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Voltage Drop Apportionment in Eskom's Distribution Networks

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Thesis presented for the degree of

MASTERS IN ENGINEERING

Department of Electrical Engineering
Faculty of the Built Environment

UNIVERSITY OF CAPE TOWN

March 2002

ABSTRACT

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Date: March 2002

Keywords: Voltage drop, voltage apportionment, voltage control

The maximum permissible voltage operating ranges and voltage drops are often the primary constraint in the planning and designing of electrical distribution systems. Due to the total absence of any voltage regulation and apportionment guide in Eskom Distribution, and given the considerable changes in the South African Electricity Act and equipment specifications in recent years, standardised approaches and values were required for application in the Eskom Distribution business.

Traditional distribution networks consist of a primary Medium Voltage (MV) system supplying distributed customer loads via secondary Low Voltage (LV) networks. The customers supplied by the LV networks experience the combined effects of the voltage drops in both the primary MV and secondary LV systems. In order to provide customers with satisfactory voltage regulation any decisions regarding the one system level in turn effect the other. Research was required to establish these relationships, and based on typical practices and restrictions determine the recommended maximum voltage ranges and drops in both the primary MV and secondary LV networks.

Recommended voltage regulation limits and apportionment were calculated separately for urban and rural networks, and for both normal and abnormal network conditions. The calculated values take into account a wide range of variables such as:

- The requirement to keep the voltages at the customer's point of supply (meter) within licence and contractual limits.
- The requirement to keep the voltages at the customer's "appliance" (after the meter) within regulation limits such that these appliances will operate as required taking into account factors such as efficiency and life span.
- The operating voltages of network equipment, such as transformers, taking into account factors such as efficiency and life span.
- The characteristics and specifications of both past and present distribution equipment such as distribution transformers with various nominal secondary voltages and De-Energised Tap Switch ranges and step sizes

The recommended values for voltage variations and apportionment are maximum values only, and the optimal voltage drops in both the MV and LV networks could vary considerably if the relative costs of the MV and LV systems and the capitalisation of load losses are included in the evaluation. The recommended values are maximums within which the network must be designed to operate if contractual/license obligations and acceptable appliance operating voltages are to be achieved for reasonable LV design practices both within the Eskom network and customer's premise. In certain applications such as rural electrification where load densities are low and LV networks can be extensive,

the optimal apportionment could differ considerably from the limits provided for urban and rural type networks.

ACKNOWLEDGEMENTS

The author would like to thank Eskom Distribution Eastern Region, Eskom Research, Eskom Distribution Technology, and Professor C T Gaunt for their support and assistance.

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ABBREVIATIONS

NRS	National Regulatory Standard
SABS	South African Bureau of Standards
HV	High Voltage (>33kV)
MV	Medium Voltage (>1000V)
LV	Low Voltage (\leq 1000V)
FACT	Flexible AC Transmission
DG	Distributed Generation
DSM	Demand Side Management
LDC	Line Drop Compensation
VC	Voltage Compounding
LC	Load Compensation
OLTC	On Load Tap Changer
DETS	De Energised Tap Switch
rms	route mean square
pu	per unit
DOL	Direct On Line
LF	Load Factor
LR	Load Ratio
PF	Power Factor
EPRI	Electric Power Research Institute
CVR	Conservative Voltage Reduction
EL	End of Line
NPV	Net Present Value
TLL	Thermal Loading Limit
ELL	Economic Loading Limit
TLR	Thermal Load Reach
ELR	Economic Load Reach
NB	Network Breaker
1 ϕ	Single Phase
B ϕ	Bi Phase
3 ϕ	Three Phase
Trfr	Transformer
kV	Kilo Volt
kVA	Kilo Volt Ampere
U	Network classification: Urban
R1	Network classification: Rural with 380/220V transformers and contracts
R2	Network classification: Rural without any 380/220V transformers or contracts

TERMINOLOGY

This document uses the international terminology of “bi” phase that in Eskom is often referred to as “dual” phase.

Eskom personnel frequently refer to MV and LV networks as “reticulation” systems, whereas this document uses the international terminology of “distribution”.

The connection of relatively low-density domestic customers in predominately rural and peri-urban areas to the electrical grid via distribution transformers and LV networks is commonly referred to in Eskom as “electrification”. Traditionally customers in rural areas have been connected to the grid via dedicated distribution transformers. These customers would typically be smallholdings that may contain both domestic and agricultural load components. With “electrification” type load the load magnitudes and densities are such that several domestic customers are connected to a common distribution transformer using relatively extensive LV networks. These LV networks typically have a supply radius of between 200m and 500m. Domestic loads in rural areas can include farmhouses, which may be supplied by dedicated distribution transformers. In the context of this document “electrification” type load refers to low energy consumption (<200kWh/month) domestic customer that are supplied via fairly extensive LV networks (supply radius >100m) where several customers are supplied utilising a single distribution transformer.

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1 INTRODUCTION AND OVERVIEW

When power, and hence current, flow in an electrical system the voltage drops over the network impedances result in a change in the magnitude of the delivered voltage. There are different types of voltage variations, such as those resulting from system faults, load rejection, motor starting, non-linear loads and rapidly varying loads. This research focuses on the calculation of recommended steady state voltage regulation limits due to normal load variations over typical load cycles that usually repeat themselves over hours, days, or months. Steady state voltage regulation values describe how variations in the load magnitude (due to normal customer usage patterns) act in conjunction with the network and its associated devices and control techniques to effect the voltage magnitude delivered to the customer. Voltage regulation at a particular point in the network is typically calculated as the difference between the maximum and minimum voltages at that point over a particular time period, which may vary from a day, to a month or even as long as a year.

Due to the simple physics of voltage drops, and the costs of the materials through which currents must flow, the allowable voltage variation is a major cost factor and restriction in the planning and designing of electrical systems. As will be shown in latter sections, voltage regulation limits become a key (and in many cases the primary) constraint, and are largely dependent on the density (load per unit area of land) of the load and the nature of the existing electrical infrastructure. At the distribution level where the system voltages are relatively low due to the requirement to economically reticulate and transform primary MV voltages to the secondary LV service voltages, voltage regulation limits are often the most significant factor, and dictate the selection of voltage levels, conductor sizes and technologies.

While the customer only experiences the end result, the electrical network required to generate, transmit and finally distribute the power consists of different levels. Each of these network levels has specific objectives and characteristics. The network levels are often considered in relative isolation, however they each play a vital and complementary role in the delivery of electrical power of an acceptable level of quality and reliability. The quality and reliability of the power delivered to customers is related to the cost of the associated electrical network. Improved power quality and reliability (reduced voltage distortion and/or variation and increased availability) can often only be achieved at the expense of increased network cost. Electrical network planning and design should aim to optimise the selection and sizing of key network attributes such that the life cycle cost of the entire system is minimised taking into account the costs and inconvenience experienced by the customers due to non-ideal supply quality.

This research combines both the theoretical and practical issues in the calculation of voltage regulation limits and the apportionment of the allowable voltage drops between the primary MV distribution and secondary LV service levels. An overview of the sections and how they fit together follows.

The equipment used to deliver electrical power is individually straightforward, however most distribution systems are quite complex due to the interactions of literally thousands of these interconnected elements. Achieving economy and reliability involves careful balancing of a myriad of mutual interactions and cost trade-offs. Section 2 introduces many of these fundamental concepts and trade-offs. It documents a wide range of factors that influence distribution planning and design, with specific emphasis on how voltage levels and voltage regulation limits influence practices and equipment specifications. The interactions and core responsibilities and objectives of each of the system levels and their components are

introduced. It contains largely generalised information based on typical practices in many utilities, and is not specific to Eskom or any single utility. As a result not only are concepts introduced, but some of the significant differences between utilities are explored. Due to the different load densities, characteristics and QOS and reliability requirements, approaches may vary significantly and no one technique is necessarily better than another technique.

As the relative magnitudes of technical losses are closely linked to voltage regulation, section 2 also introduces the basic techniques for the use of linearised relationships for equipment sizing as a function of loading levels such that the net sum of the losses costs and capital costs are minimised. The optimisation of the relationship between the costs of capital and losses is a key objective, however the resultant voltages which are applied to equipment and consumer appliances must still fall within the design specifications. Some of these equipment and appliance operating voltage limits are introduced. Voltage regulation levels also influence the amount of energy drawn from the network, and the implications and summaries of some practical experiences are highlighted. The section goes on to introduce the various voltage control techniques used in distribution systems, as well as some voltage regulation limits and apportionment levels used in American and European utilities. Some of the issues and techniques in the optimisation of distribution network planning are introduced.

The ideal equipment specifications and network characteristics could be established using purely theoretical approaches, however these would need to be tempered with the practical restrictions due to factors which are generally outside of the network planners sphere of influence. Section 3 builds on the issues raised in section 2 with a more in depth analysis of the key factors, with specific emphasis on local (South African and specifically Eskom) requirements and restrictions. Section 3 begins by providing a history of the South African regulatory standards and Eskom's supply contracts, such that Eskom's obligations (in the form of allowable voltage regulation) to both its existing and future customers are understood. The influence of the regulatory standards and Eskom's supply contracts on associated equipment specifications such as distribution transformers is also summarised. The typical operating voltage ranges of consumer appliances are briefly covered to establish the relationships between Eskom's licence and contractual obligations and the performance of the end use appliances under these extremes of voltage regulation.

The voltages at the customers supply point may meet the utilities' contractual and licence obligations, however the performance of the appliance will be effected by the voltage drop within the customer's premise (between the meter point and end use appliance). Section 3 documents the South African Bureau of Standards requirements and recommendations for these voltage drops.

Section 3 goes on to describe Eskom's past and present practices for the maximum allowable voltage drops in LV networks in both urban and rural areas. Eskom Distribution's present MV network maximum operating voltage restrictions, voltage control methodology and typical voltage control settings conclude this section.

Based on the results of a survey of Eskom Distribution's reticulation network planning practices, section 4 provides a high level summary of the decision logic typically used when evaluating networks and strengthening / expansion options. Present assumptions, issues and practices linked to voltage regulation limits are discussed.

In section 3 the characteristics of motor loads and transformers were identified as possible key limitations in the establishment of network voltage regulation limits. In section 5 the

effects of voltage variations on motor performance and life span are investigated to establish recommended motor operating voltage ranges for different types of motor applications. The limits include both normal and abnormal network conditions. Based on typical transformer flux characteristics, and the relationships between load and no-load losses, the recommended maximum transformer flux levels are also investigated.

The allowable voltage drops and limits in both the MV and LV systems are dictated by the combinations of many factors. These include the type of voltage control used, equipment specifications, assumptions used in the design of the MV and LV systems, contractual and licence obligations at the supply point, and the voltage requirements of the end use appliances. While sections 3 and 5 documented these factors in relative isolation, section 6 explores the interaction of these factors. A model is developed which enables the allowable MV and LV voltage regulation limits to be calculated for any given combination of these factors. The model facilitates the evaluation of different voltage control techniques and the optimisation of distribution MV/LV transformer tap positions. The model provides the maximum, but not necessarily optimal limits for the voltage drops in both the MV and LV systems.

Based on the results obtained from the model developed in section 6, section 7 establishes the recommended maximum voltage variations and voltage drops in both MV and LV networks. Three classifications of networks are catered for, with a single classification for urban, and two classifications for rural networks. Two ranges of recommended MV voltage variations are provided for each classification to cater for both normal and abnormal network conditions. The recommendations build on the concepts supported by the NRS 048, with different limits for planning and compliance.

Section 8 goes on to illustrate the application of the recommended limits in practical examples for both urban and rural networks using actual network and load data. The practical implications of different voltage control methodologies and the possible effects of not complying with the recommended limits are discussed in the context of the practical examples.

The key factors that form the basis for the voltage regulation limit model, and conclusions of the research are summarised in section 9. It is stressed that the recommended limits are typical maximum values, and the optimal values could vary considerably in different applications such as rural networks supplying significant LV systems such as electrification load.

Some of the practical issues that may arise as a result of the application of the recommended limits proposed by the research are documented in section 10. These include recommendations and implications for the modelling of source voltages for loadflow studies, single phase distribution transformer DETS tap range and step size considerations, optimisation and control of distribution transformer tap positions in the field, and the implications of utilising non-standard voltage drop and apportionment limits. The requirement to classify MV networks is also discussed such that the appropriate MV limits and associated LV voltage drop apportionment can be practically applied.

A broad range of variables effects the model results and recommendations. In certain instances simplifications and assumptions are used in the model inputs. Section 11 provides areas for improvement and further research such that the techniques can be further refined to provide increased confidence and accuracy. Two key factors significantly affecting the model results are the recommended transformer flux limits and three phase motor operating voltage limits. Both of these limitations should be researched further.

The research results are based on an essentially deterministic approach that does not take into account all the interdependencies and probabilities that can be associated with many of the factors influencing the final results and recommendations. Instead of putting a single value to factors, statistical techniques could be used such that the results are associated with a confidence level, enabling the risks to be quantified when using the model to make decisions.

Further research could also be undertaken to develop models to explore the cost implications of applying the recommended limits. This could be extended to develop a financial optimisation model for planning and design parameters. This model should take into account capital costs, technical loss costs and variations in revenue due to less than ideal voltage regulation. The apportionment limits calculated by such a model could be significantly different to those proposed by this research.

Should there be any significant changes in the model input variables, the model results and recommended limits will need to be reassessed.

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2 FACTORS INFLUENCING VOLTAGE REGULATION

Voltage regulation can simply be described as the steady state voltage level change due to normal load variations in the electrical network. Many voltage variations are related to planning decisions made in the sizing and configuration of the networks (see table 2.1 below). This research focuses on steady state voltage regulation.

Disturbance	Duration	Effect on system	Typical cause
Voltage regulation	Steady State	Typically $\pm 10\%$ voltage	Normal system voltage variation resulting from load changes
Voltage swing	10 cycles to 5 min	Typically $\pm 30\%$ voltage	Motor starting, shock loads, furnace loads, welders, chippers etc.
Voltage flicker	Variable	Voltage variations	Repetitive voltage swings or transients
Voltage wave shape distortion	Variable	Fundamental or harmonic voltage up to +200%	Current harmonics drawn by non-linear loads such as saturated inductors.
Voltage unbalance	Steady State	Typically up to 10% voltage variation among phases of three phase systems	Single-phase or unbalanced loads on a three phase system

Table 2.1: Electric power system voltage variations that are not typically fault related (excludes fault related disturbances such as single phasing, voltage dips, surges, spikes, and outages) [1].

While the focus of this research is on distribution steady state voltage regulation, voltage regulation is only one of many factors that can necessitate system strengthening and influence network expansion and design. In most cases the optimal solution will be influenced and dictated by many factors, and voltage regulation can not be considered in isolation. This section introduces many of these factors as they relate to voltage regulation.

2.1 FACTORS INFLUENCING NETWORK STRENGTHENING, EXPANSION AND DESIGN

When evaluating an existing or proposed distribution system, the following factors should be taken into consideration. Some of the factors have safety and regulatory/licence requirements and hence can not be compromised, while others will only have longer term implications in the form of increased life cycle costs that may not be apparent when only comparing initial capital costs. In some cases, such as with QOS issues, it can be very difficult to put a monetary value to issues and the selection of the most appropriate design can become subjective. Note that many of these factors are directly or indirectly related to voltage regulation limits. Some of the factors touched on below will be developed further in the body of this document.

2.1.1 The Existing Electrical System

The existing electrical system plays a critical role in influencing the nature of upgrades and or extensions to meet the requirements of new and existing customers. The existing electrical system is characterised by the following:

- **Sub-transmission system:** Consists of sub-transmission lines supplying sub-transmission substations that transform the sub-transmission voltage to the required distribution voltage. Sub-transmission voltages typically range from 25kV to 230kV, but in the South African context are limited to 132kV. The sub-transmission system usually consists of a grid of interconnected lines, substations, and switching stations such that substations are supplied by more than one sub-transmission line thus improving reliability. In some cases (mainly rural areas) sub-transmission substations are supplied by radial lines, with no alternative sub-transmission supply. Internationally, in the first half of the 20th century, extensive use was made of sub-transmission voltages between 25kV and 46kV. However due to increased load densities and the requirement to move power over greater distances these former sub-transmission voltages have in many cases been recycled as distribution voltages [2]. As a result, voltages such as 33kV can be and are used as both sub-transmission and distribution voltages.
- **Distribution system:** Distribution voltages typically vary between 3.3kV and 35kV. Customers are either supplied directly at the distribution voltage (large customers), or at the LV service voltage level via distribution substations that transform the local distribution voltage to the service voltage. Service voltage levels vary internationally, with the American standard of 240/120V bi/single phase and the European (and South African) standard of 400/230V three/single phase.

The technologies, voltage levels, conductor sizes and other attributes of the existing electrical network hugely influence the power transfer capabilities and reliability levels. The starting point for any planning exercise to strengthen or extend a network is a suitably accurate network model such that the system's response to network or load changes, operations and faults can be simulated to produce suitably accurate results.

2.1.2 Loads and Load Models

Load models and data are essential to enable the calculation of loading levels and voltage regulation magnitudes for the purposes of planning electrical networks. The required information would include, but not necessarily be limited to:

- Load magnitude, including forecast
- Power factor
- Load type (load's response to changes in voltage : either one or a combination of constant impedance, current or power)
- Usage patterns including load factors. This information could be extended to developing statistical and other models for evaluating / calculating load co-incidence.

Considerable research and development has taken place into the arena of load estimation, load forecasting and load modelling [2, 3, 4, 5, 6, 7]. The locally developed "Herman Beta" approach to a statistically based calculation methodology for LV voltage drop is in widespread use in South Africa, and is presently accepted by the NRS as the most acceptable tool for the calculation of LV voltage drops with stochastic homogeneous load types [4]. The Herman Beta method supersedes older deterministic approaches utilising unbalance and diversity correction factors such as those documented in [8]. Research is presently underway to extend a statistically based approach to non-homogeneous load types on both MV and LV networks, and to use a signal based approach to evaluate the QOS risk in LV voltage drop calculations [77].

2.1.3 Equipment Thermal and Fault Level Ratings

Current carrying primary equipment (such as transformers, lines, switches, breakers, current transformers etc) have both normal thermal current carrying and fault level capabilities, which should not be exceeded. The overloading of equipment such as cables and transformers results in overheating of the insulating medium used in their construction, and this overheating results in accelerated ageing and ultimately premature failure. In the case of overhead lines overloading could result in local conductor joint heating problems, but the main concern is with regards to excessive conductor sagging resulting in unsatisfactory clearances.

Power transformers: As a transformer's internal voltage drop is dependent on the transformer's loading level, transformer loading practices influence voltage regulation. While the additional thermal capacity of power transformers (due to allowances in ambient temperatures and load profiles where applicable) can enable these units to be operated at above nameplate ratings (resulting in increased internal voltage drop). This additional capacity should usually only be reserved for abnormal system conditions. Due to ageing and energy losses it is usually not economically viable to select a transformer such that it will be operated at above its nameplate rating indefinitely [9, 10]. Likewise it is also not usually economically viable to oversize a transformer as the savings in copper losses are achieved at the expense of increased no-load losses.

Power lines: As with transformers, the voltage drop over a power line is directly related to the line's loading level. Considerable research into line and cable thermal ratings has taken place. Ratings are application specific due to the influence of environmental and installation factors [11, 12]. Studies using typical energy costs and load characteristics, show that at a distribution level it is not usually economical to regularly operate lines and cables at close to or above their thermal limits due to increased lifecycle costs at higher loading levels. The economic loading limit of a line or cable is typically between 30% and 70% of its thermal rating [2]. Note however that this applies to new lines. If an existing line is loaded in excess of its economic loading limit it may be cheaper to operate the line at this level. This will result in relatively high losses costs, but these costs will generally be less than the costs of upgrading the line or other forms of strengthening. Economic loading limits and the theory thereof is discussed further in section 2.3.1.

2.1.4 Performance and Quality of Supply

Network performance, the sub-transmission and distribution technologies and voltage levels directly influence network reliability and QOS. At a distribution level the use of higher voltages (to reduce copper losses, increase thermal capacity, improve voltage regulation and increase load reach) result in longer networks supplying more customers per feeder as compared with lower voltage distribution [13, 14]. In order to maintain satisfactory network performance, additional sectionalising or feeder automation may need to be installed when using higher distribution voltages. The impact on performance and QOS of various network strengthening / expansion alternatives should be an integral part of the evaluation process. Several approaches have been tabled to apply a monetary value to QOS phenomenon [15, 16], such that electrical systems can be designed to optimise the trade-off between QOS costs and network design costs.

Due to their dependence on upstream network technology, voltage and impedance, the fault level and voltage regulation at a particular point in the network will be related and decisions regarding regulation limits will influence the networks performance for QOS related phenomenon such as:

- Voltage flicker due to rapidly varying loads
- Voltage unbalance
- Voltage dips due to faults and motor starting
- Harmonics due to non-linear loads

Voltage regulation limits can also effect the performance levels and maintainability of a network as stringent regulation limits during normal network configuration may in turn provide capacity for load shifting during abnormal periods when broader regulation limits could be accommodated. Many utilities allow wider regulation limits during abnormal network conditions to facilitate the back feeding of customers [7, 17].

2.1.5 Equipment and Technology Standards

The options when designing or extending a network are limited by accepted practices, standards and equipment specifications. Many of these standards and equipment specifications are based on associated assumptions. Changes in these founding assumptions could have a significant impact in the standards and specifications. If for example a voltage regulator's tap range is based on the assumption that the distribution voltage will not fall below 95% of nominal, then changing the minimum distribution voltage level will impact on the required voltage regulator tap range.

The following standards and specifications for common distribution practices and equipment affect voltage regulation limits in distribution systems.

- **Technology:** Five main technologies are used in distribution systems, and the application is largely dependent on utility standards. Technology has a major impact on voltage regulation [18, 19].
 - Three phase 4 wire (STAR): Three phase conductors (120° phase displacement) with a neutral conductor. Three phase loads are connected in delta, and single phase loads are connected between phase and neutral. Provided loads are reasonably balanced there should be minimal neutral current. Applicable to MV and LV systems.
 - Three phase 3 wire (DELTA): Three phase conductors (120° phase displacement) with no neutral conductor. Three phase loads are connected in delta, and single phase loads are connected between phase and phase. Any load unbalance is reflected as unbalanced and vectorially displaced phase currents. Applicable to MV and LV systems.
 - Single phase: Single phase conductors and a neutral conductor, where all load current returns in the neutral conductor. Applicable to MV and LV systems.
 - Bi phase: 3 wire with two phase conductors and a single neutral conductor. The two phase conductors are 180° out of phase and single phase loads can be connected between phase and neutral or between phase and phase, where the phase to phase connection results in double the supply voltage of the phase to neutral connection. Provided single phase loads connected between phase and neutral are reasonably balanced, the neutral return current should be minimal. Bi phase is commonly referred to in Eskom as dual phase. Only applicable to LV systems.
 - Single Wire Earth Return (SWER): Essentially the same as single phase except that instead of a dedicated neutral conductor the body of the earth is used as the neutral. Single phase transformers are connected between phase and earth to produce the standard service voltage. Voltage unbalance (when supplied from three phase systems), interference and protection constraints typically limit the application of SWER. Only applicable to MV systems.

- **Distribution voltage levels** (nominal distribution voltages): A utility will limit the choice of available standard distribution voltages. In many cases (as with minor extensions) the voltage level is predetermined by the existing distribution system, and the selection of the most appropriate voltage level only becomes an issue in greenfield projects, or in situations where the existing distribution voltage level is inadequate. Standard distribution voltages commonly found in American and European / South African networks are tabled below.

European and South African	American
2.2kV	No common equivalent
3.3kV	4.16kV
6.6kV	
11kV	12.47kV
22kV	25kV
33kV	34.5kV

Table 2.1.5.1: Standard distribution voltages commonly found in American [2], and European and South African [20] networks

The choice of the distribution voltage is probably the most significant factor in the overall distribution system cost [2]. Due to the significantly increased economic load reach of higher distribution voltages, there has been an increasing trend to use higher distribution voltages (22kV and 33kV in the South African context), with many utilities opting to upgrade existing systems to these higher voltage levels [13, 14].

- **Service voltage levels** (nominal service voltages): Almost without exception utilities standardise on one service voltage level. The service voltage level plays a significant role in the approach to distribution, and influences the relationship between distribution level and service level voltage regulation and voltage drop apportionment. There are two main schools of thought [2, 7] :
 - American: The “American” approach utilises a relatively low (with respect to the European voltages) service voltage of 120V single phase and 240V bi phase for its domestic and light commercial consumers. Three phase supplies (240V and 480V) are made available for larger consumers with three phase motor loads. However the vast majority of LV reticulation is performed using the 120V/240V three wire (bi phase) approach in which larger loads such as heating are connected between the two phases (240V) and smaller loads are connected between phase and neutral (120V). The LV system can’t typically effectively (economically) distribute power beyond a hundred meters for the typical load densities found in residential and commercial areas [2]. As a result the service areas (and hence loads) supplied by distribution transformers are small. The majority of distribution transformers are single phase units connected between phase and neutral on the primary 4 wire (STAR) three phase distribution system. Distribution transformers are typically rated between 15kVA and 75kVA. The service voltage is truly a service voltage, and is not generally used to distribute power to many customers. As a result the bulk of the voltage drop usually occurs in the distribution system. The apportionment between the distribution and service level voltage drops usually results in most of the voltage regulation occurring in the MV level.
 - European: The “European” approach typically utilises a three phase 400/230V service voltage. When compared with the American 240/120V standard, the three phase 400/230V service voltage can be used to economically distribute power over appreciable distances for the typical load densities found in urban and rural areas [2]. By comparison a European 400V service level system can typically transfer the same load a distance of roughly 4 times that of an American 240/120V system using the same volume of conductor material. As a consequence, with the European approach the service level is used to distribute power to several

customers. This results in fewer, but larger, three phase distribution transformers, which typically range between 100kVA and 500kVA in size. As the majority of the distribution transformers are three phase units, 3 wire (DELTA) three phase MV distribution is used avoiding the additional cost of a neutral conductor. Due to the fact that the service level is effectively used to distribute power, the voltage drop in the service level is usually higher than that of the comparable "American" system. The economic apportionment of voltage regulation may result in the LV service level receiving the bulk of the allowable voltage drop. Two of the factors that support the "European" approach are economy of scale and load diversity. By using the service level to distribute power, larger distribution transformers are required. The cost differential between transformers is not directly proportional to rating i.e. a 200kVA transformer will cost less than two 100kVA units. Likewise with the European approach more customers are supplied per distribution transformer. This results in improved load diversity, and less transformation capacity is required to service an area. The diversity of loads at the service level also results in improved voltage regulation and losses when a sufficiently large numbers of customers are supplied by the same transformer and service backbone, as is the case with the European approach.

- As a result of the fundamental differences between the American and European approaches the apportionment of capital costs between the distribution and service levels varies considerably between the two different approaches. This will have a bearing on the optimal voltage drop apportionment between the distribution and service levels. No one approach is necessarily better than the other and the optimal approach is situation dependent.
- Approach utilised in South Africa: The practices in South Africa are largely based on the European approach in that three phase service is used to distribute power from relatively large distribution transformers. This practice is however limited to built-up areas where the load densities justify the use of three phase service reticulation. In rural areas where the load densities are relatively low, single and bi phase service level technologies are used to supply groups of customers, however many customers are supplied by dedicated distribution transformers. Eskom will supply individual customers with up to 2MVA at the local three phase service voltage level of 400V [21]. For larger supplies Eskom requires that the customer take a bulk supply at the local distribution MV level.
- **Conductor sizes:** A utility standardises on a range of conductor types and sizes used in its systems at both a MV distribution and LV service level. Eskom Distribution has specified its standard conductors [22]. This standardisation practice extends to types of construction, insulation and the size and material of the phase and neutral conductors. These factors have a major impact on thermal capacity and voltage regulation.
 - Minimum conductor size is usually dictated by mechanical and fault level rating considerations. In overhead line systems the conductors need to have sufficient mechanical strength such that conductor spans can be reasonably long and lightning strikes will not result in unacceptable failure rates. In cable networks the fault level requirements will usually limit the minimum cable size.
 - Maximum conductor size is usually dictated by cost constraints as traditional construction techniques (such as woodpole) can no longer be used for unusually large conductors and the increase in cost starts to become exponential at these larger conductor sizes. As losses and voltage drop are related to both the line's impedance and voltage, higher distribution voltages with smaller phase conductors are usually preferred [2].
- **Sub-transmission transformer specifications:** Sub-transmission transformers are used to transform the sub-transmission voltage to the required distribution voltage level, and in the context of this document HV/MV transformers are referred to as sub-

transmission transformers. The voltage regulation limits dictate two aspects of the sub-transmission transformer design / specification.

- **On Load Tap Changer (OLTC):** The OLTC is used (usually in conjunction with an automatic control scheme) to change the effective turns ratio to either buck or boost the supply voltage. OLTC operation is used to compensate for changes in the sub-transmission supply voltage, and can also be used to compensate for voltage drops in the distribution system. This concept is developed further in section 2.6. The OLTC voltage range (for both bucking and boosting) is directly linked to voltage regulation limits in both the sub-transmission and distribution networks. The step size is linked to QOS requirements pertaining to voltage flicker, and is not only dictated by voltage regulation limits.
- **Transformer core losses:** No-load or iron losses are a function of the magnitude of the transformer core flux. Transformers are designed for a normal operating voltage, and iron losses increase exponentially with the transformer supply voltage. This concept is developed further in section 5.2. The transformer operating voltage is directly linked to voltage regulation limits in both the sub-transmission and distribution networks.
- **Distribution transformer specifications:** Distribution transformers are used to transform the distribution voltage to the required service voltage level. In the context of this document MV/LV transformers are referred to as distribution transformers. As with sub-transmission transformers, the tap range and operating design voltage are largely dictated by the voltage regulation limits. Distribution transformers differ from their sub-transmission counterparts in that the tap changer is usually not an OLTC, but is rather a De-Energised Tap Switch (DETS). With a DETS the turns ratio can be adjusted in relatively coarse steps, but adjustment is not carried out on load and can not be automated via a suitable control system.
- **Voltage regulators:** Voltage regulators are used to either buck or boost distribution voltages. Voltage regulators can be used in conjunction with fixed tap transformers instead of transformers fitted with OLTCs. Voltage regulators can be installed at almost any point in the distribution system where voltage bucking / boosting is required. Reference [23] contains details of their operation and capabilities. While there are many types of voltage regulators, the most common type consists of an auto-transformer arrangement. As with sub-transmission and distribution transformers, the tap range and operating voltage are dictated by the voltage regulation limits.
- **Shunt capacitor banks:** Shunt capacitor banks are used to reduce system losses, release network capacity and improve voltage regulation. As a constant impedance device, the amount of leading current drawn by a shunt capacitor is directly proportional to the size of the bank and the magnitude of the supply voltage. As the voltage drop increases, so the voltage supplied to the capacitor bank decreases and the amount of reactive VARs “injected” into the systems also decreases. The resultant cycle can result in voltage collapse, and a capacitor banks effectiveness is influenced by the voltage regulation limits. Furthermore as the capacitive current is proportional to the supply voltage, and the internal capacitor bank losses are proportional to this current squared, the internal capacitor bank losses increase exponentially with supply voltage. Over voltages are generally only of concern with fixed capacitor banks, as switched units will be disconnected during periods of low loading when the voltages may rise to unacceptable levels. Due to the relationship between injected VARs, losses and voltage, capacitor specifications are closely linked to the maximum anticipated voltage levels and the regulation limits.
- **Series capacitor banks:** Series capacitor banks are used to compensate for the inductive component of overhead lines, and are usually used to solve stability and QOS issues surrounding fault level shortfalls and voltage dips and flicker due to motor starting and cyclic loading. Series capacitor banks are not usually used to solely

address steady state voltage regulation problems. The operation and specification of a series capacitor bank is not significantly effected by regulation limits, however the requirement for a series capacitor bank may be closely linked to regulation limits.

- **Equipment insulation:** While the insulation levels of transformers, lines and cables are influenced by the nominal supply voltage level, other factors such as lightning and switching surges usually dictate the insulation requirements. Insulation levels should not be confused with maximum operating voltage levels as the insulation of, for example a transformer, may be adequate, but the maximum operating voltage may be limited by other factors such as core flux levels.

2.2 NETWORK STRENGTHENING AND EXPANSION OPTIONS IN DISTRIBUTION SYSTEMS

Evaluating the optimal regulation limits for an existing or new distribution system will usually require careful analysis of the factors described in section 2.1. The analysis of an existing network and determination of the optimal regulation limits will be further influenced by the types of strengthening that could be performed. These strengthening options will be situation dependent and would typically include the following (note that these alternatives are primarily used at the MV distribution level, but many are equally applicable at the LV service level).

- **Control methodology:** The adjustment of voltage control settings and the application of functionality such as Line Drop Compensation or Voltage Compounding can significantly improve voltage regulation. In many cases modification to the control methodology may not completely solve voltage regulation problems, but may enable other system strengthening options to be delayed.
- **Reconfiguration and load balancing:** Shifting of normally open points to move load between networks and sections of network. Changing the phase connection of loads and unbalanced line technologies to improve current and voltage unbalance.
- **Line re-template:** By increasing the template temperature of an overhead line the thermal capacity of the line can be increased i.e. check that increased conductor sag can be tolerated.
- **Line re-conductor:** Increasing the conductor size of an existing line. This may require additional structures in critical spans, but in many cases the line will need to be completely rebuilt as the existing structures may not have been designed for the larger conductor. As discussed further in section 2.3.1, the line inductance does not decrease linearly with increasing conductor size, and larger conductors may not solve voltage regulation problems.
- **Capacitor banks:** Only suitable for feeders with poor power factors (<90%), and the effectiveness of capacitor banks are hampered by the relatively low X/R ratios that are usually found in distribution systems.
- **Voltage regulators:** Address the symptoms of voltage regulation, but do not reduce system losses or address QOS problems relating to inadequate fault level.
- **Changing technology:** Converting single to bi phase, and single and bi phase technologies to three phase.
- **Increasing distribution voltage:** While very effective, this drastic solution is hampered by the practical difficulty of re-insulating lines and replacing distribution transformers. Once a distribution voltage is entrenched in an area it is very difficult to justify a change to a higher distribution voltage, as other alternatives such as regulators and overlays are usually more cost effective. A higher distribution voltage may have been the best solution had it been implemented in the initial design. However once the "mistake" using

the lower voltage has already been made other forms of strengthening are usually preferred.

- **Voltage overlay:** By extending the sub-transmission system to inject into the distribution network additional distribution feeders can be created by splitting up the existing feeders. The effected distribution feeders become shorter and supply less load. Both the voltage regulation and QOS are improved. This concept can be extended to the service level where the distribution network can be extended via an additional distribution substation(s) to split the service feeder(s).
- **Distributed generation (DG):** While the impact of DG has yet to be felt in South Africa, the effect distributed generators have on voltage regulation in distribution systems can be dramatic [24]. As the technology matures so DG will compete with traditional alternatives to solving voltage regulation problems. In particular DG will become increasingly more attractive to address loadflow related shortfalls in existing networks where the distribution lines and voltages are already established, and the loading is either highly seasonal and / or has a low load factor.
- **Micro Flexible AC Transmission (μ FACT) devices:** With the advent of modern switching devices such as the IGBT, power electronic devices that have historically been the domain of transmission systems are starting to find applications in distribution systems. μ FACT devices will become increasingly more attractive as the costs continue to drop due to advances in the power electronics industry [25]. Typical μ FACT devices include distribution SVCs, active harmonic filters and voltage dip proofing equipment. μ FACTs and power electronics are closely linked to DG as many DG sources such as windmills do not generate electricity at the power system frequency (50Hz in South Africa) and power electronics are required to produce the required frequency and synchronisation for interconnection with the grid. The use of power electronic devices to address steady state voltage regulation problems in LV networks enables the local supply voltages to drop well below normally acceptable limits (typically 40% below nominal). The power electronics provide electronic voltage regulation thereby ensuring acceptable customer supply voltages. This enables increased MV and/or LV voltage drops [26, 27, 28].
- **Demand side solutions (DSM):** The options listed above are essentially supply side solutions in that the problem is solved via changes to the distribution system without modifications to the customers load characteristics. In certain cases distribution system shortfalls can be addressed, and life cycle costs reduced, by modifications to the customer load via load shifting and energy efficiency initiatives. Common examples are respectively the use of electric geyser control (historically referred to as ripple control) and compact florescent lighting.

2.3 TECHNICAL LOSSES

When sizing distribution networks the primary focus of the designer should be to minimise life cycle costs within the constraints of utility standards pertaining to factors such as system performance, QOS, voltage regulation and thermal loading. Designs may vary significantly from the optimal solution if only initial capital costs are used for the evaluation of different design alternatives. One of the key factors influencing life cycle cost are the cost of technical losses which can be broken into two broad categories; copper losses and iron losses.

2.3.1 Copper Losses: Economic Loading Limits for Power Lines

When AC current flows in a conductor with an impedance $Z = R + jX$ the conductor “consumes” real and reactive power: $P = I^2R$ and $Q = I^2X$. This results in two losses due to current flowing in the conductor.

- **Energy loss:** The active power during peak loading ($P = I_{\max}^2 R$) is usually adjusted by a Loss Load Factor (linked to the load factor) to obtain the average power consumed by the conductor. When multiplied by the number of hours in a year the average power loss is converted into average energy (kWh), which when multiplied by the cost of generation becomes the capitalised energy cost per annum. Note that the cost of generation in the context of energy loss refers to the generation running cost (R/kWh), which is primarily determined by the fuel cost. The energy cost is dependent on the real (P) power consumption.
- **Demand loss:** The real and reactive power consumed by conductors results in an apparent power consumption (S) which must be supplied by the grid generation. As a result generation and network capacity must be available to supply this apparent power (loss demand). When the cost of this additional generation and network capacity (usually expressed in an annual R/kVA) is multiplied by the apparent power consumed by the conductor, the annual demand cost is obtained. Note that the cost of generation in the context of demand loss refers to the annualised capital cost (R/kVA) pertaining to simply having the generator and network installed and available to supply load (in this cases the losses in the conductor). The demand cost is dependent on both the real (P) and reactive (Q) power consumption.

The life cycle cost of a power line consists of the following basic components:

- **Capital:** Installation cost including design, materials and labour. Occurs in year 1
- **Losses:** Energy and demand costs that occur every year
- **Maintenance:** Line maintenance and general repair costs that occur every year

The total life cycle cost of a line can be expressed as a Net Present Value (NPV) which is influenced by the following main factors:

- **Net Discount Rate:** The effective cost of capital which is calculated from the inflation and money lending rates.
- **Evaluation period:** Typically the anticipated life span of the line
- **Initial load:** The load to be supplied by the line in year 1
- **Load growth:** Usually expressed in % growth per annum
- **Power factor:** Power factor of the load supplied by the line
- **Load factor:** Load factor of the load supplied by the line
- **Demand loss cost:** Both initial and forecasted demand loss cost over the evaluation period
- **Energy loss cost:** Both initial and forecasted energy loss cost over the evaluation period

For any given set of the above factors the NPV of a conductor can be calculated for a particular loading, and the NPV can be plotted as a function of initial line loading. By plotting a conductor set (range of conductors typically used by a utility) the economic loading limits of each conductor can be graphically illustrated [2].

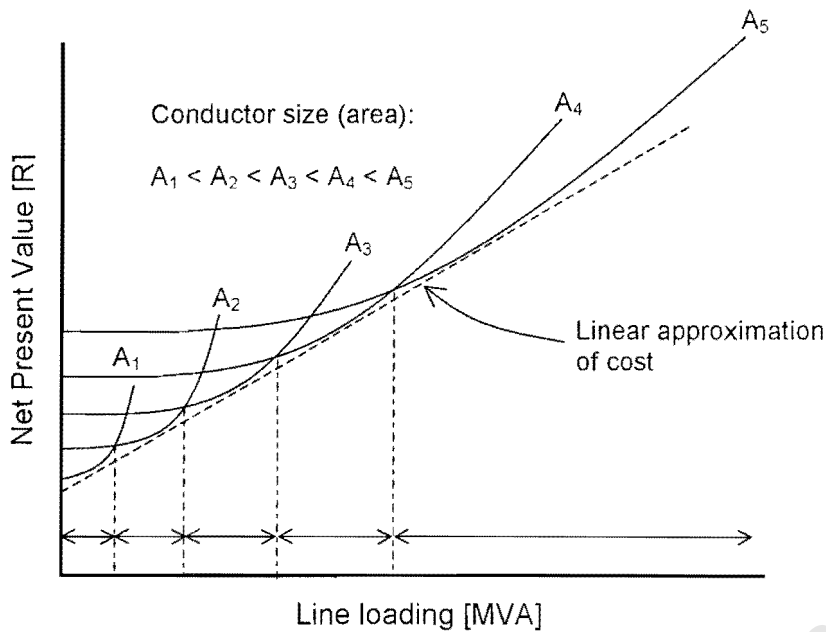


Figure 2.3.1.1: Illustration of Net Present Values as a function of initial line loading for a typical range of conductor sizes for a particular technology and voltage level [2]. NPV are per unit of line length

For a given set of conditions, a conductor will have an economic loading range for which it will result in the lowest NPV life cycle cost when compared with the other conductors in the conductor set. The NPV loading curves can be calculated for conductor sets at different voltage levels and technologies.

For a given voltage regulation limit, the distance a conductor (associated with a voltage and technology) can move load when loaded at its Thermal Load Limit (TLL) is referred to as its Thermal Load Reach (TLR). When a conductor is loaded at its Economic Load Limit (ELL) the resultant distance at which regulation limits are at the allowed maximum is referred to as its Economic Load Reach (ELR). As the ELL for a conductor is typically between 30% and 70% of its TLL [2], the ELR will usually be between 140% and 330% of the TLR.

The following interesting relationships and observations can be made:

- ELR is simply an indication of the distance beyond which additional costs will be incurred if distribution is to be performed using a particular voltage and technology.
- Because the inductance of an overhead line reduces proportional to the natural log of the ratio of the phase spacing to conductor radius, the inductance does not reduce linearly with increased conductor size. As a result the ELR reduces for larger conductors when compared with smaller conductors operated at the same voltage.
- In order for larger conductors to provide the same ELR as smaller conductors the ELL of these larger conductor must be reduced. The maximum recommended loading level of the larger conductor must be reduced to provide the same load reach due to the non-linear relationship between line impedance and conductor size.
- For the same voltage regulation limits, increasing the nominal voltage results in increased ELL and ELR.
- The ideal feeder length is the ELR.
- For a required load reach there is an optimal voltage and technology that can support the required load at the required distance whilst minimising costs.

- Reducing the allowable voltage regulation limits reduces the ELR and higher voltages are required for optimal economics.

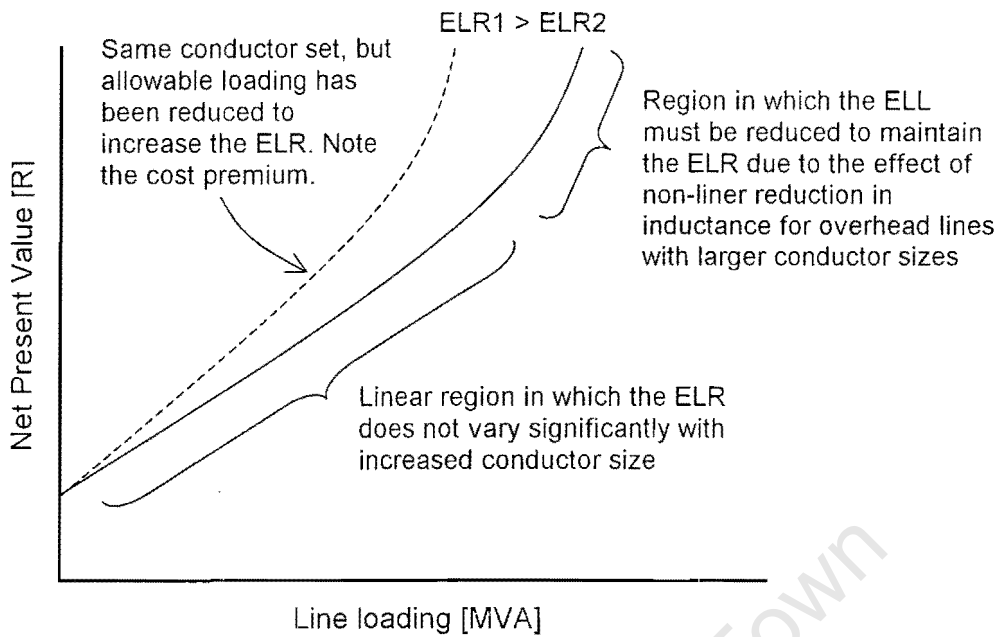


Figure 2.3.1.2: Illustration of the reduction of the ELL to maintain the same ELR for larger conductors [2]. Also illustrates the cost premium that will be paid to increase the ELR by reducing the ELL.

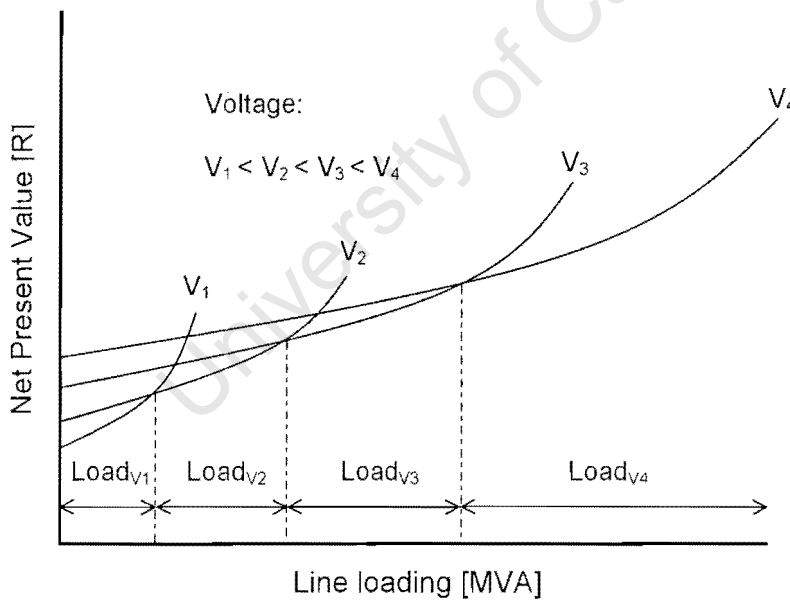


Figure 2.3.1.3: Illustration of the NPV cost relationships for the same conductor set at four different voltages to illustrate the optimal loading ranges for the four different voltages [2].

If the average distance power is to be moved over a MV feeder is less than the ELR, and conductors are sized based on their ELL such that the life cycle cost is minimised, the voltage regulation on the feeder extremities will be less than recommended limits. If the average distance power is to be moved over a MV feeder is greater than the ELR, conductors must be selected to meet the voltage drop limits, and the optimal network design will result in the maximum allowable voltage regulation at the feeder extremities. For

distances greater than the ELR the optimal design results in the utilisation of the available voltage drop.

The calculation of ELL and ELR limits for conductors involves finding the optimal trade off between capital costs, and life cycle costs due to technical losses. The calculation of life cycle technical loss costs falls outside of the scope of this research, and typical values for ELL and ELR limits in Eskom distribution are not provided in this report.

2.3.2 Iron losses: Transformers

There are two basic forms of energy losses in transformers.

No-load losses due to the magnetisation of the core are a function of the core flux (and hence applied voltage), and do not vary significantly with the load current.

Load losses due to copper (I^2R) losses and eddy currents as a result of the transformer's leakage flux are roughly proportional to the square of the load current.

Standard component losses for distribution transformers are included in appendix A. Due to core saturation the no-load losses are very sensitive to the magnitude of the applied voltage, and a small increase in voltage can result in a disproportionately large increase in the magnetisation current and hence core losses. Typical per-unit values for core losses as a function of the per-unit core flux (where 1pu core flux is the resultant flux when rated voltage is applied to the transformer in nominal tap) are tabled below.

Core Flux (per unit)	Core losses (per unit)
1.00	1.00
1.05	1.15
1.10	1.60

Table 2.3.2.1: Typical per unitised core loss values as a function of core flux [29]

As with power lines the capitalisation of losses can be used to determine the optimal designs and power ratings of transformers for a given load type and magnitude. From a loss perspective the main difference between lines and transformers is the presence of no-load losses in transformers. When selecting a transformer the potentially conflicting requirements between load and no load losses needs to be evaluated, and the optimal selection will be influenced by the nature (load profile) of the load being supplied [30]. Optimised designs for transformers supplying loads with high load factors will result in lower load losses as compared with optimal designs for low load factors. As a result the loss cost values (typically R/kW) used to capitalise no-load losses costs should be roughly the same for typical sub-transmission and distribution transformers. However the loss cost values used to capitalise load losses costs for sub-transmission and distribution transformers should vary considerably. This is due to the significant variations in loading levels and load factors that these two types of transformer supply. Due to diversity the load factor of the load supplied by sub-transmission transformers will be higher than that supplied by distribution units. Furthermore sub-transmission transformers are often paralleled to provide redundancy, resulting in normal loading levels well below thermal ratings, and the loss cost figures should reflect this.

2.4 EQUIPMENT OPERATING VOLTAGES

Equipment can be broken into two main groups; that which is used to supply the electrical power (network equipment), and that which consumes the electrical power in the form of appliances such as motors (customer loads).

2.4.1 Network Equipment

The South African standard nominal system voltages and their associated highest values are specified in the SABS 1019 Standard voltages, currents and insulation levels for electricity supply [20]. The highest equipment voltage (U_m) is 110% of the nominal system voltage (U_n) for MV systems. U_m and U_n are defined as:

Highest voltage for equipment (U_m): The highest rms phase-to-phase voltage for which the equipment is designed in respect of its insulation as well as other characteristics which relate to this voltage in the relevant equipment specifications.

Nominal voltage of a three phase system (U_n): The rms phase-to-phase voltage by which a system is designed and to which certain operating characteristics of the system are related.

The MV insulation of, for example, a distribution transformer may be designed to be continuously operated at U_m i.e. 110% U_n , however the operating characteristics such as no-load losses, temperature rises and life span will generally be specified against U_n . As a result while the equipment may be capable of operating continuously at U_m , this can only be achieved at the expense of other attributes such as maximum loading levels.

Section 5.2 contains detail on Eskom's transformer design specifications and operating limits as these affect the maximum allowable system voltages.

2.4.2 Customer Loads

Equipment operating voltages vary significantly between countries, different devices and voltage levels. While a specific appliance may have an associated maximum voltage range within which it will function satisfactorily, it may only be able to operate near the extremes of this voltage range at the expense of attributes such as life span, performance and efficiency. The operating voltage ranges for appliances are usually standardised nationally, and due to the forces of the global market place, there is continual pressure to rationalise and standardise specifications. Internationally most non-industrial type appliances will provide satisfactory operation for a $\pm 10\%$ voltage variation [31]. Utilisation voltages for appliances in the United States and South Africa are briefly discussed in section 2.7.

Section 3.2 contains additional detail on the voltage regulation requirements of South African end use appliances such as domestic appliances and motors.

2.5 VOLTAGE REGULATION AND ENERGY CONSUMPTION

The amount of energy consumed by appliances varies with the magnitude of the applied voltage. Considerable research into the voltage dependency of loads has been performed for both dynamic system modelling, and the effects on demand and energy consumption due to Conservative Voltage Reduction (CVR).

Most loads will draw more active and reactive power if the supply voltage is increased. The possible increased consumption must be considered in light of the types of load being supplied. Heating devices (such as stoves and geysers) consume power at a faster rate

when the voltage is higher. However these devices achieve their function in less time so unless their efficiencies vary significantly with the magnitude of the applied voltage, they consume the same amount of energy in order to fulfil a given function.

Considerable research into the relationships between voltage, demand and energy consumption has been performed. The results of applied research in reference [32] concluded that for every 1% reduction in the average voltage supplied to the consumer the energy consumption reduces by between 0.9% and 1.6% for residential, 0.5% to 1.2% for commercial, and 0.6% and 1.2% for industrial loads. Other recommended values [33] for different load types as a function of a 1% reduction in average voltage are a energy consumption reduction of 0.76% for residential, 0.99% for commercial, and 0.41% for industrial loads. Measurement of 15 distribution circuits supplying a non-coincident peak demand of 80.2MVA of mixed load in the United States (which included rural areas), resulted in an average 0.71% reduction in energy consumption per 1% reduction in the source sending busbar voltage [34]. Selected results of an EPRI laboratory analysis of common American household appliances are plotted below.

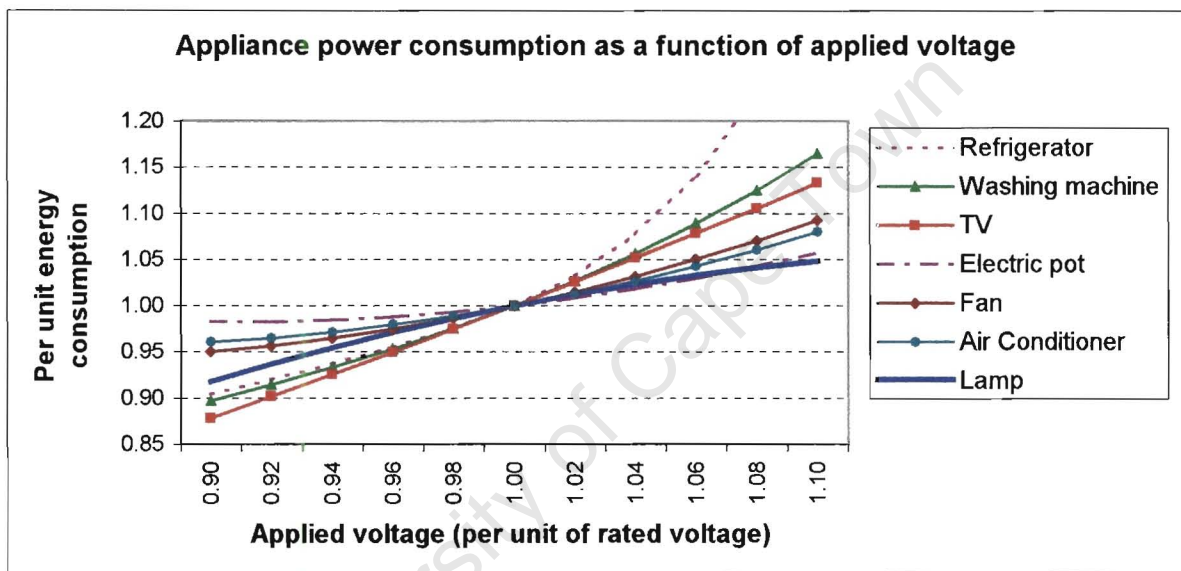


Figure 2.5.1: Typical appliance power consumption as a function of applied voltage as derived by EPRI from a statistical analysis of laboratory measurement [35]

The EPRI work illustrated in figure 2.5.1 must be viewed with the necessary caution. While the amount of energy drawn by an appliance may vary with the magnitude of the applied voltage at a particular instant in time, the total energy consumed by the appliance may not vary significantly over an extended period of time. Energy consumption will only increase for constant impedance or current type loads that are not self regulating i.e. they do not control their operation, and energy consumption is effected by the magnitude of the applied voltage. An example would be incandescent lighting.

“Power consumption” can be a misleading term. The results of the EPRI models can be used when evaluating short-term (measured in minutes or hours) demand reduction due to voltage variations, but could not be directly applied to assess the longer-term (measured in days, months or years) impact of voltage variations on revenue.

The practice of reducing substation busbar voltage levels has been carried out by many utilities as an emergency procedure to reduce peak demand levels during critical loading periods. As the voltage reduction is temporary the abnormal operating voltage ranges for appliances are often utilised, and significant reductions in demand can be achieved [35].

With the advent of the Arab Oil Embargo in 1973 many predominately US and European utilities have investigated and implemented CVR programs to reduce generation costs [33]. CVR essentially involves reducing the voltage supplied to customers such that they consume less energy. Note that this is performed at the expense of reduced revenue. While it may be practical to implement CVR in areas with high load densities where networks are thermally limited, reducing the sending voltage (to reduce the average voltage) is often simply not feasible in rural networks limited by voltage regulation constraints. The economics of power distribution in rural areas can be in complete opposition to CVR requirements, as additional network strengthening would be required to provide additional capacity such that sending voltages could be reduced.

Designing a network with a larger voltage drop (as compared with a reduced voltage drop) will result in the following associated costs:

- As the average supply voltage is reduced, the energy consumption and hence revenue obtained from the customers will decrease. Note that this will not apply to constant energy loads such as cooking, water heating and refrigeration.
- In order to keep voltages within acceptable limits there is reduced scope for both temporary and permanent CVR

CVR has not be utilised in Eskom's Distribution networks, and given the present surplus in generation capacity and relatively low generation costs there have been no moves in this direction. However reducing the voltage drops in distribution networks will enable the utility to increase revenue, and when generation capacity becomes a major issue, CVR could be applied during peak generation periods. Note that with the advent of switch mode power supplies (modern electronic equipment such as TVs) and electronic ballasts (modern fluorescent lamps), appliances are becoming increasing voltage insensitive. These devices effectively behave as constant power loads. The scope for CVR may decrease in the future as equipment becomes increasing voltage insensitive. This trend may continue as appliance manufacturers aim to provide for a global customer base where nominal service voltage levels may vary considerably between different countries.

2.6 VOLTAGE CONTROL METHODOLOGY

The type of voltage control utilised in the distribution system plays a significant role in utilising the available regulation range. In order to provide acceptable voltages at all customer installations the various components of the electrical system (sub-transmission, MV distribution and LV service level) all need to work in unison. However the interaction between these systems is complex due to the stochastic nature of the loads. The techniques utilised to compensate for the voltage drops in each of the system levels are documented below.

2.6.1 On-load Tap-Changers

Transformers can be fitted with On-Load Tap Changers (OLTC) which are used to physically adjust the tap ratio of the transformer such that it can buck, boost or buck and boost the voltage. By adjusting the tap ratio in discrete steps the voltage on the transformers secondary can be controlled in discrete steps. Due to the cost and maintenance implications of OLTC mechanisms, they are generally only installed on sub-transmission transformers. The Eskom standard specification for an OLTC is a 5% buck and 15% boost in a total of 17 tap positions i.e. a tap step size of 1.25% [29].

A voltage control relay is used to adjust the OLTC tap position such that the required level of bucking or boosting is performed. There are four basic control techniques.

Fixed voltage: The transformer secondary (typically the MV busbar) voltage is held constant at a predetermined setpoint. Due to the fact that the OLTC has discrete step sizes, the voltage can only be controlled within a voltage control window that will always be larger than the step size. The controller hence controls the voltage to fall within the setpoint and bandwidth. If the voltage deviates from this acceptable range, the controller will adjust the tap ratio such that the voltage falls within the required range. In order to limit the number of tap change operations, the voltage control window is typically set to roughly double the step size. This form of voltage control provides a relatively constant source voltage for the downstream MV system provided the sub-transmission and transformer internal voltage drops do not exceed the boost capabilities of the OLTC. A typical Eskom voltage setpoint for a distribution MV busbar would be 103%, with a dead band of $\pm 1.2\%$. This implies that the MV busbar voltage could vary between $103\% - 1.2\% = 101.8\%$ and $103\% + 1.2\% = 104.2\%$.

With fixed voltage control the regulated secondary voltage is not a function of the transformer loading, and at any time could fall within the top or bottom halves of the voltage control window. During peak MV network loading the regulated MV busbar voltage may be a minimum, and rise to a maximum during off-peak loading periods.

Line Drop Compensation (LDC): Instead of controlling the voltage at the secondary of the transformer, it is preferable to control the voltage at the load centre of the MV network such that the voltage at this load centre is kept relatively constant. By modelling the series impedance of the MV lines between the MV source and load centre the voltage drop over this impedance can be factored into the voltage control such that the setpoint is adjusted to regulate the remote load centre. The net result is that the MV voltage regulation at the majority of the customer installations is reduced, and this enables increased distribution transformer tap boosting without the risk of over voltages during light loading conditions. In extreme applications, to facilitate maximum allowable LV feeder voltage drop, LDC can be applied to attempt to keep the MV feeder end of line voltage constant via the use of relatively high sending voltages during peak load conditions [36].

The required settings are a function of the conductor characteristics between the MV source and load centre. In most distribution systems loads are distributed over the MV feeders. In these cases LDC is used to regulate the virtual (equivalent) load centre such that while the voltage at all customers will not be held constant, the voltage variations between peak and off-peak loads will be minimised.

While LDC is a simple concept, in reality it can be difficult to implement. In most distribution substations a MV busbar supplies several outgoing MV feeders, each of which may have different load characteristics (different magnitudes and peak at different times), and different virtual load centres (varying backbone conductor types, line lengths and distribution of loads).

Voltage Compounding / Load Compensation: Due to the practical difficulties of utilising LDC on OLTC control schemes for transformers supplying multiple feeders a simplified form of control is employed whereby the MV busbar voltage is made proportional to the total transformer (or substation) loading. This form of voltage control is commonly referred to as Voltage Compounding (VC) or Load Compensation (LC). Essentially the voltage setpoint is made proportional to the loading for a given power factor. This simplified approach solves the problem of different conductor types with multiple feeders, but still has

major drawbacks and limitations. Large changes in system power factor can result in significant compensation errors. The effectiveness is limited by the extent of coincidence between load peaks on the outgoing feeders, and the control settings need to be constantly checked and updated as the networks evolve and the loading and impedance characteristics of the system change. Settings for normal system configurations may be completely unacceptable during contingencies.

None the less VC does make the sending voltage proportional to the total MV system load, and this does facilitate the use of distribution transformer tap boosting.

Remote busbar control: In LDC control schemes the setpoint voltage is adjusted based on an estimated calculation of the load centre voltage. Using a suitable telecommunications system the voltage at a particular point in the network can be controlled directly [37]. The problem of multiple load centres being fed from a single source OLTC transformer is however not addressed, and the application is limited due to the generally prohibitive cost of the telecommunications link.

2.6.2 De-Energised Tap Switches

Practices vary between utilities, but distribution transformers are generally fitted with a De-Energised Tap Switch (DETS) which provides for limited bucking or boosting of the input MV voltage in relatively large step sizes (typically $\pm 5\%$ in 2.5% steps). Unlike an OLTC the DETS can not be used to vary the tap ratio on-load, and is not motorised or controlled. The DETS tap positions are set based on the anticipated MV system voltages at that particular distribution transformer location, and would not typically be adjusted more frequently than once per annum. The use of the available DETS tap positions are largely dictated by the form of voltage control utilised on the source MV busbar. Models for the optimisation of distribution transformer DETS tap positions have been developed and are being utilised by many utilities [38, 39].

2.6.3 Switching of Shunt Compensation

Switched shunt capacitors in MV distribution networks can have a significant impact on the MV voltages and need to be taken into consideration when applying voltage control techniques and settings [40]. While various types of shunt capacitor switching control are utilised, by far the most common are power factor and voltage control. The application of fixed capacitor banks can lead to leading power factors and a potential voltage rise (Ferranti effect) during light loading conditions. The severity of the voltage rise will depend on the network impedances and extent of over compensation.

2.6.4 Busbar versus Feeder Voltage Control

With reference to the above voltage control methodologies and issues, there are two main approaches to distribution network voltage control.

Substation busbar voltage control: In relatively high load density areas such as typical urban, commercial and industrial areas the MV feeders are typically limited by thermal ratings and not voltage regulation [2, 36]. As a result reducing the allowable MV voltage regulation range does not significantly impact on the cost of the distribution system and fixed busbar voltage control can be utilised. "Large" (generally >20MVA) transformers fitted with OLTC schemes are used to regulate the MV busbar voltage, which supplies multiple MV feeders (typically between 4 and 20). The transformers OLTCs are used to compensate for voltage drops in the sub-transmission network and sub-transmission transformer. The

cost per unit of load regulated is low, and due to the fact that redundancy of transformation capacity is usually provided, maintenance of the OLTC schemes is generally not a problem. Voltage compounding can be performed in order to improve the voltage regulation seen by the majority of the customers.

Individual feeder voltage control: In rural areas where the load densities are low and networks are generally limited by voltage regulation constraints, the improved voltage regulation characteristics of LDC can justify the use of fixed tap source (sub-transmission) transformers with voltage regulators on each of the outgoing MV feeders. The voltage regulators compensate for the voltage drops in the sub-transmission network, the transformer's internal voltage drop, and the MV feeder via the application of LDC. As each feeder is regulated individually LDC is relatively simple to apply as the load diversity and different impedance characteristics between feeders are not an issue. Due to the relatively low load densities each substation only supplies a couple of MV feeders (typically between 2 and 4) and individual compensation is cost effective. The fixed tap sub-transmission transformers offer improved reliability (no tapped windings and OLTC scheme with moving parts) which is significant considering that transformation redundancy is usually not provided. Transformation is also simpler enabling the use of single phase transformers to "build" three phase units (with a spare single phase transformer on site). The regulator maintenance costs will be significantly higher, but should not require any outages as feeders can be swung onto other feeder regulators during maintenance. In addition to the voltage regulators at the MV source substation, additional voltage regulators can be installed as required at various points down the MV feeder [41]. This practice is used extensively in rural areas in the United States. Note that individual feeder voltage control results in increased substation capital and maintenance costs as compared with substation busbar voltage control. When evaluating individual feeder voltage control the increased substation cost needs to be compared with the associated cost savings in the downstream distribution network(s) due to improved voltage control.

2.6.5 MV Boosting versus LV Boosting

In order to minimise the cost of LV networks supplying domestic customers, the allowable LV voltage drop often needs to be maximised, and there are two major approaches to achieving increased LV voltages during peak load conditions. The approaches differ in the location of the voltage "boosting".

MV boosting: The transformation ratios of distribution transformers are such that for a nominal MV voltage the output LV voltage is the rated service voltage (for example an 11kV to 400V transformer). The MV sending voltage at the source substation is increased to relatively high levels such that when the local MV voltage is a maximum the output LV voltage is at the top of the allowable LV regulation range. If for example the maximum LV voltage is nominal +10%, then the maximum MV voltage could be as high as 110%. This approach places additional stress on MV line and equipment insulation, and the source sub-transmission transformer must be capable of producing the high MV sending voltages. Both the sub-transmission and distribution transformers must be capable of operating at the associated high levels of fluxing. The merits of MV boosting are debated for the Italian national electricity utility in reference [36].

LV boosting: The transformation ratio of distribution transformers are such that for a nominal MV voltage the output LV voltage is the maximum rated service voltage (for example an 11kV to 400V+10%=440V transformer). The MV sending voltage at the source substation is not boosted above rated voltage and the stress on the MV equipment and transformer fluxing is reduced. This practice is followed in the United Kingdom [42].

2.6.7 MV feeder source voltage control and DETS interaction

In order to increase the magnitude of the voltage supplied to customers on feeder extremities during peak loading conditions it is desirable to maximise the amount of distribution transformer DETS boosting. The maximum DETS boosting at a particular point in the network is limited by the maximum MV voltage at that point as excessive DETS boosting will result in unacceptably high service voltages and/or transformer over fluxing. The maximum MV voltage is dependent on the characteristics of the load, feeder, voltage control settings and methodology. By utilising appropriate voltage control settings and methodologies such that DETS boosting can be maximised the maximum MV and/or LV voltage drops can be maximised.

This concept is illustrated in figures 2.6.7.1 and 2.6.7.2 below. Note that this is a fictitious example, and that the DETS step sizes and other associated implications are not necessarily representative of Eskom or any utilities specific networks and equipment. For the purposes of the example the distribution transformers have a 10% boost range and 5% step size. The LV service voltages at all customers must be kept with $\pm 10\%$ of nominal.

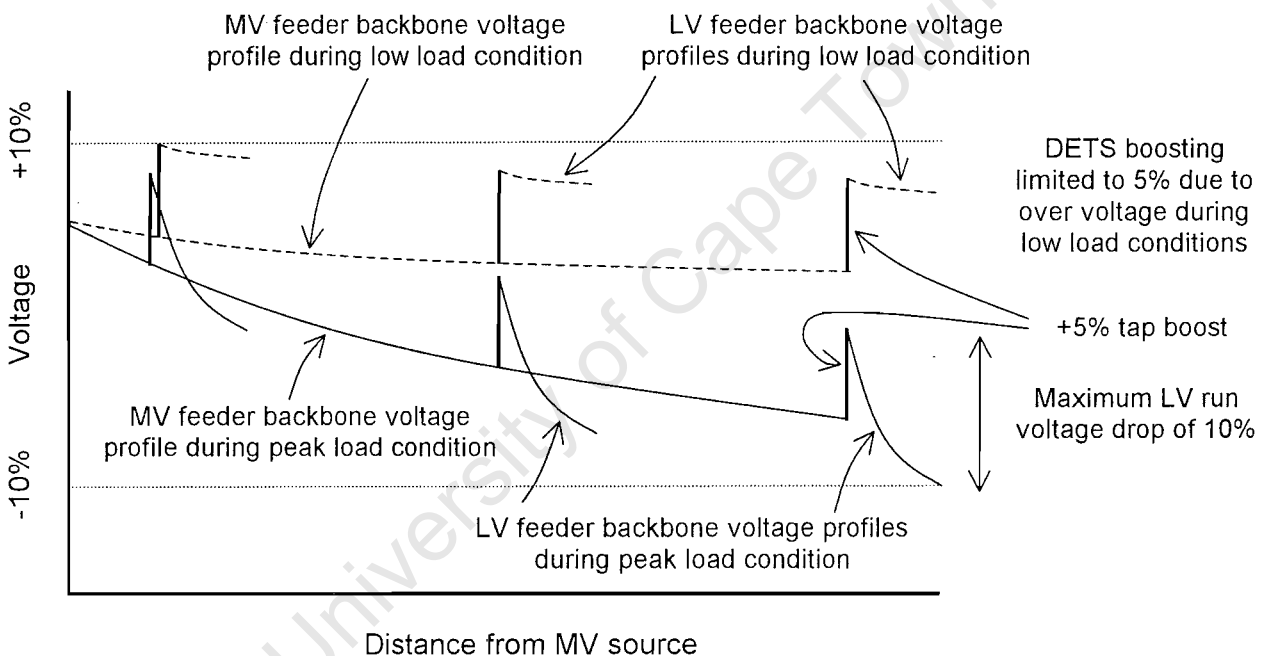


Figure 2.6.7.1: Illustration of the limitations and implications of limiting DETS tap boosting using fixed voltage control techniques on the source MV voltage

In figure 2.6.7.1 the maximum allowable DETS tap boost is limited to 5% due to the limitation on the maximum LV voltage when the source MV voltage is held constant during both peak and low load conditions. As a result, for the given MV feeder voltage drop characteristics during peak loading, the maximum LV voltage drop must be limited to less than 10% at the feeder extremities in order to meet the minimum voltage criteria at the last LV customer(s).

By reducing the MV source voltage during low load conditions the maximum DETS boost can be increased to 10% for those distribution transformers near the MV feeder extremities. This is illustrated in figure 2.6.7.2. Note that the source MV voltage remains unchanged during the peak load condition, and the maximum LV voltage drop can be increased from

10% to 15%. Due to the very nature of this form of voltage control the maximum MV voltage (which in turn dictates the maximum allowable DETS boosting) varies along the MV feeder and will occur during peak and low load conditions at the start and end of the MV feeder respectively.

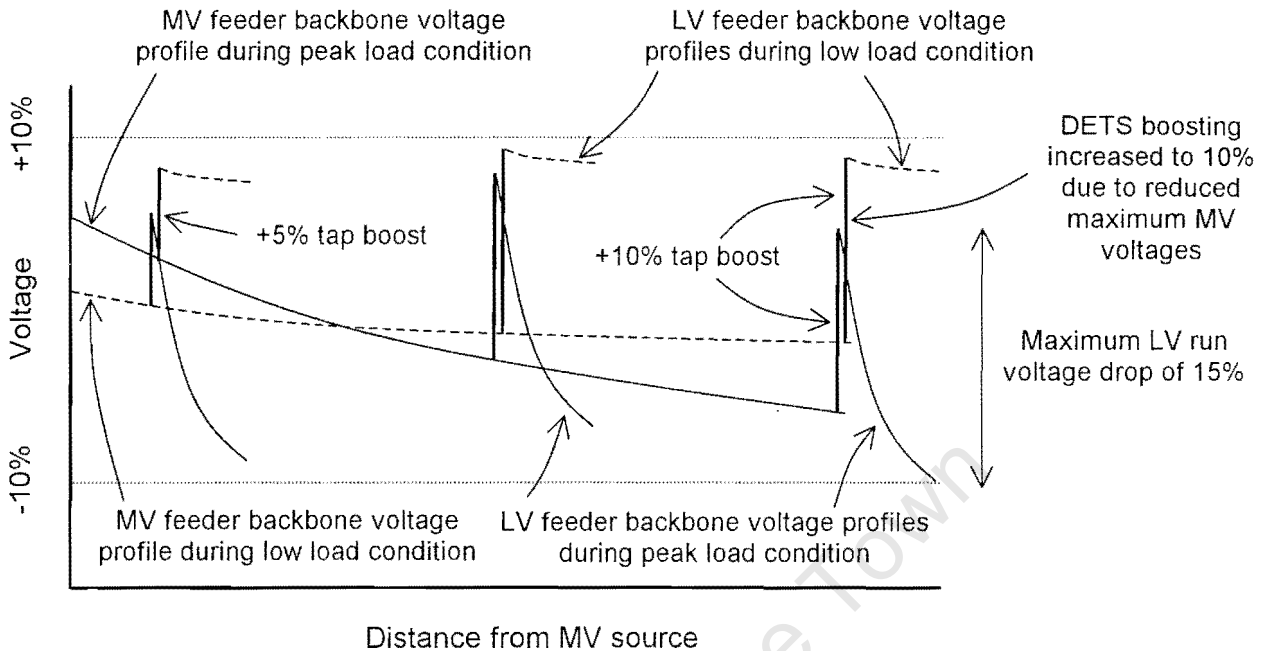


Figure 2.6.7.2: Illustration of increased DETS tap boosting using voltage compounding or line drop compensation voltage control techniques on the source MV voltage

2.6.7 Modern Voltage Control Relays

With the advent of modern microprocessor based voltage control relays many of the limitations associated with older electromechanical devices have been addressed. Various progressive voltage control methodologies can be applied using standard voltage control relays without associated risks such as definite time delays during over voltage conditions and sustained over voltages due to abnormal load peaks. In addition the use of circulating current schemes enable MV networks to be paralleled. In short modern processing power is facilitating the application of more progressive voltage control methodologies such as LDC [42]. As the additional functionality is typically software based, it is provided as part of the standard voltage control relay functionality (at little or no additional cost).

2.7 VOLTAGE REGULATION LIMITS AND APPORTIONMENT

Reliability and economic issues aside, the key objective of the distribution system is to provide customers with power at voltage levels for which appliances and equipment will operate with acceptable levels of performance and efficiency. As documented in section 2.1.5, the primary MV distribution system and secondary LV service levels need to operate together to provide adequate supply voltages to all customers. Customers taking supply at the LV service level experience the combined effect of the voltage drops in both the MV and LV systems as the distribution transformers are operated with fixed taps.

For any utility the following will apply:

Utilisation voltages: These are the rated voltages and voltages ranges for which appliances and equipment must be designed to operate satisfactorily. The voltages at the appliance itself should not fall outside of these limits. These limits are standardised nationally, and usually fall in line with internationally acceptable values due to the requirement to be able to use the same appliances in different countries.

Service voltages: These are the rated voltages and voltage ranges at which supply is provided to a customer and is usually the point of load metering for billing purposes. These values are usually contracted with the customer, and default values are standardised nationally. Practices between countries can vary considerably even if the same utilisation voltage level and range are being used.

Customer internal voltage drop: The service voltages ranges are narrower than utilisation ranges to cater for the voltage drop in the customers electrical system between the point of supply and end appliance. Based on the standardised utilisation and service levels the maximum value for the customers internal voltage drop is standardised nationally, but could and does vary between countries.

In the United States the utilisation and service voltage levels and ranges are specified in the ANSI C84.1-1995 [7]. An extract of representative MV and LV voltage is included in table 2.7.1 below.

Voltage Level	Maximum Service and Utilisation levels		Minimum Service level		Minimum Utilisation level		Customer Internal Wiring	
	Range A	Range B	Range A	Range B	Range A	Range B	Range A	Range B
LV (110V)	105.0%	105.8%	95.0%	91.6%	91.7%	88.3%	3.3%	3.3%
MV (13.8kV)	105.0%	105.2%	97.5%	95.0%	90.0%	86.1%	7.5%	8.9%
MV (23kV)	105.0%	105.8%	97.5%	95.0%	*	*	*	*
MV (34.5kV)	105.0%	105.8%	97.5%	95.0%	*	*	*	*

Table 2.7.1: Standard nominal system voltage ranges for American electrical power system (ANSI C84.1-1995) [7]. * Utilisation equipment does not generally operate directly at these voltage levels

The main observations for the United States standard are:

- It provides for two voltage ranges. Range A values are for normal network conditions, and all appliances should be designed to give fully satisfactory performance throughout this range. Range B values apply to abnormal network states, and appliances should be able to operate (albeit with reduced performance levels or efficiency) or self protect themselves from damage. The standard is not specific on the allowable duration of Range B operation.
- The LV utilisation voltage is +5% -8.3% (13.3%) for Range A, and +5.8% -11.7% (17.5%) for Range B
- The MV utilisation voltage (where applicable) is +5% -10% (15%) for Range A, and +5.2% -13.9% (19.1%) for Range B
- The LV service voltage level is +5% -5% (10%) for Range A, and +5.8% - 8.4% (14.2%) for Range B
- The MV service voltage level is +5% -2.5% (7.5%) for Range A, and +5.8% - 5% (10.8%) for Range B
- The LV and MV customer internal wiring maximum voltage drops are 3.3% and 7.5% respectively

In South Africa there is no standardised voltage range for abnormal system conditions. While the assessment methodology specified by the NRS048 [79] does disregard the worst 5% voltage variations over a 24 hour period, only one compatibility level is provided against which voltage variations are assessed. If an abnormal network condition persists for more than 5% of a 24 hour period (i.e. > 72 minutes) then the voltage during this abnormal network condition will be the assessed voltage level if the minimum voltage occurs during the abnormal network state. This is discussed further in section 3.1.2.

The most recent specifications for normal system conditions are summarised in table 2.7.2 below. Additional detail including the historical nominal voltages and ranges is provided in section 3.1.

Voltage Level	Maximum Service and Utilisation levels	Minimum Service level	Minimum Utilisation level	Customer Internal Wiring
LV (230V)	110%	90%	85%	5%
MV (11kV)	105%	95%	*	*
MV (22, 33kV)	105%	95%	*	*

Table 2.7.2: Standard nominal system voltage ranges for new supplies in South African electrical networks [43, 44, 45].

* Utilisation and maximum customer internal voltage drops are not specified at MV. Only the MV service level is specified, and for bulk MV supplies the customer must ensure that their internal voltage drop is acceptable for the equipment they are using [46]. The minimum utilisation level of 85% for LV supplies is calculated as the minimum service level minus the maximum allowable customer internal wiring voltage drop i.e. $90\% - 5\% = 85\%$.

The main observations for the most recent South African standard are:

- The LV utilisation and service voltages are +10% -85% (25%) and +10% -10% (20%) respectively.
- The standard MV service voltage is +5% -5% (10%).
- The maximum LV customer internal wiring voltage drop is 5%.
- As most domestic appliances will work at -20% of nominal voltage, the service voltage can drop to 85% for short term abnormal operating conditions, but this is not an official standard [47]. Note that due to the assessment methodology, the service voltage could drop to 80% for short periods of time, and still comply with NRS048.

The allowable voltage drops and optimal apportionment between the MV and LV systems are dependent on the above standards, and the nature and density of the load being supplied. Practices can and do vary considerably between utilities and even within utilities depending on the types of networks.

The United States practice of using 120V LV service voltage will influence the optimal apportionment between MV and LV voltage regulation as compared with the South African standard of 230V. The following summary table of the apportionment practices of the MV and LV voltage drops of 10 utilities in the United States does give an indication of the large variations in the practices in the United States (even though the utilisation and service level voltages and ranges are standardised).

Utility	Service area type	Max MV	Min MV	MV Range	MV to Service
1	Dense urban area	105.8%	100.0%	5.8%	5.0%
2	Dense urban area	105.0%	97.5%	7.5%	2.5%
3	Urban/suburban	105.0%	95.0%	10.0%	0.0%
4	Urban/suburban	104.2%	95.8%	8.3%	0.8%
5	Urban	105.8%	102.5%	3.3%	7.5%
	Rural	105.8%	99.2%	6.7%	4.2%
6	Suburban and rural	104.2%	94.2%	10.0%	-0.8%
7	Urban	104.2%	96.7%	7.5%	1.7%
	Rural	105.8%	93.3%	12.5%	-1.7%
8	Urban and rural	105.8%	95.8%	10.0%	0.8%
9	Rural, mountainous	105.0%	96.7%	8.3%	1.7%
10	Rural, mountainous	105.8%	94.2%	11.7%	-0.8%

Table 2.7.3: Medium voltage design standards for 10 utilities in the United States [2]

MV voltage regulation ranges varies from 3.3% for dense load areas, through to 12.5% for rural areas where load densities are very low and distribution transformers will be located very close to the load they are supplying. The resultant allowable voltage drop over the distribution transformer and LV network to the service points (customer meters) is given by "MV to Service", and vary from a maximum of 7.5% to a minimum of -1.7%. These "MV to service" values do not take into consideration the boosting of the DETS taps on the distribution transformers, and as such some of the values are negative (with the transformer boost setting they will be positive, but small values).

Eskom Distribution does not have a voltage apportionment standard, and practices vary considerably between Distribution Regions, with some allowing an MV voltage drop of 11.5% while others are far more restrictive and limit MV regulation to 7% (see section 4).

The French utility EDF have historically used a regulation apportionment of 11% for the LV and 7.5% for the MV, with the MV regulation allowed to increase to 14% during contingencies [17].

2.8 OPTIMISATION TECHNIQUES FOR SIZING AND DESIGNING ELECTRICAL NETWORKS

The distribution system provides the delivery of an electric utility's product, electric energy, to customer sites. While the equipment used to perform this function is individually straightforward, most distribution systems are quite complex due to the interactions of literally thousands of these interconnected elements.

While the initial capital cost of a Distribution system is of prime importance, it in many cases only accounts for less than half of the total life cycle cost [2]. Other associated costs that should be considered during the planning and design stages include:

- **Maintenance costs:** While these costs will be influenced by the quality of the equipment used, more expensive systems (due to for example providing redundancy via ring feeds) generally require increased maintenance. For the purposes of network planning the common practice is to assume that the maintenance costs are fixed as a percentage of the capital cost of the system, with a figure of 1.5% per annum used in one optimisation technique [48].
- **Reliability costs:** These are the costs associated with the inconvenience to customers and the loss of revenue due to outages, and will be influenced by the configuration of

the distribution system (radial, ring etc.) and the exposure to faults (typically related to the lengths of the networks below protection devices).

- **Technical losses costs:** While technical losses are typically below 8% of the total power supplied to customers, the life cycle costs of generating and delivering this wasted energy are extremely significant. In certain cases these losses costs can exceed the capital costs of the system [2]. Where systems have been designed and extended without due regard for the costs associated with technical losses, the technical losses can reach high levels, and a figure of 21% is quoted for the Indian transmission and distribution systems in 1984 [49].

The initial capital costs and their associated life cycle costs are heavily influenced by the interactions between the various levels of the distribution system, namely sub-transmission, primary distribution feeders (MV systems) and secondary service levels (LV systems). The choice of the optimal network layout, technologies, voltage levels, and conductor and transformer sizes is extremely complicated. This difficult problem is further complicated by the nature of the growth in developing areas. Customers do not all arrive at the same time and they seldom draw their final saturated loads in the initial year of their connection to the grid. There is always risk associated with load growth, and this in many cases necessitates a phased development whereby initial systems are reinforced to delay capital expenditure. A previously undeveloped area may evolve from a rural area into an urban area, and the distribution system needs to evolve as the needs of the area change. This may require the initial use of long MV feeders, which with additional sub-transmission overlays are reduced to medium and then ultimately short MV feeders providing increased power transformer capabilities with improved reliability [50]. The time phasing of capital expenditure is a critical variable in the optimising of distribution systems.

At this stage the distinction between network planning and design needs to be drawn. Network planning typically has a medium to longer term focus, and aims to provide network capacity in an optimal manner via the selection of the appropriate major network attributes such as voltage levels, technologies and backbone conductor sizes. Network planning activities should aim to achieve the near optimal relationships between the different levels of the electrical system (sub-transmission, MV distribution, and LV service). Due to the level of uncertainty regarding the location, magnitude and characteristics of the loads to be supplied, network-planning decisions often need to be made with very limited data.

Network design on the other hand typically involves the detailed sizing and routing of lines and transformers where the voltage levels and technologies are given quantities (e.g. 11kV three phase) and the actual physical location and energy requirements of the customers (both existing and new) are relatively well defined.

As a result network design optimisation typically involves evaluating the costs associated with a range of options which meet requirements for voltage regulation and thermal loading. Techniques utilising dynamic programming and least cost state transition have been established [51, 52, 53], and basically determine the preferred alternative by consideration of all of the permutations. The optimisation algorithms simply aim to reduce the number of iterations required to determine the optimal solution. While suitable for network design, the data requirements are too extensive to apply to network planning studies.

While many techniques look at optimising the design of networks within a network level (e.g. service or primary MV) the optimal interaction between levels (which should be a major focus of network planning) is generally overlooked. Most approaches only aim to minimise life cycle costs while keeping customer voltages within existing limits. The costs due to potential loss of revenue and customer dissatisfaction due to less than perfect

voltage regulation are generally not included. Only one of the researched optimisation techniques (the French Utility EDF investigations into voltage quality and regulation [17]) looked to put a cost to the voltage regulation magnitude seen by the customers.

2.8 SUMMARY

Voltage regulation limits and apportionment affect, and are in turn affected by, a host of parameters ranging from equipment specifications and distribution technologies, to less tangible factors such as life cycle costs due to technical losses and energy consumption. While utilities aim to keep customer voltages within acceptable limits, practices vary considerably.

The distances over which electrical power can be transported by power lines and cables are influenced by conductor sizes, voltage levels, technologies and voltage regulation limits. When due consideration is given for the cost of technical losses, each conductor has a particular loading range within which it will provide optimal power transfer for a given technology and voltage level. Increasing voltage regulation limits enables a conductor to transport the same load over greater distances, and reduced nominal voltage levels are required to economically reticulate an area.

The voltage regulation in a network is not only effected by the physical nature of the equipment (lines, transformers etc.), but also by the nature of the voltage control utilised for that particular network. Optimising voltage control methodologies and settings can reduce voltage regulation levels, resulting in increased network capacity in networks that are limited by voltage drop constraints.

Decisions regarding one part of the distribution network in turn effect other parts. No single approach is necessarily better than another. A wide range of parameters, some of which will fall outside of the planner's sphere of influence, will influence the optimal solution.

3 FACTORS INFLUENCING PRACTICAL VOLTAGE LIMITS IN ESKOM'S DISTRIBUTION NETWORKS

This section builds on the basic principles documented in section 2, and looks at the practical issues and implications of voltage drops and voltage regulation in Eskom's distribution networks. The present and historical voltage levels and regulation requirements are documented, along with how these requirements have influenced equipment specifications and voltage regulation limits in both MV and LV networks.

The major components of a typical distribution network are illustrated in the simplified diagram below.

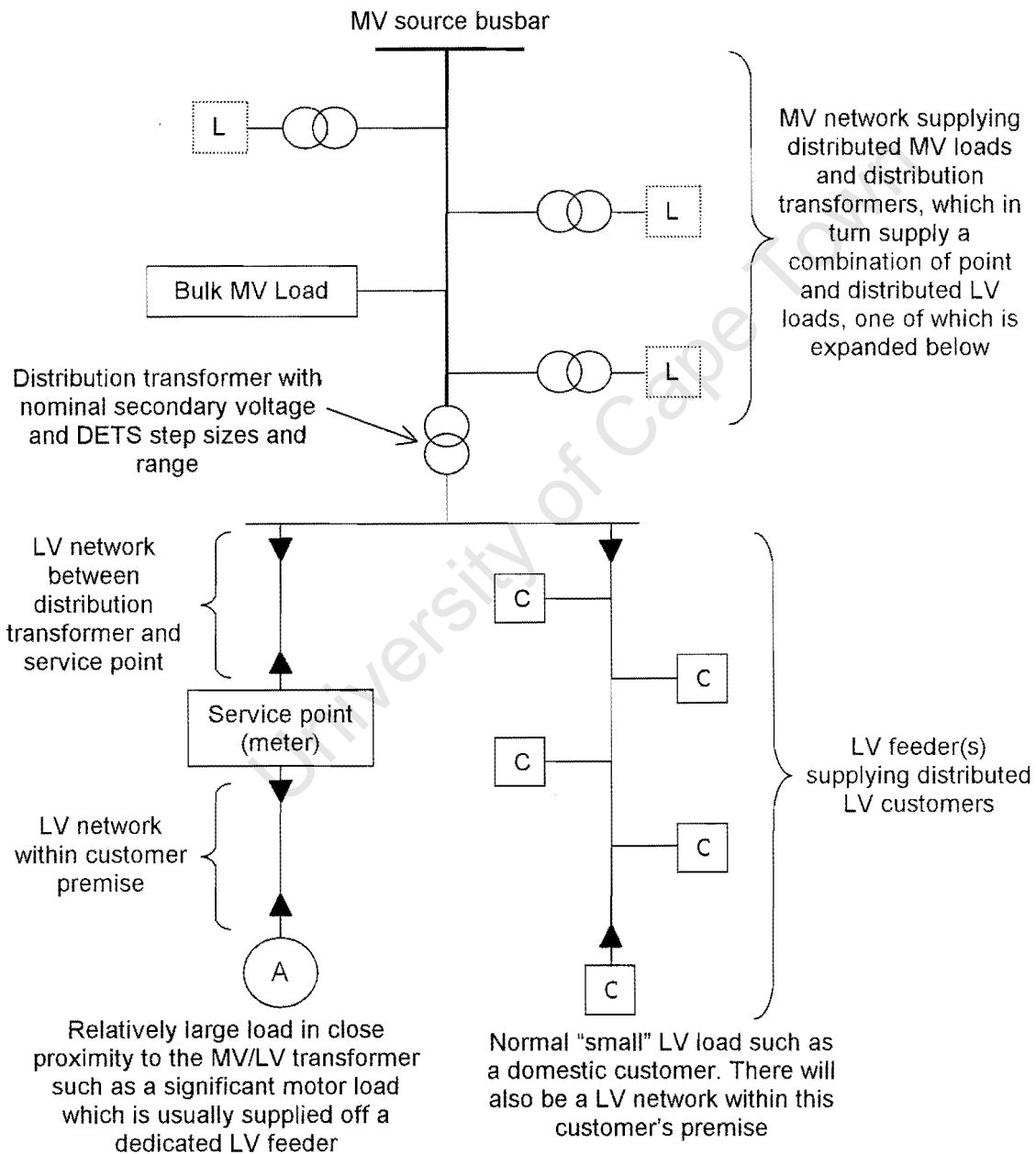


Figure 3.1: Simplified representation of the major components in a typical MV/LV distribution system supplying distributed MV and LV loads

3.1 SOUTH AFRICAN SERVICE VOLTAGE LEVELS AND REGULATION RANGES

3.1.1 Historical and Present Voltage Levels and Regulation Ranges

This section describes how the South African Electricity Regulation has changed over the last 12 years and is based on references [43, 44]. It covers Eskom Distribution's historical service voltage ranges and associated distribution transformer specifications. The service voltage ranges and associated equipment specifications are Eskom distribution specific, and may have varied significantly for other supply authorities such as municipalities.

Prior to 1990:

- The standard nominal LV service voltage was 380/220V with an allowable variation of $\pm 5\%$. Some municipalities (such as Pretoria) however operated 440/250V systems.
- Single phase distribution transformers had nominal secondary voltages of 220V, and DETS tap settings of -5% , 0 and $+5\%$
- Three phase distribution transformers had nominal secondary voltages of 380V, and DETS tap settings of -5% , -2.5% , 0, $+2.5\%$ and $+5\%$
- While the regulatory standard allowed for a service voltage variation of $\pm 5\%$, Eskom contracted at $\pm 7.5\%$ for both MV and LV customers

1990, the Regulation is amended:

- The standard nominal LV service voltage was changed to 400/230V with the allowable variation increased to $\pm 6\%$. The change in nominal voltage was only effective for new supplies, and all LV supplies after 2004. This was to fall in line with international trends to standardise on a 400/230V LV service voltage, see IEC 38 [31].
- For existing LV supplies where the contracted voltage was $< 400/230V$ (e.g. existing 380/220V supplies), the new nominal voltage and range was changed to 400/230V $+6\%$ -10%
- For existing LV supplies where the contracted voltage was $> 400/230V$, (e.g. existing 440/250V supplies) the new nominal voltage and range was changed to 400/230V $+10\%$ -6%
- This resulted in all LV supplies being changed to a nominal service voltage of 400/230V, but with different allowable ranges depending on their previous contracted values
- In the absence of any agreement to the contrary the voltage variation for MV service voltages is $\pm 5\%$. As Eskom customers were and still are contracted at $\pm 7.5\%$, the existing contracts for MV customers still hold. New customers can take supply with the allowable variation of $\pm 5\%$, but this is open to negotiation between the utility and the customer, and the Eskom default contract value remains at $\pm 7.5\%$ [54].
- The distribution transformer specification was changed such that single phase distribution transformers had nominal secondary voltages of 230V, and DETS tap settings of -5% , 0 and $+5\%$ on the new 230V base
- Three phase distribution transformers were changed to have nominal secondary voltages of 400V, and DETS tap settings of -5% , -2.5% , 0, $+2.5\%$ and $+5\%$ on the new 400V base

1996, the Regulation is amended and is still in this form:

- In order to cater for increased LV voltage drop in new domestic electrification projects and further align with the IEC 38 [31], the standard nominal LV service voltage was kept unchanged at 400/230V but the allowable variation was increased to $\pm 10\%$.

- For LV supplies <500V the Regulation states that the standard voltage shall be 400/230V, with an allowable voltage variation of $\pm 10\%$. The Regulation does not however make any mention of the validity of existing agreements/contracts as with MV supplies i.e. it does not clearly state that the standard voltage and voltage variation of 400/230V and $\pm 10\%$ respectively supersede existing contracts for voltages <500V. The validity of the existing 380/220V contract is hence open to interpretation, and Eskom's obligation to enforce these older contracts is debatable. With regards to Regulation 9 of the Electricity Regulation there are two basic interpretations as regards the validity of 400/230V $\pm 7.5\%$ and 380/220V $\pm 7.5\%$ contracts:
 - 1) The contract is invalidated / superseded: Eskom have no obligation to enforce the original contracted nominal voltage and voltage variation, and the standard voltage and voltage variation is 400/230V and $\pm 10\%$ respectively.
 - 2) The contract holds where it does not conflict with the Regulation: According to the Electricity Regulation, 9(2)(a), the voltage delivered to the customer's LV terminals must be 400/230V with a deviation of less than 10%, i.e. between 360/207V and 440/253V. The Regulation does not state that a smaller deviation can not be contracted with the customer, and hence in the case of a customer having a specific contract, those conditions hold where they do not conflict with the Regulation. The above means that for a customer who has a contract of 380V $\pm 7.5\%$, the supplied voltage must be held between 360/207V and 408.5/235.9V i.e. 400/230V $-10\% +2.1\%$.
- For existing supplies that do not have contracts (many municipalities don't have special contracts in place with their customer agreements are established by bylaws), the new 400/230V nominal voltage and $\pm 10\%$ regulation range apply. Older 380/220V requirements fall away completely in the absence of a 380/220V contract.
- The Regulation clearly states that for MV supplies existing contracts still hold, and provides a default voltage variation of $\pm 5\%$ from the declared or agreed voltage if no such agreement exists. In the event of a conflict the Regulation does not take preference over existing contracts.
- In order to enable sufficient LV boosting such that the $+10\%$ LV range can be utilised the distribution transformer specification was changed such that single phase distribution transformers have nominal secondary voltages of 240V, and DETS tap settings of -5% , 0 and $+5\%$ on the 240V base
- Three phase distribution transformers were changed to have nominal secondary voltages of 415V, and DETS tap settings of -6% , -3% , 0, $+3\%$ and $+6\%$ on the 415V base

When establishing voltage regulation limits the probability of and risks associated with, not meeting these contractual and licence obligations needs to be assessed. As legislation may over rule existing contracts, and the intent of 1996 the amendment to the Electricity Regulation was to standardise on a 400/230V $\pm 10\%$ LV voltage, the validity of 380/220V contracts is very questionable. Eskom could take the stand that these contracts have been superseded by the amendments to the Regulation and hence no longer need to be enforced. It is not the intent of this research to take a particular stand on this matter and for the purposes of this research the requirements and effects of complying with 380/220V contracts have been included. The recommendations could however be further refined / simplified to take into account the possible Eskom stance that 380/220V contracts will not be honoured.

The changes in the electricity Regulation has resulted in a range of equipment, such as distribution transformers, and LV appliances designed for significantly different nominal voltage levels and variations around these voltage levels. Any voltage apportionment

standard needs to be able to cater for the likely combinations of this equipment and appliances.

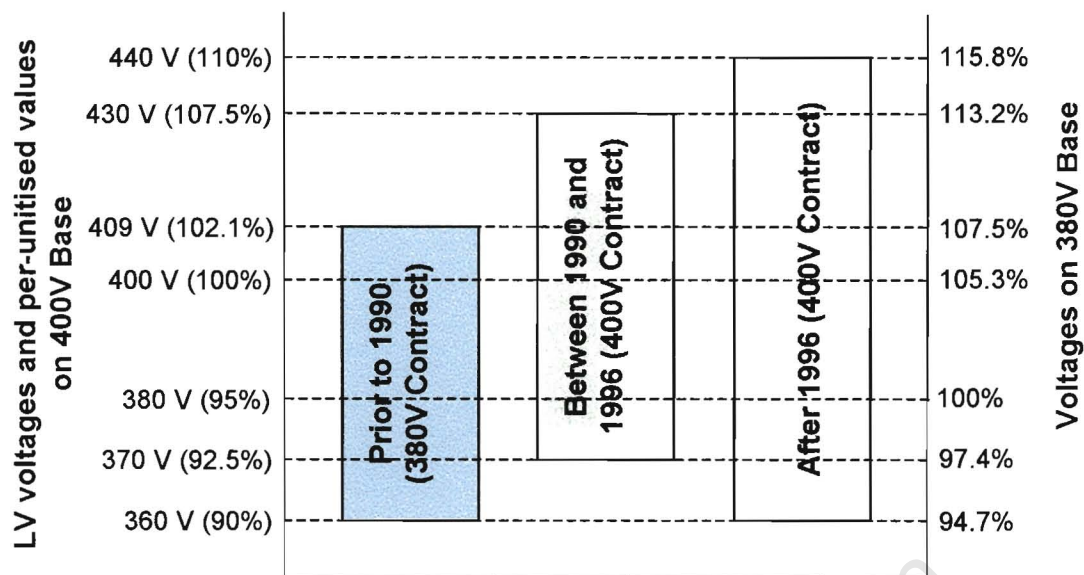


Figure 3.1.1.1: Graphical representation of present day contractual and licence requirements for allowable voltage deviations for existing Eskom customers. Customers in municipalities which don't have contracted nominal voltages and regulation ranges default to the "After 1996" 400/230V $\pm 10\%$ values.

3.1.2 Assessment of Voltage Regulation (NRS 048)

The requirements for the compliance with regulatory standards for voltage regulation are specified in the NRS 048 [79]. The NRS 048 uses the concept of determining an assessed level of voltage regulation based on a statistical adjustment of the measured values. The assessed level is then compared with the compatibility level (which is the required minimum standard). The compatibility levels supported by the NRS 048 are the maximum voltage variations as specified by the 1996 amendment to the Electricity Regulation (see table 3.2.1.2).

Voltage level [V]	Compatibility level [%]
< 500	± 10
≥ 500	± 5

NOTE – For nominal system voltages above 500 V, in the absence of any agreement to the contrary, the supply voltage shall not deviate from the declared voltage or agreed voltage by more than 5 % for any period longer than 10 consecutive minutes.

Table 3.1.2.1: Maximum deviation from standard or declared voltages, Table 4 in NRS 048-2:1996 [79].

The method in which the assessed level is calculated from the measured data is described in the following extract from the NRS 048.

"The assessment period is a minimum of 7 continuous days.

On each phase of the supply voltage, for each 24 h day (00:00 to 24:00) the highest 10 min root-mean-square values of the supply voltage within which the voltage remains for 95 % of the time are recorded for each phase and the highest of these is retained as a daily value.

Similarly, the lowest 10 min root-mean-square values of the supply voltage within which the voltage remains for 95% of the time are recorded for each phase and the lowest of these is retained as a daily value.

The assessed levels which are to be compared with the compatibility levels are the highest and lowest daily values over the full assessment period.” [79]

Based on the assessment method, the 10 minute rms voltages at a point of supply can drop below the compatibility level and still comply with the NRS 048 provided these “low” voltage conditions are limited to less than 5% of the day i.e less than 72 minutes a day. This has significant implications, especially with very peaky loads such as domestic, and specifically electrification loads.

The NRS 048 supports the concept of the utilisation of planning levels that are more restrictive (less voltage regulation) than the compatibility levels. The NRS 048 does not specify what the planning levels should be, but rather states that the planning levels should take into consideration *“the confidence the utility has in the data available for planning, and the type of equipment utilised by customers” [79].*

3.2 APPLIANCE VOLTAGE OPERATING RANGES

The permissible voltage variations for customer equipment vary depending on the nature of the device and the types of applications and surroundings in which it will typically be used. Prior to 1990 the South African Electricity Regulation specified an LV service level variation of $\pm 5\%$, which when combined with the maximum permissible LV voltage drop in the customer premise of 5% resulted in a maximum appliance utilisation voltage range of $+5\%$ - 10% . Most appliances would however provide satisfactory operation at wider levels of voltage variation. Provided the customer voltage drops were relatively small, this practice enabled the voltage variations at motors to be kept close to within the $\pm 5\%$ variation specified by the SABS1804 [55].

In order to facilitate the electrification of LV domestic customers in peri-urban and rural areas, the South African LV service level variation was increased to $\pm 10\%$ in 1996. This relaxing of the allowable LV voltage variation was not intended for use with significant (three phase) motor loads, and the SABS1804 allowable voltage variations for motors remains at $\pm 5\%$, but may be increased to $\pm 10\%$ in the future (see section 3.2.2.1).

In short the voltage regulation requirements for more industrial types loads such as three phase motors are different to domestic type appliances, and the regulation requirements of these two major appliance classifications must be differentiated.

3.2.1 Typical Domestic Loads

While there is an associated reduction in performance and efficiency, South African domestic type appliances will provide satisfactory performance for a voltage regulation range of $\pm 10\%$. In fact most domestic appliances will work at -20% of nominal voltage, but this should not be a long term operating condition [47].

While considerable research and experimentation on the voltage dependent performance of typical domestic appliances has been performed, the simple conclusion is that provided the service voltage level is kept within $\pm 10\%$, for reasonable premise wiring practices in

accordance with SABS 0142, South African domestic appliances should provide satisfactory operation.

3.2.2 Motors

As the torque generated by induction motors is generally proportional to the square of the applied voltage, and efficiencies and insulation life span are also closely linked to voltage regulation, motors are very sensitive to voltage variations. Ensuring that motor operating voltages are within acceptable limits will adequately provide for the voltage regulation requirements of other load types.

3.2.2.1 Three phase motors

Motors are designed to meet the SABS1804 [55] specification, which refers to the IEC 60034 [56] standard for motor ratings and performance. The IEC 60034 classifies voltage and frequency variations from rated quantities as being either zone A or zone B. In the case of Eskom distribution systems where frequency variations are very small, zone A voltage variations are limited at $\pm 5\%$, and zone B at $\pm 10\%$. For both zone A and zone B voltage variations the motor should still be able to perform its primary function, which is to supply rated torque. The motor should be able to operate continuously at the zone A limits (voltage variation of $\pm 5\%$ for no frequency variation), but need not comply with the performance and temperature rises specifications at rated voltage and frequency. i.e. efficiency and life span may be compromised but will not typically be significant. The motor can be operated at the zone B limits (voltage variation of $\pm 10\%$ for no frequency variation), but "*Extended operation at the perimeter of zone B is not recommended*" [56].

Based on the IEC 60034, the SABS1804 states that "*In the past, motors have been designed to operate with a $\pm 5\%$ voltage variation, with occasional short periods at $\pm 10\%$* " [55]. With reference to the change in the Electricity Regulation in 1996, SABS1804 goes on to state that "*This means that in future, motors will have to be designed for the $\pm 10\%$ variation*" [55]. It does not however state when this change will take place.

The effects of voltage regulation on three phase motors are developed further in section 5.1.

3.2.2.2 Single phase motors

With the recent drive to use single phase technologies such as phase to phase MV and Single Wire Earth Return (SWER) in distribution networks, a range of large (2.2kW to 22kW) single phase LV motors were developed locally in conjunction with Alstom [57]. These motors are designed with relatively high voltage variations in mind, and according to the supplier [57] can be continuously operated at $\pm 10\%$ without any significant loss of life.

Smaller (<2.2kW) single phase LV motors on the other hand are generally not as robust with regards to allowable voltage variations as manufacturers tend to keep core costs to a minimum in this highly competitive segment of the market [57].

3.3 LV DESIGN PRACTICES BETWEEN THE SERVICE POINT AND END APPLIANCE

The maximum voltage drop in a customer's premise between the LV service point (meter) and end use appliance is limited to 5% by the SABS 0142 [45]. All premises with LV wiring

should comply with this specification. This maximum voltage drop includes motor starting conditions. Given that the voltage drop during starting will generally be greater than the drop during normal motor running conditions, the running voltages will generally be significantly less than 5%. SABS 0198 states that "*The voltage drop on 600/1000V cables used to connect squirrel cage induction motors to direct on-line starters is normally limited to 2.5% at the normal full load current of the motor*" [46]. This is reinforced by the local South African Aberdare cable facts and figures book which also states that cables must be sized such that voltage drops in the customers premise during motor starting do not exceed 5% [58]. The Aberdare guide also uses basic calculation methods for voltage drop, which do not take into account that the current drawn by motors when starting has a poor power factor. The voltage drop during motor starting is not directly proportional to the running voltage drop due to the relatively low X/R ratios of LV cables. Sizing LV systems supplying motors started DOL using the methodology proposed in the Aberdare guide will typically result in running voltages in good agreement with the 2.5% drop recommended in SABS 0198.

Eskom's advisory service for farmers, AGRELEK, also provides tables and guides for use by the service agents when advising customers on LV network designs for new or extensions to existing supplies. The sizing of LV cables, and even intermediate voltage systems, takes the maximum 5% limit stipulated in the SABS 0142 into consideration [57, 58].

In summary, the voltage drop in the customer's premise between the service point and end appliance should always be less than 5% (including motor starting and distant loads such as centre pivots). In the case of motors started DOL the voltage drop during normal motor running conditions should be less than 2.5%.

3.4 ESKOM LV DESIGN PRACTICES AND VOLTAGE DROP APPORTIONMENT

While the previous section looked at practices between the service point and end appliance, this section provides a summary of Eskom's present LV design practices between the distribution transformer and service point. It also describes how LV design practices influence the voltage drop apportionment between the MV and LV systems.

3.4.1 Rural Areas Supplying Relatively Few (typically one) Customers Per Distribution Transformer

Prior to the advent of rural domestic electrification, due to the distances between customers in rural areas a customer was almost without exception supplied with a dedicated distribution transformer. This resulted in very small LV systems between the transformer and supply point. A group of customers could be supplied by a single transformer, but only if they were in close proximity to one another. The recommended cables sizes between the transformers and service points for these types of supplies typically results in a maximum voltage drop of 2.5% [59].

Due to the relatively small voltage drops between the distribution transformers and service points, the allowable MV regulation ranges are relatively large, and account for the historical minimum MV voltage of between 95% and 92.5% for rural networks (see section 4.2).

3.4.2 Medium to High Load Density Urban and Peri-Urban Electrification Areas

As documented in section 2.1.5, in higher load density areas it becomes economic and hence preferable to use the 400/230V LV service voltage to reticulate a relatively large numbers of LV customers via LV feeder networks supplied by relatively few "large" distribution transformers (typically in the range between 200kVA and 500kVA).

As the allowable voltage drop is the main limiting factor in the LV network design, the choice of the maximum permissible LV voltage drop is critical, and will in turn have a major impact on the allowable minimum voltage levels in the primary MV system.

While it would appear that a standard apportionment guide would be essential, there do not appear to be any Eskom standards for recommended practices. Several Eskom internal documents illustrate the high level merits of LDC [43], but do not specify actual recommended apportionment levels for different types of load densities, voltage control methodologies and networks.

Sources of typical apportionment levels for urban networks are the withdrawn SABS 0150 (Guidelines for the design of electricity distribution networks in residential townships) [61], an Eskom Electrification Planning Guide [62] and the NRS 034-1 [4]. The SABS 0150 guideline was published in 1983, and reflects the regulatory limitation at that point in time of a maximum $\pm 5\%$ voltage variation for LV supplies. The Eskom Electrification Planning Guide was produced in 1993, and is hence based on the Electricity Regulation and Eskom contracts at that time, which specified maximum voltage deviations from the nominal 230V voltage level of $\pm 6\%$ and $\pm 7.5\%$ respectively. The figures quoted in the NRS 034-1: 1993, are however based on the same nominal voltage of 230V, but with an allowable deviation of $\pm 10\%$.

Location	SABS 0150: 1983	Eskom, Electrification Planning Guide: 1993	NRS 034-1: 1999
MV source and feeder	2%	5.5%	6%
Distribution Transformer drop	2%	2%	2%
Distribution Transformer boost	Not given	-4%	0%
LV feeder	6%	6%	8%
LV service connection		1.5%	2%
Total	10%	11% (15% for no boosting)	18%

Table 3.4.2.1: Summary of typical voltage apportionment quoted in the SABS 0150 [61] Eskom Electrification Planning Guide [62], and the NRS 034-1 [4].

The values in the Eskom Electrification Planning Guide allowed for a 4% voltage boost via the use of transformers with 416V secondary voltages. Note that if it is assumed that the source MV busbar is operated at a fixed voltage (no LDC or Load Compounding), the maximum voltage regulation seen by the customer would be in the region of $11\% + 4\% = 15\%$, which is on the limit of the $\pm 7.5\%$ contracted value. The use of the 4% transformer boost does not reduce the magnitude of the voltage regulation range, but rather increases the LV voltage during all loading conditions. In order to keep the LV service voltages above 92.5% the source MV voltage would need to be operated at 103.5%. Note that the total voltage drop in the LV system is $6\% + 1.5\% = 7.5\%$ which corresponds with the $\pm 7.5\%$ contracted value.

The values in the NRS 034-1: 1999 do not cater for any distribution transformer boosting, and the total voltage regulation range of 18% is close to the maximum allowable variation

of 20%, with a small margin of reserve. This is consistent with the NRS 048, which recommends the use of planning levels that are more restrictive than their associated compatibility levels. Note that the total voltage drop in the LV system is $8\%+2\%=10\%$ which corresponds with the $\pm 10\%$ contracted value.

Based on conversations and feedback from local Eskom Engineering staff [63], three observations can be made:

- Eskom planners and designers involved in LV networks prior to the change to the Electricity Regulation in 1990 used to allow for a maximum LV drop of 5%, which corresponds with the SABS 0142 limit of 5% for the internal wiring of premises. The figure of 5% is also in close agreement with the example apportionment provided in SABS 0150. The use of a 5% LV voltage drop would also have enabled planners and designers to use the conductor selection tables in the SABS 0142. It is most likely that Eskom's LV networks designed prior to 1990 will be based on a 5% voltage drop limit, or close there to. Municipal utilities followed AMEU guidelines, which became SABS 0150, and LV voltage drop was typically 6% in these municipal networks [61].
- With the advent of modern computer voltage drop calculation software the need for conductor selection based on standard tables (such as those in the SABS 0142) became less of an issue. This combined with the amendment of the Electricity Regulation in 1990 may have resulted in many LV systems between 1990 and 1996 being designed based on a 7.5% voltage drop limit (this is supported by the typical apportionment given in the 1993 Eskom Electrification Planning Guide).
- The relaxing of the LV regulation limit to $\pm 10\%$ has resulted in a further increase in the allowable LV voltage drop to 10%. And it is likely that most LV networks designed after 1996 are based on a 10% voltage drop limit (this is supported by the typical apportionment given in the 1999 NRS 034-1).

3.4.3 Low Load Density Rural Electrification Areas

With the advent of rural domestic electrification the grid electrification of low density areas using relatively large LV transformer zones became a necessity. As these LV systems are critically limited by voltage regulation due to the very low load densities, the relatively low MV voltages found in rural networks (often less than 97%) resulted in costly LV designs. Using the first version of Electech, the effect and sensitivity of typical stand sizes and local MV supply voltage levels on the capital cost per connection was established [64].

LV voltage drop limit	Stand size: 1648 m ²		Stand size: 3846 m ²		Stand size: 7225 m ²	
	R / connection	R savings / connection	R / connection	R savings / connection	R / connection	R savings / connection
5.0%	R 1537		R 2100		R 2944	
7.5%	R 1402	R 135	R 1976	R 124	R 2592	R 352
10.0%	R 1366	R 171	R 1908	R 192	R 2466	R 478
12.5%	R 1336	R 201	R 1840	R 260	R 2428	R 516
15.0%	R 1305	R 232	R 1800	R 300	R 2359	R 585

Table 3.4.3.1: Anticipated LV connection costs and associated savings for various LV voltage drop limits as a function of stand size as provided by the original Electech model [64]. Costs are in year 1998 Rands.

The results in table 3.4.3.1 and figure 3.4.3.2 were provided to network planners such that the trade off between the cost of improving the MV voltage regulation and the cost of the associated LV could be optimised for each electrification project. This has resulted in customised MV voltage regulation limits, and hence voltage drop apportionment, for each

rural electrification project. As is evident from figure 3.4.3.2 below, the results from the first Electech model show that for relatively large stand sizes the resultant LV network cost increases significantly when the allowable LV voltage drop falls below 10%.

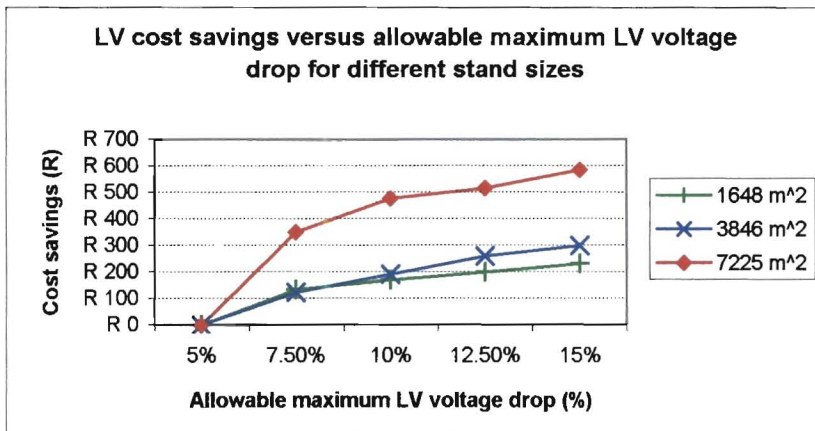


Figure 3.4.3.2: Graphical representation of table 3.4.3.1. Anticipated LV capital cost savings per connection for various maximum LV voltage drop constraints and stand sizes [64]. Costs are in year 1998 Rands.

If, for example, 1000 customers with an average stand size of 7225 m² were to be connected to the grid and the MV voltage improved such that the LV voltage drop limit could be increased from 5% to 10%, referring to table 3.4.3.1 above, a savings of 1000*R478=R478 000 could be achieved in the LV. This MV strengthening would only be cost effective if the MV system improvement can be achieved for less than R478 000.

This basic model has been the basis for voltage regulation apportionment between MV and LV networks in rural electrification projects since 1999. Note that it is purely based on capital costs, and does not take technical losses costs and energy consumption levels into account.

3.4.4 Electronic LV Voltage Regulation

Voltage drop is a major limitation, and hence cost factor, in LV networks in low load density areas. The use of electronic voltage regulators to boost low voltages and hence increase LV load reach was researched jointly by the University of Stellenbosch and Eskom [28]. After consideration of various combinations for the location of the voltage boosting, the research concluded that the most cost-effective approach is to perform single phase voltage regulation at the pole top boxes. While intermediate fuses would typically be required in the LV backbone, LV feeder lengths could be extended to up to 1900m for typical low-income domestic loads. While the cost of technical losses was not adequately addressed in the research, the use of these devices will have merit in certain applications. The research only considered the use of the electronic regulators to extend LV zones for traditional MV input voltages, and did not look at compensating for relatively low (<95%) MV voltages.

The practicality of introducing electronic voltage regulation equipment into rural systems will hamper its application, however it may have merit, especially when used as part of an upgrade strategy, or temporary solution until traditional strengthening can be performed.

3.5 TRANSFORMER OPERATING VOLTAGES

As documented in section 2.4.1, the MV insulation of, for example, a distribution transformer may be designed to be continuously operated at U_m i.e. 110% U_n , however the operating characteristics such as no-load losses, temperature rises and life-span will generally be specified against U_n . As a result, while the transformers may be capable of operating continuously at U_m , this can only be achieved at the expense of other attributes such as maximum loading levels. In the case of sub-transmission and distribution transformers designed to Eskom's present specifications, the maximum fluxing levels on these transformers may significantly restrict the maximum allowable system voltages, and this issue is researched further in section 5.2.

3.6 ESKOM'S RECOMMENDED MAXIMUM OPERATING VOLTAGES FOR DISTRIBUTION NETWORKS

Eskom Distribution have standardised that the maximum operating voltages for sub-transmission and reticulation (distribution) networks will be 104% and 105% of U_n respectively [65]. These limits are derived from the perceived acceptable fluxing levels for source sub-transmission transformers and do not take into account acceptable fluxing levels for distribution transformers, nor the contractual and appliance voltage regulation requirements for MV and LV customers. The limits only specify the maximum HV and MV system voltages, and do not provide recommended minimum HV or MV system voltages, nor is voltage apportionment between MV and LV systems covered.

3.7 ESKOM'S VOLTAGE CONTROL METHODOLOGY FOR DISTRIBUTION NETWORKS

With reference to sections 2.6.4 and 4.2, the Eskom Distribution practice is to perform substation busbar voltage control using OLTC mechanisms on the sub-transmission source transformers for substations supplying both urban and rural networks. In Eskom Distribution's "Central" Region the relatively high load densities result in predominately MV and LV cable networks, and voltage regulation is not usually a major constraint. Furthermore as the sub-transmission voltage regulation is typically less than 3%, sub-transmission transformers can be operated on fixed tap unless they are high impedance units [66].

The practice of utilising transformer OLTCs to regulate substation busbars has been entrenched by the comparatively high cost of multiple voltage regulators (imported from the United States) as compared with OLTC transformers (manufactured locally). However the possible cost savings in opting for individual feeder voltage regulation for rural networks have not been quantified in Eskom. Furthermore there is very limited application of load compensation of substation busbar voltages, and there is little or no optimisation of voltage control settings and distribution transformer DETS tap positions (see section 4.2).

Referring to sections 2.6.5 and 4.2, Eskom utilise a hybrid approach whereby voltage boosting is performed in both the MV and LV networks. The common practice is to use a fixed voltage control methodology and run the MV "sending" busbar voltage at a setpoint of 103% with a dead band of $\pm 1.2\%$ [67]. Newer Eskom distribution transformers have a fixed no-load boost of 240/230 i.e. 4.35% for single phase transformers, and 415/400 i.e. 3.75% for three phase units.

Eskom Distribution's recommended voltage control relay settings philosophy for OLTC tapchange schemes is documented in SCSASAAS4 [67], and the salient points are as follows:

- Typical bandwidths for HV/HV and sub-transmission HV/MV transformers are $\pm 1.4\%$ and $\pm 1.2\%$ respectively
- Typical initial time delays are 70 seconds for a 2.2% voltage variation for a HV/HV transformer, and 110 seconds for a 2.4% voltage variation for a HV/MV transformer
- The bandwidth and time delays are selected such that HV/HV transformers reacts first for any voltage change, but the HV/MV transformers keep their load side voltages within narrower limits. This is recommended due to that fact that most customers are supplied on the load side of HV/MV transformers
- The recommended maximum sending voltage at which a rapid step down operation is initiated is 110% of rated voltage

The above settings philosophy enables the upstream HV/HV transformers to first react to voltage variations in the HV system due to load changes. The downstream sub-transmission transformers react slightly slower, but control the voltage seen by the majority of the customers (supplied by the distribution system) in a slightly tighter band of allowable variation.

3.8 SUMMARY

The changes in the South African Electricity Regulation over the last 12 years have resulted in considerable variations in nominal service voltage levels and maximum voltage variations. Equipment specifications and network designs have been influenced by these changes. While most domestic appliances will operate satisfactorily in line with the 1996 change to 400/230V base and $\pm 10\%$ voltage variation, many three phase motors are still designed for a $\pm 5\%$ voltage variation. Many customers connected prior to 1990 have 380/220V $\pm 7.5\%$ contracts. Older 380/220V equipment operated by these customers may not be compatible with the present standard 400/230V $\pm 10\%$ service voltage.

The voltages at the customer's appliance are influenced by the voltage drops in both the utility's grid and customer's local network. The LV voltage drop within the customer's premise is limited by SABS 0142 to a maximum of 5%. Modern (post 1990) LV appliances should be able to operate within the voltage range of 400/230V +10% -15%.

Many LV networks in Eskom's urban areas have historically been designed for a 5% voltage drop. Since the post 1990 changes in the South African Electricity Regulation, LV networks in urban areas have typically been designed for a 7.5% to 10% voltage drop. There has however been no standardisation practice for these allowable LV voltage drops. In rural areas customers have historically been supplied by dedicated distribution transformers. In rural systems LV networks have been very limited, with no standardisation on the maximum LV voltage drops. With the advent of rural electrification significant LV systems have been designed in rural applications. In many cases the LV voltage drops in rural electrification areas have been customised on a per project basis, utilising a basic trade off analysis between MV and LV network capital costs.

4 PRESENT ESKOM DISTRIBUTION PLANNING PRACTICES AND ASSUMPTIONS

This section investigates Eskom's present distribution planning practices and assumptions, with specific emphasis on how these considerations influence voltage regulation.

4.1 ESKOM DISTRIBUTION PLANNING PRACTICES

As part of the network planning function, Eskom distribution network planning technicians and engineers are involved in the continual cycle of network evaluation and expansion planning. Network simulations are performed to identify network constraints and analyse solutions that will provide for a range of possible scenarios as dictated by network performance, refurbishment and load forecasts. At the heart of the simulations are loadflow and fault level studies. Special studies are performed as required and may include harmonic analysis, motor starting, voltage flicker, dynamics and stability. A very high level process flow is illustrated below.

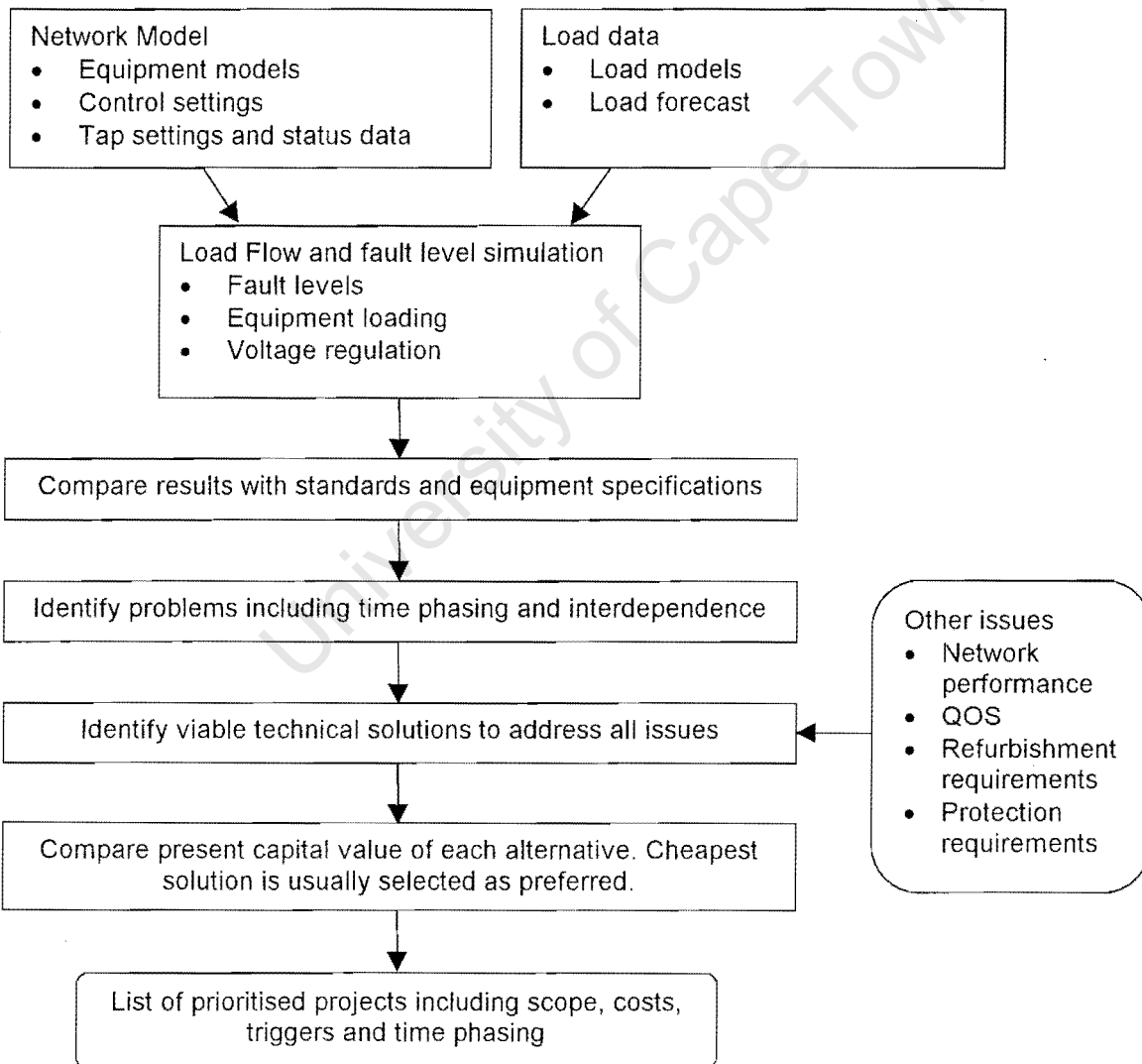


Figure 4.1: Process presently followed by Eskom network planners when planning distribution systems [68, 69]

The following shortfalls exist in the present practice:

- Issues such as network performance and QOS are generally of secondary importance and are not quantified or capitalised. The selection of the preferred alternative where network performance issues are perceived as having a major bearing is usually a subjective decision.
- Alternatives are selected on the basis of minimal capital cost without regard for life cycle costing. The cost of capital is factored into the decision process in that the savings in deferring capital expenditure are taken into account via the calculation of the present value of an inter-dependent group of time phased projects. Life cycle costs in the form of losses, maintenance and loss of revenue are not factored into the usual decision making process. With few exceptions, networks are not planned, designed and expanded with these life cycle costs in mind. Eskom expansion planning is presently largely driven by the requirement to keep capital expenditure to a minimum, and the true costs of decisions made in this environment still need to be quantified.
- The inter-dependence and relationships between the various system levels is generally not understood. The planner may not appreciate or understand the impact a decision may have on another area of the network or life cycle cost. This is heightened by the fact that different planners are usually responsible for the sub-transmission, distribution and service levels. This problem can be most effectively managed via staff training and the establishment of utility guidelines and standards that take these factors into account. Without suitable guidelines and standards the optimisation of the overall network cannot be achieved.
- Decisions are made without quantification of all of the associated costs and risks.

4.2 PRESENT ESKOM DISTRIBUTION NETWORK PLANNING ASSUMPTIONS FOR VOLTAGE CONTROL AND VOLTAGE REGULATION LIMITS

A survey of Eskom's present Distribution (reticulation) network planning and operating practices was conducted, with specific emphasis on voltage regulation. A questionnaire was compiled, and submitted to network planning representatives in each of Eskom's seven Distribution Regions. The completed questionnaires are included in appendix B and the results can be summarised as follows. Note that the questionnaire included more general planning issues, but only that part of the questionnaire directly targeting voltage regulation and apportionment issues has been included in appendix B.

- There is very limited (<5%) application of Line Drop Compensation (LDC) and Load Compensation (LC), and almost all tap-change voltage control relays are operated in a fixed voltage control mode.
- There is very little customisation of voltage control settings, and only one Distribution Region appears to have a process to cater for the optimisation / control of voltage control settings.
- Assumptions for the MV busbar sending voltage at peak vary from 102% to 104% between the Distribution Regions.
- Except for one Distribution Region, the planners assume that the peak and off-peak sending voltages are of the same magnitude, and the effect of the voltage control "window" is not being taken into consideration.
- In most Distribution Regions, for feeders supplying bulk MV customers the local MV supply voltage (end of line) is allowed to drop to 95%. Western Region allows the MV voltage to drop to 92.5%. Eastern Region will also allow the MV to drop to 92.5% in

rural networks, but only as a temporary measure until the required strengthening can be performed (typically less than 1 to 2 years). The resultant maximum MV voltage regulation range for Western Region is 104%-92.5%=11.5%, while most Distribution Regions will only permit a maximum MV regulation of 102%-95%=7%, a considerable difference between the Regions.

- The same minimum MV voltage limits (typically 95%) are generally used regardless of whether there are any bulk supplies on a network i.e. generally speaking the MV voltage is allowed to drop to the same level regardless of the type of customer and supplied voltage level.
- For bulk (MV) supplies planners are not differentiating between $\pm 5\%$ and $\pm 7.5\%$ contracts. The actual contracted value is only taken into consideration in special cases, and is not the norm. This information is not readily available.
- Planners are not differentiating between older 380V $\pm 7.5\%$ and 400V $\pm 10\%$ LV supply contracts. This information is not readily available, and is not being used to influence the allowable MV regulation range on a particular feeder.
- Network databases can not differentiate between 380/220V, 400/230V and 415/240V distribution transformers, and as a result the effect of different combinations of the above are not used to influence allowable MV regulation limits.
- In general the De-Energised Tap Switch (DETS) positions of distribution transformers are not known, and there are no systems and databases to adequately manage and capture this data. Southern Region use actual tap positions in urban network designs, while Western Region have established a voltage control process to standardise DETS tap positions for different transformers.
- Those Distribution Regions involved in significant rural electrification are optimising MV voltage regulation limits to reduce overall connection costs (trade off between MV and LV costs). However there are no suitable databases to capture these voltage regulation requirements against distribution transformers or electrification projects.
- Except for Southern Region, all the Distribution Regions indicated that electrification project design reports (containing the design parameters such as ADMD, MV supply voltage requirements etc) are not readily available, and in many cases can not be sourced at all.
- There does not appear to be any standard for allowable LV voltage regulation apportionment, and practices vary even within Distribution Regions i.e. one LV designer may limit the voltage drop in LV networks to say 10%, while another may assume a maximum limit of 5%.

4.3 SUMMARY

Eskom's present distribution planning practices are focused on minimising initial capital costs. MV and LV networks are designed in relative isolation leading to sub-optimisation. Apart from very simple capital discounting, life cycle costing analysis is not being performed. The least capital cost alternative is usually preferred, without due consideration for technical loss and reliability life cycle costs.

Distribution transformer DETS tap positions are not being managed or optimised. Planners, designers and system operators are not differentiating between different contractual obligations. The assumptions and design parameters used in both MV and LV networks planning and designing are not being suitably captured for future reference.

5 KEY FACTORS INFLUENCING VOLTAGE REGULATION LIMITS

In sections 2 and 3 limits for motor operating voltages and transformer fluxing levels were identified as key factors in establishing distribution network operating voltage limits, and are researched further in this section.

5.1 THREE PHASE MOTOR OPERATING VOLTAGES

With reference to section 3.2.2.1, three phase motors specified against SABS1804 are typically designed for a normal system voltage variation of $\pm 5\%$ at the motor terminals. This allowable voltage variation is far more restrictive than the standard $\pm 10\%$ service level variation for LV supplies (380V contracts aside) and as such needed to be investigated in further detail.

Three phase LV motors can be grouped into three broad categories [57]:

Small: <7.5kW
Medium: $\geq 7.5\text{kW}$ and $< 37\text{kW}$
Large: $\geq 37\text{kW}$ and $< 400\text{kW}$

The life span of a motor's insulation is a function of its temperature rise. The general rule of thumb is that the life span will roughly halve for every 10 degree rise in the insulation temperature [57]. The anticipated design life span of insulation that is continuously operated at its rated temperature is typically 20 years. Most manufacturers however design for a given insulation class, and then use one level higher, and this practice should result in an anticipated insulation life well in excess of 20 years [57].

Based on feedback [57], for small and medium LV motors operated continuously at rated output power, at rated ambient temperatures and altitude, and under ideal voltage waveforms (no unbalance, harmonics, dips, spikes etc), the anticipated life span as a function of supplied voltage variation will typically be:

- $\pm 0\%$ +20 years. If nominal voltage is applied the temperature rise will be the rated temperature rise, and as a higher class of insulation is generally used the life span should be greater than 20 years
- $\pm 5\%$ 20 years. If the supply deviates continuously by a maximum of $\pm 5\%$ the temperature rise will typically increase by 10degrees, with an associated halving of the insulation life. However due to the higher than minimum insulation used, the normal design life of 20 years should still be achieved.
- $\pm 10\%$ 10 to 20 years. If the supply deviates continuously by a maximum of $\pm 10\%$ the temperature rise will typically increase by 20degrees, with an associated quartering of the insulation life. However due to the higher than minimum insulation used, a design life of between 10 and 20 years should be achieved.

Due to the increased safety margins used in the design of larger ($> 30\text{kW}$) LV motors, the anticipated insulation life spans (as effected by voltage variations) will typically be slightly better (longer) than those for small and medium LV motors.

Note that the above life spans are based on continual operation at the associated voltage variations. In reality the supply voltage will vary with the network load cycle, and motors

may only experience the extreme voltage limits for relatively short periods of time (perhaps a few hours a day, or days a month).

With small and medium LV motors the core flux levels are relatively high compared with larger (>30kW) motors. As a result the losses and hence temperature rises in these small and medium motors are typically lower when operated at lower voltages as compared with correspondingly higher voltages. Larger LV motors are however typically designed with lower core flux levels, and the load losses are more significant. Given the choice, small and medium LV motors should be operated at lower rather than higher voltages, and visa versa for large LV motors [57].

The rule of thumb for motors delivering between 80% and 100% of rated power is that the temperature rise is proportional to the square of the output power [57]. A motor operating at 90% of rated power will typically experience a per unit temperature rise of 0.9² i.e. 0.81pu and this will typically double its insulation life. The size of the motor in relation to the magnitude of the load it is driving will have a major impact on the associated insulation life.

Any over sizing of a motor in relation to its anticipated power output requirement will provide increased insulation life which could be offset (utilised) by less than ideal operating voltage levels, voltage unbalance and harmonics. A brief telephonic survey of local motor and pump suppliers in Kwa-Zulu Natal established a typical sizing safety factor of 20%. The typical effect of voltage unbalance, supplied voltage variation, and motor sizing safety factors on the output torque and anticipated insulation life are tabled below.

Sizing Safety Factor	Voltage Unbalance	V=100% ±0%		V=100% ±5%		V=100% ±7.5%		V=100% ±10%				
		Torque	Life	Torque	Life	Torque	Life	Torque	Life			
0%	0%	100%	100%	110%	50%	116%	35%	121%	25%			
	2%		62%		90%		30%		86%	20%	14%	
	3.5%		14%				6%			3%	2%	
10%	0%	110%	287%	121%	164%	127%	123%	133%	93%			
	2%		196%		99%		107%		94%	78%	58%	
	3.5%		59%				28%			19%	13%	
20%	0%	120%	737%	132%	474%	139%	378%	145%	302%			
	2%		545%		108%		337%		103%	264%	97%	207%
	3.5%		211%				116%			86%	63%	
30%	0%	130%	1692%	143%	1206%	150%	1016%	157%	855%			
	2%		1343%		117%		930%		111%	772%	105%	641%
	3.5%		650%				412%			326%	258%	

Table 5.1.1: High level values for typical torque and insulation life for small and medium LV motors as a function of the applied voltage deviation and voltage unbalance level. Two values of torque are provided, the first is at the maximum voltage, and the second is at the minimum voltage.

Referring to table 5.1.1 above, a motor operated continuously at -7.5% of its rated voltage, and under a voltage unbalance of 2%, with a sizing safety factor of 20%, will produce a torque of 103% as compared with a motor sized with zero safety factor and rated applied voltage. In this case provided the calculations used to determine the torque requirement for the load are correct, no torque related problems should occur. The insulation life of the motor should exceed 264% as compared with a motor operated continuously at rated output power with rated applied voltage. Note, if the motor is operated continuously (100% load factor) 100% life span equates to 20 years or more due to the use of one level higher insulation class. In reality most motors in rural applications are only operated for a few hours a day, with large seasonal fluctuations. Duty cycles will very seldom exceed 50%, so in reality the normal insulation life of 20 years can typically be doubled. Applying this

assumed 50% duty cycle to the above example, 264% life span should result in over 100 years of insulation life. If the sizing safety factor for this example were 0%, the torque would reduce to 86% (which may cause problems), and the insulation life would reduce to 20% which with an assumed duty cycle of 50% equates to an estimated insulation life span of 16 years. As the temperature rise and hence insulation life is proportional to the square of the motor output, the reduction in motor insulation life due to increased or reduced supply voltages is very sensitive to the magnitude of the safety factor used in sizing the motor. This is graphically illustrated in figure 5.1.2 below. Note that table 5.1.1 is based on continual operation of the motor at the associated increased or reduced voltage level. In reality the average voltage will almost always fall closer to the rated voltage due to the periodic voltage fluctuations as a result of load variations in the electrical network. For the purposes of insulation ageing, while not quite so straight forward, the average voltage during motor operation will dictate its ageing and the above table needs to be viewed in light of this.

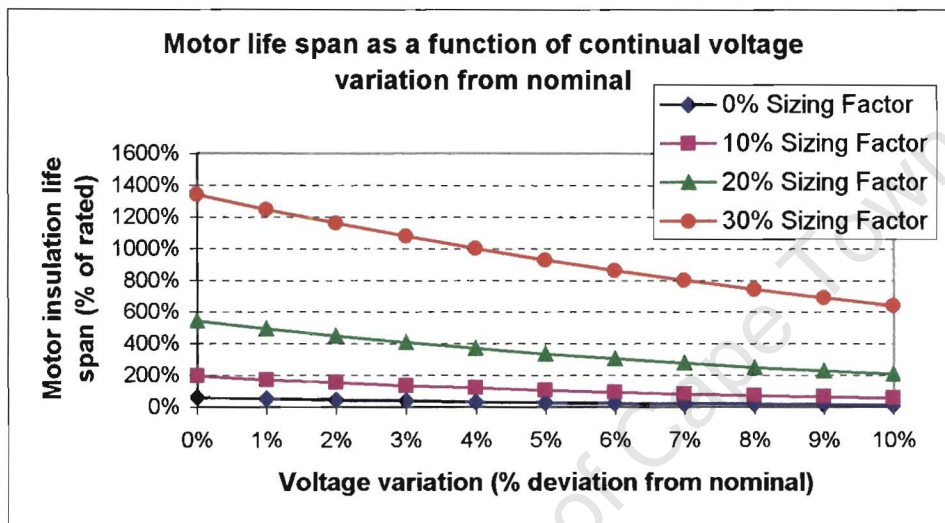


Figure 5.1.2: Motor insulation life span as a function of continual voltage variation from nominal for different motor sizing safety factor with a voltage unbalance level of 2%.

Based in the above table and discussions, the following recommendations for voltage regulation limits for LV three phase motors can be made.

- For large (>30kW) LV motors, distribution tap positions should be set to provide higher rather than lower supply voltages.
- For small and medium (<30kW) LV motors, distribution tap positions should be set to provide lower rather than higher supply voltages.
- Ideally networks should be designed to provide a maximum voltage deviation at the motor terminals of $\pm 5\%$. This will ensure that with a typical sizing safety factor of between 10% and 20% at least 20 years of insulation life should be achieved even if voltage unbalance levels are high (3.5%).
- In networks where there are a relatively large number of motors and motor duty cycles are high (such as in traditional commercial and industrial areas), the network should be planned such that a maximum voltage variation of $\pm 5\%$ at the motor terminals should be achievable. This could only be achieved if the voltage drops in the customer premise are reasonable (comply with recommended standards). In order to delay strengthening and provide for the necessary lead times associated with capital projects, this allowable variation can be temporarily increased to $\pm 7.5\%$. Customer complaints may occur if this

$\pm 7.5\%$ condition is allowed to persist for significant periods of time (typically months or years), and should only be allowed where there is a plan to strengthen the network.

- In rural networks where motor duty cycles are low (as is the case in many rural feeders supplying seasonal agricultural pumping load), where practical the network should be planned such that a maximum voltage variation of $\pm 7.5\%$ at the motor terminals should be achievable. The value will provide adequate (>20 year) insulation life for typical motor sizing safety factors and relatively high levels of voltage unbalance. Problems may occur with motors where the unbalance levels are significant ($\geq 2\%$), and the motor sizing safety factors are low (<10%). The $\pm 7.5\%$ value corresponds with the contracted regulation value for older LV supply contracts, hence its selection as compared with a value of say 7%. Where rural network strengthening costs are prohibitively expensive the allowable regulation range could be increased to $\pm 10\%$, but may result in customer complaints due to either high or low motor running voltages.

5.2 TRANSFORMER OPERATING VOLTAGES

Eskom Distribution's present recommended maximum system voltages are closely linked to perceived maximum recommended transformer fluxing levels, and as such the maximum fluxing levels of both sub-transmission and distribution transformers needed to be researched further.

5.2.1 Distribution Transformers

The ageing of paper insulation in oil filled transformers is dependent on the magnitude and duration of the internal temperature rise due to the load and no-load losses, in conjunction with the load duration and ambient temperature [70]. For a typical distribution transformer the ratio of the load to no-load losses is generally in the region of 4:1 [71]. Eskom's distribution transformers are designed to the SABS780 [71], which only places restrictions of the maximum no-load loss at rated voltage. When evaluating tenders for the purchase of new transformers Eskom Distribution capitalise the load and no-load losses such that different manufacturers can compete on an equal basis. While the loss values must still fall below the maximum figures specified in SABS780, the actual loss values may vary considerably between manufacturers. On the one hand a manufacturer may produce a low loss design (where the savings in losses offset the additional capital cost) while another may produce a relatively high loss design (where the core is operating close to saturation). For the higher loss design a slight increase in the applied voltage could result in a significant increase in no-load losses, resulting in increased life cycle costs and possibly even reduced transformer life. Typical per unitised core loss values as functions of the core flux are provided in table 2.3.2.1.

While the SABS780 does not specify maximum values of core losses at flux values above 1pu, it does refer to the IEC60076 which states that the transformer should be "*capable of continuous service without damage with 5% over voltage*" [72]. It however does not state that the transformer can supply rated power for this 1.05pu flux condition, as the power rating is specified against the nominal tap ratio for rated voltage i.e. 1pu flux. Furthermore the IEC60067 goes on to state that this "105% over voltage" should be reserved for "relatively rare cases". The specification to which Eskom Distribution's transformers are designed would hence require that the transformer be de-rated if it is to be operated at flux levels greater than 1pu with the design load profiles and ambient temperatures.

It has been a common distribution practice to operate MV busbars at voltages well in excess of 1pu, and typically the "sending" MV voltage setpoint is 103%, but may be as high as 105%. While it is difficult to quantify the failure mechanism of distribution transformers,

MV systems have been operating at these voltage levels (transformer flux of 1.03 to 1.05pu) for many years and there is no clear indication that fluxing levels are contributing to premature transformer failure [73].

With reference to table 2.3.2.1, if the transformer flux is increase to 1.05pu then the no-load losses typically increase by 15%. Given that the load loss is generally 4 times that of the no-load loss, the total transformer internal loss will only rise to $(1.15+4)/(1+4)=1.03$ pu i.e. increase by 3% if we assume that it is supplying rated load current. Comparatively a 5% increase in rated load current will result in a $1.05^2=1.1$ pu increase in the load losses, and the total transformer internal loss will rise to $(1+1.1*4)/(1+4)=1.08$ pu i.e. increase by 8%. The internal losses and hence transformer ageing is far more sensitive to increases in load current as compared with fluxing levels at flux levels below 1.05pu. Operating the transformer at a flux of 1.1pu will typically require that the no-load current be reduced to $\sqrt{(4+1-1.6)/4}=0.92$ pu i.e. 92% of rated load current. Note that this is a very simple approximation and does take into account the source of the heating (the physical locations and mechanisms of core and winding losses).

The above basic calculations are also conservative as they are based on the design parameters of constant load at rated ambient temperature. In reality while distribution transformers may be operated at flux levels in excess of 1pu during light load conditions, it is unlikely that these transformers will be drawing rated load during these light load periods. In addition the ambient temperatures will in almost all cases be lower than design values. Transformer loading is generally of far greater consequence, and the accepted practice is that distribution transformers can be safely operated at 1.05pu flux [74]. Appropriate care should be exercised if fluxing transformers above 1.05pu where there is a good probability of the local transformer load coinciding with this “high” flux level and high ambient temperature.

5.2.2 Sub-Transmission HV/MV “Large Power” Transformers

Eskom Distribution’s “large power” transformers up to 132kV, in the range of 2.5MVA to 80MVA, are used to transform the HV sub-transmission voltages to the local MV distribution voltages. These transformers are specified to the SCSSCAAD3 [29] which falls in line with SABS 1019 in that “*The system highest voltages (U_m) will be $1.1 U_n$, and “a maximum continuous overflux of 0.1pu”*. As with the SABS780 for distribution transformers, power ratings are based on rated voltage and principle tap position i.e. 1pu flux, and strictly speaking the transformer should be de-rated if operated at flux levels greater than 1pu. As with distribution transformers the internal losses will be more sensitive to variations in load current, and no temperature rise problems are anticipated if flux levels are kept below 1.05pu.

Referring to the IEC60073, “large power” transformers in the United States are [72]:

- a) “*Capable of delivering rated output MVA, at a lagging power factor of 80% or higher with 105% rated secondary voltage without exceeding the guaranteed temperature rises*” and
- b) “*the transformer is capable of operating at no-load with the primary voltage required for condition a) or 110% rated voltage, whichever is higher, without exceeding the guaranteed temperature rises*”

The United States specification is hence stricter and supports increased operating voltages.

SCSSCAAD3 also specifies maximum temporary overvoltages. It however does not indicate the effect or design specifications for cumulative temporary overvoltages.

Temporary over voltage magnitude	Time duration
1.00 U_m i.e. 1.10 U_n	Continuous
1.05 U_m i.e. 1.155 U_n	5 minutes
1.25 U_m i.e. 1.375 U_n	5 seconds
1.50 U_m i.e. 1.65 U_n	1 second
1.70 U_m i.e. 1.87 U_n	0.25 seconds

Table 5.2.2.1: SCSSCAAD3, Maximum overvoltages without damage [29]

5.2.3 Eskom Distribution's Present Standard Maximum Operating Voltages and the Implications on Transformer Fluxing Levels

With reference to section 3.6, the present Eskom Distribution standard maximum operating voltage for reticulation networks is 105% of U_n [65], and the following resultant observations can be made as regards transformers and LV networks.

- The steady state fluxing levels of sub-transmission transformers should not exceed 105%, and this practice will typically prevent significant damage to these transformers in the cases of load rejection.
- Older 380/220V and 400/230V transformers in nominal tap position will experience maximum flux levels of 1.05pu and the maximum secondary LV voltages will be 105%, which is near the top of the design +5% operating range of three phase motors.
- Newer 240V and 415V transformers in nominal tap position will experience maximum flux levels of 1.05pu and the maximum secondary LV voltages will be 109.6% and 108.9% respectively on a 400/230V base, which is near the top of the +10% range for domestic supplies.

Note that while the Eskom Distribution standard limits the maximum MV source voltage to 105%, due to the deadband of the voltage control window, the MV voltage at the regulated busbar may rise to the setpoint + deadband. As a result the maximum MV system voltage (ignoring any voltage rises due to leading power factors) will typically be slightly greater than the setpoint. However the average maximum system voltage will be the setpoint value, and it is this average maximum value which should be used when placing upper limits on maximum steady state system operating voltages.

5.3 SUMMARY

The steady state voltage variations during running conditions influences a motor's output torque, efficiency and insulation ageing. Most three phase motors are designed for a continual voltage variation of $\pm 5\%$. These motors can be operated at wider voltage variations with no relative loss life or performance provided they are sufficiently de-rated. If customers with significant ($\geq 7.5\text{kW}$) three phase motor loads are supplied in relatively close proximity to distribution transformers, the networks should be designed such that the following maximum motor voltage variations will be experienced for typical LV wiring practices within the customer's premise:

Urban, $\pm 5\%$ and $\pm 7.5\%$ during normal and abnormal network conditions respectively
Rural, $\pm 7.5\%$ and $\pm 10\%$ during normal and abnormal network conditions respectively

Due to present and historical design specifications, Eskom's sub-transmission and distribution transformers inherently limit the maximum system voltages due to core flux limitations. The research recommends that the maximum steady state core flux be limited to 105%.

6 VOLTAGE REGULATION LIMIT MODEL

The allowable voltage drops and limits in both the MV and LV systems are dictated by the combinations of many factors. These include the type of voltage control, equipment specifications, assumptions used in the design of the MV and LV systems, contractual and licence obligations at the supply point, and the voltage requirements of the end use appliances. Sections 3 and 5 documented these factors in relative isolation. Section 6 explores the interaction of these factors utilising a model which enables the allowable MV and LV voltage regulation limits to be calculated for any given combination of these factors. The model enables the effect of different voltage control techniques and the optimisation of distribution transformer tap positions to be analysed. The model provides the maximum, but not necessarily optimal limits for the voltage drops and limits in both the MV and LV systems.

6.1 VOLTAGE DROP CALCULATIONS

The equations for the calculation of the voltages at various points in the LV network, and optimal transformer tap positions as functions of MV system voltages, equipment / appliance specifications and LV network design assumptions are detailed below.

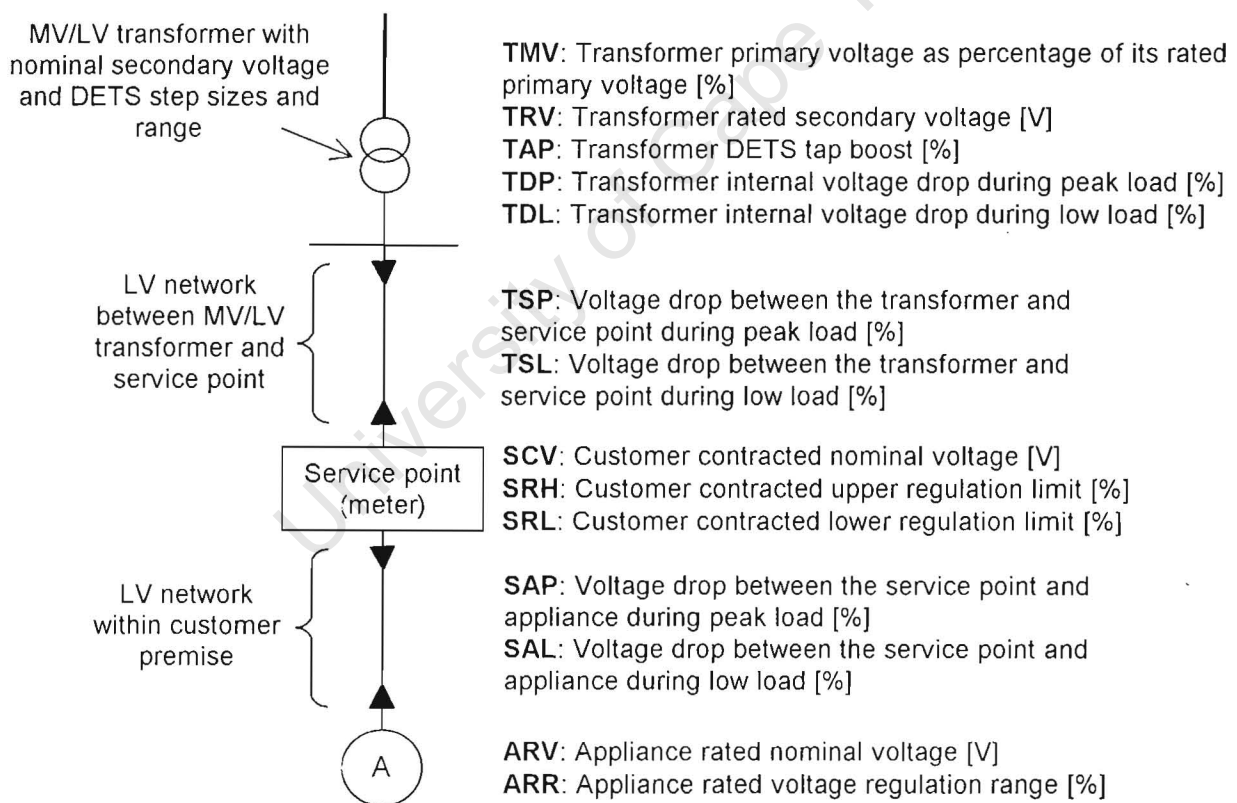


Figure 6.1: Graphical representation of the equipment, service, and appliance specifications and voltage drops during peak and low load conditions

The voltage at the service point during peak loading SVP [V] is given by:

$$SVP = \frac{TMV \cdot TRV}{(1 - TAP)} - TRV \cdot TDP - SCV \cdot TSP \quad (1)$$

The voltage at the service point during low loading SVL [V] is given by:

$$SVL = \frac{TMV \cdot TRV}{(1 - TAP)} - TRV \cdot TDL - SCV \cdot TSL \quad (2)$$

The voltage at the appliance during peak loading AVP [V] is given by:

$$AVP = SVP - ARV \cdot SAP \quad (3)$$

The voltage at the appliance during low loading AVL [V] is given by:

$$AVL = SVL - ARV \cdot SAL \quad (4)$$

The minimum MV voltage MVSL [%] required to keep within the minimum contracted value at the service point is given by:

$$MVSL = \frac{[SCV \cdot (1 + SRL + TSP) + TDP \cdot TRV] \cdot (1 - TAP)}{TRV} \quad (5)$$

The maximum MV voltage MVSP [%] required to keep within the maximum contracted value at the service point is given by:

$$MVSP = \frac{[SCV \cdot (1 + SRH + TSL) + TDL \cdot TRV] \cdot (1 - TAP)}{TRV} \quad (6)$$

The minimum MV voltage MVAL [%] required to keep within the appliance design minimum voltage at the appliance is given by:

$$MVAL = \frac{[ARV \cdot (1 - ARR + SAP) + SCV \cdot TSP + TDP \cdot TRV] \cdot (1 - TAP)}{TRV} \quad (7)$$

The maximum MV voltage MVAP [%] required to keep within the appliance design maximum voltage at the appliance is given by:

$$MVAP = \frac{[ARV \cdot (1 + ARR + SAL) + SCV \cdot TSL + TDL \cdot TRV] \cdot (1 - TAP)}{TRV} \quad (8)$$

The optimal tap boost TAPS [%] that results in the upper regulation limit at the service point for a given maximum MV voltage MVH [%] is given by:

$$TAPS = \frac{TRV \cdot MVH}{SCV \cdot (1 + SRH + TSL) + TRV \cdot TDL} \quad (9)$$

The optimal tap boost TAPA [%] that results in the upper regulation limit at the appliance for a given maximum MV voltage MVH [%] is given by:

$$TAPA = \frac{TRV \cdot MVH}{ARV \cdot (1 + ARR + SAL) + SCV \cdot TSL + TRV \cdot TDL} \quad (10)$$

6.2 VOLTAGE LIMIT MODEL DESCRIPTION

Based on the equations in section 6.1, an Excel based model was developed to investigate the relationships between the different levels of the distribution network, and how design practices, licence and contractual agreements, and appliance requirements influence MV voltage regulation limits. A basic description of the model follows.

Motors are generally considered to be the most critical and hence (from a voltage regulation perspective) limiting loads. The model evaluates how the requirements to meet contractual / licence and motor design operating voltages ranges dictates the allowable MV voltage regulation limits, and the resultant LV feeder voltage drops for other customers.

6.2.1 Basic Data

Data in the model (such as equipment specification, contractual limits etc.) can be easily modified to establish the implications of a combination of factors. The model contains editable data for:

Motor specifications: Rated voltage and allowable regulation range. The model includes 380V and 400V three phase motors, as well as 230V single phase motors.

Service contract / licence agreements: The regulation requirements at the service point can be specified against a certain motor. For example a 380V motor may have a recommended voltage range of $\pm 5\%$, but it could be supplied by a 380V $\pm 7.5\%$ contract.

Distribution Transformer specifications: The nominal voltages, maximum allowable flux levels, impedances, and DETS tap ranges and step sizes are included for a wide range of distribution transformers typically used by Eskom. These include 380V, 400V, 415V three phase, 220V, 230V, 240V single phase, and 480V bi phase units.

Distribution Transformer loading levels: The typical maximum and minimum loading levels for distribution transformers supplying motor loads are specified, along with the load power factors during both peak and low load conditions. These loading levels are used to establish the related internal voltage drops in the transformer.

LV design parameters: The typical maximum and minimum voltage drops between the distribution transformer, service point, and motors during peak and low loading conditions in the local LV network.

As there is considerable uncertainty with many of the parameters such as the LV network design assumptions, the model includes three ranges of values such that the relative differences can be easily viewed and compared with one another. This also facilitates the establishment of a range of possible scenarios such that a best, middle of the road, and worst case combination of values can be evaluated simultaneously to help establish the sensitivity of the results to the input parameters.

6.2.2 Model Options

The model caters for a range of user adjustable options that include:

Flux limiting: Determines if the maximum flux specified against the transformer specification must be enforced, or whether tap positions can be automatically selected that result in higher than specified levels of fluxing.

Fixed versus optimal tapping: A transformer can be fixed on any one of its available tap positions, or else the model can automatically select the optimal transformer tap. This enables the impact of not using these DETS taps to be evaluated.

Auto tapping voltage reference: The distribution transformer tap position can be optimised based on either meeting the upper regulation requirements of the service point or appliance. If transformer taps are selected based on the service point contractual / licence requirements this could result in a higher than recommended voltage on the appliance where appliance voltage limits are more restrictive than their associated service point restrictions. This is often the case with motor load. A customer may for example have a 400V $\pm 10\%$ contract, but be supplying a 400V $\pm 5\%$ motor load. Setting the tap position to meet the +10% contractual requirement could overflux the motor.

Enforce contract / licence limits: For each combination of transformer, supply contract and motor the option to enforce the contract / licence limits at the service point is provided. If these limits are set to be ignored for a certain combination of the above, then the resultant restrictions are not utilised in calculating the allowable MV regulation limits. This enables the assessment of the impact on the allowable MV regulation of making the conscious decision not to comply with certain contracts, such as a new 400V contracted customer supplied by an old 380V secondary transformer.

Enforce motor limits: For each combination of transformer, supply contract and motor the option to enforce the recommended motor regulation limits at the motor is provided. If these limits are set to be ignored for a certain combination of the above, then the resultant restrictions are not utilised in calculating the allowable MV regulation limits. This enables the assessment of the impact on the allowable MV regulation in making the conscious decision not to comply with certain motor operating requirements, such as a new 400V motor supplied by an old 380V secondary transformer.

6.2.3 Voltage Limit Data

In order to establish the maximum and minimum allowable distribution transformer DETS tap boosting, the maximum end of line MV voltage, and minimum sending MV voltage are required, and will be dependent on the type of voltage control utilised, and load factor.

The maximum end of line MV voltage dictates how much boosting of the end of line distribution transformers can be performed. If fixed voltage control is utilised, and the load factor is very low, the maximum end of line MV voltage could be of very similar magnitude to the peak sending voltage. Varying this maximum end of line MV voltage will enable the impact on the allowable minimum end of line MV voltage, and hence maximum allowable MV regulation, to be determined.

When utilising voltage control methodologies such as LDC it may be desirable to significantly increase sending voltages during peak loading conditions. This may require the bucking of distribution transformer DETS taps for those units in relative close proximity to

the source (where the voltage drop between the source and these transformers is not significant). The maximum level of distribution transformer bucking that can be performed before a local low voltage problem may arise will depend on the minimum sending MV voltage.

6.2.4 Calculations and Available Results

A high level description of the model calculations (using the basic data and options) and results follows.

- For the selected options and specifications, the allowable maximum and minimum MV voltages are calculated for each selected combination of transformer, contract / licence agreement, and motor. Where enabled, auto tapping of transformers will be performed to determine their optimal DETS tap positions given maximum and minimum receiving and sending MV voltages respectively, and where selected, allowable transformer flux levels.
- The highest minimum MV and lowest maximum MV voltage of all the allowed combinations are then selected. Keeping within these limits will ensure that the voltage, and transformer flux level requirements of each allowed combination are met.
- Using these maximum and minimum MV voltages the actual maximum and minimum voltages at both the service point and appliance are calculated for each option. So if the MV limits are calculated on the basis that the requirements of a given combination will not be met, the resultant voltages at the service point and appliance for this and all of the other combinations will be displayed. This enables the severity of a decision to be analysed.
- The above-mentioned maximum and minimum MV voltages are calculated separately for the requirements to meet the service level and appliance voltage limits. This enables the required limits to meet contractual / licence agreements to be compared with those required ensuring satisfactory appliance voltages.
- Based on the variation in MV voltage the allowed maximum LV voltage drop is calculated for each of the combinations of transformers and motors.

Screen dumps and sample outputs from the model are provided in appendix C.

6.3 CALCULATED VOLTAGE LIMITS AND APPORTIONMENT TO MEET BOTH LICENCE/CONTRACTUAL AND APPLIANCE VOLTAGE LIMITS

Multiple studies were performed with the model using Eskom's standard equipment specifications, contracts and licence agreements in order to establish trends and recommended voltage regulation limits. The studies include the calculation of the MV limits such that both the requirements of Eskom's license / contractual obligations and recommended appliance operating voltages are met. For reasonable LV design practices the limits will ensure that provided distribution transformer DETS taps are correctly adjusted, the voltage limits seen by appliances will result in satisfactory operation without any significant loss of life or reduced efficiency. These limits would provide the basis for voltage limits and apportionment for a national utility that has both the best interests of itself and its customers in mind.

Section 6.4 contains the results of studies where only Eskom's license / contractual obligations are enforced, and recommended appliance operating voltages are not taken into consideration. The use of these calculated limits will ensure that for suitably adjusted

distribution transformer DETS tap positions all license / contractual obligations are met, but the voltages delivered to appliances such as three phase motor loads may result in customer dissatisfaction for typical LV design practices. These limits would be the basis for a utility that aims to maximise returns without possible due consideration for the national interests of the country as a whole.

The recommended contractual / license requirements and recommend motor supply voltages to be used by planners are provided in table 6.3.1 below. Two ranges of allowable motor voltage regulation are defined; Normal limits for the planning and designing of future systems, and abnormal for system contingencies and delaying the strengthening of existing networks.

Specification	400V Three Phase	380V Three Phase	230V Single Phase
Motor rated voltage	400V	380V	230V
Motor regulation range for Urban (normal)	±5%	±5%	±10%
Motor regulation range Urban (abnormal)	±7.5%	±7.5%	±10%
Motor regulation range for Rural (normal)	±7.5%	±7.5%	±10%
Motor regulation range Rural (abnormal)	±10%	±10%	±12.5%
Service nominal voltage	400V	380V	230V
Service regulation range for contracts before 1996 (normal)	±7.5%	-5.26% +7.5%	±7.5%
Service regulation range for contracts before 1996 (abnormal)	±7.5%	±7.5%	±7.5%
Service regulation range for contracts after 1996 (normal)	±10%	N/A	±10%
Service regulation range for contracts after 1996 (abnormal)	±10%	N/A	±10%

Table 6.3.1: Service point and motor voltage levels and recommended allowable deviations for typical motor loads during both normal and abnormal network states

Transformer	Specification	Value
Three phase 415V secondary	Nominal secondary voltage	415/240V
	DETS tap range and step size	-6%, -3%, 0, +3%, +6%
	Maximum flux level	1.05pu
Three phase 400V secondary	Nominal secondary voltage	400/230V
	DETS tap range and step size	-5%, -2.5%, 0, +2.5%, +5%
	Maximum flux level	1.05pu
Three phase 380V secondary	Nominal secondary voltage	380/220V
	DETS tap range and step size	-5%, -2.5%, 0, +2.5%, +5%
	Maximum flux level	1.05pu
Single phase 220V secondary	Nominal secondary voltage	220V
	DETS tap range and step size	-5%, 0, +5%
	Maximum flux level	1.05pu
Single phase 230V secondary	Nominal secondary voltage	230V
	DETS tap range and step size	-5%, 0, +5%
	Maximum flux level	1.05pu
Single phase 240V secondary	Nominal secondary voltage	240V
	DETS tap range and step size	-5%, 0, +5%
	Maximum flux level	1.05pu
Bi phase 240V secondary	Nominal secondary voltage	480/240V
	DETS tap range and step size	-6%, -3%, 0, +3%, +6%
	Maximum flux level	1.05pu

Table 6.3.2: Typical transformer specification data used in the calculation of the allowable MV voltage regulation limits (see section 3.1)

Planners should use the abnormal limits where necessary to delay the required completion date for strengthening projects. The allowable MV voltage regulation calculated based on

the abnormal limits will result in a slightly wider allowable voltage regulation range, which is not ideal but should still result in compliance with contractual / license requirements and satisfactory motor operation provided the LV network is reasonably designed. The “normal” and “abnormal” limits are analogous to the “planning” and “compatibility” levels supported by the NRS 048.

For the purposes of network planning, reasonable distribution transformer and LV network sizing and design parameters for urban and rural type networks are provided in table 6.3.3 below. Urban type networks will typically supply either or a combination of medium to upper income domestic, commercial and or light industrial loads, where load densities are typically in excess of 200kVA/km². These networks will usually (but not necessarily) be of cable construction. Rural type networks typically supply lower density loads such as small to medium scale agriculture and smallholdings. Rural networks are usually constructed on overhead lines, and load densities are usually below 200kVA/km².

Specification	Urban	Rural
Transformer impedence	4%	4%
Transformer loading during peak load	90%	70%
Transformer loading during low load	30%	0%
LV load power factor during peak load	0.95	0.9
LV load power factor during low load	0.95	0.9
LV voltage drop between transformer and service during peak load	2%	1%
LV voltage drop between transformer and service during low load	1%	0.5%
LV voltage drop between service and motor during peak load	2.5%	2.5%
LV voltage drop between service and motor during low load	0.5%	0.5%

Table 6.3.3: Typical installation data for local LV system supplying a significant motor load. These parameters are used in the calculation of the allowable MV voltage regulation limits for rural and urban type networks

The detailed results obtained using the voltage regulation limit model are included in appendix D.

6.3.1 Urban Type Networks

Based on the model results the following observations can be made for typical urban networks supplying a mixture of transformers, contracts and motors:

- Given the wide range of transformers and contracts, it is impossible to regulate the source busbar such that contract and license obligations are met if all transformers are operated on nominal tap.
- If there are no 380V transformers, 380V contracts or 380V motors, it is possible to meet licence requirements with all 415/240V and 400/230V transformers in nominal tap. However it is not practically possible to meet motor voltage regulation requirements for typical LV design practices.
- It is essential that DETS tapping is performed to provide adequate motor supply voltages for all transformer and motor combinations. In many cases the optimal tap position may be the nominal tap position. Standardisation on any one tap position for a given type of transformer without due regard for the type of load will result in motor running voltages outside of the proposed limits in certain applications.

- 380V transformers supplying 400V motors severely restrict the allowable MV voltage regulation limits if the 400V motor operating limits are to be met. When these cases occur there are two basic scenarios. Either the 400V motors are sufficiently oversized (de-rated) such that they can operate continuously for a $\pm 10\%$ voltage variation (without unacceptable loss of life), or the 380V transformer must be changed. Note that in cases where customers have older 380V contracts supplied by 380V transformers, and where customers replace the older 380V equipment with newer 400V equipment, the contractual limits will still be met but the appliance voltages may be unacceptable if the motor sizing safety factors are insufficient. In these cases the customers may complain of low voltages, with the obvious solution being to upgrade to a 400V contract and change the transformer. It is however unclear as to which party (the customer or Eskom) should carry the cost of replacing the distribution transformer, and this issue had not been resolved at the time of the finalisation of this research. For the purposes of the calculation of acceptable MV voltage drops and apportionment, the contractual obligations of 400V contracts will be enforced when these customers are supplied by 380V transformers. However the recommended motor operating ranges will not be enforced when 380/220V transformers are used to supply 400/230V motors.
- Limiting transformer flux levels to 105% does not have a major impact on the allowable voltage regulation limits, however restricting flux levels to 100% will have a massive impact.
- When end of line voltages do not recover above 100%, the maximum flux limits no longer restrict the allowable taps.
- Due to the higher secondary transformer voltages for newer 415/240V transformers, limiting flux levels to 105% does not limit the use of DETS taps with new transformers as is the case with older units.
- The restriction to three tap positions and a step size of 5% with single phase transformers restricts the allowable LV voltage drop for single phase transformers as compared with three and bi phase transformers which have 5 tap positions and a smaller step size.
- The distribution transformer specification changed following the 1996 amendments to the Electricity Regulation, and by 1998 any new distribution transformers installed by Eskom in networks should have nominal secondary voltages of 415/240V. As a result any new systems or network expansions after 1998 should only contain 415/240V transformers and 400/230V contracts, and are referred to in this document as "new" networks. "New" networks (without the inherent limitations of older 400/230V or 380/220V transformers and 380/220V motors) have wider allowable MV regulation limits.

The following maximum voltage regulation limits were calculated for urban type networks.

Urban type networks with a mixture of transformers and motors (motor voltage limits are not enforced for 380/220V transformer and 400/230V motor combinations)		Maximum end of line MV voltage		
		≥102.5%	<102.5% & ≥100%	<100%
Normal limits	Maximum MV source voltage	104.3%	104.3%	104.3%
	Minimum end of line MV voltage	102.0%	99.5%	96.9%
	Maximum MV voltage drop	2.3%	4.8%	7.4%
Abnormal limits	Maximum MV source voltage	106.2%	106.2%	106.2%
	Minimum end of line MV voltage	99.5%	97.0%	94.6%
	Maximum MV voltage drop	6.7%	9.2%	11.6%
Maximum 400/230V LV voltage drops for domestic connections	LV : 415V 3φ Trfr: 400V Motor	10.5%	10.5%	10.0%
	LV : 400V 3φ Trfr: 400V Motor	9.5%	8.5%	8.0%
	LV : 415V 3φ Trfr: 380V Motor	7.5%	5.0%	5.0%
	LV : 400V 3φ Trfr: 380V Motor	7.0%	5.5%	5.0%
	LV : 380V 3φ Trfr: 380V Motor	4.5%	3.5%	3.0%
	LV : 415V 3φ Trfr: Domestic	13.0%	11.0%	11.0%
	LV : 400V 3φ Trfr: Domestic	9.5%	8.5%	8.0%
	LV : 380V 3φ Trfr: Domestic	4.5%	3.5%	3.0%
	LV : 230V 1φ Trfr: Domestic	9.5%	7.0%	5.5%
	LV : 240V 1φ Trfr: Domestic	13.5%	11.0%	9.5%
	LV : 240V Bφ Trfr: Domestic	13.5%	12.0%	11.5%

Table 6.3.1.1: Calculated maximum voltage regulation limits to meet both licence/contractual and appliance voltage limits for existing urban networks that contain a mixture of distribution transformers and domestic and motor loads. All common transformer and motor combinations are supported, but while contractual limits for 380/220V transformer and 400/230V contract/motor combinations will be met, the recommended motor operating voltage range for these combinations is not enforced

Referring to table 6.3.1.1, if the MV voltage drops to 99.5% at the end of the network, and recovers to between 100% and 102.5%, domestic customers can be connected to a 415V transformer supplying a 400V motor load, but the LV voltage drop must be limited to 10.5%. If a 400V transformer is used this allowable voltage drop decreases to 8.5%.

The resultant allowable LV voltage drops are in good agreement with the historical apportionment limits documented in section 3.4.

Transformer	Maximum LV voltage drop
415/240V transformers with no 380V contracts	Between 13.5% and 10.0%
400/230V transformers with no 380V contracts	Between 9.5% and 5.5%
380/220V transformers*	Between 4.5% and 3.0%
415V and 400V transformers with 380V contracts	Between 7.5% and 5.0%

Table 6.3.1.2: Calculated maximum LV voltage drops for ±10% 400/230V domestic type customers in urban networks.

* In order to increase the allowable voltage drop above 3% to 5%, the flux levels of 380V transformers on feeder extremities may exceed 105%, but should not exceed 107%

For customers supplied in relatively close proximity to the distribution transformers, the normal and abnormal MV limits provided in table 6.3.1.1 result in compliance with ±7.5% 380/220V and ±10% 400/230V contracts. However service voltages will fall marginally below contracted limits for ±7.5% 400/230V customers (connected between 1990 and 1996) supplied by 380/220V transformers.

The use of the abnormal limits in table 6.3.1.1 will result in an increased voltage regulation at both motor and domestic loads of an additional $\pm 2.5\%$. If the maximum allowable LV voltage drops have been utilised the LV service voltages for domestic customers on the extremities of the LV feeders may drop to 87.5% (90%-2.5%). This increased voltage regulation is considered acceptable for domestic customers on feeder extremities. This is due to that fact that the local “low” voltage conditions should not persist for more than a few hours a day, and in many cases may be limited to less than 1 hour a day. While the maximum 10 minute rms voltage variation may exceed the 90% compatibility level, the assessed voltage regulation as per the NRS048 may in fact remain within limits due to the disregarding of the worst 5% of the voltage readings for each day. The network should however not be operated indefinitely under these conditions.

For “new” networks the maximum allowable flux levels on the transformers do not critically limit the allowable MV voltage regulation, and the results are provided in table 6.3.1.3. The maximum LV voltage drop varies between 11.5% and 7.0%. Reducing the minimum end of line MV voltage limits to those associated with a mixture of transformers and motors (table 6.3.1.1) will enable this LV voltage drop limit to be increased slightly but not significantly above the 11.5% to 7.0% range. This only slight increase is due to the fact that the minimum end of line MV voltages are similar regardless of whether there are any 380/220V motors and 380/220V or 400/230V transformers. The abnormal limits tabled below enable the use of higher sending MV voltages, however the practical limitations on the flux levels of the source sub-transmission transformer will limit the application of these higher sending voltages.

“New” Urban type networks with only 415/240V transformers and 400/230V motors		Maximum end of line MV voltage		
		$\geq 103.5\%$	$< 103.5\%$ & $\geq 100.5\%$	$< 100.5\%$
Normal limits	Maximum MV source voltage	106.6%	106.6%	106.6%
	Minimum end of line MV voltage	101.4%	98.4%	95.5%
	Maximum MV voltage drop	5.2%	8.2%	11.1%
Abnormal limits	Maximum MV source voltage	110.3%	110.3%	110.3%
	Minimum end of line MV voltage	96.0%	93.1%	93.1%
	Maximum MV voltage drop	14.3%	17.2%	17.2%
Maximum 400/230V LV voltage drop for domestic connections	LV : 415V 3 ϕ Trfr: 400V Motor	9.5%	9.5%	7.5%
	LV : 415V 3 ϕ Trfr: Domestic	11.0%	11.0%	9.5%
	LV : 240V 1 ϕ Trfr: Domestic	9.5%	10.0%	7.0%
	LV : 240V B ϕ Trfr: Domestic	11.5%	10.5%	10.0%

Table 6.3.1.3: Calculated maximum voltage regulation limits to meet both licence/contractual and appliance voltage limits for “new” urban networks that contain domestic loads, 415/240V transformers and 400/230V motors i.e. no older 380/220V motors/contracts and 380/220V or 400/230V transformers

Provided the maximum MV sending voltages are limited to 105% to restrict sub-transmission transformer fluxing to acceptable levels, for both existing and “new” networks in urban areas the use of the recommended limits in tables 6.3.1.1 and 6.3.1.3 above will result in MV voltage regulation within $\pm 5\%$. As such these limits will meet the contractual and licence obligations of directly connected “bulk” MV customers (unless there is a special supply agreement limiting MV regulation to less than $\pm 5\%$).

6.3.2 Rural Type Networks

For typical rural networks supplying a mixture of transformers, contracts and motors, the same general comments apply as for urban type networks. Note that as with urban networks the recommended motor operating voltage limits for 380/220V transformer and 400/230V motor combinations are not enforced. If the limitation of a contracted voltage variation of $\pm 7.5\%$ is enforced for 400/230V supplies connected between 1990 and 1996 the calculated MV limits are restricted when these customers are supplied by 380/220V transformers, and the MV minimum voltages in table 6.3.2.1 below would typically increase by 2.5%. However the real requirement to meet this $\pm 7.5\%$ limitation is debatable. It is unlikely that these $\pm 7.5\%$ 400/230V customers will be supplied by 380/220V transformers in rural areas, as customers would have typically had a dedicated transformer installed as part of their connection, and this would have been a 400/230V unit. Hence the requirement to meet $\pm 7.5\%$ 400/230V contracts supplied by 380/220V transformers is not enforced in calculating the limits summarised in table 6.3.2.1 below.

Rural type networks with a mixture of transformers and motors (motor voltage limits are not enforced for 380/220V transformer and 400/230V motor combinations)		Maximum end of line MV voltage			
		$\geq 105\%$	$< 105\% \& \geq 102.5\%$	$< 102.5\% \& \geq 100\%$	$< 100\%$
Normal limits	Maximum MV source voltage	104.8%	104.8%	104.8%	104.8%
	Minimum end of line MV voltage	100.7%	98.0%	95.8%	93.3%
	Maximum MV voltage drop	4.1%	6.8%	9.0%	11.5%
Abnormal limits ¹	Maximum MV source voltage	104.8%	104.8%	104.8%	104.8%
	Minimum end of line MV voltage	100.5%	98.0%	95.7%	93.1%
	Maximum MV voltage drop	4.3%	6.8%	9.1%	11.7%
Abnormal limits ²	Maximum MV source voltage	104.8%	104.8%	104.8%	104.8%
	Minimum end of line MV voltage	98.1%	95.7%	93.3%	90.9%
	Maximum MV voltage drop	6.7%	9.1%	11.5%	13.9%
Maximum 400/230V LV voltage drops for domestic connections	LV : 415V 3 ϕ Trfr: 400V Motor	9.0%	9.5%	7.0%	7.5%
	LV : 400V 3 ϕ Trfr: 400V Motor	6.0%	6.0%	5.0%	4.0%
	LV : 415V 3 ϕ Trfr: 380V Motor	6.5%	4.0%	3.0%	2.0%
	LV : 400V 3 ϕ Trfr: 380V Motor	6.0%	4.0%	3.5%	3.0%
	LV : 380V 3 ϕ Trfr: 380V Motor	1.5%	1.0%	0.5%	0%
	LV : 415V 3 ϕ Trfr: Domestic	9.0%	9.5%	7.0%	7.5%
	LV : 400V 3 ϕ Trfr: Domestic	6.0%	6.0%	5.0%	4.0%
	LV : 380V 3 ϕ Trfr: Domestic	1.5%	1.0%	0.5%	0%
	LV : 230V 1 ϕ Trfr: Domestic	4.0%	6.0%	3.5%	2.0%
	LV : 240V 1 ϕ Trfr: Domestic	8.0%	10.0%	8.0%	5.5%
LV : 240V B ϕ Trfr: Domestic	10.0%	10.0%	8.0%	8.0%	

Table 6.3.2.1: Calculated maximum voltage regulation limits to meet both licence/contractual and appliance voltage limits for existing rural networks that contain typical domestic and non-domestic loads, and a mixture of distribution transformers and motors.

In table 6.3.2.1 all common transformer and motor combinations are supported, but while contractual limits for 380/220V transformer and $\pm 10\%$ 400/230V contract/motor combinations will be met, the recommended motor operating voltage range for these combinations is not enforced. There are two ranges of abnormal limits: ¹ 380/220V contracts supplied by 380/220V transformers are enforced with the limitations imposed by the 1996 change to the Electricity Regulation. ² 380/220V contracts supplied by 380/220V transformers are enforced without the limitations imposed by the 1996 change to the electricity Regulation.

While both ranges for the abnormal limits will result in motor voltages within those provided in table 6.3.1, the limitations of the 380V contract become the primary constraint. Referring to section 3.1, while the allowable regulation range for 380V customers was contracted at $\pm 7.5\%$, the bottom of this 380V range conflicts with the 400V -10% limit imposed by the 1996 change to the electricity Regulation. As a result the lower bound of the 380V contract should ideally be restricted to 380V -5.26% . Under contingencies it should be considered acceptable to drop the 1996 limitation and only enforce the original 380V $\pm 7.5\%$ limit. From a practical perspective 380V contracts only need to be met where customers have 380V equipment. 380V equipment such as motors will operate adequately during contingencies with voltages at -7.5% of nominal, hence it is considered acceptable to drop the 1996 Electricity Regulation limitation during contingencies. This enables an additional 2.3% voltage drop in the MV system.

Referring to table 6.3.2.1 above, if the MV voltage drops to 95.8% at the end of the network, and recovers to between 100% and 102.5%, domestic customers can be connected to a 415V transformer supplying a 400V motor load, but the LV voltage drop must be limited to 7%. If a 400V transformer is used this allowable voltage drop decreases to 5%.

Transformer	Maximum LV voltage drop
415/240V transformers with no 380V contracts	Between 9.5% and 7.0%
400/230V transformers with no 380V contracts	Between 6.0% and 2.0%
380/220V transformers*	Between 1.5% and 0.0%
415/240V and 400/230V transformers with 380V contracts	Between 6.5% and 2.0%

Table 6.3.2.2: Calculated maximum LV voltage drops for $\pm 10\%$ 400/230V domestic type customers in rural networks.

* In order to increase the allowable voltage drop above 0% to 2.5%, the flux levels of 380V transformers on feeder extremities may exceed 105%, but should not exceed 107%. The use of 380/220V transformers to supply 400/230V domestic customers using significant LV networks will always be a major problem and should be avoided as the allowable LV voltage drop is extremely prohibitive

As would be expected, the resultant allowable LV voltage drops in rural networks are less than for typical urban networks.

For "new" rural networks the maximum allowable flux levels on the transformers do not critically limit the allowable MV voltage regulation, and the results are provided in table 6.3.2.3 below. A maximum LV voltage drop for domestic connections of between 6.5% and 3% would be suitable. Reducing the minimum end of line MV voltage limits to those associated with a mixture of transformers and motors (table 6.3.2.1 above) will enable this LV voltage drop limit to be increased to between 9.5% and 6%. As with urban networks, the abnormal limits enable the use of higher sending voltages, but will be practically difficult to implement. In reality the maximum sending voltage will typically be limited to 105% due to flux limitation on the source sub-transmission transformer.

"New" Rural type networks with only 415/240V transformers and 400/230V motors		Maximum end of line MV voltage			
		≥105%	<105% & ≥102.5%	<102.5% & ≥100%	<100%
Normal limits	Maximum MV source voltage	110.3%	110.3%	110.3%	110.3%
	Minimum end of line MV voltage	97.6%	94.7%	91.9%	91.9%
	Maximum MV voltage drop	12.7%	15.6%	18.4%	18.4%
Abnormal limits	Maximum MV source voltage	110.3%	110.3%	110.3%	110.3%
	Minimum end of line MV voltage	96.4%	92.3%	91.8%	89.6%
	Maximum MV voltage drop	13.9%	18.0%	18.5%	20.7%
Maximum LV voltage drops for domestic connections	LV : 415V 3φ Trfr: 400V Motor	6.0%	5.5%	3.0%	6.0%
	LV : 415V 3φ Trfr: Domestic	6.0%	6.0%	3.0%	6.0%
	LV : 240V 1φ Trfr: Domestic	5.0%	5.5%	3.5%	5.0%
	LV : 240V Bφ Trfr: Domestic	6.5%	6.5%	3.5%	6.5%

Table 6.3.2.3: Allowable voltage regulation limits to meet both licence/contractual and appliance voltage limits for "new" rural networks that contain domestic loads and 415/240V transformers and 400/230V motors i.e. no older 380/220V motors/contracts and 380/220V or 400/230V transformers

Apart from the values on the last column in table 6.3.2.1 (in which case the end of line MV voltage does not recover above 100%) the calculated MV regulation ranges for rural networks will fall within $\pm 5\%$. As such these MV limits will not present a problem for directly connected bulk MV supplies with $\pm 5\%$ contracts. The MV voltage limits recommended in the last column of table 6.3.2.1 can be used for rural MV networks with bulk MV customers (where the EL MV voltage does not recover above 100%) provided the default voltage variation for bulk supplies of $\pm 7.5\%$ has been contracted with the bulk customers.

6.4 CALCULATED VOLTAGE LIMITS AND APPORTIONMENT TO ONLY MEET LICENCE/CONTRACTUAL REQUIREMENTS

The results calculated in section 6.3 include the requirement that appliance operating voltages fall within recommended limits for reasonable LV network design practices. In certain instances the requirement to meet the appliance operating voltage ranges may limit the maximum allowable voltage drops. This may result in more costly distribution systems (especially in rural type networks where voltage regulation is often a critical constraint). If a utility's major focus is to maximise returns it could adopt the stance that it only aims to provide voltages at the service point such that it meets its license / contractual obligations. The customers would then have to ensure that their appliances are suitably designed or derated such that they will operate acceptably at the resultant utilisation voltages.

This section contains the results of studies where only Eskom's license / contractual obligations are met, and recommended appliance operating voltages are not taken into consideration.

Eskom's contractual / license requirements for LV customers are provided in table 6.4.1 below. As only a single range of values are contracted with the customer and provided in regulatory standards, only a single range of values is provided (no normal and abnormal system limits).

Specification	400/230V Contract	380/220V Contract
Service nominal voltage	400/230V	380/220V
Service regulation range for contracts before 1996	±7.5%	-5.26% +7.5%
Service regulation range for contracts after 1996	±10%	N/A

Table 6.4.1: Service point contractual/licence limits for LV supplies

The same distribution transformer specifications are used as those in table 6.3.2.

As with the limits calculated in section 6.3, the results are provided separately for both urban and rural type networks with reasonable distribution transformer and LV network sizing and design parameters as provided in table 6.4.2 below.

Specification	Urban	Rural
Transformer impedance	4%	4%
Transformer loading during peak load	90%	70%
Transformer loading during low load	30%	0%
LV load power factor during peak load	0.95	0.9
LV load power factor during low load	0.95	0.9
LV voltage drop between transformer and service during peak load	2%	1%
LV voltage drop between transformer and service during low load	1%	0.5%

Table 6.4.2: Typical installation data for local LV system supplying customers in relative close proximity to the distribution transformer

6.4.1 Urban Type Networks

The following maximum voltage regulation limits were calculated for urban type networks containing a mixture of common transformers and contracts. It is assumed that some of the 400/230V customers were connected between 1990 and 1996 and hence have ±7.5% contracts that are enforced in the calculated results provided in table 6.4.1.1 below.

Urban type networks with a mixture of common transformers and contracts, where ±7.5% 400/230V contracts are enforced		Maximum end of line MV voltage		
		≥102.5%	<102.5% & ≥100%	<100%
Normal limits	Maximum MV source voltage	105.0%	105.0%	105.0%
	Minimum end of line MV voltage	102.0%	101.3%	96.9%
	Maximum MV voltage drop	3.0%	3.7%	8.1%
Maximum 400/230V LV voltage drops	LV : 415V 3φ Trfr: 400V Contract	13.3%	12.6%	11.5%
	LV : 400V 3φ Trfr: 400V Contract	9.6%	9.4%	8.5%
	LV : 380V 3φ Trfr: 400V Contract	4.6%	4.4%	3.6%
	LV : 415V 3φ Trfr: 380V Contract	7.3%	8.1%	7.3%
	LV : 400V 3φ Trfr: 380V Contract	8.0%	8.7%	7.3%
	LV : 380V 3φ Trfr: 380V Contract	4.6%	4.4%	3.6%
	LV : 220V 1φ Trfr: 230V Contract	5.2%	4.6%	1.8%
	LV : 230V 1φ Trfr: 230V Contract	9.6%	8.9%	6.0%
	LV : 240V 1φ Trfr: 230V Contract	13.9%	13.2%	10.1%
LV : 240V Bφ Trfr: 230V Contract	13.5%	13.2%	11.7%	

Table 6.4.1.1: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for existing urban networks that contain a mixture of distribution transformers and contracts including 380/220V transformers supplying ±7.5% 400/230V contracts. The ±7.5% limitation is imposed for 400/230V LV supplies.

The real requirement to comply with the $\pm 7.5\%$ limitation for 400/230V customers connected between 1990 and 1996 is debatable, and table 6.4.1.2 contains the results if the limitation of $\pm 10\%$ (not $\pm 7.5\%$) is imposed for all 400/230V supplies.

Urban type networks with a mixture of common transformers and contracts, where $\pm 7.5\%$ 400/230V contracts are NOT enforced		Maximum End Of Line MV voltage		
		$\geq 102.5\%$	$< 102.5\%$ & $\geq 100\%$	$< 100\%$
Normal limits	Maximum MV source voltage	105.0%	105.0%	105.0%
	Minimum end of line MV voltage	99.4%	98.7%	94.4%
	Maximum MV voltage drop	5.6%	6.3%	10.6%
Maximum 400/230V LV voltage drops	LV : 415V 3 ϕ Trfr: 400V Contract	10.6%	10.2%	9.0%
	LV : 400V 3 ϕ Trfr: 400V Contract	7.0%	7.7%	6.4%
	LV : 380V 3 ϕ Trfr: 400V Contract	2.1%	2.8%	1.6%
	LV : 415V 3 ϕ Trfr: 380V Contract	4.8%	6.8%	5.4%
	LV : 400V 3 ϕ Trfr: 380V Contract	5.8%	6.3%	4.9%
	LV : 380V 3 ϕ Trfr: 380V Contract	2.0%	2.8%	1.6%
	LV : 220V 1 ϕ Trfr: 230V Contract	1.9%	2.6%	0.0%
	LV : 230V 1 ϕ Trfr: 230V Contract	6.1%	6.3%	3.9%
	LV : 240V 1 ϕ Trfr: 230V Contract	10.3%	10.5%	8.0%
	LV : 240V B ϕ Trfr: 230V Contract	11.2%	10.8%	9.5%

Table 6.4.1.2: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for existing urban networks that contain a mixture of distribution transformers and contracts including 380/220V transformers supplying $\pm 10\%$ 400/230V contracts. The $\pm 7.5\%$ limitation is NOT imposed for 400/230V LV supplies and the post 1996 value of $\pm 10\%$ has been enforced.

The resultant MV voltage limits documented in table 6.4.1.2 above fall between the normal and abnormal limits provided in table 6.3.1.1, where the values in table 6.3.1.1 take into account the recommended motor operating voltage limits.

One of the constraints on the allowable MV limits is the requirement to meet licence obligations for 400/230V contracts that are being supplied by 380/220V transformers. This practical limitation can be overcome in the field by simply replacing these older transformers with new 415/240V units. If 380/220V transformers supplying 400/230V contracts are not supported and the transformer is assumed to be upgraded to either a 400/230V or 415/240V transformer the results are as summarised in table 6.4.1.3 below. Note that under these conditions the MV limits are governed by the requirement to meet $\pm 7.5\%$ 380/220V contracts supplied by 380/220V transformers. In so doing the regulation experienced by 400/230V customers in relative close proximity to the 400/230V or 415/240V distribution transformers will fall within $\pm 7.5\%$, and $\pm 7.5\%$ 400/230V contracts are not a constraint.

Urban type networks with a mixture of transformers and contracts, where 380/220V transformer 400/230V contracts combinations are NOT supported		Maximum End Of Line MV voltage		
		≥102.5%	<102.5% & ≥100%	<100%
Normal limits	Maximum MV source voltage	106.2%	106.2%	106.2%
	Minimum end of line MV voltage	99.3%	96.8%	94.3%
	Maximum MV voltage drop	6.9%	9.4%	11.9%
Maximum 400/230V LV voltage drops	LV : 415V 3φ Trfr: 400V Contract	10.5%	8.8%	8.9%
	LV : 400V 3φ Trfr: 400V Contract	6.9%	6.1%	6.6%
	LV : 415V 3φ Trfr: 380V Contract	4.7%	5.0%	5.3%
	LV : 400V 3φ Trfr: 380V Contract	5.7%	4.4%	4.9%
	LV : 380V 3φ Trfr: 380V Contract	2.0%	1.3%	1.7%
	LV : 230V 1φ Trfr: 230V Contract	6.0%	4.4%	4.1%
	LV : 240V 1φ Trfr: 230V Contract	10.2%	8.5%	8.2%
	LV : 240V Bφ Trfr: 230V Contract	11.1%	9.4%	9.5%

Table 6.4.1.3: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for existing urban networks that contain a mixture of distribution transformers and contracts where 380/220V transformers supplying 400/230V contracts are NOT supported

Without the constraints imposed by 380/220V transformer and 400/230V contract combinations, the MV regulation limits only increase slightly when the end of line MV voltage recovers to between 102.5% and 100% during the low load condition.

If the constraints imposed by 380/220V contracts and 380/220V transformers are not enforced (no 380/220V equipment or contracts what so ever), the limitation of $\pm 7.5\%$ 400/230V contracts becomes the primary constraint and the results are provided in table 6.4.1.4 below. These limits could be used for urban networks typically built between 1990 and 1998, or for networks older than 1990 but where all 380/220V customer contracts have been upgraded to 400/230V and all 380/220V transformers have been replaced with 400/230V or 415/240V units.

Urban type networks with 415/240V and 400/230V transformers and $\pm 7.5\%$ 400/230V contracts (no 380/220V transformers or 380/220V contracts)		Maximum End Of Line MV voltage		
		≥105%	<105% & ≥100%	<100%
Normal limits	Maximum MV source voltage	110.1%	110.1%	110.1%
	Minimum end of line MV voltage	101.9%	97.0%	92.2%
	Maximum MV voltage drop	8.2%	13.1%	17.9%
Maximum 400/230V LV voltage drops	LV : 415V 3φ Trfr: 400V Contract	10.1%	8.1%	7.0%
	LV : 400V 3φ Trfr: 400V Contract	6.8%	4.6%	4.6%
	LV : 230V 1φ Trfr: 230V Contract	4.6%	4.6%	2.3%
	LV : 240V 1φ Trfr: 230V Contract	8.7%	6.9%	5.4%
	LV : 240V Bφ Trfr: 230V Contract	10.7%	8.7%	7.6%

Table 6.4.1.4: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for existing urban networks with 415/240V and 400/230V transformers and $\pm 7.5\%$ 400/230V contracts (no 380/220V transformers or 380/220V contracts)

If in addition to removing the constraints imposed by 380/220V contracts and 380/220V transformers, the $\pm 7.5\%$ limitation for 400/230V supplies is not enforced and only $\pm 10\%$ 400/230V contracts are met, the MV limits can be significantly increased as per the results in table 6.4.1.5.

Urban type networks with 415/240V and 400/230V transformers and $\pm 10\%$ 400/230V contracts (no 380/220V transformers or 380/220V contracts)		Maximum end of line MV voltage	
		$\geq 100\%$	$< 100\%$
Normal limits	Maximum MV source voltage	110.3%	110.3%
	Minimum end of line MV voltage	94.5%	89.8%
	Maximum MV voltage drop	15.8%	20.5%
Maximum 400/230V LV voltage drops	LV : 415V 3 ϕ Trfr: 400V Contract	5.5%	5.6%
	LV : 400V 3 ϕ Trfr: 400V Contract	2.0%	2.0%
	LV : 230V 1 ϕ Trfr: 230V Contract	2.0%	0.3%
	LV : 240V 1 ϕ Trfr: 230V Contract	6.1%	4.2%
	LV : 240V B ϕ Trfr: 230V Contract	6.1%	6.1%

Table 6.4.1.5: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for existing urban networks with 415/240V and 400/230V transformers and $\pm 10\%$ 400/230V contracts (no 380/220V transformers or 380/220V contracts)

In "new" urban networks which will only contain 415/240V transformers and $\pm 10\%$ 400/230V LV contracts, the allowable MV voltage limits can be increased significantly as shown in table 6.4.1.6 below, but this is achieved at the expense of reduced maximum allowable voltage drops for LV feeders. These limits could be used for urban networks typically built after 1998.

"New" Urban type networks with only 415/240V transformers and $\pm 10\%$ 400/230V contracts		Maximum end of line MV voltage		
		$\geq 105\%$	$< 105\%$ & $\geq 100\%$	$< 100\%$
Normal limits	Maximum MV source voltage	110.3%	110.3%	110.3%
	Minimum end of line MV voltage	95.2%	91.2%	88.5%
	Maximum MV voltage drop	15.1%	19.1%	21.8%
Maximum 400/230V LV voltage drop	LV : 415V 3 ϕ Trfr: 400V Contract	3.4%	2.0%	2.0%
	LV : 240V 1 ϕ Trfr: 230V Contract	2.0%	2.6%	0.9%
	LV : 240V B ϕ Trfr: 230V Contract	3.9%	2.6%	2.7%

Table 6.4.1.6: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for "new" urban networks that contain 415/240V transformers and $\pm 10\%$ 400/230V contracts

6.4.2 Rural Type Networks

The following maximum voltage regulation limits were calculated for rural type networks containing a mixture of common transformers and contracts. It is assumed that some of the 400/230V customers were connected between 1990 and 1996 and hence have $\pm 7.5\%$ contracts that are enforced in the calculated results provided in table 6.4.2.1 below.

Rural type networks with a mixture of common transformers and contracts, where $\pm 7.5\%$ 400/230V contracts are enforced		Maximum end of line MV voltage			
		$\geq 105\%$	$< 105\% \text{ \& } \geq 102.5\%$	$< 102.5\% \text{ \& } \geq 100\%$	$< 100\%$
Normal limits	Maximum MV source voltage	104.8%	104.8%	104.8%	104.8%
	Minimum end of line MV voltage	103.2%	100.6%	98.1%	95.6%
	Maximum MV voltage drop	1.6%	4.2%	6.7%	9.2%
Maximum 400/230V LV voltage drops	LV : 415V 3 ϕ Trfr: 400V Contract	11.8%	9.1%	9.6%	10.1%
	LV : 400V 3 ϕ Trfr: 400V Contract	8.6%	8.5%	7.5%	6.8%
	LV : 380V 3 ϕ Trfr: 400V Contract	3.6%	3.6%	2.7%	2.0%
	LV : 415V 3 ϕ Trfr: 380V Contract	8.8%	6.3%	4.1%	4.1%
	LV : 400V 3 ϕ Trfr: 380V Contract	6.2%	6.0%	5.4%	4.8%
	LV : 380V 3 ϕ Trfr: 380V Contract	3.6%	3.6%	2.7%	2.0%
	LV : 220V 1 ϕ Trfr: 230V Contract	2.0%	4.2%	1.8%	0.2%
	LV : 230V 1 ϕ Trfr: 230V Contract	6.2%	8.5%	6.0%	4.3%
	LV : 240V 1 ϕ Trfr: 230V Contract	10.3%	12.8%	10.2%	8.4%
LV : 240V B ϕ Trfr: 230V Contract	12.3%	12.8%	10.5%	10.6%	

Table 6.4.2.1: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for existing rural networks that contain a mixture of distribution transformers and contracts including 380/220V transformers supplying $\pm 7.5\%$ 400/230V contracts. The $\pm 7.5\%$ limitation is imposed for all 400/230V LV supplies.

The limits in table 6.4.2.1 above could typically be used in rural networks constructed prior to 1990 where there are bound to be 380/220V contracts and transformers.

The real requirement to comply with the $\pm 7.5\%$ limitation for 400/230V customers connected between 1990 and 1996 is debatable, and table 6.4.2.2 contains the results if the limitation of $\pm 10\%$ (not $\pm 7.5\%$) is imposed for 400/230V supplies.

Rural type networks with a mixture of common transformers and contracts, where $\pm 10\%$ 400/230V contracts are enforced		Maximum end of line MV voltage			
		$\geq 105\%$	$< 105\% \text{ \& } \geq 102.5\%$	$< 102.5\% \text{ \& } \geq 100\%$	$< 100\%$
Normal limits	Maximum MV source voltage	104.8%	104.8%	104.8%	104.8%
	Minimum end of line MV voltage	102.2%	98.0%	97.4%	93.1%
	Maximum MV voltage drop	2.6%	6.8%	7.4%	11.7%
Maximum 400/230V LV voltage drops	LV : 415V 3 ϕ Trfr: 400V Contract	10.7%	9.5%	9.2%	7.4%
	LV : 400V 3 ϕ Trfr: 400V Contract	7.6%	5.9%	7.0%	5.1%
	LV : 380V 3 ϕ Trfr: 400V Contract	2.7%	1.0%	2.1%	0.3%
	LV : 415V 3 ϕ Trfr: 380V Contract	7.9%	3.7%	3.5%	1.6%
	LV : 400V 3 ϕ Trfr: 380V Contract	5.3%	3.5%	4.9%	3.2%
	LV : 380V 3 ϕ Trfr: 380V Contract	2.8%	1.0%	2.1%	0.3%
	LV : 220V 1 ϕ Trfr: 230V Contract	1.2%	1.7%	1.0%	0.0%
	LV : 230V 1 ϕ Trfr: 230V Contract	5.3%	5.9%	5.3%	2.6%
	LV : 240V 1 ϕ Trfr: 230V Contract	9.4%	10.1%	9.4%	6.7%
LV : 240V B ϕ Trfr: 230V Contract	11.4%	10.1%	9.8%	7.9%	

Table 6.4.2.2: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for existing rural networks that contain a mixture of distribution transformers and contracts including 380/220V transformers supplying $\pm 10\%$ 400/230V contracts. The $\pm 7.5\%$ limitation is NOT imposed for 400/230V LV supplies and the post 1996 value of $\pm 10\%$ has been enforced.

The resultant MV voltage limits in table 6.4.2.2 are similar to those calculated for normal network conditions in section 6.3.2 and provided in table 6.3.2.1, where the values calculated in section 6.3.2 take into account the recommended operating voltage limits of

motors in rural applications. Regardless of the requirement to meet recommended motor operating voltages it is the requirement to meet the licence obligations for 380V contracts that restricts the MV voltage limits in rural networks, hence the very similar values to those in table 6.3.2.1. In meeting the licence obligations in rural areas with 380V contracts the resultant MV voltage limits will also provide motor voltages within recommended limits for reasonable LV design practices.

As with urban networks the requirement to meet licence limits for 400/230V contracts that are being supplied by 380/220V transformers constrains the allowable MV limits in certain applications. If 380/220V transformers supplying 400/230V contracts are not supported, and the transformer is assumed to be upgraded to either a 400V or 415V transformer, the results are as summarised in table 6.4.2.3 below, and are practically identical to those calculated in section 6.3.2 and summarised in table 6.3.2.1. Note that under these conditions the MV limits are governed by the requirement to meet $\pm 7.5\%$ 380/220V contracts supplied by 380/220V transformers. In so doing the regulation experienced by 400/230V customers in relative close proximity to the 400/230V or 415/240V distribution transformers will fall within $\pm 7.5\%$, and $\pm 7.5\%$ 400/230V contracts are not a constraint.

Rural type networks with a mixture of transformers and contracts (380/220V transformer and 400/230V contract combinations are NOT supported)		Maximum end of line MV voltage			
		$\geq 105\%$	$< 105\% \& \geq 102.5\%$	$< 102.5\% \& \geq 100\%$	$< 100\%$
Normal limits	Maximum MV source voltage	104.8%	104.8%	104.8%	104.8%
	Minimum end of line MV voltage	100.4%	98.0%	95.5%	93.1%
	Maximum MV voltage drop	4.4%	6.8%	9.3%	11.7%
Maximum 400/230V LV voltage drops	LV : 415V 3 ϕ Trfr: 400V Contract	8.9%	9.5%	8.2%	7.4%
	LV : 400V 3 ϕ Trfr: 400V Contract	5.8%	5.9%	5.8%	5.1%
	LV : 415V 3 ϕ Trfr: 380V Contract	6.1%	3.7%	2.5%	1.6%
	LV : 400V 3 ϕ Trfr: 380V Contract	3.5%	3.5%	3.4%	3.2%
	LV : 380V 3 ϕ Trfr: 380V Contract	1.0%	1.0%	1.0%	0.3%
	LV : 230V 1 ϕ Trfr: 230V Contract	3.5%	5.9%	3.4%	2.6%
	LV : 240V 1 ϕ Trfr: 230V Contract	7.6%	10.1%	7.4%	6.7%
LV : 240V B ϕ Trfr: 230V Contract	9.5%	10.1%	8.8%	7.9%	

Table 6.4.2.3: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for existing rural networks that contain a mixture of distribution transformers and contracts where 380/220V transformers supplying 400/230V contracts are NOT supported

As with urban networks, removing the constraint of 380/220V transformer and 400/230V contract combinations increases the allowable MV limits only slightly when compared with the values in table 6.4.2.2. This increase only occurs where the end of line MV voltage recovers to greater than 105%, or between 102.5% and 100%.

If the constraints imposed by 380/220V contracts and 380/220V transformers are not enforced (no 380/220V equipment or contracts what so ever), the limitation of $\pm 7.5\%$ 400/230V contracts becomes the primary constraint and the results are provided in table 6.4.2.4 below. These limits could be used for rural networks typically built between 1990 and 1998, or for networks older than 1990 but where all 380/220V customer contracts have been upgraded to 400/2330V and all 380/220V transformers have been replaced with 400/230V or 415/240V units. The use of these limits will typically result in a 400V motor maximum operating voltage range of $\pm 10\%$.

Rural type networks with 415/240V and 400/230V transformers and $\pm 7.5\%$ 400/230V contracts (no 380/220V transformers or 380/220V contracts)		Maximum end of line MV voltage			
		$\geq 105\%$	$< 105\% \text{ \& } \geq 102.5\%$	$< 102.5\% \text{ \& } \geq 100\%$	$< 100\%$
Normal limits	Maximum MV source voltage	110.3%	110.3%	110.3%	110.3%
	Minimum end of line MV voltage	98.1%	95.7%	93.3%	90.9%
	Maximum MV voltage drop	12.2%	14.6%	17.0%	19.4%
Maximum 400/230V LV voltage drops	LV : 415V 3 ϕ Trfr: 400V Contract	6.6%	5.6%	4.6%	5.0%
	LV : 400V 3 ϕ Trfr: 400V Contract	3.6%	3.6%	2.8%	3.0%
	LV : 230V 1 ϕ Trfr: 230V Contract	1.3%	2.3%	1.2%	0.6%
	LV : 240V 1 ϕ Trfr: 230V Contract	5.3%	6.3%	5.1%	4.5%
	LV : 240V B ϕ Trfr: 230V Contract	7.2%	7.7%	6.0%	5.6%

Table 6.4.2.4: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for existing rural networks with 415/240V and 400/230V transformers and $\pm 7.5\%$ 400/230V contracts (no 380/220V transformers or 380/220V contracts)

If in addition to removing the constraints imposed by 380/220V contracts and 380/220V transformers, the $\pm 7.5\%$ limitation for 400/230V supplies is not enforced and only $\pm 10\%$ 400/230V contracts are met, the MV limits can be significantly increased as per the results in table 6.4.2.5 below. The use of these limits will result in a 400V motor typical maximum operating voltage range of $+10\% -12.5\%$.

Rural type networks with 415/240V and 400/230V transformers and $\pm 10\%$ 400/230V contracts (no 380/220V transformers or 380/220V contracts)		Maximum end of line MV voltage		
		$\geq 105\%$	$< 105\% \text{ \& } \geq 100\%$	$< 100\%$
Normal limits	Maximum MV source voltage	110.3%	110.3%	110.3%
	Minimum end of line MV voltage	97.9%	93.2%	88.6%
	Maximum MV voltage drop	12.4%	17.1%	21.7%
Maximum 400/230V LV voltage drops	LV : 415V 3 ϕ Trfr: 400V Contract	6.4%	4.5%	3.7%
	LV : 400V 3 ϕ Trfr: 400V Contract	3.4%	1.0%	1.0%
	LV : 230V 1 ϕ Trfr: 230V Contract	1.0%	1.0%	0.0%
	LV : 240V 1 ϕ Trfr: 230V Contract	5.1%	5.0%	3.4%
	LV : 240V B ϕ Trfr: 230V Contract	7.0%	5.0%	4.2%

Table 6.4.2.5: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for existing rural networks with 415/240V and 400/230V transformers and $\pm 10\%$ 400/230V contracts (no 380/220V transformers or 380/220V contracts)

In "new" rural networks the allowable MV voltage limits can be increased significantly as shown in table 6.4.2.6 below, but this is achieved at the expense of reduced maximum allowable voltage drops for LV feeders.

"New" Rural type networks with only 415/240V transformers and $\pm 10\%$ 400/230V contracts		Maximum end of line MV voltage			
		$\geq 105\%$	$< 105\% \text{ \& } \geq 102.5\%$	$< 102.5\% \text{ \& } \geq 100\%$	$< 100\%$
Normal limits	Maximum MV source voltage	110.3%	110.3%	110.3%	110.3%
	Minimum end of line MV voltage	93.9%	89.9%	89.4%	87.2%
	Maximum MV voltage drop	16.4%	20.4%	20.9%	23.1%
Maximum 400/230V LV voltage drops	LV : 415V 3 ϕ Trfr: 400V Contract	2.4%	1.0%	3.4%	1.0%
	LV : 240V 1 ϕ Trfr: 230V Contract	1.0%	1.6%	1.0%	1.0%
	LV : 240V B ϕ Trfr: 230V Contract	2.9%	1.6%	4.0%	1.6%

Table 6.4.2.6: Calculated maximum voltage regulation limits to only meet licence/contractual voltage limits for "new" rural networks that contain 415/240V transformers and $\pm 10\%$ 400/230V contracts

6.5 SUMMARY

The voltage regulation limit model enables the assessment of combinations of distribution transformer nominal voltages, flux limitations, DETS characteristics, LV design practices, contractual/licence obligations and appliance operating voltage requirements.

The calculated minimum MV voltage at a particular point in a network is dependent on the maximum DETS boost allowed on the local distribution transformer. The maximum distribution transformer DETS boost is limited by a combination of the maximum MV voltage, service/appliance voltage limit and maximum transformer flux limit. With 380/220V and 400/230V transformers the limitation on the maximum flux level of 105% can undesirably restrict the maximum DETS tap boost. In the case of 415/240V transformers the maximum motor voltages restrict the maximum DETS boost.

The presence of older 380/220V transformers and contracts in urban networks limits the maximum LV voltage drops in the LV networks supplied by these effected distribution transformers.

The presence of older 380/220V transformers and contracts in rural networks limits the maximum MV voltage drops as compared with rural networks that only contain 400/230V contracts, and 400/230V and 415/240V transformers. The calculated MV voltage limits in networks containing 380/220V transformers and contracts however result in motor running voltages within the recommend limits. In addition the resultant LV voltage drops are in agreement with historical and present LV design practices.

7 RECOMMENDED MAXIMUM VOLTAGE REGULATION AND VOLTAGE DROP APPORTIONMENT LIMITS

In order to facilitate the practical implementation of voltage limits and apportionment it is necessary to settle on a reduced set of apportionment limits which offer an acceptable compromise and cover most of the likely combinations of equipment specifications and licence and contractual obligations.

The results obtained from the voltage regulation limit model (see section 6) are based on reasonable LV design practices, and typical parameters for equipment, contractual/license obligations and appliance operating voltage ranges. These results however need to be simplified and refined to become directly applicable. This section provides recommended limits for three classifications of network. It describes the basis for the classifications, and the voltage drop apportionment limits associated with each classification. The selection criteria to be used for network classification selection are summarised, and the customisation of voltage drop limits and apportionment is introduced.

7.1 BASIS FOR THE RECOMMENDATIONS

The following sections contain additional detail supporting the recommendation that separate limits and apportionment be provided for the following three classifications of network:

- Urban networks (U): Applies to all urban networks
- Rural networks with 380/220V transformers and contracts (R1): These networks were typically constructed prior to 1990 and hence contain 380/220V transformers and contracts
- Rural networks without 380/220V transformers or contracts (R2): These networks were typically constructed after 1990 (or for networks constructed prior to 1990 where the 380/220V transformers and contracts have been upgraded)

7.1.1 Alignment with Present Practices

The recommendations must have practical align with the typical LV voltage drops that have historically been used by network planners and designers (see section 3.4). If extensive LV systems have been designed for a voltage drop of 5%, and the new recommended limits require this maximum voltage drop to be decreased to 3%, considerable additional capital will be required. The implementation of such limits would be very difficult to motivate. The recommended limits should aim to complement the existing design practices, and provide upgrade alternatives such that the optimal apportionment between MV and LV voltage drops can be achieved in the longer term as older networks are upgraded and refurbished.

7.1.2 Standardised LV Apportionment for the Entire Feeder

The maximum allowable LV voltage drops are based on the limits at the feeder extremities. If these LV limits are used in the design of LV networks closer to the feeder source, the MV regulation will be better (less). As a result the end of line LV service voltages will be better (closer to nominal) for these LV systems closer to the feeder source. In theory it would be possible to calculate the maximum allowable LV voltage drop for each LV network supplied

by each distribution transformer on an MV feeder. This would however be extremely calculation intensive and would also require customised LV voltage drop limits to be stored for each local LV network. Not only would the practical implications possibly be difficult and costly to overcome, but the networks and the loads they supply are also dynamic and can change drastically.

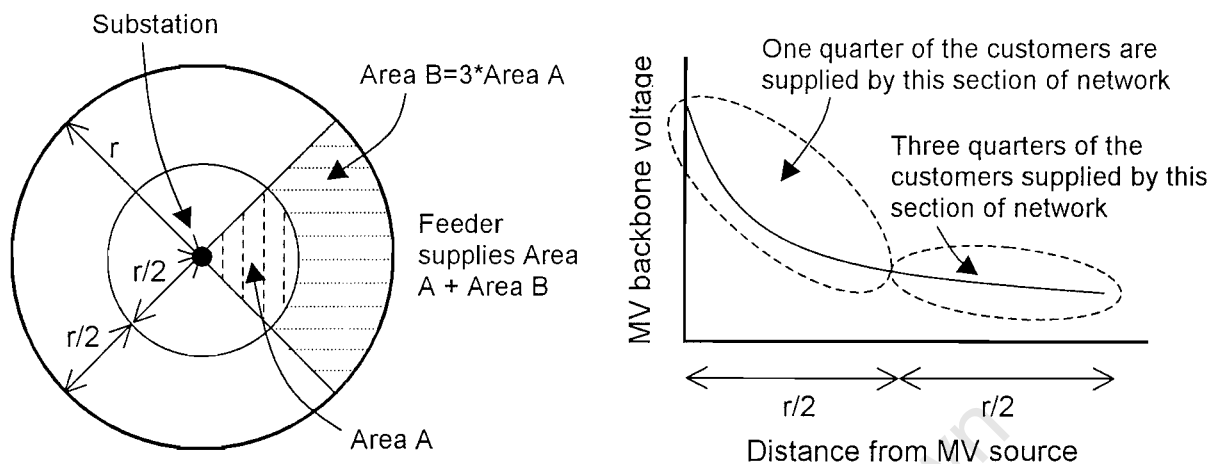


Figure 7.1.2: Simplified illustration of urban feeder layout and backbone voltage drop

Referring to figure 7.1.2, due to the physical nature of MV feeder layouts most of the customers are supplied by the feeder extremities (only one quarter of the customers in the illustration are supplied off the first half of the MV feeder backbone). Furthermore due to the load distribution and use of standardised MV backbone conductors, the majority of the MV feeder voltage drop usually occurs within a relatively short distance from the source. The net effect of these two practical conditions is that the MV voltages supplying the majority of the customers will be at or close to the minimum MV voltage on the feeder. As a result it is recommended that the allowable LV voltage drops be standardised based on the limitations of the feeder extremities, in the knowledge that the regulation of the LV networks supplied close to the feeder source will typically be well within required limits. Should developments in systems and other requirements facilitate the calculation of customised LV limits, and research show that the potential cost savings in designing for higher LV voltage drops adequately covers this additional expense, then this premise of a single value for use over the entire feeder can be revisited.

7.1.3 Standardised Apportionment for Urban Networks

The presence of 380/220V transformers and contracts has been identified as a limitation on the maximum MV voltage limits. It must be established whether different apportionment levels are justified for urban networks that contain older 380/220V transformers and contracts, and urban networks that only contain 400/230V contracts, and 400/230V and 415/240V transformers.

Referring to tables 6.3.1.1 and 6.3.1.2, the maximum MV source voltages are 104.3% and 106.6% for urban networks with and without 380/220V contracts respectively. When 415/240V transformers are used to supply 380/220V contracts the maximum MV voltage must be limited to 104.3% if the upper +7.5% voltage limit of the 380/220V contract is to be met. This takes into account that 415/240V transformers are capable of bucking by a maximum of 6%. If the limitation of the 380/220V contract is removed, the maximum MV

voltage can be increased to 106.6%. However due to flux limitations on the source sub-transmission transformer this increased MV range can not be utilised.

Referring to tables 6.3.1.1 and 6.3.1.2, the minimum end of line MV voltages drop by between 0.5% and 1.5% if 380/220V contractual limits are met i.e. the allowable MV voltage drop increases slightly without the restrictions of the 380/220V contract.

In summary the useable MV voltage range in urban networks is not significantly effected by the presence of 380/220V contracts. This is as a result of the flux limitations on the source sub-transmission transformer, and the requirement to keep significant three phase motor operating voltages with $\pm 5\%$ of nominal voltage (could be 380V or 400V motors).

This research recommends that a single set of MV and LV voltage limits and apportionment figures be used for all urban networks i.e. the same MV and LV limits should be used in urban networks regardless of whether these networks contain any 380/220V contracts, transformers or motors.

7.1.4 Standardised Apportionment for Rural Networks

Referring to tables 6.4.2.2 and 6.4.2.4 the presence of 380/220V transformers and contracts in rural networks reduces the allowable MV voltage drop by 2.5%. Unlike urban networks the wider motor operating limits catered for in rural networks does not inherently limit the MV such that 380/220V transformers and contracts are not the primary limitation. As a result two classifications of rural network are provided, to cater for rural networks both with and without 380/220V transformers and contracts.

7.1.5 Standardised LV Apportionment for Different LV Technologies

Eskom's distribution transformer secondary voltages and DETS tap ranges and step sizes vary for each of the LV technology options. These slight changes influence the transformer secondary voltages. The LV voltage drop limit is related to the fineness of the adjustment of the transformer DETS boost or buck. More tap positions with smaller step sizes result in better utilisation of the available voltage regulation range, and hence increased maximum LV voltage drop. Single phase transformers only have three tap positions while three and bi phase transformers have 5 tap positions. As a result the allowable LV voltage drops for single phase transformers are in certain instances less than for bi phase and three phase units (see tables 6.3.1.1 and 6.3.2.1). The recommended maximum voltage drops for LV networks are based on bi phase and three phase transformer DETS characteristics. This simplification may in certain applications result in low service voltages for LV networks supplied by single phase transformers, but is considered acceptable for the following reasons:

- For practical reasons it is desirable to have the same limits for single, bi and three phase systems, especially since networks and upgrade paths can consist of a mixture of compatible technologies.
- With reference to tables 6.3.1.1 and 6.3.2.1 the difference in calculated allowable LV voltage drop between single and bi/three phase transformers only becomes appreciable when the end of line MV voltages drop below 99.5% and 98% for urban and rural networks respectively.
- Any problems will generally be limited to rural networks, as the number of single phase transformers in urban networks is typically very low.
- The possible error in using this simplification is an end of line service voltage drop of 2% and 3% below the recommended minimum values for rural and urban networks

respectively i.e. 88% and 87% service voltages. The error figures are calculated by comparing the maximum LV voltage drop limits (in tables 6.3.1.1 and 6.3.2.1) for three and bi phase transformers with those calculated for single phase transformers.

- The limitation of the single phase transformer DETS taps will only occur in certain applications in a zone on an MV feeder where the MV voltages are relatively low, but the end of line voltage recovers above 100%. Under these conditions if the DETS 5% boost were to be utilised the 105% limit on the transformer flux would be exceeded. This limitation will only occur for a section of the feeder (not the entire feeder), and can be overcome if the maximum flux levels for single phase transformers are allowed to be exceeded. If situations occur where the LV (based on the recommended apportionment) fed from a single phase transformer does result in low service voltages, the transformer DETS 5% boost could be used resulting in high, but not dangerous levels of flux (typically between 105% and 107%).

7.1.6 Enforcement of Motor Regulation Ranges and $\pm 7.5\%$ 400/230V Contracts

Two of the main issues that need to be addressed are whether the recommended appliance (typically three phase motor) operating voltage ranges and $\pm 7.5\%$ 400/230V contracts should be enforced when deciding on MV system voltage limits.

7.1.6.1 Urban type networks

In urban type networks where load densities are relatively high, MV voltage regulation seldom exceeds 5%. Research into the optimal voltage drop limit for LV networks supplying domestic type loads concluded that the recommended LV voltage drop typically falls between 8.2% and 20.5% [75]. The research did not consider the optimisation between MV and LV voltage drops, and as such the recommended LV voltage drops may be sub-optimised. The research does however show that, where possible, it is desirable to provide an apportionment standard that tries to facilitate increased LV voltage drop magnitudes. In ensuring that recommended operating voltage ranges for motors supplied in close proximity to distribution transformers in urban networks are met, the calculated values in tables 6.3.1.1 and 6.3.1.2 provide for a reasonable compromise between MV and LV regulation in line with present and historical LV design practices. These limits also ensure that the voltages delivered to any $\pm 7.5\%$ 400/230V contract customers in relatively close proximity to the distribution transformers will fall within the contracted range. The voltages near the extremities of LV feeders may fall outside of $\pm 7.5\%$ but within $\pm 10\%$, so it is highly unlikely that $\pm 7.5\%$ 400/230V customers on LV feeder extremities would complain as they would typically be domestic type loads. Larger customers with sensitive equipment and $\pm 7.5\%$ 400/230V contracts will usually be located in close proximity to the distribution transformers.

As documented in section 6.4, the larger MV voltage drops possible in urban networks could only be achieved at the expense of reduced LV voltage drops. Due to the load types and load densities supplied by MV systems, these larger MV voltage drops are not recommended as the economic sizing of the MV feeders will typically result in MV voltage drops within the ranges catered for in tables 6.3.1.1 and 6.3.1.2.

The limits for urban networks should be based on the principle that the recommended motor operating voltage ranges and $\pm 7.5\%$ LV contracts will be met where these motors and $\pm 7.5\%$ LV contracts are supplied in close proximity to the distribution transformers. This also results in an acceptable compromise between primary MV and secondary LV system voltage drops.

7.1.6.2 Rural type networks

In rural networks if the limitation of a contracted voltage variation of $\pm 7.5\%$ is enforced for 400/230V supplies (connected between 1990 and 1996) the calculated MV limits are restricted when these customers are supplied by 380/220V transformers. The real requirement to meet this $\pm 7.5\%$ limitation is debatable. Furthermore it is unlikely that these $\pm 7.5\%$ 400/230V customers are supplied by 380/220V transformers in rural areas, as these customers would have typically had a dedicated transformer installed as part of their connection. This transformer would have been a 400/230V unit. As a result the recommended limits for rural networks will not ensure that $\pm 7.5\%$ 400/230V contracts supplied by 380/220V transformers will be complied with. Where isolated problems occur, the 380/220V transformer can be replaced with a 415/240V unit.

In rural networks with 380/220V transformers supplying 380/220V and $\pm 10\%$ 400/230V contracts the requirement to meet the licence / contractual obligations inherently results in MV voltage limits that provide motor operating voltages within those recommended for significant rural type motor applications (for typical LV network design practices). As a result for most networks constructed prior to 1990 (containing 380/220V transformers and contracts) the voltage limits are dictated by the licence / contractual obligations, and not the recommended motor operating voltages. However in networks constructed after 1990 that do not have any 380/220V transformers or contracts (or for older networks where 380/220V transformers and contracts have been upgraded) the recommended motor operating voltage ranges could dictate the voltage limits and apportionment. Referring to figure 3.1.1, note that as the bottom of the voltage windows for 380/220V and $\pm 10\%$ 400/230V contracts are the same, it is the presence of 380/220V transformers and not 380/220V contracts that is the key limitation on the minimum MV voltage. The presence of 380/220V contracts however limits the amount of distribution transformer boosting, and hence restricts allowable maximum LV voltage drops. In summary 380/220V transformers restrict the minimum MV voltage, and 380/220V contracts limit the maximum LV voltage drop.

Increasing the recommended three phase motor operating voltage range above $\pm 7.5\%$ for rural networks without any 380/220V equipment or contracts will enable wider MV limits which are achieved at the expense of reduced allowable LV voltage drop. In systems with very limited LV networks this could result in significant cost savings.

In summary, in rural networks containing 380/220V transformers and contracts the associated MV limits to meet the contractual/licence obligations will result in motor operating voltages less than $\pm 7.5\%$. In rural networks that do not contain any 380/220V transformers or contracts the maximum motor operating voltage range should be increased to $\pm 10\%$ to facilitate increased maximum MV voltage drops.

7.1.7 Increasing the Maximum Recommended Voltage Drops of LV Networks Supplied by 380/220V Transformers

If the transformer flux level is limited to 105% when using 380/220V transformers to supply 400/230V LV customers, the allowable LV voltage drop is extremely prohibitive in both urban and rural networks. Referring to table 6.3.1.1, if the flux limit of 105% is met the maximum LV voltage drop below 380/220V transformers in urban networks must be limited to between 3% and 4.5%. As documented in section 3.4.2, many older 380/220V networks have been designed for a LV voltage drop of 5%. This conflict has arisen due to the differences between the lower limits for 380/220V and 400/230V contracts. $380V - 7.5\% = 400V - 12.1\%$. If the 400/230V $\pm 10\%$ contract is to be enforced the LV voltage drops in LV

networks supplied by 380/220V transformers must be reduced by roughly 12.1% - 10% = 2.1%.

In order to provide for the existing older 380/220V network limitations there are two options:

- 1) Reduce the allowable MV voltage drop by between 0.5% and 2% depending on the extent by which the MV voltage recovers during the low load condition
- 2) Allow the 380/220V transformer maximum flux level to be increased to 107%

Option 2 is preferred for the following reasons:

- Many regions have been operating 380/220V transformers at flux levels between 105% and 110%. The real impact of this operational practice has not been properly quantified, but it would appear to be an acceptable practice
- The MV voltage drop limits provided in tables 6.3.1.1 and 6.3.2.1 are already considered to be relatively restrictive in comparison with the existing practices in certain regions
- These 380/220V transformers are relatively old and many may be due for replacement anyway. Should the unit fail under operation at these higher flux levels it will typically be replaced with a new 415/240V transformer and any over fluxing problems no longer exist due to the much higher secondary LV nominal voltage
- The 105% flux level will only need to be exceeded near MV feeder extremities, and then only when the minimum MV end of line voltages approach the recommended minimum values. Not all 380/220V transformers on a feeder will be required to operate at these increased flux levels.

The LV voltage drop limits for 400/230V domestic type customers supplied by 380/220V transformers are hence based on the knowledge that in order to provide adequate service voltages the flux levels on these 380/220V transformers may exceed 105%.

7.1.8 LV Feeder Voltage Drop for Significant Three Phase Motor Loads

The MV limits recommended for each of the classifications of network will result in acceptable three phase motor operating voltages provided these motor loads are supplied in relatively close proximity to the distribution transformers. For each of the classifications of MV network, limits are provided for the maximum voltage drops in the LV networks supplying significant three phase motor loads. In each case an "ideal" and "maximum" LV voltage drop is provided. The "ideal" voltage drop will meet the recommended motor operating voltages for that particular network classification. The "maximum" voltage drop will not ensure that recommended motor operating voltage are met, but will ensure compliance of the contractual/licence obligations at the point of supply.

Designers should attempt to ensure that the LV voltage drops are below the "ideal" value, but should the cost premium prove to be prohibitive the "maximum" value could be used but will require that the motor(s) be typically de-rated by 10% to 20%.

The "ideal" and "maximum" values are analogous to the "planning" and "compatibility" levels supported by the NRS 048.

7.2 NETWORK CLASSIFICATIONS AND RECOMMENDED LIMITS

The next sub-sections provide recommended limits and apportionment for three basic network classifications, and with reference to figures 7.2.1 and 7.2.2, the following definitions and descriptions apply:

Normal limits: The “Normal” limits for MV voltage regulation should be used for the planning and designing of new networks, and extensions to and strengthening of existing MV systems. The normal limits are the equivalent of the “planning” levels supported by the NRS 048.

Abnormal limits: The “Abnormal” limits for MV voltage regulation should be used when evaluating system contingencies (abnormal system states such as temporary network reconfigurations due to equipment failure). These abnormal limits can also be used by planners to delay need dates and provide the necessary lead times for strengthening projects. Networks should not be operated indefinitely at the recommended abnormal limits. The use of the abnormal limits may result in violation of contractual limits for customers on the extremities of feeders. The abnormal limits are the equivalent of the “compatibility” levels supported by the NRS 048. The implications of the abnormal limits are discussed further in section 10.6.

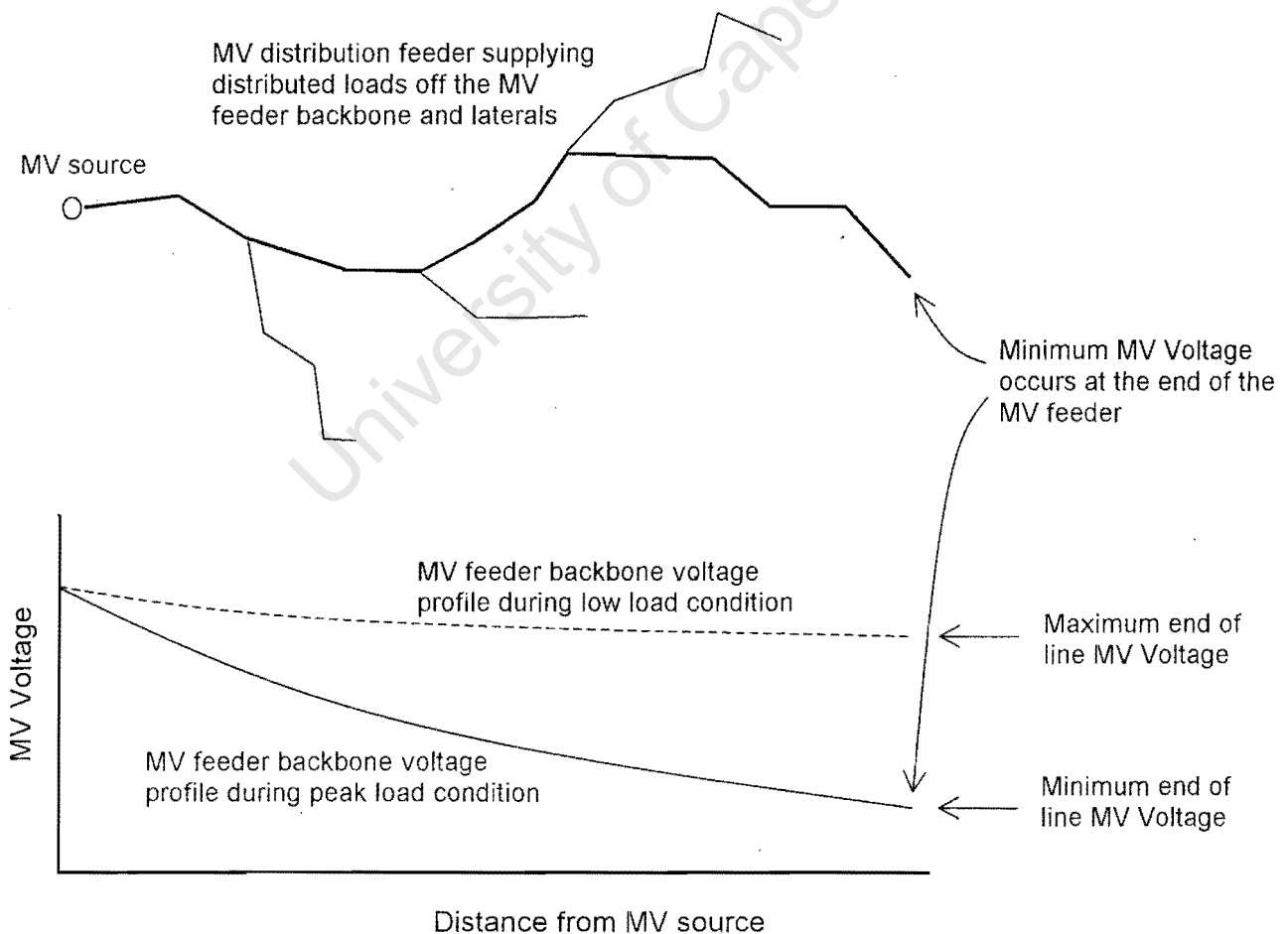


Figure 7.2.1: Illustration of a radial distribution feeder and its associated voltage profile during peak and low load conditions.

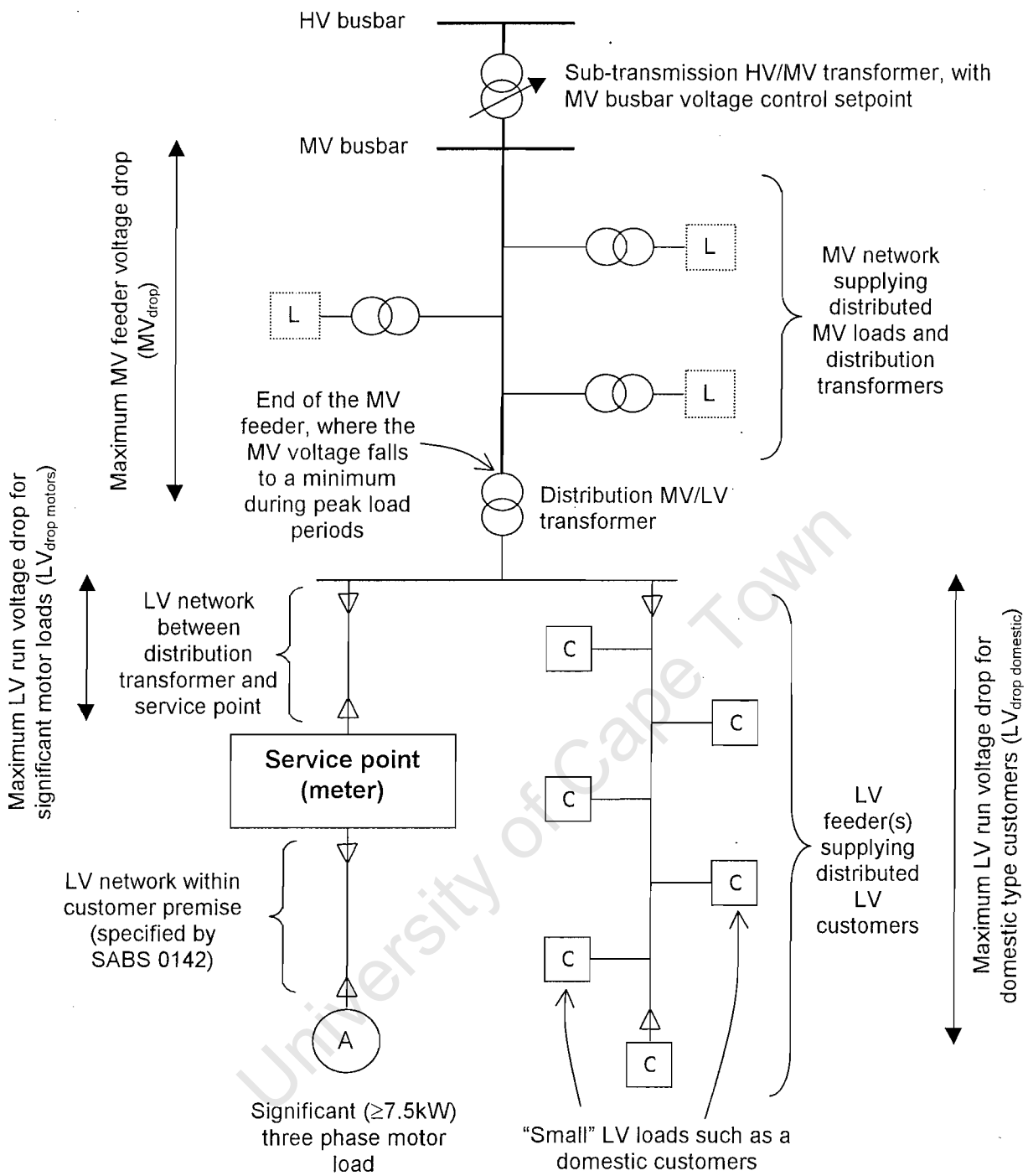


Figure 7.2.2: Illustration of the major components of a distribution network, including the associated voltage drops for which maximum recommended limits are provided.

Maximum MV source setpoint: The maximum recommended setpoint voltage for the MV source sub-transmission transformer OLTC control relay. This limit is imposed to prevent unacceptable over fluxing of the sub-transmission and distribution transformers, and to limit both transient and steady state over voltage magnitudes. As the "sending" MV source voltage varies about the setpoint with an adjustable (user defined) bandwidth, in reality the maximum MV source sending voltage will be slightly higher than the setpoint, and the maximum setpoint value takes this bandwidth into account.

Maximum end of line MV voltage: The maximum MV voltage at the point in the network at which the minimum MV voltage occurs (typically the end of the MV feeder). While most distribution transformers have DETS settings that enable the local LV voltage to be boosted above nominal, the ability to utilise these tap positions is limited by over voltage and flux constraints. The ability to use the DETS settings to boost the LV voltage and thereby enable increased MV and/or LV voltage drops is limited by the extent by which the local MV voltage recovers (rises) during low load conditions. In order to determine the level of allowable LV boosting (via the DETS), and hence minimum allowable MV system limits, the maximum MV voltage is required at the point at which the MV voltage drops to a minimum. This point will usually be at the end of the MV feeder, but could be on the source side of downstream voltage regulators where the minimum MV voltage occurs just before the regulator installation.

Minimum end of line MV voltage: The minimum MV voltage on the feeder, which as discussed above, will usually occur during peak load conditions at the end of the feeder. The maximum and minimum “end of line” MV voltages are the corresponding voltages on the source side of a voltage regulator installation if the minimum MV voltage occurs at that point in the network. This would be the case where the MV voltage on the incoming side of the voltage regulator is lower than the MV voltage at the end of the MV feeder.

Maximum MV voltage drop (MV_{drop} in figure 7.2.2): The maximum MV voltage drop is the recommended maximum MV voltage drop between the MV source and the point of minimum MV voltage (usually the end of the MV feeder). It is simply the difference between the maximum MV source voltage setpoint and the minimum MV voltage as proposed by the research.

Maximum LV voltage drop for domestic type customers ($LV_{drop\ domestic}$ in figure 7.2.2): The maximum LV voltage drop for domestic type customers is the recommended maximum LV voltage drop between the distribution transformer and the customer service point (meter) for domestic type LV supplies. These customers would include all single phase, light commercial and other loads which do not contain any significant ($\geq 7.5\text{kW}$) three phase motors.

Maximum LV voltage drop for significant motor loads ($LV_{drop\ motors}$ in figure 7.2.2): The maximum LV voltage drop for significant motor loads is the recommended maximum LV voltage drop between the distribution transformer and the customer service point (meter) for significant ($\geq 7.5\text{kW}$) three phase LV motor supplies. The voltage drop should, where reasonable, be kept within the “ideal” limits provided as this will ensure that the motor operating voltages will be acceptable for reasonable LV wiring practices in the customers premise. The “maximum” limits can be used (ensuring compliance with licence obligations) but motor operating voltages will typically require that the motor be significantly de-rated.

7.2.1 Urban Networks (U)

U: Urban type networks with a mixture of transformers and motors		Maximum end of line MV voltage		
		≥102.5%	<102.5% & ≥100%	<100%
Normal limits	Maximum MV source setpoint (a)	104%		
	Minimum end of line MV voltage (b)	102.0%	99.5%	97.0%
	Maximum MV voltage drop (c)	2.0%	4.5%	7.0%
Abnormal limits	Maximum MV source setpoint	105%		
	Minimum end of line MV voltage	99.5%	97.0%	94.5%
	Maximum MV voltage drop	5.5%	8.0%	10.5%

Table 7.2.1.1: Recommended maximum MV voltage regulation limits for urban networks

Referring to the above table, note that the maximum MV voltage drop (c) is simply the difference between the sending MV voltage (a) and minimum end of line MV voltage (b). If the sending MV voltage is set lower than the maximum permissible value (a), the maximum MV voltage drop (c) must be reduced accordingly.

For “new” (post 1998) urban networks with 415/240V transformers and 400/230V motors (no older 380/220V motors and 380/220V or 400/230V transformers) the maximum sending MV voltage can be increased from 104% to 105% for both normal and abnormal conditions. This is due to the fact that these networks do not have any 380/220V contracts, which when supplied by 415/240V transformers are the primary limitation on the maximum MV voltage.

Transformer	Maximum LV voltage drop
415/240V transformers with no 380V contracts	11%
400/230V transformers with no 380V contracts	8.5%
380/220V transformers	5%
415/240V and 400/230V transformers with 380V contracts	5%

Table 7.2.1.2: Recommended maximum 400/230V LV voltage drops for domestic type customers ($LV_{drop\ domestic}$) in urban networks

Transformer	Ideal LV voltage drop	Maximum LV voltage drop
415/240V	≤5%	11%
400/230V	≤2%	8.5%

Table 7.2.1.3: Recommended 400V LV voltage drops are for significant ($\geq 7.5\text{kW}$) 400V three phase motor loads ($LV_{drop\ motors}$) in urban networks. The “ideal” and “maximum” values will result in maximum motor operating voltages of $\pm 5\%$ and $\pm 12.5\%$ respectively for reasonable LV design practices in the customers premise

Note that the recommended MV regulation limits will also ensure compliance for any bulk MV customers with $\pm 5\%$ supply contracts.

7.2.2 Rural Networks with 380/220V Transformers and Contracts (R1)

R1: Rural type networks with a mixture of transformers and motors		Maximum end of line MV voltage			
		≥105%	<105% & ≥102.5%	<102.5% & ≥100%	<100%
Normal limits	Maximum MV source setpoint	105%			
	Minimum end of line MV voltage	100.5%	98.0%	95.5%	93.5%
	Maximum MV voltage drop	4.5%	7.0%	9.5%	11.5%
Abnormal limits	Maximum MV source setpoint	105%			
	Minimum end of line MV voltage	98.0%	95.5%	93.5%	91.0%
	Maximum MV voltage drop	7.0%	9.5%	11.5%	14.0%

Table 7.2.2.1: Recommended maximum MV voltage regulation limits for rural networks that have 380/220V transformers and contracts. These limits would apply to most rural feeders constructed prior to 1990

Transformer	Maximum LV voltage drop
415/240V transformers with no 380V contracts	7.5%
400/230V transformers with no 380V contracts	5%
380/220V transformers	2.5%
415/240V and 400/230V transformers with 380V contracts	2.5%

Table 7.2.2.2: Recommended maximum 400/230V LV voltage drops for domestic type customers ($LV_{drop\ domestic}$) in rural networks that have 380/220V transformers and contracts

Transformer	Ideal LV voltage drop	Maximum LV voltage drop
415/240V	≤4%	7.5%
400/230V	≤1%	5%

Table 7.2.2.3: Recommended 400V LV voltage drops are for significant ($\geq 7.5\text{kW}$) 400V three phase motor loads ($LV_{drop\ motors}$) in rural networks that have 380/220V transformers and contracts. The “ideal” and “maximum” values will result in maximum motor operating voltages of $\pm 7.5\%$ and $\pm 12.5\%$ respectively for reasonable LV design practices in the customers premise

The recommended MV regulation limits will in most cases result in compliance for bulk MV customers with $\pm 5\%$ supply contracts. The MV should only be allowed to drop below 95% (but not below 93.5% during normal conditions) if the end of line MV voltage does not recover above 100%. This less than 95% voltage condition is acceptable if the bulk MV supplies experiencing these MV voltages below 95% have standard $\pm 7.5\%$ supply contracts. The MV system could be operated below 95% with $\pm 5\%$ supply contracts if the frequency and duration of the “excessive” regulation were considered acceptable in relation to the cost required to provide the contracted regulation limits. In these cases each situation would need to be evaluated on its individual merits taking into account the sensitivity of the customer load and possible repercussions due to not complying with the supply contract and or license agreements.

7.2.3 Rural Networks with no 380/220V Transformers or Contracts (R2)

R2: Rural type networks with 415/240V and 400/230V transformers and 400/230V contracts (no 380/220V transformers or 380/220V contracts)		Maximum end of line MV voltage			
		≥105%	<105% & ≥102.5%	<102.5% & ≥100%	<100%
Normal limits	Maximum MV source setpoint	105%			
	Minimum end of line MV voltage	98.0%	95.5%	93.0%	91.0%
	Maximum MV voltage drop	7.0%	9.5%	12.0%	14.0%
Abnormal limits	Maximum MV source setpoint	106%			
	Minimum end of line MV voltage	98.0%	93.0%		88.5%
	Maximum MV voltage drop	8.0%	13.0%		17.5%

Table 7.2.3.1: Recommended maximum MV voltage limits for rural networks that do not have any 380/220V transformers or contracts. These limits would apply to most rural feeders constructed after 1990

Note that under abnormal conditions the maximum MV source setpoint can be increased to 106% as compared with the 105% limit for R1 networks. This is due to the fact that these networks do not have any 380/220V contracts, which when supplied by 415/240V transformers are the primary limitation on the maximum MV voltage. Increasing the setpoint above 106% is not recommended due to the flux limitations on the source sub-transmission transformer.

Transformer	Maximum LV voltage drop
415/240V transformers with no 380V contracts	5%
400/230V transformers with no 380V contracts	2.5%

Table 7.2.3.2: Recommended maximum 400/230V LV voltage drops for domestic type customers ($LV_{drop\ domestic}$) in rural networks that do not have any 380/220V transformers or contracts

Transformer	Ideal LV voltage drop	Maximum LV voltage drop
415/240V	≤2.5%	5%
400/230V	≤1%	2.5%

Table 7.2.3.3: Recommended 400V LV voltage drops are for significant ($\geq 7.5\text{kW}$) 400V three phase motor loads ($LV_{drop\ motors}$) in rural networks that do not have any 380/220V transformers or contracts. The "ideal" and "maximum" values will result in maximum motor operating voltages of $\pm 10\%$ and $\pm 12.5\%$ respectively for reasonable LV design practices in the customers premise

The presence of any bulk MV supplies may limit the application of the recommended minimum MV voltages. With reference to table 7.2.3.1 above, as the vast majority of MV bulk supplies have contracted voltage variations of $\pm 7.5\%$, a minimum MV voltage of 93% should be acceptable, and the recommended limit of 91% would need to be raised to 92.5%.

7.3 MOTOR DE-RATING FACTORS

The recommended limits for each of the three network classifications described in section 7.2 will ensure that the contractual/licence obligations at the service points are met. The associated motor operating voltage variations differ for each of the network classifications due to the requirement to maximise LV and MV voltage drops in urban and rural networks respectively. If significant ($\geq 7.5\text{kW}$) motor loads are supplied in relatively close proximity to distribution transformers (see table 7.3.2), motors supplied by urban networks should not

need to be de-rated. Motors supplied on the extremities of rural feeders will typically need to be de-rated (see table 7.3.2).

Network Classification	Typical maximum motor voltage variation	Associated motor de-rating factor
Urban (U)	±5%	0%
Rural with 380/220V transformers and contracts (R1)	±7.5%	0% to 10%
Rural with no 380/220V transformers or contracts (R2)	±10%	10% to 20%

Table 7.3.2: Typical maximum motor voltage variations and associated typical de-rating factors for three phase motor loads if the LV networks between the distribution transformer and supply point are designed in accordance with the "ideal" voltage drop limits provided in tables 7.2.1.3, 7.2.2.3 and 7.2.3.3.

Designing LV networks supplying significant motor loads using the "maximum" limits provided in tables 7.2.1.3, 7.2.2.3 and 7.2.3.3 will result in typical maximum motor voltage variations of ±12.5% for all three network classifications. As documented in section 7.1.8 this practice should be avoided where possible. While Eskom should aim to keep the significant motor load LV runs below the "ideal" limits these limits will not be guaranteed. Eskom will only ensure compliance with the contractual/licence obligations at the point of supply. Many customers will however receive voltages well within the maximum limits due to their physical location in the network. The onus should be on the customer (with the assistance of the utility where necessary) to ensure that the customer's appliances (such as significant motor loads) are self protecting in the event that overheating occurs due to insufficient motor de-rating.

7.4 NETWORK CLASSIFICATIONS FOR ELECTRIFICATION LOAD

Rural networks are characterised by low load densities, and in the absence of electrification type load, customers are usually supplied via dedicated distribution transformers and LV networks are relatively small. On the other extreme urban networks have high load densities and extensive LV networks where many customers are supplied per distribution transformer. In reality any given network (such as a rural feeder supplying extensive electrification load) may fall between these two extremes, and the recommended MV and LV limits and apportionment could lie between the limits of the two extremes.

There are 9.6m households in South Africa, of which over 70% have been electrified. Of the electrified households, 70% are in rural areas and 30% in urban areas. A total of 2.9m households presently do not have access to electricity, and the majority of the households (2.2m) are in rural areas [78]. Due to ongoing commitments to rural electrification the bulk of the new connections and network expansions in Eskom's distribution networks will be to supply rural electrification load.

The maximum LV voltage drops for domestic/electrification type connections are provided in tables 7.2.1.2, 7.2.2.2 and 7.2.3.2 for each of the three network classifications (U, R1 and R2). Assuming that the new electrification customers are supplied by 415/240V transformers the maximum LV voltage drop and associated LV capital cost savings are provided in table 7.4.1, where the relative cost savings are based on table 3.4.3.1.

Network Classification	Maximum LV voltage drop	Relative cost savings: 1648m ² stand	Relative cost savings: 3846m ² stand	Relative cost savings: 7225m ² stand
Urban (U)	11%	R183	R219	R493
Rural with 380/220V transformers and contracts (R1)	7.5%	R135	R124	R352
Rural with no 380/220V transformers or contracts (R2)	5%	NIL (reference)		

Table 7.4.1: Maximum LV voltage drop limits for domestic/electrification loads and the associated LV network capital savings per connection for the three network classifications and stand sizes. Cost are in 1998 Rands based on table 3.4.3.1

All three of the network classifications can be used to supply electrification load. They differ in the apportionment between MV and LV voltage drops. No one classification is necessarily better than the other ones. In certain cases it may be very cost effective to provide a strong MV source and hence enable the use of the urban (U) limits thereby maximising the allowable LV voltage drop. In other cases it may be more cost effective to allow for increased MV voltage drop at the expense of reduced LV voltage drop and use the limits for R1 or R2 networks.

With reference to figure 3.4.3.2, rural electrification LV network cost savings start to drop off significantly for LV voltage drops greater than 7.5%. It is recommended that the default apportionment for rural electrification projects be based on the R1 network classification i.e. a 7.5% LV voltage drop limit. Note that these are default limits and are not necessarily optimal for a given situation. Network planners would need to assess the impact of utilising the recommended limits for each electrification project. This concept is illustrated using two basic examples.

Example 1: A rural feeder does not contain any older 380/220V transformers or contracts, and is required to supply a small electrification project of 300 connections. No additional electrification connections are forecasted on the feeder. Using the feeder load forecast it is established that the end of line MV voltage at the electrification site will drop to 96% during peak loading, and recover to between 102.5% and 105% during low load periods. Referring to table 7.2.2.1 this condition would not be acceptable for a normal network condition as the MV voltage drops below the limit of 98%. The planner has two options (for the purposes of this example):

- 1) Perform MV system strengthening and use U limits. In this case it is assumed that a single phase voltage regulator is required at a cost of R150k. This will enable the MV voltage at the electrification site to fall within the limits for an urban network. An 11% LV voltage drop could be used.
- 2) Use the apportionment limits for a R2 classification i.e. a rural feeder that does not have any 380/220V transformer or contracts. Referring to table 7.2.3.1, under these conditions the MV voltage could be allowed to drop to 95.5% and the LV voltage drop would need to be reduced to 5%.

By installing a voltage regulator option 1 allows the LV voltage drop at the electrification site to be increased from 5% (option 2) to 11%. Assuming a stand size of 7225m² and referring to table 7.4.1, this will result in an estimated LV network cost savings of approximately $R493 * 300 = R148k$. The LV cost savings is of the same order of magnitude as the voltage regulator cost. In this case either option could be selected, and a more detailed analysis including the effects of losses and performance should be performed. If the network does

contain 380/220V transformers or contracts, option 2 could only be implemented if these are upgraded, and the associated costs would need to be included in the comparison.

Example 2: It is planned to supply 5000 electrification connections in a greenfield area. The planner has two options (for the purposes of this example):

- 1) Extend a neighbouring rural feeder into the area, and utilise the limits for a R1 classification. MV strengthening would be required to keep the MV voltages within the limits for R1, and is estimated to cost R2.5m. A LV voltage drop of 7.5% could be used.
- 2) Overlay the sub-transmission to create a new MV source such that the limits for urban (U) networks can be utilised. The capital cost is estimated at R7m, and a LV voltage drop of 11% could be used

By providing a new MV source option 2 allows the LV voltage drop at the electrification site to be increased from 7.5% (option 1) to 11%. Assuming a stand size of 7225m² and referring to table 3.4.3.1, this will result in an estimated LV network cost savings of approximately (R493 – R352) * 5000 = R 705k. The cost of the sub-transmission overlay is not recovered by the LV connection savings. Unless there are other significant factors option 1 would be selected as preferred.

The above examples are simplistic, but do illustrate the concept that the optimal apportionment is dependent on the nature of the networks and associated strengthening costs. The optimal apportionment should also take into consideration other associated life cycle costs (losses, revenue and maintenance), and reliability and QOS issues.

7.5 SELECTING THE APPROPRIATE NETWORK CLASSIFICATION

In order to use the appropriate voltage limits and apportionment, distribution feeders will need to be classified as U, R1 or R2. The following general principles apply.

- Urban networks should always be classified as urban (U). In rare cases where the costs of enforcing the MV voltage drop limits are very prohibitive the R1 limits could be utilised, but the LV voltage drop would need to be reduced accordingly. In many cases this will not be practically feasible due to the existing LV network designs. Utilisation of the R1 limits will also result in increased motor voltage variations, which could cause problems with light industrial loads.
- Rural networks containing 380/220V transformers and contracts should be classified as R1. This would be the default classification for all rural feeders unless the planner knows that the feeder in question does not contain any 380/220V transformers and contracts.
 - If substantial electrification (typically more than 1000 connections) is to be supplied by a R1 feeder, the planner should assess the possible cost savings of utilising U limits. This could typically be achieved via the installation of a MV voltage regulator. The existing LV networks on the feeder would not need to be upgraded as the allowable LV voltage drop is increased.
 - If a R1 feeder supplies very little (typically fewer than 300 connections) or no electrification, and the MV voltage drop is prohibitive, the planner should investigate the alternative of upgrading the 380/220V transformers and contracts. R2 limits could then be utilised, but the LV voltage drops would need to be reduced accordingly. As the LV networks in rural feeders without significant electrification load are very limited this option should be practically feasible. It should not require major upgrades to LV systems. Utilisation of the R2 limits will result in increased, but acceptable, motor voltage variations.

- Rural networks that do not contain 380/220V transformers or contracts should be classified as R2. If significant electrification (typically more than 300 connections in the context of a R2 network) is to be supplied by a R2 feeder, the planner should assess the possible cost savings of utilising R1 or possibly even U limits. This could typically be achieved via the installation of a MV voltage regulator. The existing LV networks on the feeder would not need to be upgraded as the allowable LV voltage drop is increased.

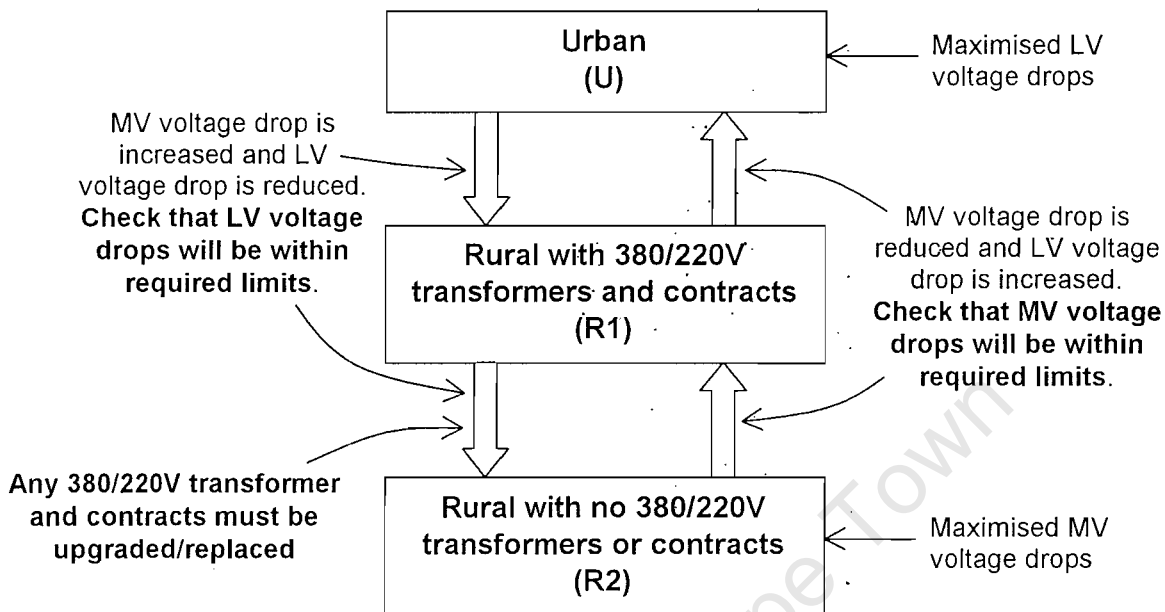


Figure 7.5.1: Transition between network classifications

When classifying feeders, the design parameters of the existing LV networks must be taken into consideration. In rural areas the MV voltage drop limits may be dictated by the design requirements of electrification projects. In these cases it is the electrification LV design that limits the MV voltage drops, and not motor operating voltage recommendations or the presence of 380/220V transformers or contracts.

In cases where the costs of complying with the MV or LV voltage drop limits associated with a particular classification become prohibitive, the network planner will need to assess the feasibility of changing network classifications i.e. evaluate the scope and costs of MV versus LV upgrades.

It is possible that a single feeder may consist of classification zones. This however contradicts the stance of one set of LV apportionment for an entire feeder, and would typically be limited to an electrification project, or small town fed off a rural feeder. This is graphically illustrated below.

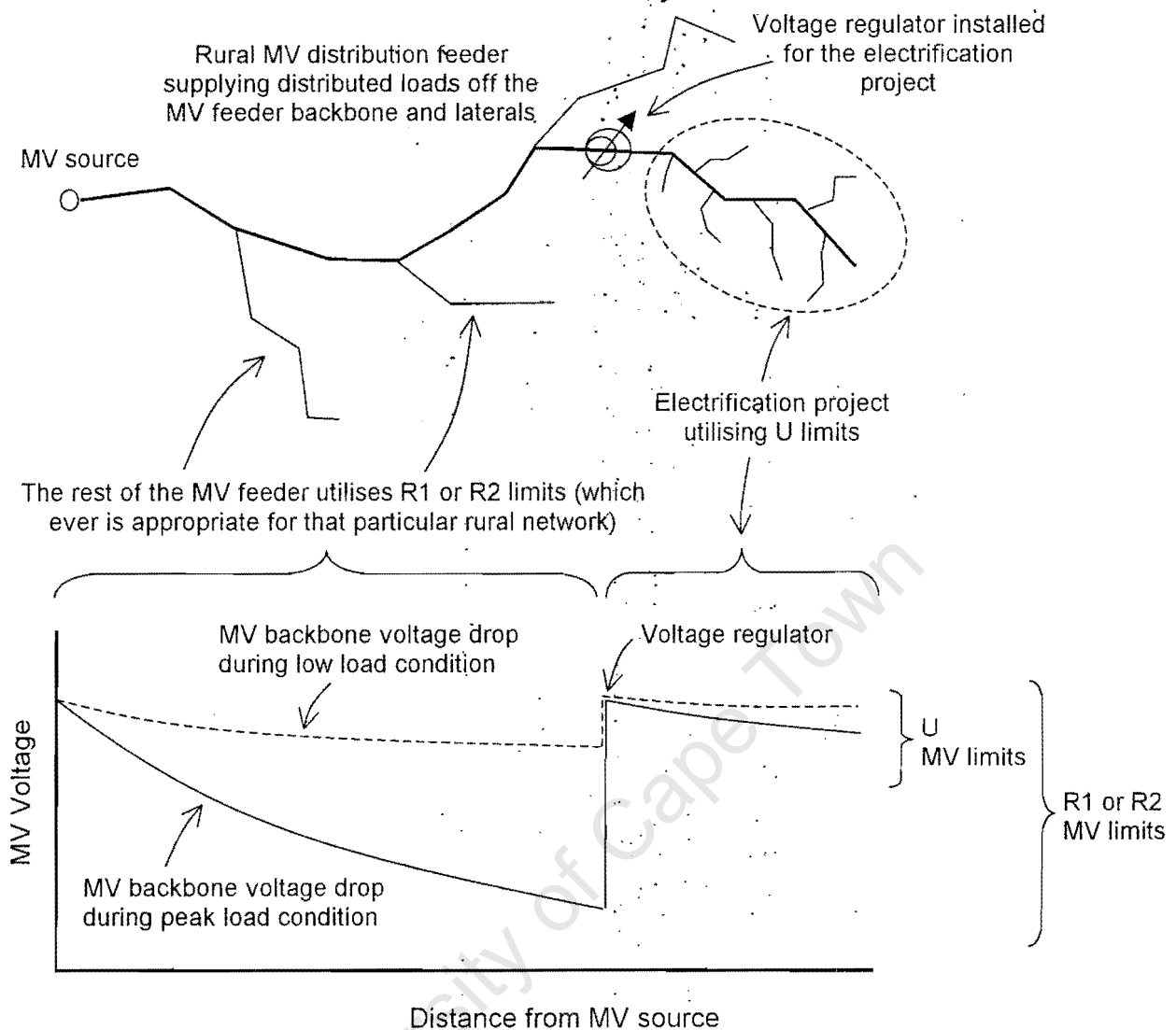


Figure 7.5.2: Illustration of the concept that a single MV feeder may have more than one network classification zone

7.6 CUSTOMISING VOLTAGE DROPS AND APPORTIONMENT

Section 7.5 documented the selection of a particular network classification. The optimal voltage drops in both the MV and LV networks could vary considerably from those recommended for a particular classification if the relative costs of the MV and LV systems and the capitalisation of load losses are included in the evaluation.

The recommended regulation limits and apportionment could be customised on a per case basis. The MV voltage drop could be reduced to increase the allowable LV voltage drop and visa versa. A 1% increase in the acceptable minimum end of line MV voltage translates to a 1% increase in LV voltage drop. Referring to the limits for an urban network in table 7.2.1.1. If, for example, line drop compensation or voltage compounding were utilised such that the end of line MV voltage does not recover to above 102.5% and the normal network minimum end of line MV voltage was limited to 102% (and not 99.5% as in table 7.2.1.1) the LV voltage drops could be increased by 2.5%. The revised maximum LV voltage drops would be as tabled below:

Transformer	Maximum LV voltage drop
415/240V transformers with no 380V contracts	11% + 2.5% = 13.5%
400/230V transformers with no 380V contracts	8.5% + 2.5% = 11%
380/220V transformers	5% + 2.5% = 7.5%
415/240V and 400/230V transformers with 380V contracts	5% + 2.5% = 7.5%

Table 7.6.1: Revised maximum LV voltage drops if the recommended MV voltage drop is reduced by 2.5% in urban networks.

Any deviation from the standard apportionment limits provided for each network classification should be clearly documented and available for future reference by planners and designers. There would need to be a clear business case to use non-standard apportionment. Where possible planners should stick to the three classifications and their associated limits recommended by this research.

7.7 SUMMARY

Three default network classifications are provided and should cater for most practical applications. For each network classification the associated MV and LV voltage limits are provided, including recommendations for LV network design to facilitate satisfactory motor operating voltages.

A single category is provided for urban networks. The urban (U) limits maximise the allowable LV voltage drop, and will ensure that three phase motor operating voltage variations are less than $\pm 5\%$ when these motors are supplied in relative close proximity to the distribution transformers. Motors should not need to be de-rated due to voltage regulation considerations. The presence of 380/220V transformers and contracts only limits the maximum LV voltage drop for the LV networks supplied by these effected distribution transformers.

Two categories are provided for rural networks, and differentiate between networks that contain 380/220V transformers and contracts, and networks which only contain new 400/230V contracts and 400/230V and 415/240V transformers.

In rural networks containing 380/220V transformers or contracts the R1 limits should be utilised. The R1 limits offer a compromise between MV and LV voltage drops, and will ensure that three phase motor operating voltage variations are less than $\pm 7.5\%$ when these motors are supplied in relative close proximity to the distribution transformers. Motors will typically need to be de-rated by 10%.

In rural networks that do not contain 380/220V transformers or contracts the R2 limits can be utilised. The R2 limits maximise the allowable MV voltage drop. Three phase motor operating voltage variations are less than $\pm 10\%$ when these motors are supplied in relative close proximity to the distribution transformers. Motors will typically need to be de-rated by between 10% and 20%. While all contractual/licence obligations at the point of supply will be met, the use of these limits where motor sizing factors are less than 10% may result in customer complaints.

The utilisation of the normal MV limits will ensure that for reasonable LV design practices, all point of supply voltages will meet regulatory/licence requirements. The abnormal MV limits may result in violation of supply voltages on the extremities of LV feeders that are supplied by distribution transformers on the extremities of the MV feeder.

An analogy can be drawn between the “normal” and “abnormal” MV limits proposed by this research, and the “planning” and “compatibility” levels supported by the NRS 048.

Maximum end of line MV voltage	Classification					
	Urban U		Rural R1		Rural R2	
	Normal	Abnormal	Normal	Abnormal	Normal	Abnormal
≥105%	2%	5.5%	4.5%	7%	7%	8%
<105% & ≥102.5%			7%	9.5%	9.5%	13%
<102.5% & ≥100%	4.5%	8%	9.5%	11.5%	12%	13%
<100%	7%	10.5%	11.5%	14%	14%	17.5%

Table 7.7.1: Maximum MV voltage drops as a function of the maximum end of line MV voltage

A single maximum LV voltage drop is provided for LV networks supplied by distribution transformers with different nominal voltages. The presence of customers with 380/220V contracts will limit the maximum LV voltage drop when 400/230V or 415/240V transformers supply these 380/220V customers. It may be desirable to provide “planning” levels that are more restrictive (less voltage drop) than the values provided in table 7.7.2. This would be in keeping with the philosophy of the NRS 048. However the level of risk used in the calculation of the LV voltage drops could be adjusted to differentiate between planning and compatibility levels.

Transformer	Classification		
	Urban U	Rural R1	Rural R2
415/240V transformers with no 380V contracts	11%	7.5%	5%
400/230V transformers with no 380V contracts	8.5%	5%	2.5%
380/220V transformers	5%	2.5%	N/A
415/240V and 400/230V transformers with 380V contracts	5%	2.5%	N/A

Table 7.7.2: Maximum LV voltage drops for domestic customers

In keeping with the philosophy of the NRS 048, which states that planning levels should take into consideration “the type of equipment utilised by the customer” [79], two ranges of LV voltage drops are provided for significant three phase motor loads. The “ideal” and “maximum” values are analogous to the “planning” and “compatibility” levels supported by the NRS 048.

Transformer	Classification					
	Urban U		Rural R1		Rural R2	
	Ideal	Max	Ideal	Max	Ideal	Max
415/240V transformers	≤5%	11%	≤4%	7.5%	≤2.5%	5%
400/230V transformers	≤2%	8.5%	≤1%	5%	≤1%	2.5%

Table 7.7.3: Ideal and maximum LV voltage drops for significant (≥7.5kW) three phase motor loads

While the limits can be customised, it is recommended that planners stick to the defaults provided for each of the three classifications.

8 APPLICATION OF THE RECOMMENDATIONS

The application of the recommended classifications and associated limits is illustrated using examples based on actual networks in Eskom's Eastern Region.

In the following examples the calculation of the peak and low-load MV system voltage drops are performed using network load demand data based on the statistical properties of this data. The calculation of the maximum demand of a load based on its statistical properties is a function of the required level of confidence and is given by [76]:

$$\text{Maximum Demand} = \mu + Z_{\alpha} \cdot \sigma \quad (11)$$

Where μ and σ are the mean and standard deviation of the load respectively, and Z_{α} can be found for different levels of confidence, typical values for which are tabled below.

Z_{α}	Confidence Level
1.29	90%
2	98%
3	99.9%

Table 8.1: Confidence levels for maximum demand calculations

For the purposes of the following examples a confidence level of 98% is used. The appropriateness and implications of this confidence level are not covered by this research.

8.1 URBAN TYPE MV NETWORK (IXOPO NB1)

Ixopo NB1 is an 11kV feeder that supplies the large rural town of Ixopo in Kwa-Zulu Natal. It supplies a mixture of commercial and residential load, with very limited light industrial loads. With reference to the detailed load data in appendix E1, 10 months demand data in 30 minute demand intervals between January and October 2001 was analysed. This network energy and demand data measured at the feeder source includes all the downstream technical and non-technical losses. Over the sample period the feeder peaked at 3.33MVA during July 2001. The network peaks at 9:00am on weekdays, and the low-load condition occurs during the early mornings around 3:00am.

Ixopo NB1 consists of 9.4km of overhead MV line, 9.4km of buried MV cable and has 52 distribution transformers with an installed transformation capacity of 9.05MVA. LV network data is not readily available. The MV feeder 11kV backbone line length is 5km.

The mean value of the load during the network peak $\mu_{\text{Peak}} = 2395$ kVA

The standard deviation of the load during the network peak $\sigma_{\text{Peak}} = 260.6$ kVA

The mean value of the load during the network low-load $\mu_{\text{Low-load}} = 1091$ kVA

The standard deviation of the load during the network low-load $\sigma_{\text{Low-load}} = 100.2$ kVA

Using a confidence level of 98% ($Z_{\alpha} = 2$) the peak and low-load values are:

The load during peak $L_{\text{Peak}} = 2395 + 2 \cdot 260.6 = 2916.2$ kVA

The load during low-load $L_{\text{Low-load}} = 1091 - 2 \cdot 100.2 = 890.6$ kVA

Note that the peak loading of 2.92MVA calculated using a 98% confidence level is significantly less than the actual measured network peak of 3.33MVA. Note that this

3.33MVA peak could have been due to an abnormal network condition such as cold load pick-up following an outage.

While the load factor is 0.60 the load ratio (ratio between low-load and peak load) is:

$$\text{Load Ratio} = 890.6 / 2916.2 = 0.31$$

The system power factors during peak and low-load conditions are 0.95 and 0.85 respectively.

Loadflow studies were performed using the ReticMaster loadflow package to calculate the MV system voltage drops during both peak and low-load conditions for different voltage control settings and methodologies utilised at the feeder source. Loads were modelled as constant current type loads, and were evenly distributed over the available distribution transformation capacity on the feeder. Load growth for the purposes of this example is assumed to be 5% per annum.

Three source voltage control settings / methodologies were simulated:

- 1: Fixed voltage control with a setpoint of 103% and bandwidth of $\pm 1.2\%$.
- 2: Fixed voltage control with a setpoint of 104% and bandwidth of $\pm 1.2\%$.
- 3: Line Drop Compensation (LDC) with a setpoint of 100%, bandwidth of $\pm 1.2\%$ and primary system impedance of $1.135 + j1.355\Omega$.

Year	Feeder loading		1: EL MV voltage 103% Fixed Voltage		2: EL MV voltage 104% Fixed Voltage		3: EL MV voltage LDC	
	Max load (kVA)	Min load (kVA)	Min Voltage	Max Voltage	Min Voltage	Max Voltage	Min Voltage	Max Voltage
2001	2916	891	99.7%	101.9%	100.7%	102.9%	99.7%	99.7%
2002	3049	939	99.6%	101.9%	100.6%	102.8%	99.8%	99.6%
2003	3197	985	99.4%	101.8%	100.4%	102.8%	99.7%	99.7%
2004	3375	1043	99.2%	101.7%	100.2%	102.7%	99.8%	99.6%
2005	3552	1100	99.0%	101.6%	100.0%	102.6%	99.7%	99.7%
2006	3730	1154	98.8%	101.6%	99.8%	102.6%	99.8%	99.7%
2007	3908	1212	98.6%	101.5%	99.6%	102.5%	99.8%	99.7%
2008	4085	1276	98.3%	101.4%	99.3%	102.4%	99.9%	99.7%
2009	4322	1342	98.1%	101.3%	99.1%	102.3%	99.9%	99.6%
2010	4529	1406	97.8%	101.2%	98.8%	102.2%	99.8%	99.7%

Table 8.1.1: Network loadings and End of Line (EL) MV voltages for different voltage control settings and methodologies on Ixopo NB1. Results are provided for the existing network load, and over a 10 year period based on an assumed growth rate of 5% per annum. Values shaded in light grey indicate values below recommended normal system limits for U networks, while values shaded in dark grey fall outside recommended abnormal limits for U networks.

Referring to table 8.1.1 above, if conventional fixed voltage control with a setpoint of 103% is utilised on the source OLTC sub-transmission transformer, the end of line MV voltage recovers to between 101.2% and 101.9% during the low-load condition. With reference to table 7.2.1.1 for urban (U) type networks, this results in a recommended minimum end of line MV voltage of 99.5% and 97% for normal and abnormal network conditions respectively. For year 2003 and beyond the values for the minimum end of line MV voltage fall between these values for this form of voltage control and the implications are as follows:

- If the LV feeders near the MV feeder extremities have been designed for the voltage drops as per the recommended maximum limits provided in table 7.2.1.2 for U networks, the service voltages at domestic type customers' on the extremities of the LV feeders will drop to between 90% and 88.5% during the network peak.
- For reasonably designed customer LV networks the voltages on three phase motors supplied by distribution transformers near the MV feeder extremities will fall between $\pm 5\%$ and $\pm 7.5\%$.

While increasing the sending voltage setpoint to 104% increases the minimum end of line MV voltage during the peak load, this is done at the expense of the low-load voltage recovery. As the end of line MV voltage recovers to above 102.5% the minimum end of line MV voltages are 102% and 99.5% for normal and abnormal network conditions respectively. Simply increasing the sending voltage setpoint using fixed voltage control does not improve the networks voltage regulation characteristics, as this would require certain transformer DETS tap boosting to be reduced to keep within recommended maximum fluxing levels.

Ixopo NB1 is fed by a dedicated 22/11kV transformer with its own OLTC scheme. Furthermore there is no interconnectivity with other rural networks in the area as these other networks are all 22kV. As a result it would be very simple to apply LDC to the 11kV busbar voltage control relay as problems associated with load diversity and load shifting between feeders will not occur. LDC settings were calculated in accordance with the recommendations in reference [23], and result in peak load sending voltages of 104%, but reduces the low-load sending voltage such that the end of line MV voltage does not recover above 100%. Under these conditions the minimum end of line MV voltage should not fall below 97% and 94.5% for normal and abnormal network conditions respectively. The voltages with the LDC applied are all well within normal network limits for the existing system and with the forecasted load increase.

In the above case the planner would have the following options:

- 1) Strengthen the MV feeder to reduce the MV voltage drop to within the limits of an Urban (U) network
- 2) Continue operating the network using the fixed voltage control methodology in the knowledge that voltages will fall between the normal and abnormal limits during network peaks. This may result in customer complaints, which would need to be handled accordingly. Note that due to the assessment technique used by the NRS 048 the network may still meet the required compatibility levels.
- 3) Apply LDC to ensure adequate voltages
- 4) Adopt the MV voltage limits for R1 rural feeders. By using the wider MV voltage limits for R1 feeders the allowable LV voltage drops would need to be reduced accordingly. If an investigation showed that the LV voltage drops on the feeder extremities fall within the limits for R1 feeders then the R1 MV limits could be used. Alternatively the LV networks supplied on the MV feeder extremities could be strengthened to bring their voltage drops to within those for R1 systems.

8.2 RURAL TYPE MV NETWORK (GOWRIE NB23)

Gowrie NB23 11/22kV feeder supplies mixed rural loads in the vicinity of the small rural town of Nottingham Road in the Midlands in Kwa-Zulu Natal. It supplies a mixture of smallholdings, agricultural and pumping load. With reference to the detailed load data in appendix E2, 9 months demand data in 30 minute demand intervals between February and October 2001 was analysed. This network energy and demand data measured at the

feeder source includes all the downstream technical and non-technical losses. Over the sample period the feeder peaked at 2.2MVA during August 2001. The network peaks in the late afternoons (16:00) on weekdays, and the low-load condition occurs during the early mornings at around 3:00am.

Gowrie NB23 consists of 125.1km of overhead MV line, 0.3km of buried MV cable and has 131 distribution transformers with an installed transformation capacity of 7.0MVA. LV network data is not readily available, but there is very little Eskom owned LV network due to the lack of any electrification or dense residential type load. The first 14km of backbone is 11kV, where after the MV voltage is transformed to 22kV using 2 * 1MVA 11/22kV step-up transformers, and the 22kV backbone then extends for an additional 24km.

The mean value of the load during the network peak $\mu_{Peak} = 1515$ kVA

The standard deviation of the load during the network peak $\sigma_{Peak} = 343.2$ kVA

The mean value of the load during the network low-load $\mu_{Low-load} = 695$ kVA

The standard deviation of the load during the network low-load $\sigma_{Low-load} = 132.1$ kVA

Using a confidence level of 98% ($Z_{\alpha} = 2$) the peak and low-load values are:

The load during peak $L_{Peak} = 1515 + 2 * 343.2 = 2201.6$ kVA

The load during low-load $L_{Low-load} = 695 - 2 * 132.1 = 430.3$ kVA

Note that the peak loading of 2201.6kVA calculated using a 98% confidence level is of the same magnitude as the actual measured network peak of 2191kVA.

While the load factor is 0.51 the Load Ratio = $430.3 / 2201.6 = 0.20$

The system power factor is 0.9 during peak and low-load conditions.

Loadflow studies were performed as for the Ixopo feeder, but load growth is assumed to be 3% per annum.

Due to previously identified excessive MV voltage regulation on this network the following planned remedial actions have been factored into the analysis and the results are for the modified system:

- A fixed 22kV shunt capacitor bank is to be installed roughly half way down the feeder
- A switched 22kV shunt capacitor bank is to be installed near the end of the feeder
- Roughly 350kVA of peak load is to be swung onto a neighbouring MV feeder

Similar source voltage control settings / methodologies were simulated as for the Ixopo feeder, but with voltage compounding instead of LDC:

1: Fixed voltage control with a setpoint of 104% and bandwidth of $\pm 1.2\%$.

2: Fixed voltage control with a setpoint of 105% and bandwidth of $\pm 1.2\%$.

3: Voltage Compounding (VC) with a setpoint of 96%, bandwidth of $\pm 1.2\%$ and primary system impedance of $1.459 + j1.742\Omega$.

Note that the VC settings take into account that the 20MVA 88/11kV sub-transmission transformer at Gowrie substation supplies several 11kV feeders. Fortunately there is a high degree of load co-incidence between these feeders as they all supply very similar load types.

Year	Feeder loading		1: EL MV voltage 104% Fixed Voltage		2: EL MV voltage 105% Fixed Voltage		3: EL MV voltage Voltage Compound	
	Max load (kVA)	Min load (kVA)	Min Voltage	Max Voltage	Min Voltage	Max Voltage	Min Voltage	Max Voltage
2001	1665	377	95.0%	103.6%	96.1%	104.6%	94.6%	98.9%
2002	1710	384	94.5%	103.5%	95.5%	104.5%	94.4%	98.9%
2003	1758	391	93.9%	103.4%	95.0%	104.4%	94.1%	99.0%
2004	1806	398	93.4%	103.3%	94.5%	104.3%	93.9%	99.0%
2005	1869	407	92.7%	103.1%	93.8%	104.2%	93.6%	99.2%
2006	1917	415	92.2%	103.0%	93.3%	104.1%	93.4%	99.2%
2007	1965	422	91.7%	102.9%	92.8%	104.0%	93.3%	99.2%
2008	2031	432	91.0%	102.8%	92.1%	103.8%	93.0%	99.2%
2009	2097	442	90.3%	102.7%	91.4%	103.7%	92.7%	99.4%
2010	2148	451	89.8%	102.6%	90.8%	103.6%	92.5%	99.1%

Table 8.2.1: Network loadings and End of Line (EL) MV voltages for different voltage control settings and methodologies on Gowrie NB23. Results are provided for the modified (post load shift) existing network load, and over a forecasted 10 year period based on an assumed growth rate of 3% per annum. Values shaded in light grey indicate values below the normal system limits in table 7.2.2 for R1 networks, while values shaded in dark grey fall outside the abnormal limits in table 7.2.2 for R1 networks.

8.2.1 Application of the Limits for R1 Rural Networks (contains 380/220V Transformers and Contracts)

Gowrie NB23 is relatively old and it is likely that there are 380/220V transformers and customers in the section of 11kV backbone. As a result the limits in table 7.2.2.1 for R1 networks have been used to evaluate the calculated MV voltage limits.

Referring to table 8.2.1 above, if conventional fixed voltage control with a setpoint of 104% is utilised on the source OLTC sub-transmission transformer, the end of line MV voltage recovers to between 102.6% and 103.6% during the low-load condition. With reference to table 7.2.2.1, for a R1 rural network the resultant recommended minimum end of line MV voltages are 98% and 95.5% for normal and abnormal network conditions respectively. The values for the minimum end of line MV voltage fall below the abnormal limits if this form of voltage control is utilised, and the implications are as follows:

- If the LV feeders near the MV feeder extremities have been designed for the voltage drops as per the recommended maximum limits documented in section 7.2.2 for R1 networks, the service voltages at domestic type customers on the extremities of LV feeders will drop to 86.5% in 2001 and 83.2% in 2010 during the network peak.
- For reasonably designed customer LV networks the voltage variations on three phase motors supplied by distribution transformers near the MV feeder extremities will exceed $\pm 10\%$.

While increasing the sending voltage setpoint to 105% increases the minimum end of line MV voltage during the peak load condition, the low-load voltage recovery still restricts the maximum allowable distribution transformer DETS boosting. Simply increasing the sending voltage setpoint using fixed voltage control does not significantly improve the networks voltage regulation characteristics.

Taking into consideration the level of load co-incidence between NB23 and the other MV feeders supplied by Gowrie 88/11kV substation, Voltage Compounding settings were calculated. The VC settings result in peak load sending voltages of 105%, but reduced low-

load sending voltages such that the end of line MV voltage does not recover above 100%. Under these conditions the minimum end of line MV voltage should not be allowed to fall below 93.5% and 91% for normal and abnormal network conditions respectively. The voltages with the VC applied are within normal network limits until 2005, where after the voltages fall between the normal and abnormal limits.

The operation of this network using fixed voltage control will result in the abnormal limits being exceeded, and should not be considered as a viable option. The planner would have the following alternatives:

- 1) Strengthen the MV feeder to reduce the MV voltage drop to within the limits for R1 networks
- 2) Apply Voltage Compounding, which will solve the medium term voltage problem, and improve the voltage regulation characteristics of all the MV feeders supplied from Gowrie substation. If the forecasted load growth materialise such that the normal system limits are exceeded even with VC applied, there would be two basic options. Either strengthening must be performed, or if the load is considered to have saturated (or is very close to saturation) the abnormal limits could be used bearing in mind that customers may complain of low voltages, and selected LV networks on MV feeder extremities may need to be strengthened. Ideally the feeder should be designed to meet the normal limits. However once the system is built the cost implications of meeting the normal limits may be considerable. Under these conditions the abnormal limits could be used, but would need to be carefully evaluated. The evaluation should take into consideration the costs of the MV strengthening, sensitivity of the customers supplied, and the frequency and duration of the "low" voltage conditions. Note that due to the assessment technique used by the NRS 048 the use of the abnormal MV limits may still meet the required compatibility levels.

8.2.2 Application of the Limits for R2 Rural Networks (no 380/220V Transformers or Contracts)

The restrictions imposed by 380/220V transformers and contracts will necessitate that either the MV network be strengthened or voltage compounding be applied. As the majority of the network was upgraded to 22kV in the early 1990s there should be relatively few 380/220 transformers. By replacing any 380/220V transformers with 415/240V units and upgrading 380/220V contracts to the new 400/230V standard, the recommended limits for R2 networks in table 7.2.3.1 could be used. Note that in instances where customers have 380V equipment supplied by 380V contracts the upgrading of the contract to 400V may require that some of the customers 380V equipment be replaced. In these cases Eskom should possibly be prepared to pay towards these costs if the savings in planning for the higher MV voltage drops allowed by the removal of the 380V contract are significantly larger than the costs of upgrading the customers equipment.

With reference to table 7.2.3.1, for a maximum end of line MV voltages of between 105% and 102.5%, the MV voltage can be allowed to drop to 95.5%. Hence fixed voltage control with a setpoint of 105% could be used at Gowrie substation, and the normal system limits would be exceeded in 2003, and the abnormal limits in 2007. By applying voltage compounding such that the end of line MV voltage does not recover above 100%, the minimum recommended MV voltage during normal conditions is 91%, which would be adequate for the entire forecast period.

8.3 LV NETWORK DESIGN

Situation: A network designer needs to determine the maximum allowable LV voltage drop over a LV feeder supplying farm worker houses from a 400/230V secondary distribution transformer on a R1 rural MV feeder.

Solution: Referring to section 7.2.2, the maximum LV drop is 5%. If the transformer nominal secondary voltage is 415/240V or 380/220V the maximum recommended LV drops are 7.5% and 2.5% respectively.

Situation: A network designer needs to determine the maximum allowable LV voltage drop over a LV feeder supplying farm worker houses from a 415/240V secondary distribution transformer on a R2 rural MV feeder.

Solution: Referring to section 7.2.3, the maximum LV drop is 5%. If the transformer nominal secondary voltage is 400/230V the maximum recommended LV drop is 2.5%.

Situation: A network designer needs to determine the maximum allowable LV voltage drop over a LV feeder supplying domestic customers from a 400/230V secondary distribution transformer on an urban (U) MV feeder.

Solution: Referring to section 7.2.1, the maximum LV drop is 8.5%. If the transformer nominal secondary voltage is 415/240V or 380/220V the maximum recommended LV drops are 11% and 5% respectively.

Situation: A network designer needs to determine the maximum allowable LV voltage drop over a LV feeder supplying farm worker houses from a 415/240V secondary distribution transformer supplying a 380/220V contract (customer has 380V motors) on a R1 rural MV feeder.

Solution: Referring to section 7.2.2, the maximum LV drop is 2.5%.

Situation: A network designer needs to determine the maximum allowable LV voltage drop over a LV feeder supplying a 22kW three phase motor load from a 400V secondary distribution transformer on an urban (U) MV feeder.

Solution: Referring to section 7.2.1, ideally the LV drop should be kept below 2%, and should not exceed a maximum of 8.5%. Note that a 380V transformer should not be used to supply a significant 400V motor load as the 400V motor would need to be significantly de-rated even if it is located in close proximity to the 380V distribution transformer. If a 415V transformer were to be used to supply the motor the LV drop should ideally be kept below 5%, and should not exceed a maximum of 11%.

Where 380/220V or 400/230V transformers place undesirable limits on LV voltage drops, the costs of designing to these lower voltage drops should be compared with changing the transformers to 415/240V units and allowing for a larger LV voltage drop. The comparison should include the technical losses and life cycle costs taking into consideration the age and condition of the existing transformer.

Similarly where existing 380/220V contracts below existing 415/240V or 400/230V transformers limit the allowable LV voltage drops for other customers to be supplied off these transformers, consideration should be given to upgrading the 380/220V contracts to the 400/230V standard.

8.4 SUMMARY

The recommended classifications and associated voltage regulation limits and apportionment can be used by network planners and designers to ensure that electrical network will provide customers with satisfactory voltages.

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9 CONCLUSIONS

The following factors were identified, which influence the recommended maximum MV and LV voltage regulation limits and apportionment:

- The requirement to keep the voltages at the customer's point of supply (meter) within licence and contractual limits.
- The requirement to keep the voltages at the customer's "appliance" (after the meter) within regulation limits such that these appliances will operate as required taking into account factors such as efficiency and life span.
- The operating voltages of network equipment such as transformers taking into account factors such as efficiency and life span.
- The characteristics and specifications of both past and present distribution equipment such as distribution transformer nominal secondary voltages and DETS tap ranges and step sizes.

In order to cater for increased MV voltage regulation in rural systems (which are typically critically limited by maximum allowable voltage regulation limits) recommended voltage regulation limits and apportionment were calculated separately for urban and rural networks. In comparison with urban networks, the additional MV regulation allowed in rural networks is achieved at the expense of wider motor operating voltage ranges, and reduced allowable maximum LV voltage drops. Rural networks themselves are split into two categories to differentiate between networks containing 380/220V transformers and contracts, and those that only supply 400/230V contracts and 400/230V and 415/240V transformers.

Two ranges of recommended MV voltage variations are provided for all three classifications of network (U, R1 and R2). The "normal" network limits will ensure that provided LV networks are appropriately designed and distribution transformer DETS taps are adjusted as required, the licence and contractual limits at the service point will be met, and appliances will operate as required with acceptable performance and life span. All MV networks should be planned / designed to operate within these normal limits and strengthening projects should ensure that these limits are met. The "abnormal" network limits will still result in compliance with licence and contractual limits at the service point for customers with dedicated distribution transformers. However service voltages for domestic type customers on the extremities of LV feeders which are in turn supplied on the extremities of the MV feeder will fall slightly below the 90% limit. The abnormal network limits will generally still provide acceptable appliance operating voltages, but performance and life span may be compromised. Operation at these increased limits should not be allowed indefinitely. The abnormal limits should be used during network contingencies, and can also be used to delay the required completion date for network strengthening projects. The "normal" and "abnormal" limits are analogous to the "planning" and "compatibility" levels supported by the NRS 048.

Recommended maximum LV voltage drops are provided for each network classification and distribution transformer nominal secondary voltage. In keeping with the NRS048, "ideal" and "maximum" LV voltage drop limits are provided for networks supplying significant ($\geq 7.5\text{kW}$) three phase motor loads.

The recommended values for voltage variations and apportionment are maximum values only, and the optimal voltage drops in both the MV and LV networks could vary considerably if the relative costs of the MV and LV systems and the capitalisation of load

losses are included in the evaluation. The recommended values are maximums within which the network must be designed to operate if contractual/license obligations and acceptable appliance operating voltages are to be achieved for reasonable LV design practices both within the Eskom network and customer's premise. In certain applications such as rural electrification where load densities are low and LV networks can be extensive, the optimal apportionment could differ considerably from the limits provided for urban and rural type networks.

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10 PRACTICAL CONSIDERATIONS

There are several practical considerations that will influence the application of the recommended classifications and associated limits.

10.1 SOURCE VOLTAGE VARIATIONS FOR PEAK AND LOW-LOAD CONDITIONS

The maximum sending MV voltages recommended in the tables in section 7 are the recommended maximum setpoint voltage for the voltage control relay at the MV source. The actual sending MV voltage at the source will vary within the specified bandwidth. Take for example a setpoint of 104% and bandwidth of $\pm 1.2\%$. The actual sending MV voltage could fall anywhere between $104\% - 1.2\% = 102.8\%$ and $104\% + 1.2\% = 105.2\%$. Due to the source sub-transmission transformer's internal voltage drop the MV sending voltage during the local MV network peak will typically tend to fall towards the bottom of the voltage control window (102.8%) and recover towards the top of the window (105.2%) during the local MV network low-load condition. It is however unlikely that the sending MV voltage will remain at the extremities of the control window for extended periods of time. The mean value of the sending voltage will tend to be the setpoint in most fixed voltage control applications.

When performing loadflow studies to establish the network response and voltage levels during peak and low-load conditions using fixed voltage control, it is recommended that the bandwidth be ignored. The setpoint voltage should be used for both peak and low load conditions. This simplification is considered acceptable as the proposed voltage regulation ranges and voltage drop limits are closely linked to average motor and transformer fluxing levels over extended periods of time.

10.2 DISTRIBUTION TRANSFORMER DETS TAP POSITION ADJUSTMENT AND OPTIMISATION

The application of the recommended limits requires that distribution transformer DETS taps be suitably set on the extremities of MV feeders approaching the recommended MV regulation limits. Techniques and systems are required for the optimisation of these transformer taps, and the voltage control settings at the source and any other voltage control relays. The practicalities of controlling these DETS tap positions may necessitate that the MV and LV limits proposed in this research are revisited.

10.3 SINGLE PHASE DISTRIBUTION TRANSFORMER DETS TAP RANGE AND STEP SIZE

As documented in section 7, under certain conditions the allowable LV voltage drops for LV networks fed from single phase transformers are less than for bi and three phase units due to the single phase transformer DETS step size of 5% and 3 tap positions. The recommended maximum LV voltage drops based on bi and three phase transformer DETS characteristics. If this simplification results in an unacceptable number of low voltage conditions or unacceptable transformer fluxing levels when applied to LV systems supplied by single phase transformers, the single phase transformer DETS tap step size and range should be carefully evaluated.

10.4 STORAGE OF CUSTOMISED VOLTAGE REGULATION AND APPORTIONMENT LIMITS

If limits other than those recommended for the three network categories are to be used for a particular network (such as for a feeder supplying considerable rural electrification), the storage and access to these customised limits needs to be addressed. Any "non-standard" network requirements must be easily identifiable, and the required information must be readily available for future reference.

10.5 THE CLASSIFICATION OF NETWORKS

In order to use the appropriate MV system limits and associated LV voltage drops the network must be classified.

The Eskom Distribution Network Planning function should include the classification of MV feeders. Where necessary this should include the identification of classification zones on feeders. This information should be easily accessible to both MV and LV network planners and designers.

10.6 COMPLIANCE WITH THE NRS 048

Provided the LV networks are designed with the maximum LV voltage drop limits associated with their classification, the use of the normal system MV limits should result in compliance with NRS 048.

When the abnormal MV limits are used, the LV service voltages on LV feeder extremities that are in turn fed by distribution transformers on the MV feeder extremities will typically fall between 90% and 88.5%. This assumes that the maximum LV voltage drop for the particular network category is being fully utilised by the LV network. Due to the assessment method used by NRS 048, the network may still comply with the compatibility levels. Use of the abnormal MV limits will usually still provide compliance with NRS 048, but networks should not be planned/designed to operate at these levels indefinitely.

10.7 LV NETWORK DESIGN STANDARDISATION IN RURAL NETWORKS

As older 380/220V transformers fail they will be replaced with new 415/240V units. Older 380/220V customer appliances will gradually be replaced with 400/230V equipment, and 380/220V contracts will be upgraded to 400/230V contracts. As a result limitations due to the presence of 380/220V transformers and contracts will eventually fall away. In the future R1 networks that do not supply significant LV networks such as rural electrification could be changed to a R2 classification. This could only be facilitated if the LV voltage drops are compatible with R2 networks, where the LV voltage drop limits for R2 networks are more restrictive than those for R1 networks.

Eskom should consider designing all LV networks in rural areas that will supply limited electrification load (typically less than 100 connections per feeder) with the LV voltage drop limits for R2 networks.

11 FURTHER RESEARCH

There are several areas for refinement and further research such that the recommendations can be improved.

11.1 PROBABILISTIC AS OPPOSED TO DETERMINISTIC APPROACH

The approach utilised in calculating the recommended voltage limits and apportionment in this research is inherently deterministic in that a single or small range of input values are used which are considered to be representative. This approach could be enhanced into a probabilistic method using statistical data for the various input parameters such that the recommended voltages and limits could be calculated for a given level of confidence. This could be combined with statistical models for voltage drop calculations to provide a complete risk based planning tool for distribution systems taking into account the characteristics of the network, load and customer appliances. From a very high level, statistical models and relationships could possibly be established / developed for the following:

- MV source voltage variations for different types of voltage control and load characteristics
- LV design practices between the distribution transformer and service point for both residential and non-residential type customers
- LV design practices within the customer's premise
- The loading of the distribution transformer and its associated internal voltage drop during network peak and low-load conditions
- Maximum allowable transformer fluxing levels as a function of load characteristics and voltage control methodologies
- The relationship between the transformers secondary voltage (380/220V, 400/230V, 415/240V) and the contract and appliance voltages. For example what is the probability of 380/220V transformer being used to supply a 400/230V motor?
- Motor performance and life span as a function of voltage regulation taking into account design and sizing practices, safety factors, unbalance, and harmonics. The duration of the high or low voltage condition also needs to be taken into consideration.
- The operation, efficiency and life span characteristics of non motor appliances as a function of voltage variations

11.2 TRANSFORMER MAXIMUM FLUX LEVELS

The maximum recommended flux levels for sub-transmission and distribution transformers designed according to Eskom specifications limit the maximum and minimum MV system voltages. Larger MV and or LV voltage drops could be achieved if the maximum recommended flux levels are increased via further research into these flux levels and possible changes to the transformer specifications.

11.3 MOTOR OPERATING VOLTAGE RANGES AND DE-RATING FACTORS

The limitations imposed by the present motor standard of a voltage variation of $\pm 5\%$ are significant, and the responses of motors to variations in voltage should be researched further to refine the limits recommended in this research.

The standard LV voltage variation for all new LV supplies is $\pm 10\%$, and it is in both Eskom and the customers interests if appliances such as three phase motors can operate for a voltage variation of $\pm 10\%$. In order to achieve this there are two basic options. Either the motor specification must be changed in line with a voltage variation of $\pm 10\%$, or motors designed to existing practices must be suitably de-rated. The $\pm 5\%$ motor design limit is very well entrenched and imported motors are designed to the IEC 60034 with no apparent plans to change from the $\pm 5\%$ standard. It may prove to be practically very difficult to change the SABS 1804 motor specification in line with a $\pm 10\%$ voltage variation and still enable local suppliers to compete with importers. It may be easier and more practical to simply establish the required de-rating values for existing design practices such that motors designed to the IEC 60034 voltage variation of $\pm 5\%$ can be used with voltage variations of $\pm 10\%$ for the same level of performance.

Research should be performed to establish this required level of de-rating such that this information can possibly be included in the customer's supply contract. This will enable significant three phase motor loads to be supplied by relatively long LV feeders. If the customer is not prepared to de-rate motors and simply can not tolerate voltage variations greater than $\pm 5\%$ then the customer must take a bulk MV supply with suitable contracted voltage variation limits. Alternatively the customer should install local compensating equipment such as an electronic voltage regulator.

11.4 THE CALCULATION OF OPTIMAL VOLTAGE REGULATION AND APPORTIONMENT LIMITS

The optimal voltage variations and apportionment between MV and LV systems may vary considerably from the maximum recommended values provided by this research. A financial optimisation model could be developed to establish the optimal limits for different applications, and would need to take the following factors into consideration:

- The type of load being supplied, including its electrical and spatial characteristics (how much load is required and how far apart are the customers)
- MV and LV equipment standards and specifications as these influence the electrical characteristics of different lines, transformers and distribution technologies (three phase, phase to phase, SWER, single phase and bi phase)
- The capital cost characteristics of MV and LV systems for different technologies, conductors and voltage levels
- The life cycle costs of technical losses in MV and LV systems
- Maintenance life cycle costs
- The effect of voltage regulation on revenue

11.5 REVIEW OF MODEL RESULTS AND RECOMMENDATIONS

The recommended limits for both rural and urban networks should be reassessed if there are any significant changes in any of the factors influencing the model results. These factors would include changes in regulatory limits, and equipment specifications such as transformer flux characteristics and motor operating voltage ranges.

As discussed in section 3.1, the validity of Eskom's 380/220V $\pm 7.5\%$ supply contracts is questionable and Eskom could take the stance that these contracts have been superseded by the amendments to the Electricity Regulation. This would remove the limitations imposed by these older contracts such that LV networks supplying these customers could be

operated at higher LV voltages. Alternatively Eskom could embark on a program to change existing 380/220V contracts to the new 400/230V $\pm 10\%$ standard. The benefits to Eskom of invalidating or upgrading these 380/220V contracts can be summarised as follows:

- Increased maximum allowable LV feeder voltage drops in LV systems containing these 380/220V contracts which are in turn supplied by 400/230V and/or 415/240V transformers. In an urban network the LV voltage drop can be increased from 5% to 8.5% or 11% for 400/230V and 415/240V transformers respectively.
- Increased maximum allowable MV system voltage drops in rural networks no 380/220V transformers. In rural networks that do not supply any electrification load, replacing 380/220V transformer with 400/230V or 415/240V units will typically allow for an additional 2.5% MV voltage drop.
- Standardised distribution transformer DETS tap positions. Operational staff won't need to identify the presence of customers with 380/220V contracts, and this will simplify the calculation and application of DETS tap positions.
- Increased revenue due to higher average LV voltages in transformer zones supplying customers with 380/220V contracts.
- Without the significant restriction imposed by the 380/220V contract on the maximum LV voltage, there would be very little real requirement for buck tap positions on distribution transformers, and the DETS step size and range could be further refined.

12 CONCLUDING REMARKS

Prior to this research Eskom's distribution network planners and designers had no standardised practices or recommendations for the selection of maximum voltage drops in both MV and LV systems.

The research provides apportionment limits for three classifications of network, and should cater for Eskom's network planning and design requirements.

A financial optimisation of planning and design parameters taking into account capital costs, technical losses costs and variations in revenue due to less than ideal voltage regulation could result in significantly different values to those proposed by this research. Two key questions remain unanswered:

- 1) Are the recommended maximum LV voltage drops in urban networks optimal? If 415/240V transformers are used for new network extensions in high-density urban networks, is a voltage drop of 11% too high given the load factors of these networks? Will the inclusion of the life cycle cost of losses and revenue result in recommended maximum LV voltage drops in line with the historical LV voltage drops of 5% or less?
- 2) Are the recommended maximum MV voltage drops in rural networks optimal? Utilising electronic voltage regulators and modern voltage insensitive appliances, should MV and LV voltage drop limits be significantly increased? Given the low load factors in these rural networks, would a combined MV/LV voltage drop larger than 20% result in reduced life cycle costs?

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APPENDIX A: DISTRIBUTION TRANSFORMER LOSSES

Rated no-load secondary voltage (V)	Rated Power (kVA)	No-load loss (W)			Load Loss (W)
		Up to 12kV	24kV	36kV	
121 or 242 single phase	5	40			160
	16	80	100		400
	25	110	140	160	530
420 or 550 three phase	25	120	150	170	570
	50	180	220	250	1000
	100	300	360	400	1700
	200	520	600	650	2700
	315	720	840	890	3800
	500	1100	1180	1230	5400
	1000	1900	1950	2000	9500

Table A1: Rated no-load and load losses for common Eskom distribution transformers as per the SABS780: 1998 [71]. Note that losses are maximum allowable values measured at rated current and voltage in nominal tap for the load and no-load losses respectively.

APPENDIX B: COMPLETED QUESTIONNAIRES ON ESKOM DISTRIBUTION PLANNING PRACTICES AND ASSUMPTIONS AS REGARDS VOLTAGE REGULATION LIMITS AND APPORTIONMENT

The following questionnaire was compiled and sent to reticulation planning representatives in each of Eskom Distributions operating Regions.

<i>Description</i>	<i>Issues</i>
Sending voltage ¹	Are you using fixed voltage or line drop compensation / voltage compounding?
	Do you have custom settings for different substations based on actual settings data?
	What assumption of sending voltage do you use for feeder peak load conditions (e.g. 104%)?
	What assumption of sending voltage do you use for feeder low load conditions (e.g. 104%)?
Maximum and minimum MV limits for networks with bulk MV supplies ²	Maximum and minimum MV levels? What is the basis for these limits?
	Do you differentiate between newer ($\pm 5\%$) and older ($\pm 7.5\%$) contracts?
Maximum and minimum MV limits for networks with NO bulk MV supplies ³	Maximum and minimum MV levels? What is the basis for these limits?
	Do you differentiate between newer (400V) and older (380V) contracts?
MV/LV transformers ⁴	Do you differentiate between 380V, 400V and 415V transformers? How do the assumptions regarding your MV/LV transformers effect the allowable MV limits?
	Do you know, or make assumptions for, the tap position?
Customised MV limits ⁵	Are you optimising / customising MV regulation for electrification projects?
	If so how are you recording this requirement such that future planners will know what regulation limits need to be maintained at a point in the network (for an electrification project)?
Electrification design parameters ⁶	Do you have access to the electrification LV design parameters for projects (assumptions of MV voltages, design ADMDs, transformer tap positions etc)?

Table B.1: Questionnaire sent to distribution network planning representatives

¹ MV feeder source sending voltage

² MV voltage limits for feeders supplying bulk MV supplies i.e. customers that take supply directly at the local reticulation MV voltage

³ MV voltage limits for feeders, which are NOT supplying bulk MV supplies i.e only have Small Power Users (SPUs) supplied at LV

⁴ MV/LV distribution transformers

⁵ Optimising the MV voltage limits to result in least cost design via trade off between MV and LV costs:

⁶ Electrification design details as they influence / dictate the requirements on the MV system

B1 EASTERN REGION

<i>Description</i>	<i>Used?</i>	<i>Issues</i>	<i>Comments / Answers</i>
Sending voltage ¹		Are you using fixed voltage or line drop compensation / voltage compounding?	We do have limited application of LDC, but most busbars are operated at a fixed voltage.
		Do you have custom settings for different substations based on actual settings data?	In cases where increased voltages are required to address system limitations. Not widely used.
		What assumption of sending voltage do you use for feeder peak load conditions (e.g. 104%)?	102% unless actual settings are known including the effect of LDC.
		What assumption of sending voltage do you use for feeder low load conditions (e.g. 104%)?	104% unless actual settings are known including the effect of LDC.
Maximum and minimum MV limits for networks with bulk MV supplies ²		Maximum and minimum MV levels? What is the basis for these limits?	105% to 95% for new LPU supplies. 105% to 92,5% for older LPU supplies on networks also supplying SPUs. For dedicated LPU (fed directly from sub-transmission substation) supplies 105% to 95% regardless of age.
		Do you differentiate between newer ($\pm 5\%$) and older ($\pm 7.5\%$) contracts?	Do not have any system to provide simple feedback on customer's contract. If MV voltages are going to fall between 92.5% and 95%, will assess possible risk including the size and number of customer affected by the possible "low" voltage condition, and the duration of the expected low voltage condition. Hence if the majority of the LPU contracts are $\pm 7.5\%$, will allow voltage to drop to 92.5% provided it does not do so on a regular basis. No hard and fast rules.

Table B1.1: Eastern Region present network planning practices and assumptions as regards voltage regulation limits and apportionment

Maximum and minimum MV limits for networks with NO bulk MV supplies ³		Maximum and minimum MV levels? What is the basis for these limits?	105% to 92.5%, but will allow MV to drop to 90% while “stretching” the network prior to reinforcement. This only applies to rural type supplies where customers are supplied via dedicated MV/LV transformers with minimal LV runs. This will generally enable acceptable voltages for motor loads provided they are in close proximity to the LV supply points. In urban areas where the required MV regulation is unknown, the MV voltage should generally not drop below 95%.
		Do you differentiate between newer (400V) and older (380V) contracts?	NO, this information is not readily available. Voltage regulation limits are based on the assumption that problems may be experienced with older 380V motors while attempting to stretch the network.
MV/LV transformers ⁴		Do you differentiate between 380V, 400V and 415V transformers? How do the assumptions regarding your MV/LV trfrs effect the allowable MV limits?	No, unfortunately not. MV regulation limits are hence not optimised and not tailored for each rural feeder supplying non-electrification load.
		Do you know, or make assumptions for, the tap position?	Tap position is unknown and not recorded.
Customised MV limits ⁵		Are you optimising / customising MV regulation for electrification projects?	Yes
		If so how are you recording this requirement such that future planners will know what regulation limits need to be maintained at a point in the network (for an electrification project)?	The requirements are captured in the electrification project design parameters, which should be archived electronically for future reference, but presently this is not the case. Need to be able to capture this data against a MV/LV transformer. This is a major issue.
Electrification design parameters ⁶		Do you have access to the electrification LV design parameters for projects (assumptions of MV voltages, design ADMDs, trfr tap positions etc)?	Unfortunately access is limited, and there is no proper filing or reference system.

Table B1.1 continued

B2 CENTRAL REGION

<i>Description</i>	<i>Used?</i>	<i>Issues</i>	<i>Comments / Answers</i>
Sending voltage ¹		Are you using fixed voltage or line drop compensation / voltage compounding?	Fixed voltage
		Do you have custom settings for different substations based on actual settings data?	No
		What assumption of sending voltage do you use for feeder peak load conditions (e.g. 104%)?	102%
		What assumption of sending voltage do you use for feeder low load conditions (e.g. 104%)?	102%
Maximum and minimum MV limits for networks with bulk MV supplies ²		Maximum and minimum MV levels? What is the basis for these limits?	105% - 95%
		Do you differentiate between newer ($\pm 5\%$) and older ($\pm 7.5\%$) contracts?	No
Maximum and minimum MV limits for networks with NO bulk MV supplies ³		Maximum and minimum MV levels? What is the basis for these limits?	105% - 95%
		Do you differentiate between newer (400V) and older (380V) contracts?	No
MV/LV transformers ⁴		Do you differentiate between 380V, 400V and 415V transformers? How do the assumptions regarding your MV/LV trfrs effect the allowable MV limits?	Only 400V
		Do you know, or make assumptions for, the tap position?	No
Customised MV limits ⁵		Are you optimising / customising MV regulation for electrification projects?	N/A
		If so how are you recording this requirement such that future planners will know what regulation limits need to be maintained, at a point in the network (for an electrification project)?	N/A
Electrification design parameters ⁶		Do you have access to the electrification LV design parameters for projects (assumptions of MV voltages, design ADMDs, trfr tap positions etc)?	N/A

Table B2.1: Central Region present network planning practices and assumptions as regards voltage regulation limits and apportionment

B3 NORTH EAST REGION

<i>Description</i>	<i>Used?</i>	<i>Issues</i>	<i>Comments / Answers</i>
Sending voltage ¹	yes	Are you using fixed voltage or line drop compensation / voltage compounding?	no
		Do you have custom settings for different substations based on actual settings data?	Do not understand
		What assumption of sending voltage do you use for feeder peak load conditions (e.g. 104%)?	PSSE input voltage
		What assumption of sending voltage do you use for feeder low load conditions (e.g. 104%)?	PSSE input voltage
Maximum and minimum MV limits for networks with bulk MV supplies ²		Maximum and minimum MV levels? What is the basis for these limits?	103 and 95%
		Do you differentiate between newer ($\pm 5\%$) and older ($\pm 7.5\%$) contracts?	Yes 5 is what I use
Maximum and minimum MV limits for networks with NO bulk MV supplies ³		Maximum and minimum MV levels? What is the basis for these limits?	Yes, NRS limits for all customers
		Do you differentiate between newer (400V) and older (380V) contracts?	Yes, use 400V
MV/LV transformers ⁴		Do you differentiate between 380V, 400V and 415V transformers? How do the assumptions regarding your MV/LV trfrs effect the allowable MV limits?	Not too clear
		Do you know, or make assumptions for, the tap position?	Make assumptions
Customized MV limits ⁵		Are you optimising / customising MV regulation for electrification projects?	At MV supply point only
		If so how are you recording this requirement such that future planners will know what regulation limits need to be maintained at a point in the network (for an electrification project)?	N/A to me
Electrification design parameters ⁶		Do you have access to the electrification LV design parameters for projects (assumptions of MV voltages, design ADMDs, trfr tap positions etc)?	No

Table B.3.1: North East Region present network planning practices and assumptions as regards voltage regulation limits and apportionment

B4 NORTH WEST REGION

Description	Used?	Issues	Comments / Answers
Sending voltage ¹		Are you using fixed voltage or line drop compensation / voltage compounding?	Fixed voltage
		Do you have custom settings for different substations based on actual settings data?	Sometimes
		What assumption of sending voltage do you use for feeder peak load conditions (e.g. 104%)?	103%
		What assumption of sending voltage do you use for feeder low load conditions (e.g. 104%)?	103%
Maximum and minimum MV limits for networks with bulk MV supplies ²		Maximum and minimum MV levels? What is the basis for these limits?	Mostly allow for 7.5% regulation.
		Do you differentiate between newer ($\pm 5\%$) and older ($\pm 7.5\%$) contracts?	In Some cases (Where the planner is aware of newer 5% contracts)
Maximum and minimum MV limits for networks with NO bulk MV supplies ³		Maximum and minimum MV levels? What is the basis for these limits?	Allow for 10% regulation.
		Do you differentiate between newer (400V) and older (380V) contracts?	No
MV/LV transformers ⁴		Do you differentiate between 380V, 400V and 415V transformers? How do the assumptions regarding your MV/LV trfrs effect the allowable MV limits?	No, mostly use default value from Reni.
		Do you know, or make assumptions for, the tap position?	No – Info not available
Customised MV limits ⁵		Are you optimising / customising MV regulation for electrification projects?	Yes
		If so how are you recording this requirement such that future planners will know what regulation limits need to be maintained at a point in the network (for an electrification project)?	Yes, the requirements are customised to a agreed level stated in the planning proposal for the project.
Electrification design parameters ⁶		Do you have access to the electrification LV design parameters for projects (assumptions of MV voltages, design ADMDs, trfr tap positions etc)?	No, this info is rarely available.

Table B4.1: North West Region present network planning practices and assumptions as regards voltage regulation limits and apportionment

B5 SOUTHERN REGION

<i>Description</i>	<i>Used?</i>	<i>Issues</i>	<i>Comments / Answers</i>
Sending voltage ¹	1.03pu	Are you using fixed voltage or line drop compensation / voltage compounding?	Fixed voltage
		Do you have custom settings for different substations based on actual settings data?	No, mostly fixed on 1.03pu
		What assumption of sending voltage do you use for feeder peak load conditions (e.g. 104%)?	103%
		What assumption of sending voltage do you use for feeder low load conditions (e.g. 104%)?	103%
Maximum and minimum MV limits for networks with bulk MV supplies ²	Yes	Maximum and minimum MV levels? What is the basis for these limits?	Statutory reasons, trigger for when low voltage is going to occur.
		Do you differentiate between newer ($\pm 5\%$) and older ($\pm 7.5\%$) contracts?	Generally no, but sometimes do depending on the criticality of a particular customer.
Maximum and minimum MV limits for networks with NO bulk MV supplies ³	Yes,	Maximum and minimum MV levels? What is the basis for these limits?	Determines when reinforcement is required. Maximum can be 105% but generally set at 103%. Minimum is 7.5% from nominal.
		Do you differentiate between newer (400V) and older (380V) contracts?	No
MV/LV transformers ⁴		Do you differentiate between 380V, 400V and 415V transformers? How do the assumptions regarding your MV/LV trfr effect the allowable MV limits?	Yes, on urban networks only. Design is on the basis of what's in the field.
		Do you know, or make assumptions for, the tap position?	No, assume nominal tap
Customised MV limits ⁵		Are you optimising / customising MV regulation for electrification projects?	Yes, there is a chart that determines tap ranges
		If so how are you recording this requirement such that future planners will know what regulation limits need to be maintained at a point in the network (for an electrification project)?	Use a chart, also electrification planning reports are written.
Electrification design parameters ⁶		Do you have access to the electrification LV design parameters for projects (assumptions of MV voltages, design ADMDs, trfr tap positions etc)?	Yes

Table B5.1: Southern Region present network planning practices and assumptions as regards voltage regulation limits and apportionment

B6 WESTERN REGION

Description	Used?	Issues	Comments / Answers
Sending voltage ¹		Are you using fixed voltage or line drop compensation / voltage compounding?	AVR "VTJC" normally set on 105% (disable LDC) & simulate on 104% to allow for dead band If any settings deviate from the standard settings it should be documented via the voltage control process
		Do you have custom settings for different substations based on actual settings data?	Voltage control process caters for any custom changes
		What assumption of sending voltage do you use for feeder peak load conditions (e.g. 104%)?	104 %
		What assumption of sending voltage do you use for feeder low load conditions (e.g. 104%)?	104 %
Maximum and minimum MV limits for networks with bulk MV supplies ²		Maximum and minimum MV levels? What is the basis for these limits?	105 % TO 92,5% According to ESKOM HV contracts
		Do you differentiate between newer ($\pm 5\%$) and older ($\pm 7.5\%$) contracts?	No, all contracts still specifies +/- 7.5%
Maximum and minimum MV limits for networks with NO bulk MV supplies ³		Maximum and minimum MV levels? What is the basis for these limits?	106 % TO 92,5%
		Do you differentiate between newer (400V) and older (380V) contracts?	Transformers are mixed, model MV network
MV/LV transformers ⁴		Do you differentiate between 380V, 400V and 415V transformers? How do the assumptions regarding your MV/LV trfrs effect the allowable MV limits?	Standard tap positions should be followed according to the voltage control process
		Do you know, or make assumptions for, the tap position?	Model MV network
Customised MV limits ⁵		Are you optimising / customising MV regulation for electrification projects?	No very limited electrification loads on Cape feeders
		If so how are you recording this requirement such that future planners will know what regulation limits need to be maintained at a point in the network (for an electrification project)?	N/A
Electrification design parameters ⁶		Do you have access to the electrification LV design parameters for projects (assumptions of MV voltages, design ADMDs, trfr tap positions etc)?	Request voltage levels when doing design. Assume ADMD of 0.5 to 1,2 for new projects

Table B6.1: Western Region present network planning practices and assumptions as regards voltage regulation limits and apportionment

B7 NORTHERN REGION

The questionnaire was not completed.

University of Cape Town

APPENDIX C: SCREEN DUMPS AND SAMPLE RESULTS FROM THE VOLTAGE REGULATION LIMIT MODEL

Sample screen dumps and results from the voltage regulation limit model are provided to illustrate the calculation of allowable voltage drops and the resultant distribution transformer tap positions and flux levels.

400V Motor	Urban N
Customer supply contract	400
Supply contract lower reg limit	-10.00%
Supply contract upper reg limit	10.00%
Motor rated voltage	400
Motor rated regulation range	5.00%
380V Motor	Urban N
Customer supply contract	380
Supply contract lower reg limit	-5.26%
Supply contract upper reg limit	7.50%
Motor rated voltage	380
Motor rated regulation range	5.00%
230V 1p Motor	Urban N
Customer supply contract	230
Supply contract lower reg limit	-10.00%
Supply contract upper reg limit	10.00%
Motor rated voltage	230
Motor rated regulation range	10.00%

Installation parameters	Urban N
LV voltage drop between MV/LV trfr and customer meter during max loading	2.00%
LV voltage drop between customer meter and motor during max loading	2.50%
LV voltage drop between MV/LV trfr and customer meter during min loading	1.00%
LV voltage drop between customer meter and motor during min loading	0.50%
Transformer impedance	4.00%
Transformer X/R ratio	2.00
Transformer R	1.79%
Transformer X	3.58%
Transformer peak load	90.00%
Peak load power factor	95.00%
Transformer internal v drop on-load	2.53%
Transformer low load	30.00%
Low load power factor	95.00%
Transformer internal v drop off-load	0.84%

230/400V LV contracts	
Rated voltage (three phase)	400
Rated voltage (single phase)	230
Supply contract lower reg limit	-10.00%
Supply contract upper reg limit	10.00%

Figure C1: Basic input data describing motor operating voltages, contractual and licence obligations, and voltage drops in the distribution transformer and LV network during peak and low-load periods. Standard distribution transformer data (nominal secondary voltages, DETS tap range and step size, and maximum allowed flux levels) must also be provided but are not illustrated in this figure.

Installation combinations and DETS tap control					
Adjust taps based on motor maximum voltage rating	y				
Motor and Transformer combinations	Enforce Contract	Enforce Motor limits	Tap number	Tap Ratio	Flux limiting
400V Motor supplied by 415V transformer	y	y	a	#N/A	y
400V Motor supplied by 400V transformer	y	y	a	#N/A	y
400V Motor supplied by 380V transformer	n	n	a	#N/A	y
380V Motor supplied by 415V transformer	y	y	a	#N/A	y
380V Motor supplied by 400V transformer	y	y	a	#N/A	y
380V Motor supplied by 380V transformer	y	y	a	#N/A	y
230V Motor supplied by 220V 1p transformer	n	n	a	#N/A	y
230V Motor supplied by 230V 1p transformer	y	y	a	#N/A	y
230V Motor supplied by 240V 1p transformer	y	y	a	#N/A	y
230V Motor supplied by 240V Dp transformer	y	y	a	#N/A	y

Voltage control and recovery characteristics	
Maximum MV Receiving Voltage	99.00%
Minimum MV Sending Voltage	103.00%

Figure C2: Study set-up options where the combinations of motors, transformers and contracts are selected. For any selected combination the user can fix the distribution transformer DETS in one of its tap positions, or the user can opt for the model to automatically select the best tap position based on the various input parameters. The user also has the option of whether or not to enforce the maximum allowed flux level associated with a particular distribution transformer.

Voltage setpoint	100.0%
Voltage bandwidth (+-)	0.5%
Load Ratio	40.0%
LDC voltage compound	6.0%
MV voltage drop at peak	10.0%
Peak Sending voltage	105.5%
Off peak sending voltage	102.9%
Minimum EOL voltage	95.5%
Maximum EOL voltage	98.9%

Figure C3: Study set-up options describing the type of voltage control methodology and settings on the MV source, the load characteristic being supplied, and MV voltage drop during peak load conditions. The MV voltages during both peak and low-load conditions are calculated.

Based on the input parameters specified in figures C1, C2 and C3, for each of the selected combinations of transformer and motor the required transformer DETS positions are calculated for each point down the MV feeder backbone. The results for a 415V transformer supplying a 400V motor are illustrated below.

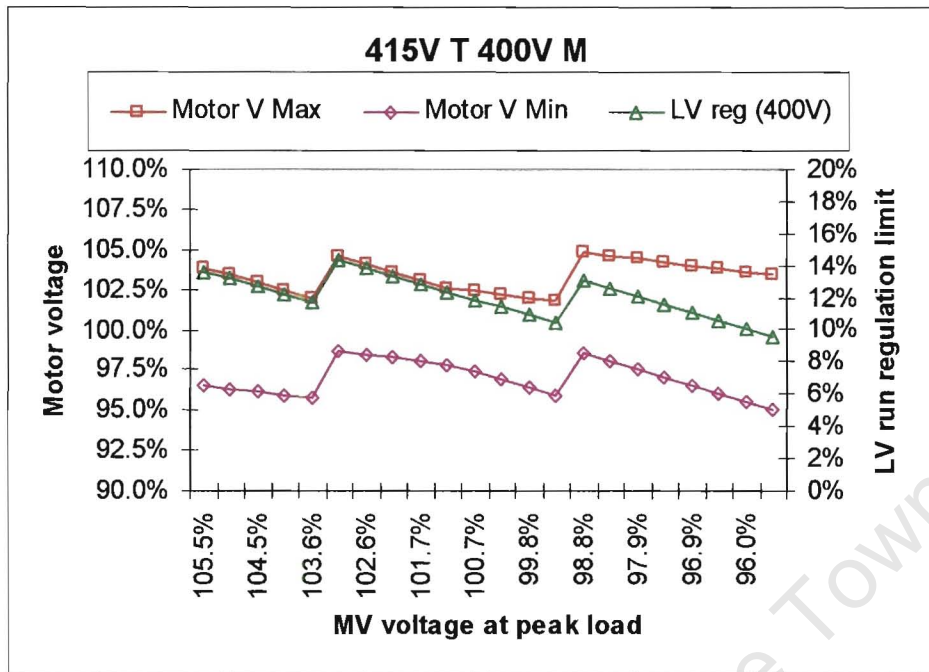


Figure C4: Motor maximum and minimum voltages and allowable LV voltage drop for domestic customers supplied off a 415V transformer feeding a 400V motor at various points down the MV feeder. Note that the motor voltages fall with the $\pm 5\%$ limit recommended for urban networks. The two fluctuations in voltage are due to the use of the transformer DETS.

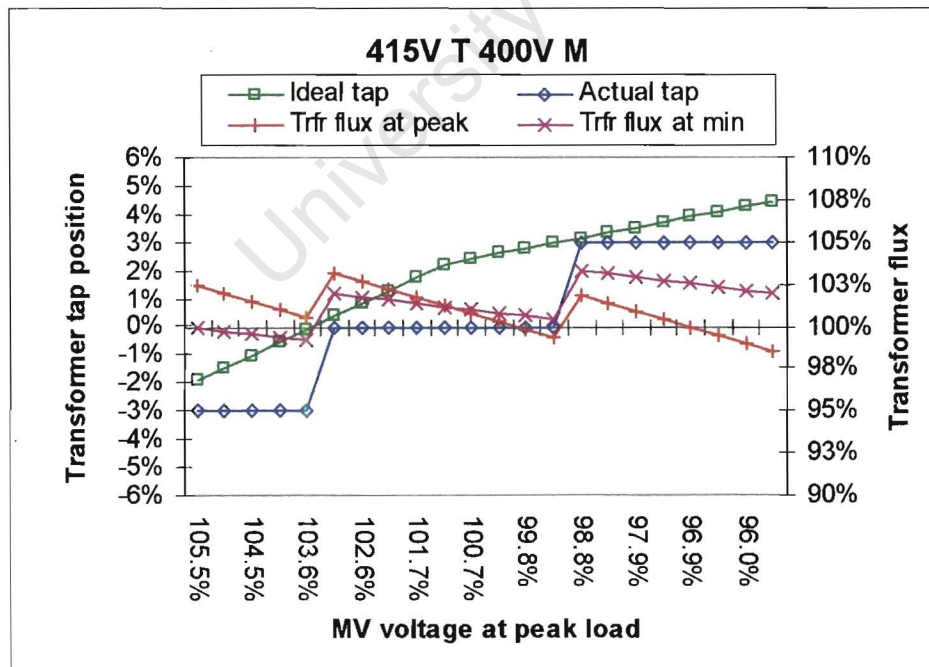


Figure C5: Corresponding to figure C4, the transformer tap position and flux levels (during peak and low-load conditions) are illustrated at the various points down the MV feeder.

Referring to figures C4 and C5:

- In order to keep within the +5% limit for the 400V motor the distribution transformers situated in the network where the MV voltage at peak falls between 105.5% and 103% must be bucked by one tap position i.e. -3%.
- For those transformers situated in the network where the MV voltage at peak falls between 103% and 99%, the low-load MV voltage recovery is such that these transformers can be operated on nominal tap without exceeding the +5% motor limit. These transformers can not however be boosted.
- For those transformers situated in the network where the MV voltage at peak falls below 99%, the low-load MV voltage recovery is such that these transformers can be operated on a 3% boost tap without exceeding the +5% motor limit.
- In all cases (three tap positions) the transformer maximum flux of 105% is not exceeded
- LV networks close to the MV source could be designed for a maximum LV voltage drop of approximately 13%.
- LV networks on the extremities of the MV feeder could be designed for a maximum LV voltage drop of approximately 10%.
- For this combination of 415V transformer and 400V motor the MV feeder voltage could be allowed to drop to 95.5% without any anticipated voltage problems.

For the identical network, but the combination of a 400V transformer supplying a 400V motor, the results are illustrated in figures C6 and C7 below, and the key observations are as follows:

- In order to keep transformer flux levels below 105% the distribution transformers situated in the network where the MV voltage at peak falls between 105.5% and 104% must be bucked by one tap position i.e. -2.5%.
- For those transformers situated in the network where the MV voltage at peak falls between 104% and 102%, the low-load MV voltage recovery is such that these transformers can be operated on nominal tap without exceeding the maximum flux or +5% motor limits. These transformers can not however be boosted.
- For those transformers situated in the network where the MV voltage at peak falls between 102% and 98%, the low-load MV voltage recovery is such that these transformers can be operated on a +2.5% boost without exceeding the maximum flux or +5% motor limits. These transformers can not however be boosted to +5%.
- For those transformers situated in the network where the MV voltage at peak falls below 98%, the low-load MV voltage recovery is such that these transformers can be operated on a 5% boost tap.
- Motor voltages fall below the -5% limit recommended for urban networks when the MV feeder voltage drops below roughly 100%. As a result if the network contains this combination of transformer and motor the EL MV voltage should not be allowed to drop below 100% for the given voltage control methodology and settings.
- LV networks close to the MV source could be designed for a maximum LV voltage drop of approximately 10%.
- Provided the minimum EL MV voltage is kept above 100%, the LV networks on the extremities of the MV feeder could be designed for a maximum LV voltage drop of approximately 8%.

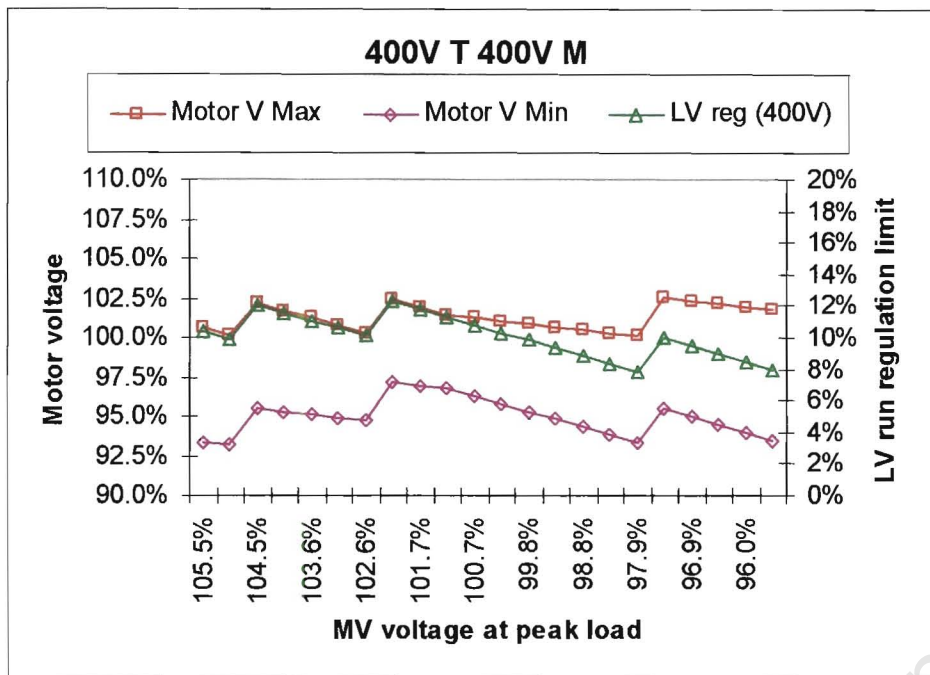


Figure C6: Motor maximum and minimum voltages and allowable LV voltage drop for domestic customers supplied off a 400V transformer feeding a 400V motor at various points down the MV feeder. Note that the motor voltages fall below the -5% limit recommended for urban networks when the MV feeder voltage drops below roughly 100%. The three fluctuations in voltage are due to the use of the transformer DETS.

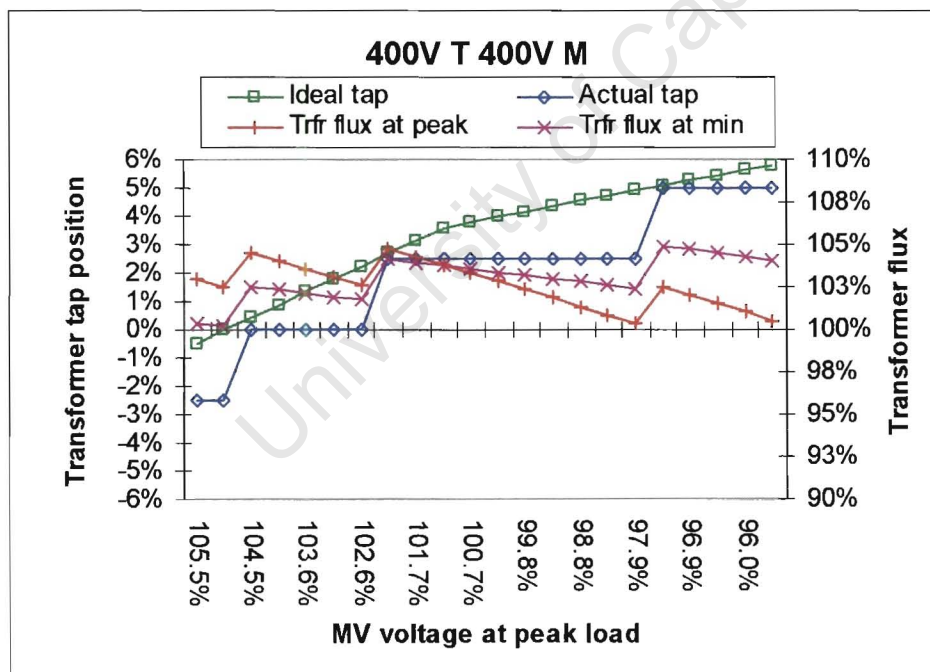


Figure C7: Corresponding to figure C6, the transformer tap position and flux levels (during peak and low-load conditions) are illustrated at the various points down the MV feeder.

APPENDIX D: VOLTAGE REGULATION LIMIT MODEL DETAILED RESULTS

Where DETS transformer tapping is enable, the preferred tap position is selected based on allowable flux levels (when selected) and the maximum motor voltages (not the contractual limits at the service point). Setting the taps based on the service voltages can result in motor over voltages and unnecessary over fluxing of transformers.

D1 URBAN TYPE NETWORKS

D1.1 UA: URBAN, Normal Network Condition, and a Mixture of Motors and Transformers

Case UA1: Maximum end of line voltage is 102% and minimum MV sending voltage is 103%. The requirements of all common motors, transformers and supply contracts and licence obligations are included. All transformer DETS taps are locked in nominal tap, and flux limiting is enabled

Case UA2: As for case UA1, but with no 380V or 220V transformers supplying 400V or 230V motors respectively

Case UA3: As for case UA1, but no 380V motors, contracts or transformers

Case UA4: As for case UA1, but with DETS tapping enabled

Case UA5: As for case UA4, but with no 380V or 220V transformers supplying 400V or 230V motors respectively

Case UA6: As for case UA5, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case UA7: As for case UA5, but maximum EL voltage recovers to 104% and not 102%

Case UA8: As for case UA7, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case UA9: As for case UA5, but maximum EL voltage recovers to 103%

Case UA10: As for case UA9, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case UA11: As for case UA5, but maximum EL voltage only recovers to 101%

Case UA12: As for case UA11, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case UA13: As for case UA5, but maximum EL voltage only recovers to 100%

Case UA14: As for case UA13, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case UA15: As for case UA5, but maximum EL voltage only recovers to 99%

Case UA16: As for case UA15, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case UA17: As for case UA5, but maximum EL voltage only recovers to 98%

Case UA18: As for case UA17, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

	Case UA1				Case UA2				Case UA3				Case UA4				Case UA5				Case UA6				Case UA7							
	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F
400V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
400V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
400V 3 ϕ Motor 380V 3 ϕ Trfr	Y	Y	N	Y	N	N	N	Y	N	N	N	Y	Y	Y	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	N	Y	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	N	Y	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3 ϕ Motor 380V 3 ϕ Trfr	Y	Y	N	Y	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
230V 1 ϕ Motor 220V 1 ϕ Trfr	Y	Y	N	Y	N	N	N	Y	N	N	N	Y	Y	Y	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1 ϕ Motor 230V 1 ϕ Trfr	Y	Y	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1 ϕ Motor 240V 1 ϕ Trfr	Y	Y	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1 ϕ Motor 240V D ϕ Trfr	Y	Y	N	Y	Y	Y	N	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Maximum MV EL voltage	102%				102%				102%				102%				102%				102%				104%							
Minimum MV source voltage	103%				103%				103%				103%				103%				103%				105%							
Results																																
Maximum MV sending voltage to meet service range	Can't be done				Can't be done				105.0%				105.0%				106.2%				106.2%				106.2%							
Minimum MV sending voltage to meet service range									94.5%				98.7%				96.8%				94.5%				99.3%							
Maximum MV sending voltage to meet motor range									103.5%				Can't be done				104.3%				104.3%				104.3%							
Minimum MV sending voltage to meet motor range									102.0%				Can't be done				99.5%				99.5%				102.0%							
Maximum MV/LV transformer flux to meet motor and service ranges	N/A				N/A				103.5%				N/A				104.6%				104.6%				104.3%							

Table D1.1: Normal network condition, and a mixture of motors and transformers (S: Enforce service agreement, M: Enforce motor requirements, A: Enable auto tapping, F: Enforce flux limits)

	Case UA8				Case UA9				Case UA10				Case UA11				Case UA12				Case UA13				Case UA14							
	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F
400V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
400V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
400V 3 ϕ Motor 380V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3 ϕ Motor 380V 3 ϕ Trfr	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
230V 1 ϕ Motor 220V 1 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1 ϕ Motor 230V 1 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1 ϕ Motor 240V 1 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1 ϕ Motor 240V D ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Maximum MV EL voltage	104%				103%				103%				101%				101%				100%				100%							
Minimum MV source voltage	105%				104%				104%				103%				103%				103%				103%							
Results																																
Maximum MV sending voltage to meet service range	106.2%				106.2%				106.2%				106.2%				106.2%				106.2%				106.2%							
Minimum MV sending voltage to meet service range	96.8%				99.3%				94.5%				96.8%				94.5%				96.8%				94.5%							
Maximum MV sending voltage to meet motor range	104.3%				104.3%				104.3%				104.3%				104.3%				104.3%				104.3%							
Minimum MV sending voltage to meet motor range	101.4%				102.0%				99.5%				99.5%				98.4%				99.5%				97.1%							
Maximum MV/LV transformer flux to meet motor and service ranges	106.7%				104.3%				105.6%				104.3%				106.3%				104.3%				105.3%							

Table D1.1 continued

	Case UA15				Case UA16				Case UA17				Case UA18			
	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F
400V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
400V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N
400V 3 ϕ Motor 380V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3 ϕ Motor 380V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N
230V 1 ϕ Motor 220V 1 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1 ϕ Motor 230V 1 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1 ϕ Motor 240V 1 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1 ϕ Motor 240V D ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Maximum MV EL voltage	99%				99%				98%				98%			
Minimum MV source voltage	103%				103%				103%				103%			
Results																
Maximum MV sending voltage to meet service range	106.2%				106.2%				106.2%				106.2%			
Minimum MV sending voltage to meet service range	94.3%				94.3%				94.3%				94.3%			
Maximum MV sending voltage to meet motor range	104.3%				104.3%				104.3%				104.3%			
Minimum MV sending voltage to meet motor range	96.9%				96.9%				96.9%				96.9%			
Maximum MV/LV transformer flux to meet motor and service ranges	104.3%				104.3%				104.3%				104.3%			

Table D1.1 continued

D1.2 UB: URBAN, Abnormal Network Condition, and a Mixture of Motors and Transformers

Case UB1: Maximum end of line voltage is 104% and minimum MV sending voltage is 105%. The requirements of all common motors, transformers and supply contracts and licence obligations are included except for 380V or 220V transformers supplying 400V or 230V motors respectively. Transformer DETS taps and flux limiting are enabled

Case UB2: As for case UB1, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case UB3: As for case UB1, but maximum EL voltage recovers to 102% and not 104%

Case UB4: As for case UB3, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case UB5: As for case UB1, but maximum EL voltage recovers to 100% and not 104%

Case UB6: As for case UB5, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case UB7: As for case UB1, but maximum EL voltage recovers to 98% and not 104%

Case UB8: As for case UB7, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

	Case UB1				Case UB2				Case UB3				Case UB4				Case UB5				Case UB6				Case UB7							
	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F
400V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
400V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
400V 3 ϕ Motor 380V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3 ϕ Motor 380V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
230V 1 ϕ Motor 220V 1 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1 ϕ Motor 230V 1 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1 ϕ Motor 240V 1 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1 ϕ Motor 240V D ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Maximum MV EL voltage	104%				104%				102%				102%				100%				100%				98%							
Minimum MV source voltage	105%				105%				103%				103%				103%				103%				103%							
Results																																
Maximum MV sending voltage to meet service range	106.2%				106.2%				106.2%				106.2%				106.2%				106.2%				106.2%							
Minimum MV sending voltage to meet service range	99.3%				96.8%				96.8%				94.5%				96.8%				94.5%				94.3%							
Maximum MV sending voltage to meet motor range	106.7%				106.7%				106.7%				106.7%				106.7%				106.7%				106.7%							
Minimum MV sending voltage to meet motor range	99.5%				97.0%				97.0%				97.0%				97.0%				97.0%				94.6%							
Maximum MV/LV transformer flux to meet motor and service ranges	104.1%				109.5%				104.6%				107.4%				104.1%				104.1%				104.1%							

Table D1.2: Abnormal network condition, and a mixture of motors and transformers

	Case UB8			
	S	M	A	F
400V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y
400V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	Y	N
400V 3 ϕ Motor 380V 3 ϕ Trfr	N	N	Y	Y
380V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y
380V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	Y	Y
380V 3 ϕ Motor 380V 3 ϕ Trfr	Y	Y	Y	N
230V 1 ϕ Motor 220V 1 ϕ Trfr	N	N	Y	Y
230V 1 ϕ Motor 230V 1 ϕ Trfr	Y	Y	Y	Y
230V 1 ϕ Motor 240V 1 ϕ Trfr	Y	Y	Y	Y
230V 1 ϕ Motor 240V D ϕ Trfr	Y	Y	Y	Y
Maximum MV EL voltage	98%			
Minimum MV source voltage	103%			
Results				
Maximum MV sending voltage to meet service range	106.2%			
Minimum MV sending voltage to meet service range	94.3%			
Maximum MV sending voltage to meet motor range	106.7%			
Minimum MV sending voltage to meet motor range	94.6%			
Maximum MV/LV transformer flux to meet motor and service ranges	104.1%			

Table D1.2 continued

D1.3 UC: URBAN, Normal Network Condition, and only “newer” 415/240V Transformers and 400/230V motors

As flux level are low due to the higher secondary transformer voltages, limiting flux levels to 105% does not limit the use of DETS taps with new transformers.

Case UC1: Maximum end of line voltage is 104% and minimum MV sending voltage is 105%. Only new 415/240V transformers and 400/230V motors are included. Flux limiting and DETS tapping is enabled

Case UC2: As for case UC1, but maximum EL voltage recovers to 102% and not 104%

Case UC3: As for case UC1, but maximum EL voltage recovers to 100% and not 104%

Case UC4: As for case UC1, but maximum EL voltage recovers to 98% and not 104%

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	Case UC1				Case UC2				Case UC3				Case UC4			
	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F
400V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
400V 3 ϕ Motor 400V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
400V 3 ϕ Motor 380V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3 ϕ Motor 415V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3 ϕ Motor 400V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3 ϕ Motor 380V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1 ϕ Motor 220V 1 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1 ϕ Motor 230V 1 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1 ϕ Motor 240V 1 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1 ϕ Motor 240V D ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Maximum MV EL voltage	104%				102%				100%				98%			
Minimum MV source voltage	105%				103%				103%				103%			
Results																
Maximum MV sending voltage to meet service range	110.3%				110.3%				110.3%				110.3%			
Minimum MV sending voltage to meet service range	91.2%				91.2%				90.7%				86.2%			
Maximum MV sending voltage to meet motor range	109.7%				106.6%				106.6%				106.6%			
Minimum MV sending voltage to meet motor range	101.4%				98.4%				95.5%				95.5%			
Maximum MV/LV transformer flux to meet motor and service ranges	104.5%				102.0%				103.5%				101.5%			

Table D1.3: Normal network condition, and only "newer" 415/240V transformers and 400/230V motors are included

D2 RURAL TYPE NETWORKS

D2.1 RA: RURAL, Normal Network Condition, and a Mixture of Motors and Transformers

Case RA1: Maximum end of line voltage is 102% and minimum MV sending voltage is 103%. The requirements of all common motors, transformers and supply contracts and licence obligations are included. All transformer DETS taps are locked in nominal tap, and flux limiting is enabled

Case RA2: As for case RA1, but with no 380V or 220V transformers supplying 400V or 230V motors respectively

Case RA3: As for case RA1, but no 380V motors, contracts or transformers

Case RA4: As for case RA1, but with DETS tapping enabled

Case RA5: As for case RA4, but with no 380V or 220V transformers supplying 400V or 230V motors respectively

Case RA6: As for case RA5, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case RA7: As for case RA5, but maximum EL voltage recovers to 104% and not 102%

Case RA8: As for case RA7, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case RA9: As for case RA5, but maximum EL voltage recovers to 103%

Case RA10: As for case RA9, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case RA11: As for case RA5, but maximum EL voltage only recovers to 101%

Case RA12: As for case RA11, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case RA13: As for case RA5, but maximum EL voltage only recovers to 100%

Case RA14: As for case RA13, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case RA15: As for case RA5, but maximum EL voltage only recovers to 99%

Case RA16: As for case RA15, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case RA17: As for case RA5, but maximum EL voltage only recovers to 98%

Case RA18: As for case RA17, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

	Case RA8				Case RA9				Case RA10				Case RA11				Case RA12				Case RA13				Case RA14											
	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F				
400V 3φ Motor 415V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
400V 3φ Motor 400V 3φ Trfr	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N
400V 3φ Motor 380V 3φ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3φ Motor 415V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3φ Motor 400V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3φ Motor 380V 3φ Trfr	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	N
230V 1φ Motor 220V 1φ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1φ Motor 230V 1φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1φ Motor 240V 1φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1φ Motor 240V Dφ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Maximum MV EL voltage	104%				103%				103%				101%				101%				100%				100%											
Minimum MV source voltage	105%				104%				104%				103%				103%				103%				103%											
Results																																				
Maximum MV sending voltage to meet service range	104.8%				104.8%				104.8%				104.8%				104.8%				104.8%				104.8%											
Minimum MV sending voltage to meet service range	95.5%				98.0%				95.5%				95.5%				93.2%				95.5%				93.2%											
Maximum MV sending voltage to meet motor range	105.3%				105.3%				105.3%				105.3%				105.3%				105.3%				105.3%											
Minimum MV sending voltage to meet motor range	95.8%				98.2%				95.7%				95.8%				95.7%				95.8%				95.7%											
Maximum MV/LV transformer flux to meet motor and service ranges	106.7%				103.0%				108.4%				103.6%				106.3%				102.6%				105.3%											

Table D2.1 continued

	Case RA15				Case RA16				Case RA17				Case RA18			
	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F
400V 3φ Motor 415V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
400V 3φ Motor 400V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N
400V 3φ Motor 380V 3φ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3φ Motor 415V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3φ Motor 400V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3φ Motor 380V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N
230V 1φ Motor 220V 1φ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1φ Motor 230V 1φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1φ Motor 240V 1φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1φ Motor 240V Dφ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Maximum MV EL voltage	99%				99%				98%				98%			
Minimum MV source voltage	103%				103%				103%				103%			
Results																
Maximum MV sending voltage to meet service range	104.8%				104.8%				104.8%				104.8%			
Minimum MV sending voltage to meet service range	93.1%				93.1%				93.1%				93.1%			
Maximum MV sending voltage to meet motor range	105.3%				105.3%				105.3%				105.3%			
Minimum MV sending voltage to meet motor range	93.3%				93.3%				93.3%				93.3%			
Maximum MV/LV transformer flux to meet motor and service ranges	104.2%				104.2%				103.2%				103.2%			

Table D2.1 continued

D2.2 RB: RURAL, Abnormal Network Condition, and a Mixture of Motors and Transformers

Case RB1: Maximum end of line voltage is 104% and minimum MV sending voltage is 105%. The requirements of all common motors, transformers and supply contracts and licence obligations are included except for 380V or 220V transformers supplying 400V or 230V motors respectively. Transformer DETS taps and flux limiting are enabled

Case RB2: As for case RB1, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case RB3: As for case RB1, but maximum EL voltage recovers to 102% and not 104%

Case RB4: As for case RB3, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case RB5: As for case RB1, but maximum EL voltage recovers to 100% and not 104%

Case RB6: As for case RB5, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

Case RB7: As for case RB1, but maximum EL voltage recovers to 98% and not 104%

Case RB8: As for case RB7, but no flux limiting of 380V and 400V secondary transformers supplying 380V and 400V motors respectively

	Case RB1				Case RB2				Case RB3				Case RB4				Case RB5				Case RB6				Case RB7							
	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F
400V 3φ Motor 415V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
400V 3φ Motor 400V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y
400V 3φ Motor 380V 3φ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3φ Motor 415V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3φ Motor 400V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
380V 3φ Motor 380V 3φ Trfr	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y
230V 1φ Motor 220V 1φ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1φ Motor 230V 1φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1φ Motor 240V 1φ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1φ Motor 240V Dφ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Maximum MV EL voltage	104%				104%				102%				102%				100%				100%				98%							
Minimum MV source voltage	105%				105%				103%				103%				103%				103%				103%							
Results																																
Maximum MV sending voltage to meet service range	104.8%				104.8%				104.8%				104.8%				104.8%				104.8%				104.8%							
Minimum MV sending voltage to meet service range	95.7%				93.3%				93.3%				93.2%				93.3%				93.2%				90.9%							
Maximum MV sending voltage to meet motor range	107.7%				107.7%				107.7%				107.7%				107.7%				107.7%				107.7%							
Minimum MV sending voltage to meet motor range	95.7%				93.2%				93.3%				93.2%				93.3%				93.2%				90.9%							
Maximum MV/LV transformer flux to meet motor and service ranges	104.0%				106.9%				104.6%				104.9%				102.6%				102.8%				103.2%							

Table D2.2: Abnormal network condition, and a mixture of motors and transformers

	Case RB8			
	S	M	A	F
400V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y
400V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	Y	N
400V 3 ϕ Motor 380V 3 ϕ Trfr	N	N	Y	Y
380V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y
380V 3 ϕ Motor 400V 3 ϕ Trfr	Y	Y	Y	Y
380V 3 ϕ Motor 380V 3 ϕ Trfr	Y	Y	Y	N
230V 1 ϕ Motor 220V 1 ϕ Trfr	N	N	Y	Y
230V 1 ϕ Motor 230V 1 ϕ Trfr	Y	Y	Y	Y
230V 1 ϕ Motor 240V 1 ϕ Trfr	Y	Y	Y	Y
230V 1 ϕ Motor 240V D ϕ Trfr	Y	Y	Y	Y
Maximum MV EL voltage	98%			
Minimum MV source voltage	103%			
Results				
Maximum MV sending voltage to meet service range	104.8%			
Minimum MV sending voltage to meet service range	90.9%			
Maximum MV sending voltage to meet motor range	107.7%			
Minimum MV sending voltage to meet motor range	90.9%			
Maximum MV/LV transformer flux to meet motor and service ranges	103.2%			

Table D2.2 continued

D2.3 RC: RURAL, Normal Network Condition, and only “newer” 415/240V Transformers and 400/230V Motors

As flux levels are low due to the higher secondary transformer voltages, limiting flux levels to 105% does not limit the use of DETS taps with new transformers.

Case RC1: Maximum end of line voltage is 104% and minimum MV sending voltage is 105%. Only new 415/240V transformers and 400/230V motors are included. Flux limiting and DETS tapping is enabled

Case RC2: As for case RC1, but maximum EL voltage recovers to 102% and not 104%

Case RC3: As for case RC1, but maximum EL voltage recovers to 100% and not 104%

Case RC4: As for case RC1, but maximum EL voltage recovers to 98% and not 104%

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	Case RC1				Case RC2				Case RC3				Case RC4			
	S	M	A	F	S	M	A	F	S	M	A	F	S	M	A	F
400V 3 ϕ Motor 415V 3 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
400V 3 ϕ Motor 400V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
400V 3 ϕ Motor 380V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3 ϕ Motor 415V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3 ϕ Motor 400V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
380V 3 ϕ Motor 380V 3 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1 ϕ Motor 220V 1 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1 ϕ Motor 230V 1 ϕ Trfr	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
230V 1 ϕ Motor 240V 1 ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
230V 1 ϕ Motor 240V D ϕ Trfr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Maximum MV EL voltage	104%				102%				100%				98%			
Minimum MV source voltage	105%				103%				103%				103%			
Results																
Maximum MV sending voltage to meet service range	110.3%				110.3%				110.3%				110.3%			
Minimum MV sending voltage to meet service range	89.9%				89.9%				89.4%				85.0%			
Maximum MV sending voltage to meet motor range	110.3%				110.3%				110.3%				110.3%			
Minimum MV sending voltage to meet motor range	94.7%				94.7%				91.9%				89.1%			
Maximum MV/LV transformer flux to meet motor and service ranges	104.0%				104.0%				104.0%				104.0%			

Table D2.3: Normal network condition, and only "newer" 415/240V transformers and 400/230V motors are included

APPENDIX E: LOAD DATA USED IN APPLICATION EXAMPLES

E1 IXOPO NB1 (RURAL TOWN)

Ixopo NB1 is an 11kV feeder that supplies the large rural town of Ixopo in Kwa-Zulu Natal. It supplies a mixture of commercial and residential load, with very limited light industrial loads. The load data at the feeder source includes all the downstream technical and non-technical losses.

- 10 months demand data in 30 minute demand intervals between January and October 2001.
- Due the 132/22kV transformer failure at Ixopo substation, zero load was recorded between 20 May and 2 June, and this period has been excluded from the sample.

Month	Jan	Feb	Mar	April	May	Jun	July	Aug	Sept	Oct
Average demand (kVA)	1631	1690	1722	1646	1784	1852	1866	1852	1778	1730
Maximum demand (kVA)	2462	2463	2535	2508	2642	2802	3330	2868	3153	2654

Table E1.1: Ixopo NB1 monthly average and maximum demands for load data in 2001. Values are in kVA.

Time	Sunday		Saturday		Weekday	
	Mean	Std dev	Mean	Std dev	Mean	Std dev
0:00	1155	39.83	1197	50.04	1185	109.5
1:00	1114	38.28	1143	50.36	1120	97.92
2:00	1090	40.33	1117	51.18	1097	94.25
3:00	1076	41.64	1103	50.57	1091	100.2
4:00	1072	43.35	1101	48.43	1098	112.9
5:00	1120	49.32	1171	58.63	1235	85.9
6:00	1265	70.65	1398	94.36	1759	211.2
7:00	1578	108.1	1761	127.2	2165	277.6
8:00	1728	296	2148	157.3	2319	253.2
9:00	1772	315.2	2297	151.7	2395	260.6
10:00	1737	309	2248	165	2340	224.9
11:00	1687	298.2	2172	167.7	2261	217.6
12:00	1628	289.5	2061	162.4	2200	203.7
13:00	1513	263.9	1867	141.1	2107	201.1
14:00	1394	242.3	1635	134.4	2046	200.2
15:00	1342	232.2	1554	129.5	2063	217.9
16:00	1406	247.9	1617	139.7	2143	247.7
17:00	1610	197.1	1713	169.6	2146	237.8
18:00	1905	243.4	1953	226.5	2217	291.9
19:00	1992	205	1987	178	2214	236.3
20:00	1904	178.2	1886	138.3	2073	203.5
21:00	1690	148	1699	121.5	1846	163.2
22:00	1423	98.91	1482	86.66	1558	113.9
23:00	1230	58.24	1296	60.31	1325	88.05

Table E1.2: Ixopo NB1 annual mean and standard deviations for each daily demand interval. Values are in kVA, and are based on the load data for January through to October 2001.

The load factor is 0.60

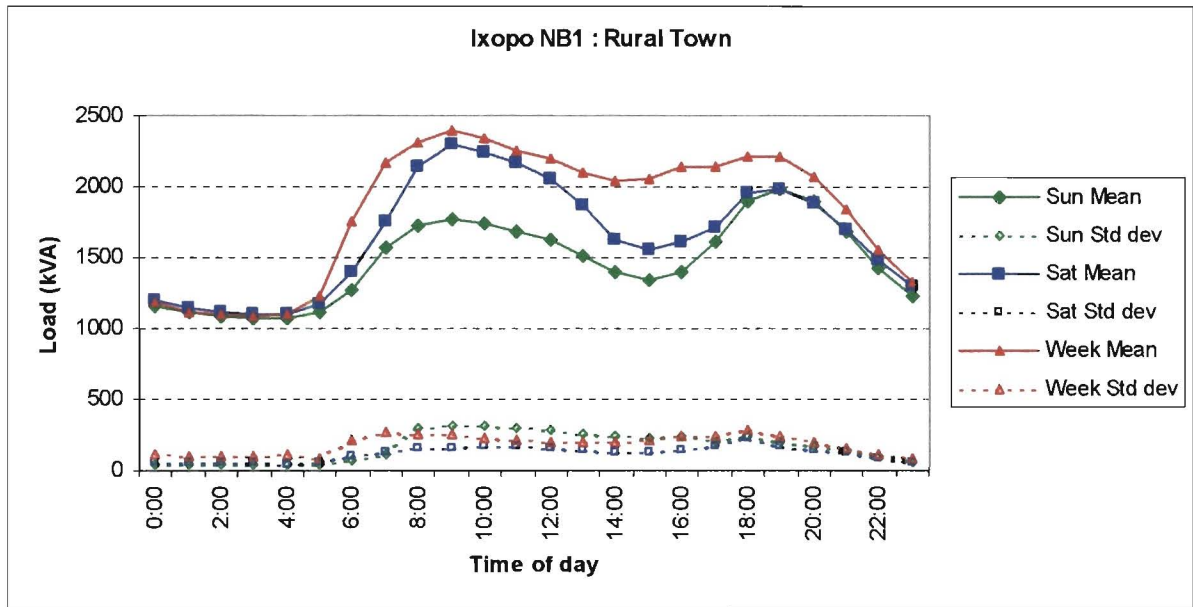


Figure E1.3: Graphical representation of Ixopo NB1 load annual mean and standard deviation (data in table E1.2)

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E2 GOWRIE NB23 (MIXED RURAL)

Gowrie NB23 11/22kV feeder supplies mixed rural loads in the vicinity of the small rural town of Nottingham Road in the Midlands in Kwa-Zulu Natal. It supplies a mixture of smallholdings, agricultural and pumping loads. The load data at the substation includes all the downstream technical and non-technical losses.

- 9 months demand data in 30 minute demand intervals between February and October 2001.

Month	Feb	Mar	April	May	Jun	July	Aug	Sept	Oct
Average demand (kVA)	836	975	907	1143	1313	1311	1367	1126	1108
Maximum demand (kVA)	1424	1704	1570	1907	2043	2029	2191	1861	1853

Table E2.1: Gowrie NB23 monthly average and maximum demands for load data in 2001. Values are in kVA.

Time	Sunday		Saturday		Weekday	
	Mean	Std dev	Mean	Std dev	Mean	Std dev
0:00	716	103.5	788	134.6	773	163.3
1:00	718	104.0	783	145.7	720	147.1
2:00	698	98.3	760	135.4	700	138.1
3:00	691	97.2	745	125.0	694	132.1
4:00	726	99.0	778	125.3	727	133.6
5:00	840	97.9	900	113.6	863	117.4
6:00	943	103.1	1021	117.3	1048	119.7
7:00	1079	122.0	1185	138.4	1233	157.2
8:00	1240	160.2	1334	174.3	1387	216.5
9:00	1255	180.1	1378	206.8	1457	276.6
10:00	1177	186.3	1362	227.0	1461	332.8
11:00	1092	179.5	1302	246.8	1436	362.6
12:00	1048	166.8	1259	250.1	1444	358.9
13:00	995	158.3	1210	247.9	1370	364.7
14:00	956	158.2	1156	237.9	1317	347.1
15:00	992	146.4	1183	226.5	1423	340.8
16:00	1059	141.8	1250	209.8	1515	343.1
17:00	1104	134.7	1302	199.2	1496	320.0
18:00	1182	153.1	1350	189.1	1502	299.9
19:00	1180	143.2	1318	181.9	1454	261.6
20:00	1076	134.9	1171	165.8	1299	238.7
21:00	944	128.4	1039	160.1	1128	217.9
22:00	828	120.6	929	141.5	980	196.2
23:00	736	105.5	827	128.1	863	176.0

Table E2.2: Gowrie NB23 annual mean and standard deviations for each daily demand interval. Values are in kVA, and are based on the load data for February through to October 2001.

The load factor is 0.51

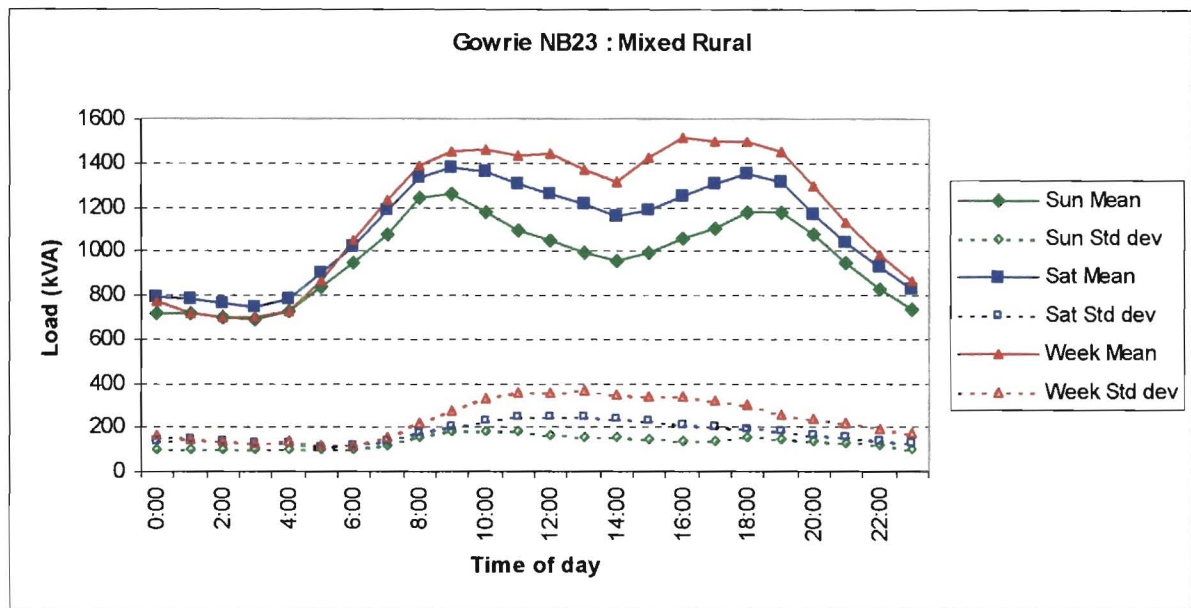


Figure E2.3: Graphical representation of Gowrie NB23 load annual mean and standard deviation (data in table E2.2)

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