify the source of the distortion by merely observing the waveforms [2][3]. Using the flow of power to determine the source of harmonics has been tried in the past without success [2][3]. The reactive power flow provides no useful information and the real power flow is not conclusive.

Loads can be of two types, namely non-distorting (linear) and distorting (non-linear)[4]. A non-distorting load is one, which causes no change in the distortion of the voltage waveform. Any other load that changes the voltage waveform is a distorting load.

There can be three types of distorting loads:

1. Desirable distorting loads are loads, which decrease the relative harmonic levels, if harmonics are present.
2. Undesirable distorting loads are loads that amplify the relative harmonic levels if harmonics are present.
3. Distortion generating loads draw harmonic currents even when they are presented with a purely sinusoidal voltage waveform. Because of the harmonic current demand, and the source impedance, the voltage gets distorted.

A purely resistive load is a non-distorting load under all conditions. Inductive and capacitive loads are linear loads and they do not increase the distortion when the original voltage waveform is undistorted. They will be distorting loads, when the voltage waveform is already distorted. The impedances of such loads depend on frequency. When a distorted voltage is supplied to the terminals of such a load, the current demand at the various frequencies will not bear the same ratio to the corresponding voltages. Hence the voltage drop at each frequency will not be in the same proportion. The voltage waveform will alter in shape after the introduction of an inductance or capacitance, unless the original voltage is purely sinusoidal.

A typical load will be made up of portions of non-distorting and distorting loads. Table 2.1 contains a list of several harmonic sources.

Table 2.1 Various types of harmonic sources

Rectifiers		
Type	**Application**	**Typical ratings**
Single phase half wave and full wave	• Electronic devices • Television and communication receivers • Computers • Battery charges	0 – 30 kW
Three phase, six-pulse	• Commercial DC sources • Electroplating • Battery chargers • Ultrasonic heaters • DC motors • Mainframe computers • Radio transmitters	20 – 1000 kW
Three phase, twelve-pulse	• DC motors • Industrial DC sources • Transportation systems • DC arc furnaces • Smelters • Electrolysis cells • SVCs • HVDC transmission	Above 1 MW
High phase order	• Smelters • DC arc furnaces • Electrolysis cells	Above 50 MW
Inverters		
Three phase, six-pulse	• Small solar photovoltanic panels • UPSs	Up to 1 MW
Three phase, twelve pulse	• Solar photovoltanic panels • UPSs • HVDC systems	Above 1 MW
Other		
• Rotating AC machines • Fluorescent lighting • Glow discharge lighting (Xenon, Neon, Krypton, Mercury vapor, pressurized Sodium vapour and others) • Overexcited transformers • Transformer magnetizing current • Adjustable speed drives • Light dimmers • Electric heating controllers		

2.1 Harmonic penetration in a power system

A power system consists of many nodes and branches, thus forming an interconnected grid [13]. A branch consists of one element (power line, cable) or a number of elements in series and all elements of a branch carry the same current under all conditions. A node (bus) is the terminal by means of which a branch can be connected to other branches (the PCC in figure

2.1). Preferably, there should be a sinusoidal voltage present at all busses throughout the power system with a single fixed frequency of 50 Hz (figure 2.2).

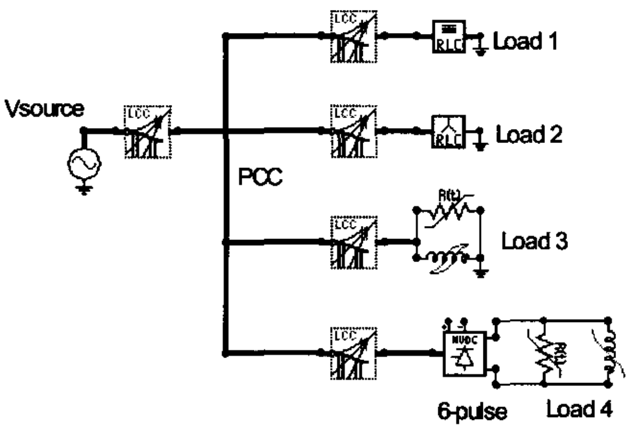


Figure 2.1 Sinusoidal voltage source feeding combination of linear and non-linear loads

However, in a power system non-linear loads are connected to some of these buses (load 4 for example in figure 2.1). These non-linear loads can cause changes to the ideal sinusoidal voltage waveform observed at the PCC. Harmonic voltage drops over system impedances result from the harmonic currents flowing through frequency dependent impedances. It causes a non-ideal non-sinusoidal voltage signal at the common bus (PCC). This voltage drops superimpose on to the 50 Hz voltage, resulting in a non-sinusoidal shaped waveform, also termed a distorted wave. This distorted wave is fed to all other customers, independent whether they are linear or non-linear. The harmonic currents "propagates" thus through the network. A non-linear load is therefore capable of "injecting" harmonic currents back into the power grid. It is reasonable to view these non-linear loads as harmonic current sources, which implicate that these non-linear loads can be modelled as harmonic current sources in parallel with an appropriate immittance.

The bus, at which the non-linear load is connected, is connected to at least one other bus in the power system. The non-sinusoidal voltage will in turn generate harmonic currents in the other branches connected to the bus even if only linear impedances are connected to these branches. Observe the voltage (figure 2.2 and 2.3) at the source and it's frequency spectrum (all quantities scaled to p.u.):

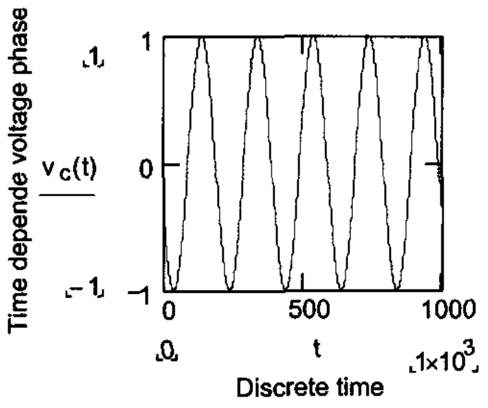


Figure 2.2 Pure sinusoidal voltage source signal

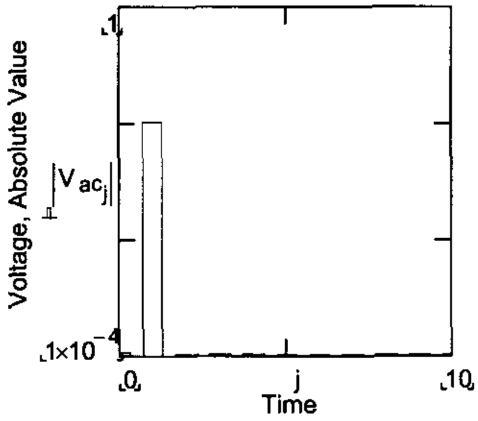


Figure 2.3 Frequency content: only fundamental.

The current withdrawn by a typical 6-pulse three-phase rectifier as in load 4 (figure 4 and 5):

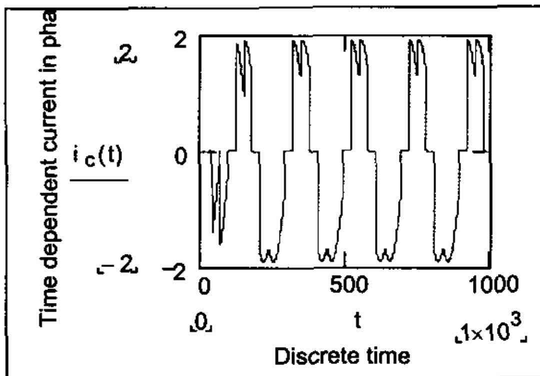


Figure 2.4 Non-linear load current.

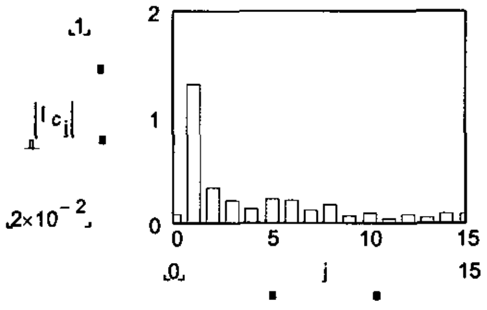


Figure 2.5 Frequency spectrum: fundamental and harmonics.

However, the voltage signal at the PCC does no longer have a similar shape, due to the impedances between the source and the PCC, as well as the impedances feeding the 6-pulse rectifier, the voltage signal looks as follows:

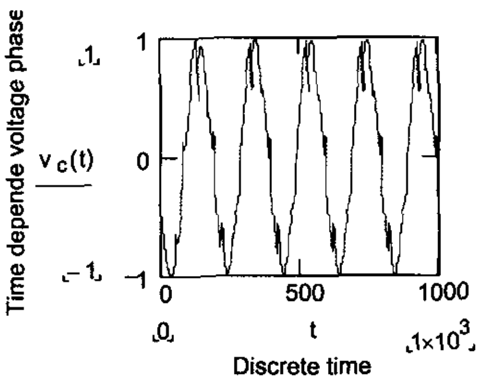


Figure 2.6 Voltage waveform at PCC

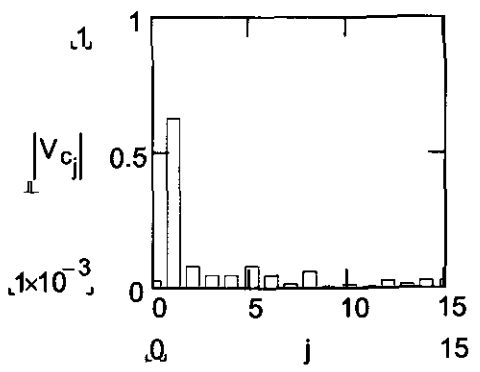


Figure 2.7 Frequency spectra of distorted signal.

All the loads connected at the PCC are now supplied with such a distorted voltage signal. Harmonics are propagated through the entire power system, causing distortion at remote buses in the system. This phenomenon is classically termed "harmonic penetration".

2.2 Effects of harmonics in a power system and on equipment

a) Capacitors

Shunt capacitors are used to improve power factor and voltage, and it has a significant influence on harmonic levels. Capacitors do not generate harmonics, but provide network loops for possible resonant conditions. The addition of capacitors can tune the system to resonate near a harmonic frequency, that is present in the load current or system voltage. Large currents or voltages at that frequency will be produced.

The resonant frequency of a low voltage system with a capacitor bank can be found from [12]

$$n = \sqrt{\frac{Q_s}{Q_c}} \tag{2.1}$$

where,

n - is the order of the harmonic at which resonance may occur,
Q_s - is the available short circuit kVA and
Q_c - is the kVAr rating of the bank.

In low voltage installations, the following guidelines may be followed [39]:

i. When the kVA rating of the harmonic producing load is less than 10% of the transformer kVA rating, then capacitors can be applied without concern for resonance.

ii. When the kVA of the harmonic producing load is less than 30% of the transformer kVA rating and the capacitor kVAr is less than 20% of the transformer kVA rating, then capacitors can be applied without concern for resonance.

iii. When the kVA rating of the harmonic producing load is more than 30% of the transformer kVA rating, then capacitors should be applied as filters.

The above guidelines are applicable when transformers are used that has impedances of 5 - 6% and the system impedance behind the transformer is less than 1% on the transformer base value.

The effect that the harmonic components can have on the capacitor is to cause additional heating and higher dielectric stress. Many harmonic problems appear at the shunt capacitor banks in the form of blown fuses or capacitor unit failures. The problems arise because the capacitor is part of the resonant loop and the current or voltage magnification will be the highest at that location.

If the harmonic currents are above the allowable limits, the following remedies may be undertaken:

1. The capacitors may be relocated to other parts of the circuit to reduce overcurrent due to near resonance. The harmonic generating loads and the capacitor bank should not share the same transformer.

2. To prevent third harmonics from flowing through the capacitors, the neutral to ground connection may be removed for wye connected utility capacitors banks. It must be ensured that the bank insulation and switch load interrupting rating is adequate before the neutral to ground connection is removed;

3. The above-mentioned remedies may not always be successful and it may be necessary to add a tuning reactor. The purpose of the reactor will be to adjust the

resonant frequency away from the current or voltage harmonic frequencies. When a reactor is added it can result in an increase of voltage or current loading on a capacitor.

The impedance of a capacitor decreases as the frequency increases and the capacitor current will be

$$I_n = n(V_n) \tag{2.2}$$

where,

I_n - is the percent harmonic current,
n - is the harmonic number, and
V_n - is the percent harmonic voltage applied.

For equation (2.2), it can be seen that if the capacitor voltage has a 15% seventh harmonic component, then the resultant capacitor current will be 105%. The previous mentioned example demonstrates why spurious fuses blowing in capacitor banks are often a symptom of harmonic problems.

The capacitors that are used in filter banks permit the control of harmonic distortion as well as the benefits associated with power factor correction. The addition of a reactor increases the capacitor voltage because the capacitor must cancel the small voltage drop introduced across the reactor, therefore the capacitors in filter banks are often rated at least 10% higher than the nominal system voltage. If the filter resonates near the system harmonic frequency, the filter may sink harmonic currents from distant loads and the current carrying capacity of the conductors may need to be increased.

b) Circuit breakers and fuses

There is evidence [40, 41] that harmonic distortion of the current can influence the interruption capability of circuit breakers. Load current can be distorted and low-level faults may contain high percentages of distorted load current. Distorted load currents cannot influence high-level faults currents. When load distortion is present, it can result in higher $\frac{di}{dt}$ at zero crossing than for a sinusoidal waveform, thus making interruption more difficult.

Because fuses are thermally actuated, they are inherent rms overcurrent devices [41]. The link in some utility distribution fuses consists of several ribbons that are susceptible to skin effect heating by harmonic currents.

c) Conductors

Harmonic currents can cause heating in conductors that is greater than expected for the rms value of the current in two mechanisms.

The first mechanism is due to current redistribution within the conductor and includes the skin effect and the proximity effect. The skin effect is due to the shielding of the inner portion of the conductor by the outer layer. The current is concentrated on the outer layer, therefore the effective resistance of the conductor is increased. The skin effect increases with frequency and conductor diameter.

The proximity effect is due to the magnetic field of conductors distorting the current distribution in adjacent conductors. The proximity effect is much less pronounced than the skin effect [39] in round wires. Metal sheats and conduit also contribute to the proximity effect.

The second mechanism causes abnormally high currents in the neutral conductor of three phase 4-wire distribution systems, which are feeding single-phase loads. Loads such as switched-mode power supplies, produce significant third harmonic currents and balanced fundamental frequency three-phase current will result in no neutral current. However, in three-phase circuits, third harmonic currents add rather than cancel in the neutral and can be as much as 1.7 times the phase current for converter loads. The neutral conductor is normally sized the same as the phase conductors, and therefore the neutral conductor can be overloaded. This problem occurs often in commercial buildings where a three-phase distribution system feeds large single-phase electronic office equipment loads. The neutral conductor can be sized to twice the phase conductor capacity to solve the problem

d) Electronic equipment

Harmonic distortion affects electronic equipment in several ways. Several electronic circuits use the voltage zero crossing of the fundamental power frequency for timing purposes. Harmonic distortion can cause more frequent zero crossings and therefore can disrupt the operation of equipment. As an example, a household digital clock will rapidly advance the time in the presence of additional zero crossing from harmonic distortion. Any device that synchronises to the zero crossing can be considered vulnerable to disruption by harmonic distortion. Semiconductors are also often switched at zero voltage crossings to reduce electromagnetic interference and inrush currents. Multiple crossings can change the switching times of devices and disrupt operation of the equipment.

Electronic power supplies use the peak voltage of the waveform to maintain the filter capacitors at full charge. Depending on the harmonic frequency and phase relationship to the fundamental, the harmonic voltage distortion can increase or flatten the waveform peak, and the power supply will be effectively operating with over or under voltage even though the rms input voltage will be nominal. When severe distortion is present, equipment operation may be disrupted. A moderately flattened waveform may reduce effective operating voltage to the point that the equipment is vulnerable to minor sags.

Fractional and sub-harmonics can affect video displays or televisions. Fractional harmonics are frequencies that are not integer multiples of the fundamental frequency and sub-harmonics are frequencies below the fundamental. The fractional harmonics produces an amplitude modulation of the fundamental frequency.

e) Lighting

Incandescent lamps will have a loss of life when it is operated from a distorted voltage supply because lamps are sensitive to operating voltage levels. If the supply rms voltage is above the rated voltage due to harmonic distortion, the elevated filament temperature will reduce lamp life.

Besides the audible noise, there is no known effect of harmonic voltage distortion on discharge lighting. Discharge lamps such as low-pressure sodium, high-pressure metal halide, or fluorescent need inductive ballasts as a series current limiting element. Capacitors are often added to correct the power factor to near unity. Dual fluorescent lamp ballasts use lamp current phase shifting to improve power factor without capacitors. The capacitors together with the ballast inductor and the lamp may cause a resonance problem. The resonant frequency of most lamps is in the range of 75 - 80 Hz and therefore should not interact with the power supply.

f) Electromechanical and electronic protective relays

Waveform distortion does affect the performance of protective relays and may cause relays to operate improperly or to not operate when required. The waveform distortion of the load current has little effect on the fault current in most cases. However, for low magnitude faults, the load may consist of a large part of the load current and distortion can become a significant factor.

Every relay performs differently in the presence of waveform distortion and different manufacturer's models of the same type of relay respond very differently to the same distortion. Relays of the same type and model from one manufacturer may even respond differently to the same distortion. Distortion may cause a relay to fail to trip under fault conditions, or it may cause nuisance tripping when no fault exists.

g) Rotating machines

Nonsinusoidal voltages that are applied to electric machines may cause overheating, pulsating torques, or noise. Rotor overheating has been the main problem associated with voltage distortion.

Losses in electric machines are dependent upon the frequency spectrum of the applied voltage. Core and stray losses may become significant in an induction motor with a skewed rotor supplied from an inverter producing high harmonic frequencies. An increase in the operating temperature of a motor will cause a reduction in the motor operating life and single-phase motors are the most affected. The temperature rise is not uniform throughout the motor and hot spots appear near the conductors within the iron core portions. If the harmonics are time varying, the motor can tolerate higher peak distortion levels without increasing the hot spot temperature. This is possible because the motor thermal time constant is much longer than the period of the harmonic variation.

h) Telephone interference

The position of telephone and power lines on utility poles creates opportunities for power frequency interference with telephone communication. Since human hearing sensitivity and telephone response peak near 1kHz, power system harmonic frequencies can present greater problems than fundamental frequency.

There are four mechanisms of coupling the power line to the telephone line. One is loop induction in which the power line magnetic field induces a voltage in the loop formed by the two telephone conductors. The standard practice of power conductor transposition or twisted telephone pairs limits this mechanism.

The second mechanism is similar to the first except that the loop formed is between a telephone conductor and the earth. The path through the ground is created by the ground connections at opposite ends of the circuit. Since the area of the loop can be very large, this mechanism is the most common type of interference.

The third mechanism is capacitive coupling between the power conductor and the phone conductor. The inter-conductor and conductor-to-ground capacitances form a voltage divider for the power conductor potential. Single line power conductors and the reduced capacitive reactance at harmonic frequencies increase interference. Shielding the telephone conductors is effective at eliminating capacitive coupling.

The last mechanism is conductive coupling in which a local ground potential rise due to the power neutral is applied to the telephone conductor. This creates a potential between the elevated ground point and the distant ground point on the telephone circuit. A poor power neutral connection may cause abnormal local ground potential rise resulting in this form of interference.

With the introduction of cellular phones and new techniques that are used to transmit communication signals via optical fibre, the above-mentioned problem has decreased considerable.

i) Transformers

The primary effect of power system harmonics on transformers is the additional heat that is generated by the losses caused by the harmonic content of the load current. The lifespan of a transformer will be reduced if it operates above the rated temperatures. Other problems include possible resonance between the transformer inductance and system capacitance, mechanical insulation stresses (winding and lamination) due to temperature cycling and possible small core vibrations.

The primary loss components are I^2R losses, winding eddy-current losses and stray losses from electromagnetic flux in areas such as windings, core, clamp assemblies and tanks. The losses due to the I^2R component will be due to conductor heating and the skin effect. Losses from the winding eddy-current will increase with the square of the load current and the square of the frequency. Other stray losses will also increase with frequency although at a power slightly less than two.

2.3 Reducing harmonics in a power system

It will be ideal to prevent the generation of harmonics, but it is not always possible, and therefore methods [12] have to be implemented to reduce harmonics in the power system. Several methods to reduce harmonics will be discussed in this section.

2.3.1 Using harmonic filters

The primary objective of a harmonic filter is to reduce the amplitude of one or more fixed frequency currents or voltages.

When the only purpose is to prevent a particular frequency component from entering selected plant components or parts of a power system (e.g. in the case of ripple control signals) it is possible to use a series filter consisting of a parallel inductor and capacitor, which presents a large impedance to the relevant frequency. Such a solution cannot be extended to eliminate the harmonics from arising at the source because the production of harmonics by non-linear loads is essential to their normal operation.

In the case of static converters, the harmonic currents are normally prevented from entering the rest of the system by providing a shunt path of low impedance to the harmonic frequencies. Combined series and shunt filters could be designed to minimise harmonic currents and voltage in the a.c. system regardless of its impedance but they are expensive.

An effective filter adequately suppresses harmonics at the least cost and supplies some reactive power, but not all that is required. Because of the complexity and cost of filters, there have been several attempts to achieve harmonic control by other means.

2.3.2 Magnetic flux compensation

A current transformer is used to detect the harmonic components coming from the non-linear load and these are fed, through an amplifier, into the tertiary windings of a transformer in such a manner as to cause cancellation of the harmonic currents concerned. The main area of concern with this system involves the coupling of the output of the amplifier to the tertiary winding, in such a way that the fundamental current flow does not damage the amplifier. A quaternary winding and filter are used, to reduce the fundamental current in the amplifier output.

One advantage with this scheme is its ability to take account of uncharacteristic harmonics such as the third and ninth. A disadvantage with this scheme is its inability to effectively remove the lower order harmonics without the need for a very high power feedback amplifier.

2.3.3 Harmonic injection

Another means by which harmonics can be eliminated is by adding a harmonic current 180^0 out of phase to the waveform in which the undesired harmonic component is observed. The advantage of this method over filtering is that the system impedance is not part of the design criteria.

One disadvantage is the need to maintain a harmonic source in synchronism with the system. A further disadvantage is the power dissipation requirements of a harmonic generator, often up to 10% of the d.c. power of the rectifier.

2.3.4 Reducing harmonic generation

Several methods can be used to eliminate harmonics from static converters. Some of these methods are to increase the converter AC reactance (chokes), to install 12 pulse or higher order converters or to improve the thryristor control symmetry.

2.4 Conclusion

Harmonics are more of a concern now than ever before because of the fashion in with non-linear loads withdraw currents from the power system. Harmonics penetrate the power system causing voltage distortion to be present at busses that are remote in the power system, although only linear loads may be connected to these busses.

Harmonic currents travel on the outer edge of the conductors (skin effect) creating heat. This heat causes circuit breakers to trip, neutral and phase conductors to heat up, and motors and transformers to fail prematurely therefore harmonics can have a financial impact on customers who do not generate them. Several methods can be used to reduce the harmonic content in a power system but it requires additional capital investment.

Chapter 3

NON-SINUSOIDAL POWER THEORY

3.1 Aim of this chapter

In this chapter, some power theories in the presence of non-sinusoidal voltage and current waveforms will be discussed. The objective is to get a better understanding of the differences in the time domain and frequency domain approaches that are followed. Only the theories of Budeanu, Fryze and Czarnecki will be discussed.

3.2 Introduction

Power theory has been a widely debated subject in power engineering and have been inspired by the rapidly increase in non-linear loads. Power analysis studies can be carried out namely in two ways [6], [7]

1) Frequency domain approach and
2) Time domain approach.

When viewed in the frequency-domain, non-sinusoidal but periodic current and voltage waveforms can be represented by discrete frequency spectra. Frequency-domain analysis can offer a number of advantages. In the frequency domain, distortion can be quantified in terms of the complex phasor values of voltages and currents at discrete harmonic frequencies. Conventional circuit theory can be applied to individual discrete harmonic frequencies, allowing calculations to be carried out in networks. The solutions that apply to these individual harmonic frequencies can then be summated across the spectrum to furnish the aggregate or joint parameters of currents, voltages and powers. The parameters can then be transformed back into the time-domain for the reconstruction of the relevant time-dependent waveforms.

Both the frequency and time-domain waveforms of the voltage and current, which are constructed in the above manner, convey the same numerical information. When attempting to quantify the circuit behavior in terms of the classical definitions of active, reactive and apparent power, different definitions are possible.

3.1 Frequency Domain

3.1.1 Budeanu theory

Budeanu [5], [6], [8] inspired the frequency domain approach to analysis power systems in the presence of distorted waveforms in 1927. Budeanu generalised the power equation of a source in a linear circuit with sinusoidal voltage and current for circuits with periodical non-sinusoidal waveforms. He defined the reactive power as:

$$Q_B \equiv \sum_{n=1}^{\infty} U_n I_n \sin\phi_n \tag{3.1}$$

He observed that the apparent power (*S*) in non-resistive circuits at distorted voltages may be higher than that resulting from the active and reactive powers, *P* and Q_B values,

$$S^2 - \left(P^2 + Q_B^2\right) \geq 0 \tag{3.2}$$

and introduced a new quantity called the distortion power (D_B) that is defined as

$$D_B \equiv \sqrt{S^2 - P^2 - Q_B{}^2} \tag{3.3}$$

Figure 3.1 show the orthogonal representation of Budeanu's power components.. Voltage and current harmonic frequency decomposition is required before the non-active power can be calculated and then only can the distortion power be calculated.

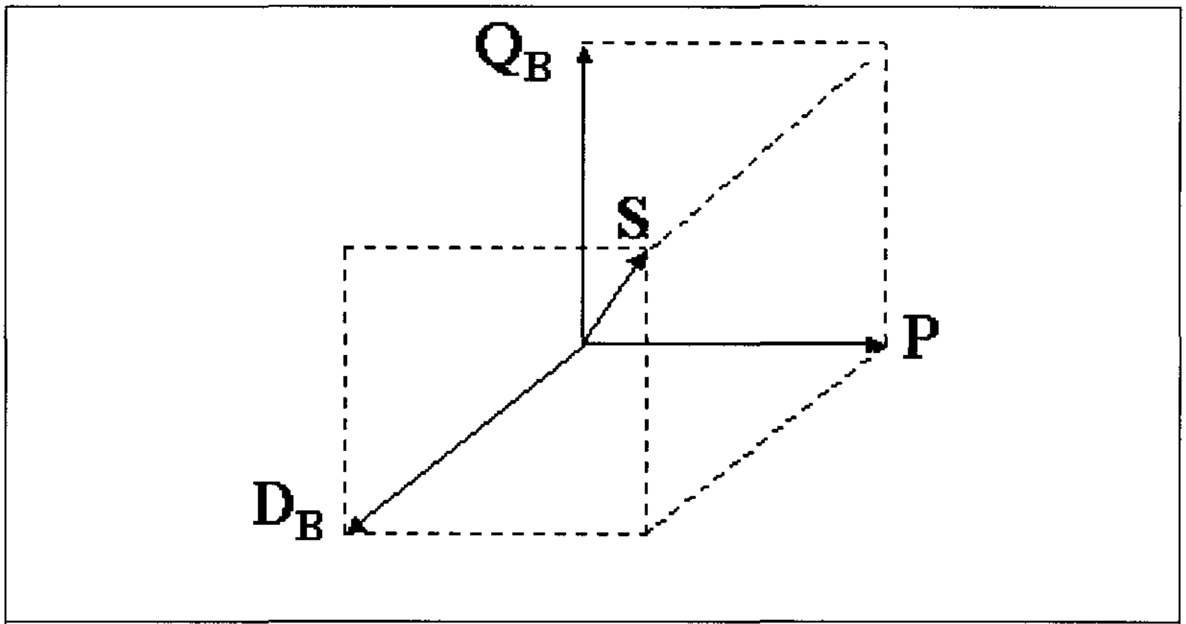


Figure 3.1 Orthogonal representation of Budeanu power components

Although S and P have the physical meaning of being the maximum capability and net rate of energy transfer of a system (just as in any other power theory), the Budeanu reactive power Q_B has no distinct physical meaning except in the single harmonic where the term describes the oscillating part of S in a linear system[5].

3.2 Time Domain

3.2.1 Fryze theory

A popular time domain power analysis technique was formulated by S. Fryze [6, 9] in 1932 thus excluding the use of a Fourier transform. He decomposed both the voltage and current into different orthogonal components in the time domain. Only the current decomposition will be discussed since the voltage decomposition also leads to the same results.

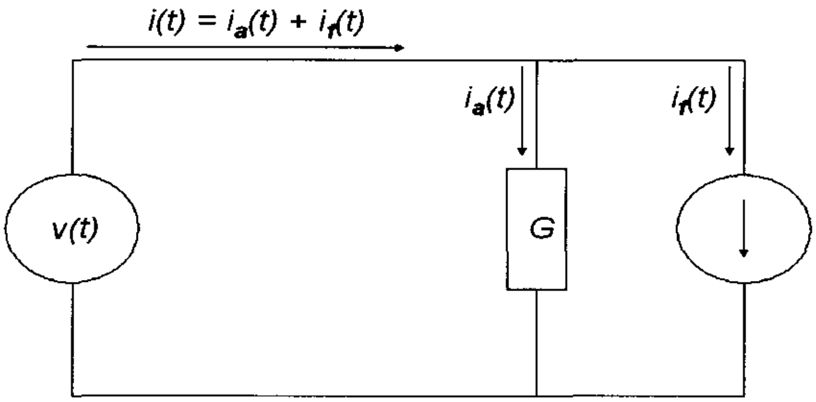


Figure 3.2 Division of the load current into active and fictitious components

Fryze divided the load current $i(t)$ into two orthogonal (see figure 3.2) components and associated the active current component $i_a(t)$ with the active power P, and the residual part of the current with a reactive power component. Fryze's reactive component known as non-active power has been renamed to fictitious power F.

The name fictitious power F describes that part of the loading power S that oscillates between the source and load and do not contribute to the nett energy transfer so that:

$$S^2 = P^2 + F^2 \tag{3.4}$$

The fictitious power F has not the same meaning as the reactive power Q (being that part of S that does not contribute to the nett energy transfer) in:

$$S^2 = P^2 + Q^2 \tag{3.5}$$

The difference is that equation (3.5) is defined for a perfect linear system with sinusoidal excitation, while F in equation (3.4) is valid for all types of systems: linear, nonlinear, single sinusoidal and multi-frequency. The fictitious power F does not only represents the power that oscillates between the load and source (Q) but also the distortion power. The active power is calculated from the effective values of the voltages and current.

The equivalent conductance G is a network parameter to which all energy transfer from the source to the load is contributing so that:

$$G = \frac{P}{V^2} \tag{3.6}$$

P: the active power.
V: the effective value of the voltage.

The active current over a period T is a scaled in-phase replica of the voltage and related to the voltage by conductance G as:

$$I_a(t) = G \cdot v(t) \tag{3.7}$$

If the active current has been calculated, the fictitious component can be found as:

$$i_f(t) = i(t) - i_a(t) \tag{3.8}$$

If the effective values of the active (I_a) and fictitious (I_f) current components are found, then the different power components can be calculated as:

$$S^2 = V^2 I_a^2 + V^2 I_f^2 = P^2 + F^2 \tag{3.9}$$

3.2.2 Czarnecki theory

3.2.2.1 Assumptions

The Czarnecki three-phase theory [9, 10] are confined to three phase circuits of the structure shown in Figure 3.3 and such a nonlinear or periodically-variant load, without magnetic couplings, that the load currents have the same period T as the source voltage.

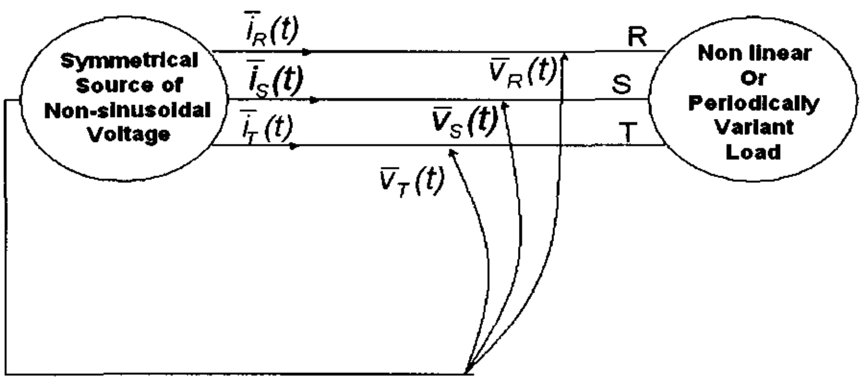


Figure 3.3 Three-phase circuit structure

The mean value of the source voltage and the load current is assumed zero. It is also assumed that the voltage source is symmetrical, of the positive sequence,

$$\begin{aligned} \bar{v}_s(t) &= \bar{v}_R(t-\frac{T}{3}) \\ \bar{v}_T(t) &= \bar{v}_R(t-\frac{T}{3}) \end{aligned} \qquad (3.10)$$

The voltages at terminals R,S and T are $\bar{v}_R(t)$, $\bar{v}_S(t)$, $\bar{v}_T(t)$ and the currents are $\bar{i}_R(t)$, $\bar{i}_S(t)$, $\bar{i}_T(t)$..

3.2.2.2 Orthogonal components of the source current in 3-phase asymmetrical circuits with sinusoidal waveforms

The equivalent conductance G_e and the equivalent susceptance B_e of the asymmetrical load (the conductance and the susceptance of a symmetrical load which at the same voltage $\bar{v}(t)$ has the same active and reactive power) are defined as:

$$\begin{aligned} G_e &\equiv \frac{P}{\left|\bar{v}(t)\right|^2} \\ B_e &\equiv -\frac{Q}{\left|\bar{v}(t)\right|^2} \end{aligned} \qquad (3.11)$$

where

$$P \equiv \mathrm{Re}(\bar{V}_R \bar{I}_R^* + \bar{V}_S \bar{I}_S^* + \bar{V}_T \bar{I}_T^*) \tag{3.12}$$

$$Q \equiv \mathrm{Im}(\bar{V}_R \bar{I}_R^* + \bar{V}_S \bar{I}_S^* + \bar{V}_T \bar{I}_T^*) \tag{3.13}$$

and $|\bar{V}|$ is the norm of vector $\bar{V}$ being equivalent to its generalized rms value.

The source current $\bar{i}(t)$ can be decomposed as follows:

$$\bar{i}(t) = \bar{i}_a(t) + \bar{i}_r(t) + \bar{i}_u(t) \tag{3.14}$$

where

$$\bar{i}_a(t) = G_e \bar{u}(t) = \sqrt{2} \cdot \mathrm{Re} \begin{bmatrix} G_e V_R \\ G_e V_S \\ G_e V_T \end{bmatrix} \left[e^{j\omega_1 t} \right] \tag{3.15}$$

$$\bar{i}_a(t) = B_e \frac{d\left[\bar{v}(t)\right]}{d(\omega_1 t)} = \sqrt{2} \cdot \mathrm{Re} \begin{bmatrix} jB_e V_R \\ jB_e V_S \\ jB_e V_T \end{bmatrix} \left[e^{j\omega_1 t} \right] \tag{3.16}$$

$$\bar{i}_u(t) = \bar{i}(t) - \bar{i}_a(t) - \bar{i}_r(t) \tag{3.17}$$

and

$$\omega_1 = \frac{2\pi}{T} \tag{3.18}$$

where ω_1 is the fundamental frequency in radians and T is the period of the fundamental waveform.

The components $\bar{i}_a(t)$, $\bar{i}_r(t)$ and $\bar{i}_u(t)$ are mutually orthogonal, so their rms values fulfill the relationship,

$$\left|\bar{i}(t)\right|^2 = \left|\bar{i}_a(t)\right|^2 + \left|\bar{i}_r(t)\right|^2 + \left|\bar{i}_u(t)\right|^2 \tag{3.19}$$

$$\begin{aligned} \left|\bar{i}_a(t)\right| &= \left|G_e\right|\left|\bar{V}\right| \\ \left|\bar{i}_r(t)\right| &= \left|B_e\right|\left|\bar{V}\right| \end{aligned} \tag{3.20}$$

$$\left|\bar{i}_h(t)\right| = \sqrt{\left|\bar{i}(t)\right|^2 - \left(\left|G_e\right|^2 + \left|B_e\right|^2\right)\left|\bar{V}\right|^2} \tag{3.21}$$

The main feature of this decomposition is the relationship between the specificcurrent components and the distinctly different properties of the circuit, such as the resistive load component $i_a(t)$, the reactive load component $i_r(t)$ and the harmonic load component $i_h(t)$.

If the load is symmetrical, its phase admittances $\bar{Y}_R$, $\bar{Y}_S$ and $\bar{Y}_T$ are mutually equal, then

$$\bar{Y}_R = \bar{Y}_S = \bar{Y}_T = G_e + jB_e \quad . \tag{3.22}$$

$$\left|\bar{i}\,(t)\right| = \left|v(t)\right|\sqrt{G_e^2 + B_e^2} \tag{3.23}$$

and $\left|\bar{i}_h(t)\right| = 0$, the source current does not contain an $i_h(t)$ component.

The current component $i_h(t)$ appears if condition (3.22) is not fulfilled. The rms value of $\left|\bar{i}_h(t)\right|$ can be used as a quantitative measure of the source current rms value increase due to the load asymmetry. Similarly, the value of $\left|\bar{i}_r(t)\right|$ is a measure of the source current rms value increase due to the reciprocating energy transmission between the source and the energy accumulating components of the load.

3.2.2.3 Three-phase asymmetrical circuit with a nonlinear or periodically variant load and a nonsinusoidal voltage source

The assumption is made that the voltage source $\bar{V}$ is composed of harmonics of order from a number set N_h. If the load is non-linear or it has periodically variant parameters, then the source current can contain harmonics of order n not only from the set N_h, but also from the larger set N_i, since such a load can generate harmonic frequencies not present in the source voltage. The source current is then decomposed into two components $i_o(t)$, composed of harmonics of order n from set N_h, and $i_g(t)$, composed of the remaining harmonics. Thus

$$\bar{i}(t) = \bar{i}_o(t) + \bar{i}_g(t) \tag{3.24}$$

Because the current components $\bar{i}_o(t), \bar{i}_g(t)$ are composed of harmonics of different frequencies, they are mutually orthogonal thus

$$\left|\bar{i}(t)\right|^2 = \left|\bar{i}_o(t)\right|^2 + \left|\bar{i}_g(t)\right|^2 \tag{3.25}$$

At a specific frequency $n\omega_1$, an equivalent conductance G_{ne} and susceptance B_{ne} can be defined as

$$\begin{aligned} G_{ne} &= \frac{P_n}{\left|\bar{V}_n(t)\right|^2} \\ B_{ne} &= \frac{Q_n}{\left|\bar{V}_n(t)\right|^2} \end{aligned} \tag{3.26}$$

where

$$\left|\bar{V}_n\right| = \sqrt{\bar{V}_{nR}^2 + \bar{V}_{nS}^2 + \bar{V}_{nT}^2} \tag{3.27}$$

$$P_n = \mathrm{Re}(\bar{V}_{nR}\bar{I}_{nR}^{*} + \bar{V}_{nS}\bar{I}_{nS}^{*} + \bar{V}_{nT}\bar{I}_{nT}^{*}) \tag{3.28}$$

$$Q_n = \mathrm{Im}(\bar{V}_{nR}\bar{I}_{nR}^{*} + \bar{V}_{nS}\bar{I}_{nS}^{*} + \bar{V}_{nT}\bar{I}_{nT}^{*}) \tag{3.29}$$

Each harmonic component $\bar{i}_n(t)$ of the current $\bar{i}_o(t)$ can be decomposed just in the same manner, as the source current $\bar{i}(t)$ in the circuit with sinusoidal waveforms was decomposed as

$$\bar{i}(t) = \sum_{n=N_h} \left(\bar{i}_{na}(t) + \bar{i}_{nr}(t) + \bar{i}_{nh}(t)\right) \tag{3.30}$$

where

$$\bar{i}_{na}(t) = G_{ne}\bar{v}_n(t) \tag{3.31}$$

$$\bar{i}_{nr}(t) = B_{ne}\frac{d}{d(\omega_1 t)}\bar{v}_n \tag{3.32}$$

$$\bar{i}_{nh}(t) = \bar{i}_n(t) - \bar{i}_{na}(t) - \bar{i}_{nr}(t) \tag{3.33}$$

The equivalent conductance G_e of the asymmetrical non-linear load at the non-sinusoidal voltage $\bar{v}(t)$ can be defined as the conductance of a symmetrical load which at the same voltage $\bar{v}(t)$ has the same active power P as the primary load therefore

$$G_e = \frac{P}{|\bar{v}(t)|^2} \tag{3.34}$$

The following currents are defined as:

$$\bar{i}_a(t) = G_e\bar{v}(t) \tag{3.35}$$

$$\bar{i}_s(t) = \left(\sum_{n \in N_h} \bar{i}_{na}(t)\right) - \bar{i}_a(t) \tag{3.36}$$

$$\bar{i}_r(t) = \sum_{n \in N_h} \bar{i}_{nr}(t) \tag{3.37}$$

$$\bar{i}_h(t) = \sum_{n \in N_h} \bar{i}_{nh}(t) \tag{3.38}$$

The current components of equations 3.35, 3.36, 3.37 and 3.38 are composed of mutually orthogonal components $\bar{i}_{na}(t)$, $\bar{i}_{nr}(t)$ and $\bar{i}_{nh}(t)$. The current components $\bar{i}_a(t)$, $\bar{i}_s(t)$, $\bar{i}_r(t)$ and $\bar{i}_h(t)$ are orthogonal and therefore the source current in a 3-phase asymmetrical circuit with a source of nonsinusoidal voltage and a non-linear load or a load with periodically variant parameters can be decomposed into five orthogonal components. The five load current components are

$$\bar{i}(t) = \bar{i}_a(t) + \bar{i}_s(t) + \bar{i}_r(t) + \bar{i}_h(t) + \bar{i}_g(t) \tag{3.39}$$

which rms values fulfill the relation

$$|\bar{i}(t)|^2 = |\bar{i}_a(t)|^2 + |\bar{i}_s(t)|^2 + |\bar{i}_r(t)|^2 + |\bar{i}_h(t)|^2 + |\bar{i}_g(t)|^2 \tag{3.40}$$

The current components are;

$\bar{i}_a(t)$: This current is a generalisation of the Fryze active current. The active current of rms value

$$|\bar{i}_a(t)| = G_e |\bar{v}(t)| \tag{3.41}$$

is indispensable for active power transmission. The remaining four increase the rms value of the source but accomplish no useful result.

$\bar{i}_s(t)$: Scattered current. This component appears in the source current if the equivalent conductance of the load G_{ne} changes with harmonic order n (if they are scattered around the value G_e), such as the skin effect on transmission lines. The rms value of the scattered current is

$$|\bar{i}_s(t)| = \sqrt{\sum_{n\in N_h} (G_{ne} - G_e)^2 |\bar{v}_n(t)|^2} \tag{3.42}$$

$\bar{i}_r(t)$: Reactive current. This components represents the reciprocating energy transmission between the source and load due to capacitors or inductors in the load. It presence is related to the presence of harmonic reactive power Q_n and has a rms value of

$$|\bar{i}_r(t)| = \sqrt{\sum_{n\in N_h} B_{ne}{}^2 |\bar{v}_n(t)|^2} = \sqrt{\sum_{n\in N_h} \frac{Q_n^2}{|\bar{v}_n(t)|^2}} \tag{3.43}$$

$\bar{i}_h(t)$: Unbalanced current. This is a result due to the asymmetry of the load and has a rms value of

$$\left|\bar{i}_h(t)\right| = \sqrt{\sum_{n\in N_h}\left[\left|\bar{i}_n(t)\right|^2 - (G_{ne}^2 + B_{ne}{}^2)\left|\bar{v}_n(t)\right|^2\right]} \tag{3.44}$$

$\bar{i}_g(t)$: Generated current. It is composed of current harmonics, which are generated with the load's nonlinearity or with the periodical variance of its parameters such as arc furnace parameters with an rms value of

$$\left|\bar{i}_g(t)\right| = \sqrt{\sum_{n\in N_g}\left|\bar{i}_n(t)\right|^2} \tag{3.45}$$

Multiplying equation 3.40 with $\left|\bar{v}(t)\right|^2$ results in the power equation of the circuit of the form

$$S^2 = P^2 + D_s^2 + Q_r^2 + D_h^2 + D_g^2 \tag{3.46}$$

3.3 Conclusion

The distortion power (D_B) defined by Budeanu was the measure of the increase in apparent power (S) because of the waveform distortion and D_B disappears if the current waveform (*i(t)*) is not distorted against the voltage waveform (*v(t)*). The problems [5], [8] with Budeanu's theory is that the reactive power (Q_B) and distorted power (D_B) do not possess the attributes that can be related to the power phenomena in circuits with nonsinusoidal waveforms and the distorted power value also does not provide information related to the waveform distortion. If the voltage at the pcc is distorted, then the current consumed by a linear load will be distorted as well. The distortion power will not provide any useful information whether the load is linear or not and on locating the harmonic source.

The Fryze power theory conforms to one of the important requirements for a power theory in that the active current $i_a(t)$ is associated with the transfer of the average power to the load in a predefined period. The fictitious (non-active) current and power fails to contribute any information for compensation purposes [6] and on localization of distortion sources. Fryze's decomposition only serves to label the group of components that do not contribute to energy transfer.

With reference to Czarnecki power theorem, if some harmonics, which are generated in the load, have the same frequency as the harmonics of the source voltage, then the source current cannot be decomposed in the suggested manner. If the source has an internal impedance, then the harmonics generated in the load affect the voltage at the RST terminals, so the number sets of the voltage and of the current harmonic orders N_u and N_i may not differ mutually.

Chapter 4

QUALITY OF SUPPLY STANDARDS

4.1 Aim of chapter

The aim of this chapter is to discuss the NRS 048 (South Africa), IEEE 519-1992 (America) and IEC 61000-3-2 (Europe) standards on harmonic apportioning with reference to the voltage and current limits that are set as well as the apportioning procedure that is followed. A comparative evaluation of the previous mentioned standards will be done and the aim is also to see if these standards can be implemented in a tariff strategy.

4.2 Introduction

Efforts are being made to regulate the levels of harmonics injected in the system through the introduction of standard guidelines and recommended practices.

The purpose of the power quality standards relating to power system harmonics is [12]:

1. To control the distortion of the power system current (limiting harmonic current injection from individual customers) and voltage waveforms to levels that the system and it's associated components can tolerate.
2. To provide customers connected to the power system with a voltage supply waveform, which is suitable for their particular needs.
3. To ensure that the power system does not interfere with the operation of other systems such as telephone networks.

All existing harmonic standards can be broadly classified into two types, the *system* (connection) *standards* and the *equipment standards* [37]. The system standards deal with the connection of large harmonic-producing loads to supply systems, while the equipment standards deal with the harmonic performance of a piece of equipment. Since many harmonic-related problems results from interaction between the utility system and the customer load, the system standards are more concern to utilities at present.

The equipment standards can be further divided into the harmonic emission standards and the harmonic susceptibility standards. In many cases, these standards are applied to equipment of utilization voltage level. The equipment standards are therefore of more interest to manufactures.

4.3 South African Power Quality Standard

4.3.1 NRS 048 part 2 : Minimum standards

4.3.1.1 Scope

Part 2 of the NRS 048 describes the voltage quality parameters that affect the normal operation of electricity dependent processes of customers. The minimum standards in this part of the NRS 048 is intended to be applied as a measure of the power quality at the point of supply to the end customers of electricity utilities.

4.3.1.2 Voltage harmonics

The maximum levels for harmonics on the LV and MV networks are given in table 4.1. The total harmonic distortion of the supply voltage, including all harmonics up to the order 40, must not exceed 8 %.

4.3.2 NRS 048 part 4 : Application guidelines for utilities and their customers

4.3.2.1 Scope

Part 4 of the NRS 048 gives guidance to the utilities and their customers on the application of the quality of supply standards. It describes a suggested technical procedure for the connection of a new customer or the evaluation of an existing customer regarding harmonics, voltage unbalance and voltage flicker during contract negotiations. A judgmental approach is also outlined for the calculation of a specific customer's contribution to the total allowable pollution at a given PCC .

Table 4.1 The maximum levels for harmonic voltages expressed as a percentage of the declared voltage of the LV and MV power systems

Odd harmonics non-multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Order n	**Harmonic voltage** (%)	**Order** *n*	**Harmonic voltage** %	**Order** *n*	**Harmonic voltage** %
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,3	6	0,5
13	3	21	0,2	8	0,5
17	2	>21	0,2	10	0,5
19	1,5			12	0,2
23	1,5			>12	0,2
25	1,5				
>25	0,2 + 1,3 × 25/h				
Total harmonic distortion (THD) ≤ 8 %					
NOTE — For each harmonic, the harmonic voltage distortion level is given as a percentage of the magnitude of the declared (fundamental frequency) voltage					

4.3.2.2 Recommended procedure for apportioning quality of supply parameters

Three stages of acceptance exits during contract negotiations with any new customer or evaluation of an existing namely:

1. **Acceptance dependent on the network minimum designed operating three-phase fault level.**

A load that must be connected to a voltage of 132 kV and below, with a rating of less than 25 MVA, may immediately be connected to a PCC if the maximum designed loading is less than 1 % of the minimum designed operating three-phase PCC fault level.

2. **Acceptance as per prescribed proportioning guideline**

Different QoS levels will be apportioned for loads, rated below 25MVA, that exceeds 1 %

of the minimum designed operating 3 phase PCC fault level and that must be connected at a voltage below 132 kV. The apportioning will be based on the ratio of the load rating and installed capacity under the minimum designed operating three-phase PCC fault level, according to a fixed procedure that will be discussed in section **4.3.2.3.** All the loads that must be connected to a voltage of 132 kV or above, with ratings of 25 MVA and above, will be subject to special analysis. This analysis will be discussed below.

3. Acceptance per detailed special impact assessment

A fixed procedure would not be sufficient to ensure compliance with the network for large distorting loads such as arc-furnaces, traction, static var compensators, mine winders, etc., or loads connected at a voltage of 132 kV and above or loads larger than 25 MVA in rating. Each such installation must be planned and designed individually on a case-by-case basis for both the utility and the customer.

Table 4.2 Customer categorization

Method of acceptance	PCC voltage (kV)	Load maximum demand (MVA)	Load maximum demand as % of minimum designed operating three-phase PCC fault level
A - Accept	< 132 kV	< 25 MVA **	< 1 %
B - Apportion	< 132 kV	< 25 MVA **	> 1 %
C - Specialist analysis	≥ 132 kV	≥ 25 MVA	—
Note — Care should be taken where PFC capacitors or underground cables are involved.			

4.3.2.3 Apportioning procedure

a) Harmonics

It is not a simple process to determine what the effect of upstream voltage distortion is at a specific PCC, without switching off all the loads that is connected to the PCC. A general equation is define, based on thorough experimental measurements, for the summation of harmonics or reduction of harmonic levels at a specific busbar due to upstream harmonics [15]:

$$V_{n,pcc(new)} = \left[V_{n,pcc}^{a} - 0.7V_{n,us}^{a}\right]^{\frac{1}{a}} \tag{4.1}$$

where

$V_{n,pcc(new)}$ - New % Voltage Compatibility Level of Harmonic order n at the PCC.
$V_{n,pcc}$ - % Voltage Compatibility Level of Harmonic order n at PCC]
$V_{n,us}$ - % Upstream Harmonic Voltage of Order n at the PCC
and

a = 1 for Harmonics 3, 5, 7
a = 1.4 for Harmonics 11,13
a = 2 for Harmonics > 13 and other than mentioned above.

Equation 4.1 gives a method for reducing the set harmonic levels at the PCC due to upstream harmonics. Where upstream harmonics are very stochastic (i.e. no coincidence) as commonly found in large transmission networks with no direct customers, a value of **a = 2** is typically used in all cases.

Where the upstream levels are so excessive that the PCC limit is reduced by more than 50 %, a detailed approach would be required involving specialists for both the utility and the customer.

The available distortion must now be distributed fairly amongst all new customers to be connected at the PCC. The only applicable parameters known when connecting a new customer or evaluating an existing one at the PCC, are the installed capacity at minimum designed operating 3-phase fault level and the customer notified maximum demand. Using these parameters for proportional allocation at the PCC the following equation is used:

$$V_{n,p} = V_{n,pcc(new)} \times \left[\frac{MVA_{md}}{MVA_i}\right]^{\frac{1}{a}} \qquad (4.2)$$

where

$V_{n,p}$ - Maximum % Proportional Voltage of Harmonic order n for the New Customer
$V_{n,pcc(new)}$ - % Voltage Compatibility Level of Harmonic order n at PCC
a - As previously described at equation 4.1
MVA_{md} - Customer notified maximum demand
MVA_i - Installed capacity at minimum designed operating 3-phase fault level

Equation 4.2 allows for a fair distribution of the allowable harmonic voltage distortion by all customers that are connected to the PCC. It also makes provision for the connection of future prospective clients, ensuring that the total allowable distortion capabilities of the PCC is used to their full capacity once all customers are connected. Where the addition of a new apportioned customer causes the busbar harmonic level to be exceeded, the utility will be responsible for ensuring proper network compliance, taking cognisance of the fact that the supply impedance is highly non-linear under resonance conditions.

To obtain the proportioned harmonic current injection by a specific customer, the following equation can be used assuming linear supply impedance:

$$I_{n,p} = \frac{V_{n,p}}{X_{\sup} \times n} \tag{4.3}$$

where

$I_{n,p}$ - The allowable apportioned harmonic current injection of the specific customer

n - The harmonic number

X_{sup} - The 50 Hz minimum designed operating 3-phase fault level supply impedance as calculated below:

$$X_{\sup} = \frac{V_{line}^2}{MVA_{fl}} \tag{4.4}$$

where

V_{line} - The PCC line voltage in volts

MVA_{fl} - The minimum designed operating 3-phase fault level.

Whenever capacitor banks or long underground cables are present on either side of the supply transformer, great care should be taken in applying the above equations, as possible resonant conditions may exist at characteristic harmonic frequencies, which would cause the supply impedance to be extremely non-linear at that frequency.

The harmonic number n at which a capacitor bank is in resonance with the supply (series or parallel) is approximately given by:

$$n \approx \sqrt{\frac{MVA_{sc}}{MVAr_{cap}}} \tag{3.5}$$

where

MVA_{sc} - The different network 3 phase operating fault levels

$MVAr_{cap}$ - The capacitor bank 3 phase rating.

If the resonant frequency is close to the frequencies of existing harmonics or harmonics of the proposed installation, specialist analysis is required, rather than a simplistic approach. The above equations may however, be used to give an indication of proportional projection but an in-depth system impact study would be required to ensure proper operation.

Where the specific nature of distorting loads is known, the above proportioning can be relaxed under some circumstances by dividing $I_{n,p}$ (equation 4.3) by the factor in table 4.3 below.

Table 4.3 Diversity factors

Type and operating conditions of multiple harmonic generators	**Typical diversity factors**
Controlled or uncontrolled converters when a single converter provides 60 % or more of the arithmetic total of the harmonic currents of all the equipment in the installation	1,0
Uncontrolled converters (rectifiers)	0,9
Controlled converters operating on co-ordinated duty cycles (fair probability of coincidence)	0,75
Controlled converters operating independently with uncoordinated duty cycles (low probability of coincidence)	
(a) ≤ 3 converters	0,6
(b) ≥ 4 converters	0,5
A single arc-furnace providing more than 60 % of the arithmetic total harmonic current of the installation	1,0
Multiple arc-furnaces each providing less than 60 % of the arithmetic total harmonic current of the installation	0,75

4.3.2.4 Recommended planning levels

a) Recommended planning levels for harmonic voltage on HV and EHV systems

Table 4.4 Indicative values of planning levels for harmonic voltage in % of the rated voltage of HV and EHV power systems

Odd harmonics non multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Order *n*	Harmonic voltage (%) HV-EHV	Order *n*	Harmonic voltage (%) HV-EHV	Order *n*	Harmonic voltage (%) HV-EHV
5	2	3	2	2	1,5
7	2	9	1	4	1
11	1,5	15	0,3	6	0,5
13	1,5	21	0,2	8	0,4
17	1	>21	0,2	10	0,4
19	1			12	0,2
23	0,7			>12	0,2
25	0,7				
>25	0,2 + 0,5 × 25/n				
Total harmonic distortion (THD): 3 % in HV networks					

b) Recommended planning levels for interharmonics

The term interharmonics refer to those frequencies that are not integral harmonics of the supply fundamental frequency at which the supply system is designed to operate (e.g., 50 Hz or 60 Hz).

A compatibility level limit of 0,5 % up to the 50th harmonic should be used on LV and MV systems. A planning level limit of 0,2 % up to the 50th harmonic should be used on MV and HV systems.

4.4 IEEE 519 – 1992 – IEEE recommended practice and requirements for harmonic control in electrical power systems (United States of America)

4.4.1 Scope

This recommended practice intends to establish goals for the design of electrical systems that include both linear and non-linear loads. The voltage and current waveforms that may exist throughout the system are described, and waveform distortion goals for the system designer are established. The interface between sources and loads is described as the point of common coupling and observance of the design goals will minimize interference between electrical equipment.

This recommended practice address steady-state limitations. Transient conditions exceeding these limitations may be encountered. The IEEE 519-1992 sets the quality of power that is to be provided at the point of common coupling but does not cover the effects of radio-frequency interference, however it does include electromagnetic interference with communication systems.

4.4.2 Recommended practices for individual consumers

4.4.2.1 Development of current distortion limits

It is necessary to define what is meant by normal system characteristics. For this document it is assumed that the system can be characterized by a short-circuit impedance. The effect of capacitors is neglected. This is a conservative assumption for higher frequencies at which capacitors can provide low impedance paths for harmonic currents to flow. At lower frequencies, resonant conditions could cause the system impedance to be greater than the assumed short-circuit impedance. The effect of loads is also neglected. The most important effect of loads is to provide damping near resonant frequencies, thereby reducing the impedance seen by the harmonic current source.

The harmonic voltage distortion on the system will be a function of the total injected harmonic current and the system impedance at each of the harmonic frequencies. The total injected harmonic current will depend on the number of individual customers injecting harmonic currents and the size of each customer. A reasonable approach to limiting the harmonic currents for individual customers is to make the limits dependent upon the customer size. Larger customers will have limits that are more stringent because they represent a larger portion of the total system load.

The objective of the current limits are to limit the maximum individual frequency harmonic voltage to 3% of the fundamental and the voltage THD to 5% for systems without a major parallel resonance at one of the injected harmonic frequencies. The current distortion limits developed assume that there will be some diversity between the harmonic currents injected by different customers. This diversity can be in the form of different harmonic components being injected, differences in the phase angles of the individual harmonic currents, or differences in the harmonic injection vs. time profiles.

In recognition of this diversity, the current limits were developed so that the maximum individual frequency harmonic voltage caused by a single customer will not exceed the limits in table 4.5 for systems that can be characterized by a short-circuit impedance.

Table 4.5 Basis for Harmonic Current Limit

SCR at PCC	Maximum Individual Frequency Harmonic Voltage (%)	Related Assumption
10	2.5 – 3.0%	Dedicated system
20	2.0 – 2.5%	1 – 2 large customers
50	1.0 – 1.5%	A few relatively large customers
100	0.5 – 1.0%	5 – 20 medium size customers
1000	0.05 – 0.10%	Many small customers

4.4.2.2 Current Distortion Limits

The harmonic distortion caused by a single consumer should be limited to an acceptable level at any point in the system and the entire system should be operated without substantial harmonic distortion anywhere in the system. The harmonic distortion limits recommended by the IEEE 512-1992 establish the maximum allowable current distortion for a consumer.

The recommended current distortion limits are concerned with the following indice:

TDD: Total demand distortion, harmonic current distortion in % of maximum demand load current (15 or 30 min demand)

The limits listed in tables 4.6, 4.7 and 4.8 should be used as system design values for the "worst case" for normal operation (conditions lasting longer than one hour). For shorter periods, during start-ups or unusual conditions, the limits may be exceeded by 50%. These tables are applicable to six-pulse rectifiers and general distortion situations. When phase shift transformers or converters with pulse numbers (q) higher then six are used, the limits for the characteristic harmonic orders are increased by a factor equal to $\sqrt{\frac{q}{6}}$ provided that the amplitudes of the non-characteristic harmonic orders are less than 25% of the limits specified in the tables.

Table 4.6 Current distortion limits for general distribution systems (120 V to 69 000 V)

<table>
<tr><td colspan="7">Maximum Harmonic Current Distortion in Percent of I_L</td></tr>
<tr><td colspan="7">Individual Harmonic Order (Odd Harmonics)</td></tr>
<tr><td>$\frac{I_{SC}}{I_L}$</td><td>< 11</td><td>$11 \,.\, n < 17$</td><td>$17 \,.\, n < 23$</td><td>$23 \,.\, n < 35$</td><td>$35 \,.\, n$</td><td>TDD</td></tr>
<tr><td>< 20*</td><td>4.0</td><td>2.0</td><td>1.5</td><td>0.6</td><td>0.3</td><td>5.0</td></tr>
<tr><td>20 < 50</td><td>7.0</td><td>3.5</td><td>2.5</td><td>1.0</td><td>0.5</td><td>8.0</td></tr>
<tr><td>50 < 100</td><td>10.0</td><td>4.5</td><td>4.0</td><td>1.5</td><td>0.7</td><td>12.0</td></tr>
<tr><td>100 < 1000</td><td>12.0</td><td>5.5</td><td>5.0</td><td>2.0</td><td>1.0</td><td>15.0</td></tr>
<tr><td>> 1000</td><td>15.0</td><td>7.0</td><td>6.0</td><td>2.5</td><td>1.4</td><td>20.0</td></tr>
<tr><td colspan="7">Even harmonics are limited to 25% of the odd harmonic limits above.</td></tr>
<tr><td colspan="7">Current distortion limits that results in a dc offset, e.g. half-wave converters, are not allowed</td></tr>
<tr><td colspan="7">*All power generation equipment is limited to these values of current distortion, regardless of actual $\frac{I_{SC}}{I_L}$.</td></tr>
<tr><td colspan="7">I_{SC} = Maximum short-circuit current at PCC
I_L = Maximum demand load current (fundamental frequency component) at PCC</td></tr>
</table>

The harmonic current limits in Table 4.6 are based on the size of the load with respect to the size of the power system to which the load is connected. The ratio $\frac{I_{SC}}{I_L}$ is the ratio of the short-circuit current available at the PCC, to the maximum fundamental load current. The load current I_L must be calculated as the average current of the maximum demand for the preceding 12 months. As the size of the user load decreases with respect to the size of the system, the percentage of harmonic current that the user is allowed to inject into the utility system increases.

Table 4.7 Current distortion limits for general distribution systems

(69 001 V to 161 000V)

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
$\frac{I_{SC}}{I_L}$	< 11	11 . n < 17	17 . n < 23	23 . n < 35	35 . n	TDD
< 20*	2.0	1.0	0.75	0.3	0.15	2.5
20 < 50	3.5	1.75	1.25	0.5	0.25	4.0
50 < 100	5.0	2.25	2.0	0.75	0.35	6.0
100 < 1000	6.0	2.75	2.5	1.0	0.5	7.5
> 1000	7.5	3.5	3.0	1.25	0.7	10.0
Even harmonics are limited to 25% of the odd harmonic limits above.						
Current distortion limits that results in a dc offset, e.g. half-wave converters, are not allowed						
*All power generation equipment is limited to these values of current distortion, regardless of actual $\frac{I_{SC}}{I_L}$.						
I_{SC} = Maximum short-circuit current at PCC I_L = Maximum demand load current (fundamental frequency component) at PCC						

Table 4.8 Current distortion limits for general distribution systems (> 161 000V)

Individual Harmonic Order (Odd Harmonics)						
$\frac{I_{SC}}{I_L}$	< 11	11 . n < 17	17 . n < 23	23 . n < 35	35 . n	THD
< 50*	2.0	1.0	0.75	0.3	0.15	2.5
. 50	3.0	1.5	1.15	0.45	0.22	3.75
Even harmonics are limited to 25% of the odd harmonic limits above.						
Current distortion limits that results in a dc offset, e.g. half-wave converters, are not allowed						
*All power generation equipment is limited to these values of current distortion, regardless of actual $\frac{I_{SC}}{I_L}$.						
I_{SC} = Maximum short-circuit current at PCC I_L = Maximum demand load current (fundamental frequency component) at PCC						

All generation whether connected to the distribution or transmission system, is treated like utility distribution and is therefore held to these recommended practices.

4.5 IEC 61000-3-2 (Europe)

This standard describes the emission testing requirement and limits for harmonic currents of electrical / electronic equipment connected to low voltage power mains networks. It specifies limits for harmonic currents produced by the product under test conditions and applies to equipment which draws less than 16 A per phase. All electronic/electrical products are covered by the standard (e.g. computers, audio and video equipment, light dimmers, fluorescent lights, air conditioners, refrigerators, etc.). Table 4.9 gives the different classes of the type of equipment.

Table 4.9 Classification of equipment

Classification of Equipment	
Class A	Balanced 3-phase & permanent tools, appliances, entertainment gear, dimmers
Class B	Portable tools
Class C	Lighting equipment (except incandescent dimmers)
Class D	Personal computers, monitors, & TV's – Equipment having a special waveform and a active power input of P≤ 600 W

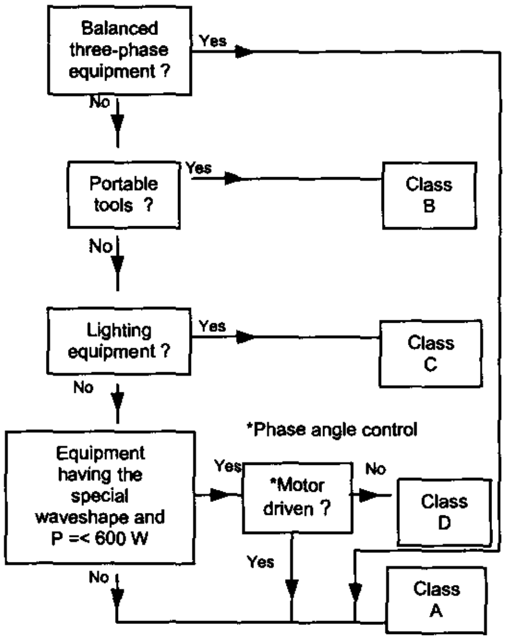


Figure 4.1 Block diagram for classification of equipment

Figure 4.1 gives a method that can be used to classify the different types of equipment.

4.6 NRS 048 vs IEEE 519-1992 vs IEC 61000-3-2

Table 4.10 NRS 048 vs IEEE 519-1992 vs IEC 61000-3-2

NRS 048

Compatibility levels for harmonic voltages for LV (≤ 1000 V) and MV (1 kV < V ≤ 44 kV) power systems

Odd harmonics non-multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Order (h)	Harmonic voltage (%)	Order (h)	Harmonic voltage (%)	Order (h)	Harmonic voltage (%)
5	6	3	5	2	2
7	5	9	1,5	4	1
11	3,5	15	0,3	6	0,5
13	3	21	0,2	8	0,5
17	2	>21	0,2	10	0,5
19	1,5			12	0,2
23	1,5			>12	0,2
25	1,5				
>25	0,2 + 1,3 × 25/h				

Total harmonic distortion (THD) ≤ 8 %

For each harmonic, the harmonic voltage distortion compatibility level is given as a percentage of the magnitude of the declared (fundamental frequency) voltage

Indicative values of planning levels for harmonic voltage as a % of the rated voltage of HV (44 kV < V ≤ 220 kV) and EHV (220 kV < V ≤ 400 kV) power systems

Odd harmonics non multiple of 3		Odd harmonics multiple of 3		Even harmonics	
Order h	Harmonic voltage (%) HV-EHV	Order h	Harmonic voltage (%) HV-EHV	Order h	Harmonic voltage (%) HV-EHV
5	2	3	2	2	1,5
7	2	9	1	4	1
11	1,5	15	0,3	6	0,5
13	1,5	21	0,2	8	0,4
17	1	>21	0,2	10	0,4
19	1			12	0,2
23	0,7			>12	0,2
25	0,7				
>25	0,2 + 0,5 × 25/h				

Total harmonic distortion (THD): 3 % in HV networks

Interharmonics: A compatibility level limit of 0,5 % up to the 50th harmonic should be used on LV and MV systems. A planning level limit of 0,2 % up to the 50th harmonic should be used on MV and HV systems.

IEEE 519-1992

Current distortion limits for general distribution systems (120 V to 69 000 V)

Maximum Harmonic Current Distortion in Percent of I_L
TDD: Total demand distortion, harmonic current distortion in % of maximum demand load current (15 or 30 min demand)

Individual Harmonic Order (Odd Harmonics)

SCR	< 11	11 . h < 17	17 . h < 23	23 . h < 35	35 . h	TDD
< 20*	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortion limits that results in a dc offset, e.g. half-wave converters, are not allowed. *All power generation equipment is limited to these values of current distortion, regardless of actual SCR.

Current distortion limits for general distribution systems (69 001 V to 161 000V)

Maximum Harmonic Current Distortion in Percent of I_L

Individual Harmonic Order (Odd Harmonics)

SCR	< 11	11 . h < 17	17 . h < 23	23 . h < 35	35 . h	TDD
< 20*	2.0	1.0	0.75	0.3	0.15	2.5
20 < 50	3.5	1.75	1.25	0.5	0.25	4.0
50 < 100	5.0	2.25	2.0	0.75	0.35	6.0
100 < 1000	6.0	2.75	2.5	1.0	0.5	7.5
> 1000	7.5	3.5	3.0	1.25	0.7	10.0

Current distortion limits for general distribution systems (> 161 000V)

< 50*	2.0	1.0	0.75	0.3	0.15	2.5
. 50	3.0	1.5	1.15	0.45	0.22	3.75

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 to 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

IEC 61000-3-2

Limits for Class A equipment

Harmonic order (n)	Maximum permissible harmonic currents
Odd harmonics	
3	2.30
5	1.14
7	0.77
9	0.40
11	0.33
13	0.21
15 ≤ n ≤ 39	$0.15\ \frac{15}{n}$
Even harmonics	
2	1.08
4	0.43
6	0.30
8 ≤ n ≤ 40	$0.23\ \frac{8}{n}$

Limits for Class C equipment

Harmonic order (n)	Maximum permissible harmonic current as a percentage of the input current at fundamental frequency (%)
2	2
3	30 • λ*
5	10
7	7
9	5
11 ≤ n ≤ 39 (odd harmonics only)	3

λ* Is the circuit power factor

Limits for Class D equipment

Harmonic order (n)	Maximum permissible harmonic current per watt (mA/W)	Maximum permissible harmonic current (A)
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
11 ≤ n ≤ 39 (odd harmonics only)	$\frac{3.85}{n}$	See Class A

Limits of Class B equipment = 1.5 * limits of Class A equipment

4.8 Time-varying nature of measured harmonics

Measurements have shown that harmonic content in a waveform varies with time [37]. Direct applications of harmonic limits to measured data would result in ambiguous conclusions depending on which instant is sampled to check against the limit. Harmonics are a steady-state concept. The Fourier transformation assumes that a waveform would repeat itself forever. This is not true in reality and, therefore, the concept of sampling window is used.

When a practical waveform is processed by windowed Fourier transformations, time-varying harmonics are generated. Each harmonic spectrum corresponds to each windowed section of the waveform. Different window sizes (number of cycles included in FFT) give different harmonic spectrum.

A rational limit on time-varying harmonics must be based on how harmonics affect utilities and their customers. Some harmonic effects such as metering errors and accelerated equipment aging are the accumulated results of harmonics. Other effects such as malfunction of electronic devices can be caused by only a short burst of large harmonic distortions. Therefore, a practical limit shall take into account not only the accumulated duration of harmonics over a period but also the actual duration of a sudden harmonic burst.

The IEEE 519 discussed the concern on accumulated harmonics and the concept of probabilistic distribution plats was introduced. However, the problem of harmonic burst is not addressed by the majority of standards. Harmonic bursts should be of more concern because most harmonic-caused problems are related to them.

4.9 Conclusion

Different approaches are followed in the NRS 048 and IEEE 519-1992 to determine the prescribed voltage and current distortion limits. The IEEE 519-1992 sets limits for the harmonics of not only the current caused by the operation of the loads of individual consumers, but also the supply voltage. The NRS 048 sets harmonic limits for the supply voltage but do not provide current harmonic limits for the operation of loads, as in the IEEE 519-1992. The NRS 048 sets harmonic voltage limits only and leaves the harmonic producers responsible for reducing their respective harmonic currents so that the system voltage limits are not violated.

The IEC 61000-3-2 sets limits for the harmonic currents emitted by a single appliance and is applicable to manufactures of these appliances. When equipment is manufactured in compliance with this standard, the harmonic currents injected into the power system are limited, therefore reducing resulting voltage waveform distortion.

The standards discussed above can be used in a tariff strategy only as a measure to determine if a customer exceeds the harmonic limits. If a customer exceeds there prescribe limits a tariff scheme will have to be developed that can be used to penalize the customer.

Chapter 5

ESKOM'S SUPPLY CONTRACTS FOR KEY CUSTOMERS

5.1 Aim of chapter

The aim of this chapter is to discuss the supply contract that exists between the utility (Eskom) and their key customers. The objective is to see if the contracts contains any information on penalities, if a customer exceeds their allowable distortion or incentive, if their install compensation equipment, and if not, can it be included in the contract.

5.2 Introduction

The supply contact [11] that exist between the utility and key customers consist out of 4 sections, which is as follows:

1. Section A: General,
2. Section B: Financial,
3. Section C: Technical and
4. Section D: Legal.

There is also 2 annexures that are incorporated into the document:

i. Annexure A - Price List and
ii. Annexure B - Quality of Supply

A brief discussion of each of the sections and annexures will be given in 5.3.

5.3 Supply contract

5.3.1 Section A: General

This section gives an indication of the parties that are involved in the agreement, the interpretation and definitions, scheduled date for commencement of supply and the period of agreement.

5.3.2 Section B: Financial

The price of the electricity, connection fee and monthly rental is indicated. The payment and security of the electrical account, capital expenditures and costs incurred in setting up the supply or upgrade is set out here and who are liable.

5.3.3 Section C: Technical

The customers notified demand, point of delivery, power factor and phase balance are specified. The form and quality of electricity to be supplied are given but with a more detailed explanation in annexure B. The utility's liabilities towards the customers in the event of losses due to technical problems are set out. The equipment and apparatus to be supplied by the utility and the customer, as well as their maintenance schedule is given.

5.3.4 Section D: Legal

The breach of terms and conditions are described as well as the utility's rights-of-way (route for access to equipment) on the property of the customer. The supply contract can only be changed with the consent of both parties (the utility and customer). The customer's obligation towards ensuring a safe electrical environment is also stipulated and they are prohibited to supply electricity to a third party.

5.3.5 Annexure A - Price List

There are different tariff structures available for large and small customers.

5.3.6 Annexure B - Quality of Supply Specifications

The voltage at the point of common coupling is specified.

5.3.6.1 Utility's obligations

a. Continuity or reduction of supply

The utility must give the customer not less than fourteen days written notice of any planned interruptions as well as use its best endeavors to restrict the frequency and duration of unplanned interruptions in any twelve consecutive months to an agreed number respectively, subject to the provision that interruptions in the supply caused by external forces are specifically excluded.

In the event of the prescribed limits being exceeded, the utility must respond appropriately to improve the continuity of the supply as soon as is practicable. The customer will be informed by the utility of the remedial action that it intends taking and when the situation can be expected to normalize.

b. Voltage Quality

The utility must ensure that quality of the voltage that is delivered to a customer must comply with the limit (harmonics, unbalance and flicker) that is specified in Part 2 of the NRS048 and must respond appropriately in the event that the voltage quality limits are being exceeded.

The utility must take the necessary remedial action when the sum of the consumer interaction at the point of common coupling exceeds the voltage quality, if all consumers connected to the point of common coupling are within their individually allocated apportionment.

The supply voltage may differ 7.5% above or below the declared voltage for a period longer than ten consecutive minutes and the voltage levels must be assessed according to part 2 of NRS 048.

c. Voltage Dips

The utility must strive to eliminate or to minimize the number of voltage dips that could cause plant production disruptions. The utility must ensure that the number of non-coincidental voltage dips of type(s) S, T, X and Z [as illustrated in the Figure 5.1: Voltage Dip Window] recorded at the point of common coupling in any 12 consecutive months do not exceed the numbers that were agreed upon respectively. All voltage dips caused by unavoidable circumstances (as listed in Part 4 of NRS 048 or as may be decided by the National Electricity Regulator) or those originating from the customer's load or equipment due to the starting of large loads or faults within the customer's electrical installation, are specifically excluded.

If the total number of voltage dips of any one of the specified types exceeding the maximum number of occurrences that were agreed upon then the utility will take appropriate measures to rectify the situation as soon as is practicable.

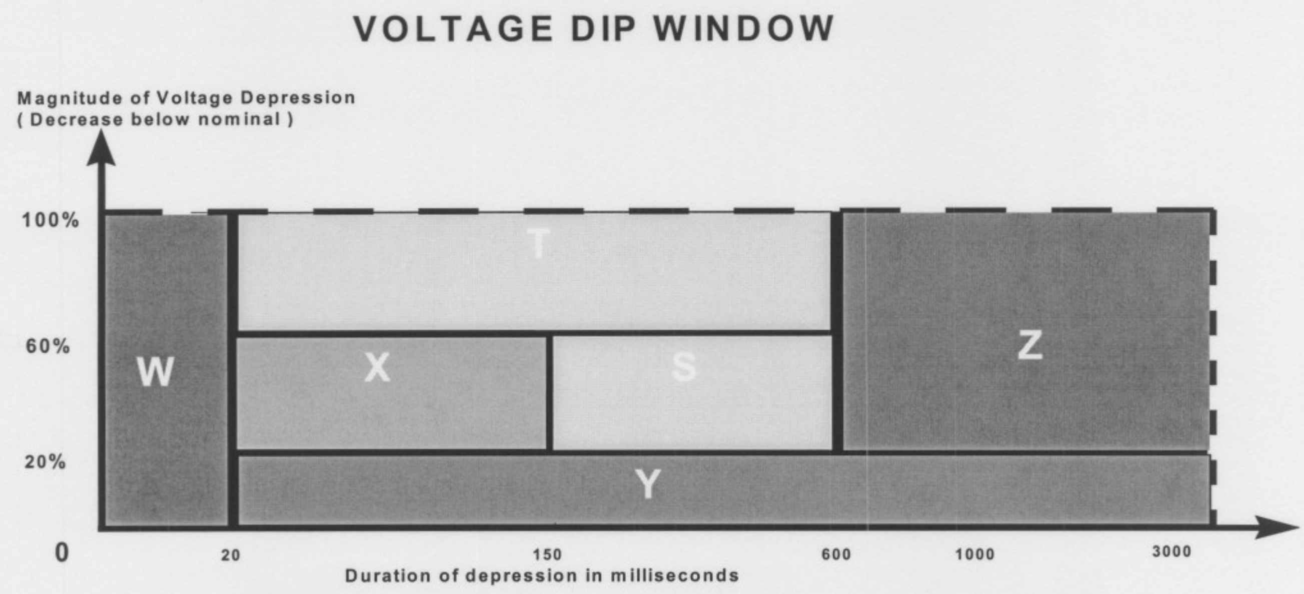


Figure 5.1 Voltage Dip Window

5.3.6.2 The Customer's obligations

The customer is responsible to use the supply in such a manner that their operations do not interfere with an efficient and economical supply to other consumers. Each customer must ensure that any voltage distortions caused by their load or equipment at any time shall not exceed the limits that was specified.

a. Fault levels and notified maximum demands

The fault level and maximum demand for the customer are specified here.

b. Harmonic current injection

The maximum permissible harmonic current that the customer can inject at the point of common coupling is specified as follows:

Harmonic Order	2	3	4	5	7	9	11	13	23	25
Current (A)										

Table 5.1 Specification for harmonic injection for customers

A quality of supply specialist will advise what harmonics should be detailed. All other harmonics must be in accordance with the voltage harmonic limits as specified in Part 2 of NRS 048.

c. Voltage flicker

The customer's contribution to the flicker at the point of common coupling is specified using both the Short-term and Long term flicker indexes.

d. Voltage unbalance

The customer's contribution to the voltage unbalance at the point of common coupling is specified as a percentage value.

e. Voltage dips

The customer must strive to eliminate or minimize the number of voltage dips originating from its load or equipment due to faults within its electrical installation. The customer must also ensure that the total number of voltage dips of type(s) S, T, X and Z that are recorded by the utility at the point of common coupling in any 12 consecutive months, do not exceed the specified numbers that were agreed upon respectively.

f. Rapid Voltage Change

The customer must ensure that rapid voltage changes that originate from its load or equipment due to the starting of large loads or the switching of equipment do not exceed the emission limits that are given in table 5.2.

Table 5.2 Emission limits

Number of changes per hour r	Percentage Change in the Voltage	
	If customer's declared voltage ≤44kV	If customer's declared voltage >44kV
$r<1$	4	3
$1<r<=10$	3	2,5
$10<r<=100$	2	1,5
$100<r<1000$	1,25	1

The above table must be adapted to allow for the specific supply voltage (i.e. ≤ 44kV or > 44kV) and the measurements are made at the point of common coupling.

5.3.6.3 Remedial action and notice of extensions

If any one of the voltage quality limits that are specified above, are exceeded, it will be required from the customer to reduce loading or at its own expense install corrective equipment or take other measures that are necessary to reduce the voltage distortion caused by the customer's load or equipment to within the specified limits.

It is the responsibility of the utility to monitor the harmonic currents that are injectioned, the voltage flicker and voltage unbalance, to ensure that the limits that are specified are not exceeded. In the event of an infringement, the customer shall be informed by facsimile so that remedial action may be taken immediately or within a specified timeframe.

The customer must give adequate notice in writing to the utility of any intended extensions, upgrading of the customer's plant, the installation of power factor correction equipment or any other changes which may impact the power quality or system impedance, to enable countermeasures to be taken.

5.3.6.4 Measurement / Variation of quality of supply

It is the responsibility of the utility to monitor the quality of supply (continuity, the voltage harmonics, voltage unbalance, voltage regulation and voltage dips) at the point of common coupling. The utility and the customer must collaborate in drawing up appropriate operational procedures to facilitate the monitoring and reporting of the quality of supply. Appropriate metering equipment will be installed by the utility at the point of common coupling for this purpose.

In consideration of the capital expenditure and costs to be incurred by the utility for the above-mentioned actions, the customer will pay a specific amount to the utility. As the metering equipment will eventually be replaced, the customer shall pay to the utility the capital expenditure and costs that will be incurred by the utility in the replacement of the metering equipment; subject to the parties agreeing on when to replace the metering equipment and the specifications of the metering equipment.

The power quality must be measured in accordance with the requirements specified in Part 3 of NRS 048 and the relevant assessment method prescribed in Part 2 of the NRS 048 must be applied to the measured quantities. The harmonic current injection, voltage flicker, voltage unbalance and voltage dips limits specified, may be revised if any of the fault levels or notified maximum demands change.

The maximum permissible number of voltage dips will be reviewed annually by the customer and utility, as well as several actions that can be taken to achieve a mutually acceptable frequency of voltage dip occurrences.

5.3.6.5 Future amendments of Eskom's enabling legislation or distribution license

The standards and limits that are set out is subject to change by amendments to either the Electricity Act or the Eskom Distribution License.

5.4 Conclusion

The responsibilities of the utility and the customer with respect to maintaining the power quality are set out very clearly in the contract but no penalties are assigned to any power quality violations by either the utility or customers.

However, the utility is still responsible to take remedial action when the sum of the consumer interaction at the point of common coupling exceeds the voltage quality, if all consumers connected to the point of common coupling are within their individually allocated apportionment. If a tariff strategy is implemented that will give incentives to customers that reduce their impact on the power system, the utility will benefit because it will improve the overall power quality of the power system. Changes to the supply contract can only be made if both parties (utility and customer) agree, and therefore both must benefit from a tariff structure.

Chapter 6

ESKOM'S TARIFF STRUCTURE

6.1 Aim of chapter

The aim of this chapter is to discuss Eskom's tariff structure. The objective is to see what components is included into the tariff structure and if there is cost allocation for waveform distortion.

6.2 How are tariffs made up?

The following components, depending on the tariff, can make up a bill:

6.2.1 (Active) energy charge

A charge linked to each kilowatt-hour (kWh) or unit of energy consumed. The amount of electricity used over a period of time is measured in kilowatt-hours (kWh). Kilowatt-hours are determined by multiplying the number of kilowatts required by the number of hours of use. This charge increases every year with the annual price increase.

6.2.2 Basic charge

A fixed monthly charge is payable for each point of delivery, whether electricity is consumed or not. This charge increases every year with the annual price increase and is a contribution towards Eskom's fixed costs, such as capital, meter reading, billing, maintenance, etc. This contribution differs for each tariff.

6.2.3 Connection fee

The connection fee is payable upfront in cash for the connection of a new supply point, and is a contribution towards the cost of providing the supply.

6.2.4 Demand charge

Payable for each kilovolt ampere (kVA) or kilowatt (kW) of the maximum demand supplied during the month. It is calculated by integrating the measured demand over half-hourly periods for kVA or hourly periods for kW measured supplies on Nightsave, and half-hourly periods for kW measured supplies on Megaflex. Nightsave and Megaflex is the names of different tariff structures.

6.2.5 Monthly rental

The monthly rental is a contribution to the capital cost of providing a supply and is payable each month in addition to the tariff charges. Monthly rentals are calculated using a 15,50% (2001) discount rate, and can be paid over any period of up to 25 years. The capitalisation factor for 25 years is 1,242% per month. The customer has an option of making a cash payment instead of the monthly payments. For some tariffs the monthly rental is rebated (not beyond extinction) as described with the respective tariffs.

6.2.6 Reactive energy charge

This charge applies only to Megaflex, Miniflex and Ruraflex. Megaflex, Miniflex and Ruraflex is the names of different tariff structures. It is levied on every excess kilovar-hour (kvarh) registered. If the customer's installation is operating at a power factor (PF) of 0,96 or better, there will be no reactive energy charge. The method of calculating this excess differs and is described with the respective tariff. This charge increases every year with the annual price increase.

6.2.7 Transmission percentage surcharge

The demand charge (where applicable), active energy charges and reactive energy charge (where applicable) are subject to a transmission surcharge after the voltage discount has been granted, depending on the distance from Johannesburg.

6.2.8 Voltage discount

Electricity is transmitted at as high a voltage as practical to make transmission efficient. At times it has to be transformed to a lower voltage before being supplied to a customer. The higher the supply voltage, the higher the voltage discount granted. This is calculated as a percentage of demand (where applicable) and active energy charges.

6.3 Overview of components of different tariff structures

Table 6.1 Components of different tariff structures

Different Tariffs	Active energy charge			Basic charge	Demand charge	Monthly rental	Reactive energy	Transmission % surcharge	Voltage discount
Nightsave	●			●	●	●		●	●
	Peak	Standard	Off-peak						
Megaflex	●	●	●	●	●	●	●	●	●
Miniflex	●	●	●	●		●	●	●	●
Ruraflex	●	●	●	●		●	●	●	●
Homelight	●								
Homepower	●			●		●			
Business rate 1	●			●		●			
Business rate 2	●			●		●			
Business rate 3	●			●		●			
Business rate 4	●								
	High	Low							
Landrate 1	●	●		●		●			
Landrate 2	●	●		●		●			
Landrate 3	●	●		●		●			
Landrate 4	●			●		●			
Landrate Dx	Fixed charge per month								

6.4 Conclusion

It can be seen that different tariff strategies exits that comprises of different components but there is no tariff scheme that allocate the cost of waveform distortion.

Chapter 7

POWER QUALITY INDICES AND DEFINITIONS

7.1 Aim of chapter

The aim of this chapter is to discuss different power quality indices and definitions that can be used to quantify harmonic distortion in a power system.

7.2 Introduction

It is common in all branches of engineering to use indices and definitions as a tool to represent, quantify, and compare complex phenomena.

The study of electric power quality is the study of voltage and current waveforms, and their comparison to perfect sinusoidal waveforms. Common power quality indices that are in use can be found in Table 7.1 [12, 16, 28]. These indices have evolved over the years from practical experience.

These indices are widely used in power engineering and many have been adapted for use in standards, equipment specifications, qualification of equipment for specific applications and safety specification.

7.3 Practical definitions that can be use to quantify harmonic distortion

The single and three phase power definitions discussed below, is from the IEEE Working Group On Nonsinusiodal Situations.

Table 7.1 Common power quality indices

Index	Definition	Main application
Total Harmonic Distortion	$ITHD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h}}{I_1}$ $VTHD = \frac{\sqrt{\sum_{h=2}^{\infty} V_h}}{V_1}$	General purpose Standards
Power Factor	$\frac{P_{tot}}{\lvert V_{rms} \rvert \lvert I_{rms} \rvert}$	Potentially in revenue metering
Telephone influence factor	$\frac{\sqrt{\sum_{i=2}^{\infty} w_i^2 I_i}}{I_{rms}}$	Audio circuit interference
C message index	$\frac{\sqrt{\sum_{i=2}^{\infty} c_i^2 I_i}}{I_{rms}}$	Communications interference
IT product	$\sqrt{\sum_{i=1}^{\infty} w_i^2 I_i}$	Audio circuit interference shunt capacitor stress
VT product	$\sqrt{\sum_{i=1}^{\infty} w_i^2 V_i}$	Voltage distortion index
K factor	$\frac{\sum_{h=1}^{\infty} h^2 I_h^2}{\sum_{h=1}^{\infty} I_h^2}$	Transformer derating
Crest factor	$\frac{V_{peak}}{V_{rms}}$	Dielectric stress
Unbalanced Factor	$\frac{\lvert V_- \rvert}{\lvert V_+ \rvert}$	Three phase circuit balance
Flicker factor	$\frac{\Delta V}{\lvert V \rvert}$	Incandescent lamp operation; Bus voltage regulation; Sufficiency of short circuit capacity

7.3.1 Single-phase powers

The voltage and current function can be defined with respect to time as [29]:

$$v(t) = V_0 + \sqrt{2}\sum_{h\neq 0}^{\infty} V_h sin(h\omega t + \alpha_h) \tag{7.1}$$

$v(t)$ is the instantaneous voltage
V_0 is the average value
V_h is the rms value of voltage harmonic h
α_h is the phase angle the voltage harmonic h

and

$$i(t) = I_0 + \sqrt{2}\sum_{h\neq 0}^{\infty} I_h sin(h\omega t + \beta_h) \tag{7.2}$$

$i(t)$ is the instantaneous current

I_0 is the dc component

I_h is the rms value of the current harmonic h

β_h is the phase angle of the current harmonic h.

The rms voltage and current are defined as:

$$V = \sqrt{\sum_{h=0}^{\infty} V_h^2} \tag{7.3}$$

and

$$I = \sqrt{\sum_{h=0}^{\infty} I_h^2} \tag{7.4}$$

If the fundamental component V_1 and I_1 is seperated from the harmonic components V_H and I_H then

$$V^2 = V_1^2 + V_H^2 \tag{7.5}$$

and

$$I^2 = I_1^2 + I_H^2 \tag{7.6}$$

are obtained, where

$$V_H^2 = \sum_{h\neq 1} V_h^2 \tag{7.7}$$

and

$$I_H^2 = \sum_{h \neq 1} I_h^2 . \tag{7.8}$$

From equations (7.7) and (7.8), the Apparent Power S can be calculated,

$$\begin{aligned} S^2 &= (VI)^2 \\ &= (V_1 I_1)^2 + (V_1 I_H)^2 + (V_H I_1)^2 + (V_H I_H)^2 \end{aligned} \tag{7.9}$$

The Apparent Power S has two components:

$$S^2 = S_1^2 + S_N^2 \tag{7.10}$$

where

$$S_1^2 = (V_1 I_1)^2 = P_1^2 + Q_1^2 \tag{7.11}$$

$$P_1 = V_1 I_1 \cos\theta_1 \tag{7.12}$$

$$Q_1 = V_1 I_1 \sin\theta_1 \tag{7.13}$$

$$\theta_1 = \alpha_1 - \beta_1 \tag{7.14}$$

S_1 is the Fundamental Apparent Power, which is resolved into the Fundamental Active Power P_1 and the Fundamental Reactive Power Q_1.

The Nonactive Power N [29] can be defined in a conventional way as:

$$N = \sqrt{S^2 - P^2} \tag{7.15}$$

The Non-fundamental Apparent Power S_N consists of three components:

$$S_N^2 = (V_1 I_H)^2 + (V_H I_1)^2 + (V_H I_H)^2 \tag{7.16}$$

The first component is the product of the fundamental rms voltage and harmonic rms current. This is the dominant term and even in the extreme case when the voltage is perfectly sinusoidal this term exists if $I_H > 0$. This term, $V_1 I_H$, may be named Current Distortion Power.

The second term, $V_1 I_H$, is the product of the fundamental rms current and the harmonic rms voltage. This term may be called the Voltage Distortion Power, and it is a reflection of the voltage distortion at the observed bus.

The third component may be called the Harmonic Apparent Power and can be resolved as follows:

$$S_H^2 = (V_H I_H)^2 = P_H^2 + N_H^2 \tag{7.17}$$

where

$$P_H = \sum_{h \neq 1} V_h I_h \cos\theta_h \tag{7.18}$$

$$\theta_h = \alpha_h - \beta_h \tag{7.19}.$$

P_H is the Total Harmonic Active Power and the remaining component N_H is the the Total Harmonic Nonactive Power

A direction of flow may be assigned to P_1 and Q_1 but no direction of flow may be assigned to the three components of S_N [32]. These components are only formal products; unlike such terms as active power, they have no physical meaning. These formal components can serve as useful indicators of the operation of a network.

If equation (7.16) is divided by (7.11) then the usefulness becomes clearer;

$$\left(\frac{S_N}{S_1}\right)^2 = \left(\frac{I_H}{I_1}\right)^2 + \left(\frac{V_H}{V_1}\right)^2 + \left(\frac{V_H I_H}{V_1 I_1}\right)^2 \tag{7.20}$$

Equation (7.20) can also be re-written as a function of the Total Harmonic Distortion of the voltage and current,

$$\left(\frac{S_N}{S_1}\right)^2 = (ITHD)^2 + (VTHD)^2 + (ITHD \cdot VTHD)^2 \tag{7.21}$$

In contrast, the *ITHD* is generally higher then the *VTHD*.

If the *ITHD* > 20% and the *VTHD* < 5% then equation (7.21) can be approximitated as follows [29];

$$\frac{S_N}{S_1} \approx ITHD \tag{7.22}$$

The error of the approximation in equation (7.22) is less then 1% for ITHD greater then 40%. A better approximation can be obtained with the flowing expression:

$$\left(\frac{S_N}{S_1}\right) \approx \sqrt{(ITHD)^2 + (VTHD)^2} \tag{7.23}$$

Using the approximation of the normalized Non-fundamental Apparent Power given in equation (7.23), for $VTHD < 5\%$ the error is less then 0.15 %.

The normalized Harmonic Apparent Power can be calculated as;

$$\frac{S_H}{S_1} = \frac{V_H I_H}{V_1 I_1} = ITHD \cdot VTHD \tag{7.24}$$

The harmonic apparent power S_H is much smaller then the non-fundamental apparent power S_N and does not convey enough information on a non-linear load.

The measurement of P_H or $\int P_H dt$ is not a effective way to evaluate harmonic power flow, because some harmonic orders may generate power while others dissipate power in the observed load, leading to cancellation in the P_H term. Only a complete listing of the harmonic voltage and current phasors can lead to a clear understanding of the contributions made by each harmonic to the electric energy flow.

The value S_N and the normalised value $\frac{S_N}{S_1}$ are much better indicators of the level of harmonic "pollution" then the value of P_H. A non-linear load will be characterized by a low ratio of $\frac{S_N}{S_1}$ [29]. Increased current distortion will not necessarily increase the value of P_H but will always increase the normalised value of $\frac{S_N}{S_1}$.

5.3.2 Three-phase powers

The System Apparent Power S_e or Equivalent Apparent Power can be defined as [33, 34, 35];

$$S_e = 3V_e I_e \tag{7.25}$$

where

$$V_e = \sqrt{\frac{V_a^2 + V_b^2 + V_c^2}{3}} \tag{7.26}$$

$$I_e = \sqrt{\frac{I_a^2 + I_b^2 + I_c^2}{3}} \tag{7.27}$$

For a four-conductor system V_a, V_b and V_c are line-to-neutral rms voltages. For a three-conductor system, the equivalent voltage V_e may be calculated using equation (7.28), where V_a, V_b and V_c are line voltages measured from an artificial neutral point (the star point of three non-reactive resistors), or

$$V_e = \sqrt{\frac{V_{ab}^2 + V_{bc}^2 + V_{ca}^2}{9}} \tag{7.28}$$

where the rms voltages are measured from phase to phase. The equivalent current I_e is calculated from the rms current I_a, I_b and I_c.

The equivalent voltage and current may be seperated into two components:

$$\begin{aligned} V_e^2 &= V_{e1}^2 + V_{eH}^2 \\ I_e^2 &= I_{e1}^2 + I_{eH}^2 \end{aligned} \tag{7.29}$$

where the index 1 marks the fundamental rms components:

$$V_{e1}^2 = \frac{V_{a1}^2 + V_{b1}^2 + V_{c1}^2}{3}$$

$$I_{e1}^2 = \frac{I_{a1}^2 + I_{b1}^2 + I_{c1}^2}{3} \qquad (7.30)$$

and the index H marks the totalised non-fundamental rms components:

$$V_{eH}^2 = \sum_{h \neq 1} \left(\frac{V_{ah}^2 + V_{bh}^2 + V_{ch}^2}{3} \right)$$

$$I_{eH}^2 = \sum_{h \neq 1} \left(\frac{I_{ah}^2 + I_{bh}^2 + I_{ch}^2}{3} \right) \qquad (7.31)$$

The Fundamental Apparent Power can be separated from the Non-fundamental Apparent Power,

$$S_e^2 = S_{e1}^2 + S_{eN}^2 \qquad (7.32)$$

The equivalent Total Harmonic Distortions

$$VTHD_e = \frac{V_{eH}}{V_{e1}}$$

$$ITHD_e = \frac{I_{eH}}{I_{e1}} \qquad (7.33)$$

allows the expression of the normalised Non-fundamental Apparent Power $\frac{S_{eN}}{S_{e1}}$ to be defined as:

$$\left(\frac{S_{eN}}{S_{e1}} \right)^2 = (ITHD_e)^2 + (VTHD_e)^2 + (ITHD_e \cdot VTHD_e)^2 \qquad (7.34)$$

In the case of unbalanced polyphase systems, the definition of another Apparent Power component becomes inevitable. Unbalanced loads convert part of the fundamental positive sequence active power into fundamental negative and zero sequence active power [34]. The same is true for reactive power.

Like harmonics, the negative and zero sequence powers are a form of "pollution" in that they add to line and rotating equipment losses. Just as users expect a nearly pure fundamental voltage to be delivered with minimal harmonics, they also expect a nearly pure positive sequence voltage to be delivered with minimal negative and zero sequences.

The degree of unbalance in the fundamental Apparent Power S_{e1} can be divided into two terms:

$$S_{e1}^2 = S_1^{+^2} + S_{u1}^2 \tag{7.35}$$

where $S_1^+ = 3V_1^+ I_1^+$ is the Positive sequence Fundamental Apparent Power and V_1^+, I_1^+ are the rms values of the positive sequence fundamental voltage and current.

The component S_{u1} is the Unbalanced Fundamental Apparent Power and contains a minute active power component (usually a negative value) and a nonactive component.

This approach to decomposing the System Apparent Power S_e has the following useful features[29]:

- Separates the Fundamental Apparent Power and its Active and Reactive components from the Non-fundamental Apparent Power.
- Provides a useful measure of the degree of harmonic "pollution" in the normalised ratio $\frac{S_N}{S_{e1}}$.
- Provides a useful measure of the degree of unbalance "pollution" in the normalised ratio $\frac{S_{u1}}{S_{e1}}$.

7.4 Power factor

To encourage a more efficient use of the power system, utilities can impose power factor charges for their commercial and industrial customers. These charges can be an added component of the monthly bill imposed on customers whose average power factor falls below a predetermined value, or a power factor multiplier M [36] can be used to adjust the monthly bill.

There is no universally accepted form of the multiplier M in terms of the power factor, but Figure 7.1 [36] gives a general description. The function of the multiplier is to increase the bill of customers with low lagging power factor loads, $M > 1.0$ and rebate those whose loads have a high lagging power factor or a leading power factor $M < 1.0$.

The total monthly bill (T) is then based on: the peak demand D_{max}, the energy used E, the demand and the energy rates r_d and r_e and the multiplier M,

$$T = \left[r_d D_{\max} + r_e E\right] M \qquad (7.36).$$

The upper value of M (for low lagging power factor) is about 1.33. This is a practical power factor penalty. The lower limit is about 0.95.

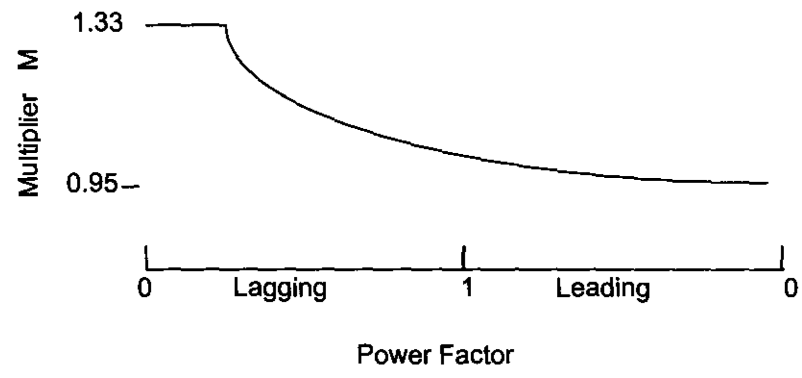


Figure 7.1 General description of the Multiplier *M*

The power factor may be defined as the ratio of the active power to the apparent power (the true power factor - *TPF*) or as the cosine of the angle between the voltage and current for the fundamental frequency only (the displacement power factor - *DPF*) [36].

The power factor can be used to quantify the effectiveness of the electric energy flow in a system:

$$TPF=\frac{P}{S}=\frac{(P_1+P_H)}{S} \tag{7.25}$$

Isolating P_1, Q_1 and S_1 from the non-fundamental power makes it easy to follow the uncorrupted fundamental power flow of the electric energy, and makes easier the application of engineering economic techniques (such as power factor correction capacitors).

The Displacement Power Factor (*DPF*),

$$DPF=\frac{P_1}{S_1}=\cos(\theta_V-\theta_I) \tag{7.26}$$

remains a significant value where the fundamental power is monitored separately from the non-fundamental.

In the presence of harmonics *TPF* is smaller than *DPF*. When the load current distortion is low, the difference between the *TPF* and the *DPF* is small, but when the load current is distorted significantly the TPF may be much lower than the DPF.

Meters that measure apparent power based on:

$$S=\sum_{h=1}^{\infty}V_h I_h \tag{7.27}$$

do not result in progressive billing of harmonics. All the frequencies are assumed to have the same effect on system losses. In reality high frequency currents, produce higher losses in transformers and system feeders [36]. In order to account for these higher losses, it was suggested [20] to adjust the apparent power and power factor reading by introducing weighting factors for the measured currents so that

$$S=\sum_{h=1}^{\infty}V_h I_{hA} \qquad (7.28).$$

This results in a harmonically adjusted power factor, *HPF*

$$HPF = \frac{P}{\sum_{h=1}^{\infty} VI_{hA}} \tag{7.29}$$

where

$$I_{hA} = \sqrt{\sum_{N=1} (K_N I_N)^2} \tag{7.30}$$

$K_N = N^{1.33}$ implied in the IEEE 519 and $K_N = \sqrt{N}$ which is related to the resistive skin effect in conductors [36] appear to be reasonable weighting factors.

The power factor in a system is rarely constant even at a measuring point at a service entrance. Instantaneous measurement of power factor can give significant errors therefore time domain averaging must be used [36]. The averaging may be the averaging of samples of the power factor (e.g. taken every 15 minutes), or it may be a mix of average active power (e.g. the total energy used in a given time interval divided by the length of that time interval) divided by the average apparent power (i.e. kVAh divided by interval time)

7.5 Total Harmonic Distortion

The total current harmonic distortion is defined as [48]:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \tag{7.31}$$

where I_1 is the current at the fundamental frequency and I_h is the current at different harmonic frequencies. The *THD* index has been used extensively to generally characterise the amplitude of harmonics expressed as a ratio the amplitude [28]. If no fundamental component exists, the *THD* becomes infinite. This will be the case, for example, for the signal

$$i(t) = \cos(3\omega_0 t) + \cos(5\omega_0 t) \qquad (7.32).$$

This situation occurs in cases in which the power frequency voltages and currents are modulated electronically by sub-synchronous switching or by the distortion of the control signals used to develop switching strategies. If a 50 Hz voltage is switched as in a pulse width modulator drive for an induction motor, and the control signal is developed digitally, the resulting induction motor stator voltages will contain Fourier components of $50 \pm f_m$ where f_m is a low frequency (e.g. 0.2 Hz), and there is no true component of the induction motor voltage at 50 Hz.

An alternative definition that represents the harmonic distortion as a ratio, termed the distortion index (*DIN*), overcomes the mathematical restriction of the classical *THD* formulation:

$$DIN = \frac{\left[\sqrt{\sum_{i=2}^{\infty} I_i^2}\right]}{\left[\sqrt{\sum_{i=1}^{\infty} I_i^2}\right]} \tag{7.33}$$

The difficulty with use of *DIN* in place of *THD* relates to standardisation. The IEEE and many other international organisations have promoted the use of *THD* rather then *DIN*. The two indices are simply related by there definitions,

$$DIN = \frac{THD}{\sqrt{1+THD^2}} \tag{7.34}$$

and

$$THD = \frac{DIN}{\sqrt{1-DIN^2}} \tag{7.35}$$

For cases of low harmonic distortion, the Taylor series expansions for the forms $\frac{1}{1+x}$ and $\sqrt{1+x}$ can be used to obtain the following approximations

$$DIN \approx THD(1 - \frac{1}{2}THD^2) \quad (7.36)$$

$$THD \approx DIN(1 + \frac{1}{2}DIN^2) \quad (7.32).$$

For many low distortion cases, *DIN* and *THD* are about the same[28]..

7.6 Conclusion

Harmonic distortion is a power quality issue such as voltage dips or flicker and it must be identified and quantified. Where these harmonic distortion levels are excessive, steps must be taken to reduce it, which then requires identifying the sources.

The indices or power definitions that are used for quantifying harmonic distortion for revenue purposes, must give a good compromise between theoretical aspects and practical applicability. Such a index should thus be interpreted against a physical phenomena as engineers design can only compensate physical phenomena.

The indices or definitions that are eventually used in a possible tariff structure must also aid in the quantification of the effectiveness of energy flow in a system.

Chapter 8

PROPOSED TARIFF STRUCTURE

8.1 Aim of chapter

The aim of this chapter is to discuss the characteristics of a tariff structure and to make possible tariff suggestion.

8.2 Pricing problem

A satisfactory pricing solution should address the several economic and regulatory aspects of the harmonics problem:

i. Nonsinusoidal voltages and currents in a power system impose unintended financial burden on ratepayers who did not contributed to the generation thereof. The revenue and cost effects of harmonics must be included in a utility's revenue requirement,. This is similar to a case of water pollution, in that few factories discharge waste into a river and all the residents along the river pay for the clean-up. It is an unfair situation as "fair" would have been the situation were the customer only pay for the energy required to sustain production levels of a plant. Thus, a satisfactory pricing solution must mirror the relationship between harmonics and their effects on a power system.

ii. The utility must have knowledge on the cause of the distortion observed in the power system in order to apply appropriate remedial action. Recall that the utility itself does not cause the distortion, the utility generate near-perfect 50 Hz energy, but the nature of the interconnected power system is the factor that distortion at a certain node can unavoidable influence geographically separated nodes. The utility could manage the situation by some extent, for example installing power factor correction equipment, extra transmission lines to lower the system impedance, but this extra capital expenditure will be eventually reflected by the revenue the utility will collect from all customers connected to this power system. This is similar to the water pollution example in which many factories share one sewer and each factory's discharge is not monitored. Therefore a pricing solution must be accompanied by monitoring.

iii. The relative amount of distortion contributed by a certain customer cannot be determined continuously in an interconnected power system by single point measurements at that customer. The result is that a utility cannot price this undesirable attribute of electricity consumption.

iv. Relative distortion contribution can be measured if all nodes in the power system will be measured continuously and synchronously. Such high metering cost may prevent a system wide implementation of mandatory harmonics pricing.

v. Whether a utility can implement harmonic pricing depends thus on the technoligical features and capability of the utility's current billing system. Costly revision of a utility's billing system will be unacceptable.

vi. The pricing solution must be relatively simple to win regulatory and customer acceptance.

8.2 Characteristics of a tariff strategy

The tariff or incentive scheme, unfortunately faces two major technical challenges [19]:

1. To separate the relative harmonic contributions of the utility and the customer at the PCC. Harmonic generating customers can only be penalized for the portion that they have contributed relatively to the total distortion observed at the PCC. In other words- a method of discrimination between who has contributed how much, must exist.

2. To isolate the effect of impedance variation on harmonic limit violations. Unavoidable utility impedances changes are part of the dynamic management of the energy system and can often result in increased or decrease harmonic contribution from the customer. This situation requires that the customer must be accommodated for the difference in harmonic contribution.

Considerable research is being done to determine reliable measuring techniques to solve the above-mentioned problems [18,19,20,22,23,24].

A tariff system aiming at regulating the level of distortion in the power system, should have the following characteristics [20]:

i. It must be practical. Extreme penalties that will never be imposed make no sense, as in disconnecting the customers who fail to comply with the limits. Customers must be able to predict the effects on their electricity expenses if changes are made in their power system, which could influence the power quality at the PCC.

ii. It must provide economic penalties for generating harmonics and economic incentives when waveform distortion is decreasing at the PCC, therefore encouraging desirable behavior and disencouraging undesired behavior.

iii. Any economic penalties must be directly related to the increased costs borne by the utility or neighboring customers due to increased waveform distortion caused by a specific customer. The increased costs caused by that customer must be readily measurable.

iv. It must be compatible with the existing tariff structures, or rather, as little change to existing tariff structures should be required.

v. It must be progressive. The more the waveform distortion, the greater the economic penalty levied.

vi. The tariff structure must be relatively easy to implement. The minimum changes to existing operations and instrumentation must be necessary, a minimum of new concepts must be introduced.

8.3 Tariff Strategies

One possible incentive to encourage customers to remain in within the limits set by the utility is to establish a regulation that requires them to do so. However, what happens if a customer does not comply with their limits? Does the utility disconnect the customer? This is impractical since because the consumers that generate large harmonic currents are important contributors to the utilities revenue. A strategy that defines the process to achieve the ultimate power quality goal, must exist and which necessitate co-operation between utility and customer.

Energy-efficiency rebate programs can be established, to provide an immediate financial incentive to customers for switching to more energy efficient and "power-quality friendly" loads. This program may provide full or partial rebates to customers who install thermal insulation, or who will install adjustable speed drives or equipment that produces less harmonic distorting (equipment that comply with the IEC standards - therefore trying to limit the harmonics that each appliance can inject into the network). Rebates can be denied for any loads that does not meet the guidelines that is established or the rebate can be reduced based on the TCHD of the load's current.

Customers could be grouped in different tariff rate classes based on factors such as size and type of loads, because the lower the levels of harmonic currents injected into the system the lower the resulting voltage waveform distortion at the point of common coupling. Within each class, customers having the same load profile should pay the same tariff or receive the same incentive.

It is firstly necessary to establish why an electrical utility may lose revenue when waveforms are non-sinusoidal. Typically, an electric energy account is based on the following principle:

$$W = \int_0^\tau P \; dt \tag{8.1}$$

In the above, P represents the Total Real Power "flowing" through the measuring point, τ represents the accounting time interval of power consumption and W represents the total energy consumed/delivered during that time interval.

The Total Real Power in formula (met cross-reference) represents an aggregated total of real power over all the harmonics found in the voltage and current as observed at the load terminals:

$$P = \sum_n P_n \tag{8.2}$$

$$P_n = \mathrm{Re}\{S_n\} = \mathrm{Re}\{V_n I_n^*\} \tag{8.3}$$

In the above P_n represents the Harmonic Real Power of harmonic order n, V_n is the harmonic voltage phasor of harmonic order h, I_h^* is the complex conjugate of the harmonic current phasor of order n.

If the positive reference direction of fundamental current is chosen such that it is flowing into the load, the direction of the fundamental active power will be positive whilst the harmonic real power will be negative [26], [21] if this load is a non-linear load which converts part of the fundamental acitve power to harmonic active power Such a load is thus termed as "*consuming*" fundamental real power whilst "*generating*" harmonic real power. (With the assumption that only one non-linear load is connected at this three-phase PCC.) The energy at harmonic frequencies is transmitted from the load backwards towards the source because the sinusoidal supply voltage source is seen from the load terminals as a passive circuit and the load generated current harmonics dissipate real power in the supply resistance.

The total real power flowing through the measuring point will thus be:

$$P = P_1 - \Delta P_h \tag{8.4}$$

The fundamental real power (P_1) is higher than the total real power received by the load (P) with a value of ΔP_h. It is important to note (in cross-reference formula) that the utility has only received income based on the lower value of P (excluding the indirect factors associated with generating transmitting, and dissipating the higher value of power.) The fundamental real power thus also "transmits" the harmonic real power.

8.3.1 Suggested tariff strategy 1:

Assume a customer with non-linear loads is charged [22] for fundamental energy W_1 only

$$W_1 = \int_0^T P_1 \, dt \tag{8.5}$$

As explained above, the fundamental harmonic real power P_1 contains both the total real power P and the harmonic real powers ΔP_h dissipated in the distribution system. The energy losses represent a loss of income to the utility, as this energy was part of the original energy input to the generation process. Observe that the utility loose income due to the harmonics and due to the increase in P_1, (ΔP_1). This extra amount of fundamental real power has to be transported in the transmission system, which implicates an increase in the fundamental losses in the system. A very simple tariff system suggested underneath will be a beneficial strategy to the utility:

The monetary cost of energy delivered can then be calculated as:

$$\text{Monthly electricity cost} = \text{Cost of } W_1 = C_1 * W_1 \qquad (8.6)$$

where C_1 is the energy cost rate.

The revenue lost due to the this power loss could thus be partially recovered if the above energy W_1 is charged to non-linear customers as it includes the energy cost caused by ΔP_h. However, it does not necessarily reflect the cost of increase in distribution equipment ratings needed to transport a higher amount of energy. In addition, it does not reflect the increase in losses caused in the distribution system due to the increase in P_1 (ΔP_1). This loss component could not be recovered with the above strategy. Observe that the losses caused by ΔP_1 is a function of the power system configuration, which is a dynamic phenomenon not linked to the instrumentation which provide the tariff data.

8.3.2 Suggested tariff strategy 2:

Another approach is to bill the customer for W as in equation 8.1, and then add a component [21] representing the energy dissipated in the distribution system by the load generated current harmonics, which is:

$$W_h = \int_0^T (P_1 - P)\, dt. \qquad (8.7)$$

The goal is that this extra component take into account the harmful impact of the load generated current harmonics on the distribution system. It should also represents the possible cost of various mitigation measures that could be needed for harmonic compensation and the protection of sensitive loads. The additional component W_h should be priced accord to the induced extra costs, which will be a higher rate then the rate for W.

The monetary cost of energy delivered to a non-linear customer should now be calculated as:

$$\text{Monthly electricity cost} = \text{Cost of } W + \text{Cost of } W_h = C \times W + C_h \times W_h \qquad (8.8)$$

Where C and C_h is the cost of the different energies, such that $C_h > C$.

An important feature of this method is that full harmonic analysis is not needed to measure the real power losses, only P and P_h should be known, instrumentation complexity is thus not a major concern.

Another feature is that the non-linear customer who "sinks" harmonic currents, in other words, the customer who will be dissipating harmonic real power that originates at adjacent non-linear customers, will be compensated as it's monthly bill will automatically be adjusted downwards (a negative W_h). The linear customer, who is supplied with a distorted voltage, and forced to accept harmonic real power, will pay less, implicating that the utility loose income due to problems caused by interconnected non-linear customers and the utility should thus be recovering such loss by the penalty collected from the interconnected non-linear customer

A distorted voltage signal applied to a linear load will cause harmonic currents (and harmonic real powers) to be consumed by the linear load. Only in the case of a pure resistive load, harmonic real power is useful when it is then converted to heat. If the linear load is a linear rotating load these harmonic real power received by the rotating load is not converted to useful energy. The harmonic current sets up harmonic fluxes, which causes harmonic torque components, which are not necessarily in the same direction as the fundamental torque component. The net shaft torque is reduced causing a reduction in the mechanical output power. This effect in combination with the additional I^2R losses result in sub-optimum utilisation of the magnetic circuit in the energy-conversion. Also in this case, the customer should rather pay for W_1 and not for W.

An asymmetrical voltage source or unbalanced load cause additional problems for the customer with induction motors, as the negative sequence real power does not produce any useful work. In fact, if the ratio between the negative sequence and the positive sequence component in the voltage is only 3.5 %, the motor temperature can rise by 25 % [18]. An energy calculation based only on the positive sequence voltage supplied by the utility, will in this case be fairer to this customer.

8.3.3 Suggested tariff strategy 3:

If it is possible to measure, a customer's monthly electricity bill should contain an additional component representing its relative contribution to the total distortion of the voltage waveform at the point of common coupling. An aggregated total for the month can be calculated based on a mutually agreed-on method according to the apportioned amount of harmonic contribution allowed for this customer. If the customer's contribution is within or much lower then the apportioned limits, this should be acknowledged. Customers who deliberately install compensating equipment will be compensated in paying less. It could thus be possible that a customer could recover the cost of installing compensating equipment. This approach will thus enable a decrease in the total distortion observed at the PCC.

However, a sound measurement technique is needed to quantify the different relative harmonic contributions at the PCC. Continuous measurements will be required at the PCC in order to establish what long-term benefit compensating equipment installed at customers plants have on the voltage waveform distortion observed at the PCC. It will also require continuous monitoring to accommodate for changes in plant configuration and operation. The tariff incentives must then be based on these measurements. It is clear that it will be a "time-dependent" incentive, in other words the incentive could be negative if the measurements indicate that the customer is at certain times not adhering to agreed-on harmonic contribution.

A practical problem with this approach is to distinguish between the relative harmonic contributions of each non-linear customer towards the total distortion observed. It is not possible to use the direction of harmonic real powers in single point measurements for tariff calculation in endeavours to dissuade consumers from generating distortion. Phase-controlled line commutated AC/DC multiphase converters exhibit the ability of exporting and importing harmonic real powers at the individual harmonic frequencies. In addition, these magnitudes and angles change with relative changes in the firing angles of the converters. This observation was verified both by means of a frequency domain and time domain modelling approach [26], [27]. All the loading and supply nodes for the PCC under investigation, must be measured continuously and synchronously in order to verify possible exchange of harmonic active power.

One of the challenges that are facing a tariff structure is thus to separate the harmonic contributions of the utility and customer harmonic sources at the PCC. Recent research have indicated that the following global index [47] measured for each line *k*,

$$V_k = \frac{1}{3}\left(\frac{\varepsilon_{slq_k}^{-1}}{\varepsilon_{slq_s}^{-1}} + \frac{\varepsilon_{HGI_k}}{\varepsilon_{HGI_s}} + \frac{\eta_k^+}{\eta_s^+} \right) \tag{8.9}$$

provides more correct information on the location of the sources producing distortion than each of the individual indexes. The subscript *s* refers to the line supplying the PCC. However, this index requires simultaneous measurements at both the supply and at the load but not synchronised up to a high precision in time.

The harmonic global index ε_{HGI} can be defined as,

$$\varepsilon_{HGI} = \frac{\left\| I_{\sum L} \right\|^2}{\left\| I_{\sum s} \right\|^2} \tag{8.10}$$

where $I_{\sum L}$ and $I_{\sum s}$ are the vectors of the three-phase collective rms values of the current components associated with the harmonic active powers flowing from the load backward to the source and the harmonic active powers flowing from the source toward s the load, respectively.

The supply and loading quality can be defined as,

$$\varepsilon_{slq} = \frac{P_{\sum}}{P_{\sum +1}} \tag{8.11}$$

where $P_{\sum +1}$ is the total active power associated with the fundamental frequency, positive sequence components of voltages and currents.

The ratios of the global total harmonic distortion factors are defined as,

$$\eta^+ = \frac{GTHD_{I+}}{GTHD_{V+}} \tag{8.12}$$

with

$$GTHD_{V+} = \sqrt{\frac{V_{\sum}^2}{V_{\sum +1}^2} - 1}, \qquad GTHD_{I+} = \sqrt{\frac{I_{\sum}^2}{I_{\sum +1}^2} - 1} \tag{8.13}.$$

$V_{\sum_{+1}}$, $I_{\sum_{+1}}$ is the rms collective values of the fundamental frequency, positive sequence components of voltages and currents.

It was showed that if $v_k = 1$, the system is working under sinusoidal balanced conditions. If $v_k > 1$ then the source producing distortion is connected to line *k* but if $v_k < 1$ then the distortion is injected by the supply. Therefore, the index v_k can be used to locate the source that is causing the distortion.

8.3.4 Suggested tariff strategy 4

It is relatively easy to separate the power flow at a service entrance into power flow at the fundamental and power flow at various harmonic frequencies. It might be in the same direction as the fundamental power, or may be in the opposite direction, but only simple frequency domain analysis is required

This can allow the utility to charge different amounts for different frequencies. The charges can also be progressive therefore the higher the frequency the higher the charge,

$$Monthly\,\cos t = A \cdot P_{50} + B \cdot P_{100} + C \cdot P_{150} + \ldots\ldots \qquad (8.15)$$

where A,B,C,... is the cost of different harmonic powers such that A <<< B <<< C < <<... .

In the case where there is minimal voltage distortion, there will be minimal harmonic power flow regardless of the level of harmonic currents which is the ideal situation. The utility can however not always maintain such low supply impedance configurations to each non-linear customer

8.3.5 Suggested tariff strategy 5:

Assume that only kVA-hours is considered. It automatically eliminates any requirements for power factor penalties. This approach is not progressive because it fails to discourage higher-order harmonics more than lower-order harmonics. It treats one ampére at the 39th harmonic as though it has the same cost implication as one ampére withdrawn at the fundamental frequency.

8.3.6 Suggested tariff strategy 6:

Assume that the tariff system make use of true power factor. The true power factor (*TPF*) is defined as,

$$TPF=\frac{P}{S}=\frac{(P_1+P_H)}{S}=\frac{(P_1+P_H)}{E_{rms}\cdot I_{rms}} \tag{8.16}$$

Displacement power factor (DPF) is defined as:

$$DPF=\frac{P_1}{S_1}=\cos(\theta_V-\theta_I) \tag{8.17}$$

In the case of non-distorted voltages and currents, DPF and TPF are numerically identical. When distortion is present, TPF is always lower than the DPF. Therefore, TPF can be used to discourage distortion. This approach might be easy to implement since it only requires the changing of one definition of power factor to another.

8.3.7 Suggested tariff strategy 7

Charge for the "harmonic adjusted power factor". The "harmonic adjustment power factor" is defined as [20]

$$HPF = \frac{P}{E_H \cdot I_H} \tag{8.18}$$

where P is the total active power, including both fundamental power and harmonic power, and E_H and I_H are frequency-weighted rms voltage and current with the following form:

$$E_H = \left[\sum_{N=1}^{50} C_N \cdot E_N^2 \right]^{\frac{1}{2}} \tag{8.19}$$

E_H - Harmonic adjusted rms voltage
N - Harmonic order
C_N - Weighting factor from some voltage weights table
E_N - Measured voltage at harmonic order N

$$I_H = \left[\sum_{N=1}^{50} K_N \cdot I_N^2 \right]^{\frac{1}{2}} \tag{8.20}$$

I_H - Harmonic adjusted rms current
N - Harmonic order
K_N - Weighting factor from some current weights table
I_N - Measured current at harmonic order N

The weighting factor for the fundamental is always 1. The weighting factors for higher-order harmonic currents are always chosen to be greater than one (e.g. if the weighting factor of the fifth harmonic is 5, an ampére drawn at the fifth harmonic will cost the customer five times as much as a fundamental ampére in an *HPF* calculation).

There can be several possible weighting factors for the harmonic currents.One possibility can be:

$$K_N = N \tag{8.21}$$

where K_N is the weighting factor and N is the harmonic order. It implies that, for power factor calculations, an amp at the fifth harmonic costs 5 times as an amp at the fundamental, and an amp at the 19th harmonic cost 19 times as much.

A second possibility,

$$K_N = N^{1.333} \tag{8.22}$$

is implied by the IEEE 519 Table 10.2, which shows that the effects of higher order harmonics are somewhat worse than their order would imply. A reasonable approximation of the harmonic current weighting in table 10.2 is $N^{1.333}$. For even harmonics, the IEEE 519 Table 10.2 can be followed and the weights for even harmonics would be 4.0 N^2, where N is the harmonic order.

The *HPF* penalties will only be applied when the prescribed limits are exceeded at the point of common coupling.

A third possibility is:

$$K_N = \sqrt{N} \qquad (8.23).$$

The resistance of a conductor increases with frequency because high frequency currents tend to flow near a conductor's outer surface. This phenomenon is known as resistive skin effect [42]. Depending on the conductor size and conductivity, the skin effect may or may not be significant at the fundamental frequency, but it can be significant for higher-order harmonics. The skin effect is significant if the "skin depth" is equal to or less than the conductor radius. As the skin depth becomes small in relation to the conductor radius, the term "well-developed" skin effect applies, which implies that the conductor resistance increases as the square root of the frequency. This indicates that $K_N = \sqrt{N}$ weighting may be appropriate where resistive losses in large conductors are the main concern.

With regarding to voltage weighting, it is possible that the weights for voltages could be set to 1; alternatively, the weights for harmonic voltages could be less than one, or even zero, which would imply that voltage delivered at harmonic frequencies is worth less than voltage delivered at the fundamental frequency.

8.3.8 Suggested tariff strategy 8

One of the main disadvantages of the total harmonic current distortion is that all frequencies are weighted equally. It is defined as:

$$THCD = \frac{\sqrt{\sum_{i=2}^{\infty} I_i}}{I_1} \tag{8.25}$$

The implication is that a 5 % current *THD* is obtained, when the only harmonic is the third harmonic cannot be distinguished from the *THD* when the only harmonic is, for example the 47th. These different harmonics have different effects on the power system.

If a weighting factor K_N (as discussed in 8.3.10) is introduced, then equation 8.20 can be written as,

$$Current \quad Distortion = \frac{\sqrt{\sum_{N=2}^{\infty} K_N \cdot I_N}}{I_1} \tag{8.26}$$

The weighting factors for higher-order harmonic currents can now be chosen to be greater than one. Therefore, all frequencies can be treated differently.

8.3.9 Suggested tariff strategy 9

A utility can charge different amounts for currents at different frequencies. The charges can also be progressive therefore the higher the frequency the higher the charge:

$$Monthly\cos t = Current\ \ Cost + \left[A \cdot (I_{100} - I_{\lim(100)}) + B \cdot (I_{150} - I_{\lim(150)}) + C \cdot (I_{200} - I_{\lim(200)}) + \ldots\ldots\right] \tag{8.27}$$

such that if ($I_{N\text{-}actual} < I_{lim(N)}$) then $(I_N - I_{\lim(N)}) = 0$.

$A,B,C,\ldots$ - is the cost of different harmonic currents such that $A <<< B <<< C <..$

$I_{100,\ 150,\ 200,\ \ldots\ldots}$ - is the normalised measured rms current

$I_{lim(100),\ lim(150),\ \ldots.}$ - is the current limits that are prescribed in the IEEE 519-1992

8.3.10 Suggested tariff strategy 10

An additional charge can be added onto the current cost of a customer that are based on the ratio of $\frac{S_N}{S_1}$, because a increase in the current distortion will always increase the normalized value of $\frac{S_N}{S_1}$.

8.4 Conclusion

Several approaches may be taken in developing a tariff or incentive structure to encourage load behavior that has a minimal harmonic impact.

Chapter 9

Measurements and results

9.1 Aim of chapter

The aim of this chapter is to evaluate the tariff suggestions that were made in chapter 8 using measured data.

9.2 Introduction

Digital signal processing techniques can only be used when a analog signal is converted into its digital representation. This is implemented by using a analog-to-digital converter. If a analog signal *x(t)* is sampled every Δt seconds, then the time interval Δt is known as the sampling interval or sampling period. It's reciprocal, $1/\Delta t$, is known as the sampling frequency, with units of samples/seconds. Each of the discrete values of *x(t)* at t=0, Δt, $2\Delta t$, $3\Delta t$, *etc.*, is known as a sample.

The signal *x(t)* can therefore be represented by the discrete set of samples,

$$\{x(0), x(\Delta t), x(2\Delta t), x(3\Delta t), \ldots, x(k\Delta t), \ldots\}.$$

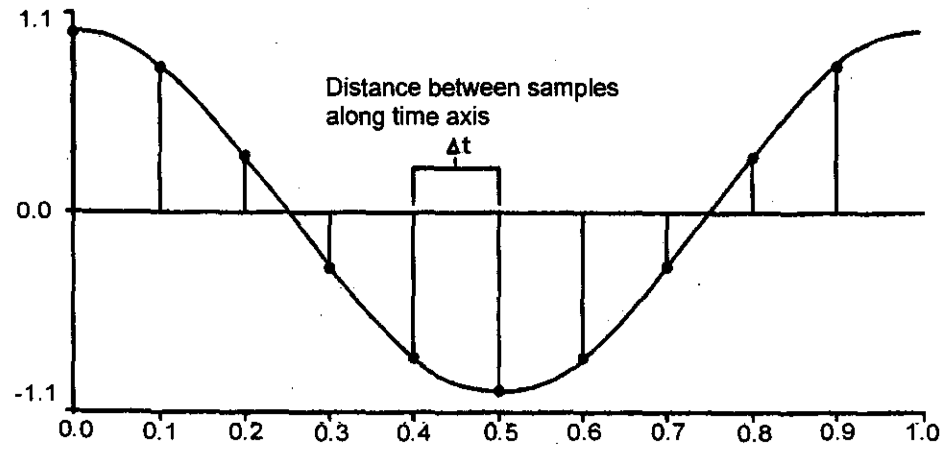


Figure 9.1 Analog Signal and corresponding sampled version

Figure 9.1 shows an analog signal and it's corresponding sampled version. The sampled interval is Δt. From figure 9.1, it can be observed that the samples are defined at discrete points in time.

The sampling rate determines how often an analog-to-digital (A/D) conversion takes place. A fast sampling rate acquires more points in a given time and can therefore form a better representation of the original signal than a slow sampling rate. Sampling too slowly may result in a poor representation of your analog signal. Figure 9.2 shows an adequately sampled signal, as well as the effects of under sampling.

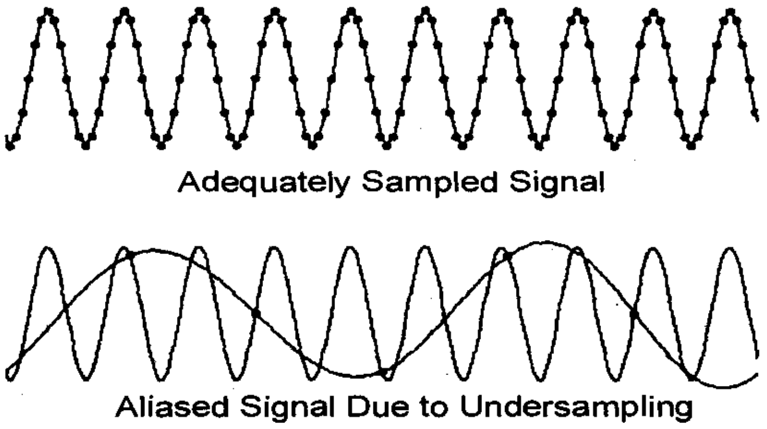


Figure 9.2 Aliasing effects of an improper sampling rate

The effect of under sampling is that the signal appears as if it has a different frequency than it truly does. This misrepresentation of a signal is called an alias.

9.3 Aliasing

According to Shannon's theorem [46], to avoid aliasing you must sample at a rate greater than twice the maximum frequency component in the signal that are acquired. For a given rate, the maximum frequency that can be represented accurately, without aliasing, is known as the Nyquist frequency. The Nyquist frequency is one half the sampling frequency. Signals with frequency components above the Nyquist frequency will appear aliased between DC and the Nyquist frequency. The alias frequency is the absolute value of the difference between the frequency of the input signal and the closest integer multiple of the sampling rate.

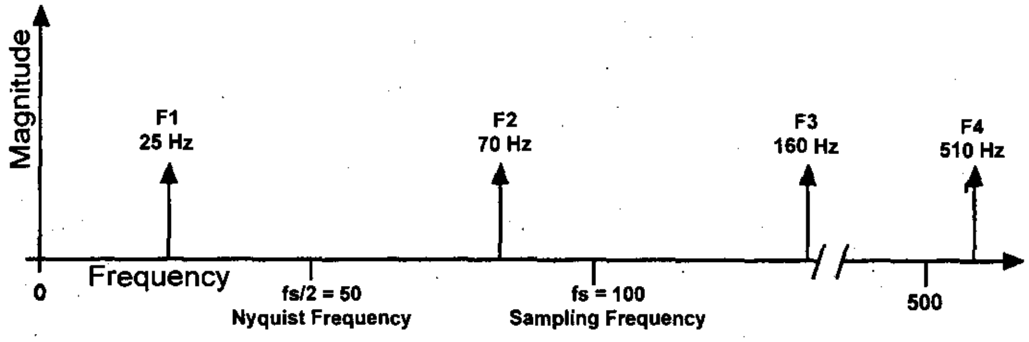


Figure 9.3 Actual signal frequency components

Figure 9.3 and 9.4 illustrate this phenomenon. For example, assume f_s, the sampling frequency, are 100 Hz. Also, assume the input signal contains the following frequencies - 25 Hz, 70 Hz, 160 Hz and 510 Hz. These frequencies are shown in figure 9.3.

In figure 9.4, we see that frequencies below the Nyquist frequencies ($f_s/2$ = 50 Hz) are sampled correctly. Frequencies above the Nyquist frequency appears as aliases. For example, F1 (25 Hz) appears at the correct frequency, but F2 (70 Hz), F3 (160 Hz), and F4 (510 Hz) have aliases at 30 Hz, 40 Hz, and 10 Hz, respectively. To calculate the alias frequency, use the following equation:

Alias frequency = ABS (Closest Integer Multiple of Sampling Freq. - Input Freq.)

where ABS means "the absolute value". For example,

$$\text{Alias F2} = |100-70| = 30 \text{ Hz}$$

$$\text{Alias F3} = |(2)100 - 160| = 40 \text{ Hz}$$

$$\text{Alias F4} = |(5)100-510| = 10 \text{ Hz}$$

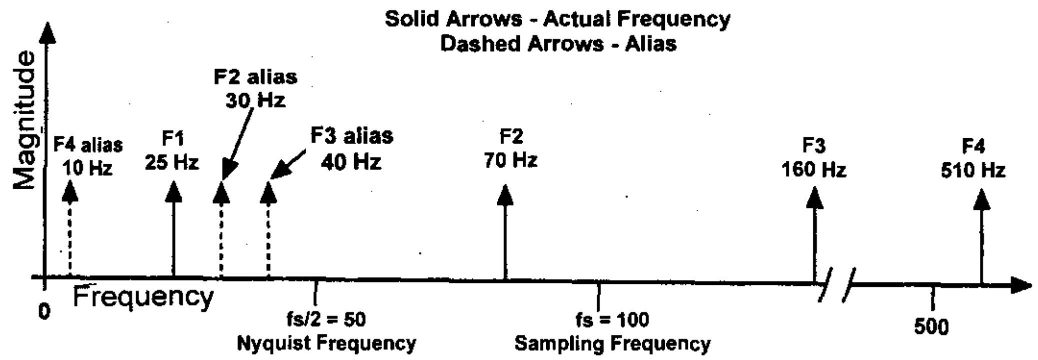
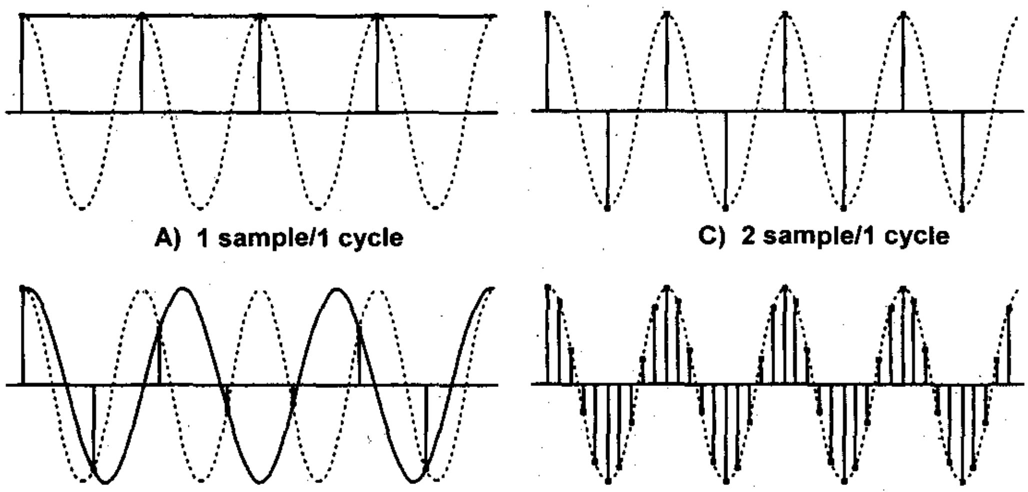


Figure 9.4 Signal frequency components and aliases

The sampling rate should be at least twice the maximum frequency of the signal that is being sampled. The maximum frequency of the input signal should be less than or equal to half of the sampling rate. To be completely sure that the frequency content of the input signal is limited, and contains no pickup of stray signals (such as power line frequencies or from the local radio stations), a low pass filter (a filter that passes low frequencies but attenuates the high frequencies) is added before the sampler and the ADC (analog to digital converter). This filter is called an anti-aliasing filter because by attenuating the higher frequencies (greater than Nyquist), it prevents the aliasing components from being sampled. Because before the sampler and the ADC, the signal that is sampled is still a analog filter, and the anti-aliasing filter is an analog filter.


A) 1 sample/1 cycle

C) 2 sample/1 cycle

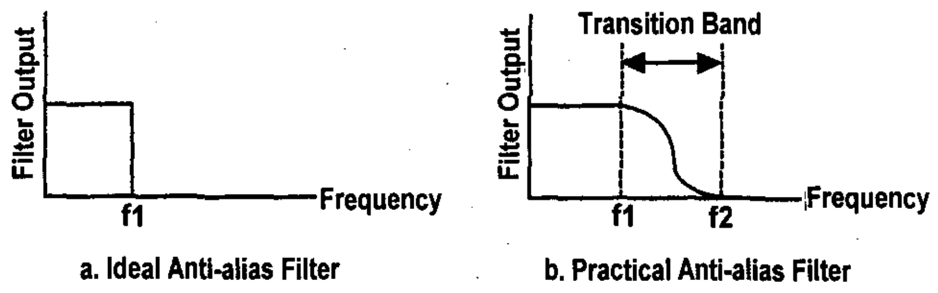
B) 7 sample/4 cycle

D) 10 sample/1 cycle

Figure 9.5 Effects of sampling at different rates

Figure 9.5 shows the effects of various sampling rates. In case a (figure 9.5(a)), the sine wave of frequency *f* is sampled at the same frequency f_s (samples/sec) = *f* (cycles/sec), or at 1 sample per cycle. The reconstructed waveform appears as an alias at DC. As you increase the sampling to 7 samples/4 cycles, as in case b (figure 9.5(b)), the waveform increases in frequency, but aliases to a frequency less than the original signal (3 cycles instead of 4). The sampling rate in case b is $f_s = (7/4)f$. If the sampling rate is increased to $f_s = 2f$, the sampled waveform has the correct frequency (the same number of cycles), and can be reconstructed as the original sinusoidal wave, as shown in case c (figure 9.5(c))

For time-domain processing, it may be important to increase your sampling rate so that the samples more closely represent the original signal. By increasing the sampling rate to well above *f*, ($f_s = 10f$ or 10 cycles/cycle), the sampled waveform can accurately be reproduce, as shwn in case d ((figure 9.5(d)). An ideal anti-aliasing filter is shown in figure 9.6(a).



a. Ideal Anti-alias Filter

b. Practical Anti-alias Filter

Figure 9.6 Ideal versus Practical anti-aliasing filter

It passes all the desired input frequencies (below f_1) and cuts off all the undesired frequencies (above f_1). However, such a filter is not physically realizable and in practice filters look as shown in figure 9.6(b). They pass all frequencies smaller then f_1 , and cut-off all frequencies greater than f_2 . The region between f_1 and f_2 is known as the transition band, which contains a gradual attenuation of the input frequencies. Although it is preferable that only frequencies smaller than f_1 passes through the filter, this signals in the transition band could still cause aliasing. Therefore, in practice, the sampling frequency should be greater then two times the highest frequency in the transition band.

9.2 Measurement set up

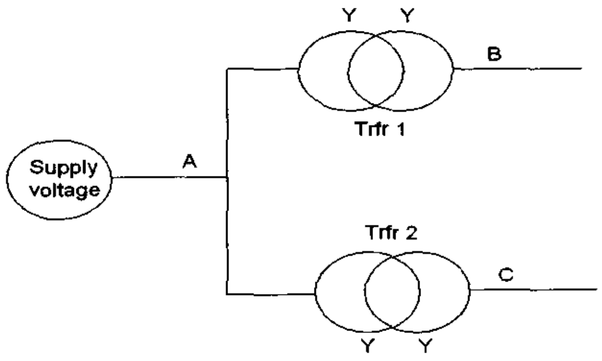


Figure 9.7 Network used in measurements but without the loads

All 3 phase voltages and line currents were measured at nodes *A*, *B* and *C* (see figure 9.7). The loads that were connected to transformer 1 (see figure 9.7) were resistive loads and the loads connected to transformer 2 consisted of a six-pulse converter and a three-phase rectifier.

First a set of measurements where performed with only the six pulse converter connected to transformer 2 and then a second set of measurements where performed with both the six pulse converter and the three phase rectifier connected to transformer 2. The resistive loads connected to transformer 1 where kept constant during each set of measurements.

The instrumentation setup used in the measurements can be seen in figure 9.8

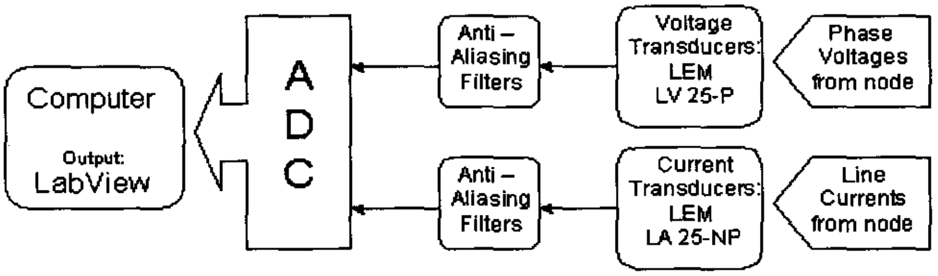


Figure 9.8 Instrumentation used in measuring the voltages and currents from nodes A, B and C

The anti-aliasing filters that were designed and developed, were a combination between Butterworth filters and Switched-capacitor filters (see figure 9.9).

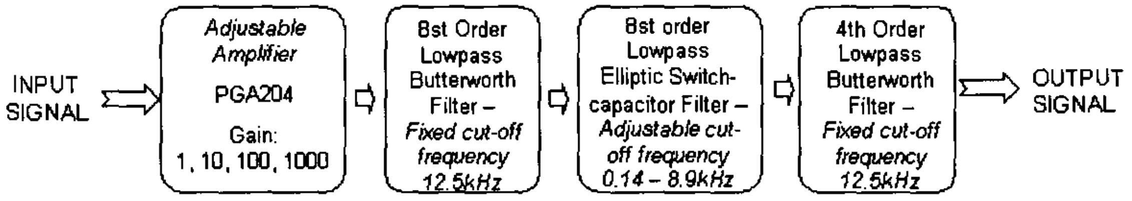


Figure 9.9 Anti-aliasing filter unit

The cut-off frequency of the filters were set at 2250 Hz during the measurements and the filter response can be seen in figure 9.10.

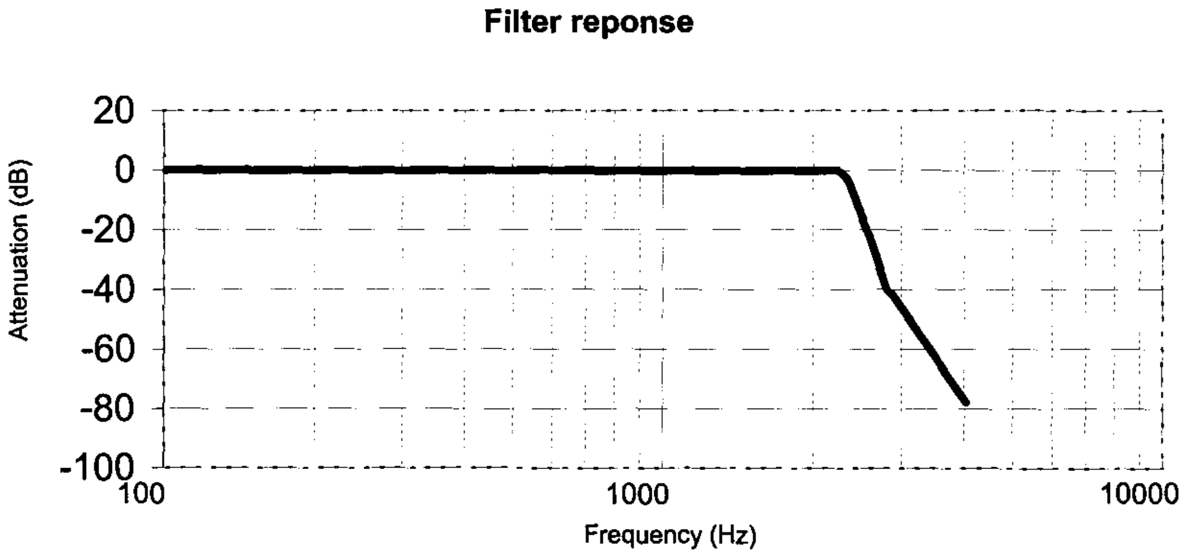


Figure 9.10 Filter response of anti-aliasing filter unit

9.4 Results

The rms current, *VTHD* and *ITHD* of each waveform were calculated using the IEEE definitions, defined in equations (7.27) and (7.33).

9.4.1 Measurements at nodes without any loads connected to the transformers

Measurements were done of the supply voltages (at node A see figure 9.7) and the voltages on the secondary side of the transformers (at node B and C see figure 9.7), without any loads connected to the transformers.

From table 9.1 and figure's 9.10 - 9.12, it can be seen that the voltage present in the Electrical laboratory was distorted before any experiments were performed. The distortion is the result of the many computer loads that are present at the university.

Table 9.1 Indexes calculated from data obtained from measurements at nodes

	Node A **(At supply)**	**Node B** **(At linear loads)**	**Node C** **(At non-linear loads)**
VTHD (%)	4.677983	4.677657	4.653022
V_{rms}	227.263418	233.671098	232.248577

The maximum voltage distortion prescribed by the NRS 048 part 4 is 8 % and by the IEEE 519-1992 is 5%. With reference to the NRS 048 part 4, the voltage distortion is ≈3.4% below the allowable level, but with respect to the IEEE 519-1992, the limit is close to the maximum value. If additional customers are added onto the network, they will be limited with respect to the distortion that they can produce.

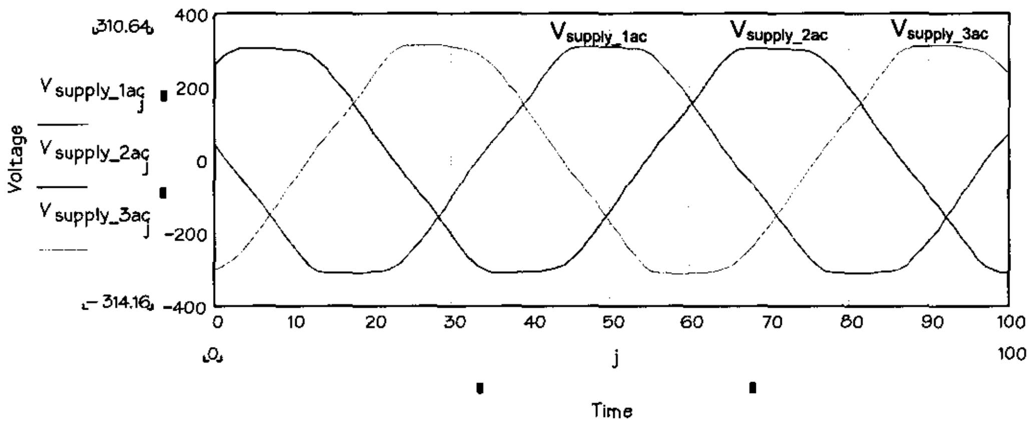


Figure 9.10 Voltage measured at node A

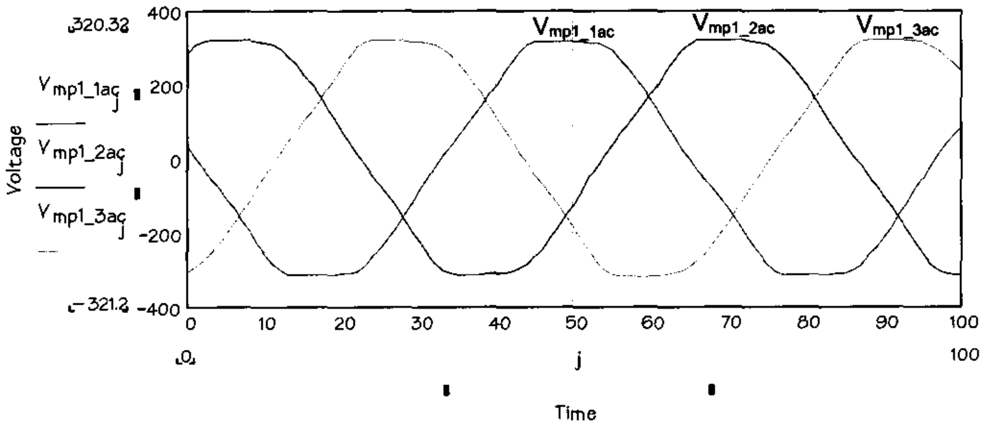


Figure 9.11 Voltage measured at node B

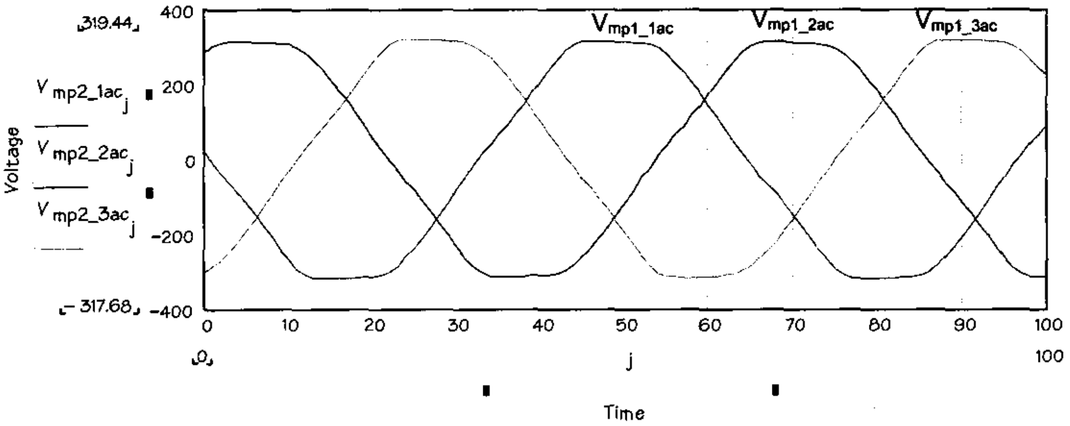


Figure 9.12 Voltage measured at node C

9.4.2 Measurements at nodes with linear loads connected to node B and only a six-pulse converter to node C

Table 9.2 Indexes calculated from data obtained from measurements at nodes

	Node A **(At supply)**	**Node B** **(At linear loads)**	**Node C** **(At non-linear loads)**
***VTHD* (%)**	4.234968	4.319143	4.248139
V_{rms} (V)	215.926859	216.198979	220.072813
I_{rms} (A)		4.180361	0.461529
***ITHD* (%)**		4.284598	24.190674

SLI		1.001508	1.004786
$\frac{ITHD}{VTHD}$		0.998854	5.694417

From figure 9.16 and table 9.2 it can be seen that the load current at node B is distorted although the load is linear. This is the result of the voltage distortion that was present at the PCC before any experiments where perform. If the *VTHD* values of table 9.1 and table 9.2 is compared it can be seen that the distortion did not increase, this is due to the small rms current (see figure 9.18 and table 9.2) of the nonlinear load. The ratio of $\frac{ITHD}{VTHD} \approx 1$ for the linear load and for the non-linear load it was $\frac{ITHD}{VTHD} > 1$. This result was obtained for all the measurements (see table 9.3 and table 9.4).

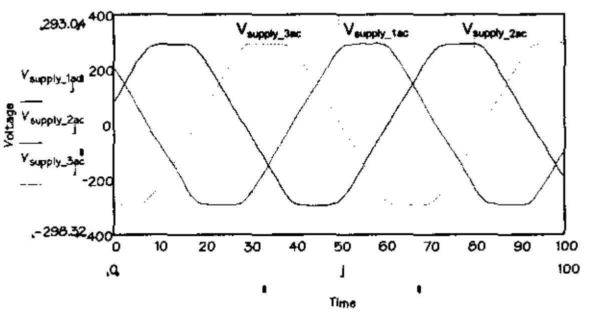


Figure 9.13 Phase voltages measured at node A

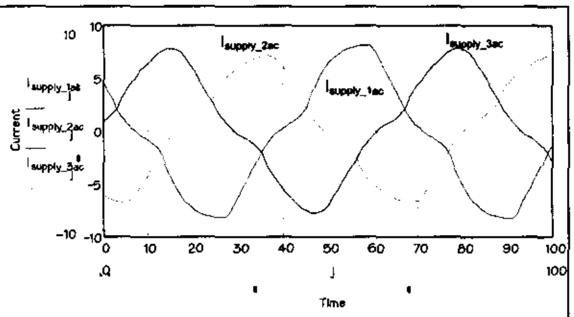


Figure 9.14 Phase currents measured at node A

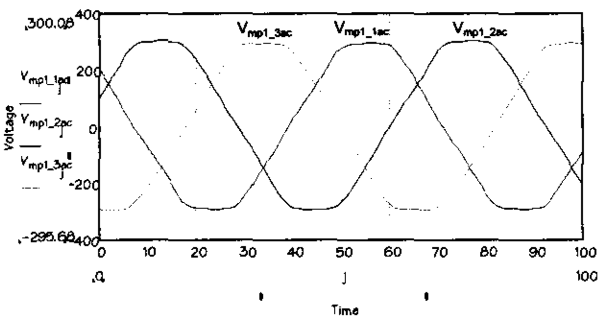


Figure 9.15 Phase voltages measured at node B

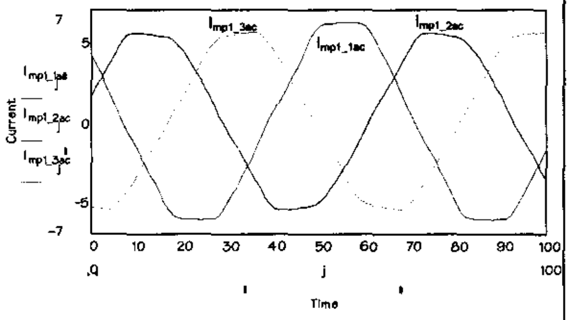


Figure 9.16 Phase currents measured at node B

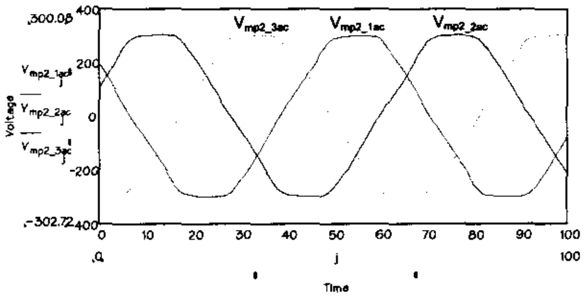


Figure 9.17 Phase voltages measured at node C

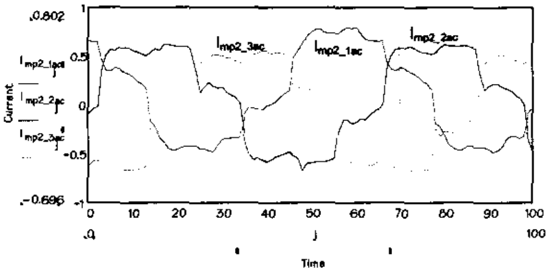


Figure 9.18 Phase currents measured at node C

9.4.3 Measurements at nodes with resistive loads connected to node B, with a six-pulse converter and three phase rectifier connected to node C

With an increase in the current of the nonlinear load (see table 9.3 and figure 9.24), the voltage distortion also increased due to higher voltage drops occurring across the supply impedances (see figure 9.19). Due to the increase in the voltage waveform distortion, there was an increase in the current waveform distortion of the linear load (see table 9.3, figure 9.21 and figure 9.22). Figure 9.20 shows the supply current and it can be seen that the distortion of the waveform also increased when it is compared with figure 9.14.

Table 9.3 Indexes calculated from data obtained from measurements at nodes

	Node A	Node B	Node C
VTHD (%)	5.460349	5.502396	5.990431
I_{rms} (A)		4.118745	4.512831
ITHD (%)		5.551872	26.545141
SLI		1.002261	0.999884
$\frac{ITHD}{VTHD}$		0.976129	4.431257

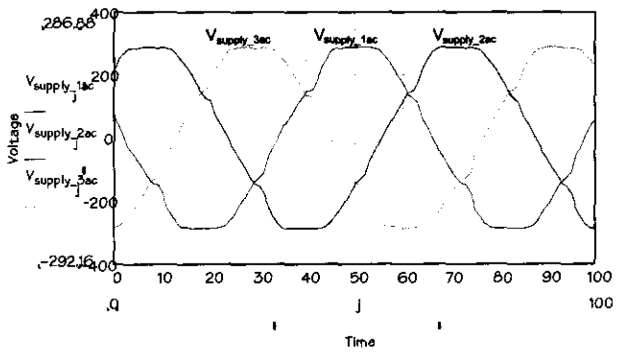


Figure 9.19 Phase voltages measured at node A

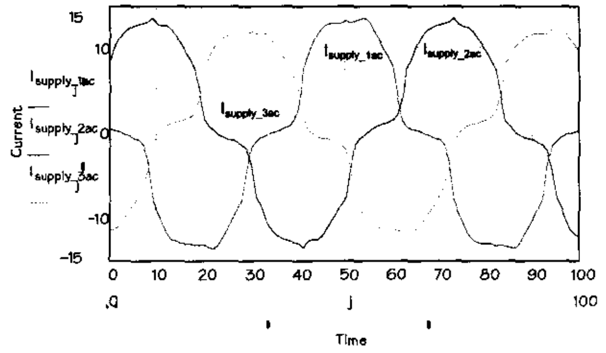


Figure 9.20 Phase currents measured at node A

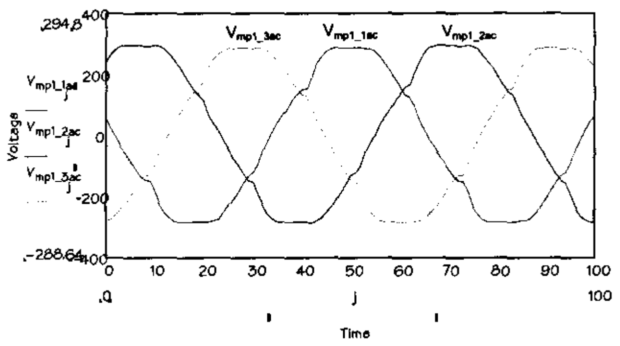


Figure 9.21 Phase voltages measured at node B

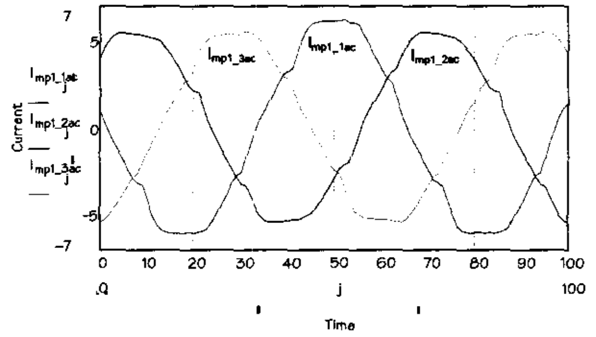


Figure 9.22 Phase currents measured at node B

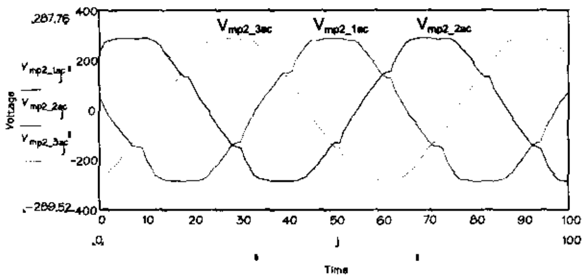


Figure 9.23 Phase voltages measured at node C

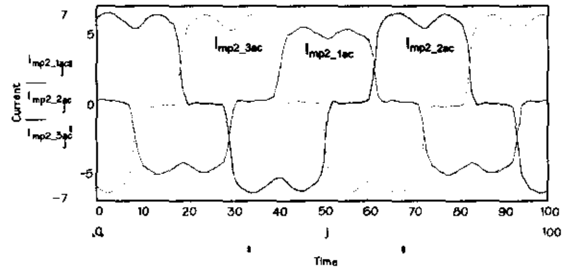


Figure 9.24 Phase currents measured at node C

9.4.4 Measurements at nodes with only an increase of loading at node C

With a further increase of the current of the nonlinear load (see table 9.4 and figure 9.30) the voltage distortion also increased. Due to the increase in the voltage waveform distortion, there was an increase in the current waveform distortion of the linear load (see table 9.4, figure 9.27 and figure 9.28).

Table 9.4 Indexes calculated from data obtained from measurements at nodes

	Node A	Node B	Node C
VTHD (%)	6.379074	6.513283	7.278494
V_{rms} (V)	210.008365	206.954689	201.704882
I_{rms} (A)		4.075877	6.782437
ITHD (%)		6.700745	25.47083
SLI		1.003288	0.997256
$\frac{ITHD}{VTHD}$		1.010832	3.499464

If additional non-linear customers were connected to the PCC the voltage distortion can increase above the allowable limits prescribed by the NRS 048 and the utility will be forced to do compensation, to allow the network to develop. If compensation is not performed than new customers will not be allowed to pollute the network and it would not be fair.

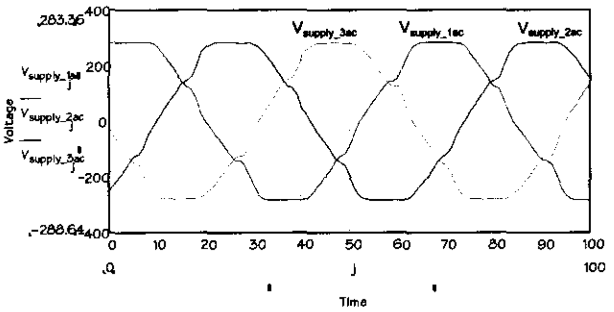


Figure 9.25 Phase voltages measured at node A

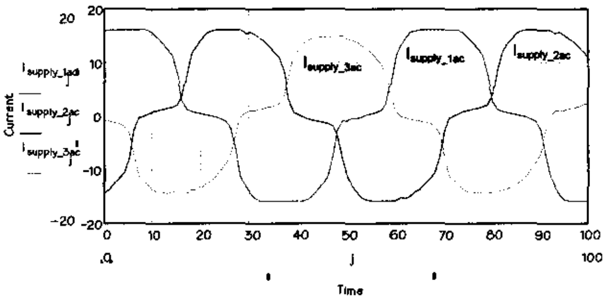


Figure 9.26 Phase currents measured at node A

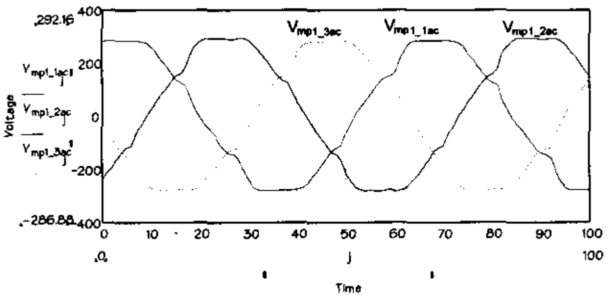


Figure 9.27 Phase voltages measured at node B

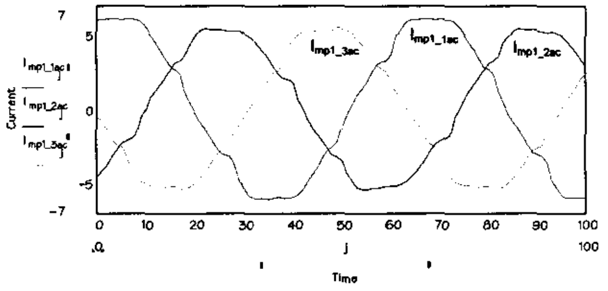


Figure 9.28 Phase currents measured at node B

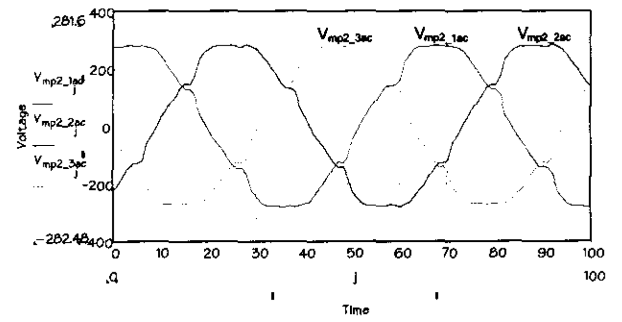


Figure 9.29 Phase voltages measured at node C

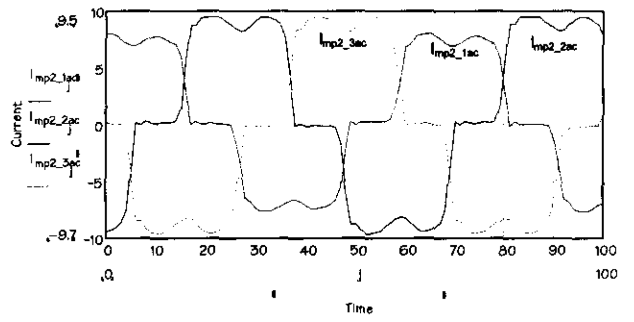


Figure 9.30 Phase current measured at node C

9.4.5 Evaluation of different strategies

9.4.5.1 Tariff strategy 1

A customer having non-linear loads must be charged for energy W_1 as defined in equation 8.7.

Table 9.5 Energy W_1 calculated over a period of 30 seconds

	Node B: Resistive load, Node C: Six-pulse converter	Node B: Resistive load, Node C: Six-pulse converter + Three phase rectifier	Increase in loading at node C, load at node B stay constant
Node B	2280 J	2183.5 J	2127.4
Node C	238.7 J	2278.3 J	3317.7 J

From table 9.5 it can be seen that the energy that is calculated based on the fundamental power remains the same for the linear. Energy consumed by the non-linear load increases as the load current increases for the non-linear load.

The fundamental power also transmits the harmonic powers that are injected back into the power system by non-linear loads, so any revenue that were lost can be recovered.

The energy consumed by any load that do not inject harmonic powers back into the power system will not be effected by an increase in voltage distortion at the point of common coupling.

9.4.5.2 Tariff strategy 2

The additional component W_h should be priced accord to the induced extra costs, which will be a higher rate then the rate for W.

It can be seen from table 9.6 that the linear load absorbs harmonic power and as the voltage distortion increase there is a increase in the harmonic powers that are absorbed by the linear load. It can also be seen that with an increase of the non-linear load current, the harmonic powers that this load inject into the power system also increases.

From figure 9.31 it can be seen that at some harmonic frequencies the non-linear load absorbs power and at other frequencies they inject power into the system. By summing al these powers, the customer does get compensation for absorbing power.

Table 9.6 Energy W_h calculated over a period of 30 seconds

	Node B: Resistive load, Node C: Six-pulse converter	**Node B: Resistive load, Node C: Six-pulse converter + Three phase rectifier**	**Increase in loading at node C, load at node B stay constant**
Node B	-3.437831 J	-4.936276	-6.994916
Node C	-1.142242 J	0.264043	9.105337

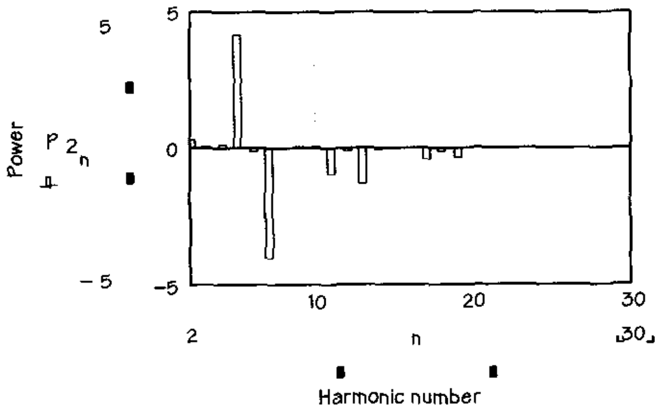


Figure 9.31 Harmonic Power spectrum of phase 2 of the nonlinear load connected to node C

9.4.5.3 Tariff strategy 4

A utility can charge different amounts for powers at different frequencies.

Table 9.7 Values of the power spectrum

	Watt (W)	Node B: Resistive load, Node C: Six-pulse converter	Node B: Resistive load, Node C: Six-pulse converter + Three phase rectifier	Increase in loading at node C, load at node B stay constant
Node B	P_1	2695.87349	2581.743423	2515.392142
	P_2	0.913031985	0.783370295	0.869330235
	P_3			1.27949743
	P_5	1.796473331	1.07287488	0.905129315
	P_7	0.701448539	2.436722221	3.79165055
Node C	P_1	282.21	2693.810511	3922.855201
	P_2		0.9070P74527	1.232185204
	P_3		1.172926815	2.219962857
	P_5	1.3115	8.925682254	4.855145898
	P_7		-4.443584893	-8.837486582
	P_{11}		-2.248671392	-3.223243687
	P_{13}		-1.666355392	-3.269670964
	P_{17}		-0.559870949	-1.04509724
	P_{19}		-0.528031643	-0.770419952

From table 9.7 it can be seen that the linear load only absorb harmonic powers as was expected. At higher frequencies, the non-linear loads connected to node C inject harmonic powers into the power systems and at the lower harmonic frequencies, the non-linear loads absorb harmonic powers, this is due to the distortion that was present when the loads was connected to the PCC.

If this strategy is used, and a load absorbs power at frequencies higher then the fundamental, then the sign of the power must be negative and if a load inject power into the power system then the sign of the power must be positive.

When the above discrimination is used, then customers will be compensated if they absorb harmonic powers and they will be penalized if they inject harmonic powers.

9.4.5.4 Tariff strategy 6

Charge for true power factor

Table 9.8 Values of the *TPF* and *DPF* that was calculated

		Node B: Resistive load, Node C: Six-pulse converter	**Node B: Resistive load, Node C: Six-pulse converter + Three phase rectifier**	**Increase in loading at node C, load at node B stay constant**
Node B	***TPF***	0.998148	0.999543	0.999578
	DPF	0.99818	0.999559	0.999602
Node C	***TPF***	0.954409	0.995867	0.995137
	DPF	0.953722	0.995277	0.994194

From table 9.8 it can be seen that the values of the *TPF* and *DPF* is the same.

With reference to the linear load, it can be seen from table 9.7 that the powers that are absorb is very small therefore it does not have any effect on the *TPF*.

With reference to the non-linear loads, it can be seen from table 9.7 that the loads absorb and inject powers therefore the summation of these powers result to a small value, and does not have any effect on the *TPF*.

9.4.5.5 Tariff strategy 7

Charge for the "harmonic adjustment power factor" (HPF).

Table 9.9 *HPF* calculated at different weighting factors

HPF	Weighting factor	Node B: Resistive load, Node C: Six-pulse converter	Node B: Resistive load, Node C: Six-pulse converter + Three phase rectifier	Increase in loading at node C, load at node B stay constant
Node B	$h^{0.5}$	0.996674	0.996379	0.995122
	h^{1}	0.99379	0.988681	0.984812
	$h^{1.3}$	0.989444	0.97536	0.967796
Node C	$h^{0.5}$	0.892319	0.917198	0.918498
	h^{1}	0.798574	0.824975	0.834386
	$h^{1.3}$	0.6852	0.724396	0.74258

From table 9.9 it can be seen that the *HPF* for the linear load at different weighting factors remains relatively high (above 0.96) but there is a slight decrease as the weighting factors increase.

For the non-linear loads, the *HPF* decreases as the weighting factors increase (see table 9.9).

9.4.5.6 Tariff strategy 8

By introducing weighting factors, a new index (equation 8.26) can be defined that are based on the total harmonic current distortion index.

Table 9.10 Current distortion values calculated

Current distortion (%)	Weighting factor	Node B: Resistive load, Node C: Six-pulse converter	Node B: Resistive load, Node C: Six-pulse converter + Three phase rectifier	Increase in loading at node C, load at node B stay constant
Node B	$h^{0.5}$	6.435564	8.881204	10.705322
	h^{1}	9.973975	15.407872	18.188148
	$h^{1.3}$	13.694609	22.817726	26.504847
Node C	$h^{0.5}$	38.926393	41.784724	39.864135
	h^{1}	66.306458	67.434776	63.606558
	$h^{1.3}$	98.010209	94.424346	88.007081

From table 9.10 it can be seen that the value of the current distortion increases as the weighting factors increase. The increase that occurs due to higher weighting factors is also substantially bigger for the non-linear loads as for the linear loads.

It would be unfair to add a additional charge to a customer having only linear loads since the load current is distorted as a result of the voltage that where distorted at the customers supply point.

From table 9.7 it can be seen that at the lower order harmonics (2nd, 3rd and 5th) the non-linear loads connected to node C absorbs harmonic powers and the current distortion is the result of the voltage that are present at the supply point of the loads. At higher harmonic frequencies, the non-linear loads inject power back into the power system.

Equation 8.26 can be divided into two different indices where each one addresses the current distortion as a result of the direction of the power flow. The indices can be defined as:

$$Distortion_{S-L} = \frac{\sqrt{\sum_{N=2}^{\infty} K_N \cdot I_{N_{S-L}}}}{I_1} \tag{9.2}$$

where $I_{N_{S-L}}$ is defined as the current that is a result of power flow from the source to the load, and

$$Distortion_{L-S} = \frac{\sqrt{\sum_{N=2}^{\infty} K_N \cdot I_{N_{L-S}}}}{I_1} \tag{9.3}$$

where $I_{N_{L-S}}$ is defined as the current that is a result of power flow from the load to the source.

These index, $Distortion_{S-L}$ will then be the distortion as a result of power flowing from the source to the load, and it can be used to give a incentive to the customer. These index, $Distortion_{L-S}$ will then be the distortion as a result of power flowing from the load to the source, and it can be used to give a penalize the customer.

9.4.5.7 Tariff strategy 9

A utility can charge different amounts for currents at different frequencies

Table 9.11 Current values calculated

		Current limits IEEE 519-1992 (% of fundamental)	Direction of power flow	Node B: Resistive load, Node C: Six-pulse converter	Node B: Resistive load, Node C: Six-pulse converter + Three phase rectifier	Increase in loading at node C, load at node B stay constant
Node B	I_1 (A)		+	12.5036615	12.30933843	12.19282372
	I_2 (%)	2.5	+	1.70940832	1.682811876	1.757772694
	I_3	10	+			2.324979837
	I_5	10	+	2.836412246	2.178908359	1.900545225
	I_7	10	+	1.688478051	3.223642385	4.181403896
Node C	I_1 (A)		+	1.34575883	13.02850585	19.6043439
	I_2 (%)	2.5	+		1.839682038	1.780769985
	I_3	10	+		2.737382714	2.776035172
	I_5	10	+	16.96937021	22.51881195	21.50153143
	I_7	10	-		8.195200342	8.937795643
	I_{11}	4.5	-		6.368416314	5.919925221
	I_{13}	4.5	-		4.33037037	4.207684997
	I_{17}	4.5	-		2.812917124	2.332614707
	I_{19}	4.0	-		2.264368112	1.763352723

The value of the fundamental current is given in amperes, whereas the currents at the different harmonic frequencies are given as a percentage of the fundamental so that it can be compared with the limits given by the IEEE 519-1992.

The current values in Table 9.11 that is associated with power flow from the load to the source must be subtracted from the harmonic limits that were agreed upon by the utility and customer.

Discrimination must also be made between linear and non-linear loads because these harmonic currents are a result of the distorted voltages that was present at the supply point of the load. The ratio of the *ITHD* and *VTHD* give an indication whether the load connected to the PCC is linear or not (see tables 9.2, 9.3 and 9.4). For a linear load, the ratio is approximately 1 and for the nonlinear loads it is higher then 1.

The short-circuit current in the laboratory was measured and the value is 1380 A. The maximum demand load current was 19.60 A and the short circuit ratio was calculated as 70.41. The harmonic limits were then obtained from table 4.6 and listed in table 9.11.

It can be seen from table 9.11 that the measured values at the fifth and seventh harmonics are above the limits prescribed by the IEEE 519-1992. The fifth harmonic power is absorbed by the load and must be the result of the supply voltage that was distorted, initially. The customer can therefore not be penalized for absorbing the harmonic power. At the seventh harmonic frequency, the load injects powers back into the system, and the current limit exceeds the allowed limit prescribed by the IEEE 519-1992. A customer can be penalized with respect to the percentage that the limit is exceeded.

9.4.5.8 Tariff strategy 11

Add an additional charge based on the ratio of $\frac{S_N}{S_1}$.

Table 9.11 Current values calculated

		Node B: Resistive load, Node C: Six-pulse converter	Node B: Resistive load, Node C: Six-pulse converter + Three phase rectifier	Increase in loading at node C, load at node B stay constant
Node B	$\frac{S_N}{S_1}$	0.18316	0.23027	0.275141
Node C	$\frac{S_N}{S_1}$	0.736019	0.814002	0.799022

The ratio of $\frac{S_N}{S_1}$ is smaller for the linear load connected to node B, then for the non-linear load connected to node C. As the current distortion increases (see tables 9.2, 9.3 and 9.4), the normalized ratio of $\frac{S_N}{S_1}$ also increases.

9.5 Conclusion

The IEEE 519-1992 and the NRS 048 can only be use to measure whether a customer exceeds the allowable limits, and a additional method will have to be obtained to penalise customers who exceed their limits. Each customer's limit should be prescribed in terms of the amount of harmonic current that the can emit into the power system and the utilities obligation must be prescribed in terms of the voltage limits.

The direction of harmonic active power flow was shown by [26][27] to be inconclusive in identifying the type of load to be linear or non-linear, but it is not desirable for any load to inject harmonic powers into the power system. If a load exhibits characteristics of injecting active powers at harmonic frequencies into the power system, it contributes to the distortion and losses, and therefore it should be penalized.

All the tariff strategies that was evaluated, except for strategy 6 (*DPF* vs. *TPF*), was progressive.

Strategy 11 ($\frac{S_N}{S_1}$), 7 (*HPF*) and 8 ($ITHD_{modified}$) is not discrimitive meaning that penalties could be added to a customer that has only linear loads and that is undesirable. The numeric values obtained from these strategies shows a difference between the types of loads. The ratio of $\frac{ITHD}{VTHD}$ gives an indication whether the loads is linear or non-linear, and it could be used as a prerequisite before adding a penalty to a customers account.

Strategy 1 (W_1) is conclusive but do not take into account the additional losses due to the harmonic powers that are injected back into the power system and additional costs. Strategy 2 (W_h) do take into account since additional cost can be added and since P_h is the summation of all the harmonic powers, a customer will get compensation for absorbing harmonic powers.

Strategies 4 (powers at different frequencies) and 7 (currents at different frequencies) can be used to penalize and give incentives to the customers since they focus on individual harmonic frequency components. If strategy 6 is modified as discussed in 9.3.4.6 it can also be used.

Chapter 9

9.1 Conclusion

It is evident that harmonic pollution of power network is widely diverse and causes problems for utilities as well as customers. The impact that these harmonics can have on the network and other equipment operating from it can range from a minor annoyance to system disfunction and disruption in operation. Increased cost resulting from harmonic currents and voltages are shared at present by all ratepayers. As stated in the Energy Policy White Paper, electricity tariffs shall be cost reflective in the medium to long term [45]. Cost reflectivity means that tariffs shall be based closely as possible on the underlying cost of supply plus a reasonable profit margin. Rate structures must be modified to more fairly allocate these increased costs.

The supply contracts for key customers of Eskom (discussed in chapter 6), describes both the utility as well as the customers obligations with respect to power quality issues. There are no economic penalties incorporated into their tariff structures or contracts, (discussed in chapter 7) for when the prescribed harmonic apportioning limits are exceeded or economic incentives for improving the power quality of their plant.

If economic incentives are introduced, then customers will benefit by designing or improving the plants to reduce their harmonic distortion. This property should stimulate the investment of money to linearise plants. Such actions will improve the energy flow of the entire power system and will benefit the utility in an economic sense. Economic penalties will thus force customers to take power quality issues seriously.

Compliance with the voltage and current distortion limits of Harmonic Apportioning Standards will result in relatively low harmonic power being produced at non-linear loads. It will reduce harmonics in the system and system losses related to current harmonics.

The implementation of harmonic pricing should commence with mandatory metering of large customers, followed by a voluntary rate options for small customers.

Several approaches may be taken in modifying rate structures that encourage load behavior that has a minimal harmonic impact. The indices or power definitions that are used for quantifying harmonic distortion for revenue purposes, must present a good compromise between theoretical aspects and practical applicability, as such it must be useful and practical. These definitions or indices should be tested extensively in the field, and must be able to adapt to the various practical situations. The indices or definitions should be evaluated as to the possibility of implementation in new electronic revenue meters. These meters must be able to measure the appropriate quantities required

9.2 Conference contributions

The following papers were presented and published with regards to this research in the respective conferences proceedings:

1. Bezuidenhout S.L., Rens A.P.J., "Comments on a comparative study into the application of the NRS 048 (South Africa), IEC 61000-3-2 and IEEE 519-1992 on harmonic apportioning in a discrimitive tariff structure", 3rd Southern African Power Quality Conference (SAPQ), Livingstone - Zambia, Session 4 – Implementing Power Quality Standards, 31 October – 2 November 2001, pp. 1 – 12

2. Bezuidenhout S.L, Rens A.P.J, "Comments on a comparative study into the application of the NRS 048 (South Africa), IEC 61000-3-2 and IEEE 519-1992 on harmonic apportioning in a discrimitive tariff structure", SAUPEC 2002, Vaal Triangle Technikon, 31 January 2002 – 1 February 2002 pp. 249 - 255

3. Bezuidenhout S.L, Rens A.P.J, "Considerations on tariff strategies for nonsinusiodal conditions", 6th Africon Conference in Africa, George, 2 – 4 October 2002, Vol. 2, pp. 823 - 828

The paper that was presented at the 6th Africon Conference was also submitted for publication in the transactions of the South African Institute For Electrical Engineers (SAIEE).

9.3 Future work

A change in the billing structure of a utility that may affects many customers and a utilities business can be a sensitive matter, which involves not only technical, but also economical and legal issues. Therefore, a change in the billing structure requires very strong, reliable and convincing justification, based mainly on economical analysis and these studies should be done to further a holistic solution to the quest of establishing a comprehensive management structure of non-sinusoidal conditions in a power system.

List of References

1. Task Force on Harmonics Modeling and Simulation, Modeling and simulation of the propagation of harmonics in electric power networks, Part I: Concepts, models and simulation techniques, IEEE Transactions on Power Delivery, Vol. 11, No. 1, January 1996, pp. 452 - 465

2. Swart P H, van Wyk J D, Case M J, "On Techniques for Localization of Sources Producing Distortion in Three Phase Networks", ETEP, Vol. 6, No. 6, Nov. 1996, pp 391-396

3. Rens A P J, Swart P H; On Techniques for the Localization of multiple distortion sources in three-phase networks: time domain verification, Fifth International Workshop on Power Definition and Measurements under Nonsinusoidal Conditions, Milan, October 2000, pp 55 –60

4. Srinivan K, On separating customer and supply side harmonic contributions, IEEE Transactions on Power Delivery, Vol. 112, April 1996, pp. 1003 - 1012

5. Czarnecki L.S, "What is wrong with the Budeanu concept of Reactive and Distortion Power and why it should be abandoned.", IEEE Transactions on Instrumentation and Measurement, Vol. IM-35, no. 3, September 1987, pp. 834 – 837

6. Depenbrock M, Marshall D.A., van Wyk J.D., "Formulating requirements for a universal applicable power theory as control algorithm in power compensators", Second International Workshop on Power definitions and Measurement under Non-sinusoidal Conditions, Stresa Italy, September 1993

7. Swart P.H., van Wyk J.D., "Definitions of Power under Distorted condition", The South African Institute of Electrical Engineers Power Section Tutorial

8. Czarnecki L.S, "Distortion power in systems with nonsinusiodal voltage", IEEE proceedings-B, Vol. 139, No. 3, May 1993, pp. 276 - 280

9. van Wyk J.D, "The measurement and compensation of reactive power in distribution systems with harmonics: Course NE4."

10. Czarnecki L,S, "Orthogonal decomposition of the currents in a 3-phase non-linear asymmetrical circuit with a nonsinusoidal voltage source.", IEEE Transactions on Instrumentation and Measurement, Vol. 37, no. 3, March 1988, pp. 30 - 34

11. Eskom, " Electricity Supply Agreement - Contract for Key Customers"

12. Arrilaga J, Bradly D A, & Bodger D A, Power System Harmonics, John Wiley & Sons Ltd, 1983.

13. Glover J D, Sarma M, 1994. Power System Analysis and design. PWS Publishing Company Boston, 1994.

14. NRS 048-2:1996

15. NRS 048-4:1996 Draft 1

16. IEEE 519-1992: IEEE Recommended Practices and Requirements for Harmonic

Control in Electric Power Systems

17. IEC 61000-3-2: Limits for harmonic current emissions (equipment input current ≤ 16 A per phase)

18. EPRI REPORT No. EM-2037, Techniques for energy conservation in AC motor driven systems.

19. Xu W, Liu Y, A method for determining customer and utility harmonic contributions at the point of common coupling, IEEE Transactions on Power Delivery, Vol. 15, No. 2, April 2000, pp. 804 - 811

20. McEachern A, Grady W M, Moncrief W A, Heydt G T, McGranaghan M, Revenue and Harmonics: An Evaluation of some proposed rate structures, IEEE Transactions on Power Delivery, Vol. 10, No. 1, January 1995, pp. 474 – 482

21. Czarnecki LS, Comments on Active Power Flow and Energy Accounts in Electrical Systems with Nonsinusoidal Waveforms and Asymmetry, IEEE Transactions on Power Delivery, Vol. 11, No. 3, July 1996

22. Sawicki J, Galewsi M, Economical definition of distortion power, Proceeding of the Spring Seminar on Nonsinusoidal Systems, Zielona Gora University, Poland, 1989

23. Sasdelli R, Muscas C, Perreto L, A VI-based measurement system for sharing the customer and supply responsibility for harmonic distortion, IEEE Transactions on Instrumentation and Measurement, Vol. 47, No. 5, October 1998, pp. 1335 –1340

24. Emanuel AE, On the assessment of harmonic pollution of power system, IEEE Transactions on Power delivery, Vol. 103, July 1995, pp. 1693 – 1698

25. Srinivan K, On separating customer and supply side harmonic contributions, IEEE Transactions on Power Delivery, Vol. 112, April 1996, pp. 1003 - 1012

26. Swart P H, van Wyk J D, Case M J, On Techniques for Localization of Sources Producing Distortion in Three Phase Networks, ETEP, Vol. 6, No. 6, Nov. 1996, pp 391-396

27. Rens A P J, Swart P H; On Techniques for the Localization of multiple distortion sources in three-phase networks: time domain verification, Fifth International Workshop on Power Definition and Measurements under Nonsinusoidal Conditions, Milan, October 2000, pp 55 –60.

28. Heydt G T, Jewell W T, Pitfalls of Electric Power Quality Indices, IEEE Transactions on Power Delivery, Vol. 13, No. 2, April 1998, pp. 570 - 576

29. IEEE Working Group On Nonsinusiodal Situations: Effects of Meter Performance and Definitions of Power, Practical Definitions for Powers in Systems with Nonsinusoidal Waveforms and Unbalanced Loads: A Discussion, IEEE Transactions o Power Delivery, Vol. 11, No. 1, January 1996, pp. 79 - 101

30. Arseneau R, Heydt G T, Kempker M J, Application of IEEE Standard 519-1992 Harmonic Limits for Revenue Billing Meters, IEEE Transactions on Power Delivery, Vol. 12, No. 1, January 1997, pp. 346 - 352

31. Sabin D D, Brooks D L, Sundaram A, Indices for Assessing Harmonic Distortion from Power Quality Measurements: Definitions and Benchmark Data, IEEE Transactions on Power Delivery, Vol. 14, No. 2, April 1999, pp. 489 - 496

32. Enslin J, Van Wyk J, Measurement and Compensation of Fictitious Power Under Nonsinusoidal Voltage and Current Conditions, IEEE Transactions on Instrumentation and Measurement, 1988

33. Filipski P S, Arseneau R, Definitions and Measurement of Apparent Power Under Distorted Waveform Conditions, IEEE Tutorial Course on Nonsinusoidal Situations: Effects of Performance of Meters, 1990, pp. 35 - 42

34. Emanuel A E, On the Definition of Power Factor and Apparent Power in Unbalanced Polyphase Circuits, IEEE Transactions on Power Delivery, Vol. 8, No. 3, July 1993, pp. 841 - 852

35. Emanuel A E, Apparent Power Definitions For Three-Phase Systems, IEEE Transactions on Power Delivery, Vol. 14, No. 3, July 1999, pp. 767 - 772

36. Arseneau R, Heydt G T, Kempker M J, Application of IEEE Standard 519-1992 Harmonic Limits for Revenue Billing Meters, IEEE Transactions on Power Delivery, Vol. 12, No. 1, January 1997, pp. 346 - 352

37. Xu W, Mansour Y, Siggers C, Hughes M B, Developing Utility Harmonic Regulations based on IEEE STD 519, IEEE Transactions on Power Delivery, Vol. 10, No. 3, July 1995, pp. 1423 - 1431

38. Seeto D, He S, Woo C, Pricing electric harmonics, Energy Vol. 20, no. 7, 1995, pp. 617 - 621

39. Report of the IEEE Task Force on the Effects of Harmonics on Equipment, Effects of Harmonics on Equipment, IEEE Transactions on Power Delivery, Vol. 8, No. 2, April 1993, pp. 672 -680

40. Lembo F, D'Onofrio VH, Distribution Harmonics Cause Breaker Problems, Electrical World, September 1981, pp. 121 - 122

41. Brozek JP, The Effects of Harmonics on Overcurrent Protection Devices, Proc. 1990 IAS, 1990, pp. 1965 - 1967

42. Heydt GT, Electric Power Quality, Stars in a Circle publications, Lafayette, Indiana, 1991

43. ANSI/IEEE C57.110-1986, IEEE Recommended Practice for Establishing Transformer Capability when Supplying Nonsinusoidal Load Currents

44. Kerszenbaum I, Mazur A, Mistry M, Frank J, Specifying dry-type distribution transformers for solid-state applications", IEEE transactions on industry Application, Vol. IA-22, No. 1, January/February 1986, pp. 161 - 177

45. Ellman M, The wholesale electricity pricing system (WEPS), Power Journal of the South African Institute of Electrical Engineers, Energize September/October 2001, pp. 34 - 36

46. National Instruments, LabVIEW Measurements Manual, July 2000 Edition, Part

Number 322661A-01

47. Cristaldi L, Ferrero A, Salicone S, A Distributed System for Electric Power Quality Measurements, IEEE Transactions on Instrumentation and measurement, Vol. 51, No. 4, August 2002, pp. 776 – 781

48. Mohan N, Undeland, Robbins W.P, Power Electronics: Converters, Applications, and Design, Second Edition, John Wiley & Sons Inc., New York , 1995