STUDY OF THE EFFECTS OF HARMONICS IN THE DESIGN OF TRANSMISSION NETWORK SHUNT COMPENSATORS: NETWORK SIMULATION AND ANALYSIS METHODS

In fulfillment of Master of Science in Electric Power and Energy Systems, University of KwaZulu-Natal

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"As the candidate's Supervisor I agree/~~do not agree~~ to the submission of this thesis.

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Abstract

The management of parallel and series resonance conditions is important for ensuring that harmonic levels are managed on utility networks, and that shunt compensators are able to operate without constraints for various network conditions (states). For these and similar problems, harmonic impedance assessment of the ac network is required for the design of ac filter or shunt capacitor bank installations. This is particularly important for large installations connected to HV or EHV systems, because resonances at these voltage levels tend to be highly un-damped resulting in potentially damaging voltage and current amplification.

The objective of this dissertation was to develop and demonstrate a design methodology which makes use of network impedance assessment methods to provide robust harmonic integration of large shunt compensators into a transmission and HVDC systems.

The design methodology has two aspects. The first part considers network modeling, evaluation of different models and simulation of harmonic impedance. In the second part, methods of analyzing and assessing the simulated harmonic impedance are developed.

A detailed step-by-step approach was taken in the development of the design methodology. The methodology was documented as a guideline and accompanied by the development of an Excel tool that can be used to assess the simulated harmonic impedance. The Excel tool permits a systematic assessment of the simulated network impedance where shunt compensators are integrated into transmission systems. The tool also ensures that the design of transmission and HVDC ac shunt compensation is optimally robust in terms of harmonic resonances.

The theoretical and computational review has been tested and demonstrated on the existing Eskom Transmission system through several case studies. The results have shown the merits of the design methodology.

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Abbreviations, Symbols and Definitions,

Abbreviations

CIGRÉ	International Council on Large Electric Systems
Dx:	Distribution
EHV:	Extra High Voltage
FACTS:	Flexible AC Transmission Systems
HV:	High Voltage
HVDC:	High Voltage Direct Current
IEC:	International Electro-technical Commission
IEEE:	Institute of Electrical and Electronics Engineers
NRS:	National Regulating Standards
PCC:	Point of Common Coupling
PFC:	Power Factor Correction
SVC:	Static Var Compensator
THD:	Total Harmonic Distortion
Tx:	Transmission
VT:	Voltage Transformer

Symbols

h	Harmonic number (i.e. 5 refers to the 250Hz component)
h_r	Harmonic number at which resonance will occur
h_T	Harmonic number at which a harmonic filter is tuned
I_{SC}	System Short circuit current (A)
$I(h)$	Harmonic current (A)
$I_e(h)$	Harmonic current emission for an individual load (A)
$I_E(h)$	Harmonic current emission for all loads (A)
$K_e(h)$	Voltage amplification factor for local load emission
I_{rms}	Total r.m.s current – 50Hz and harmonic components (A)
ω	Frequency (radians/sec)
ω_r	Resonant frequency
$X_C(h)$	Harmonic impedance of shunt reactive compensation (Ω or p.u.).
$X_N(h)$	Simplified network harmonic reactance (Ω or p.u.).
$Z_N(h)$	Simplified network harmonic impedance (Ω or p.u.).
$Z_{pcc}(h)$	Simulated system impedance at the PCC with shunt compensation (Ω).
S_{FL}	System fault level (MVA)
V_{pcc}	Line voltage at the PCC (kV)

Definitions

The following definitions have been sourced from reference [3, 28 & 29]:

Compatibility level: "Is a reference value used for coordinating the emission and immunity of utility or customer equipment".

Emission level: "Is the magnitude of the disturbing voltage (or current) vector, which the considered installation gives rise to at the point of evaluation".

Emission limits: "Is the maximum level for a particular device, equipment, system or disturbing installation as a whole".

Filter, damped (shunt): "A filter generally consisting of combinations of capacitors, inductors, and resistors that have been selected in such a way as to present low impedance over a broad range of frequencies. The filter usually has a relatively low *Q (X/R)"*.

Filter, high pass (shunt): "A filter having a single transmission band extending from some cut-off frequency, not zero, up to infinite frequency".

Filter, shunt: "A type of filter that reduces harmonics by providing a low-impedance path to shunt the harmonics from the source away from the system to be protected".

Filter, tuned (shunt): "A filter generally consisting of combinations of capacitors, inductors, and resistors selected to present relative minimum impedance to one or more specific frequencies. Tuned filters generally have a relatively high *Q (X/R)"*.

Harmonic: "A sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency".

Harmonic, characteristic: "Those harmonics produced by semiconductor converter equipment in the course of normal operation. In a six-pulse converter, the characteristic harmonics are the non-triple odd harmonics, for example, the 5th, 7th, 11th, 13th, etc.".

Nonlinear load: "A load that draws a non-sinusoidal current wave when supplied by a sinusoidal voltage source".

Planning levels: "Are harmonic voltages that can be used for the purpose of determining emission limits, taking into consideration all distorting installations. They are generally equal to or lower than compatibility levels and they should allow co-ordination of harmonic voltages between different voltage levels".

Point of Common Coupling (PCC): "Is the point in the public supply stream, which is electrically closest to the installation concerned, at which other installations are, or could be, connected. The PCC is a point located upstream of the considered installation".

Total harmonic distortion (THD): "The ratio of the root-mean-square of the harmonic content to the root-mean-square value of the fundamental quantity, expressed as a percentage of the fundamental".

CHAPTER 1

PART 1

INTRODUCTION

1.1 Overview

Over the next decade with large load growth on the South African network, the network will need to be stretched to its maximum capacity. A key component of stretching the network is the extensive use of shunt compensation, HVDC systems and flexible AC transmission system technologies such as SVCs systems in order to control MVAr flows, provide voltage support, and ensure voltage stability. At the same time the growing number of harmonic generating loads and FACTS technologies implies that harmonic resonances need to be carefully managed in order to meet regulatory and contractual limits on harmonic distortions. Management of harmonics and system resonances constitutes an important part in the design and operation of shunt and/or filter banks for transmission and HVDC systems.

Management of System Resonances:

The resonance conditions in transmission systems arise due to the interaction of the generally inductive network at power frequency with utility capacitors, customer power factor correction capacitors, and transmission line capacitance [1]. Generally the system reactance of an inductive network changes from capacitive to inductive at lower frequencies and inductive to capacitive at higher frequencies, causing a number of resonance points at which the system is purely resistive [1].

Where shunt capacitor installations interact with a system, parallel resonance may arise at harmonic frequencies. The effects of this can be the system impedance variation with frequency and the creation of natural resonant frequencies at harmonic frequencies mostly in the range of 150 to 650Hz [2]. This has an amplification effect on the harmonics of an existing network and excessive voltages might be generated across the capacitor units. As a result, harmonic levels may be exceeded at the busbar where a shunt capacitor bank is connected and even the worst case tripping of the capacitor bank.

Therefore management of such resonance conditions is important where shunt compensator installations result in resonant conditions. Robust designs such as de-tuned filter banks or filters (where necessary) must be considered.

It is important to highlight that management of system resonances where sources of harmonics are not definite, is a challenge. In such cases harmonic orders and their magnitudes are usually not known. As a result, de-tuned filter banks are mostly applied rather than filter banks. De-tuned filter banks are not designed to absorb harmonics of a specific frequency i.e. 5^{th} harmonic; however their main purpose is to provide low impedance at parallel resonant frequencies

Management of harmonics:

If there is a presence of resonance conditions in the supply network, the power system harmonics generated by customer loads, HVDC and FACTS devices can be harmful to the quality of the supply voltage. Over the past decades, due to a rapidly increasing demand of power electronic device in industries, non-linear loads (harmonic producing loads) have dominated a larger portion of the total connected load in the power system [2]. The harmonics injected by these loads and/ or devices into the supply network can be controlled by designing robust shunt filter banks. In these cases harmonic currents produced can be determined through calculations hence filter banks are designed specifically to absorb harmonics of specific frequencies. The design of AC filters become one of the main factors in planning and design of the HVDC and FACTS devices.

Uncontrolled resonances in the network are not desirable from a utility or customer point of view. The management of harmonics and system resonances can be summarized as follows:

(i) By designing robust shunt filter banks.

(ii) By placing emission levels contracts between a utility and a customer. The limits placed on these emission levels are directly impacted by the system harmonic impedance.

Mitigating the system resonances and harmonics is a crucial task, hence shunt compensation equipment must be carefully designed in order to minimize losses, increase revenue and prevent damaging effects of harmonics. For the design of AC filter or shunt capacitor banks, harmonic impedance assessment of the ac network is required. This is particularly important for large installations connected to HV or EHV systems, where conventional rule-of-thumb based on simple calculations is no longer sufficient [3]. However, assessing the network harmonic impedance is a very complex task, and moreover, the impedance is continuously changing with loads, network configurations and system conditions [4]. The calculation of network impedance at various frequencies requires the modeling of system elements which must depict the characteristics of the network and the accuracy of results is dependent on the real model representation.

The network impedance can be evaluated by site measurements and digital simulations using state advanced power system software. The site measurements provide data such as voltage distortion levels, THD and harmonic currents; required to validate digital simulations. In this regard digital simulations are amongst other functions used to calculate network impedance, voltage distortions (where harmonic current sources are modeled) and design of component ratings [2]. This is important for design and cost requirements during planning stages.

Currently, there is limited guidance available within Eskom and International bodies for the design and integration of large shunt banks into transmission networks. A lot of work has been done by International organizations such as CIGRÉ on AC filter design for HVDC systems. However, a gap still exists on harmonic impedance assessment and consideration of background harmonics when designing shunt banks and de-tuned banks for both ac transmission and HVDC systems.

1.2 Hypothesis

A design methodology can be developed and demonstrated which makes use of network impedance assessment methods to provide the robust harmonic integration of large shunt compensators into a transmission and HVDC systems.

1.3 Research Objectives

The aim of this dissertation project is to evaluate the effects of harmonics in the design of transmission system shunt compensators. Develop a procedure (design methodology) that can be used as a guideline for integration of large transmission and HVDC shunt compensators with respect to the following objectives:

(i) To investigate the influence of the currently applied system element models in network impedance calculation i.e. transformers and transmission lines;

(ii) Evaluate existing methodologies of ac network modeling for the purpose of harmonic studies;

(iii) To determine the network impedance amplification factors when shunt capacitor / filter banks are integrated into the transmission system.

1.4 Research Methodology

This research work was mostly of simulation and theoretical nature. The above objectives were achieved by applying the following methodology:

(i) A comprehensive review of the issues relating to network models and their behavior in harmonic domain was undertaken. This review addressed the application of different models suitable for network impedance calculation for both HVDC AC filters and transmission shunt compensation design, leading to improved assessment of both merits and costs of reactive shunt compensation design options. The effects of shunt capacitor and filter banks installation on network impedance was reviewed extensively.

(ii) The case studies used are based on Eskom network. The network data was collected from PSSE and PowerFactory Eskom's case files.

(iii) The power system simulation package PSCAD/EMTDC was used to simulate network impedances and evaluate the effect of harmonics on the design of transmission shunt capacitor and filter banks.

(iv) MATLAB software was also used to demonstrate the characteristics of CIGRÉ system models such as; transformers and transmission lines at harmonic frequencies.

(v) A design methodology was developed and documented. This was achieved by compiling a procedure for network modeling, network impedance simulation and assessment. Part of the procedure was to develop an Excel tool to facilitate the network impedance assessment for the design of shunt capacitor and filter banks. A step by step process is summarized in a chart.

(vi) The application of the design methodology on the existing Eskom Transmission system was demonstrated in order to assess practicality of the methodology. This demonstration is undertaken in the form of several case studies. The selection of case studies was based on various network factors and conditions such as different system capacity (high and low fault levels).

(vii) Benchmarking of the simulated network impedance conducted during the design phase of the shunt bank, with harmonic voltage distortions recorded on site after the installation of shunt bank.

1.5 Dissertation Layout

Chapter 1, Part I of this dissertation commences with an overview of the management of system harmonics and resonances due to non-linear loads and utility equipment in transmission systems. As pointed out in overview section of this chapter, emission limits contracts between a utility and a customer is one of the control measures in the management of system harmonics and resonances. In Part II, the regulatory requirements in line with recommendations by NRS, Cigré and IEC are discussed. The principles of compatibility engineering and network condition to be considered when integrating large complex loads or shunt compensation devices are also established.

Recognizing that the network modeling, simulation and impedance assessment constitutes an important part in shunt capacitor bank design, a comprehensive approach is taken on these issues. Some of the topics related to this subject include: effects of harmonics on equipment, parallel and series resonance conditions, system response characteristics and filter designs; all these have been well established and documented over the past few decades. In Chapter 2, a literature that covers the research of useful theories and practical work on the above mentioned topics, is reviewed and analyzed.

In Chapter 3, from the understanding of theories and the documented previous work, a practical approach is taken to evaluate the behavior of system element models at harmonics frequencies i.e. transformers through simulation. A design methodology based on network modeling, simulation and impedance assessment is proposed and documented in Chapter 4.
The application and practicality of the design methodology is tested on several case studies. The results are presented and documented in Chapter 5. Finally, the dissertation ends by concluding on the merits and shortcomings of the proposed design methodology and makes recommendations for future work in this area of research. The conclusion is given in Chapter 6.

PART II

EMISSION LIMITS – CONNECTION OF SHUNT COMPENSATION DEVICE OR COMPLEX LOADS

1.6 Overview

The integration of any device that alters the system harmonic impedance or complex load that introduces harmonics on the supply network requires allocation of harmonic emissions levels [3]. This allocation may apply to individual customers and large transmission equipment that generate harmonic distortion (such as SVC's and HVDC systems). The connection of a new customer installation is often accompanied by system augmentation or increased levels of shunt compensation. When the shunt reactive compensation is installed on the supply network it is most likely that it will amplify the existing harmonic voltage distortions due to resonance modes close to harmonic frequencies. Where de-tuned banks are applied on the transmission or distribution system, the current and voltage rating of these may also place additional restrictions on allowable emission levels [3].

1.7 Compatibility Engineering

The principles of managing harmonic distortion levels are based on the need to ensure levels of harmonic distortion on utility network are compatible with the immunity of customer and utility equipment. This requires that [3]:

(i) The levels of harmonic voltage distortion provided by the network service provider are such that they do not damage or substantially reduce the expected life span of customer or utility equipment.

(ii) The levels of harmonic current generated by customer plants connected to the network are coordinated such that the combined currents from all customer plants do not severely impact the levels of voltage quality on the network.

1.7.1 Planning levels

The planning levels recommended by NRS 048-2 Edition 2 and Cigré C4-07 for HV and EHV are the same, i.e. aligned with those in IEC 61000-3-6. These are considered as internal quality objectives of the networks and can be used by utilities as the basis for the management of harmonic levels on transmission and distribution systems [3].

1.7.2 Compatibility levels

The compatibility levels for harmonic voltage distortion in MV and LV networks are defined in NRS 048-2 [5]. These compatibility levels are aligned with international standards such as IEC 61000-2-2 [6] for LV systems, IEC 61000-2-4 [7] for MV systems, and EN 50160 (the European minimum standard). In the case of high voltage and extra-high voltage systems, compatibility levels are not defined, as end-use equipment is not connected at these voltage levels. The concept of a compatibility level is therefore replaced by the concept of characteristic voltage levels at these voltage levels [3].

1.7.3 Characteristic Harmonic Levels

Characteristic harmonic levels for HV and EHV systems have been defined internationally in the Cigré C4.1.07 document Power Quality Indices and Objectives for EHV, HV, and MV Systems [8]. These levels effectively define the minimum performance requirements for HV and MV network service providers.

1.7.4 Application to the integration of complex loads

The planning levels apply directly in the coordination of emission levels when integrating complex harmonic loads. Whilst the compatibility levels (for MV and LV networks) and characteristic levels apply when considering the rating of shunt capacitors or filter capacitor banks. It is possible that the characteristics levels and in some cases even the planning levels are limited at a specific site by the rating of a filter typically for harmonic components that are close to the tuning frequency in a tuned bank. This is a case under which the planning levels may be adjusted by a utility [3].

1.7.5 System Constraints Based on Shunt Filter Ratings

The installation of tuned shunt banks may place an additional restriction on the apportioning process, i.e. the need to consider the rating of a de-tuned filter. The advantage of such tuned filters is that the system impedance just above the tuned frequency is low. The disadvantage is that using the harmonic planning levels to coordinate harmonic contribution from individual customers for these characteristic harmonics may exceed the r.m.s. current rating of the reactor or the voltage rating of the capacitors. The planning levels (or the characteristic harmonic levels in case of HV and EHV networks) therefore need to be adapted to the rating of the bank. This is usually only necessary at the characteristic harmonic closest to the tuned frequency [3]. This practice also ensures that a filter bank is rated for background harmonics; it eliminates most uncertainties of overloading a filter bank or worst case tripping during certain operating conditions.

1.8 Network Conditions

Network conditions (configuration, reactive compensation, generation patterns, and loading) have a significant effect on the resonance conditions created at harmonic frequencies, as well as in the damping of such resonances. A robust shunt compensation design requires that the interaction with the system be optimized. A too narrow impedance assessment may lead to one condition that has a less probability of occurring, prescribing the design. For this reason and to ensure unrestricted operation of the shunt compensation it is important to consider a reasonable planning expansion horizon, practical and likely operating scenarios. The Cigré WG 14.30 document recommends that the network impedance definition has to cover a period up to twice as long as the planning horizon – this is specific to HVDC and FACTS filter design. The rating specifically of filter banks must be rated for such conditions.

1.8.1 Network States

Network states are often confused with network contingencies. States are defined in this report as all practical and likely combinations of:

(i) Shunt compensation,

(ii) System loading and

(iii) Generation patterns

These are considered as "normal" system conditions, and must be addressed in the shunt compensation design, as NRS 048-2:2003 specifically requires that harmonic limits be met under all network states [5].

It is not practical to consider all possible combinations of states. For this reason, some assumptions are made. The following guidelines may be provided [3]:

(i) All possible combinations of shunt compensation at or close to the PCC must be considered, as where more than one shunt device is connected, these are likely to inter-act, forming resonance peaks at new frequencies.

(ii) For each of these possible states, only the lowest load conditions need to be considered (i.e. the condition under which the voltage is kept just below typical operational limits by tapping the transformer down, rather than removing the capacitor)[1]. This will ensure that the worst-case parallel resonance conditions are addressed for most practical states.

(iii) Where local generation exists, it is recommended that the lowest practical levels of generation be used for all the above scenarios (note that this is consistent with the low-load scenario, under the further assumption that the power is supplied by other remote generators).

[1] Transmission operators tend to run the voltages high to minimize losses. Capacitors often remain connected to ensure their availability for system stability purposes, should a circuit be lost.

CHAPTER 2

LITERATURE REVIEW

Considerable amount of work has been done over the years in developing guidelines and techniques for addressing and or managing harmonic resonance problems. This literature study was undertaken to review models for power system components such as transmission lines, loads, transformers and generators, and the behavior of large power systems under harmonic polluted environments. The creation of parallel resonances due to the application of plain shunt capacitor banks for reactive power support and of using tuned capacitor banks for managing network harmonic resonance conditions is reviewed. The system response characteristics and the performance characteristics of different filter or tuned-bank topologies are addressed.

2.1 Harmonics

2.1.1 Categories of harmonics

Nonlinear devices inject harmonic current components onto the system. The system impedance versus frequency characteristics determines the harmonic voltage distortion levels. Steady-state harmonics are the primary concern in this dissertation; other related subject matters such as power system resonances and application of shunt capacitor banks, will have an impact on the system and equipment. In particular, the difference between harmonics, interharmonics, transient harmonics, and switching transients, is often not well understood. The design of a shunt bank can be critically affected in different ways by the system resonances and harmonics [9].

2.1.1.1 Steady State Harmonics

Harmonic voltages or currents are high-frequency sinusoidal components of the voltage or current at frequencies that are an integer multiple of the fundamental component. Such components are referred to by their harmonic number (e.g. h=5 refers to a 250 Hz frequency component). These are generated by most static converters, arc furnaces, or saturated iron cores. It is important to note that these frequencies are directly related to the fundamental power frequency. In this report fundamental frequency refers to 50Hz which is the frequency for South African power system grid [3].

2.1.1.2 Characteristic Harmonics

These are steady state harmonic frequencies produced by non-linear loads. For example, characteristic harmonic currents of all 6-pulse rectifiers are 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonics (±6n where n is 1, 2, 3 etc.). If the firing of the power electronic devices is symmetrical, reactance between transformer phases is balanced in the case of HVDC systems and the three phase ac network voltages are symmetrical; the magnitudes of non-characteristic which is even and triplen harmonics (harmonic components such as 3, 6, 9 etc. which are multiples of 3) are negligible [3].

2.1.1.3 Interharmonics

Interharmonics are frequency components that fall between harmonic frequencies [3]. These are typically generated by loads such as electric arcs, or converter technologies where converter output frequencies are reflected back in the AC supply (as is the case with cyclo-converters) [10].

2.1.1.4 Transient Harmonic Currents

Transient harmonic currents are caused when energizing the iron cores of transformers or reactors. These can be significant in magnitude and are related to the 50 Hz waveform. The asymmetrical nature of the energization current results in high levels of both odd and even harmonic distortion. The duration of such transient events may be up to several seconds [3].

2.1.2 Harmonic producing loads

Non-linear loads draw non-sinusoidal currents which contain fundamental and harmonic components. These loads are defined as harmonic current generators [10]. There are three main categories of harmonic producing loads (non-linear devices):

2.1.2.1 Power Electronics

Harmonic currents are generated due to switching action of power electronic devices (thyristors, diodes, transistors etc.). Below are the examples [2]:

(i) Rectifiers and or inverters
(ii) Computer power supplies
(iii) Variable speed motor drives
(iv) Induction heating

Note that cyclo-converters generate harmonics of frequencies other than multiplies of the fundamental frequency [11].

2.1.2.2 Saturable Devices

Harmonics are generated due to nonlinear characteristics of saturable elements. With a saturable device, the harmonic generation will be very dependent on the applied voltage. As the voltage is increased, the harmonic generation increases. Transformer inrush currents during energization are a good example. The magnetizing current start out very high and decays with time constant in the order of seconds. Both even and odd harmonics are present in the inrush current until it decays to the steady state magnetizing current [2]. Examples of saturable devices are:

(i) Transformers

(ii) Motors to some extent

2.1.2.3 Arcing Devices

Arc furnaces generate harmonics due to nonlinear characteristic of the arc. The arc acts like a voltage source of harmonics behind significant impedance, the effect to the power system is a current source of harmonics. A balanced three phase device will eliminate the 3^{rd} and 9^{th} harmonics. However, they are frequently retained because the arc furnace is an extremely unbalanced load during scrap meltdown. Also even harmonics may be found in the arc furnace because of erratic arcing behavior that yields unequal conduction of the current for positive and negative half-cycle [2]. Examples of such devices are:

(i) Arc furnaces

(ii) Arc welders

(iii) Fluorescent lights – fluorescent lights have a current waveform very similar to an arc furnace. Their representation is an arc which also acts like a voltage source behind impedance [2].

2.1.3 Sequence components

When harmonics are emitted by a load into a three-phase ac system, they can be analyzed in terms of their sequence components. These sequence components will propagate differently through a power system. For balanced systems, balanced loads and balanced harmonic generation, the harmonics will be generated according to sequence components as per Table 2.1 [2].

Table 2.1 – Sequence Components of Harmonics [2].

Harmonic Order	Sequence Component
1	+
2	-
3	0
4	+
5	-
6	0
7	+
8	-
9	0
10	+
11	-
12	0
13	+
14	-
15	0

The third harmonic component often is characterized by a dominant zero sequence component (it should be noted, however, that fluctuating loads such as arc furnaces may also generate substantial levels of positive and negative sequence current at triplen harmonic frequencies) [3]. The triplen harmonics flow in the zero sequence circuit in the case of balanced systems and balanced harmonic generation. This is important for single phase power supply loads which generate substantial third harmonic. If the loads are balanced on the three phases, the third harmonic neutral current will be equal to three times the third harmonic component on each phase current [2].

Transformer winding connections will affect the propagation of harmonic components. Where the zero-sequence path is short-circuited, 3rd harmonic current propagation will be blocked [3]. If a customer is fed through a star-star grounded transformer, third harmonic (which is zero sequence components) injected into the utility system will also be quite high. Delta windings can be used to control zero sequence harmonic flow in the system. It is important to note that unbalanced third harmonic components are not zero sequence – they can flow through a transformer with a delta winding. The figure below shows a typical example of a star-connected winding and a delta-connected winding.

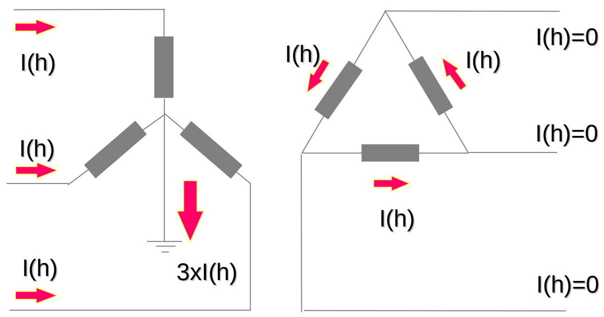


Figure 2.1- Propagation of zero-sequence harmonic current [3].

In order for symmetrical component analysis to apply at harmonic frequencies, both the circuit and the load must be balanced. Particular cases where the symmetrical component analysis would not apply include [2]:

(i) Unbalanced harmonic current generation by the load.

(ii) Unbalanced system characteristics, especially single phase capacitor banks

(iii) The need to solve for all harmonics simultaneously, this includes positive, negative and zero sequence components.

(iv) Unbalanced loads

When symmetrical component analysis does not apply, the system can be solved in the phase domain (i.e. positive-sequence model).

2.1.4 Effect of harmonic distortion

In a utility system, capacitors and transformers are the most commonly affected devices. The most commonly affected customer devices are rotating machines. Whereas a distorted current does not affect other loads, a distorted voltage affects all connected loads. Voltage distortion can result in the failure of customer owned banks and harmonic filters. Harmonic currents can significantly increase heating in anything in their path. In the least severe case there will be increased losses in lines, transformers and capacitors. In the worst case, the heating will be excessive resulting in degradation of insulation [2]. The following section discusses effects of harmonics on equipment:

2.1.4.1 Effect of harmonic component on rotating machinery

The most important effect of harmonics on machinery is increased heating due to iron and copper losses at harmonic frequencies. Harmonic pairs such as the 5^{th} and 7^{th}, can combine to cause mechanical oscillations in a turbine (generator system) or motor (load system) [12]. This occurs if the resulting rotor harmonic frequency corresponds to a mechanical resonance of the system. Harmonic currents in the rotor are a major concern due to the resultant motor heating and pulsating torques. Harmonics add to the negative sequence heating caused by unbalanced loads, unbalanced faults, unequal phase impedances, etc. [2].

2.1.4.2 Effects of harmonics on transformers

Transformer losses and heating caused by both voltage and current harmonic components is frequency dependent. Due to skin effect phenomena losses increase with frequency; harmonic components of high frequencies may be more important than lower frequency components in causing transformer heating [2].

2.1.4.3 Effect of harmonics on electronic controls

Electronic controls are often dependent on the zero crossing or peak magnitude of the voltage waveform for synchronization or control. Harmonic distortion can cause significant variations in these quantities which can adversely affect control operations, mal-operation such as commutation failures can result [2].

2.1.4.4 Effect of harmonics on capacitors

Harmonic problems often show up at capacitors first, either as nuisance fuses blowing on capacitor cans or as capacitor failures. This is because the maximum harmonic levels occur at a capacitor bank during resonance conditions [2].

2.2 Harmonics and Shunt Capacitor Banks

2.2.1 Overview

The effect of system resonance when shunt capacitor banks are introduced in a power system imposes voltages and currents that are considered higher than would be the case without system resonance [13]. The power capacitors and harmonic filters tend to introduce system resonances at critical harmonic frequencies [2]. Where capacitor banks are concerned, harmonic related problems result from the incorrect or non-optimized application of power factor correction shunt capacitor banks and filters. It is becoming more and more common to apply large capacitors at transmission voltage levels. These capacitor banks have a major effect on the frequency response characteristics. When they are switched, the overall system capacitance increases and resonant frequencies are introduced at lower order harmonics – mostly 3rd, 5th and 7th [13].

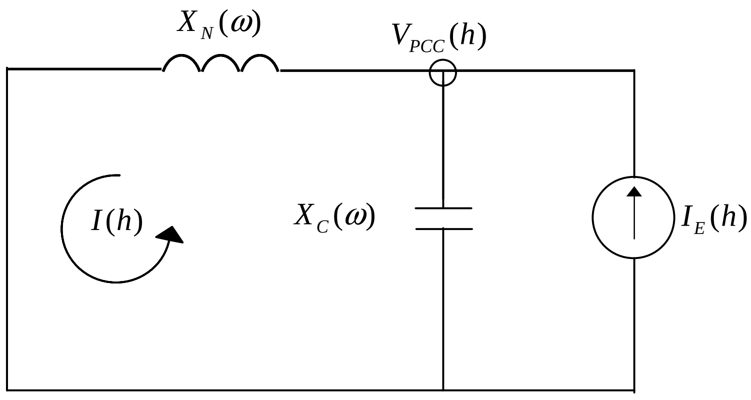
Note: The conventions used in this chapter denote the harmonic impedance and reactance in terms of the harmonic number *h* (e.g. $\mathrm{Z(h)}$ and $\mathrm{X(h)}$ respectively), where *h* is a harmonic of the fundamental frequency (e.g. 50 Hz). For more generic notation, a continuous frequency characteristic is given in radians by ω (e.g. $\mathrm{Z(\omega)}$). All currents, voltages, and impedances are vectors. Where the magnitude only is considered, this is denoted by the modulus convention, for example $\left|\mathrm{Z(h)}\right|$.

2.2.2 Ideal Circuit

In the absence of shunt compensation $\mathrm{X_C(\omega)}$ (refer to Figure 2.2) at the PCC, the harmonic current $\mathrm{I_E(h)}$ generated by all customer loads at the PCC gives rise to a harmonic voltage at the PCC that is a function of the current emission and the system impedance $\mathrm{X_N(\omega)}$ up to the PCC. The voltage at each harmonic frequency can be expressed as [3]:

$$V_{PCC}(h) = X_N(h) \cdot I_E(h) \qquad (2.1)$$

The figure below illustrates a simplified network, represented by the inductive reactance of the supply network and the capacitive reactance of the shunt capacitor bank. Note that in this simplified representation, the system impedance $\mathrm{X_N(\omega)}$ increases almost linearly with frequency.



$$I(h) >> I_E(h), when\ |X_N(\omega)| \approx |X_C(\omega)|$$

Figure 2.2 – Parallel resonance caused by a shunt capacitor at the PCC.

With the installation of a shunt capacitor at the PCC, the harmonic voltages at the PCC are given by:

$$V_{PCC}(h) = \frac{X_N(\omega) \cdot X_C(\omega)}{X_N(\omega) + X_C(\omega)} \cdot I_E(h) \qquad (2.2)$$

Where for 50 Hz systems:

$$\omega = \omega(h) = 2 \cdot \pi \cdot 50 \cdot h \qquad (2.3)$$

The ideal network and shunt capacitor impedances are given by [1]:

$$X_N(\omega) = j \cdot \omega \cdot L_N \qquad (2.4)$$

$$X_C(\omega) = -j \cdot \frac{1}{\omega \cdot C_S} \qquad (2.5)$$

Where C_S is the capacitance of the shunt capacitor installation (note that the current inrush reactor which is normally connected in series with capacitor banks especially in large installation to reduce inrush currents; is at this stage ignored).

Figure 2.3 below is a generic network impedance of an inductive supply network that is, the network impedance increases linearly and the impedance of a shunt capacitor bank.

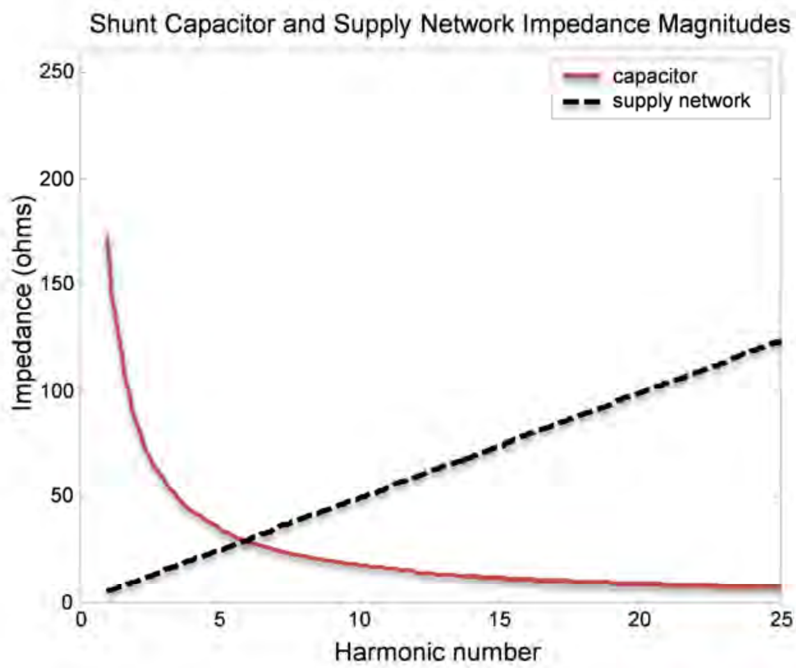


Figure 2.3 – Capacitor and supply network impedance magnitudes showing the point at which these are equal and opposite in phase (in this case close to the 6th harmonic) [3].

Substituting equation (2.4) and (2.5) to (2.2) the magnitude of the harmonic voltage at the PCC is now given by:

$$|V_{PCC}(h)| = \frac{|j \cdot \omega \cdot L_N|}{1 - \omega^2 \cdot L_N \cdot C_S} \cdot |I_E(h)| \qquad (2.6)$$

The denominator of this equation will have a magnitude of zero at a frequency of

$$\omega_r = \frac{1}{\sqrt{LC}} \qquad \text{or} \qquad f_r = \frac{1}{2 \cdot \pi \cdot \sqrt{LC}} \qquad (2.7)$$

If this frequency corresponds to a harmonic frequency generated by the customer load (i.e. $\omega_r = \omega_h$), the magnitude of the harmonic voltage at the PCC will theoretically be infinite, even for a very small current emission level. In practice, the magnitude of this voltage is limited by the resistive components of the network impedance, the shunt capacitor, and the loading of the network. This network condition is termed parallel resonance [3].

2.2.3 Capacitor Currents

Under resonance conditions, the current $I(h)$ circulating in the parallel circuit will be much larger than the total current $I_E(h)$ emitted by the loads at the PCC (i.e. the current emitted by these loads is amplified by the parallel resonance condition).

The harmonic current in the shunt capacitor can be expressed in terms of the current emitted by the load as:

$$\frac{|I_S(h)|}{|I_E(h)|} = V_{PCC}(h) \cdot j \cdot \omega \cdot C_S = \frac{\omega^2 \cdot L_N \cdot C_S}{1 - \omega^2 \cdot L_N \cdot C_S} \qquad (2.8)$$

In the ideal case, this current amplification is infinite at the resonant frequency $\omega_r = \omega_h$ [3].

2.3 System response characteristics

Transmission systems have complex frequency response characteristics. The response is not dominated by a single parallel or series resonance unless there are very large capacitors located near the source of harmonics. Line and cable capacitances result in many different resonances and long line correction is generally necessary to represent these conditions [13].
In general, conditions are more balanced on transmission systems. This may mean that single phase representation can be used for analysis of response characteristics. Computer simulations are virtually always required to analyze harmonic flow on transmission systems or complex distribution systems. [2]

The normal flow of harmonic currents is from the source of harmonics toward the utility supply. The response of the system impedance at harmonic frequencies is equally as important as the sources of harmonics [13]. Its response at each harmonic frequency determines the true impact of the non-linear load on harmonic voltage distortion. The system impedance and the presence of a capacitor bank are one of the primary variables affecting the system response characteristics other than transmission lines, harmonics produced by non-linear loads etc.

The most common harmonic resonance circuits are the following [13]:

(i) Parallel resonance within a utility system, with harmonic currents generated by the customer and resonance between utility capacitors and the supply network.

(ii) Series resonance between external harmonics (in the supply system) and capacitors within the system.

(iii) Interactive resonance between different harmonic filters within a network.

2.3.1 Parallel resonance

Parallel resonance occurs as results of interaction between generally inductive system impedance and capacitive reactance of the network or shunt capacitor bank. Where these are equal at some frequency; a parallel resonance is formed [13]. Where parallel resonance exists, high harmonic voltage distortions may arise even for small amounts of harmonic currents flowing into the power system. On the contrary, a customer with a capacitor bank will experience large and leading harmonic currents; this is an indication of parallel resonance between the system inductance and the customer's capacitor bank [1]. "If this parallel resonance is near one of the characteristic harmonics, that harmonic current will excite the 'tank' circuit, thereby causing an amplified current to oscillate between the energy storage in the inductance and the energy storage in the capacitance. This high oscillating current can cause voltage distortion and telephone interference [13].

2.3.1.1 Parallel resonance with plain (unfiltered) capacitors

When a shunt capacitor is added to the network, it tends to create natural resonant frequency of the network at harmonic frequencies in the range of 150 to 650Hz. This has amplification effect on the harmonics in an existing network [2].

Under parallel resonant conditions, the magnitude of the system impedance seen by the load at the PCC is amplified significantly, but is not infinite. The system impedance, calculated from the circuit in figure 2.2, seen at the PCC is shown in figure 2.4[2] for the system with and without the capacitor. Note that the impact of load damping is apparent by the reduction of the impedance at higher frequencies for the case with no shunt capacitor connected.

[2] It should be noted that the illustrations of circuits and impedance plots demonstrated in this section are based on generic circuits and general behavior of system response as a results of shunt capacitor or filter bank installations and system contingencies.

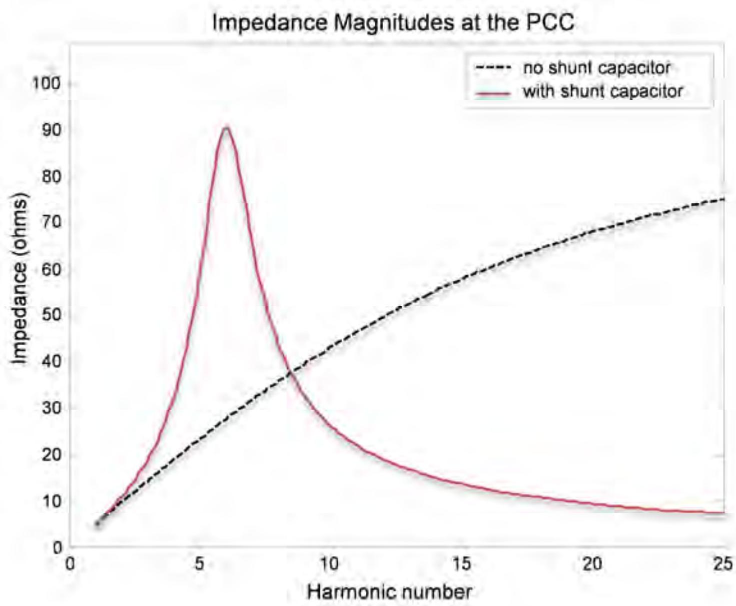


Figure 2.4 System impedance plot under system healthy conditions showing parallel resonance condition close to the 6^{th} harmonic, giving rise also to amplification at 5^{th} and 7^{th} harmonic frequencies [3].

In figure 2.4 the parallel resonance around the 5^{th} harmonic indicates that the shunt bank capacitance is effectively in parallel with the supply network, when seen from the harmonic current source. The impedance into which the harmonic current is "forced", varies with frequency, and reaches a peak at [3]:

$$f_r = \frac{1}{2 \cdot \pi \cdot \sqrt{LC}} \tag{2.9}$$

In the simplified representation of figure 2.2, the system harmonic voltage at the PCC can theoretically be infinite if the capacitive reactance and inductive reactance are equal at a characteristic harmonic frequency. In practice this harmonic voltage is significantly clamped by the resistive components of the supply network (depending on its X/R ratio) and the shunt capacitor itself while parallel loads connected to the PCC and further upstream of the PCC also provide a significant degree of damping depending on type of load and its power factor [10].

The following related implications should be noted [10]:

(i) Although maximum amplification occurs at the actual resonance frequency, the "bandwidth" of the resonance could be fairly broad, and significant amplification therefore occurs at other frequencies around the resonance frequency. At harmonic frequencies just above the actual resonance frequency the network impedance is low; this may present a low impedance path for other harmonic current sources in the network.

(ii) For a given system capacitance, the resonance frequency depends on the total supply reactive impedance, and the latter may change significantly with different supply system configurations such as transformer or line contingencies, shunt capacitor bank states or if the primary supply impedance changes.

(iii) Loads affect both the peak amplification factor and the resonance frequencies, and should be correctly modeled using special non-linear models applicable to harmonic frequencies.

2.3.1.2 System normal versus contingencies, both with shunt capacitor bank

The simplified circuit in figure 2.2 is again referred to, assuming that one transmission line or transformer is out of service. The amplification of the system impedance at the 5th harmonic corresponds to a characteristic harmonic frequency for most loads. This becomes more of a problem in contingency states, where the 3-phase fault level at the PCC drops, giving rise to a lower harmonic resonance frequency. In the example shown below, a 30% drop in fault level results in a shift of the resonance peak from the 6th harmonic to the 5th harmonic.

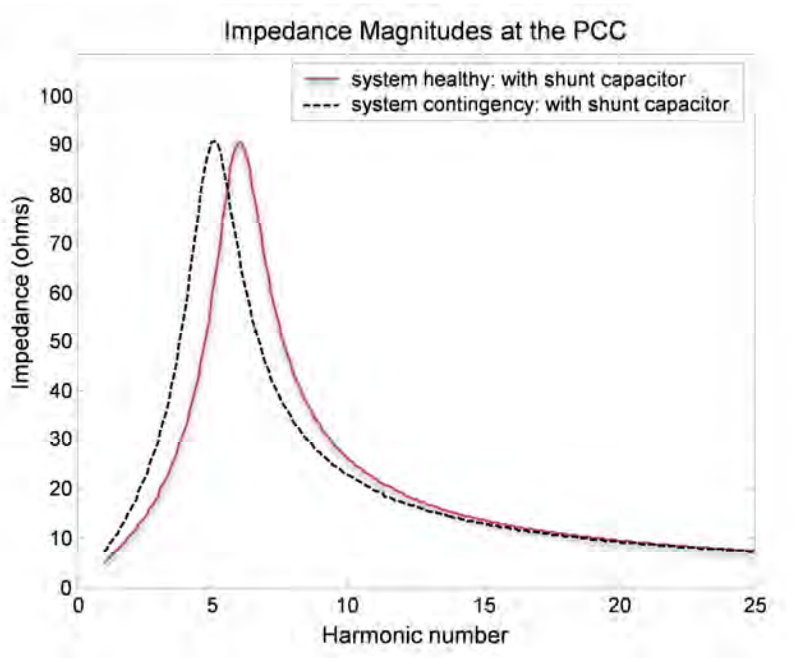


Figure 2.5 System impedance plot for an N-1 contingency state. The 30% drop in fault level causes the resonance condition to move onto the 5th harmonic [3].

Generic Assumptions

Most harmonic integration studies require harmonic simulations. Approximations however assist in comparing simulation results with expected results (i.e. verifying that no significant errors have occurred in the simulation or input of parameter values).

Looking from the harmonic source, capacitors appear to be in parallel with the system short circuit reactance. Result is very high impedance at the parallel resonance frequency. The harmonic number at which the resonance peak occurs can be determined from the fundamental frequency impedances as follows (the following equations are generic and can be used for any network to predict the resonance frequency in the network) [3]:

$$h_r = \sqrt{\frac{X_C}{X_N}} \qquad (2.10)$$

Where the network and shunt capacitor impedances are given respectively for 50 Hz systems by equations (2.4 and 2.5 in section 2.2.2)

X_N is derived from the short circuit current of the supply network and C_S can be calculated as follows:

$$C_S = \frac{Q}{\omega \cdot V^2} \qquad (2.11)$$

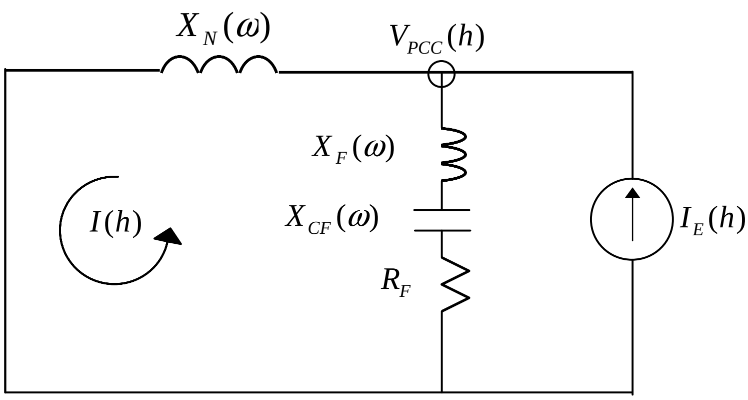
Where Q is the size of the capacitor bank and V is the busbar voltage where the bank is connected.
Another useful approximation that is accurate for systems with relatively high X/R ratios (i.e. typical transmission system) and no other nearby shunt capacitors or significant line capacitances is given by:

$$h_r = \sqrt{\frac{S_{FL}}{Q_C}} \qquad (2.12)$$

Where, S_{FL} is the three-phase fault level in MVA and Q_C is the nominal rating of the shunt bank in MVAr. If harmonic currents are injected near the resonance frequency, significant voltage distortion and magnified harmonic current levels will result [3].

2.3.1.3 Parallel resonance involving harmonic filters or tuned capacitors

Harmonic filters are used to reduce harmonics, apart from also providing power factor correction. "Tuned capacitor banks" are power factor correction capacitors which are tuned with series reactors to avoid harmful resonance, without necessarily being intended to reduce internal harmonics. Figure 2.6 below illustrates a simplified network, represented by the inductive reactance of the supply network and the primary design components required for tuned filter banks which is the reactor, resistor and capacitor bank [3].



$$I(h) >> I_E(h), when\ |X_N(\omega) + X_F(\omega)| \approx |X_{CF}(\omega)|$$

Figure 2.6 – System with a single-tuned filter bank.

In both cases, parallel resonance takes a different form to that associated with plain capacitors, in that each filter creates two resonance frequencies, the modified system impedance plot is shown in figure 2.7.

With reference to figure 2.6 and 2.7 the following two frequencies can be identified:

(i) The filter itself forms a series resonance circuit at its tuning frequency given by [3]:

$$f_S = \frac{1}{\left(2 \cdot \pi \sqrt{(L_F \cdot C_F)}\right)} \qquad (2.13)$$

This equation is derived from figure 2.6 where L_F is the inductance of the tuning reactor and C_F is the capacitance of the tuned bank. R_F is the damping resistor of the filter bank.

Most of the harmonic current at this frequency is absorbed into the filter, and a small residue flows into the supply.

(ii) The filter forms a parallel resonance circuit with the supply network at a lower frequency than the tuning frequency, this parallel resonance is given by [10]:

$$f_P = \frac{1}{2 \cdot \pi \sqrt{(L_F + L_N) \cdot C_F}} \qquad (2.14)$$

Where L_N is the equivalent supply network inductance. The difference here is that the network inductance must be considered.

These frequencies appear and can be measured on V_{PCC} busbar circuit of figure 2.6.

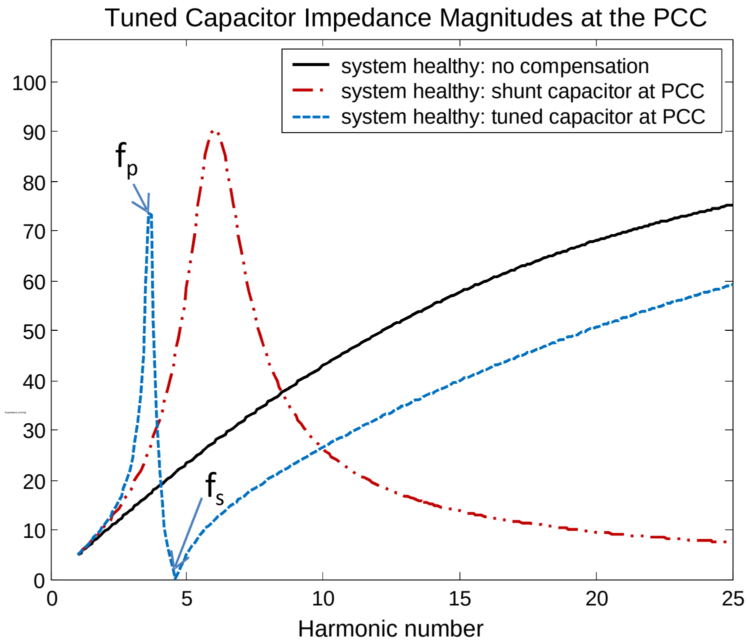


Figure 2.7 – Parallel resonance caused by a single-tuned capacitor at the 4.6th harmonic.

Accordingly, full absorption of impedance occurs at the filter's tuning frequency f_S, between the 5th and 7th harmonics while the peak amplification occurs at the combined parallel frequency f_P between the 3rd and the de-tuned frequency (below the 5th) harmonics. This is as a result of the de-tuned path created by the system impedance, the tuning reactor, and the capacitor [10]. Any tuned or de-tuned filter creates amplification at some point below its inherent tuning frequency. The difference between f_S and f_P depends on the ratio of the filter inductance and the supply inductance. If f_S and f_P are very close, the possibility exists that changes in filter capacitance or inductance may shift f_S higher and that f_P may then fall on or close to a critical harmonic frequency. On the other hand if f_S and f_P are further apart, harmful amplification may occur at lower harmonic frequencies (e.g. 5^{th} harmonic filter causing amplification at 4^{th} or even 3^{rd} harmonic). The control of resonance in systems which consist of tuned capacitors or harmonic filters is inherently linked to a general optimization of filter performance versus total filter cost [10].

2.3.2 Series resonance

Series resonance in transmission systems is a result of the series combination of capacitor banks and line or transformer inductances. It is characterized by low impedance at resonant frequency. This presents a low-impedance path for harmonic currents and tends to absorb any harmonic current of similar resonant frequency. “It can result in high voltage distortion levels between the system inductance and the capacitor in the series circuit and high currents can flow in the capacitor even for small harmonic voltages” [13].

Effect of shunt capacitors – Series resonance can also occur with the application of shunt capacitors [10]:

(i) Feeder capacitor banks in series with line inductance will result in a series resonant circuit which can present a low impedance path for harmonic currents near the resonance. Results can be high voltage distortion at the capacitor bank and telephone interference along the line.

(ii) Lower voltage capacitors at customer sites in series with the external harmonic sources at or beyond the PCC (i.e. step down transformers) form a series resonant circuit looking from the distribution and transmission system. This circuit can act like a filter, absorbing harmonics from the distribution system.

When looking from the upstream busbar, portion of the downstream supply network plus the consumer’s supply transformers in series with his capacitors form a series resonance circuit. In this case the harmonic source is external to the upstream busbar therefore it is seen as the harmonic voltage source. The result can be fuses blowing in the capacitor bank, failing capacitor units, or high harmonic voltage distortion resulting in other problems in the network. [2]

2.4 Network Models

All network studies or analysis, design start with the formulation of appropriate models. Hence, depending on the purpose of the analysis different models of the same physical system or components can be applied [14]. The frequency response of the system impedance at the bus where shunt compensation equipment is connected is the basic design tool used for satisfying the required specification in terms of harmonics and reduction of parallel resonance amplification.

Generally to define complex models requires detailed parameters and to get acceptable results of these often needs extensive work and usually the information is not available. In the subsequent sections; models of the most common network elements suitable for harmonic analysis are discussed. These include transmission lines, loads and transformers. In the subsequent sections it is assumed that symmetrical three-phase conditions apply.

2.4.1 Frequency dependence of resistance

The resistance of various power system components such as transmission lines, transformers, series reactors etc., increases with frequency; this phenomenon is called skin effect. It is important to consider this phenomenon for calculations at harmonic frequencies as it directly impacts the damping provided by equipment such as transformers and transmission lines. If the fundamental frequency resistance is used at harmonic frequencies it results in high unreasonable peaks of impedance resonances. Frequency dependence of the resistance is defined by the expression [11]:

$$R = R_1 \left(\frac{f}{f_n} \right)^{\exp} \qquad (2.15)$$

Where R_1 is the resistance at the system nominal frequency, f_n and R is the resistance at the frequency f .

The value of the resistance of various power system components of an extra high voltage system are frequency dependent. While for some parameters like generators and transformer inductance, positive sequence line inductance this variation is small or even negligible.
Other parameters such as positive sequence generators and transformer resistance, zero sequence line resistance and inductance show substantial variation with frequency which should be taken into consideration in the calculation of harmonics and switching surges.

Frequency dependent resistance associated with constant inductance will produce a frequency-dependent damping of the transient components; the variation of damping factor $\lambda = L/R$ versus frequency is also represented for generators, transformers and positive sequence line inductance [11].

2.4.2 Transmission line models and resonances

When conducting simulation studies, transmission line models have a major influence in the way that the power system responds to harmonic resonances.

Harmonic studies require accurate representation of long line models; distributed RLC traveling wave models are recommended i.e. Frequency – Dependent line models, which incorporate the frequency dependence of all parameters. The distributed line models are characterized by the inductance and capacitance which represent the magnetic and electrostatic conditions of the line and resistance and conductance which represent the line losses as illustrated in Figure 2.8 [1]. In many cases the value of shunt conductance, for short lines, is very small and hence, neglected.

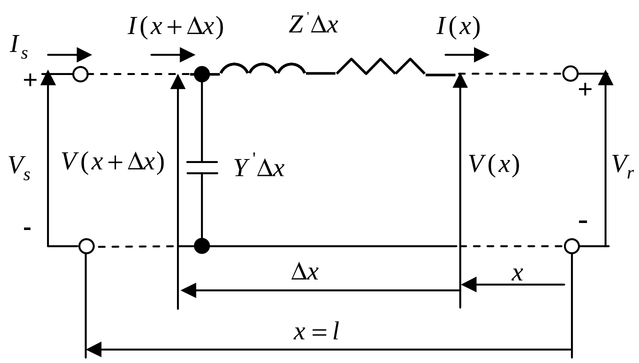


Figure 2.8 – Distributed parameter transmission line [1]

$$z = Z'\left(\frac{\sinh \gamma\ell}{\gamma\ell}\right) \tag{2.16}$$

$$\frac{Y'}{2} = \frac{\gamma\ell}{Z'}\tan\frac{\gamma\ell}{2} \tag{2.17}$$

Where,

$Y' = \sqrt{z\gamma}$, total shunt admittance

$Z' = z\ell$, total impedance of line

$\ell =$ length of transmission line in km

$z =$ series impedance of line in Ω/km

$\gamma =$ shunt admittance of line in S/km

These parameters are specific to a line or cable configuration and are dependent on type of conductors used and their geometrical arrangements. The difference in conductor geometries in high voltage ac transmission lines produces impedance asymmetry and voltage unbalance at the far end of the line [1].

This can be reduced by phase transposition, which is commonly achieved by dividing the line into three intervals of equal lengths. When studying harmonics one needs to consider the effect of transposed transmission lines. The phase transpositions are only effective at voltage levels greater than 1.0 p.u and are designed to meet fundamental frequency requirements therefore cannot be relied upon at harmonic frequencies.

The coupling between sequence networks resulting from ac transmission asymmetries can cause considerable zero sequence interference in nearby power or communication lines. While the line distance may not be sufficient to cause unacceptable zero-sequence voltage unbalance at fundamental frequency, the electrical distance at harmonic frequencies will increase proportionally to their orders. As a result the line asymmetry is expected to have a greater effect at harmonic frequencies [15].

Under perfectly balanced conditions, three-phase ac transmission lines can be represented by their single-phase positive sequence models and nominal PI circuits. In order to improve the accuracy of voltages and currents on long lines which are affected by the standing wave effects; a number of π-models are connected in series [1]. As the frequency increases, the number of nominal π sections to maintain a particular accuracy increases proportionally [1].

The impedance of a transmission line is mostly dominated by the series and shunt reactance components. Both have a period of one wavelength (1300 Hz). The series reactance is capacitive between the half and full wavelength frequencies. Contrary to this, the shunt reactance is capacitive and large at fundamental frequency, beyond half wavelength it becomes inductive [1]. As a result of this change in series inductance and capacitance, the accuracy of voltages and currents close to resonance frequencies, also changes [1].

The series resistance does not get large over the audio frequency range hence the attenuation does not increase significantly. Thus the currents with frequencies in this range will propagate large distance in the power system (i.e. 2^{nd} and 3^{rd} harmonics). The negative resistances are not physically measurable however; they give the acceptable initial conditions for a distributed transmission line model [1].

This emphasizes the need for distributed transmission line models as opposed to lumped transmission models.

2.4.3 Load modeling

The important components of the system load with effects on the system frequency response characteristics are [2]:

(i) The resistive portion of the load provides damping that affects the system impedance near or at resonant frequencies; thereby reducing parallel resonance at harmonic frequencies. The harmonic currents flow through a less resistance path therefore, higher loading levels in the system result in lower impedance at parallel resonances.

(ii) Motor loads and other dynamic loads that contribute to the short-circuit capacity of the system do not provide significant damping of resonance peaks but can shift the frequencies at which resonances occur. These loads appear in parallel with the system short-circuit inductances when calculating resonant frequencies.

(iii) The step-down transformer becomes important at higher frequencies because it is a reactance in series with the load.

Loads supplied by the network form the main element as far as resonant frequency damping is concerned. However, it is particularly difficult to obtain an accurate estimate of impedances able to represent them for harmonic simulations. Values and position of these loads are highly time variable. Loads can be represented in the harmonic mode using three methods [4]:

First method: the equivalent reactance to the loads is neglected, by considering it infinite; if P_{50} represents the active power at fundamental frequency, controlled by these loads, it is considered that they are equivalent to a resistance of value $R = \frac{{U_N}^2}{P_{50}}$ (2.18)

U_N is the nominal voltage at fundamental frequency.

When the harmonic number increases, it may be necessary to use larger values of R, of the order 1.3R for the 5^{th} harmonic and 2R for the 10^{th} harmonic [15].

Second method: the equivalent resistance to the load is estimated as above, but associated with the reactance connected in parallel with it.

Third method: this method is obtained from the results of experiments involving measurements performed on medium voltage outputs using audio-frequency ripple-control generators [15].
Over a frequency range of harmonics corresponding between the 5^{th} and 20^{th} harmonics approximately, the loads can be represented by a reactance X_S in series with resistance R, this assembly being connected in parallel with reactance X_P.

In general, system loads have only a minimal effect on overall system response characteristics unless the system is near a resonant frequency. When close to resonance, the effect of the load is to reduce the peak resonant impedance (damping) or to shift the resonant frequency (motor inductance) [15]. The application of the above models depends on the type of loads being represented.

2.4.4 Transformer modeling

There are two components that are of most interest in a transformer, leakage and magnetizing impedance. Normally the magnetizing impedance is much larger than the leakage impedance when the transformer is not operating in the saturation region. With a saturable device the harmonic generation will be very dependent on the applied voltage, as the voltage is increased; the harmonic generation increases [16]. If the transformer is not a significant source of harmonics, the magnetizing impedance can be ignored. For harmonic analysis, if the transformer is mostly likely to operate on saturation, a representation of the transformer should include a harmonic current source.
There are two methods of representing the transformer discussed herein first method is representing the transformer by its positive sequence reactance and the conventional method is that of representing the transformer by a resistance R_S in series with an assembly consisting of leakage

reactance in parallel with a resistance R_p. Resistances R_S and R_P are constant and can be estimated by the following expressions [15]:

$$90 < \frac{U_N^2}{S_N \cdot R_S} < 110 \quad \text{and}$$

$$13 < \frac{S_N \cdot R_P}{U_N^2} < 30 \qquad (2.19)$$

Where U_N is the rated voltage and S_N the rated power of the transformer.

In the second method, which is the latest improvement of the first model, estimate for R_S and R_P has been introduced, as follows [4]:

$$R_S = \frac{X_1}{\tan \psi_1} \qquad (2.20)$$

$$R_P = 10 \cdot X_1 \cdot \tan \psi_1 \qquad (2.21)$$

The frequency dependence of the resistance accounts for the increased transformer core losses with frequency due to skin effect.

2.4.5 Generator modeling

In the case of generators it is usually sufficient to present them with their sub-transient reactance and by a resistance equaling to [4]:

$$R_1 = 0.1 \cdot X_d'' \qquad (2.22)$$

Where X_d'' is the sub-transient reactance of the generator. At any harmonic number the reactance is:

$$X_h = h \cdot X_d'' \qquad (2.23)$$

When presenting a reduced equivalence of the network, the impedance of the network can be derived from the short circuit current of the network under nominal voltage. In order to consider the skin effect the fundamental frequency value of the resistance R_1 is multiplied by the square root of the harmonic number.

2.5 Shunt Compensation Topologies and Rating Requirement

The primary objective of a filter is to reduce the amplitude of one or more fixed frequency currents or voltages. Shunt filters and de-tuned shunt capacitor banks are commonly used for creating a low impedance path, thus diverting harmonic currents from flowing into the supply system. The principles of applying harmonic filters is based on reducing harmonic current emission levels and of using tuned capacitor banks is management of network harmonic resonance conditions. Shunt filters are relatively easy to design as the harmonic current emission levels are easily determined and interharmonics are not a problem. Where inter-harmonics are present, filters with damping are also applied. This is to ensure that unwanted inter-harmonic distortion does not occur [3].

The quality of a filter Q, determines the level of damping and in this regard filters may be of low damping type (high Q) such as single tuned filter or they may be of the high damping type (low Q); (i.e. C-type). The high Q filter has narrow bandwidth and are sharply tuned to one of the lower harmonic frequencies (e.g. the fifth). High-pass filters normally have a low Q value, typically in the range of 0.5 – 5, in order to provide damping over a broader range of higher harmonic orders [1].

2.5.1 Single-tuned LC filter

A single tuned filter is a series RLC circuit tuned to one harmonic frequency. Its impedance is defined as [3]:

$$Z_1 = R + j\left(\omega L - \frac{1}{\omega C}\right) \qquad (2.24)$$

An option to control the harmonic voltage distortions at the PCC is to tune the shunt bank at a frequency below the characteristic harmonic frequency (typically 3% to 8% below this frequency) or in some cases at the characteristic harmonic. This approach is generally effective for only one frequency although double tuned filters can be designed with additional components. Single-tuned filters can be categorized as follows, as an example 5th harmonic current or resonance frequency is considered. Section 2.5.1.1 to 2.5.1.2 except where other reference is quoted, is referenced to [17]:

2.5.1.1 De-tuned filter (tuning between 4.4 to 4.8 harmonic orders)

If capacitor banks are required to improve power factor and at the same time reduce harmonic voltage distortions, de-tuned filters are applied. A de-tuned bank has lower risk and costs less than a tuned filter bank.

2.5.1.2 Tuned filter (tuning between 4.8 and 5.0 harmonic orders)

If harmonic filters are required to provide MVARs but mainly to reduce harmonic distortion to acceptable limits like in HVDC, FACTS systems etc.; tuned filter bank are normally applied. Since it will attract most harmonic currents from the industrial and utility systems, it presents a high level of risk. Harmonic load growth and power system changes should be considered, together with ambient voltage distortion level and other factors that may have an effect on parallel resonance and tuning frequency [17].

The filter quality factor Q for tuned, de-tuned filters is defined as the ratio of the reactance of an inductor at resonance frequency, to the resistance, i.e. [1].

$$Q = X_0 / R \tag{2.25}$$

The filter band pass (BP) is defined as the resonant point or range of frequencies where the filter reactance equals its resistance. The band pass of a filter is defined by [1]:

$BP = \omega_n / Q$, where ω_n is the resonance angular frequency. In general the tuned frequency of a filter will deviate from its nominal value due to the following reasons [5]:

(i) Range of possible fundamental frequency variations;

(ii) Capacitance and inductance changes due to ageing and variations in ambient temperature;

(iii) De-tuning due to manufacturing tolerances on the capacitor and the reactor.

(iv) Changes in the capacitor values due to failure of elements in the capacitors.

From the above discussion, it can be noted that a small change in the tuned frequency can result in a significant difference in harmonic current flowing through the filter bank thus affecting filter performance. It may also have an effect on the system resonance. Generally, tuning or de-tuning is subjective to the objective of filtering, negative system interaction and at times by economics.

2.5.2 High-pass filters

High-pass filters are most appropriate where voltage notching (caused by line-to-line short circuits that occur during commutation) needs to be attenuated to prevent ringing on the system. The high damping required at these frequencies will generally not allow sufficient damping at the tuned frequency of a C-type filter [3].

The quality factor of high-pass filters is the reciprocal of that of tuned filters, i.e.

$$Q = R/X$$

High-pass filters are generally more economical than C-type filters where single-tuned filters are already applied, and high-frequency attenuation is required. This is because the cost of the auxiliary capacitor generally is high (as this increases as the tuned frequency of the filter increases) [18].

The high-pass sometimes referred to as damped filters, offer several advantages [1]:

(i) Its performance and rating is less sensitive to the de-tuning effects.

(ii) Because of its broad bandwidth, is not required to divide a filter into parallel branches.

(iii) Tuned filters often create parallel resonance below a tuned frequency. This parallel resonance may result in the amplification of lower order harmonic frequencies.

Damped filters have the following main disadvantages [1]:

(i) High MVAr rating is needed to achieve the required filtering performance.

(ii) The losses are generally high.

There are four categories of high-pass filters (damped filters) and are shown in figure 2.9, i.e. first order, second order, third order and C-type [1]:

(i) The **first order** – losses at fundamental frequency are excessively high; therefore it is not normally used.

(ii) The **second order** also has higher fundamental frequency losses but provides the best filtering performance.

(iii) The main advantage of **3rd order** over second order is a major reduction at fundamental frequency loss, due to the presence of capacitor C2 which increases the impedance. In addition, the rating of C_2 is very small compared with C_1.

(iv) The newly introduced **C-type** has the advantages of both second and third order filters in terms of filtering performance. The fundamental frequency losses are significantly low, since C_2 and L are series tuned at a certain frequency. However, this filter is more sensitive to fundamental frequency and component value variations [3].

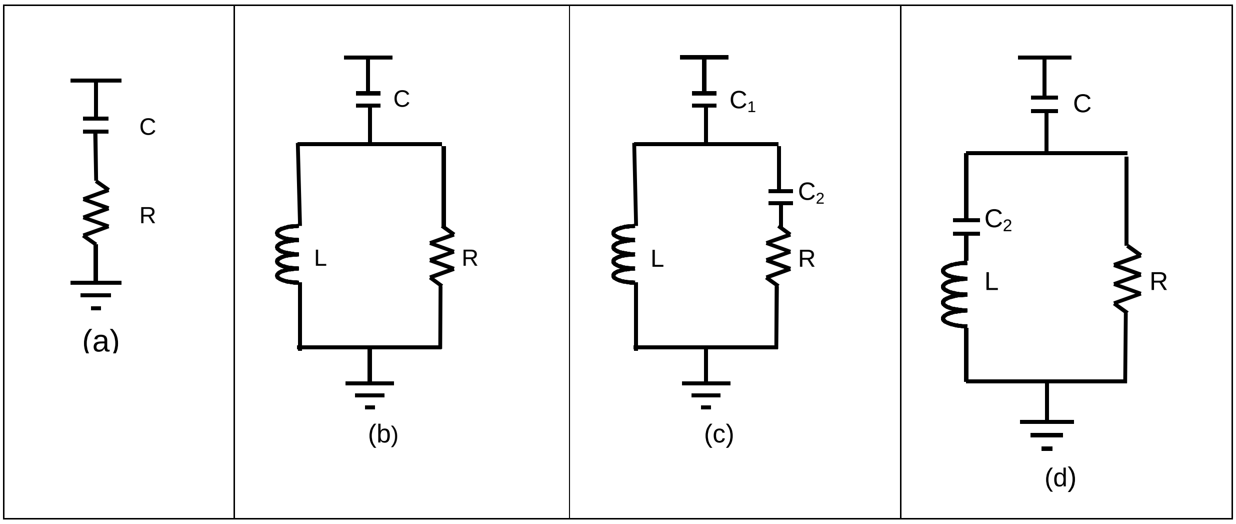


Figure 2.9 – Damped Filter Configurations [3]

2.5.3 Basic principles of C-type filter

The C-type filter is a modified high-pass filter that overcomes the problem of high fundamental frequency losses in the damping resistor of a damped LC filter, by short-circuiting this resistor through an auxiliary tuned circuit at fundamental frequency. This reduces the operating cost of the filter. The same reactor is used for the auxiliary tuning circuit as for the primary filter in order to save capital cost and maximize the reliability of the filter [3].

The C-type shunt bank has the added advantage from a system point of view in that both under-damped resonance modes are not created when installed, and that the frequency response of the network remains largely unaffected if not improved [3].

2.6 Comparative Filter Performance Characteristics

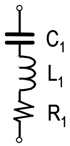
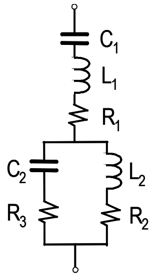
A differentiation can be made between the design philosophy of a harmonic filter and a de-tuned utility capacitor bank. A harmonic filter is designed to absorb load harmonic current emission levels by providing a low impedance path (or by injecting out-of-phase harmonic current vectors in the case of active filters); whereas a de-tuned bank is designed to manage harmonic resonances which occur due to the interaction of shunt capacitor bank impedance with system impedance at harmonic frequencies [3].

A comparison of individual filter performance characteristics for the key parameters defined is presented, in the table below. It should be noted that shunt filters may interact where more than one type or topology is applied; this needs to be assessed carefully during the design phase. The application of various combinations of filter types needs to be assessed in terms of the local load harmonic spectrum, the harmonic performance prescribed, and the harmonic system impedance response [3].

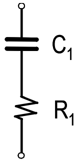
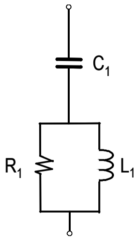
Table 2.2 – Parameters that define the properties of a filter.

Parameter	**Description**
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.
Bandwidth	The range of harmonic frequencies at which the filter provides attenuation. Ideally this should be wide.
Sensitivity	The sensitivity of the attenuation level due to deviations in the fundamental frequency, component values, and temperature drift. The design should be robust for variations.
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.
50 Hz losses	The losses in the filter at 50 Hz only. These losses are always unwanted. Note that the total losses in a filter are a function of the harmonic spectrum that it absorbs.
Capacitor size	The size of capacitor required may be very large, possibly resulting in excessive reactive power at 50 Hz (i.e. more than required for power factor correction) in the case of high power factor load. Ideally this should be small
Cost	The capital cost of the installation only. (Operational losses are included in the assessment of the 50 Hz losses).
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 – and at least not amplified significantly.

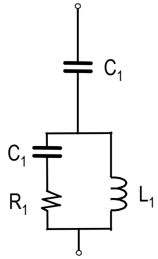
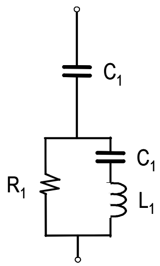
Table 2.3– Summary analysis of filter properties [3].

Filter Type	**Attenuation**	**Bandwidth**	**Sensitivity**	**Amplification**	**50Hz losses**	**Capacit or Size**	**Dynamics**	**Cost**
Single-tuned 	Very high close to the tuning frequency. NOTE 1: A function of the harmonic and the tuning frequency NOTE 2: Decreases for large values of filter resistance	Very narrow. NOTE 1: Increases for large values of filter resistance	High.	High at frequencies below the tuning frequency. NOTE: Decreases for larger values of filter resistance.	Low	Small	Poor / medium NOTE 1: Depending on the Q of the filter.	Low. 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. NOTE 1: A function of the harmonic and the tuning frequency. NOTE 2: Decreases for large values of filter resistance.	Very narrow. NOTE: Increases for larger values of filter resistance.	High.	High at frequencies below the tuning frequency. NOTE: Decreases for larger values of filter resistance.	Low.	Small.	Poor / medium. NOTE 1: Depending on the Q of the filter.	Low / medium. NOTE 1: Lower for HV applications than two single-tuned filters due to lower reactor impulse voltage requirements.

Summary analysis of shunt filter properties (continued)

Filter Type	**Attenuation**	**Bandwidth**	**Sensitivity**	**Amplification**	**50Hz losses**	**Capacitor Size**	**Dynamics**	**Cost**
1st order damped 	Low.	Very wide.	Low.	Low.	Very high. NOTE 1: Seldom used for this reason.	Very large. NOTE 1: Seldom used for this reason.	Good.	High.
2nd order damped 	Medium.	Wide.	Low.	Low.	High.	Medium	Good	High.

Summary analysis of shunt filter properties (continued)

Filter Type	**Attenuation**	**Bandwidth**	**Sensitivity**	**Amplification**	**50Hz losses**	**Capacitor Size**	**Dynamics**	**Cost**
3rd order damped 	Medium.	Wide.	Low.	Low.	Medium.	Medium. 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. NOTE 1: More sensitive than other damped filters. NOTE 2: Changes in the 50 Hz tuned circuit will result in larger 50 Hz losses.	Low.	Very low. .	Medium. .	Good.	High.

2.7 Sizing Conventions – Actual MVAr Output vs. Installed MVAr for Filter Banks

The size (MVAr) of a filter or tuned bank is defined by the reactive power supplied by the unit to the network at the fundamental frequency (i.e. 50 Hz). The difference between the actual MVAr output versus the installed MVAr should be considered during a design phase. Converting a shunt capacitor of a given MVAr rating to a filter will result in a lower reactive power output of the bank if no capacitor units are added on the shunt bank. This is due to the filter reactor which changes the effective MVAr output of the bank [19]. Conversely, a shunt filter required to deliver a certain amount of MVArs at the power frequency needs to be designed with an additional capacitive MVAr rating [17].

Capacitor units for filter banks are rated above normal system voltage levels, in terms of voltage ratings, due to the following reasons:

(i) The introduction of the tuning reactors results in higher harmonic impedances at high frequencies – when compared with the case for a pure shunt capacitor. This impedance can be reduced by increasing the size of the damping resistor. This has the advantage of reducing harmonics at higher harmonic frequencies. The disadvantages are that the fundamental frequency losses may be significant. In addition the tuning reactors cause a fundamental voltage rise on the capacitors. The fundamental voltage rise can be calculated as follows [17]:

$$V_{rise} = \frac{N^2}{N^2 - 1} \tag{2.28}$$

Where, V_{rise} is the fundamental voltage rise due to filter reactor; N is the tuning point of filter bank.

This inherent voltage rise requires higher rating (than the nominal system voltage) of the capacitor units used in the filter bank.

(ii) The harmonic voltage rise on the capacitors due to harmonic currents flowing into the filter bank.

Due to the reasons noted above, the total MVAr installed in the filter bank will always be higher than the actual MVAr output of the filter bank. For most 5th harmonic filter banks, the installed MVAr can be as high as 25% to 40% more than the actual output [17].

CHAPTER 3

ANALYSIS OF ELEMENT MODELS

This chapter describes the assumptions and evaluates some of the existing and currently applied network models for the ac network harmonic impedance calculation as seen from the bus of study. The characteristics of these models at harmonic frequencies are demonstrated through simulations by using tools like MATLAB, HAP[3] and PSCAD.

The accuracy of system impedance at harmonic frequencies largely depends on correct modelling and representation of frequency dependant system elements. This influences the damping of the network at harmonic frequencies. The system simulation models and network analysis undertaken are substantiated with International guidelines and standards endorsed by organizations such as Cigré and IEEE recommended practices and available benchmark results. The application of methods and techniques developed in this research project on the Eskom Transmission system are based on network data, specific site measurements, and historical records from the Eskom National Power Quality Measurements Database.

3.1 System Models and Simulations

3.1.1 Assumptions

3.1.1.1 The simulation technique used for the evaluation of network models is based on a single phase, frequency dependent representation [4]. The majority of the transmission lines considered in the network model were less than 100 km long (the modeled network as shown in figure 3.1 below has the majority of short transmission lines). The implication is that:

(i) Some cross-coupling between sequence components that may occur is not modeled, and

(ii) Zero-sequence harmonic components are not considered (these tend to be low in the transmission system due to the many transformer delta tertiaries and the star-delta winding configuration of most HV/MV transformers.

[3] ABB's Harmonic Analysis Program

3.1.1.2 The transmission lines and transformers inductance and capacitance can be assumed to be constant and independent of the frequency, while the resistance will increase with frequency due to skin effect. Hence this phenomenon was considered in the following models [1]:

1. AC lines, long-line equivalent π with frequency dependent losses
2. Transformers with frequency dependent losses

3.1.1.3 The models adopted were based on the Cigré recommended models [4] and other methods were tested.

3.1.1.4 All the simulations are calculated from the same network and case file.

3.1.2 Background AC Network for impedance calculation

This AC network was modeled on HAP program, different system element models such as transformers, transmission lines and loads were simulated to compare and evaluate their behavior at harmonic frequencies. The harmonic impedance results for different system element models discussed in section 3.1.3 to 3.1.5 below were calculated at Poseidon 275kV busbar (figure 3.1 below).

The network configuration used to demonstrate the frequency response of transformer models was different to that used for transmission lines and load models; hence the harmonic impedance plots are not comparable.

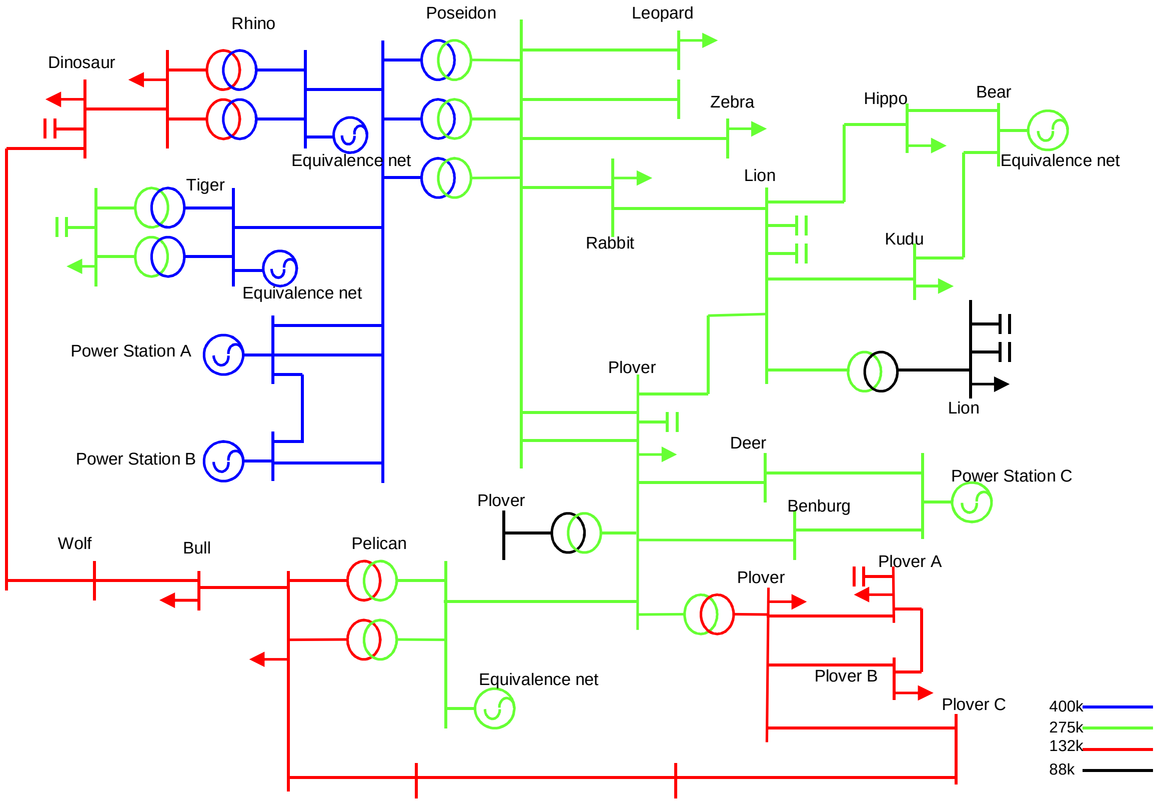


Figure 3.1 – AC network considered for the simulation of harmonic impedance discussed in this section

3.1.3 Generators

The generators were modeled as resistance in series with inductance, deduced from the sub-transient short circuit current (magnitude and phase) of the network under nominal voltage [12]. No damping at high frequencies was assumed for the generators.

3.1.4 Transformers

Two transformer models with frequency dependent resistance were evaluated; that is Cigré and SIMPOW transformer models. .

First model, SIMPOW[4] model with the frequency dependent resistance given by [21]:

$$R(f) = R_1 \cdot \left[\frac{f}{f_1} \right]^{rexp}, \qquad (3.1)$$

Where R_1 is the transformer resistance at the system nominal fundamental frequency f_1,

[4] SIMPOW is the power system simulation software used by ABB.

$r\exp$ is assumed to be 1.1, based on the measurements taken for the time constant $\lambda = L/R$ versus frequency between 50Hz to 2000Hz for different voltage levels. In order not to introduce too much damping at resonance frequencies the value $r\exp = 1.1$ can be used as a general typical figure for the resistance of power transformers, if no better information is available [11].
Alternatively the following equation can be applied to estimate the damping factor [21]

$$r\exp = \frac{\log\left(\frac{R(f)}{R_1}\right)}{\log\left(\frac{f}{f_1}\right)} \qquad (3.2)$$

Second model, Cigré Model with the following equations [4]:

$$R_1 = \frac{h \cdot X_1}{\tan\psi_1} \qquad (3.3)$$

where:

R_1 is the transformer resistance at the system nominal fundamental frequency f_1

X_1 is the leakage reactance of the transformer at fundamental frequency.

$$\tan\psi_1 = \exp\left[0.693 + 0.796 \cdot \ln S_n - 0.0421 \cdot (\ln S_n)^2\right] \qquad (3.4)$$

S_n, is the rated power of the transformer.

The behavior of Cigré and SIMPOW transformer models at harmonic frequencies was simulated on HAP program for the network presented in figure 3.1. These transformer models were evaluated under similar network conditions. At low frequencies they are comparable, however at high frequencies Cigré model slightly increases exponentially whilst the SIMPOW model increases linearly. The linear increase of SIMPOW model can be expected due to the damping introduced by $r\exp = 1.1$ [11]. The SIMPOW model is slightly more conservative at low harmonic frequencies compared with the Cigré model. The application of these models mostly depends on the user and the sensitivity of the study.
In addition to the two models discussed above, a transformer model with no frequency dependence was also evaluated and compared against the Cigré and SIMPOW models. Figure 3.2 below is the harmonic impedance results for the three transformer models.

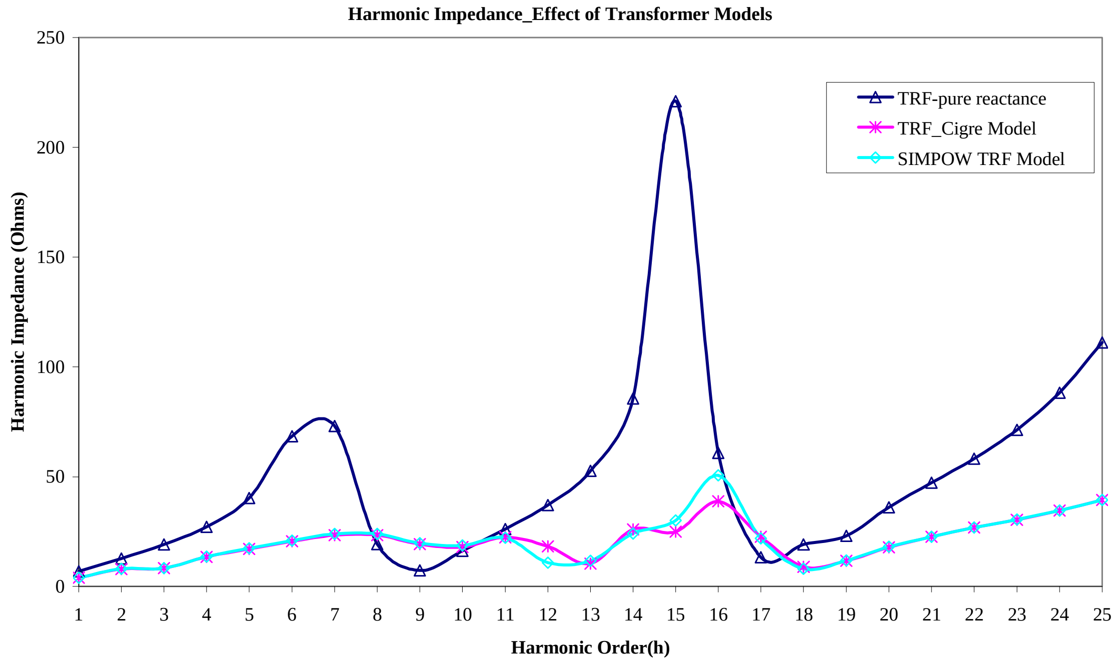


Figure 3.2 – Comparison of frequency characteristics of transformer models

From the impedance plot it is evident that if the transformers are modeled with their reactance only, the results can be too pessimistic; figure 3.2 compares the transformer models with damping and without damping. In practical terms the resistance of the transformer should not be ignored for harmonic impedance studies, since it increases with frequency due to skin effect.

3.1.5 Transmission lines

AC transmission lines were represented by equivalent π models with frequency dependent series resistance. The frequency dependent resistance given in equation (3.1) was again applied.

Where, rexp was assumed to be 0.55, the calculation of this damping factor is the same as that of the SIMPOW model for transformers. With reference to the equivalent system models in Figure 3.1, the harmonic impedance was calculated at Poseidon 275kV bus, Figure 3.3 is the result of the simulation which compares different line damping factors i.e. 0.75 and 0.55. At lower frequencies (up to the 12^{th} harmonic) there is no noticeable change between the two factors due to the fact that the short circuit impedance of the transmission line is mainly inductive at low frequencies up to half wave length [1], therefore less damping effect at lower frequencies regardless of the damping factor.

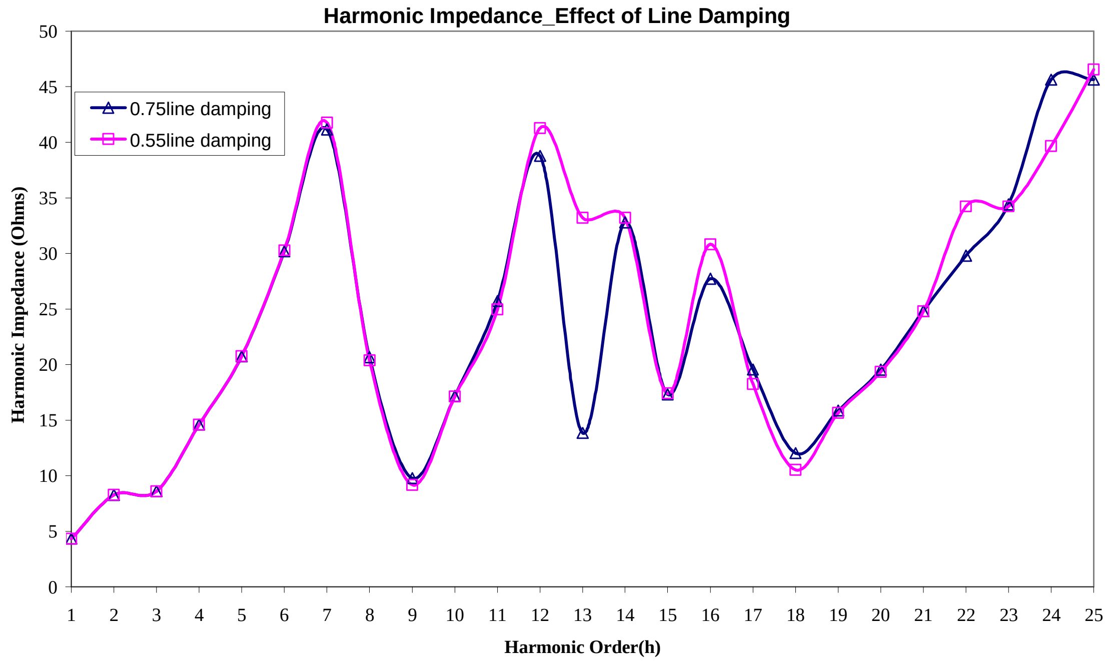


Figure 3.3 – Effect of line damping on system impedance and at harmonic frequencies

3.1.6 Loads

The difference in the calculated impedance at the resonance frequency can vary significantly depending on the load model. This is demonstrated by comparing the parallel load model with the series load model. Figure 3.4 below is an example of the Cigré parallel load model, where R, X_S & X_P are derived from the active and reactive power flow parameters.

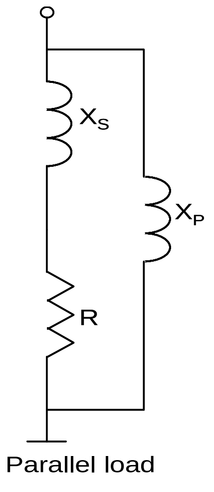


Figure 3.4 – Cigré Parallel Load Models [4]

The impact of load modeling on the resulting harmonic impedances is particularly relevant at resonant frequencies. For this particular network, the study reveals that the network impedance is reduced at low frequencies where parallel load model is used. This impedance plot is obtained from Poseidon 275kV bus deduced from the equivalent system model in Figure 3.1. The parallel load model provides a reasonable damping over a wide range of frequencies, it can be used if there is knowledge about the types of loads in the system however; it is acceptable from a (conservative) design perspective not to assume any level of damping from the system by using series load models.

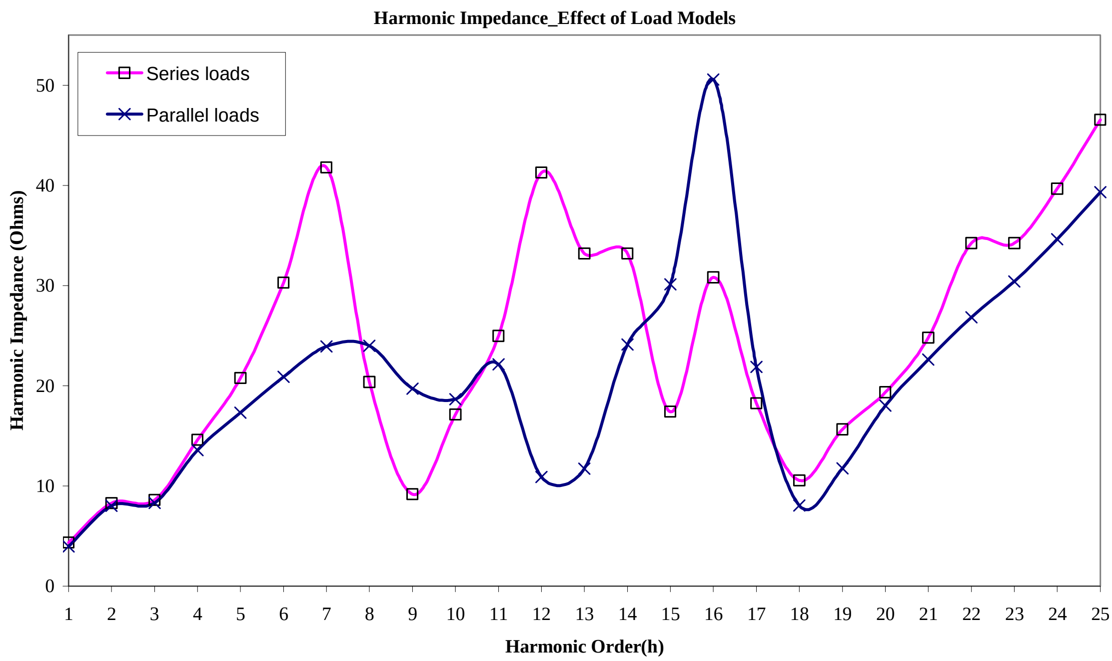


Figure 3.5 – Series and Parallel Load Models with same line damping and transformer model (Cigré Model)

CHAPTER 4

PROPOSED DESIGN GUIDELINE

A developed generic methodology for ensuring that the design of transmission shunt compensation is optimally robust in terms of harmonic resonances is demonstrated in this chapter with advanced guidelines that can be used for the integration of shunt compensators in the transmission networks. It is essential that a design of a shunt capacitor bank reflects its life expectancy; this can be achieved by ensuring that all likely operating scenarios are considered, future network developments. However, deriving the network impedance over a long planning horizon is always limited by the availability of reliable network data.

A procedure for network modeling, system impedance assessment and integration of shunt capacitor banks is proposed and discussed in this chapter. It must be noted that a too narrow harmonic impedance assessment may result in a weak shunt capacitor or filter bank design such that operational restrictions on the operation of the bank may be imposed. On the other hand too optimistic design may not be economically justifiable.The procedure is summarized in the chart below; details of the processes are discussed in the following sections from 4.1 to 4.3.

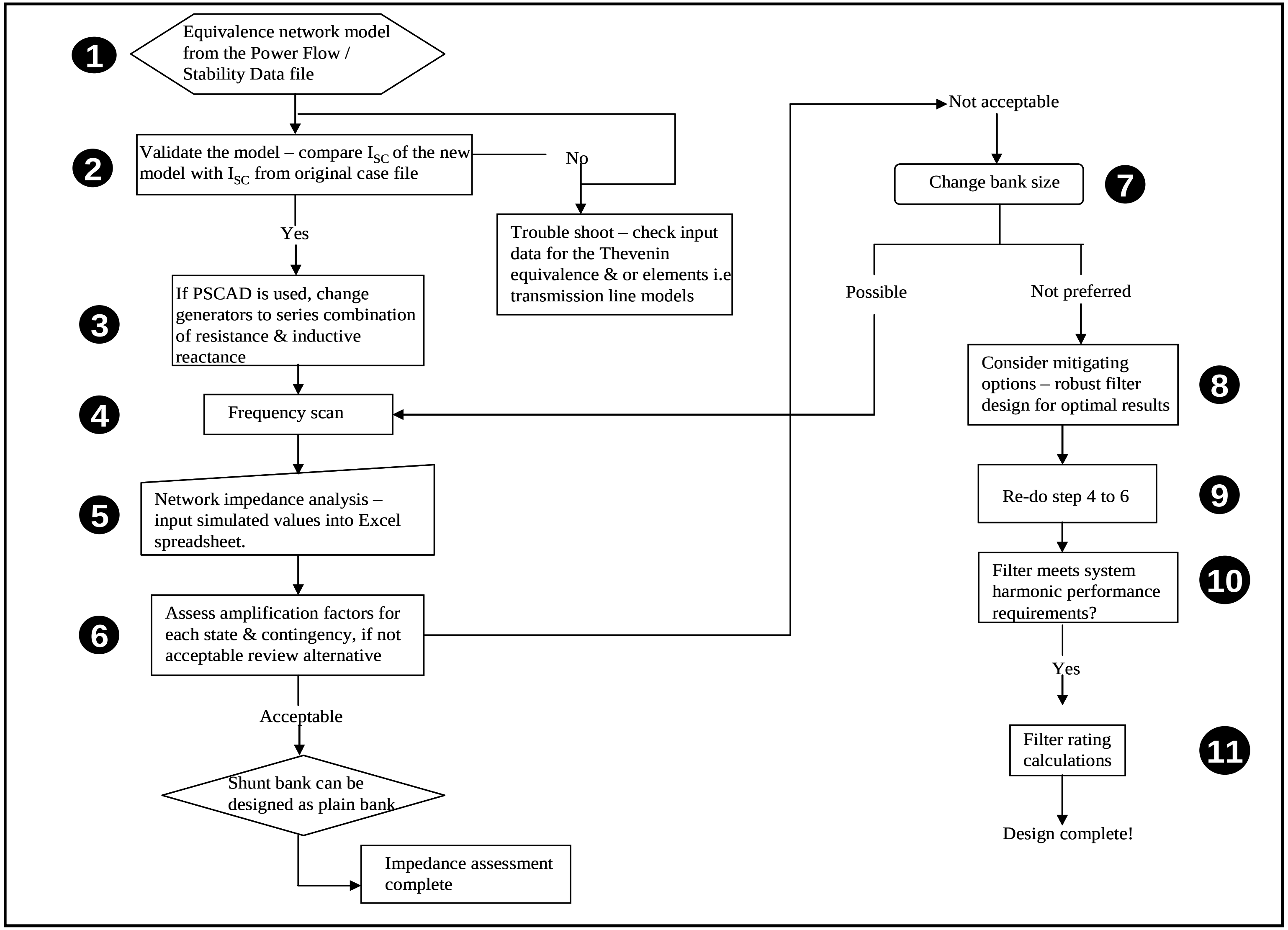


Chart 4.1: Guideline for network impedance assessment and integration of shunt capacitor banks in transmission systems

4.1 Network Modeling and System Impedance Calculation

The following design methodology is proposed:

Step 1: Developing the harmonic network model

(i) The sizing of a capacitor bank is determined during the planning phase.

(ii) Model the existing and future transmission networks. The design of a shunt capacitor bank must meet the existing and future system requirements in terms of harmonic resonances. With changes in system capacity i.e. increased system capacity, system resonances change to higher frequencies, harmonic voltage distortions are reduced and the magnitude of system impedance at resonance frequencies is reduced. If this phenomenon is not studied during the design phase, there may be operational constrains imposed on the shunt bank and the system particularly in the case where the system short-circuit capacity is reduced.

(iii) Generators, lines, transformers and series or shunt devices must be approximated with equivalent impedance at the fundamental frequency. The initial conditions are always based on fundamental frequency as the data is always available. Some system elements such as generators, loads, capacitors have constant impedance and for frequency dependent system elements the response at harmonic frequencies is largely determined by the type of model used. In the case of transmission lines distributed frequency - dependent transmission line models shall be used [12].

(iv) Equivalent network must be developed from conventional positive sequence power flow and stability data. In the case of steady-state harmonic analysis, the modeling of the positive sequence network is generally considered suitable [3]. For the following reasons:

- Zero sequence components are generally limited by transformer delta windings (e.g. tertiary windings).
- The network positive and negative sequence components are similar.

(v) The transmission equivalent network must be modeled in detailed level due to the presence of loads, transformers, long transmission lines and capacitor banks. Representing the transmission network by a short-circuit equivalent may not reflect the real system response characteristics at harmonic frequencies. The system harmonic impedance varies with different network configuration, load and generation patterns hence some of the resonance points may be omitted during calculations if short-circuit equivalent is used [22].

(vi) Loads and capacitors must be modeled as constant impedance at fundamental frequency.

(vii) For conservative approach loads can be modeled as series loads rather than parallel loads unless details of load types are available. For transmission network studies, loads are usually lumped distribution network derived from active and reactive power flows therefore; details of load types are not considered [12].

Step 2: Verification of model

(i) Once the equivalent network has been constructed, the accuracy of the model must be verified. Two methods maybe used to validate the accuracy of the model; the fault level and the load flow comparison. If PSCAD is used, fault levels on PSCAD model must be compared with the fault level of the source network i.e. PSS/E or PowerFactory. If PowerFactory is used, the fault levels of the equivalent network can be compared with the fault levels of the original network. Using the load flow to verify the results – after running the equivalent model in steady state; the busbar voltage and phase angle, the active and reactive power through the transmission lines can be compared with the steady state results obtained from PSS/E or PowerFactory.

Step 3: Representation of generation and system loading

(i) If PSCAD is used, change the generators model to impedance representation such that the resistance is in series with inductance, for the purpose of calculating the network harmonic impedance [12].

(ii) Consider a minimum loading of 75% in the transmission and distribution network. In most cases system operators tend to keep the shunt banks in the network during low load conditions for system stability reasons and to minimize losses.

Step 4: Execution of harmonic simulations

(i) Perform frequency scans in order to derive the harmonic impedance of a network by injecting one per unit (1A) sinusoidal current at the busbar of study. Also investigate the effect of installing a capacitor bank on the impedance of the nearest substations. This 1A current is injected at a range of frequencies.

(ii) Identify all relevant N-1 contingencies and System States (capacitor banks and generation patterns) in the immediate and future transmission network. Any of these conditions and system contingencies will lead to system impedance change; if a plain or filter capacitor bank is designed its operation should not be constrained by these changes. A frequency scan must again be performed for N-1 contingencies.

(iii) System states i.e. reactive devices and system loading status. For example where more than one shunt capacitor bank is connected close or in the surrounding point of study, these may interact with each other thereby creating undesirable resonances.

Step 5: Assessing the harmonic impedances and associated harmonic amplification

(i) When all network contingencies have been performed, check for adverse interactions of the capacitor bank with the system impedance. A developed methodology in Excel Spreadsheet can be used to evaluate amplifications as a result of a capacitor bank installation.

4.2 System Impedance Assessment and Integration of Shunt Compensators

When installing shunt reactive compensation on the supply network, a question that is often raised is how to limit its contribution to increased harmonic voltage distortions; typically resulting from amplification of existing levels due to resonance modes close to harmonic frequencies. Ideally no amplification is allowed – however this has significant cost impacts due to the technologies employed (i.e. C-type banks).

The contribution of shunt banks to harmonic voltage distortions is different from other loads in a system in that it is not summed with the contribution of other loads as it is not a current source. Instead, its contribution is defined in terms of its amplification or attenuation of the background and injected harmonics. The level of amplification or attenuation will vary for each harmonic. For the different network conditions, the background and local amplification factors are not likely to be the same. A practical approach would be to define a maximum amplification factor allowed for each harmonic [3].

In the case of local emissions where the shunt bank is connected, the performance of the shunt bank is verified against the amplification factor, this is a function of the simulated system impedance at the PCC. All that is required is the simulated results for the existing (old) system impedance envelope[5], and those for the new compensated system impedance envelope [3]. The voltage amplification factor at PCC can be calculated as follows:

$$K_e(h) = \frac{\left|Z_{pcc}(h)\right|_{new}}{\left|Z_{pcc}(h)\right|_{old}} \qquad (4.1)$$

where:

$K_e(h)$ is the voltage amplification factor at PCC.

$Z_{pcc}(h)$ is the simulated system harmonic impedance at the PCC. New is the compensated network, old is uncompensated network.

In some cases, the actual (old) system impedance envelope may not be as appropriate as a reference. Three such cases are [3]:

(i) For some harmonics where the existing system provides a very low system impedance. The introduction of the shunt bank may then give rise to a substantial increase in the impedance, although the new system harmonic impedance may still be low.

(ii) Where the existing system itself may have very high impedances close to parallel resonance conditions. The introduction of the shunt compensation may amplify this further.

(iii) Where the installation of shunt compensation accompanies major system changes or expansions of system.

For any of the above reasons a more “objective” reference point is adopted in the development of Excel spreadsheet. For transmission systems where the X/R ratio is relatively low, a “reference harmonic impedance” based on the system fault level is applied, as follows:

$$K_e(h) = \frac{\left|Z_{pcc}(h)\right|_{new}}{\left(\dfrac{V_{pcc}^2}{S_{FL}}\right).h} \qquad (4.2)$$

where:

$K_e(h)$ is the voltage amplification factor for local load emissions.

$Z_{pcc}(h)$ is the simulated system impedance at the PCC with shunt compensation (ohms).

---

[5] The simulated harmonic impedance magnitude is equivalent to the magnitude of the harmonic voltage at the PCC for a 1A harmonic current injection at the PCC. The impedance envelope represents various system conditions (system states, contingencies, and future evolutions).

S_{FL} is the system fault level (MVA).

V_{pcc} is the line voltage at the PCC (kV).

Having evaluated the amplification factors above, a methodology in Excel tool was developed; the maximum allowable amplification factors are recommended and are documented in Table 4.1 below. This Excel tool was developed to support the simulation results and the methodology is based on a step-by-step application of the "latest" existing techniques for harmonic simulation and shunt compensation design such as IEEE Std 519-1992 [13].

NRS 048-4 states that "amplification of the system impedance (due to shunt bank installation) in excess of three times the linear impedance may be considered excessive" [23]. The use of this spreadsheet to assess the network harmonic impedance, aims to give a practical approach and an indication of when to de-tune a shunt bank or adequate to install a plain shunt capacitor where resonant conditions occur, also with the consideration of background harmonics.

Table 4.1 – Recommended maximum amplification factors.

	System State Analysis	
Factor K	**System Healthy**	**System Contingencies**
K ≤1.5	Good	Good
1.5< K ≤ 2	Acceptable [OK]	Good
2 < K ≤ 3	Conditionally acceptable (Note1,2) [POOR]	Acceptable
K > 3	Unacceptable [BAD]	Unacceptable
NOTE 1: Not acceptable in the case of harmonics other than 3, 5, 7, 11, 13 etc. NOTE 2: May require specific constraints to be placed on operation of the shunt bank or filter.		

The definition of an "acceptable" amplification factor will depend on the system under study (in particular the level of existing harmonic emissions and to what degree these have been contracted). In the case of significant system changes (e.g. fault level changes in excess of 10%, and network expansions), the recommended maximum levels are provided in the Table 4.1.

An advantage of applying amplification factors as a criterion is that these can be evaluated by switching the filter or shunt capacitor in or out.

The application of this ranking criterion is demonstrated through case studies in Chapter 6.

4.2.1 Application Guideline for Excel Tool

When all the steps in section 4.1 have been completed, the following steps must be followed:

Step 6: Assess amplification factors

(i) Determine linear harmonic impedance using system fault level according to equation (4.2) – input into spreadsheet. A template for the Excel Spreadsheet is given in Table 4.2 below.

(ii) Review amplification factors (design criteria) – input into spreadsheet.

(iii) Input impedance values at the busbar of study, simulated according to section 4.1 guideline.

(iv) Assess amplification factors for each state and contingency.

(v) Highlight concerns: System healthy amplification factors (i.e. $K \leq 2$) and system contingency amplification factors (i.e. $K \leq 3$).

(vi) If amplification is within the limits, a plain bank can be designed and impedance assessment can be concluded. But if the amplification is not acceptable that is $K>3$, review alternative capacitor size.

Step 7: Mitigation options for parallel resonances

(i) Sometimes it may not be acceptable to reduce or increase the capacitor size due to system requirements and step voltage change when the shunt capacitor in energized. For this reason and other, a de-tuned filter bank design may be considered.

(ii) Determine the tuning frequency and reactor impedance necessary to achieve the desired tuning. The reactor rating shall be based on fundamental frequency current plus harmonic current.

Step 8 (repeat of step 4 to 6)

(i) Frequency scans must again be performed to calculate the network impedance with a de-tuned filter bank or alternative capacitor size.

(ii) Check the capacitor voltages and currents to ensure they are within acceptable limits

(iii) N-1 contingencies must be considered to ensure the filter design mitigates resonance conditions under all contingencies which may be deemed critical for a tuned filter bank to be in-service during such, or most likely to occur.

Table 4.2: Network Impedance Analysis Tool

filter banks in nearby substations should be considered

system impedance based on system MVA

Z_{50}(ohms)	Good	OK	Poor	Bad
5.08	1.5	2	3	>

on this row is the system linear impedance

Option	**Capacitors** 72 Mvar	**Filters** 72 Mvar	**Contingencies**	**Harmonic** **2**	**3**	**5**	**7**	**9**	**11**	**13**	**Ranking** **2**	**3**	**5**	**7**	**9**	**11**	**13**
											10.16	15.24	25.4	35.56	45.72	55.88	66.04
1	2	0	Healthy								Good	Good	Good	Good	Good	Good	Good
State 1 75% Load			Trf Out								Good	Good	Good	Good	Good	Good	Good
			Jupiter-Mercury								Good	Good	Good	Good	Good	Good	Good
			Jupiter-Merensky								Good	Good	Good	Good	Good	Good	Good
			Jupiter-Omega								Good	Good	Good	Good	Good	Good	Good
			Mercury-Alpha								Good	Good	Good	Good	Good	Good	Good
			2xMercury-Alpha								Good	Good	Good	Good	Good	Good	Good

transmission line contingencies

Input simulated system Impedance values for defined harmonic orders

the definition of good or bad will be dtermined by the impedance values

input values

output results

CHAPTER 5

APPLICATION STUDIES

The methodology discussed in Chapter 4 is demonstrated below by considering three case studies. The capacitor bank sizes for these case studies were determined during the planning phase. Load flow studies to demonstrate and justify the rating of a shunt bank size are therefore not part of this study. In Eskom standard shunt capacitor bank sizes are applied at different voltage levels of the transmission and distribution system[6], for example, on a 132kV busbar the standard bank sizes are either 36 MVAr or 72MVAr and for the 275kV networks the standard bank size are 150MVAr or 100MVAr. Switching a 150MVAr shunt bank on a 132kV busbar can cause high switching surges on a busbar and thus to avoid this condition, a 2x72MVAr shunt banks are usually installed where required. The other advantage of installing a 2x72MVAr shunt bank rather than 1x150MVAr shunt bank is the flexibility to switch out one bank especially during light loads as well as increased maintenance opportunities.

The case studies were undertaken in order to assess the ac network impedance, evaluate the effect of harmonics on the design of ac transmission network's shunt capacitor banks and to demonstrate the application and practicability of the developed methodology to the existing Eskom Transmission system. The purpose of these case studies is to illustrate that the frequency response of any power system depends on various factors such as system capacity (i.e. high and low fault level systems), amount of shunt compensation, harmonic polluted environments and combination of these factors.
The simulated case studies are based on different networks, conditions and shunt bank topologies.

The ac system can be considered strong from two aspects, firstly the system impedance may be low, secondly the system voltage (or mechanical inertia) may be high [12]. In addition to these aspects, a stiff or high fault level system is generally categorized by other two factors, firstly if the existing equipment fault current limits are exceeded; that particular system has become strong. Secondly, fault levels of between 30 and 50kA constitute a strong network. Such networks are less prone to dips and more stable where voltage quality is concerned.

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[6] This does not negate the need for load flow studies.

A low fault level or short circuit capacity means the network is weak. The substation considered herein for a low short circuit capacity is furthest from generation in terms of distance therefore suffers from voltage depression.

The network impedance for the case studies discussed in this section is analyzed and depicted in two methods. Firstly the results are shown in impedance plots. Secondly, the Table 4.2 is further used to analyze the network impedance results.

The first study case looks at the integration of 2x150MVAr shunt banks on high fault level system with 2x150MVAr existing shunt capacitor banks on 275kV bus. The simulation results are validated with site measurement of voltage distortions and THD taken a year later after the installation of the additional capacitor banks.

The second study case looks at the integration of 2x72MVAr shunt capacitor banks on a low fault level system, resulting in system resonance at characteristic harmonic. A filter design option is evaluated and recommendations are made. When the harmonic integration study of 132kV, 2x72MVAr shunt banks was conducted, the substation was not in existence hence there were no records of the harmonic voltages or currents. The network impedance assessment was crucial and the only decisive case for the choice of capacitor banks topology.

Third study case evaluates harmonic impedances through simulations where shunt capacitor banks resonate with system impedance at characteristic harmonics after years of operation, resulting in high THD levels above 4%. Venus substation has 2x36MVAr shunt capacitor banks on 132kV busbar installed in the late 1980's. At the time of installation; there were no voltage distortion problems until 2001. The sudden change in system response is investigated and simulation results are compared with site measurements.

5.1 Case A: High fault level system with 4x150MVAr shunt capacitor banks

The shunt capacitor banks discussed in this case study were installed to support the reactive power deficiency at Pluto substation. This study evaluates the impact on the network impedance when 2x150 MVAr are added in the system with existing 2x150MVAr banks on the 275kV busbar. At the time of study the short circuit capacity of this substation was 10958.8MVA (at 275kV) and the corresponding X/R ratio of 20.7.

5.1.1 System Description

Pluto substation is constructed with two voltage levels 400/275 kV. This substation is integrated with more than one power source with high fault levels and has no direct supply to customer loads except supplying other transmission substations. The substation is equipped with 1x700MVA and 3x800MVA, 400/275kV coupling transformers and 2x150MVAr existing capacitor banks. Due to a strong integration of this substation with parallel networks, the network impedance is generally expected to be low and the impedance of the transformers plays a bigger role at low frequencies by providing damping.

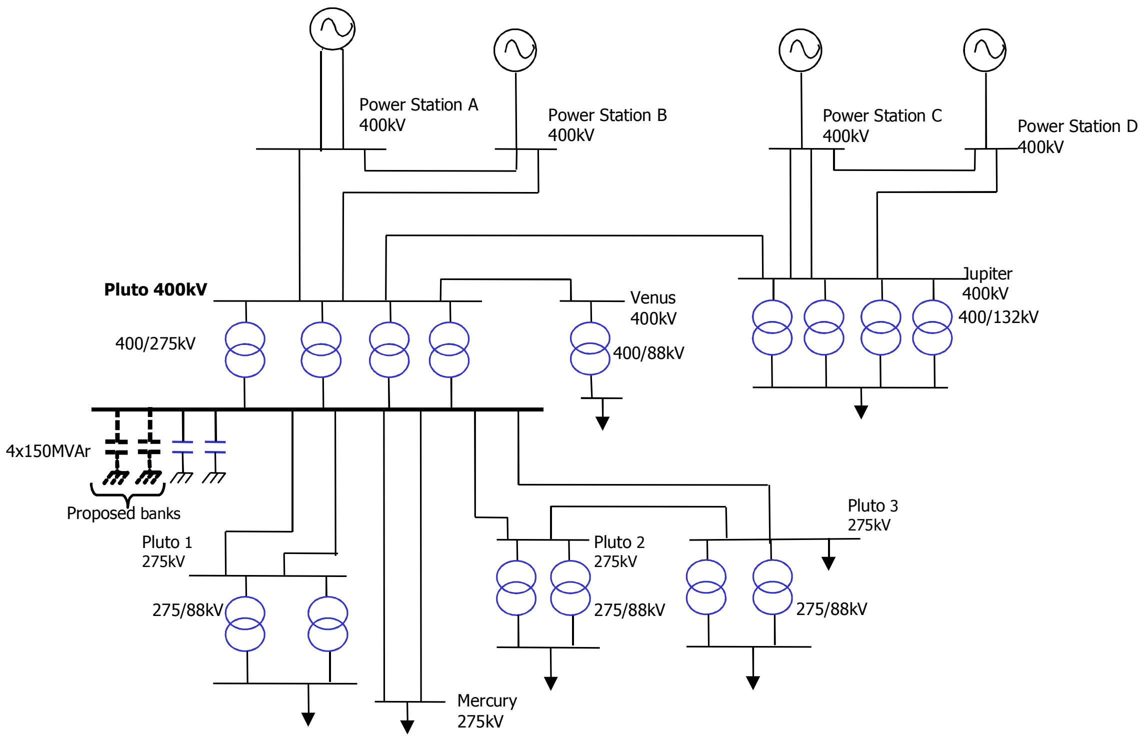

Figure 5.1 – Network diagram for Pluto 400kV substation and surround area

5.1.2 Network Impedance Analysis

Figure 5.2 below illustrates the simulation results of this case study presented in the form of harmonic impedance plots. Different shunt bank states were evaluated, the network is naturally tuned around the 13th harmonic resulting in a parallel resonance at the 9th harmonic (no bank plot). With the installation of shunt capacitor banks, the 9th harmonic parallel resonance shifts to low order harmonics depending on the number of shunt banks in-service[7].

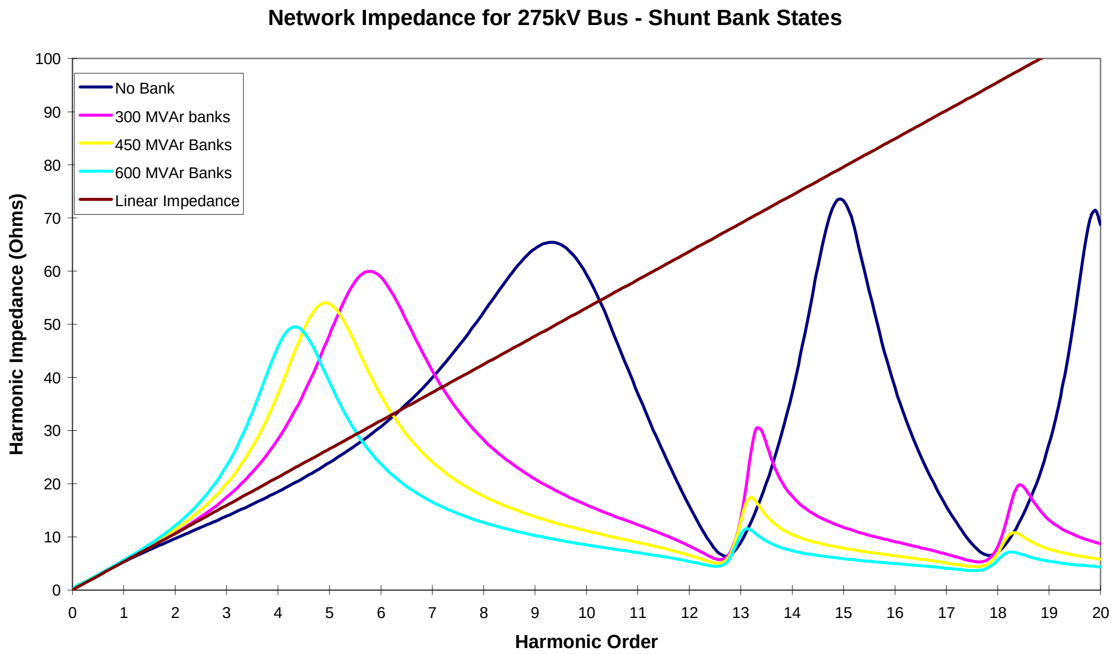

Figure 5.2 – High fault level with 2x300 MVAr shunt capacitor banks

Assuming inductive system impedance, the resonant frequency will occur at frequency f_P as follows [22]:

$$f_P = f \cdot \sqrt{\frac{S_S}{S_C}} \qquad (5.1)$$

Where S_S, is the system fault level and S_C is the size of the capacitor bank. For 600MVAr shunt capacitor banks, the resonant frequency f_P is 215Hz. This resonance frequency corresponds with the simulated results on figure 5.2, for the system state with 600MVAr shunt capacitor banks in-service.

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[7] A parallel resonance is created between the system impedance and the shunt capacitor [26].

Assuming the system fault level remains the same at Pluto substation, the more shunt capacitor banks are installed, the resonance frequency shifts to low frequencies. This is validated in figure 5.2 above.

5.1.3 Validation of simulation results with voltage distortion measurements

The voltage distortion results presented below were measured a year later after the installation of the additional 2x150MVAr shunt banks discussed above.

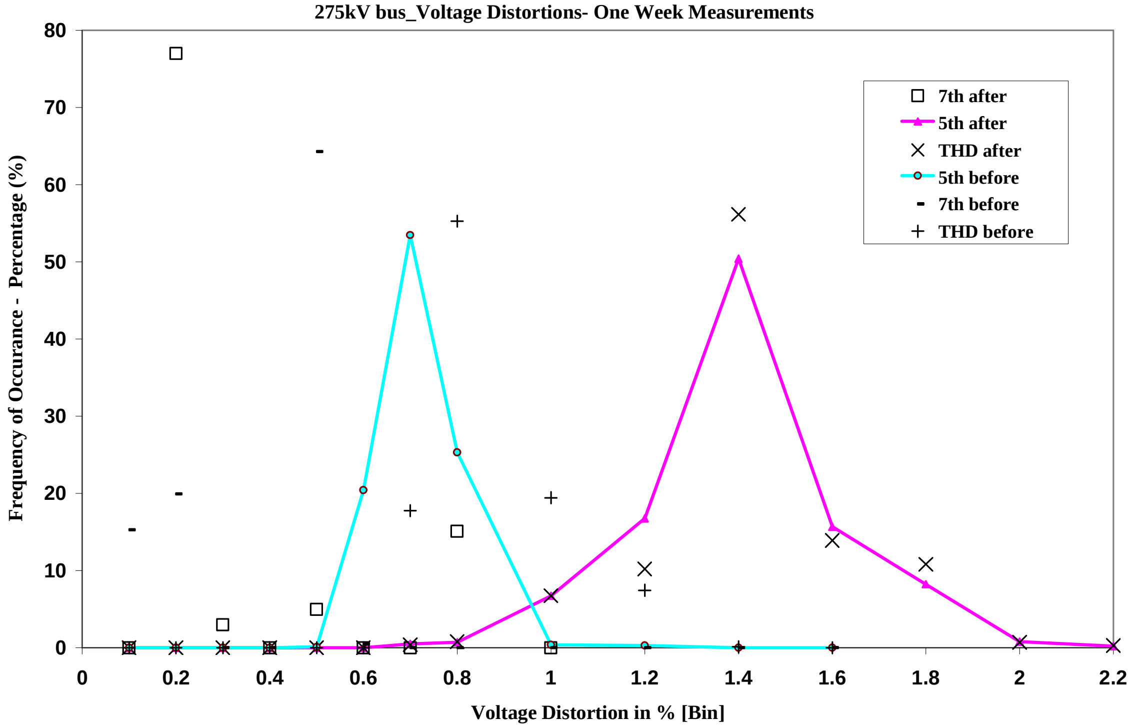

Figure 5.3 – Harmonic voltage distortion before and after 2x150MVAr shunt banks installation

The data presented in these plots was retrieved from Eskom's quality of supply data base; the harmonic voltages are measured through a Capacitive Voltage Transformer which is not accurate at frequencies above 50Hz. The measurement error can be in the range of 0.2 to 1.2p.u. of correct values for some harmonic orders. However if calibration tests have been carried out, most errors may be corrected [24]. The results are therefore not 100% accurate but acceptable for the purpose of this study. These CVT are also used for power quality measurements, and thus calibrated yearly. This plot validates the simulation results of system response presented in figure 5.2, for example the 5th harmonic voltage distortion is increased by at least more than 50% from the value of 0.7 to 1.4% when 2x150 MVAr shunt capacitor banks are added on the system.

5.2 Case B: Shunt compensation at low fault level.

This case study also assesses the network impedance of a system with low fault level, 340MVA at 132kV bus, where 2x72MVAr shunt capacitor banks are installed on the network and resulting in harmonic resonances. The shunt capacitors were required to support the MVArs at Omega substation. The approach adopted in this study was that for various contingencies, the harmonic impedance at each of the characteristic harmonics should not be excessive (should not be amplified by more than a factor of three (3) according to NRS048-2) and the amplification with the shunt banks in-service was considered.

5.2.1 System Description

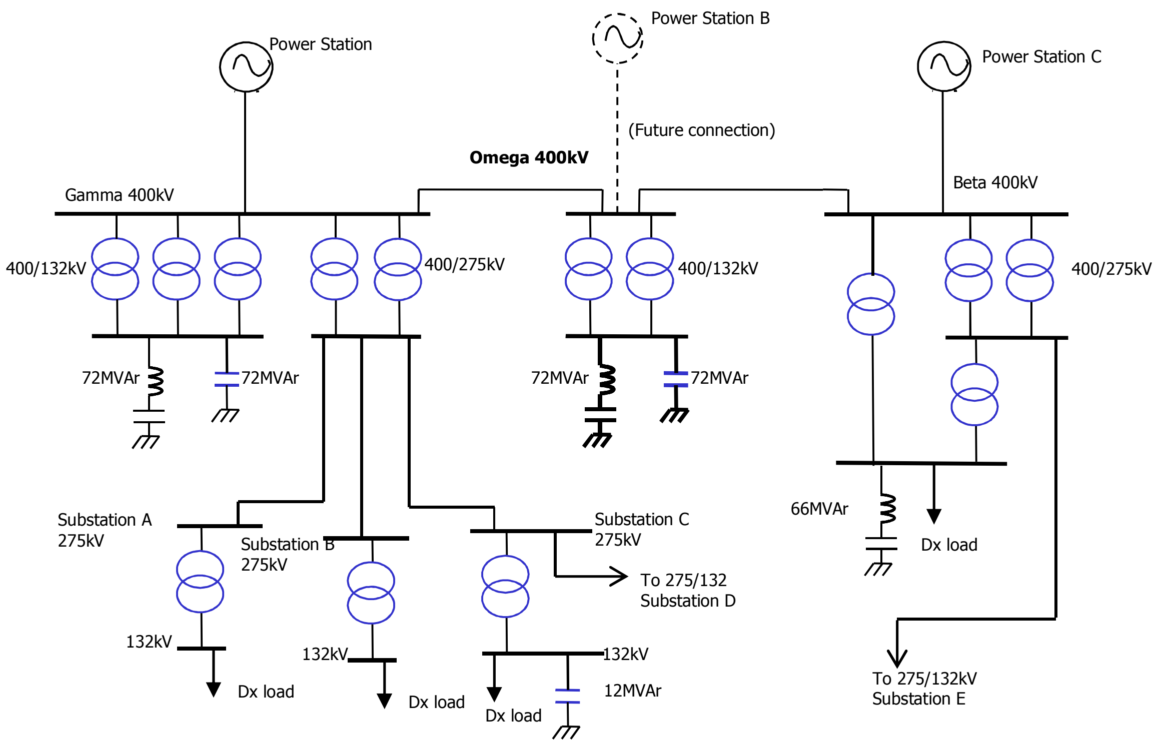

Figure 5.4 – Network diagram for Omega substation

Omega substation was looped from the existing Gamma – Beta 400kV line. The construction of a new 400 kV, 224km line from Power Station B to the new Omega Substation was planned for future. The substation is located 40 kilometers north of Beta, as close as possible to one of the biggest customers. The substation is equipped with two 500MVA, 400/132kV coupling transformers.

5.2.2 Network Impedance Analysis

The initial proposal was to install 2x100 MVAr shunt capacitor banks on 132 kV bus in order to support the voltage at this substation. There were two limitations with this option firstly the voltage switching step of each shunt bank was more than 3% limit, secondly the presence of 5^{th} harmonic resonance (shown in figure 5.5 below) which would have required expensive and much more robust single de-tuned filter to overcome lower order harmonic resonances such as 3^{rd} and 2^{nd} harmonics. The introduction of 2x72 MVAr shunt capacitor banks also introduced a parallel resonance around 250Hz and 600Hz which is not desirable from the quality of supply perspective.

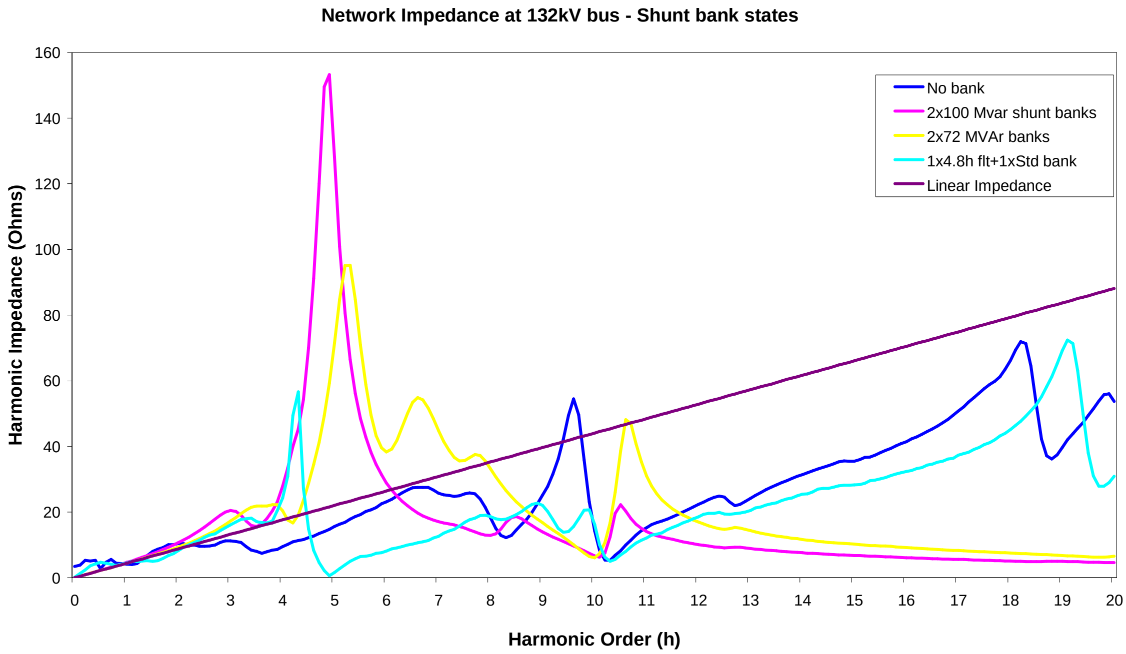

Figure 5.5 – Impedance plot for shunt compensation at low fault level

This plot depicts system harmonic impedance with 2x100MVAr, 2x72MVAr capacitor banks and a combination of 72MVAr capacitor bank and 72MVAr de-tuned filter bank. The application of 1x72MVAr shunt bank did not introduce any parallel resonances at characteristic harmonics when the de-tuned filter bank is out of service. Hence a decision to de-tune only one bank was technically and economically acceptable.

The network impedance was further assessed by applying the spreadsheet method in order to determine the impedance amplification with the bank connected in the system.

Table 5.1 – Ranking of the harmonic impedance amplification as per Table 4.1

Zf(ohms)	Good	OK	Poor	Bad
5.08	1.5	2	3	>

Option	Capacitor Filters 72 Mvar	72 Mvar	Contingencies	Harmonic 2	3	5	7	9	11	13	Ranking 2	3	5	7	9	11	13
											10.16	16.24	25.4	35.56	45.72	55.88	66.04
1	2	0	Healthy	9.37	17.26	71.47	45.19	16.79	31.29	14.34	Good	Good	Poor	Good	Good	Good	Good
State 1 75% Load			Trf Out	14.81	28.75	128.74	33.52	16.49	15.62	11.43	Good	OK	Bad	Good	Good	Good	Good
			Omega-Gamma	11.31	21.79	134.64	24.46	5.71	28.66	14.32	Good	Good	Bad	Good	Good	Good	Good
			Omega-Beta	11.70	22.61	109.88	38.87	17.83	14.50	14.26	Good	Good	Bad	Good	Good	Good	Good
			Omega-P StationB	11.59	21.64	91.40	46.60	20.73	10.17	12.48	Good	Good	Bad	Good	Good	Good	Good
			Gamma-P StationA	9.59	17.58	68.25	37.87	23.57	31.60	14.31	Good	Good	Poor	Good	Good	Good	Good
2	1	1	Healthy	9.61	19.57	3.78	26.31	83.94	40.56	126.63	Good	Good	Good	Good	OK	Good	OK
State 1 75% Load			Trf Out	15.12	35.05	4.07	38.39	86.92	115.00	39.36	Good	Poor	Good	Good	OK	Poor	Good
			Omega-Gamma	11.72	25.48	3.95	75.83	6.87	47.30	127.39	Good	OK	Good	Poor	Good	Good	OK
			Omega-Beta	12.02	26.33	3.90	27.04	148.77	9.08	124.02	Good	OK	Good	Good	Bad	Good	OK
			Omega-P StationB	11.87	24.71	3.78	26.05	183.31	14.10	54.18	Good	OK	Good	Good	Bad	Good	Good
			Gamma-P StationA	9.89	19.92	3.77	30.42	48.02	39.93	126.60	Good	Good	Good	Good	Good	Good	OK

Two options are presented in Table 6.1, firstly 2x72MVAr capacitor banks are considered. Second option is the consideration of 1x72MVAr capacitor bank and 1x72MVAr de-tuned filter bank.

Looking at Option1, under normal (Healthy) operating conditions with 2x72MVAR shunt banks the amplification of the 5th harmonic impedance indicates a poor (2<k<3) and bad conditions for number of contingencies which are most likely to occur such as transformer outage. The effect is that if both capacitor banks are in service, high voltage distortions can be expected on this busbar even for small harmonic current injections and the capacitor banks may not be operable.

Based on this analysis a decision was taken to de-tune one of the capacitor banks at 240Hz, this option proved to be adequate for this application. The harmonic impedance results are presented in Option2 and the impedance plot is shown in figure 5.5 above. The other factors that influenced this decision were the history of the 5^{th} harmonic resonances at the nearby substations and the mining activities in the vicinity.

With de-tuning on of the capacitor banks, the 5th harmonic resonance is damped however, 3rd harmonic impedance is increased under certain system contingencies, as a result of parallel frequency caused by the filter below its inherent tuning frequency. The amplification of the 9th harmonic is not too much of a concern due to these reasons: the restoration time for lines is usually quick less than five days. The 9^{th} harmonic currents are only produced by the 6-pulse generators under unbalanced conditions.

5.3 Case C: Shunt compensation at harmonic polluted environment

One of the most common reasons why harmonic limits are exceeded on transmission and sub-transmission systems are changes in the parallel resonance frequencies associated with a given shunt capacitor. Such changes typically arise when:

(i) New lines or transformers are installed on the network (increasing the fault level and hence increasing the resonance frequency).

(ii) The system is re-configured and a normally-open point is created (decreasing the fault level and hence decreasing the resonance frequency).

(iii) Loading is moved from one system to another (reducing the natural damping at frequencies close to a parallel resonance frequency).

A good example of the above scenario was the exceedence of the 5^{th} harmonic voltage distortion thus Total Harmonic Distortion (THD). The 2x36 MVAr, 132kV shunt capacitor banks at Atlas were installed in the late 1980’s. No harmonic problems were experienced in the past due to presence of these shunt capacitor banks but around year 2001 5^{th} harmonic distortion levels were exceeded far beyond the NRS-048 limits. The 2x36 MVAR shunt banks could no longer be operated together due to high voltage distortions induced across the shunt capacitor banks resulting in one or both bank(s) tripping.

5.3.1 System Description

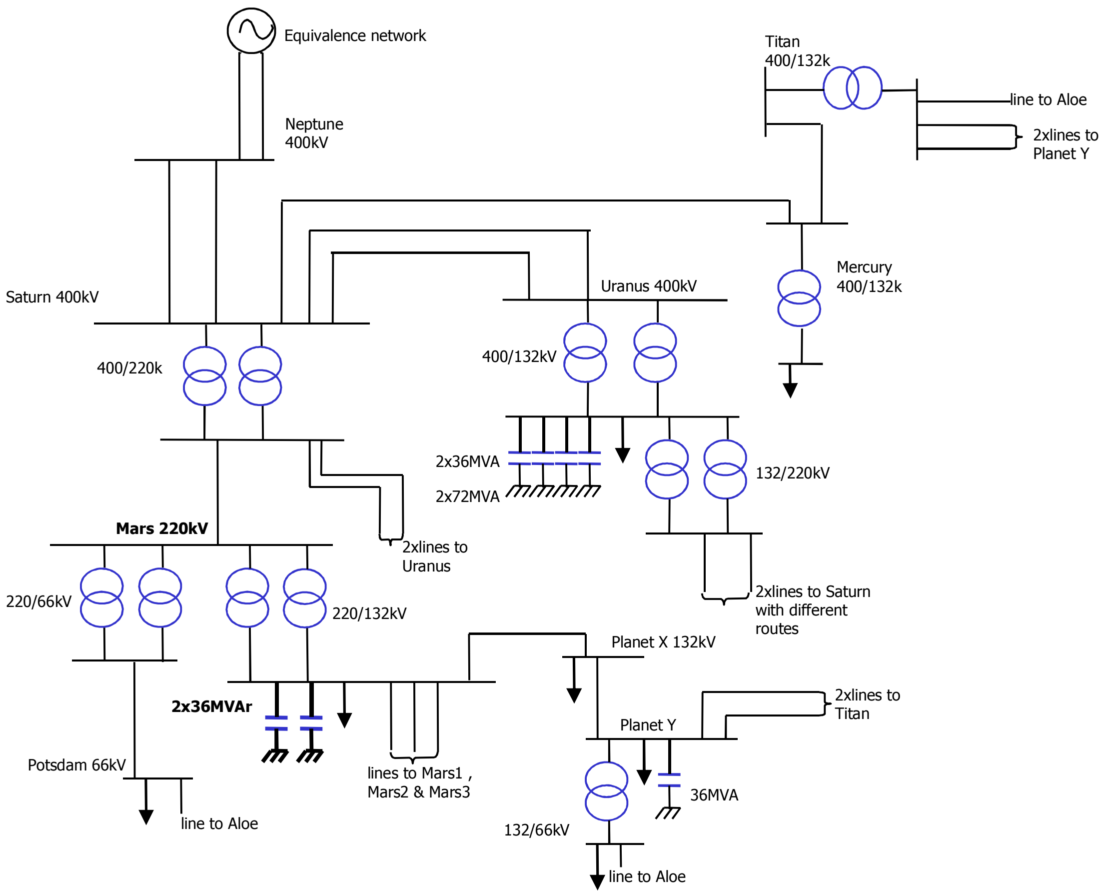

Figure 5.6 – Network diagram for Mars substation

Mars substation is mainly supplied from 1x220kV, 160km line and very far from generation source. The substation is equipped with 2x250 MVA, 220/132kV and 2x90 MVA, 220/66kV transformers. This substation supplies distribution network and some direct customers, it is meshed network which makes it extremely difficult to determine the direction of harmonic current flow.

5.3.2 Site Measurements and Network Impedance Analysis

The mechanism giving rise to these excessive levels was demonstrated by both simulation and practical measurements. A brief analysis of THD as measured from Venus substation 132kV bus is depicted in figure 5.7 below; these measurements were obtained from Eskom's Quality of Supply Data base.

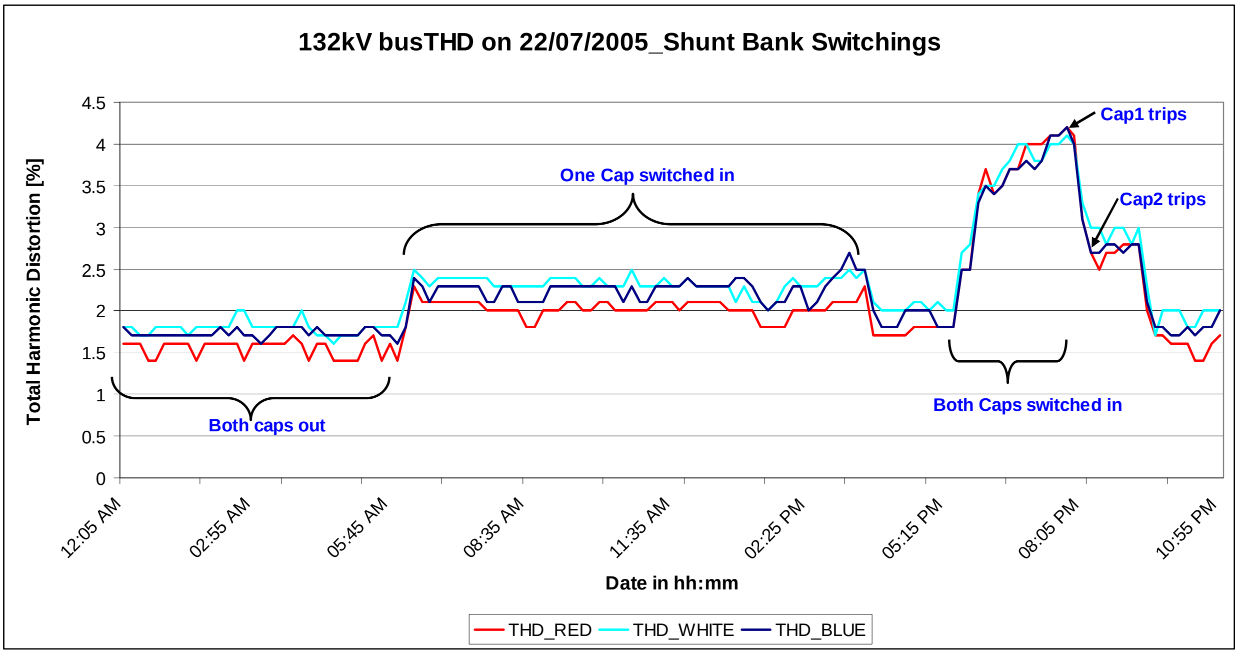

Figure 5.7 – Total Harmonic Distortion of a system where shunt banks resonate with the system at the 5^{th} harmonic, resulting in extremely high THD.

This network is supplied from one long transmission line it is therefore a weak system. If we consider the reasons for change in system parallel resonances as discussed above, no system strengthening has directly taken place at this substation in past few years. However the upstream network has been strengthened with new transformers, lines, series capacitor banks and a new substation at 400kV level. The system capacity has definitely changed due to a source that has become stronger. The system configuration is still the same as when the capacitor banks were installed.

There are two possible factors influencing the high voltage distortions at this substation, firstly the system capacity has increased due to upstream network strengthening, shifting the parallel resonance caused by 2x36 MVAR shunt banks to the 5^{th} harmonic. Secondly, it could be possible that some customers are not meeting their emission limits. Furthermore the shunt banks provide a low impedance path for harmonics thereby “trapping” all the 5^{th} harmonic currents injected by these loads into the system, causing high voltage distortions at the point of connection. Based on the investigations i.e. site measurements and simulation studies conducted, it can be concluded combination of these two factors is the cause for high voltage distortions.

The network impedance of this system was assessed by doing frequency scan and the results were found to correspond with THD measurements analyzed above. The simulation results are presented in Figure 5.8. It can be noted that with 2x36 MVAR shunt banks connected in the system, the 5th harmonic resonance exists, from the plot below it is clear that 5th harmonic dominates the THD on this busbar, exceeding the limits as indicated in figure 5.7,

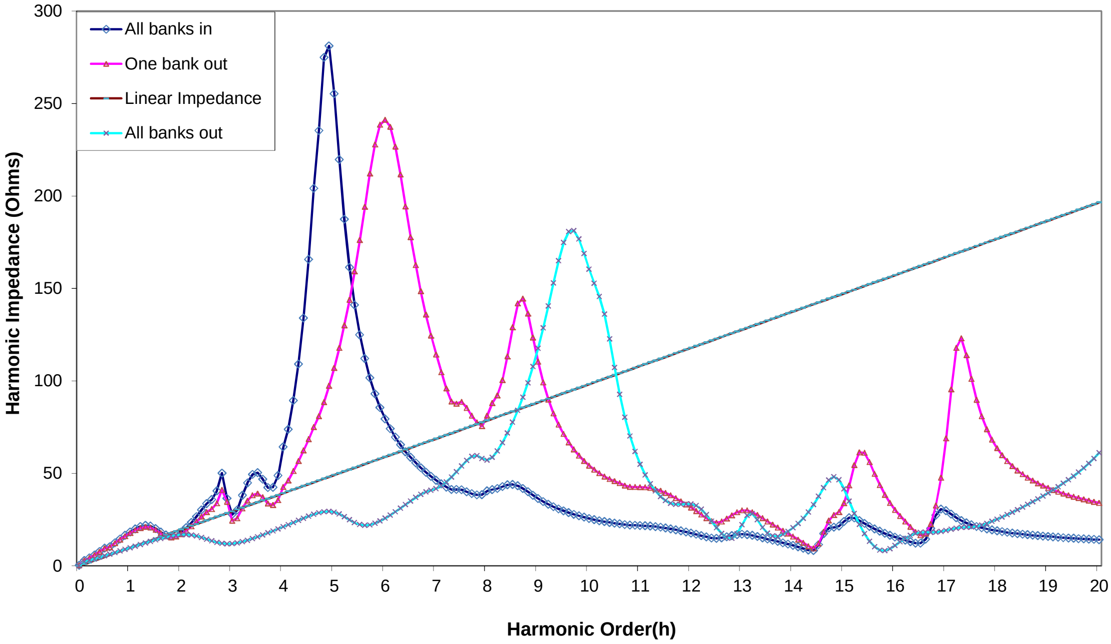

Figure 5.8 – Parallel resonance at the 5th harmonic caused by 2x36MVAR shunt banks: Harmonic polluted environment

5.4 Series resonance due to lower voltage capacitors

The purpose of this study is to demonstrate series resonance phenomena in upstream network due to the utility shunt capacitor banks (or customer power factor correction capacitor banks) connected on the remote busbar of the network. An example is given below on figure 5.9 where the shunt capacitor is connected on the remote customer C's plant. For such a case the series resonance circuit is formed with busbar 1 and 2.This resonance condition occurs at a frequency largely determined by the customer C's transformer impedance and the size of the capacitor bank. The other condition considered herein is the case where the utility capacitor is connected at the remote busbar2.

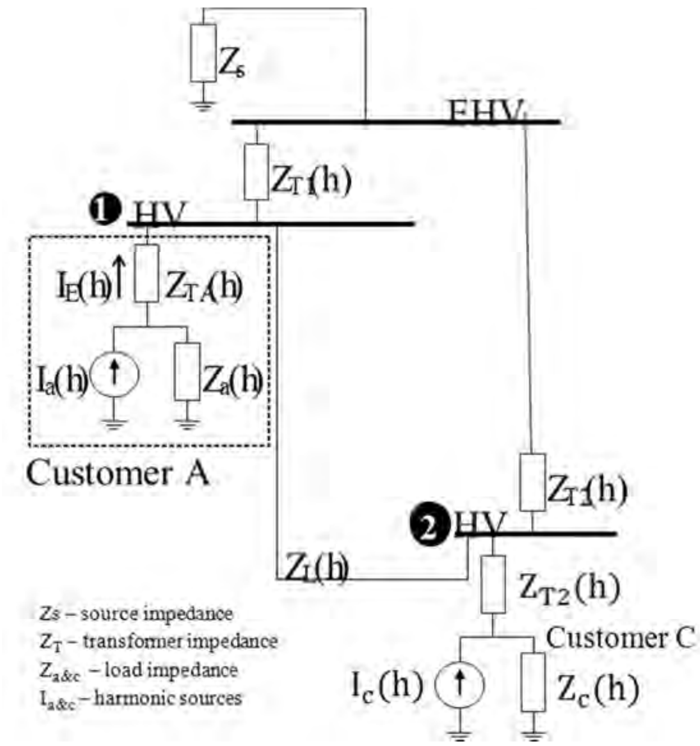

Figure 5.9 – Example of a single line diagram of series resonance circuit [25].

Simulation studies were conducted in the form of frequency scans to demonstrate the above mentioned series resonance phenomena (utility shunt bank connected on busbar 2). Figure 5.10 depict the driving point impedance at busbar2 and 1 of the above circuit. As annotated on the graph, the lowest straight line is the driving point impedance on busbar 2 with no shunt capacitor bank whilst the line with highest parallel resonance at 235Hz is the same busbar after integration of shunt capacitor bank. The other curves depict the busbar 1 impedances with and without the shunt capacitor at the remote busbar 2.

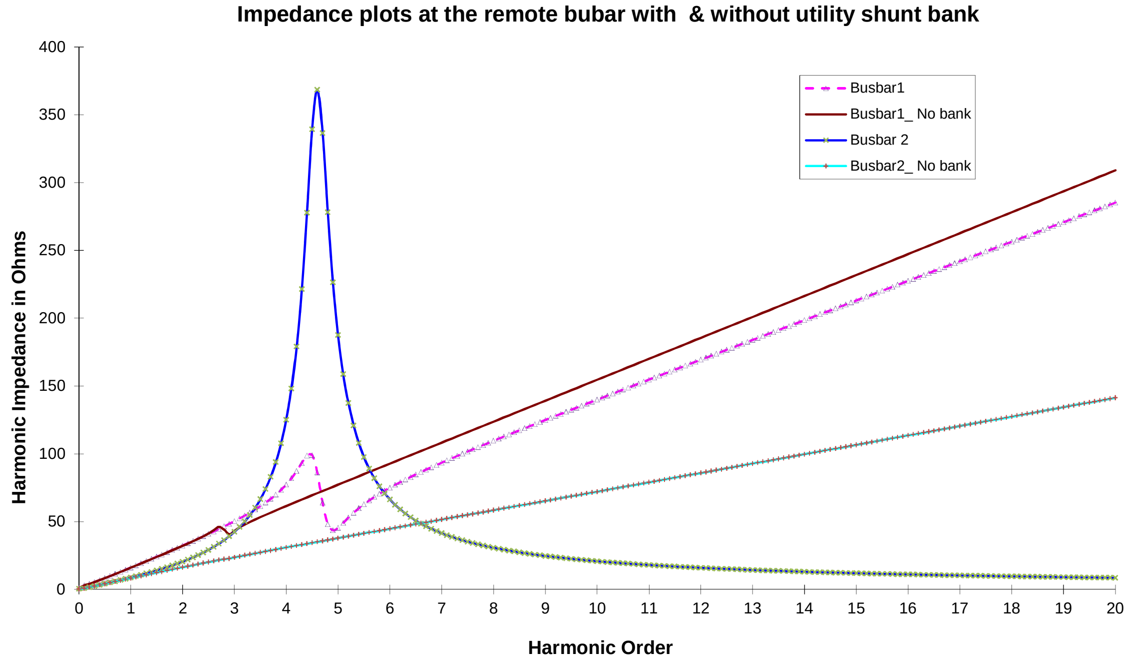

Figure 5.10 – Impedance Plot for the above series resonance circuit.

As illustrated on the plot, the parallel resonance at 235Hz on busbar 2 appears as series resonance on busbar 1. It is slightly shifted to 250Hz due to the transformer impedance and can also be influenced by the line impedance depending on the line length. As results of this series resonance the impedance at resonance frequency is also reduced by approximately 42% of the reference impedance without the shunt capacitor. This circuit has filter characteristics, which means it can absorb harmonic currents from other sources in the network. The low impedance presented by the series resonance may amplify the harmonic currents generated by customer A hence affecting the harmonic voltage distortions on busbar2. Depending on the damping that arises from customer loads, the voltage distortions at this resonance frequency may be low.

CHAPTER 6

CONCLUSION

The management of system harmonics and resonances are important aspects of the design of shunt capacitor installations and of the integration of large complex loads.

A design methodology has been developed and demonstrated which makes use of network impedance assessment methods to provide the robust harmonic integration of large shunt compensators into a transmission and HVDC systems. Demonstration of the methodology has been achieved through several case studies related to different types of networks.

The merits and shortcomings of the proposed design methodology can be summarized as follows:

Merits:

(i) The design methodology has proved to be practical and provides guidance in terms of network impedance amplification where shunt capacitor banks are applied in the system. Case study A is a good example where the results of the simulations conducted before the additional 2x150 MVAR shunt banks were installed on the 275kV busbar, correlates with the voltage distortion measurements taken after the commissioning of these 2x150 MVAR shunt banks.

(ii) The methodology ensures that the design of transmission shunt compensation is optimally robust in terms of harmonic resonances. Robust means the shunt compensators are able to operate without constraints for various network conditions. It also ensures that system resonances are well managed where shunt capacitor installations result in parallel resonance conditions.

(iii) It gives guidance on shunt capacitor bank topology to be applied where system resonance conditions exist. The choice of shunt capacitor bank topology depends on the following:

- simulated network impedance results,
- outcome of assessment,
- economics and
- application requirements.

Depending on the system requirements and operating procedures, contingencies such as transformer outage can be used as decisive case for a filter design if such a condition results in parallel resonance at a characteristic harmonic(s).

Shortcomings:

(iv) The existing voltage distortions at the bus of study must be considered and evaluated in conjunction with the results of network impedance assessment.

(v) An inherent short-coming is that the methodology requires the network to be simulated – in many cases, the future evolution of the network is not clear.

In conclusion, the design methodology proposed in this dissertation provides a practical approach to shunt capacitor bank design and integration for both AC transmission and HVDC systems.

6.1 Recommendations

The following work is recommended for future studies:

(i) The development of more robust “rules-of-thumb” for the interaction of different shunt compensator designs with different types of systems – for example evaluation of the impact of the system X/R ratio in relation to expected system resonances.

(ii) The work conducted in this study does not address the rating of de-tuned or filter banks. Evaluation and inclusion of background harmonics in the rating of shunt compensators should be developed further.

CHAPTER 7

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