# IMPLICATIONS OF APPLYING DIFFERENT VAR SUPPORT TECHNOLOGIES IN THE ESKOM TRANSMISSION NETWORK WITH PARTICULAR EMPHASIS ON THE LIFECYCLE COST

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

Johannesburg, 2011

**DECLARATION**

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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(Signature of Candidate)

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## *Abstract*

Lifecycle cost implications of applying different VAr support technologies in the Eskom Transmission network have been investigated, taking into consideration the following VAr support options:

- Plain capacitor bank.
- Plain capacitor bank with expansion capability.
- De-tuned capacitor bank.
- C-type filter.

The investigation has showed that for a 275kV 150 MVAr capacitor bank, the lifecycle cost of a C-type filter bank is 1, 73 times that of a plain capacitor bank and 1, 31 times that of a de-tuned capacitor bank, evaluated over a 20 years period. This high cost of the C-type filter bank is mainly due to the initial capital cost, as the operational cost of the de-tuned capacitor bank is higher than the other topologies. A change in the dielectric medium used for the capacitor units from PCB to all film dielectric has reduced the operational cost drastically.

The performance of the C-type filter is better during inrush and transient conditions and therefore provides higher reliability. Additionally, a C-type filter has better harmonic performance, and provides harmonic damping over a range of frequencies.

***In memory of my late parents***
***Pule and***
***Nodathini Ramorapeli***

## *Acknowledgements*

I hereby wish to express my sincere gratitude to a large number of special individuals who have inspired me to complete this thesis:

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- To my late brother Thabo, you might have been gone but your spirit lives on.
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# 1. Introduction

Power quality has in the past 15-20 years been prioritised by utilities, customers and the regulator in the wake of the economic costs associated with poor quality of supply. Customer awareness of poor power quality has also increased due to the sensitive nature of modern loads and due to the increasing deployment of nonlinear loads, such as power converters, computers and arc furnaces. As a result, the planning of electrical networks in the short, medium to long term has to ensure that the power quality delivered to customers is sustainable in the long term.

The deviation of the voltage waveform supplied by the public network from the ideal sinusoid (i.e. the level of distortion of the voltage waveform), can be described in terms of the presence of voltage harmonics. These harmonics can be either integer multiples of the fundamental power frequency or non-integer multiples (inter-harmonics). In the presence of harmonic resonance where shunt capacitors are installed in the system, harmonics get amplified to levels that might be excessive, as shown in Figure 1.1.

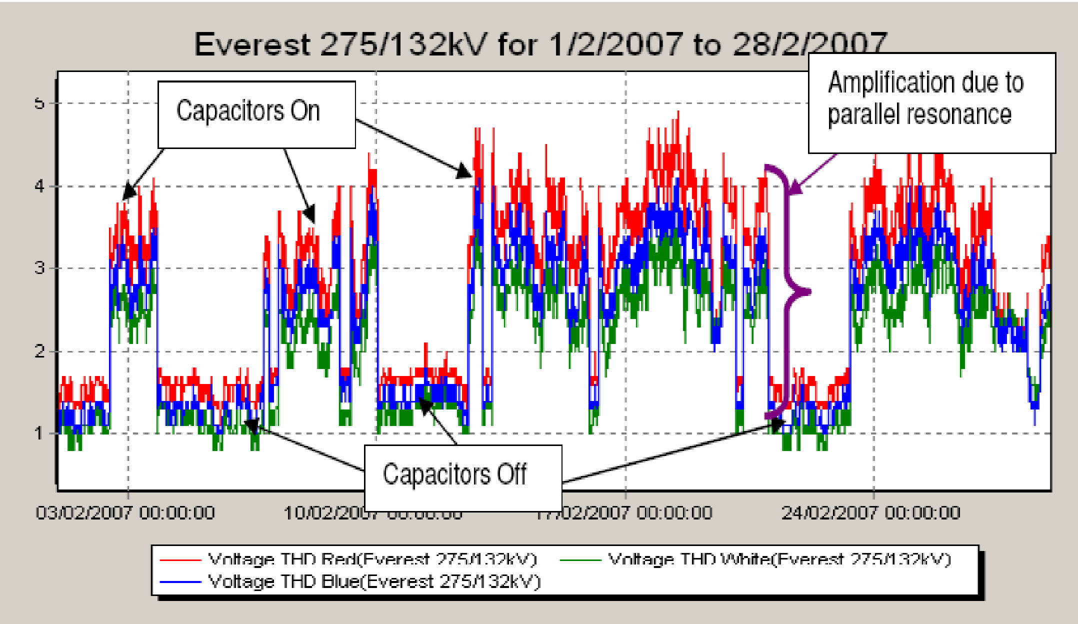



*Figure 1.1: High levels of THD due to a parallel harmonic resonance caused by the switching of a capacitor bank at Everest substation*

This study will focus on the lifecycle cost implications of applying various shunt capacitor bank topologies in the Eskom Transmission network.

The work done in this study was broken down into the following chapters:
Chapter 2 explains the concept of harmonic distortion, showing briefly examples on how harmonics are generated in the electrical power system. The effects and mitigation options available as well as the planning and compatibility levels are also discussed.

One of the most important factors influencing the levels of voltage harmonics are shunt capacitor banks in the power system that can cause resonance. Shunt capacitor banks have the function of improving the power transfer capability of a power system as well as voltage magnitude improvement, especially during high loading periods. Chapter 3 discusses harmonic resonance and factors influencing it, while Chapter 4 analyzes the planning considerations required for the control and management of harmonics in a power system. A rule-of-thumb equation is developed here, as a first line investigation tool to determine if the planned capacitor bank will cause resonance in the system.

Chapter 5 discusses the currently installed shunt capacitor banks in the Eskom Transmission network taking into consideration the current trends of THD levels. The aim is to evaluate their resonance frequencies and to introduce initiatives in managing harmonic levels where resonance is a problem. Chapter 6 will thereafter look at the initial costs of installing various shunt capacitor bank topologies, while Chapter 7 will look at the performance of different topologies with more emphasis on plain capacitor banks vs. C-type filters. Chapter 8 discusses the operational costs for various shunt capacitor bank topologies with more emphasis on the dielectric losses and power losses. The overall lifecycle cost implications of applying various VAr support topologies are discussed in Chapter 9.

Chapter 10 deals with the overall model for the lifecycle costing for shunt capacitor banks in the Eskom Transmission system as well as discussing some shortcomings of this study and future work that still needs to be done.

In the past 2-3 years, the electricity demand is South Africa has risen above expectation to the point where the spare capacity that was always available in the system was reduced. As a result, shunt capacitor banks installed in the power system that were otherwise used mainly during contingencies are now frequently used to improve the transfer of power from the generating stations to load centres. Some of these shunt capacitor banks are causing harmonic resonance near the fifth harmonic frequency and are therefore amplifying the harmonics levels at that point of supply to levels greater than the planning levels and at some substations to levels greater than the compatibility levels.

Figure 1.2 shows the THD exceedances (Eskom Business Plan and Eskom Operational Health Dashboard) for all the Eskom Transmission sites from 2001 to 2009 against the 5% target. It can be seen here that the THD exceedances have increased over the years, especially after 2006. The Eskom Business Plan is used for internal reporting and therefore the limit is lower than the Eskom Operational Health Dashboard limit. For the Eskom Business Plan limit the NRS planning limit of 3% is used for most of the sites, while the NRS compatibility limit of 4% is used for the Eskom Operational Health Dashboard.

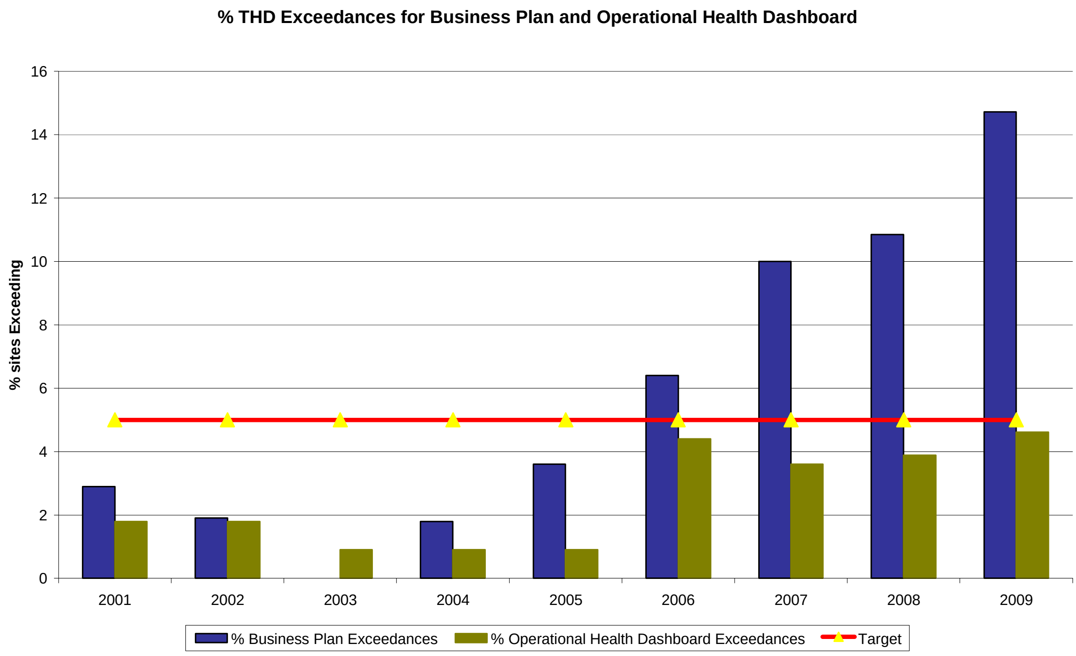



*Figure 1.2: % THD exceedances for Business Plan and Operational Health Dashboard [17]*

The 2008 – 2009 THD exceedances were analysed and it was found that 72% were due to shunt capacitor banks resonating with the system near the fifth harmonic frequency, as shown on Figure 1.3.

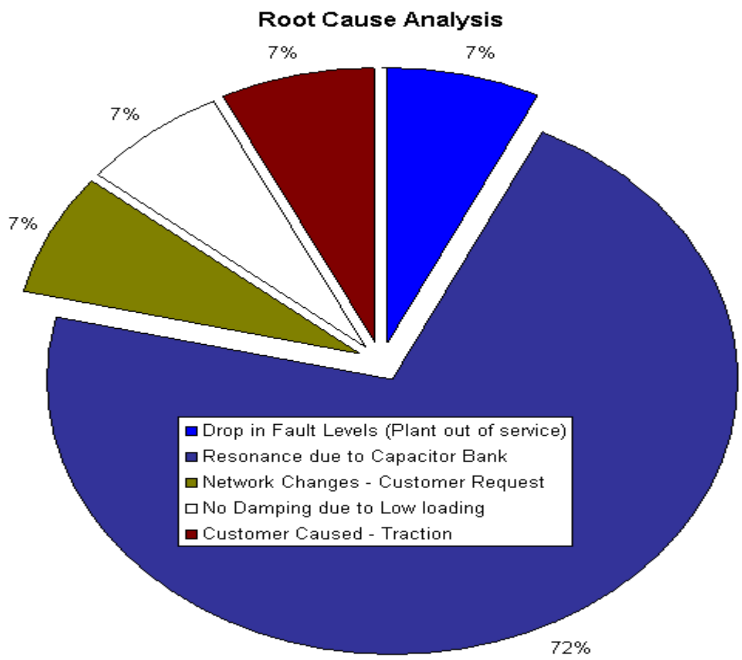



*Figure 1.3: Root cause analysis for high THD levels in Eskom Transmission networks for 2008-2009 financial year [17]*

The rapidly expanding Eskom Transmission network will require VAr support in the form of shunt capacitor banks and therefore proper lifecycle costing of this equipment needs to be understood, so that proper investment decisions can be made by the organisation.

# 2. Harmonics

## *2.1 Introduction*

In this chapter, harmonics will be discussed in terms of causes, effects and the mitigation options available. The tone will be set in this chapter to enable the reader to understand the issues related to harmonics.

## *2.2 Explanation of harmonics*

When power is generated at power stations, the voltage waveforms are nearly perfect sinusoids. However, the voltage and current waveforms can become distorted within the power system.

The distorted waveform can be resolved, using Fourier analysis, into its fundamental component and its harmonic components. The fundamental component is normally at a frequency of 50Hz and the harmonics are at frequencies that are integer multiples of the fundamental (50Hz) frequency.

The integer multiple of the fundamental frequency gives the harmonic order, h. Thus the third harmonic would have a frequency of 150Hz, the fifth harmonic a frequency of 250Hz etc.

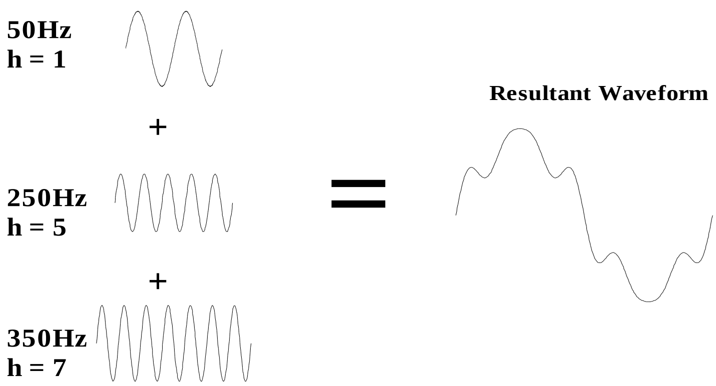



*Figure 2.1: Distorted sinusoid*

As the frequencies of the harmonics increase, their magnitudes tend to decrease.

The way harmonic currents flow is dependent on the impedance of the network at that frequency. In the absence of capacitor banks in the direct vicinity of the harmonic source, harmonic currents will always tend to flow back towards the supply source. However, if there is a capacitor bank nearby, the flow of harmonic currents will depend on which path has the lower impedance.

In order to quantify the amount of harmonics present within the waveform, the Total Harmonic Distortion (THD) is used. The THD is defined as the square root of the sum of the squares of the voltage or current harmonics expressed in per unit of the fundamental component for voltage harmonics and in Amps for current harmonics. In mathematical terms, it is:

$$THD = \sqrt{\sum_h V(h)^2} \qquad [2.1]$$

Where V(h) is the magnitude (% of the fundamental) of harmonic component h

### *2.3 Causes of harmonics*

Nonlinear loads are the primary cause of harmonics within a power system. Traditional loads (e.g. incandescent lighting, heating, direct-on-line motors etc) draw a sinusoidal current. However, nonlinear loads draw non-sinusoidal current. For example, the current drawn by a three-phase diode bridge supplying a VSD consists of a pair of current pulses during each voltage half cycle.

Examples of nonlinear loads are:

- Variable Speed Drives (VSDs)
- Arc furnaces
- Saturated transformers

The non-sinusoidal currents, suggesting the presence of current harmonics, produce harmonic voltage drops across the supply impedances and hence the supply voltage waveform contains voltage harmonics. Generally the harmonic content present in current waveforms is far greater than the harmonic content in the voltage waveform because of low supply impedance. Nonlinear loads are appearing in ever-increasing numbers and in very large power ratings.

### *2.4 Effects of harmonics*

Harmonics in a power system have the following effects: [6, 7, 21, 22]

- Increased resistive losses in transformers, capacitors, cables, lines, motors, and neutral conductors. These resistive ($I^2R$) losses are compounded by skin effect.
- Increased winding eddy-current and stray load losses in transformers.
- Overvoltages across capacitors (usually due to resonances).
- Control circuit and protection relay maloperation (due to multiple zero-crossings that arise with high levels of distortion).
- Audible noise in transformers, reactors, filters and motors.
- Interference with telecommunication circuits due to coupling.

## 2.5 Mitigation options

Solutions to harmonic problems generally address one or more of the following: [6]

<u>Design interventions:</u>
Physical reduction of the harmonic currents generated by a given item of equipment (for example, the use of active rectifiers in variable speed drives rather than a simple diode bridge).

<u>Filtering:</u>
The diversion of harmonic currents away from the system (using passive filters), or the injection of phase-shifted harmonic components, giving rise to cancellation (using the phase shift characteristics of transformer winding configurations, or active filtering).

<u>Reducing the system impedance:</u>
Increasing the system short circuit power and avoiding system resonance conditions at harmonic frequencies.

## 2.6 Planning and compatibility levels for harmonics

The compatibility levels defined in IEC are reference values for the coordination of equipment emission levels and immunity levels. Some countries (such as the UK and South Africa) have adopted these levels (and the term compatibility level) as the harmonic objectives for their networks. Tables 2.1 and 2.2 shows the compatibility levels defined by NRS 048-2, based on the IEC 61000-2-2 and IEC 61000-2-34 compatibility levels. The compatibility level for total harmonic distortion (THD) is specified as 8% for MV and LV. Table 2.3 shows the planning levels for EHV/HV and MV.

Table 2.1: NRS048-2 MV and LV harmonic compatibility levels.

MV and LV Compatibility Levels

| Odd harmonics (non-multiple of 3) | | Odd harmonics (multiple of 3) | | Even harmonics | |
|---|---|---|---|---|---|
| Order | % | Order | % | Order | % |
| 5 | 6 | 3 | 5 | 2 | 2 |
| 7 | 5 | 9 | 1.5 | 4 | 1 |
| 11 | 3.5 | 15 | 0.3 | 6 | 0.5 |
| 13 | 3 | 21 | 0.2 | 8 | 0.5 |
| 17 | 2 | >21 | 0.2 | 10 | 0.5 |
| 19 | 1.5 | | | 12 | 0.2 |
| 23 | 1.5 | | | >12 | 0.2 |
| 25 | 1.5 | | | | |
| >25 | 0.2+ 1.3x25/h | | | | |

THD : 8%

Table 2.2: NRS 048-2 HV and EHV voltage compatibility levels.

| **Harmonic order (h)** | **HV – EHV Harmonic Voltage (%)** |
|---|---|
| 3 | 2.5 |
| 5 | 3 |
| 7 | 2.5 |
| 11 | 1.7 |
| 13 | 1.7 |
| 17 | 1.2 |
| 19 | 1.2 |
| 23 | 0.8 |
| 25 | 0.8 |
| THD | 4 |

Table 2.3: NRS048-4 Indicative harmonic planning levels.

| **Odd order non-triplen** | | | **Odd order triplen** | | | **Even order** | | |
|---|---|---|---|---|---|---|---|---|
| **h** | **Harmonic voltage %** | | **h** | **Harmonic voltage %** | | **h** | **Harmonic voltage %** | |
| | **MV** | **HV-EHV** | | **MV** | **HV-EHV** | | **MV** | **HV-EHV** |
| 5 | 5 | 2 | 3 | 4 | 2 | 2 | 1,6 | 1.5 |
| 7 | 4 | 2 | 9 | 1.2 | 1 | 4 | 1 | 1 |
| 11 | 3 | 1.5 | 15 | 0.3 | 0.3 | 6 | 0.5 | 0.5 |
| 13 | 2.5 | 1.5 | 21 | 0.2 * | 0.2 * | 8 | 0.4 | 0.4 |
| 17 | 1.6 | 1 | >21 | 0.2 * | 0.2 * | 10 | 0.4 | 0.4 |
| 19 | 1.2 | 1 | | | | 12 | 0.2 * | 0.2 * |
| 23 | 1.2 | 0,7 | | | | >12 | 0.2 * | 0.2 * |
| 25 | 1.2 | 0,7 | | | | | | |
| >25 | 0.2 + 0.5 (25/h) | 0.2 + 0.5 (25/h) | | | | | | |
| Note 1: Total harmonic distortion (THD): 6.5% at MV and 3 % at HV-EHV. | | | | | | | | |

# 3. Harmonic resonance

## 3.1 Introduction

The levels of harmonics can be amplified as a result of resonance within the power system. Resonance occurs at specific frequencies, which are determined by the capacitive (primarily shunt capacitor banks) and inductive (primarily power transformers) components. During resonance, the inductive and capacitive components have equal reactance but opposite sign, and these frequencies are then termed the "resonant frequencies". The resonant frequency is determined by using the following formula:

$$f_{resonance} = \frac{1}{2\pi\sqrt{LC}} \qquad [3.1]$$

Where:
$f_{resonance}$ = is the resonant frequency, in Hertz
L = is the filter inductance, in henrys
C = is the filter capacitance, in farads

Resonance within the network can either be "series" or "parallel", depending upon where in the network the harmonic source is. Figures 3.1 and 3.2 illustrate situations of series and parallel circuits.

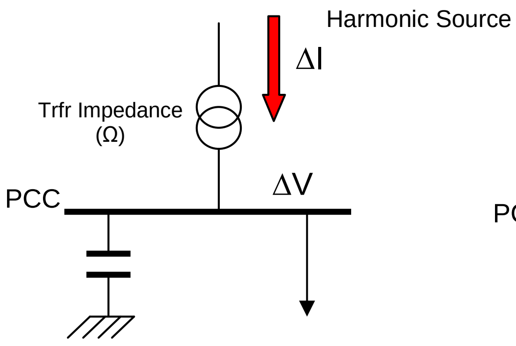



*Fig. 3.1: Series circuit*

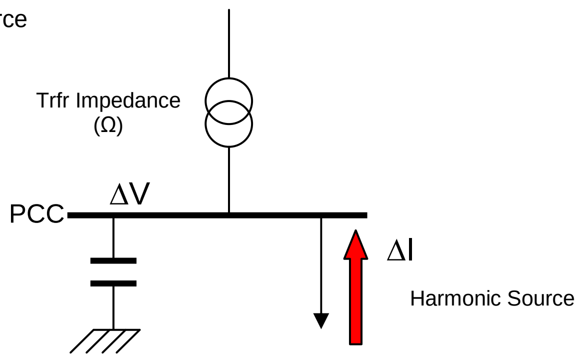



*Fig. 3.2: Parallel circuit*

Figure 3.3 and 3.4 shows impedance vs frequency (harmonic order) plots for series and parallel resonances.

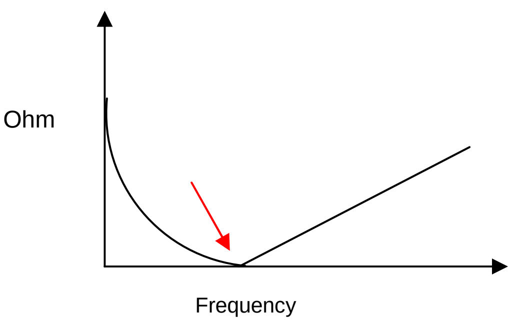



*Fig. 3.3: Series resonance*

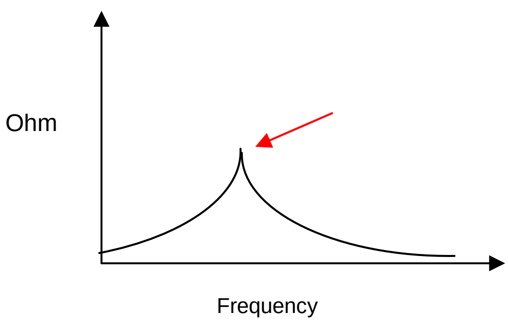



*Fig. 3.4: Parallel resonance*

### *3.2 Factors affecting the harmonic resonance frequency and the harmonic amplification factor.*

Figure 3.5 below shows the harmonic impedance plots for a network, for when there is no capacitor bank installed and for when it is installed. Without a capacitor bank the network impedance is linear with frequency. The harmonic resonance is clearly visible near the 5$^{th}$ harmonic frequency when the capacitor bank is switched on. The harmonic amplification factor near the 5$^{th}$ harmonic frequency can thus be calculated as follows:

Harmonic amplification factor ($K_h$) = Z Ω $_{(Cap\ ON)}$ / Z Ω $_{(Cap\ OFF)}$ [3.2]

$K_h$ at fifth harmonic frequency = 57.819 Ω/ 18.156Ω = 3.18

The background harmonic level at the fifth harmonic frequency will therefore get amplified by a factor of 3.18 when the capacitor bank is switched on.

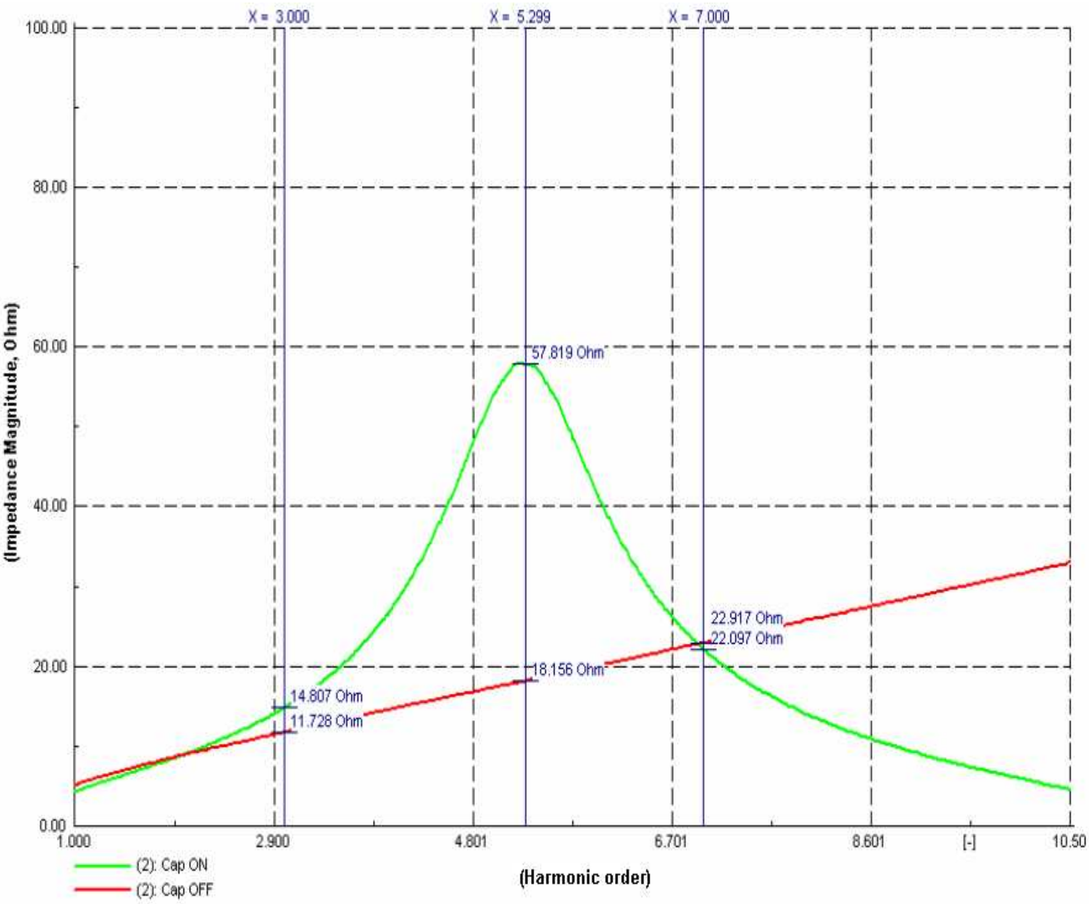



*Figure 3.5: Harmonic impedance plots illustrating harmonic amplification and resonance when a capacitor bank is switched on.*

The harmonic resonance frequency and the harmonic amplification factor are influenced by the following:

- The three phase short circuit power at that point of supply.
- The loading of the network.

- The size of the capacitor bank to be installed.
- Network contingencies.
- Shunt capacitor bank technologies.
- The load composition (active and reactive powers).

These factors will be analyzed in the form of case studies where different networks and different types of capacitor banks were utilized in the assessment of resonance.

### *3.3 Case study 1*

In this case study, the influence of short circuit power and loading patterns are analysed for different Eskom Transmission networks. This will show how the resonance frequencies and the amplification factors are affected by doing studies on three separate Eskom Transmission networks, with different characteristics, as shown on Table 3.1. Their respective network diagrams are shown on Figures 3.6 to 3.8.

Table 3.1: Network characteristics of the three Eskom Transmission sites.

| **Busbar** | **$S_{kss}$ (MVA)** | **$I_{kss}$ (kA)** | **X/R ratio** |
|---|---|---|---|
| Marathon 275kV | 5585.77 | 11.73 | 6.76 |
| Komati 275kV | 10440.74 | 21.92 | 14.36 |
| Makalu 275kV | 16080 | 33.77 | 15.9 |

Where:
$S_{kss}$ – is the three phase short circuit power, in MVA
$I_{kss}$ – is the three phase short circuit current, in kA
X/R ratio – is the ratio between the inductive reactance component and the resistive component of a network due to line and transformer impedances.

From this table, Marathon substation is seen as having the lowest short circuit power as the substation is situated far from the generation pool. The X/R ratio at this substation is also low as compared to the other substations, as it has Distribution interconnections (Distribution lines have lower X/R ratios). Komati substation on the other hand has a medium to high short circuit power, as it is situated near power stations with high X/R ratios. Makalu substation has a high short circuit power as it is situated near Lethabo power station and has a large number of parallel interconnections.

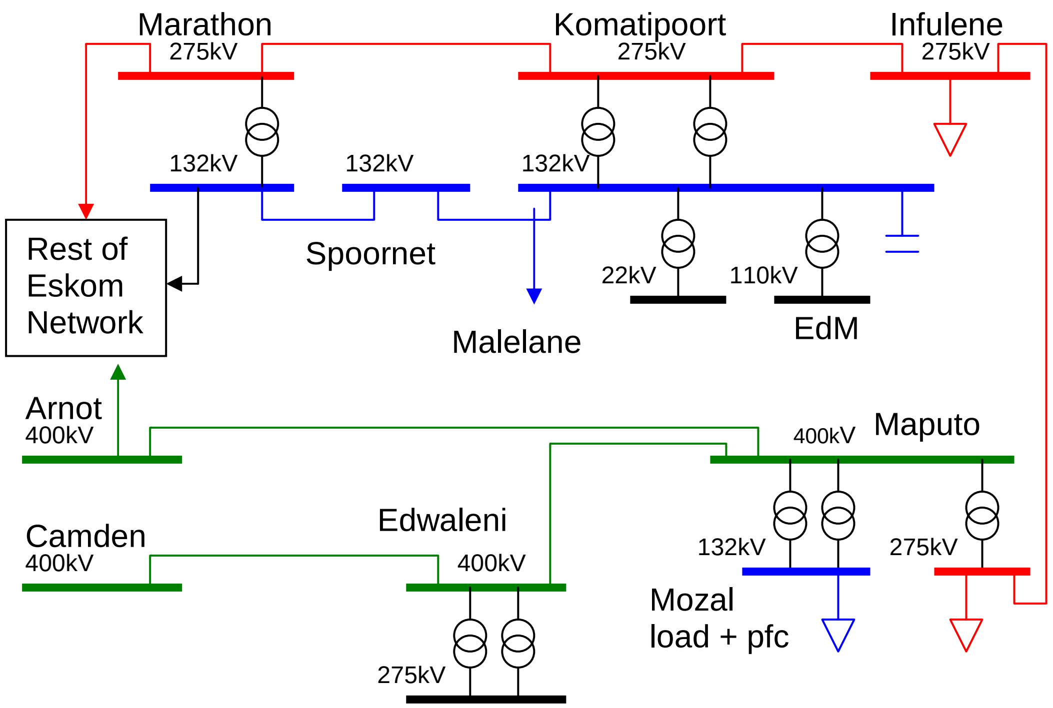



*Figure 3.6: Simplified Marathon network diagram*

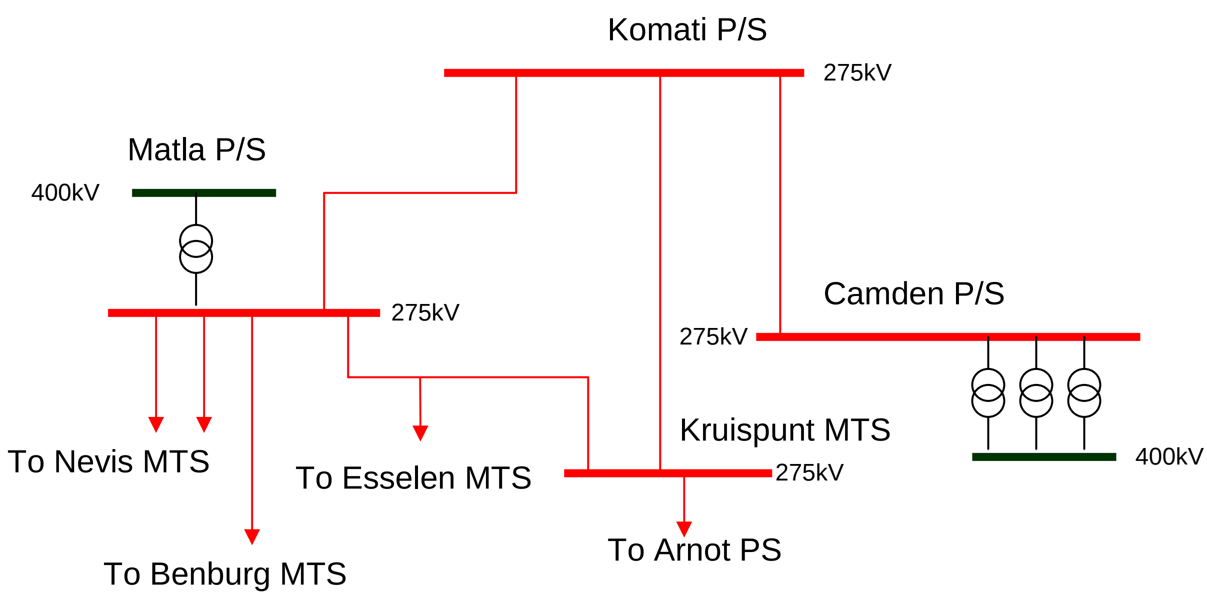



*Figure 3.7: Simplified Komati network diagram*

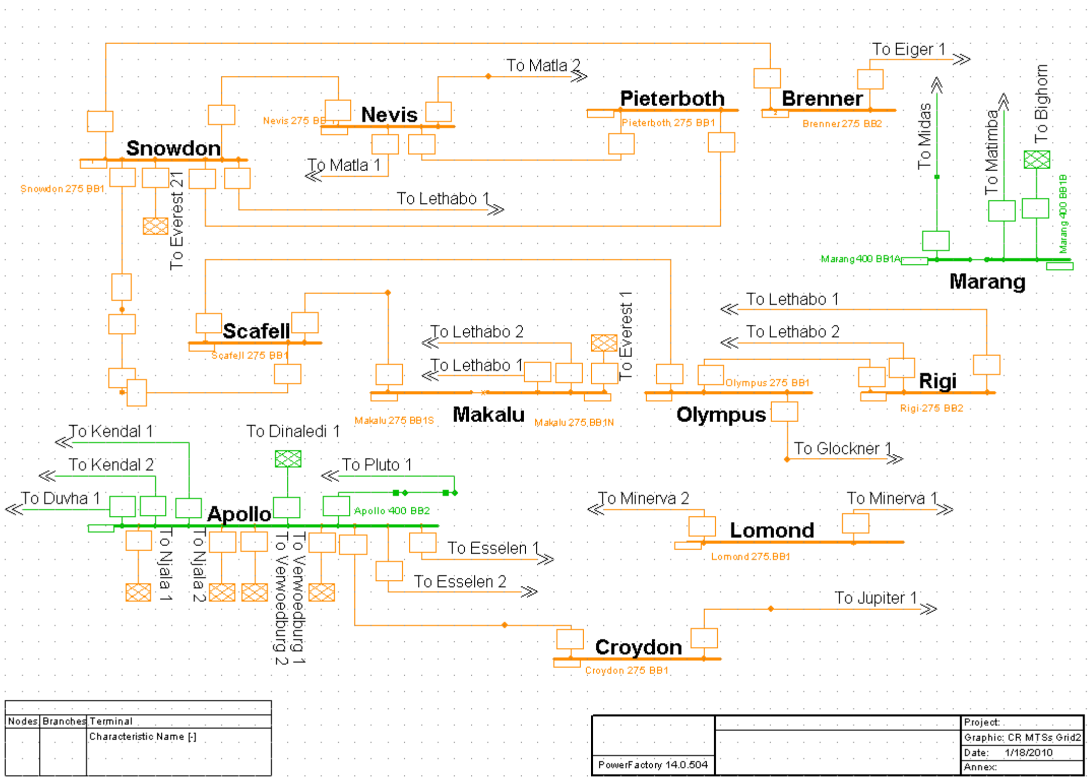



*Figure 3.8: Simplified Makalu network diagram*

For this study, a single plain capacitor bank rated at 150 MVAr was proposed for all these substations to evaluate the impact the short circuit power differences and the loading patterns per substation would have on the resonant frequency as well as on the harmonic amplification factor.

## *3.3.1 Short circuit power as a factor influencing the harmonic resonance frequency.*

Figures 3.9 to 3.11 show the harmonic impedance plots for the Marathon, Komati and Makalu 275kV busbars for when there is no capacitor bank installed and when it is installed. It can be seen that although identical capacitor banks have been installed at all these busbars, the resonance frequency per site is influenced heavily by the short circuit power at that point of connection.

With the network operating normally, the harmonic resonance frequency will be as follows:

- Marathon 275kV busbar - near the sixth harmonic frequency.
- Komati 275kV busbar - near the ninth harmonic frequency.
- Makalu 275kV busbar - between the tenth and eleventh harmonic frequencies.

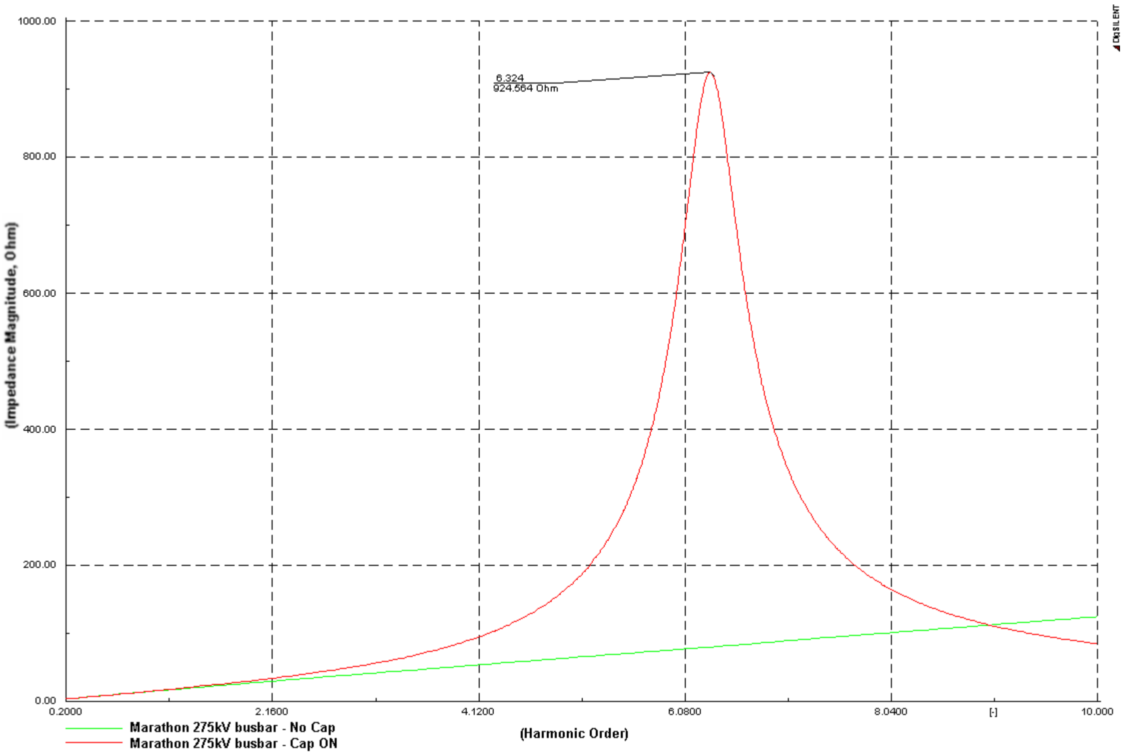



*Figure 3.9: Marathon 275kV busbar harmonic impedance plots*

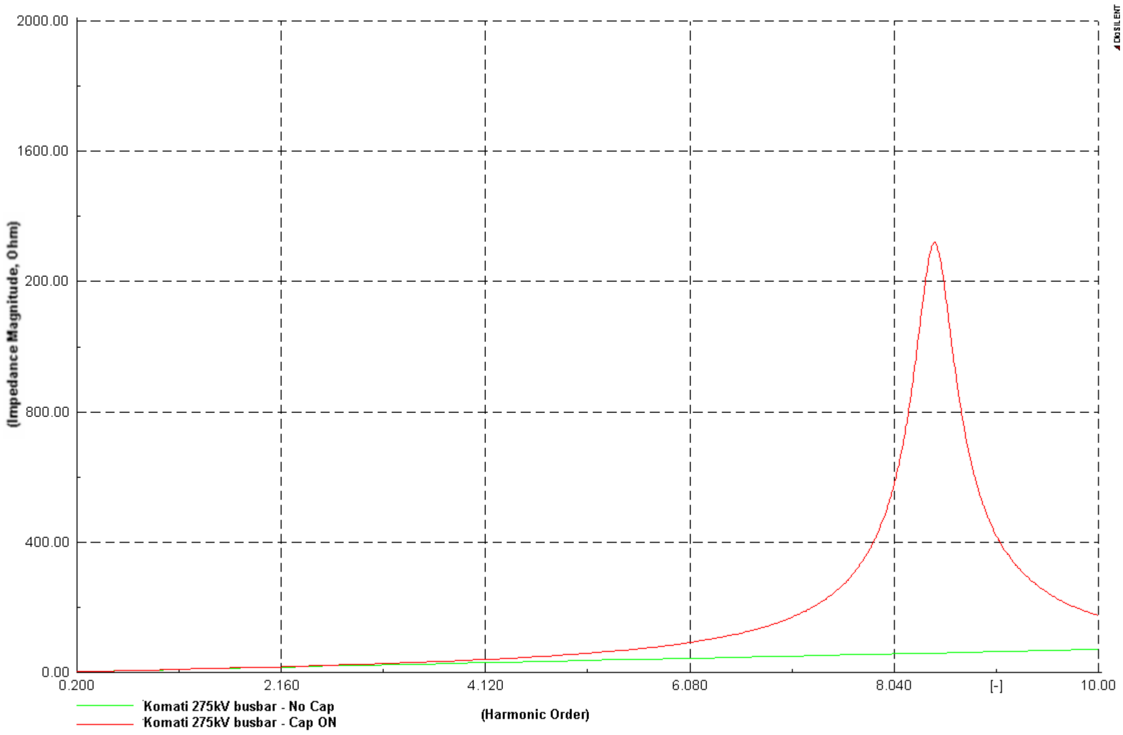



*Figure 3.10: Komati 275kV busbar harmonic impedance plots*

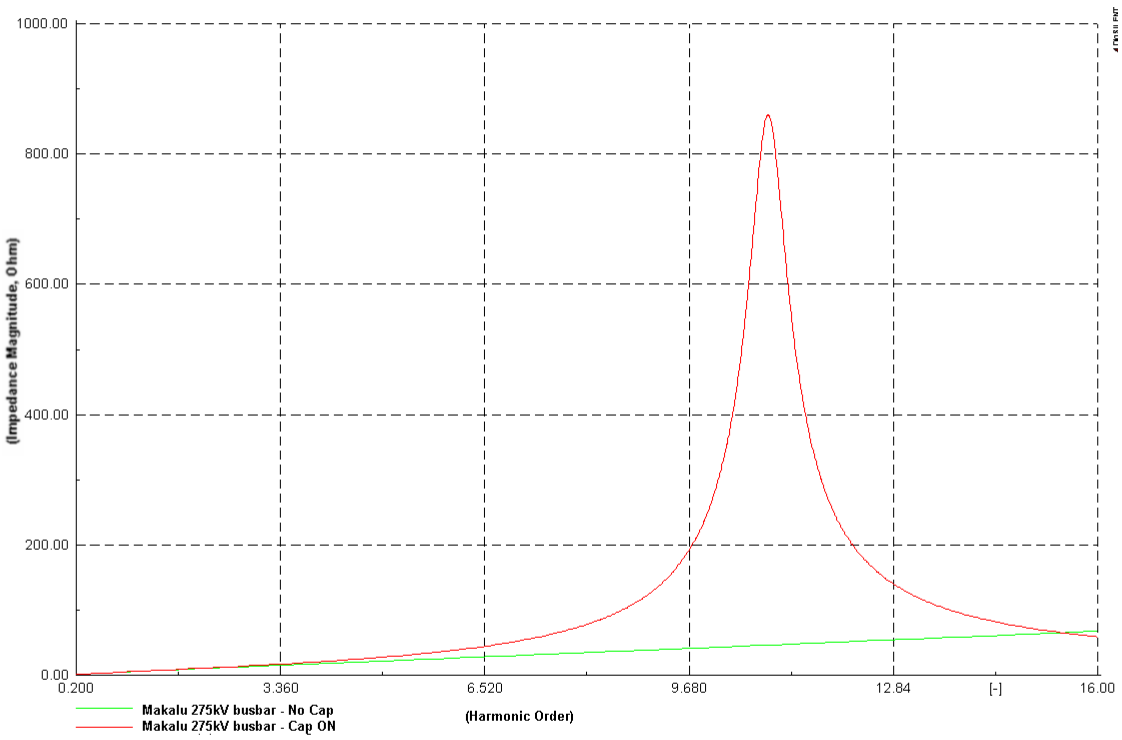



*Figure 3.11: Makalu 275kV busbar harmonic impedance plots*

## 3.3.2 Load power as a factor influencing the harmonic amplification factor

Figures 3.12 to 3.14 show the harmonic impedance plots for Marathon, Komati and Makalu 275kV busbars loaded at 25%, 50%, 75%, 100% and 120% of their normal load. It can be seen here that as the load is increased the harmonic amplification factor reduces. It can therefore be deduced that the load, especially the resistive load, plays a major role as far as harmonic damping is concerned.

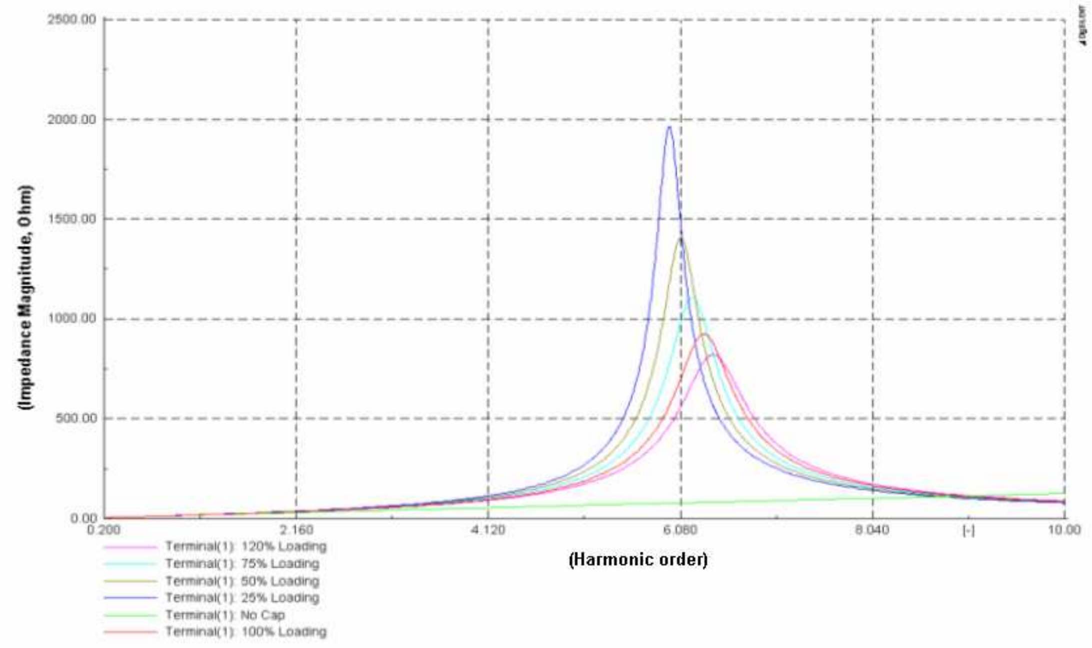



*Figure 3.12: Marathon 275kV busbar harmonic impedance plots for different loading patterns.*

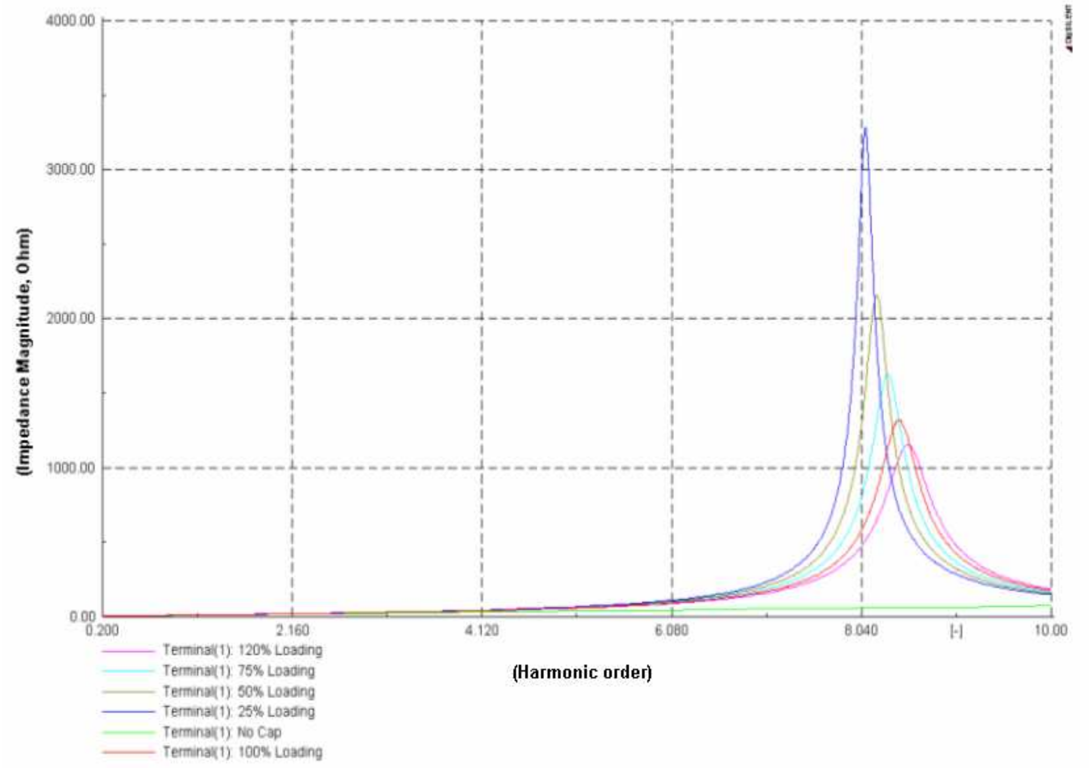



*Figure 3.13: Komati 275kV busbar harmonic impedance plots for different loading patterns*

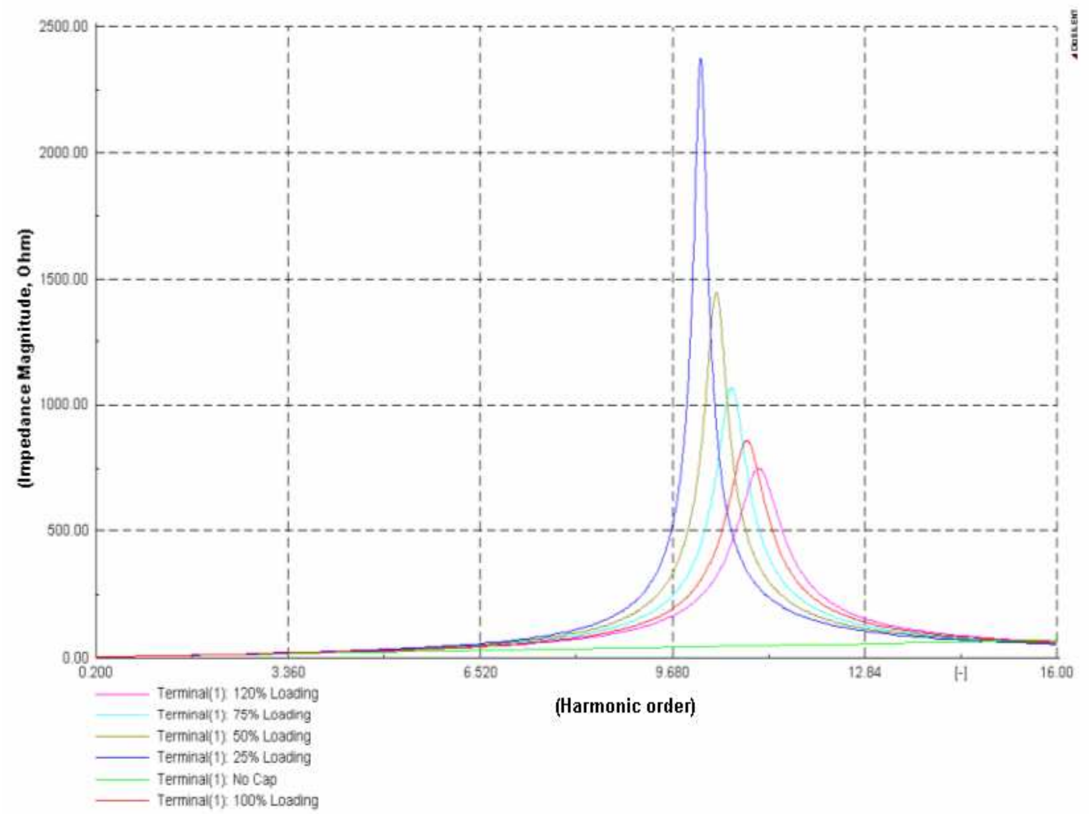



*Figure 3.14: Makalu 275kV busbar harmonic impedance plots for different loading patterns*

### *3.4 Case study 2*

In this case study the Komatipoort 132kV 40.5 MVAr capacitor bank was used to understand what impact the size of capacitor bank, the network contingencies as well as the load composition of the network have on the resonance frequency and the amplification factor. Figure 3.6 should be used to understand the Komatipoort network diagram.

Figure 3.15 shows the high THD levels experienced at Komatipoort 132kV busbar, where the capacitor bank is installed.

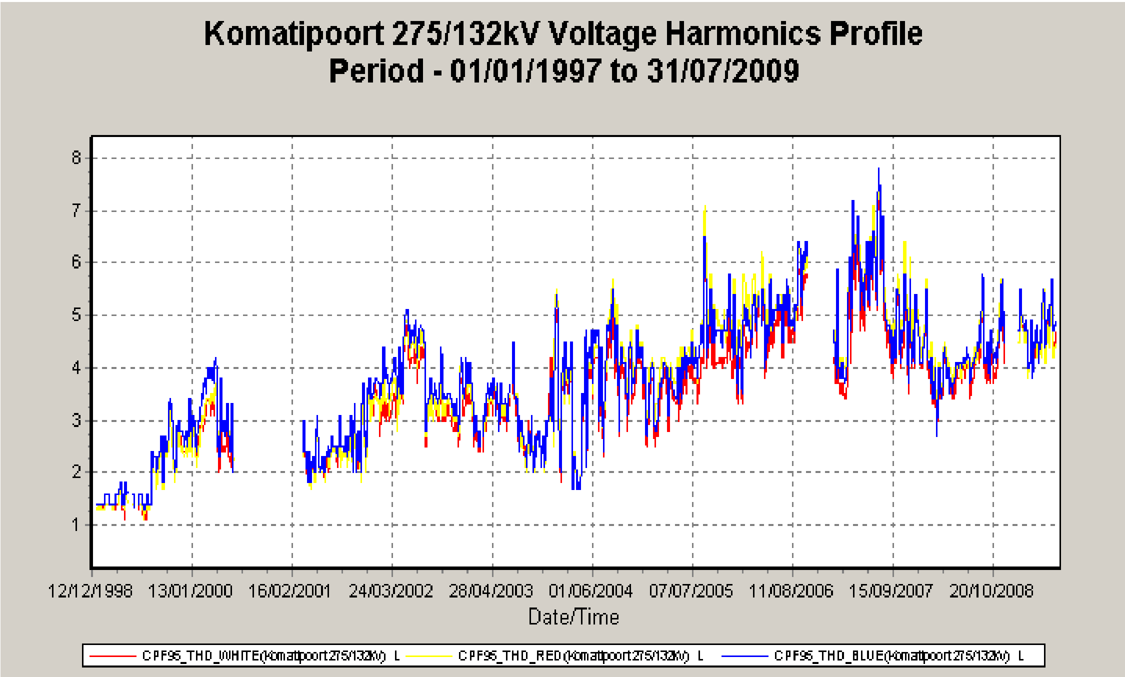



*Figure 3.15: Komatipoort 132kV THD daily values(r, w, b)*

#### <u>*3.4.1 The size of capacitor bank as a factor influencing harmonic resonance*</u>

For this study, the following shunt capacitor bank options were taken into consideration:

(i) The current 40.5 MVAr shunt capacitor bank.

(ii) The new 72 MVAr capacitor bank (on its own) with the decommissioning of the current 40.5 MVAr capacitor bank.

(iii) The current 40.5 MVAr capacitor bank with the additional 72 MVAr capacitor bank.

Figure 3.16 shows the harmonic impedance plots vs. the harmonic amplification factors for these conditions. It can be seen here that by changing the size of the capacitor bank installed the resonance frequency and amplification factor change.

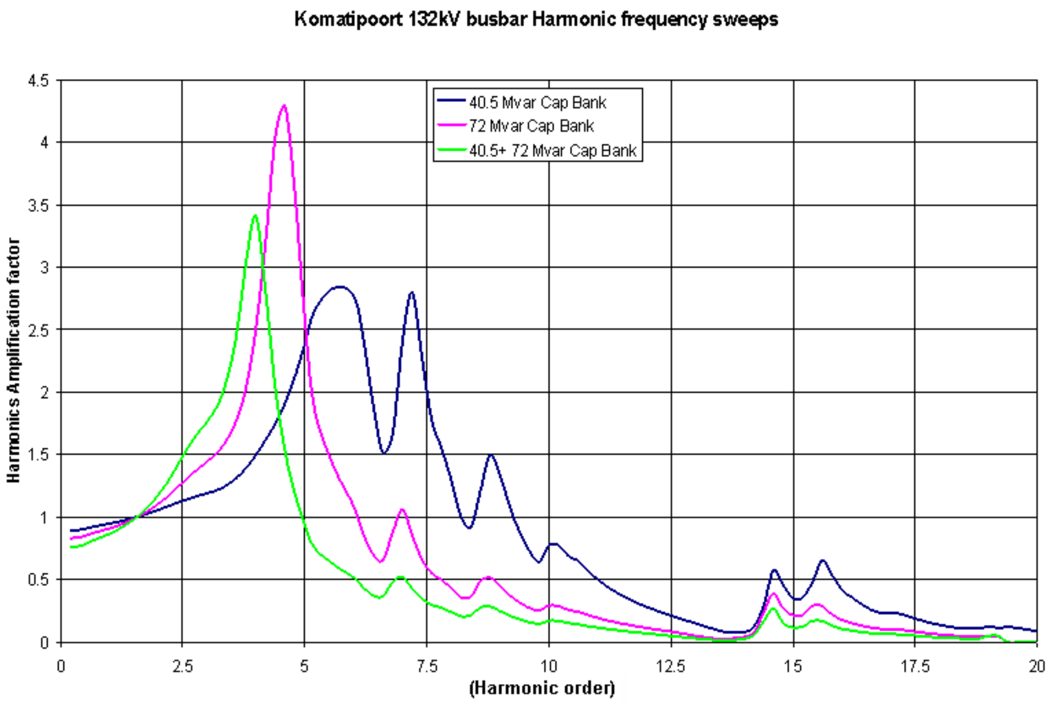



*Figure 3.16: Komatipoort 132kV busbar harmonic impedance plots for various shunt capacitor bank sizes.*

### 3.4.2 Network contingencies as a factor influencing harmonics resonance

Figure 3.17 shows the harmonic impedance plots for different scenarios with the initial 40.5 MVAr shunt capacitor bank installed. Without the capacitor bank, resonance occurs near the 13$^{th}$ harmonic frequency. This situation doesn't present any problems in the network as the background harmonic level at the thirteenth harmonic frequency is low.

The capacitor bank was then switched on for:

(i) Base case

(ii) Base case with Komatipoort Infuleni 275kV line out.

(iii) Base case with Marathon Komatipoort 275kV line out.

There is harmonic resonance near the fifth harmonic and the seventh harmonic (except for ii). The harmonic resonance at the fifth harmonic frequency is deemed to be caused by the capacitor bank resonating with the system impedance. The seventh harmonic resonance is deemed to be caused by the remote capacitor bank at Maputo, as the resonance is not visible when the Komatipoort Infuleni 275kV line is switched off.

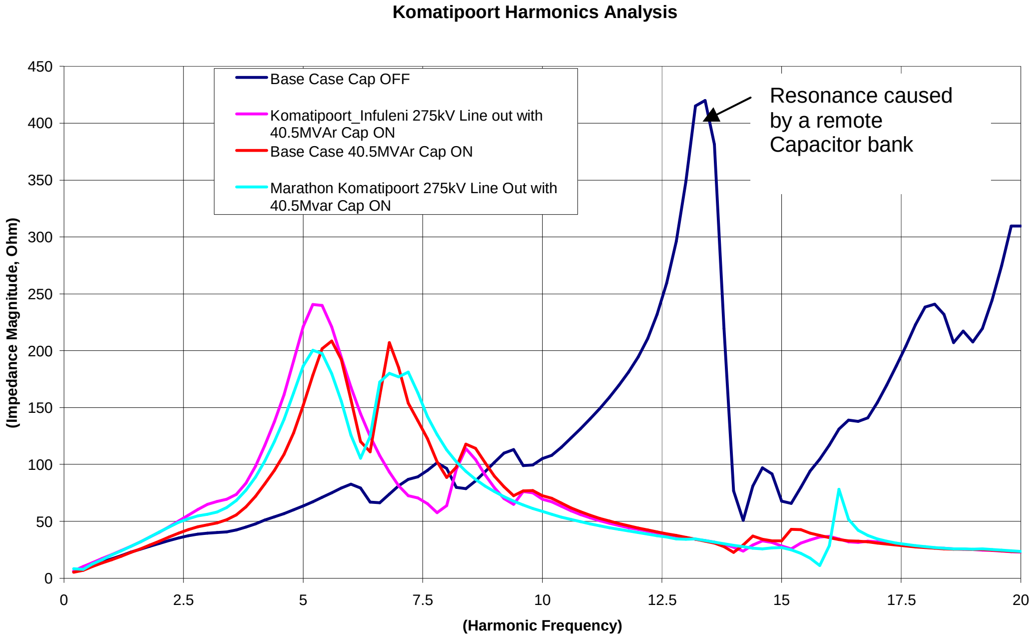



*Figure 3.17: Komatipoort 132kV busbar harmonic impedance plots for various network contingencies*

As can be seen above, the resonance frequency and harmonic impedance change with various contingencies in the network for the same capacitor bank size.

## 3.4.3 Shunt capacitor bank technologies as a factor influencing harmonic resonance

Various shunt capacitor bank technologies exist in the management and control of harmonic resonance in the system. Some of these technologies can be applied to reduce the fifth harmonic amplification factor on the Komatipoort 132kV busbar, as follows:

- Modification of the current capacitor bank into a de-tuned capacitor bank at 240 Hz to suppress the fifth harmonic voltages.
- C-type filter tuned at the third harmonic frequency to suppress the full range of harmonic frequency voltages.

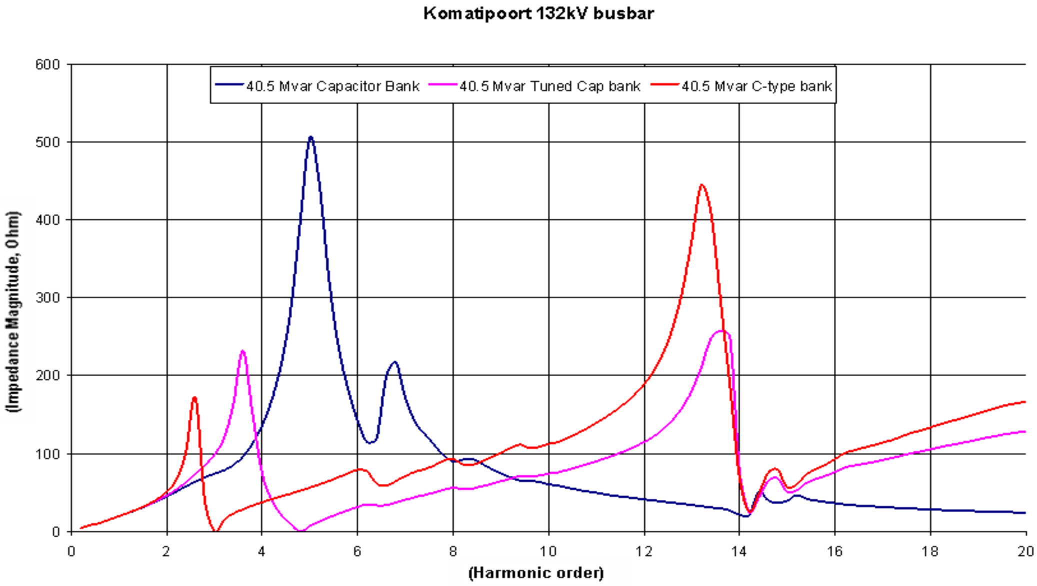



*Figure 3.18: Komatipoort 132kV busbar harmonic impedance plots for different shunt capacitor bank technologies.*

### 3.4.4 Load composition as a factor influencing harmonic resonance

Detailed measurements (THD, transformer loading) were done to determine the impact the load composition has on the resonance at the Komatipoort 132kV busbar. Simulations were also performed on DigSilent Power Factory.

Figure 3.19 shows the Komatipoort 132kV busbar three phase THD measurements for the period 14 April - 14 May 2009 and should be read in conjunction with Figures 3.20, 3.21 and 3.22.

Observations:

(1) This is the night period (21:00 to 06:00) when the 275/132kV transformers are lightly loaded and there is low harmonic damping. The Komatipoort capacitor bank is switched ON. The THD rises to levels above both the planning and compatibility limits.

(2) This is a day period (6:00 to 21:00) when the 275/132kV transformers are highly loaded and there is high harmonic damping. The Komatipoort capacitor bank is switched ON. The THD drops to levels lower than the compatibility limit and occasionally below the planning limit.

(3) The Komatipoort capacitor bank is switched off. This incident occurred during the night period and there was therefore no harmonic amplification. The THD dropped to levels lower than both the planning and compatibility limits.

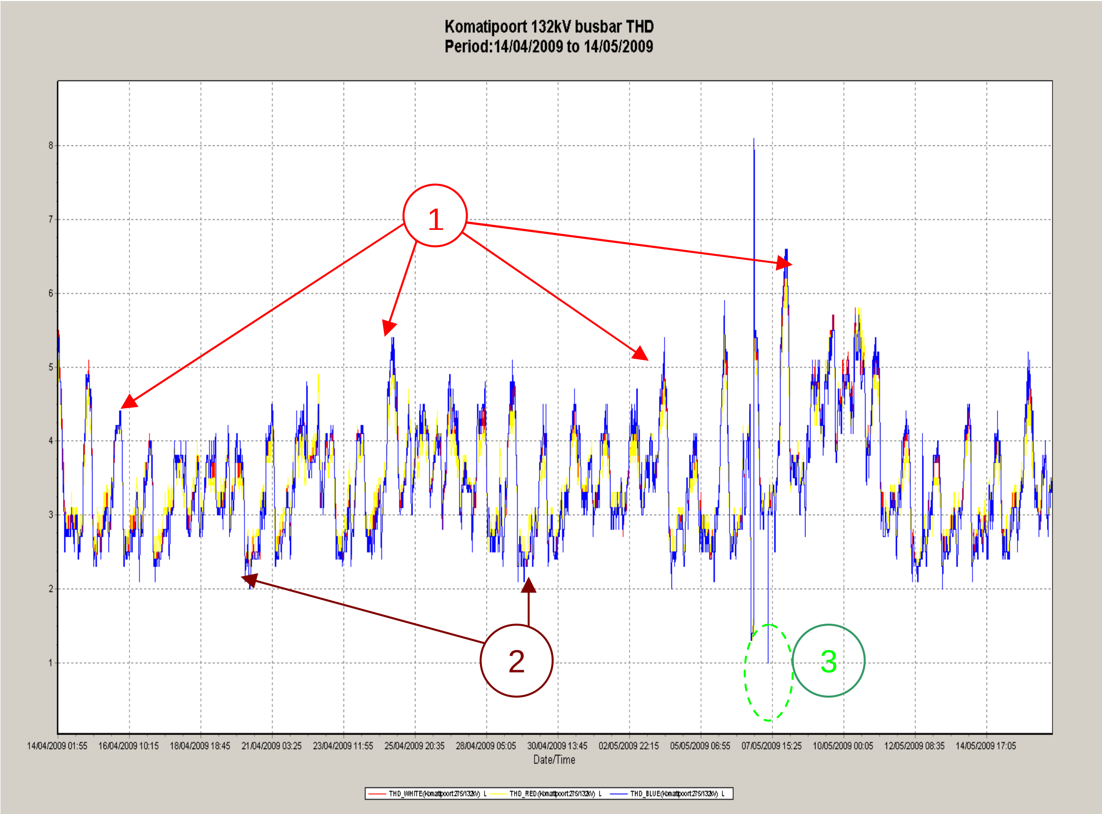



*Figure 3.19: Komatipoort 132kV bus THD measurements*

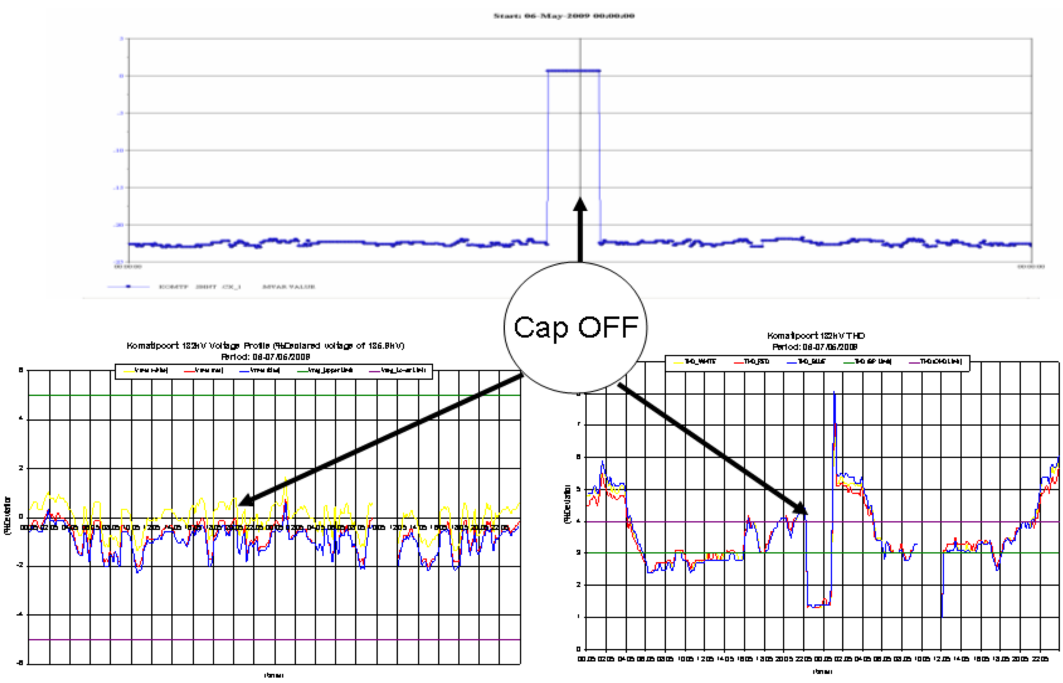



*Figure 3.20: Komatipoort 132kV busbar measurements illustrating cap off at night.*

The continuous switching of the 40.5 MVAr capacitor bank at Komatipoort plays a major role in the harmonic exceedance at the Komatipoort 132kV busbar. Figure 3.21 show the transformer loading data, while Figure 3.22 shows the MVAr loading of the Komatipoort shunt capacitor bank for the period 14-24 April 2009.

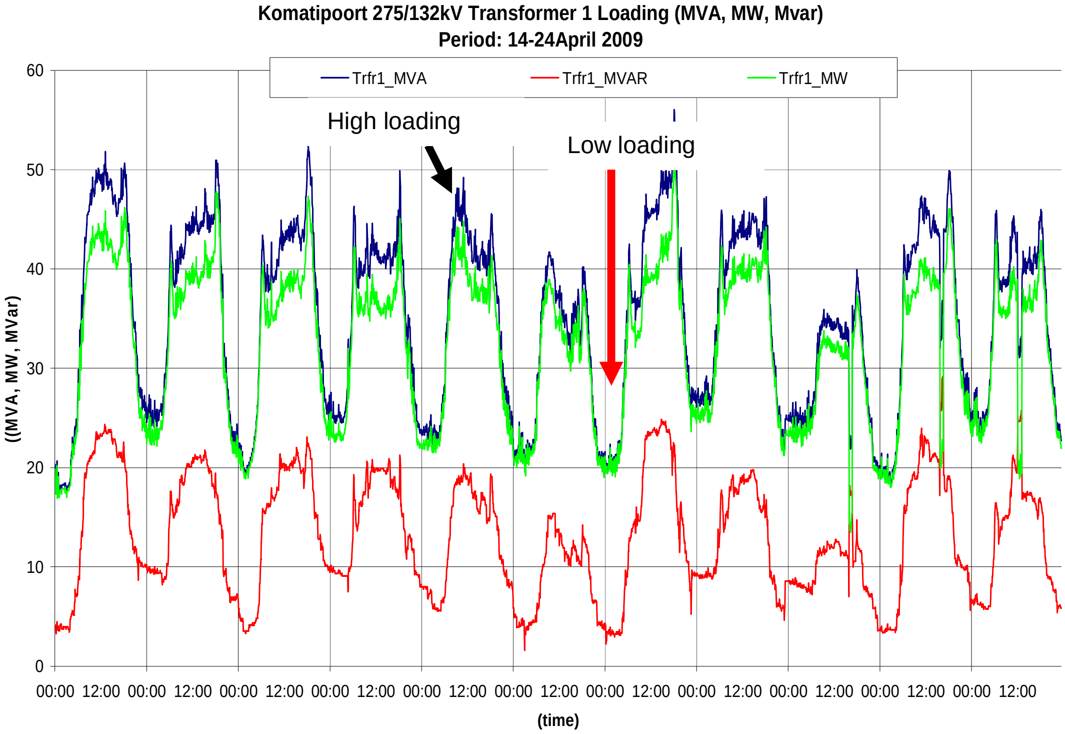



*Figure 3.21: Komatipoort transformer 1 loading (apparent, active and reactive power) measurements.*

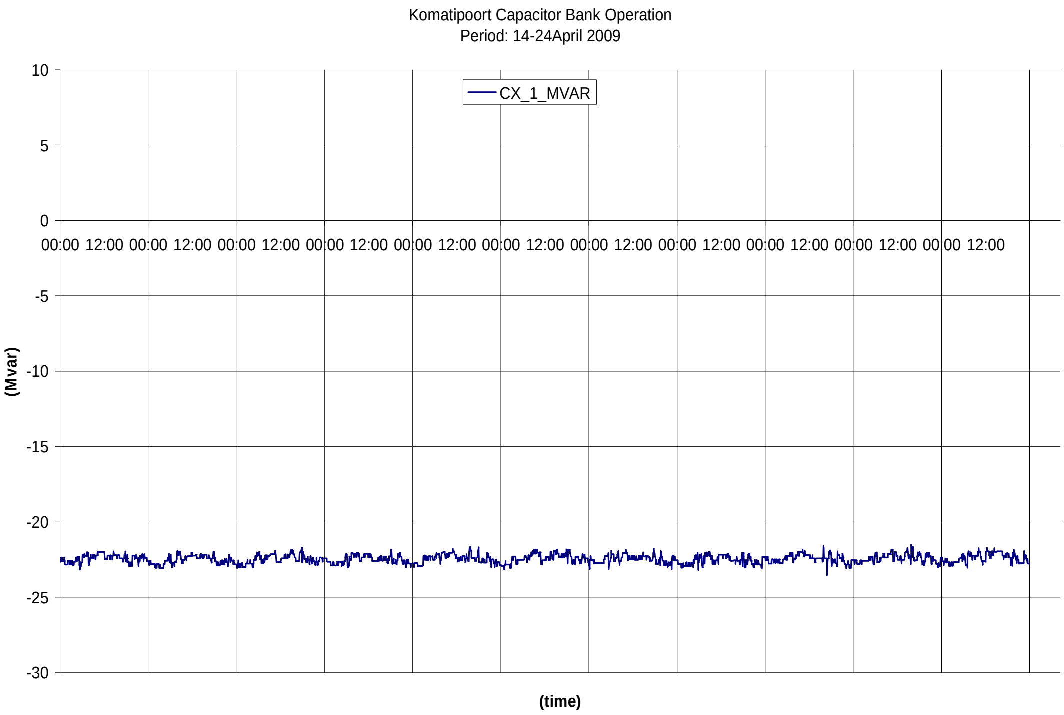



*Figure 3.22: Komatipoort 132kV capacitor bank MVAr measurements.*

Harmonic simulations were performed on DigSilent Power Factory. The aim of the simulations was to identify the resonant frequency when the 40.5 MVAr capacitor bank at Komatipoort is switched on, with different load compositions. The transformer loading data in Figure 3.21 was used for these simulations. The simulations were performed for frequencies up to the tenth harmonic.

Figure 3.23 shows the harmonic impedance plots for the following scenarios:

- When the shunt capacitor bank is switched off.
- When the shunt capacitor bank is switched on (high loading, with high resistive load composition).
- When the shunt capacitor bank is switched on (low loading, with low resistive load composition).

Observations:

- For both high and low loadings, the harmonic resonance when the capacitor bank is switched on is near the fifth harmonic frequency.
- During high loading conditions (with high resistive load composition) the fifth harmonic amplification factor is lower than during low loading conditions (with low resistive load composition).

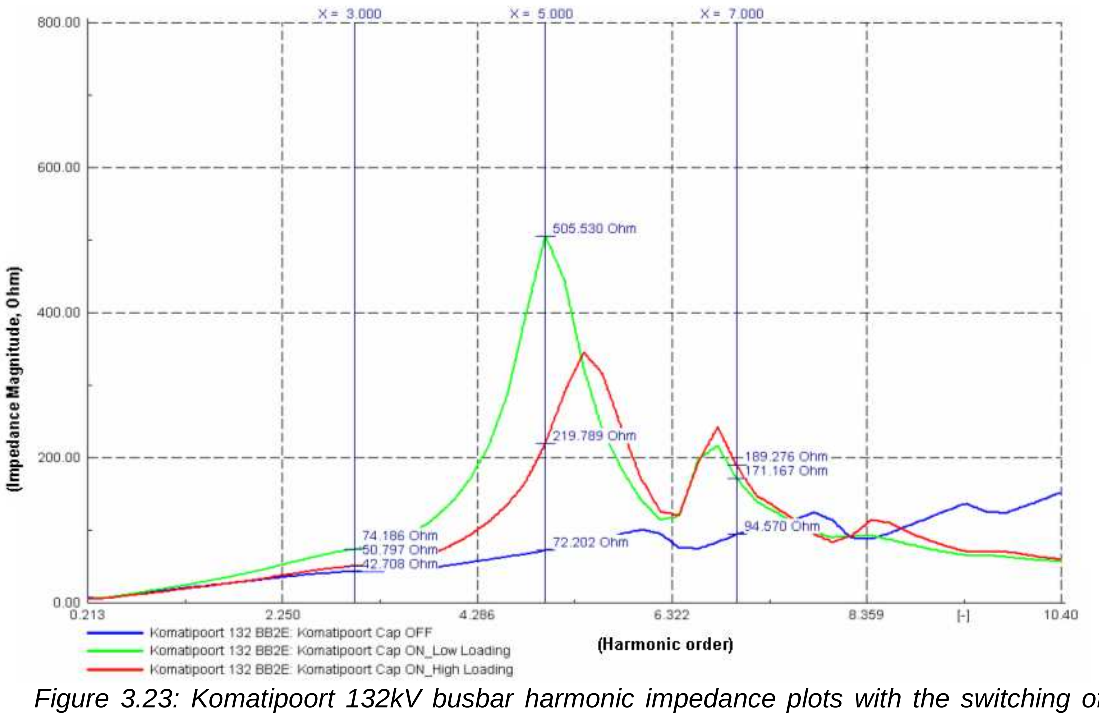



*Figure 3.23: Komatipoort 132kV busbar harmonic impedance plots with the switching of the 40.5 MVAr shunt capacitor bank for various loading patterns.*

Figure 3.24 shows the R/X polar plots for the harmonic impedance at the Komatipoort 132kV busbar. The fifth harmonic frequency impedance (resistance vs reactance) varies with the switching of the capacitor bank and the load characteristic at the Komatipoort 132kV busbar. The impact of resistive damping when the capacitor is on is clearly visible during peak loading.

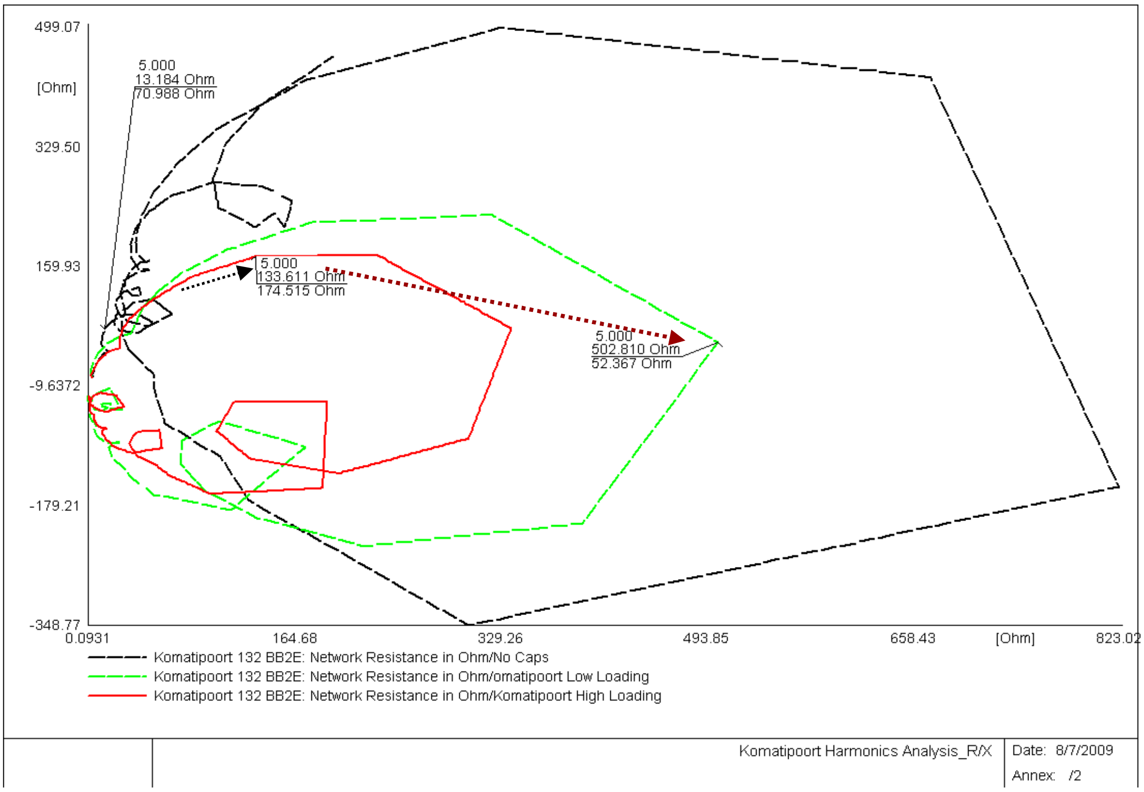



*Figure 3.24: Komatipoort 132kV busbar R/X polar plots with the 40.5 MVAr shunt capacitor bank switched for various loading patterns.*

## 3.5 Conclusions

From this study the following conclusions can be drawn:

Harmonic resonance can cause excessive harmonic levels if the operation of the network is not properly studied prior to the implementation of shunt compensation. The following factors were discussed and can be seen to have an influence on the harmonic resonance as well as the harmonic amplification factor:

- The three phase short circuit power at that point of supply.
- The loading of the network.
- The size of the capacitor bank to be installed.
- Network contingencies.
- Shunt capacitor bank technologies.
- The load composition (active and reactive powers).

With the proper understanding of these factors prior to the design and installation of a shunt capacitor bank, the planning engineer can decide on which size of the capacitor bank, bank technology and operation strategy will suit the planned capacitor bank installation.

# 4. Planning considerations for the control and management of harmonic levels

## *4.1 Introduction*

When planning EHV networks, planning engineers need to take into consideration power quality waveform parameters such as voltage regulation, voltage unbalance and voltage harmonics. This will ensure that high power quality is delivered to customers and that it meets both the IEC planning levels as well as the NRS compatibility levels.

The point of interest in this research is the planning considerations required for the network, taking into consideration the impact that shunt capacitor banks have on the harmonic amplification factor.

## *4.2 IEEE guidelines*

IEEE 519-1992 [1] provides guidelines for the control and management of harmonic levels in the power network. According to the standard, the industrial system is responsible for controlling the harmonic currents created in the industrial workplace. Since harmonic currents reflected through distribution system impedances generate harmonic voltages on the utility distribution systems, the standard proposes guidelines based on industrial distribution system design. Table 4.1 from IEEE 519-1992 defines levels of harmonic currents that an industrial user can inject into the utility distribution system.

Table 4.1: Current Distortion Limits for General Distribution Systems (120V-69kV) [1]

| Maximum Harmonic Current Distortion in % of $I_L$ Individual Harmonic Order (Odd Harmonics)[1,2] | | | | | | |
|---|---|---|---|---|---|---|
| $I_{SC}/I_L$ | <11 | $11 \le h \le 17$ | $17 \le h \le 23$ | $23 \le h \le 35$ | $35 \le h$ | TDD |
| <20[3] | 4.0 | 2.0 | 1.5 | .6 | .3 | 5.0 |
| 20 < 50 | 7.0 | 3.5 | 2.5 | 1.0 | .5 | 8.0 |
| 50 < 100 | 10.0 | 4.5 | 4.0 | 1.5 | .7 | 12.0 |
| 100 < 1000 | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| >1000 | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.0 |

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

[2] Current distortions that result in a DC offset, e.g., half-wave converters, are not allowed.

[3] All power generation equipment is limited to these values of current distortion, regardless of actual $I_{SC}/I_L$, where $I_{SC}$ = maximum short circuit current at PCC and $I_L$ = maximum demand load current (fundamental frequency component) at PCC.

Table 4.2 of IEEE 519-1992 defines the voltage distortion limits that can be reflected back onto the utility distribution system. Usually the industrial user controls the overall combined current distortion, as this will help him meet the limitations set forth in the guidelines.

Table 4.2: Voltage Distortion Limits [1]

| **Bus Voltage at PCC** | **Individual Voltage Distortion (%)** | **Total Harmonic Distortion THD** |
|---|---:|---:|
| <=69kV | 3 | 5 |
| >69kV<=161kV | 1.5 | 2.5 |
| >161kV | 1 | 1.5 |

The standard further proposes that in order to prevent or correct harmonic problems that could occur within an industrial facility, an evaluation of system harmonics should be performed if the facility conditions meet one or more of the criteria below.

- The application of capacitor banks in systems where 20% or more of the load includes other harmonic generating equipment.
- The facility has a history of harmonic related problems, including excessive capacitor fuse operation.
- During the design stage of a facility composed of capacitor banks and harmonic generating equipment.
- In facilities where restrictive power company requirements limit the harmonic injection back into their system to very small magnitudes.
- Plant expansions that add significant harmonic generating equipment operating in conjunction with capacitor banks.
- When coordinating and planning to add an emergency standby generator as an alternate power source in an industrial facility.

The well known and commonly practiced method to verify if a capacitor resonates with its supply system is to determine the ratio of the system short circuit power to the capacitor size. Resonance frequency can be estimated from this ratio, shown in Equation 4.1.

$$f_r = f_f \sqrt{\frac{S_{sc}}{Q_{cap}}} \qquad [4.1]$$

Where:
$f_r$ – is the harmonic resonance frequency, in Hz
$f_f$ – is the fundamental frequency, in Hz
$S_{sc}$ – is the short circuit power, in MVA
$Q_{cap}$ – is the size of the capacitor bank installed or to be installed, in MVAr

Experience has shown that this method is too crude to be practically useful, as the formula is based on the assumption that the system harmonic reactance is proportional to its fundamental reactance determined from the short circuit power. There is no guarantee that this assumption is valid for practical interconnected power systems.

An alternative method is to conduct harmonic power flow studies and/or harmonic impedance scan studies.

Although very useful, harmonic impedance scan studies can be too complicated for the planning engineer since the locations of harmonic sources and the source characteristic are typically unknown. Another problem is that the planning engineer will find it difficult to draw a conclusion as to the potential harmonic impact of the proposed capacitor bank once the harmonic impedance plots have been obtained. This is because the resonance frequency may or may not coincide with a harmonic order. If it does, the existence of harmonic resonance does not necessarily imply that a problem would occur, since the system resistance may provide sufficient damping to the resonance. If it does not coincide with a harmonic frequency, the system damping may still be too small so a resonance problem could still exist. Furthermore, there is the problem of how to quantify the closeness of a resonance frequency with the harmonic frequency. If the system exhibits multiple resonance frequencies, it becomes even more difficult to assess the harmonic impact of the capacitor.

### *4.3 Harmonic resonance guidelines (IEEE papers)*

In [2] the impact of reactive power compensation equipment on the harmonic impedance of high voltage networks is discussed. From this study, the design of reactive power compensation capacitor banks is evaluated on the basis of harmonic measurements and harmonic analysis in the high voltage network in the Dutch network. The aim of these measurements was to quantify the present voltage harmonic distortion in the network. The individual harmonics were recorded up to the 40$^{th}$ harmonic. The results of these measurements showed that some of the characteristic voltage harmonics were approaching the planning levels. Therefore care should be taken when capacitive reactive power compensation equipment is connected on the network, in order to avoid possible resonance frequencies near characteristic harmonic frequencies.

Harmonic analysis was done using two designs of mechanically switched capacitor banks; a pure capacitor bank design with inrush reactor and a C-type filter bank. These capacitor banks totalling 1500 MVAr are located at six locations in the 380 kV and 220 kV networks. The simulations were done using the DigSilent programme. With the simulations, various network configurations were performed and harmonic impedances calculated. From this study it was clear that the planned 1500 MVAr capacitor banks dramatically influence the harmonic impedance of the network.

Harmonic impedance plots for a plain capacitor bank and C-type filter bank are shown in Figures 4.1 and 4.2. With the plain capacitor bank, there is a dramatic change in the resonance frequencies when different contingencies are implemented. With the C-type filter in place, there is no change in the resonance frequency during different contingencies. Furthermore, the C-type filter banks provide damping over a range of frequencies.

The ten capacitor banks (1500 MVAr) in the network were switched on, and the harmonic impedance plots calculated. Resonance peaks with much more damping for the C-type filter banks were achieved compared to the plain capacitor banks. The amplification of harmonic voltages when switching in a capacitor bank at different substations also favoured the C-type filter banks, as the amplification levels should be less than 1.0 for the fourth harmonic frequency and higher.

The inrush current and voltage transient studies performed for both plain capacitor banks and C-type filters showed that the transients for a plain capacitor banks were not acceptable for such high voltage substations, while the voltage transients of the C-type filters were barely noticeable.

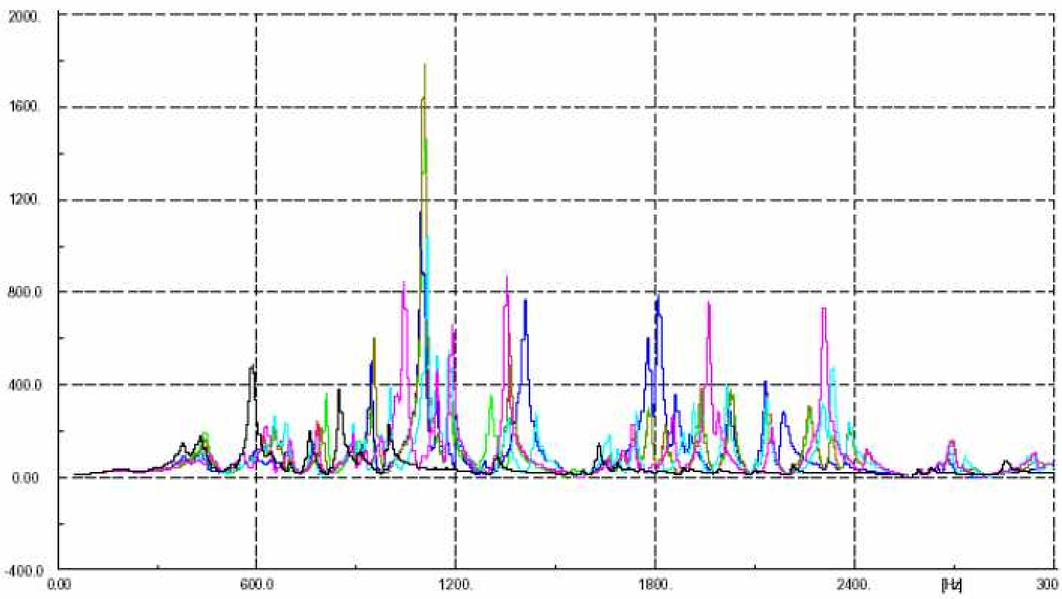



*Figure 4.1: Impedance plots for various system contingencies: 150 MVA capacitor bank [2]*

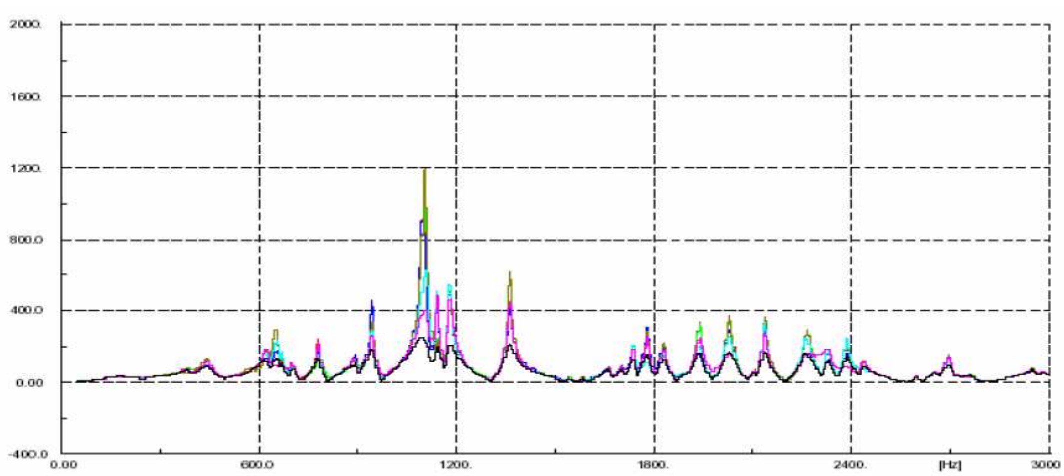



*Figure 4.2 Impedance plots for various system contingencies: 150 MVA C-type filters [2]*

A peak of more than 2 kA at 380kV was calculated for a plain bank which is not acceptable for a high voltage substation. With the C-type filters a peak with the maximum of 900 A at 380kV was calculated under the same conditions.

From all these considerations the C-type filters were the preferred choice and were thus implemented in the Dutch network. The procedure for the evaluation can be summarised as shown on the flowchart in Figure 4.3.

**MVAr needs identification**:
Identify the need to have VAr support in the network by performing load flow studies and deciding on the MVAr required at each point in the network.

↓

**Voltage harmonic measurements:**
Undertake voltage harmonic measurements at each point in the network where VAr support is required to quantify the voltage harmonics levels.
Record up to the $40^{th}$ individual harmonic frequency

↓

**Harmonic analysis:**
Decide on the two options to be used (plain capacitor bank vs. C-type filter bank).
Decide on the simulation tool to use (e.g. Digsilent Power Factory)

↓

**Simulations:**
Perform harmonic impedance calculations for different network configurations at each point and observe the change in resonant frequency.
Perform harmonic impedance calculations for different network configurations with all capacitor banks in service and observe the harmonic amplification factor damping for both topologies.
Perform transient studies for both topologies to check whether the inrush current and voltage transients will be acceptable.

↓

**Recommend the preferred option**

*Figure 4.3: Flow-chart from the guidelines for the implementation of VAr support in the Dutch Transmission network, derived from [2]*

In addition to these guidelines, [3, 4] recommend that the following considerations should be added to the simulation results:

- The skin effect of overhead lines, generators and transformers.
- Long overhead lines should be modelled with distributed parameters.
- Minimum and maximum load levels where the capacitor banks and SVC's will be in operation need to be defined.

- The load models need to be verified in terms of make-up of active, motor, constant power and reactive power loads.
- R/X polar representation of the harmonic impedances to give insight into the network characteristics at harmonic frequencies.
- The voltage harmonic measurements should be done with high quality, high bandwidth voltage dividers, as the capacitive voltage transformer (CVT) dividers give erroneous results.

In [5] a practical harmonic resonance guideline to estimate the severity of harmonic resonance is presented. The aim of this guideline is to propose an alternative method to using the ratio of the system short circuit power to the capacitor size and/or harmonic impedance plots only.

Figure 4.4 shows the Thevenin equivalent circuit of a power system and the capacitor bank to be installed, as seen from the capacitor bank busbar. E and $Z_{sys}$ are the Thevenin open-circuit voltage and Thevenin impedance respectively. $Z_{sys}$ is obtained by a harmonic impedance frequency scan study. The total harmonic impedance is the combination of the system impedance and the capacitor impedance. For each harmonic order, the total harmonic admittance can then be calculated and the ratio of the $h^{th}$ harmonic admittance $Y_h$ to the fundamental admittance $Y_1$ is defined as the harmonic resonance index

$K_h = Y_h/Y1$, h=1, 2, 3…

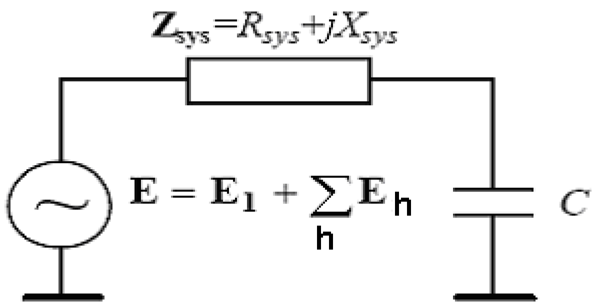



*Figure 4.4: Equivalent system with capacitor to be installed*

The resonance guideline/chart, shown in Figure 4.5, is a set of curves whose x-axis is the background voltage IHD (individual harmonic distortion) level (before the capacitor installation) and y-axis the resonance index. The curve in the chart displays a boundary below which the impact of harmonic resonance can be considered insignificant, while above which the harmonic resonance could cause problems. Detailed system harmonic analysis is therefore recommended for the latter case.

For example, the resonance index limit for a fifth harmonic frequency to which a detailed system harmonic study is not necessary with a background IHD of 1.5% is 58. However, with a resonance index of 95 a detailed system harmonic study will be necessary. This curve was established using the capacitor loading limits [30]. The flowchart for this method is shown on Figure 4.6.

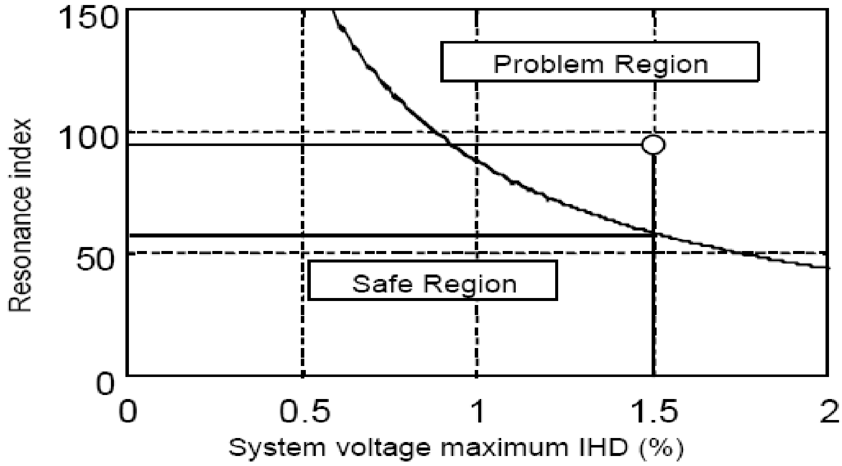



*Figure 4.5: Harmonic resonance guideline/chart [5]*

**MVAr needs identification**:
Identify the need to have VAr support in the network by performing load flow studies and deciding on the MVAr required at each point in the network.

↓

**Simulations:**
Determine the system Thevenin harmonic impedance by frequency scan studies.

↓

**Network Thevenin equivalent:**
Determine the Thevenin network equivalent circuit of a power system at the capacitor location and associated capacitor to be installed.

↓

**Harmonic resonance index:**
Calculate the total harmonic admittance for each harmonic order, by taking the ratio of the $h^{th}$ harmonic admittance $Y_h$ to the fundamental admittance $Y_1$.

↓

**Voltage distortion levels:**
Determine the system Thevenin voltage distortion and the dominant harmonic orders. If this information is not available, take the IEEE standard limit of 1.5%

↓

**Analysis:**
Find the index limit corresponding to the system voltage distortion from the proposed guideline chart. Compare the system indices with the index limits and decide if there exists a harmonic resonance problem.

↓

**Yes:**
Perform detailed harmonics studies.

**No:**
Proceed with the capacitor bank installation.

*Figure 4.6: Flow-chart for the assessment of harmonic resonance problems, derived from [5]*

In [6, 7] guidelines for the harmonic integration of large complex harmonic loads on transmission and sub-transmission networks are derived. This is achieved by integrating the allocation of harmonic emission levels for customer plants, and the design of passive shunt reactive compensation in HV and EHV systems with large sources of harmonic distortion. The role of remote capacitor banks in the system on the amplification of harmonics at the PCC (Point of common coupling) is evaluated.

These papers [6,7], indicate that, in addition to the application of IEEE 519 and IEC 61000-3-6 methods of allocating customer emission levels, two additional aspects need to be considered, i.e. (a) inclusion of customer capacitor parallel resonance conditions as an “emission” parameter, and (b) limitation of system harmonic impedance magnitude in the application of IEC 61000-3-6 methods (IEEE 519 implies that the utility will address these, as customer limits are independent of system harmonic impedance).

## *4.4 Resonance guidelines – by the author of this research report*

### *4.4.1 Introduction*

Through the understanding of the dynamic behaviour of a particular network in an power system, one can deduce some equations that can assist in the understanding of  whether the installation of a capacitor bank will be detrimental to the THD levels at a particular busbar or not.

### *4.4.2 Aim*

The aim of this guideline is to show how different components (source impedance, line impedance, transformer impedance, load impedance and capacitor) in a simple electrical circuit influence the amplification factor at the resonant harmonic frequency.

This will assist the planning engineers in determining the harmonic resonance point and the harmonic amplification factor for a planned capacitor bank installation. Known network parameters (short circuit power, loading, size of capacitor bank) will be used to determine the impact this installation will have on the harmonic performance in that network.

### *4.4.3 Methodology*

The study was undertaken by creating a simple circuit and only looking at the reactive components of the system impedance to derive the empirical formulas for different scenarios on the network.

The resistive part of the network impedance was taken as negligible due to the fact that in any transmission network, it is very small (less than 10% of the inductive component).

It is also assumed that the supply impedance of the network increases linearly with frequency.

At a particular node in a power system, the equivalent source impedance and the load impedance are determined without shunt compensation. For the second circuit the capacitive impedance is added on this system, which will reflect the addition of a capacitor bank in the system.

### *4.4.4 Rule of thumb equation*

Figure 4.7 (a) shows the simplified equivalent circuit of a power system consisting of the equivalent source impedance as well as load impedance. Figure 4.7 (b) shows the same equivalent circuit with the addition of a shunt capacitor bank. These network diagrams will now be analysed to determine the harmonic voltage amplification from case (a) to case (b).

The evaluation is done on the busbar where the proposed capacitor bank is to be installed and seen from the utility's side.

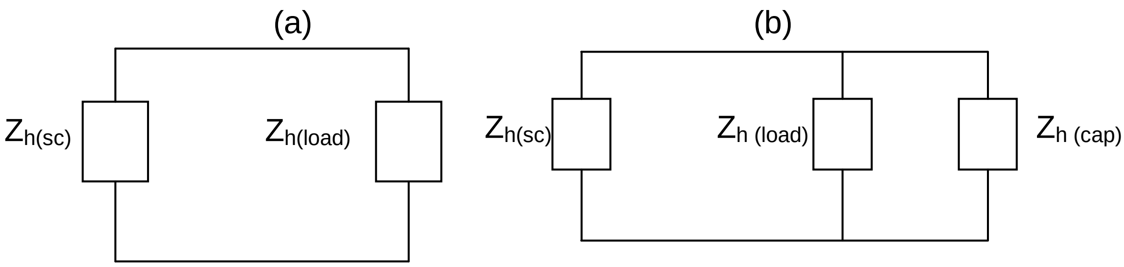



*Figure 4.7: (a) Equivalent network diagram without any shunt compensation*
*(b) Equivalent network diagram with shunt compensation*

Where:
$Z_{h(sc)}$ – is the network impedance, in Ω.
$Z_{h(load)}$ – is impedance of the load, in Ω.
$Z_{h(cap)}$– is the impedance of the capacitor bank to be installed, in Ω.

To mathematically analyse the harmonic amplification factor when the capacitor bank is being added on the system, the impedance of Figure 4.7 (b) is divided by the impedance of Figure 4.7 (a) for a parallel resonance circuit.

$$Amplification\_factor = \frac{Z'_h}{Z_h} \qquad [4.2]$$

Where:

$Z'_h$ - is the total impedance of the system when the capacitor is added on the system, in Ω.

$Z_h$ - is the total impedance of the system without the capacitor, in Ω.

The equation can be rewritten as follows:

$$Amplification\_factor = \frac{\frac{1}{Z_h}}{\frac{1}{Z'_h}} \qquad [4.3]$$

By substituting the impedances from figure 4.7 (a) and (b) the equation can be transformed as follows:

$$Amplification\_factor = \frac{\frac{1}{Z_{h(sc)}} + \frac{1}{Z_{h(load)}}}{\frac{1}{Z_{h(sc)}} + \frac{1}{Z_{h(load)}} + \frac{1}{Z_{h(cap)}}} \qquad [4.4]$$

These impedances can be substituted by known network parameters:
Short circuit power – $S_{sc}$
Load MW- $P_{load}$
Load MVAr – $Q_{load}$
Harmonic resonant order – *h*
Capacitor bank MVAr - $Q_{cap}$

Where:

$$Z_{h(sc)} = j\frac{U^2 h}{S_{SC}},\ Z_{h(load)} = \frac{U^2}{P_{Load}} + j\frac{U^2 h}{Q_{Load}},\ Z_{h(cap)} = \frac{U^2}{jQ_{Cap} \times h}$$

By substituting 1 p.u into U, where 1/j = -j:

$$Amplification\_factor = \frac{-j\frac{S_{SC}}{h} + P_{Load} - j\frac{Q_{Load}}{h}}{-j\frac{S_{SC}}{h} + P_{Load} - j\frac{Q_{Load}}{h} + jQ_{Cap} \times h} \qquad [4.5]$$

From equation 4.2, the amplification factor can be substituted as $\frac{Z'_h}{Z_h}$

$$\therefore \frac{Z'_h}{Z_h} = \frac{P_{Load} \times h - j(S_{SC} + Q_{Load})}{P_{Load} \times h + j(Q_{Cap} \times h^2 - S_{SC} - Q_{Load})} \qquad [4.6]$$

If only the magnitudes are considered, with $j^2 = -1$

$$\left[\frac{|Z'_h|}{|Z_h|}\right]^2 = \frac{P_{Load}{}^2 \times h^2 + (S_{SC} + Q_{Load})^2}{P_{Load}{}^2 \times h^2 - (Q_{Cap} \times h^2 - S_{SC} - Q_{Load})^2} \qquad [4.7]$$

The rule of thumb for the resonant frequency harmonic order is determined by [1,10]:

$$h = \sqrt{\frac{S_{sc}}{Q_{Cap}}} \qquad [4.8]$$

Then substituting for h

$$\left[\frac{|Z'_h|}{|Z_h|}\right]^2 = \frac{P_{Load}{}^2 \times \frac{S_{SC}}{Q_{Cap}} + (S_{SC} + Q_{Load})^2}{P_{Load}{}^2 \times \frac{S_{SC}}{Q_{Cap}} - (Q_{Cap} \times \frac{S_{SC}}{Q_{Cap}} - S_{SC} - Q_{Load})^2} \qquad [4.9]$$

The equation can be simplified further to

$$\left[\frac{|Z'_h|}{|Z_h|}\right]^2 = 1 + \frac{S_{SC}{}^2 + 2S_{SC} \times Q_{Load}}{P_{Load}{}^2 \times \frac{S_{SC}}{Q_{Cap}} + Q_{Load}{}^2} \qquad [4.10]$$

Assume a maximum allowance $\frac{|Z'_h|}{|Z_h|} = 2$

This assumption stems from the observations done on Transmission network measurements, where the background harmonic THD levels of 0.9-1.4% are prevalent in most stations. Therefore the harmonic amplification factor of 2 or less will result in the in the THD levels lower than the planning level of 3% e.g. 1.4 x 2 = 2.8%.

By substituting this value into equation (4.10), we get

$$\left(2^2 - 1\right) \times \left(\frac{P_{Load}{}^2 \times S_{SC}}{Q_{Cap}} + Q_{Load}{}^2\right) = S_{SC}{}^2 + 2S_{SC} \times Q_{Load}$$

From the power equation $S_{Load}{}^2 = P_{Load}{}^2 + Q_{Load}{}^2$ [4.11]

And therefore $Q_{Load}{}^2 = S_{Load}{}^2 - P_{Load}{}^2$

Then substitute $Q_{Load}{}^{2}$

$$3\times\left(\frac{P_{Load}{}^{2}\times S_{SC}}{Q_{Cap}}+S_{Load}{}^{2}-P_{Load}{}^{2}\right)=S_{SC}{}^{2}+2S_{SC}\times\sqrt{S_{Load}{}^{2}-P_{Load}{}^{2}} \qquad [4.12]$$

If $S_{Load}\times pf=P_{Load}$

Then $S_{Load}=\dfrac{P_{Load}}{pf}$

Substituting into equation (4.12)

$$3P_{Load}{}^{2}\times\left(\frac{S_{SC}}{Q_{Cap}}+\frac{1}{pf^{2}}-1\right)=S_{SC}\left(S_{SC}+2P_{Load}\times\sqrt{\frac{1}{pf^{2}}-1}\right) \qquad [4.13]$$

$$3=\frac{S_{SC}\left(S_{SC}+2P_{Load}\times\sqrt{\frac{1}{pf^{2}}-1}\right)}{P_{load}{}^{2}\times\left(\frac{S_{SC}}{Q_{Cap}}+\frac{1}{pf^{2}}-1\right)} \qquad [4.14]$$

If $\dfrac{S_{SC}\left(S_{SC}+2P_{Load}\times\sqrt{\frac{1}{pf^{2}}-1}\right)}{P_{load}{}^{2}\times\left(\frac{S_{SC}}{Q_{Cap}}+\frac{1}{pf^{2}}-1\right)}$ < 3 (No tuning) [4.15]

It can be seen here that the power factor plays a small role on the equation as a power factor of between 1 and 0.5 will have minor impact on the amplification factor. By choosing a power factor of 1, equation (4.14) can be reduced even further.

$\dfrac{S_{SC}\times Q_{Cap}}{P_{Load}}$ < 3 (No tuning) [4.16]

Equations (4.15 and 4.16) now consist of only known network parameters (short circuit power, load power, and the size of the capacitor bank.

These equations were implemented on Excel with these parameters as seen on Table 4.3. The amplification factor results using Equation 4.15 are shown. The harmonic resonance frequency using equation 4.8 is shown under the simplified equation. For a network with a capacitor bank of 18 MVAr, three phase short circuit power of 981.51 MVA and a load of 70 MW the harmonic amplification factor will be 2.2 and resonance will occur at the 7.4$^{th}$ harmonic frequency, with no tuning required.

However, if a new capacitor bank rated 40.5 MVAr was to be installed as an upgrade to the current one the amplification factor will be 3.1 and the resonance will occur at the 4.9$^{th}$ harmonic frequency. With this high amplification factor the network might need tuning depending on the background harmonic level on the 5$^{th}$ harmonic.

For example, with a background voltage harmonic level of 2.5% on the 5$^{th}$ harmonic frequency the new 5$^{th}$ harmonic voltage will be 3.1x2.5 = 7.75% when the capacitor bank is switched (without load damping). However, with a background voltage harmonic level of 1% the new 5$^{th}$ harmonic voltage will be 3.1x1 = 3.1% when the same capacitor bank is switched on.

Table 4.3: Harmonic resonance guide table

| | | | | | |
|---|---|---|---|---|---|
| **CRITERION:** | k < | 3 | | | |
| **High Load** | | | **Low Load** | | |
| Ssc | 981.51 | MVA | Ssc | 981.51 | MVA |
| P | 70 | MW | P | 70 | MW |
| PF | 0.97 | power factor | PF | 0.97 | power factor |
| Qc | 40.5 | MVAR | Qc | 18 | MVAR |
| h | 4.9 | | h | 7.4 | |
| knew | 3.1 | Need tuning | kold | 2.2 | No tuning |
| **Simplified equation:** | | | **Simplified equation:** | | |
| | | 2.8 | | | 1.9 |

## *4.5 Conclusions*

From all these various harmonic resonance guidelines, it is important to ensure that all planning considerations are taken into account for the control and management of harmonic levels, when installing a new shunt capacitor bank or upgrading the existing one in the Eskom Transmission network.

The flowchart in Figure 4.8 is therefore proposed with the aim of ensuring that the key issues are addressed before the design of the shunt capacitor bank. The harmonic resonance guideline developed in this chapter is meant to assist planning engineers who are not familiar with harmonic simulations in deciding whether the planned capacitor bank will have a negative impact on the network or not, before they request detailed harmonic simulations at a price from consultants.

The chapter has also demonstrated that harmonic problems in a power system can be avoided if a proper planning process is followed when planning the installation of shunt capacitor banks. A proper planning process ensures that the lifecycle cost for the shunt capacitor is reduced as the proposed shunt capacitor bank will be able to meet medium to long term requirements of the system.

**MVAr needs identification**:
Identify the need to have VAr support in the network by performing load flow studies and deciding on MVAr requirements for the network.

**Measurements:**
Voltage harmonics: Undertake voltage harmonic measurements at each point in the network where VAr support is required to quantify the voltage harmonic levels. Record up to the 40$^{th}$ harmonic frequency.
Power: Undertake the measurements (apparent, active and reactive power) to determine the type of loading in that network)

**Determine capacitor parameters:**
Determine various options for the capacitor bank: Size (MVAr), voltage level (132 or 275kV), short circuit level (132 or 275kV) for normal and abnormal network operation, $P_{load}$ from measurements.

**Harmonic resonance analysis:**
Insert the $S_{sc}$, $P_{load}$, pf, $Q_{cap}$ in the harmonic resonance guide to determine the resonant frequency, as well as the harmonic amplification factor. This will assist in determining whether the proposed capacitor will resonate near the important harmonic frequencies such as the fifth, as well as determining whether the amplification will meet the criterion. This should be done for various options.

**Green:**
Meeting the following:
Measured harmonic levels below the IEEE 519 standard
Reasonable amount of resistive loading
Harmonic resonant frequency not at/near the important harmonic frequencies such as fifth.
Harmonic amplification factor meeting the criterion.

**Red:**
Either one of the following:
Measured harmonic levels above the IEEE 519 standard
Little resistive loading
Harmonic resonant frequency at/near the important harmonic frequency such as fifth.
Harmonic amplification factor meeting the criterion at the important frequencies, such as the fifth harmonic.

**Detailed simulations:**
Perform detailed harmonic simulations for various options: plain, de-tuned or C-type filter to determine the suitable option.

**Lifecycle cost analysis:**
Analyse the lifecycle cost of each option to determine the optimal implementation of VAr support.

**Proceed with the design of the capacitor bank**

*Figure 4.8: Recommended flow-chart for the assessment of harmonic resonance.*

# 5. Shunt capacitor banks used in Eskom Transmission

## *5.1 Introduction*

In the Eskom Transmission networks, shunt capacitor banks are used at various voltage levels for voltage support and improvement of the transfer of power from generation stations to the load centres.

The voltage levels where shunt capacitor banks are installed are 400kV, 275 kV, 132kV and 88kV. Transmission utilises mainly 150 MVAr plain capacitor banks on the EHV network, and mainly 72 MVAr plain capacitor banks as well as 36 or 48 MVAr capacitor banks on the HV networks. Table 5.1 shows the characteristics of these capacitor banks.

Table 5.1: Shunt capacitor component values recommended in Eskom networks

| **Rated system voltage** | **Capacitor bank ratings** | | **Current limiting reactor** | | **Damping resistor** |
|---|---|---|---|---|---|
| **[kV]** | **Rating [MVAr]** | **Transfer [MW]** | **Rated Current [A]** | **Value [µH]** | **Value [Ω]** |
| 88 | 48 | 24 | 400 | 300 | 10 |
| 132 | 72 | 36 | 400 | 300 | 10 |
| 275 | 150 | 75 | 400 | 400 | 20 |

From the knowledge gained in Chapter 4, the harmonic resonance frequencies for these capacitors were calculated using equation 4.1, below:

$$f_r = f_f \sqrt{\frac{S_{sc}}{Q_{cap}}} \qquad [4.1]$$

## *5.2 Harmonic resonance calculations (EHV and HV)*

Table 5.2 shows the harmonic resonance frequency of various EHV capacitor banks using equation 4.1. The aim of this table is to further highlight the importance of having higher short circuit power in a network to assist in moving the harmonic resonance point further from the fifth harmonic frequency, as well as the implications of having parallel capacitor banks at a particular busbar.

It can be seen that the resonant frequency with most of these capacitor banks is at higher order harmonic frequencies. For networks with more than one capacitor bank, the harmonic resonance point moves towards lower harmonic frequencies when both capacitor banks are in service.

Table 5.2: Harmonic resonance analysis for 275kV shunt capacitor banks.

| **Name of capacitor bank** | **$I_{FL}$ (A)** | **Voltage (V)** | **$S_{MVA}$** | **$Q_{CAP}$** | **$f_r$** | **$f_{r\ (parallel)}$** |
|---|---|---|---|---|---|---|
| Apollo SC No1AB 275kV | 32335 | 275000 | 15401 | 150 | 10.13 | 7.16 |
| Apollo SC No2AB 275kV | 32335 | 275000 | 15401 | 150 | 10.13 | 7.16 |
| Ararat, SC No11 275kV | 14735 | 275000 | 7018 | 150 | 6.84 | |
| Bighorn, SC No1 275kV | 16603 | 275000 | 7908 | 150 | 7.26 | |
| Esselen, SC No11 275kV | 31406 | 275000 | 14959 | 150 | 9.99 | |
| Hector, SC 2 275kV | 14395 | 275000 | 6856 | 150 | 6.76 | 4.78 |
| Hector, SC No4 275kV | 14395 | 275000 | 6856 | 150 | 6.76 | 4.78 |
| Illovo , SC No 2 275kV | 9298 | 275000 | 4429 | 150 | 5.43 | 3.84 |
| Illovo, SC No4 275kV | 9298 | 275000 | 4429 | 150 | 5.43 | 3.84 |
| Impala, SC No4 275kV | 11987 | 275000 | 5709 | 150 | 6.17 | 4.36 |
| Impala, SC No2 132kV | 11987 | 275000 | 5709 | 150 | 6.17 | 4.36 |
| Jupiter, SC No 4 275kV | 28363 | 275000 | 13509 | 150 | 9.49 | 6.71 |
| Jupiter, SC No3 275kV | 28363 | 275000 | 13509 | 150 | 9.49 | 6.71 |
| Mersey, SC No1 275kV | 15696 | 275000 | 7476 | 150 | 7.06 | |
| Minerva, SC 1AB 275kV | 23210 | 275000 | 11055 | 150 | 8.58 | 6.07 |
| Minerva, SC No2AB 275kV | 23210 | 275000 | 11055 | 150 | 8.58 | 6.07 |
| Pluto, SC No1 275kV | 23001 | 275000 | 10955 | 150 | 8.55 | |

Notes:
1: The $I_{FL}$ is taken from the System Operator and Planning department 2007-2008 fault level (short circuit power) report and considers all plant to be in service.
2: It is assumed that the paralleling of capacitor banks happens when all plant is in operation as well, as the loss of a line or transformer will result in a drop in short circuit power and thus change the resonant frequency.
3. The colour coding does not necessarily indicates that there is a harmonic problem at a particular site, but illustrates the criticality of the network with regard to EHV short circuit powers, as well as the harmonic resonance

Table 5.3 shows the harmonic resonance frequency of various HV capacitor banks using equation 4.1. Similarly, the aim of this table is to further highlight the importance of having higher short circuit power in a network to assist in moving the harmonic resonance frequency further from the fifth harmonic frequency.

The resonant frequency for most of these capacitor banks is at higher order harmonics. At the substations where the short circuit powers are low, the harmonic resonance frequency is closer to the fifth harmonic frequency. Furthermore, for most of the substations where more than one capacitor bank is used in the system, the harmonic resonance frequency moves towards the fifth harmonic frequency when both capacitor banks are in use.

Table 5.3: Harmonic resonance analysis for 132 and 88kV shunt capacitor banks.

| | $I_{FL}$ (A) | Voltage (V) | $S_{MVA}$ | $Q_{CAP}$ | $f_r$ | $f_{r\ (parallel)}$ |
|---|---|---|---|---|---|---|
| Acacia, SC No1 132kV | 28279 | 132000 | 6465.49 | 72 | 9.48 | 6.70 |
| Acacia, SC No2 132kV | 28279 | 132000 | 6465.49 | 72 | 9.48 | 6.70 |
| Ararat, SC No1 88kV | 24793 | 88000 | 3778.96 | 48 | 8.87 | 6.27 |
| Ararat, SC No2 88kV | 24793 | 88000 | 3778.96 | 48 | 8.87 | 6.27 |
| Ariadne, SC No1 132kV | 17258 | 132000 | 3945.71 | 72 | 7.40 | 5.23 |
| Ariadne, SC No2 132kV | 17258 | 132000 | 3945.71 | 72 | 7.40 | 5.23 |
| Bernina, SC No1 132kV | 21418 | 132000 | 4896.81 | 72 | 8.25 | |
| Buffalo, SC No1 132kV | 9813 | 132000 | 2243.55 | 72 | 5.58 | |
| Carmel, SC No1 132kV | 21406 | 132000 | 4894.07 | 72 | 8.24 | |
| Eiger, SC No1 88kV | 23928 | 88000 | 3647.12 | 48 | 8.72 | |
| Everest, SC No1 132kV | 14675 | 132000 | 3355.16 | 72 | 6.83 | 4.83 |
| Everest, SC No2 132kV | 14675 | 132000 | 3355.16 | 72 | 6.83 | 4.83 |
| Foskor, SC No1 132kV | 8959 | 132000 | 2048.30 | 72 | 5.33 | 3.77 |
| Foskor, SC No2 132kV | 8958 | 132000 | 2048.07 | 72 | 5.33 | 3.77 |
| Georgedale, SC No1 132kV | 5206 | 132000 | 1190.25 | 72 | 4.07 | |
| Hermes, SC No2 132kV | 20822 | 132000 | 4760.55 | 72 | 8.13 | 5.75 |
| Hermes, SC No3 132kV | 20822 | 132000 | 4760.55 | 72 | 8.13 | 5.75 |
| Illovo, SC No1 132kV | 11038 | 132000 | 2523.63 | 72 | 5.92 | |
| Jupiter , SC No1 88kV | 17625 | 88000 | 2686.41 | 48 | 7.48 | 5.29 |
| Jupiter, SC No2 88kV | 17625 | 88000 | 2686.41 | 48 | 7.48 | 5.29 |
| Komatipoort, SC No 1132kV | 4239 | 132000 | 969.17 | 40.5 | 4.89 | |
| Leander, SC 2 132kV | 17226 | 132000 | 3938.39 | 36 | 10.46 | |
| Mercury, SC No1 132kV | 20431 | 132000 | 4671.15 | 72 | 8.05 | 5.70 |
| Mercury, SC No2 132kV | 20431 | 132000 | 4671.15 | 72 | 8.05 | 5.70 |
| Merensky, SC No1 132kV | 20256 | 132000 | 4631.14 | 60.5 | 8.75 | |
| Midas, SC 1 132kV | 27508 | 132000 | 6289.17 | 72 | 9.35 | |
| Pembroke, SC No1 132kV | 6498 | 132000 | 1485.64 | 36 | 6.42 | |
| Pieterboth, SC No1 88kV | 21826 | 88000 | 3326.73 | 48 | 8.33 | |
| Princess, SC No2 88kV | 20756 | 88000 | 3163.64 | 48 | 8.12 | |
| Rigi, SC No1 88kV | 26034 | 88000 | 3968.11 | 48 | 9.09 | |
| Theseus, SC 1 132kV | 19205 | 132000 | 4390.85 | 75 | 7.65 | 5.41 |
| Theseus, SC No2 132kV | 19205 | 132000 | 4390.85 | 75 | 7.65 | 5.41 |
| Trident, SC No1 88kV | 24574 | 88000 | 3745.58 | 48 | 8.83 | 6.25 |
| Trident, SC No2 88kV | 24574 | 88000 | 3745.58 | 48 | 8.83 | 6.25 |
| Umfolozi, SC No1 88kV | 13107 | 88000 | 1997.78 | 48 | 6.45 | |
| Vulcan, SC No1 132kV | 26432 | 132000 | 6043.17 | 72 | 9.16 | 6.48 |
| Vulcan, SC No2 132kV | 26432 | 132000 | 6043.17 | 72 | 9.16 | 6.48 |
| Watershed, SC No2 88kV | 6627 | 88000 | 1010.09 | 48 | 4.59 | |
| Westgate, SC 1 132kV | 16953 | 132000 | 3875.98 | 72 | 7.34 | 5.19 |
| Westgate, SC No2 132kV | 16953 | 132000 | 3875.98 | 72 | 7.34 | 5.19 |
| Witkop, SC No1 132kV | 20866 | 132000 | 4770.61 | 36 | 11.51 | 6.65 |
| Witkop, SC No2 132kV | 20866 | 132000 | 4770.61 | 72 | 8.14 | 6.65 |

Notes:
Same as in Table 5.2

### *5.3 EHV case study 1: Hector 275kV busbar*

#### *5.3.1 Background*

Figure 5.1 shows the network diagram around Hector substation. As shown on Table 5.1 there are two 150 MVAr capacitor banks at the substation installed on the 275kV busbar and there are other capacitor banks installed at various substations nearby.

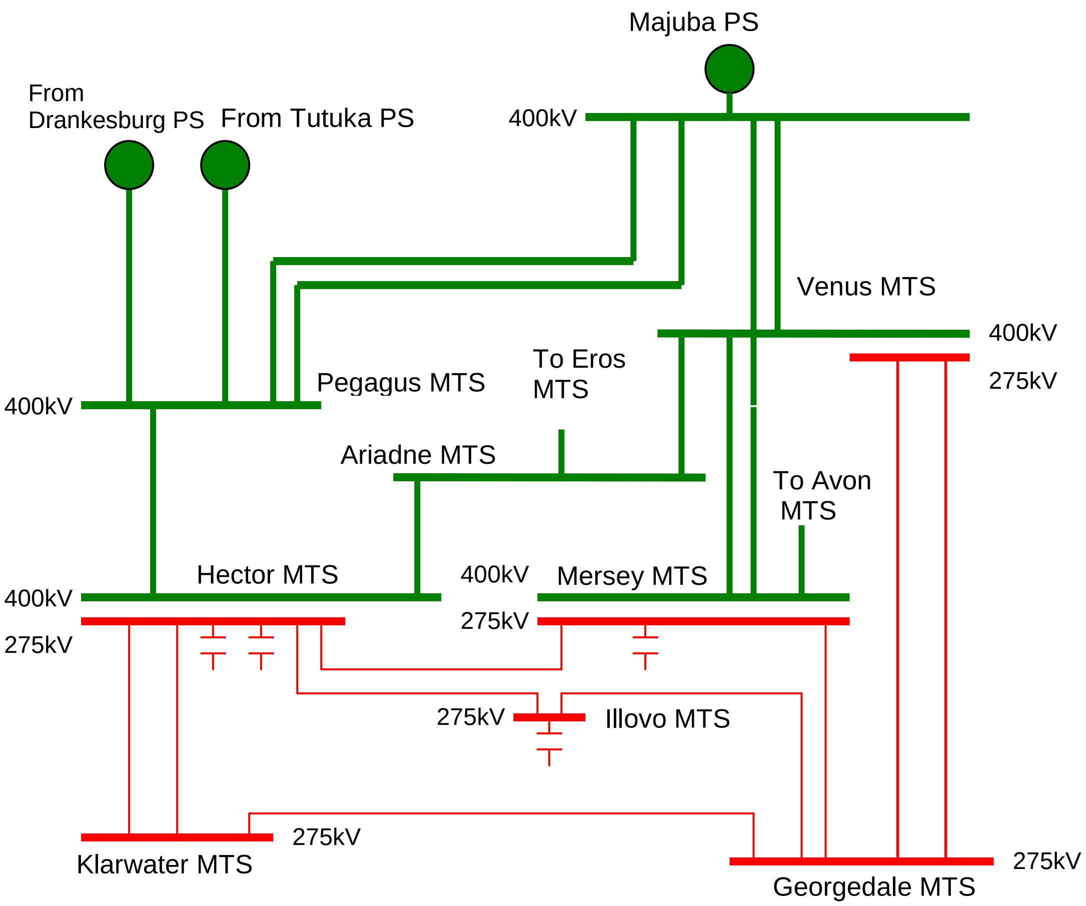



*Figure 5.1: Simplified Hector network diagram*

#### *5.3.2 Investigation*

The THD and harmonic resonance analysis was done using the following:

- The 275kV busbar THD measurement data.
- The 275kV capacitor bank MVAr measurement data.
- The 400/275kV transformer MVA measurement data.
- Harmonic simulations on DigSilent Power Factory.

The assessed measurements were for the period: 01-14 November 2009.

Figure 5.2 shows the ten minute averaged THD values for Hector 275kV busbar and the THD levels are well within both the planning (3%) and compatibility (4%) limits. These levels are maintained when either one or both capacitors are switched on and during various loading periods, as shown on Figures 5.3 – 5.4.

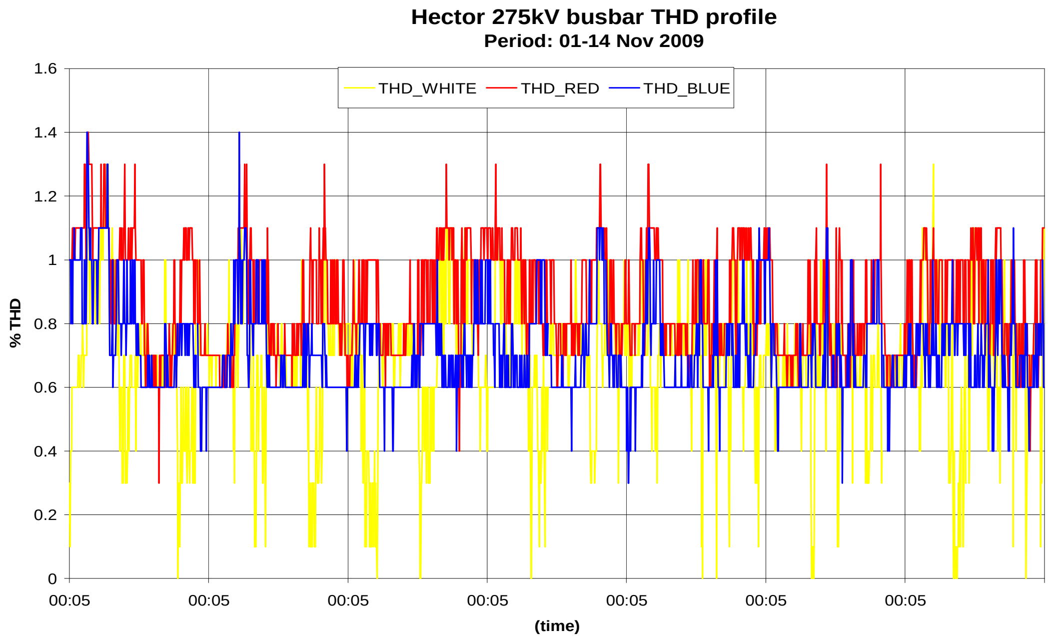



*Figure 5.2: Hector 275kV busbar voltage harmonic profile*

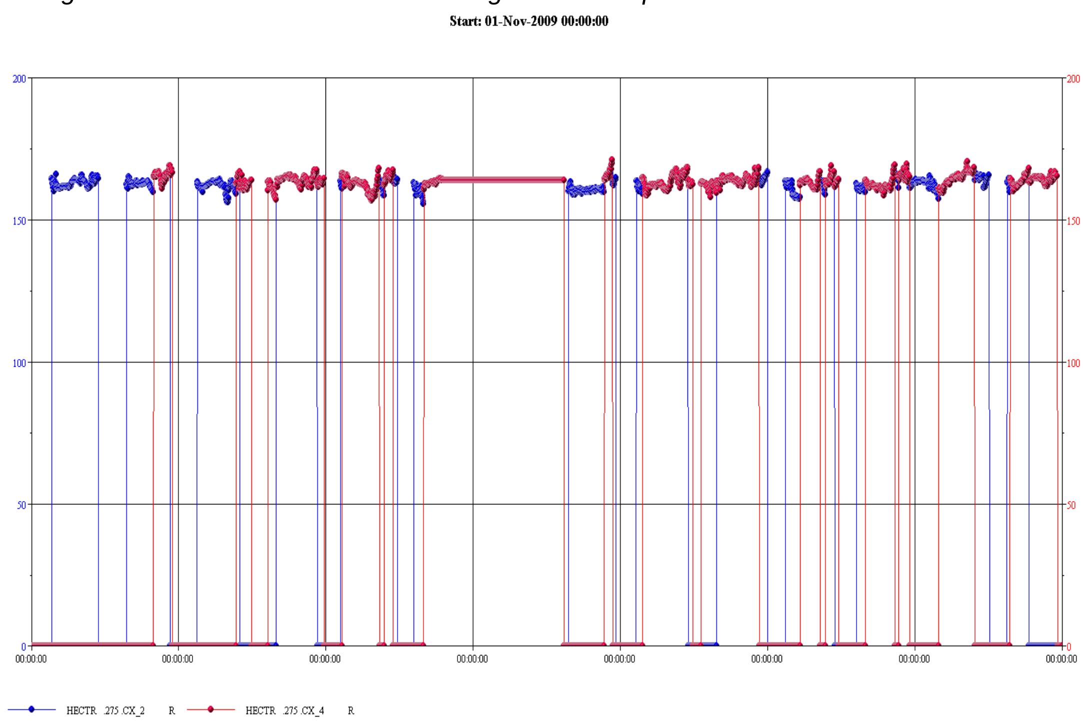



*Figure 5.3: Hector 275kV shunt capacitor bank MVAr profile*

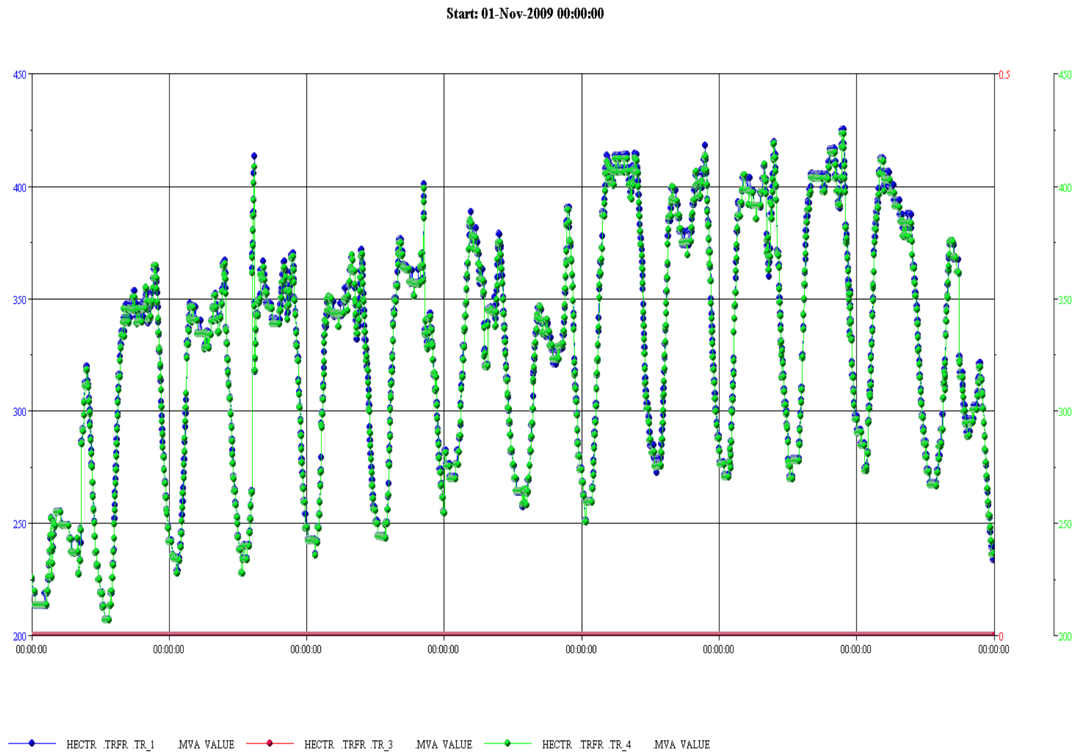



*Figure 5.4: Hector 400/ 275kV transformer MVA loading profiles*

The simulations done on DigSilent Power Factory shows that when neither of the capacitor banks is in service there is resonance near the tenth harmonic frequency, due to neighbouring capacitor banks. When one of the banks is switched on there is resonance near the ninth harmonic frequency and between the seventh and eighth harmonic frequency when both capacitor banks are switched on. There is also some form of series resonance near the sixth harmonic frequency under all conditions.

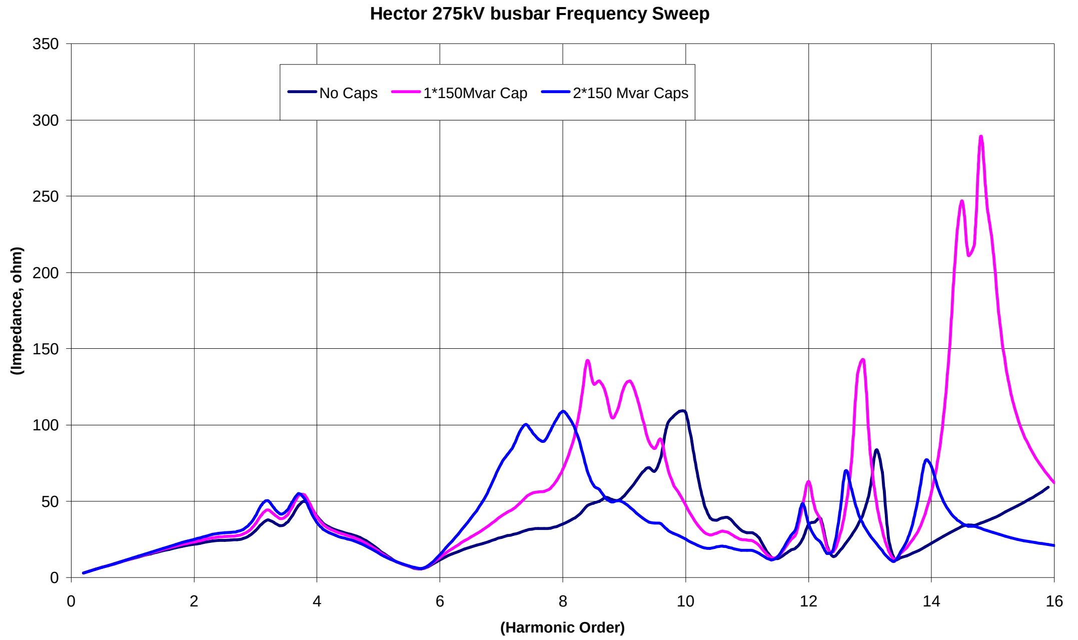



*Figure 5.5: Hector 275kV busbar harmonic impedance plots.*

### 5.3.3 Findings and conclusion

From this analysis, the switching of Hector substation capacitor banks has minimal impact on the THD levels at Hector 275kV busbar because of the following reasons:

- Resonance occurs between the seventh and ninth harmonic frequency when one or more capacitor banks are switched on.
- The background THD levels are low at that voltage level.
- The capacitor banks are switched off during lightly loaded conditions.

## 5.4 EHV case study 2: Minerva 275kV busbar

### 5.4.1 Background

Figure 5.6 shows the network diagram around Minerva substation. As shown on Table 5.1 there are two 150 MVAr shunt capacitor banks at the substation installed on the 275kV busbar and this substation is regarded as having a high short circuit power.

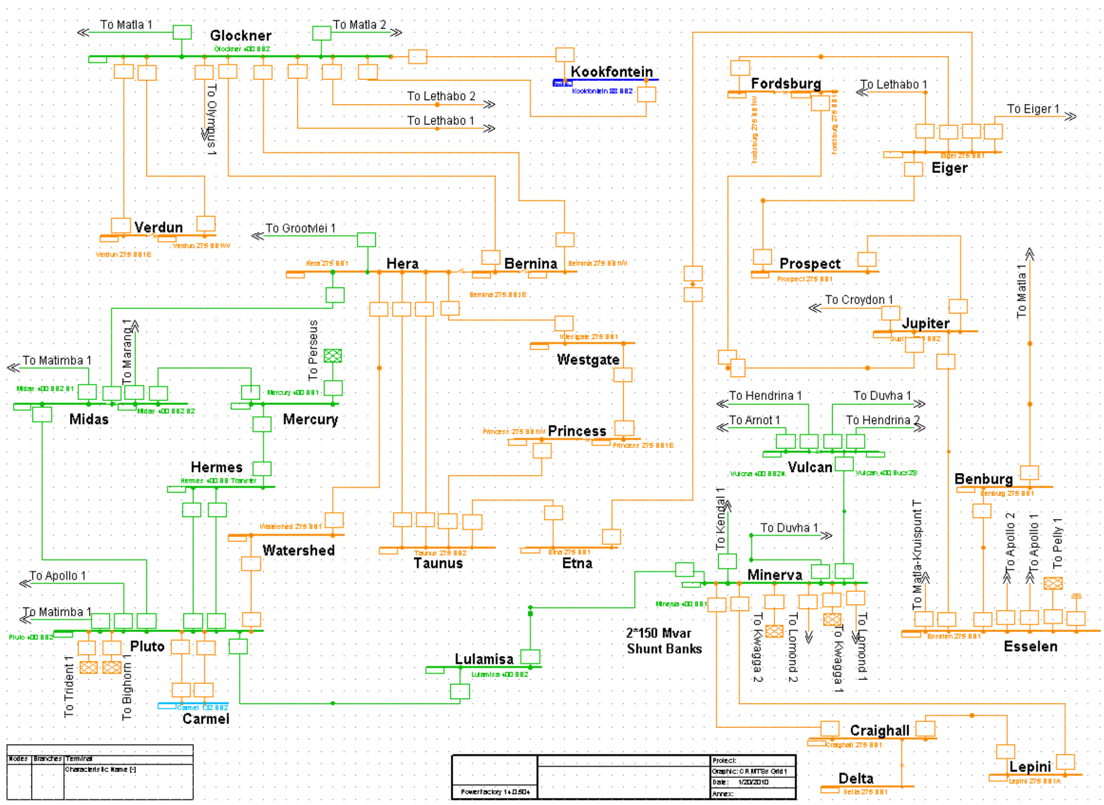



*Figure 5.6: Simplified Minerva network diagram*

### *5.4.2 Investigation*

The THD and harmonic resonance analysis was done using the following:

- The 275kV busbar THD measurement data.
- The 275kV capacitor bank MVAr measurement data.
- The 400/275kV transformer MVA measurement data.
- Harmonic simulations on Power Factory.

The assessed measurements were for the period: 14-31 August 2009.

Figure 5.7 shows the 10 minute averaged THD values for Minerva 275kV busbar and the THD levels are well within both the planning (3%) and compatibility (4%) limits. These levels are maintained when either one or both capacitors are switched on and during various loading periods, as shown on Figures 5.8 – 5.9.

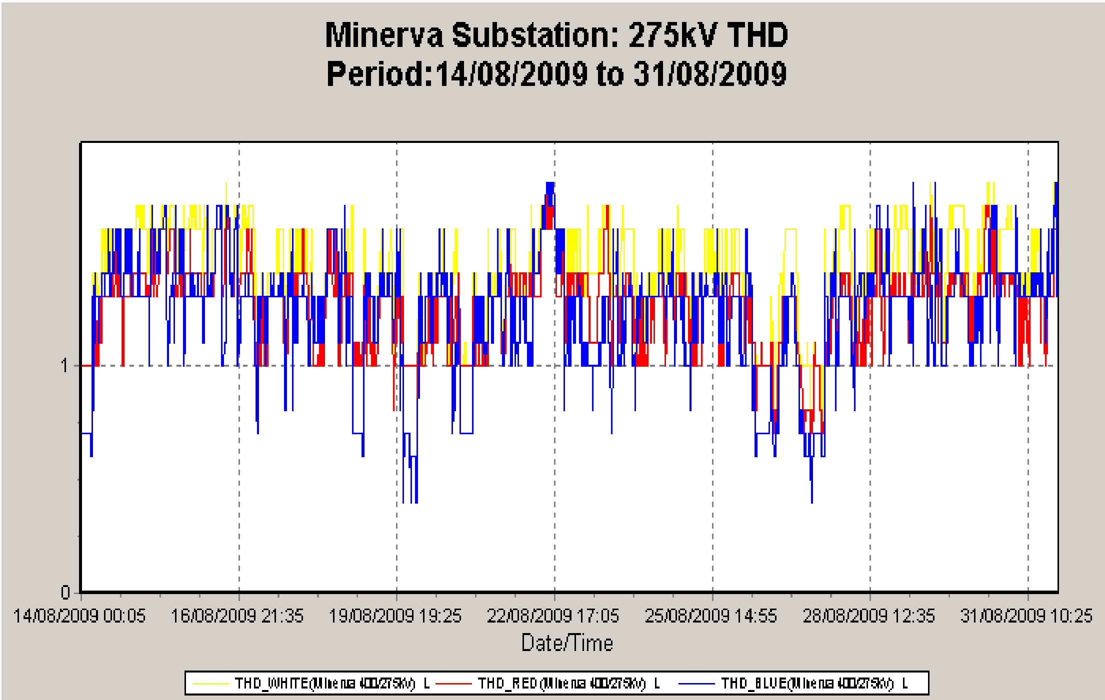



*Figure 5.7: Minerva 132kV busbar THD measurements*

Harmonic simulations (impedance plots) were performed on DigSilent Power Factory. The aim of the simulations was to identify the resonant frequencies and the amplification factors when the two 150 MVAr capacitor banks at Minerva 275kV busbar are switched on. The simulations were performed for frequencies up to the $20^{th}$ harmonic frequency.

Figure 5.10 shows the impedance plots for different combinations in capacitor switching.

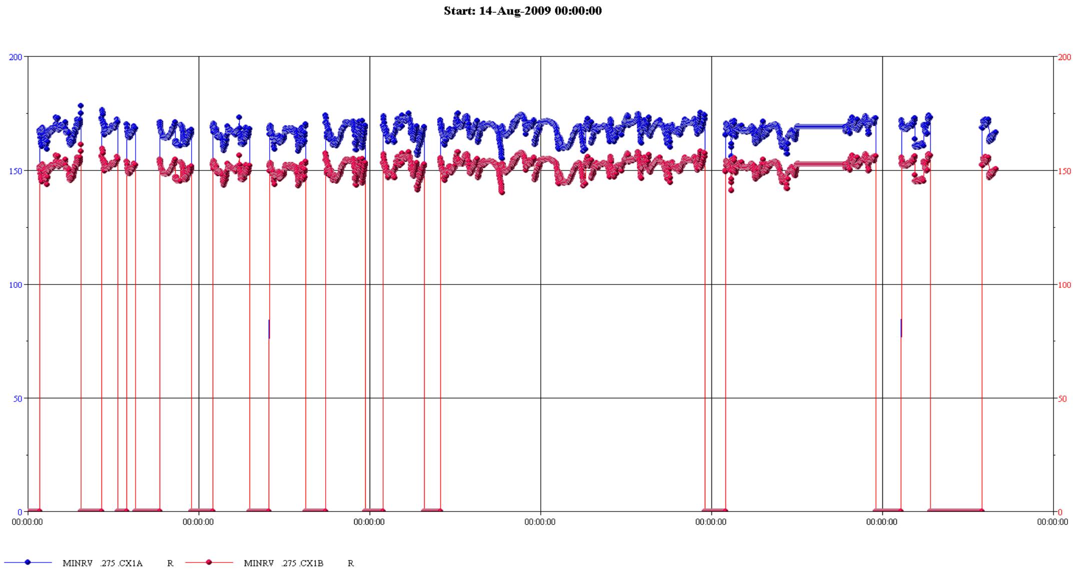



*Figure 5.8: Minerva 2x150 MVAr capacitor bank MVAr profile*

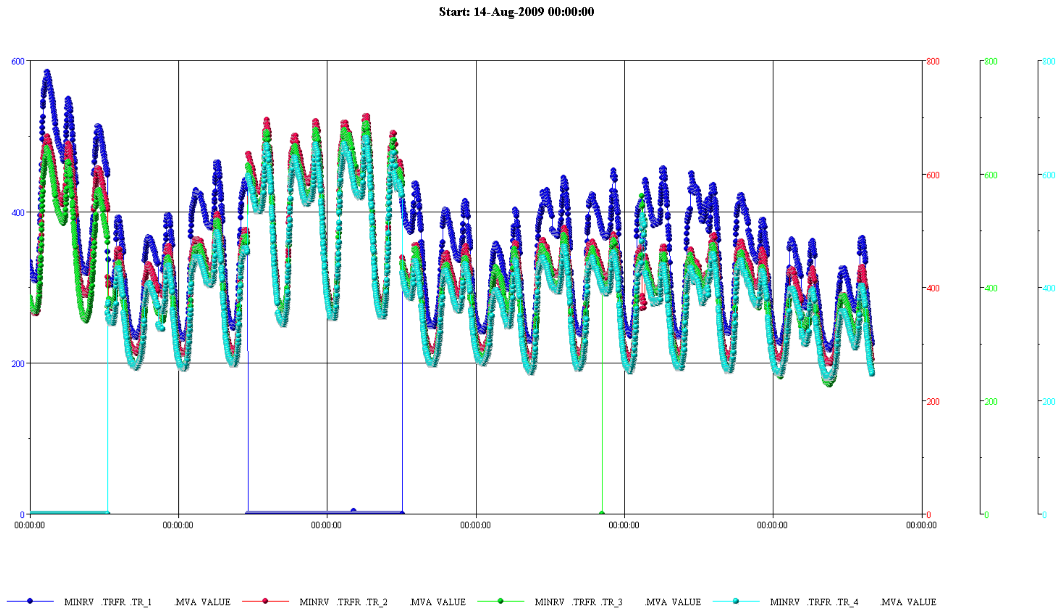



*Figure 5.9: Minerva 400/ 275kV transformer MVA loading profiles*

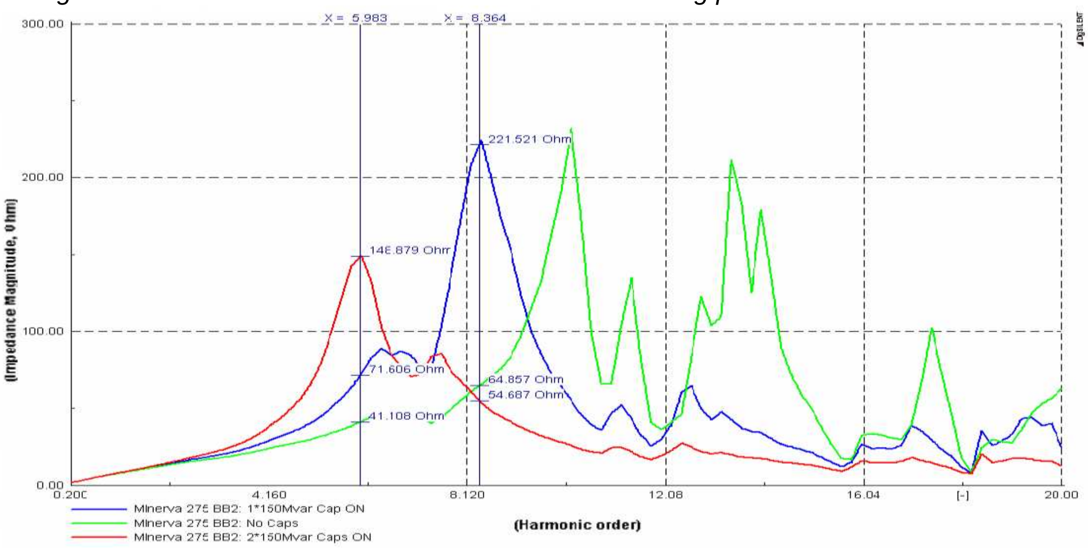



*Figure 5.10: Minerva 275kV busbar harmonic impedance plots*

Observations:

- Resonance occurs around the eighth harmonic frequency with one capacitor bank switched on.
- Resonance occurs around the sixth harmonic frequency when both capacitor banks are switched on.

### *5.4.3 Findings and conclusion*

From this analysis the switching of Minerva substation capacitor banks have minimal impact on the THD levels at Minerva 275kV busbar because of the following reasons:

- Resonance occurs between the sixth and eighth harmonic frequency when one or more capacitor banks are switched on
- The background THD levels are low at that voltage level
- The capacitor banks are properly managed as they are switched off during lightly loaded periods.

## ***5.5 HV case study 1: Westgate 132kV busbar***

### *5.5.1 Background*

Figure 5.11 shows the simplified Eskom Transmission network diagram around Westgate substation, where Eskom Transmission has two 132kV 72 MVAr capacitor banks installed for voltage support and power transfer. Other capacitor banks considered in the study were Taunus 132kV 72MVAr and Princess 132kV 48 MVAr.

### *5.5.2 Investigation*

The THD and harmonics resonance analysis was done using the following:

- The 132kV busbar THD measurement data.
- The 132kV capacitor banks MVAr measurement data.
- The 275/132kV transformers MVA measurement data.
- Harmonic simulations on DigSilent Power Factory.

Figure 5.12 shows the Westgate 132kV busbar three phase THD measurements for the period 07-24 March 2009. The shunt capacitor bank switching at Westgate 132kV busbar is also shown by lines (red, yellow and green).

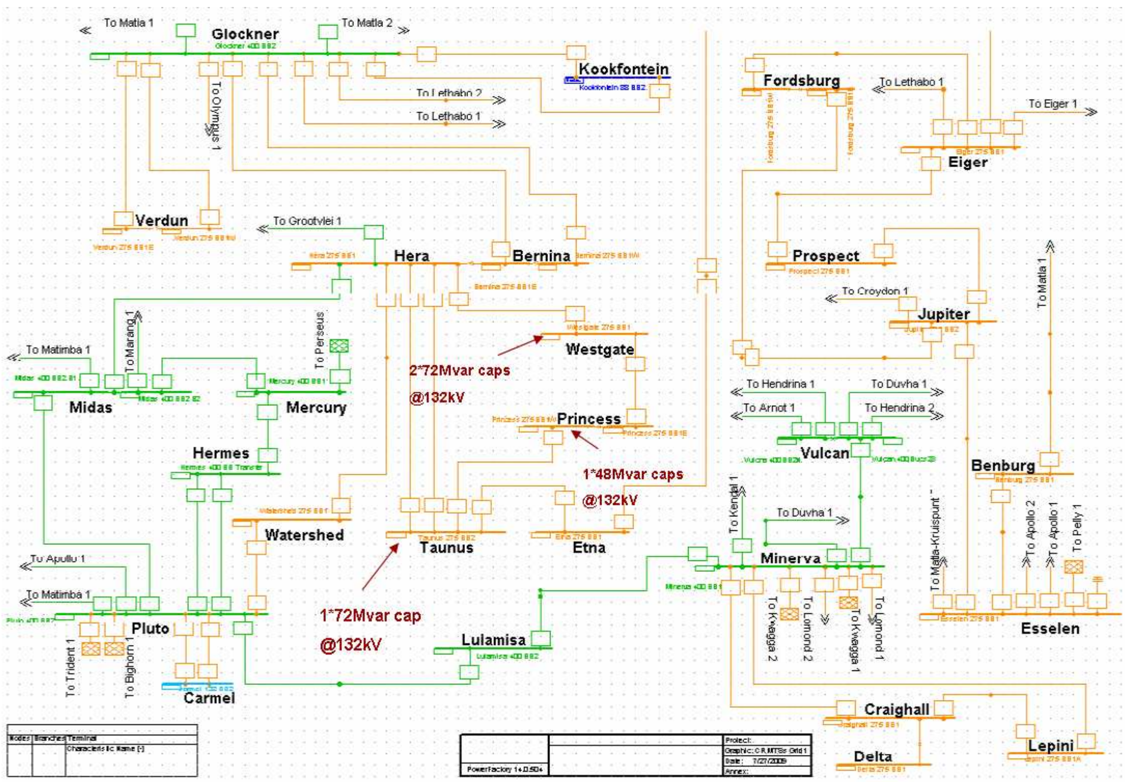



*Figure 5.11: Simplified Westgate network diagram*

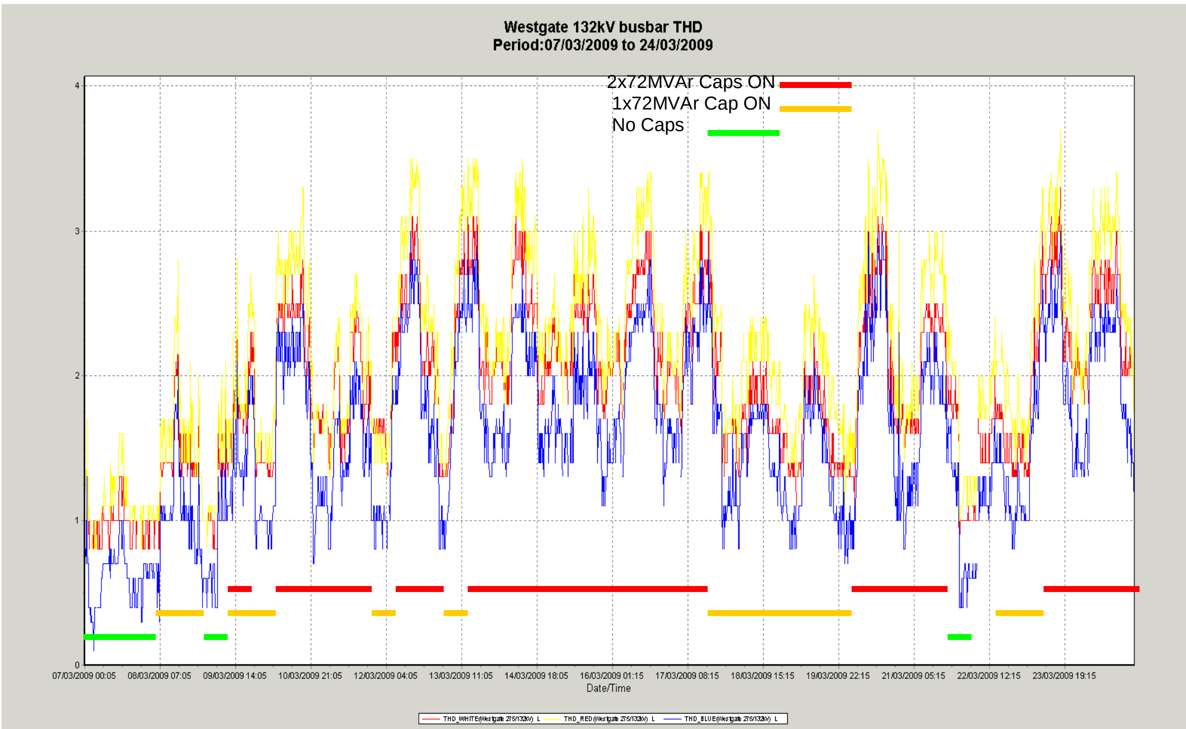



*Figure 5.12: Westgate 132kV bus THD measurements and capacitor bank switching*

Observations:

- When 2 x Westgate 132kV 72 MVAr capacitor banks are switched on, there is maximum amplification of harmonics and the THD level exceeds the planning limit of 3%, mainly on the red phase. This happens between 12:00 to 16:00.

- When 1 x Westgate 132kV 72 MVAr capacitor bank is switched on, there is a reduction in the amplification of harmonics and the THD levels are kept within the planning limit of 3%.
- When both capacitor banks are off, there is no amplification of harmonics and the THD levels are low.

The capacitor banks switching data and transformer 13 and 14 loading data for the same period are shown on Figures 5.13 and 5.14.

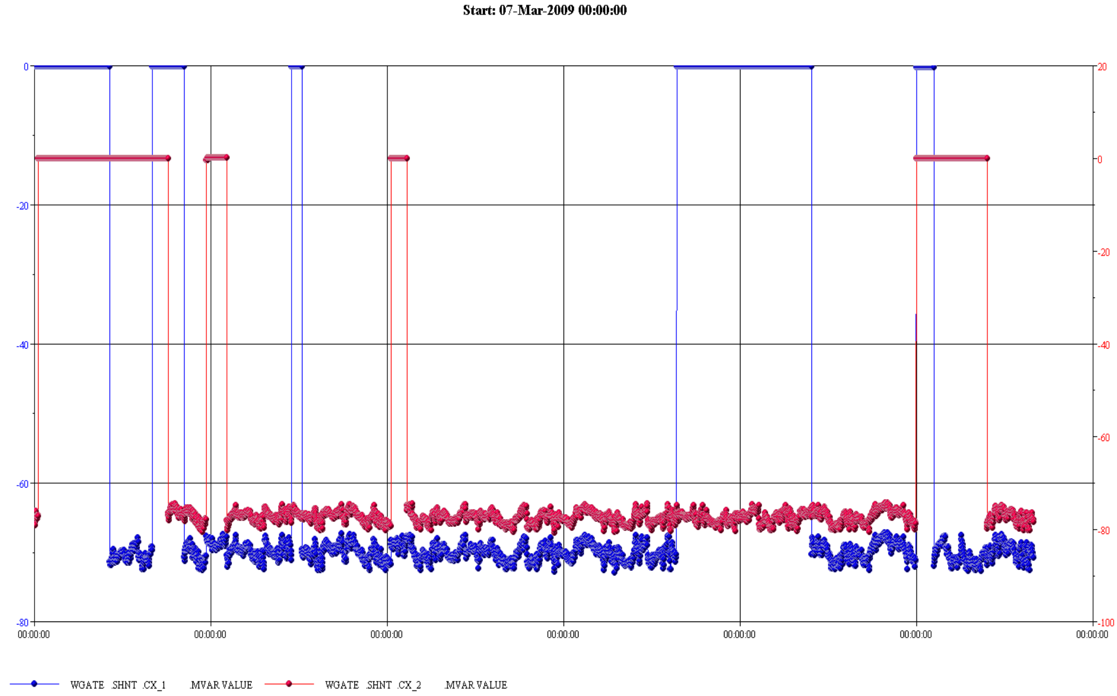



*Figure 5.13: Westgate 2x72 MVAr shunt capacitor bank MVAr profiles*

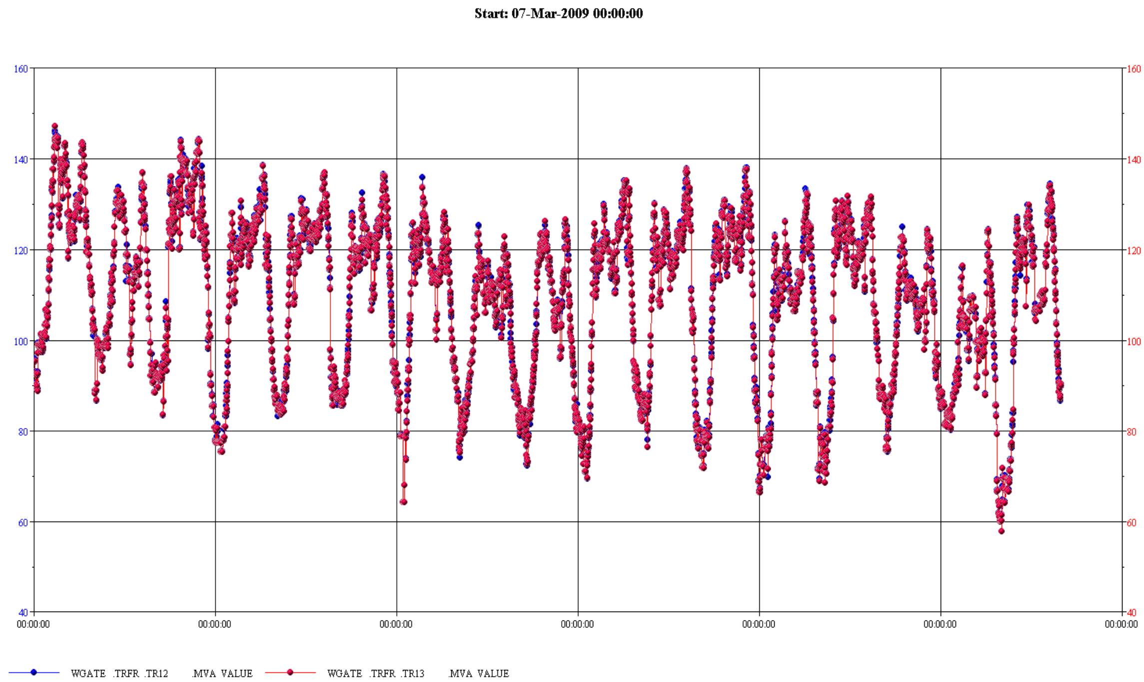



*Figure 5.14: Westgate transformer MVA loading profiles*

Harmonic simulations (impedance plots) were performed on DigSilent Power Factory. The aim of the simulations was to identify the resonant frequencies and the amplification factors when capacitor banks at various locations (Westgate, Taunus and Princess) are switched on. The simulations were performed for frequencies up to the $20^{th}$ harmonic frequency.

Figure 5.15 shows the impedance plots for different combinations in capacitor bank switching.

Observations:

- Resonance occurs near the seventh harmonic frequency with one capacitor bank switched on at Westgate substation. The fifth harmonic amplification factor is 1.6.
- Resonance occurs near the fifth harmonic frequency with both capacitor banks switched on at Westgate substation, with the amplification factor of 2.54.
- Taunus and Princess capacitor banks have minimal impact on the amplification factor and resonance frequency.

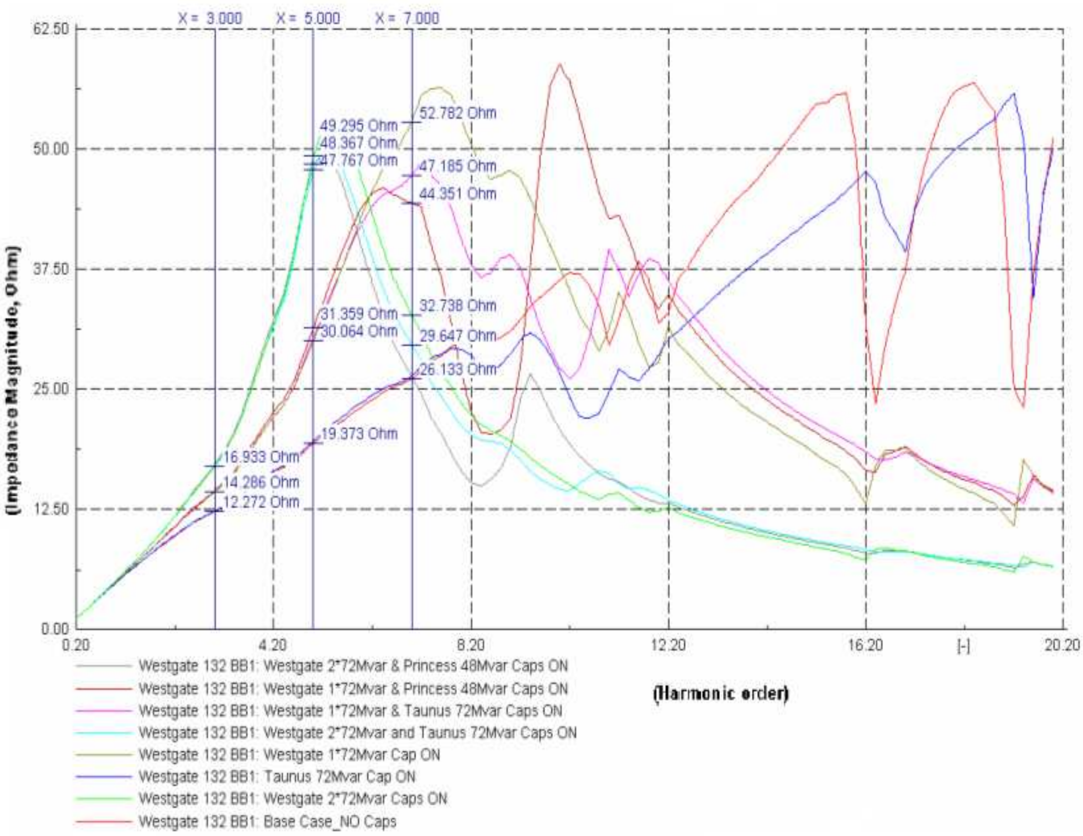



*Figure 5.15: Westgate 132kV busbar harmonic impedance plots*

### *5.5.3 Findings and conclusion*

The switching on of the Westgate capacitor banks amplifies the harmonic levels at the Westgate 132kV busbar due to the following reasons:

- When both capacitor banks are switched on resonance occurs near the fifth harmonic frequency.
- Lack of resistive load damping.
- Poor management of capacitor banks, as they are often left on even during low loading of the network.

The recommended action plan for this network was to manage the operation of the Westgate 132kV capacitor banks as follows:

Simulations show that the use of only one capacitor bank at Westgate substation in combination with the ones at Taunus and Princess Substations will reduce the amplification factor on the fifth harmonic frequency. The THD levels at Westgate 132kV busbar will therefore be managed within both the planning and compatibility limits. The second capacitor bank at Westgate substation will only be used when these combinations have been exhausted and should not be used for extended periods.

It was further recommended that in the long-term, the current shunt capacitor banks be modified into de-tuned capacitor banks. With this option both the 72 MVAr de-tuned capacitor banks can be switched on without fear of exceeding the THD limits. Detailed simulations show that the new resonant frequency will be around the fourth harmonic frequency under normal network operation and various contingencies. This option should be explored under the following conditions:

- When the THD levels at Westgate 132kV busbar have increased to levels that when either one or both capacitor banks at Westgate substation are switched on, the THD levels exceed the 4% THD compatibility limit.
- System Operations and Planning department give notice that they need the two capacitor banks on a more permanent basis at Westgate substation and the contracted THD limit cannot be increased to accommodate the new THD levels.

Without meeting these conditions, the project may not be deemed financially viable as the THD planning limit is used as internal business gatekeeper and does not form part of the NERSA licensing requirement.

## *5.6 HV case study 2: Hermes 132kV busbar*

### *5.6.1 Background*

Figure 5.16 shows the trended averaged THD ten minute values for all the phases (red, white and blue) for the period 01/07/2009 to 30/09/2009. The THD level has on several occasions exceeded the THD planning limit of 3% when both capacitor banks at Hermes substation are switched on. The switching of capacitor banks is also highlighted with different colours. The THD exceedance question will be discussed in 5.5.2.

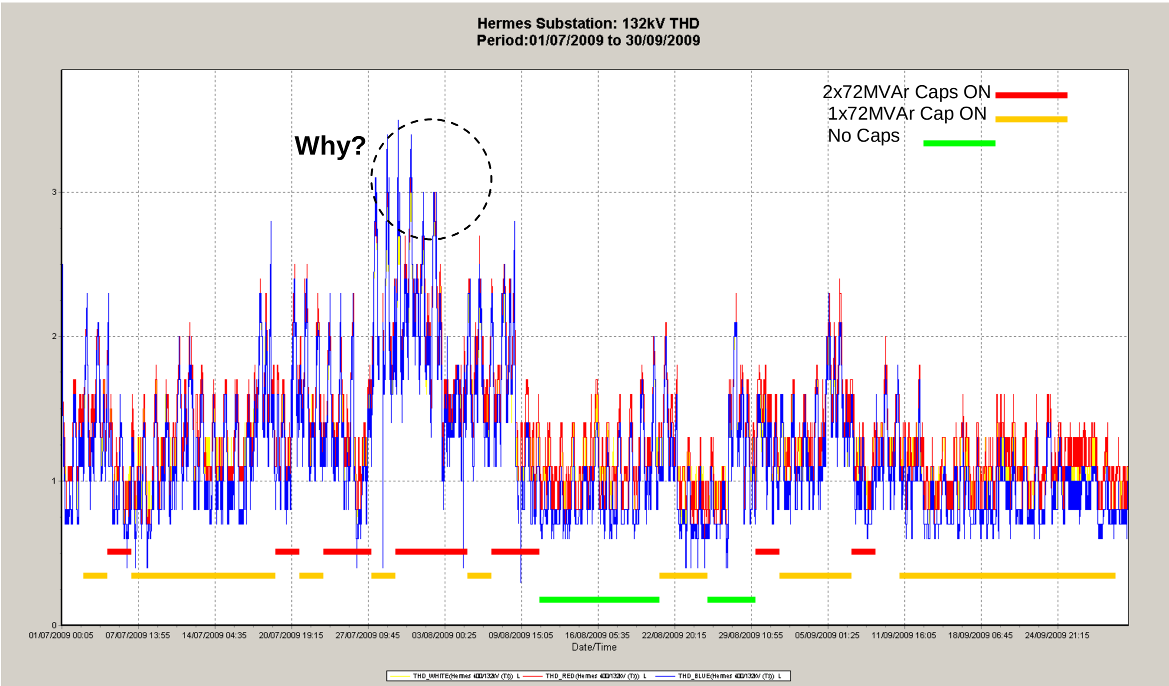



*Figure 5.16: Hermes 132kV average THD ten minute values(r, w, and b)*

The summarised transmission network diagram around Hermes substation is shown on Figure 5.17, with capacitor bank installations.

### *5.6.2 Investigation*

The THD levels at the Hermes 132kV busbar were analyzed by correlating the shunt capacitor bank switching events with THD measurements. The harmonic simulations (impedance plots) were performed for various shunt capacitor bank operations in the network to identify the resonance frequencies and their impedance magnitudes relative to the impedance of the system when there are no capacitors in service.

Figure 5.18 shows the Hermes 132kV busbar three phase THD measurements for the period 27/07/2009 to 10/08/2009. The capacitor bank switching at Hermes 132kV busbar is also shown by lines (red, yellow and green).

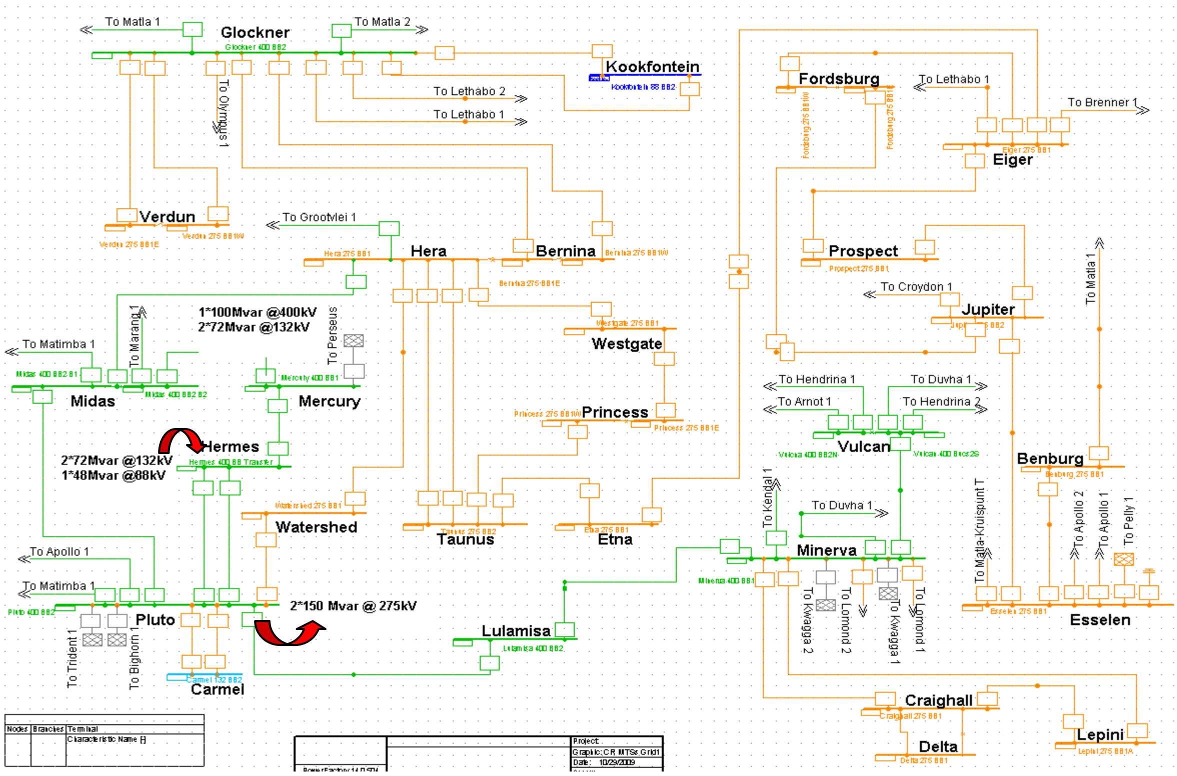


*Figure 5.17: Summarized Hermes network diagram*

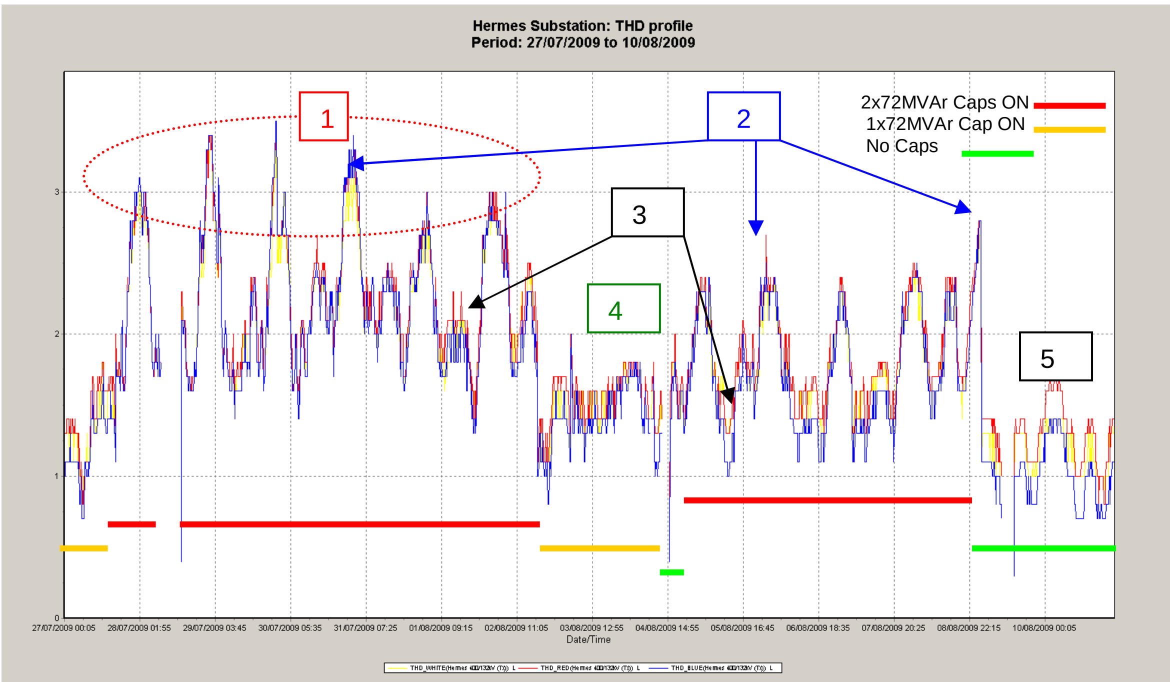



*Figure 5.18: Hermes 132kV bus THD measurements and capacitor banks switching*

Observations:

- When the two capacitor banks (2x72 MVAr) at Hermes substation are switched on there is amplification of harmonics and the THD levels reach levels closer to the planning limits of 3% during the lightly loaded period (23:00 to 04:00). This high amplification is caused by lack of resistive load damping.

- When there is plant out of service at Hermes substation shown by region 1, the harmonic amplification becomes even higher. This is caused by the drop in short circuit power on the 132kV busbar, as was the case when 400/132kV transformer 2 was out of service during the period between 27/07/2009 to 02/08/2009. Also see Figure 5.20 for the Hermes transformer loading measurements.
- Region 2 is a low loading period for the system and therefore less harmonic damping. The THD levels rise during this period, especially when both capacitor banks are switched on. From 23:00 to 04:00
- Region 3 is a high peak period for the system. The resistive part of the load assists in high damping of harmonics, even when both capacitors are switched on. THD levels are kept within the planning limit of 3%.
- Region 4 is when one capacitor bank (1x72 MVAr) is switched on. There is a reduction in the amplification of harmonics and the THD levels are kept within the planning limit of 3% regardless of the loading.
- Region 5 is when both capacitor banks are off. There is no amplification of harmonics and the THD levels are low.

Figure 5.19 shows the Hermes capacitor MVAr loading, while Figure 5.20 show the transformer MVA loading for the period 27 July 2009 to 02 August 2009.

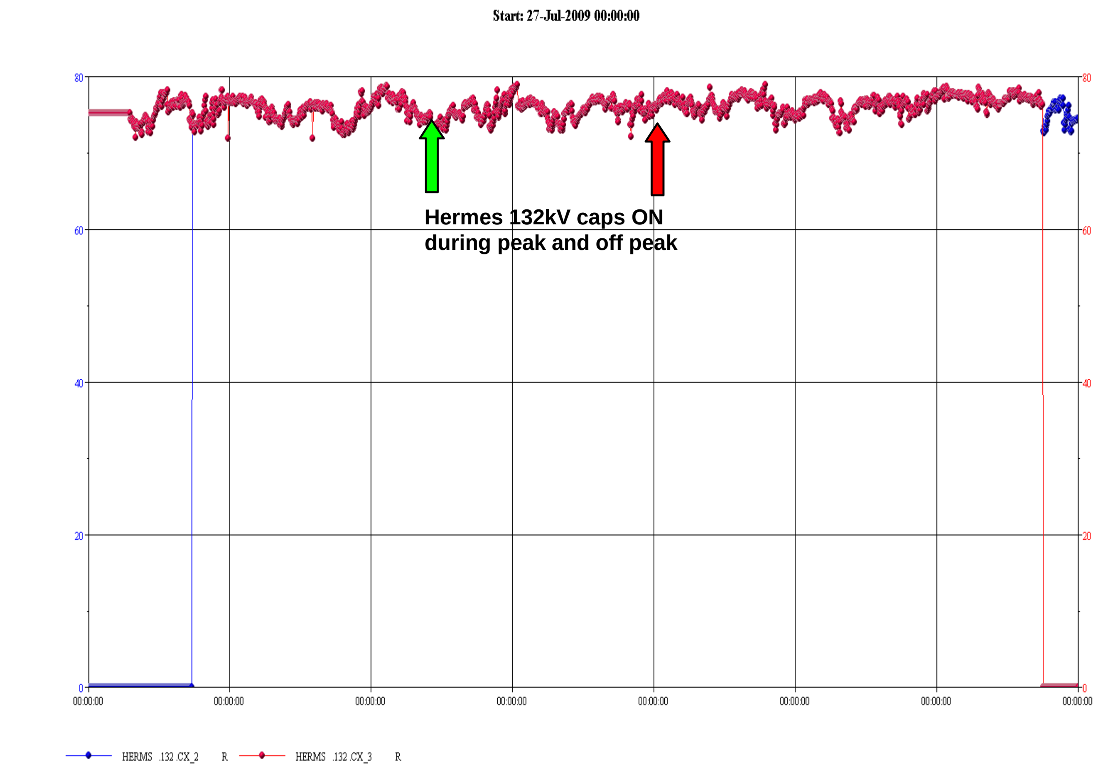



*Figure 5.19: Hermes 2x72 MVAr capacitor bank MVAr profiles.*

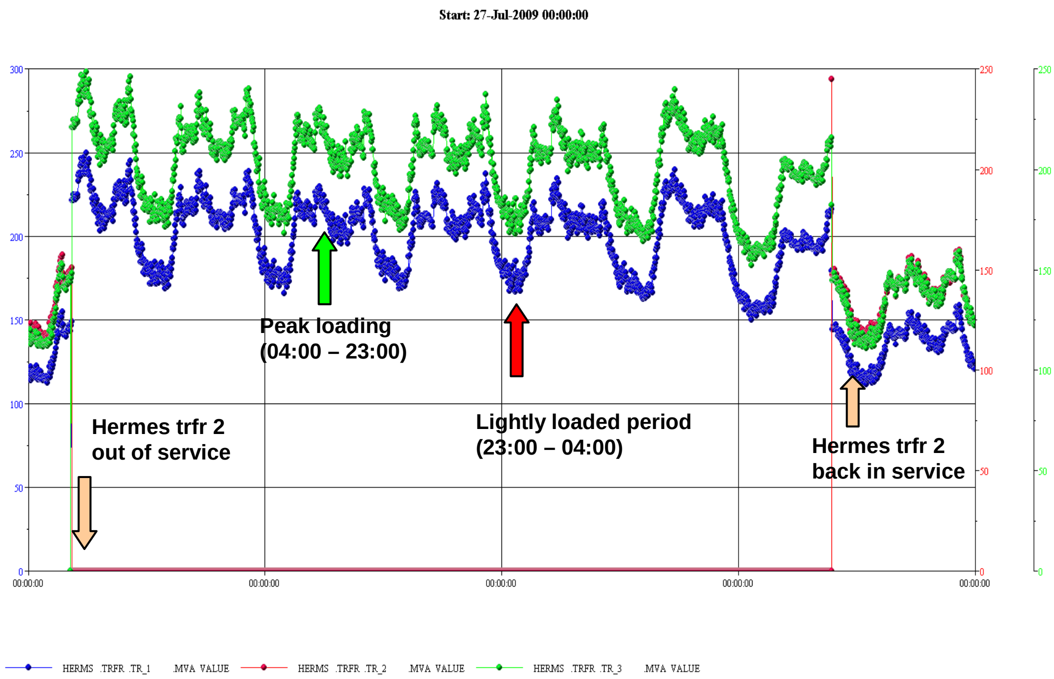



*Figure 5.20: Hermes transformer MVA loading profiles*

Harmonic simulations (impedance plots) were performed on DigSilent Power Factory. The Distribution (Central region) latest case file was used for this investigation. The aim of the simulations was to identify the resonance frequencies and the harmonic amplification factors when shunt capacitor banks at Hermes substation are switched on. The simulations were also performed for when there is a contingency at Hermes substation (one 400/132kV transformer out of service). The simulations were performed for frequencies up to the 20$^{th}$ harmonic frequency.

Figure 5.21 shows the impedance plots for different combinations of shunt capacitor bank switching at 132kV busbar, under normal operation of the network.

Observations:

- The switching of one of the capacitor banks at the Hermes 132kV busbar (either alone or with the 88kV 48 MVAr shunt capacitor bank) will have resonance at around the eighth harmonic frequency.
- The switching of two Hermes 132kV 72 MVAr capacitor banks (either alone or with the 88kV 48 MVAr shunt capacitor bank) will have resonance between the sixth and seventh harmonic frequencies, with the harmonic amplification factor of 1.75 at the fifth harmonic frequency.
- The switching of all shunt capacitor banks at Hermes substation (132kV bus – 2x72 MVAr and 88kV - 48 MVAr) will have resonance near the sixth harmonic frequency with the amplification factor of 2.26 at the fifth harmonic frequency.
- The switching of the 88kV 48 MVAr shunt capacitor bank (alone) will have more or less the same effect as that of switching both 132kV 72 MVAr shunt capacitor banks.

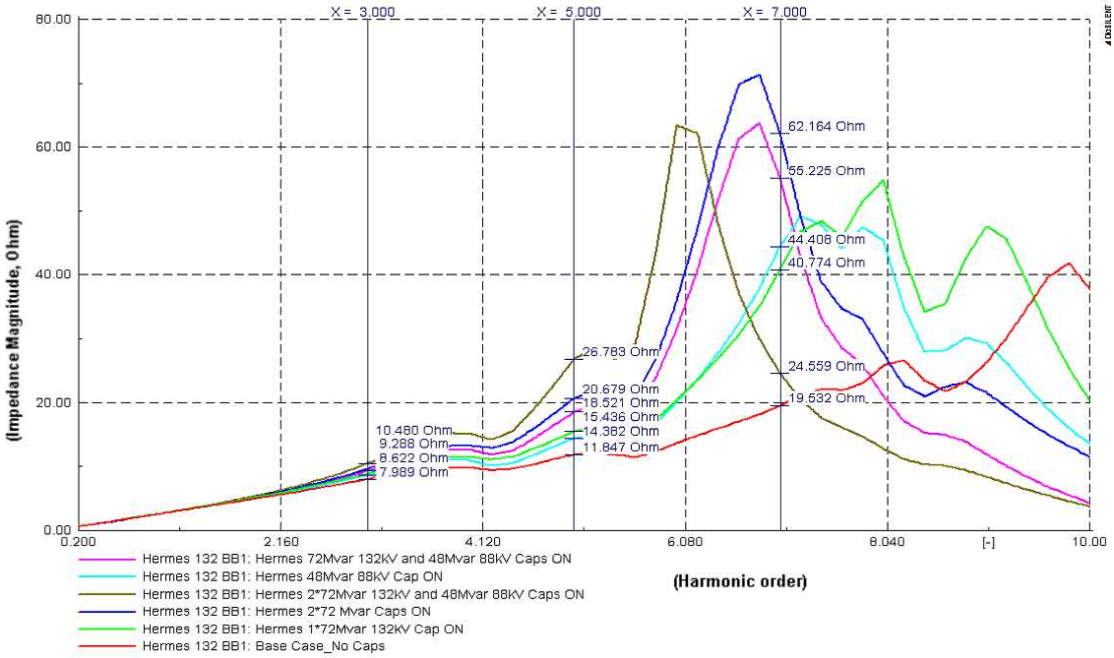



*Figure 5.21: Hermes 132kV busbar harmonic impedance plots*

Figure 5.22 shows the impedance plots for different combinations in shunt capacitor banks switching at the 132kV busbar, with Hermes transformer 2 out of service. The harmonic amplification factors are higher for this contingency due to the drop in short circuit power.

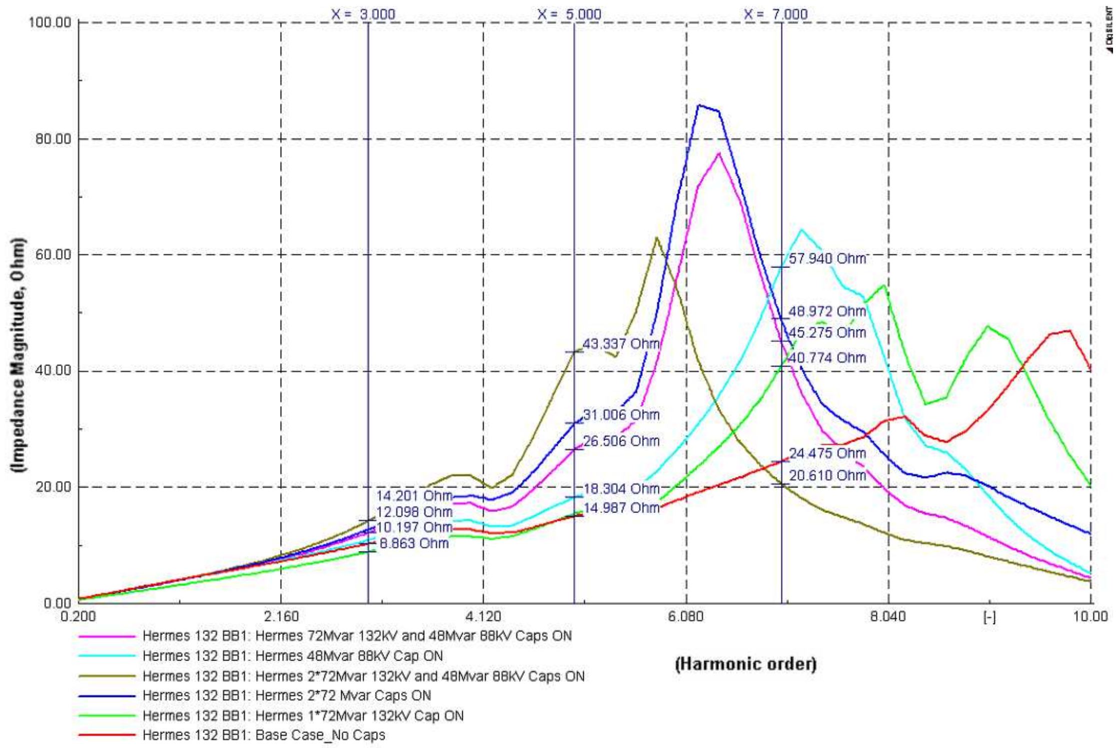



*Figure 5.22: Hermes 132kV busbar harmonic impedance plots with transformer 2 out of service*

### *5.6.3 Findings and conclusion*

From this analysis it can be seen that the switching of the Hermes substation shunt capacitor banks has a huge impact on the THD levels at the Hermes 132kV busbar because of the following reasons:

- When both capacitor banks are switched on the harmonic amplification is high near the fifth harmonic frequency
- When there is plant out of service, the short circuit power drops and this increases the amplification factor further at the fifth harmonic frequency.

It was recommended that when there is a contingency at Hermes substation one of the 72 MVAr capacitor banks on the 132kV busbar will be switched off during the off-peak period (23:00 to 04:00). This will enable the site to meet its THD planning and compatibility limits.

## *5.7 Conclusion*

This chapter has dealt with the shunt capacitor banks used in the Eskom Transmission networks installed at both EHV and HV systems. From this study, it is clear that installation of capacitor banks on the EHV network is the better option compared to installation on the HV network, especially if there is more than one capacitor bank to be installed. This is deemed to be due to the following reasons:

- Harmonics are generally low on the EHV systems, so the amplification is very low even where resonance occurs near the fifth harmonic frequency.
- High short circuit power at the EHV systems as compared to the HV systems which generally moves resonance point to higher order harmonic frequencies.
- The HV shunt capacitor banks are sometimes used to support the EHV system and this leads to the transformers being operated at leading power factors and therefore even higher harmonic amplification.

Studies done in the chapter have also demonstrated that harmonic levels can be kept within both planning and compatibility levels if the operation of shunt capacitor banks is optimised and managed.

The proper placement (EHV / HV), correct application (power transfer / power factor / voltage support) and accurate management of shunt capacitor banks ensures that the lifecycle cost of the capacitor banks is reduced in the long term. This assists in ensuring that the business does not have to invest more capital for converting these plain capacitor banks to either de-tuned capacitors banks or C-type filters in the future.

# 6. Capital cost comparison of shunt capacitor banks

## *6.1 Introduction*

In this chapter the costs of installing shunt capacitor banks at various voltage levels as well as different technologies are discussed and compared. The primary aim is to get the cost for a new shunt capacitor bank for various topologies and also to look at the cost of de-tuning or filtering in the future.

## *6.2 Capital costs: Shunt capacitor bank*

The estimated cost for the three shunt capacitor bank topologies i.e. plain, de-tuned and C-type filter based on a medium damped filter type (C-type filter, R/L = less than 8), based on a 132kV (72 MVAr) and 275kV (150 MVAr) are shown on Table 6.1, below. These costs were taken from the Eskom Transmission project management costing database [28], where the costing of all primary plant equipment, civil works and other related costs is done for the transmission projects.

Observations:

- For the 132kV capacitor bank options, the cost of a de-tuned capacitor bank is 1.58 times the cost of a plain capacitor bank, while the cost of a C-type filter is 2.1 times that of a plain capacitor bank.
- For the 275kV capacitor bank options, the cost of a de-tuned capacitor bank is 1.44 times the cost for a plain capacitor bank, while the cost of a C–type filter is 2.28 that of a plain capacitor bank.
- The cost of the 275kV 150 MVAr capacitor bank components as opposed to a 132kV 72 MVAr capacitor bank is 1.29 times (plain capacitor bank), 1.18 (de-tuned capacitor bank), 1.4 (C-type filter).

It must also be noted that the cost of both the coupling capacitors and tuning reactors in a C-type filter are proportional to their capacitances and can be reduced to a minimum, by optimal calculation of the L and C components. This will reduce the total cost of the filter.

Table 6.1: Cost comparison for different types of shunt compensation [28]

| | **132kV 72 MVAr capacitor bank** | | | **275kV 150 MVAr capacitor bank** | | |
|---|---|---|---|---|---|---|
| **Category** | **Plain (1)** | **De-tuned (2)** | **C-type (3)** | **Plain (1)** | **De-tuned (2)** | **C-type (3)** |
| Capacitor bank | R5,7 Mil | R9 Mil | R12 Mil | R7,380 Mil | R10,6 Mil | R16,816 Mil |

Notes:

(1) The costs includes units, damping reactors, unbalance VT's, neutral earthing units for plain capacitor bank

(2) The costs include units, tuning reactors and H-type CT's for a de-tuned capacitor bank.

(3) The cost includes main units, coupling units, tuning reactors, main H type CT, coupling H type CT, damping resistor, resistor CT's

### *6.3 Capital costs: Other*

The estimated costs for other items required in the installation of a shunt capacitor bank discussed in 6.2 such as civil, protection, other primary plant related equipment etc are shown on Table 6.2.

Observations:

- For the 132kV options, the other costs of a de-tuned capacitor bank are 1.036 times the cost of a plain capacitor bank, while the other costs for a C-type filter are 1.15 times that of the plain capacitor bank.
- For the 275kV options, the other costs of a de-tuned capacitor bank are 1.038 times the cost for a plain capacitor bank, while the other costs for a C-type filter are 1.148 that of the plain capacitor bank.

Table 6.2: Other costs associated with the installation of the capacitor bank [28]

| | **132kV 72 MVAr capacitor bank** | | | | **275kV 150 MVAr capacitor bank** | | |
|---|---|---|---|---|---|---|---|
| **Category** | **Plain** | **De- tuned** | **C-type** | | **Plain** | **De-tuned** | **C-type** |
| Civil Works | 2,000,000 | 2,100,000 | 2,500,000 | | 2,200,000 | 2,310,000 | 2,750,000 |
| Circuit breaker | 281,131 | 281,131 | 309,244 | | 309,244 | 309,244 | 340,169 |
| Current Transformers | 106,800 | 106,800 | 117,480 | | 117,480 | 117,480 | 129,228 |
| Isolators | 264,410 | 264,410 | 264,410 | | 290,851 | 290,851 | 290,851 |
| Surge Arrester | 33,463 | 33,463 | 33,463 | | 36,809 | 36,809 | 36,809 |
| Protection Scheme | 440,580 | 484,638 | 581,566 | | 484,638 | 533,102 | 639,722 |
| Telecommunication | 100,000 | 100,000 | 100,000 | | 110,000 | 110,000 | 110,000 |
| Measurement Rack | 100,000 | 110,000 | 121,000 | | 110,000 | 121,000 | 133,100 |
| Control | 100,000 | 100,000 | 100,000 | | 110,000 | 110,000 | 110,000 |
| Miscellaneous | 50,000 | 50,000 | 60,000 | | 55,000 | 55,000 | 66,000 |
| Cable and conductor | 500,242 | 500,242 | 600,290 | | 550,266 | 550,266 | 660,319 |
| Hardware | 100,000 | 100,000 | 100,000 | | 110,000 | 110,000 | 110,000 |
| Stringing, Earthing and Erecting | 500,000 | 550,000 | 605,000 | | 550,000 | 605,000 | 665,500 |
| Consultants | 300,000 | 330,000 | 363,000 | | 330,000 | 363,000 | 399,300 |
| Risk Allowance | 552,180 | 552,180 | 607,398 | | 607,398 | 607,398 | 668,138 |
| Labour | 700,000 | 770,000 | 924,000 | | 770,000 | 847,000 | 1,016,400 |
| General expenses | 300,000 | 300,000 | 300,000 | | 330,000 | 330,000 | 330,000 |
| Local CPA @ Date of Estimate | 163,993 | 163,993 | 163,993 | | 180,392 | 180,392 | 180,392 |
| Foreign CPA @ Date of Estimate | 54,212 | 54,212 | 54,212 | | 59,633 | 59,633 | 59,633 |
| Forex ADJ @ Date of Estimate | 154,421 | 154,421 | 154,421 | | 169,863 | 169,863 | 169,863 |
| Commodity @ Date of Estimate | 12,521 | 12,521 | 12,521 | | 13,773 | 13,773 | 13,773 |
| Local CPA @ Date of Payment | 856,246 | 856,246 | 856,246 | | 941,871 | 941,871 | 941,871 |
| Foreign CPA @ Date of Payment | 40,814 | 40,814 | 40,814 | | 44,895 | 44,895 | 44,895 |
| Forex ADJ @ Date of Payment | 35,484 | 35,484 | 35,484 | | 39,032 | 39,032 | 39,032 |
| Commodity @ Date of Payment | 134,556 | 134,556 | 134,556 | | 148,012 | 148,012 | 148,012 |
| Interest During Construction | 574,303 | 574,303 | 574,303 | | 631,733 | 631,733 | 631,733 |
| Overheads | 20,138 | 20,138 | 20,138 | | 22,152 | 22,152 | 22,152 |
| **Total** | **R8,475,494** | **R8,779,552** | **R9,733,539** | | **R9,323,043** | **R9,657,507** | **R10,706,893** |

### *6.4 Conclusion*

The cost of installing the various shunt capacitor bank topologies was discussed in detail in this chapter. It can therefore be concluded as follows:

- The overall cost of installing a 132kV, 72 MVAr de-tuned capacitor bank is 1.25 times that for installing a plain capacitor bank, while the cost of installing a C-type filter is 1.533 times that for installing a plain capacitor bank. The cost of installing a C-type filter is 1.22 the cost of a de-tuned capacitor bank.
- The overall cost of installing a 275kV, 150 MVAr de-tuned capacitor bank is 1.21 times that for installing a plain capacitor bank, while the cost of installing a C-type filter is 1.65 times that for installing a plain capacitor bank. The cost of installing a C-type filter is 1.35 the cost of a de-tuned capacitor bank.
- The overall cost of installing the 150 MVAr shunt capacitor bank on the 275kV busbar as opposed to installing the 72 MVAr shunt capacitor bank on the 132kV busbar is 1.18 times (plain capacitor bank), 1.14 (de-tuned capacitor bank), 1.27 (C-type filter).

It is quite notable to see that other costs (civil, protection, other primary related equipment etc) for the shunt capacitor bank installation reduce the price difference between various shunt capacitor bank topologies and voltage levels, as they are between 40-60% of the overall cost of the shunt capacitor bank installation. These costs should be taken seriously when a decision is made for the shunt capacitor bank options. Failure to do so will result in high cost at a later stage when converting a plain capacitor bank into either a de-tuned capacitor bank or a C-type filter, as issues such as space can be a constraint.

# 7. Performance evaluation of shunt capacitor banks

## *7.1 Introduction*

In the Eskom Transmission network most of the shunt capacitor banks installed are plain capacitor banks without any form of de-tuning or filtering. The data for the performance of these capacitor banks was retrieved from the Phoenix database system where all primary and secondary plant faults and outages in the Eskom Transmission network are logged. As there is only one recently installed C-type filter in the system the author established contact with Mark Halpin in the USA, for the performance of C-type filters installed in the United States Transmission networks.

Table 7.1 below shows the equipment KPI's (Key Performance Indicators) where shunt capacitor banks form part of these KPI's. The 2009 12mmi (12 month moving index) value indicates that there is a high number of shunt capacitor bank failures with a 12mmi value of 79. This value is way higher than the targeted value of 50.

Table 7.1: Equipment Key Performance Indicators [26]

| EQUIPMENT Key Performance Indicators | Monthly (Dec 2009) | Year to date | Year end projection | 12MMI (Dec 2009) | 2009 / 10 Target |
|---|---|---|---|---|---|
| **Severe Failures** | | | | | |
| Transformers | 0 | 3 | 4 | 3 | 6 |
| Reactors | 0 | 1 | 2 | 1 | 2 |
| **Failures** | | | | | |
| Transformers | 2 | 18 | 26 | 26 | 23 |
| Reactors | 1 | 5 | 7 | 8 | 5 |
| **Shunt Capacitors** | **8** | **67** | **82** | **79** | **50** |
| Series Capacitors | 0 | 6 | 8 | 6 | 5 |
| SVCs | 2 | 13 | 17 | 15 | 23 |
| Circuit Breakers | 1 | 15 | 24 | 27 | 40 |
| Auxiliary Transformers | 0 | 1 | 2 | 2 | |
| Auxiliary Items | 1 | 19 | 23 | 22 | 22 |
| Current Transformers | 0 | 5 | 6 | 5 | 5 |
| Isolators | 0 | 6 | 7 | 7 | 9 |
| Line Traps | 0 | 0 | 0 | 0 | 1 |
| Surge Arresters | 0 | 5 | 6 | 6 | 5 |
| Voltage Transformers | 1 | 3 | 4 | 4 | 2 |

Figure 7.1 shows the capacitor failures (monthly and 12mmi) trended against the target of 50 per year. The worst shunt capacitor performance was between 2002 and 2005 and the performance started trending negatively again from 2007 and is currently at its worst. The root cause of these failures will be discussed and elaborated in the sub sections of this chapter.

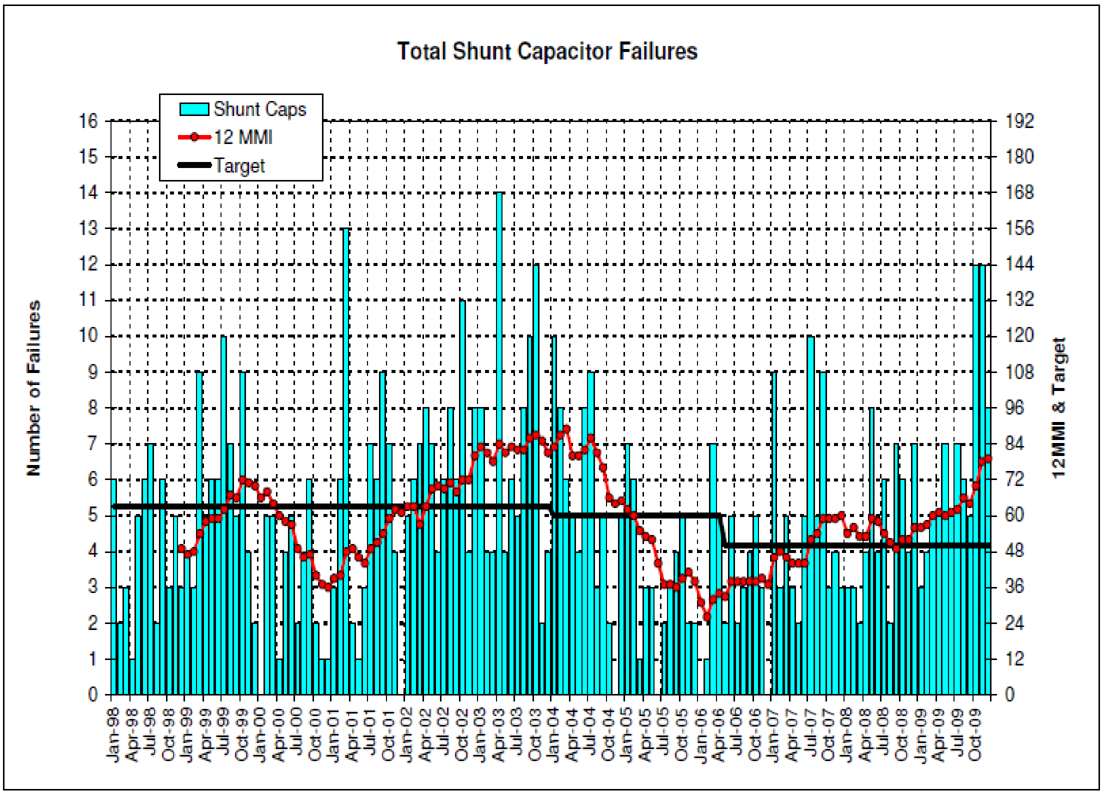



*Figure 7.1: Total shunt capacitor banks failures [26]*

## *7.2 Literature review on capacitor bank failures*

Most of the root causes for the capacitor bank failures can be attributed to the following reasons:

### *7.2.1. Capacitor failure due to inadequate voltage rating*

Capacitor banks are sometimes not properly rated to deal with periodic overvoltages and can fail when the voltage across the bank exceeds the rated voltage.

### *7.2.2 .Fuse blowing*

The fuse of a capacitor bank blows when performing its desired function such as when there is a short circuit in a capacitor bank unit or during excessive harmonic levels.

### *7.2.3 .Fuse failures*

The fuse of a capacitor bank fails when it blows without a fault being present. This can be caused by fuses not being properly rated, fatigue and incorrect application.

*7.2.4. Ferroresonance*

The capacitor banks may interact with the source or transformer inductance and produce ferroresonance. If the system is not adequately damped, then there is a possibility of capacitor or transformer failure.

*7.2.5. Harmonics*

Any nonlinear load in the system such as an arc furnace or converter produces harmonics. Filters are used to control the harmonics. If the tuning of the filters is not sharp enough, then there may be excessive harmonic currents through the capacitor bank. Harmonics cause overheating and failure of the capacitor bank units. To prevent these occurrences, protection relays are used to detect high levels of harmonics and trip the circuit.

*7.2.6. Dielectric failures*

Dielectric failures in a capacitor bank unit are caused by over voltages in excess of 110%. This can happen when an internal series group of capacitor bank unit fails, resulting in high voltage levels on the remaining internal series units.

To prevent these failures, an unbalance detection scheme that is not sensitive to system imbalances is used.

*7.2.7. Manufacturing defects*

These defects can cause the capacitor bank to fail prematurely and should be identified during the testing of capacitor bank units in the factory. If there are any manufacturing defects in the capacitor units, the failure will occur in the factory during testing.

*7.2.8. Failures due to internal stress in the capacitor units*

The presence of ripple currents, surge voltages, and high frequency oscillatory currents can cause internal stress in the capacitor units and premature failure. Ripple currents flowing through a capacitor bank cause an internal temperature rise due to power losses within a capacitor bank.

*7.2.9. Failures due to external stress*

Sometimes the capacitor banks are exposed to extreme operating conditions, including excessive ambient temperatures, humidity, temperature cycling, vibration, shock, and lack of ventilation. Such conditions can occur in substation capacitor installations and reduce the life expectancy of a capacitor bank. Forced air cooling is used in certain applications to minimize these types of failures.

## *7.3 Performance evaluation: 132 and 88kV plain capacitor banks*

The total number of failures from 1999 to 2009 for the 65 shunt capacitor banks evaluated was 579. The breakdown of the root causes for these failures is shown on Figure 7.2. It can be seen here that the majority of the faults were caused by fuse failures contributing 49%, as well as unit failures contributing 41%. The remainder of the faults were caused by protection, other primary plant related equipment etc.

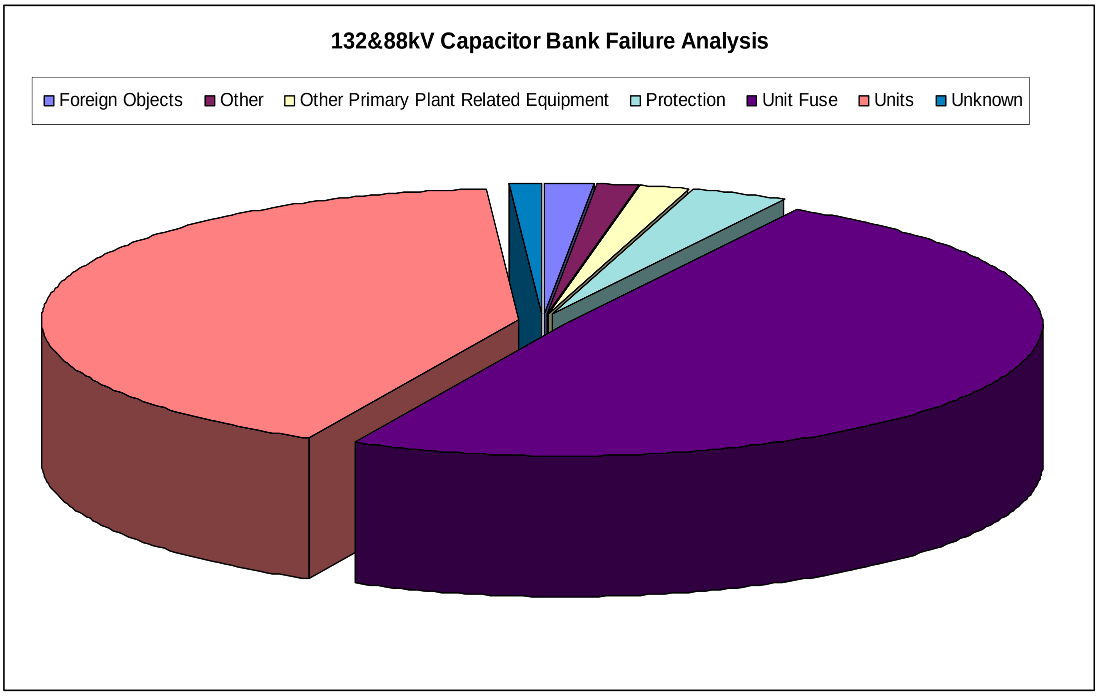



*Figure 7.2: 132kV and 88kV plain capacitor banks - root cause analysis*

These root causes were further broken down to see the underlying problems that cause these failures.

### *7.3.1 Breakdown of unit fuse failures for HV shunt capacitor banks*

Figure 7.3 shows the breakdown of fuse failures and it can be seen here that the main contributors of fuse failures are normal ageing, system overvoltage and fatigue. Failures due to normal ageing can be avoided by changing the capacitor bank fuses during maintenance.

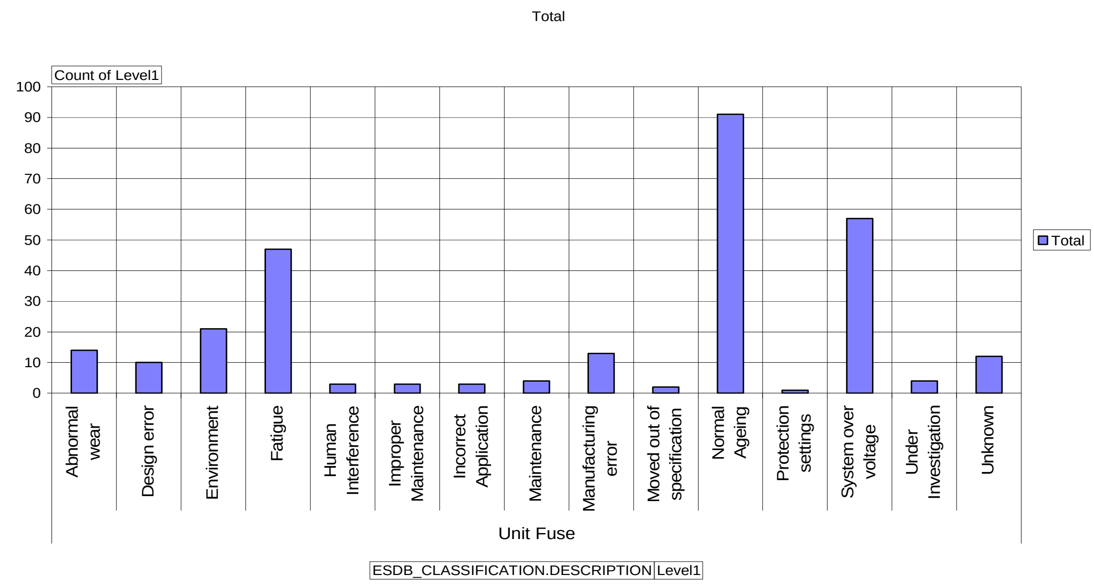



*Figure 7.3: Breakdown of unit fuse failures in HV shunt capacitor banks*

## *7.3.2 Breakdown of unit failures for HV shunt capacitor banks*

Figure 7.4 shows the breakdown of unit failures and the main contributors are normal ageing, abnormal wear and fatigue. Failures due to normal ageing and abnormal wear can be managed through maintenance. The following online condition monitoring techniques are available to assist the early detection of defects:

- Infra red scanning
- Monitoring of the unbalance signal
- Alarm conditions,
- Visual inspection of the primary equipment conducted from outside the live chamber for capacitor unit leaks and bulged cases.

Early response to these conditions may result in the preventative approach that could increase the reliability and availability index of the shunt capacitor concerned.

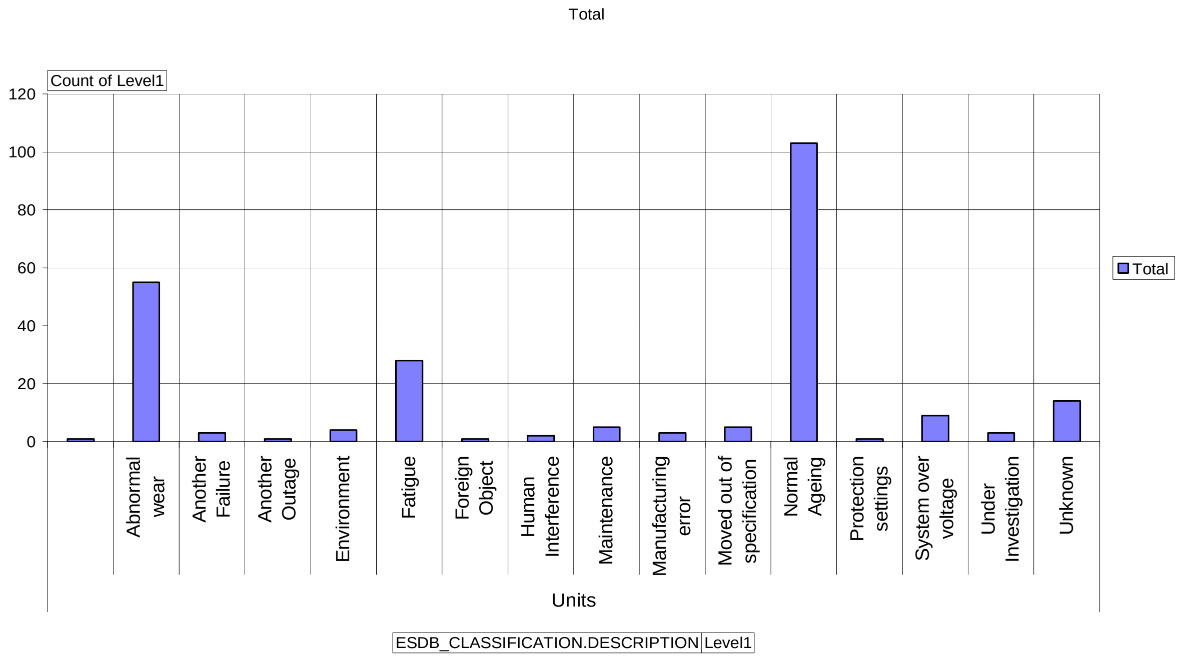



*Figure 7.4: Breakdown of unit failures in HV shunt capacitor banks*

## *7.3.3 Breakdown of protection related failures for HV shunt capacitor banks*

Figure 7.5 shows the breakdown of protection related failures. These faults are mainly caused by manufacturing and design errors as well as protection setting problems. These failures can easily be reduced if the designs (i.e. incorrect relay specifications) and manufacturing errors (i.e. incorrect unit specifications) are eliminated.

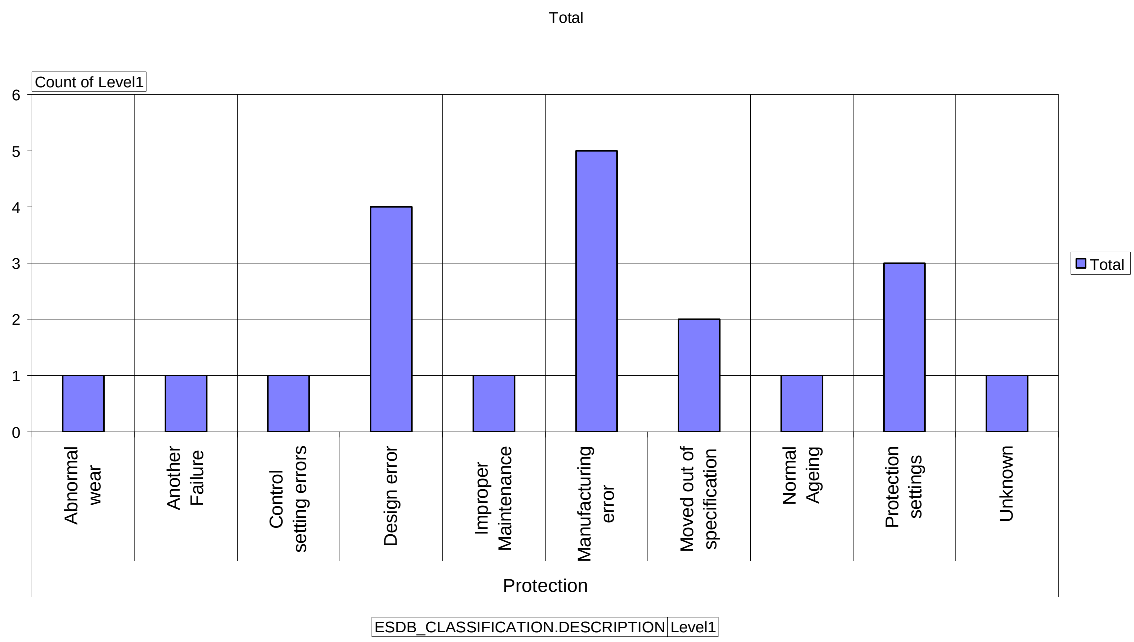



*Figure 7.5: Breakdown of protection related failures in HV shunt capacitor banks*

## *7.3.4 Breakdown of other primary plant related equipment for HV shunt capacitor banks.*

Figure 7.6 shows the breakdown of other primary plant related failures. The majority of these faults are caused by fatigue, normal ageing and maintenance. These failures can easily be reduced if proper maintenance is carried out to address loose and hot connections.

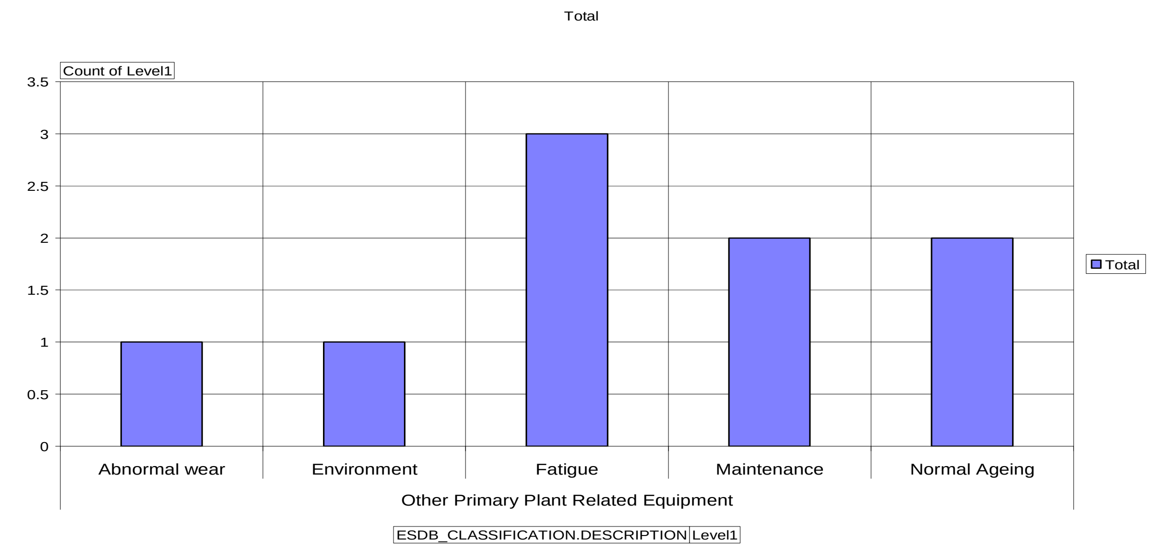



*Figure 7.6: Breakdown of other primary plant related equipment for HV shunt capacitor banks.*

## *7.3.5. Top ten poor performing HV shunt capacitor banks.*

Figure 7.7 shows the top 10 poor performing shunt capacitor banks on the transmission HV system. Spitskop No 3 132kV shunt capacitor bank contributes most of the faults and these faults are mainly unit fuse related.

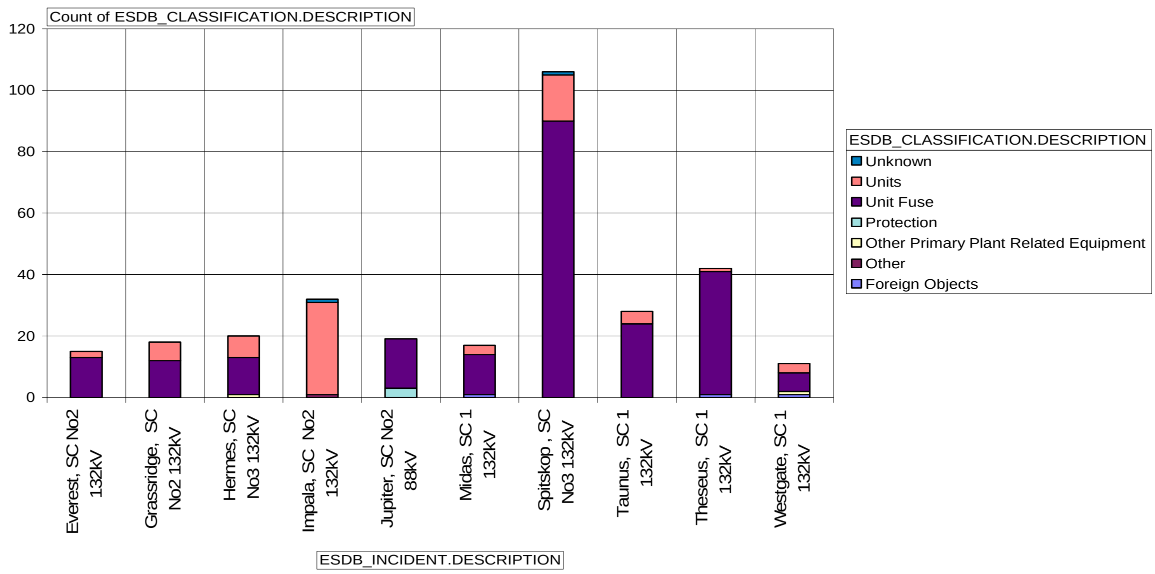



*Figure 7.7: Top ten poor performing HV shunt capacitor banks*

## *7.4 Performance evaluation: 275kV plain capacitor banks*

The evaluation was done on 25 EHV shunt capacitor banks. The total number of faults was 162 for the period 1999 to 2009. Figure 7.8 shows the summarised failure modes for 275kV shunt capacitor banks installed in the Eskom Transmission system. It can be seen here that the majority of the faults are caused by unit failures contributing 88%.

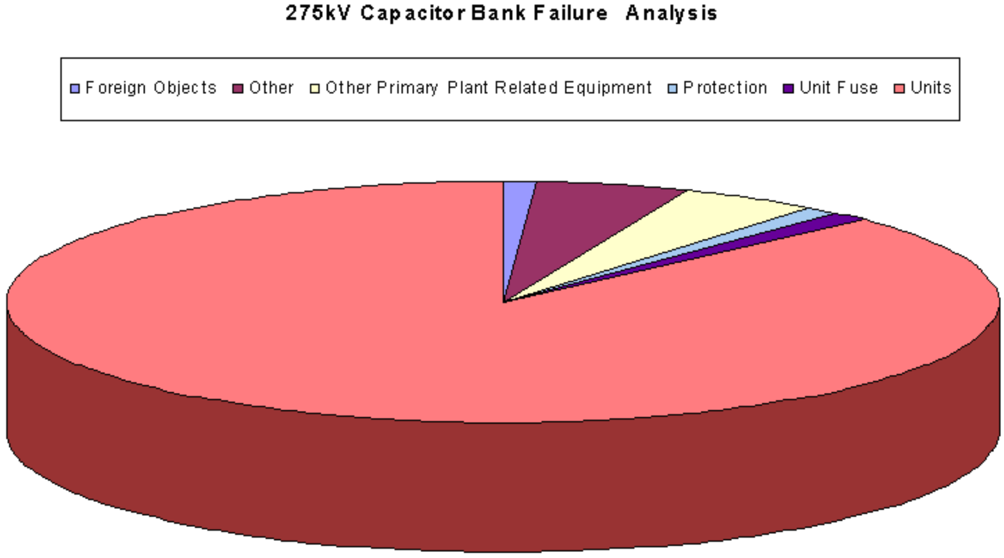



*Figure 7.8: 275kV plain capacitor banks - root cause analysis*

### <u>*7.4.1 Breakdown of unit failures for EHV shunt capacitor banks*</u>

Figure 7.9 shows the breakdown of unit failures for EHV shunt capacitors. The main contributors are abnormal wear, normal ageing and fatigue. As discussed in section 7.4.3 failures due to abnormal wear and ageing can be managed through maintenance.

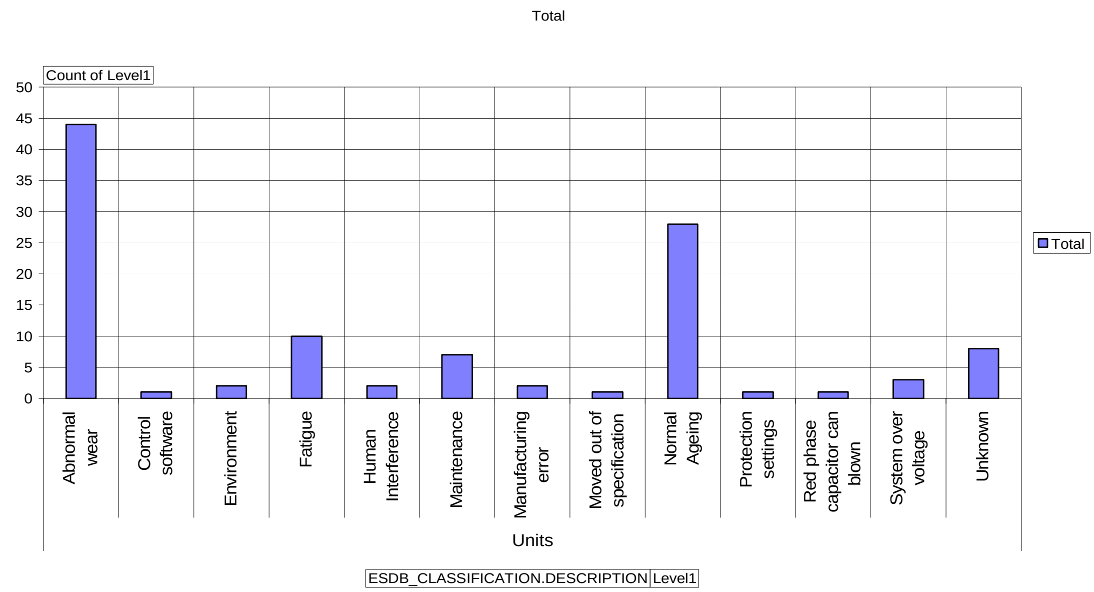



*Figure 7.9: Breakdown of unit failures for EHV shunt capacitor banks*

## *7.4.2. Other primary plant related equipment*

Figure 7.10 shows the breakdown of other primary plant related failures and although these faults are not many, it is quite notable to see that maintenance is a problem.

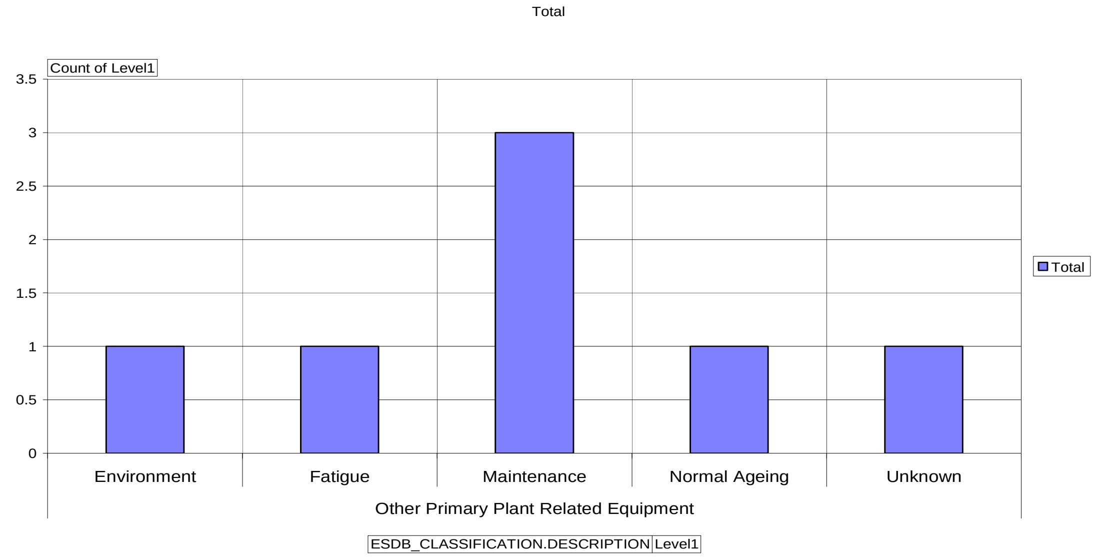



*Figure 7.10: Breakdown of other primary plant related failures on EHV shunt capacitor banks*

## *7.4.3 EHV shunt capacitors performance – per capacitor*

Figure 7.11 shows the performance of the 25 EHV shunt capacitors evaluated per site. Mersey, Jupiter, Illovo and Bighorn capacitors contributed most of the faults and these faults are mainly unit related.

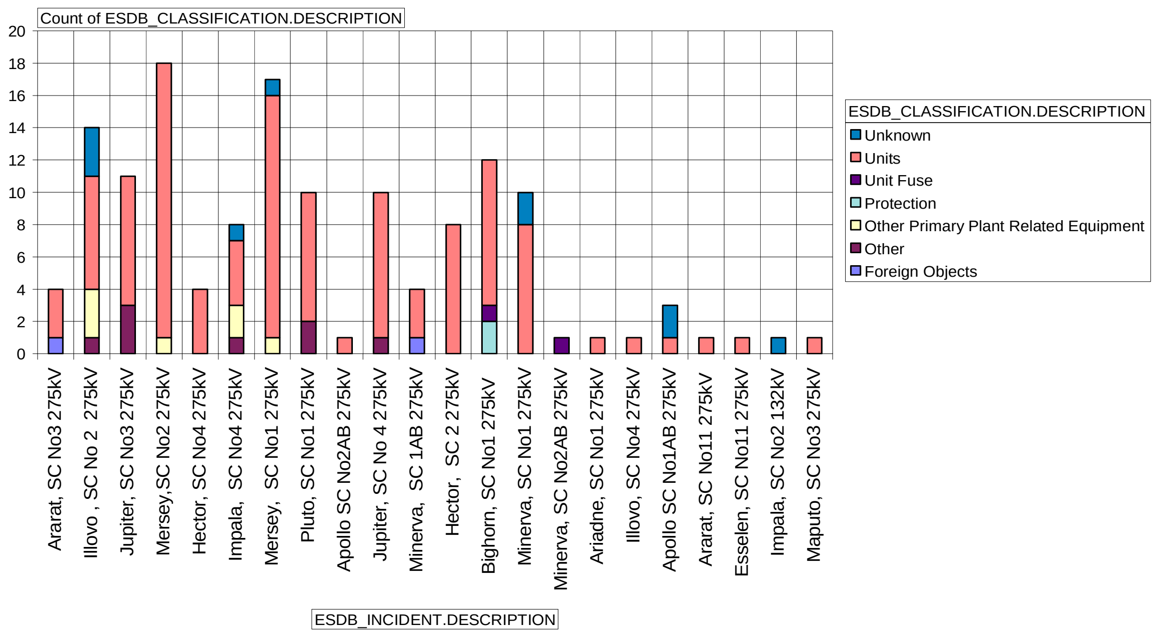



*Figure 7.11: Performance of the 25 EHV shunt capacitors evaluated per site.*

## *7.5 Performance evaluation: EHV C-type filters*

Since there is only one recently installed C-type filter bank in the Eskom Transmission network, there was no local data that could be used to evaluate the performance of these capacitors. Through email correspondence with Mark Halpin in the USA, it was found that there are four C-type filters installed on their transmission network for the past 4-5 years and they haven't experienced any failures [27].

This can be attributed to some of the following technical reasons:

- The units are still new and haven't reached their normal ageing caused by both internal and external stresses.
- They perform better during transient conditions (i.e. inrush currents and transient voltages).
- No manufacturing errors.
- No human errors when operating the banks.
- Good maintenance practices.

## *7.6 Comparative shunt capacitor bank performance*

In report [7] the comparison of individual filter performance was undertaken for the key parameters listed below:

### *7.6.1 Attenuation*

The level of harmonic current diverted by the shunt filter (i.e. a function of the impedance of the filter at the harmonic frequency in question). Ideally this should be high.

### *7.6.2 Bandwidth*

The range of harmonic frequencies at which the filter provides attenuation. Ideally this should be as wide as possible to accommodate fundamental frequency variations and component tolerances, and to accommodate any potential variations in load current harmonic frequencies.

### *7.6.3 Sensitivity*

The sensitivity of the attenuation level due to deviations in the fundamental frequency, component values, and temperature drift. High sensitivity implies significant changes in its other properties.

### *7.6.4 Amplification*

The level of amplification of harmonics due to parallel resonance with the system impedance (typically at frequencies below the tuned frequency). Ideally this should be low.

### *7.6.5 Fundamental frequency (50 Hz) losses*

These unwanted losses in the filter are at the fundamental frequency only. Note that the total losses in a filter are a function of the harmonic spectrum that it absorbs.

### *7.6.7 Capacitor size*

The size of capacitor required may be too large, possibly resulting in excessive reactive power at the fundamental frequency, i.e. more than required for power factor correction or voltage support.

### *7.6.8 Cost*

The capital cost of the installation only. Operational losses are included in the assessment of the fundamental frequency losses.

### *7.6.9 Dynamics*

The dynamic performance of the filter when switched, or when switching occurs on the system.  Ideally switching events should be damped by the filter or at least not amplified significantly.

The results are shown on Table 7.2.

## *7.7 Conclusion*

This chapter has dealt with performance issues associated with plain capacitor banks in the Eskom transmission network as well as the four C-type filters installed in the USA. The main root cause of failures on both HV and EHV plain capacitor banks are unit fuses (HV) and units (HV and EHV) and some of the underlying problems are:

- Normal and abnormal ageing
- Fatigue
- Poor maintenance
- System overvoltage

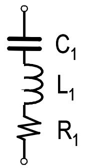
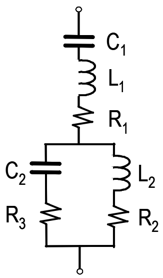
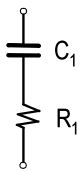
These failures can increase the lifecycle cost of the shunt capacitor bank and the power system as a whole during down time as more local generation, load shedding might be required in their absence.

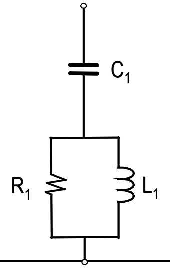
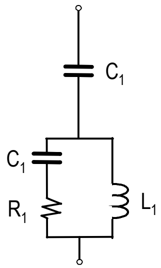
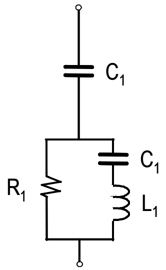
Failures due to normal ageing and abnormal wear can be managed through maintenance. The following online condition monitoring techniques are available to assist the early detection of defects [30]:

- Infrared scanning
- Monitoring of the unbalance signal
- Alarm conditions
- Visual inspection of the primary equipment conducted from outside the live chamber for capacitor unit leaks and bulged cases.

Early response to these conditions may result in the preventative approach that could increase the reliability and availability index of the shunt capacitor concerned.

Table 7.2: Comparative performance of harmonic filters and shunt capacitor banks [7]

| **Filter Type** | **Attenuation** | **Bandwidth** | **Sensitivity** | **Amplification** | **50 Hz losses** | **Capacitor Size** | **Dynamics** | **Cost** |
|---|---|---|---|---|---|---|---|---|
| Single-tuned  | Very high close to the tuning frequency.<br>NOTE 1: A function of the harmonic and the tuning frequency.<br>NOTE 2: Decreases for large values of filter resistance. | Very narrow.<br>NOTE: Increases for larger values of filter resistance. | High. | High at frequencies below the tuning frequency.<br>NOTE: Decreases for larger values of filter resistance. | Low. | Small. | Poor / medium<br>NOTE 1: Depending on the Q of the filter. | Low.<br>NOTE 1: Several single-tuned filters may however be required to control industrial plant emissions given the low bandwidth. |
| Double-tuned  | Very high close to the tuning frequency.<br>NOTE 1: A function of the harmonic and the tuning frequency.<br>NOTE 2: Decreases for large values of filter resistance. | Very narrow.<br>NOTE: Increases for larger values of filter resistance. | High. | High at frequencies below the tuning frequency.<br>NOTE: Decreases for larger values of filter resistance. | Low. | Small. | Poor / medium.<br>NOTE 1: Depending on the Q of the filter. | Low / medium.<br>NOTE 1: Lower for HV applications than two single-tuned filters due to lower reactor impulse voltage requirements. |
| 1st order damped  | Low. | Very wide. | Low. | Low. | Very high.<br>NOTE 1: Seldom used for this reason. | Very large.<br>NOTE 1: Seldom used for this reason. | Good. | High. |

| **Filter Type** | **Attenuation** | **Bandwidth** | **Sensitivity** | **Amplification** | **50 Hz losses** | **Capacitor Size** | **Dynamics** | **Cost** |
|---|---|---|---|---|---|---|---|---|
| $2^{nd}$ order damped   | Medium. | Wide. | Low. | Low. | High. | Medium. | Good. | High. |
| $3^{rd}$ order damped   | Medium. | Wide. | Low. | Low. | Medium. | Medium.<br>NOTE: The size of the capacitor in the parallel circuit is small in comparison with the main filter capacitor. | Good. | High. |
| C-type damped   | Medium. | Wide. | Medium.<br>NOTE 1: More sensitive that other damped filters.<br>NOTE 2: Changes in the 50 Hz tuned circuit will result in larger 50 Hz losses. | Low. | Very low. | Medium. | Good. | High. |

# 8. Operational cost comparison of the various VAr support technologies

## *8.1 Introduction*

Capacitor bank operational costs are mainly due to losses. These losses include dielectric losses and losses due to the damping resistor. There are additional losses for a de-tuned capacitor bank and C-type filter due to the tuning reactor resistance.

The capacitor banks installed in the 1970's had higher dielectric losses compared to the ones commissioned in more recent years. Because of the technologies available at that time, the units were built with high dielectric loss polychlorinated biphenyl (PCB) or askarel as the insulation liquid and dielectric medium.

With more research over the years, the dielectric medium used in capacitor banks has changed and the use of an all-film dielectric with low losses has reduced the dielectric losses significantly.

Other operational costs in the lifecycle of a capacitor bank are the costs associated with capacitor bank failures and harmonic investigations.

These costs will be discussed to give an insight into which topology gives greater financial savings over the lifespan of the shunt capacitor bank.

## *8.2 Cost of capacitor bank dielectric losses*

The dielectric losses of the old PCB paper/ foil dielectrics were 3 W per kVAr, compared with the new modern paper/film dielectrics with 1.3 W per kVAr and all-film dielectrics with 0.1 W per kVAr. The difference between the paper/foil dielectrics and all-film dielectrics is 2.9 W per kVAr and on a bank of 150 MVAr, it equates to 435 kW.

For example, the costs of dielectric losses for two plain capacitor banks with the same characteristics but using different dielectric mediums are shown on Table 8.1.

The following assumptions are made:

- Capacitor banks are utilised daily for 18 hours, from Monday to Friday and off during weekends. They are switched on for 261 days in a year.
- The lifespan of the shunt capacitor bank is taken as 20 years.
- There are no failures on the capacitor banks over the period due to sound maintenance practices.
- The cost of supply averages at 12c/kWh for the 20 year period.

From this Table 8.1, the dielectric losses of a capacitor bank can add significant cost if the old PCB paper / foil is used instead of an all film dielectric. This type of dielectric medium is currently being phased out on all the capacitor banks in the Transmission network due to high losses and environmental legislation, which requires the phasing out of electrical equipment utilising PCB before 2025.

Table 8.1 Cost of dielectric losses of a 275kV 150 MVAr capacitor bank

| | **PCB paper/ foil** | **Paper/film** | **All film** |
|---|---|---|---|
| Dielectric power loss [W/kVAr] | 3 | 1.3 | 0.1 |
| Cap bank size [MVAr] | 150 | 150 | 150 |
| Dielectric losses [kW] | = 3 x 150= 450 | = 1.3 x 150 = 95 | = 0.1 x 150 = 15 |
| Dielectric energy loss per hour [kWh] | = 450 x 1= 450 | = 95 x 1= 95 | = 15 x 1 = 15 |
| Energy losses per day (18 hours) [kWh] | = 450 x 18 = 8100 | = 95 x 18 = 1710 | = 15 x 18 = 270 |
| Energy losses per year (261 days) [MWh] | = 8100 x 261 = 2114 | = 1710 x 261 = 446,31 | =270 x 261 = 70,470 |
| Energy losses over lifespan (20 years) [GWh] | = 2114 x 20 = 42, 28 | =446,31 x 20 = 8926,2 | = 70,470 x 20 = 1,4094 |
| Cost of dielectric energy losses over lifespan (20 years) @ 12c/kWh [Rand] | = 42,28 x 0,12 **= R5,073 Mil** | = 8926,2 x 0,12 **= R1,071 Mil** | =1,4094 x 0,12 **=R0,1169 Mil** |

Three capacitor banks topologies were then evaluated with the aim of determining the difference in the cost associated with dielectric losses. The capacitor banks data was taken from Tables 1, 4 and 8 in Appendix D found in [29]

*<u>8.2.1 Plain capacitor bank</u>*

Using the data for the Mersey 275kV 150 MVAr plain capacitor bank and using an all-film dielectric:

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 50 \times 15{,}79\mu F} = 201{,}59\Omega$$

The size of one capacitor bank unit (with rated voltage of 6351V), is then:

$$Q_C = \frac{V^2}{X_C} = \frac{6351^2}{201{,}59} = 200kVAr/unit$$

There are 750 units installed; therefore the rated MVAr of the capacitor bank will be:

$$Total\ rated\ MVAr = 750 \times 200kVAr = 150MVAr$$

With the implementation of an all-film dielectric with 0.1W per kVAr the total dielectric losses for the capacitor bank will be:

$$Dielectric\ losses = 0{,}1W\ /\ kVAr \times 150MVAr = 15kW$$

*8.2.2 De-tuned capacitor bank*

Using the data for one of the Apollo 275kV 150 MVAr de-tuned capacitor banks using an all-paper film dielectric:

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 50 \times 15{,}79\mu F} = 201{,}59\Omega$$

The size of one capacitor bank unit (with rated voltage of 6351V), is then:

$$Q_C = \frac{V^2}{X_C} = \frac{6351^2}{201{,}59} = 200kVAr$$

There are currently 840 units installed therefore the rated MVAr of the capacitor bank is:

$$Total\ rated\ MVAr = 840 \times 200kVAr = 168MVAr$$

The extra set of parallel capacitor units (90 from the total 840) are placed in series with the 750 capacitor units for the capacitor bank to produce 150 MVAr. This is required due to the increased voltage stresses that the tuning reactor introduces.

With the implementation of an all-film dielectric with 0.1W per kVAr, the total dielectric loss for the capacitor bank is:

$$Dielectric\ losses = 0{,}1W\ /\ kVAr \times 168MVAr = 16{,}8kW$$

*8.2.3 C-type filter*

Using the data for the Esselen 275kV 150 MVAr C-type filter, but using an all-film dielectric:

Main units:

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 50 \times 6{,}31\mu F} = 504{,}4\Omega$$

The size of one capacitor unit (with voltage of 15833V), is then:

$$Q_C = \frac{V^2}{X_C} = \frac{15833^2}{504{,}4} = 497kVAr$$

Coupling units:

These coupling units are sized such that their capacitive reactance is equal to the inductive reactance at fundamental frequency. Their purpose is to prevent fundamental current from flowing through the damping resistor and therefore reducing the 50Hz losses.

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 50 \times 8{,}46\mu F} = 376{,}25\Omega$$

The size of one capacitor unit (with rated voltage of 13000V), is then:

$$Q_C = \frac{V^2}{X_C} = \frac{13000^2}{376{,}25} = 449 kVAr$$

There are currently 432 main units and 72 coupling units installed; therefore the output of the capacitor bank is:

$$Total\ rated\ MVAr = 432 \times 497 kVAr + 72 \times 449 kVAr = 247 MVAr$$

With the implementation of an all-film dielectric with 0.1W per kVAr, the total dielectric loss for the capacitor bank is:

$$Dielectric\ losses = 0{,}1W / kVAr \times 247 MVAr = 24{,}7kW$$

*8.2.4 Dielectric loss comparison (using an all film dielectric)*

The dielectric losses calculated in sections 8.2.1 to 8.2.3 were used to compare the cost difference between the three capacitor bank topologies. Assumptions used in section 8.2 were also used in this section. Table 8.2 shows that the cost due dielectric losses in the C-type filter is higher as compared to the other topologies.

Table 8.2: Cost of dielectric losses for various capacitor bank topologies

| | **Plain capacitor bank** | **De-tuned capacitor bank** | **C-type filter** |
|---|---|---|---|
| Dielectric power loss [kW] | 15 | 16,8 | 24,7 |
| Energy losses per day (18 hours) [kWh] | =15x18 =270 | = 16,8x18 = 302,4 | =24,7x18 =444,6 |
| Energy losses per year (261 days) [MWh] | =270x261 =70,47 | =302,4x261 =78,926 | =444,6x261 =116,04 |
| Energy losses over lifespan (20 years) [GWh] | = 70,47x20 =1,4094 | =78,926x20 =1,57852 | =116,04x20 = 2,3208 |
| Cost of dielectric energy losses over lifespan (20 years) @ 12c/kWh [Rand] | **=1,4094x0,12 =R 179280** | **=1,57852x0,12 =R 189422** | **=2,3208x0,12 =R 278496** |

## *8.3. Cost of damping resistor losses*

All topologies will have resistive losses due to the damping resistor. These resistors are used to limit the inrush currents when the capacitor bank is switched on and off under normal operation and during transient conditions. They also reduce resonant overvoltage when the capacitor bank is energized. They are determined through switching studies on different components of the capacitor bank.

In the case of a C-type filter there are no 50 Hz losses, as the damping resistor is short circuited through an auxiliary tuned circuit.

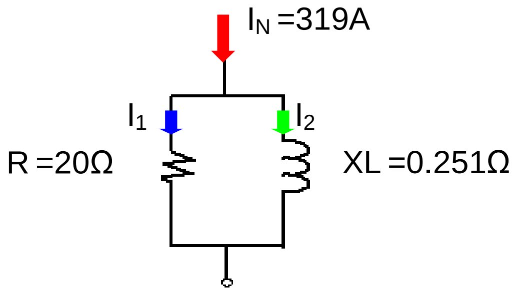
For this research report, currently installed capacitor banks at various locations will be examined to give insight on the cost associated with the damping resistor losses.

Figure 8.1 shows the single phase circuit diagram of three capacitor bank topologies with ratings on some of the 275kV 150 MVAr capacitor bank installations in the Eskom Transmission network [30].

The losses calculations are calculated with the assumption that the resistance of the damping resistor is constant with frequency over the frequency range of interest. It is further assumed that these capacitor banks are connected on the network and not at the harmonic producing load. Therefore the harmonic currents flowing through them are considered minimal and therefore omitted.

<u>Damping resistor losses - plain capacitor bank:</u>

$$X_L = 2\pi fL$$
$$X_L = 2\pi \times 50 \times 0.8mH = 0.251\Omega$$




Using the current divider rule, the fundamental current through the damping resistor is:

$$I_1 = I_N \times \left( \frac{X_L}{X_L + R} \right) = 400A \times \left( \frac{j0.25\Omega}{j0.25\Omega + 20\Omega} \right) = 4.99\angle 89{,}28A$$

$$P_{LOSS} = 3I^2R \ = 3 \times 4{,}99^2 \times 20 = 1{,}494kW$$

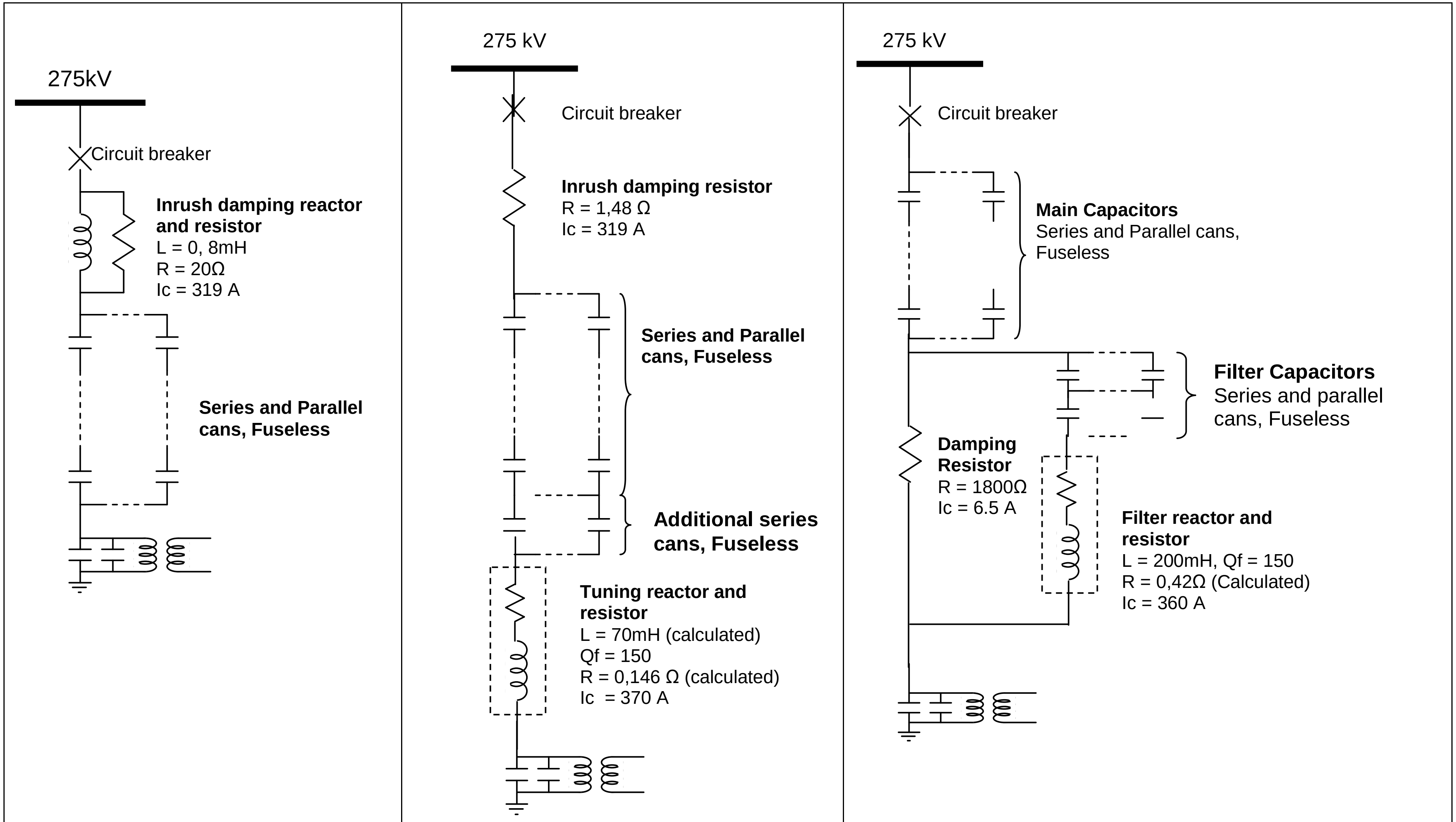
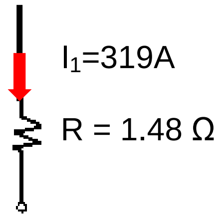


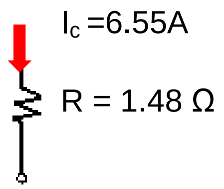

Figure 8.1 (a) Plain capacitor bank (b) De-tuned capacitor bank (c) C-type filter bank

Damping resistor losses – de-tuned capacitor bank:




$$P_{LOSS} = I^2 R \;= 319^2 \times 1{,}48 = 150{,}6kW$$

Damping resistor losses – C-type filter bank:




$$P_{LOSS} = I^2 R \;= 6{,}5^2 \times 1800 = 76kW$$

The lifecycle cost due to the damping resistor power losses can therefore be calculated as shown on Table 8.3.

Table 8.3: Calculation of lifecycle cost due to damping resistor power losses for various capacitor banks topologies.

| | **Plain capacitor bank** | **De –tuned filter $5^{th}$ harmonic** | **C-type filter $3^{rd}$ harmonic** |
|---|---|---|---|
| Damping Resistor Losses [kW] | 1,49 | 150,6 | 76 |
| Energy losses per day (18 hours) [kWh] | = 1,49 x 18 = 26,82 | = 150,66 x 18 = 2711 | = 76 x 18 = 1368 |
| Energy losses per year (261 days) [MWh] | = 36x 261 = 7 | =2711 x 261 = 707,8 | = 1368 x 261 = 357 |
| Energy losses over lifespan (20 years) [MWh] | = 7 x 20 = 0,14 | = 707,8 x 20 = 14,156013 | = 357 x 20 = 7,14096 |
| Cost of energy losses over lifespan (20 years) @ 12c/kWh [Rand] | = 0,14x 0,12 **= R16800** | =14,156013x0,12 **= R1,699 Million** | = 7,140x 0,12 **=R 856915** |

From this table, the cost associated with damping reactor resistive losses using the de-tuned capacitor bank is significantly higher than the other topologies and will contribute to the overall lifecycle cost of the capacitor bank.

### 8.4 Tuning reactor resistive losses

Additional to the damping resistor losses, the de-tuned capacitor bank and C-type filter will have resistive losses associated with the tuning reactor. This reactor shifts the harmonic resonance point in the case of a de-tuned capacitor bank and provides filtering for selected harmonic frequencies in the case of C-type filter. The size of the resistor in this reactor depends on the quality factor required. The resistance power losses for a 275 kV 150 MVAr capacitor bank can therefore be determined. The quality factor is defined as the ratio of the magnitude of the inductive reactance to the resistance at resonance and is expressed as:

$$Q_f = \frac{X_L}{R_{reactor}}$$

The tuning reactor resistance can be favourably used to vary the quality factor of the de-tuned capacitor bank / C-type filter and control the amount of desired harmonic current through it. A high Q factor will have a prominent valley at the resonant (tuning) frequency. A low Q factor will present low impedance over a range of frequencies.

A quality factor of 30 - 150 is regarded as high Q factor, while 0, 5 – 5 is regarded as low Q factor. Tuning reactors used in high voltage systems use air core reactors with a typical X/R ratio in the order of 30 – 50.

Figure 8.2 shows the harmonic impedance plots for a 275kV 150 MVAr C-type filter using various quality factors. With a high Q factor, there is a prominent valley at the resonant (tuning) frequency, whilst a low Q factor presents low impedance over a range of frequencies.

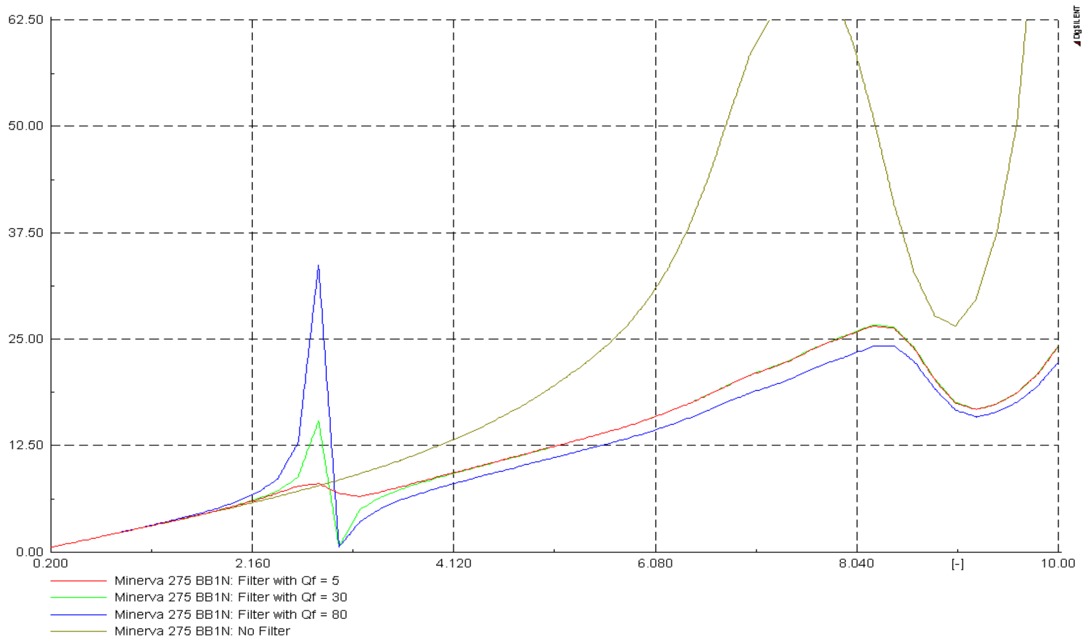



*Figure 8.2: Harmonic impedance plots for the installation of a 275kV 150 MVAr C-type filter with various Q factors.*

The losses on the tuning reactor will therefore be calculated using quality factor of 150. The following calculations are applicable in determining the size of the tuning reactor for a de-tuned capacitor bank, for a delta connected system.

$$X_C = \frac{V^2}{Q_{CAP} + Q_{cap(addititional)}}$$

Where:
$X_C$ is the capacitive reactance, in Ohms
V is the line voltage, in Volts
$Q_{CAP}$ is the size of the capacitor bank to be installed, in MVAr
$Q_{cap\ (additional)}$ is the size of the additional capacitor banks to be installed, in MVAr

The typical size of the additional capacitor bank units required to get the desired capacitor bank output is 12% of the size of the main capacitor bank.

$$X_C = \frac{275kV^2}{150MVAr + 18MVAr} = 450\Omega$$

$$C = \frac{1}{2\pi f X_C}$$

Where:
C is the size of the capacitor, in Farads
*f* is the fundamental frequency, in Hz
$X_C$ is the capacitive reactance, in Ohms

$$C = \frac{1}{2\pi \times 50 \times 450} = 7{,}07\mu F$$

For a de-tuned capacitor bank, the size of the reactor required to shift the resonance frequency from the fifth harmonic frequency is calculated as follows:

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

*Where:*

$f_r$ is the resonant frequency to be de-tuned, in Hz
L is the size of the required tuning reactor, in Henry
C is the size of the capacitance, in Farads

$$240Hz = \frac{1}{2\pi\sqrt{L \times 7{,}07\mu F}}$$

$\therefore L = 62{,}2mH$

The inductive reactance can therefore be calculated as follows:

$$X_L = 2\pi fL$$

$$X_L = 2\pi \times 50 \times 62{,}2mH = 19{,}54\Omega$$

By using air core reactors with a high q factor of 150, the following calculations are applicable in calculating reactor resistance:

$$R_{reactor} = \frac{X_L}{Q_f}$$

$$R_{reactor} = \frac{19{,}54\Omega}{150} = 0.13\Omega$$

Using continuous current through the capacitor banks, the reactor losses can be calculated.

$$Losses_{reactor} = I_{rated}{}^2 \times R_{reactor}$$

Where:
$I_{rated}$ is the fundamental current, in Amperes
$R_{reactor}$ is the reactor resistance, in Ohms

$$Losses_{reactor} = 370^2 \times 0{,}13 = 17{,}8kW$$

Using the C-type filter data on figure 8.1 (c), the reactor losses can be calculated as follows:

$$X_L = 2\pi fL$$

$$X_L = 2\pi \times 50 \times 200mH = 62{,}83\Omega$$

By using air core reactors with a high q factor of 150, the following calculations are applicable in calculating reactor resistance:

$$R_{reactor} = \frac{X_L}{Q_f}$$

$$R_{reactor} = \frac{62{,}83\Omega}{150} = 0.42\Omega$$

Using continuous current through the capacitor banks, the reactor losses can be calculated.

$$Losses_{reactor} = I_{rated}{}^{2} \times R_{reactor}$$

Where:
$I_{rated}$ is the fundamental current, in Amperes
$R_{reactor}$ is the reactor resistance, in Ohms

$$Losses_{reactor} = 360^{2} \times 0,42 = 54,3kW$$

Table 8.4 shows the calculation of the tuning reactor resistive losses for the lifecycle of the installation. From this table the cost associated with the tuning reactor resistive losses of the de-tuned capacitor is high as compared to the C-type filter. In the case of a de-tuned capacitor bank it is recommended that a tuning reactor with the highest quality factor be implemented without compromising the neighbouring harmonic frequencies. The losses associated with the tuning reactor on a C-type filter are negligible for both quality factors.

The tuning reactor resistive losses with the quality factor 80 will therefore be used for the calculation of the overall losses comparison between different topologies.

Table 8.4: Calculation of lifecycle cost due to tuning reactor resistive losses for various capacitor banks topologies.

| | **De-tuned capacitor bank 5$^{th}$ harmonic (Q =150)** | **C-type filter 3$^{rd}$ harmonic (Q = 150)** |
|---|---|---|
| Tuning reactor resistive power losses [kW] | 17,8 | 54,3 |
| Energy losses per day (18 hours) [kWh] | = 17,8x 18<br>= 320,4 | = 54,3 x 18<br>= 977 |
| Energy losses per year (261 days) [MWh] | =320,4x 261<br>= 83,6 | = 977 x 261<br>= 255 |
| Losses over lifespan (20 years) [MWh] | = 83,6 x 20<br>= 1672,5 | = 255 x 20<br>= 5102 |
| Cost of tuning reactor resistive Losses over lifespan (20 years) @ 12c/kWh [Rand] | =1672,5x 0,12<br>**= R200698** | = 5102 x 0,12<br>**=R 612243** |

## *8.5 Costs associated with failures*

The cost associated with the failure of a shunt capacitor bank can range from R50000 to R200000 or more depending on the type of failure, excluding the cost of energy not transferred. For most of the failures such as fuse or unit failure the costs can be within the prescribed range and will escalate if some other primary equipment has failed, such as reactors, current transformer, breaker etc. The cost was derived using the following assumptions:

- Each shunt capacitor bank will have between one and three failures per year and these faults will be either fuse or unit related.
- That the outage period is about 2.5 hours per fault.
- That the shunt capacitor is in service for 18 hours in a day.

The cost of energy not transferred will then be added to this cost by evaluating the transfer capability of a capacitor bank (36 MW for 132kV 72 MVAr bank and 75 MW for 275kV 150 MVAr bank), the outage period and the generation costs in c/kWh.

## *8.6 Costs associated with a harmonic investigation*

The costs associated with a harmonic investigation can be anything between R100000 and R300000 depending on the complexity of the investigation. The following details can be used as a guide when calculating these costs

- Rental costs for specialised QOS instruments.
- Travelling requirements.
- Man hour costs for secondary plant personnel (installation).
- Man hour costs for QOS specialist (programming the instruments, analysis of data and producing the report).
- Laptop and software requirements for detailed harmonic simulations.

## *8.7 Conclusion*

The operational costs of capacitor bank units have reduced over the years due to improvement in the dielectric medium used. By using an all film dielectric, a R5 million saving is attainable over the 20 years lifespan of a 275kV 150 Mvar capacitor bank.

The damping resistor power losses further increase the capacitor bank losses for various topologies. In the case of the plain capacitor bank the damping resistor is placed in parallel with the inductor to limit the losses, while the de-tuned capacitor bank has a low rating damping resistor. In the case of C-type filter bank there is low 50 Hz losses, as the damping resistor is short circuited through an auxiliary tuned circuit.

The tuning reactor power losses are applicable on the de-tuned capacitor bank as well as the C-type filter bank. These losses may vary depending on the Q-factor requirement of the system.

# 9. Lifecycle cost analysis

## *9.1 Introduction*

In this chapter the cost for implementing various topologies is evaluated taking into consideration the initial capital costs, operational costs, as well as the upgrade cost from changing from one technology to the other.

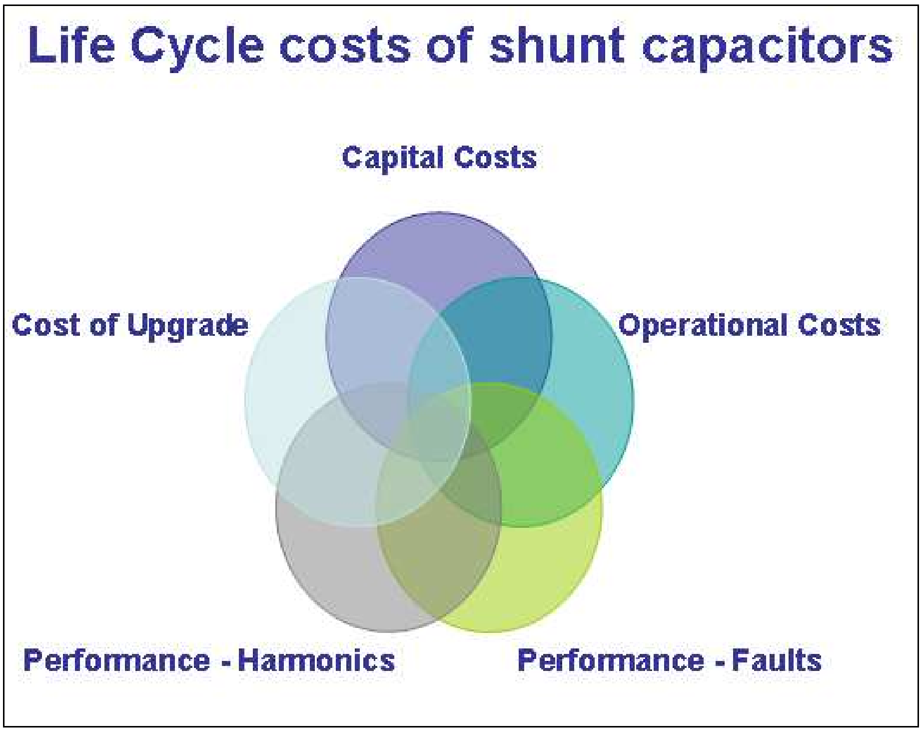



*Figure 9.1: Lifecycle cost model for shunt capacitor banks*

## *9.2 Capital cost*

Table 9.1 shows the combined costs (from Table 6.1 and 6.2) for the installation of shunt capacitor banks at different voltage levels and utilizing different topologies.

Table 9.1: Total capital cost for shunt capacitor bank in Rands.

| | 132kV 72 MVAr shunt capacitor bank | | | 275kV 150 MVAr shunt capacitor bank | | |
|---|---|---|---|---|---|---|
| **Category** | **Plain** | **De-tuned** | **C-type** | **Plain** | **De-tuned** | **C-type** |
| Capacitor bank | R 5,700 Mil | R9,000 Mil | R 12,000 Mil | R7,380 Mil | R10,600 Mil | R16,816 Mil |
| Other costs | R 8,475 Mil | R8,779 Mil | R 9,733 Mil | R 9,323 Mil | R 9,657 Mil | R 10,706 Mil |
| **Total Costs** | R 14,175 Mil | R17,779 Mil | R 21,733 Mil | R16,703 Mil | R20,257 Mil | R27,522 Mil |

The component cost for installing a C-type filter is expensive as compared to plain or de-tuned capacitor banks. However other costs such as civil, other primary related equipment etc reduces the price difference. A 132kV

72 MVAr C-type filter costs 1.52 times the price of a plain capacitor bank and 1.22 times the price of a de-tuned capacitor bank.

On the EHV system a 275kV 150 MVAr C-type filter costs 1.64 times the price of a plain capacitor bank and 1.36 times the price of a de-tuned capacitor bank.

From this analysis, it is clear that the cost of installing a C-type filter is high as compared to other topologies. The high cost is associated with the additional equipment required for this type of a system, as well as additional space requirements.

### *9.3 Operational cost*

From Tables 8.2, 8.4 and 8.6 the operational costs for different shunt capacitor bank topologies were added together to show which topology has the highest operational cost. The cost due to operational losses of the de-tuned capacitor bank have been found to be 13.18 times that of the plain capacitor bank and 2.35 times that of the C-type filter bank, as shown on Table 9.2.

Table 9.2: Cost of total losses for various capacitor bank technologies

| | **Plain capacitor bank** | **De-tuned capacitor bank** | **C-type filter bank** |
|---|---|---|---|
| Cost of dielectric Losses | R 179280.00 | R189422.00 | R 278496,00 |
| Cost of damping resistor losses | R16800 | R1,699 Million | R 856915 |
| Cost of tuning reactor resistive losses (Qf = 150) | - | R200K | R612K |
| Total Operational Cost | **R196K** | **R2,088 Million** | **R1,746 Million** |

### *9.4 Cost of upgrade from a plain to a de-tuned capacitor bank*

It is possible to consider the conversion of a plain capacitor bank into a de-tuned capacitor bank. In all cases, modifications require both civil and structural changes to accommodate new additional equipment. The conversion is achieved by reconfiguring the plain capacitor bank, utilizing the existing units.

Tuning of the plain capacitor bank will require the installation of a tuning reactor, H type CT's and the addition of an extra set of parallel capacitor cans placed in series with the existing capacitor cans. This is required due to the increased voltage stresses that the tuning reactor will introduce.

However, the costs of upgrade can be reduced by ensuring that a plain capacitor bank with expansion capability is implemented in the original design. With this in place the only additional costs will be for additional units, H-type CT's and labour.

### *9.5 Cost of upgrade from a plain capacitor bank to a C-type filter*

It is possible to consider the conversion of a plain capacitor bank into a damped C-type filter. In all cases modifications require both civil and structural changes to accommodate additional equipment. The conversion is achieved by reconfiguring the plain capacitor bank, utilizing new material. The existing capacitor bank can be relocated or the units used as spares for other existing plain capacitor banks with similar characteristics.

Converting the plain capacitor bank to a damped C-type filter will require the installation of new main units, coupling units, tuning reactors, main H-type CT's, coupling H-type CT, damping resistors and resistor CT's.

### *9.6 Conclusion*

This chapter has covered the lifecycle costs associated with a 275kV 150 MVAr capacitor bank.

By adding the capital and operational costs for different topologies, the lifecycle cost of a C-type filter bank is 1, 73 times that of a plain capacitor bank and 1, 31 times that of a de-tuned capacitor bank, evaluated over a 20 years period. This high cost of the C-type filter bank is mainly due to the initial capital cost as the operational costs of the de-tuned capacitor bank are higher than that of the C-type filter bank.

Where a plain capacitor bank is implemented, it will be beneficial to ensure that it has expansion capability. This ensures that when there is a need for an upgrade only the costs of additional components and labour are budgeted.

# 10. Conclusion and recommendations

## *10.1 Introduction*

From this study, the lifecycle cost implications of applying different VAr support technologies in the Eskom Transmission network, have been investigated, taking into consideration the following VAr support options:

- Plain capacitor bank
- Plain capacitor bank with expansion capability
- De-tuned capacitor bank
- C-type filter.

## *10.2 Evaluation for the implementation of various VAr support technologies*

The study has showed that harmonic resonance can cause excessive THD levels if the planning and operation of a network is not properly studied prior to the implementation of VAr compensation as well as during the operation of a network. The following factors are seen to have an influence on the harmonic resonance frequency as well as the harmonic amplification factor:

- The three phase short circuit power at the point of supply.
- The loading of the network.
- The size of the capacitor bank to be installed.
- Network contingencies.
- Shunt bank technologies.
- The load composition (active and reactive powers).

A harmonic resonance guideline was developed to assist planning engineers who are not familiar with harmonic simulations in deciding whether the planned shunt capacitor bank will have negative impact on the network or not, before they request detailed harmonic simulations at a price from consultants. A flowchart was also proposed with the aim of ensuring that the key issues are addressed before the design of the capacitor bank which will ensure that key issues are addressed during the planning phase of a capacitor bank. The following considerations are essential when planning a capacitor bank:

- Capacitor parameters (voltage, short circuit power, contingencies)
- Voltage harmonic measurements
- Power measurements (apparent, active and reactive powers)
- Future network expansion plans.
- Lifecycle cost analysis.

The case studies done on both the HV and EHV networks have showed that the EHV plain capacitor banks have good harmonic performance, as compared to the HV ones. The harmonic performances of HV capacitors which are causing resonance near the fifth harmonic frequency can be improved with proper operation guidelines. This will need simulations and detailed investigation per site.

The shunt capacitor bank should preferably be installed on the EHV (275kV) networks, due to the following reasons.

- High power transfer
- Good harmonic performance for a plain capacitor bank.
- Cost difference of between 15-20% for the plain capacitor bank option.
- Low operational losses.

The performance levels (faults) of plain capacitor banks have been found to be poor, but improvements can be made with improved maintenance and proper investigation and analysis of faults, especially on ageing shunt capacitor banks. The four C-type filters installed in the USA in the past six years are performing well, with no faults so far.

## *10.3 Lifecycle cost analysis*

The understanding of the current and future network characteristics will assist in proper planning of the shunt capacitor bank. This will ensure the correct placement and associated technology required for the capacitor bank and thus saves utilities money in the future. For example, the original design of the capacitor bank should incorporate a future planned large harmonic polluting load.

Capacitor banks should be operated optimally to reduce the harmonic amplification factor. During lightly loaded conditions, capacitor banks should be switched off as the capacitive reactance required by the system is minimal.

C-type filters have proved to be more reliable than other topologies. One of the reasons is that it has superior performance for turn on during inrush currents and transients conditions. This can lead to high availability of the capacitor bank and can therefore be used as motivation where a high level of availability is required on a shunt capacitor bank.

The overall capital cost of installing a 275kV, 150 MVAr de-tuned capacitor bank is 1.21 times that for installing a plain capacitor bank, while the cost of installing a C-type filter is 1.65 times that for installing a plain capacitor bank. The cost of installing a C-type filter is 1.35 the cost of a de-tuned capacitor bank.

The operational costs of capacitor bank units have reduced over the years due to improvement in the dielectric medium used. By using an all film dielectric, a R5 million saving is attainable over the 20 years lifespan of a 275 150 Mvar capacitor bank.

The damping resistor power losses on all topologies are the major losses for the capacitor banks. With the C-type filter having low 50 Hz losses, the de-tuned capacitor banks have higher losses. The cost due to operational losses of the de-tuned capacitor bank has been found to be 10, 65 times that of the plain capacitor bank and 1, 2 times that of the C-type filter bank on a 275kV 150 MVAr installation.

By adding the capital and operational costs for different topologies, the lifecycle cost of a C-type filter bank is 1, 73 times that of a plain capacitor bank and 1, 31 times that of a de-tuned capacitor bank, evaluated over a 20 years period. This high cost of the C-type filter bank is mainly due to the initial capital cost as the operational costs of the de-tuned capacitor bank are higher than that of the C-type filter bank.

## *10.4 Recommendations and future work*

The accuracy of this study is acceptable as the latest data for performance, capital costs, operational losses etc were used, but more work has to be done in the following aspects:

- C-type filters performance in the next 5-10 years and evaluated against the performance of other topologies.
- Costs associated with spares requirements for different topologies.
- The opportunity cost for when the capacitor bank is faulty.
- Research into the lifecycle cost of shunt capacitor banks in Distribution networks.

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