Cape Peninsula
University of Technology

ANALYSIS FOR ELECTRICAL ENERGY AND OVERALL EFFICIENCY IN DISTRIBUTION NETWORKS WITH HARMONIC DISTORTION

by

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DECLARATION

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

Signed **Date**

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ABSTRACT

Traditionally, harmonics are ignored in overall efficiency and energy usage studies. However, in the modern era, power systems contain levels of harmonics which can no longer be ignored by engineers, planners, energy conservationists and economists. The directions of power flows have to be considered when harmonics are present in the power network.

A methodology and new formulae for individual and overall efficiency and energy usage is developed at each frequency (f_1, h and H) and forms the main contribution to research in this field.

Two case studies were conducted; a measurement based laboratory experiment set-up and a simulated case study. In the set-up, measurements of current, voltage and power at different points in the network for the 1st, 5th and 7th frequencies were taken. Current and voltage results were used for hand calculations to prove the measured power flows and directions. The measurements were taken with a Fluke 345 three-phase harmonic power quality analyzer. For the simulated case study, a network was investigated using the DIgSILENT and SuperHarm software packages. Their results were compared and it was found that DIgSILENT is the preferred package for power results.

It was found that the total harmonic distortion limit for voltage in the simulated network exceeded an acceptable level. The harmonic mitigation solution chosen was to design a passive filter to decrease the distortion by shifting the resonance point of the network. The method to design the passive filter and its impact on efficiency and energy usage is included in the thesis.

Unique power flow direction diagrams are developed as part of the methodology and form an essential step in the derivation of the new formulae. Efficiencies, power losses and energy usage at individual and combined frequencies were determined. Results showed the negative effects of harmonics on overall efficiency, energy usage and power losses of the system. The methodology and new formulae developed was found to be effective and their application is recommended for use by industry.

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GLOSSARY

$\%I_{HD}$	Current harmonic distortion in percentage
$\%I_{THD}$	Current total harmonic distortion in percentage
$\%V_{HD}$	Voltage harmonic distortion in percentage
$\%V_{THD}$	Voltage total harmonic distortion in percentage
A	Amp, Unit of current
dt	Rate of change in time
f_1	Fundamental frequency
h	Harmonic frequency
H	Combined frequency
hch	Characteristic harmonic
Hz	Hertz, Unit of frequency
j	Imaginary part
P_h	Harmonic power
P_{in}	Input power
P_{Losses}	Power losses
P_{out}	Output power
R	Resistance
R_1	Primary resistance
R_2	Secondary resistance
R_c	Core resistance
Re	Real part
R_m	Magnetising resistance
t	Time
V	Volt, Unit of voltage
V_1	Primary voltage
V_2	Secondary voltage
W	Watt, Unit of Power
X_1	Primary reactance

X_2	**Secondary reactance**
X_m	**Magnetising reactance**
Z	**Impedance**
η	**Efficiency**
Ω	**Ohm, Unit of resistance**
ω	**Angular**
ωt	**Angular velocity**

CHAPTER 1: INTRODUCTION

1.1 Motivation

Traditionally, efficiency investigations in power systems consider only distortion-free waveforms, that is, the voltage and current waveforms are assumed to be sinusoidal (Al-Hamadi *et al.,* 2002:241; Grady *et al*., 2001:8 and Grady, 2006, chapter 1:1). Thus, when calculating energy and efficiency, only power at the fundamental frequency is usually considered. Energy is thus traditionally calculated by the formula:

$$E_1 = P_1 \times t \text{ (joules)} \tag{1.1}$$

where: E_1 = electrical energy consumed in time t (secs)
P_1 = electrical power at fundamental frequency (f_1).
Efficiency is defined as:

$$\%\eta = \frac{P_{(output)}}{P_{1(input)}} \times 100\% \tag{1.2}$$

where: $\%\eta$ = the efficiency expressed in percentage.
P_{output} = electrical or mechanical power.
$P_{1\ (input)}$ = P_1 in equation (1.1).

As energy is directly proportional to power, there is a relationship between energy and efficiency (Barbir & Gómez, 1997:1027). Power is defined as the rate of doing work, while energy is defined as electrical power multiplied by time taken for which current flows in seconds (Bhavikatti & Hegde, 2005:143). Distribution networks generally contain various types of components (elements), each with their own energy usage and individual efficiency. Together, however, they contribute to the total energy usage and overall network efficiency.

Power networks in the modern world have voltage and current waveforms that are distorted and thus contain harmonics (h). A harmonic is a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency. A number indicating the harmonic frequency is called the harmonic order; the 1^{st} harmonic is the fundamental frequency, 3^{rd} harmonic is three times and the 5^{th} harmonic is five times the fundamental frequency, etc.

In systems characteristic harmonic (*hch*) components are found and are typically currents harmonics injected by 6 pulse rectifiers. They have a harmonic order such as:

$$hch = 6k \pm 1 \tag{1.3}$$

where: k = 1, 2, 3, 4,….. Thus, 6 pulse rectifiers typically inject 5th, 7th, 11th, 13th harmonics etc.

Thus (1.1) and (1.2) no longer hold true. Today, power networks contain multiple harmonic sources, such as adjustable speed drives (ASDs), compact fluorescent lamps (CFLs), computers, etc. and they cause harmonics to penetrate network elements (Topalis *et al.*, 2001:257; Grady *et al.*, 2001:9; Chen *et al.*, 1989:171 and EL-Saadany *et al.*, 1998:259). Harmonics (h>1) can cause additional heat losses (I^2R) to that produced by the fundamental frequency component (h=1) and influence total energy usage, as well as overall system efficiency (Grady *et al.*, 2001:10 and Grady, 2006, chapter 4:1).

In today's world, systems contain levels of harmonics, which can no longer be ignored by planners, engineers, energy conservationists and economists (Grady *et al.*, 2001:11; Makram *et al.*, 1994:51; Lu *et al.*, 2000:73 and Tang *et al.*, 1989:42). In power networks containing active and passive elements, linear and/or non-linear devices, methods and formulae for calculating total energy usage and overall efficiency when harmonics are present is unknown. The role of ASDs is of particular importance when investigating energy efficiency.

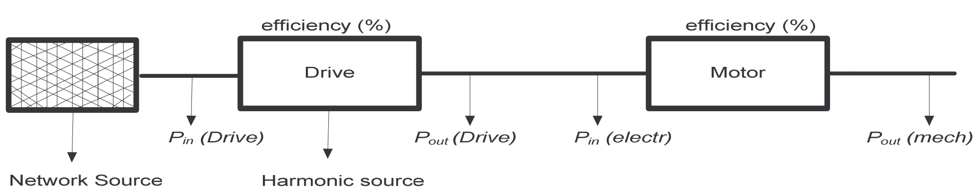


Figure 1.1: One individual ASD

An ASD consists of two main components - the drive and the motor it controls (Okrasa, 1997:7). Each component has an efficiency rating. The motor has a mechanical power output and electrical power input, while for the drive; output and input powers are electrical, as shown in Figure 1.1. These two efficiencies need to be treated separately and then together when conducting efficiency investigations. When an ASD is connected to a power system it absorbs power (P_1) at fundamental frequency (f_1) from the network source while at the same time injecting harmonics into the system producing powers at h>1 in the network components. Thus powers come from both the network source as well as the harmonic source, therefore investigating the directions of power flows is important.

A further concern is that power networks contain capacitor banks and have the potential to cause harmonic resonance (Atkinson-Hope & Folly, 2004:1393). It is therefore, also becoming prominent to mitigate harmonic levels. The impact of a mitigation solution on energy usage and overall efficiency remains unknown. A further shortcoming is that many distribution networks use inefficient incandescent lighting. Today, there are many new energy efficient technologies available and studies on their impacts are awaited (De Almeida *et al.*, 2003:673). A method of how to conduct a simulation study on energy efficiency when distorted waveforms are present using a power system and an industrial grade software tool is relatively unknown. Thus there is a need to investigate these aspects, develop new equations and for comparisons to be made to traditional distortion-free waveform methods.

1.2 Objective

The objective of this thesis is to investigate and develop a methodology that includes new formulae for evaluating energy usage, individual and overall efficiency in distribution networks when one or more non-linear loads (harmonic sources) are present. A further objective is to conduct case studies. One case study involves the application of industrial software packages and is extended to investigate the impact of a harmonic mitigation solution to minimize the effect of harmonic resonance. Another involves a measurement based laboratory experimental set-up, where hand calculations are used to prove power measurements and the direction of their flows. Also included in this set-up is the application of a modern energy efficient technology, namely, the impact of compact fluorescent lighting and its role.

1.3 Organisation of Thesis

The thesis is divided into seven chapters:

Chapter 2 is a literature review of what is known about the topic, its significance and the need for research to be conducted in this field.

Chapter 3 reviews the theory relevant to the topic, to provide a background for developing the methodology and formulae.

In Chapter 4 the contribution of the thesis is explained and includes the development of new methods and formulae to analyse individual and total efficiency and energy usage of a power network when harmonics are present.

In Chapter 5 case studies are conducted. The scenario for each case study and its purpose is explained. Software packages are applied and an experimental laboratory set-up for a measurement based study is described.

In Chapter 6 the results obtained from various case studies conducted are analysed and findings are made.

Chapter 7 conclusions and recommendations on the main contribution of the thesis are made and directions for future research are offered.

1.4 Summary

The chapter began with an introduction to harmonics on power systems as they cause distortion. The traditional formulae for calculating efficiency and energy usage were reviewed and it was explained why they no longer hold true in the modern era. The shortcomings were pointed out leading to the formulation of the objective for this investigation. The layout of how the thesis is organised is also included in this chapter.

CHAPTER 2: THEORY AND CONCEPTS

2.1 Electrical energy

There is a worldwide continuous increase in power demand; yet because of environmental concerns this hinders the expansion of traditional power systems, such as coal, nuclear, etc., forcing existing systems to be used more extensively and efficiently (Mohamed & Lee, 2006:2388). These sources supply energy to consumers via transmission and distribution networks. There is thus a need to conduct energy studies to improve efficiencies of these systems down to consumer levels as investigations in this regards are not found in published literature (Weedy & Cory, 1998:517).

2.1.1 Electrical power quality

Electrical utilities and consumers today are concerned about power outages but mostly about the introduction of power electronic devices into networks as they have a potential to cause excessive voltage and/or current distortion. Although a power system is considered by many to be reliable, this does not guarantee the quality of its delivery. The term power quality (PQ) has become one of the most prolific modern era buzzwords. The ultimate reason why there should be concern about power quality is one of productivity and economics (Dugan *et al.,* 1996:1). It is not uncommon for a power quality problem to cause a production outage lasting hours, resulting in many thousands of Rands loss in income for both supplier and clients (Dugan *et al*., 1996:1).

Ideally, electrical power flowing through a network should be supplied without interruption at constant frequency and voltage and be purely sinusoidal (Grady *et al*., 2001:8). In three-phase networks waveforms should be symmetrical. The aim of PQ is the pureness of the supply, meaning there should be no voltage variations and/or waveform distortion (Singh, 2009:151). The continually changing demands of consumers give rise to power system disturbances, causing voltage variations. Any sudden change in power delivery, voltage and/or current in a network is termed a disturbance (Chan, 1996:39). A PQ problem is any deviation in voltage, current or frequency that causes failure or malfunction of equipment. As no real power system is able to operate under perfect conditions, PQ is also described as the ability of a system to transmit and deliver electrical energy to consumers within certain limits defined by national and international standards (Dugan *et al*., 1996:1).

2.1.1.1 Average power in the sinusoidal steady-state (*P*)

To determine the average power dissipated over one cycle, the amount of work completed in a specified period should first be determined. All AC equipment has its power ratings specified in terms of the average power dissipated over one cycle (Edminister, 1965:69).

For a pure resistance:

$$P(t) = \frac{1}{T}\int_0^T vi dt \tag{2.1}$$

In sinusoidal steady-state:

$$v(t) = V_m \sin\omega t \tag{2.2}$$

$$i(t) = I_m \sin\omega t \tag{2.3}$$

$$T = \frac{2\pi}{\omega} = \frac{2\pi}{2\pi f} = \frac{1}{f} \tag{2.4}$$

where T is a period of the voltage and f is a frequency, respectively. Substituting (2.2), (2.3) and (2.4) gives:

$$P(t) = \frac{\omega}{2\pi}\int_0^{\frac{2\pi}{\omega}} V_m \sin\omega t\, I_m \sin\omega t\, dt \tag{2.5}$$

Applying the trigonometric identity, $\sin^2(\omega t) = 0.5[1 - \cos(2\omega t)]$ it becomes:

$$P(t) = \frac{\omega}{2\pi}\left[\frac{V_m I_m}{2}\left\{t - \frac{\cos(2\omega t)}{2\omega}\right\}\right]_0^{\frac{2\pi}{\omega}} \tag{2.6}$$

The cosine term is zero at both limits, thus (2.6) reduces to:

$$P(t) = \frac{V_m I_m}{2}\cos\Delta\theta \tag{2.7}$$

$\Delta\theta = \theta_v - \theta_i$, this means the cosine of phase angle between voltage and current and is called power factor (Stevenson, 1982:16).

For a pure resistance, $\Delta\theta = 0^{o}$ (voltage and current are in phase).

For a pure inductance, $\Delta\theta = 90^{o}$ (voltage leads current or current lags voltage);

For a pure capacitance, $\Delta\theta = -90^{o}$ (voltage lags current or current leads voltage).

Thus, to prove average power (2.7) is equal to root mean square (rms) power, the following equations are used.

$$V_{rms} = \frac{V_m}{\sqrt{2}} \tag{2.8}$$

$$I_{rms} = \frac{I_m}{\sqrt{2}} \tag{2.9}$$

$$P(t) = \frac{V_m I_m}{\sqrt{2} \times \sqrt{2}} \cos\Delta\theta \tag{2.10}$$

Therefore, average power equals to rms power

$$P(t) = \frac{V_m I_m}{2} \cos\Delta\theta \tag{2.11}$$

In other terms;

$$P_1 = V_1 I_1 \cos(\theta_1 - \delta_1) \tag{2.12}$$

Where: θ_1 and δ_1 are voltage and current angles, respectively.

2.1.1.2 Reactive power (*Q*)

For sinusoidal quantities, the reactive power in a single phase AC network is defined as the product of the voltage, the current, and the sine of the phase angle between them (Von Meier, 2006:70).

$$Q = VI\sin\theta \tag{2.13}$$

In which (Q) represents the average value of the power reciprocating between the load and source without carrying out any net energy transfer (Wildi, 2002:138). Reactive power has been recognised as a significant factor in the design and operation of alternating current (AC) power systems. Since the impedances of network components are predominantly reactive, the transmission of active power requires a difference in angular phase between the voltages at both sending and receiving-ends, whereas the transmission of reactive power requires the difference in the magnitude of these same voltages (Wildi, 2002:138). Reactive power is consumed by most of the network elements and loads, and it can also be supplied. Reactive power control is vital for the stability of a power system (EDSA Micro Corporation, 2002:1). For a given distribution power, minimising the total flow of reactive power may reduce losses in the system, thereby increasing system efficiency. In an alternating current system, when the voltage and current are in phase, only real power (*P*) is transmitted. That means reactive power is neither produced nor consumed (Von Meier, 2006:112).

Power triangle

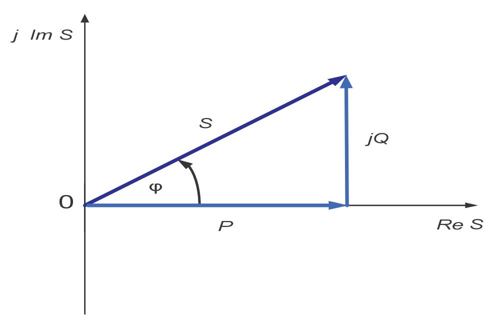


Figure 2.1: Power triangle

$$Q = \sqrt{|S|^2 - P^2} \tag{2.14}$$

2.1.1.3 Apparent power

Apparent power is the power value obtained in an AC circuit by multiplying the effective value of voltage and current (I_{rms} and V_{rms}) and they are the effective voltage and current delivered to the load. Therefore, apparent power for single phase (1ϕ) is given by:

$$|S| = |V_{rms}| \times |I_{rms}| \tag{2.15}$$

The product of *VI* is called apparent power and is indicated by the symbol *S*. The unit of *S* is volt-ampere (VA).

2.1.1.4 Complex power

The three sides *S, P* and *Q* of the power triangle shown in Figure 2.1 are obtained from the product of $VI^*(1\phi)$. Where I^* is current conjugate. The result of this product is a complex power *S*. Its real part equals the average power *P* and its imaginary part is equal to the reactive power *Q*. Consider Euler's Formulae for voltage and current, $V = Ve^{j\alpha}$ and where from $I = Ie^{j(\alpha+\theta)}$. Then,

$$S = VI^* = Ve^{j\alpha}Ie^{-j(\alpha+\theta)} = VIe^{-j\theta} = VI\cos\theta - jVI\sin\theta = P - jQ \qquad (2.16)$$

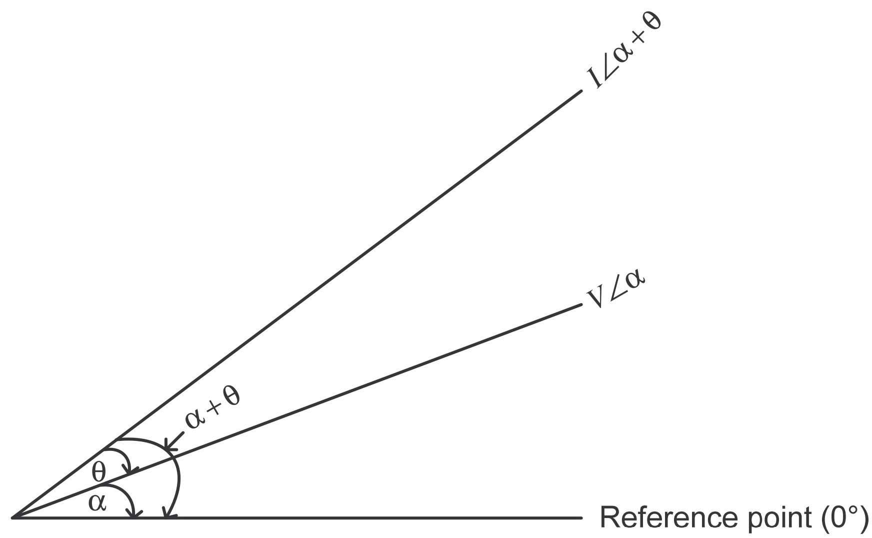


Figure 2.2: Phasor diagram representing the voltage and current phase angle

where $e^{j\alpha} = \cos\alpha + j\sin\alpha$, $-\mathrm{j}$ represents a conjugate, α alpha is a voltage phase angle and θ theta, is the angle between voltage and current (impedance angle). Current phase angle defined with $\alpha+\theta$.

The absolute value of *S* is the apparent power *S=VI. Q* will be positive when the phase angle between the voltage and current is positive, that is voltage angle > current angle, indicating current lagging voltage. Conversely, *Q* will be negative when current angle > voltage angle, which indicates current leading voltage. This agrees with the selection of a positive sign for the *Q* for an inductive circuit and a negative sign for capacitive circuit. It is important to keep this in mind when constructing a power triangle (Stevenson, 1982: 18). The apparent power is the vector sum of the real and reactive powers.

Electrical power is defined as the rate at which energy is transferred by an electric circuit. The SI (system international) unit of power is the watt. Because of a scarcity of electrical power, researchers are interested in the power consumption of various types of electrical devices. Most engineers are interested in the power generated by an alternator, the power input to an electric motor drive, or the power delivered by a television transmitter. Utility companies are concerned mainly with the power consumed by their equipment, but are not concerned with the management of power losses occurring in a system. In this thesis the work will focus mainly on a balanced network.

There are five types of electrical power. They are defined as:

a) Real (Active) power (P)
    - unit: watt (W)
b) Reactive power (Q)
    - unit: volt-amperes reactive (VARs)
c) Complex power (S)
    - unit: volt-ampere (VA)
d) Apparent power ($|S|$), that is, the absolute value of complex power S
    - Unit:volt-ampere (VA)
e) Instantaneous power (p) is the product of voltage and current at any instant and is given by:

$$p = vi \tag{2.17}$$

where p is the instantaneous power (watt), v and i are voltage (volt) and current (amp) at any given point in time (secs).

Figure 2.3 shows a passive network (Edminister, 1965:68).

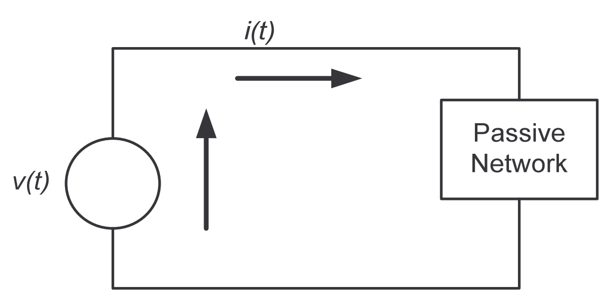


Figure 2.3: Voltage and current in time function

2.2 Power in a balanced three-phase system

The total power (P_T) delivered by a three-phase generator or absorbed by a three-phase load is found by adding the powers in each of the phases. In a balanced circuit this is the same as multiplying the power in any phase by three since the power is the same for all three-phases. If the magnitude of the voltages to neutral V_p for a star (Y)-connected load is

$$V_p = |V_{rn}| = |V_{bn}| = |V_{yn}| \tag{2.18}$$

and if the magnitude of the phase current I_p for Y-connected load is

$$I_p = |I_r| = |I_b| = |I_y| \tag{2.19}$$

The total three-phase power is $P_T = 3V_p I_p \cos\theta_p$ (2.20)

where θ_p is the angle between the phase current and the phase voltage, that is, the angle of the impedance in each phase. If V_L and I_L are the magnitudes of line-to-line voltage and current, respectively,

$$V_p = \frac{V_L}{\sqrt{3}} \text{ and } I_p = I_L \tag{2.21}$$

and substituting in (2.20) yields

$$P_T = \sqrt{3} V_L I_L \cos\theta_p \tag{2.22}$$

The total reactive powers are

$$Q_T = 3V_p I_p \sin\theta_p \tag{2.23}$$

$$Q_T = \sqrt{3} V_L I_L \sin\theta_p \tag{2.24}$$

And the total apparent powers of the load are

$$S_T = \sqrt{{P_T}^2 + {Q_T}^2} = \sqrt{3} V_L I_L \tag{2.25}$$

Equations (2.20), (2.21), and (2.25) are those usually used for balanced networks since the quantities line-to-line voltage, line current and the power factor, $\cos\theta_p$ are usually known (Edminister, 1965:68). If a load is connected in delta (Δ), the voltage across each impedance is the line-to-line voltage and the current through each impedance is the magnitude of the line current divided by $\sqrt{3}$, or

$$V_p = V_L \text{ and } I_p = \frac{I_L}{\sqrt{3}} \tag{2.26}$$

Thus equations (2.20), (2.21) and (2.25) are also valid for delta connection (Edminister, 1965:68).

2.2.1 Ac power in the sinusoidal steady-state

2.2.1.1 Pure resistive load

Figure 2.4 shows a resistive circuit (Edminister, 1965:68)

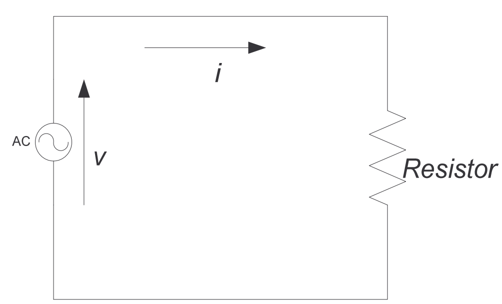


Figure 2.4: Resistive circuit

In a network consisting of only a resistor, the voltage applied to the resistance is calculated as:

$$v = V_m \sin \omega t \tag{2.27}$$

The resulting current is $i = I_m \sin \omega t$ (2.28) where V_m and I_m are peak voltage and current, and ω is the angular velocity in radians/seconds (rad/s), respectively. The corresponding power is then:

$$p = vi = V_m I_m \sin^2 \omega t \tag{2.29}$$

Since $\sin^2 x = \frac{1}{2}(1 - \cos 2x)$, then

$$p = \frac{1}{2} V_m I_m (1 - \cos 2\omega t) \tag{2.30}$$

For example: if V_m = 50 V and I_m = 20 A and if the frequency is 50 Hz, then instantaneous values for *v(t), i(t)* and *p(t)* can be derived (see Table A.1 in Appendix A.1). These waveforms are shown in Figure 2.5 (plotted in excel).

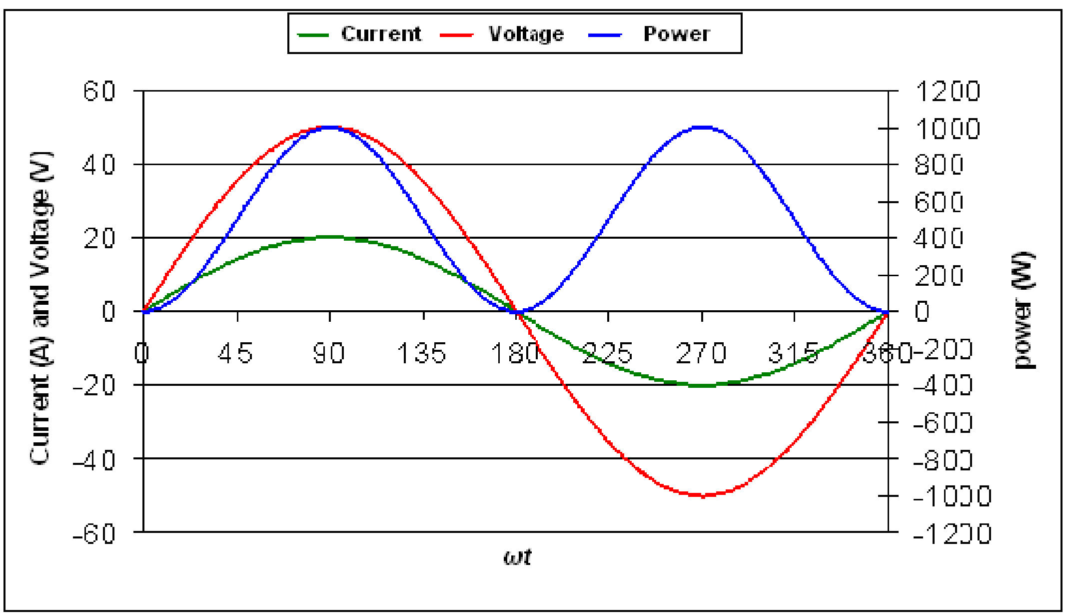


Figure 2.5: Waveform for a pure resistor load

It can be seen in Figure 2.5, the voltage and current are in phase. Consequently their product (power) is always positive. In other words, power dissipated is never negative. This is because a resistor always obtains power from the source, and then converts it into heat. Since a resistor cannot store energy, it can never return power to the source.

2.2.1.2 Pure inductive

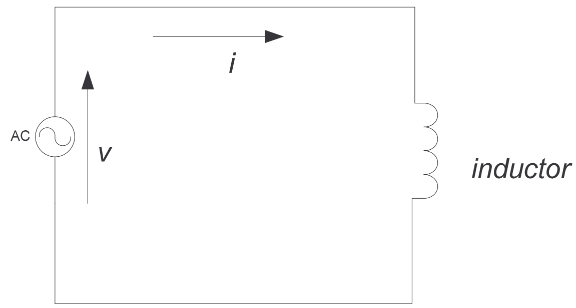


Figure 2.6: Inductive circuit

For an ideal case, the passive network consists of a pure inductive (L only) element. The inductor voltage is (Edminister, 1965:68):

$$v = V_m \sin \omega t \; , \tag{2.31}$$

and the resulting current will have the form

$$i = I_m \sin(\omega t - \pi/2) \tag{2.32}$$

therefore, power at any instant of time is

$$p = vi = V_m I_m (\sin \omega t)(\sin \omega t - \pi/2) \tag{2.33}$$

since $\sin(\omega t - \pi/2) = -\cos \omega t$ and $2 \sin x \sin x = \sin 2x$, we have

$$p = -\frac{1}{2} V_m I_m \sin 2\omega t \tag{2.34}$$

Similarly, for example; using same values for V_m and I_m as before, the instantaneous results of the currents, voltages and power are calculated in Table A.2 in Appendix A.1 and are used to plot their curves as seen in Figure 2.7.

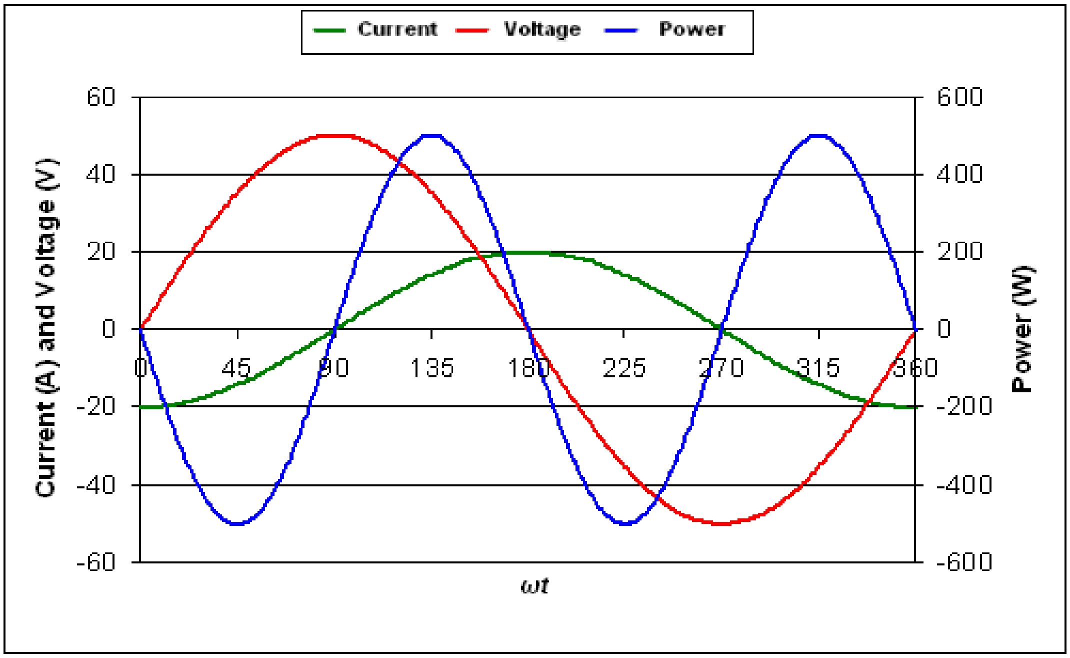


Figure 2.7: Waveform of a pure inductor

When v and i are both positive, the power flow is positive and energy is delivered from the source to the inductor.

For example: $i = 14.14\,A, v = 35.36\,V, P = vi = 35.36 \times 14.14 = 500\,W$.

When the v and i have opposite signs, power is negative and energy is flowing from the inductor to the source.

For example: $i = -14.14\,A, v = 35.36\,V, P = vi = 35.36 \times -14.14 = -500\,W$.

The average power dissipated is zero when calculated over a complete cycle. The average power as given by (2.11) when $\Delta\theta = 90^{o}$ for a pure inductor thus means its power has equal positive and negative half cycles (Edminister, 1965:68). This is because the inductor stores energy (takes it from the source) in the first half cycle and then returns all stored energy to the source during its second half cycle. Power delivered to an inductor by the source is equal to the power returned to the source by an inductor (Edminister, 1965:68). The number of cycles per second of the power waveform is twice that of the voltage and current (Edminister, 1965:68). The current lags the voltage by 90^{o}, thus a pure inductive circuit causes a lagging power factor (Stevenson, 1982: 16).

2.2.1.3 Pure capacitive

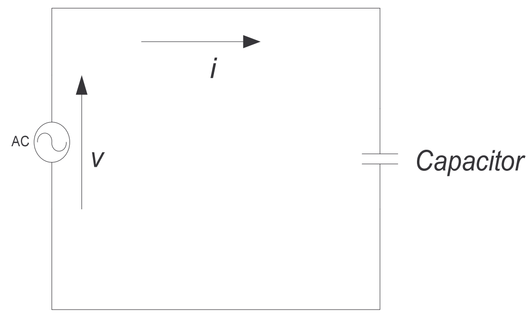


Figure 2.8: Capacitive circuit

For an ideal case, the passive network consists of a pure capacitive element. If a sinusoidal network voltage has the form (Edminister, 1965:68):

$$v = V_m \sin \omega t \text{ ,} \tag{2.35}$$

the resulting current will have the form

$$i = I_m \sin(\pi/2 - \omega t) \tag{2.36}$$

therefore, power at any instant of time is

$$p = vi = V_m I_m (\sin \omega t)(\pi/2 - \sin \omega t) \tag{2.37}$$

since $\sin(\pi/2 - \omega t) = \cos \omega t$ and $2 \sin x \sin x = \sin 2x$, we have

$$p = \frac{1}{2} V_m I_m \sin 2\omega t \tag{2.38}$$

Again, using V_m = 50 V and I_m = 20 A, the instantaneous results of the current, voltage and power at 50 Hz are calculated in Table A.3 in Appendix A.1 and these values are used to plot their curves, shown in Figure 2.9.

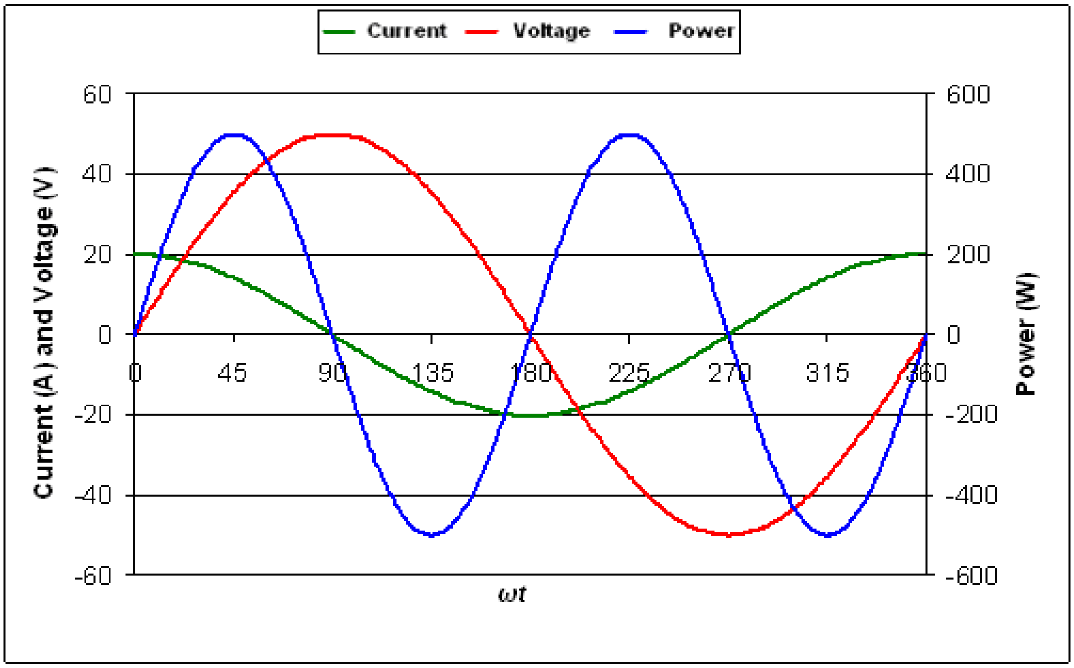


Figure 2.9: Waveform of a pure capacitor

When *v* and *i* are both positive, the power flow is positive and energy is delivered from the source to the capacitor (Edminister, 1965:68). When the *v* and *i* have opposite signs, power is negative and energy is flowing from the capacitor to the source. The average power dissipated is zero when calculated over a complete cycle. The average power as given by (2.11) when $\Delta\theta = -90^{\circ}$ for a pure capacitor thus it means the power has an equal positive and negative cycle. This is because the capacitor stores energy (takes from the source) in the first half cycle and then returns all of the stored energy to the source in the second half cycle (Edminister, 1965:68). Power delivered to the capacitor by the source is equal to the power returned to the source by the capacitor (Edminister, 1965:68). The number of cycles per second of the power waveform is twice that of the voltage and current (Edminister, 1965:68). The current leads the voltage by 90°, thus a pure capacitive circuit causes a leading power factor (Stevenson: 1982, 16).

2.2.2 Individual efficiency of network components

Knowledge of electrical power is required to understand the concept of electrical efficiency. Distribution networks generally contain many components such as transformers, cables, induction motors and ASDs, each with individual efficiency. Components are now described and their individual efficiencies defined.

2.2.2.1 Transformers

Figure 2.10 shows an equivalent circuit for a transformer (Shepherd *et al*, 1970:275).

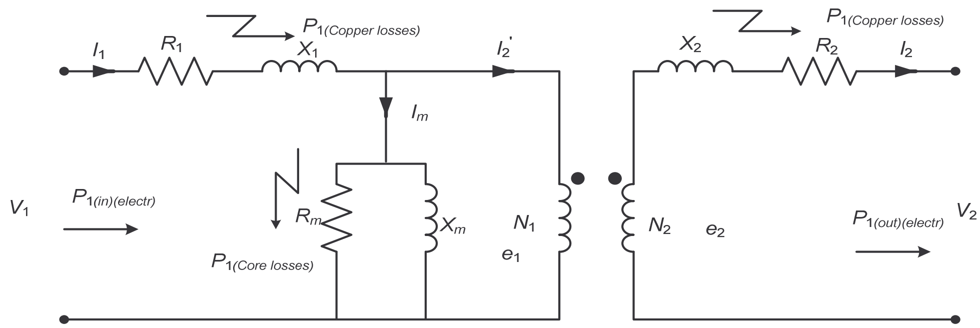


Figure 2.10: Single phase equivalent circuit of a transformer (TRF)

Where V_1 and V_2 are supply and secondary voltage; R_1 and X_1 are primary resistance and inductive reactance; R_2 and X_2 are secondary resistance and inductive reactance; R_m and X_m are magnetising resistance and inductive reactance; N_1 and N_2 are number of turns at the primary and secondary; I_1, I_2, I_m are primary, secondary and magnetising current; e_1 and e_2 are induced voltage at the primary and secondary. Capacitance in the transformer is neglected.

If $P_{1\ (core\ losses)}$ are assumed to be constant losses at f_1 (thus directly connected across supply voltage) and if the secondary R_2 and X_2 are referred to the primary side, that is I_{2p} and R_{2p} are the secondary current (I_2) and resistance (R_2) referred to the primary, then the transformer equivalent circuit becomes:

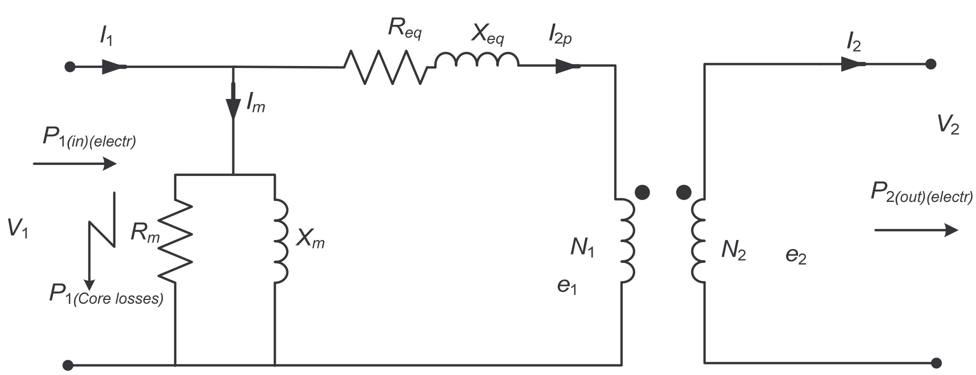


Figure 2.11: Single phase equivalent circuit of a transformer referred to primary

where: $R_{eq} = R_1 + R_{2p}\left(\frac{N_1}{N_2}\right)^2$ (2.39)

$P_{1(in)(electr)}$ and $P_{1(out)(electr)}$ are both electrical powers. $P_{1(in)(electr)}$ is the power from the source and $P_{1(out)(electr)}$ is the output power.

$$\sum P_{1(copper\ losses)} = (I_{2p})^2 R_{eq} \qquad (2.40)$$

The maximum efficiency of the transformer occurs during a condition when constant loss is equal to the variable loss (Shepherd *et al.,* 1970:275). There are two different losses in transformers; constant and variable losses.

- Constant losses are also called No-load losses $P_{1(core\ losses)}$:

No–load losses (core losses) involve the power consumed to sustain the magnetic field in a transformer's core. Core losses occur whenever a transformer is energised. Core losses are assumed not to vary with the load connected to a transformer. Hysteresis and eddy current losses cause core losses and are primarily dependent on the maximum flux density attained and on the frequency of the alternating flux (Shepherd *et al.,* 1970:275);

- variable losses are copper losses:

These losses depend on an effective operating load (I_2) connected to the transformer. The power losses in the primary and secondary transformer windings are described as copper losses. These are caused by the resistance (R_1 and R_2) of the windings.

Efficiency formula for a transformer:

Output rating is the rating of the transformer, thus the efficiency ($\%\eta$) is calculated in terms of the output power (Shepherd *et al.,* 1970:275).

$$\%\eta = \frac{Output}{Input} = \frac{Output}{Output + Losses} = \frac{V_2 I_2 \cos\phi}{V_2 I_2 \cos\phi + (I_{2p})^2 R_{eq} + P_{1(core\,losses)}}$$
$$= \frac{V_2 \cos\phi}{V_2 \cos\phi + (I_{2p})^2 R_{eq} + \dfrac{P_{1(core\,losses)}}{I_2}} \qquad (2.41)$$

2.2.2.2 Cable

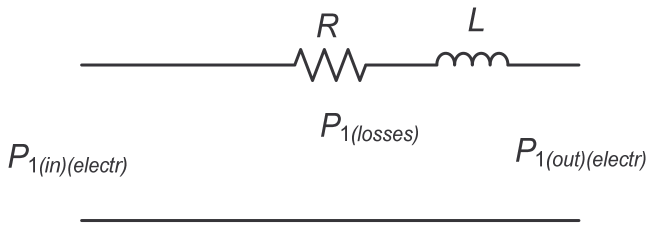


Figure 2.12: Single equivalent circuit of a cable

Figure 2.12 shows the equivalent circuit of a cable when capacitance and insulation resistance are neglected. $P_{1(in)(electr)}$ and $P_{1(out)(electr)}$ are each electrical powers. $P_{1(in)(electr)}$ is the power from the source. $P_{1(out)(electr)}$ can be obtained by subtracting $P_{1(losses)}$ from $P_{1(in)(electr)}$, where *R* and *L* are conductor resistance and inductance respectively. The $P_{1(losses)}$ depend on the length of the cable, the longer the cable, the more active the losses (Shepherd *et al.,* 1970:275).

Efficiency formula for a cable: $\%\eta = \frac{P_{1(out)(electr)}}{P_{1(in)(electr)}} \times 100\%$ (2.42)

2.2.2.3 Induction motors (IDM)

Figure 2.13 shows the equivalent circuit of a squirrel cage induction motor (Shepherd *et al.,* 1970:442)

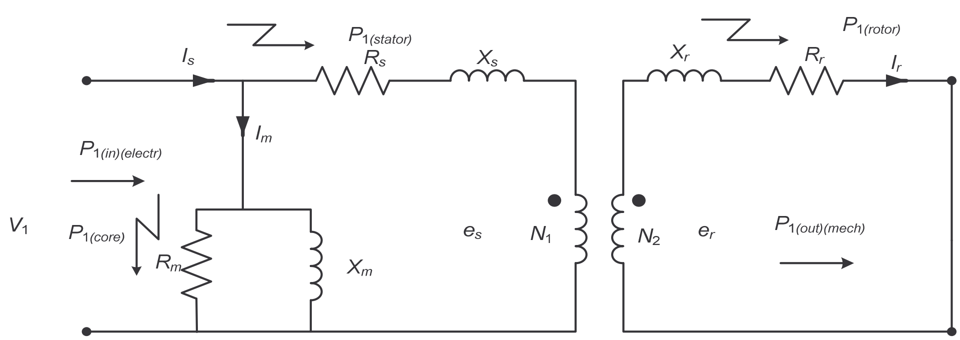


Figure 2.13: Single phase equivalent circuit of a squirrel cage induction motor (IDM)

Where R_s and X_s are stator resistance and inductive reactance; R_r and X_r are rotor resistance and inductive reactance; R_m and X_m are magnetising resistance and inductive reactance; N_1 and N_2 are number of turns at the stator and rotor; I_s, I_r, I_m are stator, rotor and magnetising current; e_s and e_r are induced voltage at the stator and rotor and V_1 is the supply voltage (Shepherd *et al.,* 1970:442). Capacitance in the induction motor is neglected.

$P_{1(in)(electr)}$ of the induction motor is a electrical power, while $P_{1(out)(mech)}$ is a mechanical power (Shepherd *et al.,* 1970:442). $P_{1(in)(electr)}$ is the power from the source. Mechanical output power of the motor is given by:

$$P_{1(out)(mech)} = T_{mech} \times \omega_{mech} \tag{2.43}$$

where $P_{1(out)(mech)}$ is in Watt (W) , T_{mech} is the torque in Newton-metre (Nm) and ω_{mech} is the mechanical speed in radians per second (rad/sec).

$$\omega_{mech} = \frac{2\pi N}{60} \tag{2.44}$$

N =Revolutions/minute (revs/min)

$$\text{Therefore, } P_{1(out)(mech)} = \frac{2\pi N T_{mech}}{60} \tag{2.45}$$

In order to determine the efficiency of the induction motor as a power converter, the various losses in the machine must first be identified (Sen, 1996:238). These losses are illustrated in the power flow diagram of Figure 2.14 (Sen, 1996:238). For three-phase machines the power input to the stator is

$$P_{1(in)(electr)} = 3V_1 I_S \cos\theta_1 \tag{2.46}$$

V_1 and I_S are the phase voltage and current and θ_1 is stator power factor at f_1. Power is lost due to the hysteresis and eddy current losses in the magnetic material of the stator core (Sen, 1996:238). The power loss in the stator winding is

$$P_{1(stator)} = 3I_S^2 R_S \tag{2.47}$$

where, R_S is the stator resistance. The remaining power, P_{ag}, crosses the air gap into the rotor. Part of it, is lost in the rotor circuit resistance.

$$P_{2(rotor)} = 3I_r^2 R_r \tag{2.48}$$

where, R_r is the rotor resistance of the rotor winding: If it is a slip-ring motor, R_r also includes any external resistance connected to the rotor circuit through slip-rings (Sen, 1996:238). Power is also lost at the rotor core. Because core losses are dependent on the frequency of the rotor, these may be assumed negligible at normal operating speeds, where rotor frequency is low.

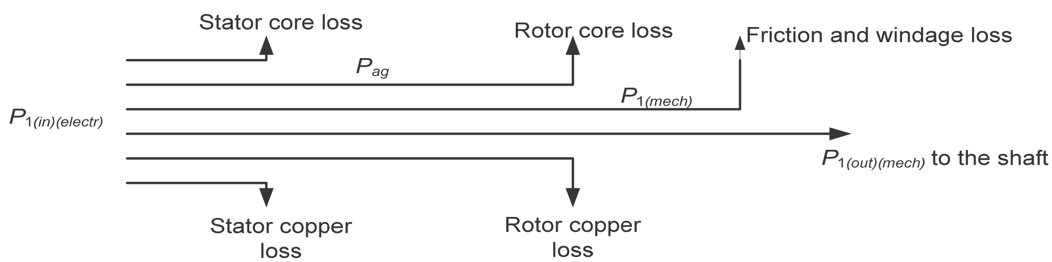


Figure 2.14: Power flow in an induction motor

The remaining power is converted into mechanical form. Part of this is lost through windage and friction, which depends on speed. The mechanical output power is the useful power output from the machine. The efficiency is highly dependent on slip. Other losses are negligible compared to copper losses, thus are generally ignored (Sen, 1996:239).

$$P_{ag} = P_{1(in)(electr)} \tag{2.49}$$

$$P_{2(rotor)} = sP_{ag} \tag{2.50}$$

$$P_{1(out)(mech)} = P_{ag}(1-s) \tag{2.51}$$

And the ideal efficiency is

$$Eff_{(ideal)} = 1 - s \tag{2.52}$$

$$\text{or } \%\eta = \frac{P_{1(out)(mech)}}{P_{1(in)(electr)}} \times 100\% \tag{2.53}$$

Sometimes $Eff_{(ideal)}$ is also called internal efficiency, as it represents the ratio of the power output to the air gap power (Sen, 1996:239). If the other losses are included, the actual efficiency is lower than the ideal efficiency. The full-load efficiency of a large induction motor may be as high as 95% (Sen, 1996:239).

To summarise, higher efficiency is reached by:

- Smaller joule losses in the stator and rotor by using more copper;
- smaller iron losses because of better iron core and,
- fewer mechanic losses because of better ventilation fans and bearings (Laboretec, 2007:4).

Apart from that, efficiency depends on the following factors:

- The capacity: larger motors have a higher efficiency;
- the number of pole pairs: the more pole pairs, the lower the efficiency and,
- the load: the smaller the load, the lower the efficiency (Laboretec, 2007:4).

2.2.2.4 Adjustable speed drive (ASD)

An electric ASD is an electrical system used to control motor speed (Okrasa, 1997:7). An ASD is capable of adjusting both the speed and torque of an induction or synchronous motor. ASDs may be referred to by a variety of names, such as variable speed drives, adjustable frequency drives or variable frequency inverters (Okrasa, 1997:1).

a) Circuit diagram of a typical drive part of ASD supplying an AC motor (Okrasa, 1997:21)

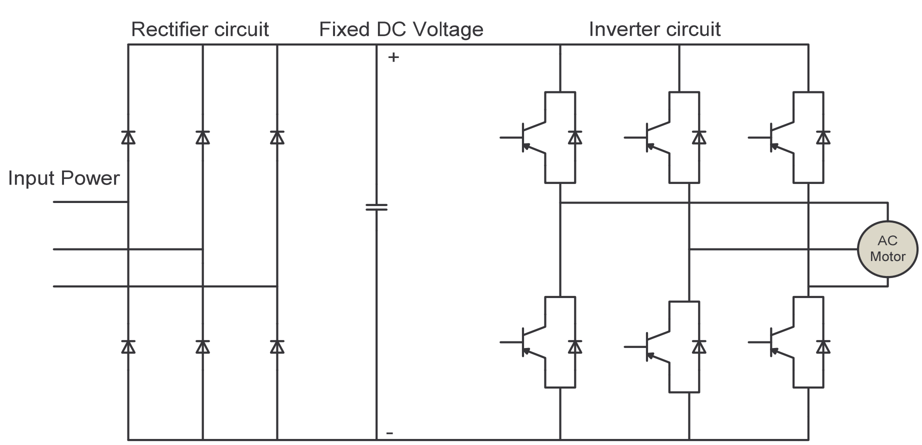


Figure 2.15: Parts of ASD

b) Block diagram of a drive and AC motor

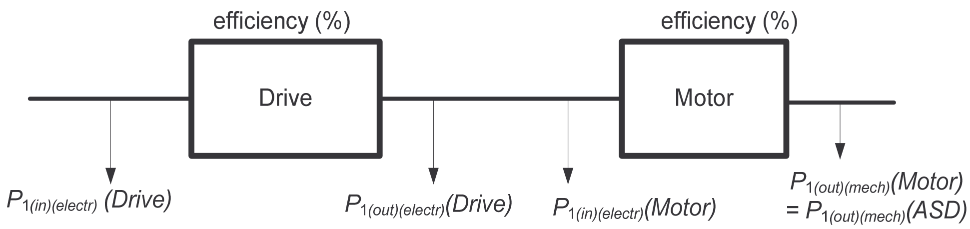


Figure 2.16: Individual ASD

$$P_{1(out)(electr)}(Drive) = P_{1(in)(electr)}(Drive) \times \eta\%(Drive) \tag{2.54}$$

Therefore, $P_{1(out)(electr)}(Drive) = P_{1(in)(electr)}(Motor)$

$$P_{1(out)(mech)}(Motor) = P_{1(in)(electr)}(Motor) \times \eta\%(Motor) \tag{2.55}$$

Therefore, equation (2.54) is the mechanical output of the ASD.

$$P_{1(out)(mech)}(ASD) = P_{1(out)(mech)}(Motor) \tag{2.56}$$

Efficiency for an ASD: $$\%\eta = \frac{P_{1(out)(mech)}(ASD)}{P_{1(in)(electr)}(Drive)} \times 100\% \tag{2.57}$$

2.3 Summary

The concepts and theory of what is known in electrical studies without power quality problems such as harmonics is discussed. Electrical power quality is defined. The known formulae of the average, reactive, apparent and complex AC power in sinusoidal steady-state are included. Pure resistor, inductor and capacitor, sinusoidal waveforms of current, voltage and power are plotted. It also includes traditional formulae to calculate individual efficiency of network components such as transformers, induction motors, etc. Power losses of different network components are discussed.

CHAPTER 3: HARMONIC DISTORTION

3.1 Harmonic Distortion

Harmonics are sinusoidal voltages or currents having frequencies which are integer multiples of the fundamental frequency, usually 50 Hz (Chan, 1996:65). Periodically distorted waveforms can be decomposed into the sum of the fundamental frequency and the harmonic waveforms (Dugan *et al.*, 2003:26). Harmonic distortion originates from the non-linear characteristics of devices and loads in a power system (Dugan *et al.*, 2003:26).

The fundamental frequency of a power system is typically 50 Hz. However, certain loads inject harmonics while drawing a 50 Hz fundamental frequency. They are called power system harmonics (Grady, 2001:8). Power quality engineers and researchers are concerned about the levels of harmonic distortion which are on the increase due to rapid introduction of power electronic-controlled loads (Singh, 2009:151). A study on harmonics in three-phase power systems was published by Steinmetz, (1916) (Singh, 2009:153). He explained that saturated iron in transformers and machines causes third harmonic currents. To block the flow of third harmonic currents, transformers need to be connected in delta. He was the first to propose this connection.

Today, power electronic-controlled loads such as ASDs and switch-mode power supplies (SMPS) are the most common sources of harmonics in power systems (Singh, 2009:153). These loads consist of the components such as diodes, etc, used to chop waveforms to control power or to convert 50 Hz AC to DC. To control motor speed, ASDs convert DC to variable frequency AC (Okrasa, 1997:3 and Von Meier, 2006:133). Power electronic loads are applied at various voltage levels, from low to high voltage. However, they have the potential to cause unacceptable levels of power system harmonic distortion which may be a problem that requires addressing.

In particular, resonance can occur at a harmonic frequency leading to a rise in voltage and/or current distortion. This can happen when the injected harmonic currents interact with system impedances. The result of resonance often leads to component failure and is a major concern (Grady, 2001:9). These distortion levels and concerns for the loss of components, led to a new field of study, called power quality (Dugan *et al.*, 2003:167). Traditionally, design and operations of power systems only considered the fundamental frequency. These conventional rules had to be adapted to accommodate potential harmonic problems (Grady, 2001:8).

Non-linear devices such as ASDs and SMPS (Televisions (TVs) and personal computers (PCs)) cause harmonic distortion in a power system. It is amazing to witness their entrance into power networks. Industrial consumers now use ASDs in their plants to improve process control and energy efficiency (Von Meier, 2006:134). ASDs improve the efficiency of motor driven equipment by matching speed to changing load requirements. It is not industrial plants (ASDs) only that are being invaded by increasing number of electronic controllers, but all commercial and residential facilities are totally dominated by SMPS (TVs and PCs) and non-linear lighting load such as compact fluorescent lamps (CFLs) (Topalis *et al.,* 2001:257 and Lai & Key, 1997:1104). The result is an increase in levels of voltage and current waveform distortion.

Traditionally, most equipment is designed to operate with a pure sinusoidal voltage and/or current waveform (no waveform distortion). This is rare in power systems in the 21st century (Dugan *et al.,* 2003:1). Three-phase power systems, especially distribution networks, are no-longer sinusoidal symmetrical systems with balanced loads, but are now non-sinusoidal asymmetrical systems; due to the large quantity of power electronic devices (e.g. CFLs, TVs and PCs) being installed in an unbalanced manner in three-phase networks (Atkinson-Hope & Stimpson, 2009:25).

The harmonic current passing through an impedance of a system causes a volt-drop for each harmonic (Dugan *et al.,* 1996:127). This results in voltage harmonics appearing at the point of common coupling (PCC) bus. The amount of voltage distortion depends on the impedance and the current. While load current harmonics cause voltage distortions, the load has no control over that distortion. Under periodic steady-state conditions, the distorted voltage and current waveforms can be studied by examining the harmonic components of the waveforms and expressed in the form of a Fourier Series (Dugan *et al.,* 1996:125).

3.1.1 Fourier Series

The sum of pure sinusoidal waveforms is known as a distorted waveform (Dugan *et al.,* 1996:125). This sum of sinusoidal waveforms is expressed as a Fourier Series and is universally applied for analysing harmonic problems as a system can be analysed separately at each harmonic (Dugan *et al.*, 2003:169). When both the positive and negative half cycles of a distorted waveform are identical, the Fourier Series contains only odd harmonics, such as the 5th, 7th, 11th, 13th etc named as characteristic harmonics (*hch*). If even harmonics are found, this is an indication something may be wrong with the system, as most harmonic sources generate odd harmonics if the supply voltage to the device is symmetrical (Dugan *et al.*, 1996:126).

Under ideal supply voltage conditions a harmonic source (e.g. convertor) draws a periodic current waveform in each phase. Its Fourier Series is comprised of fundamental and characteristics harmonic components as shown in (1.3). The magnitude of each harmonic current component (I_h) is inversely proportional to:

$$I_h = \frac{I_1}{h} \tag{3.1}$$

where: h is the harmonic number and is equal to hch ($h = hch$) when only characteristic harmonics are present, I_1 is the magnitude of the current at fundamental frequency (f_1). If f_1 is called the first harmonic then $f_1 = h_1$ and h_1 can be used instead of f_1 where it makes explanation easier. I_5 is the magnitude at the fifth harmonic (hch = 5), etc.

In a three-phase system the characteristic harmonic currents are (Atkinson-Hope, 2005:548):

$$\begin{aligned} i_R = {} & I_{1m}\cos(\omega t) - I_{5m}\cos(5\omega t) + I_{7m}\cos(7\omega t) - \\ & I_{11m}\cos(11\omega t) + I_{13m}\cos(13\omega t) - I_{17m}\cos(17\omega t) + \\ & I_{19m}\cos(19\omega t)\ldots\ldots\ldots \end{aligned} \tag{3.2}$$

$$\begin{aligned} i_Y = {} & I_{1m}\cos(\omega t - 120^{o}) - I_{5m}\cos(5\omega t - 240^{o}) + I_{7m}\cos(7\omega t - 120^{o}) - \\ & I_{11m}\cos(11\omega t - 240^{o}) + I_{13m}\cos(13\omega t - 120^{o}) - I_{17m}\cos(17\omega t - 240^{o}) + \\ & I_{19m}\cos(19\omega t - 120^{o})\ldots\ldots\ldots \end{aligned} \tag{3.3}$$

$$\begin{aligned} i_B = {} & I_{1m}\cos(\omega t + 120^{o}) - I_{5m}\cos(5\omega t + 240^{o}) + I_{7m}\cos(7\omega t + 120^{o}) - \\ & I_{11m}\cos(11\omega t + 240^{o}) + I_{13m}\cos(13\omega t + 120^{o}) - I_{17m}\cos(17\omega t + 240^{o}) + \\ & I_{19m}\cos(19\omega t + 120^{o})\ldots\ldots\ldots \end{aligned} \tag{3.4}$$

At each frequency in the series a three-phase set is found and within each set magnitudes are equal. Equations (3.2), (3.3) and (3.4) are used to determine the waveform for the complex current (I_{tot}) of the red phase. To derive such a complex waveform, for example: instantaneous values are calculated as shown in Table A.4 of Appendix A.1, where values for the harmonics are determined over a cycle as well as for the resultant complex wave. These values are then used to draw the distorted waveform in Figure 3.1 which also shows the individual harmonic component waveforms.

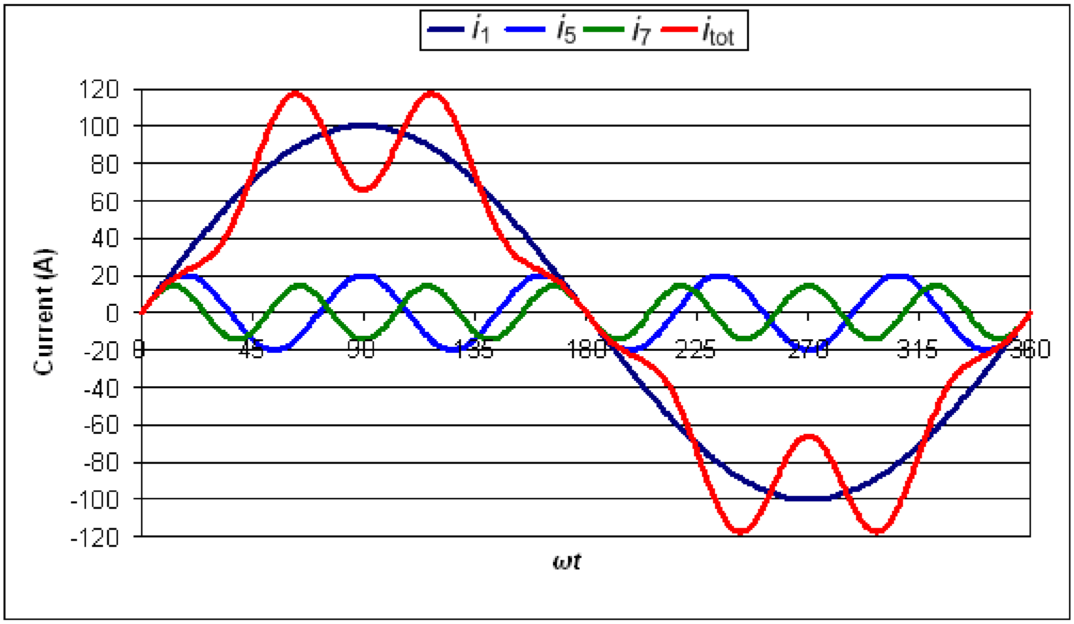


Figure 3.1: Distorted current waveform

The complex waveform in Figure 3.1 is similar to the distorted current waveform typically found at the terminals of a six-pulse converter that contains 5th and 7th harmonics. There are usually additional harmonics (*hch*) that would impose a further distortion. The magnitudes of the other harmonics, (e.g. 11th, 13th 17th, 19th, etc) are usually smaller and therefore, do not change the shape of the complex waveform too much.

3.1.2 Effective value and power

Considering a linear network with periodic applied voltage, this will cause the resulting current to contain the same harmonic terms as the voltage, but with harmonic amplitudes of different relative magnitude since the impedance varies with $h\omega$.

$$v = V_0 + \sum V_{m(h)} \sin(h\omega t + \theta_h) \text{ and } i = I_0 + \sum I_{m(h)} + \sin(h\omega t + \delta_h) \tag{3.5}$$

Where, V_0 and I_0 are the DC components, respectively, the average power p follows from integration of the instantaneous power (*p*) given by the product of *v* and *i*,

$$p = vi = \left[V_0 + \sum V_{m(h)} \sin(h\omega t + \theta_h)\right] \times \left[I_0 + \sum I_{m(h)} \sin(h\omega t + \delta_h)\right] \tag{3.6}$$

Since v and i both have periods of T sec, their product must have an integral number of its periods in T. Therefore, the average power is shown in (3.7) (Edminister, 1965:225).

$$P = \frac{1}{T}\int_0^T \left[V_0 + \sum V_{m(h)} \sin(h\omega t + \theta_h)\right] \times \left[I_0 + \sum I_{m(h)} \sin(h\omega t + \delta_h)\right] dt \tag{3.7}$$

where, the angle θ is the angle between the voltage and current at a given harmonic frequency. $V_{m(h)}$ and $I_{m(h)}$ are the maximum values of the respective sine function terms, thus:

$$P = V_0 I_0 + \frac{1}{2} V_{m1} I_{m1} \cos\theta_1 + \frac{1}{2} V_{m2} I_{m2} \cos\theta_2 + \frac{1}{2} V_{m3} I_{m3} \cos\theta_3 + ... \tag{3.8}$$

In single frequency AC circuits, the average power is $P = VI\cos\theta$ where V and I are effective (rms) voltage and current, respectively, that is:

$$V = V_{\max} / \sqrt{2} \tag{3.9}$$

$$I = I_{\max} / \sqrt{2} \tag{3.10}$$

Thus, P can be expressed in terms of a maximum value. Thus, equation (3.11) can be obtained:

$$P = \frac{1}{2} V_m I_m \cos\theta \tag{3.11}$$

3.1.3 Harmonic indices

The total harmonic distortion (THD) is a measure of the effective value of the harmonic components of a distorted waveform. It can be calculated for either voltage or current distortion as follows (Dugan *et al.*, 2003:181 and Zobaa, 2004:254):

$$\%THD = \frac{\sqrt{\sum_{h>1}^{h_{\max}} F_h^2}}{F_1} \times 100\% \tag{3.12}$$

Where F_h is the rms value of harmonic component h of the quantity F (voltage or current) and F_1, the magnitude at h=1. The distortion level caused by individual harmonic components (voltage or current magnitudes) is expressed as a percentage of the fundamental component magnitude and used as a measure of observing which harmonic component contributes more to the total harmonic distortion. The formula for its calculation is

$$\%HD = \frac{F_h}{F_1} \times 100\% \tag{3.13}$$

Therefore, equation (3.12) and (3.13) can be expressed in terms of voltage and current as follows:

$$\%V_{THD} = \frac{\sqrt{\sum_{h=2} V_h^2}}{V_1} \times 100\% \tag{3.14}$$

$$\%I_{THD} = \frac{\sqrt{\sum_{h=2} I_h^2}}{I_1} \times 100\% \tag{3.15}$$

$$\%V_{HD} = \frac{V_h}{V_1} \times 100\% \tag{3.16}$$

$$\%I_{HD} = \frac{I_h}{I_1} \times 100\% \tag{3.17}$$

Even harmonics found in the power system are usually weak as the effect of symmetrical waveforms causes them to cancel out. Third order harmonics can be present if unbalance exists depending on network configurations, and thus they appear as zero sequence components. However, characteristic harmonics are mostly found in power systems and they are the odd harmonics, namely: 5^{th}, 7^{th}, 11^{th}, 13^{th}, etc.

3.1.4 Power quantities under non-sinusoidal conditions

The IEEE power definitions under non-sinusoidal conditions are now reviewed. They are based on the trigonometric Fourier Series and its decomposition into individual harmonic frequency components. Here, *f(t)* represents instantaneous voltage or current as a function of time and F_h is the peak value of the signal component of harmonic frequency h (De La Rosa, 2006:20-23).

3.1.4.1 Instantaneous voltage and current

$$f(t)=\sum_{h=1}^{\infty} f_h(t)=\sum_{h=1}^{\infty}\sqrt{2}F_h \sin\left(h\omega_0 t+\theta_h\right) \tag{3.18}$$

3.1.4.2 Instantaneous power

$$p(t)=v(t)i(t) \tag{3.19}$$

3.1.4.3 RMS values

$$F_{rms}=\sqrt{\frac{1}{T}\int_0^T f^2(t)dt}=\sqrt{\sum_{h=1}^{\infty} F_h^2} \tag{3.20}$$

where: F_{rms} is the root mean square of function F, which in this case can be voltage or current, namely:

$$V_{rms}=\sqrt{\sum_{h=1}^{\infty} V_h^2} \tag{3.21}$$

$$I_{rms}=\sqrt{\sum_{h=1}^{\infty} I_h^2} \tag{3.22}$$

3.1.4.4 Active power

Every harmonic $(h \geq 1)$ contributes to the average power namely:

$$P=\frac{1}{T}\int_0^T p(t)dt=\sum_{h=1}^{\infty} V_h I_h \cos\left(\theta_h-\delta_h\right)=\sum_{h=1}^{\infty} P_h \tag{3.23}$$

In other terms;

$$P_h=V_h I_h \cos(\theta_h-\delta_h) \tag{3.24}$$

Where: θ_h and δ_h are voltage and current angles, respectively.

3.1.4.5 Reactive power

Like active power, each harmonic $(h \geq 1)$ component contributes to the total reactive power Q and is expressed as follows (Dugan *et al.*, 1996:131):

$$Q = \frac{1}{T}\int_0^T q(t)dt = \sum_{h=1}^{\infty} V_h I_h \sin(\theta_h - \delta_h) = \sum_{h=1}^{\infty} Q_h \tag{3.25}$$

3.1.4.6 Apparent power

The apparent power, S, is a measure of the potential impact of the load on the thermal capability of the system. It thus depends on the rms values of the distorted current and voltage. The traditional formula for apparent power "S" is (Dugan *et al.*, 1996:131):

$$S = V_{rms} \times I_{rms} \tag{3.26}$$

It was however; found that (Dugan *et al.*, 1996:131):

$$S \neq \sqrt{P^2 + Q^2} \tag{3.27}$$

To make the left hand side equal the right hand side of equation (3.27), an additional power, called distortion power D (distortion volt-amperes) was introduced:

$$S = \sqrt{P^2 + Q^2 + D^2} \tag{3.28}$$

In order to maintain the traditional formula for expressing "S", a new term denoted as "Non-Active Power (N)" was introduced.

$$S = \sqrt{P^2 + N^2} = \sqrt{P^2 + \left(Q^2 + D^2\right)} \tag{3.29}$$

Therefore, D can be determined by $D = \sqrt{S^2 - P^2 - Q^2}$ (3.30)

As S, P and Q are determinable.

3.1.5 Harmonic power flow

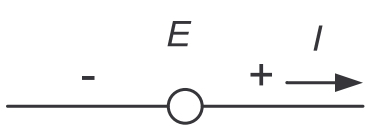
Harmonic power flow is performed to discover the harmonic distortion levels in power networks, therefore the system equations under non-sinusoidal conditions can be obtained as follows (Gursoy, 2007:15 and Arrilaga *et al.*, 1985:269):

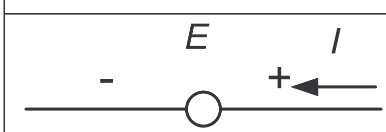
$$I_{bus(h)} = Y_{bus(h)} V_{bus(h)} \tag{3.31}$$

Where h = 2, 3, 4,……k is the harmonic order representing the integer multiples of the fundamental frequency. $I_{bus(h)}$ is the n-dimensional harmonic current injection vector, $Y_{bus(h)}$ is the $n \times n$ system harmonic admittance matrix and $V_{bus(h)}$ is the n-dimensional harmonic bus voltage vector to be solved by direct solution of the linear equation (3.31). The system harmonic admittance matrix $Y_{bus(h)}$ is formed according to the system topology using admittance of each individual power system component, which is obtained from the models for harmonic analysis (Gursoy, 2007:16).

The direction of power flow between two buses in a network depends on whether the bus is assumed to be a generator (source) or a motor (load) (Stevenson, 1982:21). This relationship defines the direction of power flow and it can be positive or negative according to Table 3.1. This gives an indication of the direction of power flows between buses. Thus, harmonic flows, like fundamental frequency power flow between two buses can also be positive or negative flows. Therefore, it is important to understand the power direction according to Table 3.1 (Stevenson, 1982:21):

Table 3.1: Power flow direction

<table>
<tr><td>Circuit diagram</td><td>Calculated from EI^*</td></tr>
<tr><td rowspan="4">

Generator action assumed</td><td>If P is +, emf supplies power</td></tr>
<tr><td>If P is -, emf absorbs power</td></tr>
<tr><td>If Q is +, emf supplies reactive power (I lags E)</td></tr>
<tr><td>If Q is -, emf absorbs reactive power (I leads E)</td></tr>
<tr><td rowspan="4">

Motor action assumed</td><td>If P is +, emf absorbs power</td></tr>
<tr><td>If P is -, emf supplies power</td></tr>
<tr><td>If Q is +, emf absorbs reactive power (I lags E)</td></tr>
<tr><td>If Q is -, emf supplies reactive power (I leads E)</td></tr>
</table>

3.1.6 Harmonic resonance

When harmonics are present in a power system, the term resonance implies the amplification of harmonic currents and voltages in a network (Bollen, 2003:10). Harmonic resonance is one of the most important considerations from a utility point of view, when wanting to ensure harmonic voltage distortion remains non-excessive (Arrilaga *et al.*, 1985:110). Another important consideration is the limitation of harmonic currents generated by customers connected to networks. As a result of the network being primarily inductive, the introduction of capacitors into the network results in harmonic network impedances that might be high or low in magnitude and resonance frequency. If this frequency corresponds with one of the harmonic frequencies, this can result in high voltages and/or currents in the network. There are commonly two types of resonances; series and parallel resonances (Zobaa, 2004:256).

3.1.6.1 Series resonance

A series LCR circuit can be built which resonates to a generator of a given frequency (Hoag, 2007:1). Then the current which flows through the circuit would have its greatest effective value. It is accomplished by choosing the inductance and capacitance reactance equal to each other. The basic resonant frequency (f_r) equation is:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{3.32}$$

Thus, at resonance, the only opposition to the flow of the current is the resistance. Figure 3.2 shows the series circuit and its resonance curve (Hoag, 2007:1).

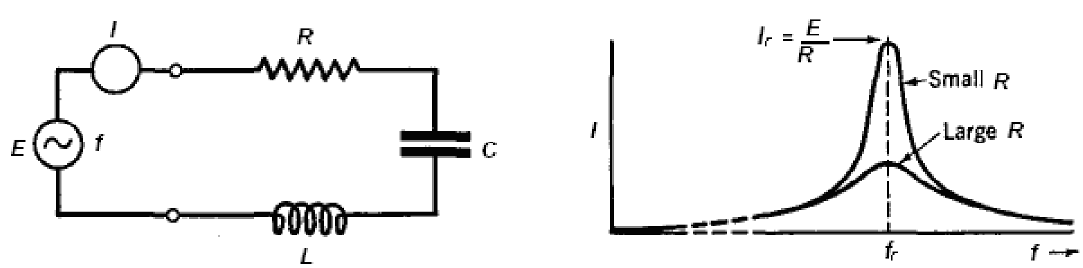


Figure 3.2: A series circuit and its resonance curve

At resonance f_r, the current is a maximum and the impedance a minimum $Z = R$. The larger the resistance in the circuit, the broader and flatter is the curve, and vice versa, showing that resistance plays a damping role (decrease in current magnitude).

3.1.6.2 Parallel resonance

Parallel resonance is the root of most problems when harmonic distortion is present in a power system (Dugan *et al.*, 2003:203). When a network has a harmonic source, a shunt capacitor (X_C) appears in parallel with the equivalent system inductance (X_T and X_{Source}) as shown in Figure 3.3 and 3.4 (Dugan *et al.*, 1996:159). The parallel combination response of inductive and capacitive reactance's seen by the source of the harmonic current becomes very large at a frequency where X_c and the total reactance ($X_T + X_{Source}$) are equal. The effect of variation in capacitor size on the impedance response (Z_h) from the harmonic sources is shown in Figure 3.5 and is compared to a case with no capacitor (Dugan *et al.*, 1996:159).

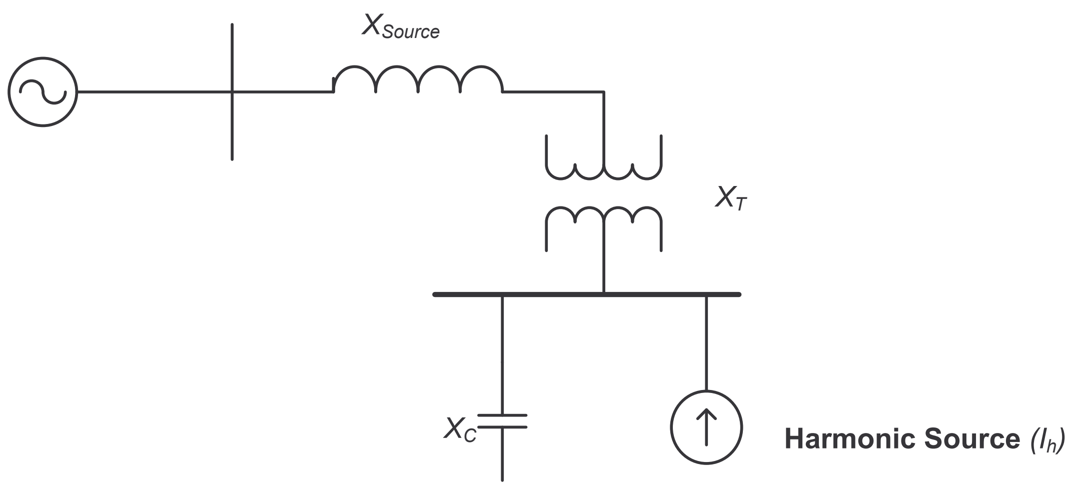


Figure 3.3: System with potential for problem parallel resonance

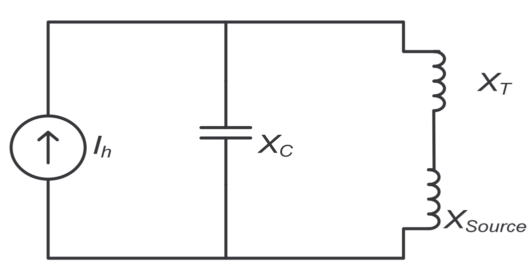


Figure 3.4: Equivalent circuit of parallel resonance

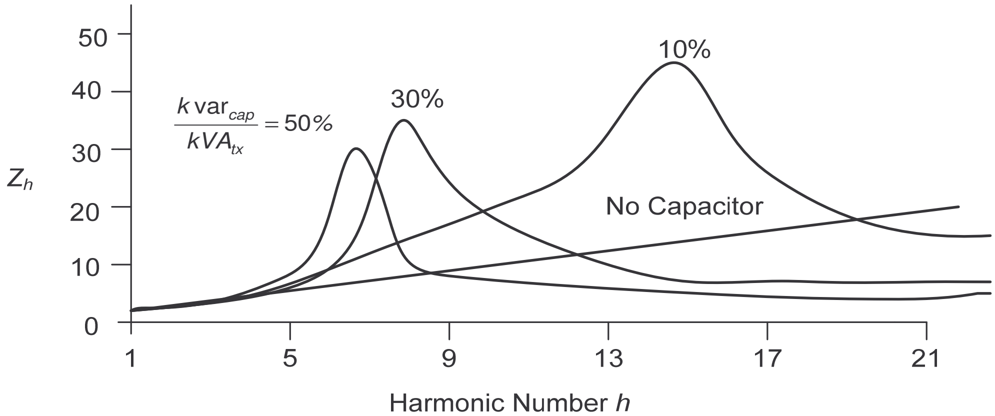


Figure 3.5: System frequency response as capacitor sizes varies

As inductance and capacitance values are not readily available, power system analysts prefer to compute the resonant harmonic frequency (h_r) as follows (Dugan *et al.*, 1996:159):

$$h_r = \sqrt{\frac{X_c}{X_{SC}}} = \sqrt{\frac{MVA_{SC}}{M\,\mathrm{var}_{cap}}} \approx \sqrt{\frac{kVA_{tx} \times 100}{k\,\mathrm{var}_{cap} \times Z_{tx}(\%)}} \tag{3.33}$$

where: X_c = capacitor reactance, X_{SC} = system short-circuit reactance, MVA_{SC} = system short-circuit MVA, $Mvar_{cap}$ = *Mvar* rating of capacitor bank, kVA_{tx} = *kVA* rating of step-down transformer, Z_{tx} = step-down transformer impedance and $kvar_{cap}$ = *kvar* rating of capacitor bank. It must be mentioned that when upstream capacitance is present in the network, then equation (3.33) may give inaccurate results (Atkinson-Hope & Folly, 2004:1393). Therefore, harmonic resonance studies are important and relevant to energy and efficiency studies, as are solutions to mitigate resonance effects.

3.2 Summary

Harmonic distortion is one of the power quality problems found in distribution networks; therefore, it is a major concern for engineers and researchers. Increase of power electronic-controlled loads (non-linear loads) such as ASD's and SMPS are common sources of harmonics in power systems. The sum of pure sinusoidal waveforms is known as distorted waveforms and is expressed as a Fourier Series, which is commonly comprised of fundamental and characteristic harmonic (odd harmonics only) components. Traditional formulae for average, apparent, reactive and complex power in non-sinusoidal conditions are reviewed and extended to a new power concept called distortion power. Total harmonic distortion of current and voltage as well as individual distortion formulae are also reviewed. The background to the direction of harmonic power flows and their representation as positive and negative values is introduced as this is relevant to the energy and efficiency studies. With harmonics, resonance is a concern; therefore, the theory on series and parallel resonance is also reviewed. In this chapter a foundation is laid for the contribution of this thesis to the field efficiency.

CHAPTER 4: CONTRIBUTION TO FIELD OF EFFICIENCY

4.1 Efficiency

Many researchers and writers have discussed efficiency of individual machines or components such as transformers, induction motors and cables, etc (Almeida *et al.,* 2005:189; Casada *et al.,* 2000:241; El-Ibiary, 2003:1205 and Holmoquist *et al.,* 2004:242). They use equation (1.2) to determine efficiency. This formula is the traditional approach, but in the modern era, where harmonic sources are present, the formula no longer holds true. Today, distribution networks contain harmonic distortion from non-linear loads. Therefore, current and voltage waveforms are no longer sinusoidal, but are distorted (complex) (Mishra *et al.,* 2007:288). Thus there is a need for power system engineers to identify and understand efficiency when harmonics are present in a network; and this is a shortcoming in literature. No method is found on how to calculate individual component and overall efficiency of a network when harmonic distortion is present, that is, with combined frequencies: fundamental and harmonic frequencies.

To calculate the overall efficiency of a network it is essential to understand the direction of power flow. Power direction at fundamental frequency is usually from source to load. Powers at harmonic frequencies are injected from the load side of a network (e.g. drive) back towards the fundamental frequency source via the other components within the network. Along every path, each component will have individual efficiencies, but together the network will have an overall efficiency. In this thesis, it is assumed that all networks are symmetrical and balanced systems. The work can however be extended to include asymmetrical unbalanced systems taking into account sequences of three-phase harmonic sets but this will form the basis of future work (Atkinson-Hope, 2005: 545).

4.2 Energy usage

Utility companies always try to estimate daily, weekly, monthly and annual energy usages. They traditionally calculate energy usage of a network by assuming that only fundamental frequency is present, equation (1.1) (Grady *et al*., 2001:10). They ignore the impact of harmonics when determining energy usage. Thus, besides energy usage at fundamental frequency, harmonic energy usage needs also to be determined and combined to provide an overall picture of the total energy usage in a network.

4.3 Power with distorted waveforms

A non-linear load, draws a current at fundamental frequency (h=1) and injects in opposite direction harmonics, see Figure 4.1(a), whereas linear loads absorb fundamental frequency and harmonic powers, when a distorted voltage is applied to them, see Figure 4.1(b) (Dugan et al., 2003:218).

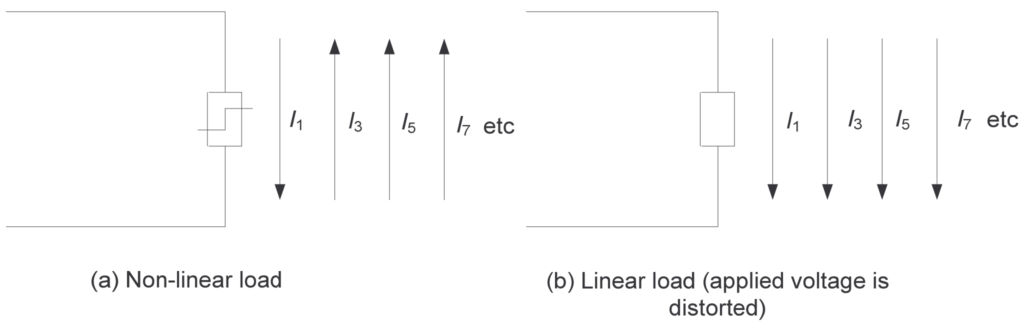


Figure 4.1: Current direction of linear and nonlinear load

Thus, a non-linear load in Figure 4.1(a) absorbs a current (I_1) and power (P_1) at fundamental frequency, while it injects into the network harmonic currents (e.g. I_3, I_5, I_7, etc) and powers (P_3, P_5, P_7, etc). This will result in a total power (P_T) where the harmonic powers are subtracted from P_1 (Dugan *et al.*, 2003:178):

$$P_T = P_1 - P_3 - P_5 - P_7 - .... \quad (4.1)$$

In contrast, in the case of a linear load, the total power is the summation of powers:

$$P_T = P_1 + P_3 + P_5 + P_7 + ... \quad (4.2)$$

The linear load thus absorbs P_1 and all the harmonic powers. Thus, when determining individual and overall efficiencies when distortion is present the roles of non-linear and linear loads needs to be taken into account.

4.4 The need of this project

The need for this project is that harmonic flows and their effect on efficiency and energy usage should no longer be ignored. Therefore, there is a need to develop formulae and a methodology to assist power system engineers, planners and energy conservationists to be able to calculate power losses and how they affect overall efficiency and energy usage when distortion is present. There is also a further need to demonstrate how harmonics affect power flows and thus efficiencies, using measurement and simulation investigations.

4.5 Contributions

The contributions of this work to the field of efficiency are:

a) Measurements

- A measurement based laboratory experiment to represent a simple radial distribution network is developed for efficiency studies when distortion is present.
- The development of indices (formulae) and a methodology for evaluating individual and overall usage of energy and efficiency when waveforms are distorted.
- Measurements of current, voltage and power at various points in a network and demonstrate how these results and power flow directions are applied through the application of the developed formulae and methodology for the calculation of individual component efficiencies and for determining the overall efficiency of the network.

b) Simulations

- A simulation based case study of a simple radial distribution network is developed that includes distortion so as to further support the effectiveness of the contribution made by the measurement study. This work also contributes the effect of resonance on efficiency when distortion is present. This includes the role of a capacitor bank and filter for the mitigation of harmonic resonance and reduction of total harmonic distortion.
- This study includes a load flow analysis to obtain power results at fundamental frequency. A harmonic penetration study with two harmonic source (a six-pulse drive) is also conducted to obtain power results and their directions at harmonic frequencies, from which individual and overall energy usage and efficiencies are determined using newly developed formulae and methodology.

c) Analysis

- Results are analysed and findings, conclusions and recommendations are made on efficiency and energy usage when distortion is present.

4.6 Software

Two software packages DIgSILENT and SuperHarm are used for the simulation investigations and to demonstrate the effectiveness of the developed formulae for evaluating overall efficiency and total energy usage when distortion is present.

4.6.1 DIgSILENT

DIgSILENT has an integrated graphical one-line interface. It includes network drawing functions, modelling and features enabling power system analyses to be conducted. This package has the capability to conduct load flow and harmonic analysis simulation studies and generate power results at all frequencies. It is thus an ideal package for conducting efficiency and energy usage when distortion is present (Atkinson-Hope & Stemmet, 2007:27).

4.6.2 SuperHarm

SuperHarm is a tool designed and dedicated for the evaluation of harmonic concerns in electric power systems. The software requires a user to develop a computer model of the system of interest and explore variations on system loads and configurations with resulting impact on system frequency response and distortion levels. It can solve both balanced and unbalanced three-phase systems and accomplishes this using phase domain nodal matrix techniques, rather than sequence component solution methods. The solution engine reads a text file created by the user that describes the network to be simulated. SuperHarm utilises TOP, an output processor tool to visualise the simulation results. The programme takes advantage of Microsoft Windows Graphical User Interface and clipboard to allow the user to easily transfer data to a Windows programme (Atkinson-Hope & Stemmet, 2007, 28).

The usage of these software tools enables a contribution to be made to the field of efficiency and energy usage when distortion exists in a power system.

4.7 Measurement analyser

4.7.1 Fluke 435

The Fluke 435 is a modern three-phase harmonic power quality analyser, manufactured in the Netherlands by Fluke Industrial B.V., a subdivision of the Fluke Corporation. The Fluke 435 can measure systems having distortion with accuracy to three decimal places. The Fluke specifications and accuracy are given in Tables A.5 and A.6 in Appendix A.1 (Fluke Corporation, 2007).

Figure 4.2: Fluke 435 harmonic analyzer

4.8 Development of formulae and methodology

Figure 4.3 illustrates the measurement based laboratory experiment set-up used to develop the new methodology and formulae for investigating efficiency and energy usage.

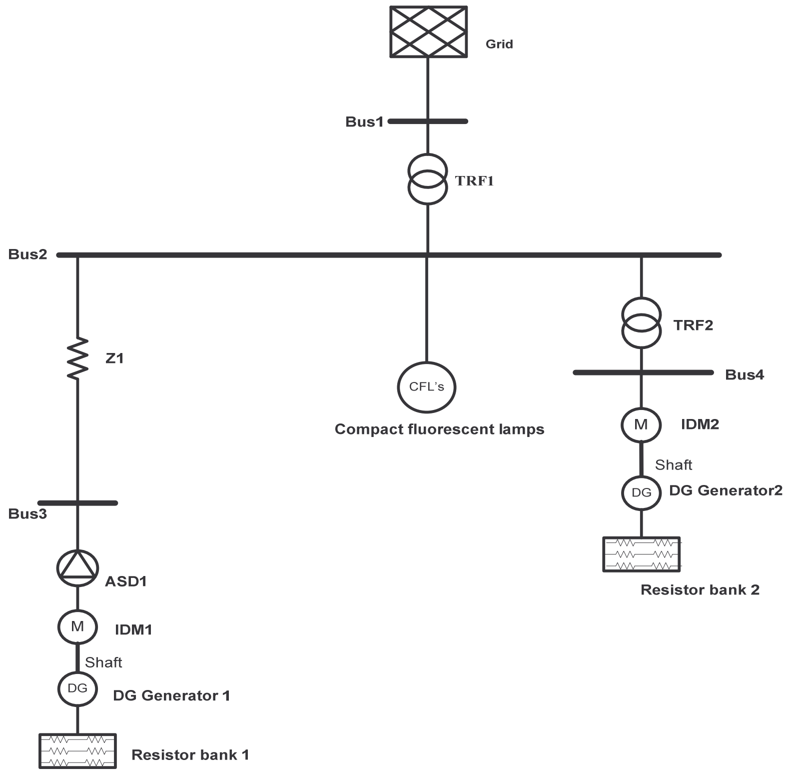


Figure 4.3: Measurement based laboratory experimental set-up

The developed network represents a simplified network of three-phase (3ϕ) radial distribution network. Bus 1 was selected as the reference busbar with a voltage of 400∠0° V and a system frequency of 50 Hz. Between bus 1 and bus 2 there is a two–winding transformer (TRF1), 400/400 V giving a ratio 1:1 and it is connected Star-Star (Yyn). Bus 2 is taken as the point of common coupling (PCC). Two AC induction motors IDM1 and IDM2 are fed and are mechanically coupled to DG Generators 1 and 2, respectively. These generators supply resistor banks 1 and 2 and are the motor loadings. In this experiment, resistor banks 1 and 2 were varied so that maximum currents of 5 A and 6 A are drawn, respectively. Transformer (TRF2) also has two windings, with the voltage rating of 380 / 220 V connected in Yyn.

The induction motor (IDM1) is controlled by a drive ASD1 and is responsible for injecting harmonics into the system as it is a non-linear load. Induction motor (IDM2), represents a linear load. A number of compact fluorescent lamps (CFL's), each with a rating at 230 V, 0.05 A and 11 W, respectively are added as extra loading and also to generate harmonics into the system as they are also non-linear loads. In each phase, 20 CFL lamps were connected in parallel giving a total of 60 CFL's making up a three-phase star load. The ratings of the equipments are as shown in the following tables.

Table 4.1: Non-linear load specifications

AC motor		**DG Generator**		**Drive**	
Name	IDM1	Name	DG1	Name	ASD1
Output power	3 B.H.P	Input speed	950 rpm	Input voltage	380/415 V
Input voltage	380 V AC	Excitation voltage	71/ 48 V DC	Input current	13 A
Input current	4.95 A	Output current	3/5 A	Output voltage	0-380 V
Frequency	50 Hz	Rating	continuous	Output current	16 A max
Speed	950 rpm			Output frequency	1-50/87 Hz
Rating	continuous			Power rating	7.5 kW
				Pulse	6

Table 4.2: Linear load specifications

AC motor		**DG Generator**	
Name	IDM2	Name	DG2
Output power	7.5 H.P	Input speed	1150 rpm
Input power	380 V AC	Excitation voltage	115 V DC
Input current	11.8 A	Output power	3 kW
Frequency	50 Hz		
Speed	965 rpm		

Table 4.3: Transformer specifications

Transformer 1		**Transformer 2**	
Name	TRF1	Name	TRF2
Primary voltage	400 V	Primary voltage	380 V
Secondary voltage	400 V	Secondary voltage	220 V
Turns ratio	1/1	Turns ratio	1/ 0.8
Connection	Yyn	Connection	Yyn

Table 4.4: Compact fluorescent lamp specifications

Compact fluorescent lamp	
Name	CFL's
Power output	11 W
Rating voltage	230 V
Rating current	0.05 A
Number per phase	20 CFL's in parallel

4.8.1 Fundamental frequency

The first step in the methodology was to develop an equivalent network for the experimental set-up developed. This is shown in Figure 4.4. Symbols were allocated for each power and these are shown in Table 4.5. This developed diagram is used for demonstrating the relationships between power flows in the system, from which efficiency formulae are developed at fundamental frequency. The arrows show the direction of power flow and the positive symbol (+) means from source (Grid) towards loads.

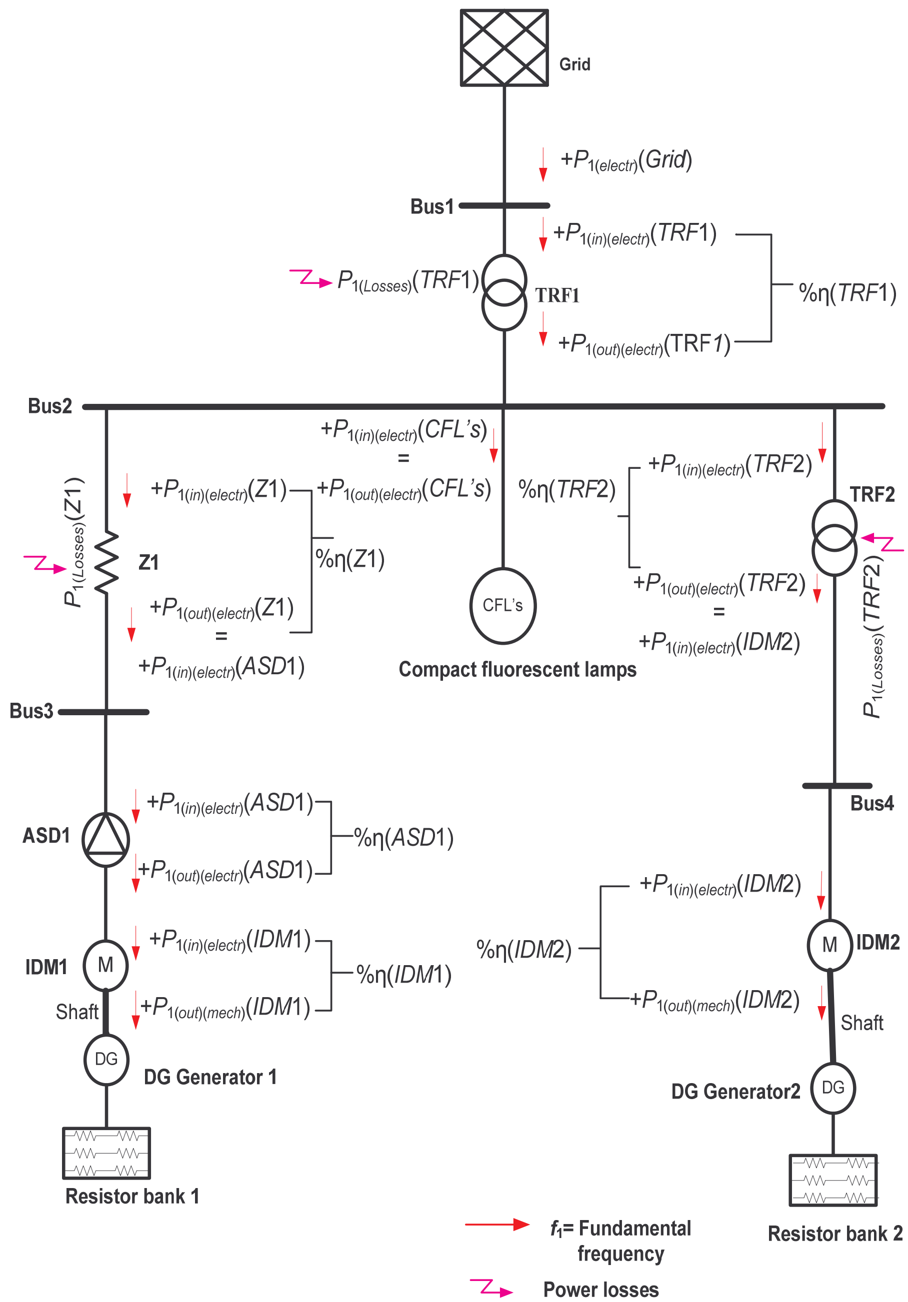


Figure 4.4: Developed equivalent network of experimental set-up

Table 4.5: Explanation of the symbols used in developed equivalent circuit

$P_{1(out)(mech)}IDM1$	Induction motor 1 mechanical output power
$P_{1(in)(electr)}IDM1$ $=$ $P_{1(out)(electr)}ASD1$	Induction motor 1 electrical input power = Adjustable speed drive 1 electrical output power
$P_{1(in)(electr)}ASD1$ $=$ $P_{1(out)(electr)}Z1$	Adjustable speed drive 1 electrical input power = impedance 1 electrical output power
$P_{1(in)(electr)}Z1$	Impedance 1 electrical input power
$P_{1(in)(electr)}CFL's$ $=$ $P_{1(out)(electr)}CFL's$	Compact fluorescent lamps electrical input power to CFL branch = Compact fluorescent electrical input power used for conversion to light output
$P_{1(out)(mech)}IDM2$	Induction motor 2 mechanical output power
$P_{1(in)(electr)}IDM2$ $=$ $P_{1(out)(electr)}TRF2$	Induction motor 2 electrical input power = Transformer 2 electrical output power
$P_{1(in)(electr)}TRF2$	Transformer 2 electrical input power
$P_{1(out)(electr)}TRF1$ $=$ $\sum[P_{1(in)(electr)}Z1 + P_{1(in)(electr)}CFL's\ P_{1(in)(electr)}TRF2]$	Transformer 1 electrical output power
$P_{1(in)(electr)}TRF1$	Transformer 1 electrical input power
$P_{1(electr)}GRID$	Grid electrical input power
$P_{1(Losses)}TRF1$	Transformer 1 power losses
$P_{1(Losses)}TRF2$	Transformer 2 power losses
$P_{1(Losses)}Z1$	Impedance 1 power losses

where, the electrical (*electr*) powers at inputs (*in*) and output (*out*) are the three-phase powers and (*out*)(*mech*) is the total mechanical output delivered by the three-phase motor.

The next step in the methodology is the development of formulae for evaluating individual and overall efficiency at (f_1). The positive (+) symbol indicates that power flows from the source (Grid) at (f_1) towards the outputs. The following formulae are used to develop the individual efficiency indices for the various components.

$$\%\eta(IDM1) = \frac{P_{1(out)(mech)}IDM1}{P_{1(in)(electr)}IDM1} \times 100\% \tag{4.3}$$

$$\%\eta(ASD1) = \frac{P_{1(out)(electr)}ASD1}{P_{1(in)(electr)}ASD1} \times 100\% \tag{4.4}$$

$$\%\eta(Z1) = \frac{P_{1(out)(electr)}Z1}{P_{1(in)(electr)}Z1} \times 100\% \tag{4.5}$$

$$\%\eta(IDM2) = \frac{P_{1(out)(mech)}IDM2}{P_{1(in)(electr)}IDM2} \times 100\% \tag{4.6}$$

$$\%\eta(TRF2) = \frac{P_{1(out)(electr)}TRF2}{P_{1(in)(electr)}TRF2} \times 100\% \tag{4.7}$$

$$\%\eta(TRF1) = \frac{P_{1(out)(electr)}TRF1}{P_{1(in)(electr)}TRF1} \times 100\% \tag{4.8}$$

The next step in the developed methodology is the development of a formula for the overall efficiency of the network at f_1. In order to define this formula the total output power (*mech*), total losses (3ϕ) and total input power (3ϕ) needs to be defined. These are defined in Table 4.6. This network has only one source (Grid) but feeds into three loads (IDM1, IDM2 and CFL's), there are six components that cause losses in the network.

Table 4.6: Power input, output and losses of a network

$P_{1(in)}$ = total input at f_1	$P_{1(electr)}$(Grid)		
$P_{1(losses)}$ = losses per compo-nent	• $P_{1(losses)}(TRF1)$ • $P_{1(losses)}(Z1)$ • $P_{1(losses)}(IDM1)$ • $P_{1(losses)}(ASD1)$ • $P_{1(losses)}(TRF2)$ • $P_{1(losses)}(IDM2)$	$\sum P_{1(losses}$ = total losses at f_1	$\sum P_{1(losses)} = \sum \begin{bmatrix} P_{1(losses)}(TRF1) + \\ P_{1(losses)}(Z1) + \\ P_{1(losses)}(IDM1) + \\ P_{1(losses)}(ASD1) + \\ P_{1(losses)}(TRF2) + \\ P_{1(losses)}(IDM2) \end{bmatrix}$
$P_{1(out)}$ = mechani cal or electrical per output branch	• $P_{1(out)(mech)}$(IDM1) • $P_{1(out)(mech)}$(IDM2) • $P_{1(out)(electr)}$(CFL's)	$\sum P_{1(out)}$ = total output at f_1	$\sum P_{1(out)} = \sum \begin{bmatrix} P_{1(out)(mech)}(IDM1) + \\ P_{1(out)(mech)}(IDM2) + \\ P_{1(out)(electr)}(CFL's) \end{bmatrix}$

Now, using (1.2) as a basis, the formula for overall efficiency is:

$$\%\eta_1 overall = \frac{\sum P_{1(out)}}{P_{1(in)}} \times 100\% \tag{4.9}$$

or

$$\%\eta_1 overall = \frac{\sum P_{1(out)}}{\sum P_{1(out)} + \sum P_{1(losses)}} \times 100\% \tag{4.10}$$

where, $P_{1(in)}$ is the three-phase input to the network at f_1. Total electrical energy usage (3ϕ) based on (1.1) at a fundamental frequency is defined as follows:

$$Total\ energy\ usage\ E_{1(electr)}Grid = P_{1(in)} \times t\ \ Joules \tag{4.11}$$

where, $E_{1(electr)}$ is the total energy usage by the three-phase network at f_1.

4.8.2 Harmonic frequency

The following step in the methodology is to develop formulae for the network in question, when harmonics are injected into the system. Figure 4.5 shows the developed network required for investigating individual efficiencies of components at harmonic frequencies $(h \neq f_1)$. The arrows show the directions of harmonic power flows.

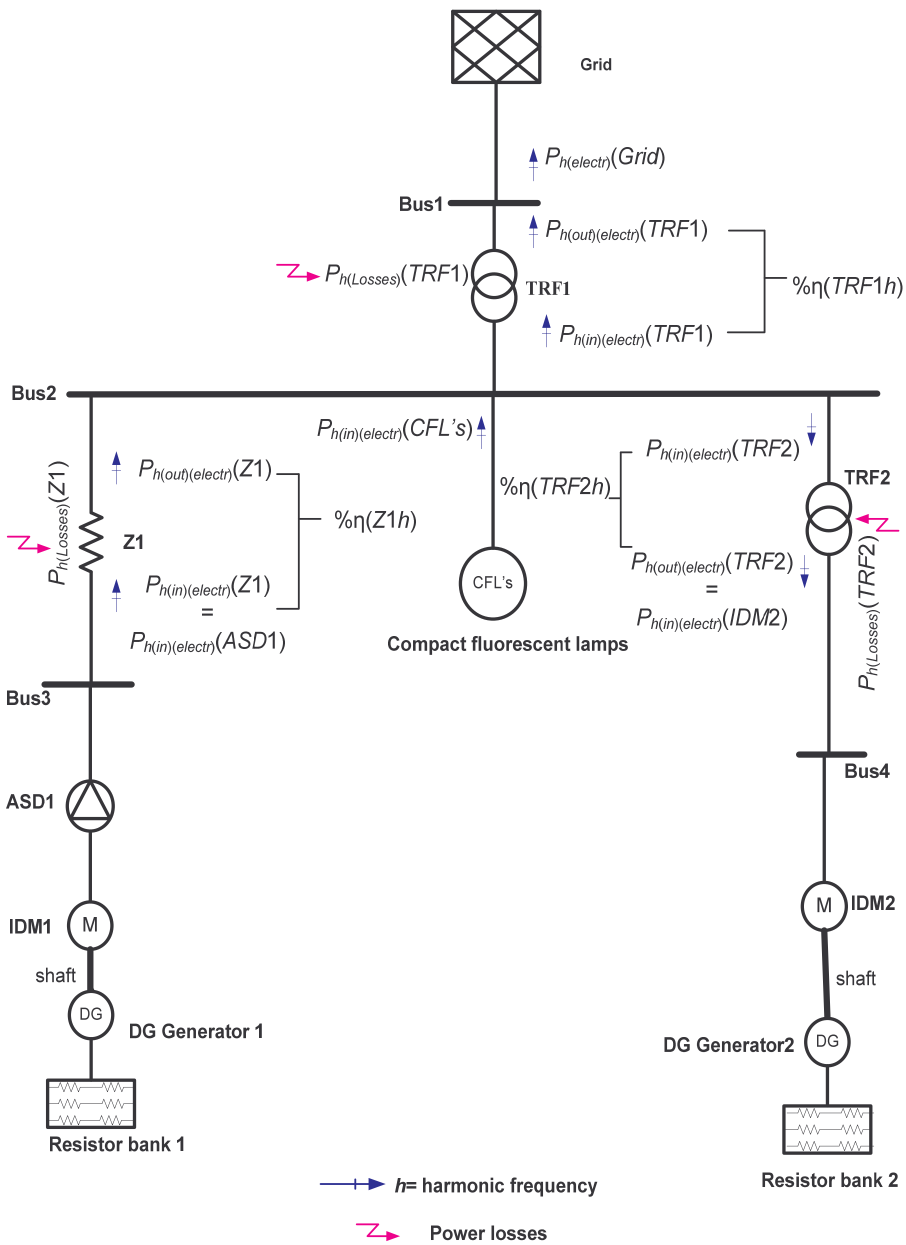


Figure 4.5: Power flows per harmonic frequency

When harmonics are present, the non-linear devices (ASD1 and CFL's) are sources; this means the non-linear devices (ASD1 and CFL's) inject harmonics and are therefore, the inputs to the network, whereas when f_1 is the only frequency in the network, the grid is the source. Under harmonic power flow conditions, the grid infeed is treated as a short circuit as it is usually treated as an ideal voltage source at f_1 (Electrotek Concepts, Inc, 2000:4-44).

Table 4.7: Explanation of the symbols used in power flows for harmonic frequency

$P_{h(in)(electr)}ASD1$ = $P_{h(in)(electr)}Z1$	Adjustable speed drive 1 electrical input power at harmonic = Impedance 1 electrical input power at harmonic
$P_{h(out)(electr)}Z1$	Impedance 1 electrical output power at harmonic
$P_{h(in)(electr)}CFL's$	Compact fluorescent lamps electrical input power at harmonic
$P_{h(in)(electr)}TRF2$	Transformer 2 electrical input power at harmonic
$P_{h(out)(electr)}TRF2$ = $P_{h(in)(electr)}IDM2$	Transformer 2 electrical output power at harmonic = Induction motor 2 electrical input power at harmonic
$P_{h(in)(electr)}TRF1$	Transformer 1 electrical input power at harmonic
$P_{h(out)(electr)}TRF1$	Transformer 1 electrical output power at harmonic
$P_{h(electr)}GRID$	Grid electrical power at harmonic = $P_{h(out)(electr)}TRF1$
$P_{h(Losses)}TRF1$	Transformer 1 power losses at harmonic
$P_{h(Losses)}TRF2$	Transformer 2 power losses at harmonic
$P_{h(Losses)}Z1$	Impedance 1 power losses at harmonic

The following formulae are developed for the individual efficiency of the various components, now using three-phase values:

$$\%\eta(Z1h) = \frac{P_{h(out)(electr)}Z1}{P_{h(in)(electr)}Z1} \times 100\% \tag{4.12}$$

$$\%\eta(TRF2h) = \frac{P_{h(out)(electr)}TRF2}{P_{h(in)(electr)}TRF2} \times 100\% \tag{4.13}$$

$$\%\eta(TRF1h) = \frac{P_{1(out)(electr)}TRF1}{P_{1(in)(electr)}TRF1} \times 100\% \tag{4.14}$$

The next step in the developed methodology is the development of a formula for the overall efficiency of the network at a harmonic frequency. In order to define this formula the total output power, total losses and total input power needs to be defined. These are defined in Table 4.8. This network has however two harmonic sources (ASD1 and CFL's) and they feed into two linear loads (IDM2 and Grid (branch)). In this network there are only three components causing losses.

Table 4.8: Power input and losses of a network

$P_{h(in)}$ = input per non-linear load	• $P_{h(in)(electr)}(ASD1)$ • $P_{h(in)(electr)}(CFL's)$	$\sum P_{h(in)}$ = total input at h	$\sum P_{h(in)} = \sum \begin{bmatrix} P_{h(in)(electr)}(ASD1) \\ P_{h(in)(electr)}(CFL's) \end{bmatrix}$
$P_{h(losses)}$ = losses per component	• $P_{h(losses)}(TRF1h)$ • $P_{h(losses)}(Z1h)$ • $P_{h(losses)}(TRF2h)$	$\sum P_{h(losses)}$ = total losses at h	$\sum P_{h(losses)} = \sum \begin{bmatrix} P_{h(losses)}(TRF1h) \\ P_{h(losses)}(Z1h) \\ P_{h(losses)}(TRF2h) \end{bmatrix}$
$P_{h(out)}$ = per output branch	• $P_{h(in)(electr)}(IDM2)$ • $P_{h(in)(electr)}(Grid)$	$\sum P_{h(out)}$ = total output at h	$\sum P_{h(out)} = \sum \begin{bmatrix} P_{h(in)(electr)}(IDM2) \\ P_{h(in)(electr)}(Grid) \end{bmatrix}$

From this, formulae are developed for the overall efficiency (3ϕ) of the network at a harmonic frequency $(h \neq f_1)$:

$$\%\eta_h overall = \frac{\sum P_{h(out)}}{\sum P_{h(in)}} \times 100\% \tag{4.15}$$

or

$$\%\eta_h overall = \frac{\sum P_{h(out)}}{\sum P_{h(out)} + \sum P_{h(Losses)}} \times 100\% \tag{4.16}$$

where, $P_{h(in)}$, $P_{h(out)}$ and $P_{h(losses)}$ are three-phase values.

The term harmonic energy is a new phenomenon in electrical power systems. It is important for utility companies to know and understand the term. As harmonic energy influences total energy usage, it requires research. As there are two harmonic sources (non-linear loads) in the network (ASD1 and CFL's), their total energy usage ($E_{T(h)}$ (3ϕ) at a harmonic frequency is dependent on their combined power input $P_{T(h)}$ (3ϕ), namely:

$$E_{T(h)} = P_{T(h)} \times t \quad Joules \tag{4.17}$$

$$E_{T(h)} = \left(P_{h(in)(electr)}(ASD1) + P_{h(in)(electr)}(CFL's)\right) \times t \quad Joules \tag{4.18}$$

4.8.3 Combined fundamental and harmonic frequencies (*H*)

The next step in the methodology is the development of new formulae for investigating individual and overall efficiencies and energy usage when distortion (*H*) is present in the network. That is, when distorted waveforms are decomposed into fundamental (f_1) and harmonic (h) frequency components. To evaluate the combined effect (H), this meant that formulae for power flows at f_1 and $h \neq f_1$ needed to be shown separately in the network and then their resultants combined into total power (P_T) equations.

But, before this development is possible, it was found essential to know the direction of power flow through each component as well as the direction at inputs and outputs. According to Dugan *et al* (2003:178) the power flow directions for linear and non-linear loads are different and these are shown on diagrams using arrows (Figures 4.1(a) and (b)) and in total power (P_T) equations by using "+" and "-" signs (4.1) and (4.2).

To confirm and develop confidence in the establishment of the directions (arrows, as well as "+" and "-" signs), it was found necessary to conduct a measurement based study on the network (Figure 4.3) using the (3ϕ) harmonic analyser described in section 4.7. The details of this investigation are described in a case study in the next chapter.

From this measurement based empirical investigation, it became possible to deduce the directions of power flows. This enabled Figure 4.6 to be developed and from which new formulae are devised for individual and overall efficiency and energy usage when f_1 and $h \neq f_1$ are combined, called combined fundamental and harmonic frequencies (H).

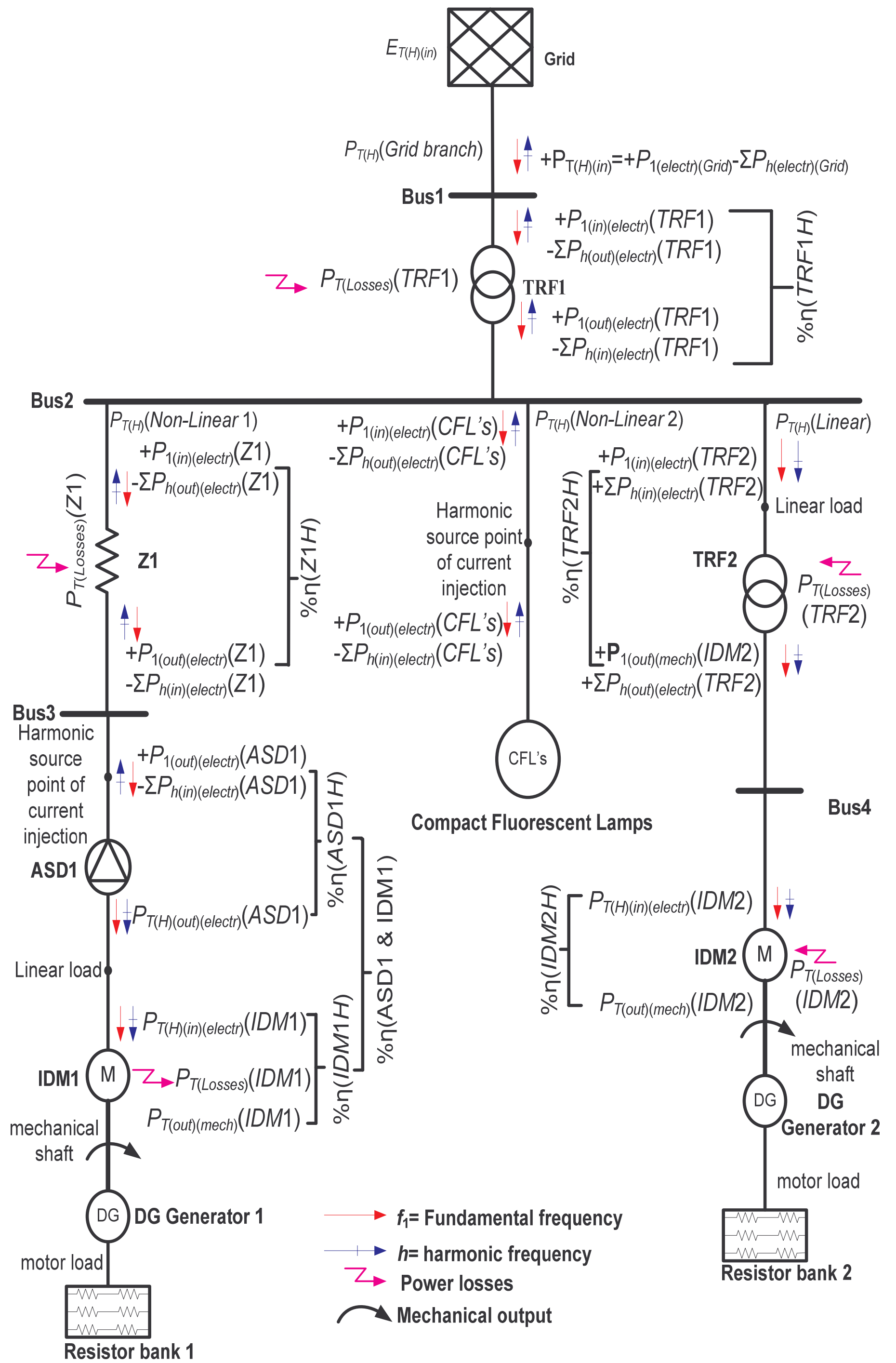


Figure 4.6: Power flows for combined frequencies

On Figure 4.6, the following symbols, arrows as well as "+" and "-"signs are used to describe the operation of the network:

Table 4.9: Explanation of the arrows and signs used

	Power directions at harmonic frequencies
	Power directions at fundamental frequency
	Power Losses
+	"+" means supplying power when acting as a source (Grid and TRF1) or absorbing power when acting as a load (Z1, CFL's and TRF2) (Table 3.1)
-	"-" means absorbing power when acting as a source (Grid and TRF1) or supplying power when acting as a load (ASD1 and CFL's) (Table 3.1)
	Mechanical power

Therefore, the total power $P_{T(H)}$ of the (3ϕ) linear, non-linear loads and grid branch are in general as follows:

Linear load $P_{T(H)(Linear)} = (P_1 + \sum P_h)Linear$ (4.19)

Non-linear loads 1 and 2 $P_{T(H)(non-linear)} = (P_1 - \sum P_h)Non-linear$ (4.20)

Grid branch $P_{T(H)(Grid\,branch)} = (P_1 - \sum P_h)Grid\,branch$ (4.21)

The following formulae are developed to calculate the individual efficiency of the various components.

$$\%\eta(Z1H) = \frac{P_{1(out)(electr)}Z1 - \sum P_{h(in)(electr)}Z1}{P_{1(in)(electr)}Z1 - \sum P_{h(out)(electr)}Z1} \times 100\% \quad (4.22)$$

$$\%\eta(TRF2H) = \frac{P_{1(out)(electr)}TRF2 + \sum P_{h(out)(electr)}TRF2}{P_{1(in)(electr)}TRF2 + \sum P_{h(in)(electr)}TRF2} \times 100\% \quad (4.23)$$

$$\%\eta(TRF1H) = \frac{P_{1(out)(electr)}TRF1 - \sum P_{h(in)(electr)}TRF1}{P_{1(in)(electr)}TRF1 - \sum P_{h(out)(electr)}TRF1} \times 100\% \quad (4.24)$$

The next step in the developed methodology is the development of a formula for the overall efficiency of the (3ϕ) network when distortion is present $(\%\eta_H overall)$. The overall efficiency when distortion is present is determined from the grid infeed (main supply point) towards the output of loads.

In order to define this formula the total output power, total losses and total input power needs to be defined. Using (4.19 to 4.21), these are defined in Table 4.10.

Table 4.10: Total power input, output and losses of a network

$P_{T(H)(in)}$	• $P_{T(H)}(Grid\ branch)$	$P_{T(H)(in)} = (P_1 - \sum P_h)\,Grid\ branch$
$P_{T(H)(losses)}$	• $P_{T(losses)}(TRF1H)$ • $P_{T(losses)}(Z1H)$ • $P_{T(losses)}(TRF2H)$	$P_{T(H)(losses)} = \sum \begin{bmatrix} P_{T(losses)}(TRF1H) \\ P_{T(losses)}(Z1H) \\ P_{T(losses)}(TRF2H) \end{bmatrix}$
$P_{T(losses)}$ $(mech)$	• $P_{T(losses)}(IDM1)$ • $P_{T(losses)}(IDM2)$	$P_{T(losses)(mech)} = \sum \begin{bmatrix} P_{T(losses)}(IDM1) \\ P_{T(losses)}(IDM2) \end{bmatrix}$
$P_{T(out)}$	• $P_{T(out)(mech)}(IDM1)$ • $P_{T(out)(mech)}(IDM2)$ • $P_{T(H)}(Non\text{-}linear\ 2)$	$P_{T(out)} = \sum \begin{bmatrix} P_{T(out)(mech)}(IDM1) + \\ P_{T(out)(mech)}(IDM2) + \\ P_{T(H)}(Non-linear\ 2) \end{bmatrix}$

Where, $P_{T(H)}$ and $P_{T(H)(losses)}$ are three-phase values, $P_{T(out)(mech)}$ and $P_{T(losses)(mech)}$ are for the three-phase motors.

Now using Table 4.10 new formulae are developed for the overall efficiency:

$$\%\eta_H overall = \frac{P_{T(out)}}{P_{T(H)(in)}} \times 100\% \tag{4.25}$$

$$\text{or,}\quad \%\eta_H overall = \frac{\sum \begin{bmatrix} P_{T(out)(mech)}(IDM1) + \\ P_{T(out)(mech)}(IDM2) + \\ P_{T(H)}(Non-linear\ 2) \end{bmatrix}}{(P_1 - \sum P_h)\,Grid\ branch} \times 100\% \tag{4.26}$$

where:

$$P_{T(H)(in)} = P_{T(out)} + P_{T(H)(losses)} + P_{T(losses)(mech)} \tag{4.27}$$

As harmonic energy influences total energy usage, a new formula (see figure 4.6) to calculate total energy usage was derived as:

$$E_{T(H)(in)} = P_{T(H)(in)} \times t \quad Joules \tag{4.28}$$

where, $E_{T(H)(in)}$ and $P_{T(H)(in)}$ are three-phase values.

4.9 Summary

Efficiency of individual elements at the fundamental frequency has been discussed by many researchers in power systems. When harmonics are present, to determine the individual and overall efficiency the direction of power must be considered. Power from f_1 is usually from the source to the load, whereas at harmonic frequency, harmonic currents are injected from the non-linear loads towards the source of supply through the components in the network. In this chapter, contributions to the field of efficiency are made. Developments of a methodology and formulae for overall efficiency and total energy usage at f_1, h and H are introduced. Direction of power at each point in the network is established for f_1, h and H. Symbols used at each frequency (f_1, h and H) are developed and explained. The use of arrows and signs is essential when conducting efficiency and energy studies when distortion is present. In this chapter the contributions are mainly the development of formulae and a methodology. Although the formulae developed in this chapter are network (case) specific, they can easily be adapted for general application and this will be shown in the simulation case study conducted in the next chapter.

CHAPTER 5: MEASUREMENT AND CASE STUDIES

In this chapter two case studies are conducted to demonstrate how individual; and overall efficiency and energy usage is determined, when a network contains one or more harmonic sources causing waveform distortion. The first case study is measurement based and is a laboratory experiment. The second case study is on a radial distribution network using simulations.

5.1 Case study 1: Laboratory Environment

For this study, a laboratory set–up was undertaken. The network has been described in Figure 4.3. It is a three-phase four-wire system and includes a linear load (IDM2), two harmonic sources (ASD1 and CFL's) and a supply branch (Grid). Measurements were taken at the seven positions as marked in Figure 5.1 (Test 1 to Test 7).

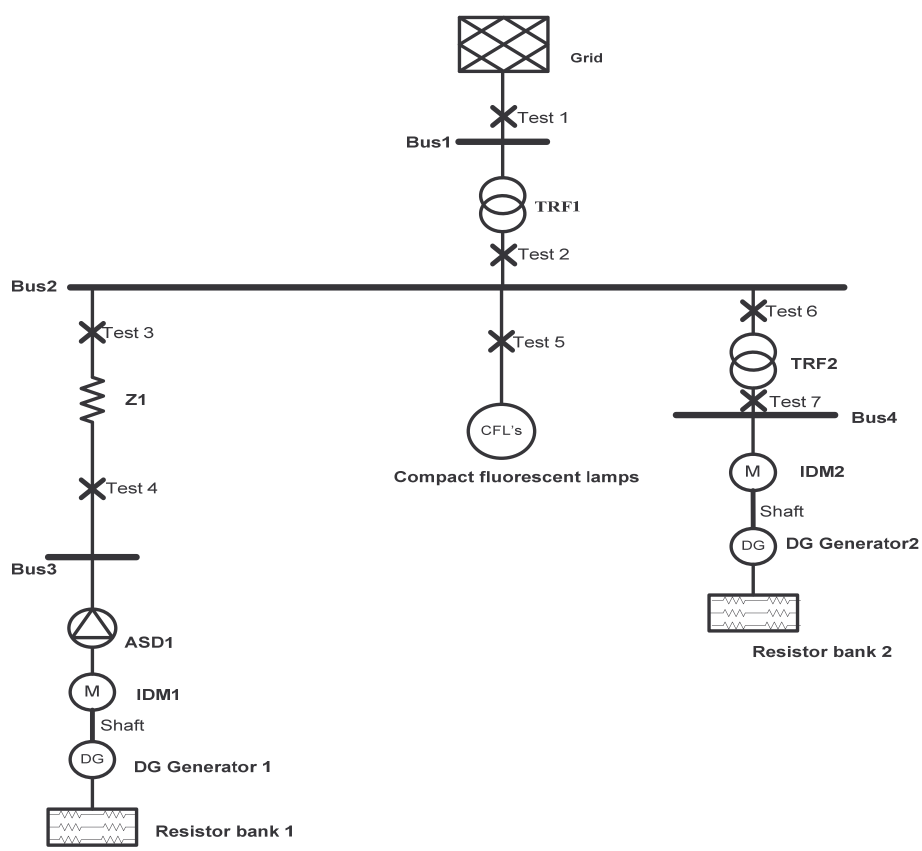


Figure 5.1: One-line diagram of a laboratory environment

Figure 5.2 is a photo of the laboratory set-up.

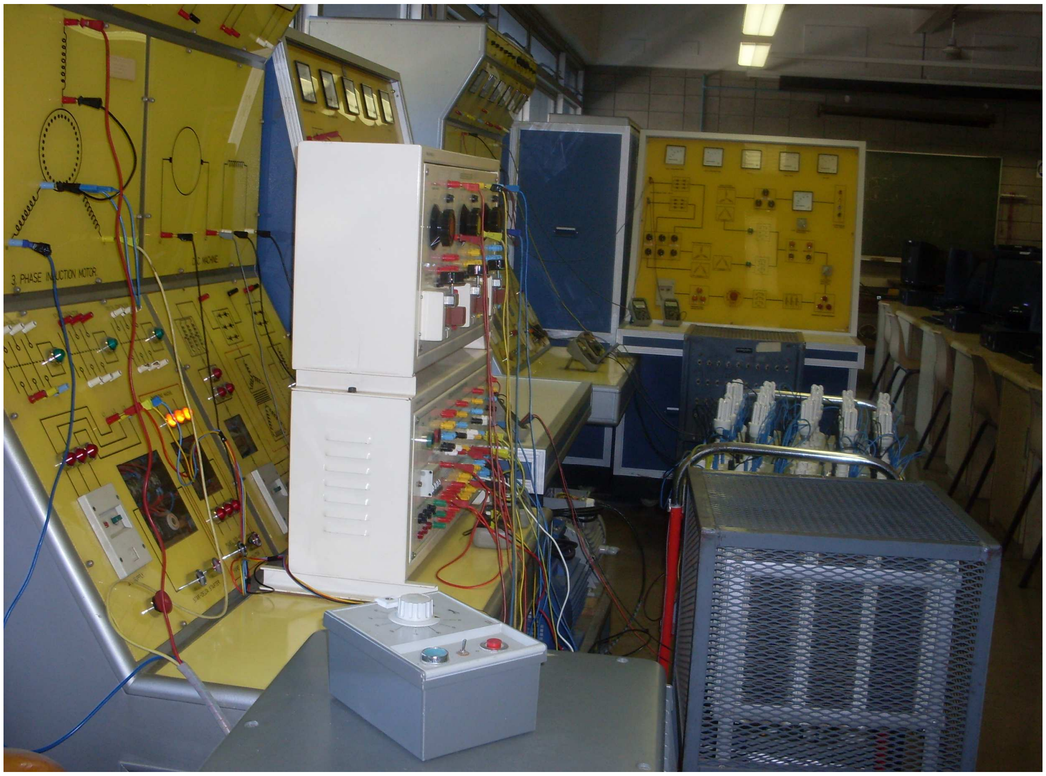


Figure 5.2: Laboratory environment set-up

5.1.1 Measurement results

For this investigation only the fundamental f_1 and two (*hch*) characteristic harmonic frequencies, 5th and 7th harmonic orders, are reported on as the other harmonic magnitudes were found to be small and would not influence the results greatly. Measurements of current and phase voltage were taken at the seven test positions, as shown in Figures 5.3. The results for current and phase voltage (red-phase) are shown in Figure 5.3. When conducting measurements the phase angle spectra for a drive (or other device) is usually with respect to the fundamental frequency component of voltage at the drive bus (or other component bus) when monitoring voltage and current at a bus. Hence, the results at each test point are given with respect to the fundamental frequency component of voltage (0°) at that position (see Figure 5.3) (Electrotek Concepts, Inc. 2000:4-30). The power per phase (1ϕ) was also measured and the results at each of the test points are recorded in Table 5.1. The three-phase (3ϕ) results were calculated assuming a balanced system. As can be seen from the power results, in column 3 of Table 5.1, the powers are expressed as "+" or "-" [see (4.1) and (4.2) and Figure 4.1]. In order to have confidence in the measured results, the voltage and current results (Figure 5.3) were used in hand calculations to determine power flow magnitudes and directions (indicated by a "+" or "-" sign), see Table 5.1. The powers are hand calculated using (2.12) for f_1 and (3.24) for $h \neq f_1$.

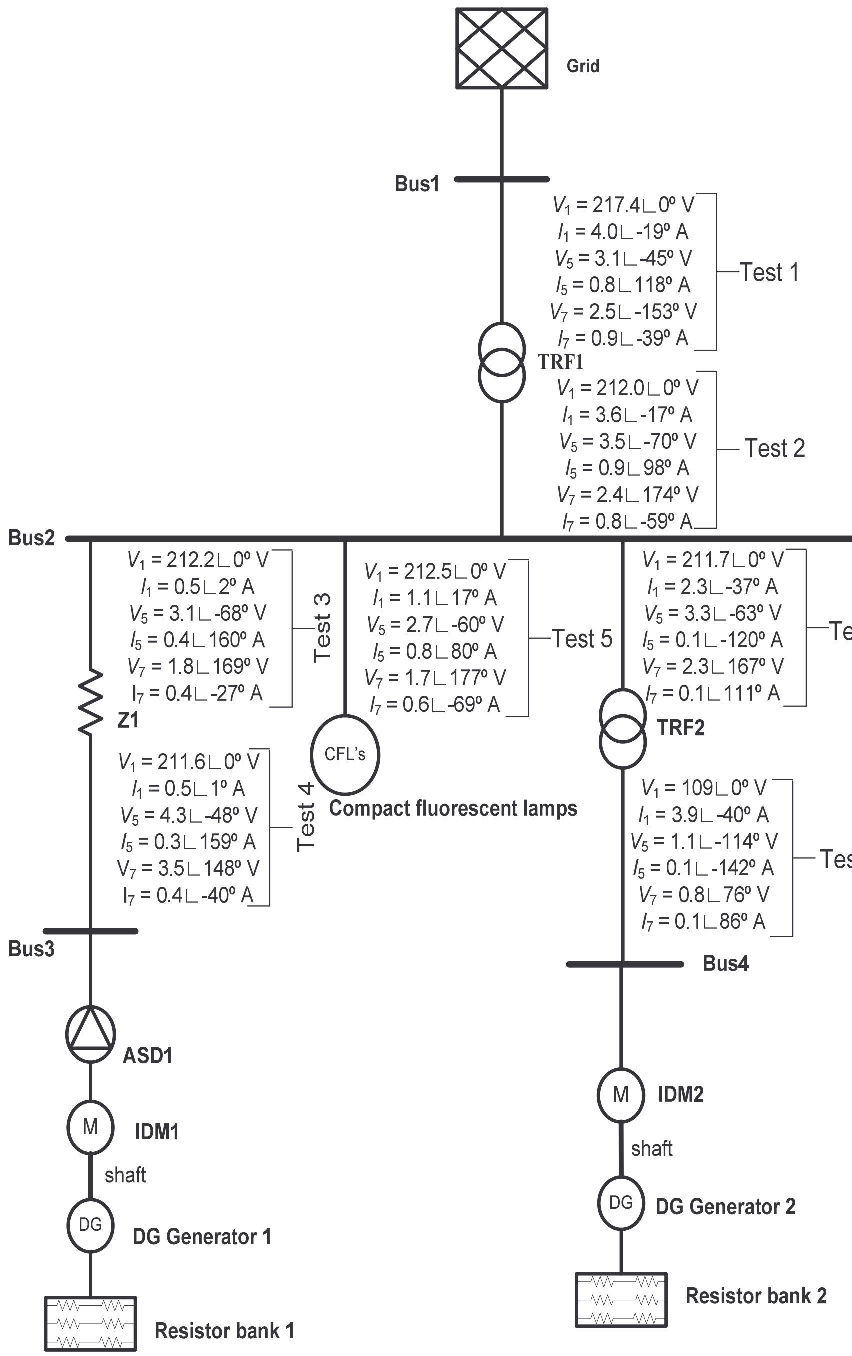
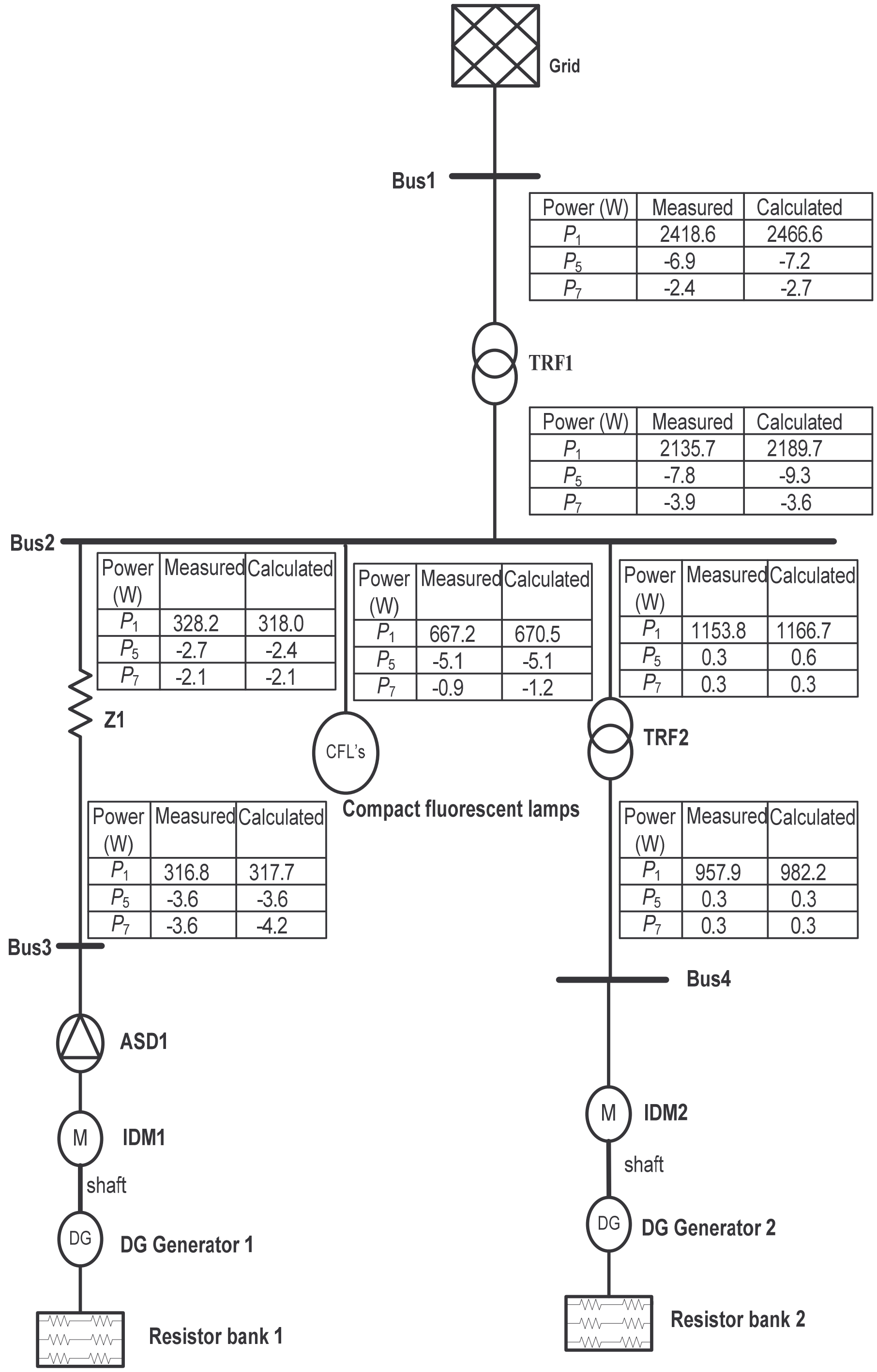


Figure 5.3: Current and voltage magnitude and angle results

Table 5.1: Case study 1: Power results

Position	P at hch	Measurement/ Calculated (W)		Equation		Hand calculation (W)	
		(1ϕ)	(3ϕ)	(1ϕ)	(3ϕ)	(1ϕ)	(3ϕ)
Test 1	P_1	+806.2	+2418.6	$P_1 = V_1 I_1 \cos(\theta_1 - \delta_1)$	$3P_1$	+822.2	+2466.6
	P_5	-2.3	-6.9	$P_5 = V_5 I_5 \cos(\theta_5 - \delta_5)$	$3P_5$	-2.4	-7.2
	P_7	-0.8	-2.4	$P_7 = V_7 I_7 \cos(\theta_7 - \delta_7)$	$3P_7$	-0.9	-2.7
Test 2	P_1	+711.9	+2135.7	$P_1 = V_1 I_1 \cos(\theta_1 - \delta_1)$	$3P_1$	+729.9	+2189.7
	P_5	-2.6	-7.8	$P_5 = V_5 I_5 \cos(\theta_5 - \delta_5)$	$3P_5$	-3.1	-9.3
	P_7	-1.3	-3.9	$P_7 = V_7 I_7 \cos(\theta_7 - \delta_7)$	$3P_7$	-1.2	-3.6
Test 3	P_1	+109.4	+328.2	$P_1 = V_1 I_1 \cos(\theta_1 - \delta_1)$	$3P_1$	+106.0	+318.0
	P_5	-0.9	-2.7	$P_5 = V_5 I_5 \cos(\theta_5 - \delta_5)$	$3P_5$	-0.8	-2.4
	P_7	-0.7	-2.1	$P_7 = V_7 I_7 \cos(\theta_7 - \delta_7)$	$3P_7$	-0.7	-2.1
Test 4	P_1	+105.6	+316.8	$P_1 = V_1 I_1 \cos(\theta_1 - \delta_1)$	$3P_1$	+105.9	+317.7
	P_5	-1.2	-3.6	$P_5 = V_5 I_5 \cos(\theta_5 - \delta_5)$	$3P_5$	-1.2	-3.6
	P_7	-1.2	-3.6	$P_7 = V_7 I_7 \cos(\theta_7 - \delta_7)$	$3P_7$	-1.4	-4.2
Test 5	P_1	+222.4	+667.2	$P_1 = V_1 I_1 \cos(\theta_1 - \delta_1)$	$3P_1$	+223.5	+670.5
	P_5	-1.7	-5.1	$P_5 = V_5 I_5 \cos(\theta_5 - \delta_5)$	$3P_5$	-1.7	-5.1
	P_7	-0.3	-0.9	$P_7 = V_7 I_7 \cos(\theta_7 - \delta_7)$	$3P_7$	-0.4	-1.2
Test 6	P_1	+384.6	+1153.8	$P_1 = V_1 I_1 \cos(\theta_1 - \delta_1)$	$3P_1$	+388.9	+1166.7
	P_5	+0.1	+0.3	$P_5 = V_5 I_5 \cos(\theta_5 - \delta_5)$	$3P_5$	+0.2	+0.6
	P_7	+0.1	+0.3	$P_7 = V_7 I_7 \cos(\theta_7 - \delta_7)$	$3P_7$	+0.1	+0.3
Test 7	P_1	+319.3	+957.9	$P_1 = V_1 I_1 \cos(\theta_1 - \delta_1)$	$3P_1$	+327.4	+982.2
	P_5	+0.1	+0.3	$P_5 = V_5 I_5 \cos(\theta_5 - \delta_5)$	$3P_5$	+0.1	+0.3
	P_7	+0.1	+0.3	$P_7 = V_7 I_7 \cos(\theta_7 - \delta_7)$	$3P_7$	+0.1	+0.3

These three-phase values are now shown on figure 5.4 where the directions of power flows are easily seen:



Power (W)	Measured	Calculated
P_1	2418.6	2466.6
P_5	-6.9	-7.2
P_7	-2.4	-2.7

Power (W)	Measured	Calculated
P_1	2135.7	2189.7
P_5	-7.8	-9.3
P_7	-3.9	-3.6

Power (W)	Measured	Calculated
P_1	328.2	318.0
P_5	-2.7	-2.4
P_7	-2.1	-2.1

Power (W)	Measured	Calculated
P_1	667.2	670.5
P_5	-5.1	-5.1
P_7	-0.9	-1.2

Power (W)	Measured	Calculated
P_1	1153.8	1166.7
P_5	0.3	0.6
P_7	0.3	0.3

Power (W)	Measured	Calculated
P_1	316.8	317.7
P_5	-3.6	-3.6
P_7	-3.6	-4.2

Power (W)	Measured	Calculated
P_1	957.9	982.2
P_5	0.3	0.3
P_7	0.3	0.3

Figure 5.4: Case study 1: Power results and directions

The results are similar; therefore, the measured results are used for the investigations. Besides magnitudes, what is of importance for efficiency and energy studies are the directions of power flows. Here the hand calculation directions agree with the measured result directions thus (4.1) and (4.2) can be applied to find the total power (P_T). The power results show that the "*hch*" powers are subtractable from the f_1 power for the non-linear loads

(ASD1 and CFL's) but are added up for the linear load (IDM2). However, in the supply branch the "*hch*" powers are subtractable. Using the measured results on Figure 5.4 the total power flows for the seven test points are calculated using (4.19, 4.20 and 4.21) and given in the following table:

Table 5.2: Total power ($P_{T(H)}$) results

Position	Equation	Hand Calculation (W)
Test 1	$P_{T(H)}(Grid\,branch) = P_1 - P_5 - P_7$	2409.3
Test 2	$P_{T(H)}(Grid\,branch) = P_1 - P_5 - P_7$	2124.0
Test 3	$P_{T(H)}(Non-linear) = P_1 - P_5 - P_7$	323.4
Test 4	$P_{T(H)}(Non-linear) = P_1 - P_5 - P_7$	309.6
Test 5	$P_{T(H)}(Non-linear) = P_1 - P_5 - P_7$	661.2
Test 6	$P_{T(H)}(Linear) = P_1 + P_5 + P_7$	1154.4
Test 7	$P_{T(H)}(Linear) = P_1 + P_5 + P_7$	958.5

The fluke instrument (section 4.7.1) is not capable of measuring the total power. It can measure total harmonic distortion (%V_{THD} and %I_{THD}). The value of total harmonic distortion for current (%I_{THD}) and voltage (%V_{THD}) was also measured and is shown in Table 5.3 according to the test number as shown in Figure 5.1. The results at Test 2 point (%V_{THD} = 7.9%) demonstrates a level of distortion at the PCC that exceeds the recommended limits of 5% (IEEE 519-1992, 1993). It is important to measure THD as it gives an indication of the level of distortion.

Table 5.3: Voltage and current total harmonic distortion results

Position	**%V_{THD}**	**%I_{THD}**
Test 1	5.1	29.4
Test 2	7.9	40.2
Test 3	7.5	75.6
Test 4	8.3	75.8
Test 5	7.8	78.7
Test 6	2.3	3.8
Test 7	2.2	3.7

The experiment clearly demonstrates the importance of the directions of power flows when distortion is present as the powers at harmonic frequencies influences the total at any position.

5.2 Simulated case study

One simulation case study (case study 2) was conducted. Both the DIgSILENT and SuperHarm software packages were used to conduct this simulation case study for comparative purpose.

5.2.1 Case study 2: Radial distribution network

Case study 2 is conducted to evaluate the effectiveness of the developed methodology for practical applications. The formulae developed were case specific and refer to methodology only. Formulae are adapted for this network configuration. A 40kV radial three-phase distribution network is used (Figure 5.5). The S_{base} for the network is 20MVA.

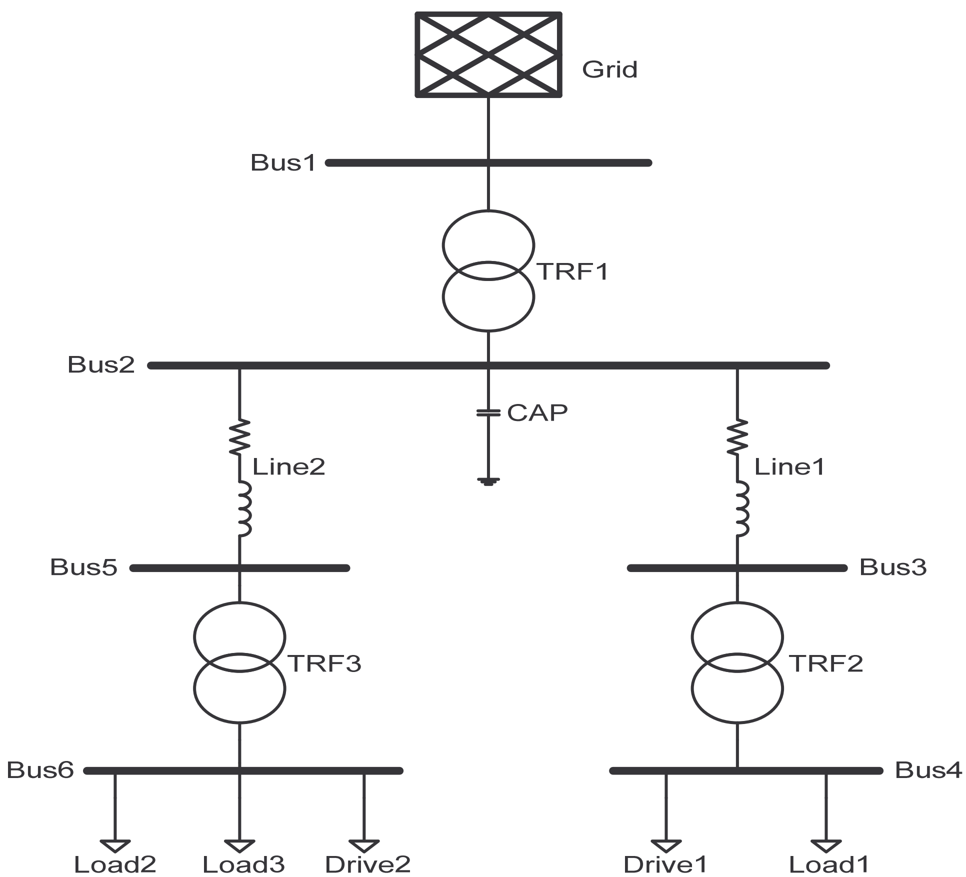


Figure 5.5: One-line-diagram of a radial distribution network

The network is supplied from a grid infeed through the transformer TRF1. At bus 2, the PCC, two radial branches are connected (lines 1 and 2). Bus 4 and 6 are the load buses and each has a harmonic source (Drive 1 and 2). The network also has a capacitor (CAP) at the PCC bus. Tables 5.4 to 5.8 describe the network parameters that are used to develop simulation models for DIgSILENT and SuperHarm.

Table 5.4: External grid data

Element	Short circuit (MVA)	Short circuit current (A)	X/R ratio
External Grid	505.7346	7.29965	15

Table 5.5: Line and capacitor data

Element	R (Ω)	X(Ω)
Line1	0.000001	0.000001
Line2	0.000001	0.000001
CAP	0.000000	50.424229

Table 5.6: Load data

Element	Voltage (kV)	MVA	Power factor (dpf)
Drive1	6	2.1	0.8
Drive2	0.4	0.25	0.8
Load1	6	2	0.5
Load2	0.4	1	0.8
Load3	0.4	0.25	0.9

Table 5.7: Transformer data

Element	Voltage (kV)	MVA	%Rs (Ω)	%Xs (Ω)	X/R	Connection
TRF1	40/12	20	1	15.1	15.1	YNyn
TRF2	12/6	5	0.9885	12	12.1	YNyn
TRF3	12/0.4	2	0.9861	7	7.1	YNyn

The non-linear loads are 6 pulse drives, Drive1 and 2 inject harmonics into the network. Studies, like case study 1 are limited to the 5th and 7th characteristic harmonic only. The spectra for the drives are given in Table 5.8.

Table 5.8: ASD harmonic current spectrum

Harmonic order	Current magnitude (%)	Current angle (◦)
5th	17.9999	110.51
7th	11.9999	82.08

5.2.1.1 DIgSILENT

The network in Figure 5.5 was first modelled in DIgSILENT. See Appendix B.1 for a summary of the models used to conduct the simulation investigation. The distorted waveforms of drives 1 and 2 are shown in figure 5.6. Figures 5.7 and 5.8 show distorted waveforms of the current and voltage at the output of TRF1 and PCC (Bus 2).

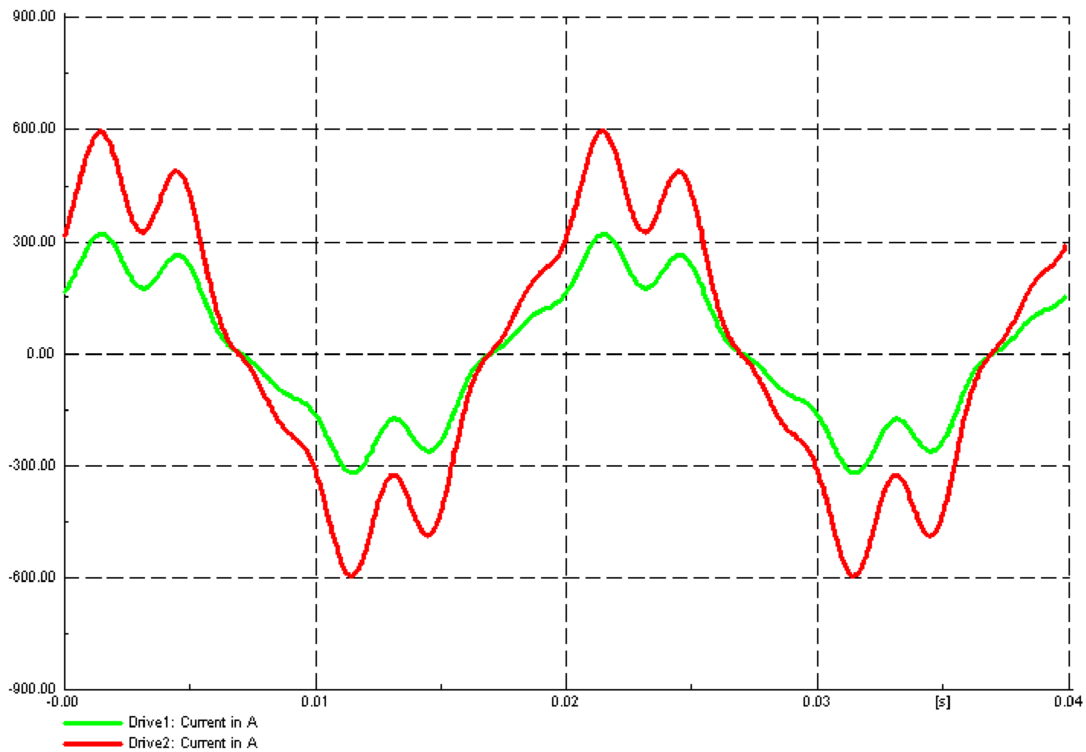


Figure 5.6: Drives 1 and 2 distorted waveforms

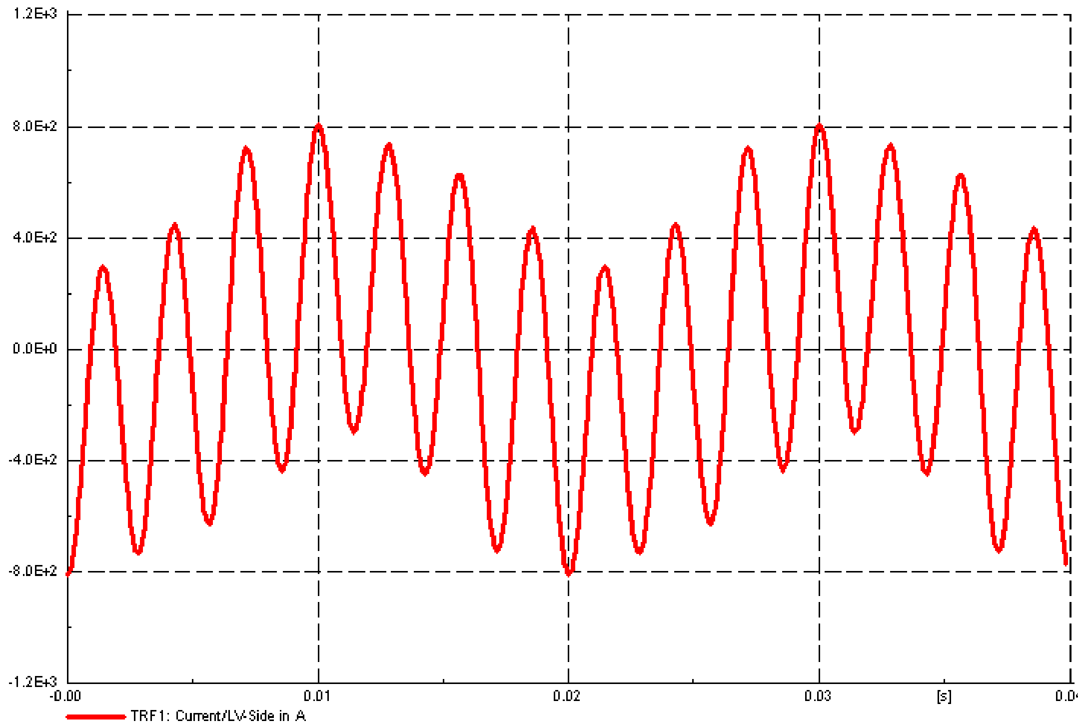


Figure 5.7: TRF1 distorted current waveform

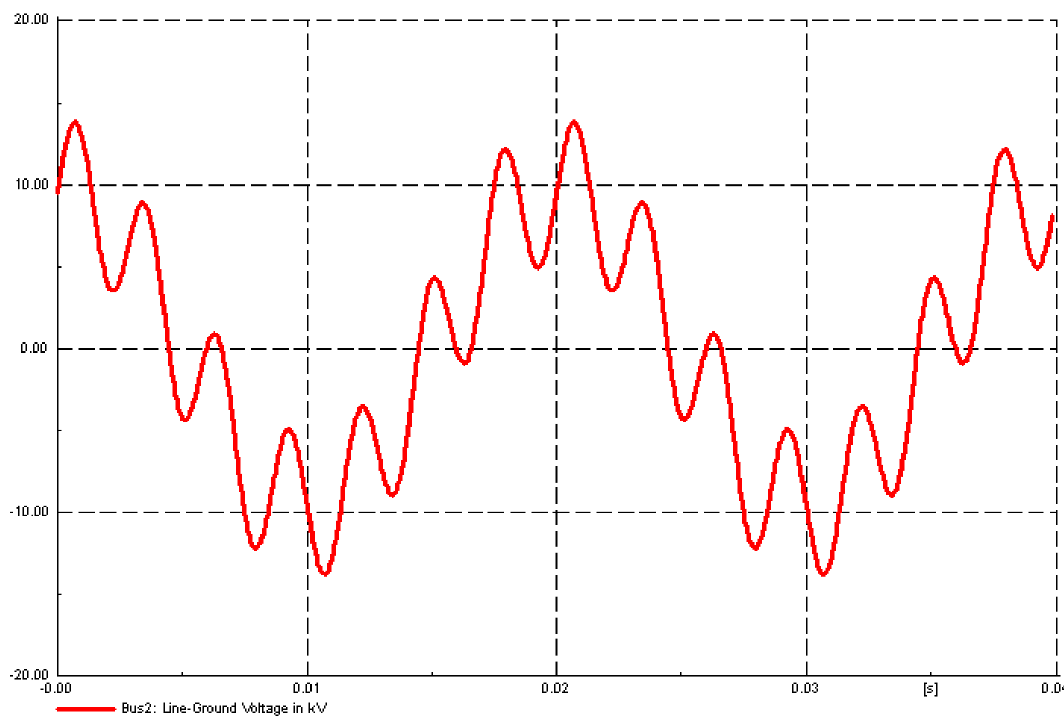


Figure 5.8: Bus 2 (PCC) distorted voltage waveform

5.2.1.2 SuperHarm versus DIgSILENT

The network in Figure 5.5 was next modelled using SuperHarm. See Appendix B.2 for the model used. The grid infeed was modelled as an ideal voltage source to obtain the same DIgSILENT results for the voltages and currents. SuperHarm only generates voltage and current results (at all frequencies), whereas DIgSILENT gives voltage, current and power results at all frequencies. The results at Bus 2 (PCC), Bus 4 and Bus 6 where the loads are connected are compared. The compared voltage and current results are as shown in Tables B.1 and B.2 in Appendix B.3. The results of the two packages were found to be similar confirming that the network modelling is correct.

5.2.1.3 Power results (Harmonic penetration study)

As DIgSILENT generates power results from the voltage and current values, they are used and are recorded in Table 5.9 and shown on the one-line-diagram of the network in Figure 5.9.

Table 5.9: Case study 2: Total power results

	Power (kW)			
Element	P_1	P_5	P_7	$P_{T(H)}$
External grid	3424.914	-	-	3424.914
TRF1 input	3424.914	-	-	3424.914
TRF1 output	3418.549	-0.282	-36.823	3381.444
Line1 input	2289.215	-0.252	-43.879	2245.084
Line1 output	2289.215	-0.252	-43.879	2245.084
TRF2 input	2289.215	-0.252	-43.879	2245.084
TRF2 output	2262.201	-0.452	-44.117	2217.632
Line2 input	1129.335	-0.029	+7.057	1122.249
Line2 output	1129.335	-0.029	+7.057	1122.249
TRF3 input	1129.335	-0.029	+7.057	1122.249
TRF3 output	1119.253	-0.034	+6.939	1112.280
Drive1	1418.096	-0.683	-48.405	1369.008
Drive2	182.735	-0.171	-4.474	178.090
Load1	844.105	0.232	4.288	848.625
Load2	730.940	0.093	7.569	738.602
Load3	205.577	0.045	3.845	209.467

The grid infeed is modelled as an ideal voltage source there are no harmonic simulation results at the external grid at TRF1 input point in the network (see Sect 5.2.1.2). Also, it should be pointed out that the power result for P_7 at Line2 and TRF2 input and output comes out positive (+) compared to P_5.

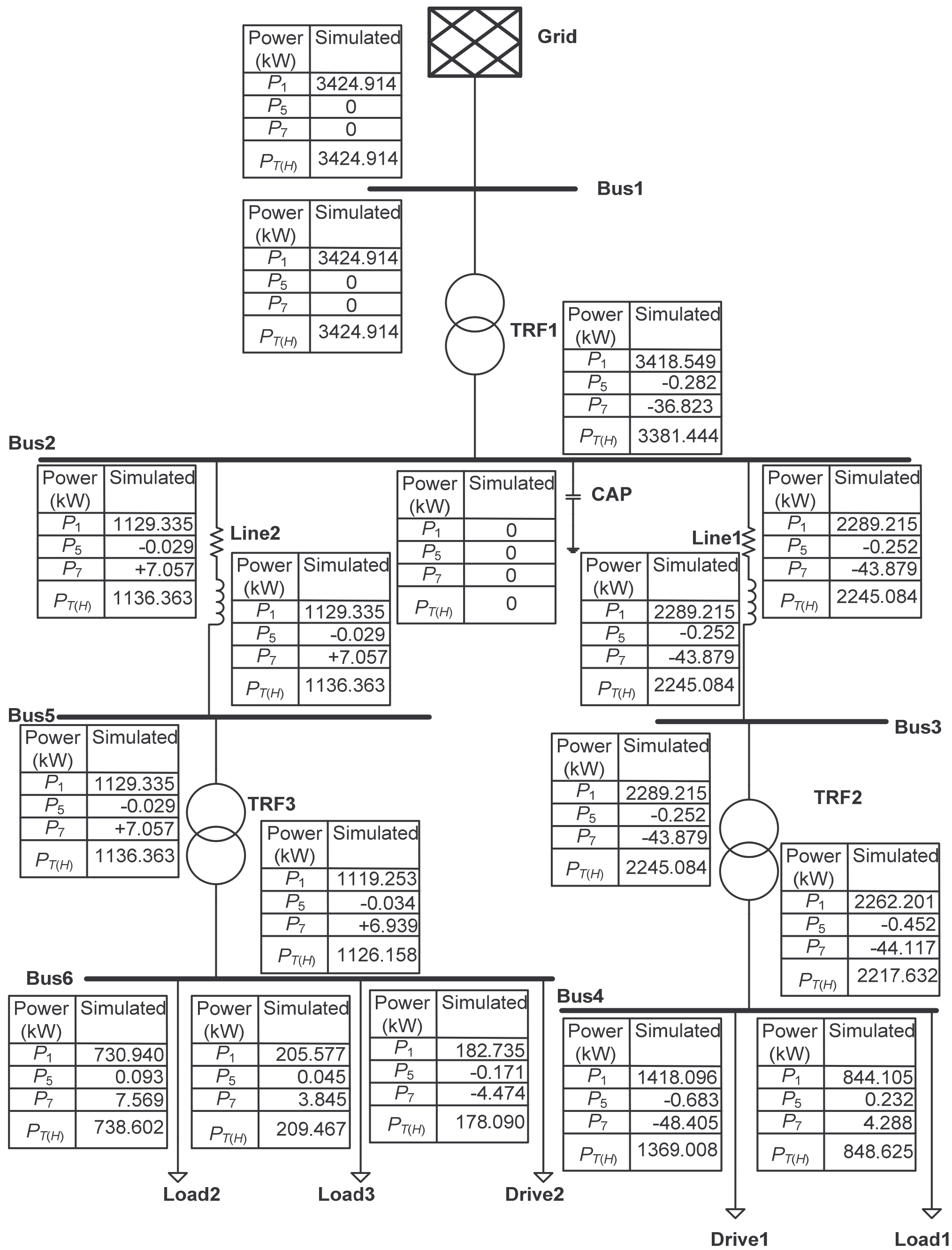


Figure 5.9: Case study 2: Power results

5.2.1.4 Resonance (Harmonic scan studies)

For networks that have capacitor banks, it is wise to determine resonance (section 3.1.6). Resonance causes amplification of voltage and/or current at the resonant frequency, which can greatly influence the individual and overall efficiencies as well as energy usage. There are two drives connected at different busbars, therefore, two impedance scans (Zscan) to determine their resonant points at their injection buses (bus 4 and 6) are needed.

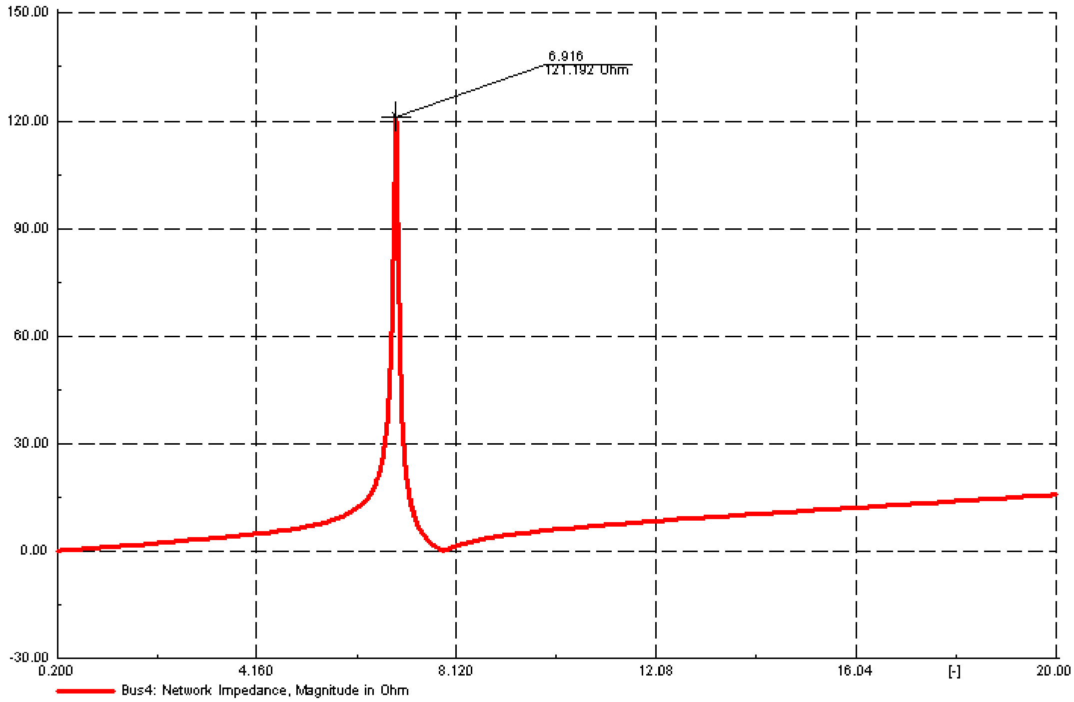


Figure 5.10: Zscan at Bus 4

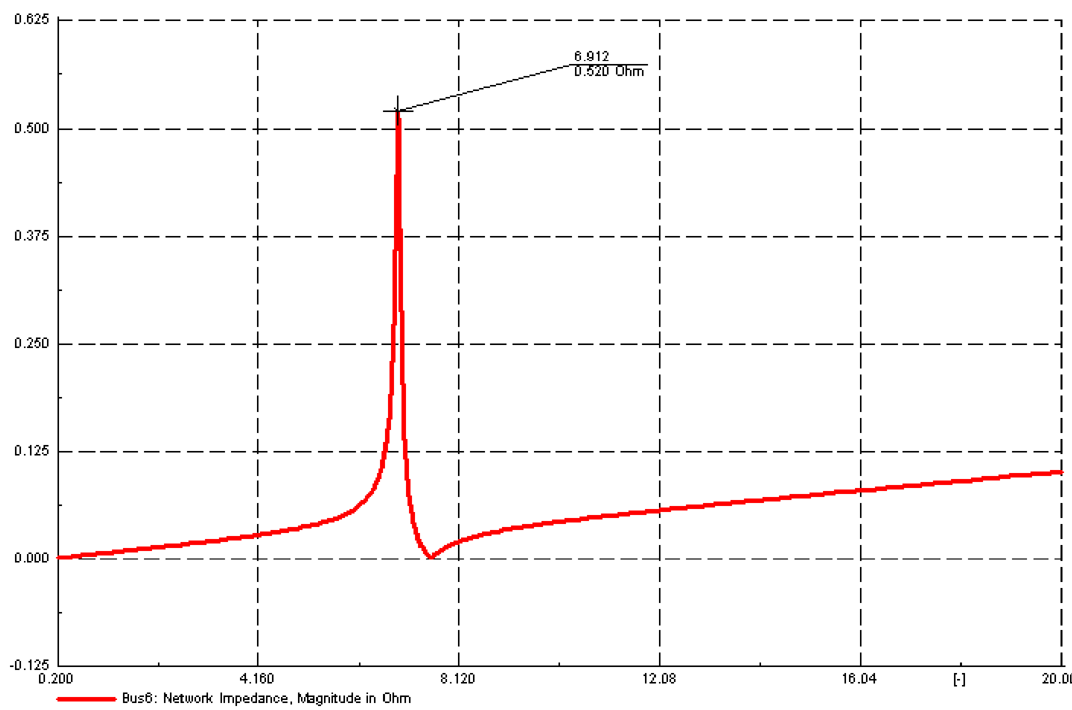


Figure 5.11: Zscan at Bus 6

Figure 5.10 shows the Zscan at Bus 4 where Drive 1 is connected and resonance occurs at the 6.916^{th} frequency, having a "Z" value of $121.192\,\Omega$. Figure 5.11 shows the Zscan at Bus 6 where resonance occurs for Drive 2 at 6.916^{th} frequency, but the "Z" value is $0.520\,\Omega$. Resonance in both cases thus occurs close to the 7th characteristic harmonic.

Resonance often causes the total harmonic voltage and current distortion levels (3.15) and (3.16) at the PCC to rise and may even exceed recommended limits provided by international standards (IEEE 1992-512, 1993). When (3.15) and (3.16) were applied, using results for voltage and current from tables B.1 and B.2 in Appendix B.3, the $\%V_{THD}$ and $\%I_{THD}$ values are:

$$\%V_{THD} = \frac{\sqrt{196.30^2 + 3142.37^2}}{6866.28} \times 100\% = 45.85\%$$

$$\%I_{THD} = \frac{\sqrt{36.10854^2 + 412.88540^2}}{171.66201} \times 100\% = 241.44\%$$

The recommended limits for a PCC voltage according to the IEEE 519-1992 standard are:

Table 5.10: Harmonic voltage distortion (%) of nominal f_1 voltage (V_n)

Bus voltage at PCC, V_n (kV)	Individual harmonic voltage distortion (%)	Total voltage distortion, V_{THD} (%)
$V_n \leq 69$	3.0	5.0
$69 < V_n \leq 161$	1.5	2.5
$V_n > 161$	1.0	1.5

5.2.1.5 Filter design

Since the $\%V_{THD}$, of the voltage exceeds the IEEE 519 limit of 5%, a passive notch harmonic filter was designed to reduce harmonic distortion. The capacitor at the PCC is utilized for the filter design. Even though resonance occurs close to the 7th harmonic, it is traditional when resonance falls in the range that includes 5th and 7th harmonics, to design a harmonic filter tuned to just below the 5th harmonic (e.g. 4.7th) called the nth point, as it usually shifts resonance points well below the lowest characteristic harmonic, thereby reducing distortion adequately. Thus the following filter design procedure is followed (Wakileh, 2001:116).

The Filter is designed for the 4.7th frequency. The following steps were followed:

Step 1: Ascertain Q_C value of 2. 85577Mvar be the capacitor size in Mvars to be used in the filter design.

Step 2: Determine, $X_C = \frac{kV^2}{Q_C}$ (5.1)

Step 3: Determine the reactance of the reactor to trap n^{th} frequency:

$$X_L = \frac{X_C}{n^2} \tag{5.2}$$

Step 4: Determine the characteristic reactance value, X_n, where,

$$X_n = X_{Ln} = X_{Cn} = \sqrt{X_L X_C} = \sqrt{\frac{L}{C}} \tag{5.3}$$

Then assume an appropriate quality factor Q to size of the resistor bank (R),

$$R = \frac{X_n}{Q} \tag{5.4}$$

Step 5: Determine the R, L and C elements of the filter

The details for the design of the filter are as shown in Appendix B.4, where the values of R, L and C elements are determined. The network is updated to include the filter.

Table 5.11 shows the results of power when the filter is connected and Figure 5.12 shows them on the one-line diagram.

Table 5.11: Total power results with passive filter

	Power (kW)			
Element	P_1	P_5	P_7	$P_{T(H)}$
External grid	3438.288	-	-	3438.288
TRF1 input	3438.288	-	-	3438.288
TRF1 output	3432.001	-0.003	-0.008	3431.990
Line1 input	2293.829	-0.054	-0.001	2293.774
Line1 output	2293.829	-0.054	-0.001	2293.774
TRF2 input	2293.829	-0.054	-0.001	2293.774
TRF2 output	2266.761	-0.268	-0.094	2266.399
Line2 input	1131.611	-0.014	-0.017	1131.580
Line2 output	1131.611	-0.014	-0.017	1131.580
TRF3 input	1131.611	-0.014	-0.017	1131.580
TRF3 output	1121.509	-0.021	-0.020	1121.468
Drive1	1420.955	-0.361	-0.145	1420.449
Drive2	183.103	-0.032	-0.031	183.040
Load1	845.806	0.093	0.051	845.950
Load2	732.414	0.008	0.007	732.429
Load3	205.991	0.004	0.004	205.999
Filter	6.561	0.065	0.009	6.635

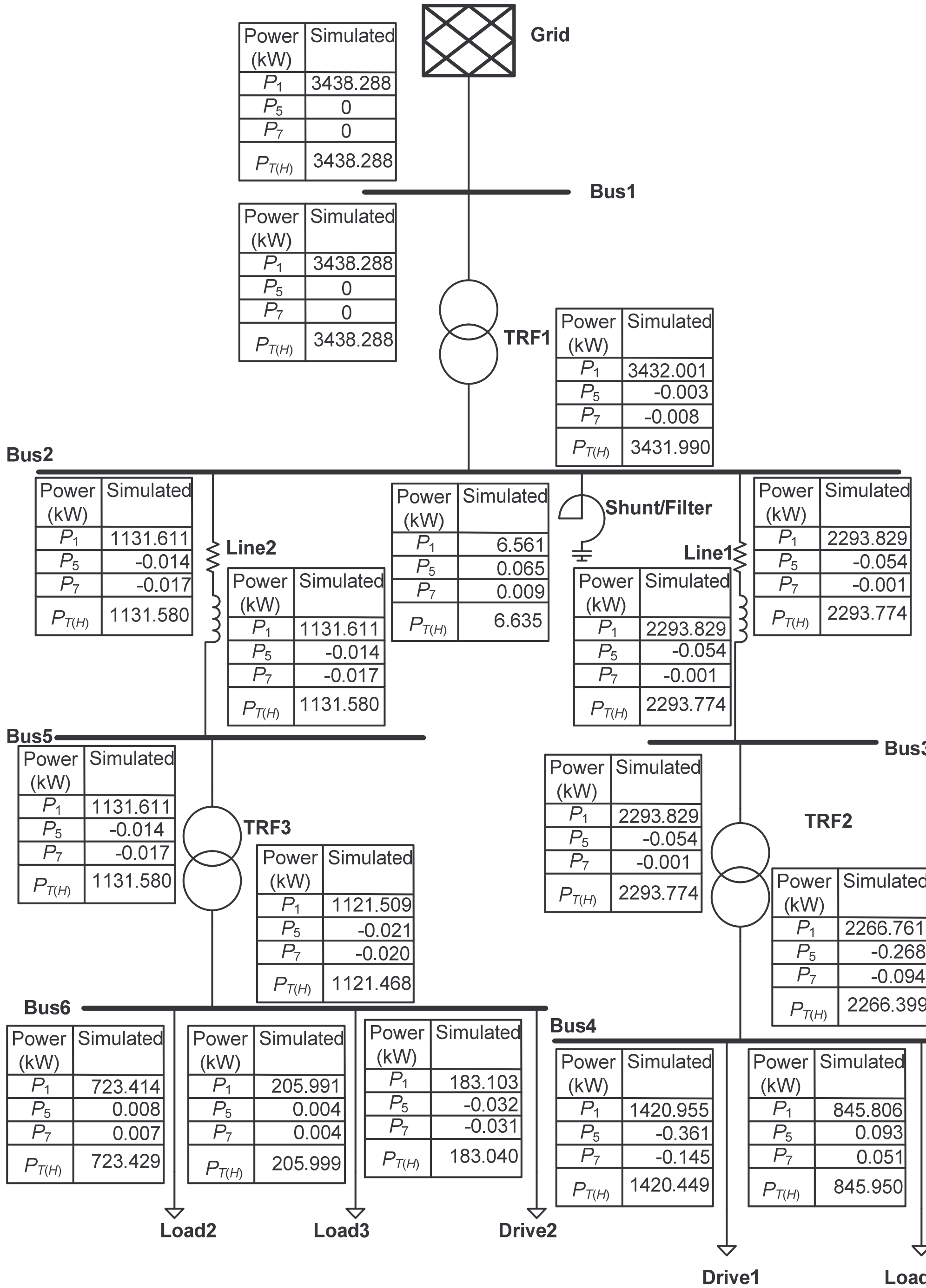


Figure 5.12: Case study 2: Power results with filter

The waveform of TRF1 (Figure 5.7) now changes to that as shown in Figure 5.13. On comparison it can be seen that the current distortion is reduced, bringing it closer to a sine wave. Bus 2 waveform (Figure 5.14) becomes virtually distortion free (sinusoidal) after the filter is installed compared to Figure 5.8.

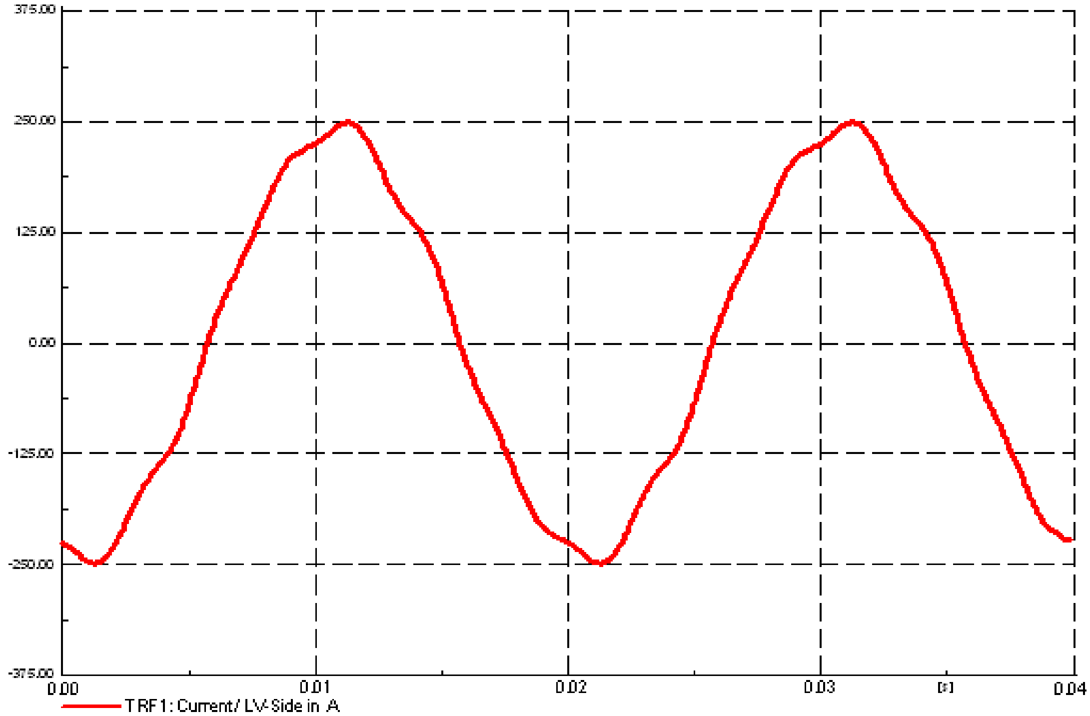


Figure 5.13: TRF1 current distorted waveform after a filter is added

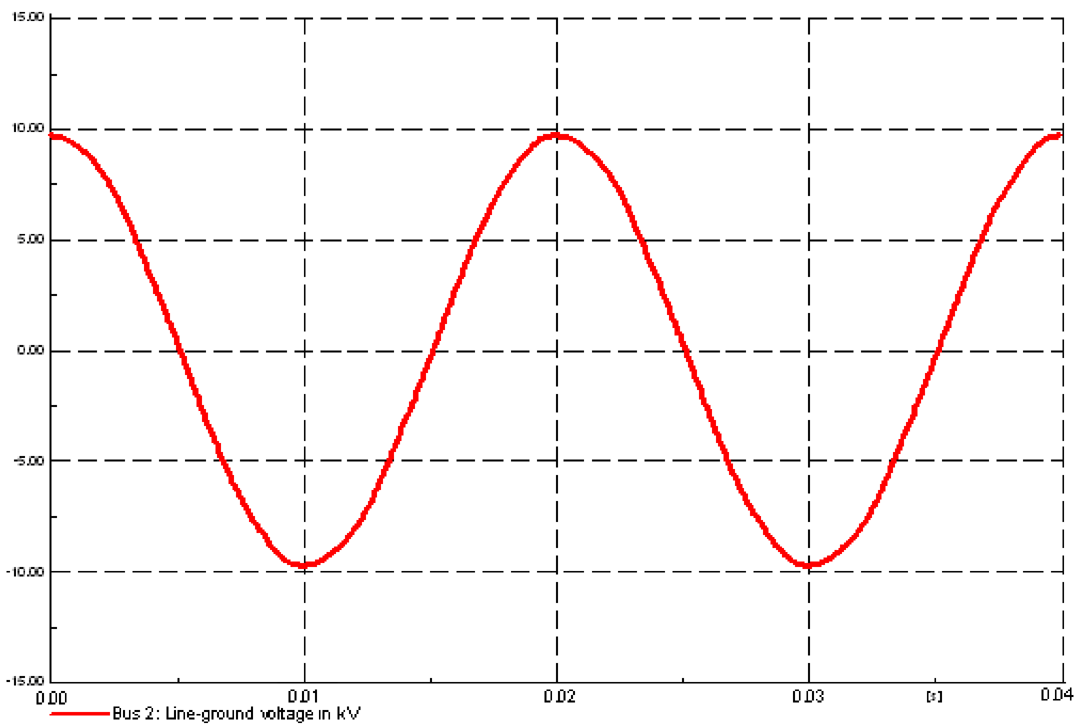


Figure 5.14: Bus 2 (PCC) distorted voltage waveform

To demonstrate that the filter shifts resonance away from the lowest characteristic harmonic namely the 5th, Zscans were re-conducted with the filter in operation. The scan for bus 4 and 6 are shown in Figures 5.15 and 5.16, respectively:

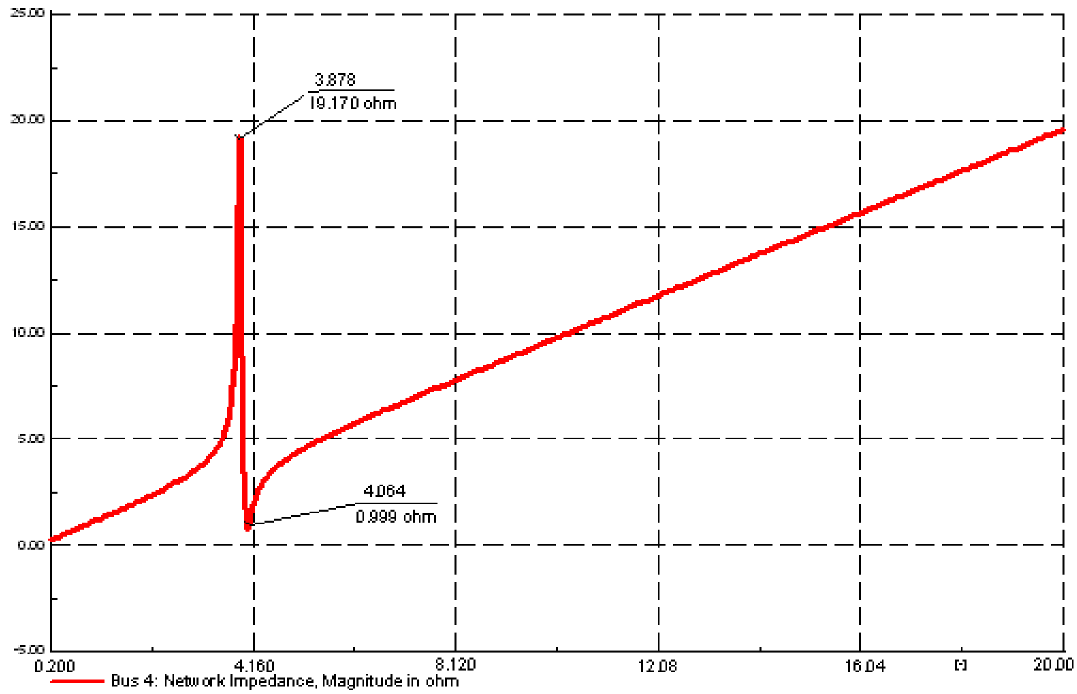


Figure 5.15: Zscan at Bus 4

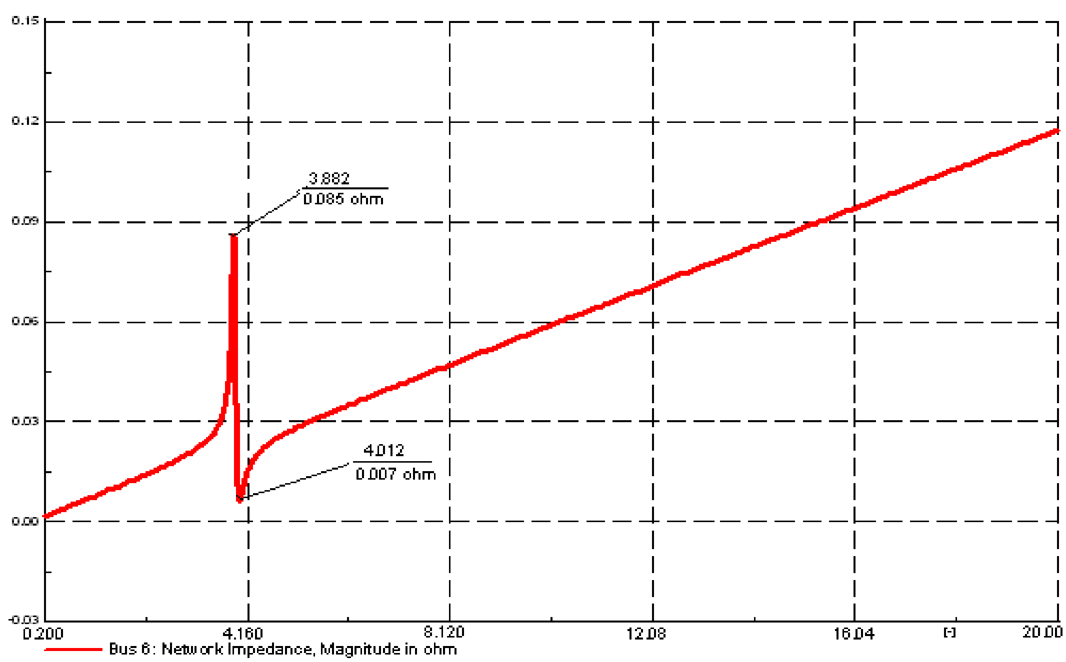


Figure 5.16: Zscan at Bus 6

After a filter was added to the network, both Zscans shows resonance point shifted to 3.878th and 3.882th frequency points, respectively (see Figures 5.15 and 5.16).

5.3 Summary

Two case studies were conducted; a measurement based laboratory experiment and simulation case study. For case study 1, measurements of current, voltage and power are taken with the harmonic power quality analyser Fluke 435 from various test positions in the network. Voltage and current results were then used to hand calculate the power flows and to establish directions in order to have confidence in measured power results. The formulae used to determine power at each position are given. Case study 2 is simulated using DIgSILENT and SuperHarm in order to compare the voltage and current results and confirm the accuracy of network modelling. The results obtained were similar in magnitude and angle. Power values at each frequency (f_1, h and H) are recorded. The $\%V_{THD}$ exceeds the recommended limit; therefore case study 2 was conducted again but with a filter to demonstrate its function in reducing distortion. Waveforms and impedance scans are plotted with and without the filter. The results of these two case studies will now be analysed in the next chapter in terms of individual and overall efficiencies and energy usage when distortion is present.

CHAPTER 6: METHODOLOGY AND ANALYSIS

In this chapter, the developed formulae are used to demonstrate the methodology to analyse the two case studies conducted to determine the individual and overall efficiencies and energy usage when distortion is present in power systems.

6.1 Case study 1

The results for case study 1 are given in Table 5.1 and Figure 5.4. They are used to demonstrate the methodology and for the analyses.

6.1.1 Efficiency methodology

The first step is to determine the individual and overall efficiencies for the network.

6.1.1.1 Fundamental frequency (f_1)

Obtain the power input to the laboratory set-up at f_1, namely:

$$P_{1(in)(electr)}(Grid) = 2418.6W$$

Now, calculate the efficiency of the individual element

TRF1

$$P_{1(Losses)}(TRF1) = P_{1(in)(electr)}(TRF1) - P_{1(out)(electr)}(TRF1) = 2418.6 - 2135.7 = 282.9\,W$$

$$\%\eta_1(TRF1) = \frac{P_{1(out)(electr)}(TRF1)}{P_{1(in)(electr)}(TRF1)} \times 100\% = \frac{2135.7}{2418.6} \times 100\% = 88.30\%$$

Z1

$$P_{1(Losses)}(Z1) = P_{1(in)(electr)}(Z1) - P_{1(out)(electr)}(Z1) = 328.2 - 316.8 = 11.4\,W$$

$$\%\eta_1(Z1) = \frac{P_{1(out)(electr)}(Z1)}{P_{1(in)(electr)}(Z1)} \times 100\% = \frac{316.8}{328.2} \times 100\% = 96.53\%$$

TRF2

$$P_{1(Losses)}(TRF2) = P_{1(in)(electr)}(TRF2) - P_{1(out)(electr)}(TRF2) = 1153.8 - 957.9 = 195.9\,W$$

$$\%\eta_1(TRF2) = \frac{P_{1(out)(electr)}(TRF2)}{P_{1(in)(electr)}(TRF2)} \times 100\% = \frac{957.9}{1153.8} \times 100\% = 83.02\%$$

ASD1 and IDM1

From, Figure 1.1, it is necessary to ascertain the efficiencies for the drive and motor respectively and from these values determine the overall efficiency of the combination.

In order to establish the efficiency of ASD1 and IDM1, the nameplate data (Table 4.1) is used. The nameplate for ASD1 gives a full load power rating of 7.5 kW (output) and input of 380 V, 13 A. As the displacement power factor (dpf) of drives are usually close to unity, the three-phase input power at full load is $\sqrt{3} \times 380 \times 13 \times 1 = 8.556\,kW$, thus its efficiency is $(7.5/8.556) \times 100\% = 87.6\%$.

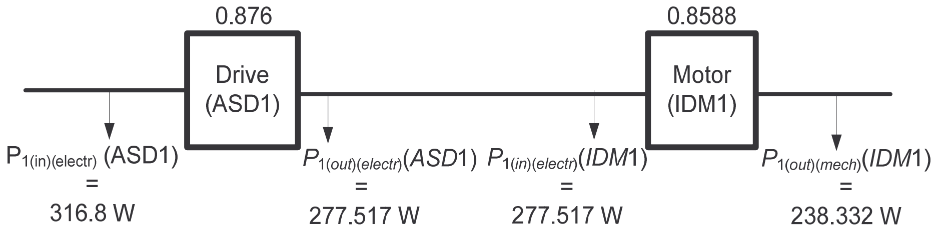
Similarly, the nameplate for IDM1 (Table 4.1) gives a full load output power of 3 HP $(3 \times 746 = 2.238\,kW)$ and a three-phase input of 380 V, 4.95 A, thus input $(\sqrt{3}V_L I_L)$ = 3.258 kVA. If a displacement power factor (dpf) of 0.8 is assumed then input power is 2.606 kW. Thus the full load efficiency for IDM1 is $(2.238/2.606) \times 100\% = 85.88\%$.

IDM2

The nameplate for IDM2 (Table 4.2) gives the full load rating power of 7.5 HP $(7.5 \times 746 = 5.595\,kW)$ and a three-phase input of 380 V, 11.8 A, thus input $(\sqrt{3}V_L I_L)$ = 7.767 kVA. If 0.8 dpf is assumed, then the input power is 6.214 kW. Its efficiency at full load is $(5.595/6.214) \times 100\% = 90.04\%$.

Overall efficiency

Efficiency curves of motors (efficiency versus load) typically have a fairly flat profile. If we assume that efficiencies ASD1 = 87.6%, IDM1 = 85.88% and IDM2 = 90.04% for the drive and/or motors remains constant as the load varies then the overall efficiency can be obtained at the load level (Figure 5.4) as follows:



$$P_{1(out)(mech)}(ASD1+IDM1) = P_{1(in)(electr)}(ASD1)\times 0.876\times 0.8588$$
$$= 316.8\times 0.876\times 0.8588 = 238.332\,W$$

$$P_{1(out)(mech)}(IDM2) = P_{1(in)(electr)}(IDM2)\times 0.9004 = 957.9\times 0.9004 = 862.493\,W$$

$$P_{1(out)} = \sum\left(P_{1(out)(mech)}(IDM1) + P_{1(out)(electr)}(CFL's) + P_{1(out)(mech)}(IDM2)\right)$$
$$= 238.332 + 667.2 + 862.493 = 1768.025\,W$$

$$P_{1(Losses)} = P_{1(in)(electr)}(Grid) - P_{1(out)} = 2418.6 - 1768.025 = 650.58\,W$$

$$\%\eta_1 overall = \frac{\sum P_{1(out)}}{P_{1(in)}}\times 100\% = \frac{1768.025}{2418.6}\times 100\% = 73.10\%$$

6.1.1.2 5th harmonic frequency (*h* = 5)

Now, calculate the efficiency of the individual element

TRF1

$$P_{5(Losses)}(TRF1) = P_{5(in)(electr)}(TRF1) - P_{5(out)(electr)}(TRF1) = (7.8 - 6.9) = 0.9\,W$$
$$\%\eta_5(TRF1) = \frac{P_{5(out)(electr)}(TRF1)}{P_{5(in)(electr)}(TRF1)}\times 100\% = \frac{6.9}{7.8}\times 100\% = 88.46\%$$

Z1

$$P_{5(Losses)}(Z1) = P_{5(in)(electr)}(Z1) - P_{5(out)(electr)}(Z1) = (3.6 - 2.7) = 0.9\,W$$
$$\%\eta_5(Z1) = \frac{P_{5(out)(electr)}(Z1)}{P_{5(in)(electr)}(Z1)}\times 100\% = \frac{2.7}{3.6}\times 100\% = 75.0\%$$

TRF2

$$P_{5(Losses)}(TRF2) = P_{5(in)(electr)}(TRF2) - P_{5(out)(electr)}(TRF2) = (0.3 - 0.3) = 0W$$
$$\%\eta_5(TRF2) = \frac{P_{5(out)(electr)}(TRF2)}{P_{5(in)(electr)}(TRF2)}\times 100\% = \frac{0.3}{0.3}\times 100\% = 100\% \quad (losses\ negligibly\ small)$$

Overall efficiency at the 5th harmonic

$$P_{5(in)} = \sum\left(P_{5(in)(electr)}(ASD1) + P_{5(in)(electr)}(CFL's)\right) = (3.6 + 5.1) = 8.7\,W$$

$$P_{5(out)} = \sum\left(P_{5(out)(electr)}(Grid) + P_{5(out)(electr)}(IDM2)\right) = (6.9 + 0.3) = 7.2\,W$$

$$P_{5(Losses)} = P_{5(in)} - P_{5(out)} = (8.7 - 7.2) = 1.5\,W$$

$$\%\eta_5\,overall = \frac{\sum P_{5(out)}}{\sum P_{5(in)}} \times 100\% = \frac{7.2}{8.7} \times 100\% = 82.76\%$$

6.1.1.3 7th harmonic frequency (*h* = 7)

Calculate the efficiency of the individual element

TRF1

$$P_{7(Losses)}(TRF1) = P_{7(in)(electr)}(TRF1) - P_{7(out)(electr)}(TRF1) = (3.9 - 2.4) = 1.5\,W$$

$$\%\eta_7(TRF1) = \frac{P_{7(out)(electr)}(TRF1)}{P_{7(in)(electr)}(TRF1)} \times 100\% = \frac{2.4}{3.9} \times 100\% = 61.54\%$$

Z1

$$P_{7(Losses)}(Z1) = P_{7(in)(electr)}(Z1) - P_{7(out)(electr)}(Z1) = (3.6 - 2.1) = 1.5\,W$$

$$\%\eta_7(Z1) = \frac{P_{7(out)(electr)}(Z1)}{P_{7(in)(electr)}(Z1)} \times 100\% = \frac{2.1}{3.6} \times 100\% = 58.33\%$$

TRF2

$$P_{7(Losses)}(TRF2) = P_{7(in)(electr)}(TRF2) - P_{7(out)(electr)}(TRF2) = (0.3 - 0.3) = 0\,W$$

$$\%\eta_7(TRF2) = \frac{P_{7(out)(electr)}(TRF2)}{P_{7(in)(electr)}(TRF2)} \times 100\% = \frac{0.3}{0.3} \times 100\% = 100\% \quad (\textit{losses negligibly small})$$

Overall efficiency at the 7th harmonic

$$P_{7(in)} = \sum\left(P_{7(in)(electr)}(ASD1) + P_{7(in)(electr)}(CFL's)\right) = (3.6 + 0.9) = 4.5\,W$$

$$P_{7(out)} = \sum\left(P_{7(out)(electr)}(Grid) + P_{7(out)(electr)}(IDM2)\right) = (2.4 + 0.3) = 2.7\,W$$

$$P_{7(Losses)} = P_{7(in)} - P_{7(out)} = (4.5 - 2.7) = 1.8\,W$$

$$\%\eta_7 overall = \frac{\sum P_{7(out)}}{\sum P_{7(in)}} \times 100\% = \frac{2.7}{4.5} \times 100\% = 60\%$$

6.1.1.4 Combined frequency

When calculating efficiency for the combined frequency operation (*H*), one works from the grid end towards the customer end of the network.

Now, calculating the individual efficiency for each element

TRF1 (Bus 1 towards Bus 2)

$$P_{T(H)(in)(electr)}(TRF1) = P_{1(in)(electr)}(TRF1) - P_{5(out)(electr)}(TRF1) - P_{7(out)(electr)}(TRF1)$$
$$= (2418.6 - 6.9 - 2.4) = 2409.3\,W \quad (Bus\,1)$$
$$P_{T(H)(out)(electr)}(TRF1) = P_{1(out)(electr)}(TRF1) - P_{5(in)(electr)}(TRF1) - P_{7(in)(electr)}(TRF1)$$
$$= (2135.7 - 7.8 - 3.9) = 2124\,W \quad (Bus\,2)$$
$$P_{T(H)(Losses)}(TRF1) = P_{T(H)(in)(electr)}(TRF1) - P_{T(H)(out)(electr)}(TRF1)$$
$$= 2409.3 - 2124 = 285.3\,W$$
$$\%\eta(TRF1H) = \frac{P_{T(H)(out)(electr)}(TRF1)}{P_{T(H)(in)(electr)}(TRF1)} \times 100\% = \frac{2124}{2409.3} \times 100\% = 88.16\%$$

Z1 (Bus 2 towards Bus 3)

$$P_{T(H)(in)(electr)}(Z1) = P_{1(in)(electr)}(Z1) - P_{5(out)(electr)}(Z1) - P_{7(out)(electr)}(Z1)$$
$$= (328.2 - 2.7 - 2.1) = 323.4\,W \quad (Bus\,2)$$
$$P_{T(H)(out)(electr)}(Z1) = P_{1(out)(electr)}(Z1) - P_{5(in)(electr)}(Z1) - P_{7(in)(electr)}(Z1)$$
$$= (316.8 - 3.6 - 3.6) = 309.6\,W \quad (Bus\,3)$$
$$P_{T(H)(Losses)}(Z1) = P_{T(H)(in)(electr)}(Z1) - P_{T(H)(out)(electr)}(Z1) = 323.4 - 309.6 = 13.8\,W$$
$$\%\eta(Z1H) = \frac{P_{T(H)(out)(electr)}(Z1)}{P_{T(H)(in)(electr)}(Z1)} \times 100\% = \frac{309.6}{323.4} \times 100\% = 95.73\%$$

TRF2 (Bus 2 towards Bus 4)

$$P_{T(H)(in)(electr)}(TRF2) = P_{1(in)(electr)}(TRF2) + P_{5(in)(electr)}(TRF2) + P_{7(in)(electr)}(TRF2)$$
$$= (1153.8 + 0.3 + 0.3) = 1154.4\,W \quad (Bus\ 2)$$
$$P_{T(H)(out)(electr)}(TRF2) = P_{1(out)(electr)}(TRF2) + P_{5(out)(electr)}(TRF2) + P_{7(out)(electr)}(TRF2)$$
$$= (957.9 + 0.3 + 0.3) = 958.5\,W \quad (Bus\ 4)$$
$$P_{T(H)(Losses)}(TRF2) = P_{T(H)(in)(electr)}(TRF2) - P_{T(H)(out)(electr)}(TRF2) = 1154.4 - 958.5 = 195.9\,W$$
$$\%\eta(TRF2H) = \frac{P_{T(H)(out)(electr)}(TRF2)}{P_{T(H)(in)(electr)}(TRF2)} \times 100\% = \frac{958.5}{1154.4} \times 100\% = 88.03\%$$

Overall efficiency of network

The overall efficiency for combined frequencies (H) is determined from the following formula (4.25) in section 4.8.3.

$$\%\eta_H overall = \frac{\sum P_{T(H)(out)}}{P_{T(H)(in)}} \times 100\%$$
$$= \frac{P_{T(H)}(IDM1) + P_{T(H)}(CFL's) + P_{T(H)}(IDM2)}{P_{1(electr)}(Grid) - P_{5(electr)}(Grid) - P_{7(electr)}(Grid)} \times 100\%$$

where:

$$P_{T(H)}(IDM1) = P_{T(H)}(ASD1 + IDM1) \times 0.876 \times 0.8588$$
$$= (316.8 - 3.6 - 3.6) \times 0.876 \times 0.8588$$
$$= 232.915\,W$$
$$P_{T(H)}(CFL's) = 667.2 - 5.1 - 0.9 = 661.2\,W$$
$$P_{T(H)}(IDM2) = P_{T(H)}(IDM2) \times 0.9004$$
$$= (957.9 + 0.3 + 0.3) \times 0.9004$$
$$= 863.033\,W$$
$$P_{T(H)(in)} = 2418.6 - 6.9 - 2.4 = 2409.3\,W$$

Therefore:

$$\%\eta_H overall = \frac{232.915 + 661.2 + 863.033}{2409.3} \times 100\%$$
$$= \frac{1757.148}{2409.3} \times 100\%$$
$$= 72.93\%$$

and

$$Total\ losses = 2409.3 - 1757.148 = 652.15W$$

6.1.2 Analysis of efficiency

Tables 6.1 and 6.2 show the summary of results obtained. These results are used to derive the comparative bar graphs shown in Figures 6.1, 6.2 and 6.3 thus comparing the results of efficiency without distortion (only sinusoidal f_1) to that with distortion (non-sinusoidal h and H).

Table 6.1: Case study 1: Efficiency of the individual elements

	Efficiency (%)			
Element	f_1	h=5	h=7	H
TRF1	88.30	88.46	61.54	88.16
Z1	96.53	75.00	58.33	95.73
TRF2	83.02	100	100	88.03
ASD1	87.60	87.60	87.60	87.60
IDM1	85.88	85.88	85.88	85.88
IDM2	90.04	90.04	90.04	90.04

Table 6.2: Case study 1: Overall efficiency of the individual elements

Overall efficiency (%)			
f_1	h=5	h=7	H
73.10	82.76	60.00	72.93

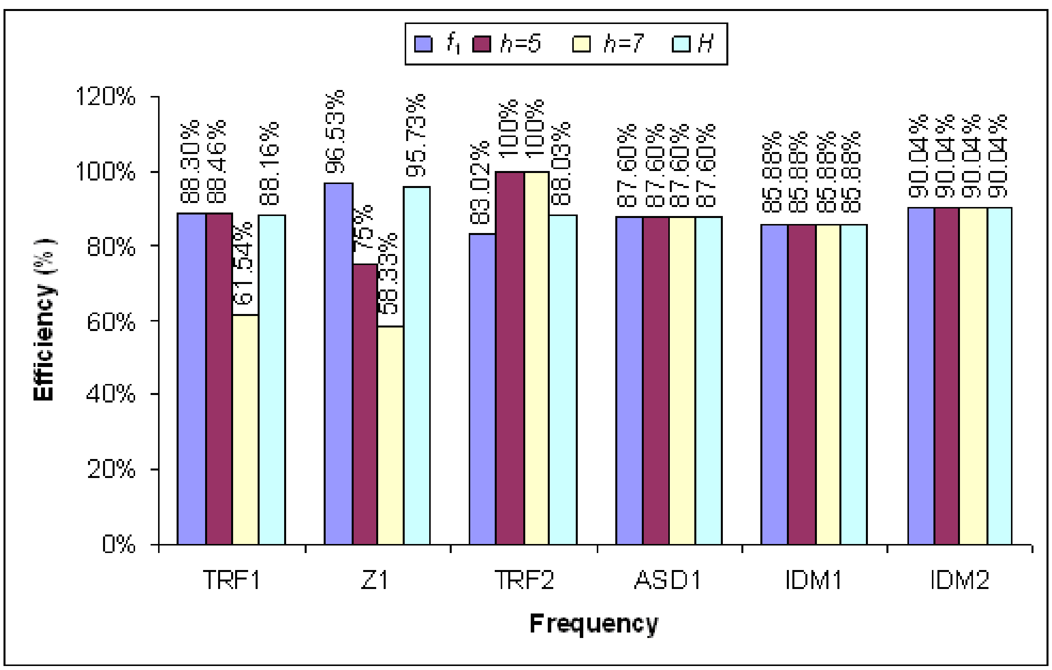


Figure 6.1: Case study 1: Comparison of efficiencies of individual elements

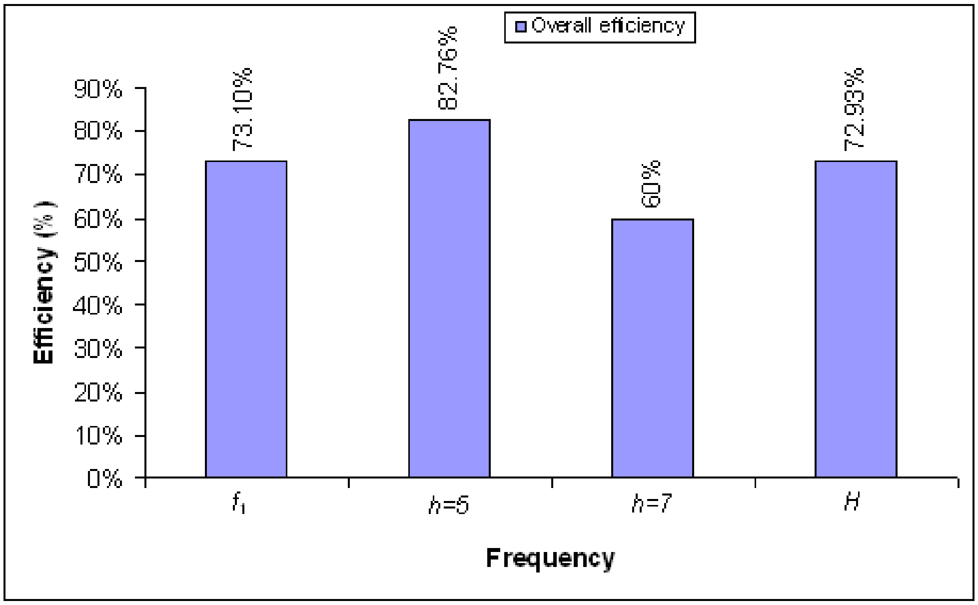


Figure 6.2: Case study 1: Comparison of overall efficiencies

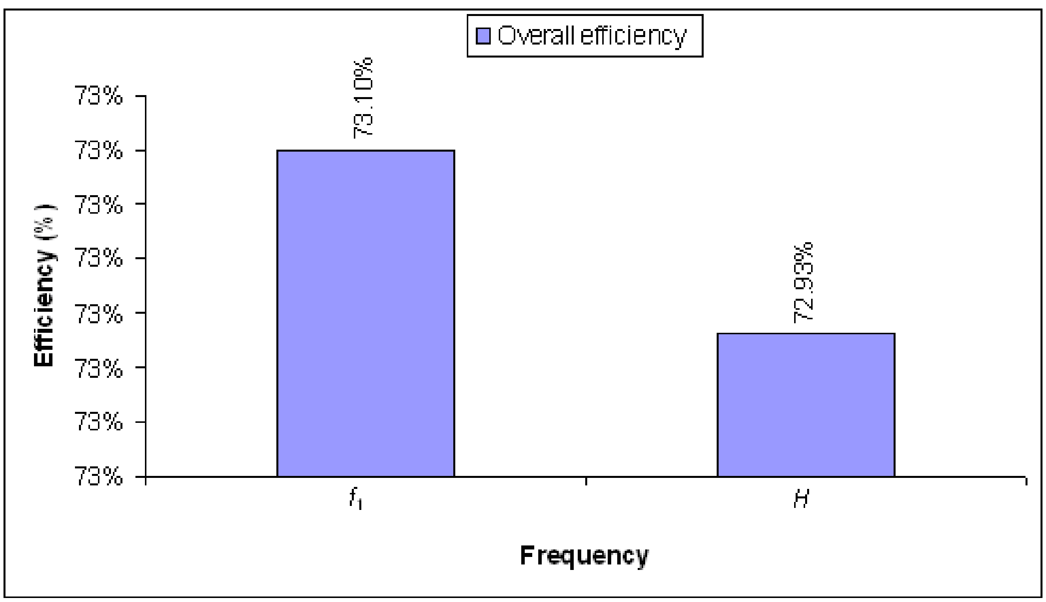


Figure 6.3: Case study 1: Comparison of (f_1) to (*H*) overall efficiencies

From this case study it was found that:

a. Efficiencies of TRF1 and Z1 are lower at *h*=7. Combined frequencies (*H*) efficiency of TRF1 is less than that of f_1 while the *H* efficiency of Z1 and TRF2 are higher than that of f_1 (Figure 6.1). It also shows that at *h*=5 & 7 that the efficiencies of TRF2 are equal approaching a 100% rating.

b. Figure 6.2 shows that the overall efficiency of a network with distortion (*H*) is less than that without distortion (f_1). This observation is shown more clearly in Figure 6.3. This also shows that the overall efficiency at *h*=5 is higher than that of f_1, *h*=7 and *H*.

According to these results, the overall efficiency of the network decreases with 0.17% as a result of distortion. It must however be noted that the purpose of this case study is to demonstrate the methodology and formulae developed. Also, in this case study the harmonic powers injected by the non-linear loads are small compared to the power at f_1. Thus in networks, where the harmonic content is a much larger percentage compared to the fundamental component, greater differences could be found.

6.1.3 Energy usage methodology

6.1.3.1 Fundamental frequency

The formula (1.1) is used to determine the fundamental frequency energy usage. $E_1 = P_1 \times t$, this formula is adapted to become case specific, namely:

$$E_1(case\ study\,1) = P_{1(in)(electr)}(Grid) \times t \tag{6.1}$$

$P_{1(in)(electr)}(Grid) = 2418.6\,W$ and if it is assumed to operate continuously for 24 hours, the energy usage for the day is:

$E_1(case\ study\,1) = P_1 \times t = P_{1(in)(electr)}(Grid) \times 24hrs = 2418.6 \times 24hrs = 58.046\,kWh$ at f_1.

6.1.3.2 5th harmonic frequency

In the case of harmonic frequency, the input power is the power from the non-linear loads.

$$E_5(case\ study\,1) = \left(P_{5(in)(electr)}(ASD1) + P_{5(in)(electr)}(CFL's)\right) \times t$$
$$= (3.6 + 5.1) \times 24 = 0.209\,kWh$$

6.1.3.3 7th harmonic frequency

$$E_7(case\ study\,1) = \left(P_{7(in)(electr)}(ASD1) + P_{7(in)(electr)}(CFL's)\right) \times t = (3.6 + 0.9) \times 24 = 0.108\,kWh$$

6.1.3.4 Total energy usage

The total energy usage of a power system depends upon the total power consumption at the input supply point to the network, therefore:

$$E_{T(H)}(case\ study\ 1) = P_{T(H)(in)}(case\ study\ 1) \times t \qquad (6.2)$$

Therefore, total energy usage:

$$E_{T(H)}(case\ study\ 1) = (2418.6 - 6.9 - 2.4) \times 24 = 57.823\ kWh$$

6.1.4 Analysis of total energy usage

The 5th and 7th harmonic energy usage, although small, needs to be considered besides the energy usage at f_1.

Table 6.3 shows the summary of energy usage results obtained. These results are used to derive the comparative bar graph, which compares the results without distortion (only sinusoidal f_1) and with distortion (non-sinusoidal H).

Table 6.3: Case study 1: Energy usage at different frequency

Energy usage (kWh)			
f_1	h=5	h=7	H
58.046	0.209	0.108	57.823

Figure 6.4 shows the difference in energy usage between a network without distortion to the network having distortion caused by 5th and 7th harmonic components.

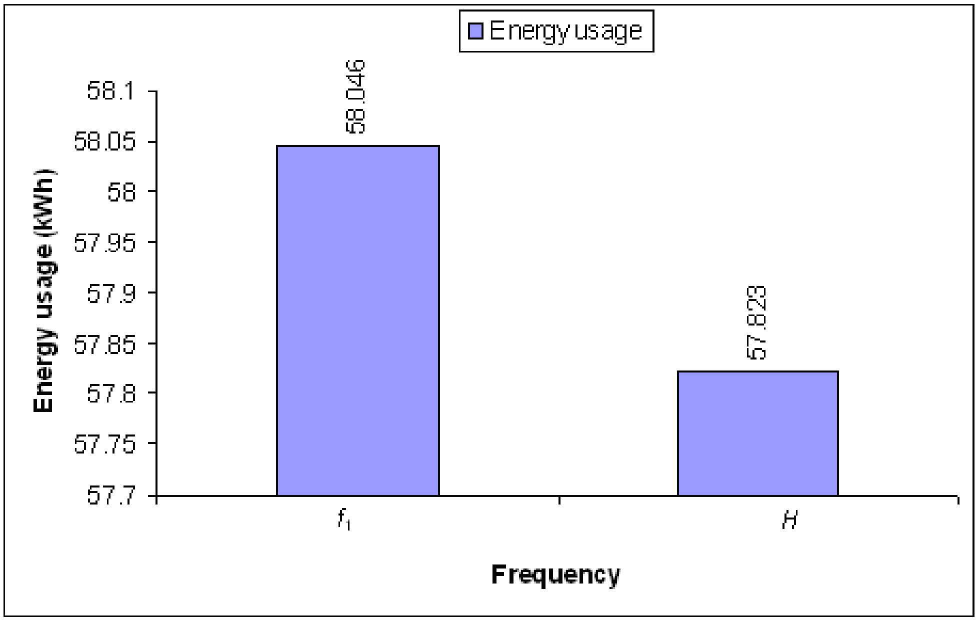


Figure 6.4: Case study 1: Comparison of total energy with and without distortion

From this case study it was found that:

a. The total energy usage without distortion (58.046 kWh) shown in Figure 6.4 is more than that with distortion (57.823 kWh). The energy usages of h=5 and h=7 shown in Table 6.3 are small compared to f_1 and H results.

According to these results, the total energy usage of the network decreases with 0.2% as a result of distortion.

6.1.5 Losses

The measurement based case study proved the importance of establishing the direction of harmonic power flow. It gives a clear understanding that power can either be negative or positive. The power flow depends on whether the element is a linear or non-linear element. Harmonics can cause additional heat losses to a transformer, increasing the total losses. The results, however, indicate that not all transformers obtain additional losses as the harmonic flows are sometimes in the opposite direction to the flow at fundamental frequency (see Table 6.4).

Table 6.4 shows that the losses increase at TRF1 due to distortion, but at TRF2 that is supplying the linear load branch, it remains the same. The power losses for the network are shown in Table 6.5.

Table 6.4: Case study 1: Power losses on transformers using measurement results

	Power Losses(kW)	
Element	f_1	***H***
TRF1	282.9	285.3
TRF2	195.9	195.9

Table 6.5: Case study 1: Power losses of a network

Power losses (W)			
f_1	***h*=5**	***h*=7**	***H***
650.58	1.5	1.8	652.15

Figure 6.5 shows that the losses increase by 1.6 W when distortion is present in the network (*H*).

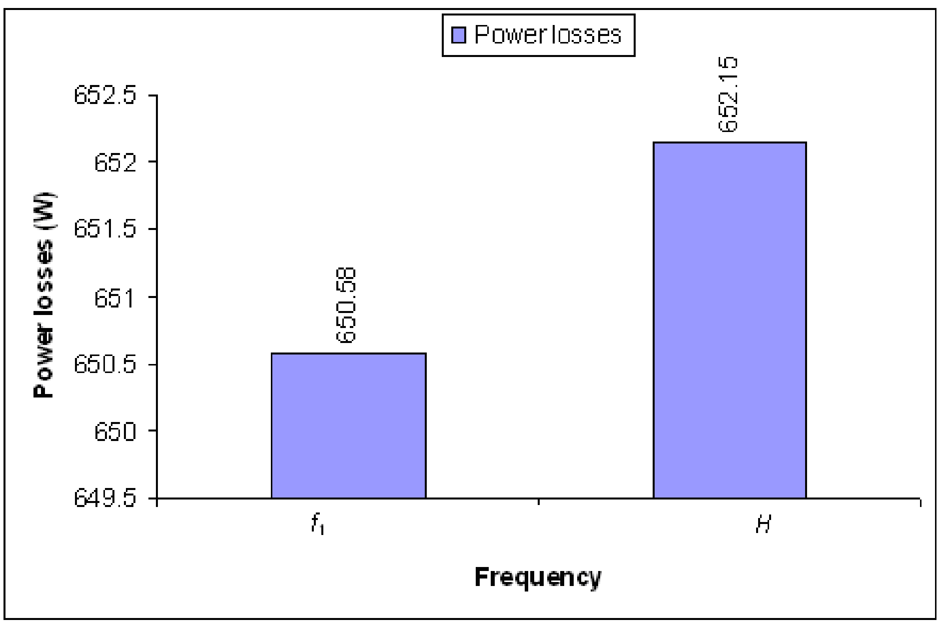


Figure 6.5: Case study 1: Comparison of network power losses

6.2 Case study 2

The results for case study 2 are given in Figures 5.9 and 5.12. They are used to demonstrate the methodology and for result analysis.

6.2.1 Case study 2: Without filter

The results given on Figure 5.9 are used for the analysis.

6.2.1.1 Efficiency methodology

The first step is to determine the individual and overall efficiencies for the network.

6.2.1.1.1 Fundamental frequency (f_1)

Obtain the power input to the network at f_1, namely:

$$P_{1(in)(electr)}(Grid) = 3429.914\,kW$$

Now, calculate the efficiency of the individual element

TRF1

$$P_{1(Losses)}(TRF1) = P_{1(in)(electr)}(TRF1) - P_{1(out)(electr)}(TRF1) = 3424.914 - 3418.549 = 6.37\,kW$$
$$\%\eta_1(TRF1) = \frac{P_{1(out)(electr)}(TRF1)}{P_{1(in)(electr)}(TRF1)} \times 100\% = \frac{3418.549}{3424.914} \times 100\% = 99.81\%$$

Line1

$$P_{1(Losses)}(Line1) = P_{1(in)(electr)}(Line1) - P_{1(out)(electr)}(Line1) = 2289.215 - 2289.215 = 0\,kW$$
$$\%\eta_1(Line1) = \frac{P_{1(out)(electr)}(Line1)}{P_{1(in)(electr)}(Line1)} \times 100\% = \frac{2289.215}{2289.215} \times 100\% = 100\% \quad (losses\ negligibly\ small)$$

Drive1 and Motor1

The efficiency of Drive1 and Motor1 are assumed as 96% and 94.1%, respectively.

Drive2 and Motor2

Likewise, the efficiency of Drive2 and Motor2 are also assumed as 96% and 94.1%, respectively.

TRF2

$$P_{1(Losses)}(TRF2) = P_{1(in)(electr)}(TRF2) - P_{1(out)(electr)}(TRF2) = 2289.215 - 2262.201 = 27.01\,kW$$

$$\%\eta_1(TRF2) = \frac{P_{1(out)(electr)}(TRF2)}{P_{1(in)(electr)}(TRF2)} \times 100\% = \frac{2262.201}{2289.215} \times 100\% = 98.82\%$$

Line2

$$P_{1(Losses)}(Line2) = P_{1(in)(electr)}(Line2) - P_{1(out)(electr)}(Line2) = 1129.335 - 1129.335 = 0\,kW$$

$$\%\eta_1(Line2) = \frac{P_{1(out)(electr)}(Line2)}{P_{1(in)(electr)}(Line2)} \times 100\% = \frac{1129.335}{1129.335} \times 100\% = 100\% \quad (\textit{losses negligibly small})$$

TRF3

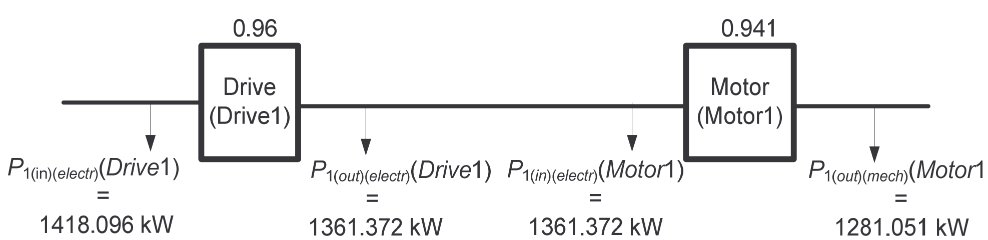
$$P_{1(Losses)}(TRF3) = P_{1(in)(electr)}(TRF3) - P_{1(out)(electr)}(TRF3) = 1129.335 - 1119.253 = 10.08\,kW$$

$$\%\eta_1(TRF3) = \frac{P_{1(out)(electr)}(TRF3)}{P_{1(in)(electr)}(TRF3)} \times 100\% = \frac{1119.253}{1129.335} \times 100\% = 99.11\%$$

Overall efficiency

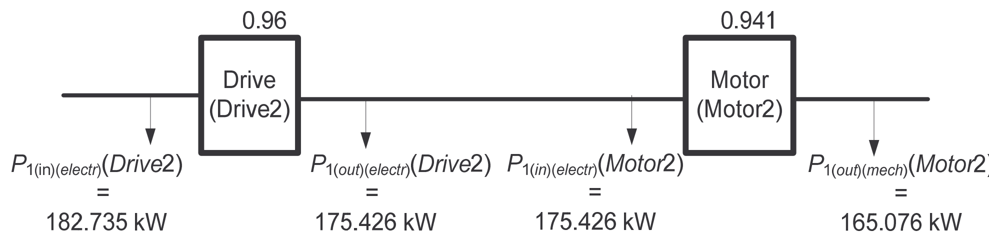
If we assume that efficiency for the drive and/or motor remain constant then the overall efficiency can be obtained as follows:

First, for Drive1:



$$P_{1(out)(mech)}(Drive1 + Motor1) = P_{1(in)(electr)}(Drive1) \times 0.96 \times 0.941$$
$$= 1418.096 \times 0.96 \times 0.941 = 1281.05\ kW$$

Now, for Drive 2,



$$P_{1(out)(mech)}(Drive2 + Motor2) = P_{1(in)(electr)}(Drive2) \times 0.96 \times 0.941$$
$$= 182.735 \times 0.96 \times 0.941 = 165.076\,kW$$

$$P_{1(out)} = \sum \begin{bmatrix} P_{1(out)(mech)}(Drive1 + Motor1) + P_{1(out)(mech)}(Drive2 + Motor2) + \\ P_{1(out)(electr)}(Load1) + P_{1(out)(electr)}(Load2) + P_{1(out)(electr)}(Load3) \end{bmatrix}$$
$$= 1281.051 + 165.076 + 844.105 + 730.940 + 205.577 = 3226.749\,kW$$

$$P_{1(Losses)} = P_{1(in)(electr)}(Grid) - P_{1(out)} = 3424.914 - 3226.749 = 198.165\,kW$$

$$\%\eta_1 overall = \frac{\sum P_{1(out)}}{P_{1(in)}} \times 100\% = \frac{3226.749}{3424.914} \times 100\% = 94.21\%$$

6.2.1.1.2 5th harmonic frequency (*h* = 5)

Now, calculate the efficiency of the individual element

TRF1

At *h*=5, there is no harmonic output as the grid infeed is an ideal voltage model, see Table 5.9. Thus, efficiency of TRF1 is not calculated at *h*=5.

Line1

$$P_{5(Losses)}(Line1) = P_{5(in)(electr)}(Line1) - P_{5(out)(electr)}(Line1) = (0.252 - 0.252) = 0\,kW$$
$$\%\eta_5(Line1) = \frac{P_{5(out)(electr)}(Line1)}{P_{5(in)(electr)}(Line1)} \times 100\% = \frac{0.252}{0.252} \times 100\% = 100\% \quad (losses\ negligibly\ small)$$

TRF2

$$P_{5(Losses)}(TRF2) = P_{5(in)(electr)}(TRF2) - P_{5(out)(electr)}(TRF2) = (0.452 - 0.252) = 0.2\,kW$$
$$\%\eta_5(TRF2) = \frac{P_{5(out)(electr)}(TRF2)}{P_{5(in)(electr)}(TRF2)} \times 100\% = \frac{0.252}{0.452} \times 100\% = 55.75\%$$

Line2

$$P_{5(Losses)}(Line2) = P_{5(in)(electr)}(Line2) - P_{5(out)(electr)}(Line2) = (0.029 - 0.029) = 0\,kW$$

$$\%\eta_5(Line2) = \frac{P_{5(out)(electr)}(Line2)}{P_{5(in)(electr)}(Line2)} \times 100\% = \frac{0.029}{0.029} \times 100\% = 100\% \quad (losses\ negligibly\ small)$$

TRF3

$$P_{5(Losses)}(TRF3) = P_{5(in)(electr)}(TRF3) - P_{5(out)(electr)}(TRF3) = (0.034 - 0.029) = 0.005\,kW$$

$$\%\eta_5(TRF3) = \frac{P_{5(out)(electr)}(TRF3)}{P_{5(in)(electr)}(TRF3)} \times 100\% = \frac{0.029}{0.034} \times 100\% = 85.29\%$$

Overall efficiency at the 5th harmonic

$$P_{5(in)} = \sum \left(P_{5(in)(electr)}(Drive1) + P_{5(in)(electr)}(Drive2)\right) = (0.683 + 0.171) = 0.854\,kW$$

$$P_{5(out)} = \sum \begin{bmatrix} P_{5(out)(electr)}(Grid\,(branch)) + P_{5(out)(electr)}(Load1) + \\ P_{5(out)(electr)}(Load2) + P_{5(out)(electr)}(Load3) \end{bmatrix}$$
$$= (0.282 + 0.232 + 0.045 + 0.093) = 0.652\,kW$$

$$P_{5(Losses)} = P_{5(in)} - P_{5(out)} = (0.854 - 0.652) = 0.202\,kW$$

$$\%\eta_5 overall = \frac{\sum P_{5(out)}}{\sum P_{5(in)}} \times 100\% = \frac{0.652}{0.854} \times 100\% = 76.35\%$$

6.2.1.1.3 7th harmonic frequency (*h* = 7)

Calculate the efficiency of the individual elements

TRF1

At *h*=7, there is no harmonic output as the grid infeed is an ideal voltage model, see Table 5.9. Thus, efficiency of TRF1 is not calculated at h=7.

Line1

$$P_{7(Losses)}(Line1) = P_{7(in)(electr)}(Line1) - P_{7(out)(electr)}(Line1) = (43.879 - 43.879) = 0\,kW$$

$$\%\eta_7(Line1) = \frac{P_{7(out)(electr)}(Line1)}{P_{7(in)(electr)}(Line1)} \times 100\% = \frac{43.879}{43.879} \times 100\% = 100\% \quad (losses\ negligibly\ small)$$

TRF2

$$P_{7(Losses)}(TRF2) = P_{7(in)(electr)}(TRF2) - P_{7(out)(electr)}(TRF2) = (44.117 - 43.879) = 0.238\,kW$$

$$\%\eta_7(TRF2) = \frac{P_{7(out)(electr)}(TRF2)}{P_{7(in)(electr)}(TRF2)} \times 100\% = \frac{43.879}{44.117} \times 100\% = 99.46\%$$

Line2

$$P_{7(Losses)}(Line2) = P_{7(in)(electr)}(Line2) - P_{7(out)(electr)}(Line2) = (7.057 - 7.057) = 0\,kW$$

$$\%\eta_7(Line2) = \frac{P_{7(out)(electr)}(Line2)}{P_{7(in)(electr)}(Line2)} \times 100\% = \frac{7.057}{7.057} \times 100\% = 100\% \quad (losses\ negligibly\ small)$$

TRF3

$$P_{7(Losses)}(TRF3) = P_{7(in)(electr)}(TRF3) - P_{7(out)(electr)}(TRF3) = (7.057 - 6.939) = 0.118\,kW$$

$$\%\eta_7(TRF3) = \frac{P_{7(out)(electr)}(TRF3)}{P_{7(in)(electr)}(TRF3)} \times 100\% = \frac{6.939}{7.057} \times 100\% = 98.33\%$$

Overall efficiency at the 7th harmonic

$$P_{7(in)} = \sum\left(P_{7(in)(electr)}(Drive1) + P_{7(in)(electr)}(Drive2)\right) = (48.405 + 4.474) = 52.879\,kW$$

$$P_{7(out)} = \sum\begin{bmatrix} P_{7(out)(electr)}(Grid\,(branch)) + P_{7(out)(electr)}(Load1) + \\ P_{7(out)(electr)}(Load2) + P_{7(out)(electr)}(Load3) \end{bmatrix}$$

$$= (36.823 + 4.288 + 7.569 + 3.845) = 52.525\,kW$$

$$P_{7(Losses)} = P_{7(in)} - P_{7(out)} = (52.879 - 52.525) = 0.354\,kW$$

$$\%\eta_7 overall = \frac{\sum P_{7(out)}}{\sum P_{7(in)}} \times 100\% = \frac{52.525}{52.879} \times 100\% = 99.33\%$$

6.2.1.1.4 Combined frequency

When calculating efficiency for the combined frequency operation (*H*), one works from the grid end towards the customer end of the network.

Now, calculating the individual efficiency for each element

TRF1 (Bus 1 towards Bus 2)

$$P_{T(H)(in)(electr)}(TRF1) = P_{1(in)(electr)}(TRF1) - P_{5(out)(electr)}(TRF1) - P_{7(out)(electr)}(TRF1)$$
$$= (3424.914 - 0 - 0) = 3424.914\,kW \quad (Bus\,1)$$
$$P_{T(H)(out)(electr)}(TRF1) = P_{1(out)(electr)}(TRF1) - P_{5(in)(electr)}(TRF1) - P_{7(in)(electr)}(TRF1)$$
$$= (3418.549 - 0.282 - 36.823) = 3381.444\,kW \quad (Bus\,2)$$
$$P_{T(H)(Losses)}(TRF1) = P_{T(H)(in)(electr)}(TRF1) - P_{T(H)(out)(electr)}(TRF1)$$
$$= 3424.914 - 3381.444 = 43.47\,kW$$
$$\%\eta(TRF1H) = \frac{P_{T(H)(out)(electr)}(TRF1)}{P_{T(H)(in)(electr)}(TRF1)} \times 100\% = \frac{3381.444}{3424.914} \times 100\% = 98.73\%$$

Line1 (Bus 2 towards Bus 3)

$$P_{T(H)(in)(electr)}(Line1) = P_{1(in)(electr)}(Line1) - P_{5(out)(electr)}(Line1) - P_{7(out)(electr)}(Line1)$$
$$= (2289.215 - 0.252 - 43.879) = 2245.084\,kW \quad (Bus\,2)$$
$$P_{T(H)(out)(electr)}(Line1) = P_{1(out)(electr)}(Line1) - P_{5(in)(electr)}(Line1) - P_{7(in)(electr)}(Line1)$$
$$= (2289.215 - 0.252 - 43.879) = 2245.084\,kW \quad (Bus\,3)$$
$$P_{T(H)(Losses)}(Line1) = P_{T(H)(in)(electr)}(Line1) - P_{T(H)(out)(electr)}(Line1)$$
$$= (2245.084 - 2245.084) = 0\,kW$$
$$\%\eta(Line1H) = \frac{P_{T(H)(out)(electr)}(Line1)}{P_{T(H)(in)(electr)}(Line1)} \times 100\% = \frac{2245.084}{2245.084} \times 100\%$$
$$= 100\% \quad (losses\ negligibly\ small)$$

TRF2 (Bus 3 towards Bus 4)

$$P_{T(H)(in)(electr)}(TRF2) = P_{1(in)(electr)}(TRF2) - P_{5(out)(electr)}(TRF2) - P_{7(out)(electr)}(TRF2)$$
$$= (2289.215 - 0.252 - 43.879) = 2245.084\,kW \ (Bus\,3)$$
$$P_{T(H)(out)(electr)}(TRF2) = P_{1(out)(electr)}(TRF2) - P_{5(in)(electr)}(TRF2) - P_{7(in)(electr)}(TRF2)$$
$$= (2262.201 - 0.452 - 44.117) = 2217.632\,kW \ (Bus\,4)$$
$$P_{T(H)(Losses)}(TRF2) = P_{T(H)(in)(electr)}(TRF2) - P_{T(H)(out)(electr)}(TRF2)$$
$$= (2245.084 - 2217.632) = 27.452\,kW$$
$$\%\eta(TRF2H) = \frac{P_{T(H)(out)(electr)}(TRF2)}{P_{T(H)(in)(electr)}(TRF2)} \times 100\% = \frac{2217.632}{2245.084} \times 100\% = 98.78\%$$

Line2 (Bus 2 towards Bus 5)

$$P_{T(H)(in)(electr)}(Line2) = P_{1(in)(electr)}(Line2) - P_{5(out)(electr)}(Line2) + P_{7(in)(electr)}(Line2)$$
$$= (1129.335 - 0.029 + 7.057) = 1136.363\,kW \quad (Bus\,2)$$
$$P_{T(H)(out)(electr)}(Line2) = P_{1(out)(electr)}(Line2) - P_{5(in)(electr)}(Line2) + P_{7(out)(electr)}(Line2)$$
$$= (1129.335 - 0.029 + 7.057) = 1136.363\,kW \quad (Bus\,5)$$
$$P_{T(H)(Losses)}(Line2) = P_{T(H)(in)(electr)}(Line2) - P_{T(H)(out)(electr)}(Line2)$$
$$= (1136.363 - 1136.363) = 0\,kW$$
$$\%\eta(Line2H) = \frac{P_{T(H)(out)(electr)}(Line2)}{P_{T(H)(in)(electr)}(Line2)} \times 100\% = \frac{1136.363}{1136.363} \times 100\%$$
$$= 100\% \quad (losses\ negligibly\ small)$$

TRF3 (Bus 5 towards Bus 6)

$$P_{T(H)(in)(electr)}(TRF3) = P_{1(in)(electr)}(TRF3) - P_{5(out)(electr)}(TRF3) + P_{7(in)(electr)}(TRF3)$$
$$= (1129.335 - 0.029 + 7.057) = 1136.363\,kW \ (Bus\,5)$$
$$P_{T(H)(out)(electr)}(TRF3) = P_{1(out)(electr)}(TRF3) - P_{5(in)(electr)}(TRF3) + P_{7(out)(electr)}(TRF3)$$
$$= (1119.253 - 0.034 + 6.939) = 1126.158\,kW \ (Bus\,6)$$
$$P_{T(H)(Losses)}(TRF3) = P_{T(H)(in)(electr)}(TRF3) - P_{T(H)(out)(electr)}(TRF3)$$
$$= (1136.363 - 1126.158) = 10.205\,kW$$
$$\%\eta(TRF3H) = \frac{P_{T(H)(out)(electr)}(TRF3)}{P_{T(H)(in)(electr)}(TRF3)} \times 100\% = \frac{1126.158}{1136.363} \times 100\% = 99.10\%$$

Overall efficiency of network

The overall efficiency for combined frequencies (H) is based on formula (4.25) in section 4.8.3, and becomes the following for case study 2:

$$\%\eta_H overall = \frac{\sum P_{T(H)(out)}}{P_{T(H)(in)}} \times 100\%$$
$$= \frac{\begin{bmatrix} P_{T(H)}(Drive1 + Motor1) + P_{T(H)}(Drive2 + Motor2) + \\ P_{T(H)}(Load1) + P_{T(H)}(Load2) + P_{T(H)}(Load3) \end{bmatrix}}{P_{1(electr)}(Grid) - P_{5(electr)}(Grid) - P_{7(electr)}(Grid)} \times 100\%$$

where (see Figure 5.9):

$$P_{T(H)}(Drive1 + Motor1) = P_{T(H)}(Drive1 + Motor1) \times 0.96 \times 0.941$$
$$= (1418.096 - 0.683 - 48.405) \times 0.96 \times 0.941$$
$$= 1369.008 \times 0.96 \times 0.941$$
$$= 1236.707\,kW$$

$$P_{T(H)}(Drive2 + Motor2) = P_{T(H)}(Drive2 + Motor2)\times\times 0.96 \times 0.941$$
$$= (182.735 - 0.171 - 4.474) \times 0.96 \times 0.941$$
$$= 178.09 \times 0.96 \times 0.941$$
$$= 160.879\, kW$$

$$P_{T(H)}(Load1) = (844.105 + 0.232 + 4.288) = 848.625\, kW$$

$$P_{T(H)}(Load2) = (730.940 + 0.093 + 7.569) = 738.602\, kW$$

$$P_{T(H)}(Load3) = (205.577 + 0.045 + 3.845) = 209.467\, kW$$

$$P_{T(H)(in)} = (3424.914 - 0 - 0) = 3424.914\, kW$$

Therefore:

$$\%\eta_H overall = \frac{1236.707 + 160.879 + 848.625 + 738.602 + 209.467}{3424.914} \times 100\%$$
$$= \frac{3194.280}{3424.914} \times 100\%$$
$$= 93.27\%$$

and

$$Total\ losses = (3424.914 - 3194.280) = 230.634\, kW$$

6.2.1.2 Analysis of efficiency

Tables 6.6 and 6.7 show the summary of results obtained. These results are used to derive the comparative bar graphs, shown in Figures 6.6, 6.7 and 6.8, that compare the results of efficiency without distortion (only sinusoidal f_1) and with distortion (non-sinusoidal h and H).

Table 6.6: Case study 2: Efficiency of the individual elements without filter

Efficiency (%)				
Element	f_1	h=5	h=7	H
TRF1	99.81	-	-	98.73
Line1	100	100	100	100
TRF2	98.82	55.75	99.46	98.78
Line2	100	100	100	100
TRF3	99.10	85.29	98.33	99.10
Drive1	96.00	96.00	96.00	96.00
Motor1	94.10	94.10	94.10	94.10
Drive2	96.00	96.00	96.00	96.00
Motor2	94.10	94.10	94.10	94.10

Table 6.7: Case study 2: Overall efficiency of the individual elements without filter

Overall efficiency (%)			
f_1	h=5	h=7	H
94.21	76.35	99.33	93.27

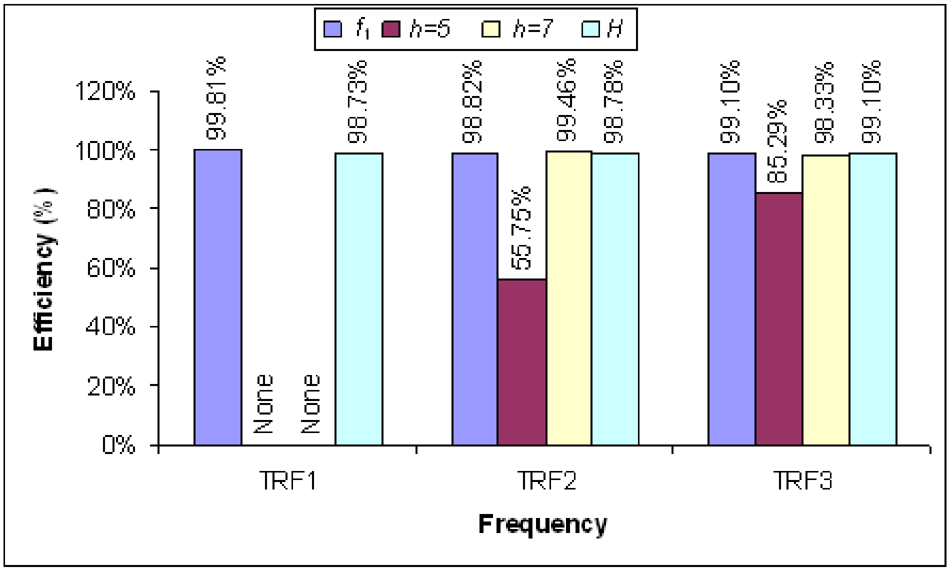


Figure 6.6: Case study 2: Comparison of transformer efficiencies without filter

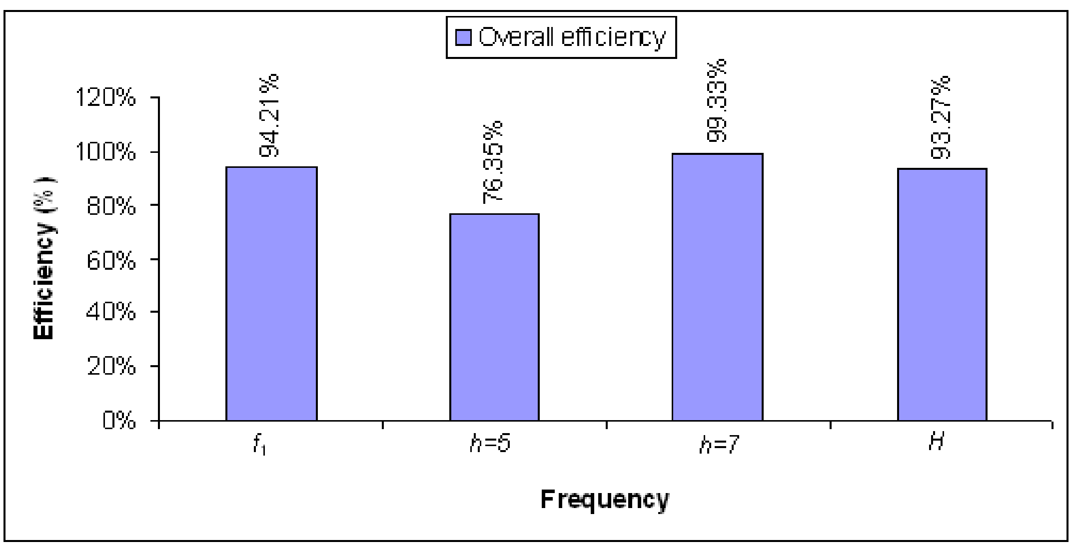


Figure 6.7: Case study 2: Comparison of overall efficiencies without filter

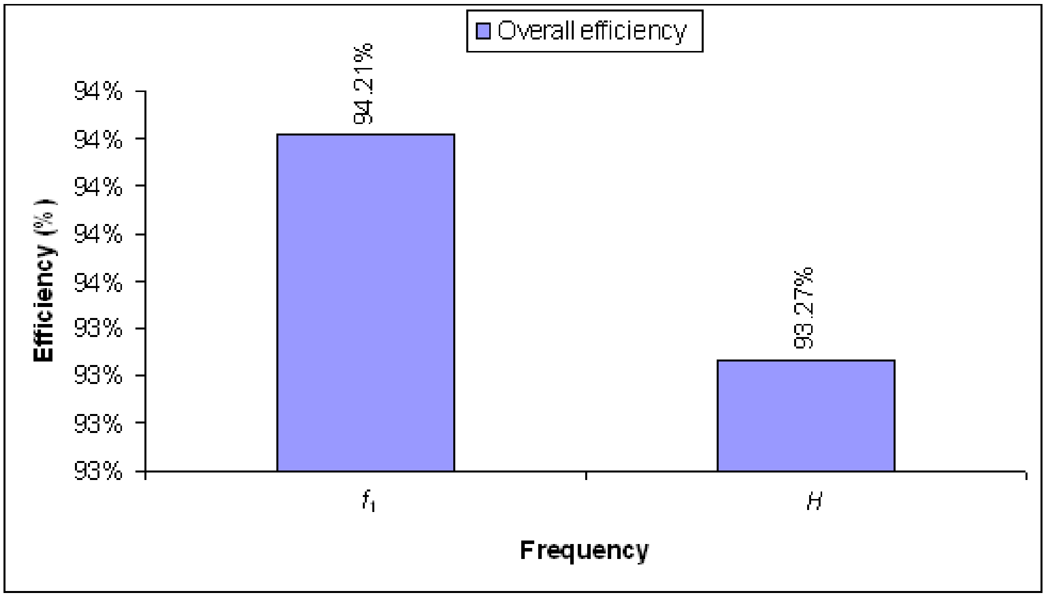


Figure 6.8: Case study 2: Comparison of f_1 to *H* overall efficiencies without filter

From this case study it was found that:

a. At h=5, the efficiency of TRF2 and TRF3 are in a lower range than f_1, h=7 and H. Efficiency of TRF3 at f_1 and H are equal at 99.10%, while for TRF1 there is a difference.
b. The overall efficiency of a network with distortion (H) shown in Figure 6.7 is less than that without distortion (f_1). This observation is shown more clearly in Figure 6.8. Also shown is that h=7 overall efficiency is higher than that of f_1, h=5 and H.

According to these results, the overall efficiency of the network decreases with 0.94% as a result of distortion.

6.2.1.3 Energy usage methodology

6.2.1.3.1 Fundamental frequency

The formula (1.1) is used to determine the fundamental frequency energy usage. The Formula, $E_1 = P_1 \times t$, is adapted to become case specific, namely:

$$E_1(case\ study\ 2) = P_{1(in)(electr)}(Grid) \times t \tag{6.3}$$

$P_{1(in)(electr)}(Grid) = 3414.914\,kW$ and 24 hours is used as the time period to calculate the energy usage for the day as:

$E_1(case\ study\ 2) = P_{1(in)(electr)}(Grid) \times 24hrs = 3424.914\,kW \times 24hrs = 82197.94\,kWh$ at f_1.

6.2.1.3.2 5th harmonic frequency

In the case of harmonic frequency, the input power is the power from the non-linear loads.

$$E_5(case\ study\ 2) = \left(P_{5(in)(electr)}(Drive1) + P_{5(in)(electr)}(Drive2)\right) \times t$$
$$= (0.683 + 0.171) \times 24 = 20.50\,kWh$$

6.2.1.3.3 7th harmonic frequency

$$E_7(case\ study\ 2) = \left(P_{7(in)(electr)}(Drive1) + P_{7(in)(electr)}(Drive2)\right) \times t$$
$$= (48.405 + 4.474) \times 24 = 1269.10kWh$$

6.2.1.3.4 Total energy usage

The total energy usage of a power system depends upon the total power consumption at fundamental and harmonic frequencies occurring at the input supply point to the network.

$$E_{T(H)}(case\ study\ 2) = P_{T(H)(in)}(case\ study\ 2) \times t \tag{6.4}$$

Therefore, total energy usage:

$$E_{T(H)}(case\ study\ 2) = (3424.914 - 0 - 0) \times 24 = 82197.94kWh$$

6.2.1.4 Analysis of total energy usage

The 5th and 7th harmonic energy usage, although small, needs to be considered besides the energy usage at f_1.

Table 6.8 shows the summary of energy usage results obtained. These results are used to derive the comparative bar graph that is comparing the results without distortion (only sinusoidal f_1) and with distortion (non-sinusoidal H).

Table 6.8: Case study 2: Energy usage at different frequencies without filter

Energy usage (kWh)			
f_1	h=5	h=7	H
82197.94	20.50	1269.10	82197.94

Figure 6.9 shows the difference in energy usage between a network without distortion to the network having distortion caused by 5th and 7th harmonic components

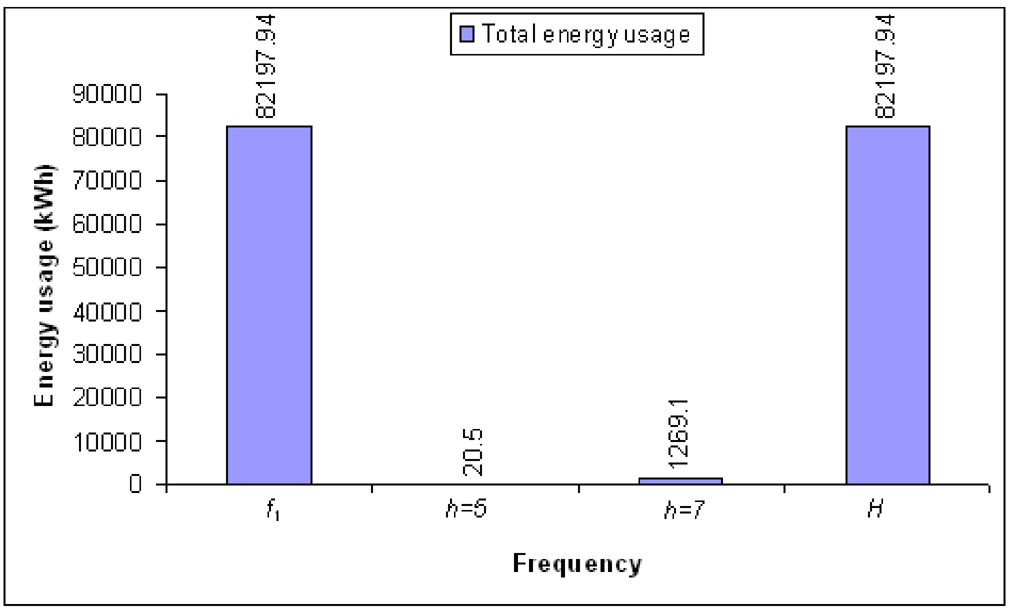


Figure 6.9: Case study 2: Comparison of total energy without filter

From this case study it was found that:

a. Total energy usage with and without distortion is equal to the power input at H and is the same as the power at f_1 since the harmonic energy is very small. Harmonic powers (h=5 and 7) at the grid are small.

6.2.1.5 Losses

Table 6.9: Case study 2: Power losses of transformers without filter

	Power Losses(kW)	
Element	f_1	***H***
TRF1	6.37	43.47
TRF2	27.01	27.45
TRF3	10.08	10.21

Table 6.9 shows that the transformer (TRF1, TRF2 and TRF3) power losses increase with distortion. The power losses of the networks at various frequencies are shown in Table 6.10.

Table 6.10: Case study 2: Power losses of network without filter

Power losses (W)			
f_1	***h*=5**	***h*=7**	***H***
198.17	0.202	0.354	230.64

Figure 6.10 shows that the losses increase with 32.47 kW when distortion is present in the network (*H*).

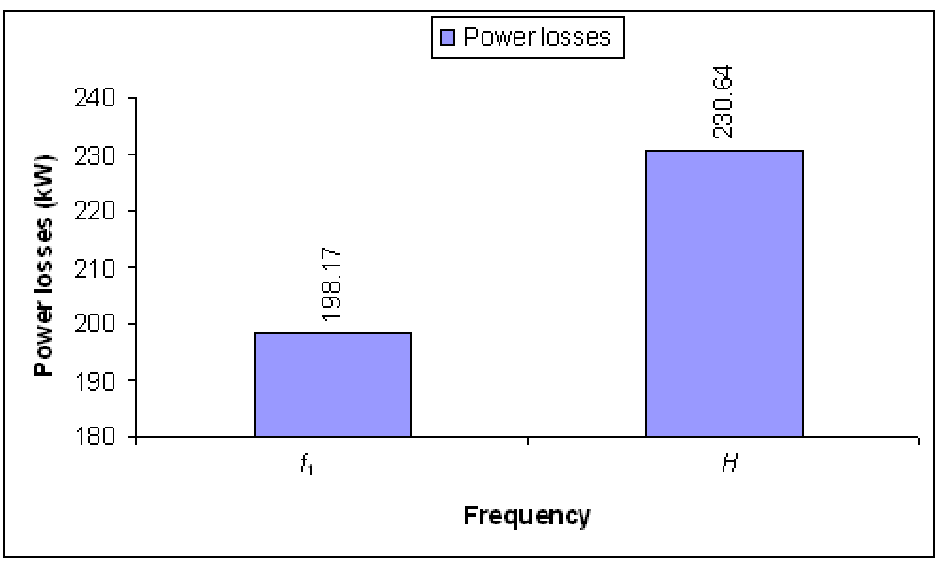


Figure 6.10: Case study 2: Comparison of power losses of a network without filter

6.2.2 Case study 2: With filter

The results given on Figure 5.12 are used for this analysis.

6.2.2.1 Efficiency methodology

The first step is to determine the individual and overall efficiencies for the network.

6.2.2.1.1 Fundamental frequency (f_1)

Obtain the power input to the network at f_1, namely:

$$P_{1(in)(electr)}(Grid) = 3438.288\,kW$$

Now, calculate the efficiency of the individual element

TRF1

$$P_{1(Losses)}(TRF1) = P_{1(in)(electr)}(TRF1) - P_{1(out)(electr)}(TRF1) = 3438.288 - 3432.001 = 6.29\,kW$$

$$\%\eta_1(TRF1) = \frac{P_{1(out)(electr)}(TRF1)}{P_{1(in)(electr)}(TRF1)} \times 100\% = \frac{3432.001}{3438.288} \times 100\% = 99.82\%$$

Line1

$$P_{1(Losses)}(Line1) = P_{1(in)(electr)}(Line1) - P_{1(out)(electr)}(Line1) = 2293.829 - 2293.829 = 0\,kW$$

$$\%\eta_1(Line1) = \frac{P_{1(out)(electr)}(Line1)}{P_{1(in)(electr)}(Line1)} \times 100\% = \frac{2293.829}{2293.829} \times 100\% = 100\% \quad (losses\ negligibly\ small)$$

TRF2

$$P_{1(Losses)}(TRF2) = P_{1(in)(electr)}(TRF2) - P_{1(out)(electr)}(TRF2) = 2293.829 - 2266.761 = 27.07\,kW$$

$$\%\eta_1(TRF2) = \frac{P_{1(out)(electr)}(TRF2)}{P_{1(in)(electr)}(TRF2)} \times 100\% = \frac{2266.761}{2293.829} \times 100\% = 98.82\%$$

Drive1 and Motor1

The efficiency of Drive1 and Motor1 are assumed as 96% and 94.1%, respectively.

Drive2 and Motor2

Likewise, the efficiency of Drive2 and Motor2 are also assumed as 96% and 94.1%, respectively.

Line2

$$P_{1(Losses)}(Line2) = P_{1(in)(electr)}(Line2) - P_{1(out)(electr)}(Line2) = 1131.611 - 1131.611 = 0\,kW$$

$$\%\eta_1(Line2) = \frac{P_{1(out)(electr)}(Line2)}{P_{1(in)(electr)}(Line2)} \times 100\% = \frac{1131.611}{1131.611} \times 100\% = 100\% \quad (\textit{losses negligibly small})$$

TRF3

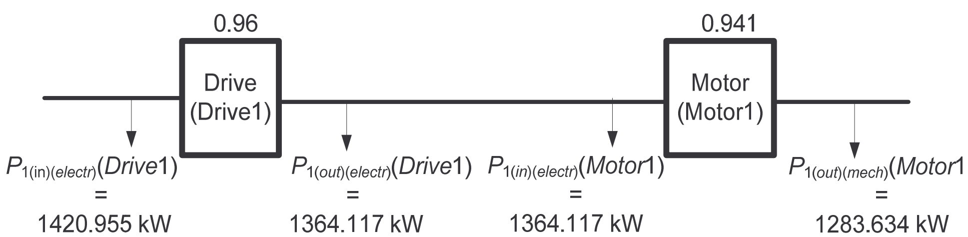
$$P_{1(Losses)}(TRF3) = P_{1(in)(electr)}(TRF3) - P_{1(out)(electr)}(TRF3) = 1131.611 - 1121.509 = 10.10\,kW$$

$$\%\eta_1(TRF3) = \frac{P_{1(out)(electr)}(TRF3)}{P_{1(in)(electr)}(TRF3)} \times 100\% = \frac{1121.509}{1131.611} \times 100\% = 99.11\%$$

Overall efficiency

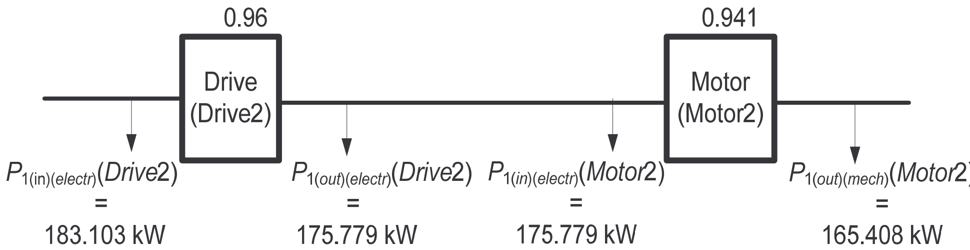
If we assume that efficiency for the drive and/ or motor remain constant then the overall efficiency can be obtained as follows:

First, for Drive1:



$$P_{1(out)(mech)}(Drive1 + Motor1) = P_{1(out)(electr)}(Drive1) \times 0.96 \times 0.941$$
$$= 1420.955 \times 0.96 \times 0.941 = 1283.634\,kW$$

Now, for Drive 2:



$$P_{1(out)(mech)}(Drive2 + Motor2) = P_{1(out)(electr)}(Drive2) \times 0.96 \times 0.941$$
$$= 183.103 \times 0.96 \times 0.941 = 165.408\, kW$$

$$P_{1(out)} = \sum \begin{bmatrix} P_{1(out)(mech)}(Drive1 + Motor1) + P_{1(out)(electr)}(Load1) + \\ P_{1(out)(mech)}(Drive2 + Motor2) + + P_{1(out)(electr)}(Load2) + \\ P_{1(out)(electr)}(Load3) + P_{1(out)(electr)}(Filter) \end{bmatrix}$$
$$= 1283.634 + 845.806 + 165.408 + 723.414 + 205.991 + 6.561 = 3230.814\, kW$$

$$P_{1(Losses)} = P_{1(in)(electr)}(Grid) - P_{1(out)} = 3438.288 - 3230.814 = 207.474\, kW$$

$$\%\eta_1 overall = \frac{\sum P_{1(out)}}{P_{1(in)}} \times 100\% = \frac{3230.814}{3438.288} \times 100\% = 93.97\%$$

6.2.2.1.2 5th harmonic frequency (*h* = 5)

Now, calculate the efficiency of the individual element

TRF1

At *h*=5, there is no harmonic output as the grid infeed is an ideal voltage source. Thus, efficiency of TRF1 is not calculated at h=5.

Line1

$$P_{5(Losses)}(Line1) = P_{5(in)(electr)}(Line1) - P_{5(out)(electr)}(Line1) = (0.054 - 0.054) = 0\, kW$$
$$\%\eta_5(Line1) = \frac{P_{5(out)(electr)}(Line1)}{P_{5(in)(electr)}(Line1)} \times 100\% = \frac{0.054}{0.054} \times 100\% = 100\% \quad (losses\ negligibly\ small)$$

TRF2

$$P_{5(Losses)}(TRF2) = P_{5(in)(electr)}(TRF2) - P_{5(out)(electr)}(TRF2) = (0.268 - 0.054) = 0.214\,kW$$

$$\%\eta_5(TRF2) = \frac{P_{5(out)(electr)}(TRF2)}{P_{5(in)(electr)}(TRF2)} \times 100\% = \frac{0.054}{0.268} \times 100\% = 20.15\%$$

Line2

$$P_{5(Losses)}(Line2) = P_{5(in)(electr)}(Line2) - P_{5(out)(electr)}(Line2) = (0.014 - 0.014) = 0\,kW$$

$$\%\eta_5(Line2) = \frac{P_{5(out)(electr)}(Line2)}{P_{5(in)(electr)}(Line2)} \times 100\% = \frac{0.014}{0.014} \times 100\% = 100\% \quad (losses\ negligibly\ small)$$

TRF3

$$P_{5(Losses)}(TRF3) = P_{5(in)(electr)}(TRF3) - P_{5(out)(electr)}(TRF3) = (0.021 - 0.014) = 0.007\,kW$$

$$\%\eta_5(TRF3) = \frac{P_{5(out)(electr)}(TRF3)}{P_{5(in)(electr)}(TRF3)} \times 100\% = \frac{0.014}{0.021} \times 100\% = 66.67\%$$

Overall efficiency at the 5th harmonic

$$P_{5(in)} = \sum\left(P_{5(in)(electr)}(Drive1) + P_{5(in)(electr)}(Drive2)\right) = (0.361 + 0.032) = 0.393\,kW$$

$$P_{5(out)} = \sum\begin{bmatrix} P_{5(out)(electr)}(Grid\,(branch)) + P_{5(out)(electr)}(Load1) + \\ P_{5(out)(electr)}(Load2) + P_{5(out)(electr)}(Load3) + P_{5(out)(electr)}(Filter) \end{bmatrix}$$

$$= (0.003 + 0.093 + 0.008 + 0.004 + 0.065) = 0.173\,kW$$

$$P_{5(Losses)} = P_{5(in)} - P_{5(out)} = (0.393 - 0.173) = 0.22\,kW$$

$$\%\eta_5 overall = \frac{\sum P_{5(out)}}{\sum P_{5(in)}} \times 100\% = \frac{0.173}{0.393} \times 100\% = 44.02\%$$

6.2.2.1.3 7th harmonic frequency (*h* = 7)

Calculate the efficiency of the individual element

TRF1

At *h*=7, there is no harmonic output as the grid infeed is an ideal voltage source. Thus, efficiency of TRF1 is not calculated at h=7.

Line1

$$P_{7(Losses)}(Line1) = P_{7(in)(electr)}(Line1) - P_{7(out)(electr)}(Line1) = (0.001 - 0.001) = 0\,kW$$

$$\%\eta_7(Line1) = \frac{P_{7(out)(electr)}(Line1)}{P_{7(in)(electr)}(Line1)} \times 100\% = \frac{0.001}{0.001} \times 100\% = 100\% \quad (losses\ negligibly\ small)$$

TRF2

$$P_{7(Losses)}(TRF2) = P_{7(in)(electr)}(TRF2) - P_{7(out)(electr)}(TRF2) = (0.094 - 0.001) = 0.093\,kW$$

$$\%\eta_7(TRF2) = \frac{P_{7(out)(electr)}(TRF2)}{P_{7(in)(electr)}(TRF2)} \times 100\% = \frac{0.001}{0.094} \times 100\% = 1.06\%$$

Line2

$$P_{7(Losses)}(Line2) = P_{7(in)(electr)}(Line2) - P_{7(out)(electr)}(Line2) = (0.017 - 0.017) = 0\,kW$$

$$\%\eta_7(Line2) = \frac{P_{7(out)(electr)}(Line2)}{P_{7(in)(electr)}(Line2)} \times 100\% = \frac{0.017}{0.017} \times 100\% = 100\% \quad (losses\ negligibly\ small)$$

TRF3

$$P_{7(Losses)}(TRF3) = P_{7(in)(electr)}(TRF3) - P_{7(out)(electr)}(TRF3) = (0.020 - 0.017) = 0.003\,kW$$

$$\%\eta_7(TRF3) = \frac{P_{7(out)(electr)}(TRF3)}{P_{7(in)(electr)}(TRF3)} \times 100\% = \frac{0.017}{0.020} \times 100\% = 85.00\%$$

Overall efficiency at the 7th harmonic

$$P_{7(in)} = \sum \left(P_{7(in)(electr)}(Drive1) + P_{7(in)(electr)}(Drive2) \right) = (0.145 + 0.031) = 0.176\,kW$$

$$P_{7(out)} = \sum \begin{bmatrix} P_{7(out)(electr)}(Grid\,(branch)) + P_{7(out)(electr)}(Load1) + \\ P_{7(out)(electr)}(Load2) + P_{7(out)(electr)}(Load3) + P_{7(out)(electr)}(Filter) \end{bmatrix}$$
$$= (0.008 + 0.051 + 0.007 + 0.004 + 0.009) = 0.079\,kW$$

$$P_{7(Losses)} = P_{7(in)} - P_{7(out)} = (0.176 - 0.079) = 0.100\,kW$$

$$\%\eta_7 overall = \frac{\sum P_{7(out)}}{\sum P_{7(in)}} \times 100\% = \frac{0.079}{0.179} \times 100\% = 44.13\%$$

6.2.2.1.4 Combined frequency

When calculating efficiency for the combined frequency operation (*H*), one works from the grid end towards the customer end of the network.

Now, calculating the individual efficiency for each element

TRF1 (Bus 1 towards Bus 2)

$$P_{T(H)(in)(electr)}(TRF1) = P_{1(in)(electr)}(TRF1) - P_{5(out)(electr)}(TRF1) - P_{7(out)(electr)}(TRF1)$$
$$= (3438.288 - 0 - 0) = 3438.288\,kW \quad (Bus\,1)$$
$$P_{T(H)(out)(electr)}(TRF1) = P_{1(out)(electr)}(TRF1) - P_{5(in)(electr)}(TRF1) - P_{7(in)(electr)}(TRF1)$$
$$= (3432.001 - 0.003 - 0.008) = 3431.990\,kW \quad (Bus\,2)$$
$$P_{T(H)(Losses)}(TRF1) = P_{T(H)(in)(electr)}(TRF1) - P_{T(H)(out)(electr)}(TRF1)$$
$$= 3438.288 - 3431.990 = 6.298\,kW$$
$$\%\eta(TRF1H) = \frac{P_{T(H)(out)(electr)}(TRF1)}{P_{T(H)(in)(electr)}(TRF1)} \times 100\% = \frac{3431.990}{3438.288} \times 100\% = 99.82\%$$

Line1 (Bus 2 towards Bus 3)

$$P_{T(H)(in)(electr)}(Line1) = P_{1(in)(electr)}(Line1) - P_{5(out)(electr)}(Line1) - P_{7(out)(electr)}(Line1)$$
$$= (2293.829 - 0.054 - 0.001) = 2293.774\,kW \quad (Bus\,2)$$
$$P_{T(H)(out)(electr)}(Line1) = P_{1(out)(electr)}(Line1) - P_{5(in)(electr)}(Line1) - P_{7(in)(electr)}(Line1)$$
$$= (2293.829 - 0.054 - 0.001) = 2293.774\,kW \quad (Bus\,3)$$
$$P_{T(H)(Losses)}(Line1) = P_{T(H)(in)(electr)}(Line1) - P_{T(H)(out)(electr)}(Line1)$$
$$= (2293.774 - 2293.774) = 0\,kW$$
$$\%\eta(Line1H) = \frac{P_{T(H)(out)(electr)}(Line1)}{P_{T(H)(in)(electr)}(Line1)} \times 100\% = \frac{2293.774}{2293.774} \times 100\%$$
$$= 100\% \quad (losses\ negligibly\ small)$$

TRF2 (Bus 3 towards Bus 4)

$$P_{T(H)(in)(electr)}(TRF2) = P_{1(in)(electr)}(TRF2) - P_{5(out)(electr)}(TRF2) - P_{7(out)(electr)}(TRF2)$$
$$= (2293.829 - 0.054 - 0.001) = 2293.774\,kW\ (Bus\,3)$$
$$P_{T(H)(out)(electr)}(TRF2) = P_{1(out)(electr)}(TRF2) - P_{5(in)(electr)}(TRF2) - P_{7(in)(electr)}(TRF2)$$
$$= (2266.761 - 0.268 - 0.094) = 2266.399\,kW\ (Bus\,4)$$
$$P_{T(H)(Losses)}(TRF2) = P_{T(H)(in)(electr)}(TRF2) - P_{T(H)(out)(electr)}(TRF2)$$
$$= (2293.774 - 2266.399) = 27.38\,kW$$
$$\%\eta(TRF2H) = \frac{P_{T(H)(out)(electr)}(TRF2)}{P_{T(H)(in)(electr)}(TRF2)} \times 100\% = \frac{2266.399}{2293.774} \times 100\% = 98.81\%$$

Line2 (Bus 2 towards Bus 5)

$$P_{T(H)(in)(electr)}(Line2) = P_{1(in)(electr)}(Line2) - P_{5(out)(electr)}(Line2) - P_{7(out)(electr)}(Line2)$$
$$= (1131.611 - 0.014 - 0.017) = 1131.580\ kW \quad (Bus\,2)$$
$$P_{T(H)(out)(electr)}(Line2) = P_{1(out)(electr)}(Line2) - P_{5(in)(electr)}(Line2) - P_{7(in)(electr)}(Line2)$$
$$= (1131.611 - 0.014 - 0.017) = 1131.580\ kW \quad (Bus\,5)$$
$$P_{T(H)(Losses)}(Line2) = P_{T(H)(in)(electr)}(Line2) - P_{T(H)(out)(electr)}(Line2)$$
$$= (1131.580 - 1131.580) = 0\ kW$$
$$\%\eta(Line2H) = \frac{P_{T(H)(out)(electr)}(Line2)}{P_{T(H)(in)(electr)}(Line2)} \times 100\% = \frac{1131.580}{1131.580} \times 100\%$$
$$= 100\% \quad (losses\ negligibly\ small)$$

TRF3 (Bus 5 towards Bus 6)

$$P_{T(H)(in)(electr)}(TRF3) = P_{1(in)(electr)}(TRF3) - P_{5(out)(electr)}(TRF3) - P_{7(out)(electr)}(TRF3)$$
$$= (1131.611 - 0.014 - 0.017) = 1131.580\ kW\ (Bus\,5)$$
$$P_{T(H)(out)(electr)}(TRF3) = P_{1(out)(electr)}(TRF3) - P_{5(in)(electr)}(TRF3) - P_{7(in)(electr)}(TRF3)$$
$$= (1121.509 - 0.021 - 0.020) = 1121.468\ kW\ (Bus\,6)$$
$$P_{T(H)(Losses)}(TRF3) = P_{T(H)(in)(electr)}(TRF3) - P_{T(H)(out)(electr)}(TRF3)$$
$$= (1131.580 - 1121.468) = 10.112\ kW$$
$$\%\eta(TRF3H) = \frac{P_{T(H)(out)(electr)}(TRF3)}{P_{T(H)(in)(electr)}(TRF3)} \times 100\% = \frac{1121.468}{1131.580} \times 100\% = 99.11\%$$

Overall efficiency of network

The overall efficiency for combined frequencies (H) is based on formula (4.25) in section 4.8.3, and becomes the following for case study 2 when a filter is added to the network, namely:

$$\%\eta_H overall = \frac{\sum P_{T(H)(out)}}{P_{T(H)(in)}} \times 100\%$$
$$= \frac{\begin{bmatrix} P_{T(H)}(Drive1 + Motor1) + P_{T(H)}(Drive2 + Motor2) + \\ P_{T(H)}(Load1) + P_{T(H)}(Load2) + P_{T(H)}(Load3) + P_{T(H)}(Filter) \end{bmatrix}}{P_{1(electr)}(Grid) - P_{5(electr)}(Grid) - P_{7(electr)}(Grid)} \times 100\%$$

where (see Figure 5.12):

$$P_{T(H)}(Drive1 + Motor1) = P_{T(H)}(Drive1 + Motor1) \times 0.96 \times 0.941$$
$$= (1420.955 - 0.361 - 0.145) \times 0.96 \times 0.941$$
$$= 1420.449 \times 0.96 \times 0.941$$
$$= 1283.177\ kW$$

$$P_{T(H)}(Drive2 + Motor2) = P_{T(H)}(Drive2 + Motor2) \times 0.96 \times 0.941$$
$$= (183.103 - 0.032 - 0.031) \times 0.96 \times 0.941$$
$$= 183.04 \times 0.96 \times 0.941$$
$$= 165.351\ kW$$

$$P_{T(H)}(Load1) = (845.806 + 0.093 + 0.051) = 845.950\ kW$$

$$P_{T(H)}(Load2) = (723.414 - 0.008 - 0.007) = 723.429\ kW$$

$$P_{T(H)}(Load3) = (205.991 + 0.004 + 0.004) = 205.999\ kW$$

$$P_{T(H)}(Filter) = (6.561 + 0.065 + 0.009) = 6.635\ kW$$

$$P_{T(H)(in)} = (3438.288 - 0 - 0) = 3438.288\ kW$$

Therefore:

$$\%\eta_H overall = \frac{1283.177 + 165.351 + 845.950 + 723.429 + 205.999 + 6.635}{3438.288} \times 100\%$$
$$= \frac{3230.541}{3438.288} \times 100\%$$
$$= 93.96\%$$

$$Total\ losses = (3438.288 - 3230.541) = 207.747\ kW$$

6.2.2.2 Analysis of efficiency

Tables 6.11 and 6.12 show the summary of results obtained. These results are used to derive the comparative bar graphs, shown in Figure 6.11, 6.12 and 6.13 and they compare the results of efficiency without distortion (only sinusoidal f_1) and with distortion (non-sinusoidal h and H).

Table 6.11: Case study 2: Efficiency of the individual elements with filter

Efficiency (%)				
Element	f_1	h=5	h=7	H
TRF1	99.82	-	-	99.82
Line1	100	100	100	100
TRF2	98.82	20.15	1.06	98.81
Line2	100	100	100	100
TRF3	99.11	66.67	85.00	99.11
Drive1	96.00	96.00	96.00	96.00
Motor1	94.10	94.10	94.10	94.10
Drive2	96.00	96.00	96.00	96.00
Motor2	94.10	94.10	94.10	94.10

Table 6.12: Case study 2: Overall efficiency of the individual elements with filter

Overall efficiency (%)			
f_1	h=5	h=7	H
93.97	44.02	44.13	93.96

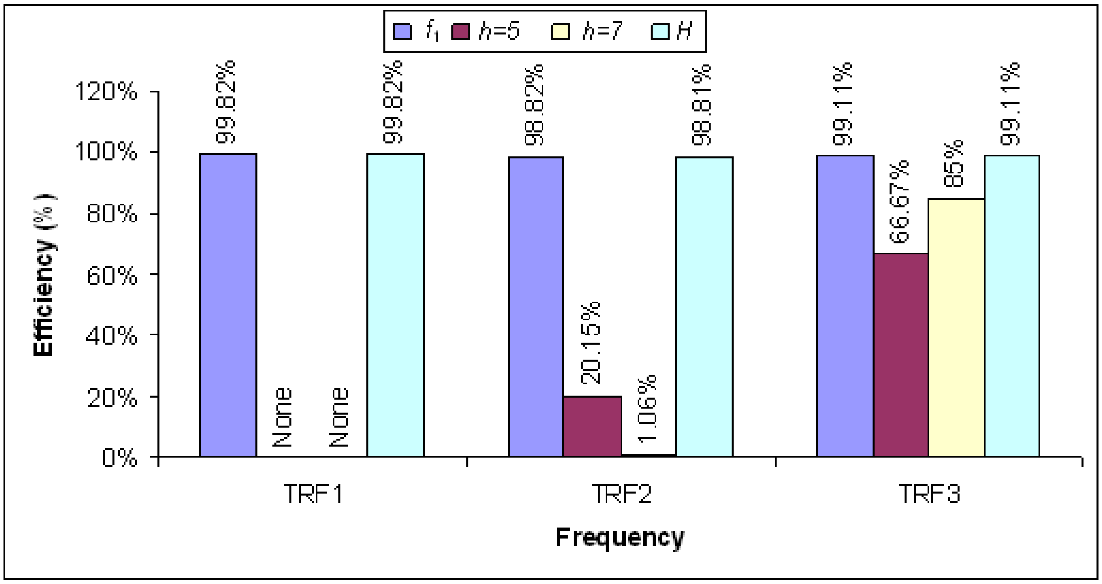


Figure 6.11: Case study 2b: Comparison of transformer efficiencies with filter

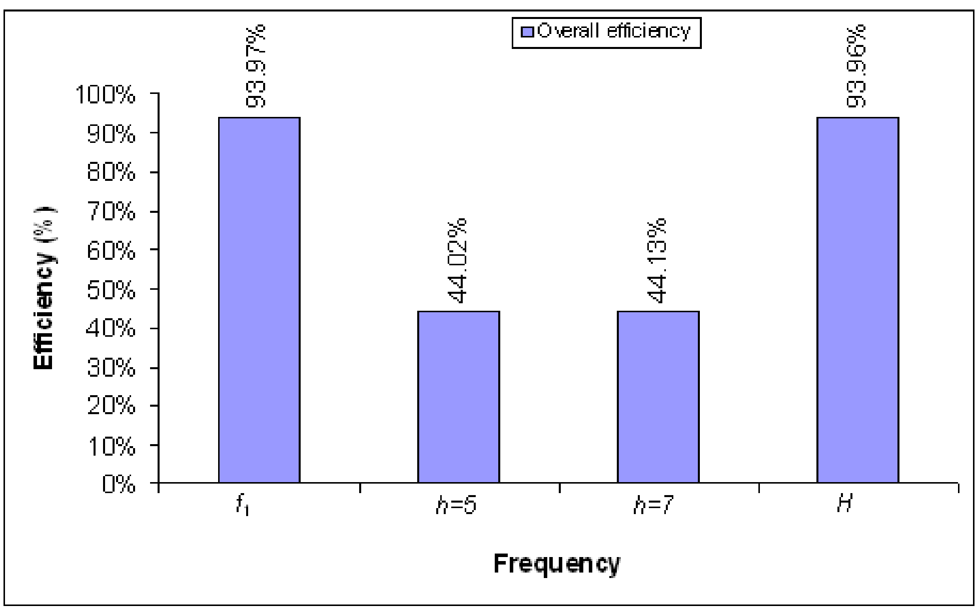


Figure 6.12: Case study 2: Comparison of overall efficiencies with filter

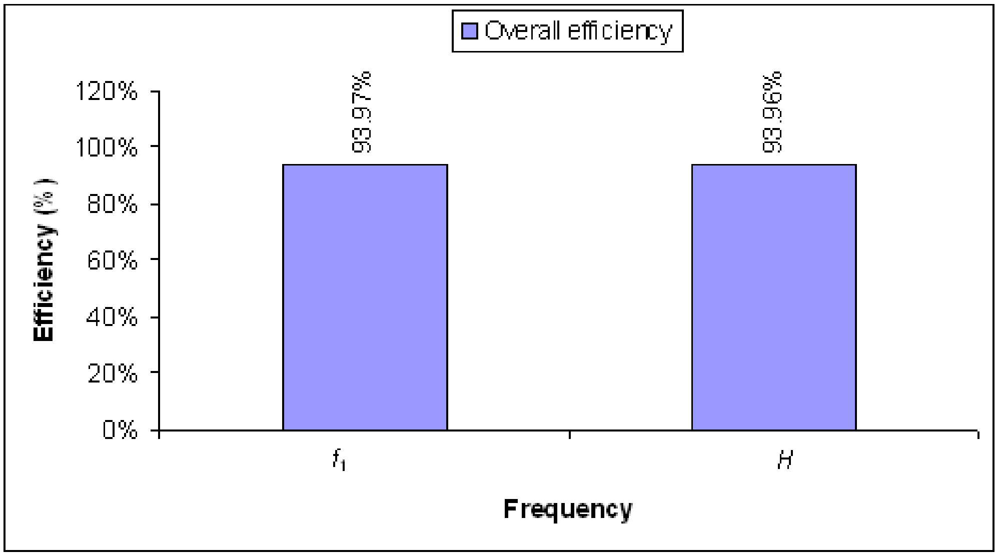


Figure 6.13: Case study 2: Comparison of f_1 to H overall efficiencies with filter

From this case study it was found that:

a. When a filter is added, the efficiency of TRF1, TRF2 and TRF3 are similar at f_1 and *H* (Figure 6.11).
b. The overall efficiency of a network with distortion (*H*) shown in Figure 6.12 is similar to that without distortion (f_1). This observation is shown more clearly in Figure 6.13.

According to these results, the overall efficiency of the network with filter is similar to that of f_1.

6.2.2.3 Energy usage methodology

6.2.2.3.1 Fundamental frequency

As $P_{1(in)(electr)}(Grid) = 3438.288\,kW$ and if 24 hours is used as the time period the energy usage for the day is:

$$E_1(case\ study\ 2) = P_{1(in)(electr)}(Grid) \times 24hrs = 3438.288\,kW \times 24hrs = 82518.91\,kWh \text{ at } f_1.$$

6.2.2.3.2 5th harmonic frequency

$$E_5(case\ study\ 2) = \left(P_{5(in)(electr)}(Drive1) + P_{5(in)(electr)}(Drive2)\right) \times t$$
$$= (0.361 + 0.032) \times 24 = 9.43\,kWh$$

6.2.2.3.3 7th harmonic frequency

$$E_7(case\ study\ 2) = \left(P_{7(in)(electr)}(Drive1) + P_{7(in)(electr)}(Drive2)\right) \times t$$
$$= (0.145 + 0.031) \times 24 = 4.22\,kWh$$

6.2.2.3.4 Total energy usage

$$E_{T(H)}(case\ study\ 2) = 3438.288\,kW \times 24\,hrs = 82518.91\,kWh$$

6.2.2.4 Analysis of total energy usage

The 5th and 7th harmonic energy usage, although small needs to be considered besides the energy usage at f_1.

Table 6.13 shows the summary of energy usage results obtained. These results are used in Figure 6.14 to show the difference in energy usage. The individual harmonic (h) usage is not included in the bar graph because it is too small.

Table 6.13: Case study 2: Energy usage at different frequencies with filter

Energy usage (kWh)			
f_1	h=5	h=7	H
82518.91	9.43	4.22	82518.91

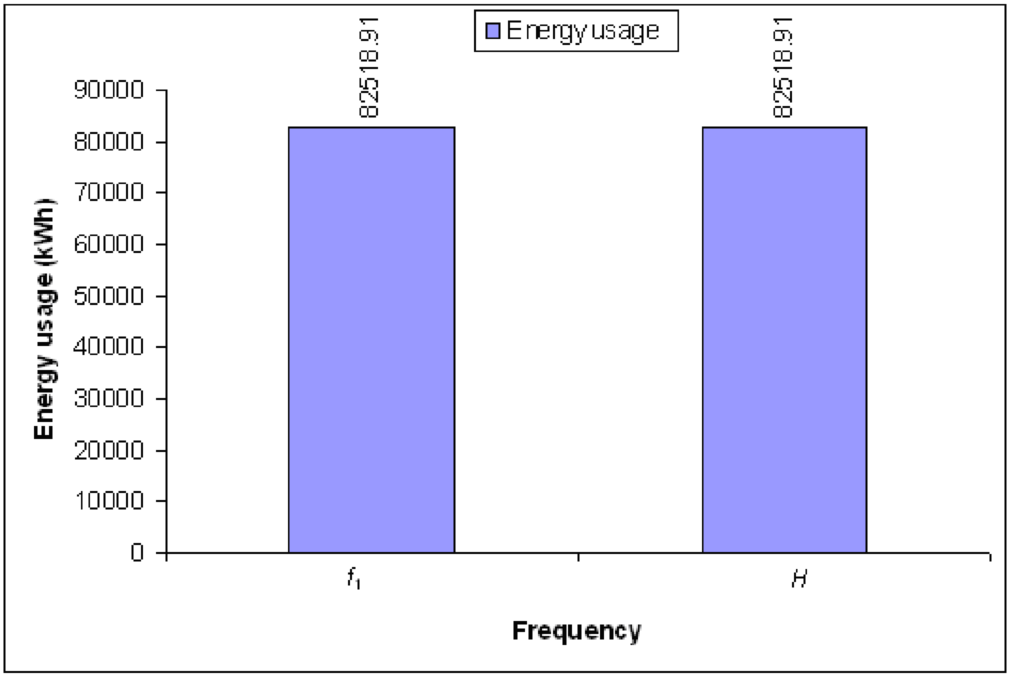


Figure 6.14: Case study 2: Comparison of total energy with filter

From this case study it was found that:

a. The Total energy usage with and without distortion is similar to the power input at *H* and it is the same as the power at f_1. Harmonic powers (h=5 and 7) at the grid are small.

6.2.2.5 Losses

Table 6.14 shows that transformer (TRF1, TRF2 and TRF3) power losses slightly increase with distortion. Table 6.15 shows the power losses of a network at various frequencies.

Table 6.14: Case study 2: Power losses of transformers with filter

	Power Losses(kW)	
Element	f_1	***H***
TRF1	6.29	6.30
TRF2	27.07	27.38
TRF3	10.10	10.11

Table 6.15: Case study 2: Power losses of network with filter

Power losses (W)			
f_1	h=5	h=7	H
207.47	0.22	0.10	207.75

Figure 6.15 shows that the losses increase with 0.28 kW with filter in the network when distortion is present in the network (*H*).

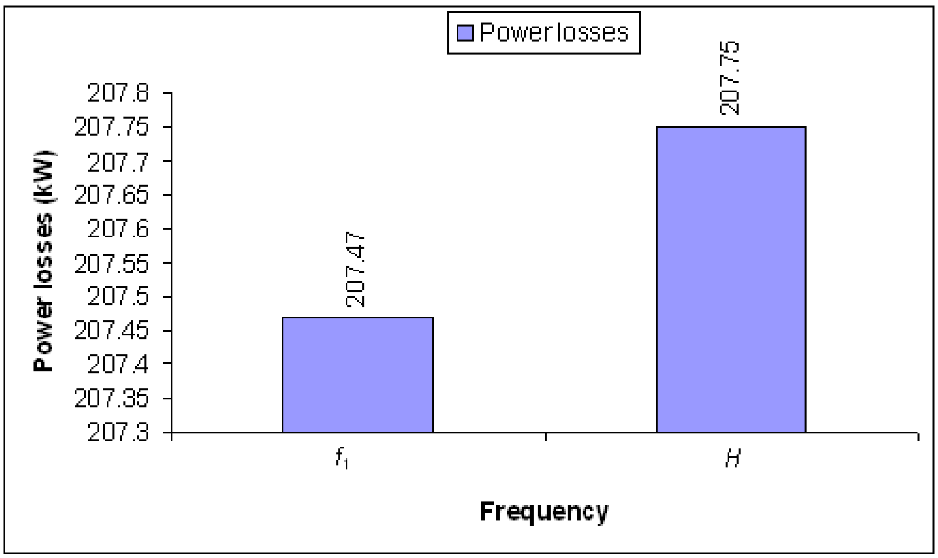


Figure 6.15: Case study 2: Comparison of power losses of network with filter

6.3 Summary

The newly developed methodology and formulae for efficiency and energy usage are used to analyse both case studies. Tables and figures are used to compare the results of individual, overall efficiency, transformer losses and total energy usage. Overall efficiency and energy usage in both case studies decrease when distortion is present. This shows that harmonics have a negative effect on overall efficiency and total energy usage of a network. With a filter added in the network, overall efficiency and energy usage with and without harmonics comes out similar in the two case studies. When harmonics are present in the network and a filter is included the power losses are reduced, whereas without a filter for both case studies conducted the power losses increase.

CHAPTER 7: CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

The objective of this research was to make a contribution to the field of efficiency and energy usage when an electrical network contains distortion arising from the presence of one or more harmonic sources in the system.

Traditionally, efficiency and energy usage in power networks are calculated only for power at fundamental frequency (f_1) while harmonics (h) and their distortion ($\%V_{THD}$ and $\%I_{THD}$) and potential heating consequences (P_{Losses}) are ignored. In the modern world, however, systems contain levels of harmonics which can no longer be ignored. To overcome this shortcoming, it was found necessary to investigate and develop a methodology that includes new formulae for evaluating individual and overall efficiencies and energy usage when one or more harmonic sources (non-linear loads) are present causing distortion and influencing power magnitudes in distribution networks.

As efficiency is dependent upon real power magnitudes, on investigation it was found essential to establish the direction of power flows in a network when harmonics are present. It was found out, in general that at a non-linear load (harmonic source), harmonic powers (P_h) are subtractable from fundamental frequency power (P_1), whereas, at a linear load, the harmonic powers (P_h) are added to the fundamental frequency power (P_1). Thus, when determining efficiency and energy usage it is concluded that the direction of power flows at all frequencies present in a network must be established, namely at the fundamental frequency (f_1), individual harmonic frequencies (h) and combined frequencies (H) and this was proven as one of the guidelines to be followed and it was thus further concluded that direction of power flows must be included in the developed methodology.

Thus, a need arose to demonstrate how harmonics affect power flow magnitudes and directions. Therefore, it was found necessary to evaluate efficiencies and energy usage using measurement and simulation investigations. Two case studies were conducted; a measurement based laboratory experiment and a simulation investigation.

For the measurement case study it was found essential to obtain a sound knowledge and understanding of the capabilities and application of the Fluke 435 harmonic power quality analyser. In particular, its ability to measure voltage and current of complex waveforms and their decomposition into harmonic components (magnitude and phase angle), while at the same time assessing its capability to measure real power magnitudes at all frequencies in the network as well as its ability to give an indication to the direction of power flows. Further, to evaluate its ability for the measurement of total harmonic distortion levels. It was found that the Fluke 435 is effective for providing the measurement results needed and it is concluded that this instrument is suitable for efficiency and energy usage investigations when distortion is present and must form part of the developed methodology to help with the new formulae derived.

Two industrial grade software packages, DIgSILENT and SuperHarm were evaluated for their capability and application to provide the required simulation results for conducting efficiency and energy usage when distortion is present. They were also applied as a case study to demonstrate the effectiveness of the developed methodology, including their capability to give results for power magnitudes and directions of power flow at all individual frequencies as well as under combined frequency (*H*) operations. Their modelling methods were also evaluated. To further prove their capabilities, it was found that both packages gave the same results as for voltage and current magnitudes and phase angles. SuperHarm, however, does not generate power magnitudes nor give the directions of flow at any frequency, whereas DIgSILENT has the capability to give results for powers at individual and combined frequencies and give an indication of flow direction. DIgSILENT also gives three-phase power results and total harmonic distortion levels. Thus, it was found that these software tools enable a contribution to be made to the field of efficiency and energy usage when distortion exists in a power system. It is further concluded that of the two software packages, DIgSILENT is the one that provides accurate power results and is the preferred package.

In case study 1, the measurement based laboratory experiment, measurements for current, voltage, $\%V_{THD}$, $\%I_{THD}$ and power were taken at different test positions in the network. Current and voltage results were used for hand calculations to prove the power flows and directions. From this experiment a new methodology and formulae were developed and is case specific. The network set-up is a typical type of configuration found in distribution systems and includes two harmonic sources (Drive and CFL's) besides a motor/transformer linear load branch which are fed from a grid infeed branch. Although case specific, it was found that the developed methodology and new formulae (Figures, 4.4 to 4.6 and Table 4.5 to 4.10) are easily adaptable to other network configurations, for instance, the one used for simulation studies. Despite the results being small in magnitude compared to real industrial set-ups, it can be concluded that the set-up was effective for assisting with the development of the methodology and the many new formulae, in particular (4.26 and 4.28), namely:

$$\%\eta_H overall = \frac{\sum \begin{bmatrix} P_{T(out)(mech)}(IDM1) + \\ P_{T(out)(mech)}(IDM2) + \\ P_{T(H)}(Non-linear\ 2) \end{bmatrix}}{(P_1 - \sum P_h)\, Grid\ branch} \times 100\%$$

$$E_{T(H)(in)} = P_{T(H)(in)} \times t \quad Joules$$

In case study 2, the simulation based DIgSILENT study was used to evaluate the effectiveness of the application of the developed methodology. The formulae developed in case study 1 was adapted for use on the 40 kV radial three-phase distribution network applied in case study 2. The configuration included two harmonic sources (Drives) and a capacitor bank at the point of common coupling in the network as well as linear loads and a grid infeed branch. The network also included transformers and lines. Similar to case study 1, a one-line-diagram was also developed for case study 2 on which is shown the power magnitudes and direction of power flows, using a system of "+" and "-" signs for all frequencies (f_1, h and H) in the system. It was found that the inclusion of this step in the methodology greatly assists with the development of new formulae as it can easily be seen which power flows are inputs and/or outputs from the directions indicated (Figure 5.4 and 5.9). It was also found that the $\%V_{THD}$ in this case study exceeded the recommended distortion level of 5%. Thus, when investigating efficiency and energy usage when distortion is present, it is essential to establish the distortion level, as in most cases, the unacceptable level is due to harmonic resonance caused by inductive and capacitive elements in a network. Therefore, impedance scan studies must be conducted to establish harmonic resonant points. In this case, resonance was found to occur near the 7^{th} harmonic, (characteristic harmonic injected by six-pulse drives). It was thus found that it was necessary to design a filter as the effects of resonance are voltage and/or current magnitude amplifications and these will affect efficiency and energy usage. A filter was designed and impedance scans (zscans) conducted demonstrated its effectiveness in shifting the resonance point below the lowest characteristic harmonic injected by the drives in the network, namely, below the 5^{th} harmonic. In both of these situations, without (Figure 5.9) and with a filter (Figure 5.12), the methodology was applied to demonstrate its effectiveness for studying efficiency and energy usage when distortion is present. Many new formulae were developed (see Chapter 6), the most important being the following:

$$\%\eta_H overall = \frac{\begin{bmatrix} P_{T(H)}(Drive1 + Motor1) + P_{T(H)}(Drive2 + Motor2) + \\ P_{T(H)}(Load1) + P_{T(H)}(Load2) + P_{T(H)}(Load3) + P_{T(H)}(Filter) \end{bmatrix}}{P_{1(electr)}(Grid) - P_{5(electr)}(Grid) - P_{7(electr)}(Grid)} \times 100\%$$

Both case studies were analysed for efficiencies and energy usage at all frequencies (f_1, h and H). Comparisons were drawn up using bar graphs. In case study 1, it was found that the overall efficiency of the network decreased by a small amount as a result of distortion. It must, however, be noted that the purpose of this case study is to demonstrate the methodology and formulae developed. Also, the harmonic powers injected by the non-linear loads are small compared to the power at fundamental frequency. Thus in networks where the harmonic content is a much larger percentage compared to the fundamental component, greater differences could be found. It was further found, in case study 1 that the total energy usage without distortion is more than that at the grid infeed point with distortion. Thus it can be concluded that the presence of harmonics, originating from harmonic sources in a network lead to a decrease in total energy usage. Also, contrary to common belief losses in the transformers (heat losses) do not always increase when harmonics are present. The losses (heat losses) depend upon whether a transformer is in a branch that includes a non-linear load or a linear load. In a linear load branch flowing towards the network output, harmonics increase losses whereas in a branch where a non-linear load injects harmonics, the losses decrease. This is also found to be the case with the grid infeed branch as harmonic power flows are in the opposite direction to the power flow at fundamental frequency. Similar results and findings to that of case study 1 were found in case study 2.

Thus, it was found that overall efficiency and energy usage in both case studies decrease when distortion is present contrary to common belief that an increase is anticipated. In pure linear load circuits when the incoming supply voltage is non-sinusoidal then energy usage would increase due to harmonic flows. However, when non-linear loads are present it has been shown the contrary is true.

Thus, it can be concluded that harmonics affect the overall efficiency of a network as the power losses at combined frequencies (H) affect the system losses. From the investigations, the results obtained, the power flow directions and the analyses conducted, it can be concluded that the methodology and formulae developed for individual and overall efficiencies and energy usage when distortion is present in a power system is effective and is highly recommended for industrial use.

7.2 Future work

As modern power systems are no longer purely linear networks operating only at fundamental frequency, but are asymmetrical unbalanced systems with distortion due to the proliferation of non-linear devices, there is a need to conduct further work on efficiency and energy usage of such systems. The work will thus extend the harmonic domain studies to the symmetrical component (sequence) domain. This is essential as systems in today's world are often utilised, especially distribution networks under contingency conditions, due to power delivery shortages and/or outages. How to conserve energy under such contingency conditions is important so as to sustain supply to as many customers as possible.

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APPENDICES

Appendix A: Waveforms results and Fluke 435 accuracy tables

Appendix A.1: Table of results used to draw waveforms

This results were used to draw the current, voltage and power waveform in excel, for both sinusoidal and non sinusoidal conditions.

Table A.1: Numerical results for pure resistor

Degree	Current	Voltage	Power
0	0	0	0
45	14.14	35.36	500
90	20	50	1000
135	14.14	35.36	500
180	0	0	0
225	-14.14	-35.36	500
270	-20	-50	1000
315	-14.14	-35.36	500
360	0	0	0

Table A.2: Numerical results for pure inductor

Degree	Current	Voltage	Power
0	-20	0	0
45	-14.14	35.36	-500
90	0	50	0
135	14.14	35.36	500.00
180	20	0	0
225	14.14	-35.36	-500
270	0	-50	0
315	-14.14	-35.36	500.00
360	-20	0	0

Table A.3: Numerical results for pure capacitor

Degree	Current	Voltage	Power
0	20	0	0
45	14.14	35.36	499.99
90	0	50	0
135	-14.14	35.36	-500
180	-20	0	0
225	-14.14	-35.36	499.99
270	0	-50	0
315	14.14	-35.36	-500
360	20	0	0

Table A.4: Numerical results for currents

Degree	i_1	i_5	i_7	i_{tot}
0	0	0	0	0
45	70.71	-14.14	-10.10	46.47
90	100	20	-14.29	105.71
135	70.71	-14.14	-10.10	46.47
180	0	0	0	0
225	-70.71	14.14	10.10	-46.47
270	-100	-20	14.29	-105.71
315	-70.71	14.14	10.10	-46.46
360	0	0	0	0

Appendix 1.2: Accuracy of Fluke 435

Table A.5: Fluke voltage, current and power accuracy

		Accuracy
Voltage and Current	RMS Voltage	+-0.1%
	RMS Current	+-0.5%
	Frequency (at 50 Hz Nominal)	+-0.01 HZ
Power	Real Power	+-1%
	Reactive Power	+-1%
	Apparent Power	+-1%
	Real Power Factor	+-0.03%
	Displacement Power Factor	+-0.03%

Table A.6: Fluke harmonic measurement accuracy

	Accuracy
Vrms Absolute	+-0.05% if <1%of Vnom; +-5% if >1% of Vnom
Arms Absolute	+-5%
Voltage THD	+-2.5%
Current THD	+-2.5%
Frequency	+-1 HZ
Phase angle	+-n x 1°

Where *n* is the harmonic order and *Vnom* is the nominal voltage of the supply in Table 2

Appendix B: Case study 2

Appendix B.1: modelling element in DIgSILENT

Components were modelled differently, as shown in figures B.1 to B.8

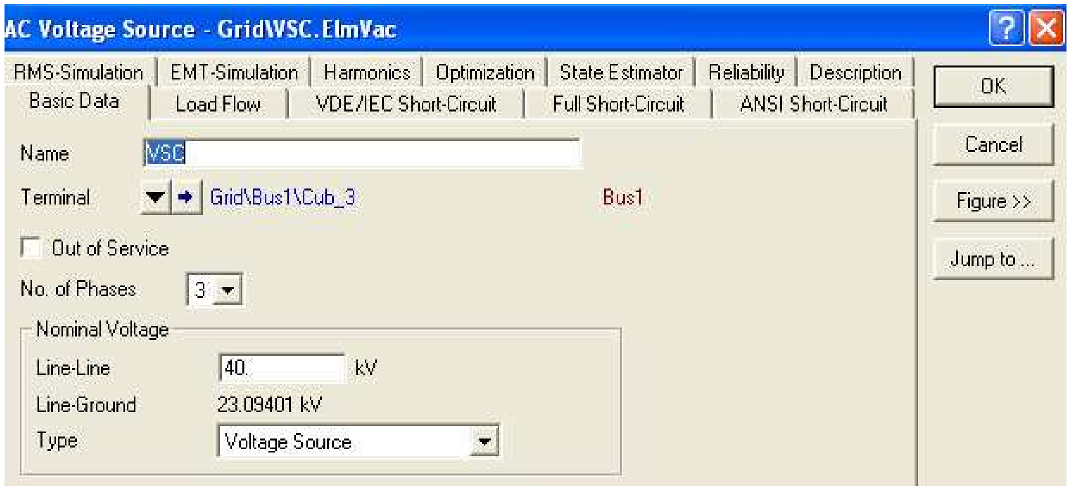

Figure B.1: Ideal voltage source

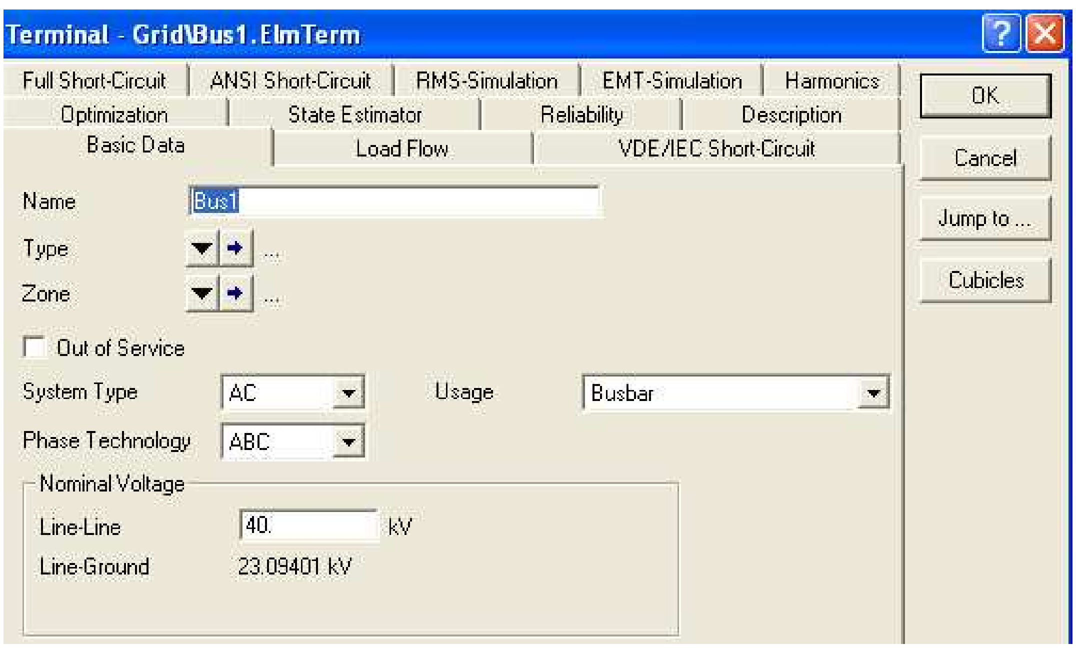

Figure B.2: Busbar modelling

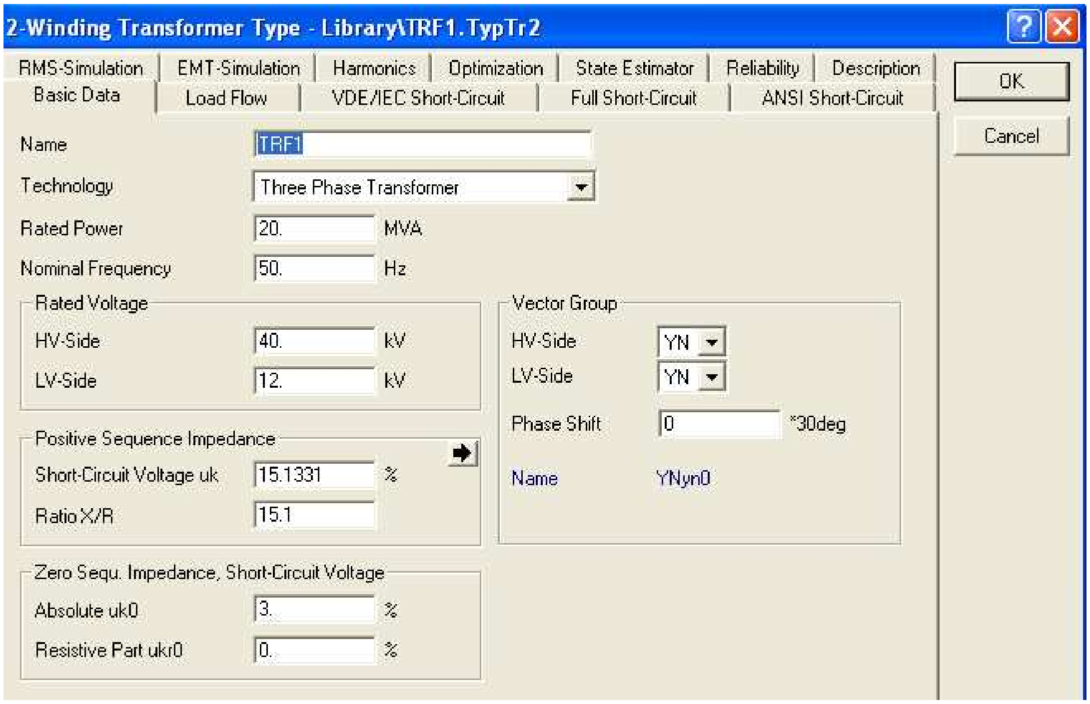

Figure B.3: Transformer modelling

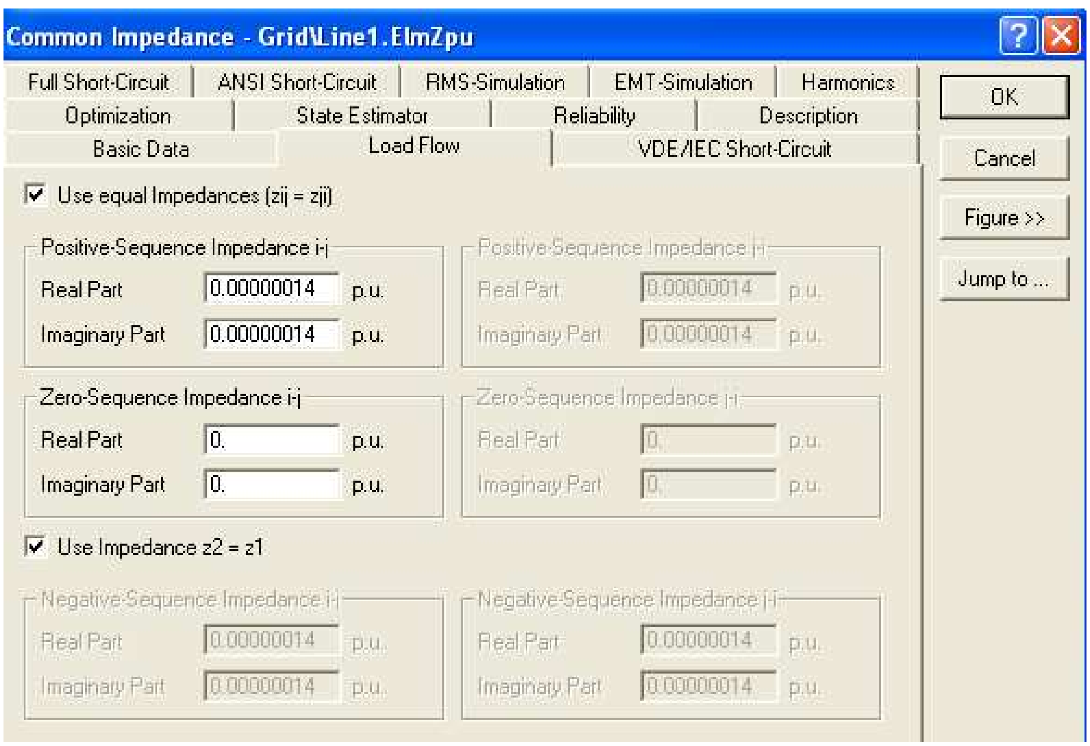

Figure B.4: Line modelling

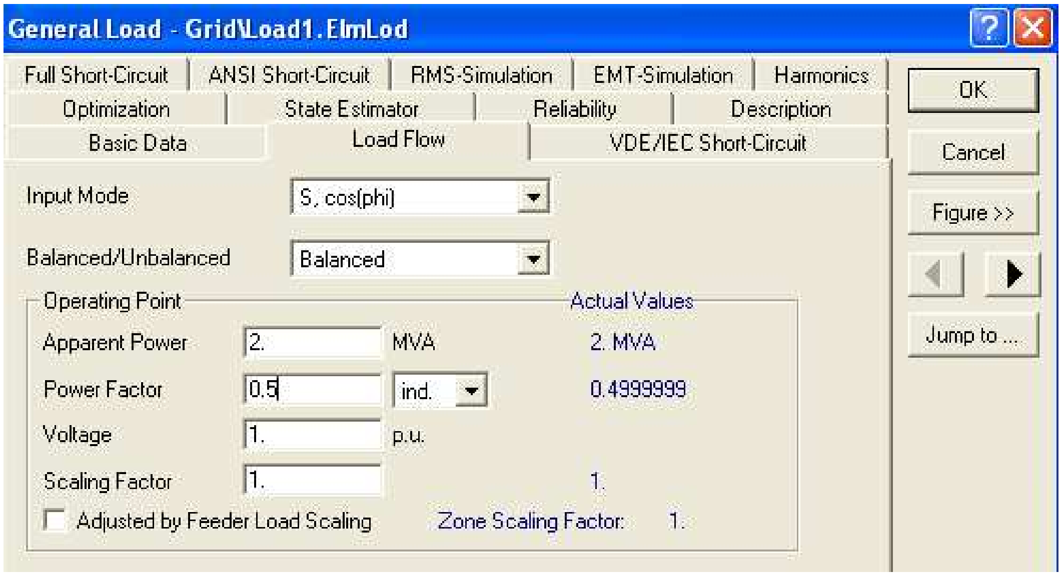

Figure B.5: Load modelling

The load modelling in Figure B.5 can be for linear loads or non-linear loads. The voltage dependence P and Q for both linear and non linear load is 2. The only difference is the full short circuit, which must be impedance for a linear load and a current source for a non-linear load.

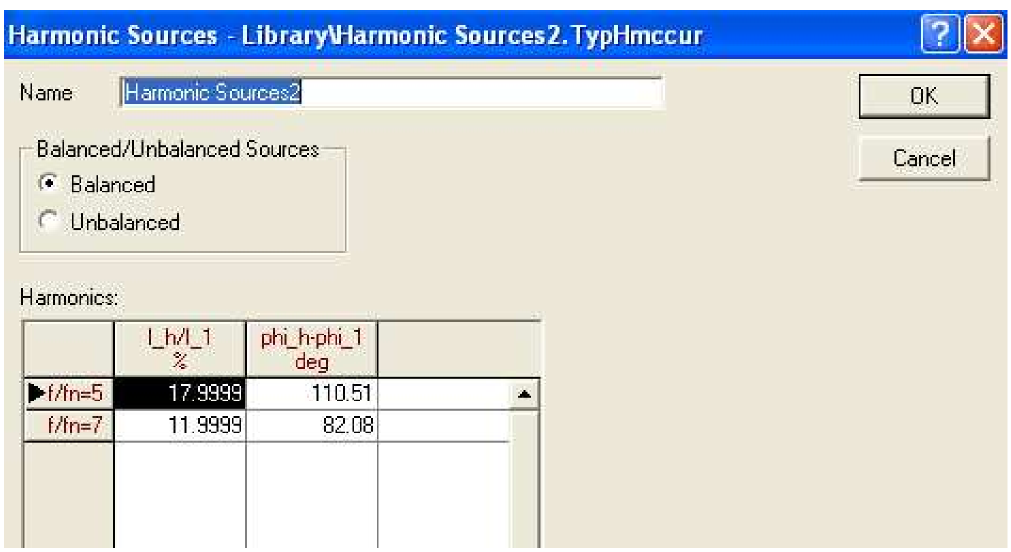

Figure B.6: Non-linear load spectrum

To be able to compare the DIgSILENT and SuperHarm results the voltage dependence P and Q for capacitor must be 2.

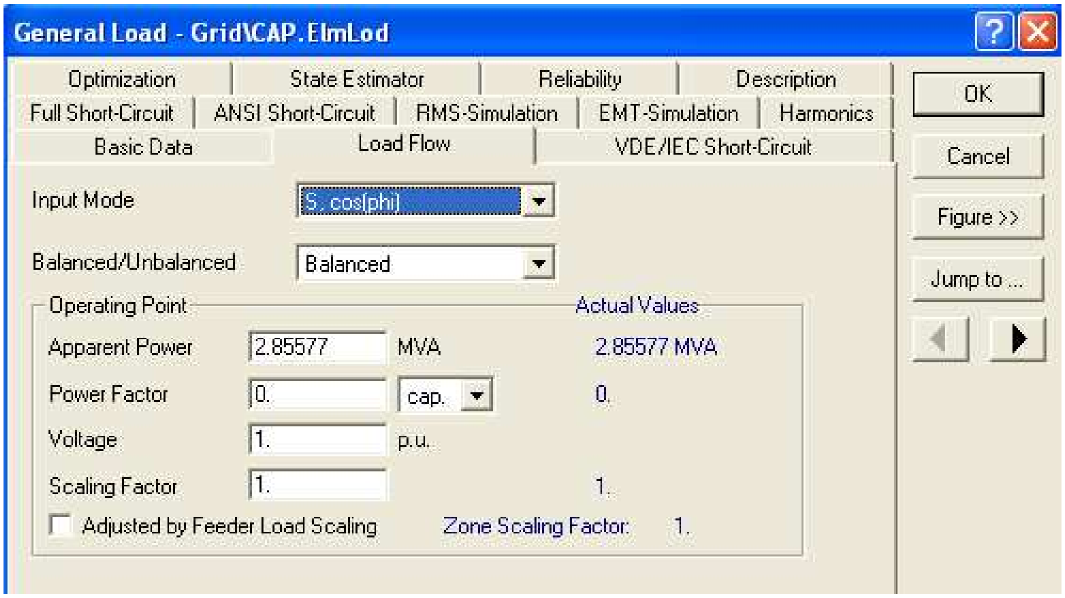

Figure B.7: Capacitor modelling

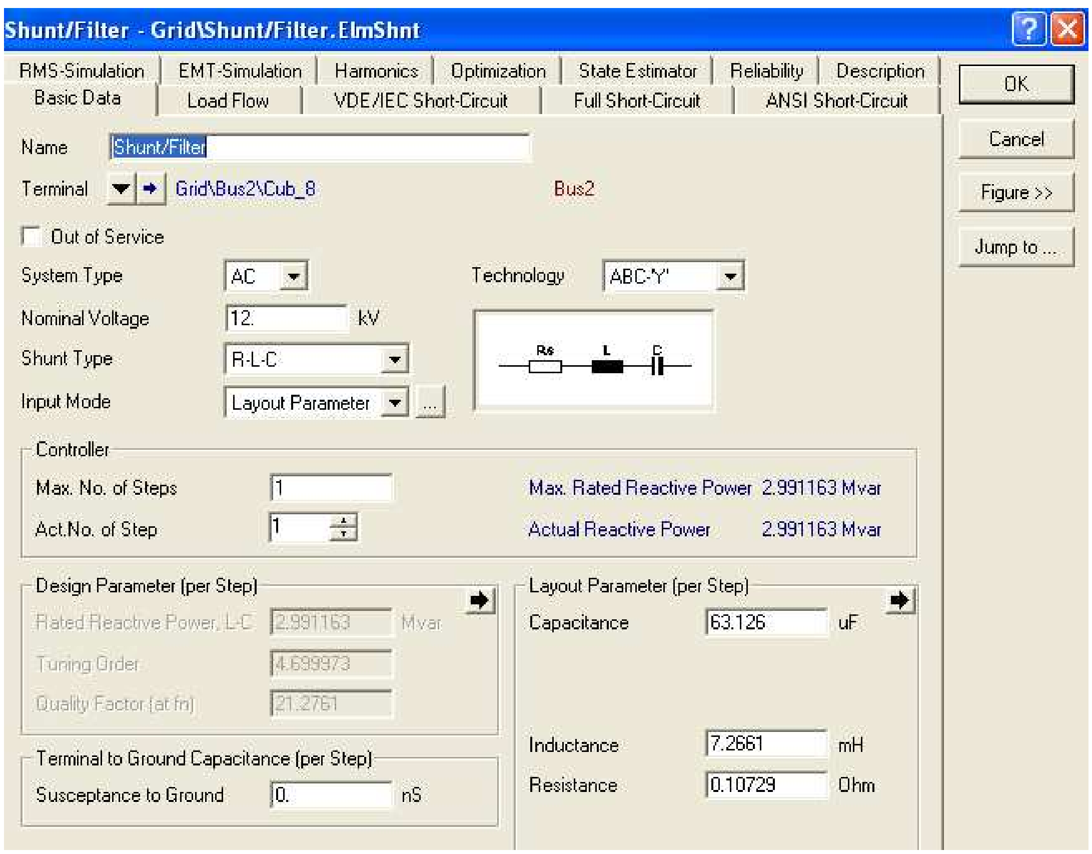

Figure B.8: Shunt/Filter modelling

Appendix B.2: SuperHarm notepad file

```
TITLE TITLE1="40 kV End-User network"
TiTle2="PF Capacitor banks at Bus 2"
Title3="Harmonic Penetration"
!
!
!Case: Harmonic Penetration case, single-phase representation
!       of a three-phase network
!
!..............VOLTAGE SOURCE...........................
!
VSOURCE NAME=VSC BUS=BUS1 MAG=23094
!
!Transformer at SOURCE
!
TRANSFORMER NAME=TRF1   MVA=20
H.1=BUS1    X.1=BUS2
kV.H=40.0   kV.X=12.0
%R.HX=1.0   %X.HX=15.1
%Imag=0     XRCONSTANT=NO
!
!.........PF CORRECTION CAPACITOR AT BUS2................
!
CAPACITOR NAME=CAP  FROM=BUS2  KV=12.0    MVA=2.85577
!
!..............DISTRIBUTION NETWORK 1...................
!
!12kV distribution line
!Note: Line capacitance is not included due to short length
!
BRANCH NAME=lINE1 FROM=BUS2 TO=BUS3 R=0.000001 x=0.000001
!
!......................CONSUMER 1.......................
!
! Transformer at entrance to Consumer 1
!
TRANSFORMER NAME=TRF2   MVA=5
```

```
H.1=BUS3      X.1=BUS4
kV.H=12.0     kV.X=6.0
%R.HX=0.9885   %X.HX=12.0
%Imag=0     XRCONSTANT=NO
!
!Linear load=100% Three-phase motor load
!
LINEARLOAD NAME=LOAD1 FROM=BUS4 KVA=2000.0 KV=6.0 DF=0.5
          %Parallel=0.0 %Series=100
!
! Three-phase harmonic source 1
!
!2.1 mVA Drive, 6Pulse, 6.0 kV
!
NONLINEARLOAD NAME=DRIVE1 BUS=BUS4 KVA=2100.0 KV=6.0 DF=0.8
TABLE=
{
{1, 202.0726,       0},//
{5,   36.3706, 110.51},
{7,   24.2487,   82.08}//
}
!
BRANCH NAME=lINE2 FROM=BUS2 TO=BUS5 R=0.000001 x=0.000001
!
!.....................CONSUMER 2..........................
!
!Transformer at entrance to Consumer 2
!
TRANSFORMER NAME=TRF3   MVA=2
H.1=BUS5      X.1=BUS6
kV.H=12.0     kV.X=0.4
%R.HX=0.9861   %X.HX=7.0
%Imag=0     XRCONSTANT=NO
!
!Linear load=100% Three-phase motor load
!
LINEARLOAD NAME=LOAD2 FROM=BUS6 KVA=1000.0 KV=0.4 DF=0.8
          %Parallel=0.0 %Series=100
```

```
!
!Linear load=100% Three-phase motor load
!
LINEARLOAD NAME=LOAD3 FROM=BUS6 KVA=250.0 KV=0.4 DF=0.9
            %Parallel=0.0 %Series=100
!
!Three-phase harmonic source 2
!
!0.25 mVA Drive, 6Pulse, 0.4 kV
!
NONLINEARLOAD NAME=DRIVE2 BUS=BUS6 KVA=250.0 KV=0.4 DF=0.8
TABLE=
{
{1, 360.8439,        0},//
{5,   64.9516, 110.51},
{7,   43.3011,   82.08}//
}
!
!..............RESULTS REQUIRED..........................
!
RETAIN VOLTAGEs=yes
RETAIN CURRENTS=yes
!End of Input File
!
....
....
```

Appendix B.3: DIgSILENT versus SuperHarm

Table B.1: Comparison of voltage and angle in DIgSILENT and SuperHarm

Bus name	Harmonic order	DIgSILENT		SuperHarm	
		Voltage magnitude (V)	Angle (°)	Voltage magnitude (V)	Angle (°)
Bus 2	1st	6866.28	-1.46618	6866.27	-1.46616
	5th	196.30	171.23776	196.29	171.23300
	7th	3142.37	-88.76508	3142.57	-88.77070
Bus 4	1st	3182.65	-4.56879	3182.69	-4.56991
	5th	229.92	171.61763	229.91	171.61400
	7th	1379.88	-86.33190	1379.97	-86.33770
Bus 6	1st	220.75	-3.60200	220.75	-3.60193
	5th	7.72	171.30314	7.72	171.29900
	7th	96.60	-89.18595	96.60	-89.19170

Table B.2: Comparison of current and angle in DIgSILENT and SuperHarm

Load name	Harmonic order	DIgSILENT		SuperHarm	
		Magnitude (A)	Angle (°)	Magnitude (A)	Angle (°)
Load 1	1st	176.81390	-64.56879	176.81600	-64.56990
	5th	2.93039	88.20440	2.93027	88.20070
	7th	12.60283	-171.61689	12.60360	-171.62300
Load 2	1st	1379.67048	-40.47190	1379.67000	-40.47180
	5th	15.53603	96.23455	15.53540	96.23060
	7th	140.39260	-168.40165	140.40200	-168.40700
Load 3	1st	344.91762	-29.44394	344.91700	-29.44390
	5th	5.11424	103.74123	5.11403	103.73700
	7th	47.17175	-162.75184	47.17480	-162.75800
TRF1 (BUS2)	1st	171.66201	163.72280	171.66200	163.72100
	5th	36.10854	81.99659	36.10700	81.99200
	7th	412.88542	-178.22306	412.91200	-178.22900
Drive 1	1st	185.65457	-41.43868	185.65700	-41.43980
	5th	33.41764	-96.68340	33.41600	-96.68900
	7th	22.27836	152.00923	22.27880	152.00100
Drive 2	1st	344.91762	-40.47189	344.91700	-40.47180
	5th	62.08483	-91.84944	62.08480	-91.84910
	7th	41.38977	158.77679	41.38990	158.77700

Appendix B.4: Filter design

For example: A 12 kV capacitor bank of 2.85577Mvars is to be used in the design of passive shunt filter tuned to 4.7.

The Q is the filter's quality factor, 30<Q<100 (Wakileh, 2001:116)

Step 1: Q_C = 2.85577 Mvars

Step 2: $X_C = \frac{12^2}{2.85577} = 50.4242\,\Omega$

Step 3: $X_L = \frac{50.4242}{4.7^2} = 2.2827\,\Omega$

Step 4: $X_n = \sqrt{50.4242 \times 2.2827} = 10.7286\,\Omega$

Assuming $Q = 100$, $\mathrm{R} = \frac{10.7286}{100} = 0.10729\,\Omega$

Step 5: If f_1 = 50 Hz $\quad L = \frac{2.2827}{2\pi \times 50} = 7.2661\ mH$

$$C = \frac{1}{2\pi \times 50 \times 50.4242} = 63.126\,\mu F$$

Therefore, $\mathrm{R} = 0.10729\,\Omega, \mathrm{L} = 7.2661\mathrm{mH}, \mathrm{C} = 63.126\,\mu\mathrm{F}$

Subject to: $Q = 100$