HARMONIC INVESTIGATION IN LOW AND MEDIUM VOLTAGE NETWORKS USING COMPUTER SIMULATION AND MEASUREMENT DEVICES

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Declaration

I declare that this dissertation is my own, unaided work, except where otherwise acknowledged. It is being submitted for the degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other university.

Signed this ___ day of __________ 20___

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Seán Robert William Egner.

Abstract

This dissertation discusses the development of an ATP model of a network to aid measurement techniques in a harmonic evaluation. A theoretical background discussion of various pieces of equipment and their significance to harmonics is included.

National Electricity Regulator (NRS 048) standards are discussed with reference to performing a basic investigation and short comings. A test study was performed on the Brandspruit Mine in Secunda.

ATP models are developed for equipment relevant to the test case, these include AC – AC converters, AC – DC converters, three phase transformers and cables. Finally the measured test case is compared to simulation results and conclusions drawn.

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I appreciate the efforts of Andreas Beutel in helping to edit the various drafts of the dissertation and for helping me with understanding some of the content covered.

In loving memory of my father
Geoffrey William Egner
1941 - 1993

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$\mathbf{k_d}$	Distribution factor for synchronous machine armature windings
$\mathbf{k_s}$	Coil-span factor for synchronous machine armature winding
$\mathbf{V_h}$	The percentage r.m.s. value of the $\mathbf{h^{th}}$ harmonic or interharmonic voltage component

List of Definitions

ADC	Analogue to Digital Converter
ATP	Alternative Transients Program, computer simulation package
CT	Current Transformer
Customer	Anyone whom purchases electricity from the national supplier
e.m.f.	Electromotive Force
Even Harmonics	Harmonics of an even (divisible by two) order
FFT	Fast Fourier Transform
HT	High Tension; of higher voltage
HV	The set of nominal voltage levels that are used in power systems for bulk transmission of electricity in the range 44 kV $< U_n \leq$ 220 kV
IGBT	Insulated Gate Bipolar Transistor
Interharmonics	Frequency components which are not an integral multiple of the fundamental frequency
LCC	Line and Cable Constants program, an ATP module
LT	Low Tension; of lower voltage

LV	Low voltage, the set of nominal voltage levels that are used for the distribution of electricity and whose upper limit is generally accepted to be an a.c. voltage of 1000 V
m.m.f.	Magnetomotive Force
MV	Medium Voltage, the set of nominal voltage levels that lie between low and high voltage in the range 1 kV $< U_n \leq$ 44 kV
NER	National Electricity Regulator
NRS	National Regulator Standards
Odd Harmonics	Harmonics of an odd (not divisible by two) order
PCC	Point of Common Coupling, the point in a network where more than one customer will be connected or is connected
PC	Personal Computer
PFC	Power Factor Correction
QoS	Quality of Supply
r.m.s.	Root–Mean–Square
SCR	Silicon Controlled Rectifier
THD	Total Harmonic Distortion
Triplen Harmonics	Harmonics of an order which is a multiple of three
Torque	A turning or twisting; tendency to turn, or cause to turn, about an axis.
UPS	Uninterruptible Power Supply
VSD	Variable speed drive (in this text it will refer to AC – AC type drives)

VT	Voltage Transformer
XLPE	Cross – Linked Polyethylene

Chapter 1

Introduction

Harmonic pollution is commonplace in electrical networks. Harmonics are generated by various pieces of equipment which are in use. In order to structure an electrical network to minimise harmonic propagation and effect, an understanding of how and where they are created is needed. From this understanding it is possible to avoid situations where harmonic propagation is accentuated.

Background harmonics exist on all networks, they are small and for all intents and purposes can be ignored. However, industry today makes use of various pieces of equipment, including VSDs and PCs, which generate additional harmonics.

Any expanding electrical network could experience maloperation due to harmonic effects. It is important to be able to predict the harmonic consequences of any changes or expansions to a network. A combination of measurements and computer simulation can be used to predict such consequences.

As the use of switch – mode powers supplies, converters and other harmonic producing equipment grows, the need to minimise the effects of the harmonics becomes of greater importance. This is because harmonic distortion of voltages in networks affects the operation of equipment as well as the electrical rating of equipment [1].

This project investigates the sources of harmonics in electrical networks, the effect of harmonics on the networks and methods to measure and predict them.

1.1 Reason for Project

Although there are government standards which deal with power quality and harmonics, the standards are based on supplier guidelines as opposed to customer guidelines. A customer has few guidelines for structuring his network to minimise the effect of harmonics on his equipment.

The project evaluates NRS 048 limits as an effective means of evaluating a customer network and making recommendations regarding the effect of future installations and alterations to the network.

1.2 Document Outline

This document details an investigation into the causes and effects of power system harmonics, as well as the measurement and simulation of power system harmonics.

The network studied was that of the Brandspruit Colliery, SASOL Mining, Secunda. The colliery was chosen as the test subject because of its continually expanding operations. As the coal is mined, the electrical network expands, changing its electrical characteristics.

A harmonic study, in accordance with government standards [2], of the live electrical network was performed. An ATP simulation of the plant was then compiled.

The correlation between the simulation results and measurements are discussed, as well as the pros and cons of each technique.

A proposed hybrid solution, combining both measurement and simulation techniques, is also discussed as a set of guidelines for harmonic evaluation of industrial networks.

Chapter 2

Background

Power system harmonics are defined as sinusoidal voltage and currents at frequencies that are integer multiples of the main generated (fundamental) frequency. They constitute the major distorting components of the mains voltage and load current waveforms [3].

Harmonic pollution in reticulation networks is becoming more widespread with the development and introduction of industrial processes which rely upon variable speed drives and other non-linear loads for their operation. Although the effect of harmonics has been noted, the onus is on the customer to take preventative measures and not the supplier.

This chapter discusses harmonic sources and their effects which occur in industrial networks. Individual pieces of equipment are discussed with reference to how they produce harmonics and what preventative measures can be taken to minimise their effects.

2.1 Harmonic Sources

Typical harmonic sources found on an industrial network include

- AC Motors

  - Synchronous
  - Induction
- Transformers
- Rectifier circuits
  - Charging stations: for battery operated vehicles
  - Network capacitance and inductance (resonance)
  - VSDs

Each of these sources is individually discussed in the following subsections.

2.1.1 AC Motors

An AC motor is a machine designed to transform electrical energy into kinetic energy. Electric machines are made up of interlinked electric and magnetic circuits. Interaction between the resultant electric currents and magnetic fields in motors results in an electromechanical energy conversion.

Rotating machines inherently generate harmonics, due in part to winding methods and slotting effects. It can be shown [1] that a three phase winding will not generate any triplen harmonics but will develop 5th and 7th order harmonics. The 5th is found to travel in a negative direction whilst the 7th is found to travel in a positive direction.

The construction methods used to make electric motors require that slots be created to house the windings, these slots result in an inconsistent airgap thickness which is referred to as slotting. Slotting effects cause the resultant machine m.m.f. wave to modulate because of permeance variation in the air gap/slot region. The permeance change can be approximated by

$$\mathbf{A}_1 + \mathbf{A}_2 \sin\left(2\mathbf{mg}\frac{2\pi\mathbf{x}}{\lambda}\right) \tag{2.1}$$

where

$\mathbf{A_1}$ = the base permeance
$\mathbf{A_2}$ = the max permeance change
$\mathbf{mg}$ = the number of slots per pole
$\mathbf{x}$ = the offset from "0" position
λ = fundamental wavelength

Discussion of harmonic generation by each of the two subgroups of AC motor, namely synchronous and induction machines follows.

Synchronous Machines

A synchronous machine operates at constant speed and frequency under steady state conditions [4]. They are used in applications where constant speed is critical. Synchronous machines are also extensively used for power generation.

Flux is not evenly distributed across the poles of a synchronous machine, especially in a salient pole design. The effective electrical phase spread of the winding, coil span and interphase connection determine the magnitude of e.m.f. harmonics within the armature.

Through the selection of a suitable distribution angle, $\mathbf{k_d}$, and coil-span factor, $\mathbf{k_s}$, it is possible to minimise or even eliminate e.m.f. harmonics. Phase connection (star or delta) will eliminate triplen harmonics in a three phase machine and is often used to do so. Coil-span is used to reduce the fifth and seventh harmonics [1].

Induction Machines

Induction motors are the most commonly used motors in industry today. They are used for applications which do not require a high degree of speed consistency. An induction motor operates at a speed slightly lower than synchronous speed. The amount of slip experienced by the motor is dependant on the machine loading, larger loads will result in a lower speed.

The rotating field of an induction motor stator has a synchronous speed of fundamental frequency times wavelength ($f_1\lambda$). The rotor speed is a function of the motor slip and is $f_1\lambda(1-s)$, the rotor current has a frequency of sf_1.

A rotor m.m.f. harmonic of order n has a wavelength of λ/n, a speed of $sf \cdot \lambda/n$ with respect to the rotor or $f\lambda(1-s)+(sf)\lambda/n$ with respect to stator. The wave can travel in either a positive or negative direction with respect to the fundamental.

The e.m.f. induced by this harmonic is equal to the ratio of speed to wavelength, which simplifies to:

$$\text{e.m.f.}_n = f(n - s(n+1)) \tag{2.2}$$

2.1.2 Transformers

Transformers are made up of electric and magnetic circuits, similar to those found in AC motors, however through the interaction of the resultant magnetic fields and electric currents an electrical energy transfer is created [4]. Transformers are used to step – up or step – down voltages within a network.

The primary current, in a transformer, is not purely sinusoidal, because the flux is not linearly proportional to magnetising current. As a transformer core becomes saturated a smaller flux change is required to generate a large primary current change, see Figure 2.1.

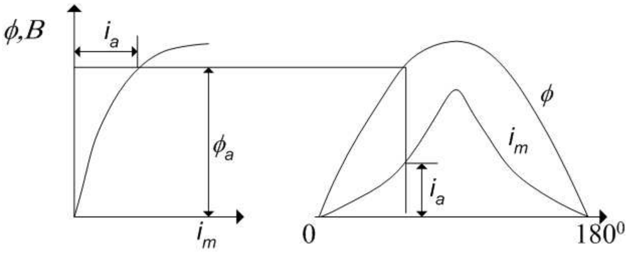

Figure 2.1: Transformer magnetisation, no hysteresis [1]

Figure 2.2 shows the effects of hysteresis[1] on the primary current. It can be seen that the magnetising current is no longer symmetrical around its maximum value.

The deformed (non – sinusoidal) current waveforms shown in Figures 2.1 and 2.2, consist of mainly triplen harmonics, particularly the third [1]. In order to minimise these triplen harmonics it is necessary to provide a current path for them, this is achieved by delta connecting the winding [6].

It is also possible to reduce the triplen harmonic m.m.f. through the use of three-limbed transformers. Triplen harmonics flow in the same direction in each limb, hence they are additive and the only return path is through the transformer oil and case [1]. This will maintain sinusoidal e.m.f. and flux density waveforms.

The effects of the magnetising current harmonics can be ignored as the transformer is loaded up because the magnetising current is approximately 0.05 p.u of the full load current in large transformers [5]. Transformers are likely to experience these problems most significantly when the system is lightly loaded and the voltage is high [1].

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[1] The rising section of hysteresis curve is used for the rising section of the magnetising current curve.

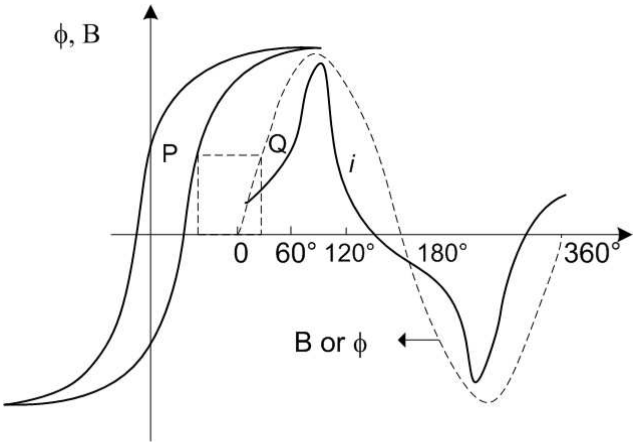

Figure 2.2: Transformer magnetisation, including hysteresis [1, 5]

It should be noted that fifth and seventh order harmonics are not corrected by these methods and should not be ignored. In order to suppress the fifth and seventh harmonics two transformers in parallel can be used, one should be delta-delta wound and the other star-star wound. Fifth and seventh harmonics will be produced which are equal in magnitude but opposite in phase, hence cancelling them from the combined input.

It is possible to create this cancelling effect in one transformer by providing a magnetic circuit which contains both a star and a delta path, as shown in Figure 2.3. A fifth and seventh harmonic excitation occurs in the two yokes (unwound) which are in phase opposition to the limb they are magnetically connected to. This effect is inherent in a five-limb transformer, which if the outer, unwound limbs were joined would create the same symmetrical shape as in Figure 2.3 [6].

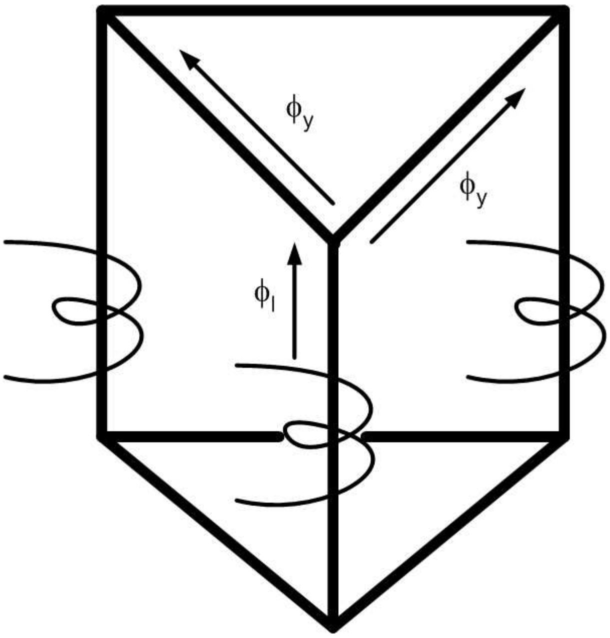

Figure 2.3: Symmetrical three phase transformer core [5]

2.1.3 Converter Circuits

Converter circuits are used to "create" alternative supplies. Typically, supplied voltage is converted to a similar voltage but with a different frequency. This is done by converting an AC voltage to DC, and then converting (reverse process) the DC to a required voltage and frequency.

A six pulse rectification circuit is obtained using a configuration similar to that shown in Figure 2.4. This is a simplified version of actual six pulse rectification, due to the fact that only diodes are used and all elements are assumed to be ideal, there is also no diode ignition voltage including in the representation.

The line voltages are shown in Figure 2.5(a) and the phase currents in Figure 2.5(b), (c) and (d). From Figures 2.4 and 2.5 it is possible to see which diodes conduct at what times during a full period.

In analysing the phase current i_a, of Figure 2.5(b), it can be seen that the positive section is the current component flowing through diode 1 (i_1), whilst the negative section is the current flowing through diode 4 ($-i_4$, where $|i_4| = |i_1|$). The current waveform coincides with the voltage waveform, V_a. The phase current i_a is found to be void of any triplen harmonics and can be represented by equation 2.3:

$$\begin{aligned}\mathbf{i_a} = \frac{2\sqrt{3}}{\pi}\mathbf{I_d}(\cos\omega\mathbf{t} - \frac{1}{5}\cos 5\omega\mathbf{t} + \frac{1}{7}\cos 7\omega\mathbf{t} - \frac{1}{11}\cos 11\omega\mathbf{t} \\ + \frac{1}{13}\cos 13\omega\mathbf{t} - \frac{1}{17}\cos 17\omega\mathbf{t} + \frac{1}{19}\cos 19\omega\mathbf{t} - \ldots)\end{aligned} \tag{2.3}$$

where

$\mathbf{i_a}$ = a phase current
$\mathbf{I_d}$ = the DC current

It should also be noted that all the current that flows through a diode will return through two others at different times; for example current through diode 1 will return through either diode 5 (as in time section 1) or diode 6 (as in time section 6), it does not return through both diode 5 and diode 6 at the

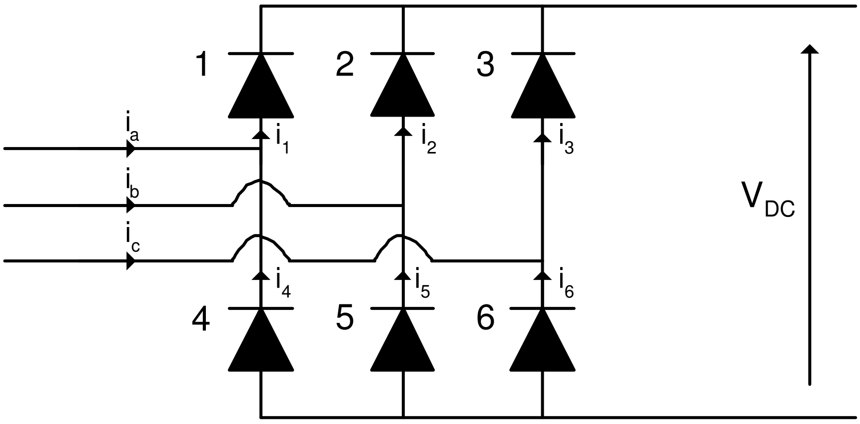

Figure 2.4: Ideal 6 pulse rectification circuit

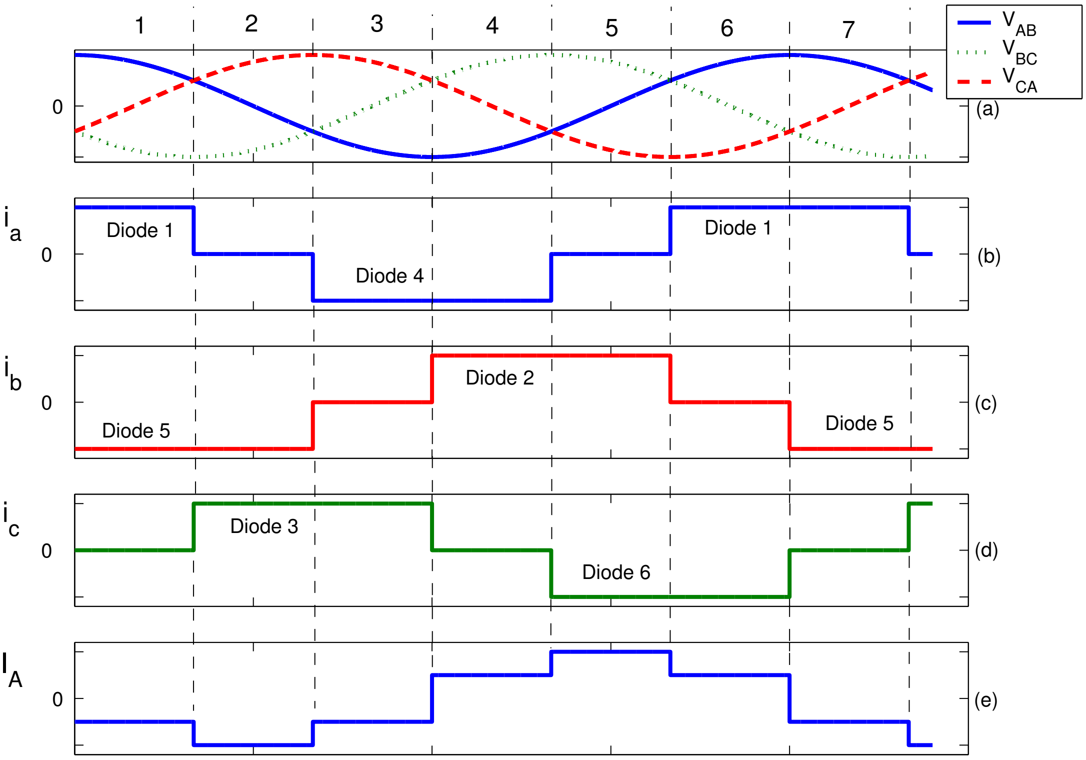

Figure 2.5: Six pulse rectification waveforms: (a) line voltages (b) - (d) phase currents (e) phase current on a $\Delta - \curlywedge$ transformer

same time.

When a delta – star transformer is used to connect to the bridge circuit, the phase current on the primary side of the transformer becomes the scaled instantaneous difference between two secondary currents (Figures 2.5(b), (c) and (d)) as shown in Figure 2.5(e) [6].

Each individual type of conversion, **AC** – **AC** or **AC** – **DC**, will have a specific circuit depending on its application. An **AC** – **AC** converter will include an inverter (either SCR or IGBT on the output of the rectifier, the inverter will be controlled to create the required AC frequency. An **AC** – **DC** converter may use a chopping circuit to reduce the **DC** voltage to the required value. These configurations effect the method in which the converter is modelled harmonically.

2.2 Harmonic Effects [1]

The main effects of voltage and current harmonics in power systems are:

- Increased losses in power generation, transmission and utilisation
- Ageing of the insulation of electrical plant components and thus a shortened useful life
- Maloperation or unexpected operation of the plant
- Misfiring of thyristors and other gating circuits

Another ill-effect of harmonics is amplification due to series and parallel resonances, between network capacitance and inductance. These resonance effects, between various pieces of equipment, can result in hunting[2] and over-voltage.

It is expensive to take preventative measures, since each network will be unique and a custom solution devised, and therefore most understanding has come

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[2] When a motor varies its speed to track changing supply frequency

from post-disaster analysis. Further, taking measurements is difficult as the harmonics are not continuous and vary subject to load, time and other equipment on the network.

2.2.1 Resonances

Resonance is defined as "A phenomenon in which a vibration or other cyclic process (such as tide cycles) of large amplitude is produced by smaller impulses, when the frequency of the external impulses is close to that of the natural cycling frequency of the process in that system [7]."

The combination of network capacitance and inductance causes resonance. The resultant amplified harmonic currents can over-stress capacitors, which will shorten the useful life of the capacitors.

Common sources of inductance are:

- Transformers
- Cables and overhead lines

Common sources of capacitance are:

- Power factor correction capacitors
- Harmonic filters
- Undamped surge capacitors
- Cables

Parallel resonance causes increased harmonic voltages and high harmonic currents in the legs of the parallel impedance, since many harmonic sources are effectively current sources. This can occur in various ways, the most common

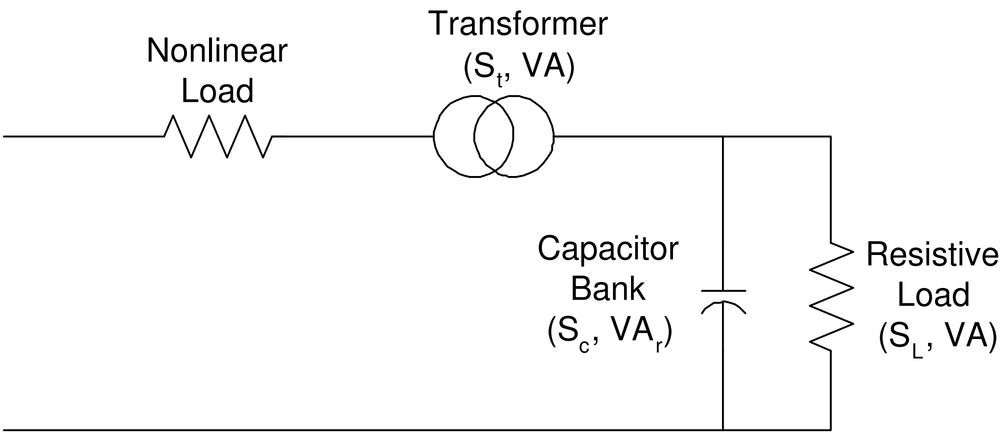

Figure 2.6: Series resonance circuit

being when a capacitance is connected to the same busbar as an harmonic source (normally inductive).

The **series resonant** condition, shown in Figure 2.6, is of concern because for relatively low harmonic voltage, high capacitor currents can flow, depending on the quality factor, Q, of the circuit. At high frequencies the load resistance becomes negligible as the capacitive reactance decreases (impedance is inversely proportional to frequency).

Should a load current harmonic be likely to have a frequency near the resonant frequency of the circuit then untuned power factor correction capacitors should be replaced with tuned capacitor banks (i.e. they should include a series inductance), which will alter the resonant frequency of the circuit [8].

A good practice is to only use untuned capacitors when no large non-linear loads are to be fed from the same supply. It is unlikely that resonance will occur with only linear load (no harmonics), and so it is not necessary to alter the resonance frequency.

2.2.2 Rotating Machines

Harmonics in a rotating machine have various effects, one is an increase in machine windage losses. The other is the creation of undesired torque pulsations. A discussion of each of these follows.

Losses

Harmonic voltages or currents cause additional power losses to be experienced in the rotor and stator windings as well as in the rotor and stator laminations. These additional losses are due to eddy current and skin effects, the greatest of which occur in the rotor. These additional power losses are probably the most serious effect of the harmonics. This conclusion can be extended to synchronous machines.

A machine's ability to deal with the additional harmonics will depend on the total additional losses and their local (rotor) and overall heating effects. The probable acceptable levels will be indicated by the level of continuous negative sequence current limitation of the machine (10 % for generators and 2 % for induction machines).

Torques

Additional harmonic torques can be produced by harmonic currents flowing in the stator windings of induction machines. This motoring action causes shaft torques in the direction of the harmonic field. The harmonics tend to cause torques in pairs, which cancel each other. The mean torque is essentially unaffected, although significant torque pulsations are created.

2.2.3 Static Power Plant

The various parts of the plant are all affected by harmonics. The major, noted, effect is the shortening of the useful life-span of equipment. Transmission lines suffer from increased losses, and hence additional heating, due to the increased r.m.s current.

Corona inception voltage could be exceeded due to the possible increase in the wave peak value (in the case of synchronised harmonics). Despite the r.m.s voltage being below the inception value the peak value may still exceed the maximum possible value.

Transformers experience increased hysteresis, eddy current losses and insulation stress. Increased copper losses cause unexpected hot spots and require increased ratings.

Usually, the first components [8] to be affected by harmonics are the power factor correction capacitors. Increasing frequencies cause the impedance of the capacitors to decrease ($\mathbf{Z} = \frac{1}{\mathbf{j}\,\omega\mathbf{C}}$). This causes susceptibility to current overloading and heating in the case of higher order harmonics. The result of these effects is nuisance tripping, failure and overheating.

2.2.4 System Protection

Distorted or degraded operating characteristics of protective relays can result from harmonics. Digital relays and algorithms, especially those dependant on sampling or zero crossing are particularly sensitive, as the waveform monitored is not purely sinusoidal (For example a distance protection relay).

In cases where the harmonic distortion is under 20 %, the changed operating characteristics present no problems, as the devices are robust enough to cope with the distortion. However with the increasing use of large power converters, the harmonic levels may exceed this acceptable level.

2.2.5 Customer Equipment

The following customer equipment can be affected by harmonics:

- *Television receivers*: Varying picture size and brightness result from harmonics which effect peak voltage.
- *Florescent and mercury arc lighting*: The capacitance in the ballast develops a resonant frequency with the inductance of the ballast and circuit. If the general harmonics correspond to the resonant frequency, excessive heating and therefore failure may result.
- *Thyristors*: Misfiring due to notching. Unexpected firing of the gating circuits.
- *Fuses*: Unnecessary failure caused by harmonic heating effects [8].
- *Surge arrestors*: Overvoltage stresses cause premature failure [8].

2.2.6 Power Measurements

Harmonics can affect measurement equipment both positively (increasing the measurement) and negatively (decreasing the measurement). This is due to the device being calibrated on a pure sinusoidal waveform. Harmonic voltages or currents reduce the ability of the meter[3] to measure fundamental frequency power.

In general, it has been found that the meters will measure high, imposing an extra cost to the consumer. This is due to the fact that harmonics are generally reflected as a higher electricity consumption, hence penalising the consumer.

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[3] Ferraris motor type kilowatt–hour meter

2.2.7 Conclusion

This chapter clarified some typical harmonic sources in industrial networks. Although the list is not exhaustive it gives a clear indication of what equipment can cause harmonics and why. The effects of harmonics on industrial equipment and consumer equipment is also highlighted.

From this chapter it is clear that harmonics are an aspect of concern and an estimate of the distortion in a network is of great importance. By understanding the harmonics generated in a network and their effect on equipment within the network, one is better able manage and operate it.

Chapter 3

Standards and Regulations

Harmonics are an inevitable fact of modern equipment used in industry and hence standards are stipulated in order to control the level of voltage and current distortion. The standards enforce a QoS that is suitable for both users and suppliers.

There are various approaches to this problem. South Africa has adopted an approach which stipulates the voltage harmonic distortion permissible at the PCC, i.e. the maximum distortion levels that a supplier may supply to a customer.

Other countries have stipulated the levels of distortion a customer may cause to the suppliers network, for example the United Kingdom, have adopted an approach which regulates the equipment that may be connected to the network, dependant on the size and type of machine and the distortion already present at the PCC [9, 10].

The NRS 048 suite of documents is the South African NERs standard on power quality, it deals with voltage harmonics and interharmonics, voltage flicker, voltage unbalance, voltage dips, voltage regulation and frequency [2, 11, 12, 13, 14].

3.1 NRS 048 – 2: Minimum Standards

Guidelines created for the NER stipulate minimum compatibility levels, assessed levels and assessment methods for use by suppliers. These guidelines are typically followed by users, as they represent conditions under which equipment will continue to operate as expected.

3.1.1 Compatibility Levels

Compatibility levels are a list of maximum harmonic voltages as a percentage of the fundamental frequency, which can be supplied at a PCC. Higher values may affect equipment adversely, see chapter 2 The following harmonic compatibility levels for LV and MV networks[1] are imposed by the NER.

Table 3.1: Compatibility levels for harmonic voltages [12]

Odd harmonics non-multiple of 3		**Odd harmonics multiple of 3**		**Even harmonics**	
Order h	**Harmonic voltage %**	**Order h**	**Harmonic voltage %**	**Order h**	**Harmonic voltage %**
5.0	6.0	3.0	5.0	2.0	2.0
7.0	5.0	9.0	1.5	4.0	1.0
11.0	3.5	15.0	0.5	6.0	0.5
13.0	3.0	21.0	0.3	8.0	0.5
> 17	$(\frac{38.59}{h}) - 0.27$	> 27	0.2	> 10	$(\frac{2.5}{\mathrm{h}}) + 0.25$
Total harmonic distortion (THD) $\leq 8\%$					
Note – For each harmonic, the harmonic voltage distortion compatibility level is given as a percentage of the magnitude of the declared (fundamental frequency) voltage					

The THD, including up to the 40^{th} harmonic, shall not exceed 8 %.

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[1] For HV networks, compatibility levels are to be stipulated in contracts as defined in [13].

3.1.2 Assessment of Site Harmonics [12]

All supply phases must be monitored. For solidly earthed star connected systems phase – to – earth voltages should be measured. Phase – to – phase voltages must be measured in delta connected systems, impedance earthed or unearthed systems.

An assessment must be conducted over a continuous seven day period, which should cover a complete cycle of shifts and typical network operating modes. Each phase must be measured separately. A ten minute r.m.s. value, $\mathbf{V_{10,h}}$ (see equation 3.1), is calculated over each ten minute period sampled at three second or less intervals (one r.m.s. value per harmonic, **h**):

$$\mathbf{V_{10,h}} = \sqrt{\frac{\sum_{1}^{\mathbf{N}}(\mathbf{V_{s,h}}^{2})}{\mathbf{N}}} \tag{3.1}$$

where

$\mathbf{V_{s,h}}$ = the measured r.m.s. values at three second intervals during the ten minute period, in volts, as in equation 3.2

$\mathbf{N}$ = the number of r.m.s values within the measured ten minute period

$\mathbf{h}$ = the harmonic order

$$\mathbf{V_{s,h}} = \sqrt{\frac{\sum_{1}^{\mathbf{N}}(\mathbf{V_{o,h}}^{2})}{\mathbf{N}}} \tag{3.2}$$

where

$\mathbf{V_{o,h}}$ = the value, in volts, of each of the samples calculated using a time–window of between 80 ms and 500 ms. Gaps between the windows are acceptable.

A total of 1008 $\mathbf{V_{s,h}}$ values are calculated per week (seven day period) for each phase and harmonic order. From these the 51^{st} highest value is extracted, this is the weekly assessed value for that particular harmonic order on that particular phase.

This is repeated for all three phases, the highest value of the 95 % non-exceedence levels for each phase, is then considered to be the assessed weekly value for that particular harmonic on all three phases (95 % non-exceedence level for a particular harmonic for the worst phase).

The above is repeated for each of the harmonics and the THD, where THD is defined as:

$$\mathrm{THD} = \frac{\sqrt{\sum_{\mathbf{h}=1}^{\mathbf{N}} \mathbf{V_h}^2}}{\mathbf{V_1}} \tag{3.3}$$

where

$\mathbf{V_h}$ = The percentage r.m.s. value of the $\mathbf{h^{th}}$ harmonic or interharmonic voltage component

$\mathbf{N}$ = the highest considered harmonic

$\mathbf{V_1}$ = Fundamental line to neutral r.m.s. voltage

In addition to recording the assessed THD level, the number of days which the THD exceeds the limit given in Table 3.1 shall also be recorded.

Under normal operating conditions, the assessed levels should not exceed the compatibility levels given in Table 3.1.

3.2 Evaluation of Measurements

The NRS 048 guidelines are useful for evaluating QoS at a PCC. Should the QoS be unsatisfactory then there is sufficient justification for complaint to the supplier [2]. They do not, however, provide for the use of harmonic producing and harmonic effected equipment within a customer network.

During the NRS 048 stipulated measurement period of one week, it is expected that the worst case scenario (harmonically) will occur, since a complete production cycle has been monitored. Figure 3.1 is an example of voltage harmonics measured over a one week period, in accordance with the guidelines.

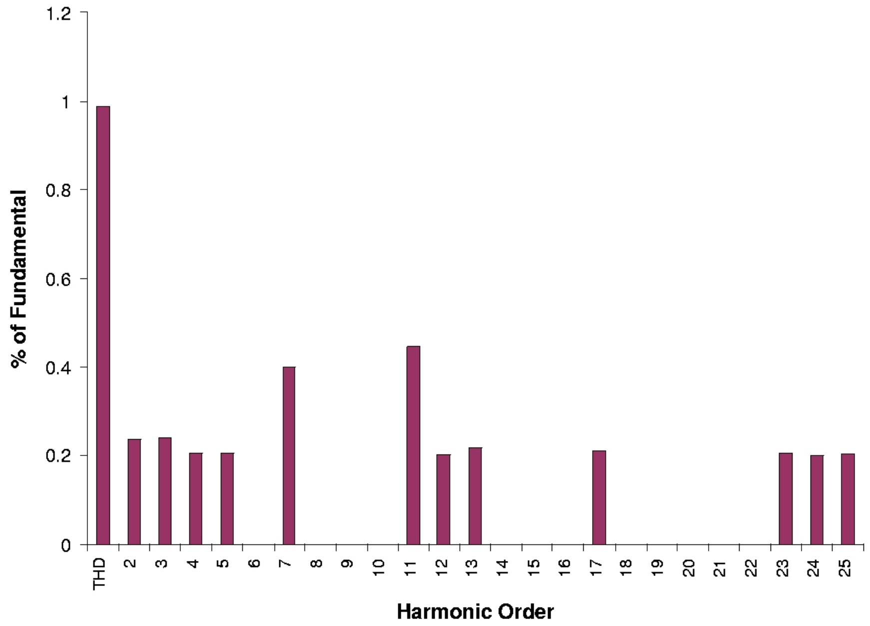


Figure 3.1: Example of incomer voltage harmonics

This worst case should be lower than the maximum permissible values stipulated by the NER [12], see Table 3.1.

3.2.1 Ideal Measurement

The ideal measurement occurs when the network harmonic voltage levels are worst, and every point within the network is measured at the same time. This allows for points with high harmonic content to be identified and evaluated.

The results of such a study could then be used to evaluate the overall harmonic levels in the network with a view to correcting or preventing adverse harmonic conditions.

3.2.2 Realistic Measurement

Unfortunately most networks are dynamic and cannot be simply manipulated to generate worst case scenarios. Production cycles, maintenance, equipment ratings and network size all affect the measurement process.

Inevitably normal operating conditions for a network do not require the equipment to operate at its rated values. Rated values are determined to allow for maximum requirements at any time. For example, a conveyor motor would be rated to start a fully loaded belt, this eventuality is rare and hence the belt motor will run continuously at a much lower value than its rating.

3.2.3 Restrictions and Uses of Measurements

The cost and availability of measurement equipment makes it almost impossible to measure every point within a network. It is reasonable to assume that the point of supply can be monitored and some spot measurements within the network can be made, this will result in an incomplete view being generated from the readings.

The readings of the PCC will identify times at which the harmonic content was high, although the source of the harmonics may not be identified, as not all required information may have been collected.

The measurements are best used as a baseline for modelling purposes and as a warning of harmonic changes within the network.

3.3 Shortfall of NRS 048: Current Harmonics

Typical consumer power electronics draw a distorted current waveform, these current harmonics are ignored by NRS 048, which is concerned only with

Figure 3.2: Example of incomer current harmonics

voltage harmonics. This is to be expected as NRS 048 is a supplier specification.

The customer needs to be aware of current harmonics within his network as they can have detrimental affects on the equipment within the network, especially power factor correction capacitors. Figure 3.2 shows the current harmonics developed during the same period as in Figure 3.1. Current harmonics add to the stress on PFC capacitors [15].

Capacitor impedance decreases with frequency, causing capacitor banks to act as harmonic sinks. These large harmonic currents also cause capacitor fuses to blow. Further, increased dielectric loses caused by harmonics create additional heating and loss − of − life to capacitor banks [16]. The dielectric loss can be represented by Equation 3.4 [3].

$$\sum_{\mathbf{n=1}}^{\infty} C \tan \delta \omega_n {V_n}^2 \tag{3.4}$$

where

$$\begin{aligned} C &= \text{Capacitance} \\ \tan\delta &= \text{the loss factor } (\tan\delta = \tfrac{R}{1/\omega C}) \\ \omega_n &= \text{angular frequency of } n^{th} \text{ harmonic} \\ V_n &= \text{r.m.s. voltage of } n^{th} \text{ harmonic} \end{aligned}$$

Power factor correction capacitors are often tuned around the third and fifth harmonic with a small series inductance. This causes the capacitor to appear inductive to higher frequencies and so prevents parallel resonances [3], since the capacitive component is negated.

3.4 Conclusion

The NRS 048 standards are issued with the intent to control the levels of pollution supplied to a customer. They do not explicitly define how a customer should structure his network, so as to minimise harmonics and their effect.

The compatibility levels are based on an maximum harmonic value that can be tolerated by equipment and so can be used as a guideline for a customers network.

Current harmonics are of concern with respect to overstressing of PFC capacitors and so, although not covered by NRS 048 , are of concern to customers.

Chapter 4

Equipment Modelling

A computer model is a mathematical representation of an actual or planned piece of equipment or network. It is used to simulate actual devices, so that engineers can predict results and verify theories of equipment or network performance.

Computer simulation is an additional tool that can be used for harmonic prediction. A correctly structured model can simulate situations that cannot be created in the working environment. Simulation allows an engineer to investigate particular aspects and scenarios which are of interest to whatever study is performed.

In order to optimise network structure harmonically, harmonic studies evaluate the worst case scenario, in which the worst possible harmonic content is found on the network. In reality, it is not always possible to force an active network into a worst case scenario, normal production cycles do not always allow it. The worst case scenario is the desired result of an NRS 048 study and is important when applying the compatibility levels and specifying equipment capable of dealing with the harmonic content.

Models should be created based on consistent assumptions and should generate results that are relevant to the study performed. Once a set of guidelines, rules of model development, have been accepted, it will make development, analysis and future modification of the models simpler and more effective.

4.1 Modelling Pre-Process

In order to create a full scale model of a network, it is necessary to have a complete understanding of the network in question, from the various types of equipment to the interconnection of said equipment. Circuit diagrams of the network will provide the basic connections and all the equipment used on the network.

4.1.1 Required Information

Each device that is to be individually modelled, has its own operating characteristics and electrical structure. The equivalent circuit used to model a device should be accurate as possible with enough detail to completely simulate the harmonic content of interest, for example up to the 40^{th} harmonic, and their effects.

Specifications of equipment from the single line diagram, such as transformer leakage impedance, load sizes and connection (star or delta) will define the necessary pieces of equipment and the level of detail included in the model.

4.1.2 Guidelines

Network size should be considered when deciding how to model a network, as larger networks require more time to develop the model and compute the solutions; and the software available can affect the complexity of the model allowed, e.g limited nodes [17] .

Most consumer networks are built up of similar pieces of equipment, therefore reducing in – house maintenance training, as technicians have to learn about fewer machines. Therefore, this practice results in a lower equipment model count and the repetitive use of models.

When creating a new model for a piece of equipment, the model results should be compared with actual current and voltage measurements taken of the equipment in isolation. The results of the simulation should coincide with the measured results, thus ensuring the validity of the equivalent circuit and model.

It is not necessary to simulate an original circuit exactly if a simpler equivalent circuit is suitable. The use of equivalent circuits will help to optimise simulation time and minimise complexity.

Models should be optimised to best represent the equipment, and should then be used as the standard model for that type of equipment throughout the plant simulation.

4.1.3 Modelling Tools

There are various simulation packages available on the market today. All packages have a different approach and interface. It is important to select a package which is affordable, comfortable and suitable to the modelling approach chosen. ATP [18] and ATPDraw [19] were selected for the evaluation discussed in this report.

Other examples of software include Simulink® [20] and DigSilent® [21].

4.2 Modelling of AC – AC Converter Circuits

Rapid development and therefore increased usage of power electronics, including powerful semiconductor devices and microprocessors which are provided in modular forms, have made the use of variable AC drive technology economically viable and an alternative to adjustable speed DC drives [22].

This increased usage implies that most industrial networks will have VSDs connected to them and hence a model will be required.

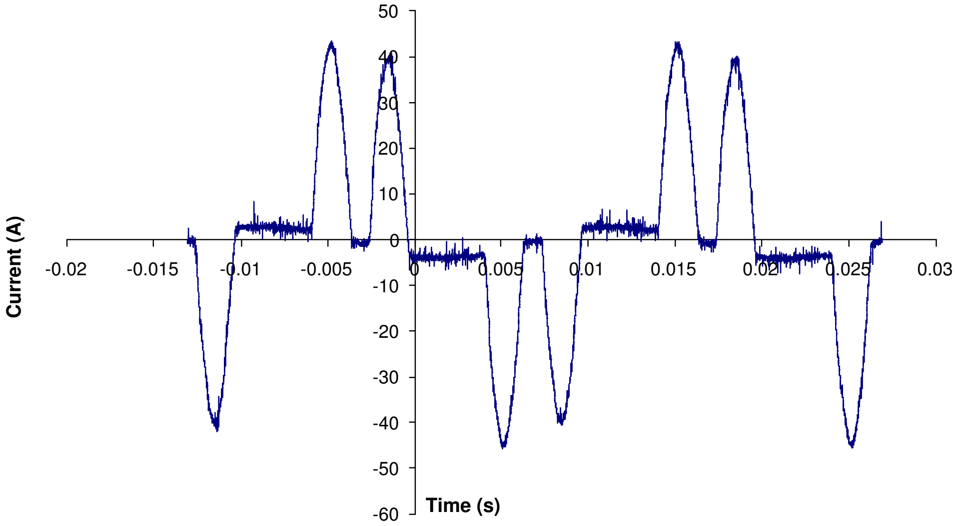


Figure 4.1: Measured line current

4.2.1 VSD Test Setup

An individual VSD was used to determine the waveforms and harmonic content created by such a drive, when unaffected by other harmonic sources. The drive was run at full load and the current and voltage waveforms were recorded. Figure 4.1 shows the current waveform, the high frequency noise can be attributed to the measurement equipment used and the environmental (machines workshop) noise. The harmonic spectrum is shown in Figure 4.2.

4.2.2 Basic Model of VSD

The basic circuit is shown in Figure 4.3. The capacitor in the DC link in the rectifier, prevents harmonics produced by the load – side inverter from being injected back through the diode bridge into the supply [23]. A basic VSD model was created based on diode technology. A resistive load was connected across the DC link, the resistance value was chosen such that the power dissipated was the same as the power consumed by the actual motor connected to the drive.

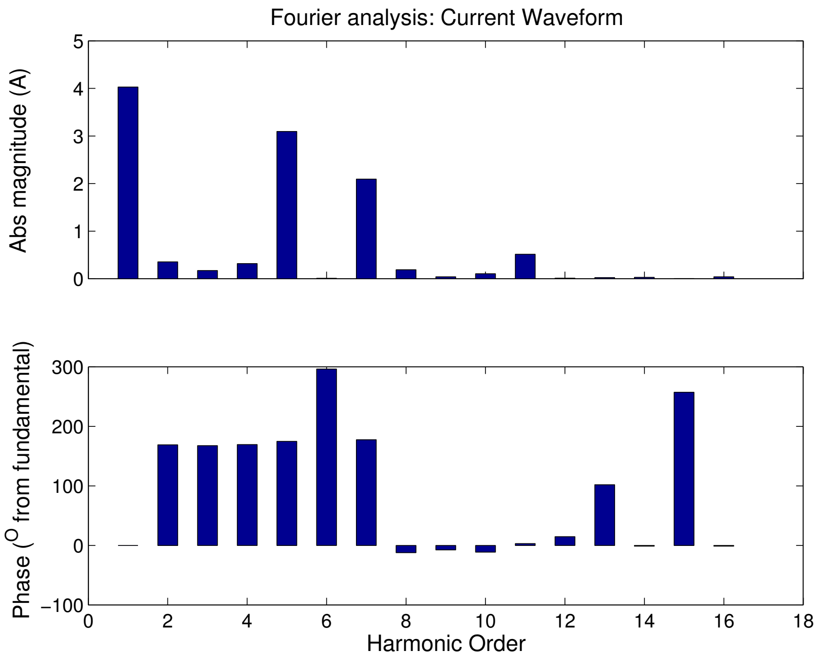


Figure 4.2: Harmonic spectrum of measured current waveform

A snubber circuit is placed in parallel with each diode, this is to help minimise transients which are dissipated through the resistive component. The snubber values used are in accordance with industry standards, with a capacitance of 0.1 μF and resistance of 47 Ω (Labelled R_{Snub} and C_{Snub} in Figure 4.3).

A capacitance across the DC output of the rectifier is used to smooth the output voltage. The DC link capacitance is a load – specific value, there is a linear relationship between capacitance and load. A rectifier with a DC link capacitance of 9400 μF for a load of 70 kW was used to determine a value for the equivalent circuit DC link capacitance [24] (Labelled C_{Smooth} in Figure 4.3).

Non-linear elements in ATP, such as diodes, require a linear element connected in series either side of it. A small resistor was used for this purpose, the value of which is 0.003 Ω. They are a requirement of the modelling program and are not a standard component in any real circuit. Symmetry resistors are used throughout the modelling process, but have a low enough value so as not to affect the overall result.

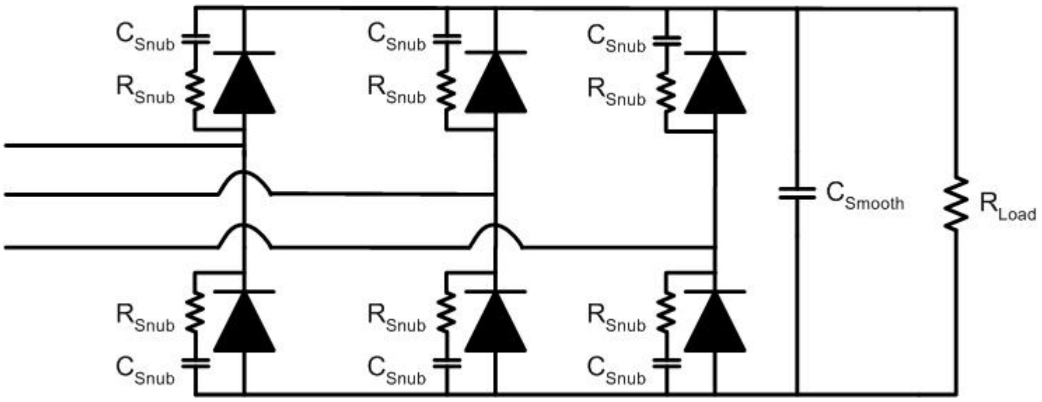


Figure 4.3: VSD model equivalent circuit

4.2.3 Evaluation of the VSD model

The completed model was tested under various condition to verify its correlation to an actual device. The individual simulations are discussed below.

Balanced Supply Simulation

An initial simulation comprising a balanced three phase supply (without source impedance) and a VSD was performed. The line current and line voltage were measured. It was found that the voltage did not visibly deviate from a 50 Hz sine wave. The current was found to have a similar waveform as that measured in Figure 4.1.

Supply Impedance Simulation

A more realistic evaluation would include a supply impedance which naturally occurs in real networks. A supply impedance was chosen, assuming a 10 kA fault level with an angle of 30 °. The values were chosen for simulation purposes only and are an approximation. The simulation determined the effect of source impedance on the current drawn by the VSD. The true fault levels, from the national supplier, will be reflected in later simulations which take into account

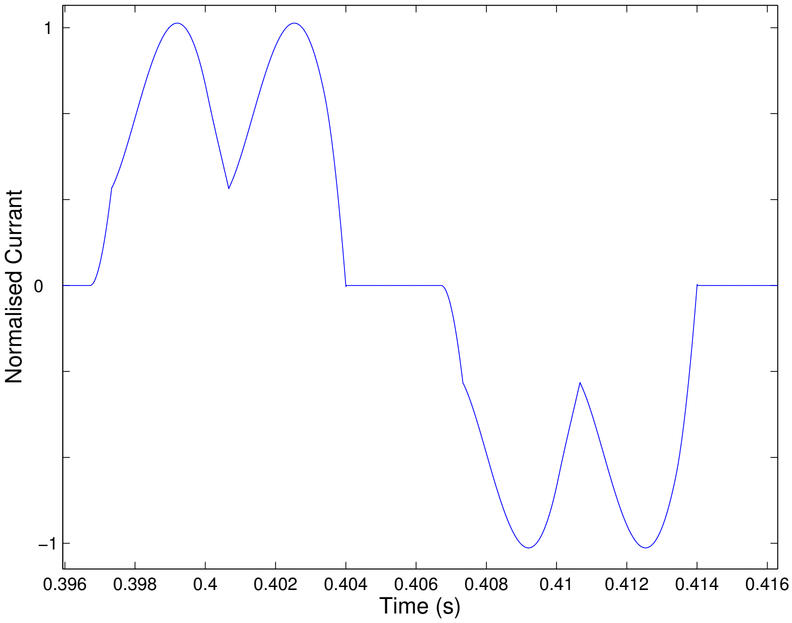


Figure 4.4: Supply – impedance – simulation current waveform

the actual network structure to be simulated.

Figure 4.4 shows the current waveform and Figure 4.5 shows the harmonic spectrum of the waveform.

Figure 4.4 shows that between the charging sections (the point where the current return path changes from one diode to another, in the rectifier), the current doesn't return to zero. This can be attributed to the low pass filtration caused by the introduction of inductance into the circuit.

Supply Voltage Unbalance

A small voltage unbalance is a possibility in a large network and so a 2 % voltage unbalance was simulated. Unbalance caused the current peaks to be of different magnitudes, as shown in Figure 4.6. This difference can be attributed to the charging voltage (voltage across the diode) of each phase being different. The harmonic spectrum is noticeably different from the balanced supply scenario, as can be seen in Figures 4.5 and 4.7.

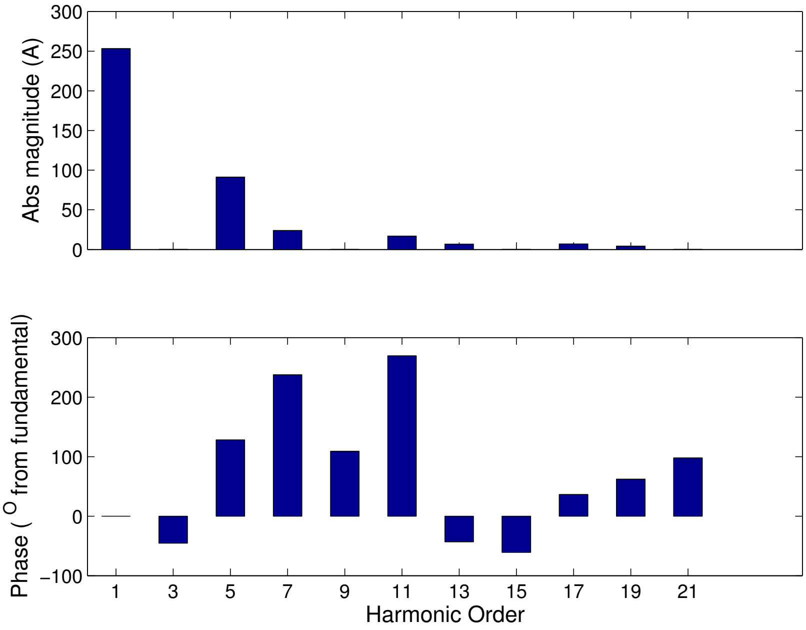


Figure 4.5: Harmonic spectrum of simulated current waveform

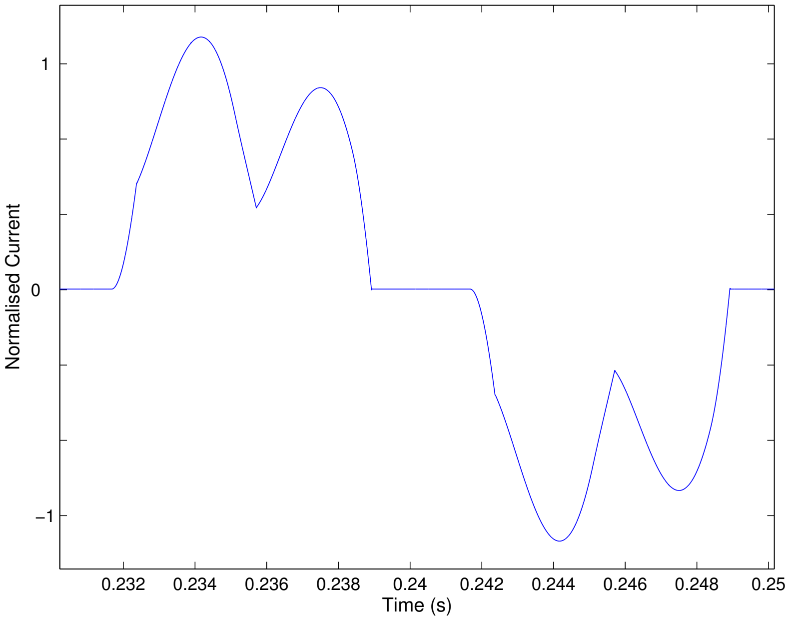


Figure 4.6: Simulated 2 % unbalance current waveform

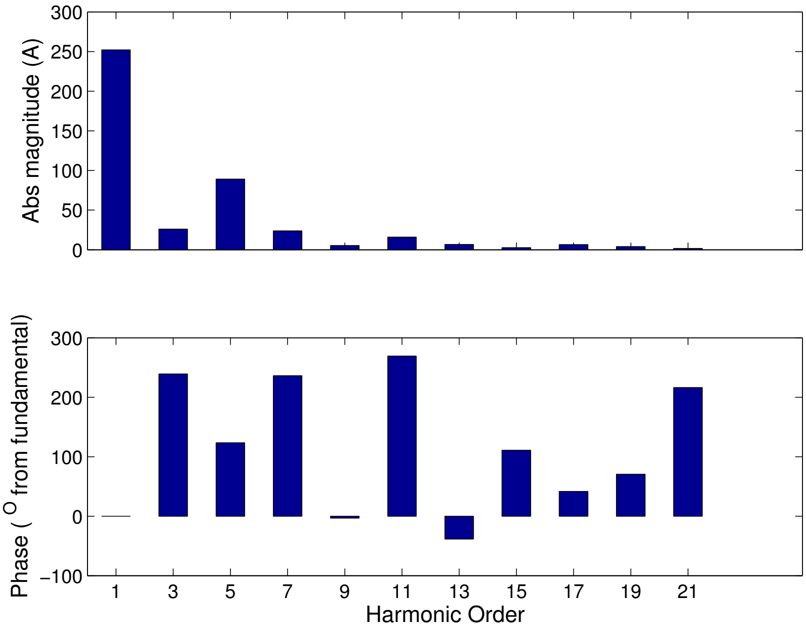
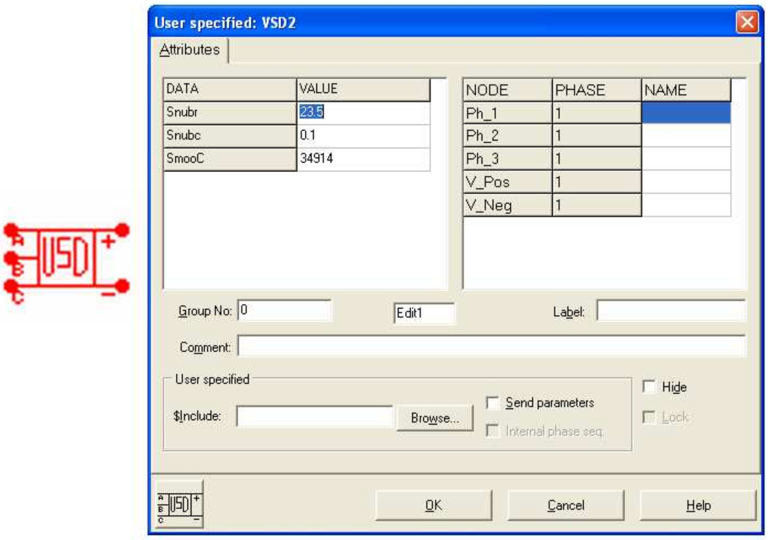


Figure 4.7: Harmonic spectrum of simulated 2 % unbalance current waveform

4.2.4 Final VSD Model

The VSD model (as per Figure 4.3) was confirmed against a simulation done in Simulink ®. The results where found to correspond. The model was written as a “data base module” for ATPDraw. The module allows the user to vary the snubber resistance, snubber capacitance and the DC link capacitance. These variables allow the module to be used to simulate a VSD of any size and configuration. The DC output and AC input were left as terminals so that the module may be connected to any other models created. Figure 4.8 shows the ATPDraw ® diagram and the data input window.

The data base module was used for the same simulations as described above (from Section 4.2.3), and the results were confirmed. Approximate simulation time is 14 seconds to simulate one current measurement for one second (Pentium IV:1.6 GHz, 384 Mb RAM). ATP was found to be faster than Simulink ®.



User specified: VSD2

Attributes

DATA	VALUE
Snubr	23.5
Snubc	0.1
SmooC	34914

NODE	PHASE	NAME
Ph_1	1	
Ph_2	1	
Ph_3	1	
V_Pos	1	
V_Neg	1	

Group No: 0

Edit1

Label:

Comment:

User specified

$Include:

Figure 4.8: VSD base module

4.3 AC – DC Converter Circuits

DC motors are widely used in industry for various operations, including traction and when a better power factor is required. It is common practice to use a chopper circuit to step down the DC output voltage of a rectifier circuit. Figure 4.9 shows a basic AC rectifier and chopping circuit.

A high frequency semiconductor switch is used to connect and disconnect the load from the DC source or rectifier. The ratio of the on – off cycle defines

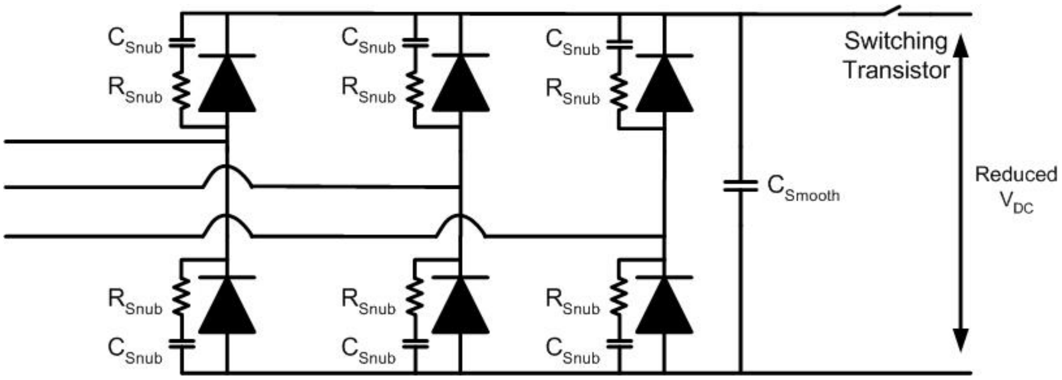


Figure 4.9: Basic rectifier and chopping circuit

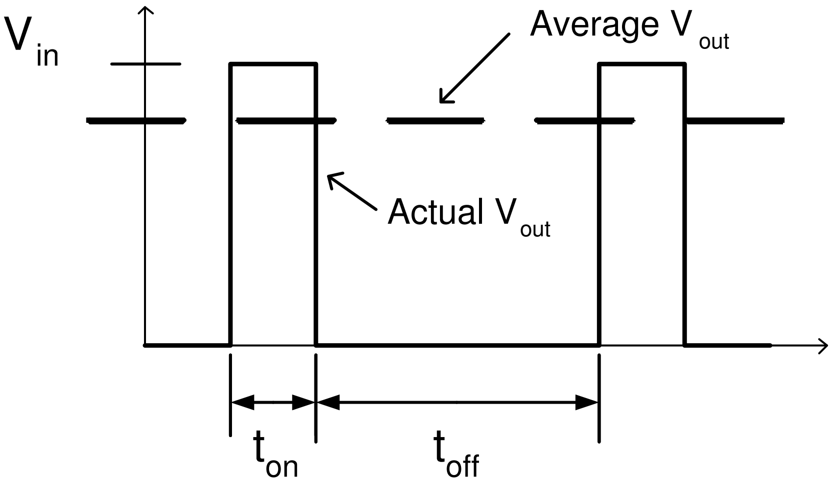


Figure 4.10: Chopper actual and average output voltage

the average value of the DC voltage received by the load, see Figure 4.10 [25]. If the ratio of switch time – on (t_{on}) to time – off (t_{off}) is 0.8, then the output voltage can be defined as in Equation 4.1.

$$\mathbf{V}_{\text{out}} = 0.8\mathbf{V}_{\text{in}} \tag{4.1}$$

where

$\mathbf{V}_{\text{out}}$ = the average DC output voltage of the chopper
$\mathbf{V}_{\text{in}}$ = the DC input voltage of the chopper

4.3.1 Basic Model of Chopper

A basic model of the rectifier and chopper circuit was developed as in Figure 4.9. The load is directly connected across the DC link and so the DC link does not act as a harmonic filter, as with the AC – AC converter. Therefore in the module the machine was represented by its armature impedance and a back e.m.f. Figure 4.11 shows the equivalent circuit used for the DC machine.

An initial simulation verified that the DC voltage supplied to the load was the desired average value. The duty cycle and back e.m.f were then varied to

Figure 4.11: DC machine equivalent circuit

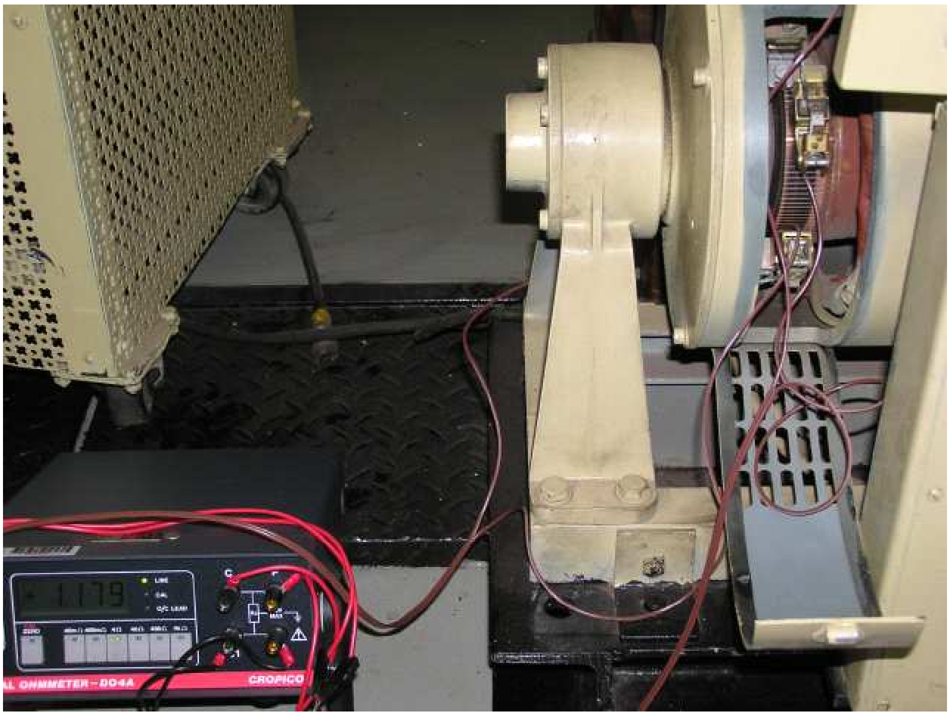


Figure 4.12: DC armature parameter measurement

obtain the required current. The voltage and current ratings where taken from actual machines. Measurements do not include brushes as they are nonlinear elements, measurements were taken using wires inserted between the brushes and the commutator as shown in Figure 4.12.

4.3.2 Chopper Model Evaluation

A simulation containing both a chopper and load was compiled. The simulations also included a transformer to confirm module interaction and that the results were as expected. Figure 4.13 shows the simulated chopper output voltage and average output voltage. The simulated load was a 24 kW DC

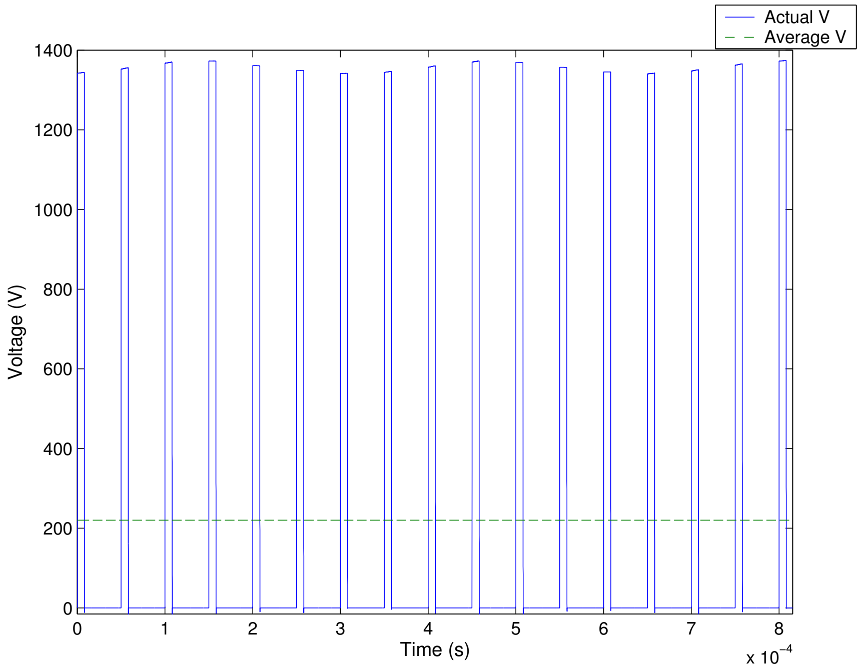


Figure 4.13: Simulated chopper output voltage and average voltage

machine of rated voltage 220 V supplied via a basic three phase transformer (see Section 4.4).

The current drawn was confirmed in the same manner and a data base module was created. The module allowed for user defined back e.m.f, DC link capacitance, load resistance, load inductance, snubber capacitance and snubber resistance.

4.4 Transformer

Transformers are designed to operate below conditions of saturation [5], implying that operation occurs in a linear region. A harmonic evaluation is done under normal operating conditions, hence saturation is not of great importance and can be ignored in a basic transformer model for steady – state simulations.

"BCTRAN" [18] is a package within ATP which allows users to create a transformer model using measured short circuit and open circuit values. ATP also allows for a three phase transformer to be defined, the leakage and magnetising impedances for each phase and the saturation curves can be individually entered.

It is possible to calculate approximate transformer impedance values using information given on the name plate and the assumption that the impedance is equally divided between the HT and LT sides of the transformer equivalent circuit. These values can then be entered into ATPs three phase transformer model.

For networks consisting of many "like" transformers (i.e. same manufacturer and specification), an average leakage impedance should be used to develop a standard model. The average impedance can be calculated using the information given on the single line diagram of the network.

The connection of the transformer will affect calculations, a factor of $\sqrt{3}$ should be included if the transformer is not of like connection on both the HT and LT sides, i.e. star – star or delta – delta. See Appendix A for calculations.

4.4.1 Model Confirmation

A delta – star transformer will induce a 30 ° phase shift between input and output currents [26]. This phase shift was confirmed by measuring an input and an output line current in an ATP simulation of the transformer, Figure 4.14 shows the results of the simulations confirming the 30 ° phase shift.

The step down ratio was also confirmed using a simple resistive load. The transformer model was found to work as expected, and a data base module was created. User options can include leakage impedance values and voltage ratios.

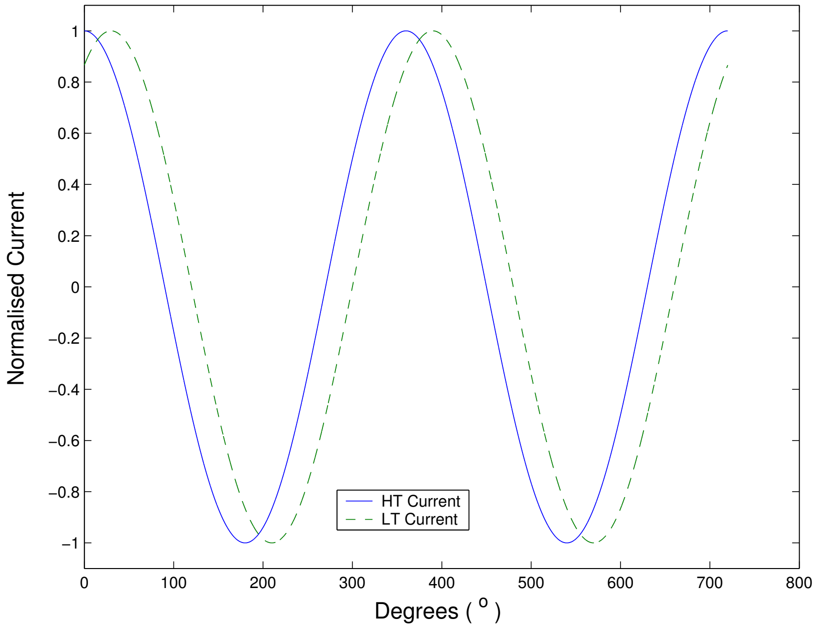


Figure 4.14: $\Delta - \curlywedge$ transformer HT and LT line currents

VSD – Transformer Module Interaction

The transformer model will have to be included in the same circuits as the VSD model and so it is important that the models produce expected results when used together.

A simple network comprising of a transformer and a VSD was simulated. The simulation appeared to be sensitive to symmetry resistance (Section 4.2.2) and the interaction between the VSD module and the transformer module also caused non-realistic results.

A short transmission line between modules forces ATP to solve the network in small subsections. This is caused by the propagation time of the transmission line (a few microseconds for a 1 km line). This delay causes the calculations for each device to be performed separately preventing undesired (mathematical) interaction between the modules. The short transmission line does not affect the overall result.

An initial simulation was done with multiple symmetry resistors (decoupling

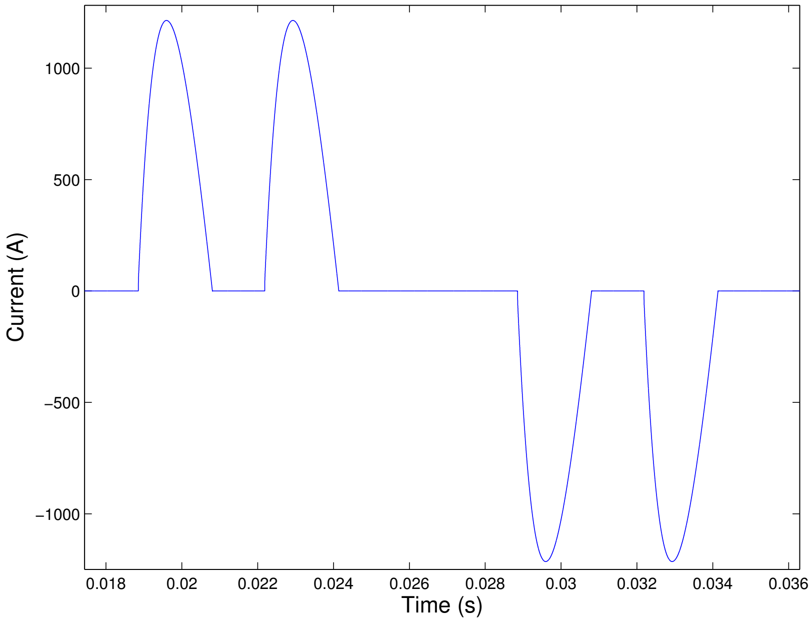


Figure 4.15: Simulated LT line current

the modules) in series with the VSD. The results are shown in Figures 4.15 and 4.16. It can be seen from the symmetry of the waveforms that no source impedance or unbalance has been included in the simulation. The distortion of the current waveform seams extreme in comparison with a purely sinusoidal wave, this is because the current drawn is for only one VSD load on the network, without any other impedances. In a fully modelled network other loads will draw sinusoidal currents, and the current drawn by the VSD will distort the pure 50 Hz waveform drawn by other equipment.

In a delta – star transformer the primary phase current is the scaled instantaneous difference between two secondary currents [5], therefore the HT current waveform, Figure 4.16, can be attributed to the delta-star conversion of the transformer [26].

With the introduction of source impedance into the model an underling 50 Hz waveform was found. This result is as expected and in accordance with actual measurements, which shows other elements to affect the overall current drawn by the system. Figure 4.17 shows the HT line current waveform. The waveform can be seen to oscillate on a 50 Hz signal.

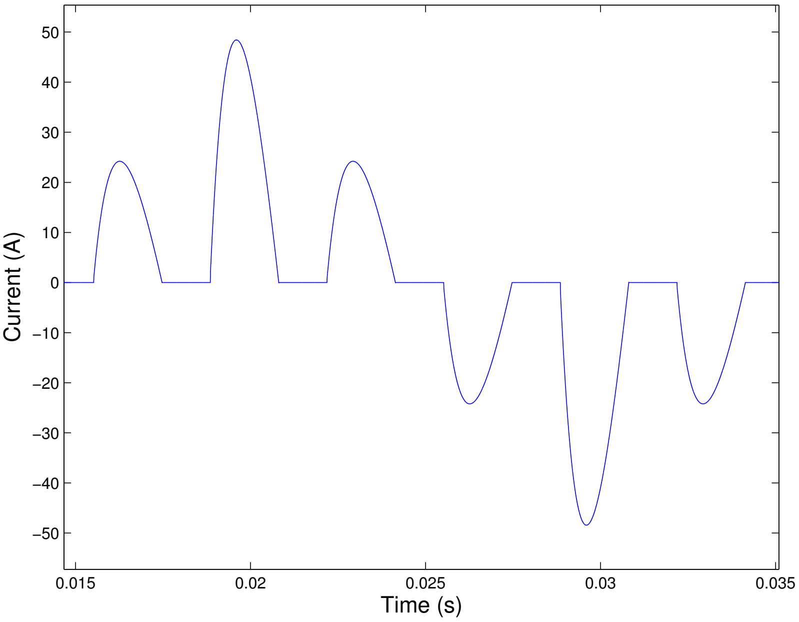


Figure 4.16: Simulated HT line current

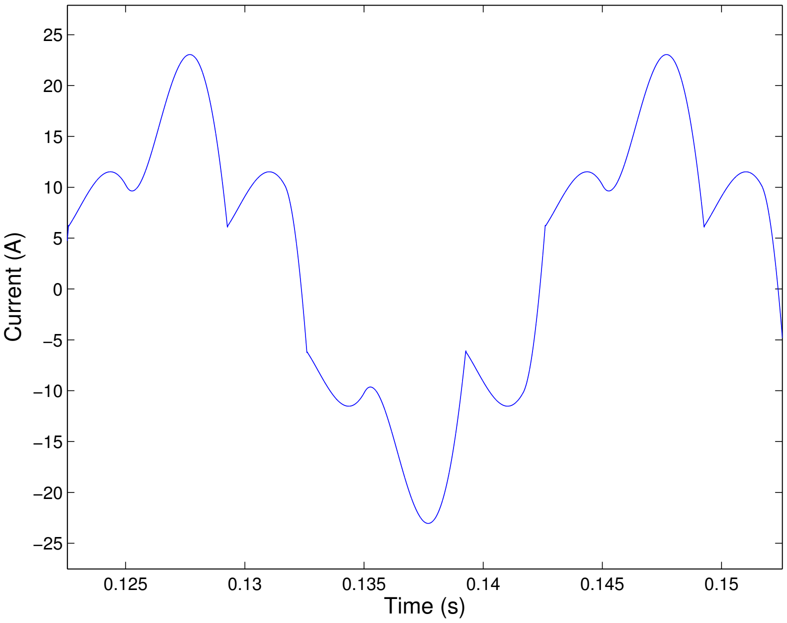


Figure 4.17: Simulated HT line current, including source impedance

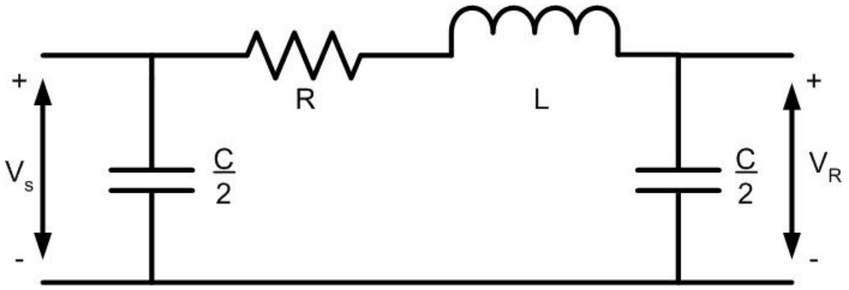


Figure 4.18: Nominal Pi Cable Model

4.5 Cable Modelling

ATPDraws “LCC” function is used to model cables. Cable geometry and electrical constants are used to create the required model. Various cable models can be created including the nominal Pi model.

A nominal Pi models is a model in which the lines shunt capacitance is divided equally and placed at the sending and receiving ends of the line. The inductance and resistance for the line is placed in series between the to capacitances. Figure 4.18

Using manufacturer data sheets [27] and material constants supplied by the supplier (See Appendix B) cable models were created. The nominal Pi model is a valid approximation for short to medium cable lengths [26], so for cables greater than 300 m, multiple sections should be used. This will maintain the validity of the model by distributing the cables impedance and shunt capacitance.

Figure 4.19 shows a cross section of a typical three core XLPE type cable as simulated with LCC. All cable lengths were measured and models were created accordingly. A short transmission line was also used to separate modules within the network.

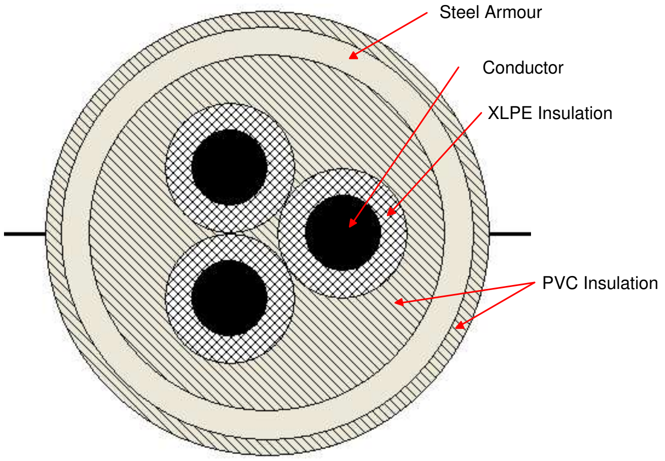


Figure 4.19: Cable Geometry

4.5.1 Model Confirmation

Cable models were confirmed using the transformer module. A network comprising a resistive load, transformer and cable was simulated. The transformer ratio and phase shift (delta – star) were checked. The phase shift did not change, and the transformer ratio was unchanged. A voltage drop was measured across long cables. From these simulations the cable models were found not to interact with other modules.

4.6 Induction Machine Modelling

The induction machine is a common piece of equipment on any industrial network, it is the workhouse of industry. An induction machine equivalent circuit is shown in Figure 4.20. The ideal transformer in Figure 4.20(a) develops the rotor e.m.f. The equivalent circuit in Figure 4.20(b) shows the rotor circuit referred to the stator side, eliminating the ideal transformer. The impedance values are scaled by the turns ratio of the ideal transformer and the load resistance is also scaled by a function of the machine slip.

4.6.1 Parameter Calculation

Using an induction motor data program [28] the inductances and resistances of the equivalent circuit of an induction motor from the "name-plate" parameters was calculated. The information on a machine name plate include

- Voltage
- Rated current
- Speed
- Number of poles
- Power

The program assumes that the stator self-inductance and rotor self-inductance (as seen from the stator side) are equal. The resulting inductances and resistances can be directly used in the UM3 (induction motor) model [18] in ATP and ATPDraw.

The following values are required to generate an equivalent circuit:

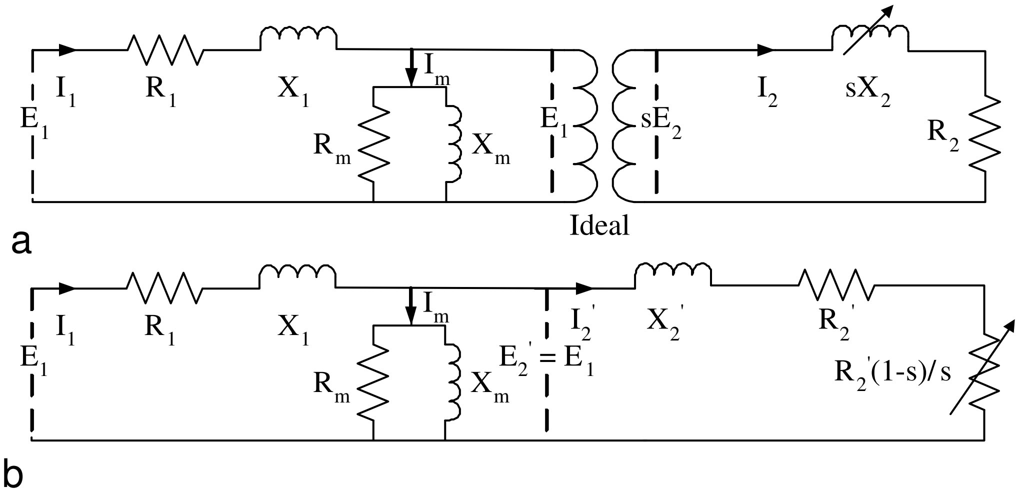


Figure 4.20: Induction Machine Equivalent Circuit [5]

- The nominal phase to phase voltage in kV. It must be greater than 0.005 kV.

- The nominal useful active power in kW, which should be greater than 0.001kW. It is assumed that the power consumed in the fictitious resistance $\frac{R_2{}'(1-s)}{s}$ of the equivalent circuit is the same as the nominal power.

- The slip at nominal voltage and power. Slip is limited between 0.001 and 0.5.

- The electrical efficiency at nominal voltage and power. It must be smaller than 1 and larger than 0.5.

- Power factor (or $\cos\theta$) at nominal voltage and power. It must be larger than 0.5 and smaller than 0.999.

- Ratio of locked rotor current (or starting current) and nominal current. Typically between six and nine.

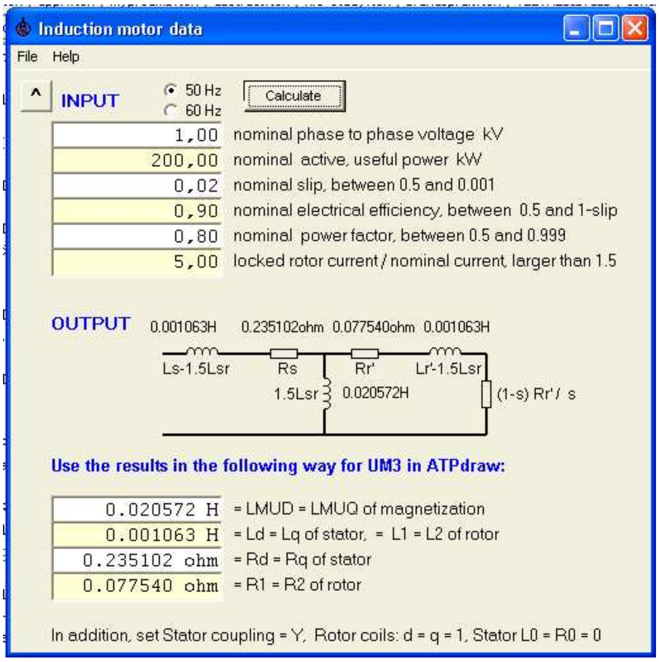
The program interface is shown in Figure 4.21. Typical efficiencies and power factors [29, 30] were used to calculate various induction machine models.

4.7 Conclusion

The individual pieces of equipment modelled in this chapter were verified through comparison with actual measurements of equipment. Therefore, they are suitable for use in a simulation of a complete network.

The models created are not an exhaustive list, but the process followed can be used to create additional models required for future studies. Namely, the use of equivalent ciruits as the basic model, simplification and comparison with actual results.

The study conducted in Section 5.4 is of network which comprises each of the machines discussed previously, and so the models will be used for the study.



INPUT

● 50 Hz
○ 60 Hz

1,00 nominal phase to phase voltage kV
200,00 nominal active, useful power kW
0,02 nominal slip, between 0.5 and 0.001
0,90 nominal electrical efficiency, between 0.5 and 1-slip
0,80 nominal power factor, between 0.5 and 0.999
5,00 locked rotor current / nominal current, larger than 1.5

Use the results in the following way for UM3 in ATPdraw:

0.020572 H = LMUD = LMUQ of magnetization
0.001063 H = Ld = Lq of stator, = L1 = L2 of rotor
0.235102 ohm = Rd = Rq of stator
0.077540 ohm = R1 = R2 of rotor

In addition, set Stator coupling = Y, Rotor coils: d = q = 1, Stator L0 = R0 = 0

Figure 4.21: Induction Motor Data Program Interface

Chapter 5

Network Analysis

In order to rapidly evaluate the harmonic state of a network, an NRS 048 type study can be performed on the network PCC with the supplier [2]. The results of such a study will indicate whether or not the network and supply are operating within harmonic limits.

The assessed state of the PCC can be used to determine possible implications of alteration or enlargement of the network; this includes the installation and removal of equipment.

This chapter discusses the approach taken to perform a study and evaluate a network using an NRS 048 type study and an ATP simulation. Measurement device selection and data processing methods are also discussed.

5.1 Brandspruit Colliery

Brandspruit Colliery is one of the five coal mines operated by SASOL mining at Secunda. The coal seam is approximately 170 m below surface. The reticulation network is an 11 kV three phase feed to the underground operations. The network is continually changing as the mining faces move further from the shaft.

5.1.1 Plant Description

Multiple transformers are used to supply power underground. The network is configured so that it can be operated from any combination of the transformers, through the use of ring feeds. This feature allows the sections of the network to be switched off for maintenance and expansions, while also providing redundancy in case of break down. It is also therefore possible to group similar equipment on the same transformer and so minimise harmonic interference to other equipment.

The conveyor belt system is driven by VSDs, manufactured by A.B.B., with belts starting in each working section. Section belts pass coal onto the main belts, which in turn transfer it to the incline belts which take it to SASOL Coal Supply.

At various strategic points, underground, substations are used to house transformers, VSDs, telemetric systems and other electric panels. Typically the voltage is stepped down to 1.1 kV except for VSD supply, which is 400 V.

Each section is supplied from a transformer which is moved with section. The 1.1 kV supplied to the section is typically used to supply the production equipment shown in Table 5.1.

Table 5.1: Typical section production equipment

Three shuttle cars	Two roofbolters
Six jet fans	One force fan
One conveyor motor	One continuous miner
One pump	One feeder breaker

5.1.2 Expansions and Alterations

The number of mining sections is dependant on equipment availability, market demand and the coal distribution. Sections will cease to operate during moving, when only machine traction and pumps are operated continuously to move the machine from one area to another.

As the mining operations expand the need for additional underground substations, conveyors extensions and additional lighting will affect the performance and operation of the network. Alterations are determined well in advance by engineering services.

5.2 Resonance Pre – Study

Before commencing a physical study, the author evaluated the network to determine the resonant frequency at various points of concern. Capacitance and inductance within the network will interact as described in Section 2.2.1.

The frequency at which a capacitance and inductance will resonate is determined using Equation 5.1

$$F_{\mathrm{R}} = \frac{1}{2\pi\sqrt{LC}} \tag{5.1}$$

Each substation was simplified to a basic inductive and resistive circuit. The network was reduced until only busbars which had a capacitive component were left, all others were combined. This simplification process make a few assumptions (See Appendix C) which aid calculation, the resonant frequency is not a hard and fast value, and may vary slightly in practice.

The overall (simplified) inductance value and capacitance value for each remaining bus bar was used to determine a resonant frequency.

The network evaluated had two PFC capacitors, one on surface at the main incomer and a second bank underground, see Figure 5.5.

The resonant frequency at the underground capacitor bank was determined to be just below the 2^{nd} harmonic, whilst the resonant frequency at the main incomer was determined to be just over the 3^{rd} harmonic. The calculations are shown in Appendix C.

5.2.1 Implications

The resonant frequencies can be used to determine what harmonic loads would adversely affect the harmonic condition.

When selecting equipment it will be important to minimise the use of loads which are known to produce harmonics at the resonant frequency. The current signature of any machine can be easily determined by performing a Fourier analysis of the machines current input.

The resonant frequency can also be used to monitor measured and simulated results, whereby frequencies around resonant value can be noted and suitably filtered or prevented.

5.3 NRS 048 Evaluation

A basic study of the Brandspruit mine was performed to understand the implications of an NRS 048 type study. The evaluation investigated the underground supply and did not, however, investigate the quality of supply to office buildings, which contain many PCs with switch mode power supplies.

5.3.1 Measurement Devices

The cost, size, availability and specification of various measuring devices, which can be used to perform an NRS 048 study, influence the choice of device used for a study. Before selecting a device an inspection of the network and measurement points should be made. Power supply, storage space and access are factors which influence this decision.

A study performed in a sub station with easy access to the panels and a 220 V mains supply could make use of any device. However should the sub station be remotely located and the availability of 220 V is limited then a more specialised device will be required.

Special care should be taken to use a suitably rated device. Panel CTs may have outputs which do not fall with in the ADC measurement range causing possible inaccurate results because the device will function on or below its operational limit.

Storage Space

PC based solutions have the advantage of large and cheap storage mediums enabling the device to measure multiple channels for extended periods of time unattended. The number of channels monitored will be limited by the ADC used. The system will however require a constant power supply and will be a large and bulky device, weighing approximately 15 kg [31].

Specialised devices may use a different storage medium which may be limited, due to the size of the device housing, board size or cost. These smaller devices may not be able to monitor multiple channels for extended periods of time and so the data would have to be copied off and the device reset at regular intervals throughout the evaluation period [32].

Power Supply

A stand alone system that does not require external power, will use a battery pack. This pack will provide power to the device for a limited period after which it will need to be changed or recharged. During this period the device will be inactive. This smaller system will however be easier to transport and install. Battery packs can be changed when data is copied off, minimising the down time of the device.

PC systems will be able to be powered by either a 110 V or 220 V supply. Provided a source is available and safe, the system can run continuously throughout the evaluation period. A UPS should be used to prevent the machine from resetting during power dips or failures.

Chosen Device

QSR2000 was used to evaluate the main incomers at the Brandspruit Colliery. QSR2000 is a software program which runs on a PC. The PC and UPS were setup in the surface substation at Brandspruit. The entire setup process took approximately two and a half hours, after which it was left to monitor various incomers for a period of one week.

An initial test was performed to check for voltage imbalance between phases. The device was run for 30 minutes on all three phases of one incomer, the resulting harmonic spectrum's for each phase were found to approximately match each other. This is confirmed by the fact that the voltage unbalance protection does not trip the network.

Having established the phases were balanced, the device was then setup to monitor voltage and current harmonics on various incomers and capacitor banks. This was done to minimise the time and cost required to perform the evaluation.

Both voltage and current harmonics were measured using the sampling method as described in NRS $048-3$. Figure 5.1(a) shows the size of the device, a standard PC, Figure 5.1(b) shows the substation with all the panels being monitored, while Figure 5.1(c) shows an individual panel, with measurements being taken from a CT and a VT.

The device was configured to monitor all harmonics up to the 25^{th} and the THD. The substation was monitored for a period of one week.

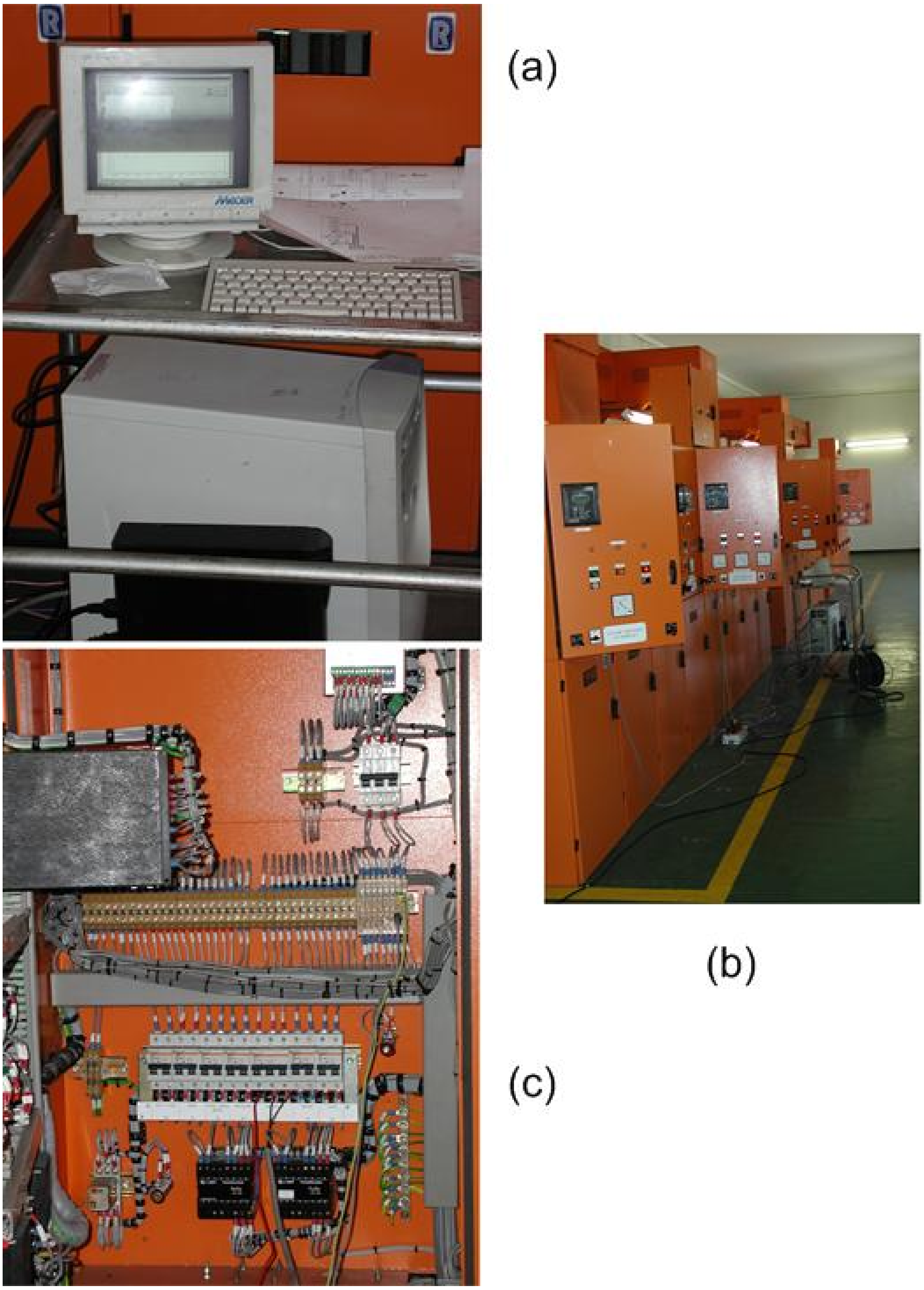


Figure 5.1: Substation evaluation

5.3.2 Data Analysis

QSR2000 has a report generating function, which analyses the data captured in accordance with NRS 048 version 1. For the authors understanding and future analysis on data captured on a machine without report writing functionality, macro code was written to perform the analysis in Microsoft Excel®. This function was used to generate the voltage harmonic spectrum and THD for the Brandspruit incomers. The results were found to be within NRS 048 limits, as shown in Figure 5.2. Appendix D is the macro code written to assess the recorded data.

An analysis of harmonic current was also performed, the harmonic spectrum indicated that current harmonics are below maximum levels (overload) acceptable for capacitor banks. As stipulated in IEC 871 [33, 34], the current overload for the capacitors is below 30%. Figure 5.3 shows the current harmonic spectrum.

Although the analysis indicates the network to be operating within harmonic limits, the continuously varying nature of the network warrants further analysis. As the network is altered it may cause harmonic situations above the acceptable limits.

5.3.3 Comments

The measurement process is simple to perform and requires little user input. The software can be used to evaluate the results in accordance with NRS 048 and clear indication of the harmonic status can be seen.

Using the compatibility levels in Chapter 3 and the results it was confirmed that Brandspruit was operating within NRS 048 limits and that there appeared to be no harmonic problem.

The results, however, do not possess enough detail to draw conclusions as to the harmonic condition at any point within the network as they do not reflect

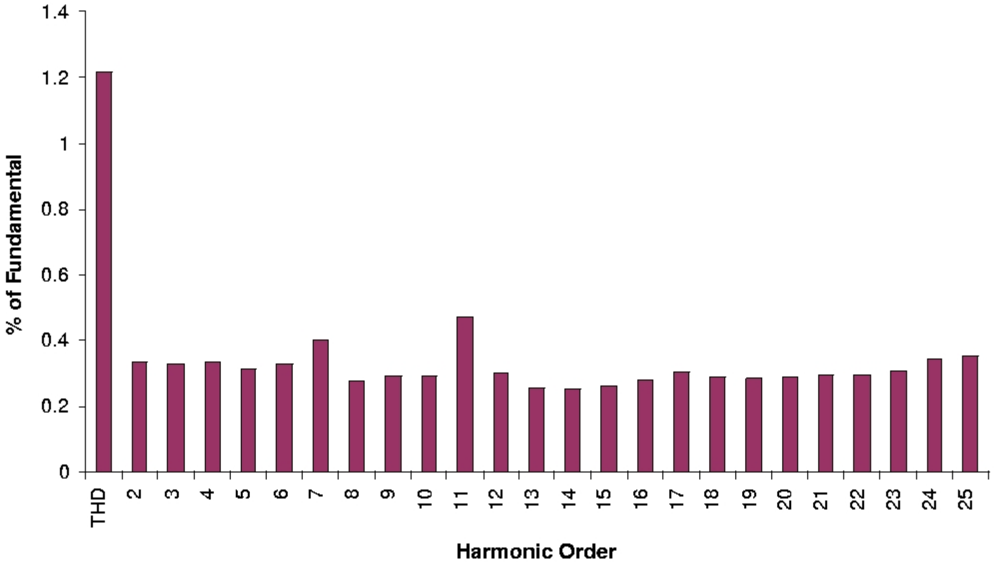


Figure 5.2: Voltage Harmonic Spectrum of Incomer

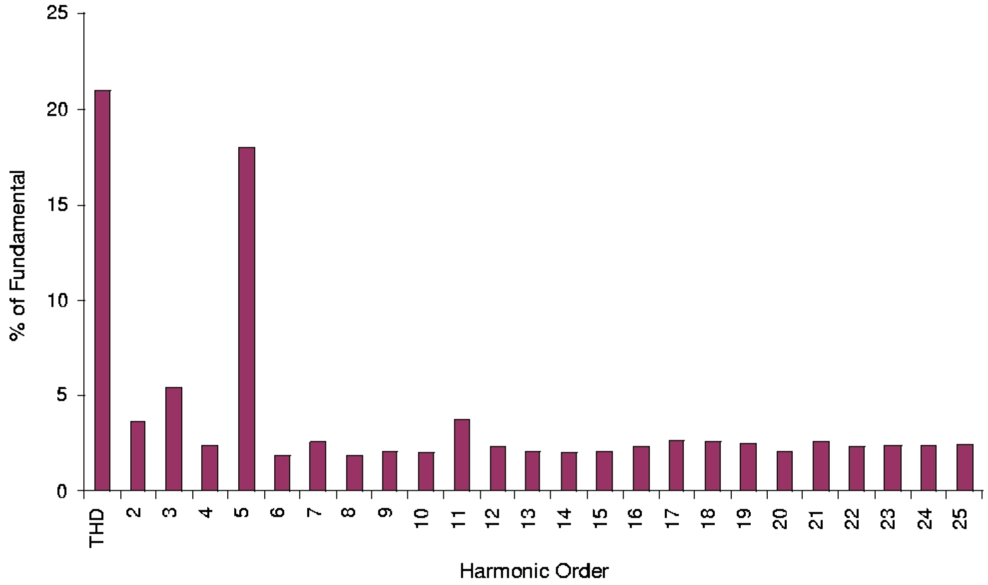


Figure 5.3: Measured Current Harmonic Spectrum of Incomer

a measurement at points other than the PCC.

The resonant frequency determined in Section 2.2.1 does not feature in the results of the NRS 048 study. This indicates that loads within the network are not generating enough 3^{rd} harmonic to cause resonance.

The current results do indicate an elevated 5^{th} harmonic which is caused by the VSDs used within the network. Figure 4.1 shows the harmonic spectrum of a typical VSD.

5.4 ATP Simulation

Although the NRS 048 measurements do not indicate an excess of harmonics, an ATP model of the network was developed and a simulation was conducted as part of this project. This was used to predict harmonic content throughout the network. The modelling process is used to help develop steps to complete a hybrid network evaluation and to allow future alterations to be modelled before they are commissioned.

An incomer and all of the associated equipment was simulated in ATP. The devices where simulated as discussed in Chapter 4. Each device of importance was modelled, and were possible devices were grouped to simplify the total model. All capacitor banks and individual VSDs were included.

As each new device or substation was added to the network the simulation was compiled to confirm that no errors had been included. Although this increased the development time it prevented a difficult debugging process of the complete network model.

5.4.1 Problems Encountered

Most errors were created through misinterpretation of the single line diagram and hence an incorrect model, such as simulating ringfeeds as closed instead of open. Incomplete information also made the development difficult and required many visits to the site to gather extra information.

ATP and ATPDraw are syntax rigid applications that are particular about the information that is entered. Some errors were created through not following the exact procedure for creating a model, the ATP Rule book[18] should be followed when a new model is created.

ATP failed to compile when cables were repeated within the ATPDraw environment, this occurred when multiple references to the same data base module were individually created. The problem was overcome by simply copying and pasting identical elements within the network model. The network diagram is shown in Figure 5.5.

5.4.2 Simulation Analysis

The completed model was then adjusted to reflect a working example of the mine's network, including the operation and non-operation of various pieces of equipment, such as capacitor banks. The result of this simulation was then compared with the NRS 048 study results.

The NRS 048 results are an indication of the highest value for each harmonic order, each maximum harmonic value may not occur at the same instant as another harmonics maximum value. The ATP simulation represents a particular setup and hence a particular set of harmonic values.

In order to best correlate the NRS 048 results and the simulated results the most significant measured harmonic(s) was selected. The model was then adjusted to create a situation where the harmonic value(s) are obtained. The situation represented a network configuration which was likely to occur. In

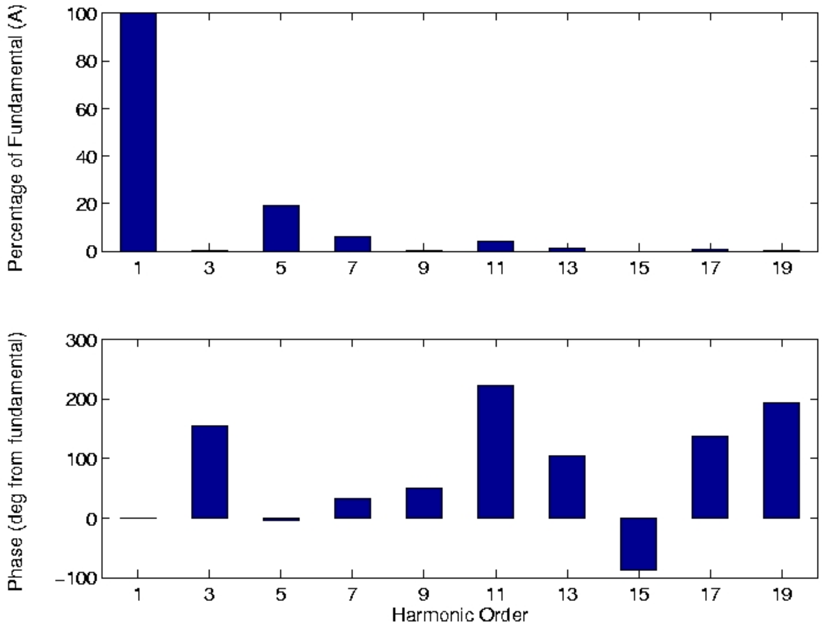


Figure 5.4: Simulated Current Harmonic Spectrum of Incomer

the case of the Brandspruit Incomer the 5^{th} harmonic was selected (See Section 5.3.3)

Figure 5.4 shows the harmonic spectrum of a situation where the model generated the same 5^{th} harmonic as the measured results in Figure 5.3. The basic structure of the network was created in ATPDraw and different equipment configurations were simulated.

These configurations included the simulation of various capacitor bank values, as they are automatically switched underground and the disconnection of various equipment, as not all equipment is run continuously. This case however, included the operation of all mining sections on the incomer as well as the power factor correction capacitors.

5.4.3 Model Confirmation

The ATP simulated results approximate the NRS 048 results. This result together with equipment model verification (Chapter 4) shows the simulation methods to be a valid alternative to NRS 048 type evaluations and a additional tool for harmonic analysis of networks.

5.4.4 Comments

The process to develop an computer model is a long and involved process, this is due to the need to confirm each stage of the development of the model, including individual equipment models.

The process of developing the model is greatly sped up for future studies, should the equipment models be reusable. The process may be too elaborate for a one off case study of a network which is not likely to change.

5.5 Investigation into the Operation of Auto – Switching Capacitor Banks at Brandspruit

The effect of the various operating states of an auto – switching underground capacitor bank were investigated. The underground capacitor is used for voltage stability in remote sections of the mine. The amount of power factor correction required at the point is dependant on the load at the point at any particular time. A single line diagram of the network is shown in Figure 5.5, it is one of Brandspruits incomers.

The normal operating state of this capacitor bank (indicated in figure 5.5), under these network conditions, is the 1200 kVAr setting. The bank will automatically switch to give the best power factor, but should one of the banks be deactivated, for example the 1200 kVAr, a timer prevents it from being switched back on again for a period of five minutes. The concern is that if a momentary change in network conditions should cause the capacitor bank to switch off and then the network conditions return to normal the capacitor bank may operate outside its specified operating parameters. The overstressing

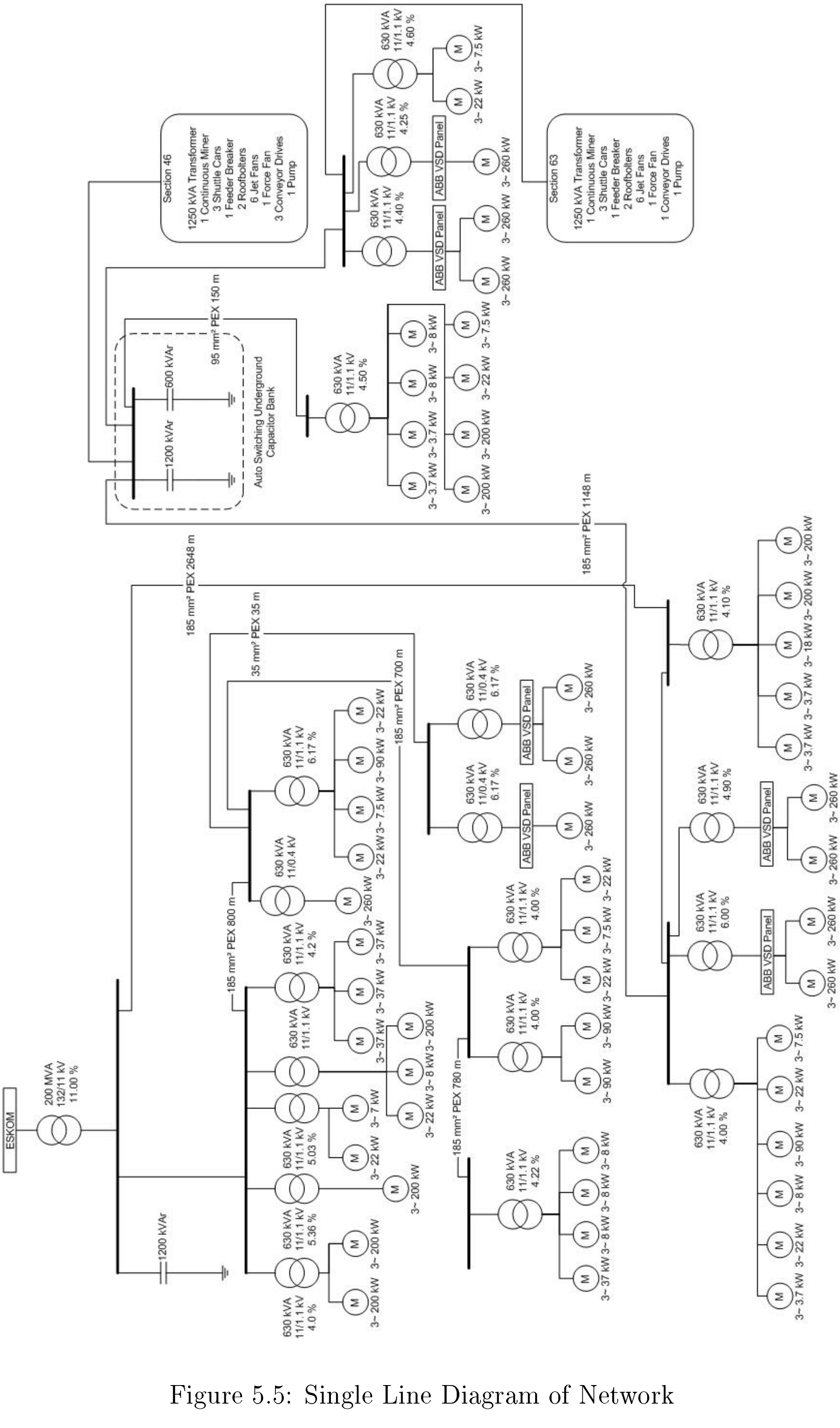


Figure 5.5: Single Line Diagram of Network

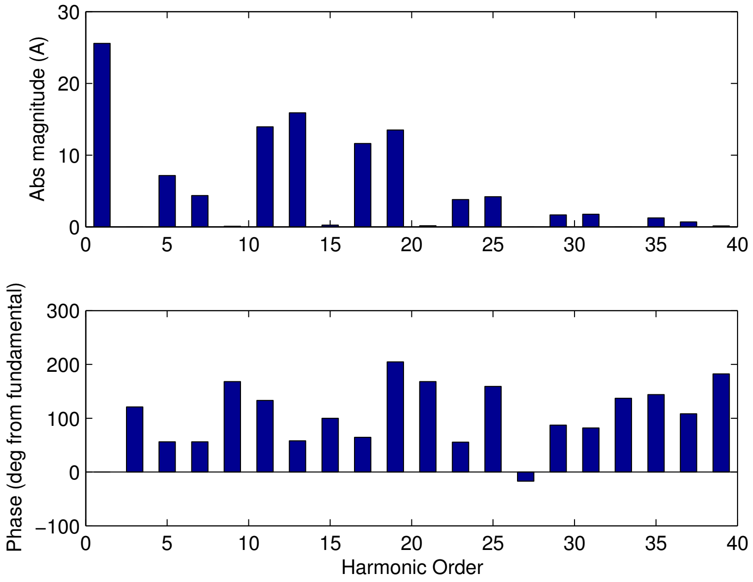


Figure 5.6: Current Harmonic Signature of 600 kVAr Capacitor

of capacitors can cause degradation of dielectrics, overheating and failure of the capacitor.

The capacitor bank was modelled in three of its settings, namely 600 kVAr, 1200 kVAr and 1800 kVAr. The rest of the network was held constant for the three simulations. Figures 5.6, 5.7 and 5.8 show the harmonic spectrum of the current drawn by the underground capacitor bank. From Figure 5.7 the current THD can be calculated to be 9.19 %.

The same calculations were performed for each of the other simulations (different capacitor bank settings), the results of which are shown in Table 5.2. The table also includes the THD, rated r.m.s current, the r.m.s value of the simulated waveform and the percentage over current.

In all three cases the capacitor bank is operated below a 30 % over current and so the opeating characteristics are suitable and the capacitor bank is not operated in a dangerous manner.

It should however be noted that the if the capacitor bank is manually operated

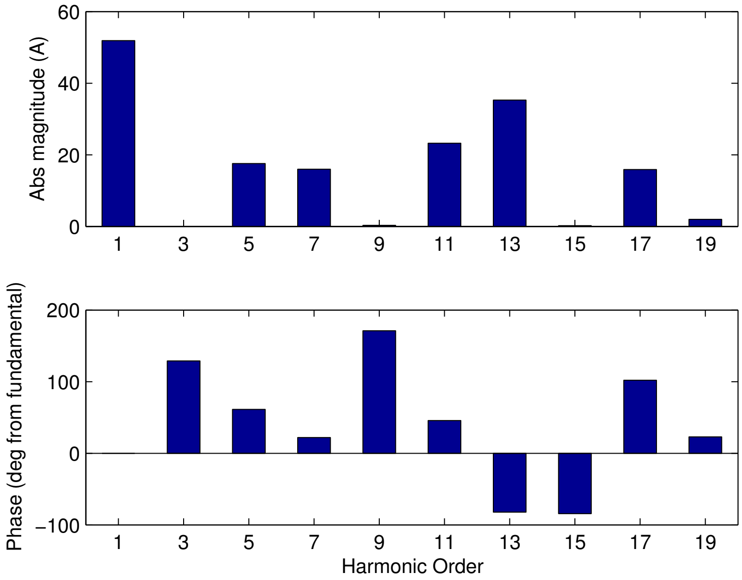


Figure 5.7: Current Harmonic Signature of 1200 kVAr Capacitor

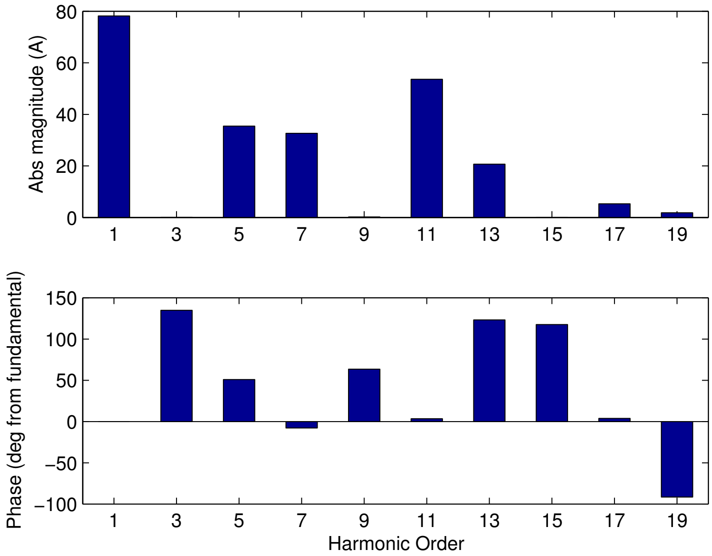


Figure 5.8: Current Harmonic Signature of 1800 kVAr Capacitor

Table 5.2: Capacitor Supply THD

	% THD	**Rated Current (A)**	**Simulated Current (A)**	**Over Current (%)**
1800 kVAr	15.52	95.0	109.7	116.1
1200 kVAr	9.19	63.0	74.9	119.0
600 kVAr	6.52	31.5	39.62	125.8

and left in a 600 kVAr state the long term affect may be detrimental as the bank will operated close to the 30 % over current regularly.

5.6 Investigation Conclusion

Although the capacitor bank operates within the bounds prescribed [33, 34] the use of the manual setting may adversely affect network performance and the expected life of the capacitor bank.

The manual bank setting should only be used for testing and maintenance purposes and not during normal production cycles.

5.7 Conclusion

The Brandspruit Incomer was evaluated according to the NRS 048 compatibility levels and it was found the voltage harmonic content was within the limits. The current harmonic were also found to be low enough so as not to overstress the capacitors used on the network.

Despite the network operating within the limits an ATP simulation was developed to evaluate harmonics within the network. The simulation was adjusted to achieve a similar 5^{th} harmonic as that found in the measurements.

The model was then used to investigate the operation of auto – switching capacitor banks underground. Recommendations were made as to the use of the auto – switching capacitor.

The chapter confirmed that both measurement and simulation could be successfully used to investigate the harmonic condition of an electrical network.

Chapter 6

Hybrid Evaluation

Although both an NRS 048 study and a simulation could be used to evaluate a network, a hybrid method making use of both methods strong points can be used. While an NRS 048 study is quick and relatively easy to perform it is focused on evaluating the quality of supply as apposed to investigating problems within a customers network.

On the other hand a computer simulation is a very theoretical approach and may not fully capture the complexity of the network. The model's integrity relies on the person whom developed it and his/her assumptions, as well as the software used.

In order to best use the tools and methods available for a study, a hybrid approach was developed making use of the best features of both methods.

6.1 Initial Analysis

The first step in a harmonic evaluation is to establish if there is in fact a harmonic condition which is of concern or if future additions and modifications will cause such a harmonic condition. The simplest and quickest method to achieve such an understanding of the network in question is to perform an abridged NRS 048 study over a full working day or two.

Comparing measured results with NRS 048 limits (see Chapter 3) it can be determined whether the network operates within acceptable limits and whether the cause is equipment within the client network or pollution from the national grid [2]. Should the results confirm there to be no cause for concern and no future “harmonic – creating” expansions or modifications are expected then no further investigation is required.

However should the results demonstrate that there is in fact a harmonic problem or there are “harmonic – creating” expansions or modifications planned for the future, a computer simulation may prove to be necessary to fully understand the problem and evaluate future expansions and modifications.

6.2 Network Modelling

Should a model be deemed necessary a complete single line diagram of the network should be acquired and verified. Models of individual pieces of equipment should be created and verified, as in Chapter 4.

The individual equipment models can then be used to simulate an entire network. The method described in Section 5.4.2 should be used to confirm the validity of the plant model.

Once the model has been confirmed it can be used to evaluate nodes within the network. Points of concern can be determined by regular faults and failures of equipment or nuisance tripping within the network. These records should be kept by the condition monitoring department and a report of regular faults can be drawn. The supply quality to power factor correction capacitors and other harmonic sensitive devices should be simulated.

Figure 6.1 shows the simulated harmonic spectrum of the current supplied to a PFC capacitor, the harmonic values are represented as a percentage of the fundamental current. The total harmonic distortion is below 30 % and so the capacitor is operating within accepted limits [33, 34].

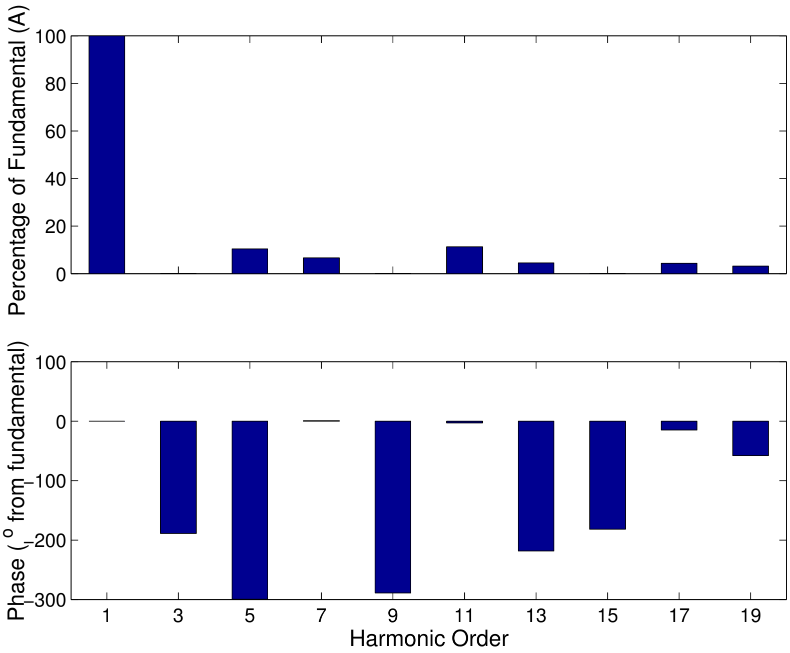


Figure 6.1: Current Supplied to Power Factor Correction Capacitor

ATP can be used to simulate the supplied voltage and current to the nodes of interest. This is far more convenient than having to travel to the node, disrupting operations to connect and then again to disconnect measuring equipment.

The results of the simulation can be used to determine and evaluate the appropriate solution to the problem, whether it be a reconfiguration of network connections, alteration of transformer connections or the introduction of harmonic filters. The proposed solution can be simulated and its effect on the overall harmonic content of the network quantified.

6.3 Conclusion

The quick physical study of the network establishes the overall harmonic condition of the network, giving an indication of whether or not further investigation is required. The abridged study is a clear indication and although not a complete study in terms of NRS 048 it is sufficient.

The modelling process gives an insight into the network making it possible to evaluate specific nodes within the network. The initial model setup can be time consuming to establish and so modelling should only be performed if there is a proper justification for it.

Newer software packages make use of gui's and are typically shipped with a large selection of standardised models [21]. It is possible to establish a network model quicker using a newer package, but the cost of the software and hardware required may become prohibitive.

This hybrid approach allows the study to be as complex or as simple as required. A brief NRS 048 study allows the harmonics to be rapidly evaluated, whilst an in depth simulation creates a forum for a thorough investigation and evaluation of solutions without raising equipment costs or disrupting production.

Chapter 7

Conclusion

The project successfully demonstrated that a combination of measurements and simulations could be used to thoroughly investigate the harmonic state of a network.

An NRS 048 study of the Brandspruit network, using a QSR2000 PC based solution, revealed that Brandspruit was operating within harmonic limits. Both the voltage and current harmonics were measured.

For the purposes of this project and the future use by Brandspruit an ATP model was created and a simulation performed. The simulation also indicated that Brandspruit currently operates within NRS 048 limits.

Individual ATP models for equipment used in the mine, including VSDs, transformers, cables and induction machines, were created and tested. The assumptions made in order to develop the model were discussed and wherever possible models were simplified to decrease processing time. This process helped build a repository of models which can be used for rapid development of network models in the future. The use of previously created models decreases the time required to develop a working model of a plant's network.

The methods and results used for these two individual approaches were used to suggest a future method which used aspects from both. The simulation is only created if needed and is confirmed via the measurements taken. NRS 048 limits [2] and IEC 871 [33, 34] specifications are used to decide whether or not the network is operating outside of harmonic limits.

The process allows for a more rapid and unobtrusive harmonic evaluation. The measurements can be taken at surface substations quickly, without disrupting production. A computer simulation of the network can then be created and compared to measurements taken. The simulation can then be configured to include all proposed corrections and hence evaluate them before implementation.

An evaluation of an underground capacitor bank revealed that the autoswitching system was suitably configured and it also indicated that the use of manual settings was not advisable as prolonged use may damage equipment.

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Appendix A

Transformer Model Calculations

A delta – star connected transformer can be approximated by three single phase transformers connected as a star on the primary side and a delta on the secondary side.

Each individual transformer can then be modelled, the transformer ratio will be given by

$$a = \frac{V_p}{V_s/\sqrt{3}}$$

where

V_p = Primary line voltage
V_s = Secondary line voltage
a = transformer turns ratio

Let

$$\begin{aligned} V_b &= V_p \\ \mathrm{kVA}_b &= \mathrm{kVA}_T/3 \end{aligned}$$

where

kVA_T = Three phase kVA rating
kVA_b = kVA base

Therefore

$$\begin{aligned} I_b &= \mathrm{kVA}_b/V_b \\ Z_b &= V_b/I_b \end{aligned}$$

where

V_b = Voltage base
I_b = Current base
Z_b = Impedance base

Using the percentage leakage impedance value for the transformer the actual leakage impedance can be found as follows

$$Z_l = Z_{\%} \times Z_b$$

where

$Z_{\%}$ = Percentage leakage impedance
Z_l = Leakage impedance value

Assuming that the impedance is equally split between the HT and LT side the values of the transformer equivalent circuit can be found

$$\begin{aligned} Z_p &= \frac{Z_l}{2} \\ Z_s &= \frac{Z_l}{2a^2} \end{aligned}$$

where

Z_p = Primary impedance
Z_s = Secondary impedance

The primary resistance and inductance and secondary resistance and inductance can then be determined and used in the ATP three phase transformer model.

Appendix B

Cable Data

As per telephonic conversation with Adriaan Klark of Aberdare Cables (Pty) Limited, Port Elizabeth. The follow cable coefficients were confirmed.

Cable armour resistivity is $\mathbf{4.52 \times 10^{-7}}$ Ωm
Relative permeability of pipe conductor is **400**
Relative permittivity of PVC insulation is **8**
Relative permittivity of XLPE insulation is **2.5**
Conductor resistivity is $\mathbf{1.7 \times 10^{-8}}$ Ωm

Appendix C

Resonance Calculations

The resonant frequecy at each of the two capcitor banks, on the Brandspruit network that was investigated, was determined. Initially all machines were accounted for and then the network was reduced to single capacitance, inductance and resistance connected to each of the two bus bars.

C.1 Machine Equivalent Circuits

The first step was to calculate an equivalent resistance and inductance for each type of machine. This included various induction machines and transformers. The results are discussed below.

C.1.1 Induction Motors

Figure C.1 shows the basic equivalent circuit of an induction machine, as used by the induction motor parameter program [28]. R_L in the induction machine model is equal to $R'_2\frac{(1-s)}{s}$.

The induction motor program was used to generate the equivalent circuit values, and these values were reduced to find the overall impedance of the machine at a particular slip. The equivalent circuit values for the various machines are

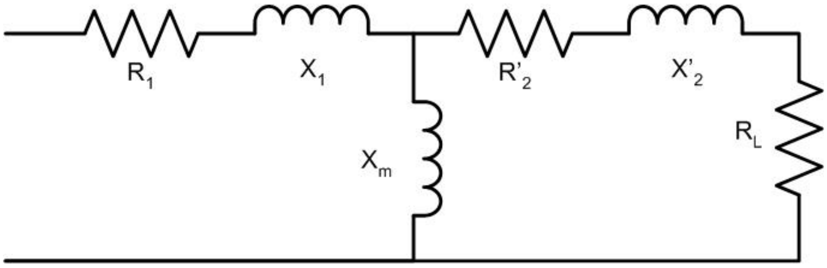

Figure C.1: Equivalent Circuit of Induction Motor

listed in Table C.1

Table C.1: Induction Motor Equivalent circuit Values

Machine Size (kW)	X_1 (H)	R_1 (Ω)	X_m (H)	R'_2 (Ω)	X'_2 (H)
200	2.78×10^{-3}	1.13×10^{-1}	4.41×10^{-2}	8.77×10^{-2}	2.78×10^{-3}
90	6.19×10^{-3}	2.50×10^{-1}	9.80×10^{-2}	1.95×10^{-1}	6.19×10^{-3}
37	6.46×10^{-4}	6.09×10^{-1}	1.28×10^{-1}	6.10×10^{-1}	6.46×10^{-4}
22	4.86×10^{-3}	1.02	2.27×10^{-1}	9.90×10^{-1}	4.86×10^{-3}
18	7.81×10^{-3}	1.25	2.83×10^{-1}	1.19	7.81×10^{-3}
8	4.40×10^{-2}	2.82	7.77×10^{-1}	2.43	4.40×10^{-2}
7.5	5.02×10^{-2}	3.00	8.55×10^{-1}	2.57	5.02×10^{-2}
7	5.79×10^{-2}	3.22	9.53×10^{-1}	2.71	5.79×10^{-2}
3.7	2.07×10^{-1}	6.07	5.79	4.19	2.07×10^{-1}

C.1.2 Transformer

The equivalent transformer circuit was calculated using the same method shown in Appendix A. The equivalent circuit used is shown in Figure C.2. The circuit is with reference to the primary side, hence all secondary values are multiplied by the "turns ration squared"

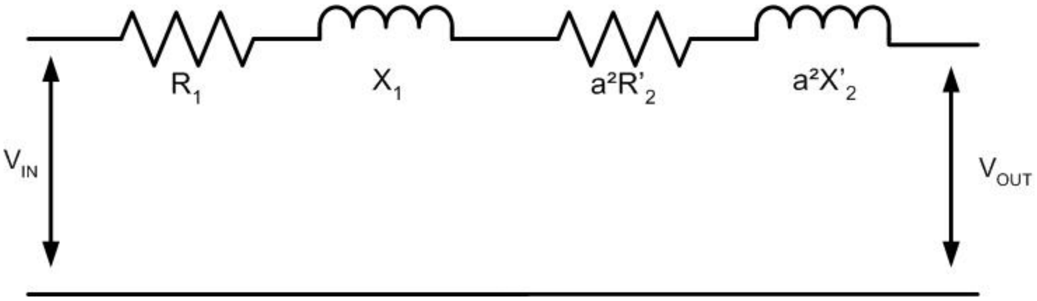

Figure C.2: Equivalent Circuit of a Transformer

Conclusion

The equivalent circuits for the machines were calculated and reduced assuming a slip of 0.95 [29, 30]. This is an assumption of the loading of a machine and does not cover all operating conditions for each machine. It is a suitable approximation as it assumes a typical operating load and is very likely to occur during production.

C.2 Network Reduction

The reduced machine circuits were grouped together to form the network as show in in Figure 5.5. The bus bars were grouped so that all inductive and resistive loads downstream of a bus bar, with capacitance, were combined. The following figures (C.3 to C.8) show the reduction of each individual bus bar to single impedance value.

The individual impedance value of each bus bar was then used to reduce the network to a single impedance (inductive and resistive) value, as shown in Figure C.9. This inductance together with the capacitive value was used to calculate the expected resonant frequency at the bus bar.

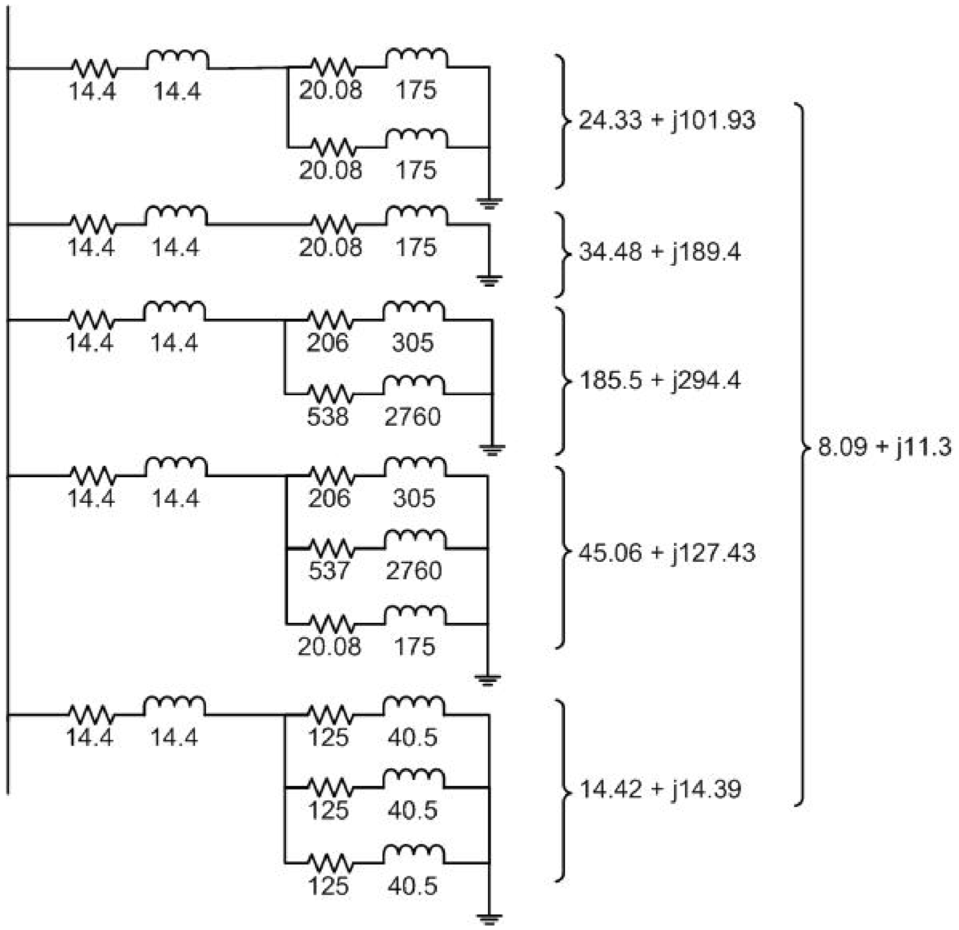

Figure C.3: Bus Bar 1 Reduction

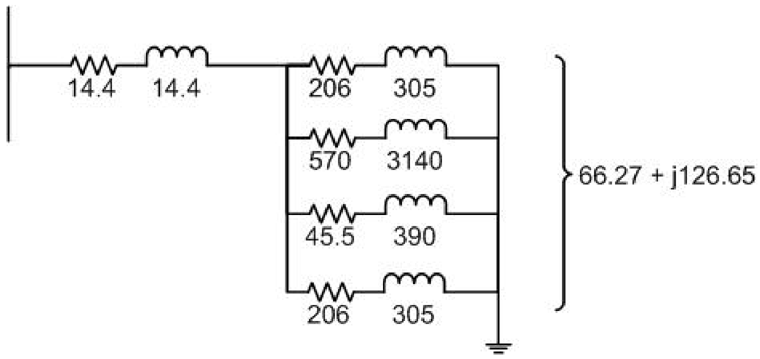

Figure C.4: Bus Bar 2 Reduction

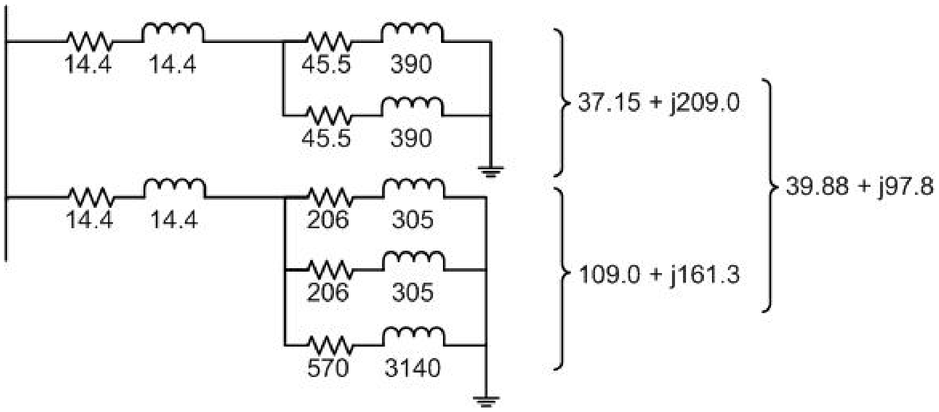

Figure C.5: Bus Bar 3 Reduction

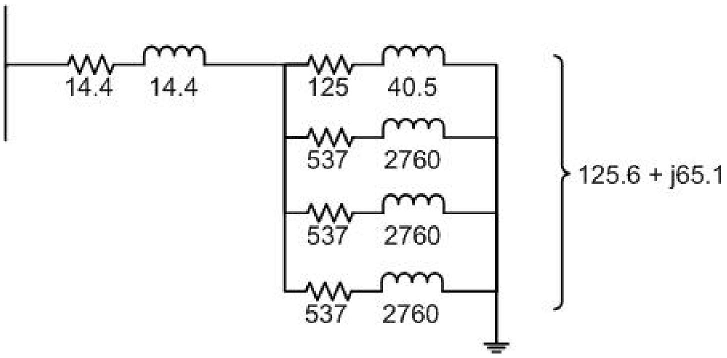

Figure C.6: Bus Bar 4 Reduction

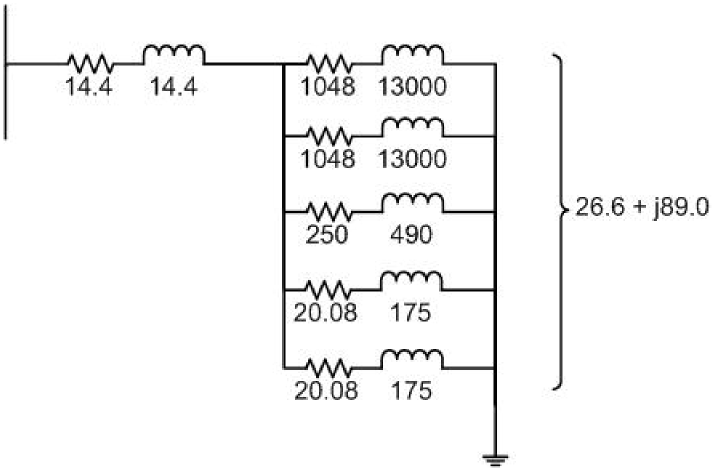

Figure C.7: Bus Bar 5 Reduction

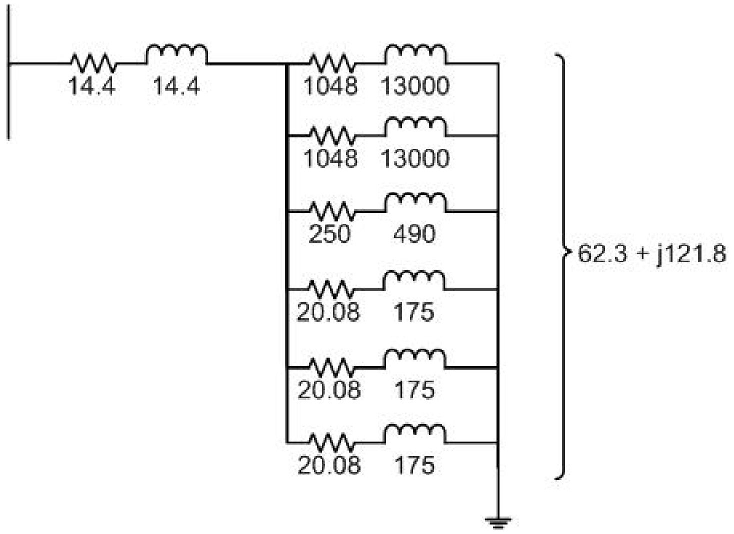

Figure C.8: Bus Bar 6 Reduction

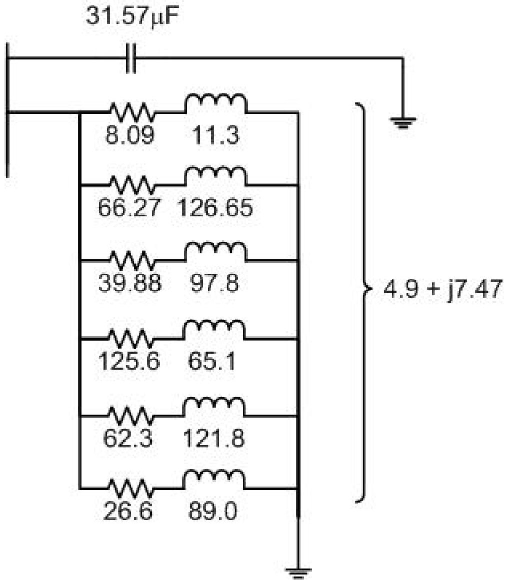

Figure C.9: Reduced Circuit for Calculation of Resonant Frequency at Surface PFC

From the impedance value the inductance was calculated in the following manner $L = \frac{X}{2\pi f} = 23.78\text{mH}$ and therefore the resonant frequency was found as follows

$$f = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{31.57\mu\text{F}\times 23.78mH}} = 183.69\text{Hz}$$

The resonant frequency is between harmonics (between 3^{rd} and 4^{th}) and hence is unlikely to be of concern.

The resonant frequency as calaculated in the same manner as above and was found to be nearly the 2^{nd} harmonic. resonance is unlicely to occur as there are no harmonic sources which produce a significant amount of 2^{nd} harmonic.

Appendix D

Excel Macro Code

This first code copies and seperates the data to different worksheets.

```
Sub column_copy()

Dim counter As Integer
Dim Junk As Integer
Dim sheetcount As Integer

Sheets.Add Count:=4
Sheets(4).Name = ("A %Fund")
Sheets(3).Name = ("A %RMS")
Sheets(2).Name = ("V %Fund")
Sheets(1).Name = ("V %RMS")


For sheetcount = 1 To 4
    'Copies the time Column
    Sheets(5).Select
        Columns(3).Select
        Selection.Copy
    Sheets(sheetcount).Select
        Cells(1, 1).Select
        ActiveSheet.Paste

    'Copies respective THD Coloumn
    Sheets(5).Select
```

```
        Columns(9 + sheetcount).Select
        Selection.Copy
    Sheets(sheetcount).Select
        Cells(1, 3).Select
        ActiveSheet.Paste

    'Copies Individual Harmonics
    For counter = 0 To 15
            Junk = counter * 4
            Sheets(5).Select
                Columns(16 + sheetcount + Junk).Select
                Selection.Copy
            Sheets(sheetcount).Select
                Cells(1, counter + 4).Select
                ActiveSheet.Paste
    Next counter
Next sheetcount
End Sub
```

This code determines the 95% value, as per NRS 048 .

```
Sub stat_check()
Dim colcount, rowcount, rowcounter As Integer
Dim comval  As Single
Dim cellform As String

For sheetcount = 1 To 4
    'select sheet to be edited
    Sheets(sheetcount).Select
    'start at the cell "A1"
    rowcount = 1
    colcount = 1

    'Count the number of rows
    While Cells(rowcount, colcount).Value <> ""
        rowcount = rowcount + 1
    Wend

    'set Headings
    Cells(rowcount + 1, 1).Value = "Mean"
```

```
Cells(rowcount + 2, 1).Value = "Standard Dev"
Cells(rowcount + 3, 1).Value = "Valid Min"
Cells(rowcount + 4, 1).Value = "Valid Max"
Cells(rowcount + 5, 1).Value = "Measured Max"

’Set up mean, standard Devation and max and min valid values
For colcount = 3 To 19
    cellform = "=average(r[-" & rowcount - 1 & "]c:R[-2]c)"
    Cells(rowcount + 1, colcount).FormulaR1C1 = cellform

    cellform = "=stdev(r[-" & rowcount & "]c:R[-3]c)"
    Cells(rowcount + 2, colcount).FormulaR1C1 = cellform
    comval = Cells(rowcount + 2, colcount)
    Cells(rowcount + 2, colcount) = comval

    Cells(rowcount + 3, colcount).FormulaR1C1 = "=R[-2]C - R[-1]c"
    comval = Cells(rowcount + 3, colcount)
    Cells(rowcount + 3, colcount) = comval

    Cells(rowcount + 4, colcount).FormulaR1C1 = "=R[-3]C + R[-2]c"
    comval = Cells(rowcount + 4, colcount)
    Cells(rowcount + 4, colcount) = comval

    cellform = "=max(r[-" & rowcount + 4 & "]c:R[-6]c)"
    Cells(rowcount + 5, colcount).FormulaR1C1 = cellform
    comval = Cells(rowcount + 5, colcount)
    Cells(rowcount + 5, colcount) = comval

Next colcount

’Make statistically irrelivant data red
For colcount = 3 To 19

 For rowcounter = 2 To rowcount
    If Cells(rowcounter, colcount).Value < Cells(rowcount + 3, colcount) Then
         Cells(rowcounter, colcount).Font.ColorIndex = 3
    End If
    Next rowcounter
    comval = Cells(rowcount + 4, colcount)
    For rowcounter = 2 To rowcount
        If Cells(rowcounter, colcount).Value > Cells(rowcount + 4, colcount) Then
```

```
                Cells(rowcounter, colcount).Font.ColorIndex = 3
            End If
        Next rowcounter
    Next colcount
Next sheetcount
End Sub
```

Run the various functions in order and saves the files.

```
Sub workall()
    Application.CutCopyMode = False
    Application.Run "'macro file.xls'!column_copy"
    Application.Run "'macro file.xls'!stat_check"
    Application.Run "'macro file.xls'!graphing"
    Application.Run "'macro file.xls'!save"
End Sub
Sub save()
    Dim strCaption As String

    strCaption = Application.Caption
    Mid(strCaption, 1, 18) = "                  "
    strCaption = Application.ActiveWorkbook.Path & "\" & Trim(strCaption) & ".xls"
    ActiveWorkbook.SaveAs FileName:=strCaption, _
    FileFormat:=xlNormal, password:="", Writerespassword:="", _
    ReadOnlyRecommended:=False, CreateBackup:=False
End Sub
```

Plots the graphs

```
Sub graphing()
    Dim rowcount, Count As Integer
    Dim strCaption As String

    strCaption = Application.Caption
    Mid(strCaption, 1, 18) = "                  "
    strCaption = Trim(strCaption)

    '---------V % RMS -----------------------------
    'Start in the first row
    rowcount = 1

    'V % RMS
```

```
Sheets("V %RMS").Select

'need to find the mean row
While Cells(rowcount, 1).Value <> "Mean"
    rowcount = rowcount + 1
Wend
'Create better Titles
With ActiveChart
    For Count = 0 To 15
        Cells(1, Count + 4).Value = 2 * Count + 1
    Next Count
End With
'add the chart
Charts.Add
ActiveChart.ChartType = xlColumnClustered
'edit here
With Sheets("V %RMS")
    ActiveChart.SetSourceData Source:=.Range("A24:A27"), PlotBy _
        :=xlColumns
    ActiveChart.SeriesCollection(1).Delete
    ActiveChart.SeriesCollection.NewSeries
    ActiveChart.SeriesCollection(1).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
    ActiveChart.SeriesCollection(1).Values = .Range(.Cells(rowcount, 5), .Cells(rowcount, 19))
    ActiveChart.SeriesCollection.NewSeries
    ActiveChart.SeriesCollection(2).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
    ActiveChart.SeriesCollection(2).Values = .Range(.Cells(rowcount + 3, 5), .Cells(rowcount + 3, 19))
    ActiveChart.SeriesCollection.NewSeries
    ActiveChart.SeriesCollection(3).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
    ActiveChart.SeriesCollection(3).Values = .Range(.Cells(rowcount + 4, 5), .Cells(rowcount + 4, 19))

End With
ActiveChart.Location Where:=xlLocationAsNewSheet, Name:="V % of RMS"

With ActiveChart
    .HasTitle = True
    .ChartTitle.Text = strCaption
    .Axes(xlCategory, xlPrimary).HasTitle = True
'and here
    .Axes(xlCategory, xlPrimary).AxisTitle.Characters.Text = "Harmonic Order"
    .Axes(xlValue, xlPrimary).HasTitle = True
    .Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "% V of RMS V"
End With
With ActiveChart.Axes(xlCategory)
    .HasMajorGridlines = False
    .HasMinorGridlines = False
End With
With ActiveChart.Axes(xlValue)
    .HasMajorGridlines = False
    .HasMinorGridlines = False
End With
ActiveChart.HasLegend = False
ActiveChart.HasDataTable = False
```

```
    ActiveChart.PlotArea.Select
    Selection.ClearFormats
'---------V %Fund ----------------------------
    'Start in the first row
    rowcount = 1

    Sheets("V %Fund").Select

    'need to find the mean row
    While Cells(rowcount, 1).Value <> "Mean"
        rowcount = rowcount + 1
    Wend
    'Create better Titles
    With ActiveChart
        For Count = 0 To 15
            Cells(1, Count + 4).Value = 2 * Count + 1
        Next Count
    End With
    'add the chart
    Charts.Add
    ActiveChart.ChartType = xlColumnClustered
    'edit here
    With Sheets("V %Fund")
        ActiveChart.SetSourceData Source:=.Range("A24:A27"), PlotBy _
            :=xlColumns
        ActiveChart.SeriesCollection(1).Delete
        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(1).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
        ActiveChart.SeriesCollection(1).Values = .Range(.Cells(rowcount, 5), .Cells(rowcount, 19))
        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(2).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
        ActiveChart.SeriesCollection(2).Values = .Range(.Cells(rowcount + 3, 5), .Cells(rowcount + 3, 19))
        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(3).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
        ActiveChart.SeriesCollection(3).Values = .Range(.Cells(rowcount + 4, 5), .Cells(rowcount + 4, 19))
    End With
    ActiveChart.Location Where:=xlLocationAsNewSheet, Name:="V % of Fundamental"

    With ActiveChart
        .HasTitle = True
        .ChartTitle.Text = strCaption
        .Axes(xlCategory, xlPrimary).HasTitle = True
        .Axes(xlCategory, xlPrimary).AxisTitle.Characters.Text = "Harmonic Order"
        .Axes(xlValue, xlPrimary).HasTitle = True
        .Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "% V of Fundamental V"
    End With
    With ActiveChart.Axes(xlCategory)
        .HasMajorGridlines = False
        .HasMinorGridlines = False
    End With
    With ActiveChart.Axes(xlValue)
        .HasMajorGridlines = False
```

```
    .HasMinorGridlines = False
End With
ActiveChart.HasLegend = False
ActiveChart.HasDataTable = False
ActiveChart.PlotArea.Select
Selection.ClearFormats

'---------A % RMS ----------------------------
'Start in the first row
rowcount = 1

Sheets("A %RMS").Select

'need to find the mean row
While Cells(rowcount, 1).Value <> "Mean"
    rowcount = rowcount + 1
Wend
'Create better Titles
With ActiveChart
    For Count = 0 To 15
        Cells(1, Count + 4).Value = 2 * Count + 1
    Next Count
End With
'add the chart
Charts.Add
ActiveChart.ChartType = xlColumnClustered
'edit here
With Sheets("A %RMS")
    ActiveChart.SetSourceData Source:=.Range("A24:A27"), PlotBy _
        :=xlColumns
    ActiveChart.SeriesCollection(1).Delete
    ActiveChart.SeriesCollection.NewSeries
    ActiveChart.SeriesCollection(1).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
    ActiveChart.SeriesCollection(1).Values = .Range(.Cells(rowcount, 5), .Cells(rowcount, 19))
    ActiveChart.SeriesCollection.NewSeries
    ActiveChart.SeriesCollection(2).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
    ActiveChart.SeriesCollection(2).Values = .Range(.Cells(rowcount + 3, 5), .Cells(rowcount + 3, 19))
    ActiveChart.SeriesCollection.NewSeries
    ActiveChart.SeriesCollection(3).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
    ActiveChart.SeriesCollection(3).Values = .Range(.Cells(rowcount + 4, 5), .Cells(rowcount + 4, 19))

End With
ActiveChart.Location Where:=xlLocationAsNewSheet, Name:="A % of RMS"

With ActiveChart
    .HasTitle = True
    .ChartTitle.Text = strCaption
    .Axes(xlCategory, xlPrimary).HasTitle = True
'and here
    .Axes(xlCategory, xlPrimary).AxisTitle.Characters.Text = "Harmonic Order"
    .Axes(xlValue, xlPrimary).HasTitle = True
    .Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "% A of RMS A"
```

```
    End With
    With ActiveChart.Axes(xlCategory)
        .HasMajorGridlines = False
        .HasMinorGridlines = False
    End With
    With ActiveChart.Axes(xlValue)
        .HasMajorGridlines = False
        .HasMinorGridlines = False
    End With
    ActiveChart.HasLegend = False
    ActiveChart.HasDataTable = False
    ActiveChart.PlotArea.Select
    Selection.ClearFormats
'---------A %Fund ----------------------------
    'Start in the first row
    rowcount = 1

    Sheets("A %Fund").Select

    'need to find the mean row
    While Cells(rowcount, 1).Value <> "Mean"
        rowcount = rowcount + 1
    Wend
    'Create better Titles
    With ActiveChart
        For Count = 0 To 15
            Cells(1, Count + 4).Value = 2 * Count + 1
        Next Count
    End With
    'add the chart
    Charts.Add
    ActiveChart.ChartType = xlColumnClustered
    'edit here
    With Sheets("A %Fund")
        ActiveChart.SetSourceData Source:=.Range("A24:A27"), PlotBy _
            :=xlColumns
        ActiveChart.SeriesCollection(1).Delete
        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(1).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
        ActiveChart.SeriesCollection(1).Values = .Range(.Cells(rowcount, 5), .Cells(rowcount, 19))
        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(2).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
        ActiveChart.SeriesCollection(2).Values = .Range(.Cells(rowcount + 3, 5), .Cells(rowcount + 3, 19))
        ActiveChart.SeriesCollection.NewSeries
        ActiveChart.SeriesCollection(3).XValues = .Range(.Cells(1, 5), .Cells(1, 19))
        ActiveChart.SeriesCollection(3).Values = .Range(.Cells(rowcount + 4, 5), .Cells(rowcount + 4, 19))

    End With
    ActiveChart.Location Where:=xlLocationAsNewSheet, Name:="A % of Fundamental"

    With ActiveChart
        .HasTitle = True
```

```
        .ChartTitle.Text = strCaption
        .Axes(xlCategory, xlPrimary).HasTitle = True
        .Axes(xlCategory, xlPrimary).AxisTitle.Characters.Text = "Harmonic Order"
        .Axes(xlValue, xlPrimary).HasTitle = True
        .Axes(xlValue, xlPrimary).AxisTitle.Characters.Text = "% A of Fundamental A"
    End With
    With ActiveChart.Axes(xlCategory)
        .HasMajorGridlines = False
        .HasMinorGridlines = False
    End With
    With ActiveChart.Axes(xlValue)
        .HasMajorGridlines = False
        .HasMinorGridlines = False
    End With
    ActiveChart.HasLegend = False
    ActiveChart.HasDataTable = False
    ActiveChart.PlotArea.Select
    Selection.ClearFormats

End Sub
```