THE APPLICATION OF VOLT/VAr OPTIMISATION ON SOUTH AFRICAN DISTRIBUTION POWER NETWORKS

by

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My parents, for being my greatest teachers.

Abstract

Electric power utilities can achieve cost savings by maximizing energy delivery efficiency and optimizing peak demand. Technical losses are influenced by both network impedances and currents. Power flow through distribution components are composed of active and reactive components. The reactive power does no real work, but contributes to the overall technical losses. By the appropriate placement and operation of reactive power compensation devices, reactive power flows could either be eliminated or significantly minimized, thus, inherently reducing technical losses. This research investigation presents a method for reactive power compensation of medium voltage radial networks as a cost-effective approach to achieve loss minimization and voltage regulation improvement. The study addresses the optimal placement of distributed shunt capacitors along distribution feeders. A mathematical formulation is developed to show that there is a specific location for a given size of capacitor bank that produces the maximum power loss reduction for a given load distribution on a network. In the Eskom distribution system, for those networks that are voltage constrained, the application of capacitors will also consider raising voltages to statutory requirements, however at the expense of the power loss reduction capability. The method developed maximizes both voltage and power loss reduction. Switching and control strategies are developed to meet these objectives throughout a day cycle. The methodology was tested on an Eskom distribution medium voltage network by power system simulation. Results obtained of improvements in voltage regulation and feeder losses are presented and discussed. The application of shunt compensation and the associated feeder voltage regulation improvement is an enabler for Conservation Voltage Reduction (CVR) that can be applied for demand reduction during peak times. Control strategies for CVR are presented, to cater for an integrated Volt/VAr solution for distribution networks. Furthermore, an assessment of CVR potential within Eskom Distribution networks is presented. This research forms the inception for a series of studies aimed at incorporating Volt/VAr optimization within Eskom Distribution networks.

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List of Abbreviations

AC	-	Alternating Current
AMI	-	Advanced Metering Interface
C	-	Network Class
CIGRE	-	French: International Council for Large Electric Systems
CVR	-	Conservation Voltage Reduction
DC	-	Direct Current
DETS	-	De-energized Tap Switch
EHV	-	Extra High Voltage
EPRI	-	Electric Power Research Institute
GMD	-	Geometric Mean Distance
GMR	-	Geometric Mean Radius
HV	-	High Voltage
HVDC	-	High Voltage Direct Current
IVVC	-	Integrated Volt/VAr Control
IVVC	-	Integrated Volt/VAr Control
km	-	Kilometre
KSACS	-	Key Sales Accounts
LPU	-	Large Power User
LTC	-	Load Tap Changer
LV	-	Low Voltage
MV	-	Medium Voltage
NER	-	National Electricity Regulator
NERSA	-	National Energy Regulator of South Africa
NERSA	-	National Energy Regulator of South Africa
OLTC	-	On Load Tap Changer
p.u.	-	Per Unit

pf	-	Power Factor
QOS	-	Quality of Supply
RTU	-	Remote Terminal Unit
RVR	-	Rapid Voltage Rise
SCADA	-	Supervisory Control and Data Acquisition
TZ	-	Tap Zone
UAP	-	Universal Access Program
V	-	Volt
VAr	-	Volt-Ampere reactive
VT	-	Voltage Transformer
VVO	-	Volt/VAr Optimisation

1 Introduction

1.1 Background

The generation, transport and consumption of electric energy were initially based on direct current (DC) technology. In 1882, the first electric central station was built in New York by Thomas Edison. This system consisted of DC generators driven by steam engines which supplied power at 110V DC to an area of approximately 1.6 km in radius. Over a short period of time, similar stations were established and in operation in many large cities throughout the world. The primary use of grid energy during this period was street lighting [1].

The first transmission line built in Germany was also in 1882, which operated at 2.4kV DC over a distance of 59km. With the development of electrical motors in 1884 [2], these were introduced into the load mix while the use of incandescent lamps continued to increase. By 1886, the DC systems were experiencing limitations because they could deliver energy only over short distances from their generating stations. Voltages could not be increased nor decreased as necessary [3].

In order to transmit power over long distances, voltage levels had to be raised to keep power losses and voltage regulation at acceptable levels. The high voltages required for transmission of power is however not suited to power generation nor load consumption. Voltage transformation therefore became a necessity [2]. In 1885 a commercially practical transformer was developed that initiated the development of an AC power system. The first three-phase AC line in the United States was installed in 1893 in California. This line was operated at 2.3kV and spanned 12km. In 1897, a 44kV transmission line was built in Utah. In 1903, a 60kV transmission line was energized in Mexico [3].

The adoption of AC power systems in the developing world over DC power systems was promoted by the advent of the power transformer, three phase power lines and the induction machine [1]. Generating, transmitting and distributing power at different voltage levels enabled power to be transmitted over long distances and allowed power consumption by loads at desired voltage levels. AC power systems also gave rise to less arduous means of interrupting currents on high voltage equipment which resulted in the physical size and cost of switchgear being reduced.

With the development of mercury arc valves in the early 1950's, HVDC systems became viable and economical for large power transfers over long distances. Today, HVDC transmission is the preferred bulk power transmission system over long distances (above 500km) compared to HVAC transmission system due to lower delivery and operating costs and it is often easier to obtain the right-of-way for DC cables due to the reduced aesthetic or environmental impact [4]-[8]. The crossover point beyond which DC transmission becomes a competitive alternative to AC transmission is approximately 500km for overhead lines and 50km for underground cables [2]. HVDC also provides an asynchronous link between systems where AC interconnections would be impractical as a result of system stability considerations or in instances where nominal frequencies of systems are different [2].

With the advent of thyristor valve converters and the cost and size of conversion equipment decreasing with increasing reliability, there has been a steady increase in the use of HVDC systems for power transmission [2]. The ac three-phase synchronous generator remains dominant in bulk power generation. The evolution of the power system from inception has thus been driven by improving power delivery efficiency, that is, the ability to transmit power over long distances, at acceptable voltage, reduced power loss and associated reduced cost of production and operation.

In the modern day AC power systems, utilities still have the potential to achieve cost savings by further optimisation of the energy delivery system and management of peak load demands. Technical losses are influenced by both network impedances and currents. Power flow through distribution components comprise of both active and reactive components with the reactive components performing no real work, but contributing to the overall technical loss. By the appropriate placement and operation of reactive compensation devices such as capacitors, reactive power flows could either be eliminated or significantly minimized, thus, inherently reducing technical losses.

According to Chetty [9], the average technical loss for distribution feeders in the Eskom KwaZulu-Natal Operating Unit was 4.2%. Some feeders have however peaked at almost triple this value. Voltage assessments of medium voltage distribution feeders indicated that approximately 35% of the feeders were operated at regulation levels that had the potential to violate customer contracted limits at points of supply. Delays in project execution accompanied by changes to natural load growth patterns have contributed to networks being operated at poor regulation levels. The Operations and Control sections of Eskom's Distribution businesses thus have a key role to play in managing the power system efficiently in the interim until network strengthening initiatives are implemented.

1.2 Objectives

This research investigation proposes to review and address the optimisation and voltage management of Eskom's distribution network aimed at increasing the power delivery efficiency and improving the voltage regulation of the current network. The study focuses on medium voltage "radially fed" networks. The main objectives of the work include the following:

(i) Study the influence of distribution network hardware on voltage regulation and efficiency.

(ii) Investigate the effectiveness of reactive power compensation of medium voltage radial networks as an effective approach to achieve loss minimization and voltage regulation improvement.

(iii) Provide guidelines for optimal capacitor placement on distribution networks.

(iv) Produce guidelines to entrench voltage management practices in distribution control centers.

(v) Review international best practice with regard to Volt/VAr optimization and recommend suitable approaches for Eskom.

It is envisaged that this research will have a significant impact on the improvement of power delivery in distribution networks.

1.3 Structure

This thesis comprises various sections. A breakdown of the structure is as follows:

Chapter 1 provides an introduction. The key drivers responsible for the evolution of the power system are described as well as the problem statement and objectives of the research are discussed.

Chapter 2 discusses losses in a power system and common technical loss minimization techniques. The theory of network components on distribution networks and the individual influence on efficiency and voltage regulation is explained through mathematical derivation.

Chapter 3 discusses the various design philosophies that are relevant for operating voltage regulation requirements in South Africa. The South African grid codes are assessed where the minimum requirements from a design and operations perspective are given. The South African quality of supply standards are reviewed where the statutory compatibility and voltage limits are provided. The concept of Eskom's network classes and tap zones are discussed and finally the optimal substation transformer control set points including SCADA alarm thresholds are derived.

Chapter 4 discusses the objectives of Volt/VAr optimisation. Various levels of implementation and the associated benefits are discussed in each case. The minimum hardware requirements for basic implementation as well as fully autonomous systems (Advanced Metering Interface [AMI] type solutions with complete Supervisory Control and Data Acquisition [SCADA] system integration versus quasi systems involving human interaction and basic SCADA interrogation) are explored. Volt/VAr implementation at established utilities is reviewed to understand decision factors, technologies, project scoping, project success criteria and results and lessons learned through field testing. An assessment of Conservation by Voltage Reduction (CVR) on Eskom distribution feeders is presented where potential demand reductions and levels of implementation given local network characteristics, is discussed. Finally, the option best suited for Eskom is provided

Chapter 5 discusses the optimal sizing, placement and switching requirements for distribution systems/network capacitors to achieve the objectives of both technical loss minimisation as well feeder voltage regulation improvements to statutory limits. Mathematical models are developed which conclude that based on the specific reactive power distribution along the length of a distribution feeder that there is a specific size and location for capacitive compensation in order to maximise technical loss reduction. Derivation and techniques are also included to calculate appropriate capacitor size and location for voltage improvement as an individual objective function. Finally, a combined method to achieve both loss savings and maintain statutory voltage is provided.

In chapter 6 the methods derived in chapter 5 are tested via power system simulation on an existing distribution feeder with known voltage regulation problems and high technical losses. Actual daily Load profiles are simulated to determine requirements over a 24-hour period where sizing and switching is optimised. The combined voltage and loss strategy is demonstrated together with quantification of improvements

Chapter 7 provides the conclusions and recommendations from the work in this study.

1.4 List of Publications

The following three publications have emanated from this thesis:

[10] D Chetty, M.M Bello, J Horne, "Eskom Distribution approach to optimize networks with high level renewable generation penetration" Paper#151, 2015 CIGRE SA Symposium, Cape town, Oct 27-29, 2015

[11] D Chetty, M.M. Bello and I.E. Davidson, "The Application of Volt/VAr Optimization on Eskom South Africa Distribution Feeders" Paper #766, 2016 CIGRE Canada Conference, Vancouver, BC, Oct 17-19, 2016.

[12] D Chetty, A. Perera, M.M. Bello and I.E. Davidson, "Performance Evaluation of Traction and Utility Network Interface: Fault Location, Protection Coordination and Management of Transient and Temporary Overvoltage" Paper #768, 2016 CIGRE Canada Conference, Vancouver, BC, Oct 17-19, 2016.

2 Literature review and the electric power system

Since the inception of electric power systems, there have been concerted efforts to increase the distances energy can be transported from sources to consumers. The primary limitations are as a result of technical loss and voltage drop constraints. A review of system losses and the influence of the distribution network equipment on efficiency and voltage regulation will be presented.

2.1 Losses on a power system

The total system losses can be described as the difference between the energy generated and the energy sold to end use customers [13]. Losses can be categorized into two components, namely non-technical losses and technical losses.

Non-technical losses which are more prevalent in distribution networks as opposed to transmission systems [14] occur primarily as a result of energy theft, faulted equipment and ineffective billing methods. The contributors to non-technical losses are provided in [15] and include:

- Non-payment of electricity bills
- Unauthorized line tapping and diversion
- Losses due to faulty meters and equipment
- Inadequate or faulty metering
- Poor revenue collection techniques
- Inadequacies and inaccuracies of meter reading
- Inaccurate customer electricity billing
- Loss/damage of equipment/hardware, e.g. protective equipment, meters, cables/conductors and switchgear
- Inaccurate estimation of non-metered supplies, e.g. public lighting, agricultural consumption, rail traction
- Inefficiency of business and technology management systems

Technical losses are inherent losses in power systems which are as a result of the dissipation of electrical energy as heat caused predominantly by current passing through power system components. The heat released is a function of the square of the current where the duration of heating results in energy dissipation into the atmosphere. This energy must be supplied by the generators but does not reach customers and is therefore considered a loss. As these losses are only due to the power network components, it is termed technical losses. The contributors to technical losses are provided in [14] and are summarized as follows:

- Conductor losses also termed copper losses which are due to joule heating or I^2R losses
- Dielectric losses which are as a result of the dielectric materials between conductors heating
- Induction losses which are due to electromagnetic fields around conductors linking to neighboring conductors or metallic hardware where currents become induced
- Radiation losses which arise when the electromagnetic fields around a conductor is radiated into free space during a wave cycle
- Transformer losses which are due to joule heating as a result of the impedances of transformer coils and due no-load losses which are made up of hysteresis and eddy current losses in the transformer core

Loss estimation techniques are provided in [14]-[16]. The techniques involve approximating the technical loss components after which the non-technical loss components can be determined by subtraction from the total system losses. A method to estimate distribution technical losses by power system simulation is provided in [14] and [16]. In [15], non-technical losses are reported to contribute an estimated 30% of revenue losses in utilities. In [17], losses have been reported to add between 6-8% to the cost of electricity and 25% to the cost of delivery. The total technical loss in Eskom's distribution system has been estimated to be 4.7% nationally [9].

This research addresses the technical loss component of system losses. Sections 2.1.1 to 2.1.5 will discuss various technical loss minimisation techniques.

2.1.1 Installation of shunt capacitor banks

One method of reducing technical losses is by the application of shunt capacitors to the distribution system. The basic idea of reactive power compensation is to reduce the reactive component of the load current flowing from the generating units through transmission lines, transformers, cables, and distribution lines. This process is achieved by connecting reactive compensating elements of opposite reactance in parallel with the load [18]. The techniques of reducing feeder electrical losses by using shunt capacitors have been dealt with by many researchers. The earliest significant work was done by R.F. Cook [18]. Cook developed peak power loss and energy loss reduction equations. Other researchers who made significant contributions are T Gönen [19], J.V. Schmill [20], N.E. Chiang [21], J.J. Grainger [22]-[23], M.M. Saied [24] and H.D. Chiang [25].

In reviewing published work, many assumptions and simplifications have been made listed as follows:

- The feeder load is assumed to be uniformly distributed or approximated by one concentrated load
- The feeder is assumed to have a uniform conductor
- Capacitor costs are neglected or assumed to be proportional to capacitor sizes
- Capacitor installation, maintenance and operation costs are neglected
- The number of capacitor banks used is arbitrarily chosen
- The values of capacitor banks used are non-standard

The solutions obtained under these assumptions may result in undesirable results. One objective of this research will be to evaluate the applicability of shunt compensation on South African distribution networks and present general and simple procedures for implementation that can be easily modified, adapted, and extended depending on local network conditions.

2.1.2 Distribution network reconfiguration

Network reconfiguration is the process of selecting an appropriate topological structure of a network for a certain objective. Technical loss minimization can be achieved by means of network reconfiguration [26]. A primary objective of network reconfiguration is to minimize power and energy losses by distributing loads as evenly as possible across interconnected but radially operated networks [27]. Network reconfiguration is a method of demand and energy loss reduction at nearly no cost to the business. It involves the shifting of loads by moving or establishing normally open points on the network. The reconfiguration of networks will impact the quality of supply, reliability and protection coordination. These factors which cannot be ignored must be evaluated in conjunction to any loss minimization objectives [10].

2.1.3 Re-conductoring

Conductors are often the largest contributors to technical losses where conductor selection must be given careful consideration during the planning and design stages of networks. For example, when a new circuit is designed, the conductor size can be increased at a modest additional cost while the energy efficiency could be significantly improved. If conductors are loaded up to or near their thermal ratings, the losses over the life of the circuit will exceed the construction costs [17].

Where existing networks experience high levels of losses, remedial action may be required in the form of development projects such as re-conductoring the heavily loaded sections of the overhead line. Re-conductoring near the source of an overhead circuit can be very economical, though it is not generally easy to upgrade underground cables for loss reduction [28]. For typical distribution lines with tapering loads, about two-thirds of total circuit losses occur in the first third of the main circuit length. Re-conductoring can typically halve these losses. It is possible to determine the load levels beyond which the existing conductor sizes should be upgraded.

2.1.4 Circulating current minimization

This technique of minimizing losses is least practiced and is associated with the voltage and reactive power scheduling. The aim is to reduce circulating VAr flow, thereby promoting flatter voltage profiles. In interconnected systems where flat voltage profiles are not maintained, circulating reactive currents will flow [29]. These increase the losses on the utility networks and are difficult to measure or account for. In order to minimize losses associated with circulating current flows in a power system, it is necessary to maintain voltages within tight limits. The transformer tap changers must also be tapped to a level where all the substations in the study area are at the same voltage level in order to reduce the circulating currents and VAr flows [30].

2.1.5 Distribution generation [31]

The changes in the economic and commercial environment of power systems design and operation have necessitated the need to consider active distribution networks, incorporating small generation sources. Distribution generation systems give the utility the potential to integrate renewable energy sources, which can be economically viable alternatives to grid connection reinforcements in certain instances. Load research studies have shown the demand pattern of most distribution systems, especially those serving mainly domestic and commercial consumers, rural and semi-urban areas, to be characterized by early morning and evening peaks, with very low consumption for the rest of the day. The poor load factor coupled with the relatively low demand, presents challenges in the design and operation of cost effective networks for such areas [31]. Distribution generation has continued to attract the attention of researchers and utilities as a possible option for improving the design and performance of networks [32].

2.2 General structure of the modern day power system

Power systems, although varying in size and structural components, have some basic properties. These are [2]:

- They are comprised of 3 phase AC systems operating at constant voltage. Both generation and transmission systems use 3 phase equipment. The larger industrial loads are three phase. Single phase residential and commercial loads are evenly distributed amongst phases as far as possible to balance out the power consumption from the 3 phase system.
- They use 3-phase synchronous machines for bulk generation. Prime movers convert primary sources of energy into mechanical energy which is in turn converted to electrical energy.
- They transmit power over large distances to consumers spread over wide areas. This requires a transmission system comprising subsystems operating at different voltage levels.

The basic structure of a modern power system is illustrated in Figure 2-1 where the power system is divided into five parts: generation, transmission, sub-transmission, distribution (Primary distribution), low voltage networks (Secondary distribution) [2]. Focus will be placed on the power delivery system which is made up predominately of overhead lines, underground cables and power transformers used to deliver electricity to end use customers at specified voltages.

The power delivery system can be classified as follows:

- Transmission: The transmission system interconnects all major generation stations and main load centres in the system. It forms the backbone of the integrated power system and operates at the highest voltage levels, typically 275kV, 400kV and 765kV. Voltages in these ranges are termed Extra High Voltage (EHV). Generator voltages are usually in the range of 11 kV to 22 kV which is stepped up to transmission voltage levels for power transmission to transmission substations. The transmission system together with the generation system is often referred to as the bulk power system.

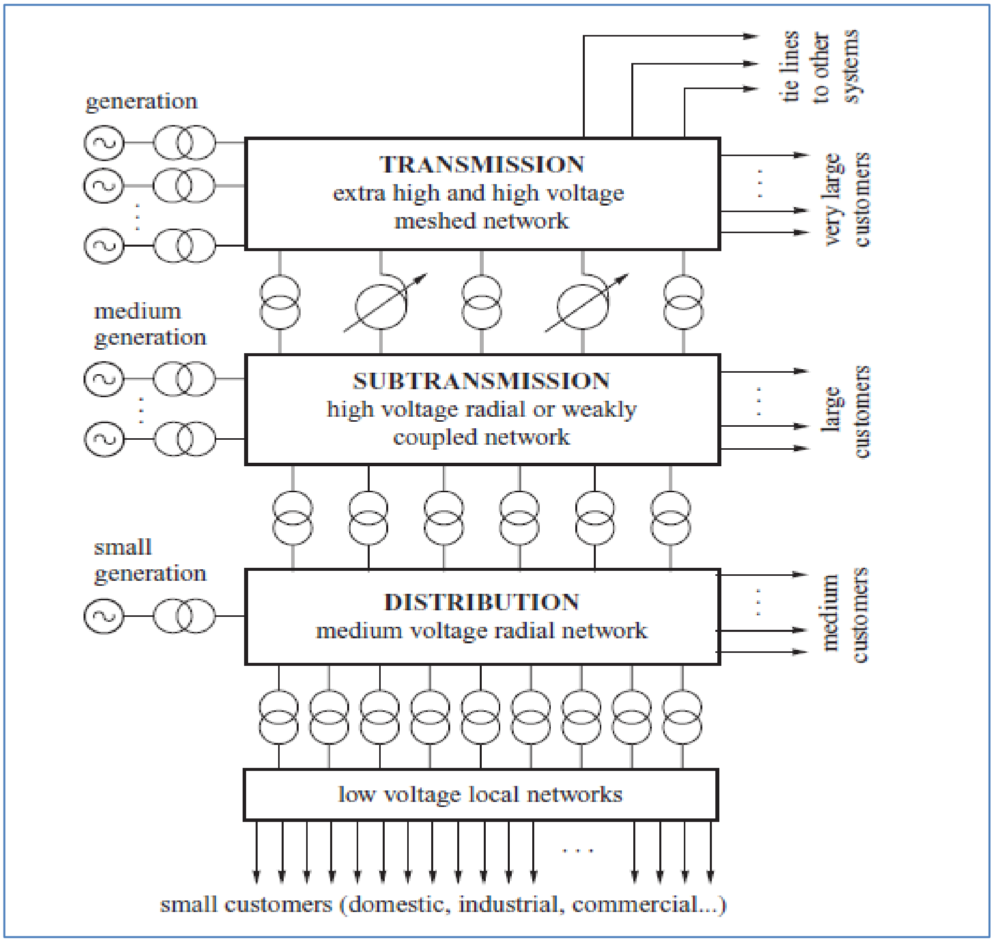

Figure 2-1: Typical power system overview [33]

- Sub-transmission: At transmission substations, voltages are stepped down to sub-transmission levels, typically 44 kV to 132 kV. This range of voltage is termed High Voltage (HV). The sub-transmission system transmits power in smaller quantities to the numerous distribution substations. Large industrial customers are commonly supplied directly from the sub-transmission systems.
- Primary distribution: The distribution system represents the final stage in the transfer of power to individual customers. The primary distribution voltage is typically between 11 kV and 33 kV, where this range is termed medium voltage (MV). Small industrial customers are supplied in bulk by primary feeders at this voltage level.

- Secondary distribution: The secondary distribution feeders supply residential and commercial customers most often at either 230V single phase or 400V three phase. This range of voltage is termed Low Voltage (LV).

Small generating plants located near load centres are often connected to sub-transmission or distribution systems directly. Interconnections to neighbouring power systems are usually formed at the transmission system level. The overall system thus consists of multiple generating sources and several layers of transmission networks. This provides a high degree of structural redundancy that enables the system to withstand unusual contingencies without service disruption to consumers [2].

The performance of the power delivery system is dependent on efficiency and regulation i.e. minimised technical losses and minimised voltage regulation. This section develops the mathematical models of key components in the power delivery system that by nature of their physical properties influences both voltage regulation and system technical losses. Mathematical models will be developed for additional components placed on the power delivery system, used to improve voltage regulation and reduce losses on the power system, to demonstrate how performance can be improved. This section has been developed using a combination of models and theory derived in [34]-[43].

2.3 Line model

A transmission line can be mathematically represented by four parameters i.e. series resistance, series inductance, shunt capacitance and shunt conductance. For load flow studies involving short and medium length lines, the conductance (leakage currents through insulators etc.) can be neglected [34]. Lines of up to 80 km in length are classified short lines where the effects of both shunt capacitance and the shunt conductance can be neglected. Lines with lengths between 80km and 240 km are classified as medium lines where the effects of shunt capacitance cannot be ignored [35]. The majority of lines in sub-transmission and distribution systems can be classified as short. There will however be instances where Sub-transmission systems will comprise medium lines especially for power delivery to remote areas.

For the purposes of this research, lines will be modeled as short consisting of only the series impedance components, however for completeness an explanation of the shunt capacitive components will also be provided. The series impedance is composed of the natural resistance (R) and inductive reactance (X_L) of the line. The shunt capacitive reactance (X_C) is due to a transmission lines natural capacitance.

Figure 2-2 shows an approximate lumped model for a transmission line represented by the Nominal Pi (π) model. In reality the series and shunt components are distributed along the length of the line, however for load flow analysis of short and medium lines, the lumped model provides sufficiently accurate results [34].

Transmission lines have capacitive effects between the various conductors and from the conductors to ground as is shown in Figure 2-3. The natural capacitance of a transmission is represented by shunt capacitors [36].

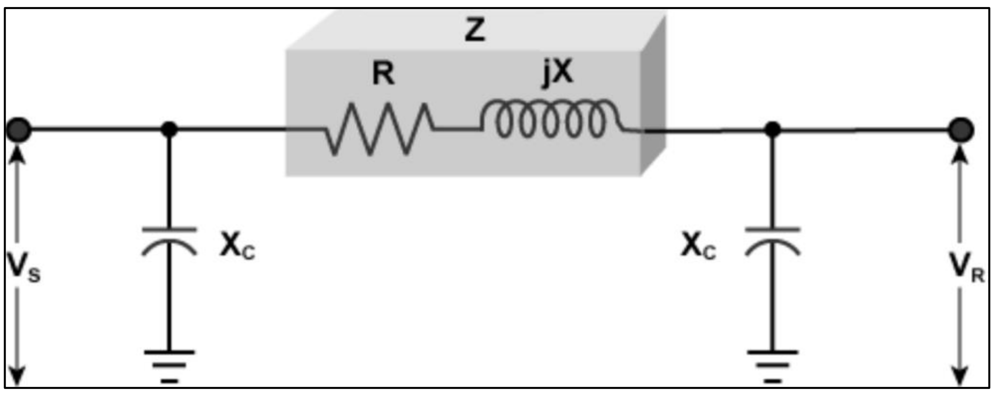

Figure 2-2: Transmission medium Line Impedance Model [36]

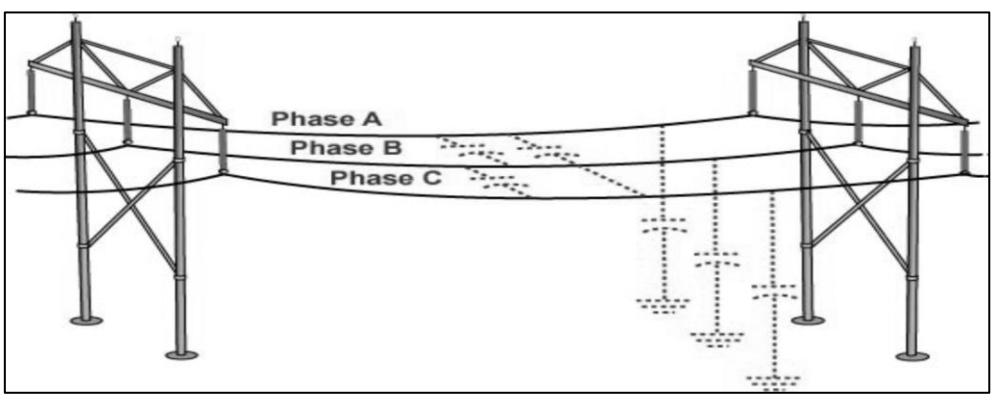

Figure 2-3: Natural Capacitance of a Transmission Line [36]

2.3.1 Resistance

The effective AC resistance Rac of a conductor in ohms can be determined by using (2.1) where I is the RMS current flowing through the conductor in amperes and $Ploss$ is the average power loss in the conductor in watts. The derivations that follow are contained in [34] discussing the series components of transmission lines.

$$Rac = \frac{Ploss}{I^2} \tag{2.1}$$

Ohmic or DC resistance *Rdc* in ohms is calculated using (2.2) where ρ is the resistivity of the conductor in ohm-m, *l* is the length in m and A is the cross section area in m^2.

$$Rdc = \frac{\rho l}{A} \tag{2.2}$$

The AC resistance will be equal to the DC resistance only if the current distribution is uniform throughout the conductor however with AC current flowing through a conductor, the current becomes non-uniformly distributed over the cross sectional area. The current density is higher at the surface of the conductor compared to the current density at the center. The consequence is that the resistance of a conductor will be higher for AC currents than for DC currents. The effect is termed the skin effect and is more pronounced at higher frequencies and conductors with large diameters. AC resistance can range up to 1.2 times DC resistance at power frequency for conventional conductors used in distribution [37]. Manufacturers will normally supply DC resistance of different conductor types in per unit length, often specified at temperature of 20°C. The resistance of a conductor *R2* at a specific temperature *t2* can be calculated using (2.3), where *R1* is resistance at a known temperature *t1*. The temperature coefficient of the conductor at 0°C is denoted by α.

$$\frac{R2}{R1} = \frac{\frac{1}{\alpha} + t2}{\frac{1}{\alpha} + t1} \tag{2.3}$$

The following can be concluded from equations (2.1) to (2.3):

- Power losses are proportional to the square of current flowing through a conductor
- Resistance increases with length but decreases as the cross section area increases
- Resistance increases with increasing temperature

2.3.2 Inductance

A simplified explanation of line inductance is provided in [38] and discussed in this section. AC current will produce a magnetic field around the wire carrying the current. Since the current is varying, so will be the magnetic field. This varying magnetic field "cuts" the conductor and a voltage is induced in the wire that acts to impede the originating current. The relationship between the current and the induced voltage is defined by a quantity called the inductance. One henry is the amount of inductance required to induce one volt when the current is changing at the rate of one ampere per second. The inductance of one phase of a transmission or distribution line is calculated by considering the self-inductance of the individual phase conductor and the mutual inductance between that phase and all other nearby phases, both of the same circuit/feeder and other nearby circuits/feeders.

These quantities are calculated based on the physical dimensions of the wires and the distances between them. The induced voltage across an inductor will be at a maximum when the rate of change of current is greatest. Because of the sinusoidal shape of the current, this occurs when the actual current is zero. Thus, the induced voltage reaches its maximum value a quarter-cycle before the current does; the voltage across an inductor is said to lead the current by 90 degrees or, conversely, the current lags the voltage by 90 degrees. [38]

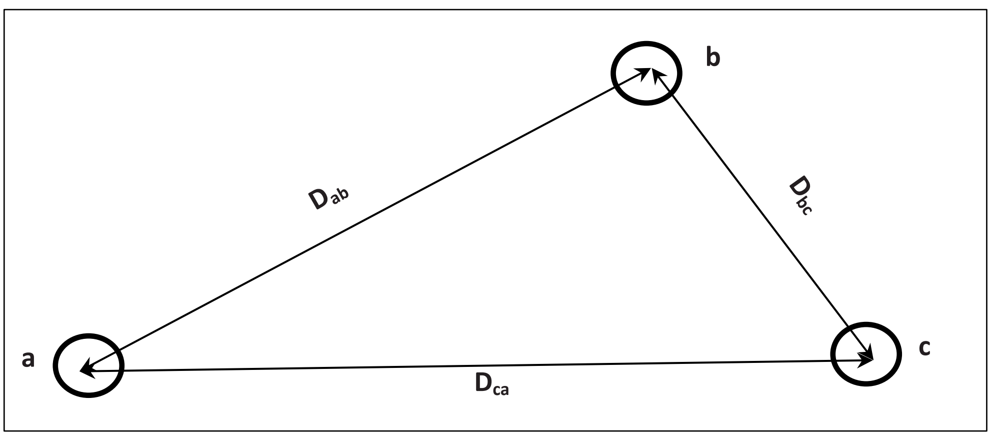

Figure 2-4: Cross sectional view of 3 phase line with unsymmetrical spacing [39]

For a transposed three phase line with unsymmetrical phase conductor spacing as shown in Figure 2-4, the inductance per phase can be calculated by (2.4) where D_{eq} is the equivalent equilateral spacing given by (2.5) and represents the mutual GMD between the three phases and where r_a'

given by (2.6) represents the self the geometric mean radius (GMR) of a phase conductor. The mathematical formulation and description is contained in [34].

$$L_{phase} = 2 * 10^{-7} \ln \frac{D_{eq}}{r_a'} \tag{2.4}$$

$$D_{eq} = \sqrt[3]{D_{ab} * D_{bc} * D_{ca}} \tag{2.5}$$

$$r_a' = r * e^{-\frac{1}{4}} \tag{2.6}$$

The voltage drop across an inductor is dependent on the inductive reactance X_l which is given in (2.7).

$$X_l = 2 * \pi * f * L \tag{2.7}$$

2.3.3 Capacitance

A simplified explanation of capacitance is provided in [38] and discussed in this section. An electric field around a charged conductor results from a potential difference between the conductor and ground. There is also a potential difference between each conductor in a three-phase circuit and with any other nearby transmission lines. The relationship between the charge and the potential difference is defined by a quantity called the capacitance. One farad is the amount of capacitance present when a charge of one coulomb produces a potential difference of one volt. The capacitance C, depends on the dimensions of the conductor and the spacing between it and the adjacent conductors and ground. The flow of charge (or current) will be greatest when the rate of change of voltage is at a maximum. This occurs when the voltage wave crosses the zero point. Thus, in an alternating current system, the current across a capacitor reaches its maximum value a quarter cycle before the voltage does; the voltage is said to lag the current by 90 degrees, or conversely, the current leads the voltage by 90 degrees. [38]

The mathematical formulation and description is contained in [34] and [39]. For a transposed three phase line with unsymmetrical phase conductor spacing as shown in Figure 2-4 [39], the capacitance per phase can be calculated by (2.8) where ε_0 is the permittivity of free space and D_{eq} is the equivalent equilateral spacing as given in (2.5).

$$C_{phase} = \frac{2 * \pi * \varepsilon_0}{\ln \frac{D_{eq}}{r}} \tag{2.8}$$

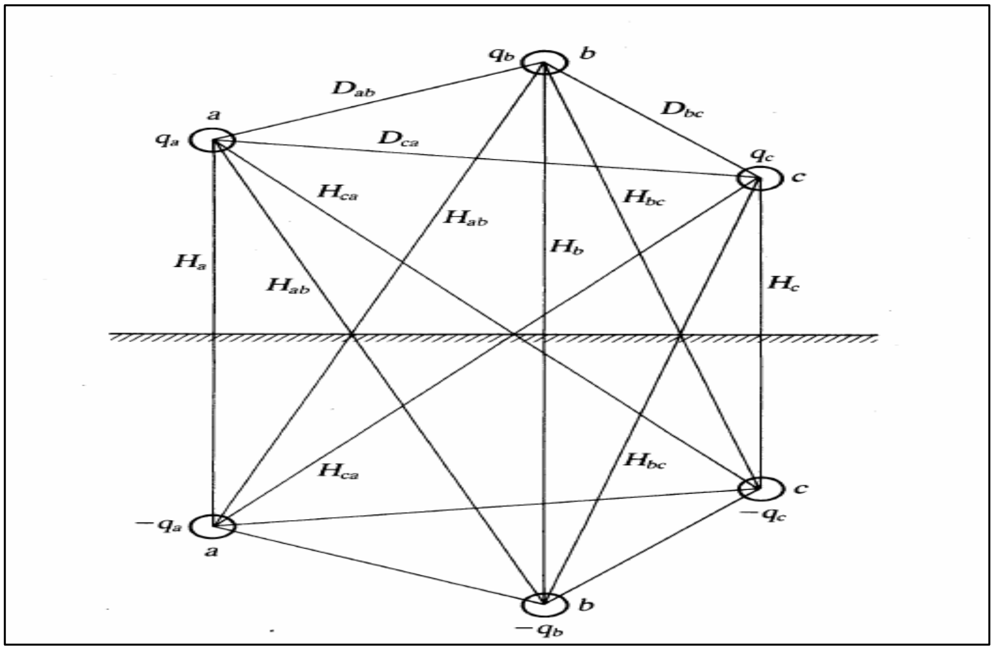

Figure 2-5: Three phase line with reflections [39]

The capacitance of overhead lines are impacted the earth which influences the electric field around the line. The effect of earth is mathematically represented by assuming a mirror image of each of the phase conductors below ground level where the distance below is equal to the distance above as shown in Figure 2-5. The mirrored conductors carry charge with opposite polarities to those conductors above ground level. The capacitance per phase is then determined by (2.9)

$$C_{phase} = \frac{2 * \pi * \varepsilon_0}{\ln \frac{D_{eq}}{r} - \ln(\sqrt[3]{H_{ab}H_{bc}H_{ca}} / \sqrt[3]{H_a H_b H_c})} \tag{2.9}$$

The voltage drop across a capacitor is dependent on the capacitive reactance X_c which is given in (2.10).

$$X_c = \frac{1}{2 * \pi * f * C} \tag{2.10}$$

In summary from [38], both inductive reactance and capacitive reactance have an impact on the relationship between voltage and current in electric circuits. Although they are both measured in ohms, they cannot be added to the resistance of the circuit since their impacts are different from that of resistance. The current through an inductor leads the voltage by 90 degrees, whereas current through a capacitor lags the voltage by 90 degrees. Because of this difference, their effects will cancel one another. The convention is to consider the effect associated with the inductive reactance as a positive value and that with the capacitive reactance a negative value. The general term, reactance, is defined as the net effect of the capacitive reactance and inductive reactance. Section 2.2 will discuss the impact these components have on the voltage regulation of a line.

2.3.4 Voltage regulation of distribution lines

Eskom distribution MV feeders are three phase and are connected in delta from substation transformers. Tee lines include dual phase and single wire earth return phase technologies [40]. The distribution lines under study in this research have a backbone lengths of up to 50km and can therefore be considered as short lines where shunt admittances are small enough to be neglected resulting in a simple equivalent circuit shown in Figure 2-6.

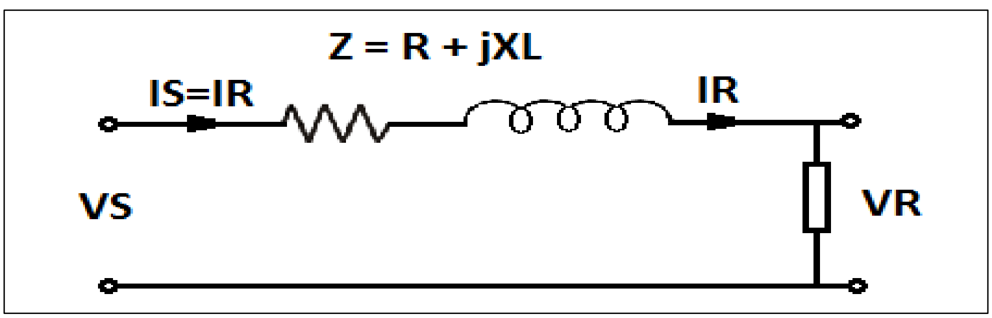

Figure 2-6: Equivalent circuit of a short line [34]

The relationship between sending and receiving end voltages and currents can be written as shown in (2.11) derived from the lumped model discussed in [34].

$$\begin{bmatrix} V_S \\ I_S \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix} \tag{2.11}$$

The voltage vector diagram for the short line is shown in Figure 2-7 for a lagging load case. From the figure the sending end voltage can be represented in terms of line impedance, receiving end voltage and load current as given by the (2.12) to (2.14)

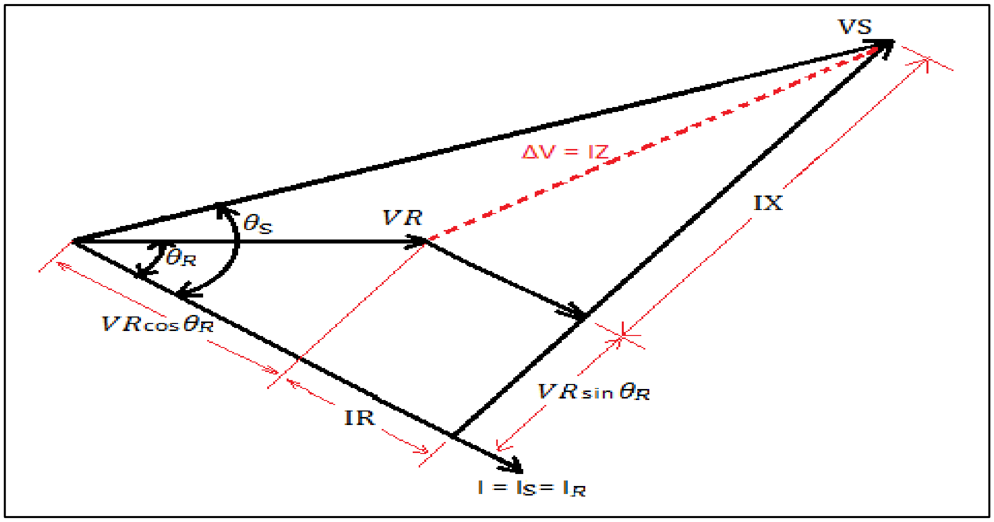

Figure 2-7: Phasor diagram of a short line with Lagging Load current [34]

$$V_S = \sqrt[2]{(V_R \cos\theta_R + IR)^2 + (V_R \sin\theta_R + IX)^2} \tag{2.12}$$

$$V_S = \sqrt[2]{V_R^2 + I^2(R^2 + X^2) + 2V_R I(R\cos\theta_R + X\sin\theta_R)} \tag{2.13}$$

$$V_S = V_R \sqrt[2]{1 + \frac{2IR}{V_R}\cos\theta_R + \frac{2IX}{V_R}\sin\theta_R + \frac{I^2(R^2 + X^2)}{V_R^2}} \tag{2.14}$$

The last term of (2.14) is negligible the sending end voltage can be approximated as given in (2.15).

$$V_S \cong V_R \sqrt[2]{1 + \frac{2IR}{V_R}\cos\theta_R + \frac{2IX}{V_R}\sin\theta_R} \tag{2.15}$$

Expanding binomially and retaining first order terms, results in the approximation of the sending end voltage given in (2.16)

$$V_S \cong V_R + I(\mathrm{R}\cos\theta_R + \mathrm{X}\sin\theta_R) \tag{2.16}$$

The voltage regulation of a transmission line is defined as the rise in voltage at the receiving end, expressed as a percentage of the full load voltage, when the full load at a specified power factor is switched off [34]. This is given in (2.17).

$$\%\ Regulation = \frac{V_{R0} - V_{RL}}{V_{RL}} * 100 \tag{2.17}$$

V_{R0} is the magnitude of the no load receiving end voltage and $V_{RL}$is the magnitude of the full load receiving end voltage at the specified power factor. For a short line, $V_{R0} = V_s$ and $V_{RL} = V_R$ therefore

$$\% \, Regulation = \frac{V_S - V_R}{V_R} * 100 \tag{2.18}$$

From (2.16), (2.18) can be rewritten as

$$\% \, Regulation \cong \frac{I(\mathrm{R} \cos \theta_R + \mathrm{X} \sin \theta_R)}{V_R} * 100 \tag{2.19}$$

In the derivation above, θ_R has been considered positive for a lagging load. It will be negative for a leading load therefore 2.19 becomes rewritten as 2.20 for this case,

$$\% \, Regulation \cong \frac{I(\mathrm{R} \cos \theta_R - \mathrm{X} \sin \theta_R)}{V_R} * 100 \tag{2.20}$$

Voltage regulation becomes negative i.e. load voltage is more than no load voltage when in (2.20)

$$\mathrm{X} \sin \theta_R > R \cos \theta_R \xrightarrow{yields} \tan \theta_R > \frac{R}{X} \tag{2.21}$$

The regulation can also be rewritten in terms of active and reactive power from (2.19) and (2.20) given by (2.22) and rewritten as a change in voltage ΔV in (2.23)

$$\% \, Regulation \cong \frac{(PR \pm QX)}{V_R^2} * 100 \tag{2.22}$$

$$\Delta V \cong \frac{(P_r R \pm Q_r X)}{V_R} \tag{2.23}$$

From equations (2.19) it can be concluded that besides the impacts of resistance and inductive reactance on voltage regulation, voltage regulation is also dependent on the load power factor. Voltage regulation improves or decreases as the power factor of a lagging load is increased. Equation (2.23) can be interpreted as active power flowing through a resistance as well as a lagging reactive power flow through and inductance will cause a voltage drop. The equation also illustrates that leading reactive VAr flow through an inductance will cause a voltage rise as will active power being generated through a resistance.

In terms of a distribution feeder, the R and X components are fixed for a given conductor. The real power component of the load can also be viewed as fixed or specified however the reactive power component can be compensated at the load, decreasing the reactive power flow through a line. By inspection, if the reactive power reduces for a lagging load, regulation or change in voltage as expressed in (2.22) and (2.23) reduces, thus improving the voltage regulation of the feeder. A further conclusion is that by reducing the reactive power flow through a feeder, the total current also decreases which implies the technical losses in the line is expected to reduce, increasing the power delivery efficiency.

2.4 Transformer model

The function of a power transformer is to transform energy from one voltage level to another as well as ensuring that energy at load points is delivered at specified voltage values. The principle of operation of a power transformer is provided in [41] and is as a result of the mutual induction between the primary and secondary windings which are magnetically coupled by a common magnetic flux. When the primary winding is connected to an alternating voltage source, an alternating flux is produced. The amplitude of this flux depends on the primary voltage and number of turns in the windings. The mutual flux links the secondary winding and induces voltage in that winding. The value of the induced voltage depends on the number of secondary turns. The efficiency of a transformer depends on the extent through which the magnetic flux links primary and secondary windings [41].

2.4.1 Equivalent circuit of transformers

The models and theory of operation of transformers is contained in [41] and [42] and discussed in this section. The equivalent circuit of a transformer is shown in Figure 2-8 which consists of a series impedance branch (R_L, X_L) representing the resistance and reactance of the windings respectively. The parameters and values related to the secondary windings have been recalculated according to the transformer turns ratio and reflected to the primary side of the transformer. Since the voltage induced by the rate of change of flux in each turn of the transformer is the same, the voltage ratio between the two windings will be the same as the ratio of the number of turns given by (2.24).

$$\frac{E_1}{N_1} = \frac{E_2}{N_2}\ or\ \frac{E_1}{E_2} = \frac{N_1}{N_2} \tag{2.24}$$

Thus, the fundamental relationship is for a transformer is established i.e. the ratio of the primary and secondary voltage is equal to the ratio of the primary and secondary winding turns. Since power is the phasor product of voltage and current and the primary power is equal to the secondary, the relationship for primary and secondary current is developed and shown in (2.25).

$$E_1 * I_1 = E_2 * I_2\ or\ \frac{E_1}{E_2} = \frac{I_2}{I_1} \tag{2.25}$$

The conversion equations with regard to the secondary impedance values shown in Figure 2-8 are given in (2.26) to (2.30).

$$R'_{L2} = R_{L2} * \left(\frac{N_1}{N_2}\right)^2 \tag{2.26}$$

$$X'_{L2} = X_{L2} * \left(\frac{N_1}{N_2}\right)^2 \tag{2.27}$$

$$E'_2 = E_1 \tag{2.28}$$

$$R_L = R_{L1} + R'_{L2} \tag{2.29}$$

$$X_L = X_{L1} + X'_{L2} \tag{2.30}$$

The shunt impedance branch (R_M, X_M) represents the transformer iron loss and magnetizing circuit when referred to the primary. The parameters of the transformer equivalent circuit can be derived from electrical measurement as well as from the physical geometry of the transformer. The values of the shunt impedance branch (R_M, X_M) can be derived from an open circuit test. The series components (R_L, X_L) are derived by a short circuit test.

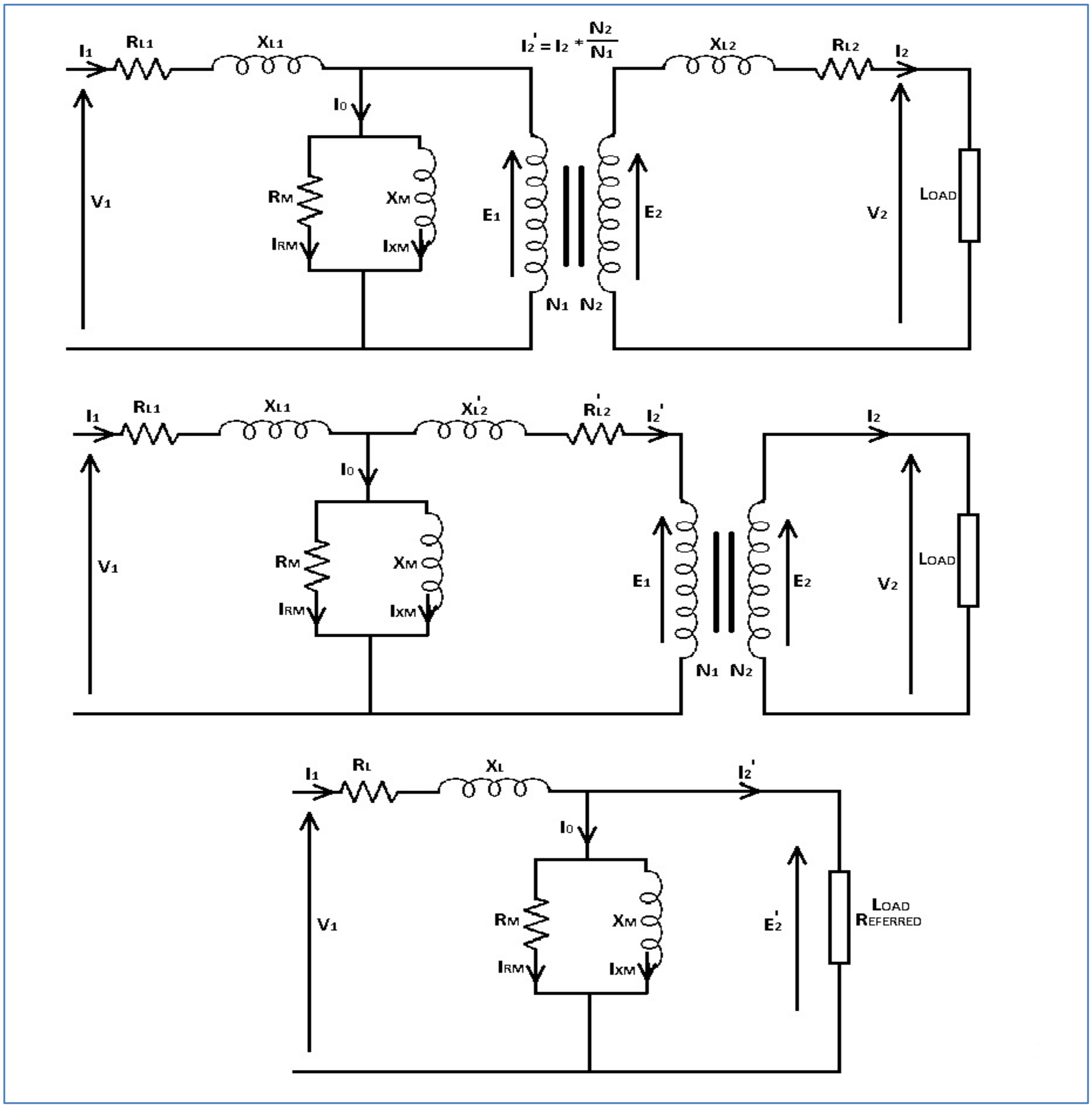

Figure 2-8: Transformer equivalent circuit and its simplification [41]

Under load conditions, the volt drop across the series impedance (R_L, X_L) is known as regulation. The leakage reactance is responsible, along with the resistance of the windings for the voltage drop within the transformer and is called the transformer impedance. The impedance is the percentage voltage drop across the transformer at rated current and can be calculated according to (2.31).

$$V_Z = Z_{\%} = \frac{I * \left(\sqrt[2]{R_L^2 + X_L^2}\right)}{E} * 100 \tag{2.31}$$

2.4.2 Voltage Regulation of a transformer

The voltage regulation of a transformer is defined for any load current as the arithmetic difference between the secondary no-load voltage E_2 and the load voltage V_2, expressed as a percentage of the no-load voltage as in (2.32).

$$\%\,Regulation = \frac{E_2 - V_2}{E_2} * 100 \tag{2.32}$$

In terms of circuit parameters given in Figure 2-8, this can be rewritten as (2.33) where Ø represents the phase angle between V_2 and I_2 , and R_2 and X_2 represent the total series resistance and reactance referred to the secondary winding respectively. The negative sign is used when the power factor is leading.

$$\%\,Regulation = \frac{I_2 * (R_2 \cos Ø \pm X_2 \sin Ø)}{E_2} * 100 \tag{2.33}$$

$$R_2 = R_{L2} * R_{L1} \left(\frac{N_2}{N_1}\right)^2 \tag{2.34}$$

$$X_2 = X_{L2} * X_{L1} \left(\frac{N_2}{N_1}\right)^2 \tag{2.35}$$

Current flow through the series impedance results in an internal voltage drop across the transformer. The regulation in a transformer given in (2.33) is analogous to (2.20) giving the regulation of a distribution line. For a transformer as for a line, voltage regulation is dependent on the magnitude of the load current, the load power factor and the impedance, in this case the series impedance of the transformer. Figure 2-9 illustrates the effect of load magnitude and power factor on internal voltage drop for a typical 10MVA transformer with an impedance of 11% and X/R ratio of 25 [42].

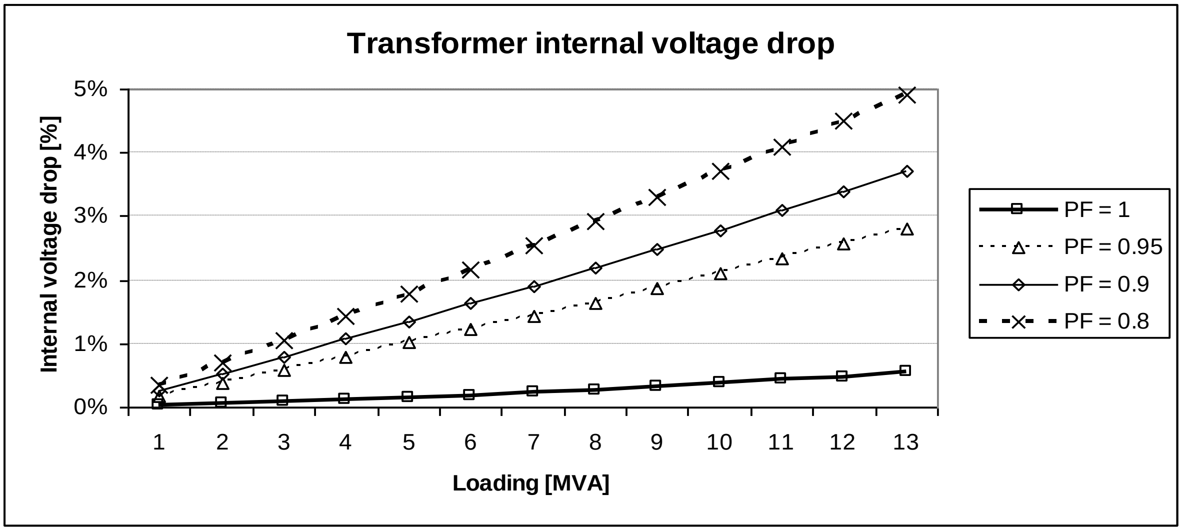

Figure 2-9: Typical 10MVA major power transformer internal voltage drop (Z=11%, X/R=25) [42]

2.4.3 Transformer Losses

Losses in a transformer are comprised of two components which are Load Losses and No-Load Losses. Load losses are determined mainly by the resistance of the transformer winding and to a lesser extent by the stray losses within the windings and structural parts of the transformer. The load losses are measured during a short circuit test. In the equivalent circuit of Figure 2-8, the load loss is related the series resistance R_L of the transformer and is given by (2.36).

$$\text{Load loss} \;=\; I^2 R_L \tag{2.36}$$

The No-Load losses are determined by the by the hysteresis losses (magnetization of the core) and eddy current losses within the core. These losses are influenced by the flux density, voltage, frequency and characteristics of the material used for core laminations. The no-load losses can be measured during an open circuit test. In the equivalent circuit of Figure 2-8, the no load losses are related to the shunt resistance R_M and is given by (2.37).

$$\text{No Load loss} \;= E^2 R_M \tag{2.37}$$

A transformer's total losses are therefore dependent on the load current and voltage once installed on the power network given that the series and shunt equivalent impedances are fixed at the design stage of the transformer. If the load current increases there will be an increase in the load losses dissipated through the series impedance as given by (2.36). With increases in load and the associated voltage drop as illustrated in Figure 2-9, if it is possible to adjust the turns ratio to obtain more secondary voltage, the increased voltage across the shunt impedance increase the no load losses as given by (2.37). The ability to adjust the secondary side voltage of a transformer will be discussed in section 2.3.4.

2.4.4 Transformer on load tap changers (OLTC)

Transformers are usually equipped with tap changers in order to regulate the secondary side voltage. The theory of operation is provided in [42] and discussed in this section. One of the windings has multiple tapping leads with each providing a different turns ratio between the primary and secondary windings. The tap changer is used to select one of these tapping leads. Each tap changer position selects a different tapping lead and hence different turns ratio. The voltage on the secondary of the transformer can be varied by changing the tap position given by the relationship in (2.24). The tap changer can hence be used to compensate for the voltage drops in the primary system and across the transformer itself. In interconnected systems tap changer settings will also influence reactive power flow.

Based on the transformer loss discussion in 2.3.3, a boost operation required to compensate for the voltage drops will reduce the transformer efficiency.

There are two main types of tap changer [42]:

- On Load Tap Changer (OLTC): An OLTC tap changer is a motorized tap changer fitted with a diverter such that the tap position can be changed with the transformer energized and supplying load. An OLTC tap changer is usually fitted with automatic voltage regulation relay whereby the secondary voltage is sampled and the tap position adjusted to keep the secondary voltage within specified limits. Alternatively the tap position can be changed via a remote control signal from a Distribution Control Center. OLTC tap changers improve the voltage regulation and power flow control of the network. OLTC tap changers also require maintenance (maintenance intervals are dependent on the insulation medium used in the diverter (oil or vacuum) and frequency of tap changer operation). OLTC tap changers are usually only installed on major power transformers ≥5MVA. In Eskom Distribution OLTC tap changers usually have a 1.25% step size and 17 tap positions providing a 5% buck and 15% boost range
- De-energized tap switch (DETS): A DETS is a manual tap selector switch where the transformer must be de-energized in order to change the tap position. The tap position

cannot be changed automatically or remotely operated. The tap switch is a simple mechanical switch with no motor or diverter, and the tap position can usually be locked in place via a padlock. DETS tap changers are usually installed on MV/LV distribution transformers, where the additional cost and maintenance of an OLTC tap changer cannot be justified. In Eskom Distribution DETS tap changers usually have a 2.5% or 3% step size and 5 tap positions providing a buck and boost range of ±5% or ±6%.

OLTC or DETS tap changers can be fitted to either the primary or secondary windings of power transformers. The location varies, but in general the tap changer tapings are located on the higher voltage winding where the load current is lower.

2.5 Medium voltage regulator model

The theory and operation of MV voltage regulators is provided in [43] and is discussed in this section. Lines have resistive and reactive impedance distributed over their length. Any current flowing along the line will result in a voltage drop over these impedances. As load current flows through the line, the current causes a resistance and reactance drop which when subtracted from the sending end voltage results in a receiving end voltage smaller than the sending end voltage. As the load increases, so the impedance voltage drop increases, and the receiving end voltage reduces. This is discussed in detail in 2.2.4 and the relationship is given by (2.19).

By installing voltage regulator on a line, the receiving end voltages can be raised (or lowered) to a desired value as illustrated in Figure 2-10. Voltage regulators are voltage sensitive and are usually automatically controlled and adjusted to maintain a constant output voltage. The theory and models that follow are contained in [43].

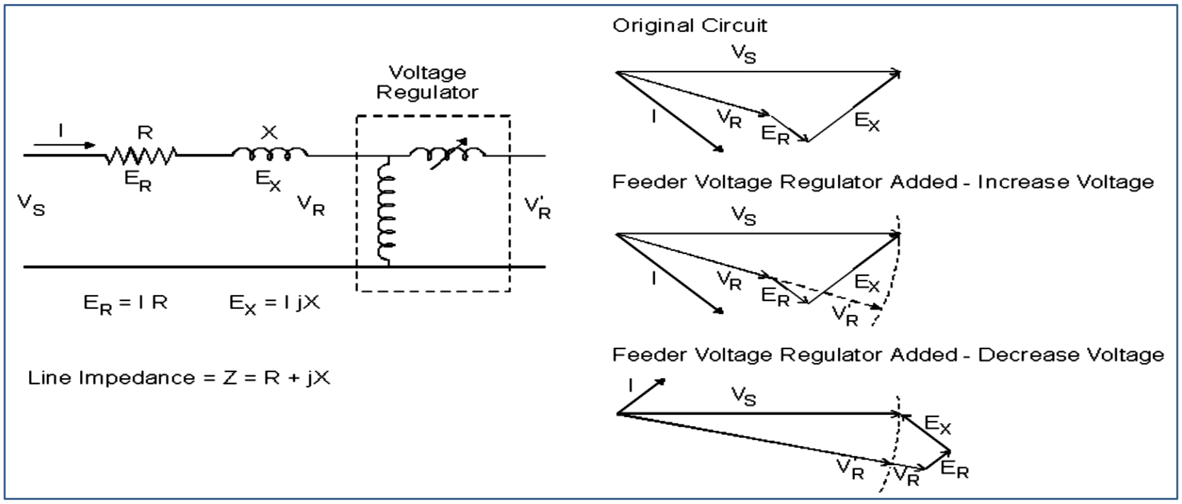

Figure 2-10: Principal of Voltage Regulator Operation [43]

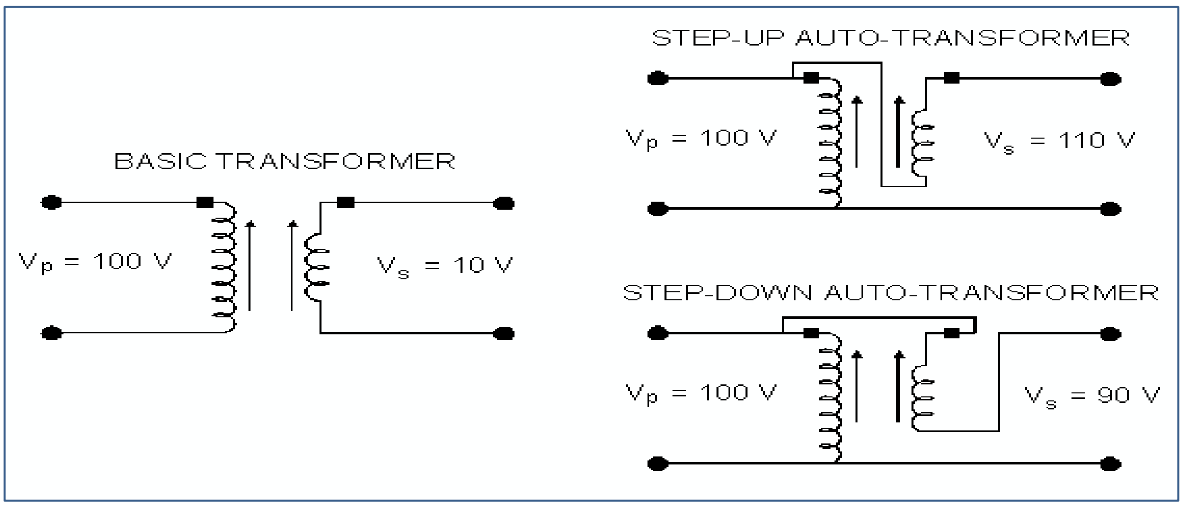

Figure 2-11: Basic Auto-Transformer Theory of Operation [43]

A step type regulator is an auto-transformer with a tap changer in which the primary and secondary windings are coupled both magnetically and electrically as indicated in Figure 2-11. If a two-winding transformer with a ratio of 10:1 is excited on the primary side with 100 volts, a voltmeter across the output terminals of the secondary side reads 10 volts. If the secondary winding is connected to the high side of the primary winding such that it will be in series with the line, the voltmeter on the output will read 110 volts (the sum of the induced voltages). This is a step-up auto-transformer (an input of 100 V is stepped up to 110 V).

When the series winding is connected such that the induced voltage in the series winding is opposite in phase to the primary winding, the voltmeter will read 90 V when 100 V is applied to the primary winding. This is a very crude regulator as the voltage can be either raised or lowered in one 10% step. A 10% step however is completely impractical due to the large scale voltage steps it would create. Finer regulation can be achieved by switching the series winding in smaller increments.

By tapping the series winding into multiple and equal steps, the voltage can be varied in small steps. The number of tap changer steps is limited to number of series winding taps, eight in the example illustrated in Figure 2-12. By installing a switch to reverse the polarity of the series winding, the regulator can both raise and lower the output voltage. A centre tapped bridging winding is also introduced to provide a seamless transition between tap positions without any high circulating currents. The bridging windings also enable the tap changer to tap the potential between two tap positions on the series winding. As a result the voltage step is halved resulting in 16 steps both up and down.

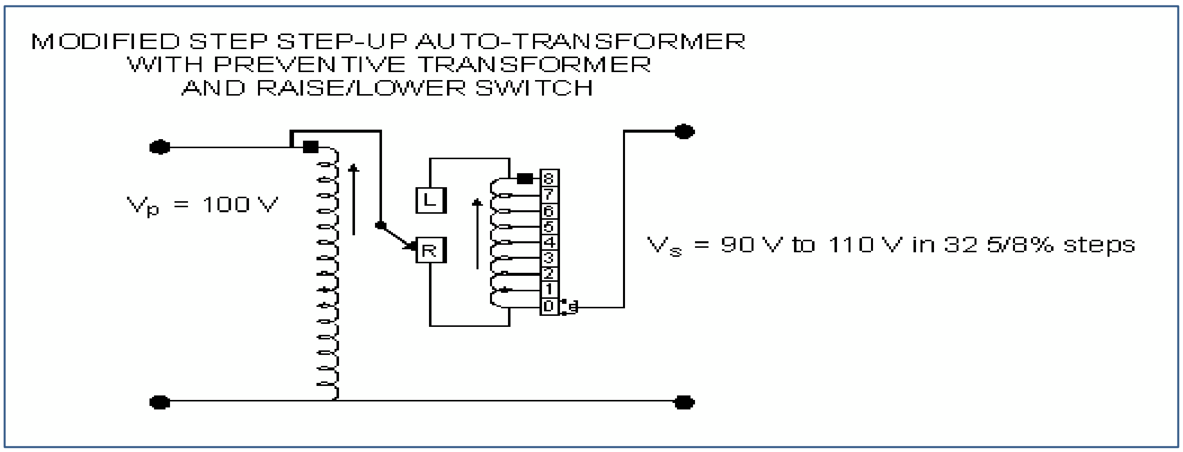

Figure 2-12: Modified Auto-Transformer Operation with Raise/Lower Switch and Bridging Transformer [43]

Voltage regulators incorporated on MV distribution networks are single phase units connected in either closed delta or open delta configuration as show in Figure 2-13 below. The open delta configuration allows the voltage to be adjusted by ±10% in steps of 0.625% and the closed delta configuration offers adjustment of ±15% in steps of 0.9375%.

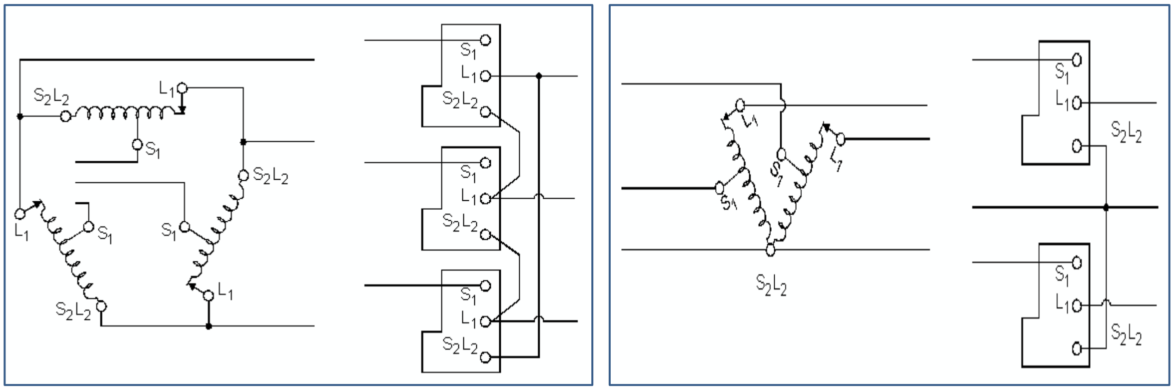

Figure 2-13 : a) Closed delta Configuration [43] b) Open delta Configuration [43]

The relationship of primary to secondary voltages and currents are given by (2.38) and (2.39) where n is the addition voltage in p.u. per tap change and T is the current tap position.

$$V_{sec} = V_{pri}(1 + nT) \tag{2.38}$$

$$I_{sec} = \frac{I_{pri}}{nT} \tag{2.39}$$

In a closed loop system with a controller, the controller will maintain the secondary voltage with a certain range, if this range is violated, the controller will initiate a tap, either up or down.

2.5.1 Regulator Losses

In a regulator, the shunt winding is connected across the source and as a result the voltage across this winding (and hence the no-load losses) will vary with the source voltage. When the regulator is bucking due to a high source voltages, the no-load losses will be relatively high. When the regulator is boosting due to a low source voltages, the no-load losses will be relatively low.

The series winding is connected on the load side, after the shunt winding. Load losses in the series winding are caused by the load current flowing through the portion of the series winding that is in circuit. When the regulator is in a neutral position the series winding is not connected and there is zero load loss in the series winding. As the regulator starts to buck or boost, so the amount of series winding in circuit increases linearly with the tap position, and the load losses increase. Note that the load losses are symmetrical about the neutral tap position. This relationship is illustrated in Figure 2-14.

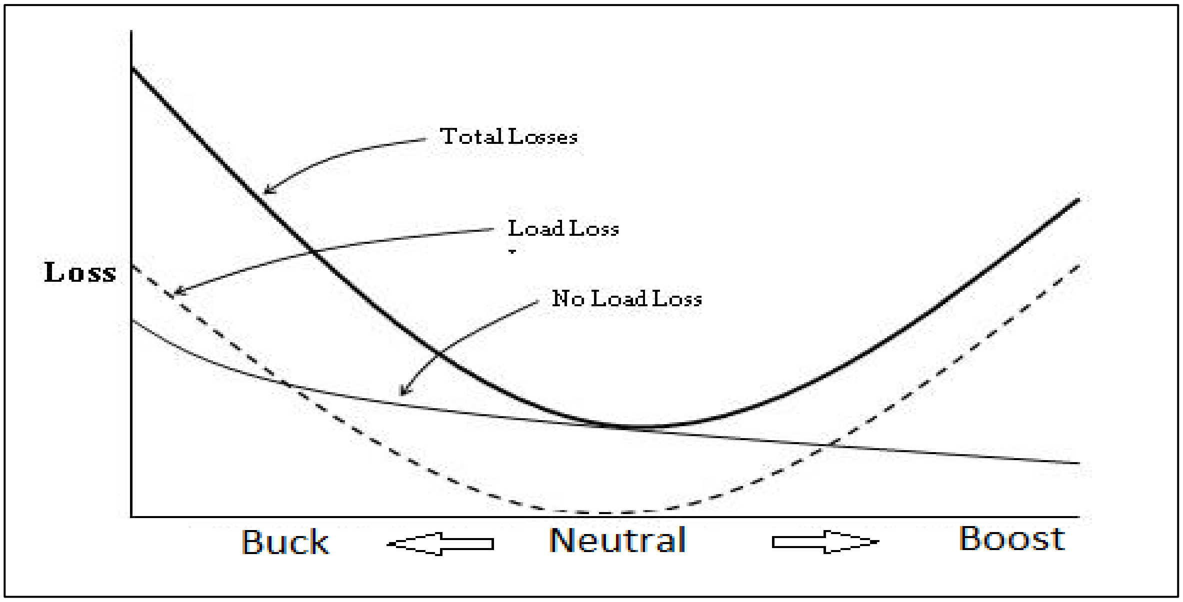

Figure 2-14: Relative Losses for a Voltage Regulator at various tap positions [43]

In summary, when regulators are employed to provide constant load voltages, the regulator's losses will vary depending on the degree of boost or buck.

2.6 Conclusion

In this chapter, a literature review of system losses as well as the basic theory and operations of the various network components of the power delivery system were discussed.

Losses were reported to add between 6-8% to the cost of electricity and 25% to the cost of delivery. The total technical loss in Eskom's distribution system has been estimated to be 4.7% nationally. Various techniques to minimise technical losses were presented.

Emphasis was placed on lines, transformers and voltage regulators which are the fundamental components making up the sub-transmission and distribution power networks that impact upon both the voltage regulation and electricity delivery efficiency.

From the analysis of lines it was concluded that the short line model consisting only the series impedance components would be sufficient to model and study voltage regulation and efficiency of distribution lines. The method for calculating a line voltage drop and voltage regulation was developed. The impact that the magnitude of load current and load power factor has on a feeders voltage drop was shown. It was also concluded by mathematical derivation that injecting a leading reactive current (capacitive) through lines natural inductive impedance will result in an improvement in voltage drop across the line. Furthermore, the capacitive compensation will reduce the load current as seen by the source which is expected to reduce the technical losses on the line. These conclusions then, prompts analysis of reactive power compensation as a means to improve feeder voltage regulation and reduce feeder technical losses which will be investigated in subsequent chapters of this research.

The basic theory and operation of transformers was presented. Through mathematical derivation, it was shown that the transformer internal voltage regulation is analogous to that of a line i.e. it is impacted by the magnitude of load current as well as the load power factor.

A brief explanation of an OLTC was given. It was concluded that for boost operations required to raise voltage that the efficiency of the transformer is reduced i.e. transformer internal losses are increased. It would therefore be beneficial to investigate other means of voltage improvement and minimize or limit tap changer operation from a loss point of view which has the positive spinoff in terms of tap changer and transformer maintenance. This will lead to more efficient operations of the power delivery network which will also form part of the research in subsequent sections.

The theory and operation of voltage regulators used to regulate distribution feeder voltages was shown. The control methods for the different configurations were discussed. The loss in efficiency at the various levels of buck and boost were also discussed.

The research will thus evaluate voltage and VAr management techniques to improve voltage regulation and reduce technical losses on the power delivery system. The research will focus on medium voltage distribution feeders where it is anticipated that the bulk of the regulation and efficiency problems lie on the power delivery system.

3 Assessment of the operating voltage regulation requirements in South Africa

In designing electric power networks or implementing major expansions to existing networks, a number of the key issues regarding the technical performance of the network at both transmission and distribution level must be ascertained. These include [44]-[46]:

(i.) Voltage regulation
(ii.) Voltage fluctuations (including rapid voltage rise, RVR)
(iii.) Electrical losses
(iv.) Distribution plant loading and utilization
(v.) Fault level
(vi.) Generation stability
(vii.) Harmonics
(viii.) Phase balancing
(ix.) Supply availability and
(x.) System security

Studies and analysis are conducted from time to time to ascertain the operating state of a network, taking into account load growth projections for the future. Undue stresses on the system or anticipated problems are determined from power flow analysis or during operation and maintenance. Such analysis include an assessment of the voltage profile, voltage regulation and fluctuations, magnitude of electrical losses, distribution plant loading and utilization, fault analysis, generation stability, the level of harmonics in the system, supply availability and system security.

3.1 South African quality of supply standards

The South African quality of supply (QOS) standards have been developed to provide specifications for QOS parameters such as voltage compatibility levels, voltage limits and voltage characteristics, which is to be used by utilities, customers, and the National Electricity Regulator (NER) as a basis for evaluating, maintaining and managing quality of supply. The focus area of this chapter is limited to voltage regulation as a major component in the Quality of Supply regulatory documents

3.1.1 Voltage compatibility levels and limits

Voltage compatibility levels and limits are specified in [47], the NRS 048-2 standard. The standard voltage for customers supplied at LV is 400 V phase to phase and 230 V phase to neutral [47]. For customers requiring supply directly at MV, HV or EHV levels, supply agreements are drawn up between utilities and customers where the required nominal supply voltages as well as declared voltages are specified.

Table 3-1 lists the compatibility levels for the magnitude of supply voltages that must be followed in the absence of any special voltage agreements written out in supply contracts between utilities and customers. For nominal system voltages greater than 500V, the supply voltage is not to deviate from the nominal voltage by more than 5% for any period longer than 10 consecutive minutes [47].

Table 3-1: Deviation from standard or declared voltages [47]

Voltage level (V)	Compatibility level (%)
< 500	± 10

Table 3-2 and Table 3-3 indicate the maximum permissible voltage limits which have been introduced to safeguard equipment against extreme exceedances of design specifications that could either lead to failure or deterioration of lifespan of equipment.

Table 3-2: Maximum deviation from standard or declared voltages [47]

Voltage level (V)	Limit (%)
< 500	± 15
≥ 500	± 10

Table 3-3: Maximum voltages for supplies to customers above 500 V [47]

Nominal Voltage (kV)	Maximum Voltage (kV)
400	420
275	300
220	245
132	145
88	100
66	72.5
44 and below	Nominal voltage + 10 %

The compatibility levels and limits specified in the NRS 0848-2 apply only at the customer's point of supply. The utility may choose not to meet these levels and limits at other nodes in the utility network where there are no direct customer supplies.

3.1.2 Guidelines for operating voltage ranges in South Africa

QOS application guidelines for utilities are specified in [48], the NRS 048-4 standard. Since in [47] it is stipulated that supply voltages do not deviate from the nominal voltage by more than 10% for LV connections as given in Table 3-2, feeder design is based on a maximum voltage variation of ±10% of the nominal voltage at the point of supply for the furthest end of line LV customer. This implies that the total voltage variation the end of line customer could experience must not exceed 20%.

Table 3-4 is a guideline in [49]; the NRS 034-1 which lists typical design considerations from MV down to LV for contributions of the various sections of the network expressed as percentages of nominal voltage to the percent voltage variation for the furthest end of line LV consumer. The guidelines for the calculation of voltage drop in distribution systems in [49] should be followed for South African distribution licensees.

Table 3-4: Voltage variation contributions expressed as percentages of nominal voltages to the percent voltage variation of furthest LV customer [49]

MV Source (with OLTC)	3%
MV Feeder	3%
MV/LV Transformer	2%
LV Feeder	8%
Service Connection	2%
Total	18%

These considerations allow for a small reserve over the maximum permitted fluctuation at the consumer's point of supply, which takes into account that the MV source might not be operated at +10 % of nominal voltage. Where an LV system is supplied by a long MV feeder, typical on rural overhead lines, the voltage variation on the MV feeder might be higher, in which case a lower percentage voltage variation will have to be adopted for the LV feeder and service connection. The practical design parameters should be based on compliance with the minimum standards for voltage regulation as set out in NRS 048-2 [49].

The standards in [47]-[49] also recognise the statistical nature of loads, especially in instances where there is significant domestic type load making up a feeder with pronounced morning and evening peaks. Network design engineers will have to make decisions on an economic basis, such that infrastructure is optimally utilized, while providing customers with acceptable voltage regulation for the majority of the time. In practice, customers at the extreme ends of feeders may experience voltages outside the prescribed limits for short periods during times of peak or minimum load [48].

In all cases, networks should be designed and operated to meet the requirements of NRS 048-2. In particular, utilities should ensure that their large customers have voltage regulation and power factor correction equipment that operates correctly, to avoid over or under voltages in a customer's network being transmitted to the utilities network. This is important not only to avoid other customers being affected by the abnormal voltage, but also to ensure that the life expectancy of plant, particularly transformers, is not reduced [48].

An illustration of the rapid deterioration of transformer life (mean time to failure) with excessive operating voltage (U) is given in [48] shown in Figure 3-1.

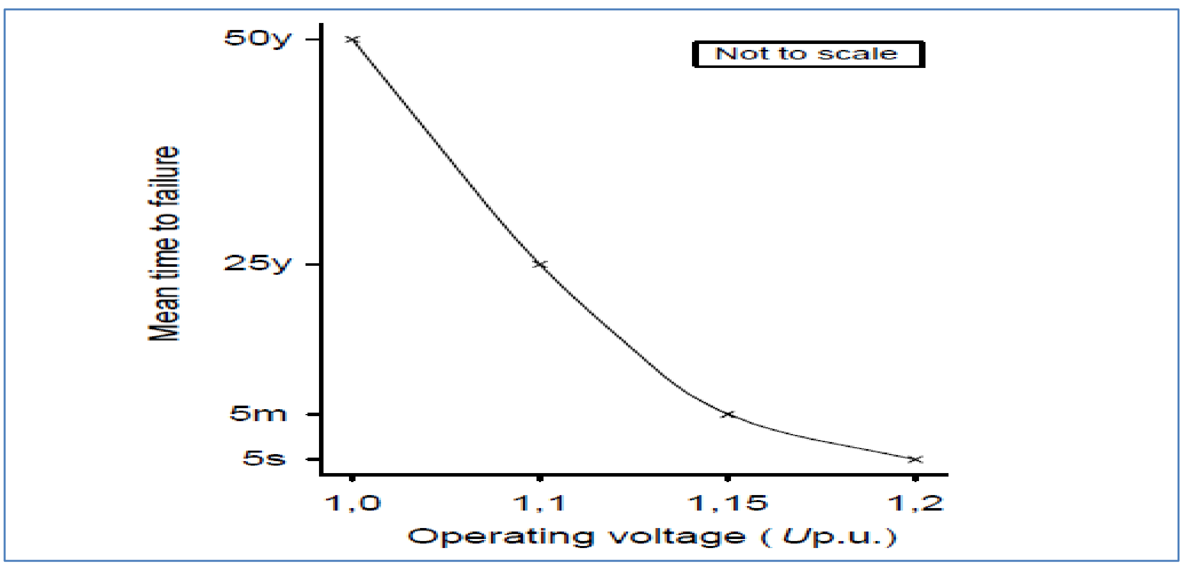

Figure 3-1: Illustration of the rapid deterioration of transformer life with excessive operating voltage [48]

3.2 South African Distribution grid code pertaining to voltage management

The primary objectives of the grid code stipulated in [50] and [51] from a planning, design and operations perspective is to ensure the following:

- To set the basic rules of connecting to the Distribution System.
- To specify the technical requirements to ensure the safety and reliability of the Distribution System.
- To set out the responsibilities and roles of the participants as far as the operation of the Distribution System is concerned and more specifically issues related to:
    - economic operation, reliability and security of the Distribution System
    - management of power quality
    - operation of the Distribution System under normal and abnormal conditions

The responsibility of the Distributor is to conduct system impact assessment studies to evaluate the impact of additional loads or embedded generation or major modification to the distribution system. The assessment conducted shall include the following where relevant:

- Voltage impact studies
- Impact on network loading
- Fault currents
- Coordination of protection systems
- Impact on the system's quality of supply
- Strengthening of the system

The Distributor shall refuse to connect any facility which the distribution impact assessment studies indicate will have a deleterious effect, exceeding the parameters laid down in the NRS 048 standards and the NERSA Power Quality Directive, when connected to the network.

The Distributor and other participants shall comply with NRS048 standards and NERSA Power Quality Directive regarding the parameters listed below:

- Voltage regulation
- Voltage unbalance
- Voltage harmonics and inter-harmonics

- Voltage flicker
- Voltage dips
- Voltage surges and switching disturbances

With regards to load power factor, customers with demand exceeding 100kVA shall ensure that the power factor shall not be less than 0.9 lagging nor shall it go leading unless otherwise agreed to with the relevant Distributor. Should the power factor go beyond these limits, participants shall take corrective action within a reasonable timeframe or as agreed between the parties, to remedy the situation.

In addition, the Distributor shall co-ordinate voltage control, demand control, operating on the Distribution System and security monitoring in order to ensure safe, reliable, and economic operation of the Distribution System. The Distributor shall operate the Distribution System within defined technical standards and equipment operational ratings. Customers shall also assist the Distributors in correcting quality of supply problems caused by the Customer's equipment connected to the Distribution System.

3.2.1 Assessments and procedures for Grid Code compliance

Through operational liaison, it was observed that most Distributors do not strictly comply with the requirements of the South African Grid codes. To ensure compliance to the System Operating and Network codes within Eskom Distribution, research was done to incorporate specific tasks, procedures and processes into the job specifications and duties of operation engineers. This is summarized in section 3.2.1.1. Section 3.2.1.2 provides a practical application on the concept of improving network performance by minimizing faults and providing effective methods for fault location and protection coordination.

3.2.1.1 The Distribution Network Operation and planning guideline [10]

A portion of this research has been involved in the development of study procedures aimed at providing technical support and guidance to Eskom's Distribution control centers, for the operational management of distribution networks. Embedded generation has added to the complexity of the distribution system, an environment new to both Operations engineers and Control room operators in Eskom Distribution. Study procedures to operationally manage distribution network including networks with embedded generation was developed to ensure that the stability and security of the distribution system is managed effectively [10].

The objective of the procedures is to maintain the power system within operating technical specification during both the normal and abnormal states of the network. Limit compliance, both steady state and dynamic, in terms of voltage, thermal loading, fault level and other grid code specifications are the primary areas of concern to operations engineers. The procedures are defined for daily, occasional and annual assessments. The bulk of the assessments are by means of power system simulation. Since Eskom Distribution makes use of the DIgSILENT Powerfactory simulation tool, the study procedures have been tailored for use in DIgSILENT, including tutorial material.

The daily procedures consists model verification and calibration to suite the specific day, an assessment of system fault levels, the determination of control modes for embedded generation, a contingency sweep of plausible system abnormalities and then dynamic simulations. The steps are iterative so any violation or change required prompts a re-initialization of a basic load flow with a re sweep of assessments. Once the operations engineer is satisfied, changes are implemented and plans are made available for future contingent states.

3.2.1.2 Performance Evaluation of Traction and Utility Network Interface: Fault Location and Protection Coordination [12]

Single phase AC traction systems pose unique challenges to power utilities at interface points of connection on the power delivery network. Traction systems are usually supplied from dedicated utility networks in order to minimize the associated negative effects on conventional three phase loads, particularly in instances where customer equipment may be sensitive to the quality of supply. The dedicated power utility network however, is exposed to faults, short duration thermal overloads, temporary overvoltage, high magnitude transient recovery voltages, load unbalance and harmonics which emanate from the traction system [12].

A method for the determination of fault location and effective discrimination between power utility and traction network faults was developed that is particularly useful in instances where there is a lack of protection coordination or difficulty in achieving coordination between the protective devices between systems [12]. The lack of protection coordination for the networks under study resulted in the utility network feeders tripping for traction system faults which lead to unnecessary outages, line patrols and investigations. Fault current "look up charts" were developed by power system simulation that a utility engineer can use to locate faults and take appropriate action. The method involves interrogation of measurement recordings that can be placed on the fault charts for location, thus making it simple to distinguish between utility and traction faults.

The method was further developed into a protection coordination philosophy by translating the fault current charts into the impedance plane. By the manipulation of the impedance reach settings, multiple utility relays can be configured to "see" or "not see" a particular fault. For a traction fault, if only a single utility relay reaches into a fault, a block signal will be instituted as the fault will be identified to be within the traction system. If the traction systems protective devices do not clear this fault in the necessary time, the utility breakers will operate in delayed time.

3.3 Voltage apportionment and associated limits used within Eskom Distribution

The planning and design criteria for voltage regulation on MV feeders within the Eskom distribution network involving voltage apportionment and limits are discussed. Eskom has defined a number of voltage apportionment limits depending on the type of network and voltage control employed in [52]. The voltage apportionment limits between the MV and L V portions of a feeder are set to ensure that LV supply voltages comply with the ± 10% limit defined in the NRS-048-2-2008 [47].

A network class is defined by the ratio of voltage drop apportionment between the MV and LV portions of a feeder where each distribution network can be classified into a specific class (C) and tap zone (TZ). The tap zone is defined by the maximum voltage experienced by a specific portion of network during minimum load. A distribution feeder can be subdivided into different network classes and tap zones depending on the voltages experienced at different locations on the network. The consideration of the different combinations of networks, distribution transformers, and target service voltage limits in Eskom Distribution has resulted in four natural groupings (classes) of allowable maximum MV and LV network voltage apportionment drops which is discussed in Table 3-5 and illustrated in Figure 3-2 showing the difference between classes graphically:

Table 3-5: Network Classes [52]

Network Class	Typical network type	Typical load density (after diversity)	Comments
C1: MV voltage drop is typically one-third of the LV voltage drop	Urban, but can also be used in rural networks with good MV voltage regulation	>200kVA/km^2	There are no restrictions on the distribution transformers
C2: MV voltage drop is typically equal to the LV voltage drop	Rural networks with urban type loads, but can also be used in urban networks with relatively poor MV voltage regulation	<200kVA/km^2	There are no restrictions on the distribution transformers
C3: MV voltage drop is typically double the LV voltage drop	Rural with no significant electrification (urban) type load	<100kVA/km^2	Should not be utilised in networks containing 380/220V transformers
C4: MV voltage drop is typically triple the LV voltage drop	Rural with no electrification (urban) type load	<100kVA/km^2	Should not be utilised in networks containing 380/220V or 400/230V transformers

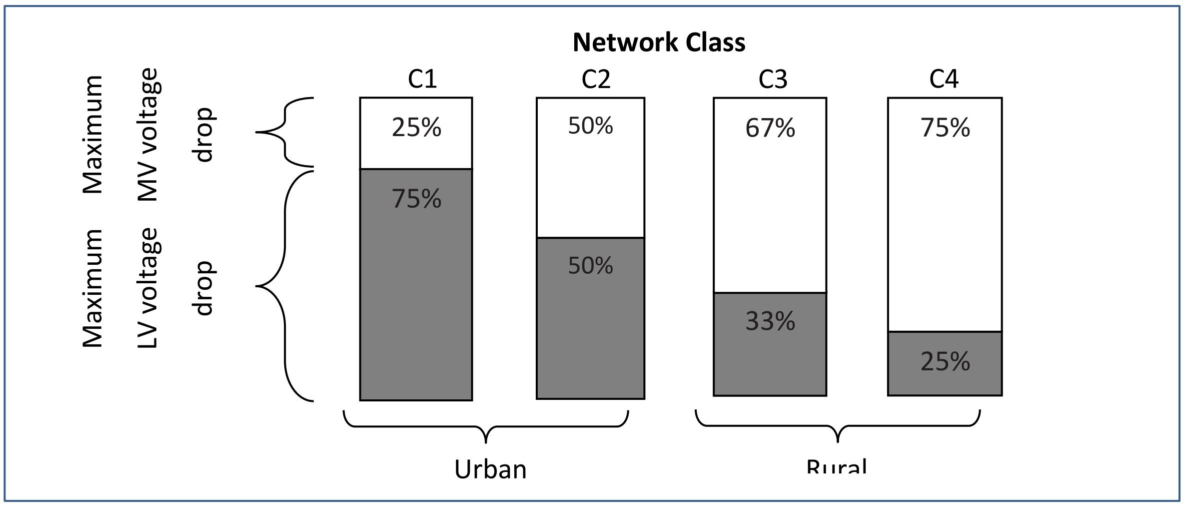

Figure 3-2: Apportionment of the maximum voltage drops in MV and LV for four Network Classes [52]

Classes C1 and C2 will typically be used in urban networks where the voltage drop in the MV network is relatively small and the LV voltage drop can be large. The transfer capacity of most urban MV networks is limited by thermal constraints.

Classes C3 and C4 will typically be used in rural networks, where the LV network voltage drop is relatively small and a larger allowance is made for the MV voltage drop, which is usually the constraint on the capacity of a rural MV feeder. The C4 class is seldom used, but would be used on rural feeders that do not supply any urban load.

Portions of the network are also classified into regions called tap zones (TZ). Tap zones specify (DETS) de-energized tap switch setting for MV/LV transformers connected within a zone. Three levels of tap zones are defined for Eskom distribution networks. Each TZ is defined by an upper and lower voltage range. The minimum voltage limit is dependent on the network class. The voltage limits ensure that the range of voltage experienced on the LV network falls within the LV voltage limits of ±10% of nominal voltage. The MV/LV transformer taps are configured based upon the expected tap zone at that point in the network. Table 3-6 shows the MV voltage limits for each network class and tap zone. The tap zone and network class is defined for a portion of network by determining the maximum voltage during minimum load and the minimum voltage during maximum load. The abnormal limits are used when evaluating network contingencies such as temporary network reconfiguration. In general most networks in Eskom distribution has been classified as C2 using TZ2 as the standard tap zone.

Table 3-6: Voltage apportionment limits per tap zone per network class [52]

Network Class		Maximum Voltage			Minimum Voltage		
		TZ1	TZ2	TZ3	TZ1	TZ2	TZ3
C1	Normal	105%	103%	100%	101.5%	99.5%	97%
	Abnormal	106%	105%	102%	99.5%	97%	94.5%
C2	Normal	105%	103%	100%	98%	95.5%	93.5%
	Abnormal	106%	105%	102%	95.5%	93.5%	91%
C3	Normal	105%	103%	100%	95.5%	93%	91%
	Abnormal	106%	105%	102%	93%	91%	88.5%
C4	Normal	105%	103%	100%	92.5%	90%	87.5%
	Abnormal	106%	105%	102%	90%	87%	85%

3.4 Voltage operating points for Eskom's Sub-transmission and Distribution System

Based on the voltage limits stipulated in the quality of supply standard in [47] as well as the voltage apportionment limits that have been designed for Eskom distribution feeders in [52], suitable HV/HV and HV/MV transformer set points with bandwidth settings for on load tap changer schemes have been specified in Table 3-8 to Table 3-11 as part of this research for the various categories of networks so that source voltages are controlled to ensure statutory voltage requirements. Further, provided that necessary monitoring devices (e.g. VT's and transducers for voltage analogs) have been placed on the networks with communication links back to the Distribution Control Centre SCADA systems, appropriate alarms limits have also been specified to enable operational action by power system controllers in attempts to manage voltage regulation within limits especially during system abnormalities or unplanned events. The abbreviations used in Table 3-8 to Table 3-11 are provided in Table 3-7.

Table 3-7: Abbreviations used in Tables 3-8 to 3-11

Abbreviation	Description
[]MIN	Absolute Minimum Statutory Limit
LLL	MV Tail End Lower SCADA Alarm Limit
LL	Bus bar Lower SCADA Alarm Limit
TCL	Tap changer Lower Bandwidth Limit
STP	Tap changer Voltage Set point
TCU	Tap changer Upper Bandwidth Limit
UL	Bus bar Upper SCADA Alarm Limit
[]MAX	Absolute Maximum Statutory Limit

Table 3-8: Transformer tap changer set points for HV/HV transformers, SCADA alarm limits and HV bus bars

Characteristics of HV networks	HV SUPPLIES (all units in % voltage)						
	[]MIN	LL	TCL	STP	TCU	UL	[]MAX
HV networks feeding customers taking supply at HV without voltage supply contracts	95	97	100.50	102	103.5 0	104	105
HV networks feeding customers taking supply at HV with voltage supply contracts	92.5	94	102.50	104	105.5 0	106	107.5
HV networks with no HV Customers, feeding shared multiple HV/MV substations where MV regulation is poor, typically C3 and C4 MV networks	92.5	94	102.50	104	105.5 0	106	107.5
HV networks with no HV Customers, feeding shared multiple HV/MV substations where MV regulation is good, typically consist C1 and C2 MV networks	88.5	90	102.50	104	105.5 0	106	107.5

Table 3-9: TZ1 transformer tap changer set points for HV/MV transformers, SCADA alarm limits for MV substation bus bars and MV end of line voltage

CLASS		MV TZ1 supplies (all units in % voltage)							
	MV:LV	[]MIN	LLL	LL	TCL	STP	TCU	UL	[]MAX
C1	25:75	99.5	101	101	101.50	103	104.50	105	106
C2	50:50	95.5	97	101	101.50	103	104.50	105	106
C3	66:33	93	95	101	101.50	103	104.50	105	106
C4	75:25	90	92	101	101.50	103	104.50	105	106

Table 3-10: TZ2 transformer tap changer set points for HV/MV transformers, SCADA alarm limits for MV substation bus bars and MV end of line voltage

CLASS		MV TZ2 supplies (all units in % voltage)							
	MV:LV	[]MIN	LLL	LL	TCL	STP	TCU	UL	[]MAX
C1	25:75	97	99	100	100.50	102	103.50	104	105
C2	50:50	93.5	95	100	100.50	102	103.50	104	105
C3	66:33	91	93	100	100.50	102	103.50	104	105
C4	75:25	87	89	100	100.50	102	103.50	104	105

Table 3-11: TZ3 transformer tap changer set points for HV/MV transformers, SCADA alarm limits for MV substation bus bars and MV end of line voltage

CLASS		MV TZ3 supplies (all units in % voltage)							
	MV:LV	[]MIN	LLL	LL	TCL	STP	TCU	UL	[]MAX
C1	25:75	94.5	96	98	98.00	99.5	101	101.5	102
C2	50:50	91	93	98	98.00	99.5	101	101.5	102
C3	66:33	88.5	90	98	98.00	99.5	101	101.5	102
C4	75:25	85	87	98	98.00	99.5	101	101.5	102

These settings and alarm limits have been implemented in Eskom's Kwa-Zulu Natal operating unit. A single setting has been applied for all HV networks for the following reasons:

- All customers fed directly from the HV network have voltage contracts in place where a maximum deviation of ±7.5% of nominal voltage has been specified.
- With networks supplying the majority of MV systems with poor voltage regulation (long highly loaded rural type feeders), HV set points apply as in the case above. This is indicated in
- Table 3-8 and has been highlighted in yellow.

A large proportion of the MV feeders in Eskom have been classified as C2 TZ2 where the set points are indicated in Table 3-10, highlighted in yellow, and have been implemented. Although the bulk of the distribution feeders in Eskom's Kwa Zulu Natal operating unit consists rural type feeders, these feeders are excessively loaded resulting in large MV voltage drops where the voltage apportionment between MV and LV similar to the C2 classification, arise.

3.5 Conclusion

A summary of the South African quality of supply standards and grid codes pertaining to voltage management was discussed in this chapter. Statutory limits for the various voltage levels were specified as well as guidelines for utilities during the planning, design and operational phases. The voltage apportionment method and associated limits used on Eskom Distribution networks was also discussed which gave rise to the implementation of HV/HV and HV/MV transformer set points and alarm limits for the operation management of voltage in distribution control centers.

Given the operational technical specification for voltages on the utility system for the various voltages levels (HV, MV and LV), the next chapter will explore approaches in distribution efficiency by the control of voltage and reactive power flow.

4 Current Volt/VAr optimization techniques and approaches

4.1 The objectives of Volt/VAr optimization

Approximately 10% of the energy produced by generation stations is lost during transmission and distribution to customers [53]. An estimated 60% of this loss occurs on distribution networks [54], [13]. As the demand for electric energy increases, power stations would need to be built and the power delivery systems would need to be expanded and/or strengthened to meet growing demands. Peak demands in a system usually lasts less than 5 percent of the time [53]. This means that some power plants may only be needed during the peak load hours where their productive capacity is utilized only occasionally. Similarly the power delivery system would be stressed only during peak periods and in some instances past the operation technical specifications of equipment. By active demand control and technical loss minimization strategies on distribution systems, the generation requirements for the grid can be reduced. Further, by freeing up capacity on the delivery system, additional load can be connected to the grid at reduced or no additional capital strengthening costs. To the environment, this implies reductions in carbon emission as well as reductions in the cost of electricity to end use customers [53].

The purpose of Volt/VAr control is to improve the efficiency of the power delivery system. This essentially involves the control of network equipment such as transformer OLTCs, capacitor banks and voltage regulators as shown in Figure 4-1 [55], in order to control the reactive power flow and manipulate the voltage regulation of feeders or subsystems which results in technical loss minimization and the ability to actively control demand.

By controlling and limiting the reactive power flow on the delivery system, losses can be reduced thereby improving the efficiency of distribution feeders. The ability to optimize the power factor on a network implies the utility has to generate and transport less power to meet demand requirements. This is achieved by the strategic placement and control of shunt capacitor banks on the system where an additional benefit is improvement in voltage regulation.

By improving the voltage regulation of feeders, demand can be reduced by purposefully reducing source voltages and exploiting the voltage dependent characteristics of load whilst maintaining statutory voltage limits. This technique is termed Conservation Voltage Reduction (CVR). A general rule of thumb is that reductions in demand between factors of 0.7 % to 1.5% are obtainable for every 1% reduction in voltage [56].

Equipment		Grid Locations	Grid Functions
Load tap changers		Substation transformers	Adjusts feeder voltages at the substation
Voltage regulators		Distribution feeders or substations	Adjusts voltages at the substation or along the feeder
Capacitor banks		Distribution feeders or substations	Compensates for reactive power and provides voltage support

Figure 4-1: Equipment for Voltage Support and Reactive Power Control [55]

Volt/VAr optimisation has been made possible through recent improvements in sensors, communications, control algorithms, and information processing technologies that monitor voltage levels throughout the distribution system [55]. Most devices required for Volt/VAr optimization is already in place in most utilities (e.g. capacitors, on load tap changers, voltage regulators) that serve local purposes however the requirements for further enhancement and optimal use of these devices involves communications and software solutions which becomes an enabler for more system wide control and optimisation.

Figure 4-2 illustrates the concept of Volt/VAr control. The baseline voltage regulation is manipulated by the substation on load tap changer, the line voltage regulator as well as the capacitor that has been placed towards the end of the feeder. In order to reduce the voltage at the substation for the purposes of CVR, the line voltage regulator must ensure that the tail end of the feeder is still within the statutory voltage requirement, in this case 114V after the substation voltage has been reduced. The capacitor has bank twofold benefit, whilst it reduces the reactive component making up the technical loss of the feeder; it also raises the voltage at the point of connection and has a flattening effect on the regulation profile. This then allows the voltage to be reduced even further at the source for a more “aggressive” demand reduction by CVR.

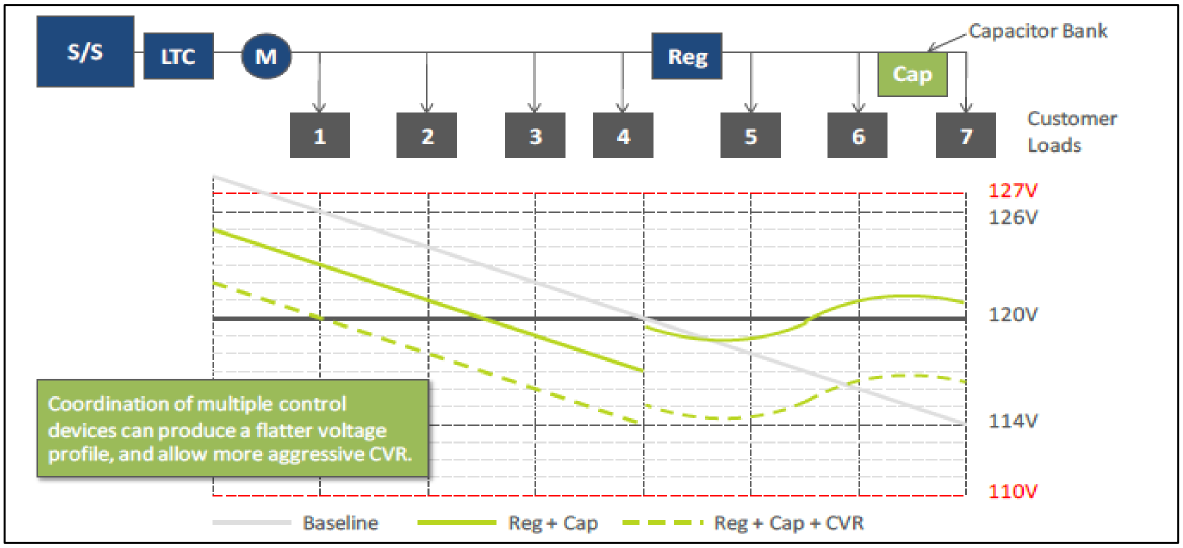

Figure 4-2: Feeder Voltage Profile showing nominal, normal and statutory voltage limit for a feeder with an OLTC, Voltage Regulator and Capacitor Bank [55]

With the application of Volt/VAr optimisation, the following benefits can be achieved:

- Improvements in the efficiency of the delivery system
- Improvements in voltage regulation of feeders
- Reductions in peak demand and the ability to selectively control demand
- Deferral of capital expenditure and improved capital asset utilization
- Reductions in electricity generation and environmental impacts
- Provision for greater operational flexibility to reduce the impacts of local network abnormalities such as line contingencies

The potential benefits depend on the specific applicability to local network conditions and characteristics. Uncertainties facing utilities that wish to incorporate Volt/VAr optimisation in their systems are summarised in the following questions [56]:

- What selection criteria to apply to determine which feeders to implement on?
- How will communications be achieved?
- What are appropriate levels of implementation?
- What is the return on investment?

The next sections explore the levels of implementation as well as implementation experiences in various utilities which will guide the author in terms of appropriate solutions for Volt/VAr management on Eskom distribution networks.

4.2 A review of the levels of implementation and minimum hardware requirements for Volt/VAr management

There are 3 typical approaches with varying degrees of effectiveness for Volt/VAr management and control [57], [19].

4.2.1 The Standalone traditional approach

In this method, Volt/VAr control for a typical distribution feeder is achieved by standalone and isolated regulating devices. The system usually comprises substation on load tap changers, line voltage regulators and capacitor banks, both fixed and switched as shown in Figure 4-3.

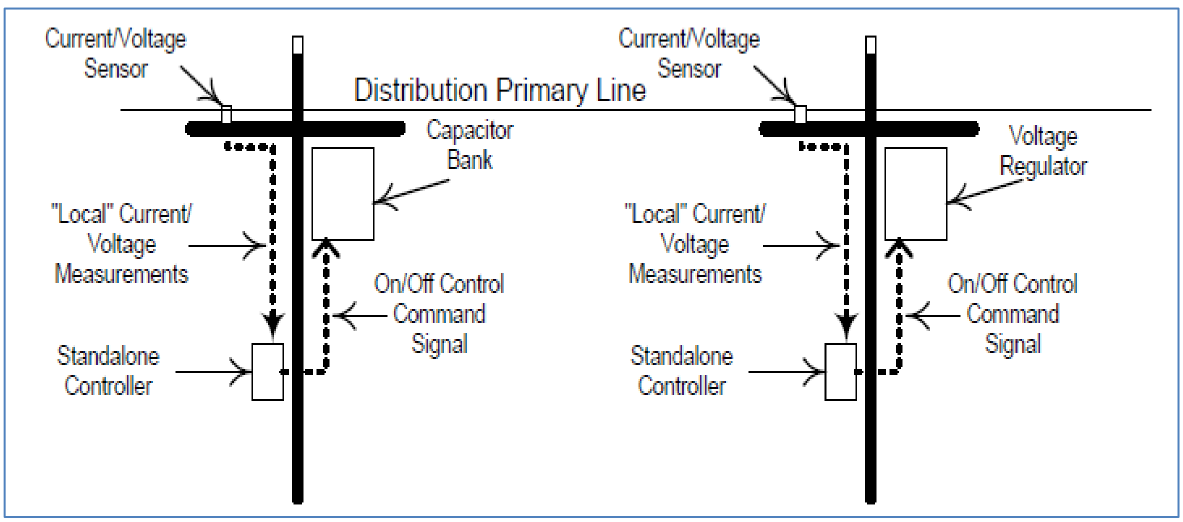

Figure 4-3: Standalone controller approach [19]

The primary objective of this approach is to ensure that voltage along distribution feeders are maintained within acceptable levels and that customers are supplied within their contracted limits for both the peak and low load scenarios [19].

Voltage and current measurements local to regulation devices are continuously processed by standalone controllers which either switch on or off the respective capacitor bank or boost/buck the respective voltage regulator. Switching or tapping is thus based on local conditions. Provided that the regulation equipment has been appropriately sized, considering feeder length, conductor type and load variation, this process ensures that voltages are maintained within specified limits.

In instances where conservation by voltage reduction (CVR) is required, a standalone Voltage regulator with line drop compensation is set to control the end of line voltage to the minimum acceptable voltage [57]. This however may require that each feeder emanating from a substation is equipped with a standalone voltage regulator. In the rare instance that all feeders emanating from a station share similar characteristics, consideration may be given to controlling voltage by the substation transformer's OLTC for the purposes of CVR.

Strengths associated with the Standalone method [57]

- The Volt/VAr devices are regarded as rudimentary and thus could be instituted into utility networks with ease
- This method can be achieved at a fairly low cost
- It is not reliant on remote communications
- Very scalable approach – can do one feeder or many

Weaknesses associated with the Standalone method [57]

- No self-monitoring features, devices could be out of service for extended periods before the utility company becomes aware. During this time there is a risk of increased losses and sub optimal voltage regulation
- Due to the lack of remote communications cannot alter functions/set points or disable regulation devices during network abnormalities or network reconfiguration
- Lacks coordination between Volt and VAr controls – not able to block counteracting control actions
- May not be suited to networks with high penetration of embedded generation

4.2.2 The Centralized SCADA approach

In this approach communications is established between the substation and the regulation devices as shown in Figure 4-4.

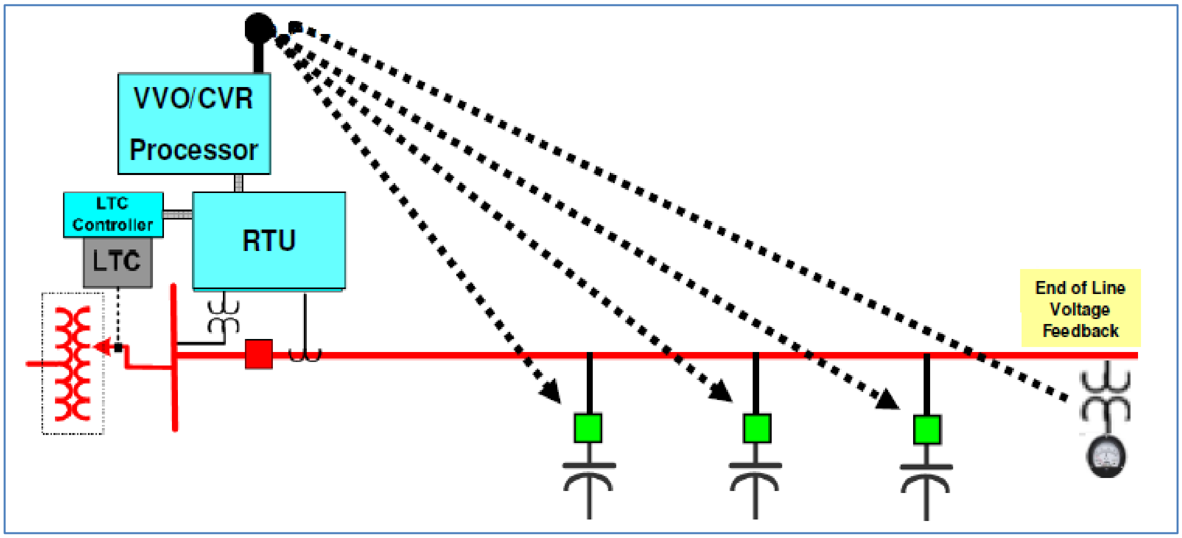

Figure 4-4: SCADA (Rule Based) Volt-VAR Control [57]

The regulation devices are continuously monitored and controlled by the substation SCADA system which consist both VAR and voltage processors. The substation remote terminal unit manages the device monitoring and control. The VVO/CVR processor contains algorithm for voltage and VAR control. The regulation devices have local measurement capability with established communication back to the substation. The common controllers made use of include PCS Utilidata “AdaptiVolt” and Cooper Power Systems IVVC [57].

In the centralized approach, the processors obtain remote measurements through substation RTU’s where control is based on a heuristic rule based approach. The VAR processor is responsible for the control of the capacitor banks whose primary function is to improve the power factor and reduce the technical losses on the feeder. One manner this could be achieved is to maintain the power factor as close to unity as possible at the source of the feeder, where capacitors may switch in when the PF reduces below a predetermined value. The voltage processor controls the on load tap changers and voltage regulators to maintain the feeder voltage within operating limits under varying load conditions however manages this voltage on the minimum side of the acceptable range in order to minimize demand by CVR.

Strengths associated with the Centralised method [57]

- Greater efficiency versus methods adopting standalone controllers
- Self-monitoring
- Can override operation during system emergencies
- Can include remote measurements in the rules

Weaknesses associated with the Centralised method [57]

- Less scalable than standalone controllers (minimum deployment is one substation)
- More complicated – requires extensive communication facilities
- Does not adapt to changing feeder configuration (rules are fixed in advance)
- Does not adapt well to varying operating needs (rules are fixed in advance)
- Overall efficiency is improved versus standalone approach, but is not necessarily optimal under all conditions
- Operation of VAR and Volt devices usually not coordinated (separate rules for cap banks & voltage regulators)
- Does not adapt well to presence of high embedded generation penetration

4.2.3 The integrated approach involving Distribution Management System (DMS) with Power System Simulation capability

The previous two methods demonstrated common disadvantages to coordinating between VAR and Volt devices. In this method the devices are coordinated and cater for varying operating states of the network including both load and topological state changes. This is achieved by the ability of close on to real time power system simulation where decisions on the optimal state and set point of voltage and VAR devices are made to suit utility-specified objective functions which may include

(i) Minimize power demand and energy consumption

(ii) Maximize energy consumption. Although this would not be desired from a consumer perspective, the function can be achieved

(iii) Minimize losses

(iv) Minimize tap changer operation and other equipment control actions

(v) Or various combinations of (i.) to (iv.)

"The benefit of utilizing a dynamic model is that the Volt/VAr optimization always uses the "as-operated" state of the network. As outages and system reconfigurations occur, the network maintains proper connectivity of loads, capacitor banks, regulators, and other feeder components. This ensures the determination of the voltage regulator taps, load tap changer taps, and switched capacitor states always uses the present operating configuration of the system" [58].

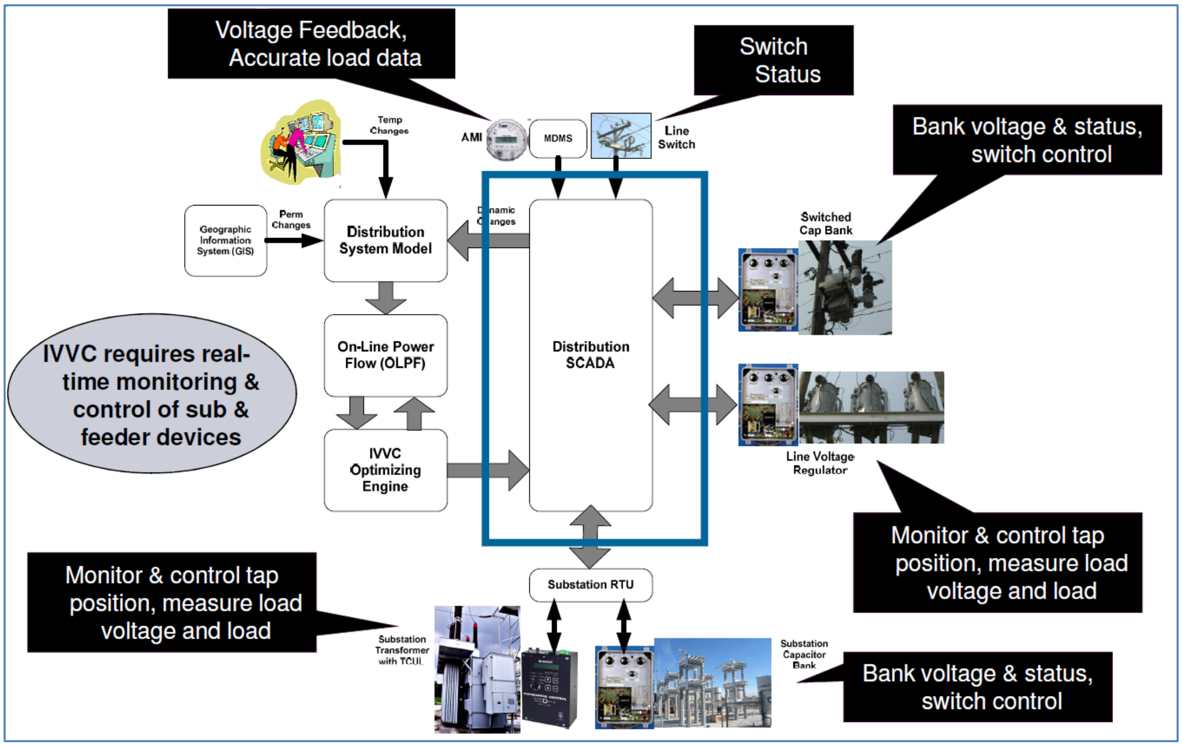

Figure 4-5: DMS Distribution Model Driven Volt-VAR Control and Optimization [57]

Figure 4-5 illustrates the integrated solution. The various inputs are fed into the Integrated Volt /VAr Control (IVVC) optimizing engine. The IVVC engine manages the tap changer settings to maintain both feeder regulations as well as settings to achieve the desired CVR, inverter and rotating machine VAr levels, capacitor switching to manage voltage regulation, capacitors switching to reduce losses and conserve system resources [19]. The load data, feeder topographical state (by means of switch status), the status and present set point of the various capacitors banks are voltage regulators, are fed into the SCADA system. Based on power flow results following load flow simulations , the IVVC optimizing engine develops a coordinated "optimal" switching plan for all voltage control devices and executes this plan.

Strengths associated with the standalone method [57]

- Fully coordinated and provided the optimal solution
- Flexible operating objectives - Accommodates varying operating objectives depending on present needs
- Able to handle complex feeder arrangements - Dynamic model updates automatically when reconfiguration occurs
- Works correctly following feeder reconfiguration
- Handles networks with high penetration of embedded generation
- Can be in incorporated as part of utility system EMS SCADA system

Weaknesses associated with the standalone method [57]

- Not very scalable – It is not feasible to use this approach for one feeder or substation due to the onerous control center requirements
- High cost to implement, operate and sustain
- Learning curve for control room personnel that will require skills training
- Lack of field proven products

4.3 A review Volt/VAr control system implementation at leading utilities

A review of Volt/VAr implementation strategies at leading utilities is discussed in order that decision factors, technologies used, results with project success criteria, and lessons learned through field testing, is understand.

4.3.1 EPRI: Green Circuit Distribution Efficiency Case Studies [59]

The EPRI Green Circuits project involved research between 22 utility companies where the primary objective was to evaluate distribution feeder efficiency improvement methods. The scope of work involved power system modelling, evaluating financial feasibility as well as field implementation. A total of 66 networks formed part of the study where field trials were implemented on 9 of the networks. The load types constituting the feeders varied between rural, urban, peri-urban, mixed commercial and combinations thereof.

The optimal solution for a given feeder depended on the local feeder characteristics e.g. load characteristics, the feeders state of phase balance, economic ranking criteria, etc. “In some cases, the most economically viable option was just voltage reduction; however, additional improvements were often economically viable also. In other cases, the optimal project included voltage reduction, phase balancing, VAR optimization, and/or targeted re-conducting." [59]

Reducing feeder voltages to the lower range of allowable limits reduced energy consumption across all the circuits. From simulations and field trials, optimizing voltages to the lower end of the American National Standards Institute range was found to reduce energy consumption between 1% and 3% on most circuits. The median reduction in consumption was 2.34%. The reduction in losses from reactive power support and phase balancing initiatives were generally small. Figure 4-6 shows the results obtained for a typical rural feeder where these points are illustrated. Overall, voltage management produced the best results providing the greatest energy reduction.

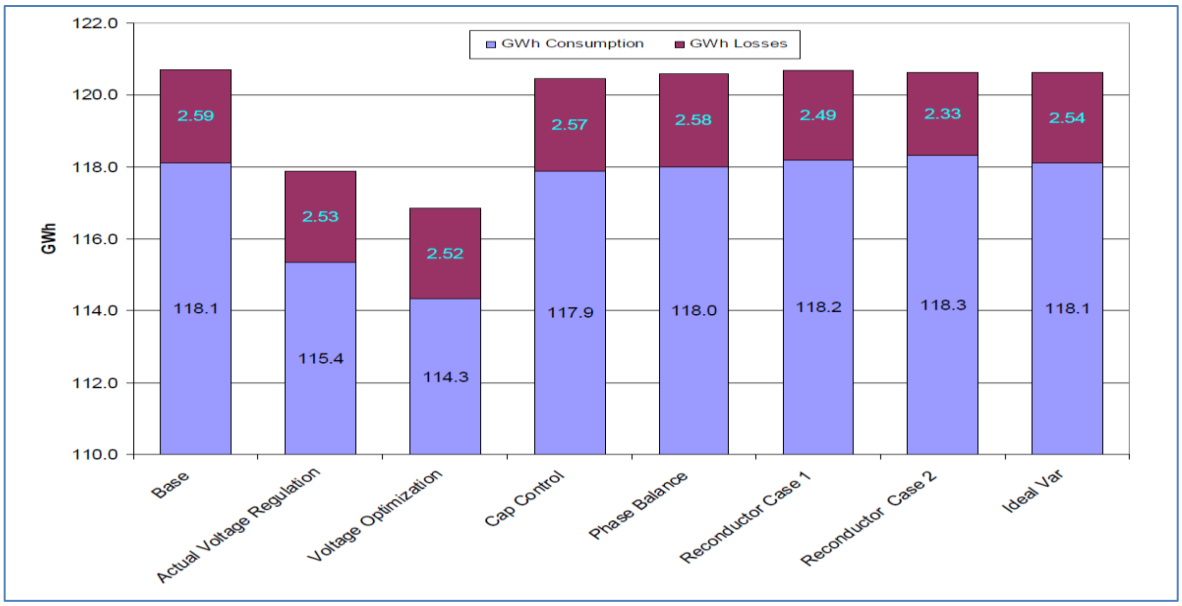

Figure 4-6: Efficiency Comparison Summary Graph [59]

It must be noted that that local characteristics play a big role in the final solution. For instance, in the context of Eskom rural networks, constrained feeders are primarily as a result of poor regulation often outside statutory limits. Here the strategy will be solutions that will enhance the voltage profiles whilst reducing losses and demand. Reactive compensation may be financially viable for this purpose as opposed to the more expensive conductor replacement or other strengthening initiatives.

Reduction in voltage for the purposes of CVR may not be viable if the voltage regulation is not firstly flattened. In the context of Eskom with regards to constrained feeders as a result of violation to minimum statutory voltages, CVR cannot be practiced without solutions to flatten out voltage profiles as an initial first step. As in Figure 4-2, a combined capacitor incorporated solution may prove to be viable and will be investigated as part of this research.

4.3.2 U.S Department of Energy; Application of Automated controls for voltage and Reactive Power Management – initial Results; Smart Grid Investment Grant Program [55]

The U.S. Department of Energy has implemented a Smart Grid investment grant program which has resulted in the deployment of smart grid technologies into a number of utility company networks. The focus of 26 of these projects involved the implementation of advanced Volt/VAr optimization technologies to improve electric distribution system operations and efficiencies where strategies to achieve one or more of the following objectives have been pursued as discussed in [55]:

- Reduction in system voltage during peak periods to shave peak demand
- Reduction in system voltage for extended periods to achieve energy conservation
- Reduction in technical losses

The initial results of 8 projects consisting 31 feeders, where data was available at the time of publication is presented in [55]. The analysis for these projects focused primarily on impacts of switching of reactive power compensation and assessing the subsequent reductions in technical losses. Two projects involving CVR is also presented.

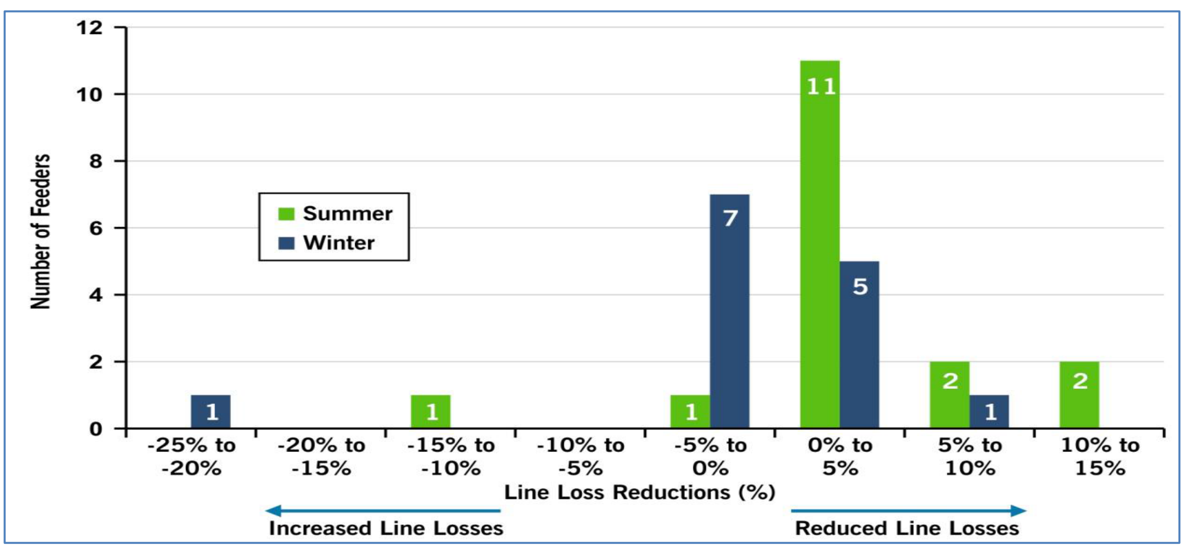

Figure 4-7: Histogram of technical loss reductions [55]

Figure 4-7 shows the ranges of technical loss reductions obtained from capacitor switching initiatives for each of the feeders. Technical loss reductions were experienced in approximately 68% of the total feeders assessed, where approximately 50% of the feeders experienced loss reductions in the 0 to 5% range. The assessment was carried out over a period of time that covered both the summer and winter months. Air-conditioning load is significant in summer and as a result of the higher inductive load (motors making up the cooling units), technical loss reduction by switching in of capacitive compensation, is higher in summer.

In [55] it is inferred that any capacitive compensation benefit in terms of technical loss is suited to systems with high inductive loads. “In general, feeders with the worst baseline power factors (i.e., those with the highest amount of inductive loads) showed the greatest reductions in technical losses. Many of the utilities are targeting their worst performing feeders. However, overcompensation for reactive power was observed in the remaining feeders, which resulted in technical loss increases. In these cases, capacitor banks were often operated for voltage support rather than reactive power compensation.”[55].

The initial assessment for CVR indicated a potential of between 1% and 2.5% for peak demand reduction. This is also consistent with the case study in 4.2.1. “In comparison to energy savings attributable to technical loss reductions, conservation voltage reduction practices have a greater impact on reducing energy requirements.” [55].

In the Eskom context relating to the possible undertaking of capacitive compensation on MV feeders, learning is that concerted effort is required in ensuring that power factor limits for LPU customers are managed as this will contribute the largest portion of the reactive component contribution to technical losses on Eskom MV feeders. In [51], the specification for the minimum customer power factor is provided i.e. a minimum power factor of 0.9 lagging for demands greater than 100kVA unless otherwise agreed with the utility. If individual customers manage their power factors, then the specification and cost for any additional compensation placed on MV feeders by the utility company as a distributed compensation device will be less onerous.

4.3.3 Utility Case Study: Volt/VAr Control at Dominion [60]

Dominion Inc. is a power utility company in the USA whose business consists Generation, Transmission and Distribution. It has implemented what it refers to as "Customer Voltage Based VVO". This section will describe the concept and offer explanation to the operations and benefits.

The key benefits as described by Dominion Inc. are the following [60]

- Achieves precise customer voltage control
- Provides substantial customer savings
- Requires no change in customer behavior
- Requires no customer purchases or incentives
- Benefits all customer classes
- Justifies investments in distribution and metering infrastructure
- Integrates with other direct load control programs
- Reduces demand, conserves energy, and reduces impact on the environment.
- Adapts to real-time system changes

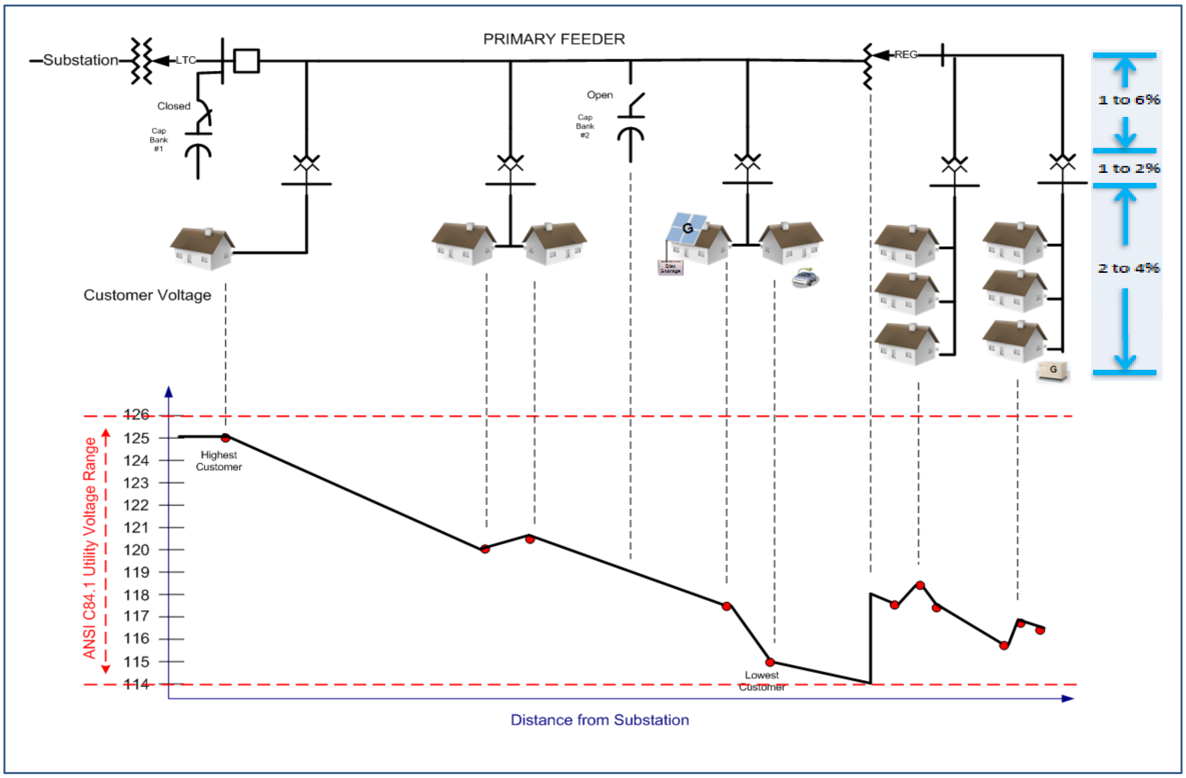

Figure 4-8: Traditional Circuit Voltage Design [60]

Figure 4-8 and Figure 4-9 contrast a conventionally operated distribution feeder equipped with regulation devices that has inherent Volt VAR Control capability to a system with AMI metering incorporated, which allows the Volt VAR control to be optimized.

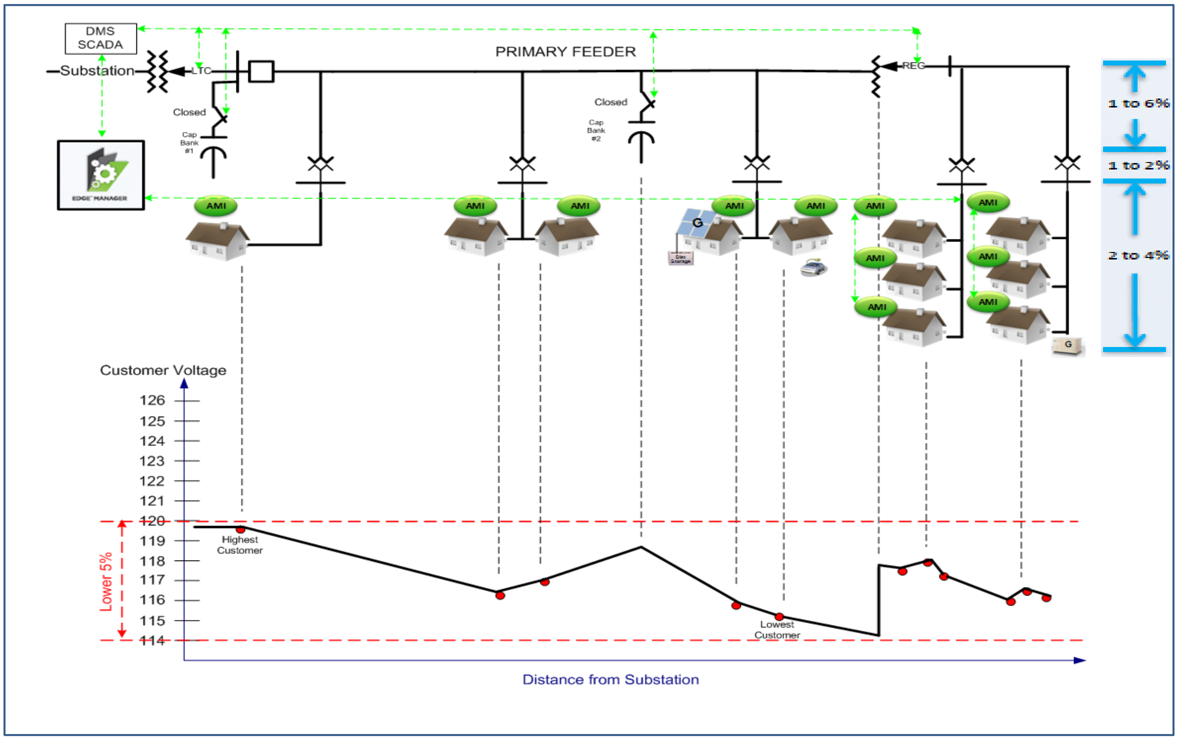

Figure 4-9: Customer Voltage Based VVO [60]

At Dominion Inc. [60], the transmission power systems are highly automated and integrated into the DMS and SCADA systems however there has been little no integration with networks at the distribution level. With the incorporation of AMI metering and GPS location data, it has become possible to determine a connectivity model per phase and subsequently control the voltage on a per phase basis. With AMI meters now integrated into the DMS SCADA system, control decisions can be made to configure CVR and coordinate the operation of capacitors, line voltage regulators, and substation on load tap changers to adjust voltages to the minimum of the voltage scale to achieve energy savings whilst satisfying all customers contractually.

Further, with real time monitoring capability, the CVR engine can make fine tune adjustments throughout a day cycle where is possible to exploit Volt VAr control to an extent where not just peak demand is curbed, but energy saving is maximized. The implementation by Dominion Power is analogous to the integrated approach discussed in section 4.2.3.

The situation in Eskom with regards to SCADA visibility and control of distribution system is in many ways very similar to the initial conditions at Dominion Inc. In order that Eskom incorporate a fully integrated approach to Volt/VAr optimization, many system upgrades to improve visibility and controllability at MV level will be required.

4.3.4 NEMA: Volt/VAr Optimization Improves Grid Efficiency; Case Studies [56]

The following are brief summaries of Volt VAR implementation and associated successes as detailed in [56].

i. The Snohomish County PUD:
"A Conservation Voltage Reduction system was installed to improve system throughput and improve power quality. Their investment of under $5 million has resulted in energy savings of 53,856 MWh/year, including reduced distribution system losses by 11,226 MWh/year while providing better voltage quality (less voltage swing) to end-use customers."

ii. The Northwest Energy Efficiency Alliance:
"13 utilities were studied for the impact of lower voltage on consumers. Their work showed voltage reductions of 2.5% resulted in energy savings of 2.07% without impact on consumer power quality."

iii. The Clinton Utilities Board:
"State-of-the-art voltage regulation technologies are being used to power 3,000 homes solely through energy savings. Utilizing Dispatchable Voltage Regulation to safely and automatically adjust end-use voltages to meet peak demand needs, Clinton has harnessed a virtual power plant by capturing otherwise lost energy to meet service needs."

iv. Oklahoma Gas & Electric:
"(OG&E) is in the process of implementing Volt/VAr optimization (VVO) across 400 feeder circuits to achieve a 75-megawatt load reduction within the next eight years. Advanced model-based VVO allows OG&E to maximize the performance and reliability of its distribution systems while significantly reducing peak demand, minimizing power losses and lowering overall operating costs."

A key learning for Eskom in these examples is the inference that additional capacity can be freed up at little or no cost with CVR. This may have many positive benefits to South Africa's Universal Access Program (UAP), where the objective is to achieve universal access to electricity by 2019 [61], especially in areas electrification is required that has known constrained systems.

4.4 Assessments for CVR on Eskom MV feeders

This section discusses the assessments carried out by the author for the application of CVR within Eskom networks following the generation emergency declared by Eskom in 2014. The objectives of the assessments were to:

- determine whether the reductions in demand and energy consumption by CVR would significantly reduce the amount of load that would be required for manual load shedding
- determine the practicality and feasibility of CVR implementation on Eskom networks
- quantify approximate demand reductions that could be achieved by the implementation of CVR
- develop a framework to guide the implementation of CVR in Eskom

The CVR assessments and conclusions will be discussed in the following sections 4.4.1 to 4.4.3 and will guide the approach taken by Eskom for the initial approach to Volt/VAr management.

4.4.1 Assumptions, considerations and initial proposals for CVR on Eskom Networks

A licensed Distributor in South Africa is obligated by the Network Code [51] and System Operating code [50] to provide customers with voltages within the limits specified by NRS048-2 [47]. The minimum voltage limits discussed in chapter 2 which is employed in Eskom defines the boundary conditions for CVR and is summarized below:

- The minimum voltage that shall be supplied to HV and MV bulk customers with no supply contract is -5% of nominal voltage.
- The minimum voltage that shall be supplied to HV and MV bulk customers with standard Eskom contracts is -7.5% of nominal voltage.
- For remaining customers fed from MV networks, the maximum permissible MV voltage drop is dependent on the Network Class and Tap Zone and can be as low as -15% for a C4-TZ3 network as given in Table 3-6 and [62] however to cater for any bulk fed MV customers on any network, the minimum MV voltage will be limited to -7.5%.

The CVR assessments would be confined to MV networks. HV networks were not to be considered as most bulk fed HV customers are equipped with HV/MV transformers internal to their plants with voltage control, where changing the HV voltages will not result in reductions in voltages at the point of utilization. Reducing the HV voltage in these instances will increase load current and thereby increase losses, which would have the opposite effect to what is required. Also at the time, other load management strategies such as load curtailment and energy conservation programs had been negotiated and established for HV supplies to large industrial and commercial customers.

A 0.7% to 1.5% reduction in energy consumption can typically be expected for a 1% reduction in voltage [56]. The magnitude of the reduction depends on the load mix. As a short term solution to yield immediate demand reductions without the need for installation of additional hardware, it was proposed that an initial 2.5% voltage reduction be considered where such reductions were not expected to result in violation of statutory voltage limits.

Should this voltage reduction not result in any instances of measured voltage violations or customer complaints then further reduction in voltage could be considered. Further, CVR would not be applied on MV networks where minimum voltages prior to application were less than 95%. A 2.5% reduction implies that a network with a minimum MV voltage of 95% prior to CVR will have a minimum voltage of 92.5%, which is at the contractual minimum limit for MV bulk supplies.

The Eskom MV voltage control strategy is achieved via the use of OLTC tap changers on HV/MV transformers. This implies that all of the MV feeders supplied by a HV/MV transformer will have the same source MV voltage. It is hence not possible to optimize the MV voltage set-point for each MV feeder independently. The minimum MV voltage set-point as required to comply with statutory voltage limits is therefore dictated by the MV feeder with the largest voltage drop. This can significantly reduce the load reduction potential of CVR.

CVR would also only be applied as a temporary measure to reduce demand during peak periods. In such cases, transformer OLTC set-point voltages would be remotely changed via signals from the SCADA system. This necessitated that the tap changer controllers have communication and capability to initiate voltage control settings changes via the SCADA system.

In summary, the initial consideration was to implement a 2.5% reduction in MV voltage set-points initiated by remote SCADA control signals on “suitable networks” that is supplied by transformers equipped with OLTCs. This would allow networks to be operated at the lower voltage setting, but in the event of system contingencies or voltage complaints, the voltage set-point could be remotely increased.

A “suitable network” is defined as follows:

- MV networks supplying urban and peri-urban areas which supply a predominantly constant impedance and current type loads
- They will typically be 11kV with a maximum MV backbone length <30km.
- They will typically be MV cable networks or short MV overhead feeders hence the 30km feeder length restriction above
- They will typically supply residential, commercial, and small industrial supplies
- The minimum MV voltage before CVR should be greater than or equal to 95%.
- Any MV LPU point of supply voltage must be greater than or equal to 92.5% after the voltage reduction
- The HV/MV transformers are operated on OLTC with set point voltage control

The above implementation will result in a 2.5% CVR on qualifying networks.

4.4.2 Network Analysis

As an initial step, it was necessary to quantify the approximate demand reductions that could be achieved by the implementation of CVR as set out in 4.4.1 and whether this would be significant to reduce the likelihood and/or extent of load shedding that was being experienced.

The load in the 6 Eskom Distribution supply areas making up the total load for South Africa is shown in Figure 4-10 [9]. The load is disaggregated to show Re-Distributor load (Municipal load) and large industrial loads also termed Key Sales Accounts (Ksacs), which is supplied by Eskom in bulk, in each of the supply areas. The remaining portion of load is supplied directly to end use customers by Eskom where this is predominately distributed through MV feeders. The Ksacs customers are bulk fed at HV voltage levels and are not suitable for CVR as discussed in 4.4.1.

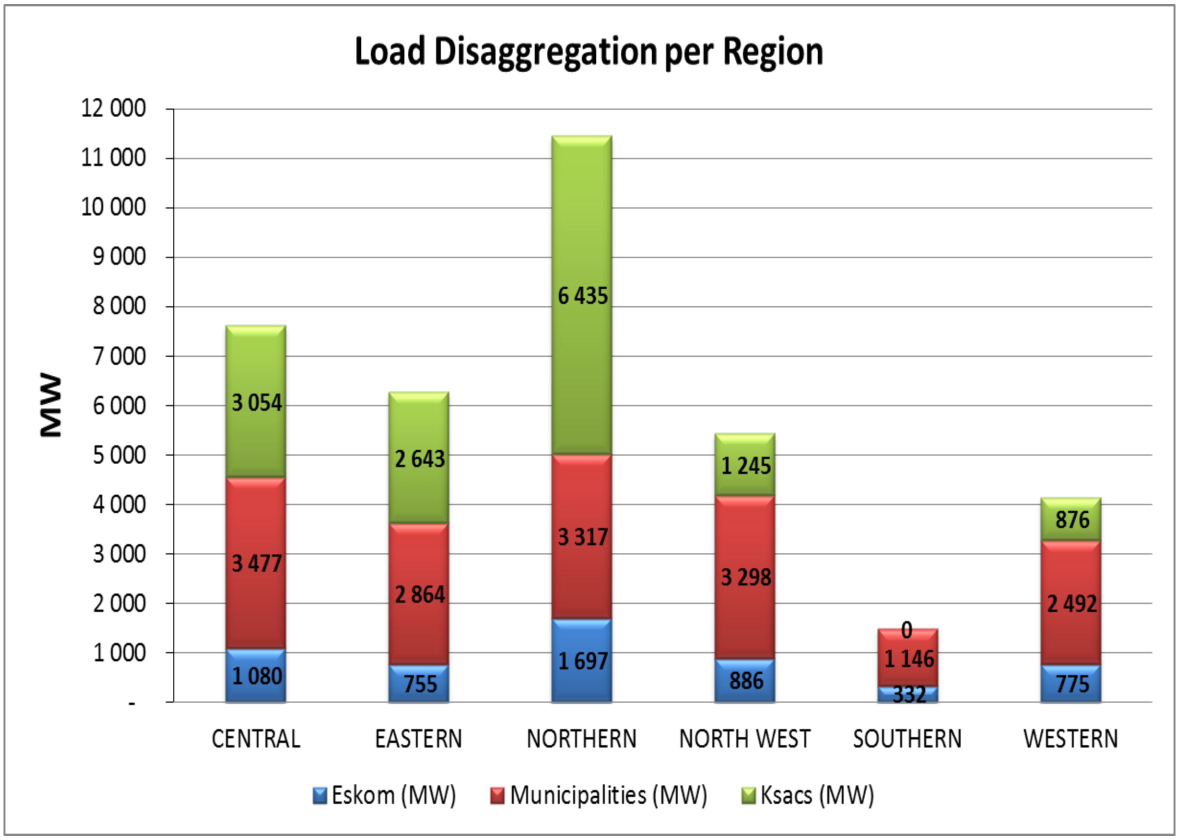

Figure 4-10: Eskom Load breakdown [9]

Figure 4-11 shows the sum of the Eskom MV feeder load and the Municipal load, per distribution supply area that would be targeted for CVR application. The ratio of the Eskom MV feeder load to load within Re-Distributors is on average 25:75 across the country. Given that, urban and peri-urban loads are normally concentrated within municipalities and metros areas supplied by Re-distributors, a larger potential for CVR application would exist within Re-distributor supplies in South Africa. However, this load cannot be controlled by Eskom for CVR unless collaborative strategies are firstly put in place between Eskom and Re-distributors which was outside the scope of the assessments and viewed as a future, long term initiatives. Given the urgency to make short term operational plans for the then generation deficiency, it resulted in a change in approach for network selection to include assessments of Eskom rural type feeders, together with the limited urban and peri-urban loads fed from within the Eskom areas of supply.

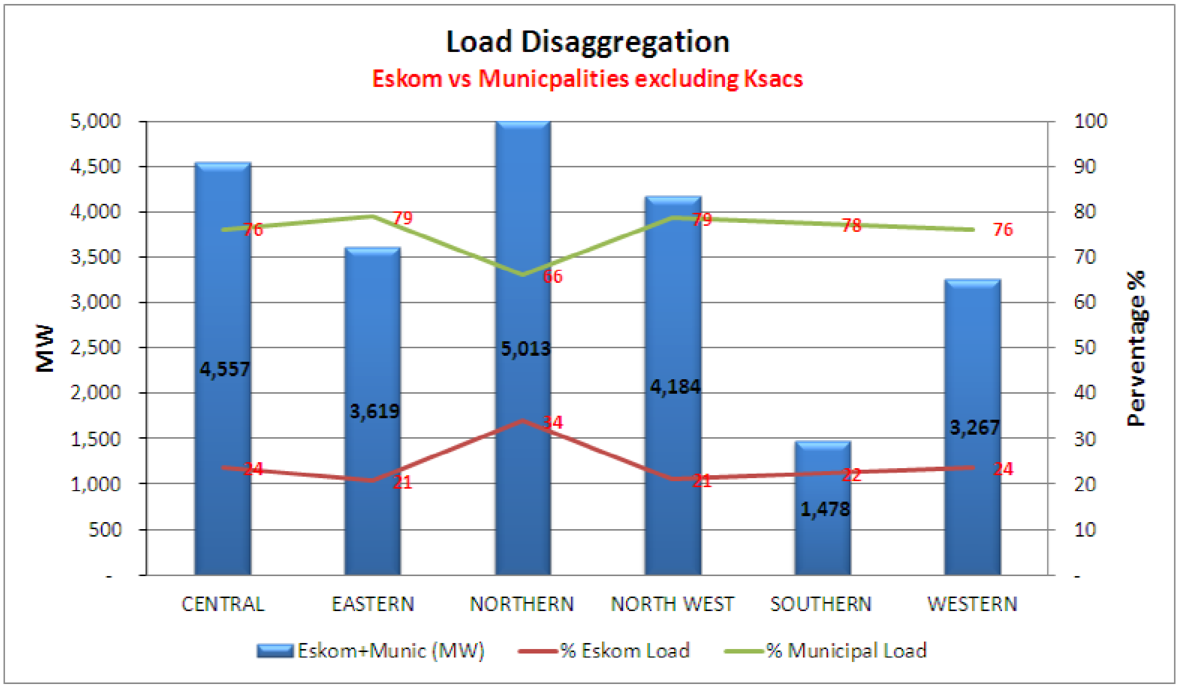

Figure 4-11: Load excluding Industrial base comparing Eskom and Municipalities [9]

For rural feeders, detailed requisite information on the magnitudes of the voltage drops is required to improve the criteria for the selection of "suitable networks". These networks are typically long with lower tail end voltages as compared to urban type networks and would therefore be more prone to violations of statutory voltage limits with the application of CVR, if not assessed in detail and flagged as not suitable. The maximum level of CVR that can be applied is that voltage reduction which results in customer voltages at the minimum statutory limits. The application of maximum levels of CVR hence requires that a suitably detailed and accurate understanding of the voltage drops in the MV and LV networks. This is achieved by load-flow analysis of the networks. If the network voltage drops are not known then CVR can only be implemented conservatively, with the voltage reduced while monitoring voltages provided there is sufficient network visibility and through customer complaints.

A sample of 201 MV feeders consisting of the various classes of networks making up the Eskom MV system was assessed to estimate the CVR capabilities of the Eskom MV feeder load, nationally. Estimated peak demand reductions for various levels of voltage reductions were obtained by power system simulation and are shown in Figure 4-12. Simulations involved basic load flow studies with the systematic reduction in source sending voltages until tail end voltages were reduced to the statutory limits in each case. The sending end power for the reduced voltage state was then compared to the system normal case, where the load reduction could be determined. The simulations were run for 5 scenarios considering different tail end limits ranging from 95% to 88% considering the lower limits of network classes 1 to 3. The 92.5% requirement was mooted as the safe and conservative approach to be followed nationally where this indicted a potential of 13MW demand reduction or a 3.75% shaving of peak load for the 201 MV feeders assessed.

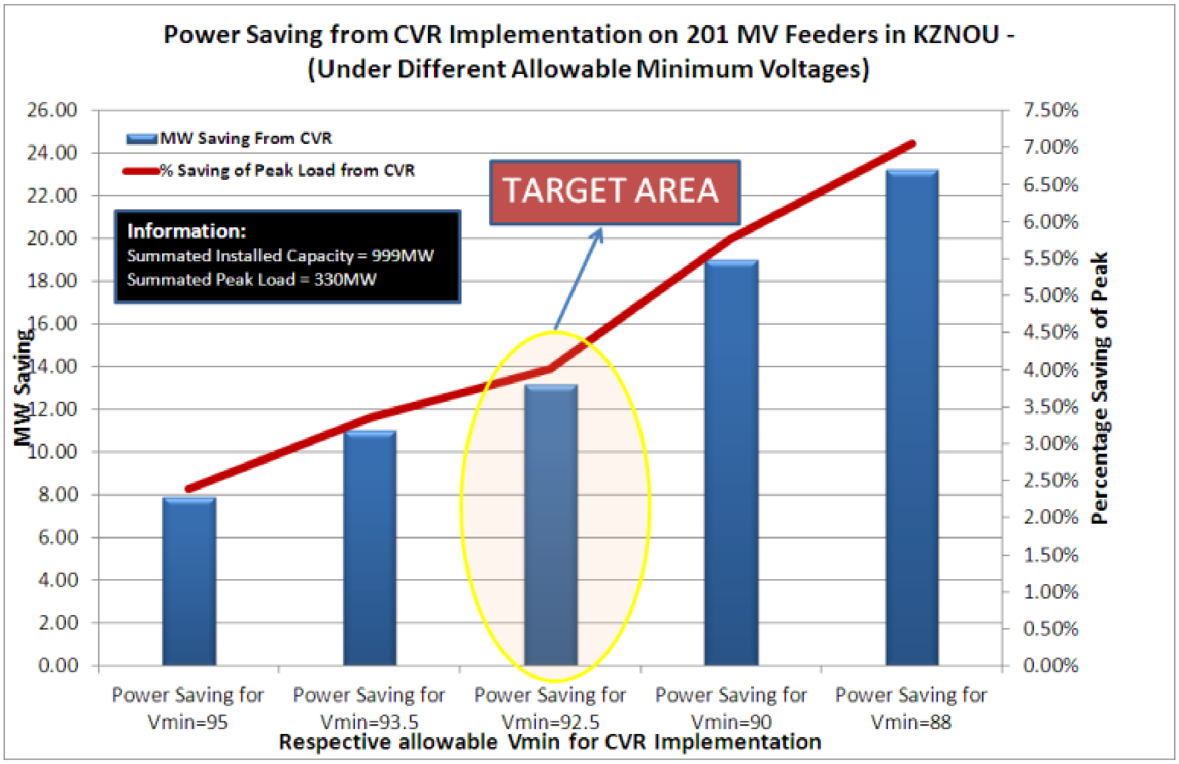

Figure 4-12: Simulation results for CVR application on 201 sample Eskom networks

Figure 4-13 shows the relationship of percentage change in voltage to percentage demand reduction for the 201 MV feeders assessed for the 92.5% lower limit scenario. The envelop of the percentage demand reduction curve closely tracks the percentage voltage reduction trend and is in agreement with literature as in [56] and [59] i.e. an approximate 1 is 1 ratio between voltage reduction and associated demand reduction for feeders with constant current and impedance type loads . The feeders with large deviations between voltage and load reduction percentages are those consisting large LPU customers with constant power type loads (pumps and larger motor load).

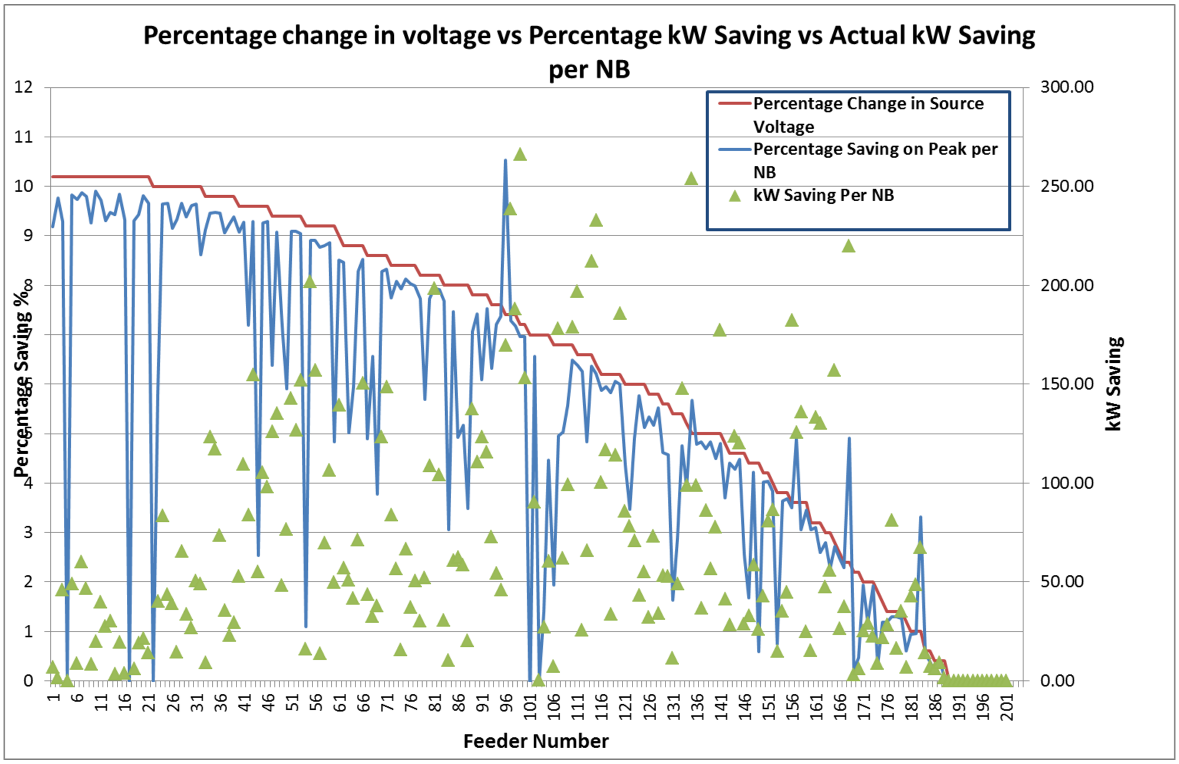

Figure 4-13: Relationship of percentage change in voltage to percentage demand reduction

The figure also shows the potential to reduce the source voltage by up to approximately 10% in instances. This applies to short lightly loaded feeders where although there is an associated percentage reduction in demand, the actual demand reduction in kW is small. CVR application on a feeder that is significantly loaded has greater potential for return in demand reduction at a smaller voltage reduction also illustrated in the figure.

By applying the percentage reduction in peak from the 201 MV feeder assessments to the total MV feeder load per distribution area, it is possible to crudely estimate the national CVR demand reduction capability in Eskom.

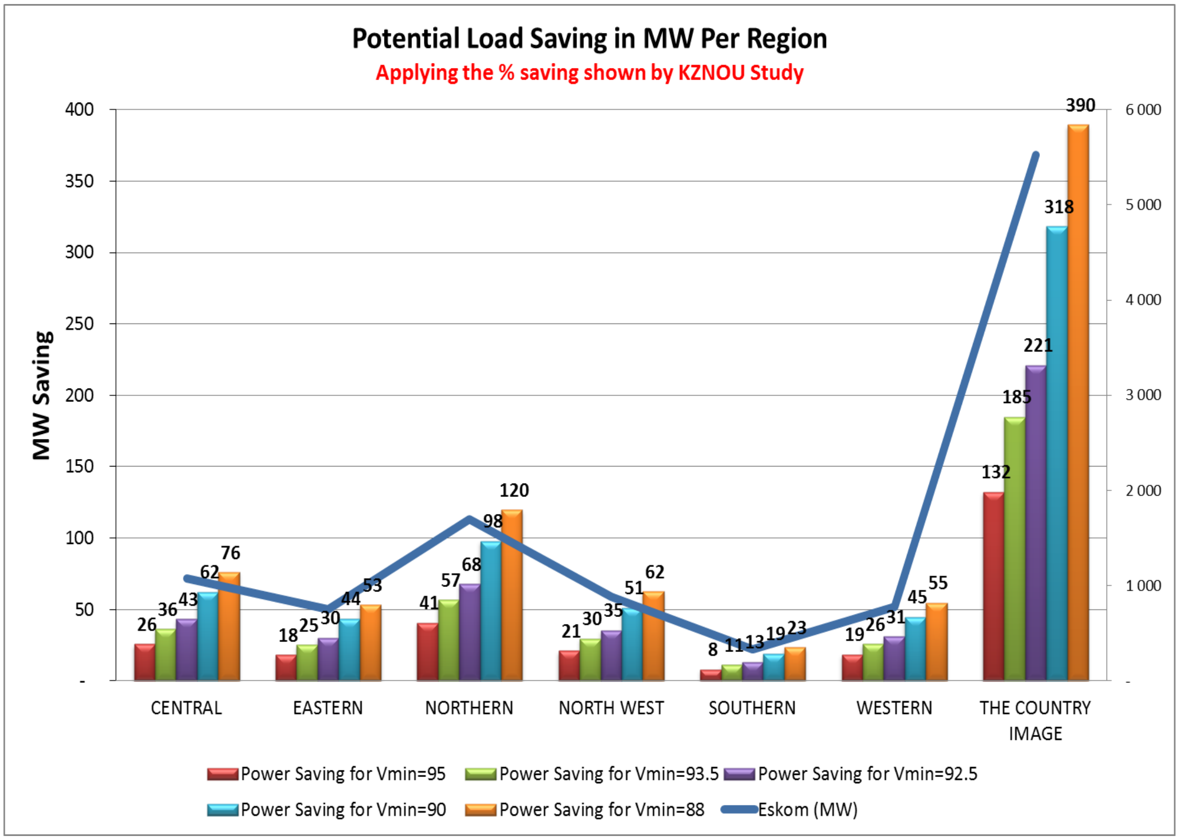

Figure 4-14: Potential demand reduction per distribution area and Country

Figure 4-14 shows extrapolated estimations for demand reduction based on the sample network simulation results given in Figure 4-12. The results indicate that the total estimated demand reduction is 221MW for the 92.5% voltage limit.

4.4.3 Recommendations and findings following the Eskom CVR assessments

The high level national estimation, excluding re-distributors and large industrial customers, based on the sample feeder benchmarks revealed that 221MW could be saved if MV source voltages were reduced down to 92.5%. The method used in the national estimation is however optimistic as sample percentages were applied to the national MV load where it was assumed to consist of similar proportions of feeder classifications and characteristics. Further, and more importantly each feeder had been assessed individually. In reality all MV feeders in a substation is supplied by the same controlled source. It is hence not possible to set MV voltages for each MV feeder independently. The minimum MV voltage set-point would be dictated by the MV feeder with the largest voltage drop. This implies that the true CVR potential would be much less than 221MW. If detailed models were available for all MV feeders in the country per substation then the analysis could be refined to the detail showing individual substation capability. The high level figures have however been useful to educate the business in terms of “rules of thumb”.

A closer estimate of the total CVR capability can be obtained by assuming a CVR voltage reduction of 2.5% on the source set point of each substation HV/MV transformer where assuming a 1:1 voltage reduction to demand reduction ratio, gives a CVR capability of approximately 138MW for the Eskom MV feeder load. The assumption here is that all feeders would have tail end voltages of greater than 95% pre CVR.

A feeder appraisal for one of the Eskom supply areas compiled by the author in [9] suggests that there is number of feeders that violate the 95% tail end voltage limit. Figure 4-15 shows the results of the MV feeder voltage appraisal where approximately 35% of customers are fed from points on back bone feeders with voltages less than 95% including customers fed below statutory limits. Assuming similar percentages on a national basis and given that voltage control is established at substation level only without mechanisms in place for individual feeder voltage control, the CVR potential in Eskom would be less than 90MW.

The recommendation made was that the demand reduction potential would be insufficient to significantly impact the rotational load shedding being practiced at the time however the decision not to pursue the CVR initiative was a business decision based on the level of effort required for the network analysis nationally versus the potential amount of load reduction.

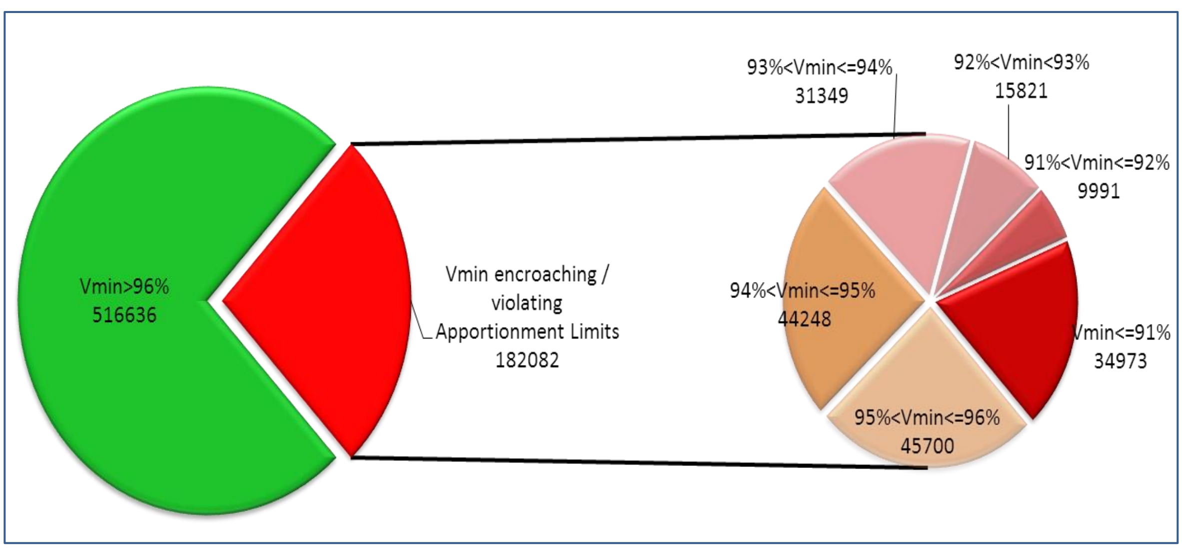

Figure 4-15: Medium voltage regulation versus customer connections; Eskom KZNOU (Eastern Region) appraisal [9]

A salient point from the assessments is that for the application of CVR detailed analysis per substation needs to be performed. CVR cannot be implemented in a blanket approach. In order to approach CVR in a safe and risk free manner, the following were identified prerequisites:

- That MV systems be appraised
- That models are calibrated by measurement and demand reductions simulated to evaluate practicality and feasibility for implementation
- That LV volt drop is studied and accounted for in simulation
- That control centers have adequate visibility and are equipped with appropriate alarms to manage possible voltage excursions past limits
- Voltages on the power system also need to be managed and maintained within an acceptable range of the nominal voltage to ensure that supply voltage at customer terminals are within limits specified in customer supply contracts and government regulations.

4.5 Conclusions

This chapter has discussed three mainstream approaches for Volt/VAr management on distribution systems with varying degrees of effectiveness. The approaches differ in the methods used to control regulation and compensation devices such as transformer on load-tap changers, line voltage regulators and capacitor banks. The benefits and weaknesses of each approach are discussed.

Reviews of Volt/VAr implementation at leading utilities, to understand decision factors, technologies, results with project scoping, project success criteria, and lessons learned through field testing are also presented as case studies.

The standalone approach to Volt VAR management given localised control of Volt VAR devices, offers little or no coordination with other Volt VAR devices in the system. Here CVR implementation is not a viable option or may be achieved with suboptimal results and with great difficulty. The standalone approach may however be suited to isolated feeders where Volt VAR devices need to be coordinated and set once off, catering for worst case conditions. Devices may be set and incorporated into either the feeder for loss minimisation objectives by reactive power compensation as shown by the implementation and positive results in [55] or for voltage regulation improvement, in cases where statutory limits have been breached.

The centralised (RTU/Substation-SCADA) method offers coordination between multiple devices on the same circuit. The logic is programmable at the substation and can be configured for individual VAr, Volt or CVR objectives (Losses, Regulation or demand reduction). The logic is rule based which is not easily adaptive to network reconfiguration changes. Given modern control schemes, it may be possible to configure alternate settings groups for network reconfiguration however it will be challenging to design setting for all network eventualities. The case studies have shown positive results to this approach as expressed in [59]

The model based method is by far the most desired however costly to implement. The communication establishment with all Volt-VAR devices is on a system wide basis. The utilization of dynamic operating data, both topographical and load data, allows this system to adapt and control Volt and VAr devices under varying operation states of the system yielding positive benefit to loss reduction, energy and demand reduction and quality of supply from a voltage regulation point of view. The assessment in [60] illustrates the fine tuning capability that is offered to Volt/VAr optimisation by AMI smart metering.

The detailed conclusions and recommendations resulting from the Eskom CVR assessment are contained in section 4.4.3. Given that in Eskom, it is not possible to set MV voltages for each MV feeder independently where the minimum MV voltage set-points for CVR would be dictated by the MV feeder with the largest voltage drop, and that many MV feeders breach minimum voltage statutory limits, CVR would not be viable until MV systems are made “compatible”. The key precursors for CVR in Eskom would be to improve voltages on feeders. Whilst the assessments showed that the CVR potential was insignificant to alter load shedding, it may offer quick short term solutions to the countries UAP program in systems that are constrained.

Given the low volume of capacitive compensation on the Eskom distribution system, as shown in Figure 4-16 [63], and the high number of potential customers exposed to voltages below contractual limits as shown in Figure 4-15, the approach to Volt VAR management that Eskom takes, should be twofold; improving voltages to within statutory limits as well as aggressively bridging the gap of reactive compensation at the distribution level which has the potential to significantly reduce technical losses on the overall grid. Note, almost all the VARs required at the distribution level is transported from the Transmission and Sub-transmission networks.

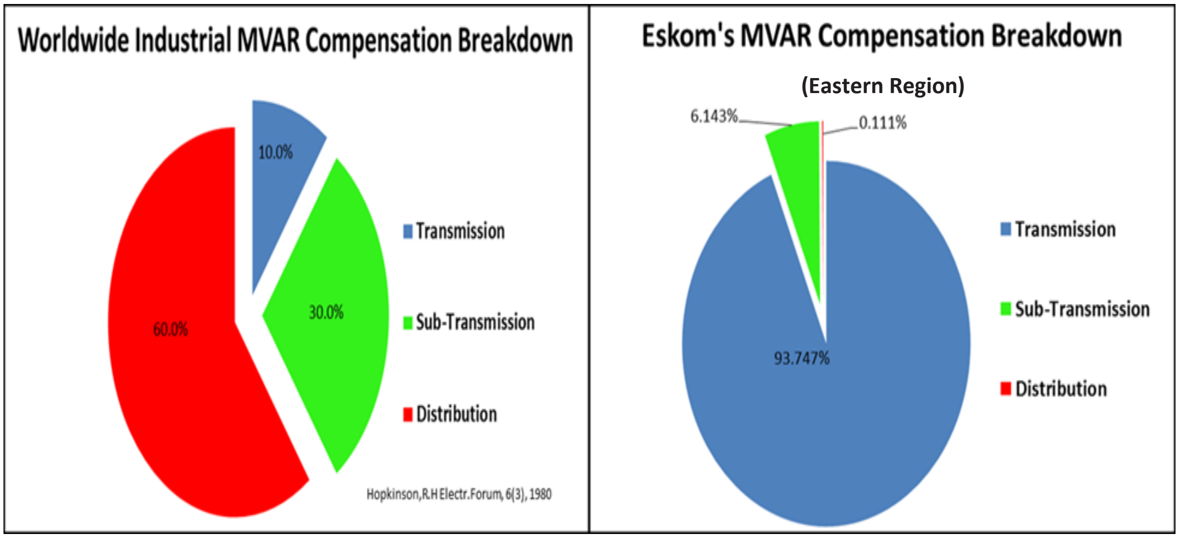

Figure 4-16: Comparison between international practices and Eskom in terms of VAR compensation per voltage level [63]

Only once this is established, will an opportunity be presented for the wide scale implementation of CVR and other Volt/VAr functions. The research will thus focus on capacitive compensation of distribution networks considering optimal sizing, placement and switching criteria. Since capacitors offer benefit to both technical loss reduction and voltage improvement at the point of installation, algorithms will be developed accordingly such that both voltage constraints and technical losses can be reduced as far as possible. This will be studied and addressed in the next chapter.

5 A model to optimize reactive power flow in distribution network feeders [11]

5.1 The theory of shunt compensation and its influence on Voltage, Current and Losses

Shunt capacitors regulate both the voltage and reactive power flow at the point of installation [34], [19], [64]. Figure 5-1 shows by way of vector diagrams that with the installation of a shunt capacitor and a subsequent improvement in power factor from θ to θ′, both the source current and the voltage drop across the feeder is reduced.

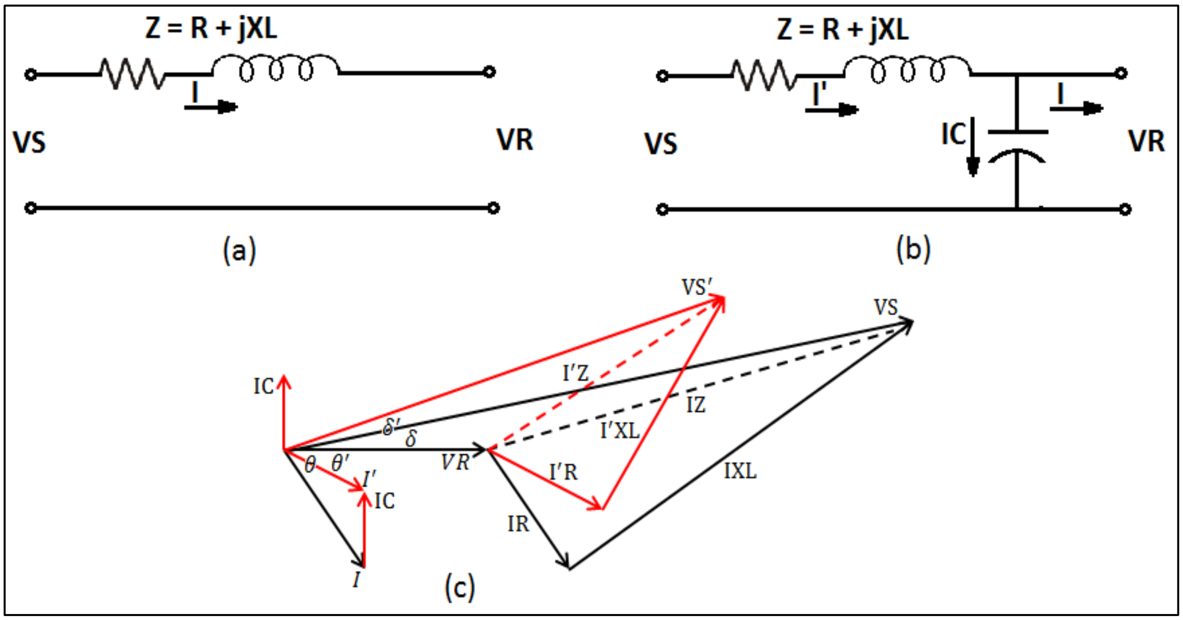

Figure 5-1: Impact of shunt compensation on regulation and current [34]

In the case of MV distribution feeders which are regarded as short lines, the voltage drop IZ can be approximated by (5.1) which has been derived in section 2.2.4 in (2.16). Equation (5.2) is an approximation for the voltage drop after the installation of the shunt capacitor. The rise in voltage V_R after the introduction of capacitive compensation is expressed in (5.3), which is calculated by the difference of (5.1) and (5.2). Equation (5.4) gives the modified feeder current magnitude after the installation of the capacitor.

$$IZ \cong I\cos\theta * R + I\sin\theta * X_L \tag{5.1}$$

$$I'Z \cong I\,cos\,\theta * R + (I\sin\theta - I_C) * X_L \tag{5.2}$$

$$V_R = IZ - I'Z = I_C * X_L \tag{5.3}$$

$$I' = \sqrt{I^2 - 2I\sin\theta I_C + I_C^2} \tag{5.4}$$

The approximate value in percentage voltage rise can be derived from (5.3) which is shown in (5.5). For a required percentage voltage rise at a specific location, the reactive compensation in kVAr can be determined by (5.6) where X_L represents the inductive impedance in Ohms from the source to the point of compensation.

$$\%V_R = \frac{\sqrt{3}\ *\ I_C\ *\ X_L}{V_{p-p} * 10} = \frac{Q_C *\ X_L}{10 * {V_{p-p}}^2} \tag{5.5}$$

$$Q_C = \frac{10 * {V_{p-p}}^2 * \%V_R}{X_L} \tag{5.6}$$

The reduction in feeder current implies a subsequent reduction in feeder losses. This however is limited to the reactive components of current as shown in (5.9) which is derived by the difference of $Ploss_b$ and $Ploss_a$, representing losses before and after compensation shown in (5.7) and (5.8) respectively.

$$Ploss_b = (Icos\theta)^2R + (Isin\theta)^2R \tag{5.7}$$

$$Ploss_a = (Icos\theta)^2R + (Isin\theta - I_c)^2R \tag{5.8}$$

$$Ploss_r = R(2Isin\theta I_C - I_C^2) \tag{5.9}$$

In summary, distribution feeder losses can be reduced by the addition of shunt capacitors to supply in part or in full, the reactive power demands of loads, lines and transformers making up the feeder. Shunt capacitors will not only reduce feeder losses but also improve the voltage profile and overall power factor of the feeder. Equations (5.1) to (5.9) allow one to size capacitors for either loss reduction or voltage boost requirements.

The mathematical formulation in this chapter is largely based on the pioneering work on the application of capacitors to distribution systems contained in [19].

5.1.1 *Loss reduction for feeders with distributed load after the application of a single shunt capacitor*

The previous section showed that the technical loss reduction by the addition of shunt capacitance is a function of only the reactive or out of phase components of current as in (5.9). Thus, to assess the loss reduction of a feeder by installation of shunt capacitors, the distribution of the lagging reactive current needs to be studied. Consider a feeder with uniformly distributed loads as shown in Figure 5-2 where I_1 and I_2 represent the reactive current at the source and tail end of the feeder respectively, then current I_x at any point x on the system can be derived from the equation of a straight line and is a function of distance from the source as is given in (5.10).

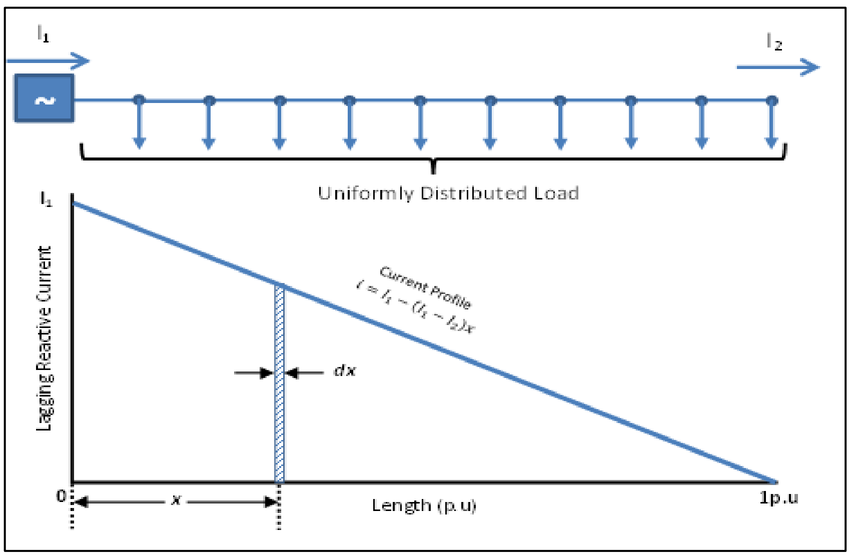

Figure 5-2: Feeder with uniformly distributed load [19]

$$I_x = I_1 - (I_1 - I_2)x \tag{5.10}$$

The differential loss of an infinitesimal line segment dx will be expressed as given in (5.11). If the length of the feeder is per unitised then the total losses for a 3 phase feeder as a result of reactive current can be calculated by integrating (5.11) from 0 to 1pu length as in (5.12) with the result expressed in (5.13).

$$dPloss = 3R[I_1 - (I_1 - I_2) * x]^2\, dx \tag{5.11}$$

$$Ploss = 3R \int_0^1 (I_1 - (I_1 - I_2)x)^2\, dx \tag{5.12}$$

$$Ploss = R(I_1^2 + I_1 I_2 + I_2^2) \tag{5.13}$$

With the insertion of a single shunt capacitor at location x_1 as shown in Figure 5-3, (5.12) and (5.14) are modified as shown in (5.14) and (5.15).

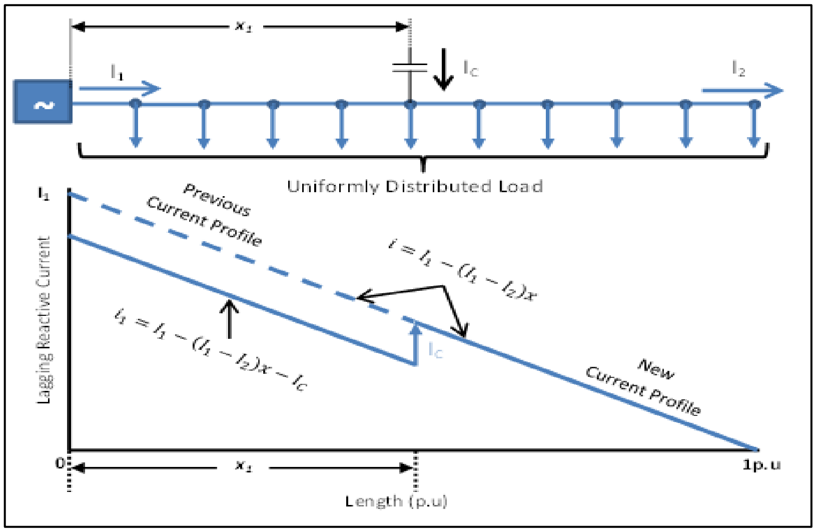

Figure 5-3: Feeder with uniformly distributed load with capacitor installed at location x1[19]

$$Ploss' = 3R\int_0^{x_1}[I_1 - (I_1 - I_2)x - I_c]^2\,dx + 3R\int_{x_1}^{1}[I_1 - (I_1 - I_2)x]^2\,dx \tag{5.14}$$

$$Ploss' = R(I_1^2 + I_1I_2 + I_2^2) + 3Rx_1[(x_1 - 2)I_1I_c - x_1I_2I_c + I_c^2] \tag{5.15}$$

The per unit loss reduction $\mathrm{Pu}Ploss_{red}$ by the addition of a capacitor can thus be derived from (5.13) and (5.15) which is simplified in (5.16) and (5.17).

$$\mathrm{Pu}Ploss_{red} = \frac{Ploss - Ploss'}{Ploss} \tag{5.16}$$

$$\mathrm{Pu}Ploss_{red} = \frac{3x_1C}{1+\lambda+\lambda^2}[(2 - x_1) + x_1\lambda - C] \tag{5.17}$$

$$\lambda = \frac{I_2}{I_1} \tag{5.18}$$

$$\mathrm{C} = \frac{I_C}{I_1} \tag{5.19}$$

The ratio of the reactive current at the end of a feeder to the source of the feeder is represented by λ which is given in (5.18) and is an indication of the distribution of reactive current along a feeder. The ratio of injected capacitive current to the total reactive current at the source is represented by the "Compensation Ratio" C given in (5.19).

For a given reactive power distribution (λ), the per unit power loss reduction ($\mathrm{PuPloss}_{\mathrm{red}}$) will vary with the compensation ratio (C) and the per unit distance (x_1) that the capacitor is located from the source. This is illustrated graphically in Figure 5-4 and Figure 5-5. For λ=0 which signifies a feeder with uniformly distributed reactive load, the maximum $\mathrm{PuPloss}_{\mathrm{red}}$ is 0.88pu with a C of 0.67 located at a distance x_1=0.67pu from the source. For λ=1 which signifies a feeder with reactive load concentrated at the tail end, the maximum $\mathrm{PuPloss}_{\mathrm{red}}$ is 1pu with a C of 1 located at x_1=1pu from the source.

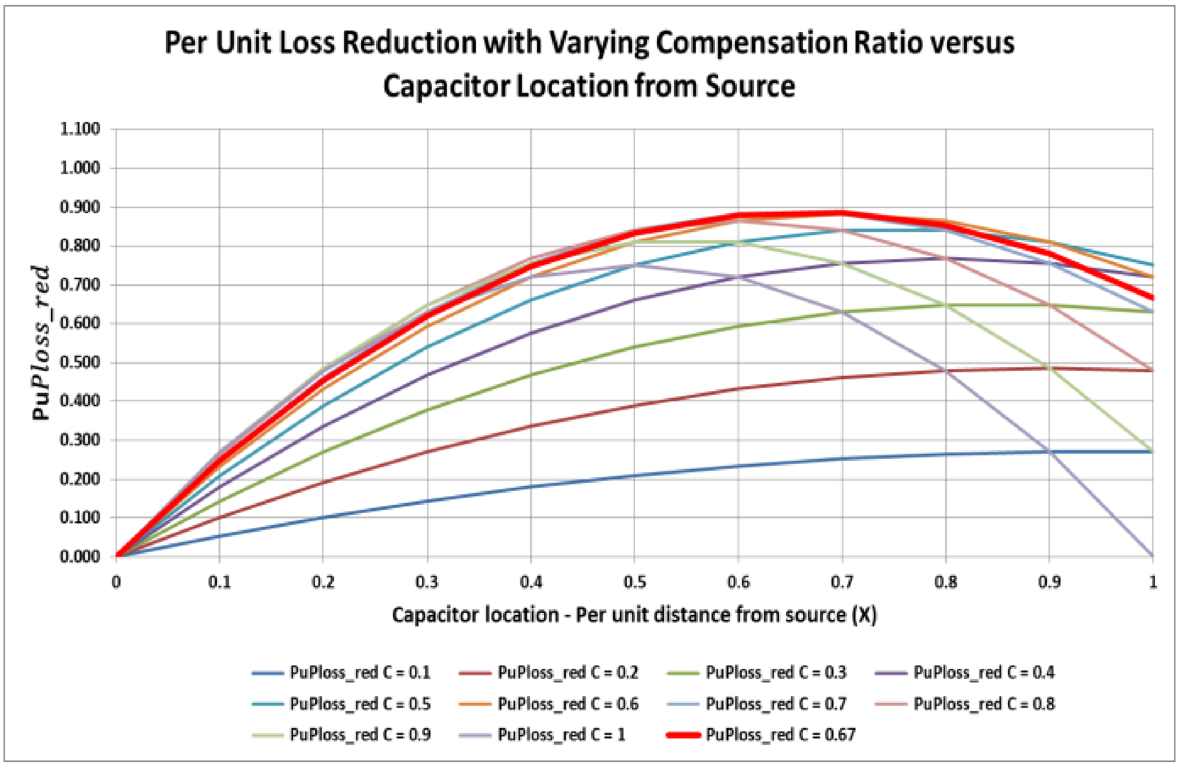

Figure 5-4: Feeder with uniformly distributed load λ =0

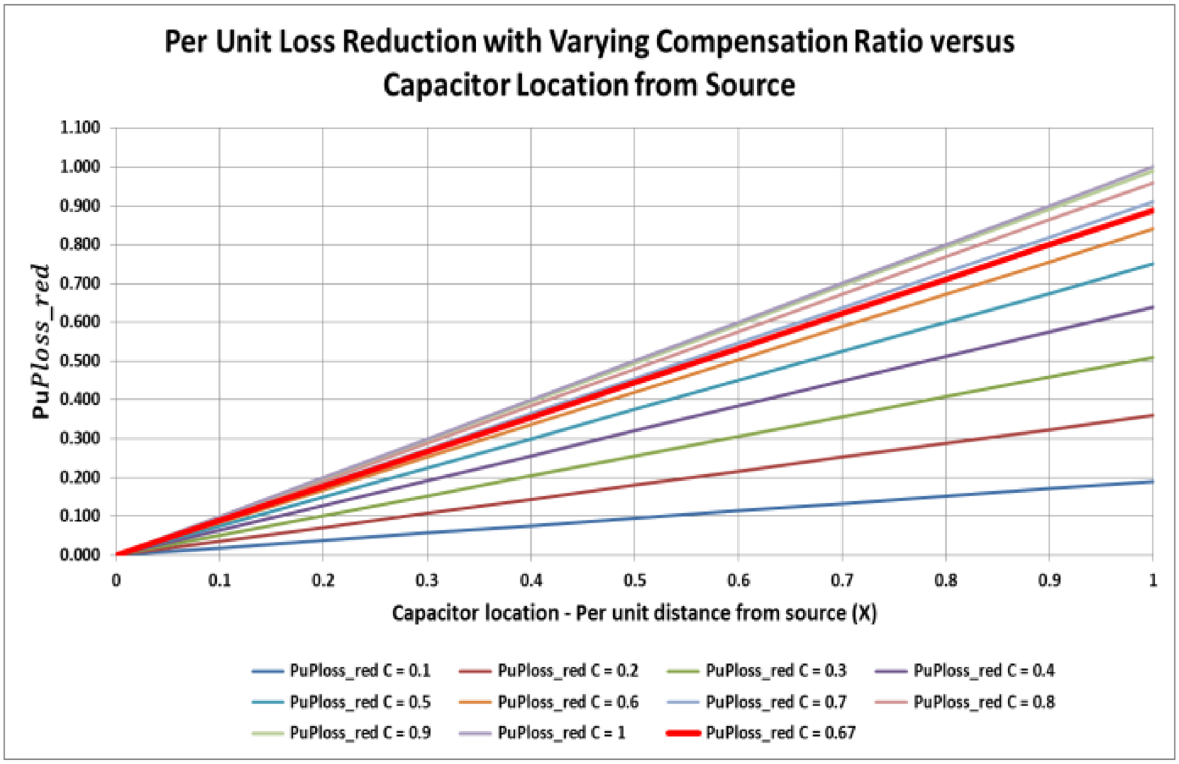

Figure 5-5: Feeder with reactive load concentrated at the tail end λ =1

Equation (5.17), Figure 5-4 and Figure 5-5 suggests that there exists an optimal compensation ratio (C) and location (x) for a given reactive power distribution (λ) such that the power loss reduction ($\mathrm{PuPloss_{red}}$) by the application of a shunt capacitor bank is maximised.

Taking the first order partial derivative of (5.17) with respect to C and setting the result to zero will yield an optimal C for a maximum $\mathrm{PuPloss_{red}}$ as shown in (5.20). Applying the partial derivative of (5.17) with respect to x and setting the result to zero will yield the optimal location for the capacitor for a maximum $\mathrm{PuPloss_{red}}$ as shown in (5.21).

$$C = 1 - \frac{1}{2}x_1 + \frac{1}{2}x_1\lambda \tag{5.20}$$

$$x_1 = \frac{1}{2}\frac{(c-2)}{(\lambda-1)} \tag{5.21}$$

Figure 5-6 and Figure 5-7 show this relationship graphically where the following key points can be summarised:

- A specific C ratio and location x_1 for a given reactive power load distribution λ, can be determined for a maximum power loss reduction.

- As λ increases from 0 to 1 which signifies reactive load moving from a perfectly uniform distribution to one in which reactive load becomes increasingly concentrated towards the tail end, the optimal C ratio and x_1 location increases.
- Depending on the load distribution λ, both the optimal C ratio and x_1 location varies from 0.67 to 1.
- The rate of change of the optimal C ratio with an increasing λ is less than that of the rate of change of ideal location x_1. For λ ≥ 0.4, the optimal location saturates at 1pu length i.e. the tail end of the feeder.
- For the same power loss reduction, a larger C is required closer to the source than towards the end. The installation closer to the end will be favored as the least cost option.

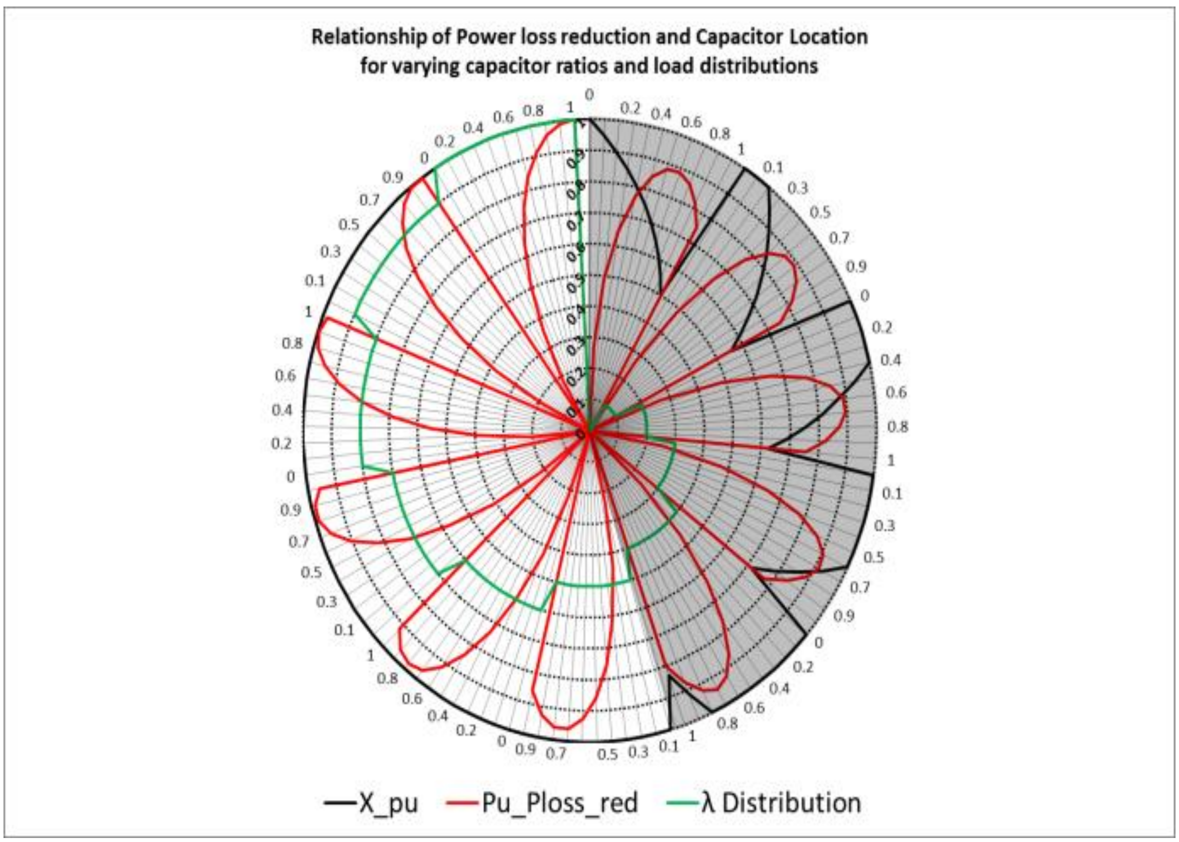

Figure 5-6: Relationship of Power loss reduction and Capacitor Location for varying capacitor ratios and load distribution

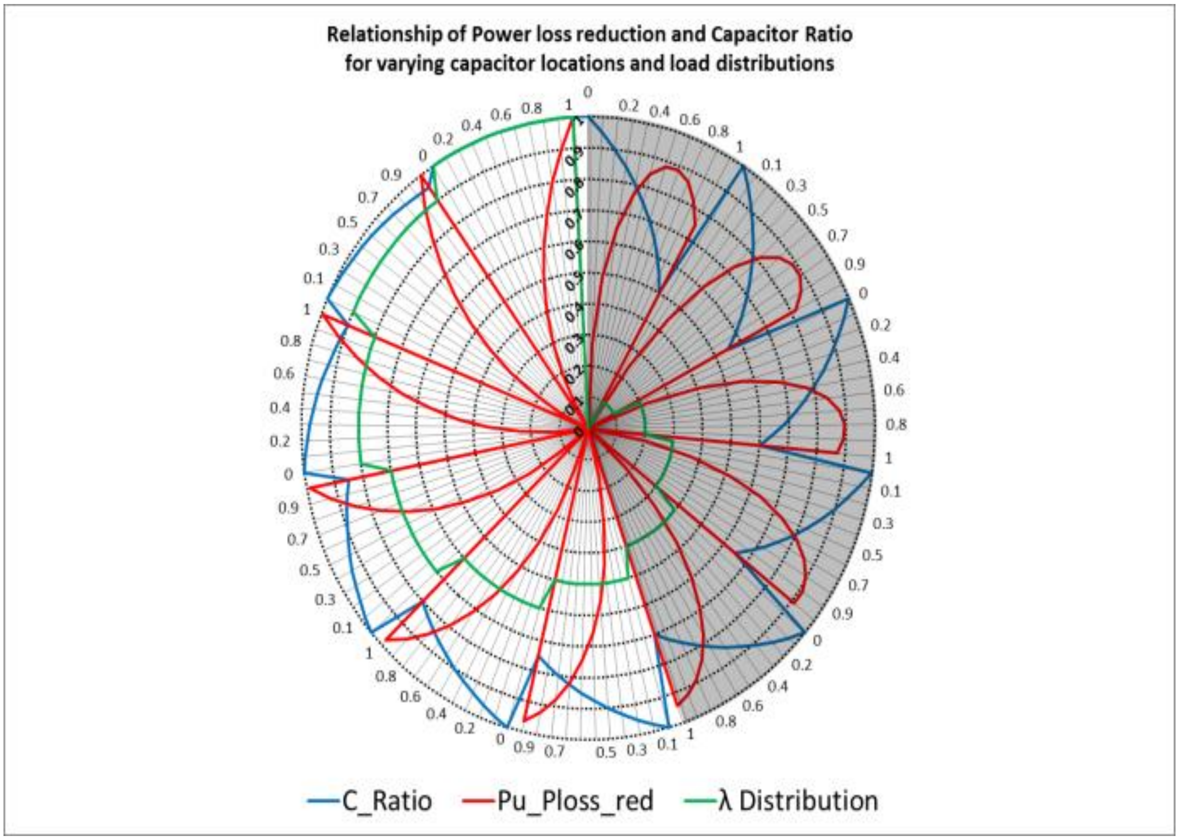

Figure 5-7: Relationship of Power loss reduction and Capacitor Ratio for varying capacitor location and load distribution

5.1.2 Loss reduction for feeders with distributed load after the application of multiple shunt capacitors

This section evaluates the benefits of multiple capacitor installation on feeders with varying reactive load distributions λ.

Assuming two capacitors of equal sizes and subsequently equal ratios C, are located at x_1 and x_2 as shown in Figure 5-8, similarly to equation (5.14) and (5.17), the equation for power loss reduction can be developed as given in (5.22).

$$\mathrm{PuPloss_{red}} = \frac{3C}{1+\lambda+\lambda^2}\{x_1[(2-x_1)+x_1\lambda-3C]+\ x_2[(2-x_2)+x_2\lambda-C]\} \qquad (5.22)$$

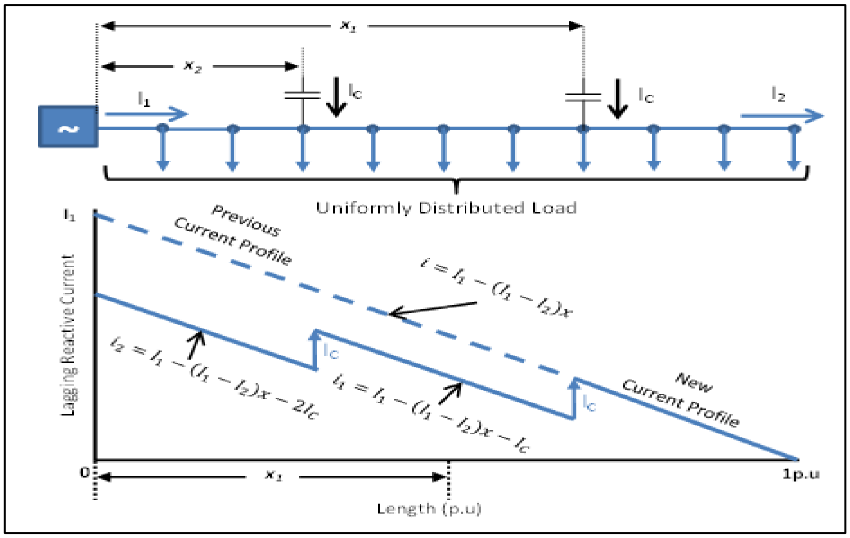

Figure 5-8: Feeder with uniformly distributed load and capacitors inserted at location x1 and x2

This can be further expanded for 3 capacitors and then up to n capacitors of equal size with the emergence of a pattern in the equations. This is given in (5.23) and (5.24).

$$\mathrm{PuPloss_{red}} = \frac{3\mathrm{C}}{1+\lambda+\lambda^2}\{x_1[(2-x_1)+x_1\lambda-5\mathrm{C}]+x_2[(2-x_2)+x_2\lambda-3\mathrm{C}] + x_3[(2-x_3)+x_3\lambda-\mathrm{C}]\} \tag{5.23}$$

$$\mathrm{PuPloss_{red}} = \frac{3\mathrm{C}}{1+\lambda+\lambda^2}\sum_{\mathrm{i}=1}^{\mathrm{n}}\{x_{\mathrm{i}}[(2-x_{\mathrm{i}})+x_{\mathrm{i}}\lambda-\mathrm{C}(2\mathrm{i}-1)]\} \tag{5.24}$$

In order to find the optimal location for the i^th capacitor, applying a partial derivative of (5.24) with respect to x_{i} and setting the result to zero, yields the optimal location for the capacitor for maximum $\mathrm{PuPloss_{red}}$ as shown in (5.25). When (5.25) is substituted into (5.24) the optimal power loss reduction is determined. Taking the first order partial derivative of (5.24) with respect to C and setting the result to zero will yield an optimal C ratio at each of the installations which is given in (5.26).

$$x_{\mathrm{iopt}} = \frac{1}{1-\lambda} - \frac{\mathrm{C}(2\mathrm{i}-1)}{2(1-\lambda)} \tag{5.25}$$

$$\mathrm{C} = \frac{2}{2\mathrm{n}+1} \tag{5.26}$$

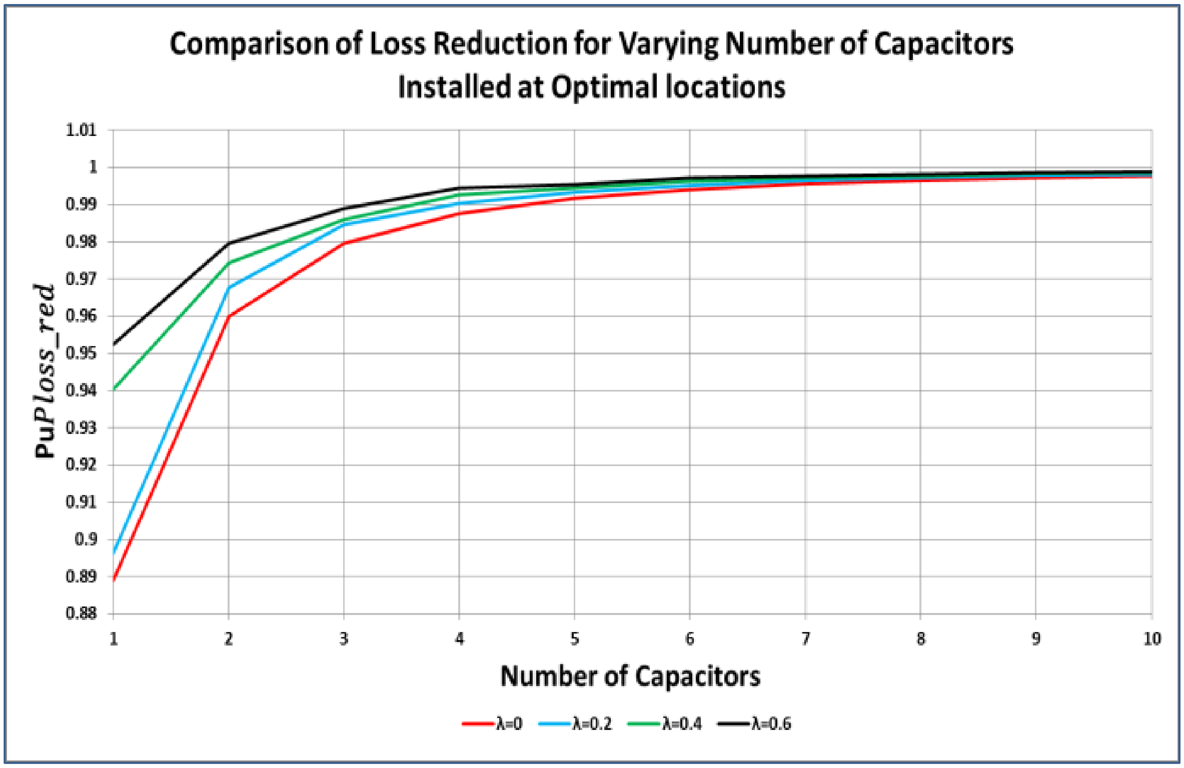

Figure 5-9: Comparison of Loss Reduction for Varying Number of Capacitors Installed at Optimal locations

Equation (5.24) is illustrated graphically in Figure 5-9 for multiple capacitors where optimal C ratios and locations x_{iopt} have been calculated. As will be observed, the increase in power loss reduction decays as the number of capacitors are increased. For e.g. a feeder with λ=0 will have an increase in power loss reduction of 8% following the installation of a 2nd capacitor. The 3rd capacitor will increase the power loss reduction by a further 2% and so on. The important point to note however is that with the increase in the number of capacitors, the total compensation ratio increases with a decaying return in loss minimisation. Further, after 2 capacitors, the cost of installation is likely to be unjustifiable from a losses point of view. Based on the lack of reactive power compensation on the Eskom Distribution system as illustrated in Figure 4-16, and given the fact that one large capacitor bank offers as much benefit as two or more capacitor banks of equal sizes, the research will initially focus on the installation of a single capacitor per network.

5.2 Proposed distribution feeder reactive power optimization model using the Area Criterion (λ)

For a uniformly distributed load as shown in Figure 5-2, the load on the backbone reduces linearly down to zero when measured from the source to the tail end. In reality a feeder rarely exhibits this ideal behaviour as a result of either large power users [65] and/or major tee-offs on the backbone. The installation of shunt capacitors on the backbone to provide distributed compensation on a feeder therefore requires as a prerequisite that the load distribution or λ of the feeder be determined. Note that major tee-offs may need to be treated as separate feeders before any decision to compensate is made. Further if large power users consume considerable reactive power, then they will need to be individually compensated.

For the determination of λ of a feeder, a calibrated power system simulation model with respect to load and impedance needs to be prepared. The reactive current flow through the backbone after a successful load flow must then be used to produce a feeder current profile versus distance plot. Per unitising the length as well as the current makes it possible to compare against a linear per unitised load distribution of λ=0 i.e. tail end current equals zero and source current equal to 1pu as given by (5.18). This is represented graphically in Figure 5-10 for 10 Eskom MV feeders with varying reactive power load distributions.

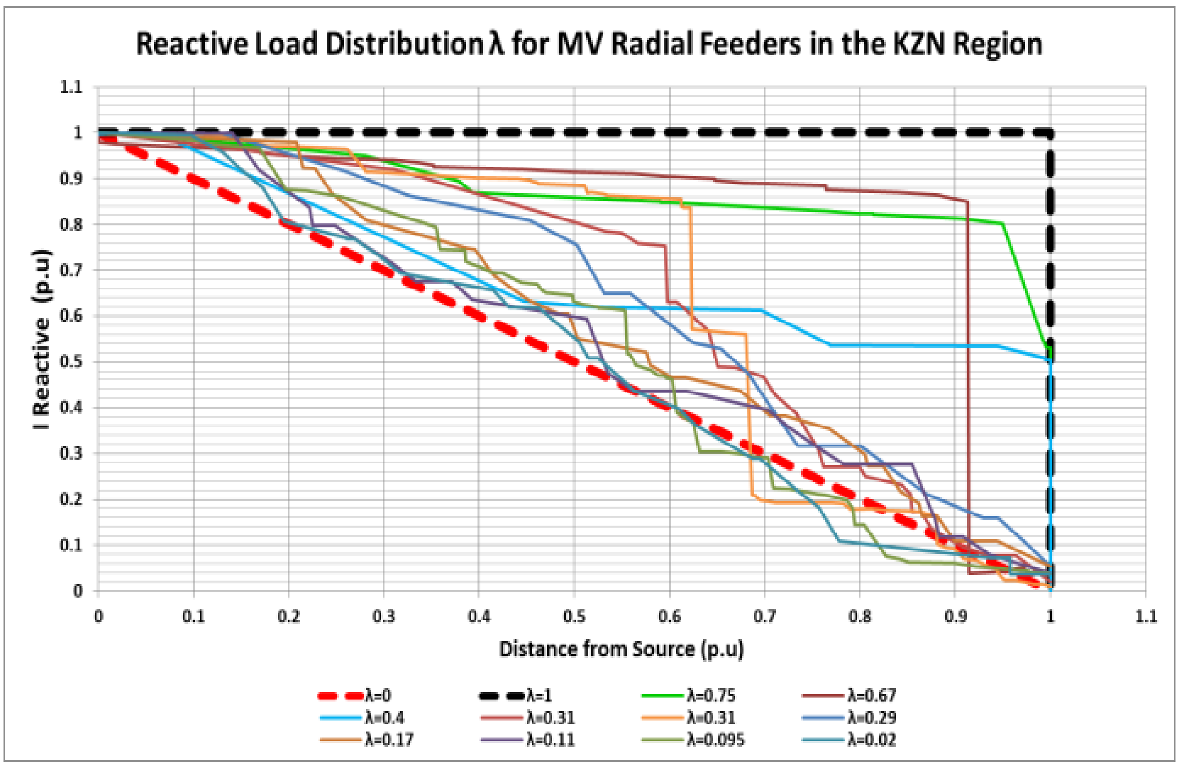

Figure 5-10: Reactive Load Distribution λ for MV Radial Feeders in the KZN Region

Assessing a feeder's load distribution against the ideal distribution in per unitised form makes it possible to compare load distributions geometrically. The difference in geometric areas under the curves between the ideal and actual profiles is related to the feeder's actual load distribution, λ_{actual}. Consider the red and black profiles in Figure 5-10 representing λ=0 and λ=1 respectively. Ignoring units, the geometric area can be calculated as 0.5 and 1 respectively. Applying (5.27), λ_{actual} can be determined.

$$\lambda_{actual} = \frac{Area\ \lambda_{actual} - Area\ \lambda_0}{Area\ \lambda_0} \tag{5.26}$$

$Area\ \lambda_{actual}$ is determined by dividing the profile up into ideal shapes i.e. triangles and rectangles where the incremental summation of these areas approximates the total area under the profile. This is based on the Riemann sum approximation methods [66], [67]. An algorithm for the determination of the reactive power load distribution is provided in Appendix A - Algorithm for the calculation of the reactive power distribution (λ) of a feeder.

5.3 Methodology with combined consideration to the loss minimization and minimum statutory voltage objectives

The previous section has described the influence of capacitors on voltage and losses independently. For networks with poor voltage regulation, if capacitors are used strictly to enforce minimum voltage limits only, it may typically result in increased losses as compared to the optimal loss configuration for that network. This implies that a combined strategy is required.

5.3.1 Methodology to size and locate capacitors based on peak feeder load

1. Networks with power factor < 0.95 and total reactive power demand (Q_{max}) > 300kvars should be considered for shunt compensation [68].

2. The power system simulation model needs to be scaled to the peak load where the λ load distribution should be determined using (5.26).

3. Determine the optimal location and size of the shunt capacitor using Figure 5-6 and Figure 5-7 for the given λ. The model is then re-adjusted by applying the capacitor on the network where this becomes the base model for further analysis.

4. If the minimum voltage of the network after the placement of the capacitor in step 3 is greater than the statutory voltage limit ($V_{statutory}$), then the optimal location (x) and sizing (Q_{opt}) has been determined. In this instance the installation of the capacitor is dictated by loss minimisation only. The final size of the capacitor then needs to be modulated to the closest integer multiple of the smallest available bank size available on the market. This will cater for any switching requirements during the low load scenario. Please note that this step,

although not stated, is required in all the assessments that follow when determining the C ratio and sizing at peak load.

5. If the minimum voltage of the network ($V_{tailend}$) is less than the statutory voltage limit after the placement of the capacitor in step 3 and λ > 0.4, then the installation of the capacitor is dictated by raising the minimum feeder voltage to the statutory limit. As illustrated in Figure 5-7, for feeders with λ > 0.4, the optimal location is at the tail end and thus the assessment entails determining the appropriate capacitor size only. From (5.5), if $(V_{statutory} - V_{tailend}) < [\frac{(Q_{max}-Q_{opt})*xl_{tail}}{10*V_{p-p}{}^2}]$ then the rating of the capacitor is given by $\left[\frac{10*V_{p-p}{}^2*(V_{statutory}-V_{tailend})}{xl_{tail}}\right] + Q_{opt}$, else the rating is equal to Q_{max} which implies a C factor of 1 is used. Note xl_{tail} represents the inductive reactance in Ohms between the source and tail end of the feeder.

6. If the minimum voltage of the network is less than the statutory voltage limit after the placement of the capacitor in step 3 and c, two assessments must carried out and compared for the optimal sizing and positioning of the shunt capacitor.

7. The first assessment is to determine if by increasing the C ratio <u>at the optimal location</u>, whether the minimum voltage objective could be met. From (5.5), it follows that if $(V_{statutory} - V_{tailend}) < [\frac{(Q_{max}-Q_{opt})*xl_{opt}}{10*V_{p-p}{}^2}]$, then the rating of the capacitor is given by $\left[\frac{10*V_{p-p}{}^2*(V_{statutory}-V_{tailend})}{xl_{opt}}\right] + Q_{opt}$, else the rating is equal to Q_{max} which implies a C factor of 1 is used. Note the C ratio is capped at 1 so as not to impact the upstream Sub-Transmission voltage regulation.

8. The second assessment is to determine if by increasing the location <u>with the optimal C ratio</u> applied, whether the minimum voltage objective could be met. Note increasing the location implies increasing the reactive impedance through which the leading capacitive current is injected. Again from (5.5), if $(V_{statutory} - V_{tailend}) < [\frac{Q_{opt}*xl_{tail}}{10*V_{p-p}{}^2}]$, then the new location can be found at that point on the backbone where the inductive impedance equals $[\frac{10*V_{p-p}{}^2*(V_{statutory}-V_{tailend})}{Q_{opt}}]$. If the condition is not satisfied, then it follows that the location should be moved to the tail end in order to maximize the reactive impedance. In this case, the assessment as listed in step 5 above needs to be carried out to determine if the size of the capacitor can be further optimized to less than Q_{max} at the tail end location. For completeness, if $(V_{statutory} - V_{tailend}) < [\frac{(Q_{max}-Q_{opt})*xl_{tail}}{10*V_{p-p}{}^2}]$ then the rating of the capacitor is given by $\left[\frac{10*V_{p-p}{}^2*(V_{statutory}-V_{tailend})}{xl_{tail}}\right] + Q_{opt}$, else the rating is equal to Q_{max} which implies a C factor of 1 is used.

9. The final step is then to compare the results of the two assessments such that the new calculated parameters results in $[\frac{V_{min\_new}}{1-PuPloss_{red}}]$ being the maximum. This final assessment ensures that the tail end voltage is maximized with maximum power loss reduction.

10. Mobile capacitor banks [68] should be considered for all cases where the C ratio required is 1 and the location set to the tail end of the feeder. The network should be strengthened to improve tail end voltages where permanent placement of capacitors for loss minimization can be reassessed.

The steps to size and locate capacitors have been summarised in the algorithms in Figure 5-11 and Figure 5-12.

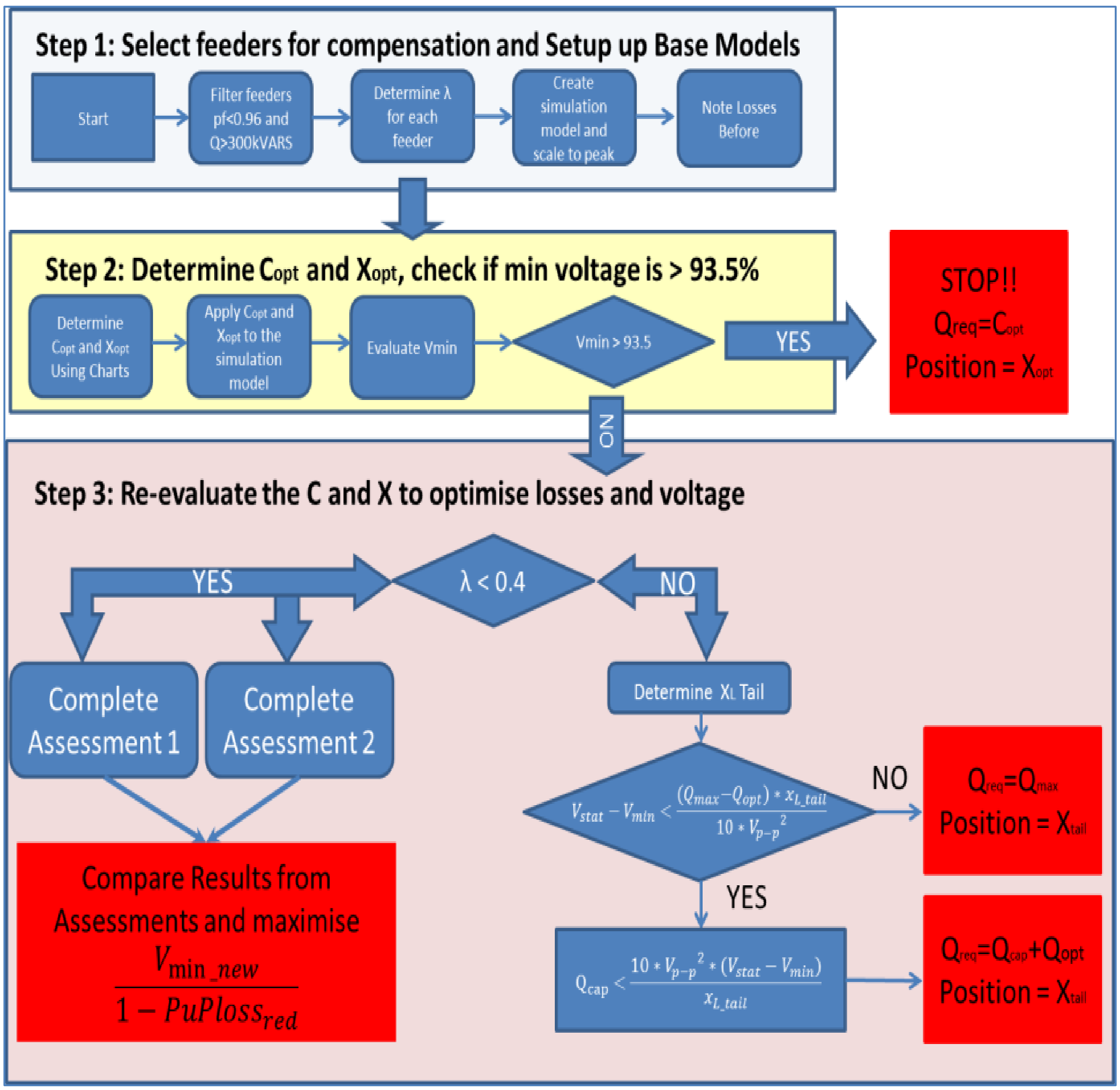

Figure 5-11: Overall algorithm for capacitor placement based on combined voltage and loss objectives

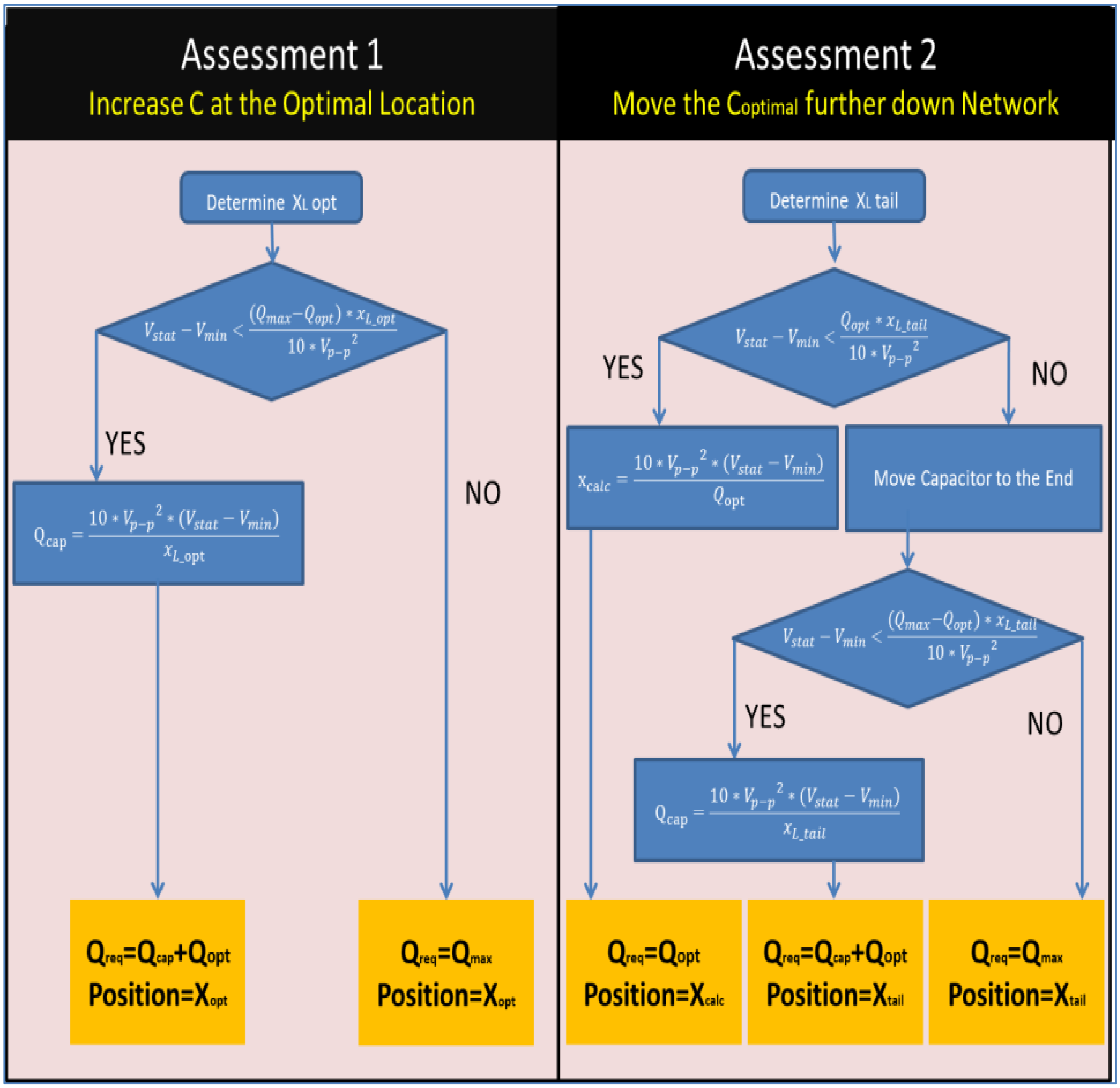

Figure 5-12: Algorithm for assessment to be carried out if minimum voltage less that statutory limit and λ > 0.4

5.3.2 Methodology to determine the switching requirements for shunt capacitor

1. To determine the switching requirements of a capacitor bank, the impact of the capacitor needs to be studied on the network under varying load conditions with keeping the location fixed as determined in section 5.3.1 above. Thus a typical day profile of the network is to be obtained.

2. Using the profiles the network can be simulated under the varying load. Take for example, a particular instance in time $\mathrm{T} = \mathrm{i}$, the power system simulation model needs to be scaled and simulated without any compensation for this instance.

3. If the minimum voltage of the network at time $\mathrm{T} = \mathrm{i}$ without any compensation is greater than the statutory voltage limit, then the size of the capacitor required is solely based on minimisation of losses on the network where using equation (19) the optimal C ratio can be calculated. The size of the capacitor then needs to be modulated to the closest integer multiple of the smallest available bank size available on the market as discussed in step 4 of section 5.3.1.

4. If the minimum voltage of the network at time $\mathrm{T} = \mathrm{i}$ without any compensation is less than the statutory voltage limit then the sizing of the capacitor should be dictated by raising the minimum feeder voltage to the statutory limit. The size of the capacitor required at time $\mathrm{T} = \mathrm{i}$ is given by $\left[\frac{10 * \mathrm{V_{p-p}}^2 * (\mathrm{V_{statutory}} - \mathrm{V_{min\_i}})}{\mathrm{xl_{tail}}}\right]$. However to ensure no increase in losses on the network if the capacitor size required is greater than the reactive power consumption of the network then the size of the capacitor required is equal to the reactive power consumption.

5. Steps 2 to 4 needs to be repeated for the various time periods in the day and the size of capacitors required under each time period should be analysed to determine the minimum, maximum and incremental step sizes required for the capacitor to ensure optimal capacitor sizing under all instances.

The algorithms for the switching requirements have been summarised in Figure 5-13.

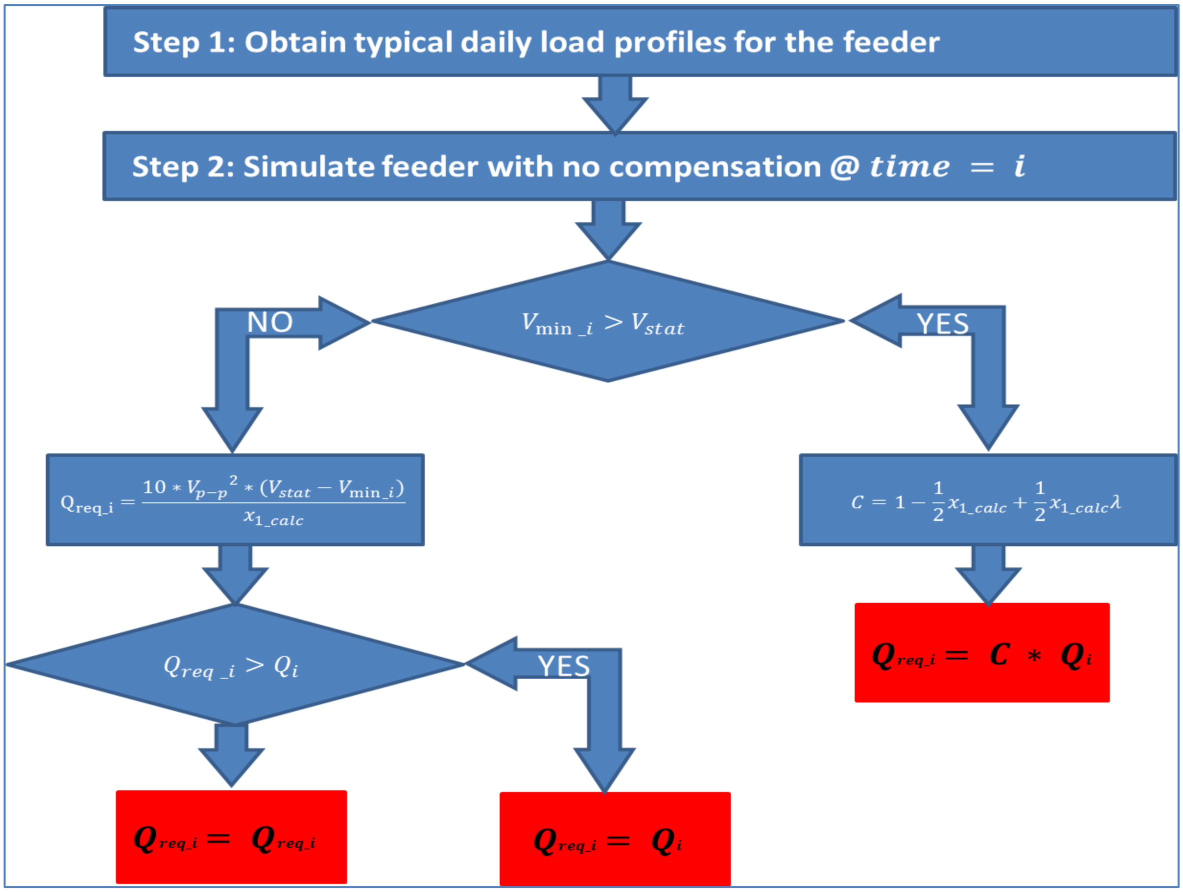

Figure 5-13: Algorithm to determine switch requirements of the capacitor installation.

5.4 Conclusion

The mathematical formulation has concluded that there is a specific location for a given size of capacitor bank that produces the maximum power loss reduction for a given reactive power distribution on a feeder. In the Eskom rural feeder context, where networks are constrained, the application of capacitors must also consider raising voltages to statutory requirements; however this may limit the power loss reduction capability. The methods developed in this chapter allow both voltage and power loss reduction to be maximised with the application shunt capacitive compensation.

If a network with poor power factor and considerable VAr consumption meets the statutory voltage requirements under all loading conditions, then the capacitor solution will incorporate reactive power compensation for technical loss reduction only. Once the reactive power distribution factor λ is determined a suitably positioned and sized capacitor can be determined by use of the look up charts in Figure 5-6 or Figure 5-7 which shows the dependency of Power loss reduction to capacitor Ratio, capacitor location and reactive load distribution.

If a network does not meet the statutory voltage requirements even after the placement following simulations for optimal size and location based on loss minimisation, then the requirements for the capacitor placement becomes focussed on voltage support where the capacitor is either increased in size at the optimal location or moved down the feeder to accrue more inductive impedance, through which leading reactive current can be injected to raise voltage. This then combines the objectives of loss minimisation and voltage support by reactive power compensation. In the extreme, the capacitor may be moved to the tail end of the feeder and increased to a size giving a C ratio of 1, such that the power factor at the source does not go into leading. This then represents the maximum capability where other means to improve voltages need to be explored if voltages remain below limits.

In chapter 2, the loss and regulation properties of lines, transformer and voltage regulators were discussed. This chapter has shown that a single capacitor installation can when optimally sized and located, reduce these quantities and thereby improve the power delivery efficiency.

6 Case Study to demonstrate the implementation of the proposed Volt/VAr model on an Eskom distribution feeder

6.1 Approach and general assumptions

Given the lack of capacitive compensation on the Eskom distribution system as a whole and the high number of customers exposed to voltages below statutory limits [9], [63], it is recommended that the initial approach to Volt/VAr management adopted by Eskom, consider both an improvement of feeder voltage regulation as well as reductions in technical losses by reactive power compensation. The application of the theory developed and learnings from previous chapters will be applied by way of simulation to an existing Eskom distribution medium voltage feeder. The feeder selection criterion includes poor voltage regulation, poor power factor and excessive energy losses. Capacitive compensation by appropriate sizing, placement and switching will be used to improve these quantities. Various configurations will be tested with results tabulated leading to an optimal solution.

6.2 Feeder information

Figure 6-1 shows a single line representation for the chosen distribution feeder (Mtubatuba 22kV NB4). The feeder has a backbone length of 30.35km and a total exposure length of 166km including the laterals. The backbone is made up of Hare and Fox conductor carrying normal ratings of 280 amps and 148 amps respectively. Other conductor parameters are shown in Table 6-1. There are 375 MV/LV transformers on the network supplying 4893 customers of which 4 are large power users (LPU). The remaining customers are rural electrification type loads following residential patterns.

Table 6-1: Backbone conductor characteristics [69]

Conductor	Current at 50°C [A]	Size [mm2]	DC resistance at 20°C [Ω/km]	X/R ratio [typical]	Max 22 kV thermal loading [MVA]
Fox	148	37	0.7822	0.43 - 0.52	5.64
Hare	280	105	0.2733	1.1 - 1.28	10.67

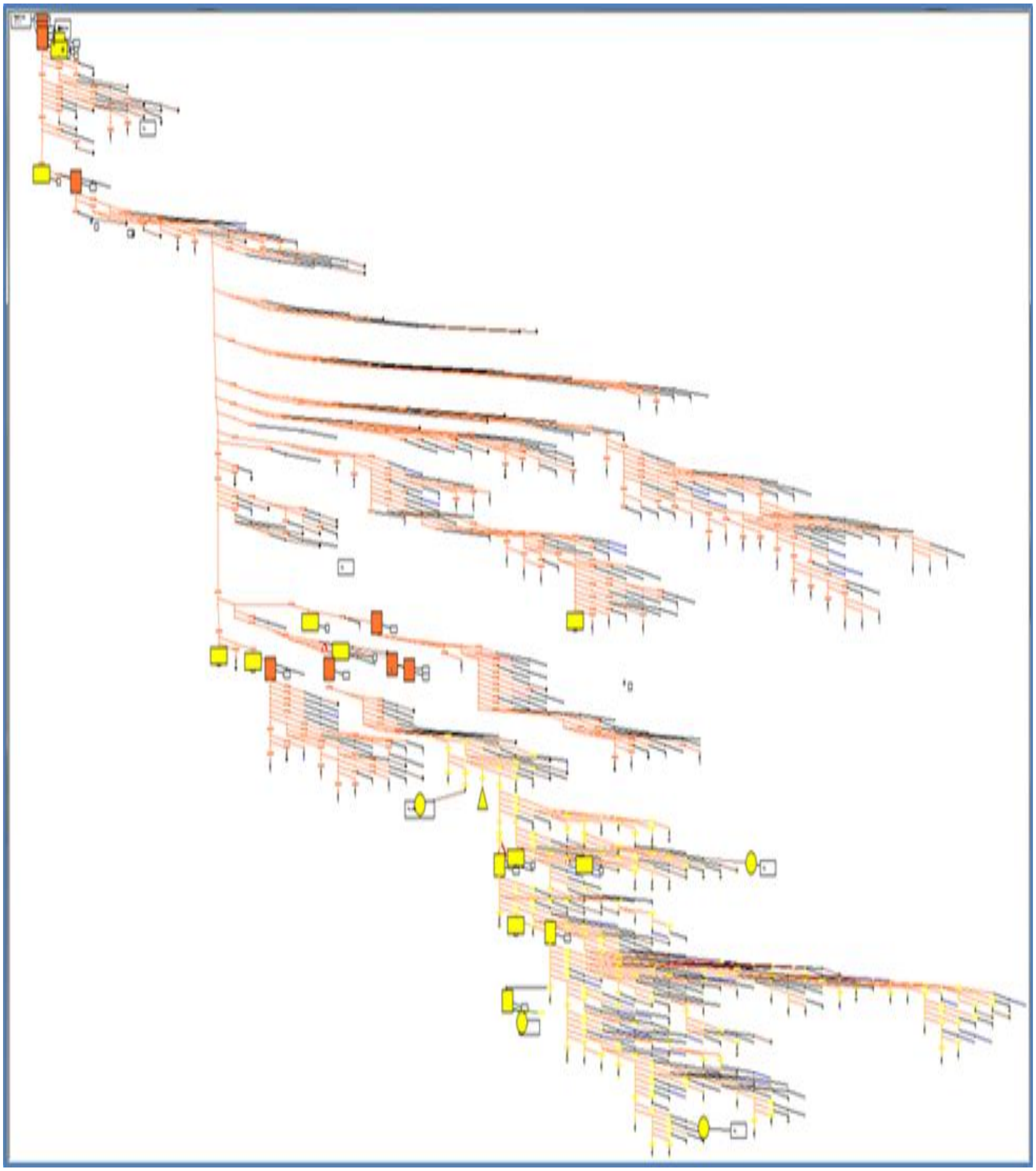

Figure 6-1: Single line diagram - Mtubatuba 22kV NB4

Statistical metering has been installed at the substation for each of the outgoing distribution feeders as well as at LPU points of supply. Meters have been configured to capture half hourly integrated measurements for active and reactive power. Figure 6-2 and Figure 6-3 show typical daily load profiles for Mtubatuba NB4 and the largest LPU fed from this feeder. This will form the basis for all the power system analysis and assessments that follow.

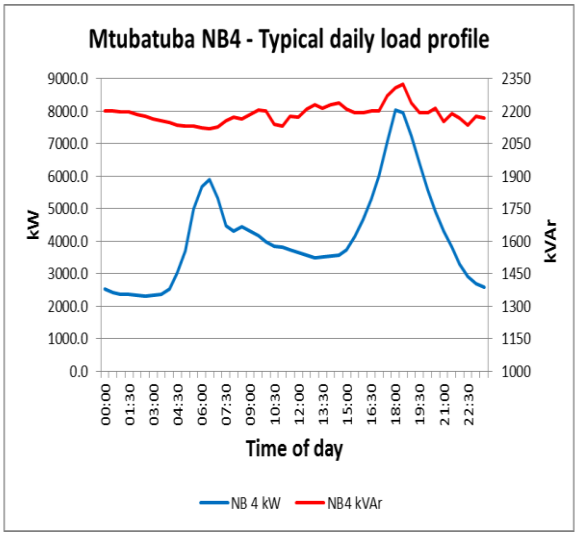

Figure 6-2: Typical day profile for Mtubtuba NB4

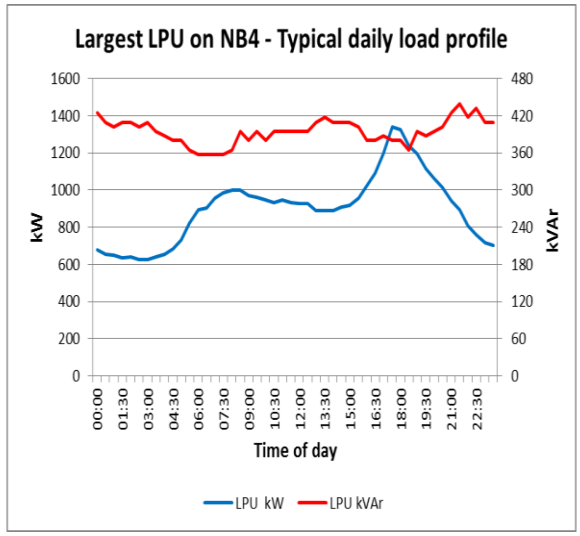

Figure 6-3: Typical day profile for municipal customer (LPU) on Mtubtuba NB4

The profiles are characteristic of residential type load, associated with morning and evening peaks. The LPU in this study is a small municipal customer sharing similar characteristics. The reactive power consumption (read from the secondary axis in both figures) indicates a fairly constant trend over a 24 hour period for both the feeder breaker and the LPU.

6.3 Power system analysis and assessment

The DIgSILENT PowerFactory software tool has been used for power system modelling and simulation. The feeder equipment data (conductor type, conductor lengths, transformers, load types etc.) have been sourced from Eskom's Smallworld database. Using Smallworld data and data provided by statistical metering, the MV feeder under study has been modelled in DIgSILENT PowerFactory. Loads have been modelled with time characteristics (half hourly data) allowing day profiles to be input where the network can be studied during various time periods in a day which is crucial to determining the switching requirements for the shunt capacitor bank . This also allows for load diversity to be catered in the model, increasing the accuracy of simulations.

6.3.1 Peak load analysis

Figure 6-2 indicates the peak load condition occurs at 18:00. The results of the simulation are shown in Table 6-2 where the loads, power factor, minimum tail end voltage and technical losses are tabulated.

Table 6-2: Results of peak load analysis at 18:00

Network peak at 18:00	kW	kVAr	kVA	PF	Vmin (p.u.)	Technical Loss (kW)
LPU	1322.59	379.64	1376.00	0.961	-	-
1_System Normal	8023.79	2308.63	8349.31	0.961	0.873	873.72

The minimum voltage on the feeder is shown to be 6.2% lower than the required limit of 93.5% for the class two tap zone 2 feeder [52]. This is indicative that some customers will be supplied voltages below statutory limits during peak times even though MV/LV transformers are set to maximum boost. This depends on where customers are fed from relative to the point of connection on the backbone. The technical loss of 10.89% is also high when compared to the distribution technical loss averages of between 3% and 7% reported in [70] and [54].

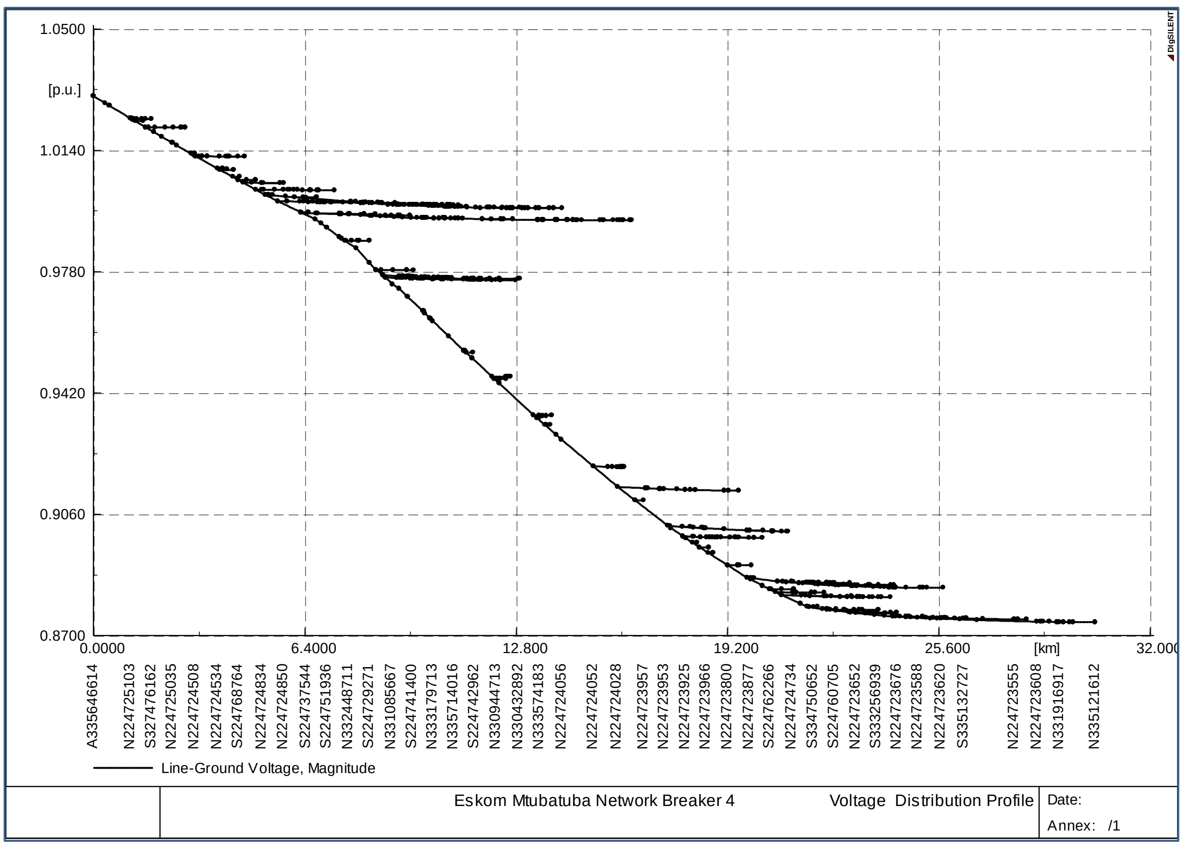

Figure 6-4: Voltage profile peak load

Figure 6-4 shows the voltage profile of the network under the peak loading condition. Note the sending end voltage is controlled by the substation on load tap changer and is set to maintain the source voltage at 1.03p.u within its tapping range. The voltage profile is produced following a load flow calculation where voltages at the various nodes are resolved and plotted against the distance away from the source. The voltage drop approximation across a line segment is given in (2.16) and is a function of line resistance, line reactance, load current and load power factor. Since the current on the backbone decreases with distance from the source for a distribution feeder (load is consumed at various points along the length of the backbone where current is cumulative towards the source), the rate of change of voltage drop across a unit length of backbone conductor (considering the line impedance components) will be greater at the source and decrease along the length of the feeder as the current drops off. As a result the shape of the voltage profile for a distribution feeder is characteristic of exponential decay, i.e. voltage decreases with distance away from the source and the rate of change of decrease, decreases also with the distance away from the source.

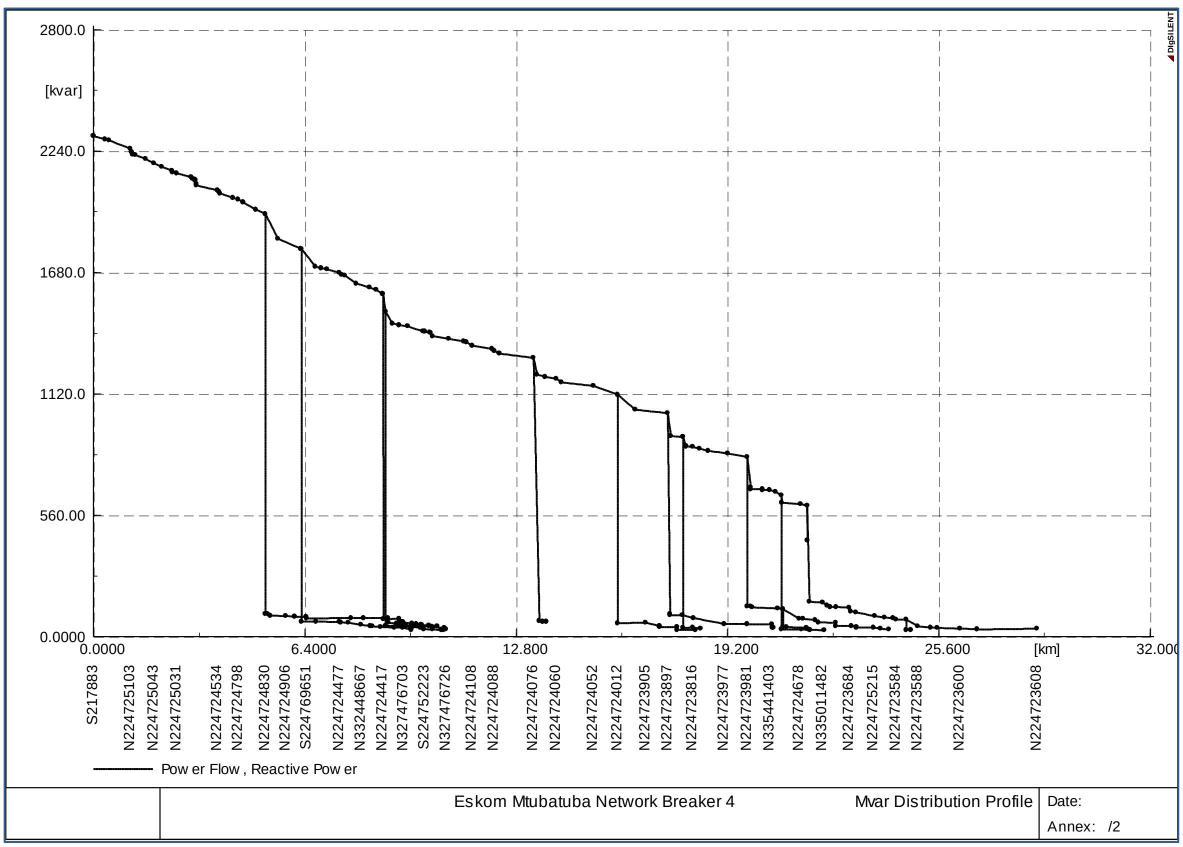

Figure 6-5: Reactive power profile – peak load

The reactive power distribution is shown in Figure 6-5 and Figure 6-6. Note, certain laterals have been omitted to show as far as possible, the backbone under consideration only. The reactive power distribution profile illustrates the reactive power flow through the backbone. After a successful load flow calculation, the reactive flows of the various branch elements are resolved. By plotting the reactive flow into or out of a node on the backbone with respect to distance of the node from the source, the reactive power distribution of the feeder is obtained. The reactive power consumed at various points or laterals on the backbone are cumulative towards the source i.e. a line segment just outside the source will carry the full reactive power of the feeder, for a line segment midway say, the reactive power flow through that segment will be all the reactive power consumed below that point on the backbone only.

In Figure 6-6, the reactive power distribution and distances are per-unitized in order to simplify comparisons and observe deviations from an ideal feeder with uniformly distributed reactive power consumption. The reactive power distribution factor (λ) can be directly determined from Figure 6-6 using the Riemann sum approximation and equation (5.26). An algorithm to automatically calculate (λ) is provided in Appendix A - Algorithm for the calculation of the reactive power distribution (λ) of a feeder.

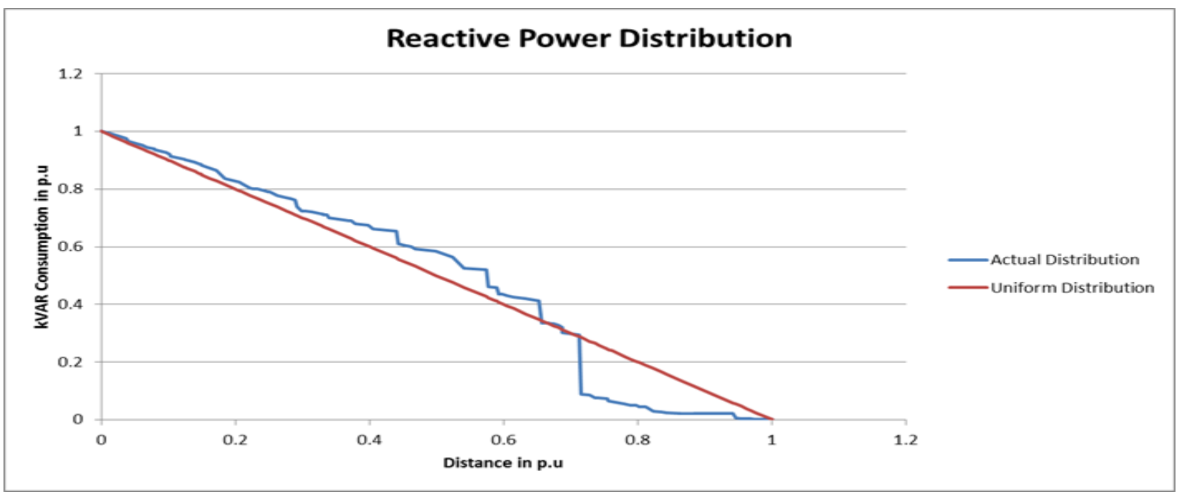

Figure 6-6: Reactive power distribution per unitised and compared with uniformly distributed load feeder

Figure 6-5 and Figure 6-6 indicate a sudden drop in reactive power at approximately 75% of the backbone length. This location corresponds to the LPU's point of supply, in this case the small municipal customer consuming considerable reactive power. By compensating this LPU to as close to unity power factor as possible, the reactive power distribution along the feeder will move closer to that of a feeder with uniform reactive power distribution. At the time of the feeder peak, the LPU reactive power consumption was measured at 379.64kVar however the LPU's individual peak consumption is 440kVAr. Since the reactive power consumption is fairly flat across a day profile as shown in Figure 6-3 and in order to cater for worst case conditions, the LPU will be compensated with a 440kVar fixed capacitor bank as an initial step where it is accepted that during certain time periods, the LPU load will go into a slightly leading power factor. This strategy will also lessen the requirements for power factor correction and reactive power compensation by the utility company, when specifying a centralised feeder capacitor for the purposes of power loss reduction.

Figure 6-7 shows the adjusted reactive power distribution for the feeder, after the LPU compensation of 440kVAr is applied to the simulation. In this instance, λ is calculated to be -0.0823 which is approximately 0, obeying the characteristics of a feeder with uniformly distributed reactive power. The charts shown in Figure 5-6 and Figure 5-7 in chapter 5 which compares the relationship of power loss reduction to capacitor location and capacitor size for a given reactive power distribution, indicates that the optimum location and size for a centralized capacitor in this case would be 67% down the backbone with capacitive compensation ratio of also 67%. Note the latter is determined only once the LPU has been compensated and the feeder reactive power compensation adjusted accordingly.

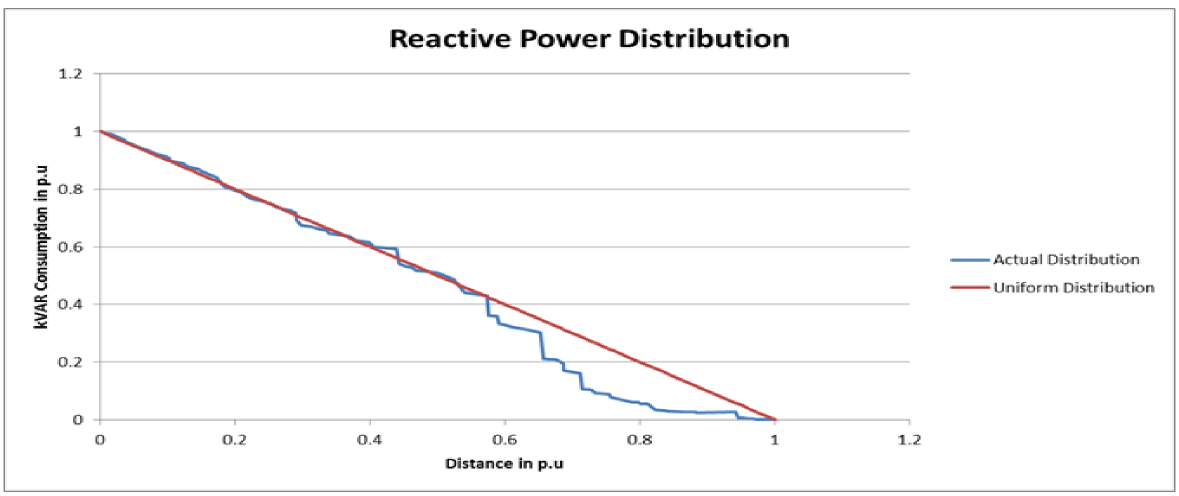

Figure 6-7: Reactive power distribution following LPU compensation of 440kVAr

Table 6-3, indicates a marginal improvement in tail end voltage which remains below minimum requirement and an approximate 36kW reduction in technical losses after the LPU compensation has been applied. Given the revised total reactive power consumption of the feeder, the centralised capacitor for power loss reduction is sized to be 67% of 1924kVArs i.e. 1289kVars. The optimal location is determined to be 20.24km away from the source.

Table 6-3: Results of peak load simulation after LPU Compensation

Network peak at 18:00	kW	kVAr	kVA	PF	Vmin (p.u.)	Technical Loss (kW)
1_System Normal (Peak)	8023.79	2308.63	8349.31	0.961	0.8731	873.72
2_LPU compensated (440kVAr)	7987.94	1923.97	8216.37	0.972	0.8805	837.85

The next steps involve determining if the centralised and optimally positioned capacitor intended to maximise power loss reduction, is also able to raise the tail end voltage to the statutory limit of 93.5%. If this is not achievable, then the algorithms developed in chapter 5 suggest 1 of two alternatives; either to increase the capacitive ratio to 1 at the optimal location or to move the optimally sized capacitor to the tail end of the feeder. If the end of line voltage is still below the statutory limit in both these instances then the capacitor is by default placed at the tail end where the capacitive ratio is set to 1 at that location. From (5.5) given in chapter 5, this will produce the maximum end of line voltage without a leading power factor measured at the source. Note in this case, there will be little or no improvement in loss reduction for the immediate feeder. Further, if more voltage support is required to achieve the statutory limit, then the capacitor will have to be resized, again using (5.5), however this will result in a leading power factor at the source and an increase in the technical losses of the feeder.

These steps are simulated and summarised in Table 6-4.

Table 6-4: Options for placement and sizing of capacitor - Peak load study

Scenario	kW	kVAr	kVA	Power factor	Minimum Voltage (p.u.)	Vrise (%)	Technical Loss (kW)	Loss Savings (kW)
1. System Normal (Peak)	8023.79	2308.63	8349.31	0.961	0.8731	-	873.72	0.00
2. LPU compensated pf=1	7987.94	1923.97	8216.37	0.972	0.8805	0.74	837.85	35.87
3. Optimal Cap at optimal location + LPU compensation	7946.34	791.65	7985.68	0.995	0.8997	2.66	796.21	77.51
4. Capacitive ratio 1 at optimal location + LPU compensation	7954.95	211.10	7957.75	1.000	0.9091	3.60	804.80	68.92
5. Optimal Cap at Tail end + LPU compensation	7972.20	811.50	8013.40	0.995	0.9087	3.57	822.07	51.65
6. Capacitive ratio 1 at Tail end + LPU compensation	8018.67	240.17	8022.26	1.000	0.9222	4.92	868.50	5.22
7. Leading Cap at Tail end + LPU compensation (sized for 0.935 p.u.)	8123.90	-438.82	8135.74	0.999	0.9374	6.43	973.78	-100.06

Scenarios 2 to 5 show improvement in feeder technical losses, however the tail end voltages albeit improved, remain below the statutory limit. The simulation result for scenario 3 indicates the maximum power loss reduction which ties up with the theory developed in chapter 5.

For scenario 7, the size of compensation required to lift the tail end voltage to the statutory limit is determined using (5.6) given in chapter 5. This is shown below.

$$Q_C = \frac{10 * V_{p-p}{}^2 * \%V_R}{X_L} = \frac{10 * 22^2 * (93.5 - 88.05)}{9.983} = 2641\text{kVAr}$$

Note that the inductive impedance can be determined from Figure 6-8, which shows the network inductive impedance versus distance from the source. The curve is produced by successive network fault simulations by incrementally advancing the fault location in each instance whilst recording and plotting the internally calculated Thevenin equivalent impedance.

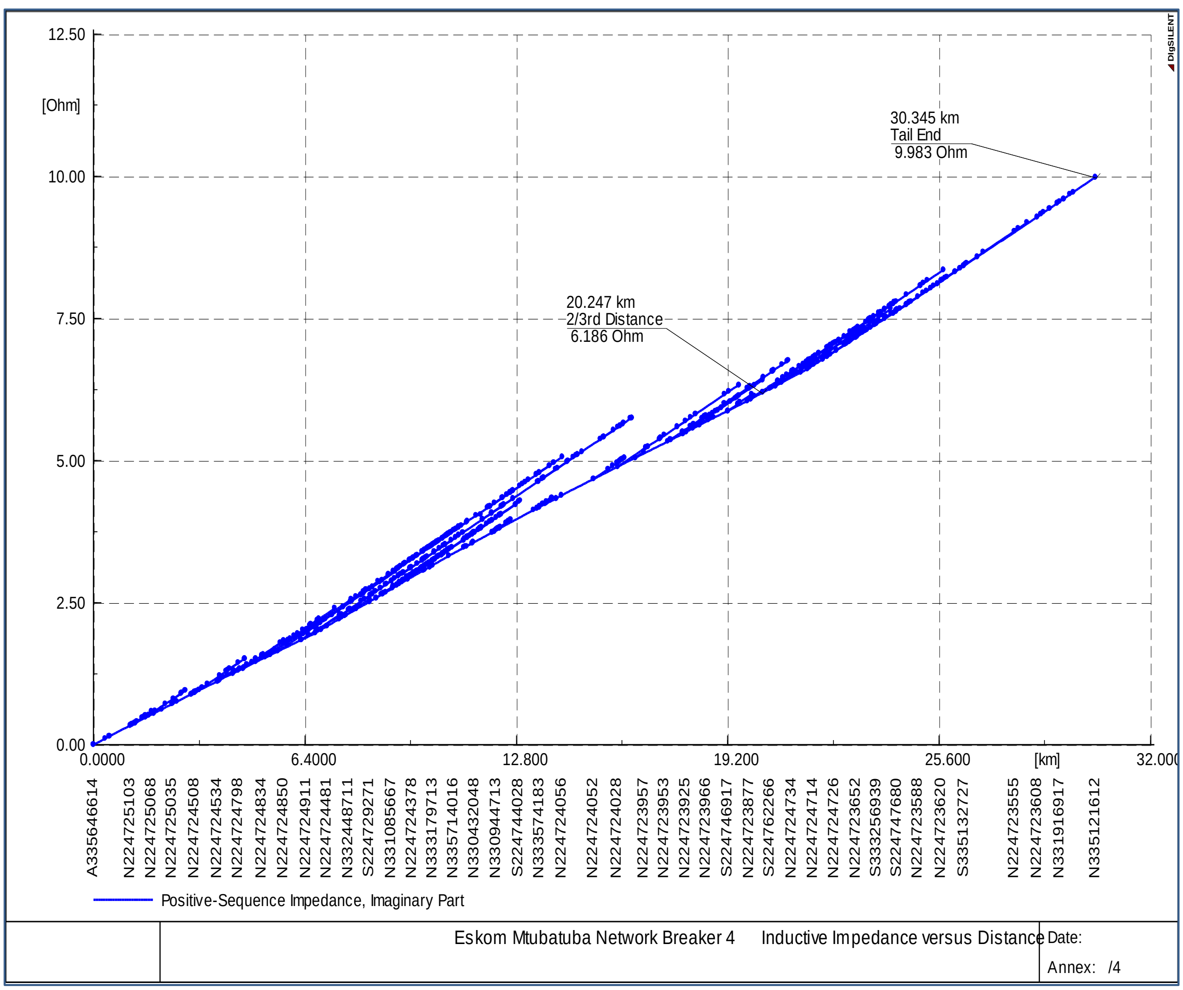

Figure 6-8: Network reactive impedance versus distance

Figure 6-9 shows the voltage regulation profiles for the various scenarios under the peak load condition.

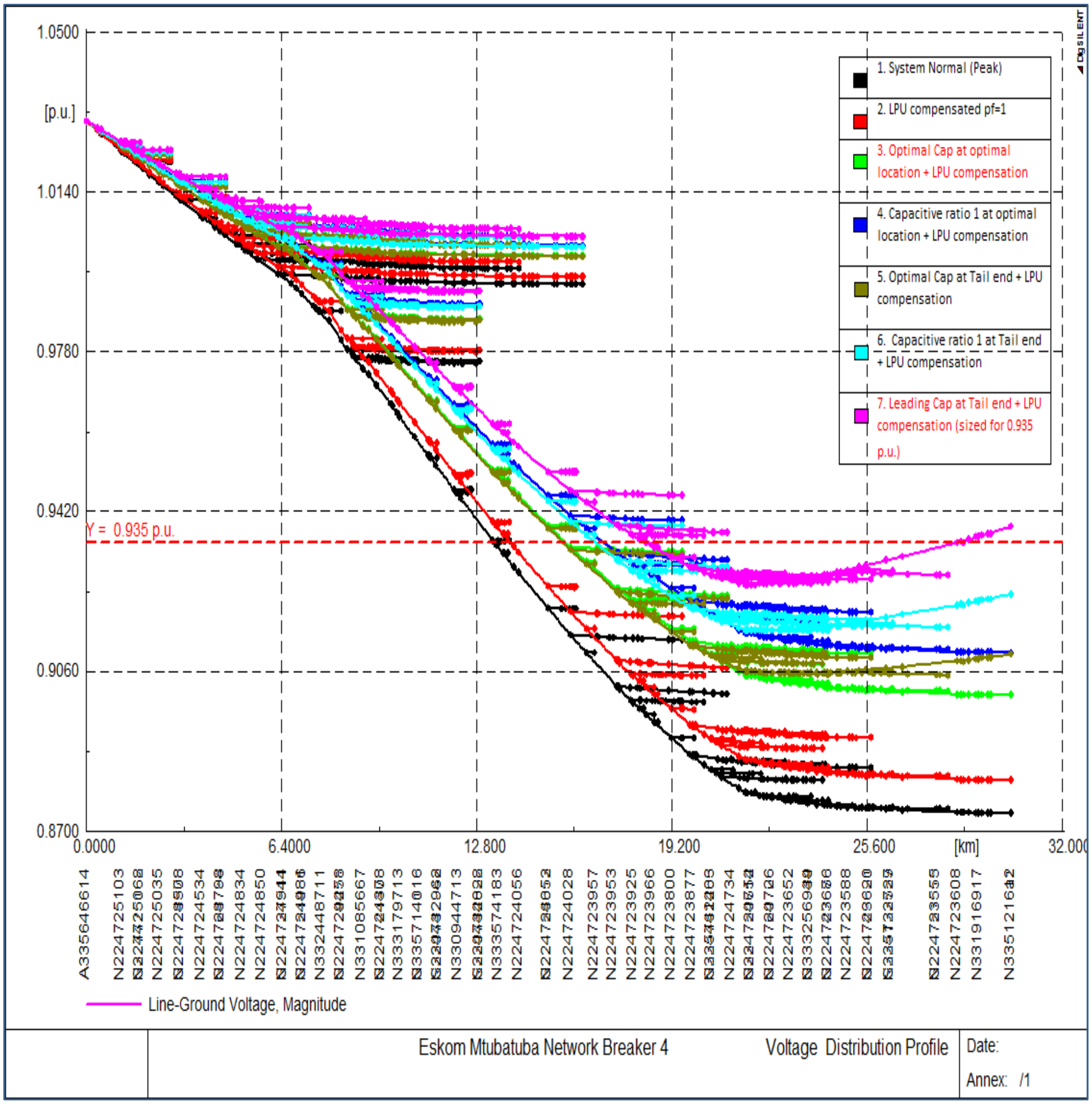

Figure 6-9: Voltage regulation profiles - peak load study

The determination of the appropriate solution however requires study of the options under the low load scenario. This will also lead into possible capacitor switching requirements.

6.3.2 Minimum load analysis

Table 6-5 shows the results of the various scenarios for the minimum load case, where the compensation devices that were sized for the peak load condition were incorporated into the simulations. The reactive power distribution as well as the total reactive power consumption for the system normal and LPU compensated cases are very similar to that of the peak load case when comparison of Figure 6-10 and Figure 6-5 is made. This is as a result of the fairly flat reactive daily load profiles indicated in Figure 6-2 and Figure 6-3. The implication is that the centralised capacitor sized and placed for technical loss reduction in the peak load case would offer similar loss benefit in the low load scenario. There is therefore no switching requirement for the centralised capacitor if this option is pursued. Note also that the technical loss reduction is at a maximum in scenario 3, again in agreement with theory.

Table 6-5: Options for placement and sizing of capacitor - Minimum load study

	kW	kVAr	kVA	Power factor	Minimum Voltage (p.u.)	Vrise (%)	Technical Loss (kW)	Loss Savings (kW)
1. System Normal (Peak)	2324.07	2174.53	3182.75	0.730	0.966	0.00	189.28	0.00
2. LPU compensated pf=1	2295.71	1711.57	2863.52	0.802	0.974	0.80	160.92	28.36
3. Optimal Cap at optimal location + LPU compensation	2280.40	379.03	2311.69	0.986	0.995	2.81	145.61	43.66
4. Capacitive ratio 1 at optimal location + LPU compensation	2306.04	-304.93	2326.11	0.991	1.005	3.81	171.25	18.03
5. Optimal Cap at Tail end + LPU compensation	2306.98	375.71	2337.38	0.987	1.005	3.86	172.19	17.08
6. Capacitive ratio 1 at Tail end + LPU compensation	2372.20	-314.97	2393.01	0.991	1.020	5.33	237.41	-48.13
7. Leading Cap at Tail end + LPU compensation (sized for 0.935 p.u.)	2504.84	-1140.53	2752.28	0.910	1.036	6.99	370.06	-180.78

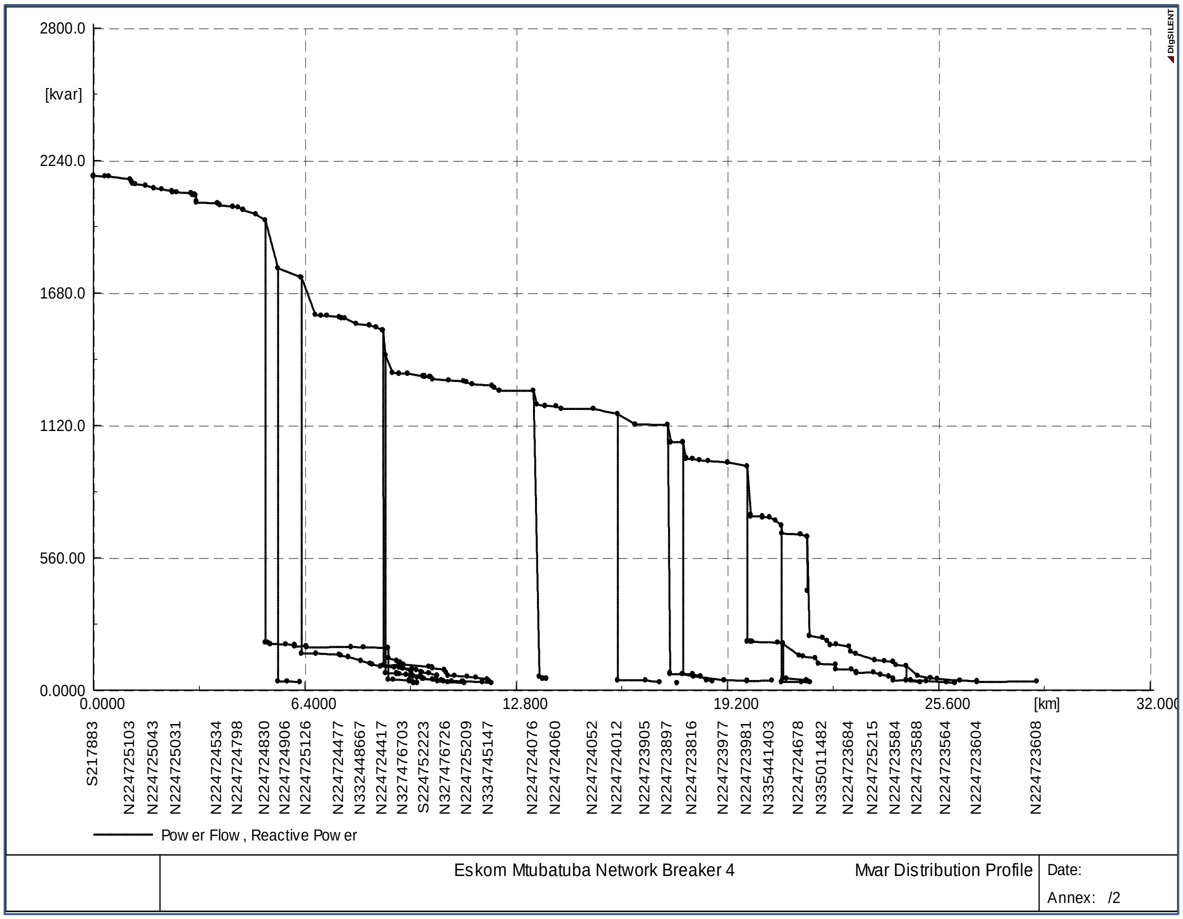

Figure 6-10: Reactive power profile – minimum load

Figure 6-11 shows the voltage regulation profiles for the various scenarios under the low load condition. Given that the system normal minimum voltage is above the statutory limit for the low load case, scenario 6 and 7, proposals to specifically increase voltages during peak load, pose risks of supplying customers with excessively high voltage during low load where the tail end voltage is equal or greater than the source side voltage. If these options are pursued, many MV/LV transformer tap positions would have to be reduced in order to manage LV voltages to within limits however this would be undesirable for the peak load case. Scenarios 6 and 7 are therefore not recommended. This however leaves no alternative for voltage improvement.

Scenario 3 achieves technical loss reductions for both the peak and minimum load cases where it can be concluded that this option would offer loss reduction throughout a day cycle, however the improvements in voltage during the peak load case is insufficient. If scenario 7 is applied only during the peak periods with scenario 3 in place, then voltage requirements would be met where over voltages during the low scenario will be avoided and technical loss reduction would be maximized. The next section will investigate this option.

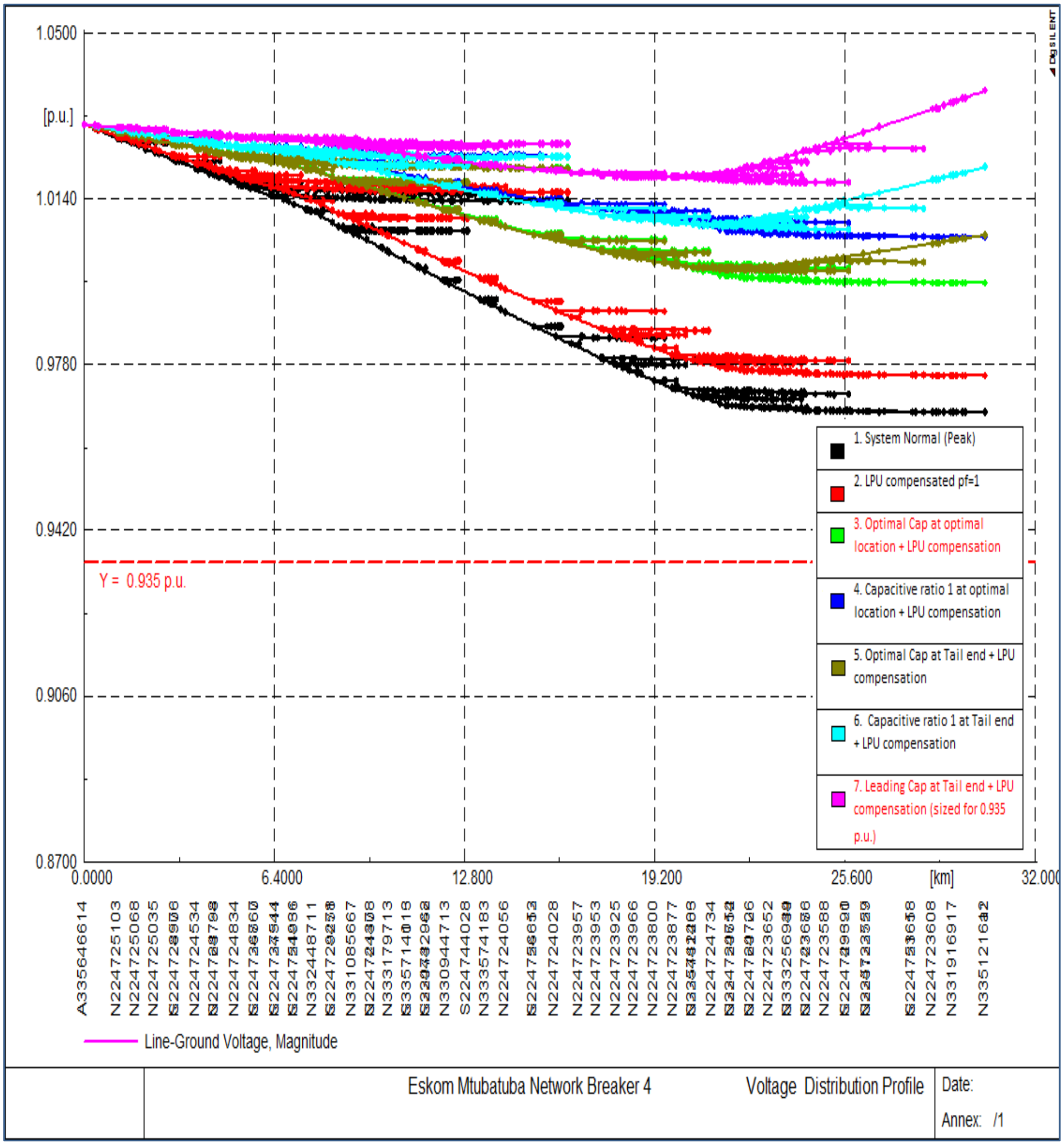

Figure 6-11: Voltage regulation profiles - Min load study

6.3.3 *Proposed Volt/VAr solution to minimize technical losses and optimize network voltage*

The conclusion of the peak and minimum load compensation studies suggests that combining the methods for loss reduction with the methods for voltage rise may be possible if the strategy employed is time based where devices are switched only when required and for the purposes that they are installed.

The peaky nature of the load profile in Figure 6-2, suggests that voltages should be studied across the day profile. Figure 6-12 shows simulated results for the end of line voltage over a day cycle where three cases are compared. These are:

1. The network normal case
2. The network with an LPU compensation of 440kVAr
3. The network with both LPU compensation and the optimally sized and located capacitor

Option 3 indicates that voltage violations will only occur over the evening peak lasting 2.5 hours from 17:30 to 19:00.

The algorithm for load flow analysis and capturing of load flow results is provided in Appendix B – DIgSILENT Powerfactory algorithm for 24 hour load flow and capturing of results .

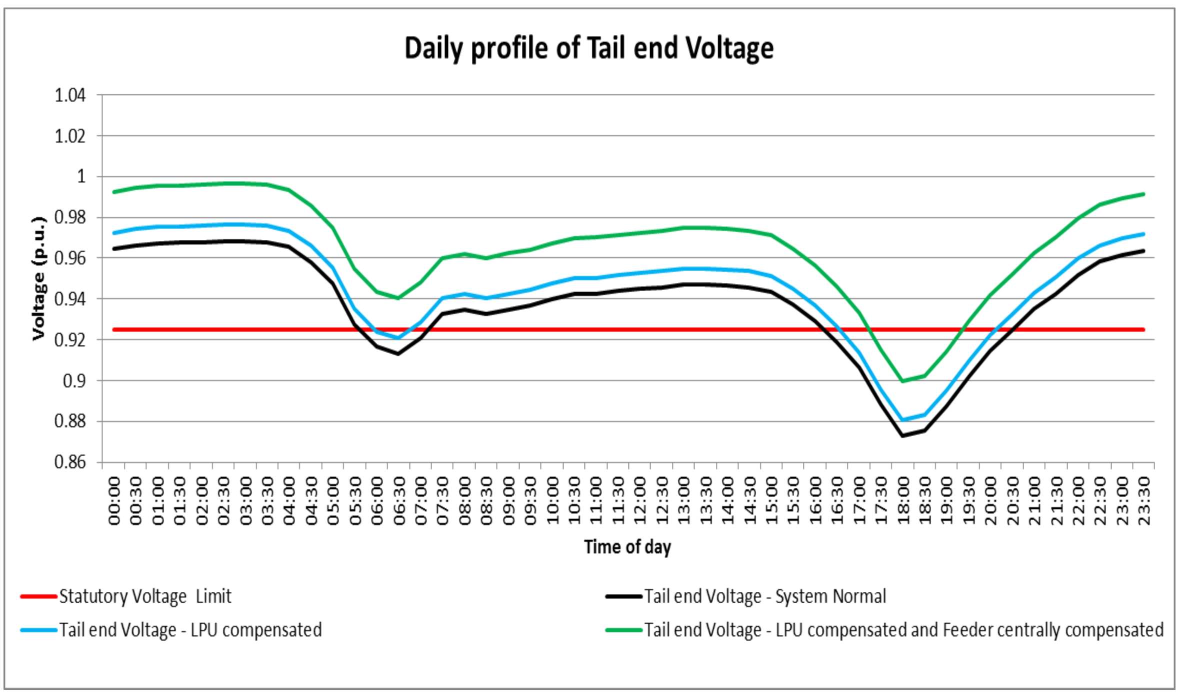

Figure 6-12: Simulated voltage profiles before and after compensation

Since it has been concluded that there is no requirement for switching, resizing or relocating the centralized capacitor, as the reactive consumption is fairly constant and the benefit to loss reduction is throughout a day, only the sizing, positioning and switching in of a second capacitor similar to the objectives for scenario 7, will be investigated. From Figure 6-12, the second capacitor will only be required between 17:30 and 19:00 daily.

From Table 6-4, the minimum tail end voltage is 0.8997 p.u., given that the LPU has been compensated by 440kVAr and that the centralized capacitor (1289kVars) at 2/3rd location has been implemented. This implies that the reactive compensation applied at the tail end (location chosen to maximize inductive impedance such that voltage rise is maximized) is required to raise the voltage at that point by 3.53%.

The size of the second capacitor is determined using (5.6) shown below.

$$Q_C = \frac{10 * V_{p-p}{}^2 * \%V_R}{X_L} = \frac{10*22^2*(3.53)}{9.983} = 1711\text{kVAr}$$

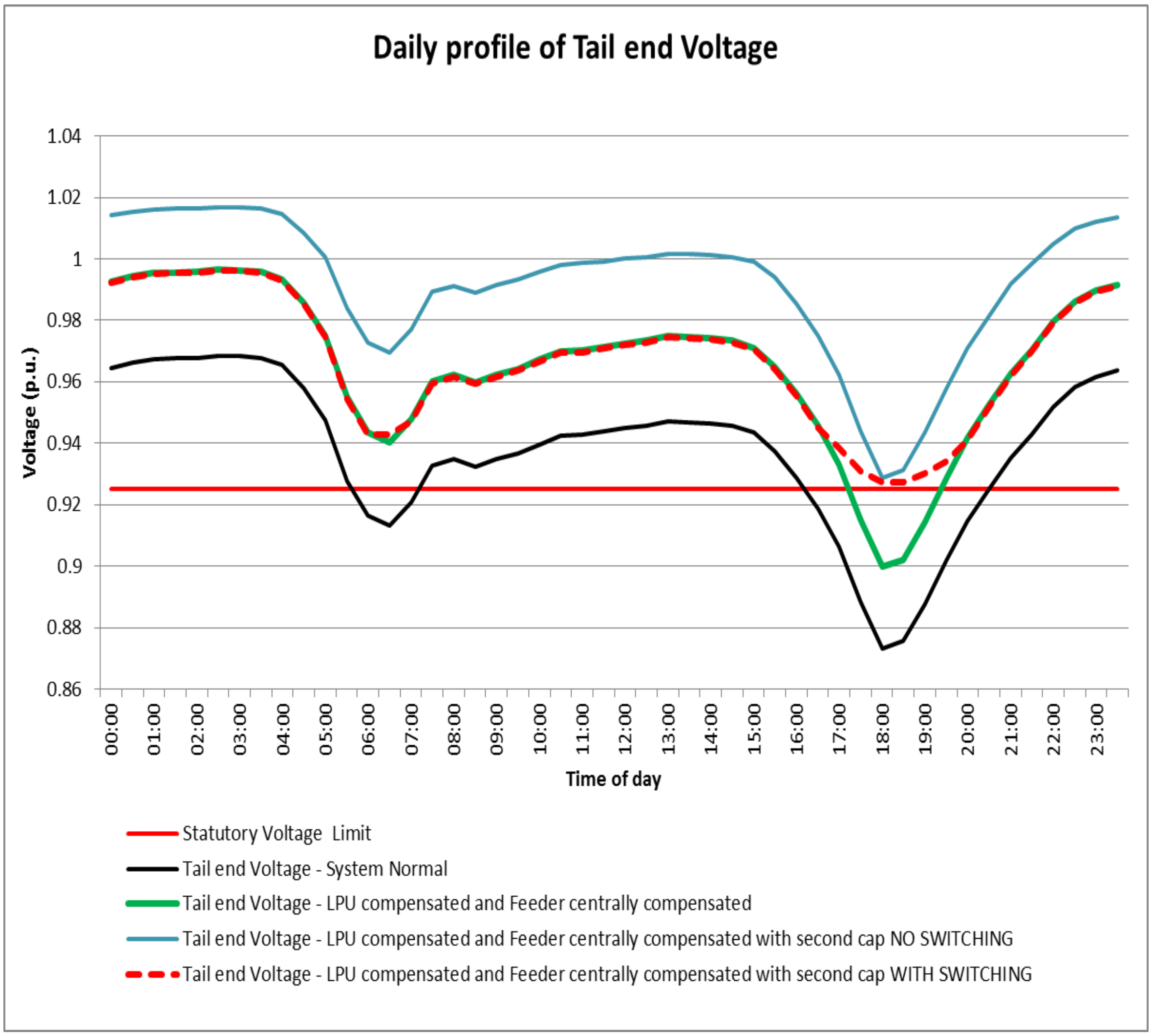

Figure 6-13: Simulated voltage profiles following addition of capacitor for voltage rise, with and without switching

Figure 6-13 shows the simulated results for the end of line voltage over a day profile with the application of the second capacitor specifically installed for voltage regulation benefit. The first simulation was run without any switching strategy and as can be seen by the blue trend, the target voltage is achieved at the peak hour, 18:00. This is in line with the theory and mathematical derivation. High voltages are however experienced outside peak times.

A voltage control scheme was then modelled as part of the capacitor element with a local set point target of the statutory requirement. The voltage profile tracks the profile for the scenario to maximize technical losses except during peak hours where the second capacitor becomes switched in to provide the necessary voltage support.

This then provides an optimal solution combining both the strategies for technical loss reduction as well as voltage regulation improvement. Note that the second capacitor is specified as a switched capacitor bank consisting of 6 steps of 300kVAr.

6.3.4 Monetary quantification of results

This section compares the results of the following scenarios in graphical form where technical losses (kW), feeder KVAr consumption and energy loss (kWh) are compared:

1. System Normal
2. LPU compensated with optimally placed capacitor
3. LPU compensated with optimally placed capacitor and second capacitor installed for voltage support with no switching
4. LPU compensated with optimally placed capacitor and second capacitor installed for voltage with switching by local set point control.

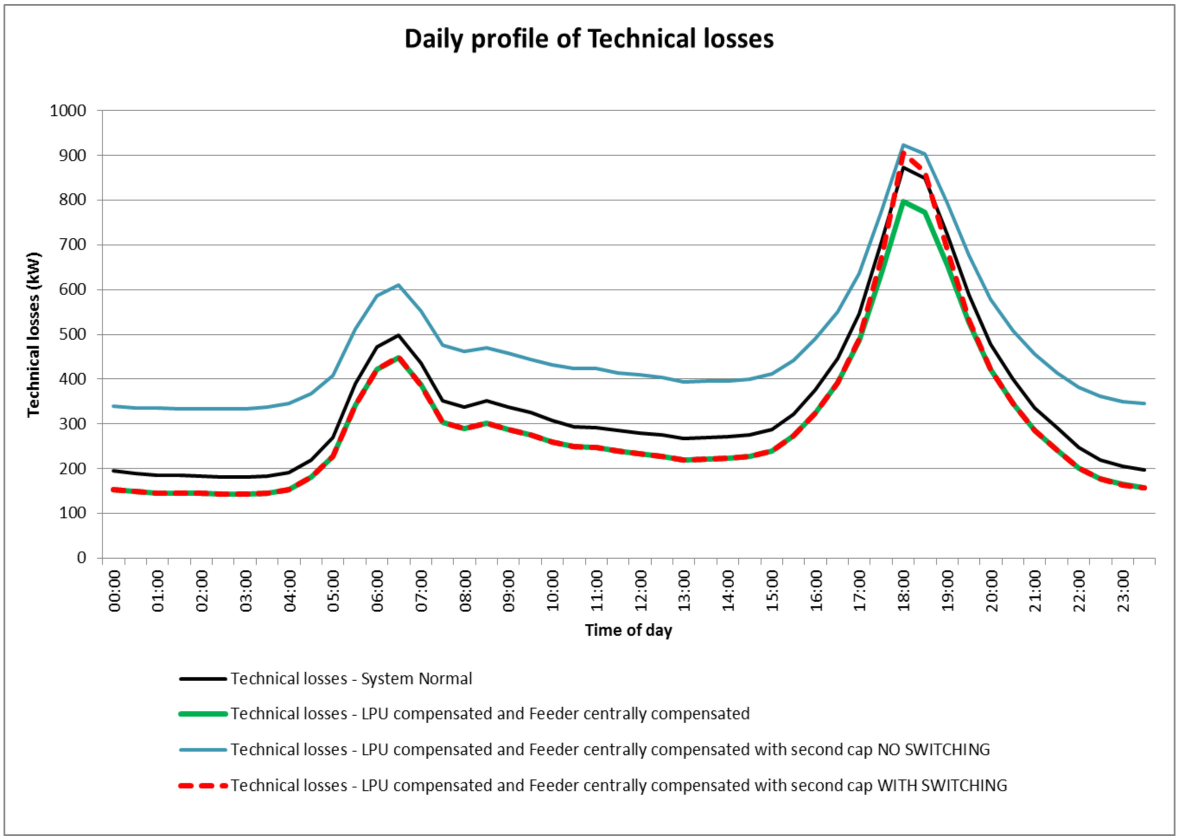

Figure 6-14: Simulated Technical loss profiles following addition of capacitor for voltage rise, with and without switching

The technical losses in the proposed solution, tracks the solution for the maximum technical loss reduction except at the evening peak when the second cap switches in for voltage support as illustrated in Figure 6-14. The area under the curves represents the loss energy in KWH and is tabulated in Table 6-6. An average residential tariff rate of R1.40/kWh has been assumed to determine possible daily rand savings.

Table 6-6: Loss energy comparisons

Scenario	Loss Energy (KWh)	Loss energy saving (kWh)	Rand saving per day (R1.40/kWh)
System Normal	8294.28995	-	-
LPU compensated and Feeder centrally compensated	7119.473	1174.81695	R 1 644.74
LPU compensated and Feeder centrally compensated with second cap NO SWITCHING	11234.0112	-2939.72125	-R 4 115.61
LPU compensated and Feeder centrally compensated with 2nd cap WITH SWITCHING	7256.3415	1037.94845	R 1 453.13

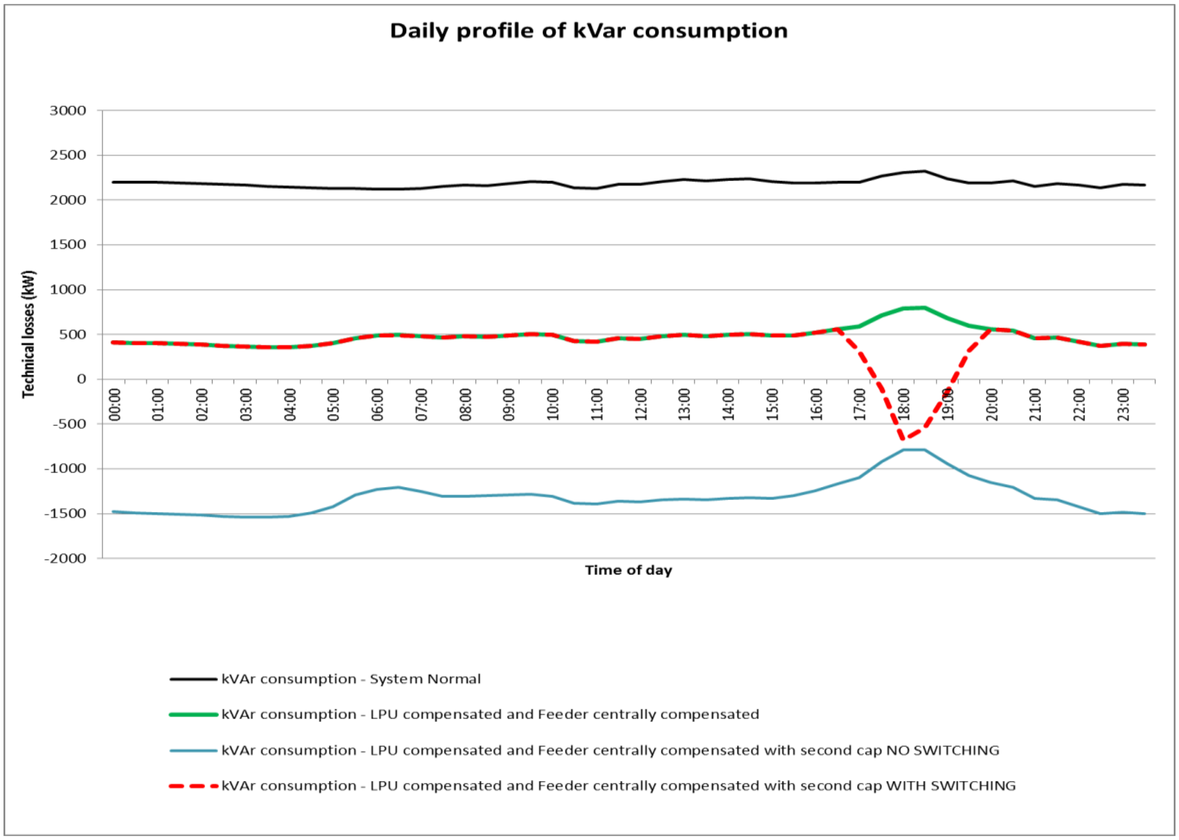

Figure 6-15: Simulated KVAr consumption following addition of capacitor for voltage rise, with and without switching

The proposed solution differs very slightly from the solution maximizing technical loss reduction, from an energy savings perspective. Both solutions provide very similar loss savings in excess of R1000 per day however the proposed option achieves the savings whilst maintaining voltages above statutory limits.

Figure 6-15 suggests that on average, that the reactive power consumption of the feeder has been reduced by approximately 1700MVArs. The feeder goes into leading power factor between 17:00 and 19:30. Whilst the upstream network has not been studied, the reduction in reactive power is expected to have cascaded benefit to voltage regulation improvement and technical loss reduction on the upstream system.

6.4 Conclusions

This chapter has demonstrated the theory and learning from previous chapters and tested the algorithms developed in chapter 5 in a practical real world example where a sample Eskom distribution feeder has been analysed.

If a network with poor power factor and considerable VAr consumption meets the statutory voltage requirements in the normal state under all loading conditions, then the solution adopted should incorporate reactive power compensation for technical loss reduction only. Once the reactive power distribution factor λ is determined, a suitably positioned and sized capacitor should be placed, where the charts developed in chapter 5 can be referenced as lookup mechanisms.

In this example, the reactive power consumption was almost constant across a day profile. In this case the centrally positioned capacitor requires no switching, however if the reactive power consumption varied considerably in a day cycle, then consideration to switching by applying the methods in chapter 5 should be given. Remote communications would be required such that the capacitor switching scheme is able to measure the reactive power consumption at the source and apply the necessary capacitive compensation ratio to determine the number of switching steps required.

For networks with both poor regulation outside limits and consuming considerable reactive power, the methods in chapter 5 should be followed initially to determine if a solution can be reached by placing and sizing a capacitor where the network voltages are improved to at least the statutory limit. If no solution is found, then the utility needs to make a decision to allow the feeder to go into leading power factor, where the compensation is sized solely based on the required voltage rise. This will generally be the case for feeders with flat demand curves. If however the feeder displays load characteristics of a residential type with defined morning and evening peaks, then the methods employed as in the test network can be evaluated which encompasses local voltage set point control for a second capacitor providing voltage support and possible remote sensing VAr switching for the centralized capacitor placed for loss reduction.

The next steps for development which is outside the scope of this research, is to appraise all Eskom distribution feeders against this criteria and evaluate benefits in each case. It is proposed that this will form phase 1 of Eskom's medium voltage Volt/VAr optimisation endeavour.

7 Conclusions and Recommendations

7.1 Conclusions

This research has investigated further alternatives to enhance the efficiency of the power delivery system by managing voltage, demand and reactive power flow also termed Volt/VAr optimisation. With more than 60% of the total losses occurring on distribution networks, and with resistive load types (best suited for demand reduction by CVR) concentrated on these networks, the research has focused on the Volt/VAr optimisation of distribution MV distribution feeders.

It was shown that for short lines the shunt capacitive component is negligible where only the series impedance components (R and X) would impact the performance of the line. It follows then that since distribution feeders are considered short, they will be net consumers of reactive power. The series impedance components will give rise to line voltage drops and power losses within the lines where the magnitudes of these quantities would depend on the magnitude of the load current.

It was shown that for boost or buck operations required for controlling network voltages, that the efficiency of these devices reduce, i.e. their losses increase.

By combining these elements into a simple model involving a fixed voltage source, a line, a voltage regulator and a load, one is able to understand the relationship between losses and voltage correction by voltage regulators on distribution feeders. As the load current increases the volt drops across both regulator and line increase including the power losses expended in each element. In an attempt to correct voltage, the regulator draws more reactive current from the source increasing losses. The conclusion is that whilst voltages are corrected, the net efficiency of the network may be reduced.

The mathematical models also discussed the effects of lagging load power factor on regulation and losses where it was shown that by correcting power factors i.e. reducing reactive power flow through a feeder, both regulation and efficiency is improved. It was also shown by mathematical derivation that injecting leading reactive currents (capacitive currents) through inductive impedances will result in improvements in voltage drops across lines and transformers. Further such capacitive current injection reduces the load current seen by sources which in turn reduces overall technical losses. This indicates that voltages can be corrected and at the same time, efficiency of the network can be increased by correcting power factors.

These conclusions prompted the investigation of reactive power compensation as a means to improve feeder voltage regulation and reduce feeder technical losses which is the basis for Volt/VAr optimisation on distribution systems. It must be noted however that overcompensating a feeder for the benefit of voltage rise will reduce efficiency where losses in lines will increase. Therefore the merits of both the voltage and loss objectives needs to assessed before making a decision for a given network.

In order to examine the feasibility of CVR and determine the technical boundaries for Volt/VAr management on South African distribution feeders, it was first necessary to understand the operating and design limits for voltage.

Network classes and tap zones determines the apportionment of voltage regulation between MV and LV networks and provides a means to determine if voltages at customer points of supply will be within limits. Based on the network classes, CVR would be most applicable on C1 and C2 networks which are typically urban type networks designed with relatively small MV voltage drops. C3 and C4 networks are unsuitable where allowances that are made for larger MV voltage drops during the design of these networks are very likely to result in voltage violations during attempted demand reduction by CVR.

The various limits have also resulted in the specification of appropriate transformer set points for OLTC schemes for the various categories of networks. Once implemented, source voltages will be controlled optimally to ensure statutory voltage requirements are met for all categories of networks. Further, SCADA alarms limits have been specified to enable operational action by power system controllers to manage voltage regulation within limits. For the implementation of CVR, it is imperative that provision is made for voltage alarms and that there is adequate visibility of network voltages at control centers, to avoid voltage violations during planned reductions in source voltage for demand reduction.

Chapter 4 discusses the objectives of Volt/VAr optimization which can be summarized as techniques to improve power delivery efficiency and the ability to selectively control demand by the placement and control of network equipment such as capacitor banks, OLTCs and voltage regulators. Three mainstream approaches for Volt/VAr management on distribution systems with varying degrees of effectiveness are presented and discussed. Reviews of Volt/VAr implementation at leading utilities, to understand decision factors, technologies, results with project scoping, project success criteria, and lessons learned through field testing are also presented as case studies. Finally, an assessment of the CVR potential within Distribution networks in Eskom and approaches for implementation, are discussed.

The standalone VVO approach involves local control of Volt and VAr devices and is suited to isolated feeders with poor communications where devices are configured once off, catering for worst case conditions. The objectives could either be improving voltage regulation on a distribution feeder by local voltage set-point control to ensure that customers are always supplied at regulatory voltages or for power factor improvement. Any switching or tapping decision is based on local measurements only. This method does not favour the application of CVR.

Eskom has adopted this approach on numerous distribution feeders where voltage regulators with local control are strategically positioned to manage voltage regulation. The use of capacitors for power factor correction on Eskom distribution networks remains rare. Capacitor placement using this approach will be best suited local voltage control. For PF correction at feeder level, communications would have to be established from the substation to the shunt device.

With the centralised VVO approach, coordination between multiple Volt and VAr devices on a feeder is possible as a result of communications and Volt/VAr processors. The control logic is programmable and can be configured for either individual or combined VAr and Volt objectives. The logic is rule based and normally not adaptive to network reconfiguration where devices may need to be remotely turned off. With the ability to process remote measurement data, the Volt/VAr processors can control both the feeder capacitors and voltage regulators to maximise loss reduction, improve power factor as well control the voltage at the lower band of the regulatory limits for demand reduction.

In Eskom, communications is established between the DMS, substations and voltage regulators however the control of the Volt and VAr devices are localised. The DMS system is primarily used to monitor power flow parameters and issue open/close commands. CVR capability could be achieved with minimal effort provided that the DMS can be configured to remotely change substation OLTC set points and voltage regulator set points based on feeder tail end measurements. The DMS system is equipped with a software platform were control logic can be programmed to issue commands based on measurements supplied as inputs. This is scope for further investigation. A simpler method for CVR could be manual remote set point adjustment by a power system controller however this will require constant monitoring of field measurements and adjusting of control set points.

The model based VVO approach makes use of dynamic operating data which provides the ability to adapt to network changes whilst controlling Volt and VAr devices on a system wide basis for various objective functions which is achieved through close to real time power system simulation. This system is based on an Integrated Volt/VAr Control (IVVC) optimising engine where based on power flow results, following load flow simulations, the IVVC optimizing engine develops and executes a coordinated "optimal" switching plan for all voltage control devices based on set targets. This is the most efficient of the three approaches and at the same time the most costly alternative which best suited for wide scale implementation and power networks that have entrenched Volt and VAr devices. In the Eskom context, this will be the least suitable approach given the present lack of Volt and VAr devices, the extent of communications and the associated lack of DMS SCADA visibility down to customer level.

Following the CVR assessments where it was concluded that the key precursors would be to improve voltages on feeders and given the low volume of capacitive compensation on the distribution system, it is recommended that Eskom's initial approach to Volt VAR management should be focussed on improving voltages to within statutory limits as well as aggressively bridging the gap of reactive compensation at the distribution level. Since capacitors offer benefit to both technical loss reduction and voltage improvement, the research then focussed on capacitive compensation of distribution networks considering optimal sizing, placement and switching criteria.

Through mathematical formulation it was shown that there is a specific location for a given size of capacitor bank that produces the maximum power loss reduction for a given reactive power distribution. Methods to determine the reactive power distribution of a feeder were provided together with reference charts that can be used to select optimal sizes and locations to achieve maximum power loss reduction.

In the Eskom distribution system, since many networks are voltage constrained, the application of capacitors must also consider providing voltage support to meet statutory limits; however considerations for voltage support may limit the power loss reduction capability. The methods developed in this chapter allow both voltage and power loss reduction to be maximised with the application shunt capacitive compensation.

If a network with poor power factor and considerable VAr consumption meets the statutory voltage requirements under all loading conditions, then the capacitor solution will incorporate reactive power compensation for technical loss reduction only. If a network does not meet the statutory voltage requirements even after the placement for power loss reduction, then the requirements must be focused on voltage support where the capacitor is either increased in size at the optimal location or moved down the feeder. This combines the objectives of loss minimization and voltage support by reactive power compensation. It is recommended that the approach as set out in chapter 5 is used by Eskom to increase the amount of reactive compensation at MV level. This will form the foundation for Volt/VAr management in Eskom and enable further enhancements.

It was concluded that after applying the methods for a combined loss reduction and voltage improvement strategy, that if a feeder remained with voltage violations than consideration should be given to operating the feeder with a leading power factor i.e. compensation ratios greater than 1 where capacitor would be located at the tail end to maximize the inductive impedance through which capacitive current would be injected, yielding the maximum voltage rise. The approach will suit networks with flat demand curves where the utility accepts leading power factors and can manage the impact on upstream networks where further studies may be required.

If however the demand profile varies analogous to that of a residential load pattern as in the example provided in chapter 6, then consideration may be given to a second capacitor with local voltage set-point control to manage voltages only during peak times limiting periods that the feeder may experience leading power factors. For the remaining hours in a day, the first capacitor positioned and sized for loss reduction will be in service where based on the feeder’s reactive power variation the cap may be permanently in service or switched. The switching can be achieved in two ways, either rule based or automated by set point control using remote VAr measurements from the source, to maintain an optimal C ratio for various periods in a day.

7.2 Recommendations for future work

The research has investigated various approaches to adopt Volt/VAr optimization within distribution systems to improve electricity delivery efficiency and demand control, particularly making recommendations and tailoring solutions for Eskom distribution feeders and systems. A number of areas have been highlighted in this work for further development. These are discussed below

7.2.1 Network Appraisals and Simulation

Applying the methodology and simulation techniques provided in this research to quantify the benefits of loss efficiency and demand reduction capability on a system wide basis will guide the level of implementation (Standalone, Centralized or and Integrated approach) to be adopted by utilities from an investment point of view. A precursor however is a complete appraisal of the distribution system for qualifying and target networks. The development of a supply industry guideline aimed at MV distribution feeder appraisal for Volt/VAr control objectives in South Africa, will be well received.

7.2.2 Implementation in constrained systems

Given the many constrained distribution feeders where new customer applications are being turned down or deferred and South Africa's target for universal access to electricity by 2019 where new networks may need to be built to accommodate additional load, it is recommended that the methods and technologies discussed in this research be simulated on selected pilot networks with known constraints and pending connections and implemented if sufficient capacity can be freed and demand reduction by CVR practiced, to allow connections. If the results are positive it should be adopted on a larger scales to accelerate the electrification program, where networks upgrades can follow at a later stage. Further, the results can be compared to simulation results to update models, assumptions and improve future investigations.

7.2.3 Impact of distribution generation and energy storage on Volt/VAr management

With the introduction of embedded generation (e.g. renewable rooftop PV) on distribution systems, voltages on distribution feeders will rise. The relationship of voltage change when injecting/consuming power through a resistance is given in (2.23). The embedded generation will pose challenges to the management and control of voltages on Distribution feeders that have traditionally been designed for load. In Eskom, the voltage apportionment method for the design of MV and LV voltage drops on distribution feeders and associated tap zones would have to be revaluated for incorporation of embedded generation.

Further, where capacitive compensation has been implemented for the purposes of loss reduction, the voltage rise by embedded generation may require the capacitor to be disconnected to avoid violation of high voltage limits. Equation (2.23) suggests that both numerator terms will increase the voltage on the feeder. The implication is that utility companies may be forced to run at poor power factors. Further, generating power at leading power factors (absorbing VArs for a generator, possible with smart inverter technology) has the effect of reducing voltage. This implies that to increase the penetration of renewables, generators may be required to absorb VArs to limit voltage rises. The VArs needs to be supplied by the utility company. The methodology for the sizing and placement of capacitors as discussed in chapter 5 will no longer be valid. Further work is required to develop a Volt/VAr optimization strategy for feeders incorporating embedded generation.

7.2.4 Implementation of Volt/VAr functions in existing DMS SCADA platforms

The Integrated Volt /VAr Control (IVVC) optimizing engine described in chapter 4 is responsible for tap changer control, voltage regulator control and capacitor control for the objectives of loss minimization, voltage regulation and demand reduction by CVR. Real time control decisions for Volt/VAr optimization, is based on state estimation, power system simulation for optimal power flow and other user specified objectives.

Based on established DMS SCADA systems in most utilities with software platforms, the IVVC functionality could potentially be implemented through software solutions in existing DMS SCADA systems. There is therefore scope for further investigation of existing DMS SCADA systems to determine if IVVC functionality can be developed within existing systems. The work will also involve suitable algorithms for Volt/VAr optimization.

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Appendix A - Algorithm for the calculation of the reactive power distribution (λ) of a feeder

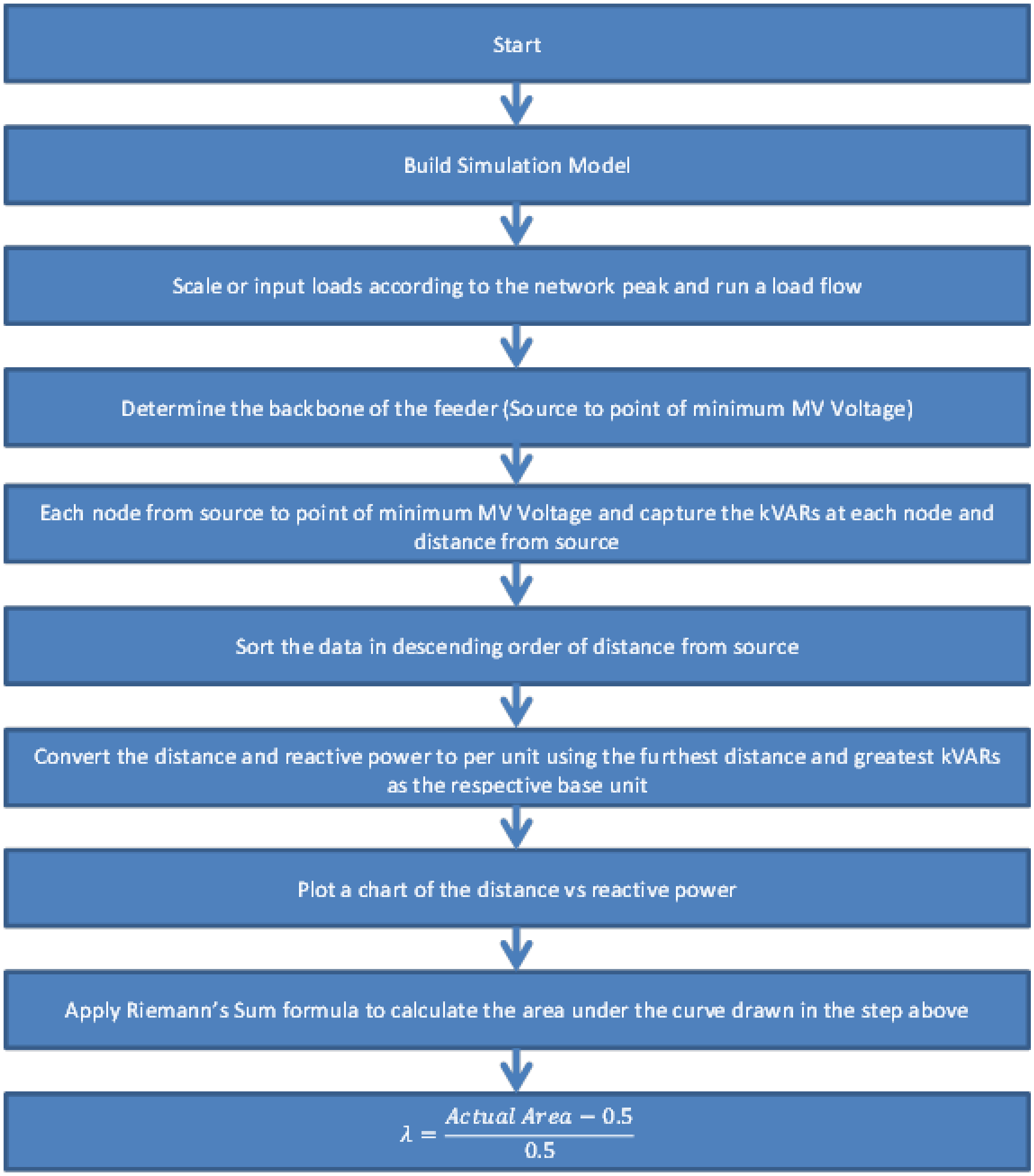

Figure A-1: Algorithm for reactive power distribution (λ) determination

Appendix B – DIgSILENT Powerfactory algorithm for 24 hour load flow and capturing of results

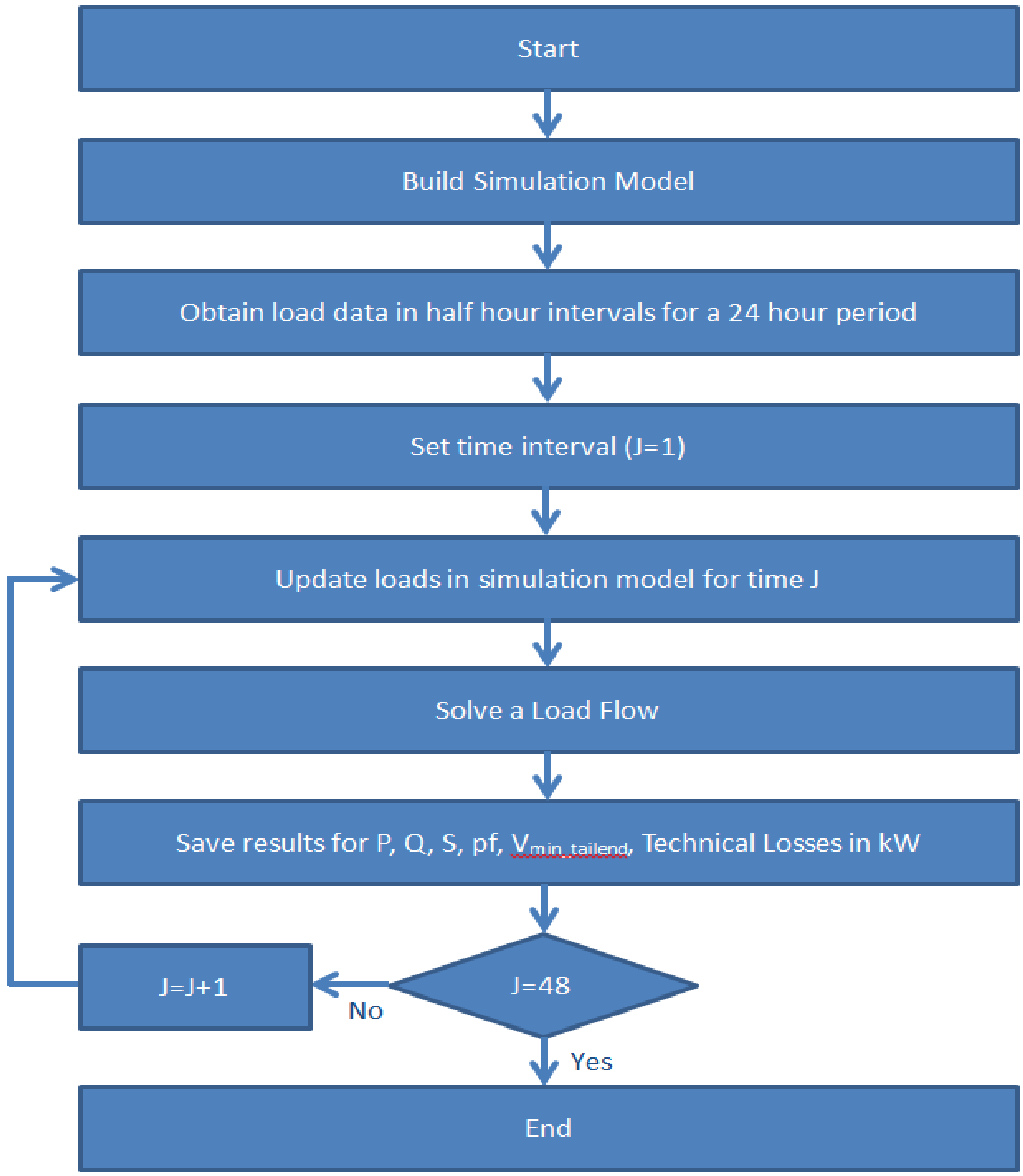

Figure B-1: DIgSILENT Powerfactory algorithm for 24 hour load flow and capturing of results