Subtransmission power system amelioration through increased power transfer

M Lyon

orcid.org/ 0000-0001-6907-8461

Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering in Electrical and Electronic Engineering* at the North-West University

Supervisor: Prof JA de Kock

Graduation: May 2022

Student number: 20488505

Research abstract

TITLE: Subtransmission power system amelioration through increased power transfer

AUTHOR: Marthinus (Marnus) Lyon

STUDY SUPERVISOR: Prof Jan de Kock

This dissertation aimed to present considerations and solutions for the amelioration of subtransmission power systems through increased power transfer by reviewing various infrastructure technologies and solution approaches. In South Africa, as a developing country, there are subtransmission grid areas where reliability and spare capacity have respectively declined and become constrained due to various aspects, such as ageing of equipment, lack of maintenance, insufficient funding, insufficient network planning, and increased electrical load growth. This study followed a qualitative descriptive approach based on a case study research design. As fundamental topics, a sample of case studies focuses on constrained overhead power lines, underground cables, and substations in a subtransmission grid setting. The results were obtained by applying the fundamental equipment characteristics through different approaches. Dissimilar approaches to increase power transfer capacity to a specific zone created multiple comparative solutions. Amelioration solutions were presented for various constraints, but no "one size fits all" solution exists. However, it was found that the first step to increased power transfer on a subtransmission line should follow a theoretical re-rating approach. After that, uprating can be achieved through innovative solutions such as the use of new hardware, component upgrades, structure strengthening and restringing. The last resorts are complete upgrades or rebuilds and establishing new infeed sources. This study was limited by not having real-time thermal rating data for analysis. It is recommended that future studies focus on the development of an operations-based statistical rating as an alternative to real-time thermal ratings.

Keywords: power distribution, power systems, substations, thermal conductivity

Research output: an article is to be published in the proceedings of the 10th CIGRE Southern Africa regional conference 2021 (Subtransmission overhead power line amelioration through increased power transfer: A review) (see Appendix 1)

Declaration

I, Marthinus (Marnus) Lyon, declare that this dissertation is a presentation of my original work, conducted under the supervision of Prof J A de Kock.

Whenever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature.

No part of this work has been submitted in the past or is being submitted, for a degree or examination at any other university or course.

Signed on this 05th day of December 2020

2020.12.18

Table of contents

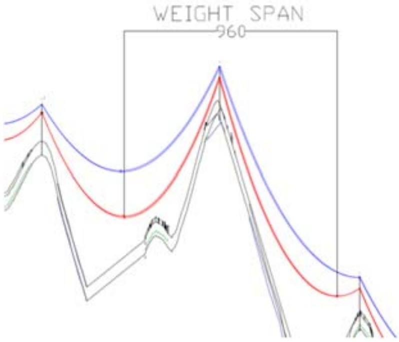
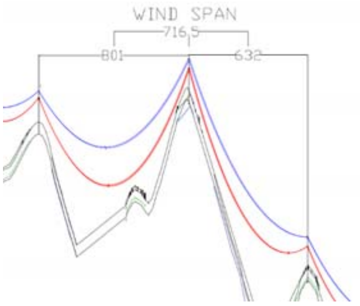
List of tables

List of figures

Terms and definitions

Term	Definition
Amelioration	The act of betterment or purposefully improving something.
Ampacity	The maximum current a conductor can carry before deterioration.
Annealing	Metallurgy process of heating and gradual cooling applied to ferrous alloys to toughen the material and remove internal stresses.
Creep (primary)	This stage of elongation is usually complete after the conductor has spent time in the running blocks with stringing or after tensioning. This stage is briefly described as the initial settling of conductor strands against each other and overcoming of the intra-strand friction within the conductor.
Creep (secondary)	The second stage of creep can usually be completed during the lifetime of the conductor, dependent on the conductor loading and weather conditions. This stage can be accelerated, especially with low sag conductors, by increasing the stringing tension to a certain percentage of the conductor's rated tensile strength before relaxing the tension and connecting to the conductor attachment sets.
Creep (tertiary)	This stage usually happens at the end of the conductor lifetime and could be due to some adverse weather conditions such as extreme winds or ice-loading.
Deterministic method	A mathematical technique where results are based on past data gathered.
Distribution Substation	Subtransmission to Medium Voltage Substation (station for transforming of subtransmission voltage levels to medium voltage including respective switching and auxiliary equipment).
Earth wire	The main purpose of the earth wire is to protect the phase conductors of high voltage line from direct lightning strikes. Earth wires are also known as ground wires, sky wires and shielding wires.
Elastic Deformation	When a metal deformed by force returns to its original dimensions after the force is removed, the metal is said to be elastically deformed [1].
Engineering Strain	Change in length of the sample divided by the original length of the sample." [1] $$\epsilon = \frac{\Delta l}{l_0}$$ *ϵ - Engineering strain (m/m)* *Δl - change in length of the sample (m)* *l_0 - the original length of the sample*
Engineering Stress	Average uni-axial force divided by the original cross-sectional area [1]. $$\sigma = \frac{F}{A_0}$$ *σ - Engineering stress (N/m^2 / Pa)* *F - Average uniaxial tensile force (N)* *A_0 – Original cross-sectional area (m^2)*
Content analysis	A systematic approach to identify and summarise the content within a qualitative data medium.
Extra-Urban	For this study, extra-urban is defined as a development settlement located between urban or metropolitan areas and less densely populated areas.
FACTS	Flexible AC transmission system.
Gross Domestic Product	A monetary measure of the market value of all the final goods and services produced in a period, often per annum.
Laser	A laser generates a highly focused narrow beam with a single wavelength and high radiant intensity used for the measurement of distances.

Term	Definition
LIDAR	Light detection and ranging system used to measure distance as well as to compute coordinates.
Level ground span	The maximum span length between support structures with equivalent structure elevation without infringing statutory clearances.
Low Voltage	Nominal voltage levels not exceeding 1000 V for alternating current and 1500 V for direct current as defined in SANS 1019-2001.
Medium Voltage	Standard nominal voltage levels of 2.2 kV, 3.3 kV, 6.6 kV, 11 kV, 22 kV, 33 kV as defined in SANS 1019-2001.
Metropolitan	The urban core of a metropolis or spatial dense town hub.
Modulus of elasticity	Stress divided by strain in the elastic region of an engineering stress-strain diagram for a metal.
N-1	The use of "n-1" refers to a systems operational criterion where the system will remain operational during the failure of any single section (i.e. single feeder outage).
N-2	The use of "n-2" refers to a systems operational criterion where the system will remain operational during the failure of any two section (i.e. outage of two feeders).
Probabilistic method	A mathematical technique where results are based on data calculated by probability.
Plastic Deformation	When a metal deformed by force does not return to its original dimensions after the force is removed, the metal is said to be plastically deformed.
Ruling span	Ruling span (RS) is an approximation of an equivalent span for a series of span and ruling span is not the average span $$RS = \sqrt{\frac{\sum_{i=1}^{i=n} L_i^3}{\sum_{i=1}^{i=n} L_i}}$$ *L is the horizontal span length projection between sequential structures from the line start to end.*
Subtransmission	Power transmitted at standard nominal voltage levels for high voltage systems of 66 kV, 88 kV and 132 kV as defined in SANS 1019-2001 (the mentioned subtransmission voltage levels are industry standard).
Sag	The maximum deviation distance between a catenary and straight-line where both lines originate from the same point and end at the same point.
Suburban	Settlement to the outskirts of an urban or metropolitan area.
Servitude	A registered deed of title prerogative to land ownership.
Span length	Horizontal projected distance between adjacent structures along a line
Thermal rating	The maximum ampacity of a conductor at a given temperature.
TOV	Temporary overvoltage.
Uplift	Occurs when the vertical upward forces on a structure exceed the downward forces due to ahead span and back span vertexes not remaining within the ahead span or back span.
Up-rating	Increase in capacity or performance.
Urban	Town hub, densely populated economic and/or political and/or residential centrum of a settlement.

Term	**Definition**
Weight span	The horizontal distance between the lowest points of two adjacent spans 
Wind span	Sum of the mid-span of two adjacent spans (half span on each side of a structure). 

List of abbreviations

A-L	**Description**	**M-Z**	**Description**
3D	Three-dimensional	m	metre
A	Ampere	ms	millisecond
AAAC	All aluminium alloy conductor	MD	Maximum demand
AAC	All aluminium conductor	MDCL	Maximum design cantilever load
AC	Alternating current	MTS	Main transmission station (Un >132 kV)
ACAR	Aluminium conductor aluminium alloy reinforced	MV	Medium voltage
ACCC	Aluminium conductor composite core	MVA	Megavolt-ampere
ACCR	Aluminium conductor composite reinforced	MW	Megawatt
ACSR	Aluminium conductor steel reinforced	NECRT	Neutral electro-magnetic couplers with neutral earthing resistors and auxiliary transformers
ACSS	Aluminium conductor steel supported	NERSA	National energy regulator of South Africa
ADMD	After diversity maximum demand (usually in kVA)	NMD	Notified maximum demand
AIS	Air-insulated switchgear	NRS	National rationalised standard (South Africa)
ANSI	American national standards institute	OFC	Oil-filled cable
ASCE	American society of civil engineers	OHGW	Overhead ground/earth wire
BS	British standard	OHL	Overhead power line
CAH	Conductor attachment height	Opex	Operational expenditure
CAIS	Cellular air-insulated switchgear	OPGW	Optical ground/earth wire
CAPEX	Capital expenditure	p.u.	per unit
CB	Circuit breaker	PLS CADD	Power line systems computer-aided design and drafting
CBD	Central business district	P	Power
Cigré	International council on large electric systems (Conseil international des grands réseaux électriques)	PPP	Public-private partnership
CHS	Circular hollow section	QoS	Quality of supply
CIC	Capital investment cost	RoW	Right of way
CT	Current transformer	rpm	revolutions per minute

A-L	Description	M-Z	Description
CSA	Corrugated seamless aluminium	RTO	Regional transmission owners
DC	Direct current	RTTR	Real-time thermal rating
DTS	Distributed temperature sensing	RTU	Remote terminal unit
ECC	Earth continuity conductor	SADC	Southern African development community
EDT	Every day temperature	SANS	South African national standard
EPRI	Electric power research institute	SCADA	Supervisory control and data acquisition
ESI	Electricity supply industry or Electrical energy supply industry	SD	Switched disconnector
FACTS	Fast AC transmission systems	SF6	Sulphur hexafluoride
FAR	Floor area ratio	SG	Surveyor general
FEM	Finite element method	SLiM	Sagging Line Mitigator
FIMT	Fibre in a metal tube	SS or S/S	Substation
GA	General arrangement	SWA	Steel wire armouring
GDP	Gross domestic product	Sw/S	Switching station
GIS	Gas-insulated switchgear	S/W	Shield wire
GMR	Geometric mean radius	SIL	Surge impedance loading
GMD	Geometric mean distance	SSEG	Small-scale embedded generation
GTACSR	Gap type ACSR	TCSC	Thyristor controlled series capacitor
HDD	Heavy-duty duct	TEA	Techno-economic evaluation
HTLS	High-temperature low sag	TEE	Thermoelectric equivalent method
HVAC	High voltage alternating current	TIC	Total investment cost
HVDC	High voltage direct current	TOC	Total operations cost
HYB	Hybrid switchgear (a combination of AIS and GIS)	Tx	Transmission
IACS	International annealed copper standard	UPFL	Unified power flow controller
ICNIRP	International Commission on Non-Ionizing Radiation Protection	UGC	Underground cable
IEC	International electro-technical commission	UTS	Ultimate tensile strength
IED	Intelligent electronic device (i.e. protection relay)	V	Volt
IEEE	Institute of electronic and electrical engineers	VA	Volt-ampere
IMTT	Inter-ministerial task team	var	Volt-ampere reactive

A-L	Description	M-Z	Description
ISO	International organisation for standardisation	SubTx	Subtransmission
kA	kilo ampere	VT	Voltage transformer
kHz	kilo hertz	SVC	Static var compensation
km	kilometre	SVL	Surge voltage limiter
kV	kilo volt	W	Watt
kVA	kilo volt-ampere	W/B	Water blocking
kvar	kilo volt-ampere reactive	XLPE	Crossed linked polyethylene
kV/m	kilovolt per metre		
LiDAR	Light detection and ranging		
LD	Load density		
LSM	Living standards measure		
LUS	Land use scheme		
LV	Low voltage		

List of symbols

Some symbols have duplicate applications and will, therefore, be listed below the respective formulas.

Symbol	Description
B	Magnetic field density
B	Susceptance
C	Capacitance
C	Catenary constant
D	Actual conductor length, i.e. catenary measurement
E	Electric field strength
f	Frequency
G	Conductance
g	Weight
H	Horizontal tension
I	Current
j	Imaginary unit (j^2=-1)
L	Inductance
L	Horizontal projected span length
P	Active power
q	Heat gain or heat loss
Q	Reactive power
R	Resistance
R_T	Thermal Resistance
r	Radius
S	Complex power
s	Vertical sag
T	Temperature
X_C	Capacitive reactance
X_L	Inductive reactance
Y	Admittance
Z	Impedance
π	Mathematical constant pi
ω	Angular frequency
θ_t	Temperature response over a period
ρ	Resistivity
ρ_T	Thermal Resistivity

CHAPTER 1 – Problem statement and research introduction

1.1 Introduction, background and rationale

Electrical energy is the heartbeat of a country's economy; therefore, unreliable supply and distribution of electrical energy have a negative implication on economic expectation [2]. Both internationally and nationally, there is an absolute requirement for reliable, efficient, and cost-effective electrical energy as well as the electrical infrastructure associated with the supply of electrical energy. Civil society takes electrical energy for granted if the associated supply is reliable. However, without the availability of electrical energy, economic development becomes impossible, the general quality of life and standard of living reduces, and typical day-to-day activities become hindered. In economic models, electrical energy is the third most crucial production factor, other than capital and labour [2].

Reluctance to execute projects to strengthen power networks could inevitably lead to a power catastrophe. The infamous 1998 Auckland Power Failure(s) in New Zealand is a notable example of the consequences of not keeping up with reliability of supply performance indicators, higher demands and implementing of modern technology [3]. The 1998 failure was the worst of five failures between 1998 and 2014 where Auckland lost power distribution to approximately 20 city blocks, for an extended period of approximately five weeks. The failures are attributed to 110 kV, 40-year-old gas-insulated cables and oil-filled cables, which eventually exceeded their thermal capacity on an abnormally dry and hot day, and faulted. The first cable failure resulted in additional load on the remaining infrastructure, which eventually also exceeded its thermal capacity and faulted. In 2001, a new tunnel was completed containing two new cables, which was followed by the installation of a third cable and decommissioning of the original cables to reinforce the electrical supply into Auckland. In 2006, the electrical energy supply to large areas within Auckland was interrupted again, this time due to rusted shackles on overhead earth wires [3]. This case proves the importance of electrical energy transfer infrastructure between the point of electrical energy supply and the point of delivery or demand, as well as the importance of maintenance and having a contingency in power transfer.

For developing countries, such as those located in Sub Saharan Africa, electrical energy plays an even more critical role as an economic stimulus, than in developed countries [4]. When not considering the generation output, South Africa has mostly averted crises, similar to the Auckland failures, by narrow margins. However, South Africa is not invulnerable to outage calamities, high levels of crime can also bring down power supplies, as happened in Johannesburg CBD [5]. The Eskom supply to City Power of Johannesburg was interrupted due to a collapsed 275 kV lattice pylon, resulting from steel cross-member theft. This is not an isolated case, and stolen lattice cross members and poor maintenance can be observed in numerous South African towns.

The NERSA compliance monitoring audits' results show various severe non-compliances to license conditions, such as old equipment, low levels of maintenance, exposure to theft, lack of planning and lack of resources [6]. To worsen the situation, in many areas "physical space" for infrastructure reduces as property usage and development increases. As population density increases, economic development and an increase in income per capita, there is a resultant shift to higher levels of electrical energy usage [7], [8], [9].

Over and above the possible natural load growth factors correlating to economic growth, rapid urbanisation and immigration into South Africa can add additional strain to electrical energy demands [10]. In many parts of South Africa, the utilities' subtransmission electrical feeders are "constrained" in terms of the thermal capability of such feeders to supply the electrical load requirements, or the subtransmission system is at the end of its anticipated service life. At the subtransmission level, the reliability lifecycle is typically 40 years to 50 years but varies between equipment type and design approaches. The infrastructure ageing factor adds to existing and increasing electrical loading strain on subtransmission infrastructure. Criminal elements practice the illegal harvesting of steel and cables, particularly copper conductors. When a feeder is rendered out-of-service due to illegal activities or other reasons, the remaining feeders forming part of the subtransmission system must accommodate the shortfall in electrical energy transfer, emphasising the importance of reliability of supply in terms of contingency conditions.

Capacity constraints on electrical infrastructure are induced over time and not instantaneously. When evaluating Eskom's results in 2011, at the power distribution or subtransmission level, for electrical network strengthening and refurbishment, there were between 800 and 1 000 constrained operational feeders in the Eskom electrical grid [11] at the time. From Eskom's integrated report [12] it is stated that Eskom feeder lines and cables in service from 2014/2015 to 2018/2019 decreased for 132 kV power lines by 263 km, decreased for 44 kV to 88 kV power lines by 2 614 km, increased by 21 km for 132 kV cables, and decreased by 172 km for 44 kV to 88 kV cables. With Eskom's financial crisis and an uncertain future for Eskom at the time of compiling this review, not nearly enough was done since the start of the energy crisis in 2007 and the number of constrained feeders in 2011 to relieve a constrained network. Even if South Africa addresses the power generation capacity crisis, power delivery from the point of generation to the end-user on the load demand side remains critical. Through inference of the above, financial constraints proved to have a crippling effect on the electricity supply industry and South Africa's economic growth.

This study investigated an amelioration of subtransmission power system through increased power transfer, from a South African perspective, employing a case study research of factors influential on electrical energy transfer capabilities for both brownfield and greenfield projects.

The research reviewed the technical aspects associated with various infrastructure types, and the focus of the study was primarily on subtransmission feeder systems. Substation and terminal equipment was a secondary focus, and increased power transfer within substations and substation terminal equipment was not essential to the study. Statutory requirements, environmental constraints, and the difficulty in obtaining new servitudes or property are significant hurdles to overcome; however, the detail of these topics does not form part of this research. The research neglects the implication of increased fault levels, to cater for increased fault levels higher rated equipment must be used and earthing and bonding must be reviewed and addressed in detail. Aspects such as lightning shielding and grounding form a fundamental part of feeder design but are also not essential to the primary focus of this study.

This study focusses on feeders at subtransmission voltage levels for urban and suburban areas, seldom exceeding a feeder length of 100 km.

1.2 Literature overview for the problem statement

Large scale and on-going development, despite slowed economic growth, resulted in the depletion of physical space (property) availability in areas, such as Johannesburg, to construct additional or new power lines on existing routes. The limited space is mainly due to the density of developable floor-to-area ratios and the higher population density in one of the largest metropolitan cities in Africa, where urbanisation is still on the increase with most of the country's residents still relocating away from rural areas to cities [13]. This property or land area constraint leads to the consideration of other power distribution alternatives such as new routes, cable systems, complete demolishing and rebuilding of existing systems and re-stringing of existing lines for increased power transfer capacity [14].

There are numerous cases where ageing infrastructure has failed, or infrastructure has poor reliability of supply. Instances of failures within a South African context are:

- Bedfordview: Leaks on two 132 kV fluid-filled cables leads to a 67-hour blackout [15];
- Brakpan: Vulcania South Substation upgrade (new 60 MVA Eskom infeed, no n-1 primary supply intake) [16];

- Constitution Hill: Fort Substation upgrades due to old equipment and loss of power to the Johannesburg inner city [17].

- Johannesburg CBD: Central and Central B Substation refurbishment due to aged equipment, 88/11 kV transformers connected to 88 kV cables without 88 kV switchgear protection – high risk for blackout and extensive damage to surrounding buildings [18];

- Johannesburg CBD: Bree Street Substation refurbishment due to aged equipment, 88/11 kV transformers connected to 88 kV cables without 88 kV switchgear protection – high risk for blackout and extensive damage to surrounding buildings [18];

- Kelvin: New 400 kV–275/132 kV Sebenza Substation infeed of 315 MVA (945 MVA final), Kelvin Substation upgrade, Prospect Substation upgrade and various lines' upgrades due to limited capacity and aged equipment risking the reliability of supply in the east of Johannesburg. Sebenza Substation reduces the loading on Prospect and Kelvin Substations and by doing so decreases the risk of power outages [19];

- Kroonstad: Repeated 66 kV oil-filled cable failures from 2011 to 2019. In 2011 power to the entire Kroonstad and Maokeng areas was lost due to failure of infrastructure, mainly 66 kV oil-filled cables, established or installed in the 1970s [20];

- Vanderbijlpark: Transformer, switchgear and protection failure at Unibijl Substation [21];

- Vanderbijlpark: CBD and surrounding area power failure for a week caused by a transformer and switchgear failure at Town Substation, a second failure with a longer outage time occurred three months after the first incident [22];

- Vanderbijlpark: Cross-member theft of lattice structure resulting in structure collapse and loss of n-1 contingency on Vanderbijlpark's primary 88 kV ring [23];

- Waltloo, Pretoria (Wildebeest): applications by industrial power user for increased capacity cannot be processed due to constraint capacity on an old electrical grid [24].

Although not all the above cases do involve failure or failure due to constrained capacity, the betterment of subtransmission systems cannot be neglected and requires thorough review throughout the equipment's service life.

1.3 Problem statement

The overloading of specifically urban and extra-urban subtransmission systems, which includes power lines, cables and substations, can be catastrophic to infrastructure, more so to constrained infrastructure. The reality of an unreliable power supply is indicative of the need to address several concerns regarding network strengthening, upgrading, replacement, refurbishment or uprating of existing subtransmission power systems or reconfiguration of the network. The reliability of a network can often be improved by reconfiguring the feeders and the substation layouts. The amelioration of subtransmission systems generally requires numerous power lines and cables, as well as substation projects, to be executed. Executing such projects will significantly contribute to increasing the reliability of supply and the prevention of possible crises due to power failures with severe economic and logistical implications. A catastrophic failure could result from exceeding thermal ratings, old technology such as pressurised oil-filled cables, the lack of maintenance and the ageing of equipment. By increasing the power transfer available to a site, the site's fault current will most likely increase if the higher fault levels are not taken into consideration, severe damage may be caused, and dangerous conditions may arise. For overhead power lines, the exceeding of conductor thermal limits can result in statutory infringements.

The Google Earth satellite images in Figure 1 illustrate, as an example, the densification of the Midrand and Tembisa areas in Johannesburg over 33 years from 1985 to 2018.

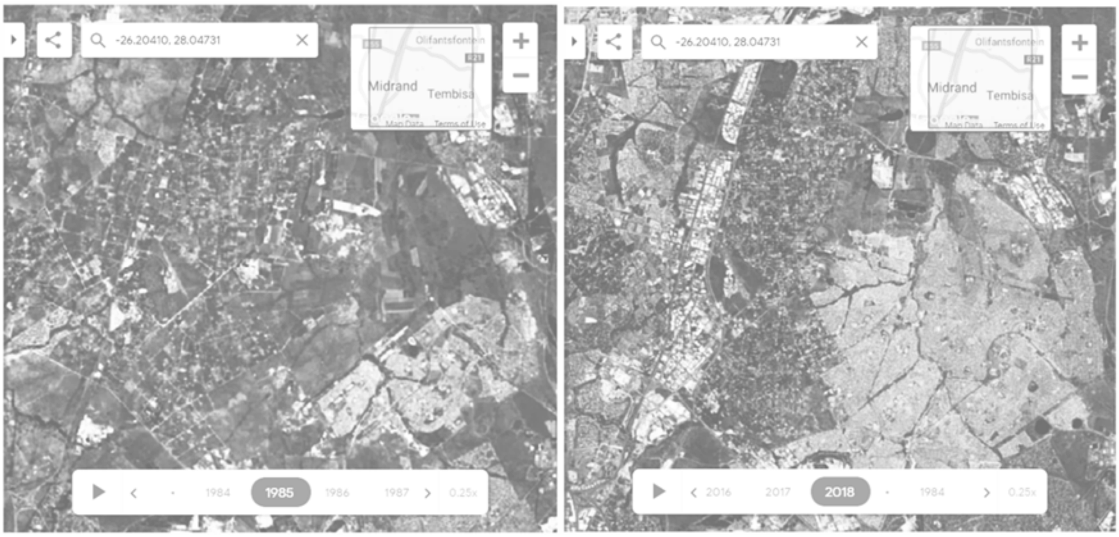


Figure 1: Midrand / Tembisa densification over 33 years [25]

1.4 Research questions

As part of the electrical conceptual research, this study investigated the basis of evaluating typical subtransmission power system performance and systematically reviews technical aspects for various upgrading, uprating, refurbishment or replacement options.

The research investigates the following:

- Available options when the demand arises to increase the electrical energy transfer into a specific area or to increase the electrical energy transfer capabilities of existing subtransmission infrastructure.
- Which methods to follow for system upgrading, system refurbishment, system strengthening or uprating.
- Comparison of equipment ratings, in reality, to theoretical approaches and limitations set by industry standards.
- Applying a practical and holistic approach to cater for planning aspects, and integrating technologies when enhancing subtransmission power systems.
- Consideration of possible creative or unorthodox solutions.

1.5 Research aim

The research aimed to explore and review the approach and considerations when determining solutions for constrained subtransmission power systems. The investigations followed a systematic enquiry to describe and explain how power transfer can be increased and the phenomena that affect power transfer.

Solutions ought to be cost-effective and technically reliable, for increasing the dependability of subtransmission power systems for various scenarios. The study focused on subtransmission power systems situated within urban and extra-urban town areas requiring improvement. The research outcome investigated factors for South African subtransmission power systems that required betterment through expansion, strengthening, uprating, upgrading or refurbishment, which are all means to an end to achieve increased power transfer.

To summarise, the essential aim of this study was to examine and gain insight and understanding of methods, through case studies, for upgrading or strengthening of subtransmission systems where the reliability of supply was compromised, or insufficient power transfer was available. Although power system reliability and power system transfer improvement can be related, the concepts differ significantly and can also be unrelated. The study was solution focussed, which excluded an in-depth investigation of the intrinsic reasons that gave rise to specific problems or needs.

1.6 Research objectives

The overall research objective was to gain a holistic understanding of how power transfer methods relate and interact within a real-life context by using multiple sources and evidence. The specific research objectives include:

- Determining the alternatives to increase power supply to a specific site or area;
- Outlining subtransmission feeder considerations;
- Comparing the equipment datasheet rating to actual capabilities in real-life scenarios;
- Techno-economic evaluation of subtransmission power system upgrades;
- Explaining typical problems expected within a subtransmission power system project in terms of infrastructure planning and considering possible solutions for subtransmission systems in high-density areas.

The main research objective was to evaluate the methods of increasing power supply between points at subtransmission level and to:

- identify possible solutions to specific cases;
- identify further research and developments required, and
- identify ambiguities between various approaches in solving the power transfer rating problem.

Beneficiaries to this study are subtransmission planning engineers in the private sector, power system or grid owners and utilities or power distribution license holders, which are reliant on an electrical grid for power distribution.

1.7 Research methodology

The research followed a qualitative descriptive approach based on case study research [26] to describe the investigation of the amelioration of subtransmission systems through increased power transfer. Furthermore, the research followed a cross-sectional time frame. Therefore, the data collected is not influenced by the data collection time. The research was conducted at a given point in time and not over an extended period. Trends over time are therefore not established. The case study research focussed on system influences rather than individual features.

This dissertation critically investigated and interpreted techno-economic considerations for specific case studies and literature, applied to subtransmission power systems that have run out of capacity, or are in dire need of upgrading or refurbishment. The case studies are an availability data sample. The availability sampling technique used was non-probability availability sampling that involved data collection from the relevant cases. The results were obtained by comparing the fundamental technological characteristic aspects applied to the case studies employing content analysis, following a systematic approach to identify and summarise the case study and characteristic technological contents. Following a qualitative approach, this study provided in-depth information regarding the enhancement of subtransmission systems by increasing the power transfer on the subtransmission feeders.

The case study research design evaluates a restricted system (a case) or multiple bounded systems over time [27]. The case study design allowed for evaluations from various viewpoints to develop an in-depth understanding of the system dynamics in a particular setting [27]. The goal of the case study research design was to include multiple operational configurations and will, therefore, provide a perspective of a subtransmission system in its entirety.

The subject matter population focused on the subtransmission level of power transfer, particularly at 66 kV, 88 kV and 132 kV voltage levels. There is no clear definition or setting apart between transmission and subtransmission or distribution voltage levels. Subtransmission voltage levels in South Africa are generally classified as nominal system voltage levels (U_n) not lower than 44 kV and not higher than 220 kV (Range B) [28], with the exclusion of the not so often used 44 kV and 220 kV voltage levels, therefore, as an industry-standard, subtransmission nominal voltage levels are 66 kV, 88 kV, and 132 kV.

The content analysis applied, involved the process whereby information was contextualised and summarised from multiple angles for the qualitative analysis of data to identify the principal research findings [29]. The content analysis was first applied to the type of technology, such as the conductor or cable type. After that, the application of the technology to a scenario was analysed. The analysis included for subtransmission power distribution is the analysis of literature applied to software packages for the calculation of feeder parameters, where these parameters are instrumental in performing the relevant studies. Feeder system upgrading or network strengthening projects were analysed based on equipment characteristics and the application thereof, such as the restringing of an existing line with various conductor types, theoretical uprating, real-time monitoring, reactive compensation or entirely new subtransmission systems.

These different methods of data gathering included engineering publications, national standards, international standards, industry practice, peer review and data available through municipal records. The investigations and reviews use the crystallisation for trustworthiness [30].

Ethics approval for this study is obtained from the North-West University Faculty of Engineering Research ethics screening (ethics clearance number: NWU-01765-19-A1). The data management policy implemented gatekeeper approval, anonymity where necessary, and exclusion of any information that could lead to security breaches or prove negligence.

1.8 Chapter division

The dissertation is divided into five chapters, as described in Figure 2's chart:

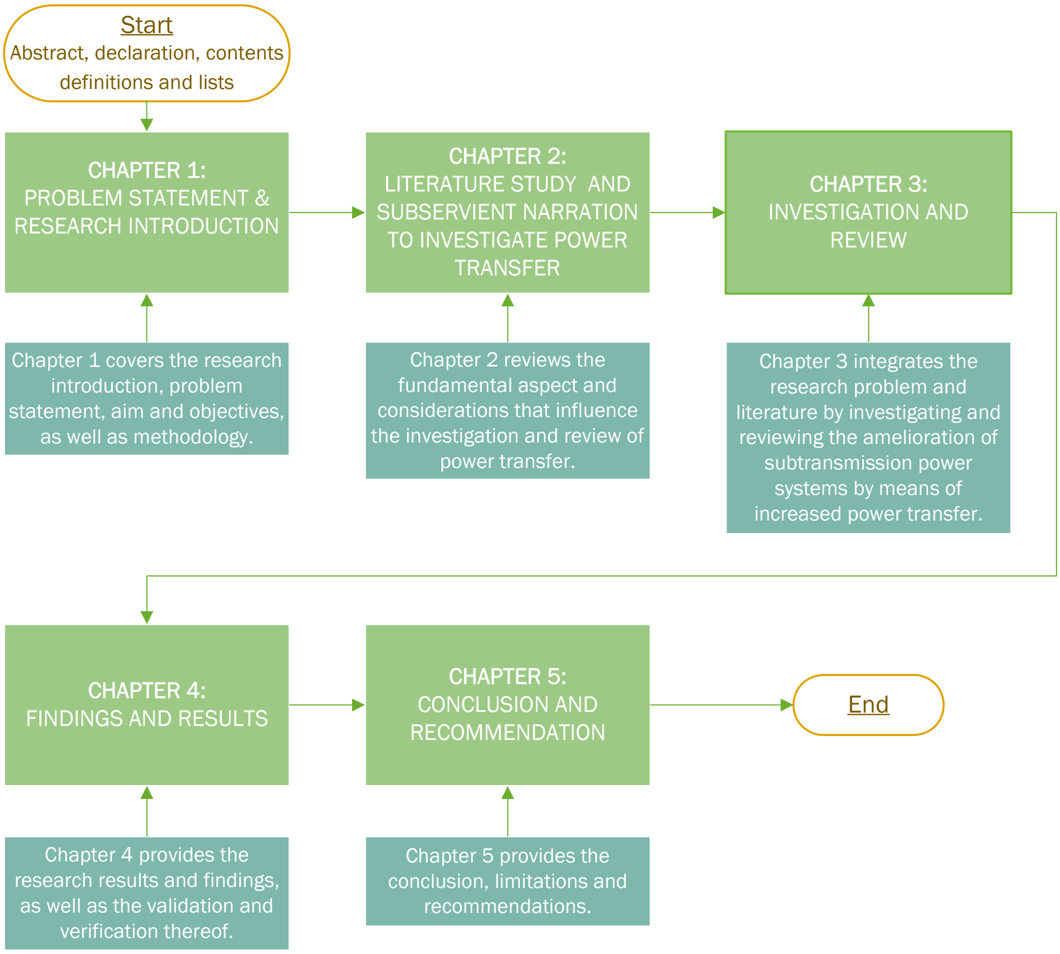


Figure 2: Dissertation outline diagram

CHAPTER 2 – Literature study, fundamental topics, and subservient narration to investigate power transfer

This chapter addresses the concepts and consideration applied to the execution of the research studies.

The two main components of the subtransmission systems investigated are substations and subtransmission feeder lines. For subtransmission feeder lines, two "subsystems" are responsible for the transfer of energy to various points in the electrical network, namely overhead power lines and cables. Due to being uncommon in South Africa, this study does not consider gas-insulated lines (GIL). Even at a high-level overview, it is not possible to explore all aspects and components of a subtransmission system in detail. Therefore, the investigation of subcomponents is limited. This study excludes rare technologies in the subtransmission environment, such as superconducting cables or gas-filled cables, and subtransmission DC systems. The narration of chapter two follows the diagram in Figure 3:

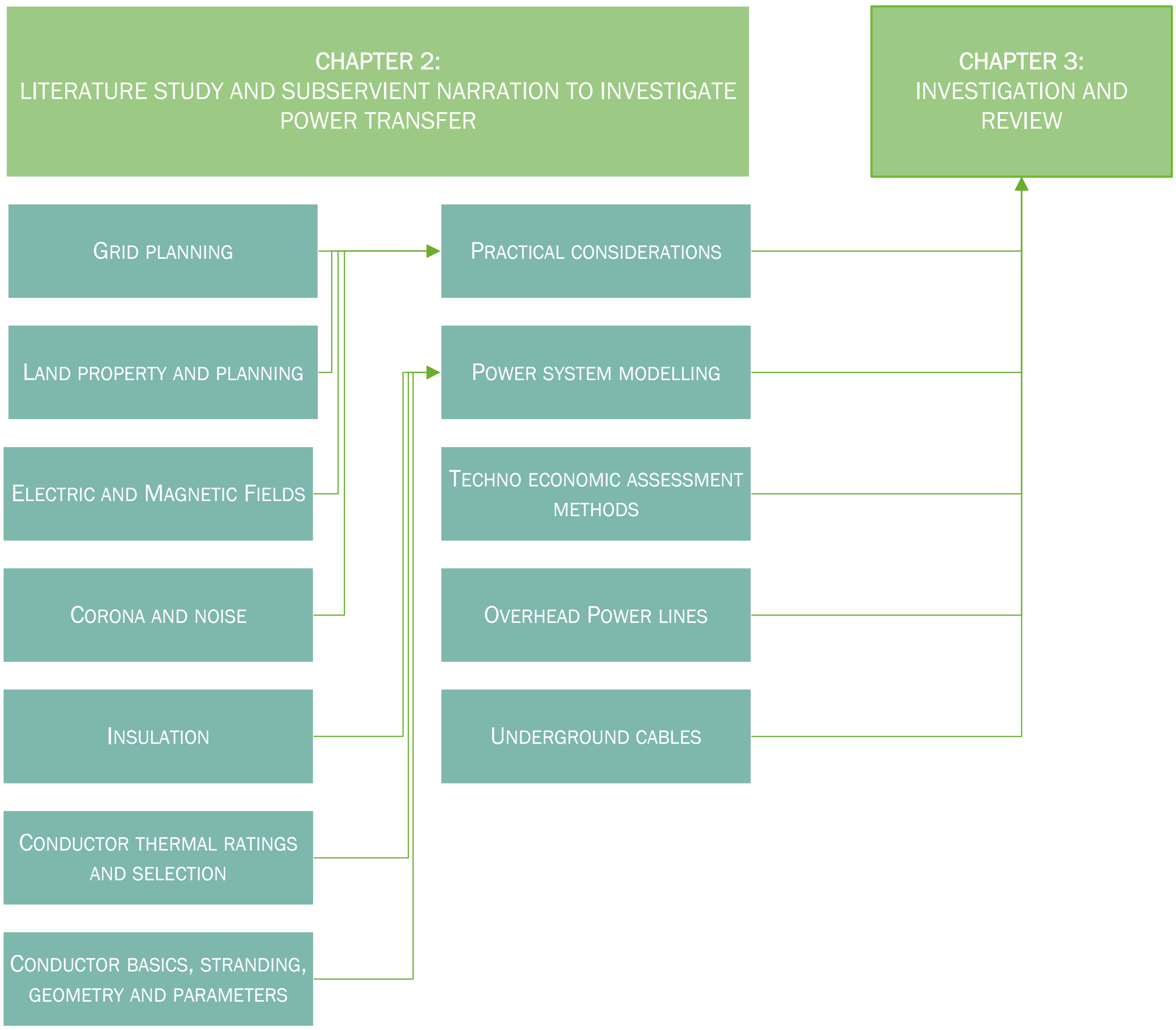


Figure 3: Chapter 2 outline diagram

2.1 Practical considerations

Regulatory requirements greatly influence the investigations into the refurbishment of existing subtransmission systems or the planning of new subtransmission systems and must be taken into consideration. Due to the sheer volume of applicable regulations, performance requirements and industry standards, only the most relevant documentation is referenced throughout the texts.

Various NRS, SANS, IEC, ASCE, ANSI, ISO, IEEE, BS and other international standards are published to cover power system designs and equipment performance aspects. The applicable standards are referenced throughout this study where needed.

Over and above possible solutions to transfer more capacity, at the subtransmission level, to electrical load nodes, the important high-level considerations influencing design approaches for projects are:

Table 1: Considerations influencing design approaches

- Future planning.	- Auxiliary systems design requirements.
- Electromagnetic compatibility.	- Constructability.
- Electrical design requirements.	- Testing and commissioning considerations.
- Statutory and legal requirements such as clearances, property ownership and zoning.	- Statutory requirements and relevant legislation.
- EMF exposure.	- Health and Safety considerations.
- Civil and Geotechnical design requirements.	- Spatial Planning and Land Use Management.
- General quality and minimum equipment performance requirements.	- Earthing performance and fault level considerations.
- Environmental conditions include climatic considerations, aesthetics, noise levels, activity footprints, biodiversity, socio-economic, environmental sensitivity, cultural and historical features.	- Mechanical design requirements.

South Africa frequently adopts international standards (mostly IEC standards), which are locally applied through the South African Bureau of Standards. Standards only become statutory requirements using the relevant parliamentary processes and government gazettes.

Although environmental aspects such as legislation, approvals, fauna and flora, fall outside the research scope for this dissertation, Table 2 reflects the implications thereof on subtransmission systems:

Table 2: Environmental condition effects [31]

ENVIRONMENTAL CONDITION	RESULTING EFFECT
Temperature	Ambient temperature influences the thermal rating of overhead conductors. Soil temperature also directly implicates the thermal rating of cables.
Wind Velocity	The wind has a cooling effect on overhead conductors.
Solar radiation	Solar radiation increases overhead conductor temperature but also affects equipment such as composite insulators and cable sealing ends.
Rainfall	Rainfall cools overhead conductor as well as cables by increasing the soil moisture content. The rain has a washing effect on insulator, cable sealing ends and surge arrestors, but is also associated with corona. Flooding must also be considered.
Humidity	Impact on insulators (flashover).
Altitude	Affects insulation coordination and voltage gradient.
Ice and snow	Cooling effect and possible additional weight to the overhead conductor.
Atmospheric pollution	Affect insulation.
Soil	Structural design, earthing requirements and safety. For cables, soil thermal resistivity and thermal stability affect the cable ampacity.
Lightning	Outage performance, insulation, earthing and shielding.
Seismic	Structural design.

The property available for infrastructure remains fundamental to the execution of projects.

Figure 4: Land usage for 88 kV overhead feeder lines

The paragraphs to follow are subservient topics to practical considerations for investigating increased power flow.

2.1.1 Grid planning

Grid planning is a preventative action that plans for increased power transfer before the actual need arises. The subtransmission system is improved through proper planning, allowing for seamless future increases in power transfer.

Methods and planning approaches are not fundamental to this study, but cannot be disregarded. Effective grid planning is likely to be the first indication that increased power transfer capacity is required. Grid planning is essential to the accurate modelling of existing electrical grid conditions, as well as the preparation for future load demands.

Planning inputs are required to apply existing loads in the correct position, determine present strengthening requirements and to determine where future strengthening will be required.

Cigré's Working Group CC.01 "Summary on planning methods for subtransmission systems" in 1991 [32], compares international planning methods for subtransmission systems. South Africa reported a standard planning horizon of 10 years, with some investment decision made on financial ratio calculations over 25 years.

A grid with n-1 operating conditions reduces the outage risk, but without proper planning, can result in overloading of feeders. An n-1 operating conditions depends on the locations of open points in an electrical grid and under fault conditions n-1 scenarios depend on the location of the failure. From international research, meeting n-1 outage constraint conditions are more or less the norm, with the exceptions of [32]:

- important load centres where n-2 conditions are introduced.
- extended subtransmission networks with relatively small loads making n-1 contingency criteria uneconomical.

In a South African context, Government Gazette of 19 December 2008 No. 31741 adopts a policy position to ensure that the cost of redundancy matches the socio/economic implication of power outages and recommends that all supplies larger than 10 MVA or voltage higher than 1000 V, be based on the principle of "n-1".

For an extremely robust electrical grid, some developed countries' design norm standardises on an n-2 reliability of supply.

The United Kingdom reported in [32] the designing of subtransmission systems to afford specific standards of supply based on the load according to the following principles. Due to the high financial impact with loss of power, the higher loads have greater security of supply.

The United Kingdom's load-based reliability indices are given in Table 3 and illustrate that better reliability should be promoted as load increases.

Table 3: UK reliability indices based on load [32]

≤ 1 MW:	In practice, some alternative supplies may be available, restoration of electrical energy supply may be reliant on the fault repair time.	
1 MW to12 MW:	Supply must be restored in three hours.	
12 MW to 60 MW:	Duplicate supplies should be available, or a form of remote control switching. Two thirds (2/3) of the load must be restored within 15 minutes.	
60 MW to1500 MW:	In this range, the possibility of a fault occurring during an arranged outage must be catered for.	
	60 MW to 300 MW:	For a single fault, all but 20 MW should be restored immediately (within 60 seconds), with the remainder to be restored within three hours. If a fault occurs during an arranged outage, 1/3 of the load must be restored within three hours, the time for restoration of the remainder shall be equal to the time taken for the restoration of the outage.
	300 MW to 1500 MW:	For a single fault, supply must be restored immediately. For a fault during arranged outages, 2/3 must be restored immediately, and 1/3 may await the restoration of the outage.
>1500 MW:	Merits a connection at transmission voltage level.	

When planning electrical grids, philosophy can be developed where reliability is based on the load requirements of the grid. With effective planning, it is possible to increase the grid reliability as the grid expands by developing and implementing an electricity supply master plan.

Master plans at subtransmission level generally addresses the electrical network requirements such as upgrades, refurbishments, and expansions for a 20-year horizon.

Based on the data gathered as part of the planning process, the level of system reliability must be selected and taken into consideration for planning. Six topical areas are identified for evaluation analysis to be applied within a system context [33]:

Table 4: Six topical system properties [33]

PROPERTY	DESCRIPTION
Affordability	Provide electric services at a cost that does not exceed customers' willingness and ability to pay for those services.
Reliability	Maintain power delivery to customers in the face of routine uncertainty in operating conditions.
- Operational Reliability	Deliver energy to meet current and near-term load obligations with existing assets under an expected range of conditions.
- Planning Reliability	Deliver energy to meet projected long-term load obligations with existing and planned assets under an expected range of conditions.
Resiliency	Withstand and recover quickly from extreme external events such as natural disasters.
- Robustness	Maintain system operations during an extreme external disruption.
- Recoverability	Return the system to regular operation following a disruption.
Flexibility	Respond to future uncertainties that may stress the system in the short term and require the system to adapt over the long term.
- Operational Flexibility	Respond to relatively short-term operational and economic variabilities uncertainties that are likely to stress the system or affect costs.
- Planning Flexibility	Adapt to variabilities and uncertainties that are likely to stress or fundamentally alter the system in the long term.
Sustainability	Provide electrical services to customers without negative impacts on natural resources, human health, or safety.
- Environmental Sustainability	Deliver power with limited impact on environmental quality and human health.
- Safety	Deliver power with minimal safety risk to workers and the general population.
Security	Resist external disruptions to the energy supply infrastructure caused by intentional physical or cyber-attacks or by limited access to critical materials from potentially hostile countries.
- Physical/Cyber Security	Prevent external threats and malicious attacks from occurring and affecting system operation.
- Supply Chain Security	Maintain and operate the system with limited reliance on suppliers (primarily raw materials) from potentially unstable or hostile countries.

Based on the load density design parameter, 40 kVA/ha for urban and 20 kVA/ha for rural, the primary substation's distribution area is determined. The load density norm is used to calculate a supply area radius. Where large consumers are located far from the primary substation, satellite switching stations are established at distribution (MV) level. To achieve n-1 conditions, dual feeders can be installed to distribution load nodes or interconnectors can be installed between load nodes by sizing feeders with sufficient capacity.

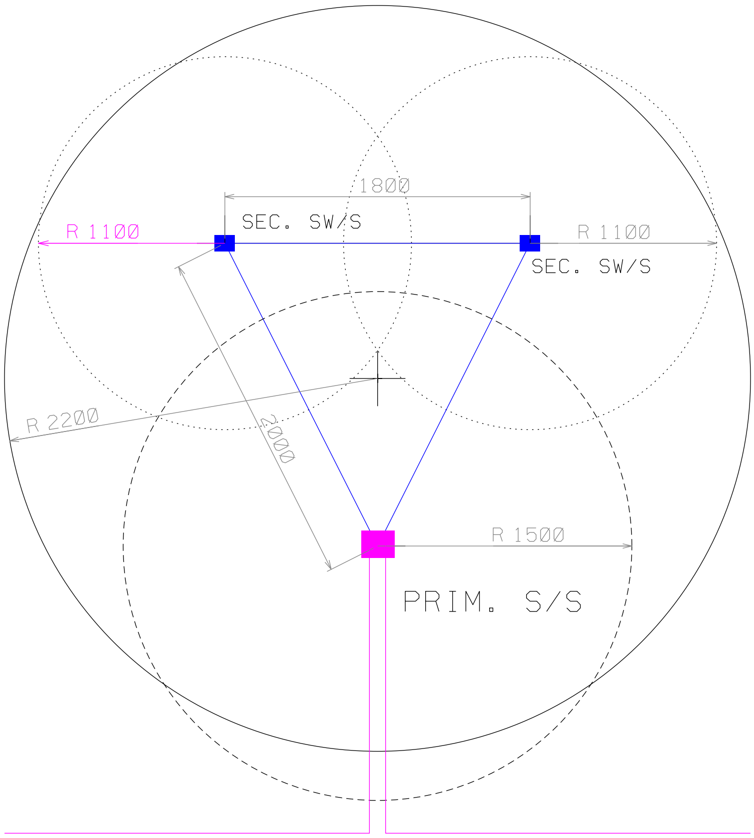


Figure 5: 60 MVA Primary substation supply area at 40 kVA/ha

For the hypothetical supply area in Figure 5, the substation supply area totals 1500 ha based on an assumed load density of 40 kVA/ha in an assumed circular area. For example, with a firm capacity of 60 MVA, the supply radius is 2.19 km, which falls within voltage drop limits. The 60 MVA firm capacity is practically achieved by using 2 x 63 MVA transformers or 3 x 31.5 MVA transformers.

Without concerning external sources, the approximated fault level of a transformer is given by the transformer rating divided by the transformer's percentage impedance.

$$Fault\ rating = \frac{Transformer\ Rating}{Percentage\ Impedance}\ MVA \qquad (1)$$

For two 63 MVA transformers with a percentage impedance of 12.06% each, in parallel operation, the fault level by applying formula (1) is 1045 MVA. Whilst for three 31.5 MVA transformers with a percentage impedance of 10.81% each, the anticipated fault level is 874 MVA when operating in parallel. Three 31.5 MVA transformer bays will come at a higher initial capital cost than two 63 MVA transformer bays, but by using the 31.5 MVA transformers a significantly lower, and safer, fault level is achieved.

In the case of 2 x 63 MVA transformers, the percentage impedance of the transformers must be increased at design stage to decrease the fault level, and this will result in higher transformer operational losses. For a percentage impedance of 13%, the medium voltage level fault current is limited to 25 kA for a 60 MVA transformer. The typical medium voltage ring feed cable used is a three-core 185 mm^2 copper conductor with XLPE insulation and steel wire armouring. The symmetrical 1-second short circuit rating of this cable is 25.1 kA. Larger core-diameter aluminium cables can be used as a lower theft-risk alternative to copper, the larger diameter is due to the higher resistivity of aluminium when compared to copper [34].

Load density for primary distribution substations varies from 15 kVA/ha to 150 kVA/ha [35]. Figure 6 was compiled from [35], showing that densities at a limit of 150 kVA/ha have a very short supply area radius.

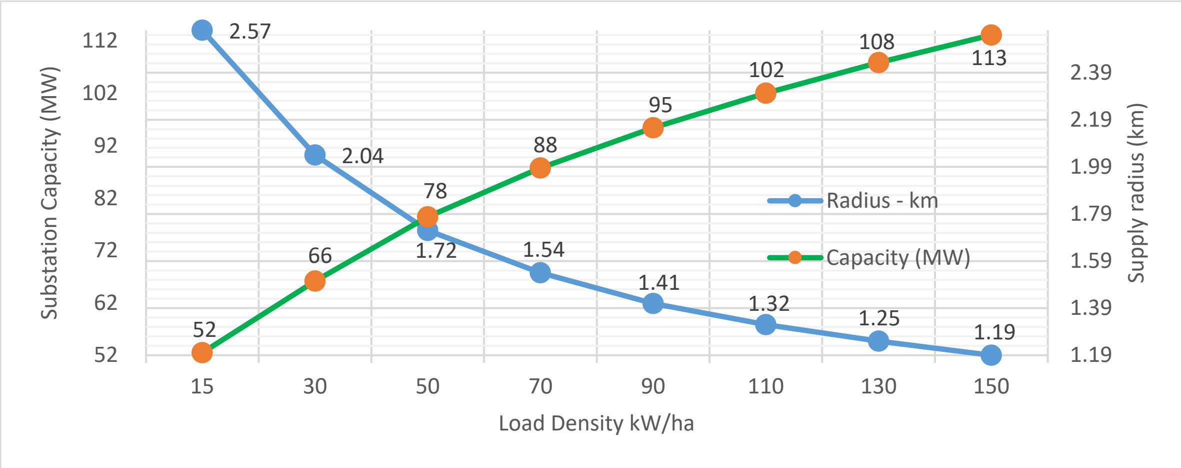


Figure 6: Load density and supply radius (data from [35])

Economical substation capacity is the capital investment cost per capacity unit in currency per VA. The supply radius for various substation capacities is calculated based on load densities, but excludes the consideration of economic substation capacity, and illustrated in Figure 7.

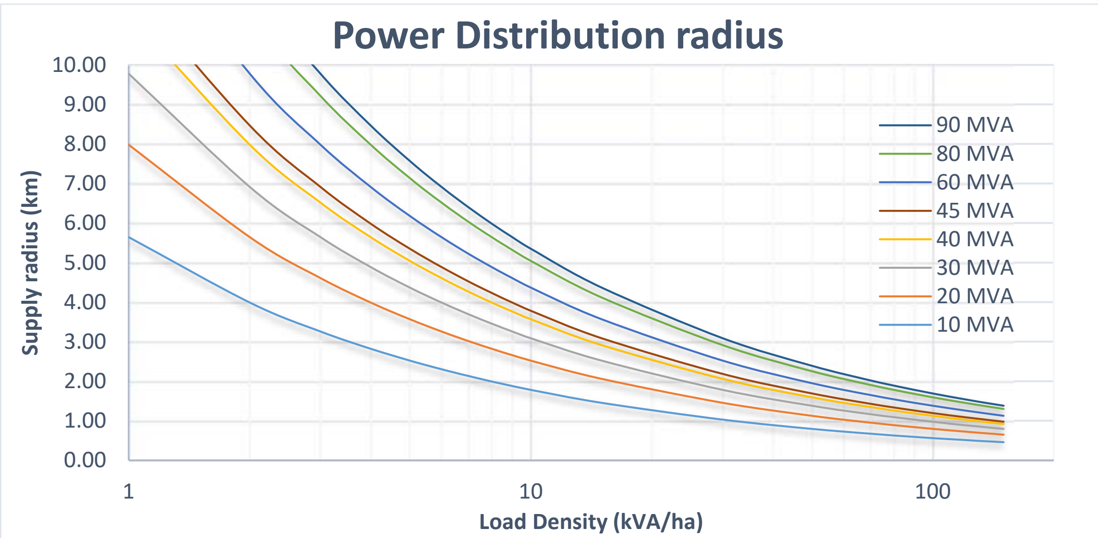


Figure 7: Substation supply radius, load density and standard capacities

A subtransmission grid and master plan, which will not be identified due to confidentiality, was the subject of applying the preceding principles with the objective to plan the power transfer capabilities within an entirely new subtransmission grid. The Town Planner's area density is an indication of the load required. For the new subtransmission grid with standard primary substations of approximately 60 MVA each (max. 89% utilisation) and a total coverage area of 9 000 ha, six primary substations will be required for a total grid capacity of 360 MVA and load density of approximately 35 kVA/ha. With servitudes provided, the entire network is planned as overhead power lines, twin-Bear ACSR is selected with a thermal rating of 700 A per conductor (max. 98% utilisation). The overhead subtransmission system will comprise of twin "Bear ACSR" conductors at 132 kV to cater for a unity load of 320 MVA, and two 315 MVA step down transformers from 400 kV to 132 kV is required at the Main Transmission Station (MTS). The subtransmission ring capacity can be reduced by equipping the MTS with 63 MVA transformers to cover one of the six subtransmission primary substation coverage areas. The network is summarised in Table 5:

Table 5: Subtransmission (SubTx) grid plan

	Bays	**Capacity**
MTS[A]	Transmission (Tx) Feeder: 3 x 400 kV (n-2)	Min. 630 MVA (See note A)
	Tx Transformer: 2 x 400 / 132 kV, (n-1)	315 MVA
	SubTx Transformer: 2 x 132 / 11 kV, (n-1)	63 MVA
Subtransmission grid	Feeder: 2 x 132 kV (n-1) Per substation	320 MVA (n-1) Entire ring feed
	Transformer: 2 x 132 / 11 kV, (n-1) Per Substation	63 MVA Per Substation
Note A: Planning shown for a single quadrant of the MTS supply area. However, line capacity considers the remaining three quadrants or additional future MTSs.		

Based on Table 5's parameters and grid planning, the spatial layout of the subtransmission network is shown in Figure 8, where the primary substations' supply areas are presented by the circular and hexagon areas. The substations are based on the load centroids with the subtransmission feeders aligned through the centre of the area. High property values could require alternatives such as cables, routing of lines around the outskirts of the area.

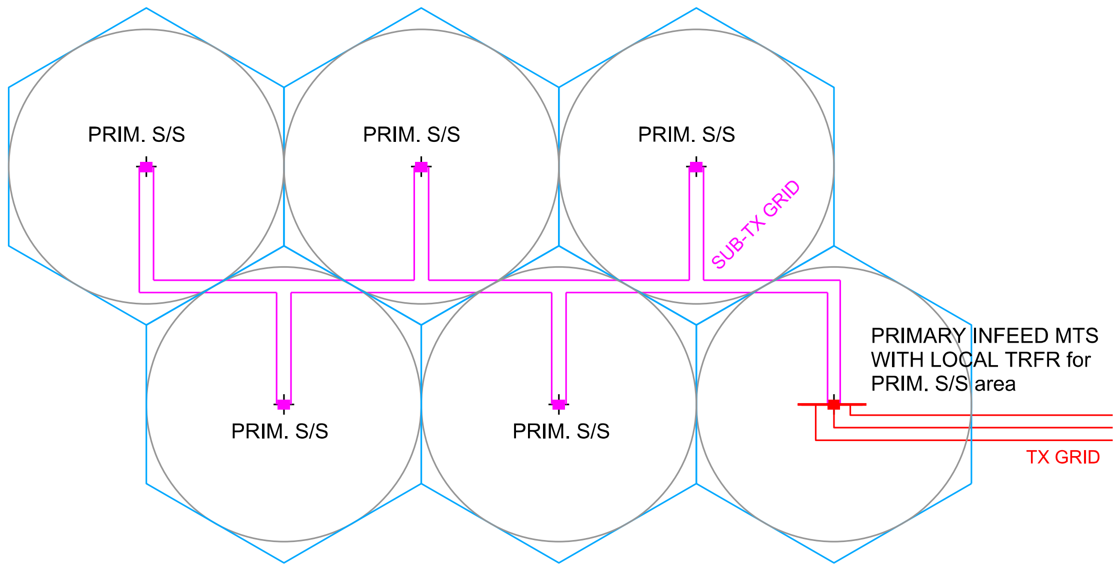


Figure 8: 360 MVA Subtransmission grid spatial layout

At subtransmission substation level, transformers can be moved between substations with the same voltage levels and vector groups, a spare transformer bay and spare transformer control panel can simplify moving a transformer from one site to another during emergency conditions.

With grid planning, the overloading of feeders can be prevented and the subtransmission backbone planning must be capacitated to cater for future load requirements. Often, in South Africa, supply authorities do not execute grid planning and do not have an electrical master plan to ensure feeders are not overloaded and that strengthening projects are executed soon enough.

Grid planning is essential to obtain the relevant data required when considering solutions to increase power transfer or ameliorate a subtransmission system by increasing the system's reliability.

2.1.2 Load profiling

Electrical energy demand is generally proportional to economic growth [7] [8] [9]. However, due to unreliable utility supply in South Africa and load shedding, many paying customers tend to reduce grid consumption by use of alternative energy sources. If utilities do not support the actioning of revenue collection, their electrical energy cost recovery ratio reduces, resulting in further financial turmoil in many cases. The management of load profiles at subtransmission intakes can reduce energy expenses and improve a utility's liquidity. The money saved can be applied to constrained areas of the subtransmission network.

Load profiling involves the gathering of historical load data and forecasting of future trends. The more a load profile resembles a flat or unity profile, the more difficult it becomes to re-rate the capacity of a feeder. Both short-term or daily profiles, as well as medium-term or seasonal profiles, must be considered to understand possible loading conditions better. For a short period, the emergency loading condition using a probabilistic rating to re-rate a feeder yield sufficient capacity at no additional cost [36] [37]. Therefore, load profiles are essential to the theoretical re-rating of subtransmission feeders to increase power transfer capacity.

Existing OHL capacity can be determined accurately with a conductor catenary survey, conductor loading at the time of the survey and corresponding climatic records. With a load profile, which includes daily and seasonal cycles, and a load growth forecast together with routine and emergency operating conditions, a cycled thermal rating can be determined for the OHL. A cyclic load will increase the line rating when compared to a unity load factor deterministic rating.

The load cycle, in Figure 9, is based on data for a small town's 60 MW infeed, which covers industrial, domestic, commercial, and most other types of loads. The profile in Figure 9 is based on actual data logging of the external grid supply into this typical South African town, with a population of approximately 170 000 people. The profile depicts the recorded minimum, maximum and average demand over 250 days, and the exceedance of the 60 MVA notified maximum demand (NMD) is shown. The maximum demand (MD) is measured based on a 30-minute integrated period, while the NMD is a contractual capacity between the supply utility and the point of delivery.

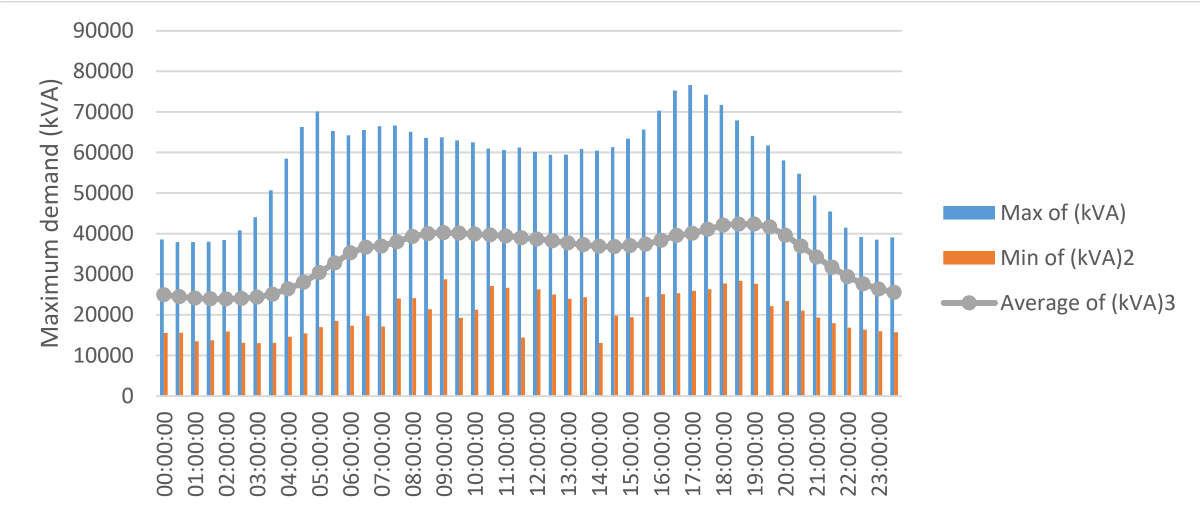


Figure 9: Typical daily load cycle for a 60 MW NMD infeed (Utility K)

Load profile data over extended periods provides valuable insight into the maximum loading that can be expected on feeders and the duration of these maximum loading conditions. Load profiles can be used to re-rate feeders or to determine a limited time emergency rating. Moreover, this specific utility use to have coal-fired steam-powered generation capacity to reduce the notified maximum demand (NMD) from the external grid, the co-generation of electrical energy would have prevented the exceedance of the NMD.

In recent years, with the advent of embedded generation distributed throughout a grid, the estimation of electrical energy flow and total usage per consumer has become more difficult. Embedded generation influences load factor, diversity (ADMD), equipment ratings, harmonics, system unbalances, distribution transformer voltage profiles (possible rises), and losses [38]. Distributed or small-scale embedded generation (SSEG) can, in certain applications, serve as peak load lopping, or baseload co-generation. This approach to peak load lopping or partial baseload cogeneration is similar to demand-side management (DSM). SSEG peak-load lopping to reduce NMD is achievable through embedded cogeneration such as natural gas-driven steam turbines. For embedded cogeneration, the generation capacity can also be de-centralised to the MV level nodes with the highest loading. This result in the unloading of the subtransmission intake and ancillary subtransmission feeders during cogeneration periods. The cost of co-generation can be reduced using a hybrid PV and steam-driven turbine generation plant, where the cost for steam turbine generation can be reduced using off-gas process steam. The Lesotho electrical network has embedded hydro-generation to slightly reduce Lesotho's dependency on the South African power grid.

South Africans are expected to use electrical energy sparingly due to the ongoing energy crisis, initiatives such as energy-efficient installations, green building design, optimising of industrial processes, and DSM are all initiatives to reduce electrical load consumption. Irrespective of the DSM initiative and misfortunes such as load shedding, South Africa is still showing economic growth. The graph in Figure 10 shows a definite, but non-steady historical GDP growth in South Africa. As referenced above, economic growth is proportional to load growth [7] [8] [9].

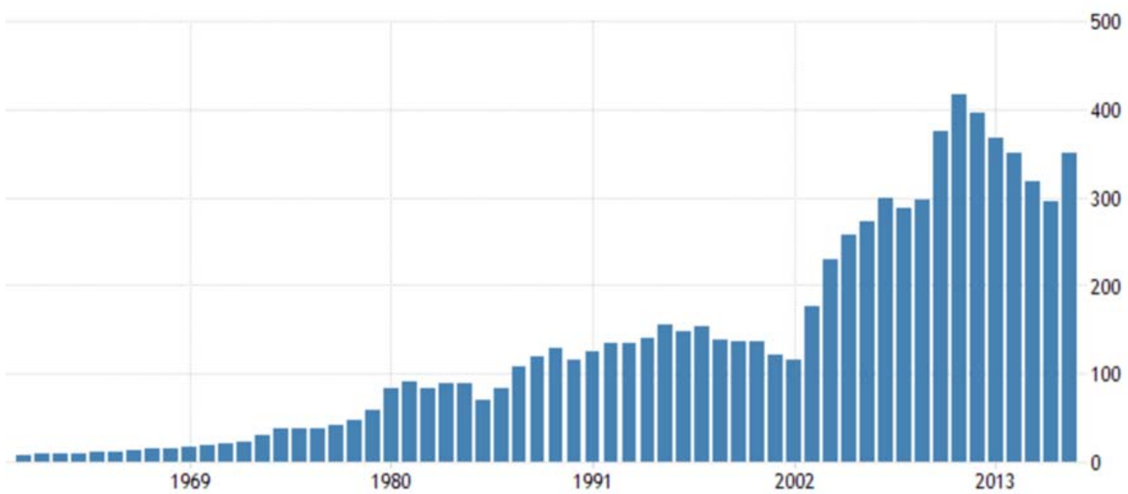


Figure 10: South Africa GDP in USD Billion [39]

The long-term data record from 2002 to 2017 for the same utility's load profile shown in Figure 9, depicts a definite and steady electrical energy demand increase (see Figure 11).

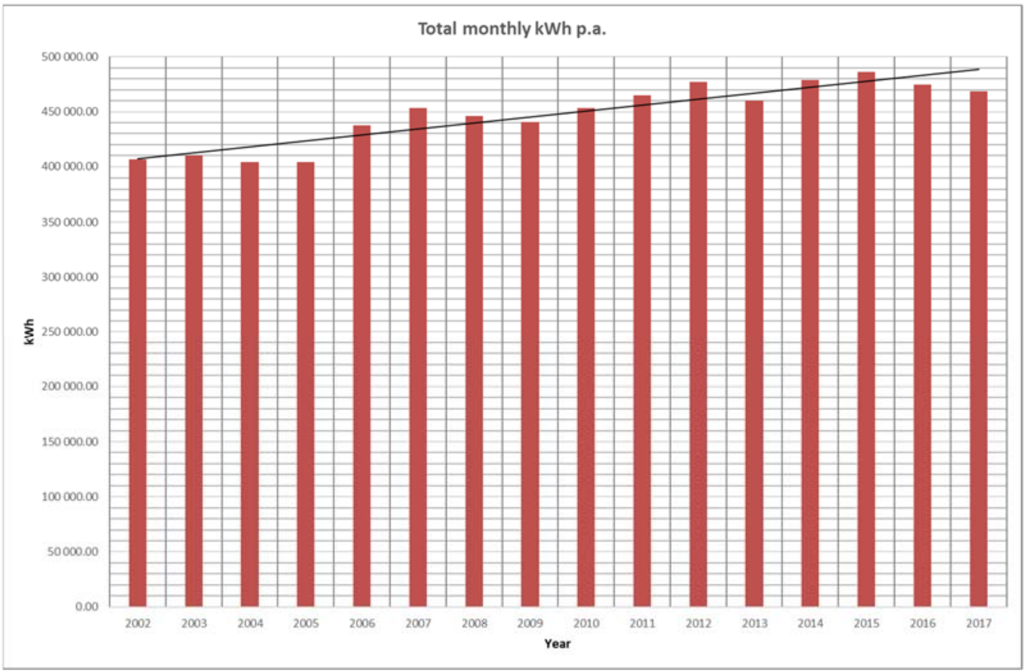


Figure 11: Actual recorded electrical energy usage for a 60 MVA NMD (Utility K)

The demand increase is irrespective of poor economic performance (limited development) during the same period and the aforementioned load reduction initiatives. In addition to the load reduction initiatives, the cost of electricity has escalated far above inflation (see Figure 12).

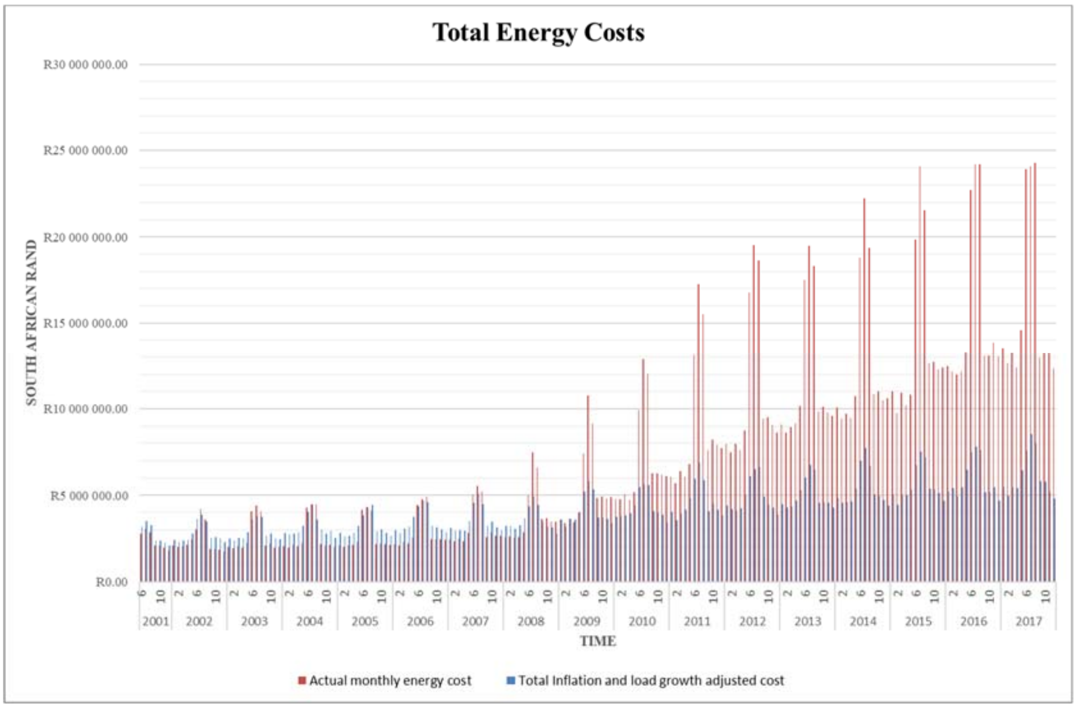


Figure 12: Inflation-adjusted tariff increases compared to actual tariff increases for Utility K

Despite all factors mentioned, there is still an increase in electrical energy demand, as shown for the utility in Figure 13.

With the load profiles, load data and extensive historical climatic data, the feeders for this utility can be uprated from the original deterministic ratings. Peak winter loads between June to August, and historic maximum load growth is perceptible in Figure 13, which shows peak demand increases from January to December each year, and load growth from 2002 to 2019.

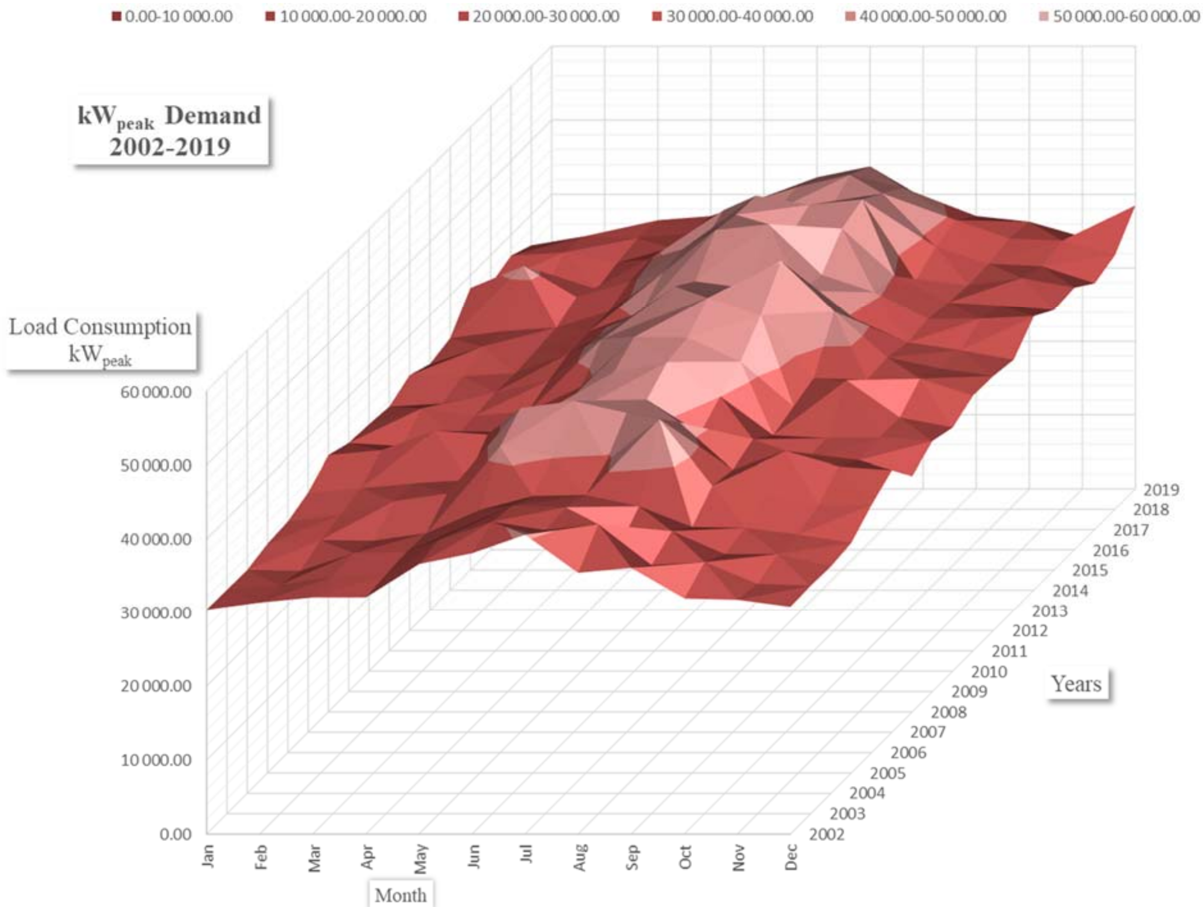


Figure 13: Recorded historical peak data for Utility K (kW)

The purpose of the Figure 13 is to show that despite all the restrictive conditions, there was a steady increase in peak demand for the specific rural utility. Throughout the service life of a subtransmission line, there is an extremely high likelihood of increases in peak demand. Depending on the margins of spare capacity and ever-increasing peak demand, any subtransmission line's capacity will be exhausted.

Load profiles, historic peak demands, statistics, and estimates on future demand are all tools used to determine the load profile to be applied when determining a subtransmission line's cyclic thermal rating. As is shown in Figure 14, peak loads during the "high" winter season together with dry conditions in various geographic locations can easily lead to drying out of the soil around buried cables. The high winter demand together with dry soil conditions will impose restrictive thermal ratings on buried cables, however, the ambient temperature and soil temperature are favourable during winter.

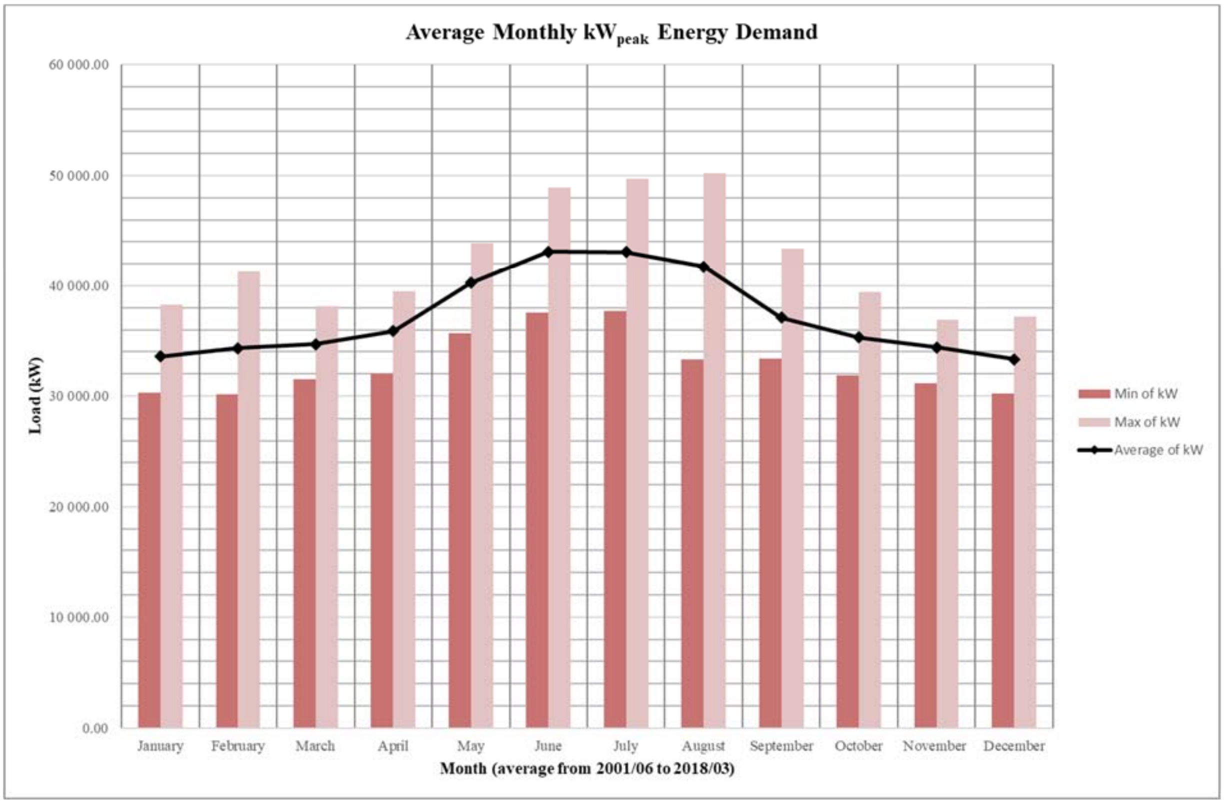


Figure 14: Recorded average peak monthly demand for Utility K (kW)

The importance of historic load profiles is its use in assisting with the determination of a load growth trend for the future expected loading of feeders. The predicted future loading of feeders provides insight into how much additional energy will be required for an overall subtransmission power system or specific feeders. Densification, due to urbanisation and economic development, contributes immensely to increased load requirements [10]. A continues increase in load requirements will eventually result in capacity shortages.

2.1.3 Fault level considerations

Depending on the method applied to increase power transfer, or how system reliability is improved, it could increase the subtransmission system's fault level.

Three-phase faults are often the most severe and the most amenable to calculation. Depending on the fault location, and the transformer winding and earthing arrangements, a single phase-to-earth fault may result in a fault current in the faulted phase exceeding the fault current that would flow in each of the phases for a balanced three-phase fault at the same location. From the sequence circuits for a three-phase fault and a single-phase-to-ground fault:

Single-phase-to-ground: $$I_{\text{pos}} = \frac{V_S}{Z_{pos}+Z_{contact}} \; \left(I_{neg} = 0;\; I_{zer} = 0\right) \quad \textbf{(2)}$$

Single-phase-to-ground: $$I_{zero} = \frac{V_S}{Z_{pos}+Z_{neg}+2\cdot(Z_{contact}+Z_{ground})} \; \left(I_{neg} = I_{zer};\; I_{pos} = I_{zer}\right) \quad \textbf{(3)}$$

Shield wires serve as partial fault return paths. Therefore, fault levels must be considered when sizing both shield wires and phase wires. Both the shield wire and phase wire must be sized to sustain the fault current according to the design principles. For cables, the bonding lead cross-sectional area and cable screens must be determined to cater for fault conditions. An increase in fault levels due to an increase in power transfer capacity will reduce the overhead line shield wires, phase conductors, and cable bonding leads fault clearing time. The earthing of support structures and terminal equipment also forms part of the fault level investigations.

2.1.4 Land areas, land ownership and land-use planning

When considering Gauteng, it is the smallest province in South Africa covering 18 178 km^2 which is 1.5% of South Africa's total area. However, Gauteng is South Africa's economic powerhouse generating a third of the country's GDP as shown in Figure 15, and is also the most populous being home to 14.3 million people in 2017, as published by Stats SA's Provincial project by sex and age (2012 to 2018) and their media presentation for GDP, in the 4th quarter of 2018 [40]. From 2016 to 2021 there was an expected nett inflow of migrants into Gauteng of 1.55 million people [41], thus increasing the demand on electrical energy.

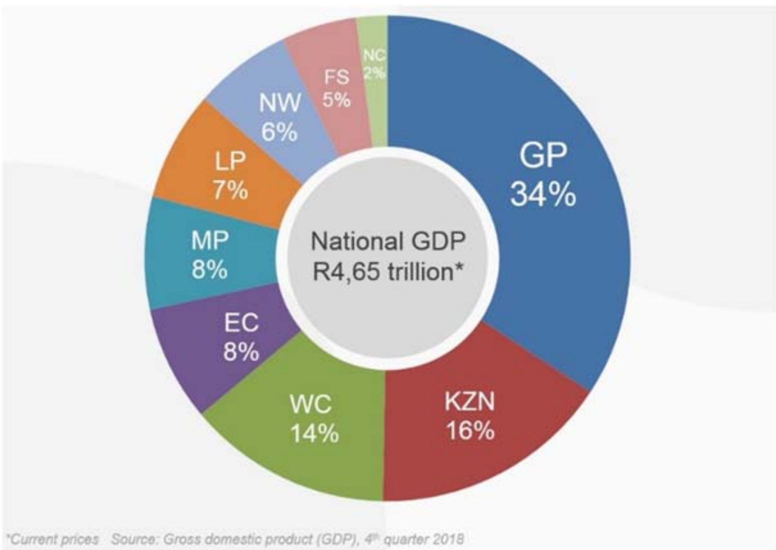


Figure 15: Stats SA provincial GDP contribution [40]

The land area available is integral to infrastructure development and the usage of existing infrastructure. A shortage of usable land for infrastructure can severely restrain economic development, whereas the availability of land can be a tremendous contribution to economic and infrastructure development for bulk and linkage services. Aspects influencing land or property requirements include, but are not limited to health and safety, environmental impact, town planning, legal requirements, electrical and magnetic fields of transmission lines, noise, property cost and technical performance of equipment suitable to extend or upgrade bulk services.

Practically, buried cables can be hidden to the naked eye following installation, but occupy a significant amount of land during construction [42]. Overhead power lines and underground cables share specific mutual requirements such as the management of vegetation and access for maintenance and repair for the duration of their life. Both technologies have compact and spacious design options. When determining options to increase power transfer, land usage and availability can be critical to the success or detriment of an option.

Various designs and technologies determine the land requirements for substations. Different design approaches exist for the same technologies, which result in fluctuations in land requirements and costs. High-strung busbar and low-profile tubular busbar are options for Air-insulated Switchgear (AIS) design approaches for outdoor substations. Alternative technologies such as hybrid switchgear (HYB) as an alternative to air-insulated switchgear (AIS) is used to reduce space required for high voltage substations. The land occupied can even be further reduced by using gas-insulated switchgear (GIS). With the use of GIS technology the required statutory clearances are reduced as a result of encapsulation and increased insulation.

Influential factors concerning land usage are outlined in paragraphs 2.1.4.1 to paragraph 2.1.4.3.

2.1.4.1 Geospatial planning

Geospatial planning and surveys are geographic information mapping systems used for the graphical depiction and planning of geographical areas. Geospatial planning and survey of existing infrastructure form an integral part of electrical grid planning.

To effectively plan electrical transmission grids, which includes the placing of substations and routing of feeders, geospatial information was obtained where available and compiled when not available. Cadastral boundaries are verified with the surveyor-general to warrant accurate placing of infrastructures. Ortho-photos greatly assists as the base map, onto which cadastral boundaries and existing infrastructure are populated. Existing infrastructure information comprises of non-electrical services such as roads, sewer, water, water- and wastewater treatment plants, traction lines and reservoirs.

In addition to a base-map, detailed survey information is required with the execution of the detail design. All services, obstacles, future developments, restricted areas, and sensitive areas are indicated on a layout plan. The layout plans generally include CAD layers providing ortho-photos, the cadastral boundaries, and servitudes, which are all valuable information regarding subtransmission feeder routes. Without geospatial information, detailed upgrade designs for both overhead lines (OHLs) und underground cables (UGCs) are not possible.

2.1.4.2 Servitudes

Servitudes are notarial provisions that facilitate an electrical supply authority in legally protecting assets and access to assets such as overhead power lines and substations. Servitudes, or right of ways, legally allows the use of subtransmission feeder routes. In some cases, to increase power transfers, the solutions can be as simple as registering a second servitude and constructing a second subtransmission feeder next to an existing feeder.

Servitudes can be measured from outer conductors of feeders or can be registered as line servitudes or area servitudes. Servitudes are acquired through a servitude agreement, which can either be capitalised or rented. Capitalised area servitudes are recommended to prevent perpetual rental fees and clearly demarcate the servitude's extent.

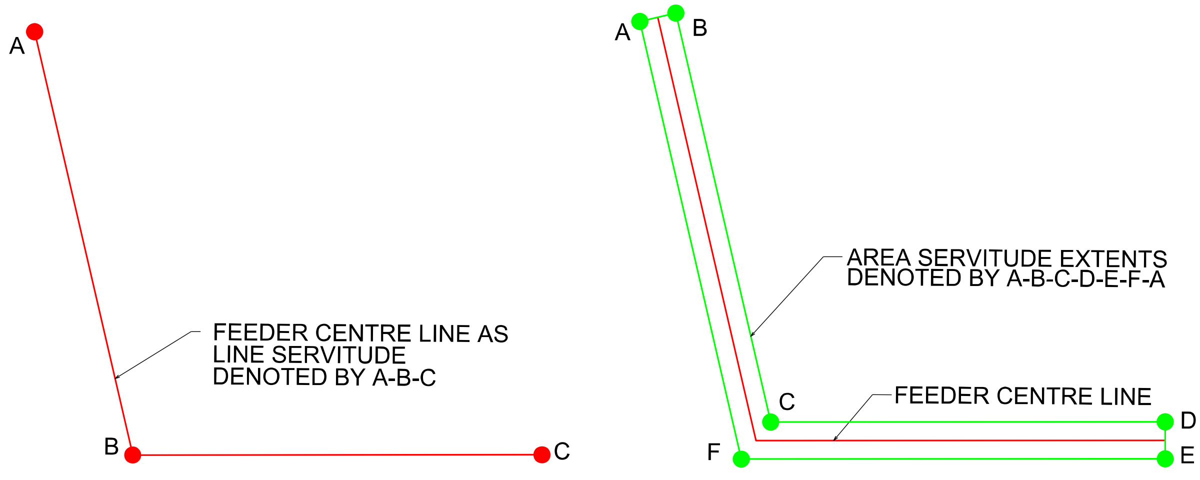


Figure 16: Line servitude vs area servitude

A common issue that may arise is when stayed structures are used for overhead power lines, depending on the structure height and stay angle, the anchors of the stay may fall outside the registered servitude. When lines are strung with a larger conductor to increase capacity, guy-anchors may be needed for self-supporting structures. These anchors must fall within the existing servitude, or further agreements must be reached.

The servitude requirements are determined by the voltage level, current rating (i.e. cable spacing) and physical size of equipment together with the space required for the safe operation of the system.

With transferring power from one position (source) to another (load), the selection of routes and how a power line traverses over an area have a tremendous influence on the feasibility of implementing or upgrading the feeder system. Aspects to consider when investigating possible new or upgraded routes for OHLs and UGCs are:

Table 6: Feeder route selection considerations

- Existing Services	- Topology or profile section of the route
- Environmental Constraints	- Safety Requirements
- Future planning such as roads, bridges, and townships	- Ease of installation (constructability)
- Clearances and restrictions	- Survey requirements

For cable installations, bend points must be planned with a radius at bends (servitudes bends are registered as chamfers), the more bend points per section, the more difficult the installations of cables become.

When new power line routes are no longer available or become too much of a deviation resulting in long and expensive lines, investigations can be done to utilise existing servitudes for compact overhead line upgrades or the addition of cable installations within overhead power line servitudes. For electrical feeders, the utilisation of existing servitudes will result in the uprating or upgrading of electrical services already installed, the addition of services or the demolishing and implementation of new electrical services.

The merits of each case are evaluated individually with the planning of servitudes or upgrading of feeder systems. Without land area or servitudes, the transfer of power between points is not possible. If existing servitudes are insufficient, the increase in power transfer capacity is complicated. Although wider servitudes are generally required for overhead power lines, the construction of overhead lines in comparison to cable installations is much less disruptive. A large amount of soil is excavated along the longitudinal cable route for underground installations, the excavated soil is stacked next to the trench whilst vehicular access is required along the route, resulting in a large construction footprint.

Most feeder line servitudes are determined according to the specific requirements of the installation such as:

- the system voltage and clearance required
- access
- population density
- number of circuits and parallel lines
- future requirements
- planning
- phase configurations
- side slopes
- transition yards
- noise
- radio interference
- electromagnetic fields
- electric fields
- undergrowth and vegetation
- span lengths
- guyed or self-supporting structures
- joint bays
- space for auxiliary equipment such as link boxes

However, the primary denominator in determining servitude widths is safety to the public and safety during operation and maintenance.

For overhead lines, the servitude width is determined by the space required for maintenance purposes and the position of the overhead conductor under maximum blowout (extreme wind) conditions at a given conductor temperature. The use of suspension insulators is discouraged to reduce conductor blowout, reduced conductor swing, and reduced support structure height. Power lines with longer ruling spans generally require wider servitudes to accommodate the wider horizontal displacement of conductors during maximum wind conditions. Figure 17 shows the cross-sectional clearance checks for an OHL.

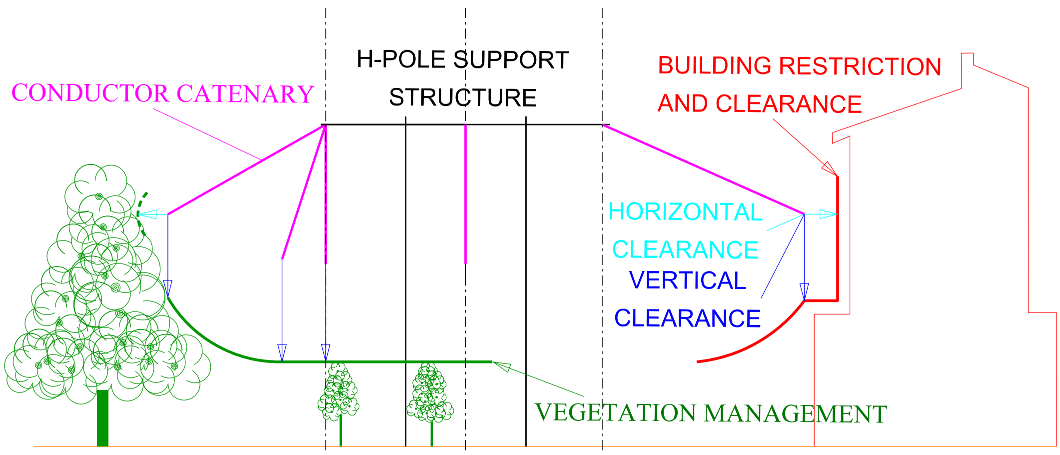


Figure 17: Clearance of conductors to buildings and vegetation (based on [43])

When considering ground clearance, higher operating temperatures of conductors result in deeper sag and less clearance. Too deep sag can become a statutory safety clearance infringement when not complying to the gazetted minimum vertical or horizontal clearances.

The required OHL servitude width is calculated by interpreting the relevant South African National Standards, equation (4) gives the formula used for calculating the required servitude width as depicted in Figure 18.

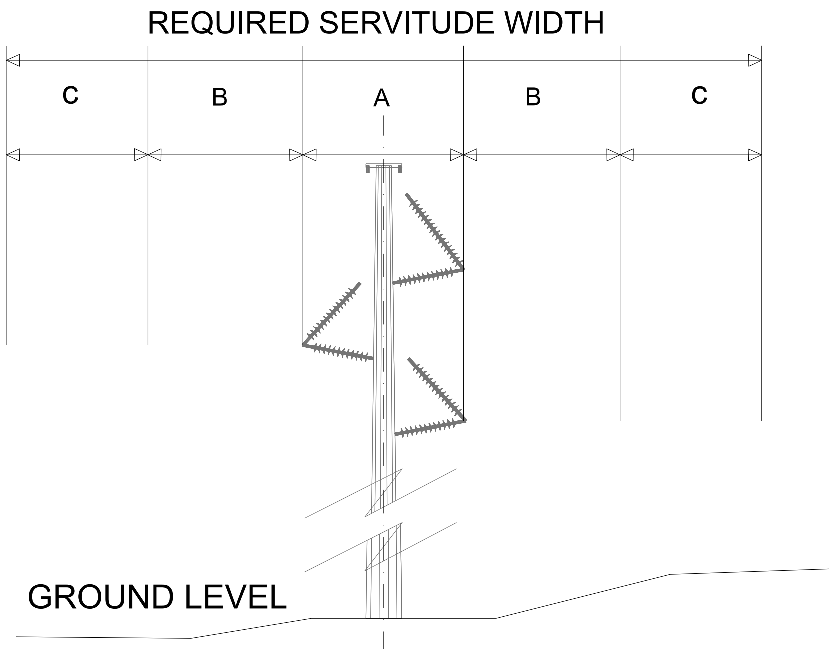


Figure 18: Calculation of servitude width

$$S_w = A + 2(B + C) \tag{4}$$

Where S_w is the required servitude width (m), A the horizontal distance from the centre line to phase conductor (m), B the calculated conductor swing or "blow out" for maximum wind pressure (including insulator swing (m) where applicable), and C, the statutory horizontal clearance to buildings or other structures (m).

For use in equation (4), the South Africa government gazetted the minimum statutory clearances for the design of overhead power lines for conditions prevailing in South Africa, these minimum values are given in Table 7. The clearance to be considered for the distinct subtransmission voltages are the minimum safety clearance for working in close proximity to energised infrastructure, the minimum vertical clearance under different circumstances and for all subtransmission line voltages a minimum horizontal clearance of three metres. As per equation (4) the horizontal clearance is determined under maximum conductor swing due to wind.

Table 7: Minimum statutory clearance for power lines [43]

<table>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td></tr>
<tr><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2"></td><td colspan="4">Minimum Vertical Clearances</td><td>Horizontal Clearances</td></tr>
<tr><td colspan="4">m</td><td>m</td></tr>
<tr><td>Highest system r.m.s. voltage</td><td>System nominal r.m.s. voltage</td><td rowspan="2">Minimum safety clearance m</td><td rowspan="2">Ground clearance, all areas</td><td rowspan="2">Roads in townships and proclaimed roads, railways*</td><td rowspan="2">To buildings, lines and between power lines</td><td rowspan="2">To telecommunication lines and between power lines</td><td rowspan="2">To all ground, building and structures not part of the power line</td></tr>
<tr><td>kV</td><td>kV</td></tr>
<tr><td colspan="8">SUBTRANSMISSION VOLTAGE LEVEL</td></tr>
<tr><td>72</td><td>66</td><td>0.77</td><td>5.7</td><td>6.9</td><td>3.2</td><td>1.4</td><td>3.0</td></tr>
<tr><td>100</td><td>88</td><td>1.00</td><td>5.9</td><td>7.1</td><td>3.4</td><td>1.6</td><td>3.0</td></tr>
<tr><td>145</td><td>132</td><td>1.45</td><td>6.3</td><td>7.5</td><td>3.8</td><td>2.0</td><td>3.0</td></tr>
<tr><td colspan="8">*Certain railway authorities may have more onerous clearance requirements.</td></tr>
</table>

Table 8 provides the general servitude widths and restrictions developed by Eskom [44] for overhead power lines. For applications where space is limited, the recommended restrictions can be reduced to suit the specific line design.

Table 8: Clearance and separation distance adapted from [44]

VOLTAGE	BUILDING RESTRICTION ON EACH SIDE OF CENTRE LINE	SEPARATION DISTANCE BETWEEN PARALLEL LINES
66 kV	11 m	14 m
88 kV	11 m	14 to 15 m
132 kV	15.5 m to 18 m	21 m (15 m to 24 m, 15 m for monopoles)

In addition to the excavations for cable installations, space is required adjacent to trenches for storage of spoil and access along the route. In urban areas, the land area taken for direct buried cables can exceed the land required for an equivalent rated overhead line during construction, and new cable installations or cable replacement in established areas can become very disruptive even when compared to overhead power lines.

The construction footprint for cables is most significant with double circuit cables where a particular centre-to-centre spacing between circuits needs to be retained to achieve a high thermal power transfer rating. The considerations in Table 9 influence the planning of cable routes:

Table 9: Cable route selection considerations

- Restrictions over the cable route (buildings, earth mounding, roads, vegetation)	- Planting of vegetation on the cable easement strip
- Drainage in tunnels	- Safety and fire protection in tunnels
- Clearing of existing vegetation	- Maintenance access
- Access to sites over the cables easement strip when the cable is installed adjacent to roads	- Theft

If not installed within the road reserves, the servitude area required for cables is the thermal spacing required for the cable system to transfer the required rating, plus additional space to fit machinery when excavating, backfilling or installing the cable.

Cable servitudes shall typically have chamfers on bend points to prevent the cable from cutting across the servitude delineation when not exceeding the allowable cable bending radius, as indicated in Figure 19:

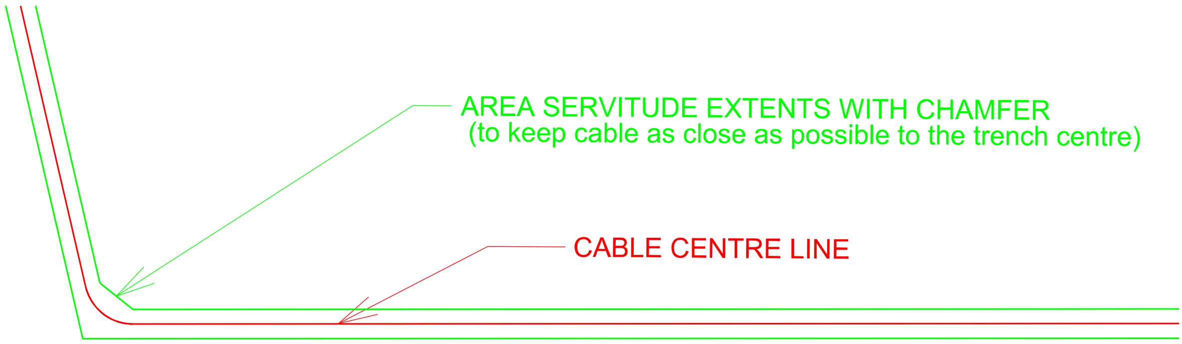


Figure 19: Underground cable servitude layout

As with stays for overhead power lines, the minimum bending radius must be considered when determining servitude positions.

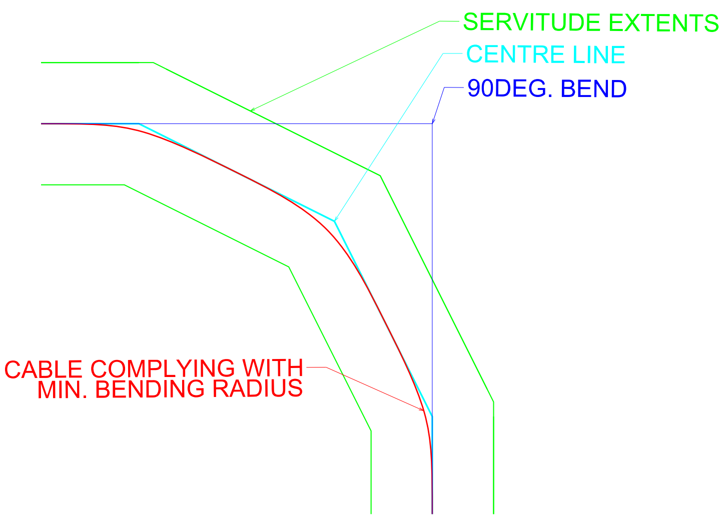


Figure 20: Cable layout within a large bending radius servitude [44]

For substations, if no additional space is available, vertical expansion of the station and compact equipment are possible solutions. The upgrading of substations for increase power transfer is not as dependant on space when compared to subtransmission feeders. The substation area required when using GIS can be less than 20% of the area required when using AIS [45].

2.1.4.3 Property cost considerations

When property valuations data and the increased load transfer required data are available, a comparison can be made between the cost of constructing a new feeder on a new route, or the costs of re-using existing routes.

City Power of Johannesburg successfully implemented the upgrading of existing ACSR circuits with low sag ACCC circuits to increase power transfer by implementing electrical grid strengthening projects before South Africa hosted the 2010 Soccer World Cup during peak winter loading. For City Power, limited time, high property cost and bureaucracy with acquiring servitudes, rendered the restringing of existing ACSR overhead power lines with ACCC the preferred solution. However, economically, conductors with high power transfer ratings due to being operable at high temperatures remain expensive [46].

When new subtransmission feeders on new routes into an area are needed for strengthening of the subtransmission system or deloading of existing feeders, OHLs and UGCs are considered. For high property values, there will be a breakeven point after which the installation of a cable becomes more cost-effective than an overhead line. Servitude cost must, therefore, form part of the evaluations of new subtransmission feeders.

2.1.5 Electric fields, magnetic fields, corona, and noise

A practical method of upgrading transfer capacity is by increasing insulation levels and equipment ratings, if necessary, and operating a system at a higher voltage. It is not always necessary to upgrade the insulation, due to common practices such as building 88 kV OHLs at an insulation level of 132 kV. The most common, highest South African voltage used at subtransmission level is 132 kV, where EMF, corona and noise impacts on feeder performance and operating conditions.

Based on measurements by Fews et al [47], 132 kV lines commonly emit corona ions. When feeders operate at 132 kV or the operating voltage is increased to 132 kV, it is recommended that EMF and corona studies be performed as a precaution. Simplified equations for EMF fields are given in the Cigré Overhead Line Green Book [48].

Electric fields can be screened; objects such as trees can disturb an electric field [49]. As shown in Figure 21, a 5 m tree growing 10 m from the centre of an electric field would effectively screen or reduce the electric field as shown by the lower curve. The upper curve is an unimpeded electric field density at ground level [49].

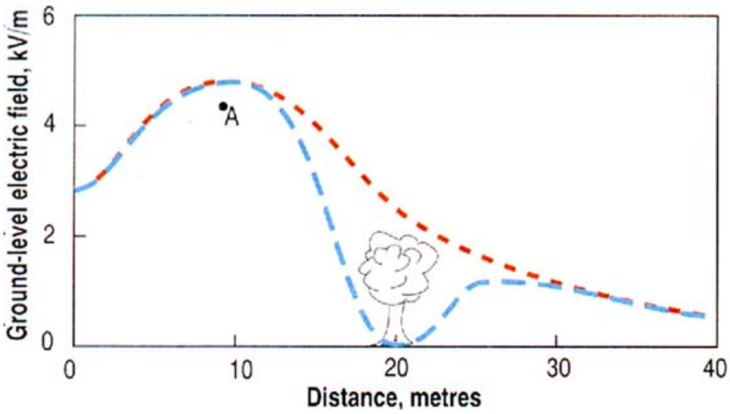


Figure 21: Electric field perturbed by a tree [49]

The magnetic field distribution also depends on phase configurations as shown in Figure 22 [49]. As opposed to electric fields, magnetic field distribution is not as easily changed or inhibited. Magnetic field strengths in the vicinity of feeder systems are mainly dependant on the conductor configuration distances, conductor orientations, and the current flowing through the conductor. Magnetic fields frequently change throughout the day as loading on the feeder system increases or decreases. Buried underground cables do not produce external electric fields due to the surrounding soil and the screens in the cables themselves. Due to most objects and buildings providing little to no screening of magnetic fields, cables still generate magnetic fields depending on the installation method. Magnetic fields are effectively managed in single-core cables by having a twisted trefoil configuration and a balanced system ideally similar to three-core cables [49], this is a geometric method where phase cancellation reduces magnetic flux. Screening is required to completely remove a cables magnetic field distribution.

The graph in Figure 22 provides an exaggerated comparison between the nett magnetic fields generated at 1 m above ground, by overhead lines and underground conductors, at a constant current for the same voltage level. The phase orientation for the OHL line is adjusted from flat to vertical while maintaining the same inter-phase spacing, resulting in a reduction of the nett magnetic flux density. For the same current and voltage level, insulated cables are placed in orientations where the outer jackets of the phases touch. Thereafter, the insulated cables' inter-phase spacing is increased in the horizontal (flat) formation, resulting that the magnetic flux density produced by the cables are higher than the magnetic flux density produced by the OHL. The magnetic flux density of the cables decays more rapidly with an increase in distance from the centre of the system.

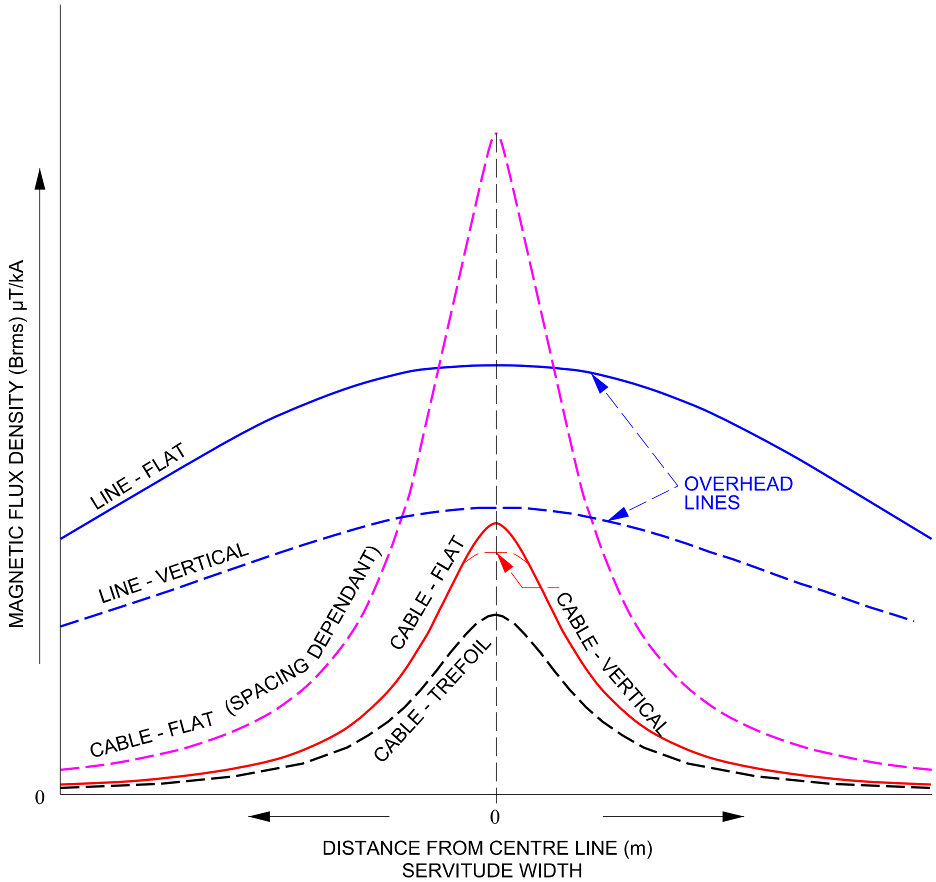


Figure 22: Typical OHL and cable magnetic field

The allowable electric and magnetic field exposures limits are based on the fundamental restriction that 10 mA/m^2 (occupational limit) and 2 mA/m^2 (public limit) are not to be exceeded. The occupational limit applies to persons knowingly working in close proximity to high magnetic flux densities, such as linesmen performing live-line maintenance or construction work on OHLs. Public limits apply to persons unintentionally being exposed to increased magnetic flux densities. The limit exposure levels set by ICNIRP [50] are given in Table 10:

Table 10: 50 Hz Electric and magnetic field exposure limits for humans [50]

Exposure	Electric field (kV/m)	Magnetic field (µT)
Occupational	10	500
Public	5	100

At the subtransmission level, corona and transformer noise are the two main aspects contributing to noise pollution. In South Africa, audible noise is governed by the Environmental Conservation Act of 1989, but may also vary depending on provincial regulations. Despite regulations there are no specific limits legislated in South Africa for noise produced by overhead power lines. An informal limit for fair-weather noise levels is 35 dBA at the servitude boundary.

When increasing a subtransmission system's power transfer capacity, larger power transformers and higher voltages can be used, but the corona and noise becomes more prominent.

Transformer vibration tends to be the most common source of noise at subtransmission level. The issue of noise due to corona becomes prominent mostly at transmission-level voltages (> 132 kV). Lower voltages are not indemnified against noise, during the execution of this study audible noise was noted due to partial discharge and leakage currents on the current transformer of 11 kV switchgear, and due to corona discharge on the arcing horns of 66 kV cable sealing ends.

Based on the frequency of the fundamental or first harmonic, 50 Hz in South Africa, a 100 Hz magnetostriction vibration and audible humming sound is generated when the transformer is energised. The frequency doubling is due to the core magnetizing and demagnetizing twice in a single 50 Hz cycle. With the magnetizing and demagnetizing of the transformer, there is a change in electromagnetic forces, the change in electromagnetic forces result in a dimensional change of magnetic material inside magnetic fields. The phenomenon is known as magnetostriction. For power transformers, the changing flux densities and subsequently changing electromagnetic forces, causes a small change in the dimensions of the transformers' core lamination sheets [51]. Sources of power transformer noise are [52]:

- Magnetic core, vibrations due to magnetostriction (magnetic forces)
- Windings, electrodynamic magnetic / magneto-motive forces cause the vibration of windings
- Aerodynamic and hydraulic noise in the cooler (heat exchanger), such as pumps for water cooling, or fans for air cooling.

Corona discharge is a current discharge, brought on by the ionisation of a medium, such as air, surrounding a conductor when the surface voltage gradient exceeds the breakdown strength of the medium. The phenomenon causes additional losses, communication interference and audible noise. The typical breakdown strength of air is roughly 30 kV/cm in a uniform electric field at atmospheric pressure in dry conditions [53]. Corona can become a significant factor when the surface voltage gradient of conductors or fittings exceeds the critical value of 30 kV_{peak}/cm or 23 kV_{rms}/cm, specifically in areas located at higher altitudes or areas with high humidity and high annual rainfall [50].

The inception gradient for corona in AC overhead conductor systems as developed by Peek's Law is given by equation (5) [50]:

$$E_c = 21m\delta\left[1+\frac{0.308}{\sqrt{r\delta}}\right] \text{ kV}_{\text{rms}}/\text{cm} \quad \textbf{(5)}$$

Where E_c is the inception gradient, m the surface roughness factor (0.7 to 0.9 for a standard stranded conductor and 1 for a perfectly smooth conductor), δ relative air density as a function between the prevailing atmospheric pressure and the ambient temperature, and r the radius of the conductor in cm,

Corona is considered at subtransmission voltage levels in urban areas where noise levels must be minimised. Noise levels and losses are increased when executing overhead line designs and phase spacing is decreased, bundle diameter is decreased, or small cross-sectional area conductors are selected.

The recommended outdoor noise limits are given in Table 11:

Table 11: SABS recommended maximum power system sound levels [54]

Area Zoning	Daytime noise (dBA)	Evenings and Weekend noise (dBA)	Night-time noise (dBA)
Rural	45	40	35
Suburban	50	45	40
Urban	55	50	45
Industrial	70	65	60

Although EMF, corona and noise are not fundamental to increased power transfer, the topics must be considered at higher voltage levels.

2.2 Power system modelling

Power system modelling is key to understanding the operational conditions of a subtransmission system. Load flow investigations contribute to understanding the sharing of power transfer between feeders, to quantify the extent to which the path of least resistance is followed in a subtransmission system.

By modelling a power system "as a whole" opposed to focussing on a single feeder provides an alternative method to increase power transfer to a given point in a network. This increased power transfer to a specific position is achievable by managing load flow through open points in the grid or by determining possible network strengthening elsewhere in the network to unload specific feeders. The feeder parameter calculated as part of power system modelling is used to determine losses, which forms part of the cost of losses in the total investment cost.

To accurately model power systems, the parameters that characterise the system under investigation must be determined. The results of the power system model are used to examine the subtransmission system performance. Sets of linear and non-linear equations are manipulated to calculate line parameters using software packages such as MATLAB, MATHCAD, EMTP Line Constants [55] DigSilent PowerFactory [56] and CDEGS. The parameters are then used to model electrical grids.

The line parameters for overhead power lines and cables must be determined. These parameters are applied to perform contingency analysis, load flow and fault level investigations. For subtransmission feeder systems, overhead power lines and underground cables are investigated. In the case of substations where transformers are modelled, transformer parameters are obtained from factory acceptance tests' data. However, for this study, transformers are mostly replaced by a general static load to model grids.

2.2.1 Insulation system

Transferring power is not possible without an insulation system as the insulation has a vital role in power systems. Designing for one insulation level higher than the operating voltage simplifies possible future upgrades and saves costs if the voltage level is increased in future. Upgrading from one insulation level to the next standard insulation level without changing the line characteristics, provides for a high increase in power transfer capability (i.e. minimum 150% for an upgrade from 88 kV to 132 kV).

Insulation plays a vital role in power systems to ensure safe equipment operation and working conditions. The primary purpose of insulation in electric apparatus is to separate circuits and conducting parts of different potentials [57], essentially preventing unwanted current flow under the influence of an electric field in some regions of a power system. Insulation can be deemed the most critical material or state of matter used in high voltage apparatus, without correct insulation levels, no individual high voltage apparatus forming part a power system can function correctly and safely.

The practical design of electrical equipment generally involves some engineering judgement and compromise, as there is no universal insulating material and no single electrical apparatus component with the exact desired properties. Westinghouse Electric Corporation, recommended in the 1960s that the following insulation aspects should be considered [57]:

Table 12: Insulation Characteristics [57]

Mechanical requirements	Electrical characteristics	Chemical characteristics	Thermal ageing
Flexibility	Dielectric breakdown strength	Resistance to common solvents	Degradation from heat
Tear strength	Insulation resistivity	Resistance to weak acids	
Shear strength	Power factor or dissipation factor	Ozone degradation	
Flexural strength	Dielectric constant	Flammability	
Tensile strength	Corona resistance (from 6000 V and above)		
Bond strength	Arc resistance		
Abrasion resistance	Moisture resistance		

Norwegian researchers initiated their investigations into their Compact Plus case in the 1990s [58]. Some technical challenges with the delivery of the project included corona and noise due to decreased phase spacing, and the use of insulators, as structural elements, required studies investigating fibre stiffness, ageing of silicone and possible insulator fatigue due to oscillations and vibrations.

Figure 23: Compact Plus line – Norway [58]

Super compact urban transmission lines, as referred to in Brazil, is a concept implementing a 138 kV voltage level on 69 kV infrastructure. From 2015 to 2020, satisfactory operation without complaints or outages was reported [58]. The installation was evaluated using corona and audible noise, radio interference, power frequency electric and magnetic fields, air gap strength for lightning impulse and switching surge, phase-to-phase switching surges, and lightning surge performance tests.

For insulated cable designs multiplicity of insulation compounds are available such as oil-based rubber, mineral-based rubber, varnished cloth, polyvinyl-chlorides, silicones, fluoro-carbons, polyethylenes, butyis, filled XLPE, and ethylene-propylene rubber [59]. For cable installations, a cable fault results in extreme damage to the cable with carbon deposits making a significant length of cable unusable. Overvoltage due to a direct lightning strike, induced overvoltage and switching impulses can result in flashovers on overhead lines if the lines' insulation level is exceeded.

There are two primary insulation ratings, which is the power frequency withstand level which is related to temporary overvoltages (TOVs) and lightning impulse withstand level which is related to lightning-induced overvoltages.

Equipment with external insulation is specified with values as per Table 13. The rating are often higher than standard international levels due to the high altitude and high lightning density on the Highveld of South Africa.

Table 13: Voltage and insulation levels in South Africa [28]

NOMINAL SYSTEM VOLTAGE	HIGHEST RMS VOLTAGE FOR EQUIPMENT	RATED SHORT TIME POWER FREQUENCY WITHSTAND VOLTAGE	RATED PEAK LIGHTING IMPULSE WITHSTAND VOLTAGE	SWITCHING IMPULSE WITHSTAND VOLTAGE
U_n (kV)	U_m (kV)	(60s) (kV)	(kV)	(kV)
66	72.5	140	350	200
88	100	150/185	380/450	278
132	145	230/275	550/650	398

When a surge occurs on a line, the minimum insulation level that an insulator must withstand is known as the Lightning Impulse (LI) withstand voltage or the Basic Insulation Level (BIL) of the insulator. The BIL is determined by the shortest distance between conductive parts of the insulator fitting to the line conductor and support structure. The distance from the conductor to the conductive part of the support structure is also referred to as the flashover distance and forms an integral part of insulation coordination of a power line.

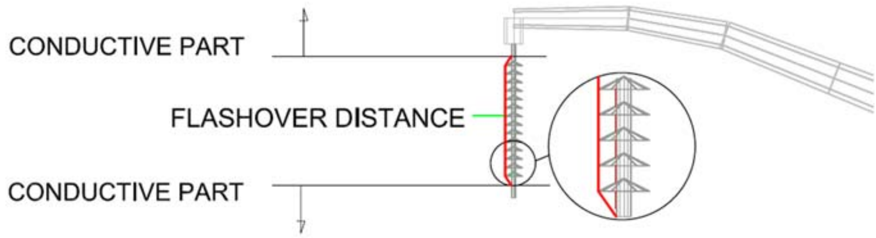


Figure 24: Insulator Arcing distance

Creepage distance is described as the shortest surface bounded distance between conductive parts. The required creepage distance of an insulator is dependent on the expected surge withstanding value of an electrical system determined by the operating voltage of the system and the pollution level of the environment.

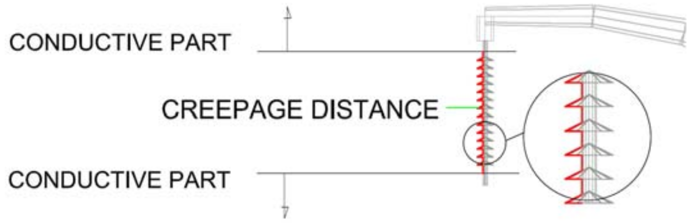


Figure 25: Insulator creepage distance

Creepage is determined by the level of pollution or contamination of the area in which a line is built. Pollution can refer to environmental pollution such as in heavy industrial or mining conditions as well as pollution due to climatic conditions such as high humidity in coastal areas or snow in icy areas. Pollution level ranges from light, with a required insulation level of 16 mm/kV phase-ground, to heavy with a required insulation level of 31 mm/kV phase-ground.

Part of insulation coordination is lightning protection; the general approach in lightning protection is either the rolling sphere method or angle of coverage method.

2.2.2 Conductor thermal ratings and selection

For overhead lines, the predominate limitation in conductor thermal rating is public safety and the risk of unsafe conditions. The factors that affect safety are conductor ground clearance, presence and size of objects below the conductors, the occurrence of voltage surges on the line and the magnitude thereof, and the possibility of a flashover due to the above [50].

For cables, the thermal dependency between phases and circuits, as well as the heat dissipation to the surrounding environment, limits the cables thermal rating.

Thermal rating of a feeder refers to the conductors' maximum allowable operating temperature considering all relevant constraints; there are various methods to calculate the conductor thermal rating. The approaches to calculating the thermal rating of a feeder are different between overhead power lines and underground cables. For overhead lines, the weather and climatic conditions are the predominant factors, whereas for cables to a lesser extent due to not having convective wind cooling when installed underground. However, the drying out of soil can be disastrous to a cable installation. Therefore, the thermal resistivity of backfill for an underground cable installation in soil should be tested in a laboratory under dried out conditions to prevent failures similar to the Auckland blackout described in [3].

Once existing OHLs are modelled, the restrictive span or multiple spans can be reviewed in detail for higher thermal ratings and solutions to increase clearance can be considered. For UGC installations, it is not practical to change the installation surroundings, to achieve optimum conditions for a maximum thermal rating.

For both overhead lines and underground cables, there is a thermal time delay when conditions influencing temperature changes. This conductor thermal time constant is used for emergency conditions when there is a step-change in the current [60].

The annealing effect of conductors is cumulative. Therefore, emergency ratings must consider the normal operating temperature in conjunction with the temperature and duration of the emergency load.

The recalculation of thermal rating or the re-rating of subtransmission feeders theoretically unlocks power transfer capacity on subtransmission feeders.

For overhead power lines, the factors influencing transfer capacity are the current flowing through the conductor, the wind speed perpendicular to the conductor, the radiation on the conductor by the sun, the ambient air temperature, and the radiation of heat from the conductor to the surroundings [61].

Algorithms, as given by [62] and [60], can be utilised for calculating conductor temperature and capacity. By using the applied comparison, the measured conductor temperature shows good correlation to the accuracy of the IEEE and CIGRÉ ampacity calculations [63].

In South Africa, Eskom moved from a conservative deterministic approach to a probabilistic approach to increase the theoretical thermal rating of the standard overhead conductors used by Eskom. Eskom based the probabilistic approach on an extensive weather database to replace the earlier Monte Carlo methods. The total probability of an accident was increased in 2010, from 1 in 1 million, to 1.2 in 1 million, for a higher thermal conductor rating. The higher accident risk at 1.2 in 1 million with a probabilistic approach is still significantly less than the deterministic risk levels [64], [65].

The thermal condition of an overhead conductor is defined by a heat balance equation. For steady-state heat balance [62]:

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_{avg})}} \quad \textbf{(6)}$$

Where q_c is the convection heat loss per unit length (W/m), q_r the radiated heat loss per unit length (W/m), q_s the heat gain from the sun (W/m),I the conductor current (A), and $R(T_{avg})$ the AC resistance of the conductor at the average temperature.

For non-steady-state heat balance [62]:

$$\frac{dT_{avg}}{dt} = \frac{1}{m.C_p}\left[R(T_{avg}).I^2 + q_s - q_c - q_r\right] \quad \textbf{(7)}$$

The variables in addition to the steady-state heat balance equation are $m.C_p$, the total heat capacity of the conduction in J/m.°C.

According to Van Staden and de Kock [66], the heat balance equations by IEEE Std 738 [62] omits magnetic heating, corona heating and evaporative cooling when compared to Cigré Working Group 22.12 [67]. Magnetic heating is also included in Cigré Working Group B2.43's calculations [60].

The recommended maximum temperature limit for normal operation of AAC, AAAC, and ACSR is between 80 °C to 100 °C. This allows a 3% loss in the original tensile strength after operating for 1000 hours at high temperatures [68].

The variation between the overhead power line's resistance and the temperature is near-linear [69]:

$$T = \frac{\frac{R}{R_{Ref}} - 1}{\propto} + T_{Ref} \quad \textbf{(8)}$$

Where T and R is the respective line temperature and resistance, R_{Ref} and T_{Ref} are the respective reference line resistance at a reference temperature and $\propto$ is the thermal coefficient of the conductor.

The OHL conductor temperature is influenced by climatic conditions captured in the heat balance equations given in [67], [62] and [60]. The graph in Figure 26 is based on the data from [67] and illustrates a base current of 600 A at wind speeds of zero, 0.5 m/s and 2 m/s for step current ratings when overloaded for a thermal time response of 3 minutes, 10 minutes and 30 minutes respectively.

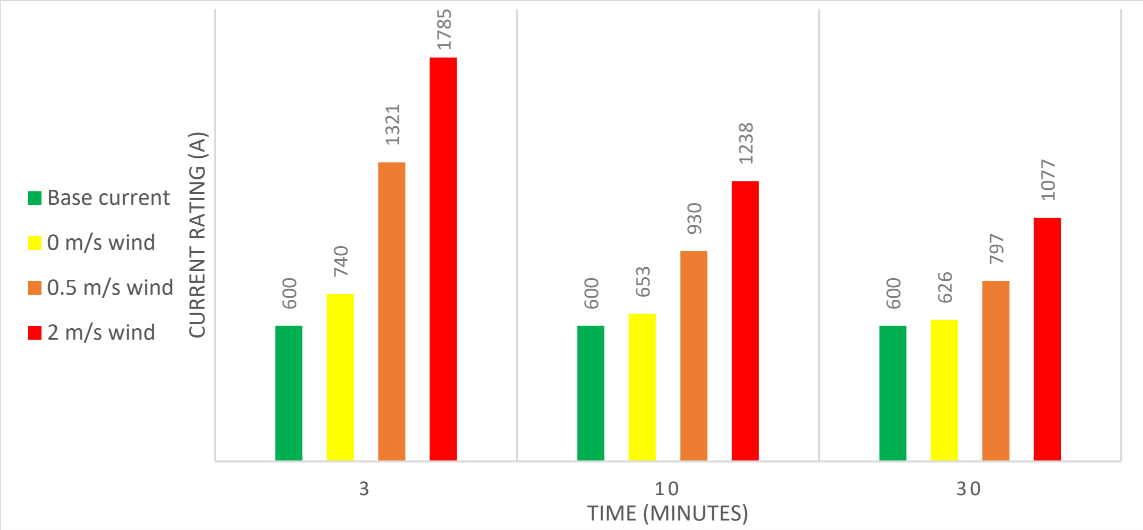


Figure 26: Thermal rating and duration for fixed wind speeds [67]

From the charts in Figure 26, a wind speed of a mere 2 m/s (7.2 km/h) has a tremendous influence on the conductor thermal response to increased current.

The main differences between overhead power lines and insulated cables fall under the categories of electrical insulation of the conductor, complexity of heat transfer, and construction methods [70].

In addition to bare overhead conductor losses, cables have dielectric losses and sheath losses. Cables are mainly subject to corona losses at terminal end equipment (cable sealing ends). Corona in cables is highly dependent on the cable insulation used.

Due to the thermal-electrical analogy of cables and diversity of materials serving conductive or insulating purposes, the thermal modelling of cables can become challenging. Various methods exist from which cable rating can be determined. These methods follow a steady-state or dynamic rating approach.

For the calculation of steady-state or dynamic ratings, the thermal cable ratings depend on a variety of factors such as:

(a) the thermal properties of the cable's surroundings (air temperature, duct filling, tunnel cooling or thermal resistivity and moisture content of the soil);

(b) the depth and method of burial;

(c) the load factor;

(d) the maximum permissible operating temperature of the cable;

(e) cooling methods (oil or gas circulation and insulation);

(f) the material types used and the method in which it is applied (strands, layers, pipes or screens);

(g) geometry (flat or trefoil, touching or spaced);

(h) single or multiple circuits;

(i) single-core or three core cables;

(j) the installation design (the type of bonding applied and transpositions).

From [71], the process for upgrading is detailed in a flowchart with the primary stages:

- Step1: the target for upgrading the situation needs to be defined;
- Step 2: existing situation needs to be assessed;
- Step 3: potential upgrade techniques need to be selected; and
- Step 4: decision-making impacts need to be evaluated.

The emergency or short-time rating of a conductor is the maximum permissible temperature or temperature rise over a period with specific boundary conditions. For maximum thermal ratings or ampacity, the thermal time constant of a cable is crucial to determine emergency or current short-term ratings. The graph from Figure 27, illustrates how step changes in current have a delayed effect on the heating and cooling of conductors.

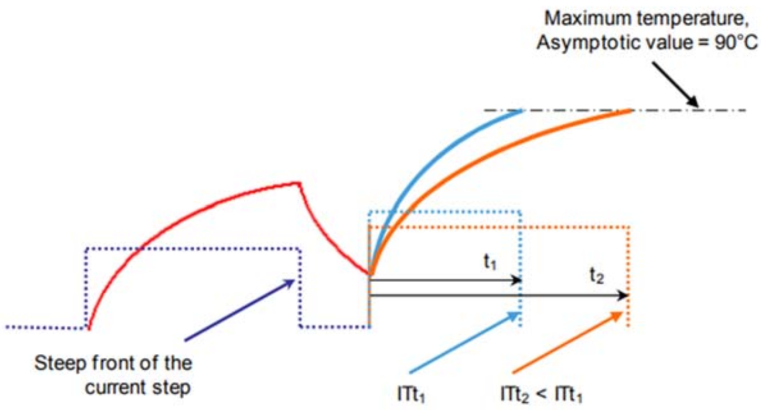


Figure 27: Cable temperature response to step changes in the current [60]

The calculation of short-term or emergency ratings are standardised in [72], the complete transient response of a cable is given by:

$$\theta_{(t)} = \theta_{c(t)} + \alpha_{(t)}\theta_{e(t)} \quad \textbf{(9)}$$

Where $\theta_{(t)}$ is the transient response over a period, $\theta_{c(t)}$ the partial temperature response over a period, $\alpha_{(t)}$ an attainment factor, and $\theta_{e(t)}$ the cable environmental temperature response.

When determining emergency ratings for conductors, the steady-state temperature limit shall not be exceeded by a scaling factor greater than two and a half. The scaling factor to determine the permissible emergency rating is calculated by applying a time-dependent load profile.

Next, the various methods of conductor thermal rating or ampacity rating are reviewed.

2.2.2.1 Deterministic method

The deterministic method typically assumes the worst-case cooling conditions for a current rating compliant with statutory regulations. For OHLs, the assumptions made based on South African conditions for ambient conditions according to [68], [73] and [50], are as follows:

For the deterministic method, the templating temperature based on the thermal rating of the line determines the allowable conductor current. The deterministic method is a conservative design practice, based on 100% load factors with allowance for emergency ratings based on transients for a given time and allowance for calculating thermal rating during fault conditions.

The graph in Figure 28 illustrates deterministic cable ratings based on assumed standard laying conditions. Cable sizes from 1200 mm^2 and larger are manufactured as Milliken sectional conductors. As the conductor cross-sectional area increases, the sheath standing voltage per kilometre increases proportionally. The 33% cross-sectional area increase from 300 mm^2 to 400 mm^2 yields approximately 12% increase in current (0.12% yield per 1 mm^2 increase). As opposed to a 25% cross-sectional area increase from 2000 mm^2 to 2500 mm^2 yielding approximately only 6% increase in current (0.012% yield per 1 mm^2 increase). The lower yield in current increase between larger diameter conductors is due to frequency-dependent effects on the cable. The highest yield in current increase is the installation of multiple cables, rather than increasing conductor diameter.

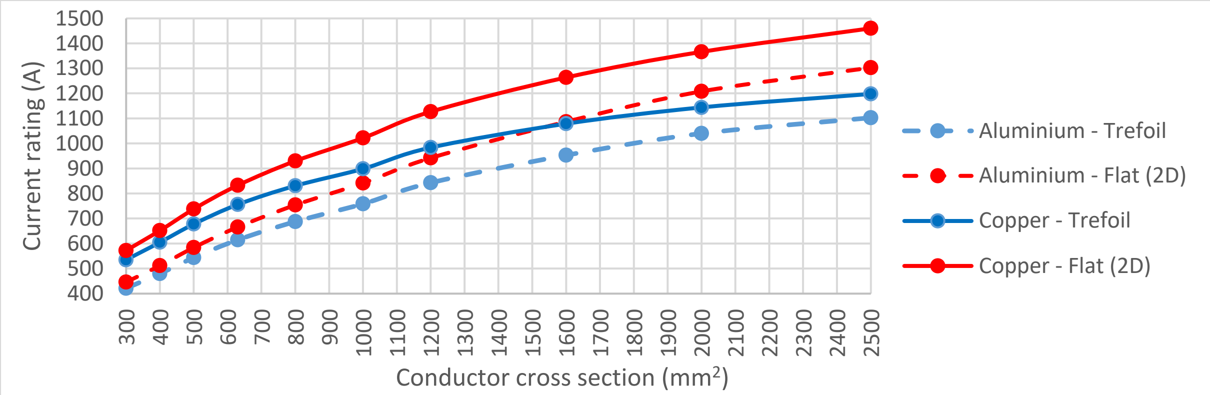


Figure 28: In-ground current rating [74]

When moving focus from cables to overhead lines, a discrepancy is noted between conductor datasheets. In overhead conductor catalogues, the current rating provided by original equipment manufacturers (OEMs) differ. It was verified with OEMs that the catalogue conductor ratings are based on deterministic ratings. Figure 29 illustrates how current ratings provided in catalogues differ. According to OEMs, the difference in ratings are because of different input parameters. When using deterministic current ratings from OEM catalogues, the input parameters used by the OEM to calculate current ratings should be evaluated to determine if the input parameters are suitable for the specific application. From Figure 29 there is a 20% difference between the highest and lowest OEM ratings.

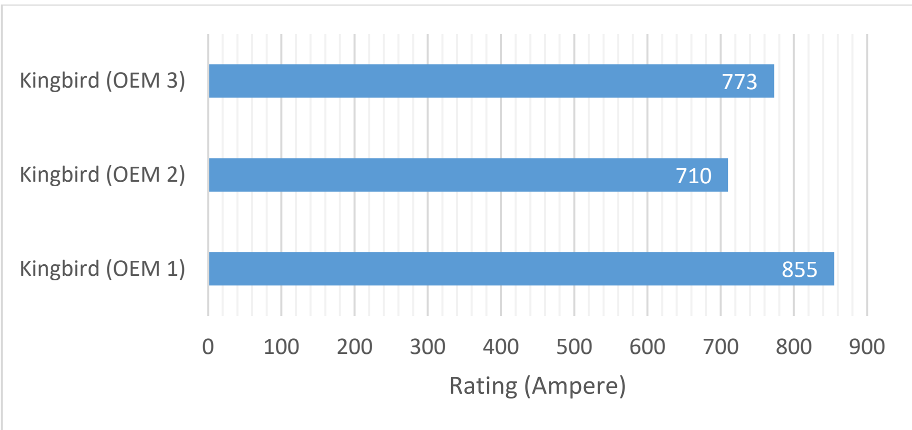


Figure 29: Different ratings for Kingbird ACSR

If the conductor ratings are calculated according to the same standard, there should be no difference in the conductor's thermal rating between manufacturers. The conductor current ratings calculated by different OEMs was not evaluated or checked for correctness as part of this study.

2.2.2.2 Probabilistic rating method for OHLs

With the probabilistic method, the risks of unsafe conditions are assessed to attempt to quantify the risks of unsafe conditions. The risk quantification is dependent on the stochastic nature of meteorological parameters. The probabilistic method is based on Cigré publication, Electra – No. 164 "*Probabilistic determination of conductor current ratings"* [75].

An Eskom directive stated that certain lines templated at 50 °C but rated at for standard current and severe ambient conditions at a temperature of 75 °C, is acceptable. These conditions were accepted due to the low probability that the line will continuously operate at rated current under severe ambient conditions such as high temperature, high solar radiation, and low wind [68].

The current ratings, load profiles and weather conditions for geographical areas shall not have a higher probability of unsafe conditions than the highest probability of unsafe conditions that already exist in the geographical area. The probability of an unsafe condition is determined by [50]:

$$P_{ACC} = P(T_C).P(I).P(Object).P(Surge).P(SI) \tag{10}$$

Where P_{ACC} is the flashover/accident probability, $P(T_C)$ the probability that a specific conductor temperature will be reached, $P(I)$ the probability of the assumed current being reached, $P(Object)$ the probability of the electrical clearance being reduced by an object, $P(Surge)$ the probability of a voltage surge, and $P(SI)$ the probability of a switching impulse transient 2.5 times per unit the system voltage.

Table 14, extracted from Cigré Working Group 22.12 report [75], compares the deterministic ratings to the probabilistic rating of Zebra ACSR:

Table 14: Deterministic vs probabilistic current rating [75]

Ratings for 428-A1/S1-54/7 Zebra ACSR							
Design Temp. °C	**Exceedance %**	**Summer rating A**		**Spring/Autumn rating A**		**Winter rating A**	
		Prev. deterministic	**Probabilistic**	**Prev. deterministic**	**Probabilistic**	**Prev. deterministic**	**Probabilistic**
65	0.1	795	826	896	910	1019	959
	3		901		994		1046
	6		930		1025		1079
	10		955		1053		1109

The percentage of exceedance, if the conductor is operated at the corresponding current continuously, is the portion of time that the conductor exceeds its design or templating temperature.

The chart from Figure 30 depicts the increase obtained in current rating for four ASCR conductor sizes by moving from a deterministic approach to a probabilistic approach:

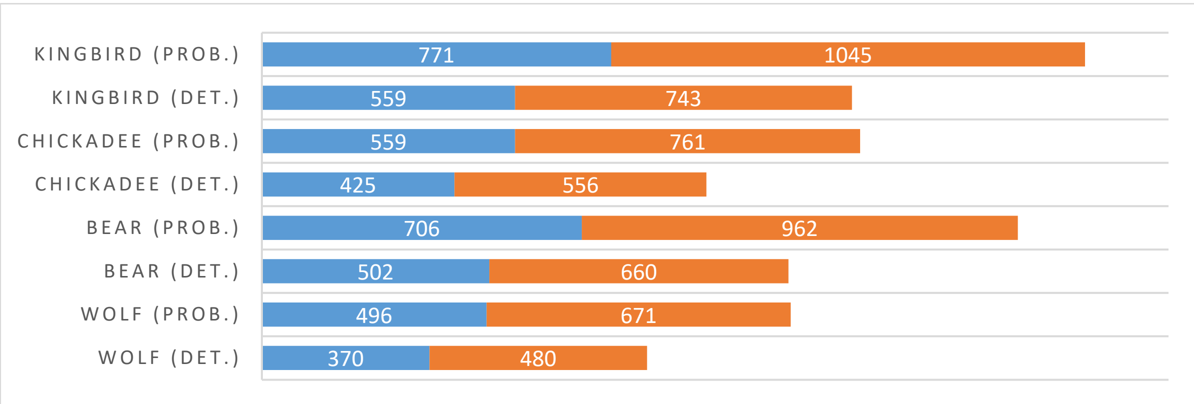


Figure 30: ACSR deterministic and probabilistic ratings [68]

For the values shown in Figure 30, the deterministic and probabilistic ratings under normal conditions are for thermal ratings at 75 °C and 70 °C respectively. The deterministic emergency rating is based on a 95 °C thermal rating, and the probabilistic emergency rating is based on a $6.00E^{-06}$ probability and serves for n-1 line configurations for emergency conditions lasting for days or weeks.

The probabilistic method allows much higher theoretical power transfer; however, a significant drawback of the probabilistic rating is the difficulty in determining parameters.

2.2.2.3 IEC and Neher-McGrath methods

The IEC 60287 and Neher-McGrath (UGC) methods are generally accepted to determine steady-state cable thermal ratings. Thermal circuit models are used to represent heat flow; for steady-state analysis, the assumption that heat-flow reached a steady-state condition is compulsory.

Significant differences between the IEC 60287 and Neher-McGrath methods in software such as “etap” are listed [76]:

- The Neher-McGrath method uses a load factor input, whereas the IEC 60287 method applies a unity load factor.
- Analytical expressions are used in IEC 60287 for cable thermal analysis for the computation of the geometric factor of three-core cable insulation; Neher-McGrath makes a reference to the paper by Simmons (1932).
- The Neher-McGrath applies thermal resistivity, power factor or loss factor, and dielectric constants. In IEC 60287, the standard defines the values used.
- Neher-McGrath has a qualitative approach to the calculation of armour magnetic losses. IEC 60287 proposes approximations.
- The cable thermal resistance can vary considerably between the two methods due to differences in insulation resistance calculations.

Other than IEC 60287:2020 SER Series for the calculation of 100% load factor ratings, IEC 60853-2:1989 and IEC 60853-3:2002 can be applied for the calculation of cyclic and emergency ratings.

One of the many distinctions between overhead power lines and underground cables is the dielectric losses in cables, overhead power lines will only have dielectric losses under specific conditions when the overhead conductor has ice loading. To calculate the dielectric losses for cables:

$$W_d = \frac{U_0^2}{R_i} = 2\pi f C U_0^2 \tan\delta \ W/m \tag{11}$$

Where W_d is the dielectric loss, U_0, the voltage between the conductor and screen or the system voltage, R_i the insulation resistance, f the system frequency, C the insulation capacitance, and $\tan\delta$ the loss factor.

In a thermal model to emulate the heat transfer from a cable, the material producing heat and the thermal resistances (R_T) are essential. The material producing heat consist of conductors, the metal sheath, the armouring, and the insulation (dielectric losses). The thermal resistances involved are those of the insulating material, bedding, and soil. Figure 31 illustrates an elementary underground cable thermal model, comprising of materials producing heat and thermal resistances.

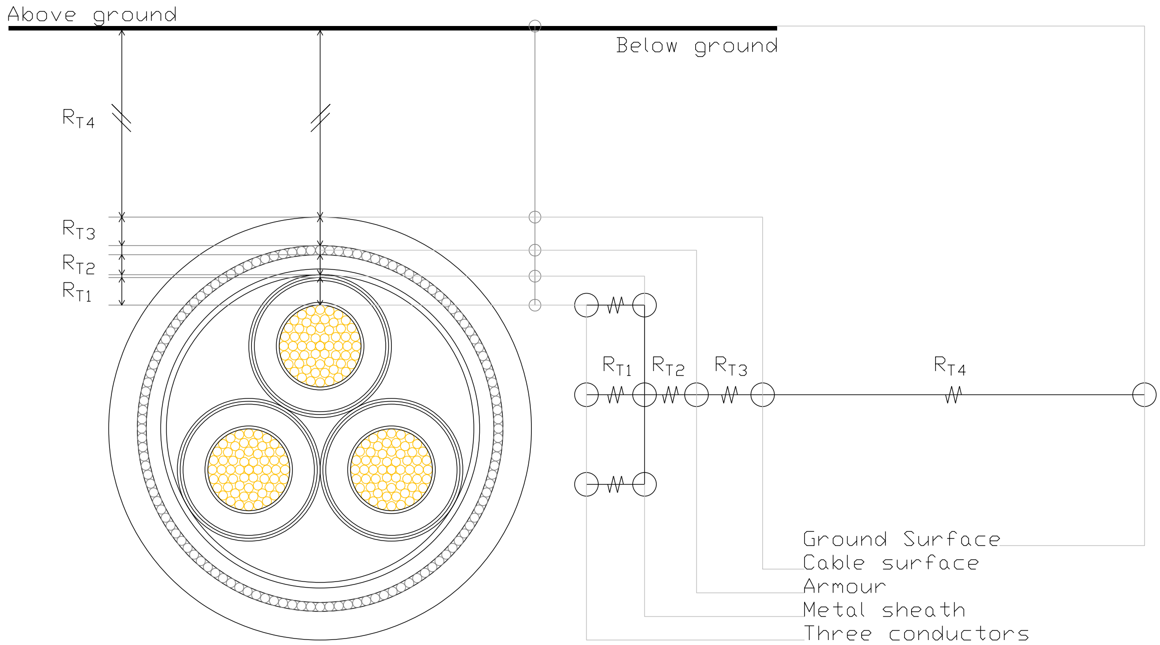


Figure 31: Elementary cable thermal model

The heat produced by the conductor (core losses) is given by I^2R_{ac}, where R_{ac} also considers the skin-effect, proximity effect, and temperature. The heat flow direction in Figure 31 is from R_{T1} in the direction of R_{T4}. The heat produced due to circulating currents emanating from all thermally interdependent conductors can be reduced through the cable bonding method. The thermal resistances are calculated by sets of equations comprising of the various thermal resistivities (ρ) of material and soil, diameters, thicknesses, and distances (i.e. the distance between the cable jacket to the top of the soil for a buried cable system). The applicable equations to calculate the ampacity for the model in Figure 31 are [77]:

$$R_{T1} = \frac{\rho_{\tau_i}}{2\pi} \ln\left(1 + \frac{2t_1}{d_c}\right) \, Km/W \tag{12}$$

$$R_{T2} = \frac{\rho_{\tau_b}}{2\pi} \ln\left(1 + \frac{2t_2}{d_s}\right) \, Km/W \tag{13}$$

$$R_{T3} = \frac{\rho_{\tau_c}}{2\pi} \ln\left(1 + \frac{2t_3}{d_a}\right) \, Km/W \tag{14}$$

$$R_{T4} = \frac{\rho_{\tau_s}}{2\pi} \ln\left(\mu + \sqrt{\mu^2 - 2}\right) \, Km/W \tag{15}$$

Where,

$$\mu = \frac{2L}{d_e} \quad \textbf{(16)}$$

$$\begin{aligned} T_c - T_o(\,^\circ C) = {} & \left(I^2 R_{ac} + \tfrac{1}{2} W_d\right) R_{T1} \\ & + [I^2 R_{ac}(1 + \lambda_1) + W_d] \cdot n R_{T2} \\ & + [I^2 R_{ac}(1 + \lambda_1 + \lambda_2) + W_d] \cdot n(R_{T3} + R_{T4}) \end{aligned} \quad \textbf{(17)}$$

From (17):

$$I = \left(\frac{T_c - T_o - W_d \left[\frac{1}{2} R_{T1} + n \cdot (R_{T2} + R_{T3} + R_{T4})\right]}{R_{ac} R_{T1} + n R_{ac}(1 + \lambda_1) R_{T2} + n R_{ac}(1 + \lambda_1 + \lambda_2)(R_{T3} + R_{T4})} \right)^{\frac{1}{2}} \quad \textbf{(18)}$$

Where,

R_{T1}, R_{T2}, R_{T3}, *and* R_{T4} *are the thermal resistance of the insulation, bedding, covering, and soil, respectively.*

ρ_{τ_i}, ρ_{τ_b}, ρ_{τ_c}, *and* ρ_{τ_s} *are the respective thermal resistivities (Kelvin metre per Watt) of the cable insulation, bedding, covering and the surrounding soil.*

The following diameters are in mm, the conductor diameter d_c*, the external diameter of the sheath* d_s*, the external diameter of the armour* d_a*, and the external diameter of the cable* d_e*.*

L *is the distance from the cable axis-to-ground surface (mm).*

t_1, t_2, *and* t_3, *are the respective thicknesses (mm) of the insulation (conductor to sheath), bedding, and the covering.*

T_c *is the conductor temperature in* $^\circ C$, *and* T_o *the soil temperature in* $^\circ C$.

λ_1 *is the ration of losses in the metal sheath to the total losses in all conductors of that cable.*

λ_2 *is the ration of losses in the armour to the total losses in all conductors of that cable.*

The number of conductors in one cable is represented by n.

The formulas in this paragraph are for static loading according to IEC 60287, for complex loading IEC 60853-2 and IEC 60853-3 apply. The formulas are used in the case studies in Chapter 3 to determine ampacity ratings for buried cables.

2.2.2.4 Thermo-electric equivalent method

Thermoelectric Equivalent (TEE) Method of determining cable rating is based on equivalent thermal circuitry by replacing electrical resistance, capacitance and current source by thermal resistance, capacitance and heat source respectively [78]. With the TEE analysis method, a thermal model and thermal parameters are used to determine cable ratings.

2.2.2.5 Finite element method and analysis (OHL and UGC)

The finite element method uses equations and algorithms for problems in a bounded 2D or 3D space by breaking down complex shapes into sub-geometries to form a nested mesh.

Finite element models can be used to accurately simulate the thermal field of conductors [79], which consider the primary sources of heat gain and heat loss influencing the radial temperature distributions of the conductor.

Figure 32 illustrates the radial temperature field of a steady-state ACSR conductor. For the specific conditions a finite element model determined the maximum temperature difference of 4 K between surface strands and the core [80].

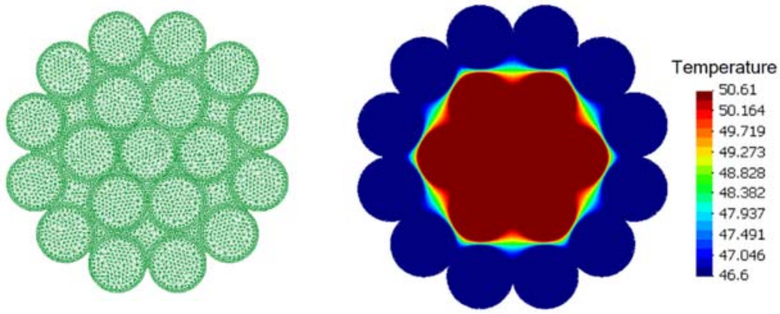


Figure 32: FEM model with a resulting radial temperature field [79]

IEC TR 62095:2003 "Electric cables - Calculations for current ratings - Finite element method" provides guidelines for the calculation of a cable's current ratings using the finite element method (FEM) through partial differential equations emulating the heat transfer of cables.

The FEM analysis implemented to determine cable rating is based on heat conduction equations together with boundary condition equations. Complex input data such as non-steady-state load profile, fluctuating meteorological data, complex geometries and complex cable assemblies require a multifaceted tool such as the FEM analysis for three-dimensional heat flow.

The accuracy of a FEM model depends on the input parameters such as the size of the bounded space, number of sub-space (grid size of the mesh created), boundary conditions, representation of losses, and variables such as time steps and load cycles.

2.2.2.6 Distributed temperature sensing and real-time or dynamic thermal monitoring systems (OHL and UGC)

Real-time or dynamic monitoring systems monitor actual conductor temperatures in real-time and considerably increases the level of confidence that safe clearance is maintained.

Measured conductor temperature corresponds with conductor temperature as calculated by using the Cigré and IEEE methods [63]. Dynamic line rating can unlock additional capacity in real-time. A forecasting engine can be used to identify possible high-risk scenarios before an event occurs.

Distribution temperature sensing (DTS) can be applied to both overhead power lines as well as cables, creating the opportunity to apply dynamic feeder rating systems. With the proper equipment, the conductor temperature can be monitored on-line, and if sensing equipment such as fibre optical cables is used for the entire longitudinal length of the feeder, the temperature at any given point along the feeder can be determined. If the monitoring system is on-line, the theoretical uprating of feeders is replaced by a management function where feeders are monitored to check the maximum operating temperature without needing inputs such as load profiles, load growth estimations and meteorological data.

Figure 33 illustrates the longitudinal temperature monitoring of a 110 kV cable with a 90 A winter load (colder above ground) and shows how the installation conditions affect the cables operating temperature [81].

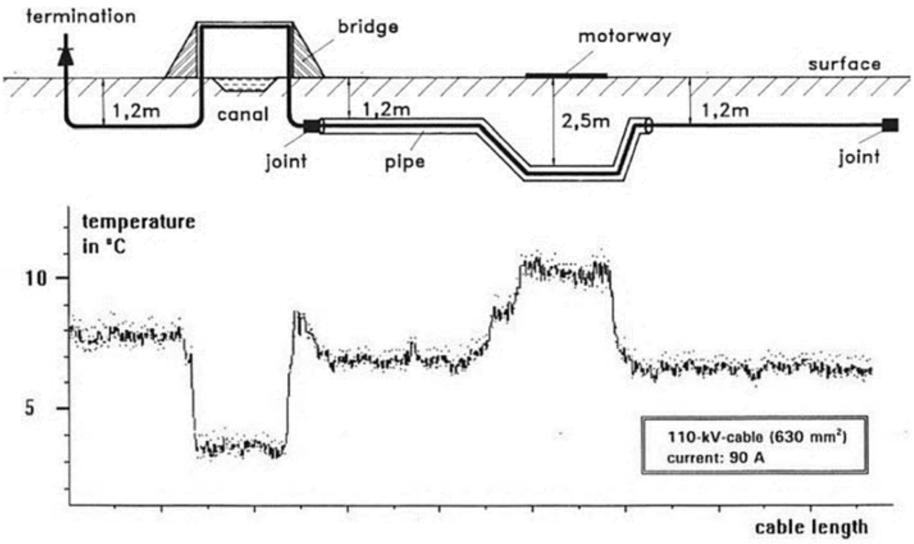


Figure 33: Distributed Temperature Sensing trace of a 110 kV cable [81]

The section of cable in Figure 33 where the measured winter temperature is the highest, is the limiting condition of the cable thermal rating. The cable temperature more than doubles from the canal crossing to the road crossing. The higher temperature in the motorway crossing is due to the increased conductor installation depth resulting in a higher thermal resistance for heat dissipation. During the summer-time the critical thermal hot-spot may be at another location along the cable installation corridor.

Due to the difficulty in adding longitudinal monitoring to existing buried cables, DTS generally forms part of the cable installation, or as a minimum allowance, is made to add a DTS system during the initial cable installation. DTS can be used for on-line dynamic rating systems or RTRR systems. The drive for DTS of underground cables comes from the following reasons [81]:

- The possibility to increase or optimise power transfer through a cable feeder or cable corridor without the high cost of replacing cables;

- The functionality to identify hot-spots along a route;
- To determining thermal limits where multiple heat sources cross;
- Becoming non-reliant on soil conditions, which are not always known and changes with meteorological conditions;
- Insufficient information about the original design thermal rating or limit;
- Verification of thermal rating models; and
- Comparison of design ratings and actual as-installed ratings.

For RTTR and dynamic temperature, sensing a feeder cable will require a DTS system and optical fibre cable. Fibres can be included within the cable using FIMT or within a separate duct strategically installed as close as possible to the expected hottest spot of the feeder cable formation. The feeder cable will determine the type of fibre to be used, multi-mode fibres are generally acceptable, and single-mode fibres are used for long-distance cables.

The use of fibres with feeder cables has the added advantage, especially in South African conditions, to monitor vibration. The vibration monitoring is interpreted to determine tampering with cables and prevent theft before cables are damaged.

Real-time thermal rating (RTTR) systems can be used to determine the cable performance for specific loading conditions and maximum utilisation of the feeders within an electrical grid by pro-actively managing load flow. For cables, the RTTR minimum real-time input data required is the longitudinal cable temperature employing DTS, current transfer of the cable in real-time, cable parameters (electrical, geometrical and thermal) and cable installation information (crossings, other services, backfill thermal resistivity) [81].

2.2.3 Conductors

In overhead power lines with non-homogenous conductor strands, the higher strength material strands are commonly used as mechanical support. The strands where the material has higher conductivity is applied around the mechanical supporting strands to form a hybridised conductor and create the conductor characteristics required. Excellent mechanical support increases the strength-weight ratio of the conductor. Overhead conductors can be made of steel, aluminium, aluminium-alloy, aluminium-clad, annealed aluminium, resin matrix carbon fibre (composite) core and aluminium matrix (composite) core.

2.2.3.1 General aspects of OHL conductor

This section gives an overview of the general aspects associated with overhead conductors. The different types of stranding material are listed, together with the different types of stranding methods. An overview is given of high temperature conductors and the associated benefits. Conductor with lower sag and higher thermal ratings is a method of increasing power transfer capacity.

There are numerous conductor technologies available that can be applied to overhead power lines. The possibilities become endless when different alternatives and combinations are investigated. The main components of a power line are the conductor, earth wire, insulators, towers or poles and foundations. The selected conductor affects the power line towers or poles, insulators, foundation, and energy transfer capability.

An in-depth study focussing on conductors for uprating of OHLs is published by [82]. Although not limited to the items listed, the typical conductors used for OHLs are:

Table 15: Common overhead conductor types

Conductor	Description
ACSR	Aluminium Conductor Steel Reinforced
AAAC	All Aluminium Alloy Conductor
ACAR	Aluminium Conductor Alloy Reinforced
ACCC	Aluminium Conductor Composite Core (composite reinforced core)
ACCR	Aluminium Conductor Composite Reinforced (aluminium oxide fibre reinforced metal matrix core)
ACSS	Aluminium Conductor Steel Supported (high strength steel core)
STACIR	Super Thermal-resistant Aluminium-alloy Conductor, Invar-Reinforced (Iron-Nickel alloy core)
G(Z)TACSR	Gap Type ACSR (high strength steel core)

ACSS, ACCR and ACCC are all high temperature (annealed aluminium) conductors with exceptional mechanical properties allowing operation at a much higher temperature for standard or emergency conditions and lower conductor sag, resulting in exciting engineering possibilities with the possibility of decreasing the number of supporting structures. If the conductor has less elongation at higher temperatures, the ground clearance and conductor position at high conductor temperatures, and during blow-out conditions, will be much less severe resulting in decreasing servitude requirements and shorter support structures for average span lengths.

For a reduction in diameter or larger conductive cross-sectional areas, a trapezoidal wrap (TW) configuration is common in ACCC conductors but is not unique to any conductor and can also be used with conventional ACSR conductors.

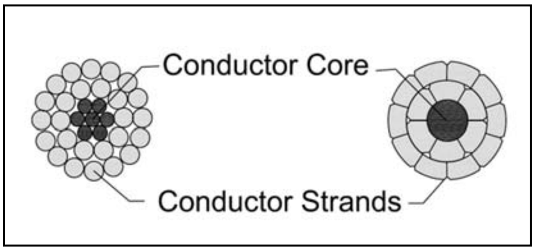


Figure 34: Concentric and trapezoidal wrapped overhead conductor

The TW conductor has advantages such as increased power transfer capabilities for the same outer diameter of a stranded conductor, reduced vibration characteristics and a smoother surface roughness factor. The smoother surface positively influences corona (reduced corona); however, for a decreased conductor diameter, the surface voltage gradient will increase corona. Disadvantages include a steady cost increase due to a more complicated manufacturing process and more aluminium, slightly increased conductor weight and possibly also some increase in ambient conductor temperature, due to less natural convection cooling. Conductors with higher thermal capabilities than conventional ACSR, developed alternative cores to allow for lower expansion with an increase in conductor temperatures. Examples of such conductors with the highest thermal ratings are ACCS, STACIR, ACSS and ACCC with metal matrix and carbon or metal composite cores.

A conductor's primary objective is to transfer electrical power. However, the mechanical characteristics of conductors have a significant role in overhead conductors. The primary physical, mechanical and electrical properties of a conductor are listed in Table 16.

Table 16: Primary OHL conductor properties

- Diameters and areas	- Modulus of elasticity (N/mm2)
- Strand ratio	- Core heat capacity
- Resistance at given temperatures and frequencies (Ohm/km)	- Stress-strain – polynomial coefficients (% stresses in MPa)
- Mechanical and thermal properties	- Material areas (mm^2)
- Ultimate Tensile Strength (UTS-kN)	- Outer strand heat capacity
- Mass and weight (kg/km and N/m respectively)	- Thermal expansion coefficient (mm/°C)
- Creep – polynomial coefficient (% stresses in MPa)	

The types of aluminium outer stranding layers used for overhead conductors are listed in Table 17.

Table 17: Aluminium types for HTLS conductors [83]

Types of Aluminium	Conductivity (%IACS)	Minimum Tensile Strength (MPa)	Max. Operating Temp. (°C)
Hard Drawn (1350-H19)	61,2	159-200	80-90
Thermal Resistant (TAI)	60	159-176	150
Super Thermal Resistant (ZTAI)	60	159-176	210
Fully Annealed (1350-HO)	63	59-97	200-250

The various core properties for the most widely used HTLS conductors are listed in Table 18.

Table 18: HTLS Conductor typical core properties [83]

Types of Core	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Thermal Expansion (x 10^{-6}/°C)
Galv. *Steel			
HS	1230-1320	207	11.5
EHS	1725-1825	207	11.5
UHS	1725-1965	207	11.5
A1, Clad Steel (ACS)			
20EHSA	1515-1620	162	13.0
14EHSA	1725-1825	174	11.8
Galvanised Invar Steel	1030-1080	162	2.8-3.6
ACCC (Polymer core)	c.2200	117	1.6
ACCR (Metal Matrix)	c.1300	216	6.3
* Alternatively, Zinc-5% Aluminium-Mischmetal Alloy (e.g. Galfan)			

Table 18 shows that ACCC has superior tensile strength as well as lower thermal expansion. From a power loss perspective, the ACCC core holds the third advantage with the core not conducting any current: all current is distributed in the outer aluminium layers of the conductor. The materials used for higher mechanical strength in core strands have higher resistances, resulting in higher losses. With a non-conductive core, ACCC does not sacrifice losses for mechanical strength.

Technological advances saw the birth of composite conductors with alternative materials to steel being used to increase conductor ampacity and improve mechanical characteristics. Alternatives to AAAC and ACSR such as ACSS, Gap type, and Invar, were introduced in the 1970s and 1980s. The early 2000s saw the introduction of hybrid type composite conductors such as ACCR and ACCC.

The graph in Figure 35 compares the sagging based on Drake size conductors and a 70 m span [84].

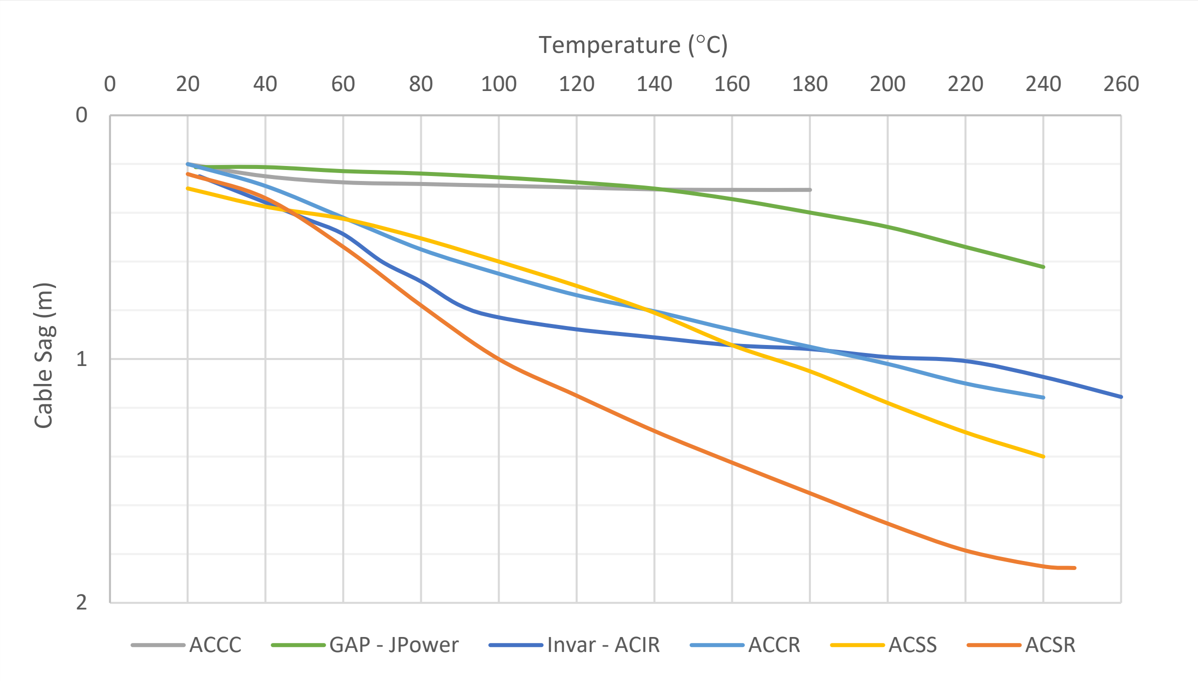


Figure 35: Temperature vs sag for various conductors [84]

For the reconductoring of an ACSR line, the sag limit or templating temperature would typically be set to 100 °C when using ACCC (max. operating temperature of 180 °C).

The ACCR composite conductors, which replace steel core strands with ceramic fibre reinforced aluminium strands as offered to the market by 3M Electrical Products Division, claim the following features: high-temperature strands, advanced composite material core, hard aluminium, low thermal expansion, high strength-to-weight ratio, and corrosion resistance.

Composite conductors with a lower resistance reduces the line losses. ACCC is another market-leading composite conductor, a single hybrid carbon and glass fibre core embedded in a high-temperature thermoset resin matrix offers the following features [84]:

- lighter core allows 28% more aluminium without additional weight;
- double the strength of steel and 60% - 70% lighter;
- line losses reduce by 30% to 40% compared to ACSR conductors with the same diameter and weight;
- the hybrid carbon composite core is more durable and lighter than steel;
- higher strength;

- self-dampening and superior fatigue resistance allows increased span lengths between fewer and shorter structures, and

- increases reliability options with operation at high temperatures for emergency conditions.

An in-depth study can determine the optimised conductor(s) size and geometric configuration to be selected for a specific purpose. However, at subtransmission, the conductor selection available to apply to projects is limited; this is mainly due to the operational difficulties with keeping stock of spare material. Therefore, there is a limited range of conductors to select from, even for large utilities. Conductor optimisation is primarily only reviewed in-depth at transmission voltage levels or for long lines.

The mechanical properties of overhead conductors to be considered are conductor elongations, conductor catenary, conductor sag and tension, and conductor vibration.

Aeolian vibration and galloping are two types of mechanical oscillations that guarantees to have a severely damaging effect on the performance of overhead lines if not catered for during the line design. Excess vibration can cause damage to vibration dampers, stress fractures to the conductor, arcing between phases or between phases and earth and increase inline resistance if aluminium strands are broken but the steel reinforcing remains intact. Subspan oscillations also occur but are more applicable to bundled conductors.

2.2.3.2 Conductor elongation

Conductors are subject to three stages of strain under a constant load at a constant temperature. Figure 36 shows the typical conductor strain over time and the resulting conductor creep.

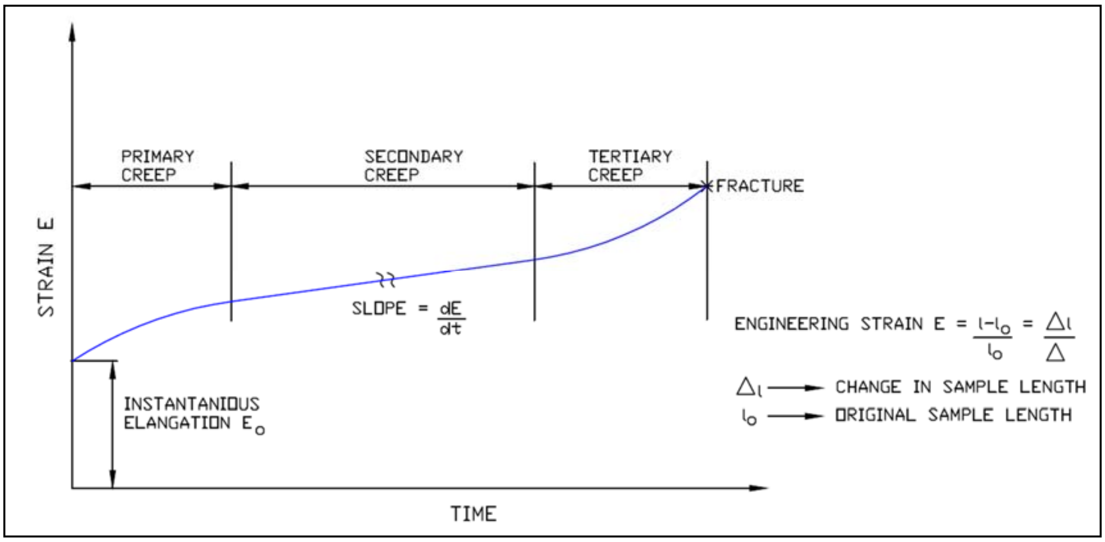


Figure 36: Conductor creep [1]

When a conductor is strung and tensioned, as with Figure 36's idealised strain curve, there are three stages of creep, namely primary creep, secondary creep, and tertiary creep, as defined under terms and definitions. Creep is generally proportional to time and slows down over the lifetime of the conductor as fewer molecular changes caused by a combination of tension, time and temperature occur in the conductor. PLS-CADD and the conductor stress-strain polynomials provided by the conductor manufacturer were used to compile Figure 37, which graphs the tension and elongation for Zebra ACSR under the initial conductor conditions and after creep has set in.

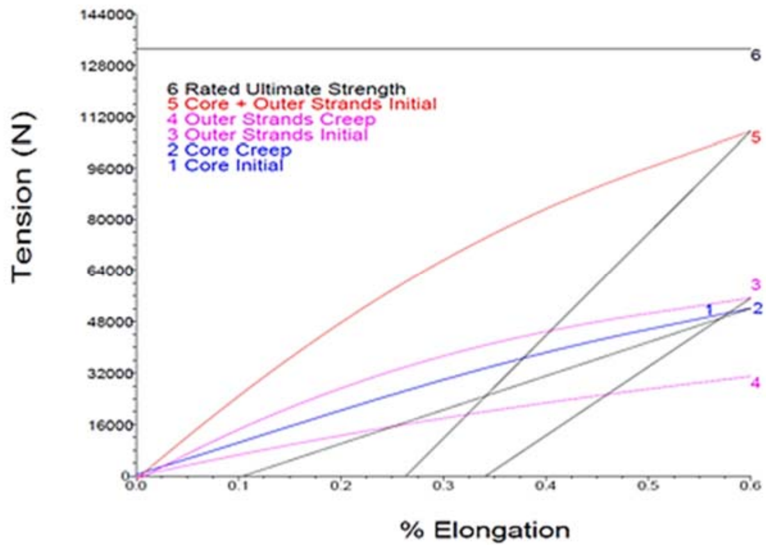


Figure 37: Stress vs elongation of a typical ACSR conductor

For conditions one, two, three, and five in Figure 37 the conductor strands elongate when subjected to a certain extent of tension. For condition four, which shows the outer conductor strands after creep, there is no elongation due to the transfer of tension to the conductor's core strands as creep conditions or tensions are applied.

2.2.3.3 Conductor catenary

Different methods are available to graphically represent the natural curvature that will be formed by a conductor due to suspension of the conductor between fixed points. The curved shape that is formed by a conductor spanning between two poles or towers is defined as the conductor or line catenary. With the flexibility and uniform weight of overhead conductor due to its cylindrical shape, the equation for representing the graphical curvature or catenary of the conductor can be expressed in exponential, hyperbolic, and expanded series forms.

For ease of use, a catenary constant or C value (in meters) is used to express the ratio between the horizontal tension applied to the conductor and the weight of the conductor. Specific C values are developed according to local and international codes of practice where the catenary constants relate to vibration for various scenarios. In South Africa, SANS101280-1 of 2013 allows for a maximum horizontal tension of 25% of the conductors UTS (ultimate tensile strength) to be applied when tensioning overhead lines. Depending on the type of material and rated strength of the mechanical load-bearing portions of the material, the C–value will differ for various types of conductors.

$$C = \frac{H_c}{g_c} \text{ (19)} \qquad \textbf{(20)}$$

Where C is the catenary constant in m, H_c the maximum allowable horizontal tension in the conductor (kg), and g_c the conductor weight per meter (kg/m).

2.2.3.4 Conductor sag and tension

Conductor tension limits are determined for certain limiting conditions such as the maximum loading on the conductor due to extreme weather conditions such as wind or ice or vibration limits for damped or un-damped conductors. Following SANS10280-1 of 2013 conductor tension limits are based on:

a The maximum initial tension is limited to 70% UTS

b Wind 1050 Pa at 15 °C using the detailed method

c Ice load with 10 mm radial ice thickness at -5 °C

d Catenary constant for damped / undamped

The -5 °C case only becomes the limiting factor for short spans. The catenary constant is often reduced from 1800 to 1700 to prevent high tensions and vibration problems for short spans.

The sag of the shield wire is limited to 90% of the conductor at 15 °C (as a rule of thumb) to ensure better lightning coverage mid-span than at the structure.

Figure 38 displays the relationship between conductor tension, length, and temperature. It can be observed that for a conductor under tension, the sag is significantly increased with an increase in temperature. All conductors under tension will elongate and increase in length over the conductor lifetime until final creep is reached. The catenary constant is selected for everyday temperatures (EDT) based on the maximum allowable horizontal tension and vibration parameters, and changes according to horizontal tension variations. “Everyday” refers to still air conditions at a reference temperature of 15 °C.

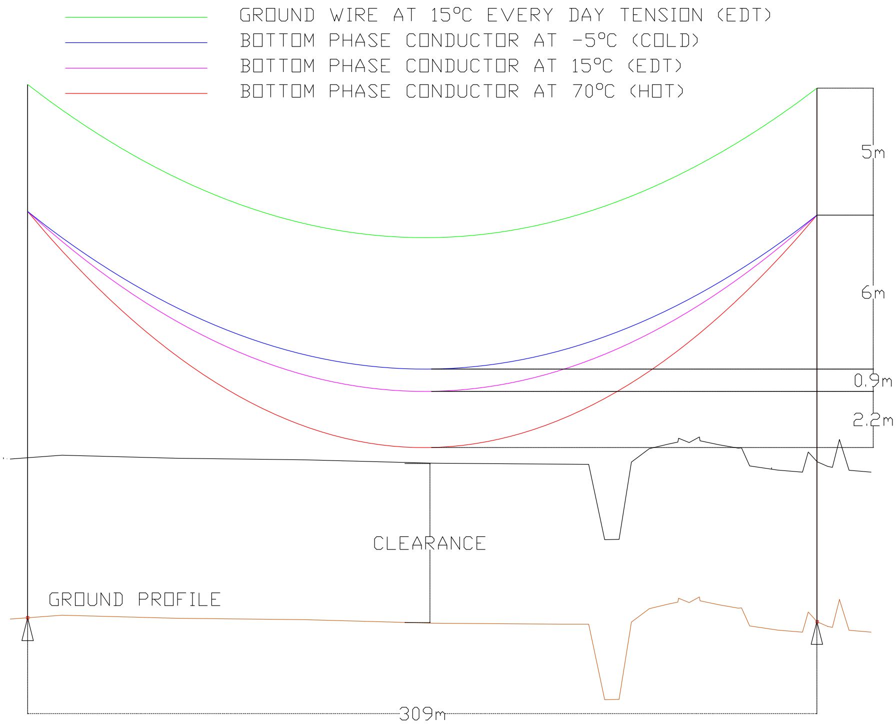


Figure 38: Sag and tension relationship for Chickadee ACSR

For the Chickadee ACSR phase conductor in Figure 38, a catenary constant of 1700 m was used (at EDT with a horizontal tension of 10 709 N), and the earth wire was a 7/3.35 steel wire at a catenary constant of 2000 m (EDT and 9 519 N horizontal tension).

Conductor sag is given by [50]:

$$s = \frac{L^2}{8C} \tag{21}$$

Where: s is vertical sag (m), and L is span length (m).

The following figure illustrates how 300 mm conductor elongation results in 6 m sag and a further 400 mm conductor elongation results in another 3.1 m sag at given conductor tensions.

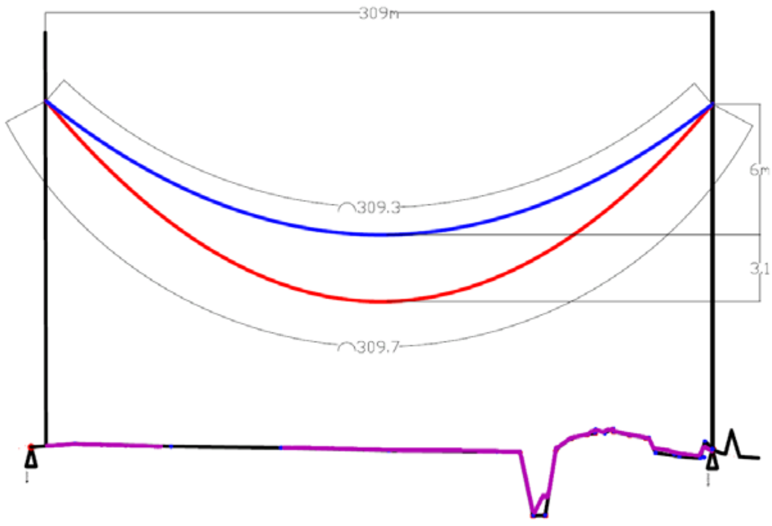


Figure 39: Sag and elongation comparison for Chickadee ACSR

The actual conductor length D is calculated as follows (parabola curve) [50]:

$$D = L + \frac{8s^2}{3L} \tag{22}$$

Where L is span length (m), S is the maximum vertical sag (m), and D is the actual conductor length (m).

Conductor slack, which is the difference between actual conductor length and span length, is:

$$slack = \frac{L^3}{24C^2} \tag{23}$$

2.2.3.5 Conductor basics, stranding, geometry and parameters

To transfer electrical energy from one location to another, the conductive mediums used are overhead power lines or underground cables, both use stranded conductors. Furthermore, within substations, switching stations, transition yards and transfer yards, hollow tubular section or solid cylindrical busbars are used.

The geometry and composition of conductors dramatically impact on the characteristics of the feeder. Therefore, the emphasis is placed on the factors that characterise the feeder performance in terms of both thermal rating and load flow analysis modelling.

The materials generally used for power transfer is aluminium, copper, steel, alloys, and composite materials to achieve the required conductor characteristics. Conductors are stranded to simplify the manufacturing process to create larger conductors by adding consecutive layers of strands. Steel wire strands mainly serve to improve the mechanical characteristics of conductors. Although copper offers better conductivity than aluminium, the cost of copper is higher than aluminium and copper poses a larger theft risk.

Overhead power lines combine the use of materials, such as aluminium and steel, to achieve characteristics such as lower sagging, longer spans, smaller cross-sections, lighter weight or higher permissible operating temperatures to achieve a higher thermal rating during normal and emergency conditions.

For cables, a homogenous conductive material type, such as either copper or aluminium, is used as the conductor in cable designs. In cable designs, the insulating material, such as XLPE, oil, oil-impregnated paper and gas, around the conductor, is a fundamental factor associated with the cable's thermal capacity and varies between designs. The insulation material's heat conduction, convection and radiation ability from the conductor to the surrounding environment determines the conductor's thermal rating. Various types of polymers, screens and armouring are used in cable, designed to achieve cable characteristics, as required.

For both overhead power lines and underground cables, the stranding and packing of layers significantly affect the conductor design and the intended design characteristics.

2.2.3.6 Regular and non-regular conductor stranding

Regular conductors, as commonly referred to, are conductors of the same strand diameters irrespective of the number of strands. Regular conductors take on a concentric form, and the maximum quantity of strands per layer remains static, irrespective of the size of the strand [85]. The following formula is deduced to calculate the number of wires or strands in a regular concentric conductor:

$$n = 1 + 3N(N + 1) \tag{24}$$

Where n is the total number of wires or strands, and N is the number of layers around the centre strand.

The cumulative strands of regular conductors with one to four layers will always be 7, 19, 37, and 61 strands.

Figure 40 illustrates the stranding relationship for regular concentric conductors:

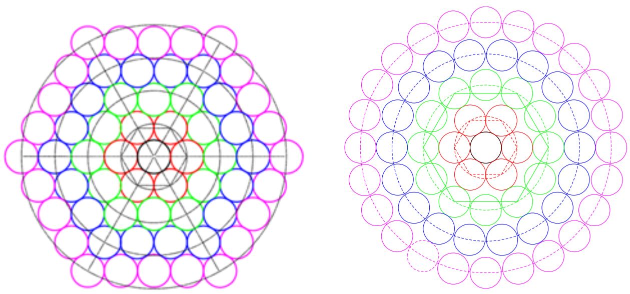


Figure 40: Five-layer hexagonal vs circular packing of strands

Due to spiralling and the changes in lay directions between each layer, the stranding geometry will take on the more circular shape.

Generally, stranding of each layer is twisted in opposite directions, i.e. the first layer clockwise, the second layer anti-clockwise, and continues alternating fashion. The manufacturer's specification determines the strand spiralling and lay lengths.

Figure 41 and Figure 42 illustrates the common aluminium to steel compositions for regular and non-regular ACSR conductors.

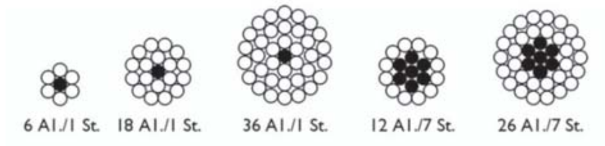


Figure 41: Regular ACSR conductor (7, 19 & 37 strands) [50]

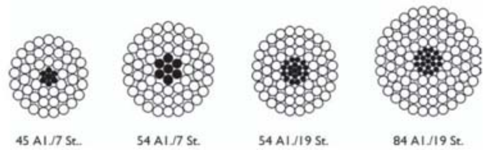


Figure 42: Non-regular ACSR conductor [50]

2.2.3.7 Conductor spiralling

Due to spiralling, the actual length of the strands in a conductor is longer than the lay of the conductor as depicted in Figure 43 [86].

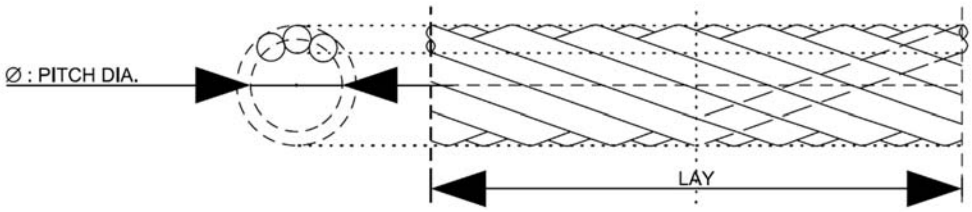


Figure 43: Spiralling of conductors [86]

The length of a single wire strand is calculated as follows:

$$l_{iw} = l_i\sqrt{1+\left(\frac{\pi D_i}{\lambda}\right)^2} \quad \textbf{(25)}$$

Where l_{iw} is the length of a single wire, l_i the length of straight wire, D_i the mean diameter of a layer and λ the lay length – all units in m.

The lay direction generally alternates between layers for increased mechanical stability and to hold strands together. Conductor spiralling causes a slightly higher conductor resistance due to the strand spiralling distance being longer than the lay distance. The resistance is determined by the strand resistivity per meter. Stranded conductors are more comfortable to manufacture than solid conductors but result in a higher total dc resistance on account of spiralling of the outer layers [34].

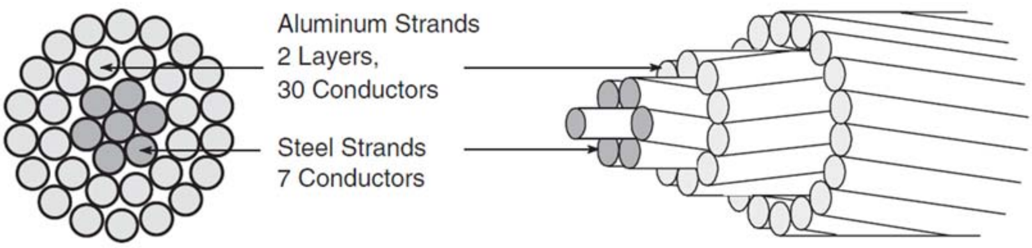


Figure 44: ACSR depicting lay directions for each layer [34]

In single-core segmental (Milliken) conductor cables, the segments are spiralled within the cable to reduce the proximity effect by preventing the same wires from always being opposite each other between cores or circuits. Each strand changes its path between the surface and centre of the conductor in its segment to reduce eddy currents, however, although spiralling assist with reducing eddy currents, the strands' length and subsequent resistances are increased.

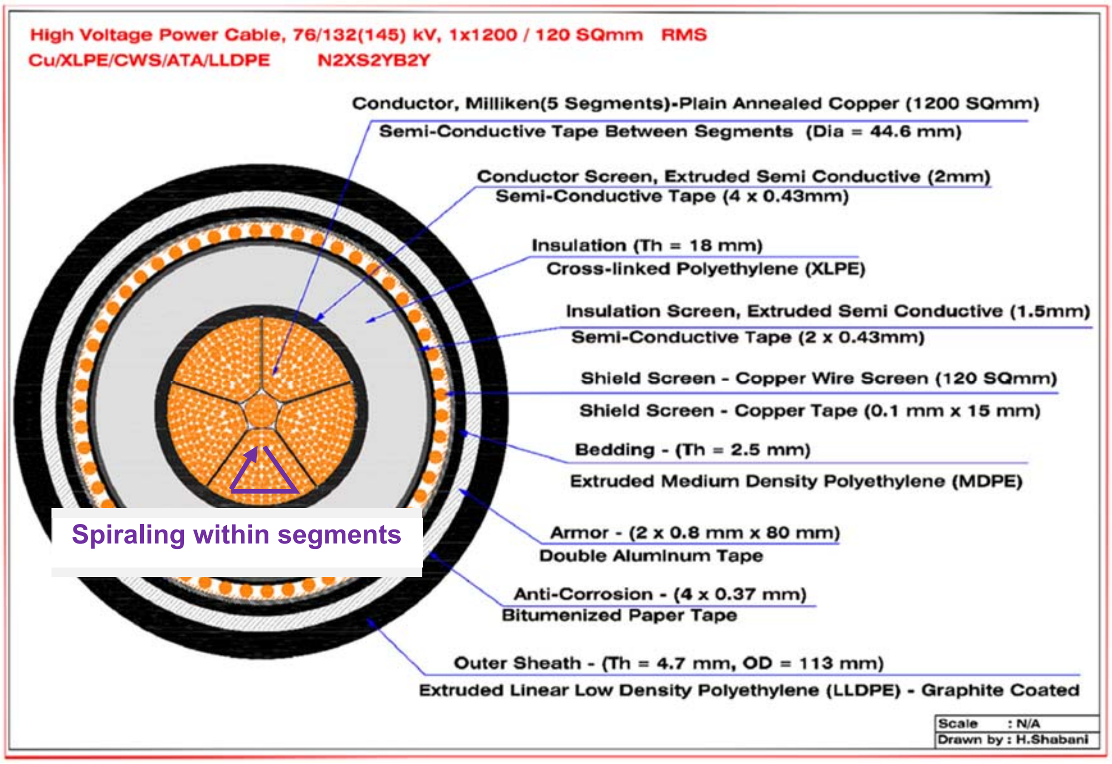


Figure 45: The construction of a large diameter (Milliken) single-core cable [87]

2.2.3.8 Frequency dependency

As frequency increases from direct current to the operating frequency of an alternating current system (50 Hz in South Africa), the alternation of current increases, and with the higher frequency the prominence of the skin effect increases [86]. A higher frequency results in increased hysteresis, eddy currents, skin effect and the proximity effect, which all contribute to conductor losses. Unless the change in current is zero in every filament or throughout the cross-sectional area of a conductor, the AC resistance to DC resistance ratio will always be higher than one, i.e. $R_{AC} > R_{DC}$ [88].

For AC, as the frequency increases the "skin effect" becomes prominent, the current density in round conductors shifts to the outer rim or surface of the conductor.

Conductor properties studied over decades conclude that, especially for single layer conductors, the AC versus DC properties differs significantly enough that the skin effect does not allow neglecting of losses in the steel [89].

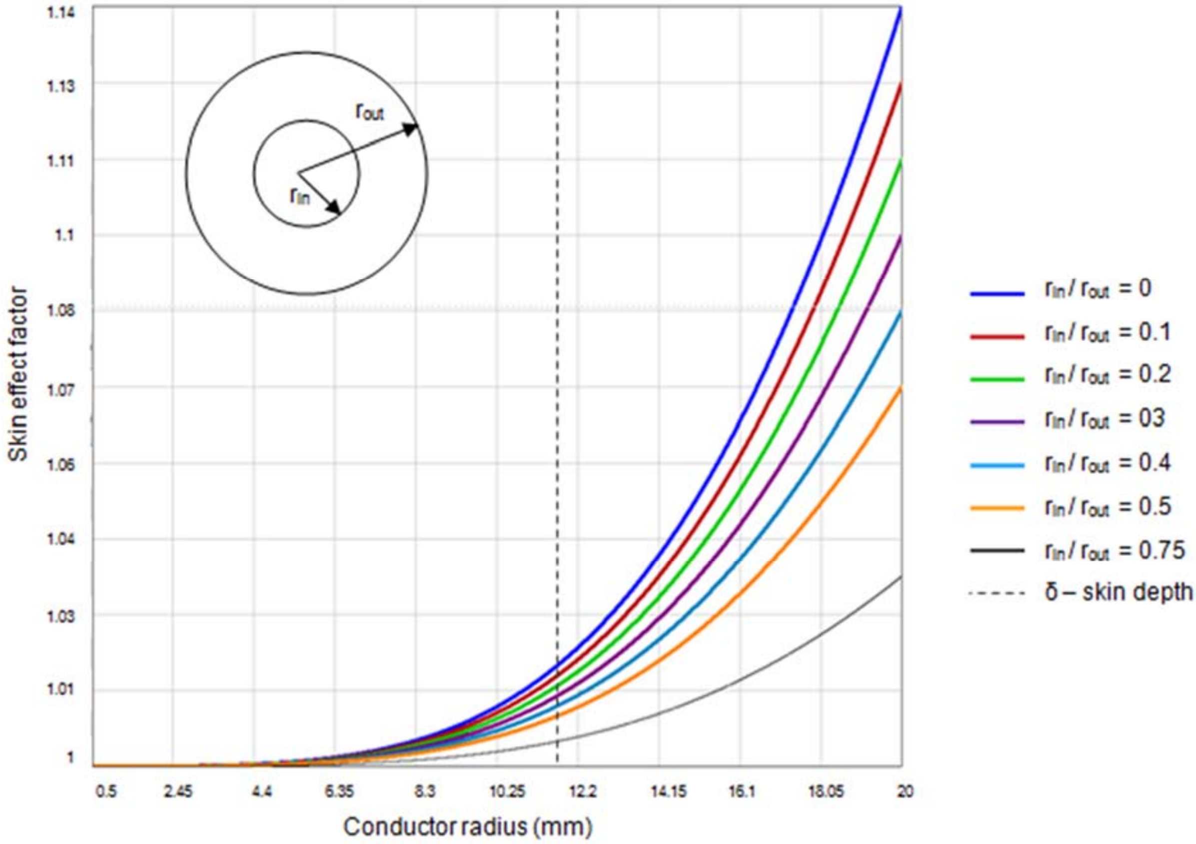


Figure 46: Skin effect factor as a function of the outer conductor radius [60]

Based on data from the EMTP Theory Book [90], the following derived graphs illustrate the increase in resistance and decrease in internal inductance due to the skin effect of an ACSR conductor. The dc resistance of “Orange” ACSR is approximately 0.0641 Ω/km:

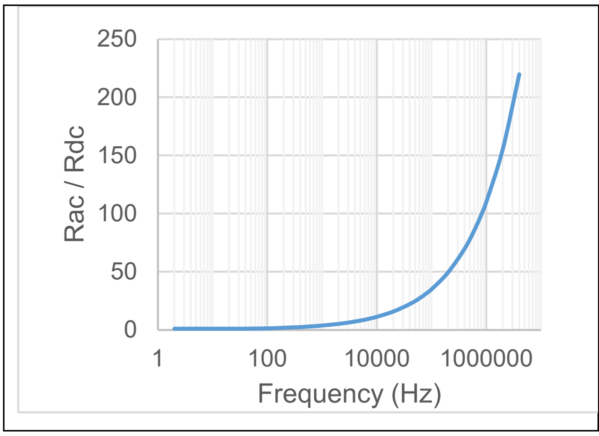


Figure 47: AC | DC Resistance ratio increase with a frequency sweep

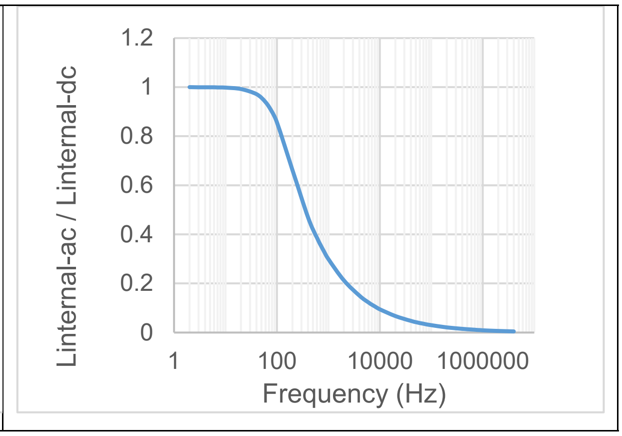


Figure 48: AC | DC Internal inductance ratio decrease with a frequency sweep

The current distribution per conductor for closely spaced conductors carrying AC is affected by their mutual inductance. Two conductors, each carrying AC spaced near each other, causes mutual inductance that affects the current distribution in each wire. When the current in both conductors' flows in the same direction, the current density at opposite sides increases and when current flows in different directions, the current density in the adjacent sides increases [91].

The proximity effect is not significant in overhead power lines due to the large spacing between phases for safety and to prevent flashovers, however, for cables, phases are spaced much closer, and the proximity effect becomes prominent [92].

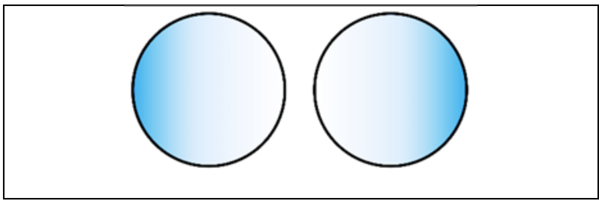


Figure 49: Proximity effect – current in the same direction

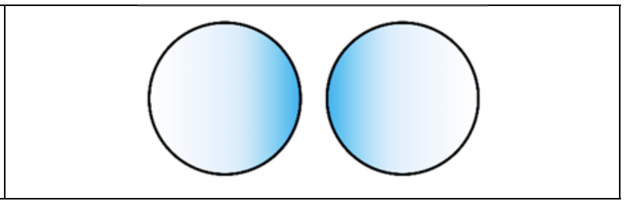


Figure 50: Proximity effect – current in opposite directions

As the skin effect increases, the contribution of the proximity effect also increases and is considered a linked phenomenon. The skin effect and proximity effect are generally neglected, however, for larger conductors (cables) the effect becomes more significant. According to [93] and [94], when evaluating screen losses for a 22.56 mm radius conductor, there is a discrepancy of 16% when compared to methods not considering skin effect and proximity effect.

Practically, the skin factor (γ_s) and proximity factor (γ_p) can be neglected for buried cables with a sufficient static rating and conductor diameter of 150 mm^2 and less [77].

For stranded conductors, such as ACSR, AC creates an alternating magnetic flux in the steel core of the conductor and alternating circular magnetic flux in non-ferrous wire strands. Hysteresis and eddy currents form in the conductor core due to the associated alternating magnetic flux [95], which contributes to higher ACSR core temperatures, as shown in Figure 51.

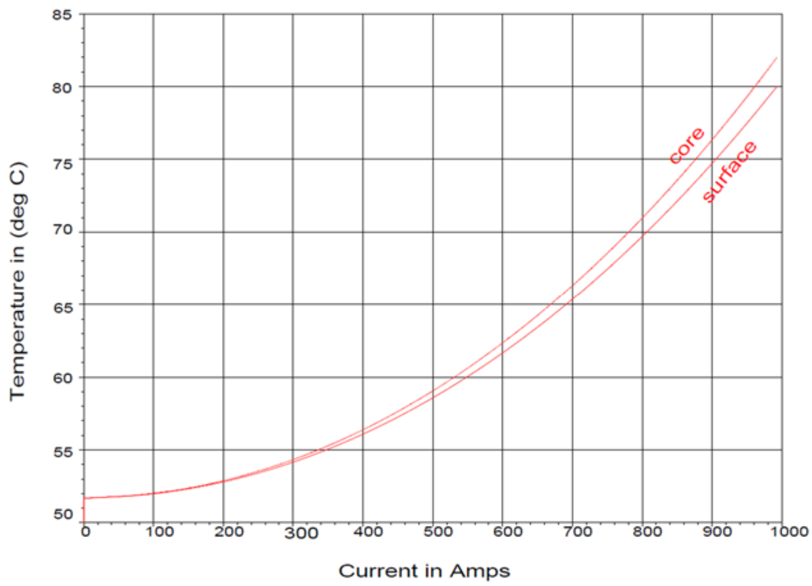


Figure 51: ACSR core and temperature comparison based on Cigré WG B2.43 [60]

When evaluating and applying the heat balance equations from [60] for steady-state conditions, Figure 51 illustrates the difference in core temperature when compared to surface temperature.

Hysteresis and eddy current losses from one layer do not cancel the axial magnetic field produced by another due to the odd number of conductor strands per layers. The magnetisation of ACSR steel core increases the resistance per unit length, and sheath circulation current (eddy currents) increases as the gap between axes increase. The sheath circulation currents produce magnetic fields over and above the conductor or cable magnetic field. If opposing lay layers are not applied the internal magnetic heating is higher.

Steel pipes are used for magnetic shielding of cables; the pipes reduce the magnetic fields introduced into the cable surroundings and offer a simple and easy-to-install cable casing for railway or river crossings. The eddy current losses for cables installed in (magnetic) steel pipes are significant and results in a considerable reduction in the cable ampacity [96].

With not applying opposing lay layers and using uneven layers, which do not effectively cancel out magnetic fields, the hysteresis losses increase, and the ampacity rating of a conductor is implicated by increasing losses resulting in a decreased current rating.

For a length of dinosaur ACSR, the AC to DC resistance ratio increases from 1.034 at 1.048 at a 1000 A_{rms} and the magnetic heating losses increases from zero to approximately 2.5 W/m for the same current range, proving the frequency dependency of losses in conductors [50]. The frequency dependency of conductors impacts on the conductor resistance, but has a negligible impact on conductor inductance.

2.2.3.9 DC to AC resistance conversions

The DC resistance and AC resistance of conductors are mostly supplied by the conductor manufacturer at a given temperature and populated into the manufacturer's datasheets. The DC resistance of the conductor is computed from the resistivity of the metal that is used in the conductor. Various methods are developed to use the DC resistance to calculate the AC resistance. The AC resistance is higher than DC resistance due to system frequency and the associated frequency effects [34], mainly due to the correction needed for the skin effect and proximity effect [97].

The following paragraphs consider R_{DC} (DC resistance), R_{AC} (AC resistance) and temperature scaling of resistance.

For current densities below 1 A/mm^2, fast calculations through simplified approximations accurately estimate the AC resistance value. However, for higher current densities up to 4 A/mm^2, a detailed model is required to determine AC resistance values accurately [92]. The AC resistance of a helically stranded conductor is influenced by the conductor's stranding construction and lay ratio, the current through the conductor, temperature, and frequency-dependent effects [92].

2.2.3.9.1 R_{DC} – DC resistance (Ω)

The DC resistance of a conductor is equal to the conductor resistance if current distribution on the cross-section of the conductor is proportionally spread [34].

$$R_{DC} = \frac{\rho l}{A}\,\Omega \tag{26}$$

Where ρ is the resistivity of conductor at a given temperature (Ωm), l the length of the conductor (m), and A the cross-section area of conductor (m^2).

The resistivity for a copper conductor and aluminium conductor at 20 °C can be obtained respectively from [34], $\rho\ 2.256E^{-8}$ Ω.m (copper) and $3.598E^{-8}$ Ω.m (aluminium). However, these values differ from the resistivity referenced in [98].

2.2.3.9.2 R_{AC} – AC resistance (Ω)

The AC resistance will always be larger than the DC resistance due to the proximity effect, eddy currents, hysteresis and the skin effect. In the conductor datasheets, mostly DC resistance is given for ACSR. Load flow studies are, however, based on the AC resistance.

Calculating the AC resistance at power frequency from the DC resistance using the X-K relationship approximation is [99]:

$$r_{ac} = K(X) r_{dc}\ \Omega \tag{27}$$

Where r_{ac} and r_{dc} is the AC resistance and DC resistance, respectively. K is the correction factor and is a function of the parameter X.

$$X = 0.063598 \times \sqrt{\mu f / r_{dc}} \tag{28}$$

Where f is the frequency of the system and μ the permeability of the conductor.

$$K = \sum_{d} a_d X^d \tag{29}$$

Where a_d is the sequence $a_d = \{1.00042; -0.00866; 0.03150; -0.04287; 0.03138; -0.00691; 0.000486752\}$ and d the index of coefficients from zero to six for the 6th order polynomial curve published by the National Bureau of Standards [34].

Alternatively, the AC resistance can be calculated from first principles, where

$$r_{ac} = r_{dc}\left[1 + \lambda_s + \lambda_p\right] \tag{30}$$

Where λ_s λ_p are the skin effect coefficient and proximity effect coefficient respectively, which can be calculated from Maxwell's equations applied to a cylindrical conductor configuration.

2.2.3.10 Conductor temperature

The resistance of any given metal is a function of temperature. For this simple reason, the conductor resistance increases with increased temperature, and therefore, the metallic resistance will also become higher at higher temperatures [34]. The same applies to a decrease in temperature or cooling effect due to wind or moist soil conditions that will result in declining resistivity. The resistance of the metal determines the DC resistance of the conductor. The DC resistance includes temperature variations depending on resistivity; this almost linear relationship considers coefficients for the conducting material such as copper or aluminium and is addressed in "*Impact of Temperature, Wind Flow, Solar Radiation, Skin Effect and Proximity Effect on Overhead Conductor"* [100].

AC and DC resistance have a linear relationship, temperature scaling from either will therefore yield the same AC to DC ratio.

Feeders are designed for maximum operating temperature. Operating beyond the design temperature can cause irreversible damage to auxiliary equipment and the conductor. At high-temperatures material can anneal, which causes an alternation to its physical properties.

2.2.3.10.1 Temperature scaling of resistance

The available datasheets from the conductor manufacturers generally stipulate the DC resistance per unit length at 20 °C. After calculating the AC resistance, these values can be scaled according to the desired temperatures [50].

$$R_2 = (M + T_2)\frac{R_1}{(M + T_1)} \tag{31}$$

($M = 228.1$ for aluminium, 234.5 for 100% annealed copper, 241.5 for 97% hard drawn copper)

Where M is the conductor constant, R_2 is the adjusted resistance for operating temperature T_2, and R1 is the manufacturer's resistance at temperature T_1. Resistances are in Ω and temperature in ^0C.

A second method of temperature scaling, used by DigSilent PowerFactory and manufacturers, is the use of the temperature coefficient of resistance. A higher temperature coefficient of resistance indicates that the resistance level is more sensitive to changes in temperatures.

$$R_{max} = R_{20}[1 + \alpha(T_{max} - 20℃)]\ \Omega \tag{32}$$

Where R_{20} is the resistance at 20℃ in Ω, T_{max} is the maximum operating temperature in ℃, R_{max} is the resistance at temperature T_{max}, and α is the temperature coefficient in K.

Manufacturer datasheets publish resistance at a certain temperature without temperature coefficients for the metal composition of conductors. To scale resistances according to temperature the relevant temperature coefficients for the conductors are required. Various sources provide the required temperature coefficient, for cables a reliable source is IEC60287-1-1:2014. From IEC 602871-1, the temperature coefficients and electrical resistivity for metals used in cables are given in Table 19.

Table 19: Metals used in cable's electrical resistivities and temperature coefficients [101]

Material	Resistivity (ρ) Ohm·m at 20°c	Temperature coefficient (α_{20}) per K at 20°C
Conductors		
Copper	1.724 1x10^{-8}	3.93 10^{-3}
Aluminium	2.826 4x10^{8}	4.03 10^{-3}
Sheaths and armour		
Lead or lead alloy	21. 4x10^{-8}	4.0 10^{-3}
Steel	13.8x10^{-8}	4.5 10^{-3}
Bronze	3.5x10^{-8}	3.0 10^{-3}
Stainless steel	70x10^{-8}	Negligible
Aluminium	2.84x10^{-8}	4.03 10^{-3}
NOTE Values for copper conductors are taken from IEC 60028. Values for aluminium conductors are taken from IEC 60889.		

2.2.3.11 Geometric mean radius

There is no specific definition for the geometric mean radius (GMR), but from various sources such as [50], [53] and [48]) the GMR can be reasoned to be the radius of conductor systems transformed to an equivalent overall circular geometry, for a uniform density per phase of such a conductor system. The conductor system may be composite, solid or bundled conductors.

The GMR for various conductor configurations are [53]:

- One solid cylindrical conductor without sub-strands

$$GMR = D_S = e^{-1/4} . r \tag{33}$$

r is the radius of the conductor / single strand in meters and D_S the GMR per phase for identical conductors with uniform current and not skin effect [50].

- One single conductor with multiple strands

$$\text{GMR} = D_S = \sqrt[n^2]{\prod_{i=1}^{n}\prod_{j=1}^{n} D_{ij}} \tag{34}$$

n is the number of solid cylindrical, and identical, subconductors and D the distances between subconductors.

Note: The geometric mean radius is generally obtainable from the manufacturer's catalogues and need not be calculated for systems where a single (stranded) conductor is installed per phase.

- Bundled conductors

$$\text{GMR} = D_{SL} = \sqrt[n^2]{\prod_{i=1}^{n}\prod_{j=1}^{n} D_{S_{ij}}} \tag{35}$$

D_{SL} is the geometric mean radius for the conductor bundle per phase and is calculated from D_S based on the assumptions that the same stranded conductors are used to create the bundle. The formula given by Equation (35) *can be reduced to a simplified form for symmetrical bundles, where d is the centre to centre distance between conductors. The calculation of D_S remains unchanged for use in the calculation of D_{SL}.*

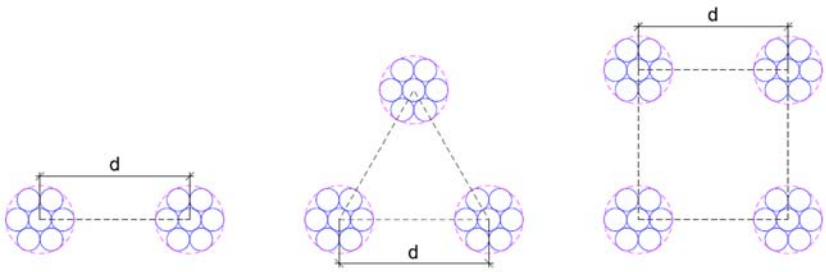


Figure 52: Equally spaced bundled conductors

- Two-conductor bundle

$$\text{GMR} = D_{SL} = \sqrt[4]{(D_s \times d)^2} = \sqrt{D_S d} \tag{36}$$

- Three-conductor bundle

$$\text{GMR} = D_{SL} = \sqrt[9]{(D_s \times d \times d)^3} = \sqrt[3]{D_S d^2} \tag{37}$$

- Four-conductor bundle

$$\text{GMR} = D_{SL} = \sqrt[16]{\left(D_s \times d \times d \times d\sqrt{2}\right)^4} = 1.091\sqrt[4]{D_S d^3} \tag{38}$$

2.2.3.12 Geometric mean distance

Following the calculation of the GMR, the geometric mean distance (GMD) can be calculated for overhead power lines. For a three-phase system, the GMD is the cube root of the spacing of the conductors' three phases.

For completely transposed and balanced three-phase systems, the GMD is defined as [53]:

$$GMD = D_{eq} = \sqrt[3]{D_{12}D_{23}D_{31}} \quad \textbf{(39)}$$

With D_{12}, D_{23}, D_{31} the distance, in metres, between phase 1 - 2, 2 - 3, and 3 - 1 respectively. Sufficient accuracy is obtained when using bundle centres for distances between phases when calculating D_{eq} if such spacing is large in comparison to bundle spacing [53].

For tower configurations with unequal phase spacing for three-phase lines, the geometric mean distance between the centres of the conductor or phase bundle is given by:

$$GMD = D_{eq} = \sqrt[3]{(D_{ab}D_{bc}D_{ca})} \text{ [m]} \quad \textbf{(40)}$$

Where D_{ab}, D_{bc}, D_{ca} are the distances between phase 1, 2, and 3 in metres, for a single circuit three-phase system. Figure 53 illustrates a flat horizontal three-phase conductor system geometry with twin bundle conductors. Conductors comprise of solid cylindrical subconductors.

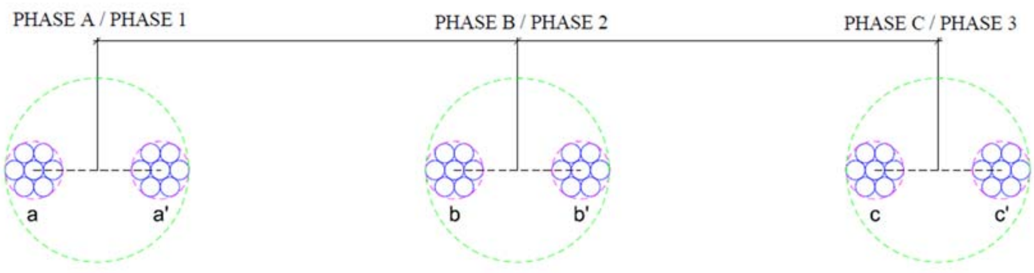


Figure 53: Three-phase geometry with bundled conductors

When considering conductor geometry for overhead power lines, it is determined that [53]:

- The internal inductance is independent of the conductor diameter, but the total inductance decreases and increases respectively with the conductor diameter if the spacing remains fixed;
- As the spacing between phases increases, even for an equilateral triangular geometry, the inductance as well as the inductive reactance of the circuit increases;
- When using bundled conductor with equal cross-sectional areas to a single conductor, the reactance of the line is reduced with the advantage of smaller line voltage drops and increased loadability;
- Both capacitance and admittance to neutral decreases as spacing increases;
- The effect of an earth plane slightly increases the capacitance of the lines. However, the effect of the earth becomes negligible at a certain height;

2.2.3.13 Cable parameters

The formulas and theoretical approaches to calculate cable parameters are similar to those of overhead power lines, but the results differ due to insulation, the difference in geometry, shielding, and screening. Due to the use of various materials in cable designs, the accurate calculation of parameters become more complex and is not further reviewed as part of this research.

2.2.3.14 Current magnitude

The higher the current that the conductor carries, the higher the resistance of the conductor. The relationship is simply because the electrical stress on the conductor increases as the current passing through the conductor increases.

The series resistance is the physical resistance of a transmission line and depends on the physical composition of a conductor at a given temperature. The term resistance effectively refers to how much resistance is given to the flow of current. Resistance is the leading cause of power loss in conductors and cables [50].

The conductor's resistance mostly determines the conductor's current rating, which is limited by the ability of the conductor to dissipate heat from its surface [34]:

$$I^2R = S(w_c + w_r) \quad W \tag{41}$$

Where, I is the conductor current capacity in Ampere, R is the conductor resistance in Ω, S the conductor surface area in mm^2, and w_c & w_r the convection loss and radiation loss, respectively in W/mm^2.

2.3 Power system modelling parameters

The calculation of power system parameters is based on the principles given under the preceding paragraphs. The load flow results verify allowable voltage drops and loading of equipment. Fault level analysis is used in protection settings and verification of equipment ratings. Contingency analysis used to identify areas where strengthening may be required or to identify overloaded feeders under contingency conditions.

The basic modelling can be extended to study harmonics, transients, motor starting, voltage change, unbalances, protection grading and much more, depending on the functionality of the software used, the purpose of the model and the level of detail included in the model.

Based on DigSilent GmbH [56], the Nominal Π model can be used to perform steady-state analysis formulated in the frequency domain for subtransmission lines. The model is based on discrete resistance, inductance, capacitance and conductance (R, L, C, G) components and can, therefore, be used for transient models. These discrete components form part of the impedance per subsystem, such as feeders and load nodes, of the grid under investigation. Subtransmission lines commonly fall within the range of overhead lines with lengths less than 250 km. At power frequency, the Nominal Π model provides satisfactory results and the approximation error can be neglected. The accuracy of the model is dependent on the factor $f \times l$ *(frequency multiplied by length)* [56].

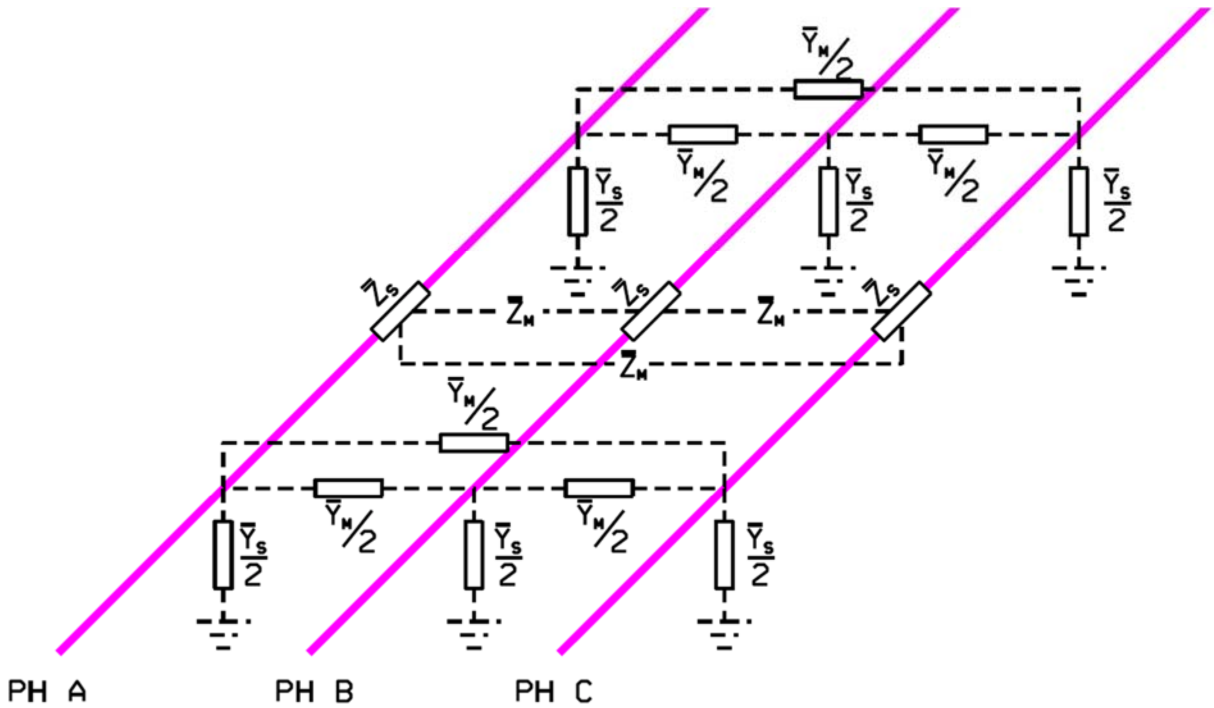


Figure 54: Equivalent PI-circuit of a line for lumped parameters based on [56]

The model in Figure 54 serves to calculate the self- and mutual impedances, and admittances. The impedance and admittance matrices are then converted from the time-domain to the frequency domain using the Fortescue transform [102].

This study does not investigate the grid source, which forms part of a transmission network. The transmission source to a subtransmission power system is mostly not within the controlled limits of the subtransmission grid operator. However, certain cases necessitate the implementation of an additional external grid infeed for strengthening, typically when the transmission source is weak, or an additional transmission source is required into the subtransmission power system. Additional transmission points of delivery often require expensive upstream network strengthening.

Some software has the functionality to investigate the electromagnetic coupling between the multi-circuit overhead line and cable systems. Multiphase load flow calculations and EMT functions are used to evaluate steady-state, as well as transient electromagnetic coupling such as the induced phase currents in a second cable system during a fault on the first cable system [103], [56].

The followings steps obtain the time-domain parameters:

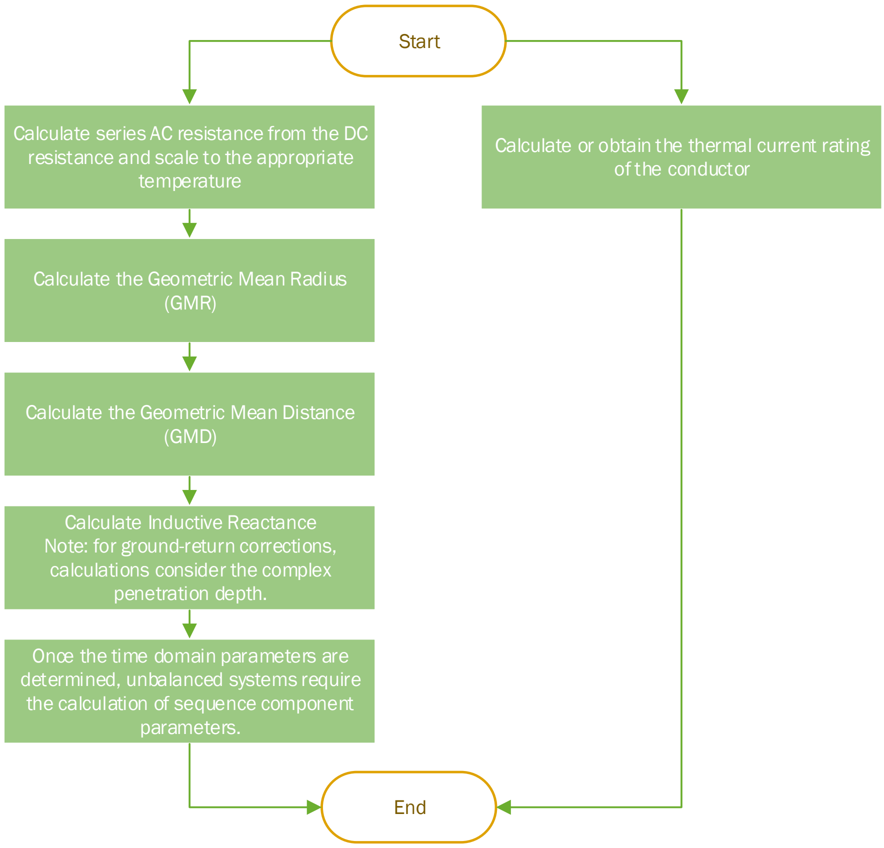


Figure 55: Parameter calculation process

2.3.1 The series resistance of feeders

Resistance is a direct function of conductor temperature where the operating temperature depicts light or heavy loading of a conductor to determine the conductor's thermal capacity [99].

The power penetration depth influences AC resistance as a function of frequency. If the skin effect is not considered, the DC resistance assumes the conductor's internal resistance [56]. The complex penetration depth must be accounted for in terms of the DC resistance, when considering the skin effect, to determine the AC resistance [56].

Line losses can be reduced by decreasing series resistance, which is possible through trapezoidal wrap strands, or at subtransmission level, by using twin conductors in place of single conductors. The merits of conductor characteristics must be evaluated according to individual cases. For similar diameters, Chickadee ACSR offers a higher current rating and lighter weight to a reduced steel content when compared to Wolf ACSR.

2.3.2 Impedance

The impedance of overhead power lines comprises of self-impedance and mutual impedance. As indicated by [55], the set of linear equations defining impedances can be split into subsets of ungrounded conductor and earth wire equations to account for the effect of earth (shielding) wires on ungrounded phase conductors. For earth returns, conductor images are plotted symmetrically across the earth plane for both overhead power lines as well as for underground cables.

The calculation of loading capacity for overhead and underground feeders follows similar approaches. Due to additional complexities for cable calculations such as loop impedances, various substrates of conductive and non-conductive material, alternative methods such as the graphical nomogram approach can be followed [104].

Software packages, such as DigSilent PowerFactory, calculates the electrical parameters for cables [103] based on certain assumptions, as qualified, and equations explicitly formulated for the impedance and admittance of cables [105].

The electrical parameters to be calculated for subtransmission feeder systems required to perform load flow and fault level studies, as well as electrical network planning, are resistance, conductor geometric orientation, inductive reactance, susceptance / capacitive reactance, sequence components and conductor current or thermal rating.

The electrical impedance between two terminals for a circuit, such as a transformer or subtransmission feeder (overhead power line or cable), is a complex number characterised in Cartesian form as follows:

$$\mathbb{Z} = R + jX \;\; [\Omega] \tag{42}$$

Where Z is the impedance, R is resistance and the real component of impedance, and jX is the reactance and the imaginary component of impedance.

Reactance separates into an inductive and capacitive reactive impedance:

$$Z_L = j\omega X_L \;\; [\Omega] \tag{43}$$

Also,

$$Z_C = \frac{1}{j\omega X_C}\ [\Omega] \tag{44}$$

Where, Z_L is the inductive reactive impedance, Z_C is the capacitive reactive impedance, and ω is the angular frequency in radians.

Note that the following reciprocal identities of the imaginary unit:

$$j \equiv e^{j\frac{\pi}{2}} \text{ and } \frac{1}{j} \equiv e^{j\left(-\frac{\pi}{2}\right)} \tag{45}$$

As first defined by Oliver Heaviside, admittance is the inverse of impedance:

$$\mathbb{Y} = G + jB\ \ [\text{S}] \tag{46}$$

Y is admittance [Siemens], G is conductance, and jB is susceptance;

For susceptance, note that:

$$B = I_m[\mathbb{Y}] = \frac{-X}{|\mathbb{Z}|^2} \tag{47}$$

2.3.3 Inductive reactance

The inductive reactance of an overhead power line can be reduced by increasing bundle sizes and reducing interphase spacing to the minimum safe distances. A reduced series line reactance will result in smaller line voltage drop and will increase the line loadability [53]. The inductive reactance is calculated by [53]:

$$X_L = 2\omega L \tag{48}$$

With $\omega = 2\pi f$:

$$L = 10^{-7}\ln\left(\frac{D_{eq}}{D_{SL}}\right) \tag{49}$$

$$\therefore X_L = 4\pi f . 10^{-7}\ln\left(\frac{D_{eq}}{D_{SL}}\right)\ \ (\Omega/\text{km}) / \textit{phase} \tag{50}$$

Where X_L is the inductive reactance in ohm per meter, ω is the angular frequency in radians, f is the power system frequency in Hertz, L is Inductance in Henry, D_{eq} – the geometric mean distance in meters between phases, D_{SL} – geometric mean radius in meters for conductors or strands of one phase;

2.3.4 Capacitive reactance or susceptance

By increasing the conductor diameter, the capacitance of a line increases, and the shunt capacitance will also increase if the phase spacing decreases. The capacitive reactance or susceptance is calculated by [53]. The susceptance is equal to the inverse of the reactive capacitance of the power lines.

$$B = 2\pi f \left[\frac{2\pi\varepsilon_0}{ln\frac{D_{eq}}{GMR}}\right] \text{ S/m} \tag{51}$$

Where B is the susceptance [S/m], f the system frequency [Hz], ε is the permittivity constant of air for overhead power lines equal to 8.85418x10-12, Deq is the geometric distance between phases and GMR is the geometric mean radius of phases.

2.3.5 Cable impedance

As stated in proceeding paragraphs, the calculation of cable parameters is more complicated. The cable and insulation parameters require the calculation of self-impedance of phase conductors, self-impedance of screen conductors, the mutual impedance between the phase and screen conductors, the mutual impedance between the phase conductors, the capacitance between the phase and screen conductors, the capacitance between the screen conductor and ground, and capacitance between the phase conductors.

2.3.6 Sequence components

Due to power system modelling software, such as Inspired Interfaces' PowaMaster requiring parameter inputs in the form of symmetrical components, the following paragraph outlines the Fortescue transform basic principles.

Sequence components are used to study unbalanced systems. Transforming time-domain phasors to three sequence symmetrical components per phasor calculates the sequence / symmetrical components. The symmetrical components simplify the analysis of unbalanced systems.

To calculate the sequence components [56]:

T is the symmetrical component transformation matrix also generally referred to as the Fortescue transformation named after Charles Legeyt Fortescue:

$$[T] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \rightarrow [T]^{-1} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \tag{52}$$

Where, $a = e^{+j120^0}$ *and* $a^2 = e^{-j120^0}$.

Using the impedance parameters of a three-phase feeder line to determine the sequence impedance matrix [104], [56]:

$$[Z_{012}] = [T]^{-1}[Z_{abc}][T] = \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} = \begin{bmatrix} Z_S + 2Z_m & 0 & 0 \\ 0 & Z_S - Z_M & 0 \\ 0 & 0 & Z_S - Z_m \end{bmatrix} \tag{53}$$

The negative sequence impedance is assumed to be equal to the positive sequence impedance [56]. Feeders have unilateral single direction power flow, excluding transients.

Where Z_a, Z_b, Z_c are the A, B and C phase impedances respectively and Z_0, Z_1, Z_2 are the zero, positive and negative sequence impedances respectively.

Averaging of Z_{aa}, Z_{bb} and Z_{cc} of $[Z_{abc}]$ calculates the self-impedance;

Averaging of Z_{ab}, Z_{ac} and Z_{bc} of $[Z_{abc}]$ calculates the mutual-impedance;

This similar applies to the admittances where:

$$[Y_{012}] = [T]^{-1}[Y_{abc}][T] = \begin{bmatrix} Y_0 & 0 & 0 \\ 0 & Y_1 & 0 \\ 0 & 0 & Y_2 \end{bmatrix} = \begin{bmatrix} Y_S + 2Y_m & 0 & 0 \\ 0 & Y_S - Y_M & 0 \\ 0 & 0 & Y_S - Y_m \end{bmatrix} \quad \textbf{(54)}$$

Soil properties and soil qualities, specifically earth resistivity, vary between geographical areas. Soil resistivity can increase the self- and mutual-impedances [106]. Therefore, earth return corrections incorporate the effects of soil resistivity in the line parameters.

2.3.7 Earth return corrections

The presence of the earth affects the reactance of an overhead conductor, to account for the presence of the earth, image charges are placed symmetrically to the overhead line underground and vice versa for underground cables with symmetrical images above ground. The magnitudes of the charges are kept constant, but the sign of the underground charges will change.

Carson's 1926 infinite integrals [107] are traditional asymptotic approximations to determine earth-return corrections [108]. Truncation errors that may be unacceptable for impedances in cases with wide conductor separation, high frequency or low earth resistivity, and lead to the proposed approach developed to calculate complex penetration depth [109], [110], [111], [112].

Correction terms for the earth return effect, where the "earth return" is replaced by a set of "earth return conductors" located below the systems phase wires, modify the conductor images and the modelling of the earth return path defined by Carson [53].

Due to the complexity of the Carson equations, computer-aided software programs are developed by institutions and individuals to compute overhead power line and underground cable impedances. Several approximations are made by [113] to simplify parameter calculations and to develop “modified” Carson’s equations, which still yields acceptable results when compared to the “full” Carson’s equations [113].

The earth return amplifies the resistance, self-impedance and mutual-impedance for increased earth resistivity, with considerable changes for low earth resistivity (zero to approximately 100 Ωm), and marginal changes for high earth resistivity [106]. However, as per Kersting and Green [113], the percentage errors as a result of varying earth resistivity remain very small, in the order of 0.03% when comparing an assumed 100 Ωm to 10 Ωm and 1 000 Ωm, respectively. Under steady-state conditions at power frequency, Kersting and Green [113] proved that either the “modified” or “full” Carson’s equations can be used for computation of impedance matrices with an error of less than 0.3% when comparing the individual elements of the resulting two impedance matrices.

Alike the frequency dependency of conductors, frequency has a significant impact on earth resistance, but a much lower impact on the earth inductance. Due to the skin effect, earth current flows closer to the surface at higher frequency resulting in a higher earth resistance due to the reduced equivalent cross-sectional area for current to flow. The self-inductance will decrease at higher frequency with the earth current flowing closer to the surface.

The calculation procedure to determine self and mutual impedances, taking into account the earth return, is to calculate the complex penetration depth, to calculate the self-impedance, calculating the mutual impedance, and eliminating earth wires [108].

A representation of an overhead transmission line, conductor spacing and the conductor’s symmetrical images for a double circuit delta geometry structure:

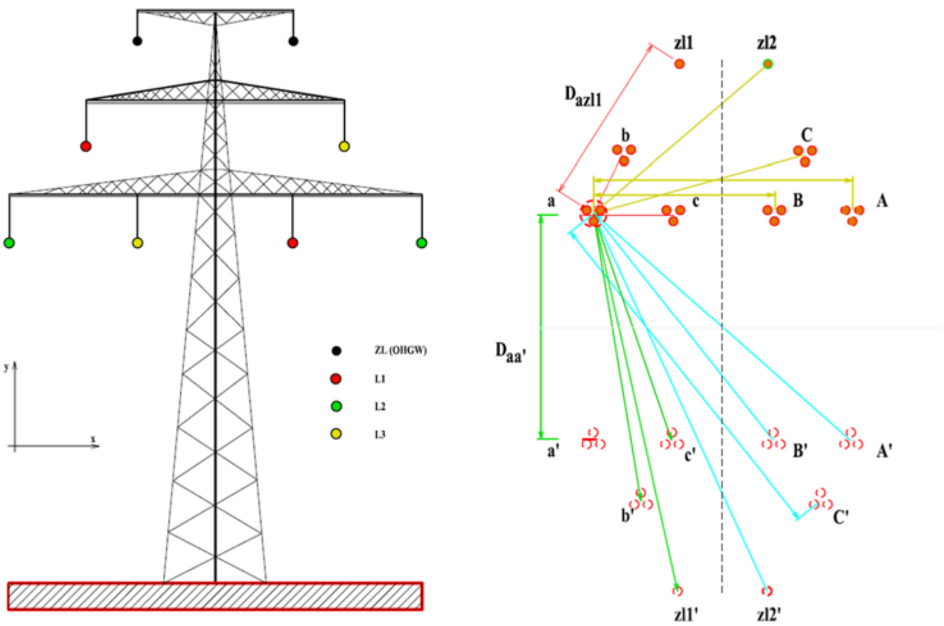


Figure 56: Overhead power line and earth replaced by conductor images [114]

2.3.8 Tower geometry

Tower or conductor geometry impacts the computation of power line electrical parameters and tower height is not that crucial to the results [115]. Line models can be based on the most common tower model, various heights of towers model or the average tower height model. This study applies the average height of towers model for simplicity.

However, the geometric orientation of the phase conductors and shielding with earth wires significantly influences line parameters. The geometric orientation depends on the number of circuits and circuit orientations such as vertical, horizontal, staggered vertical, delta, flat-delta, and so forth. The average height (h_{ave}) of the conductor above ground level for spans less than 500 m with a parabola shaped profile, is [56]:

$$h_{ave} = \frac{2}{3}h_{mid} + \frac{1}{3}h_{twr} \tag{55}$$

Where, h_{mid} *is the conductor mid-span height above ground level and* h_{twr} *is the conductor attachment height to the tower.*

For overhead power lines, the average conductor height varies with the terrain flatness, different structure heights and different conductor attachment heights to the structures. The various possible conductor configurations, varying conductor height with the terrain and climatic conditions, and varying earth resistivity contribute to the possible error. Calculations are simplified by using the relevant software tools, which assists in reducing general assumptions.

2.3.9 Cable geometry

More so for cable installations than for overhead lines, the cable configuration or formation plays a significant role in the efficiency, safety and capabilities of the system design. Cable installation geometries can be flat (horizontal), vertical and trefoil. For double circuits, the arrangements can be independent or crossed. In addition to the geometrical arrangement, bonding and transpositions significantly influence cable ratings and performance.

For cable installations, the cable configuration and spacing between phases and spacing between circuits greatly influences the thermal rating of the cable. Where a high power transfer rating must be achieved, care must be taken to select the appropriate cable configuration.

The graph in Figure 57 from [116], plots the ampacity of single-core cables as a function of conductor area. The conductor temperature is 85 °C in all cases except case 4, where the conductor temperature is reduced to 40 °C. The ratings for the different cases are taken from [116]:

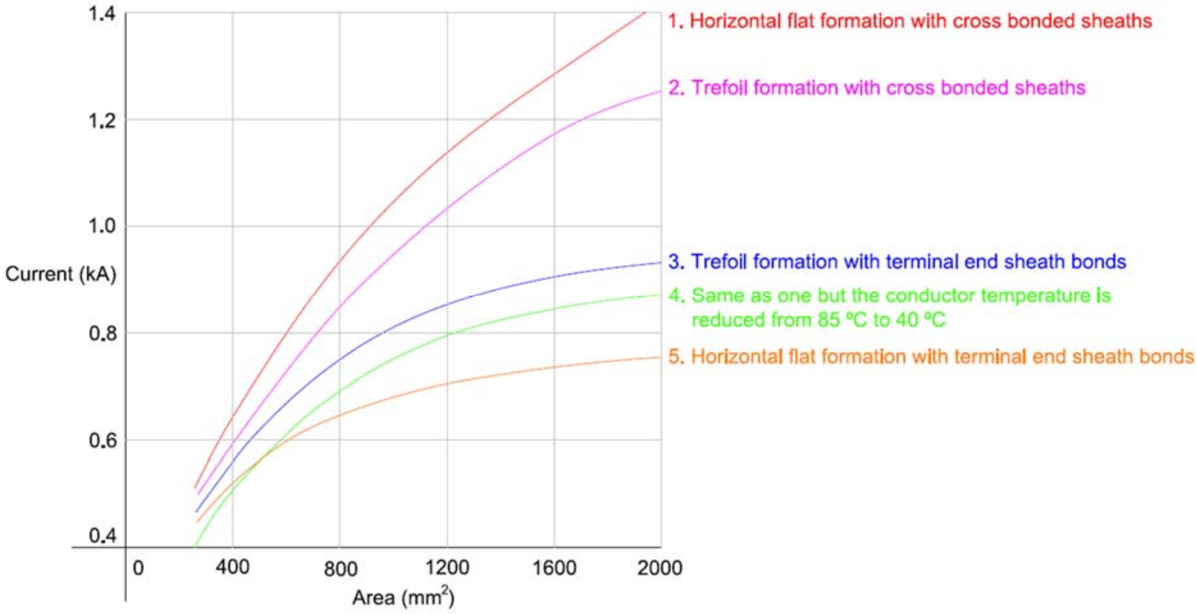


Figure 57: Ampacity vs cable configuration [116]

2.4 Techno-economic assessment methods

To be able to evaluate the most cost-effective technical solution, a financial analysis is required to evaluate the monetary implication of the options.

A techno-economic assessment (TEA) is a method applied to compare the cost-benefit relating to other predefined factors. The applications for TEAs include, but are not limited to [117]:

(a) Evaluating the economic feasibility of a specific project;

(b) Investigating the cash flows over the lifetime (financial constraints);

(c) Evaluating the likelihood of different technology scales and applications;

(d) Compare the economic quality of different technology applications providing the same service;

The TEA methods outlined are based on the European Commission's Intelligent Energy – Europe (IEE) programme [117].

Historical data, methods to forecast remaining service life expectancy, failure probability, initial investment cost, operational cost, future replacement cost, and the associated benefits are critical factors with determining preferred solutions.

2.4.1 Cost assessment

To evaluate the monetary aspects of projects, the associated expenditure amounts are divided into main components, namely capital expenditure – CAPEX, which could also be refer to as the investment cost, and the operational expenditure – OPEX, which refers to the maintenance and running costs.

2.4.1.1 Capex

Capital expenditure (Capex) related costs comprise of:

- The initial investment including planning and consulting cost;
- The administration and insurance cost – annual;
- The cost for infrastructure – annual;

Initial investment costs are generally financed by a loan (private sector) or National Treasury grant allocation (public sector) or amounts budgeted for projects. The initial investment cost involves all initial costs even though the plant is not operated. Such costs include professional service providers, statutory requirements and approvals, property/servitude costs, legal fees, connection costs and upstream network strengthening costs for increased electrical supplies. The annual cost for infrastructure and administration and insurance costs varies, depending on how a project is implemented, but typically comprises of insurance, liability insurance, fees, licenses and guarantees.

2.4.1.2 Opex

Operational expenditure (Opex) related costs comprise of the following:

- Fuel cost;
- Labour cost;
- Maintenance cost;
- Other costs;

Operational departments should aim to decrease the operational cost, which is highly dependent on the intensity of how the plant and equipment are operated.

2.4.2 Benefit assessment

The benefit assessment is the earnings from selling products. For the electrical energy supply industry, the product sold is electrical energy based on the applicable tariff, which depends on where the project is located. Tariff studies can be performed to optimise the investment rate of return by determining the most cost-efficient tariff to be used and by planning production according to network capacity charges, i.e. peak load clipping or shift planning. For municipalities, load management is usually only applied when a load control system can regulate peak loads by remote switching of devices, such as residential geysers. Where there is a power generation deficit and load shedding must be applied, other than demand-side load management, further methods of load management, such as cogeneration, are mostly impractical for municipalities. Municipalities are primarily re-distributors of power and seldom generate their own electrical energy. If storage capacity is available or if cogeneration is possible, the notified maximum demand at the point of delivery can be managed by peak load lopping.

With cogeneration and energy storage, peak load lopping can be applied to decrease the notified maximum demand without reducing the energy (kWh) consumed. By implementing peak load lopping, the supply source of electrical energy becomes localised to a grid and when planned efficiently, peak load lopping will reduce strain to an electrical grid in addition to reducing notified maximum demand charges.

Tariffs at distribution / subtransmission level typically comprises of the cost summarised below but varies between the types of tariff structures:

- Energy cost: Network capacity charge (Maximum declared demand); Low season peak energy charge; Low season standard energy charge; Low season off-peak energy charge; High season peak energy charge; High season standard energy charge; High season off-peak energy charge;

- Fixed cost: Administration charge; Service charge; Network demand charge (peak and standard); Transmission network charge; Affordable subsidy; Electrification and rural subsidy;

2.4.3 Risk assessment

Risk assessments are methodically excluded from TEAs but should be considered before a TEA to prevent irrelevance of results. Risks to be identified and addressed can be grouped as follows:

- Financial risk;

- Environmental risk;

- Health and Safety risk;
- Technical risk, and
- Social risk.

2.4.4 TEA methods

There are several methods to perform TEAs and the method should be chosen under relevance to the project, considering the various pros and cons of each method. Guidelines propose the following methods for consideration:

2.4.4.1 Static cost-benefit assessment

A simple method to compare the benefit and cost of an average year without taking interest and inflation into account with subsequent, imprecise results.

2.4.4.2 Annuity method

Considers the nett benefit, i.e. income minus costs, and spreads the initial capital investment cost over the project lifetime.

2.4.4.3 Nett cash flow table

Timeline based overview of income and cost over the project lifetime.

2.4.4.4 Nett present value (discounted cash flow)

Nett present value resembles a nett cash flow table but takes into account that outlaid capital investment is usually at the start of the project. Eskom has previously indicated that this method is used with planning methods for subtransmission systems [32].

2.4.5 Cost-benefit analysis

A wide variety of UGC and OHL technologies and combinations of different technologies can be considered to increase feeder ratings and reliability. When comparing options, the technical characteristics and life cycle costs must be analysed to determine the appropriate solution for a given scenario.

Although one single analysis method will not be suitable for all scenarios, with the exclusion of social, planning and environmental costs, the following model by Yang et al [118] is based on cable systems:

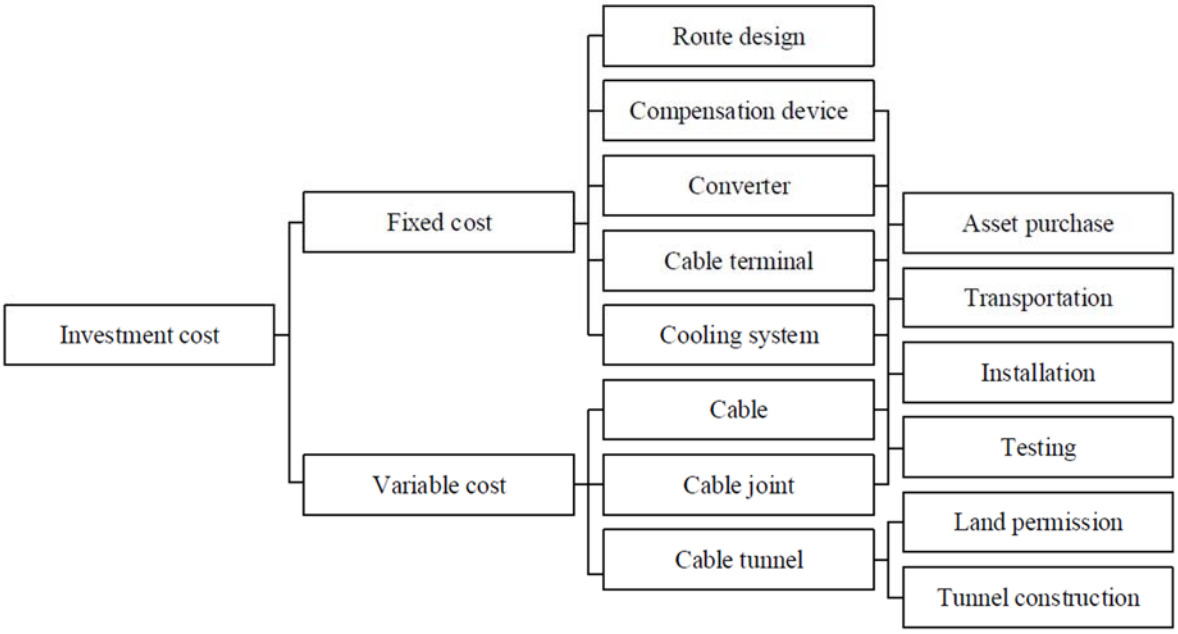


Figure 58: Feeder cable cost-benefit analysis components [118]

2.4.6 Summary

Various techno-economic assessment methods can be applied to determine and rank solutions for a given scenario. Due to variances in circumstances and different complexity levels for projects, no single method can be recommended as the ideal approach.

No single method of assessing costs versus technical performance can apply to all scenarios. Circumstances will determine the appropriate solution where the most expensive option, for the same feeder rating, could be the preferred solution due to constraints such as outage time, or project execution time.

A typical techno-economic assessment used on electrical infrastructure is a static, cost-benefit assessment, where the total investment cost (TIC) is determined by the capital investment cost (CIC) and the total operating costs or cost of losses (TOC):

$$TIC = CIC + TOC \qquad \textbf{(56)}$$

The TOC can be escalated for over a period, to evaluate the life-cycle cost of the infrastructure for options with a high CIC but low TOC. The cost-efficiency of options can be compared by determining the cost per MVA added to a feeder.

2.5 Overhead power lines

There are three main elements to overhead power lines, namely: terrain, structures (foundations, supports, guy anchors), and conductors. Other aspects can be subcategorised under one of the above items.

Not much can be done about the terrain element to increase power transfer. However, structures and conductors offer various solutions to increase power transfer on overhead power lines.

2.5.1 Structures and terrain

Elevation establishes ground levels and measures heights of services above ground. A route profile is referred to for feeder planning, where the profile is a longitudinal cross-cut section of the feeder route traversing an area.

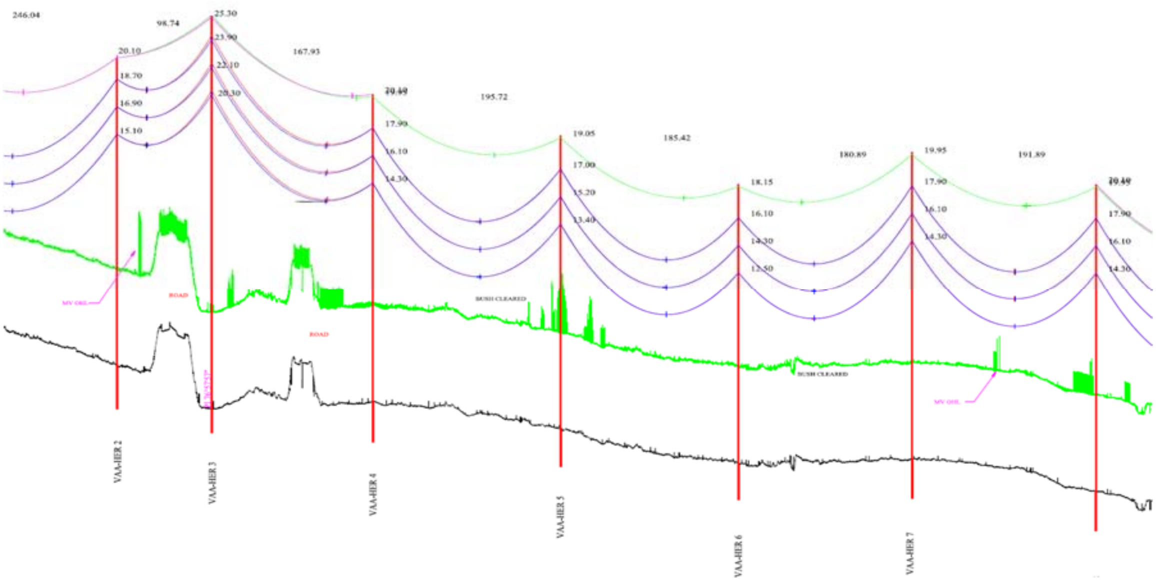


Figure 59: A section of the Vaalpark - Heron Banks route profile

The principal design criteria for structure capacity is deviation angle, minimum and maximum weight span and wind span, uplift, electrical span, and swing angle (suspension structures).

Historically in South Africa, most power lines constructed had lattice steel supporting structures. Although lattice-type structures have an overall light-weight [68], it is labour intensive to assemble with a higher margin for human error, it has a large footprint, and for specific applications, alternative structures can offer a more robust solution. Alternative structure options for subtransmission power lines are mainly steel poles and concrete poles. Concrete poles are manufactured using pre-tensioned steel reinforcing and concrete. Monolithic steel and concrete structures are used to achieve compact designs. Steel poles offer the added advantages of being easier to manufacture and design with additions such as cross-arms or curved davit arms.

Two main loads act on a structure are conductor tension and wind load. Additional loads such as ice on conductors are sometimes applied but are deemed part of the conductor weight or tension acting on the tower.

The structure capability is defined by parameters such as design, wind and weight span, line deviation angle, uplift and clashing electrical span.

Between compression and tension loading, lattice structures are optimal for compression. By adding anchors, structure types such as Guided-V and cross-rope designs are further enhanced by improving the tension performance with the use of stays.

Lattice structures comprise mostly of steel angle-iron matrices assembled to form a support structure, the use of circular hollow sections (CHS) for lattice structures are not common in South Africa due to the difficulty with connecting tubes to other members. Structure heights can be increased by adding body extensions and/or leg extensions. Often adjustments are required to standard structures for various reasons. The standard Eskom structure, reference number 247, was modified by extending the middle cross-arm to address galloping problems as shown in Figure 60. With South Africa being mostly snow-free, the 247 structure modification for galloping was required due to the planned use of the structure in a high altitude area with annual snowfall.

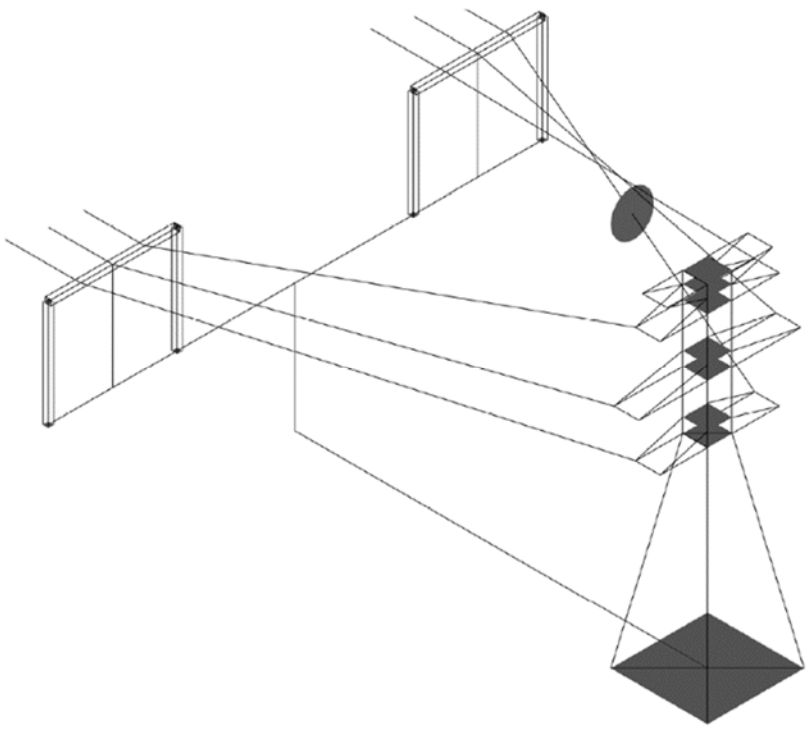


Figure 60: 247 Lattice structure with extended middle cross-arms

To increase the power transfer, Figure 61 illustrate how an existing structure can be retrofitted to increase the operating voltage by replacing the existing single conductor, 69 kV double circuits with a twin conductor, 138 kV single circuit. The number of conductors is the same, the two circuits are combined into one, and the voltage is doubled, thus the power transfer is quadrupled [119]. However, the n-1 criteria of the feeder structure are sacrificed.

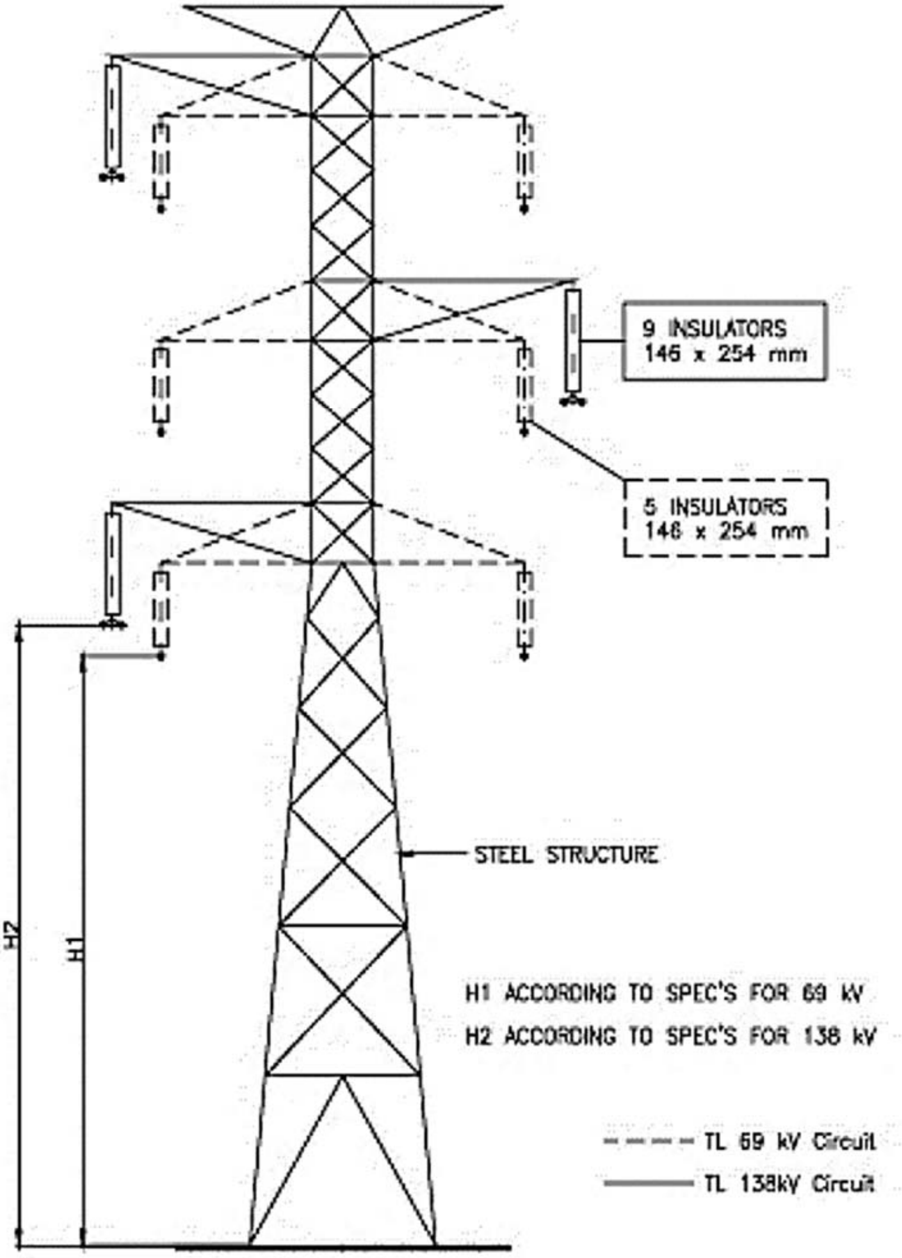


Figure 61: 69 kV Double circuit conversion into 138 kV single circuit [119]

For overhead lines, vertical space can be used more effectively, for the same footprint, by installing multiple circuits on a standard double circuit structure footprint. With the limited sizes of angle profiles, multiple circuits on lattice structures can be achieved by designing power line towers using circular hollow sections. From a simple analysis, it is concluded that CHS provides additional loading capabilities of 1.22 times of angular members, and when considering the limitation for class 3 compression, CHS is 11.7 times stronger than angle members [120]. CHS structures showcase superior withstand capabilities when compared to other cross-sections in compression, at a weight of 2.3 times less than conventional angle members with equivalent compression resistance [120]. The structures are complicated to climb, which holds maintenance challenges but acts as a theft deterrent measure. CHS structures further reduce wind loading on structures due to their reduced drag coefficient. A disadvantage of CHS structures is the increased material connection costs. The economics on full-scale structures are not tested in the industry. However, it is expected that the manufacturing cost will be higher for CHS towers but the overall cost, including installation and maintenance, significantly less.

Due to poles being mostly cylindrical, it offers superior torsional performance when compared to lattice structures. Alike lattice structures, the tension performance associated with maximum wind load conditions or broken wire conditions can be increased with the use of stays. Heavier conductors can be added to existing poles by adding and reconfiguring stay arrangements.

For compact line designs, self-supporting poles can be used. Up to a 150 kN tip load, planted poles have proven to be more cost-effective, for higher tip loads flange mounted structures become more cost-effective. An added advantage of a flange-mounted pole is that the foundation can be prepared underneath existing overhead conductors to limit the outage time required to tie into existing circuits. Compact designs allow for the more efficient use of available space and provide a solution for routing overhead power lines in high-density areas.

There are extensive options available for compact structures design, with cylindrical steel poles, the design is simplified, and custom structure can be developed to suit each specific case. The majority of older lines were built using a series of standard structures. Compact structures allow for power transfer where it might not have been possible due to space or due to disruptiveness.

Avi-faunal environmental considerations are included with the designing of compact lines, especially in subtransmission lines for reduced phase spacing compared to transmission voltage levels. Figure 62 shows the raptor electrocution, which impacts the line's reliability and supply quality.

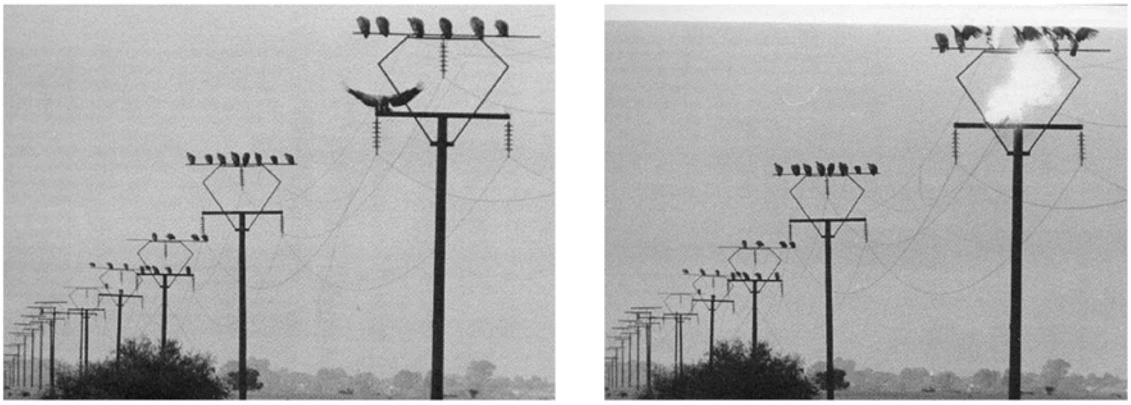


Figure 62: Bird electrocution [68]

For Figure 62, irrespective of the top cross-arm installed for perching, the bottom cross-arm should be fitted with bird guards or anti-perching devices to prevent perching below or directly above suspension insulators (bird streamers can also cause flashovers).

For the effective use of land by minimising widths or reuse of right of ways or servitudes, BOLD™ (Breakthrough Overhead Line Design) and AEP (American Electric Power) pioneered the use of compact delta structures and line design optimisation in a non-conventional approach. The "BOLD" approach requires that exceptional attention be paid to galloping criteria, rolling clearances, structure geometry, and the optimising of conductor diameter, the number of subconductors and bundle spacing. The advantages are an increased SIL due to the reduced inductance and increased capacitance of delta-configured lines, reduction in servitude widths and aesthetics. However, the use of hardware is increased, and the compact nature of the design may present some additional challenges during maintenance. The "rotation" of the delta, when compared to a "flat delta" geometry, has the added benefit of not having any conductors of the same circuit in the same horizontal plane in order not to negatively impact the allowable clashing span and retain the compact nature and efficiency advantages of a delta configuration.

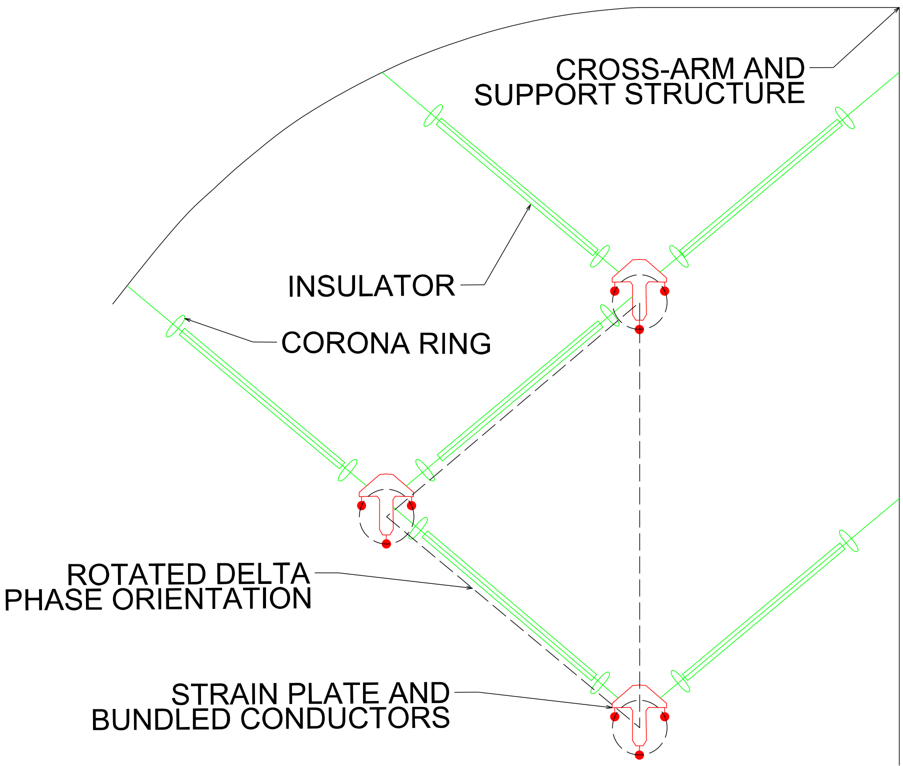


Figure 63: BOLD design approach [121]

The design extract in Figure 63 illustrates the rotated compact delta geometry, a single cross-arm and the heavy use of line hardware.

The "BOLD™" concept pioneered by AEP offers a compact overhead power line design solution with reduced tower heights, a low-profile catenary, increased capacity, lower magnetic fields, lower noise, and a lower surge impedance (higher SIL). With a BOLD™ approach, the material cost is increased, but the cost per MW capacity is lowered alongside the lowering of the line losses. The BOLD™ design approach compacts the phase geometry to the extent that a 345 kV BOLD™ was fitted to the footprint of an existing 138 kV lattice structure [121]. Figure 64 shows the comparison of the BOLD™ approach to the conventional lattice and tubular pole structure designs.

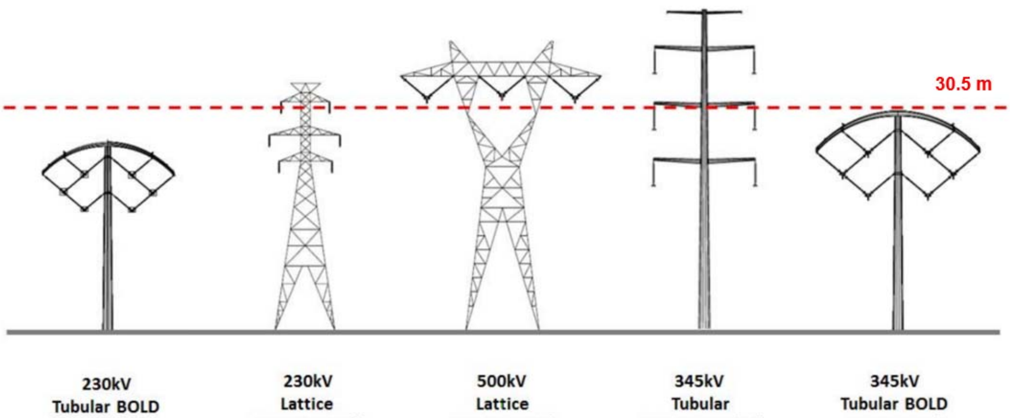


Figure 64: Highly efficient BOLD™ design [121]

Structure design has an essential role in the delivery of power transfer, there is scope to optimise structure designs as proven by the BOLD™ approach. Optimising is possible through structure reinforcement, the use of various insulated and uninsulated materials, the efficient use of hardware, the application of alternative profiles such as circular hollow sections, and increasing supportive legs to achieve compaction or add multiple circuits to a single structure.

The next paragraphs investigate the strengthening of the existing structure by reinforcing the structure body with cross-members for torsional loads.

2.5.1.1 Reinforcing existing tower designs

When rebuilding/restringing existing towers or when building new power lines with the use of heavier conductor than what the tower was initially designed for, a viable option to be considered is to increase the number of cross members to strengthen the tower. The enhanced bracing is shown in blue in Figure 65.

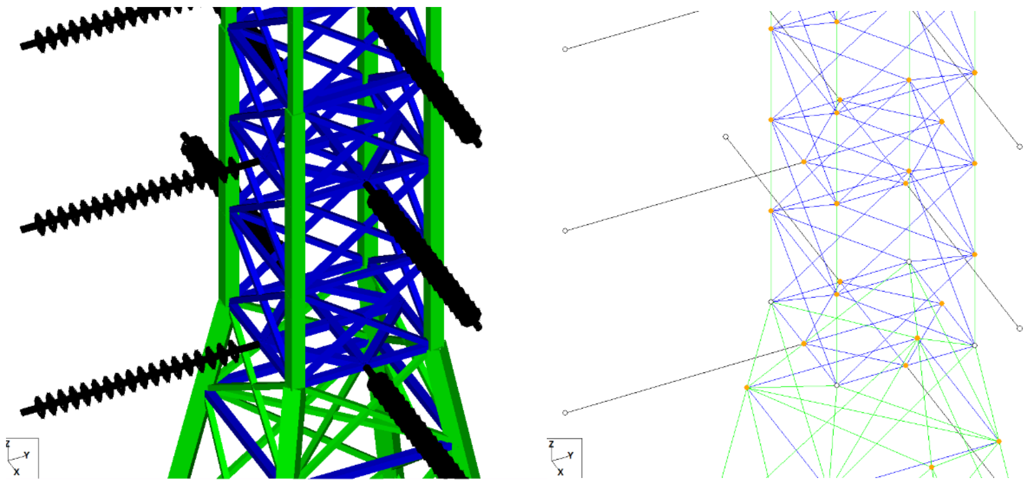


Figure 65: Strengthened lattice tower body

The colour intensity on the following illustrations shows the structure usage:

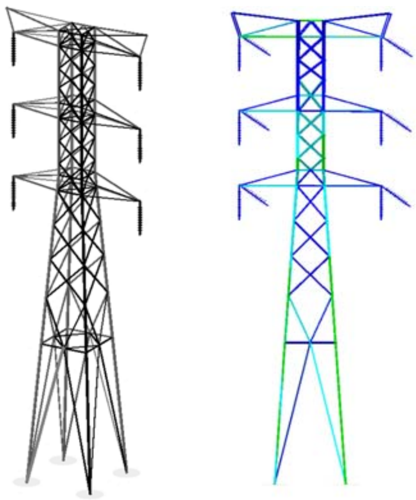


Figure 66: Geometry report for maximum structure usage

The following figure illustrates the R88 tower before and after the addition of braces to resist additional torsional forces (note the additional braces in the middle square of the tower body).

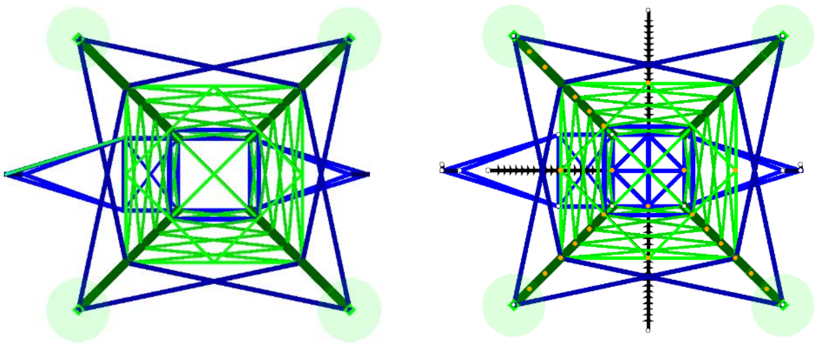


Figure 67: Strengthening using braces

2.5.1.2 Phase-to-phase overhead conductor spacing

The phase-to-phase spacing for subtransmission overhead power line conductors must be calculated to still adhere to the same regulatory requirements in mid-span than at the conductor attachment points to supporting structures. The standard "rigid" phase-to-phase spacing between phases as applicable at supporting structures, needs to be translated to mid-span where the physical movement of conductors occurs and thus changes the clearance between phases. With each phase of an overhead power line being able to move independent from the other phases, the clashing span or maximum electrical span must be calculated. When increasing the operating voltage on existing structures, the conductor spacing is likely to change, and the allowable electrical span must be recalculated.

The electrical span can, therefore, be defined as the maximum span length between conductor attachments or supports without the risk of clashing between the conductors for the entire length of the span. The phase-to-phase and phase-to-earth spacing are dependent on the electrical span, which can be calculated by the following formula [50]:

$$D = k\sqrt{\frac{(F+I)}{2}\frac{\cos\propto}{\cos\beta}} + C \tag{57}$$

Where D *is the phase-to-phase mid-span spacing (m) [D > C_{min} (C_{min} is the safe phase-to-phase clearance)],* k *the conductor differential motion coefficient (for average wind conditions k = 0.7 and for maximum wind conditions k = 0.85),* F *the maximum sag in mid-span (m),* I *the length of insulator swing (for V or post-insulator: I = 0 (m)),* $\propto$ *the vertical angle between conductors with 0° horizontal and 90° vertical (degrees - °),* β *the in-span conductor inclination angle [during wind condition corresponding to overvoltage, switching or lightning conditions (degrees - °)],* C *the phase-to-phase clearance (m).*

2.5.1.3 Line hardware, fittings and insulators

Line hardware can be used to support higher voltages on existing structures such as changing from suspension insulators to V-suspension insulators with a higher insulation level. Mid-span interphase insulators can be used for compact line designs, and line hardware can also allow for the addition of a second conductor per phase, or a larger conductor.

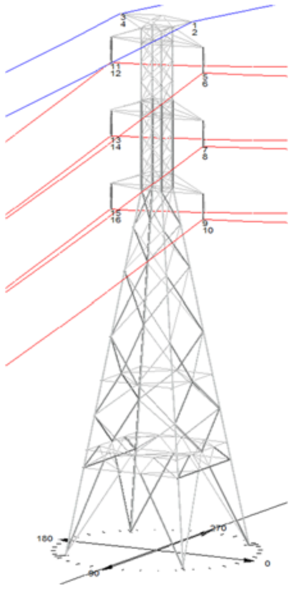


Figure 68: Vertical space consumed by suspension insulators

The primary purpose of hardware and fittings is to provide mechanical support between the overhead lines' conductor, support structure and insulators. Hardware is chosen to either restrict movement or to allow freedom of movement and must comply with an adequate mechanical strength rating for the specific application

The drawback of support structures using suspension insulators in a vertical formation is the significant increase in phase-to-phase spacing to accommodate the insulator, as well as increased spacing between the conductor and earthed support structure to accommodate insulator swing.

The use of V-suspension insulators can be applied to reduce swing and is likely to increase the conductor attachment height if suspension insulators are replaced by V-suspension insulators. In addition to V-suspension insulators, a Pivoting-V insulator set, in a pyramid shape, offers even further stability. When using rigid insulators, broken wire conditions are addressed during designs to ensure that insulators act as collapsible cross-arms to limit damage to structures.

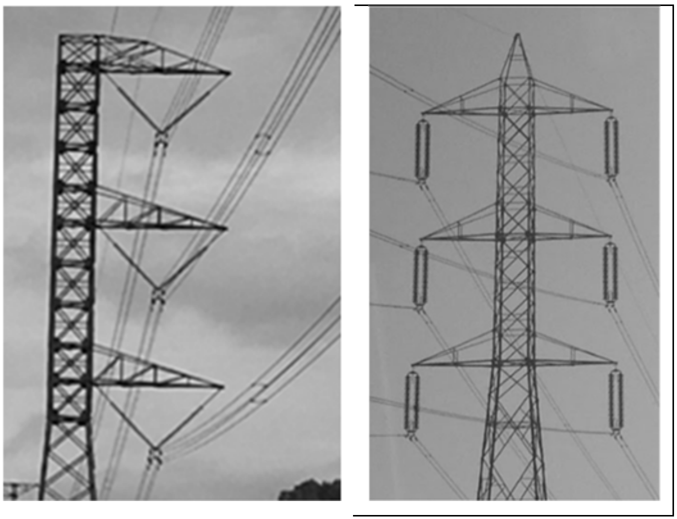


Figure 69: V-Suspension (left photo) and suspension (right photo) insulators

Figure 70 shows a case where an intermediate pole is well within its loading limits, but the insulators failed when strung with twin Chickadee conductors. The insulator fails under icy conditions and wind in a normal to all surface's direction.

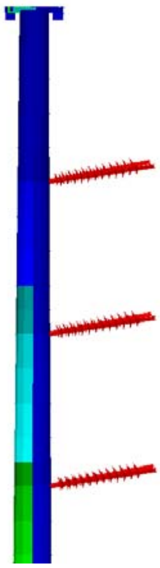


Figure 70: Insulator overloading

For the case in Figure 70, higher MDCL rated post insulators were specified for implementation, and an alternative would be to use braced insulators.

Braced insulators are a combination of suspension- and post-insulators and offer increased mechanical strength when compared with post insulators only. This increase in mechanical strength would result in a possible longer span if the post insulator were the limiting factor. The increased strength also allows for use with bundled or heavy conductors.

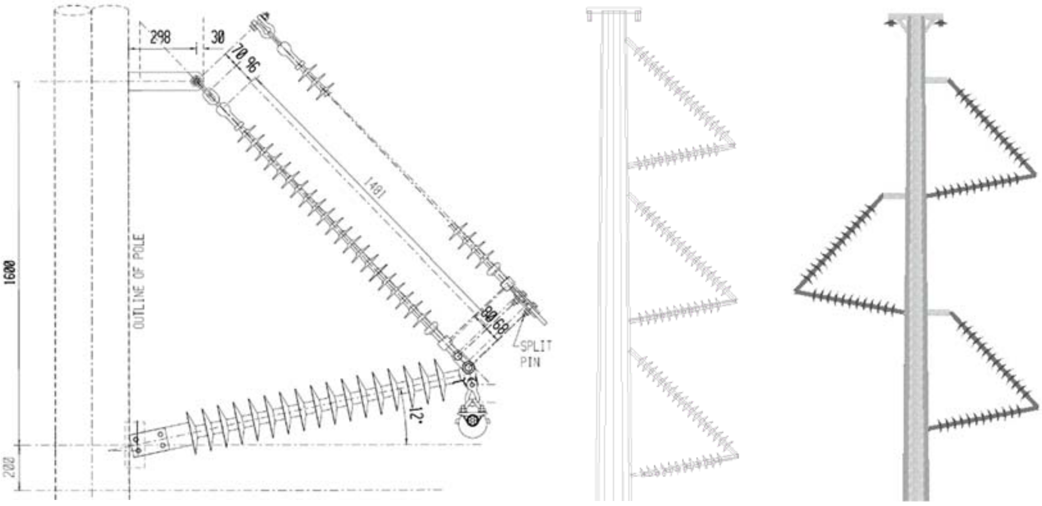


Figure 71: Braced post insulators

Inter-catenary suspenders are insulator applications to increase conductor clearance resulting in an increased thermal rating of the feeder.

From the electrical clashing span formulas discussed for a 132 kV line with a phase-to-phase clearance of 1.2 m, the maximum span lengths, based on the electrical span, is between 510 m and 560 m and a maximum sag of 18.2 m at a C value of 1800 for an H-pole structure with 4 m horizontal spacings between phases. For a compact horizontal conductor arrangement, the phase-to-phase spacing can be decreased using mid-span, inter-phase, insulators.

Insulated cross-arms can be used on structures such as H-poles to increase the clearance buffer and by doing so, allows the re-templating of a line at higher operating temperatures.

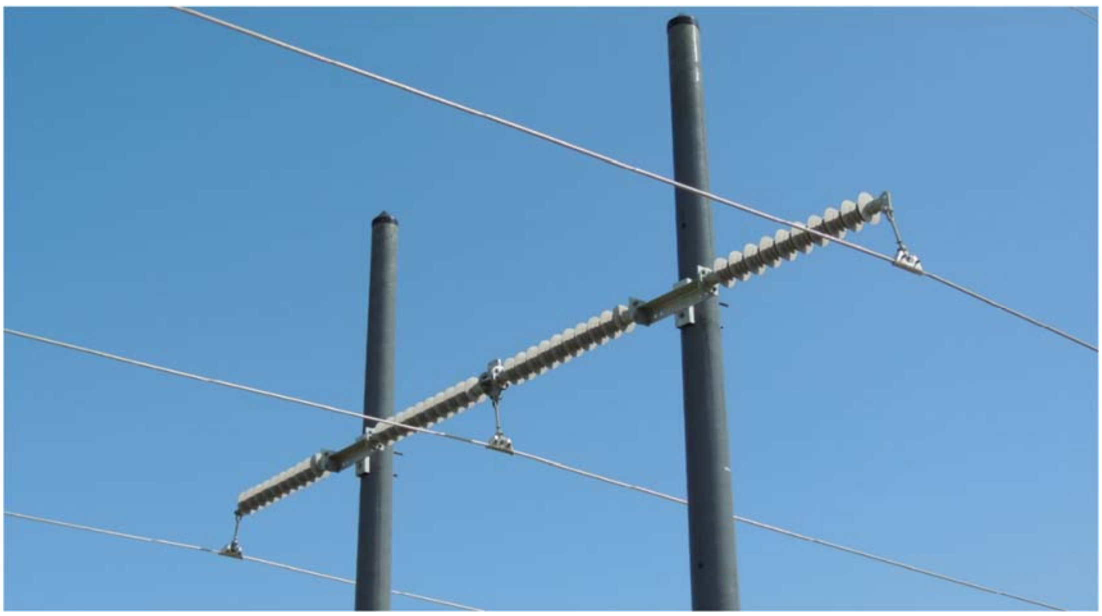


Figure 72: Insulated cross-arm on H-pole [122]

Although conductor clashing allows for over 500 m spans, for a typical 132 kV H-pole structure the conductor attachment height is approximately 13.6 m, which restricts the allowable span within the allowable clearance, tension, vibration and 70 °C thermal limits to 270 m for Chickadee conductor. The typical length of a 132 kV long-rod insulator is 1480 mm from ball to the socket. Increasing the thermal rating of the line by increasing clearance can be achieved by replacing un-insulated cross-arms and suspension insulator with insulated cross-arms. By removing the 1480 mm suspension insulator and installing an insulated cross-arm, the allowable sag is conservatively increased from 6.87 m to 8.03 m with the corresponding templating temperature increase from 70 °C to 110 °C. Although clearance is maintained at the higher operating temperature, the effect of the higher temperature on the conductor and fittings must be thoroughly investigated.

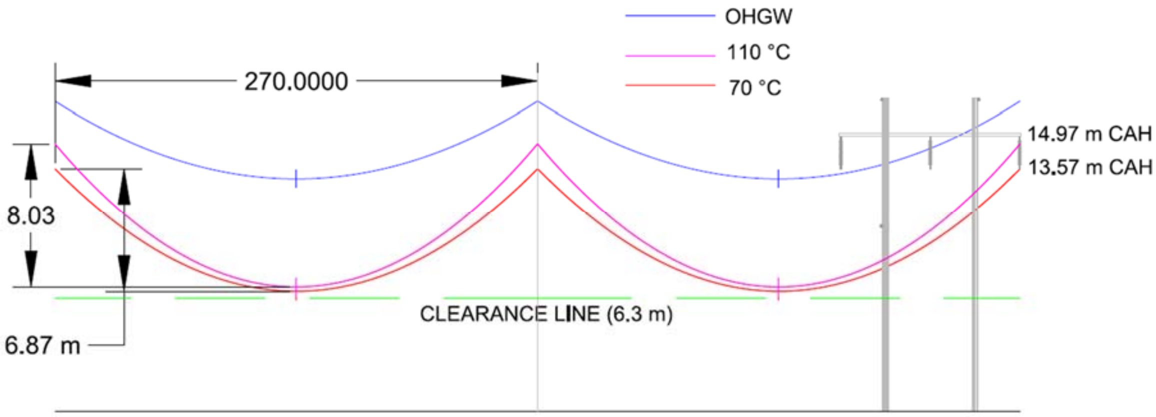


Figure 73: Increase clearance by replacing X-arm

Line voltage can be increased on existing lines by using midspan insulators. Installation is possible using “live-line” methods:

Figure 74: Installation of inter-phase spacers or mid-span insulators [122]

By removing suspension insulators to be replaced with rigid alternatives, conductor swing is decreased. The reduced swing reduces the conductor position under blow-out or maximum wind conditions, the clearance to earthed structures is reduced, and the rigidification of the insulators allows for compact line designs and possibly higher voltages on the same structure.

Suspension insulators can be applied to increase conductor clearance. A method of inexpensively increasing clearance is the use of intermediary catenary suspenders. Other than increasing the capacity of a line, this method offers a solution where infrastructure is established below a power line resulting in clearance violations. Intermediary suspenders or suspension insulators are connected from the earth conductor to phase conductors imposing an uplift to the phase conductor. With the conductor being supported by the overhead earth wire, with a high steel content, most of the conductor weight is transferred from the conductor to the shield wire resulting in the temperature effect on sagging of the conductor becoming less influential. It is estimated that the conductor current can be increased by as much as 40% at a tension increase of 15% to 17% above EDT [123], with a minimal cost implication. Figure 75 illustrates the increase in clearance, allowing for higher operating temperatures:

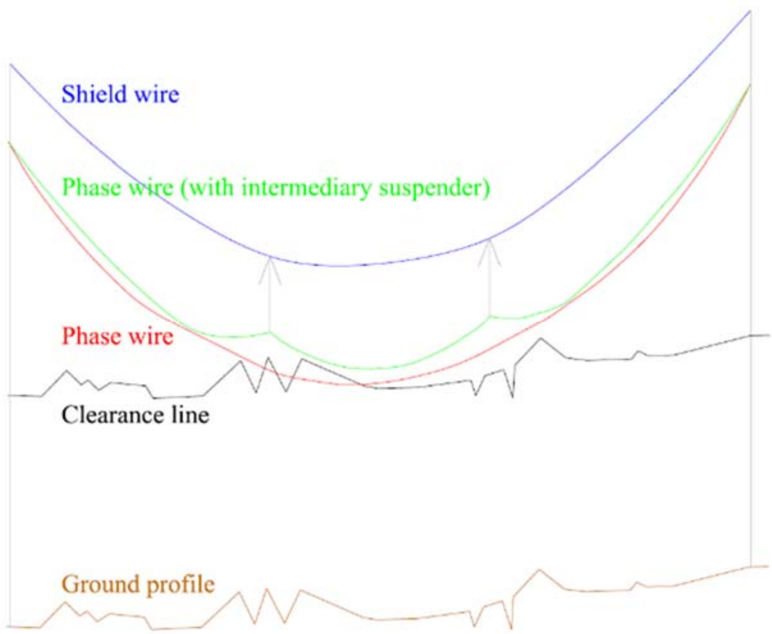


Figure 75: Inter-catenary suspenders [123]

Another passive device that induces negative sag is the sagging line mitigator (SLiM) [124]. The SLiM device can support the full breaking load of the conductor and is designed to decrease sag as the conductor temperature increases. Reducing sag with increasing temperatures is achieved through an automatic mechanical actuator. The working principle of a SLiM device is to mimic, but reverse, the axial thermal expansion of a catenary. As current passes through the actuator of the SLiM device, the actuator shrinks when heated and expands when cooled. The thermal expansion within the actuator of the SLiM device is amplified by hardware such as levers, cogs, and gears.

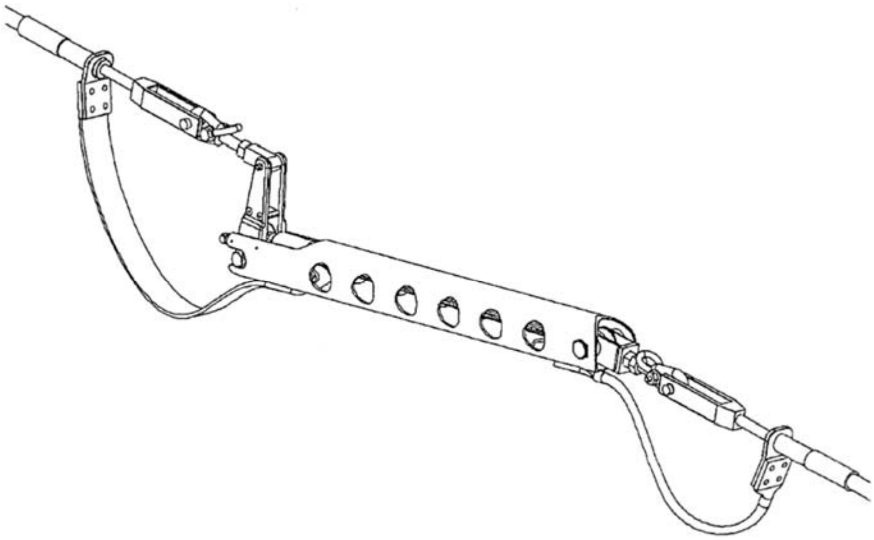


Figure 76: US patent image of a sag compensating device for suspended lines [125]

The summary below provides an overview of aspects reviewed, which are specific to overhead power lines, for the increase in power transfer.

2.5.2 Summary

Lines can be rerated using new theoretical approaches, re-tensioning of lines may also result in a further uprating. The maximum line ratings can be achieved by real-time temperature monitoring. Significant capital expenditure costs can be deferred by using a probabilistic and real-time monitoring approach.

- Firstly, an accurate load profile is required to determine the expected routine load and emergency load. Actual weather data must be obtained. Together herewith, survey methods are deployed to determine the actual line profile and conductor temperature at the given load and weather conditions.

- From the above, the line profile can be determined for various temperatures identifying spans limiting the line's thermal rating. If clearances must be increased, the most cost-effective solution must be determined.

- Real-time temperature sensing can be used to monitor and manage the line.

Although it is possible to rebuild lines under specific conditions, a complete line rebuild may be prevented if the existing structures' mechanical loading capabilities can be enhanced. By increasing the structures mechanical loading capabilities, it becomes possible to restring with larger or heavier conductors, or it can be possible to add one or more subconductors.

Structures can be enhanced through mechanical modifications, such as the extension of the middle cross-arm for vertical conductor arrangements. The middle cross arm extension will prevent phase clashing if galloping occurs and brings the straight-line vertical conductor geometry closer to a side-way delta configuration. Changing the geometry from vertical to delta will increase the line's surge impedance loading.

When evaluating alternative conductors with software packages such as PLS CADD, conductor seed files (.wir) from various manufacturers can be helpful to optimise potential solutions, due to variance in properties for the same type of conductor.

Rerating can increase the power transfer capability of overhead power lines up to 30% reasonably inexpensively when compared to new infrastructure. Methods of increasing thermal ratings by increasing overhead catenary clearance includes the use of inter-catenary suspenders, insulated cross-arms, re-tensioning with sag adjustors, excision of minor conductor lengths, grading of dirt to reduce the natural ground level, and the use of "V" insulators.

Structures can be strengthened to accommodate larger size conductors, a drastic increase in power transfer capabilities can be achieved by reconductoring towers with higher temperature conductors or conductors with superior characteristics.

Increased power transfer can be achieved by adding additional circuits to double-circuit structure footprints. This will be possible using CHS towers. Multiple circuits on a double circuit structure footprint can achieve n-2 operational contingencies, which would allow the upgrading of structures without total shutdowns. Additional expertise will be required from construction and maintenance teams. Terminating to substations with multiple circuit towers will be challenging. If additional circuits are added to existing lines, the structural foundations and strength capability needs to be thoroughly investigated.

Specialised HTLS conductors offer a potential solution more cost-effective than a full rebuild.

From [82], it is concluded that the methods for uprating include:

a Increase the maximum allowable conductor temperature for the existing conductor system;

b Replace the existing conductors with larger single conductors;

c Add a second conductor or more conductors to make a conductor bundle;

d Re-conductor with equal diameter High-Temperature, Low-Sag (HTLS) conductors;

e Probabilistic ratings;

f “Ambient-adjusted” ratings, and

g “Dynamic” ratings.

From [126], the implication of line design variations on SIL, corona, mechanical loading and thermal rating is summarised in Table 20. OHL electrical performance optimisation is achieved by varying the line impedance through reducing feeder resistance, increasing feeder susceptance and decreasing feeder reactance.

Table 20: Varying line design relationships [126]

Variation	SIL	Mechanical loading	Thermal rating	Corona
Phase spacing decrease	Good	Good (minor effect)	Neutral	Bad
Diameter bundle increase	Good	Bad (minor effect)	Neutral	Bad
Large area conductor (fewer conductors)	Bad	Good	Bad	Bad
High steel content conductor	Neutral	Bad	Good	Neutral

2.6 Underground power cables

When comparing overhead power lines with underground cables, both have advantages and disadvantages, depending on the circumstances in which they are applied. In South Africa, at the subtransmission voltage level, most feeder systems are overhead power lines. Due to the initial capital costs and historically high costs of cable, the installation thereof is limited and mainly constrained to high density, high operational risk and high property value areas. In South Africa, subtransmission cables are installed in the Johannesburg CBD for City Power of Johannesburg, Pretoria for City of Tshwane Metropolitan Municipality, various areas for City of Ekurhuleni Metropolitan Municipality, Vereeniging and Vanderbijlpark for Emfuleni Local Municipality, Kroonstad for Moqhaka Local Municipality, City of Cape Town and Sasol Industries, to name a few. The following international trends are worth mentioning [127]:

- Since the 1890s no overhead lines were built in New York City;

- Singapore’s feeders are 100% underground;
- All of the Netherland’s distribution feeders are underground;
- Since 1992 Belgium has banned overhead power lines;
- Between 1997 and 1999 Denmark replaced six 132 kV overhead lines with two new 400 kV cables;
- France’s policy is to have 25% of high voltage lines underground following winter storms in 1999.

As above, advantages and disadvantages are subject to circumstances. According to an international survey by Cigré Working Group B1.07 [70], 6.6% and 2.9% of feeder circuit lengths were underground cables at the time for voltage levels respectively between 50 kV and 109 kV, and 110 kV and 219 kV, of which 72% were cabled with extruded polymeric insulation. It is unlikely that these percentages would have drastically changed since 2007. Therefore, this research is focused more on overhead power lines than underground cables. Underground cables are manufactured with either copper or aluminium conductors, of which polymeric insulation is most common in subtransmission networks [70]. Also based on the above survey, where cables are considered throughout this research, the focus will be on extruded polymeric insulated cables.

Underground cable feeders are mainly used in high-density areas where space for overhead lines is limited; routes traverse high-value properties; severe meteorological conditions frequently damage OHLs, or OHLs are regarded as non-aesthetical with too much of a visual impact on the surroundings. As a result of insulating conductors in cables, phase spacing is drastically reduced when compared to OHLs. Insulated cables are much safer than overhead lines, but this safety comes at a significant increase in initial capital investment cost.

Criteria influencing the selection of the appropriate cable includes environmental considerations, ampacity, mechanical strength, and cost.

Table 21: Advantages of underground cables are [127]:

• Aesthetical implications are minimised, following installation, compared to overhead power lines;	• Minimal lightning risks compare to overhead power lines and not affected by ice, snow, rain, wind, dust, and smoke;
• EMF levels are low and can be contained, at additional costs;	• A higher level of safety during and post-construction.

• When not considering the cable sealing ends, the cable has no corona discharge creating audible noise, no frequency interference because of screening;	• Not as likely to cause bush fires, except for extraordinary cases such as a fault not being cleared, resulting in catastrophic damage to the cable and accessories;
• Minimised land use following installation;	• Not as influential on property valuations.
• Less affected by corrosive environments and severe climatic conditions such as ice storms, hurricanes, and tornados;	• Not as severely impacted by bush fires;

Table 22: Beneficiaries with cables [127]

BENEFICIARIES				
Benefit Type	**Utilities**	**Customers**	**Residents**	**Wider Community**
Reduced electricity price	✓	✓		✓
Reduced transmission losses	✓			✓
Lower maintenance costs	✓			
Improved electricity service		✓		
Reduced storm damage	✓	✓		✓
Reduced accidents (Inc. wildlife electrocutions)			✓	✓
Improved views / property values			✓	
Health & Environment (e.g. noise, EMF's, vegetation management)			✓	✓

Table 23: Disadvantages of underground cables (adopted from [127]):

• High initial capital investment cost (difficult to accurately determine a lifecycle cost);	• Soil thermal conditions may change over time failing such as in Auckland [3];
• A slight decrease in the cost differential between the overhead power line and underground cable over time (i.e. the cost of copper and aluminium seldom plunges);	• With proper tariff structures the cost of electrical energy increases (3-5% higher in the UK and 16% higher in Italy for undergrounding of all lines);
• Network strengthening cost and capital contributions cost is higher;	• Use of maintenance holes or tunnels may be required, not ideal working conditions;
• Difficulty in locating faults, specifically for pressurised cables;	• Trenching must be continuous and could damage sensitive areas or require the use of expensive directional drilling;
• Long outage times in case of a fault;	• Linkage to high voltage DC lines;

In addition to the listed disadvantageous cables have a high capacitance to earth, which limits the maximum cable length to below the maximum length of overhead power lines. However, the main disadvantages of underground cable installations, as opposed to overhead power lines, is the initial capital investment cost.

2.6.1 Cable design

The high capacitance of cables results in high inrush current into the cable and a high charging current for the cable. The two main limiting effects due to cable capacitance is the Ferranti effect and charging current. The Ferranti effect is when the receiving end voltage rises above the sending end voltage during no-load or lightly loaded conditions. Due to a high capacitance, the charging current of a cable can exceed the rated current. Capacitance increases with the cable length, increases with the cross-sectional area of the conductive part and slightly decreases with an increase in voltage. The decrease in capacitance with an increase in voltage is due to thicker insulation and larger spacing between phases at higher voltages. However, higher voltages will result in shorter maximum lengths for cables with equal ratings due to higher charging currents [128].

The diameter of the conducting part of the cable, the distance between phases, and the distance between each phase and earth determines a cable's capacitance. The charging current of the cable is given as a function between the cable voltage and capacitive reactance and from Figure 77 the charging current for a symmetrical three core underground cable is [128]:

$$I_c = \frac{V_{ph}}{X_c} = \frac{V_{ph}}{2\pi f C} A \quad \textbf{(58)}$$

$$I_c = 2\pi f (C_s + 3C_c) V_{ph}\, A \quad \textbf{(59)}$$

Where I_c is the charging current, V_{ph} is the phase voltage, X_c is the capacitive reactance, f is the system frequency, C is the cable capacitance, C_s is the capacitance between the conductor and cable sheat, and C_c is the capacitance between conductors.

Figure 77 shows the simplified representation of a symmetrical three-core cable where A, B, and C are the three respective phase conductors and N the three-core conductor sheath.

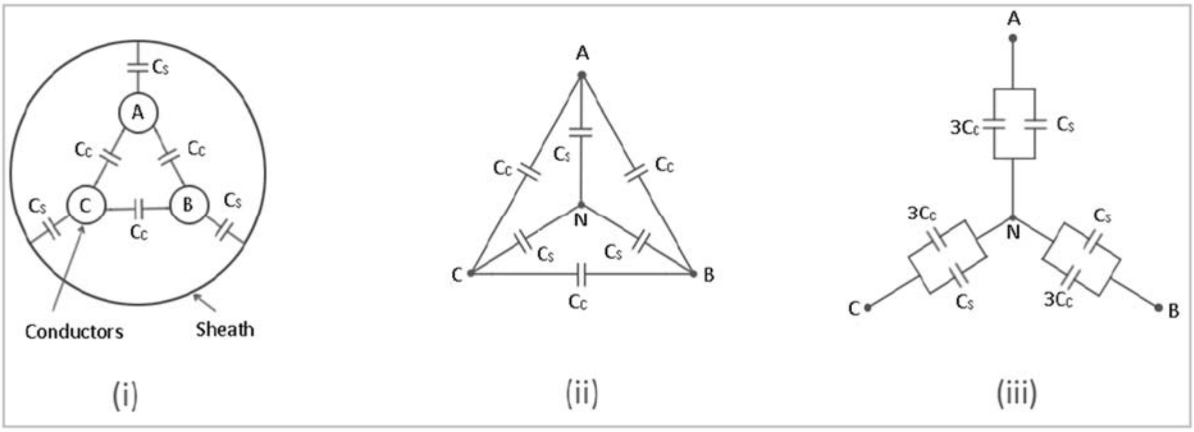


Figure 77: Capacitance of symmetrical three core underground cables [128]

Due to the relatively short lengths of subtransmission voltage level circuits (<100 km), the limitations imposed by cable capacitance is not as influential as for voltages above 132 kV. Figure 78 shows the maximum transfer capacity according to cable lengths at rated voltage, and with reactive compensation. The limitation on cable lengths as voltage increases is clear, the advantage of higher transfer capacity with HVDC cables when compared to HVAC cables is also evident.

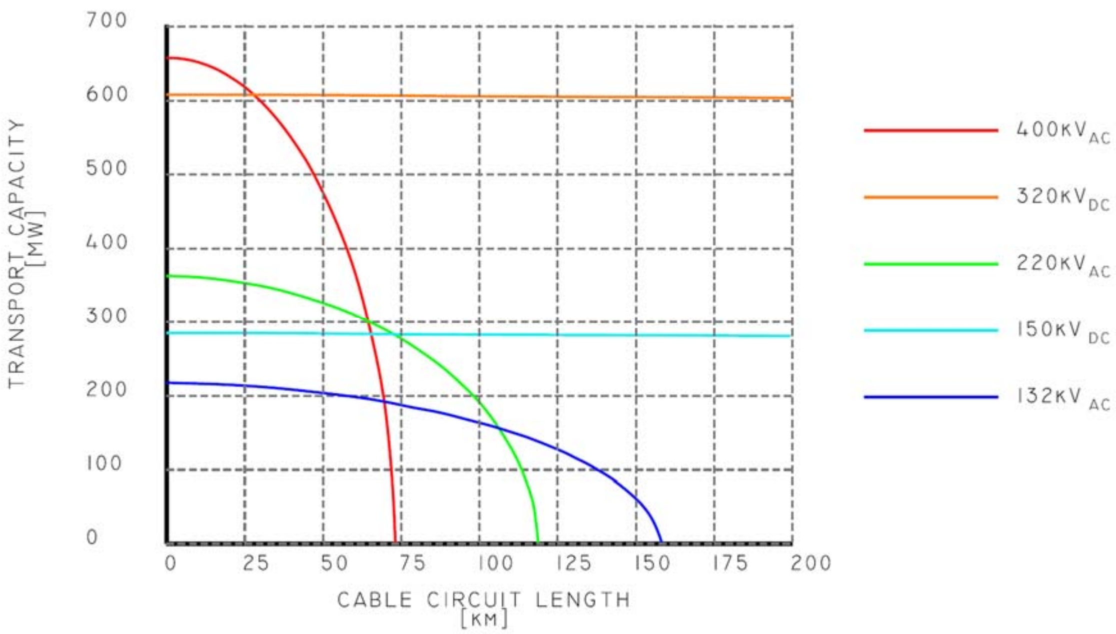


Figure 78: Transmission capacity versus length [129]

The general sentiment that power transfer capability increases with higher voltages is proven to be not true for HVAC cables [129].

Table 24 compares the various conductor configurations and benefits:

Table 24: System configuration vs characteristics [77]

Configuration	Effect on proximity effect	Effect on sheath losses	Effect on heat dissipation	Effect on interference
Trefoil vs flat	Trefoil unfavourable	Trefoil favourable	Trefoil unfavourable	Trefoil unfavourable
Trefoil touching vs spaced trefoil	Trefoil favourable	Trefoil unfavourable	Trefoil favourable	Trefoil favourable
Deeper below surface	None	None	Indifferent	Deeper favourable (1)
Double-point bonded vs single-point bonded	None	Double-point unfavourable	None	Double-point favourable
Cross bonding vs double-point bonding	None	Cross bonding favourable	None	None
Aluminium sheath vs lead sheath	None	Aluminium sheath unfavourable	None	Aluminium sheath favourable
(1) Applies only to objects at surface level - otherwise no effect				

From the manufacturers, tables are available for cables installed in ground, ducts or air, and depict various rating factors for the following laying conditions:

- Ambient air temperature
- Soil temperature
- Formation (flat / trefoil)
- Cable spacing
- Soil thermal resistivity

The respective rating factors are based upon the sheath bonding system in manufacturers' tables. Instead of using a manufacturer catalogue rating and applying derating factors, the specific cable design with installation conditions should be used to determine a more accurate rating for the specific cable. A different bonding method will affect the ampacity of the cable, as indicated in Figure 79:

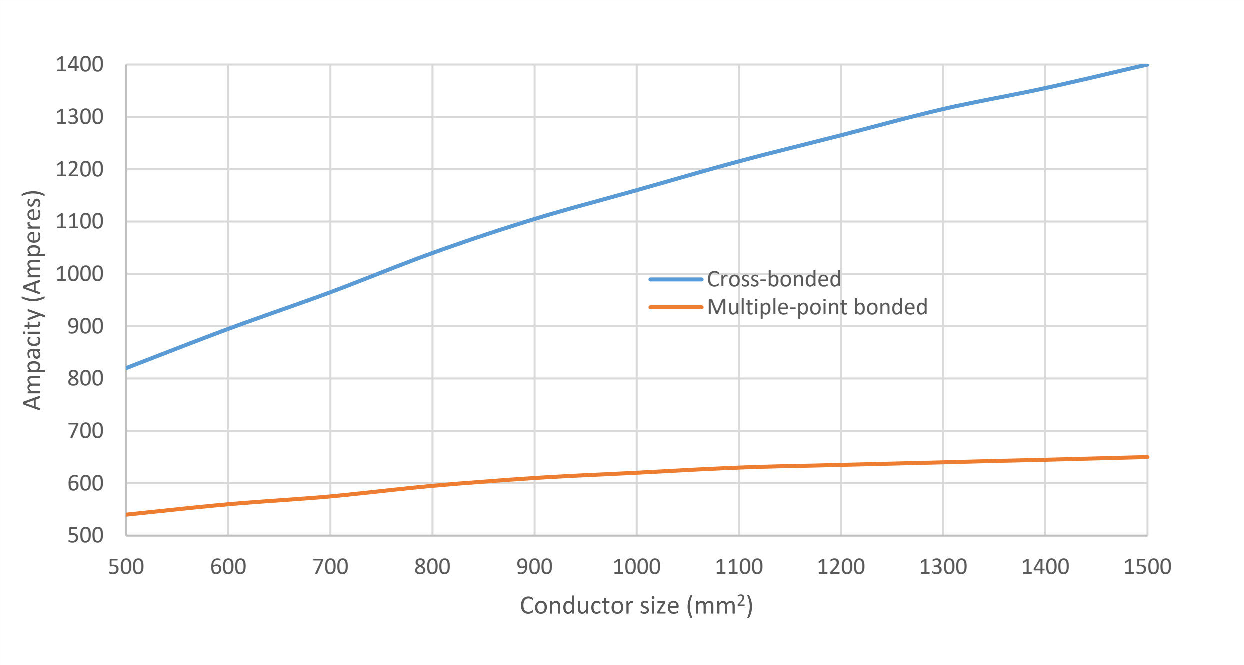


Figure 79: Sheath bonding and ampacity [130]

The major components that determine the conductor's thermal capacity or ampacity include:

- Conductor ohmic losses
- Insulation thermal resistance
- Pipe loss
- Meteorological conditions
- Conductor temperature
- Dielectric loss
- Surroundings' thermal resistivity, and
- Loading conditions.

Table 25: Bonding methods

BONDING METHOD	CABLE END STANDING VOLTAGE	SHEATH VOLTAGE LIMITER	APPLICATION
Single-end bonding	Yes	Yes	< 500 m
Double-end bonding	No	No	< 1 km and at substation connections mostly MV and LV cable installations
Cross bonding	Only at cross bonds	Yes	Yes

Flat cable formations are either cross-horizontal or independent horizontal arrangements.

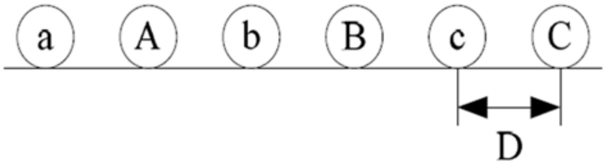


Figure 80: Cross-horizontal arrangement

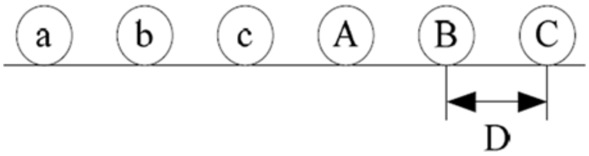


Figure 81: Independent horizontal arrangement

The cable arrangement depends on the feeder characteristics and transfer capacity required, by reducing the inter-phase spacing, induced voltages are reduced, but the thermal independence is also implicated, resulting in a lower thermal rating of the feeder. Trefoil or equilateral (spaced trefoil) provides for the lowest induced voltages.

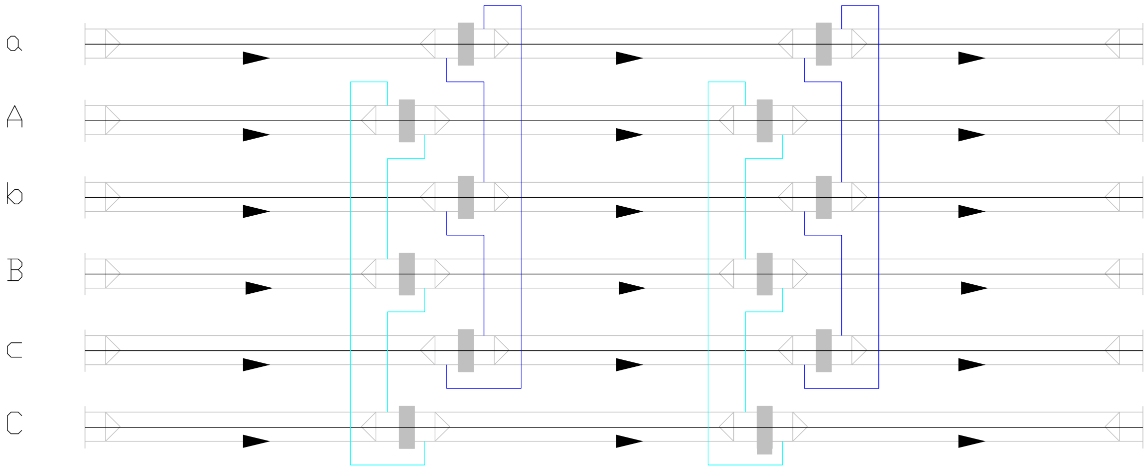


Figure 82: Cross-horizontal cable arrangement with sheath transpositions

Multiple circuits must not have a thermal effect on adjacent circuits to achieve the maximum thermal transfer capacity.

For an independent horizontal formation, the mutual coupling is most balanced in an ABC-cba formation opposed to ABC-abc. By using an ABC-cba formation, the current distribution is improved in the conductors, and shield/sheath losses are also reduced.

Laying cables in trefoil reduces the cable's magnetic field but is not ideal for heat dissipation. If cables are laid in a flat formation, the heat dissipation is easier to manage, but often requires specific bonding solutions.

2.6.2 XLPE cable

Extruded-dielectric cable primarily uses cross-linked polyethylene insulation (XLPE), although low or high-density polyethylene (LDPE/HDPE), or ethylene-propylene rubber (EPR) insulation is also used. XLPE has in recent years become a familiar acronym for cable installations and has become the market leader for new high voltage cable installations in South Africa. This is due to a much simpler design and installation method as well as reduced cost when compared to other types of UGC systems. The acceptance of XLPE cable systems into the market did, however, have hurdles to cross due to some initial quality problems. XLPE did overcome the quality issues and became very popular with the introduction of full hermitic moisture barriers. All modern XLPE high voltage cable systems for new installations in South Africa are equipped with longitudinal water blocking capabilities. Longitudinal water blocking capabilities are achieved with a layer of water-swellable tape designed to suit the conductor geometry. With by far the majority market share in South Africa, XLPE is the only type of cable system to be considered for new in-ground high voltage cable installations as part of this study.

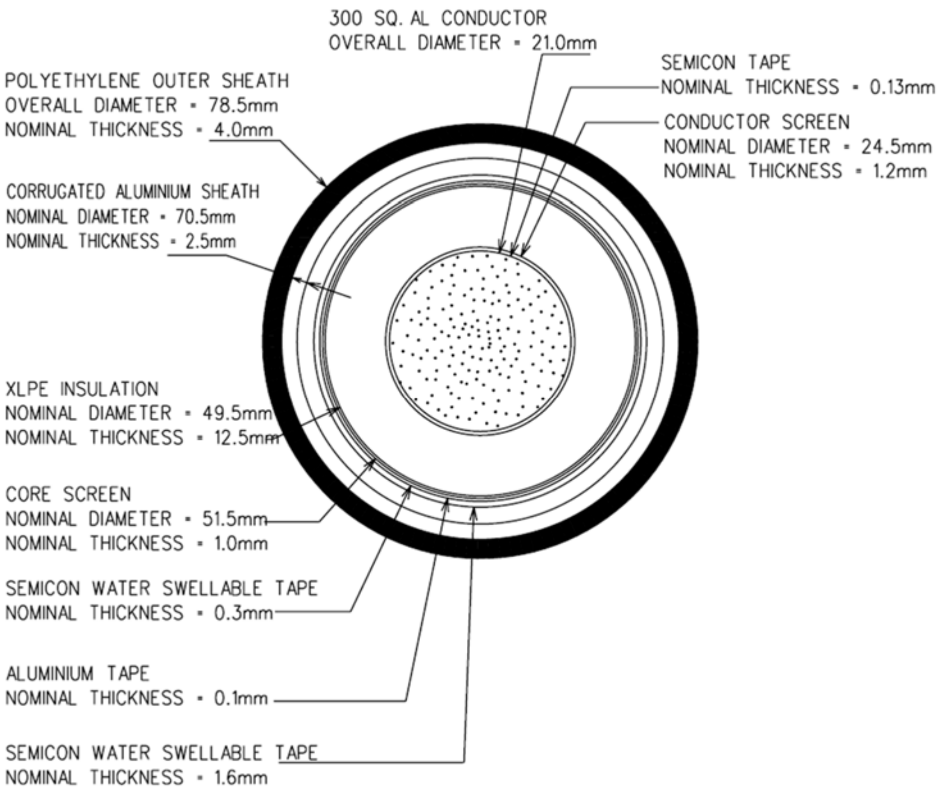


Figure 83: 66kV, XLPE, Single-core cable cross-sectional view [131]

2.6.2.1 Earthing and bonding

The calculation of sheath or shield voltages is required to reduce failures resulting from induced voltages and current. The IEEE Std 575-2014 “IEEE Guide for bonding shields and sheaths of single-conductor power cables rated 5 kV through 500 kV” is used a guide for these calculations.

Most high voltage XLPE cables specified for installation in South Africa have corrugated seamless aluminium (CSA) sheaths for mechanical protection. The CSA sheath contributes to the mechanical protection of the cable system. During operations, a voltage is induced into the metallic sheath as a function of the operating current. To minimise the sheath voltage for reduced failures and safe operation, various bonding methods are implemented to reduce the induced voltage.

The metal sheath of a cable is not unlike a single transformer winding or coil, through which current can pass. With single-point bonding, one end of the cable sheath is earthed and a voltage is induced in the cable sheath at the other cable end. Similar, mid-point bonding will result in voltages at both cable-ends. If bonded at both ends, voltage is induced and currents will flow. For both-end bonding, the highest sheath voltage will be in the cable centre. With cross-bonding, the currents per phase are 120° out of phase, and in an ideal situation, the sum of all currents should be zero. By using smart bonding methods circulating currents, overvoltage and losses are reduced. Smart bonding methods consider all bonding methods together with the use of sheath voltage limiters.

2.6.2.1.1 Both-end bonding

Bonding and earthing at the two extreme ends of a cable section reduces induced voltages and there is no standing voltage at the cable ends. No sheath voltage limiter is required. This is typically applied for short sections of cable (rarely applied to HV cables).

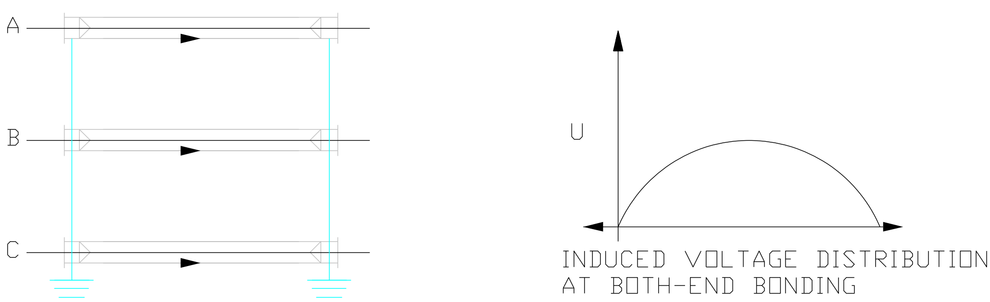


Figure 84: Both-end-bonding and sheath voltage [132], [133]

2.6.2.1.2 Single-end bonding

With the sheath earthed and bonded on one end of the cable, standing voltages are present at all other points and the highest is at the non-grounded cable-ends. Sheath voltage limiters are required to reduce the standing voltage. The method is generally applied for circuit lengths shorter than 1 km.

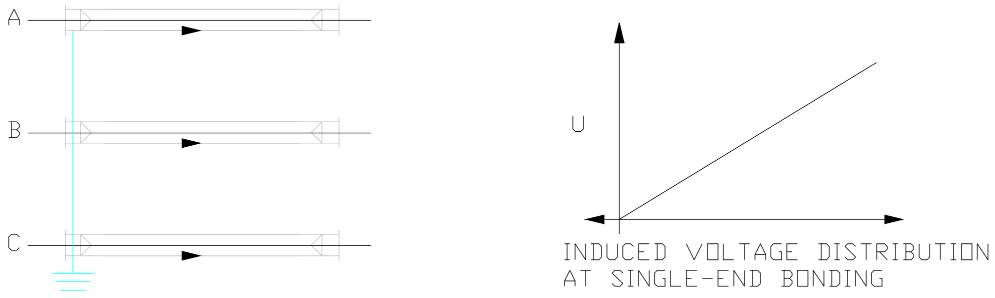


Figure 85: Single-point-bonding and sheath voltage [132], [133]

2.6.2.1.3 Cross-bonding

Cross-bonding requires the feeder cable to be separated into three minor sections. Standing voltages are present only at the cross-bonds. Sheath voltage limiters are required at the cross-bonds. This method is applied to long sections of the cable where cable joints are required.

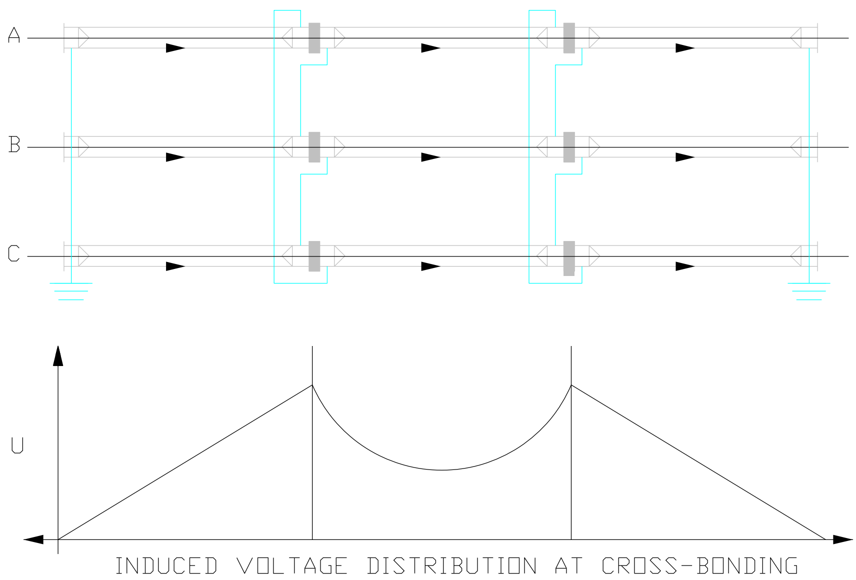


Figure 86: Cross-bonding and sheath voltage [133]

The various bonding methods are combined depending on the number of minor cable sections.

The bonding methods can be improved by transposition of the cable; the effect of transpositions is reduced with shorter lengths of cable and depends on the cable installation formation.

2.6.2.2 Thermal rating by the formation

The ampacity of XLPE cable is limited by the maximum allowable conductor temperature during operation. The thermal resistance and heat transfer or dissipation from the cable into its direct surroundings, the conductor electrical losses, and dielectric losses directly affect the conductor temperature and therefore the thermal rating. The formation or geometry in which the feeder is installed causes variations in the conductor's capability to dissipate heat. The maximum thermal capacity is generally empirically calculated by the manufacturer under the conditions of certain assumptions such as maximum ambient temperature, soil thermal resistivity, installation depth, and a unity load profile. Further derating factors can be applied based on the cable spacing and formation or geometry.

Where load profiles and cycles are available, cables can be uprated from the standard manufacturer catalogue values. Further uprating is possible through FEM analysis.

2.6.2.3 Auxiliary equipment

Auxiliary equipment for extruded cables is far less than what is required for OHLs. OHLs have an extensive bill of materials per structure, whereas underground cable auxiliaries are mostly limited to the joint positions and cable ends. The auxiliary equipment required for feeder cables (excluding the construction phase) is listed in Table 26.

Table 26: Auxiliary equipment for extruded cables

Link Boxes	Support structures and clamps
SVLs	Tape (fibre filament)
Bonding leads	Cable Sealing Ends
Earth / Ground continuity conductors	Surge Arresters
Thermal rated backfill	Pilot cable / fibre
Concrete slabs for mechanical protection	Fibre duct
Ducts and thermal conductive filling (bentonite)	
Joint bay maintenance holes	

For liquid-filled cables, the associated hydraulic auxiliary equipment is required. However, liquid-filled cables are no longer manufactured and therefore hydraulic auxiliary equipment is only maintained or replaced when faulty.

2.6.3 Summary

To increase the thermal rating of cables, limited options are available:

(a) Determine emergency or short time ratings for known load profiles;

(b) Apply special, low thermal resistivity, backfill material such as screenings, fluidised thermal backfills and low thermal resistivity soils;

(c) Integrate fibres into cable feeders for dynamic temperature sensing;

(d) Use dynamic temperature sensing for a real-time thermal rating.

2.7 Chapter summary

This chapter outlined the relevant topics and equipment or material characteristics that are fundamental, or influential, to increase the power transfer of subtransmission systems. Such fundamental topics vary in nature from physical characteristics to factors such as planning.

Due to increased loading of power systems over time, attention must be given to power system planning, with an emphasis on the reliability of supply. The loss of reliability of supply has severe safety, socio-economic, financial, logistic, and other implications. The importance of planning is to address performance at an early stage as planning serves as a roadmap to possible solutions that can be considered.

Planning is influenced by the technical characteristics and equipment properties that can be applied as possible solutions. This chapter addressed the objective of providing the technical background of practical considerations, power system modelling, emulation parameters, techno-economic assessment methods, and key features of overhead power lines and underground cables.

From a technical perspective, the background illustrated that conductor geometry significantly influences capacitive and inductive reactance. As shown, to simulate power systems, the conductor geometry is required, and the basic subtransmission line parameters must be determined. This chapter summarises high-level approaches to increase the power transfer of subtransmission systems.

This chapter presented how non-technical aspects contrast the technical aspects and impede some technical solutions. Therefore, property rights, environmental factors, safety, health and aesthetics must be factored in when considering solutions. Land must be used effectively, especially in developed areas, to deliver cost-effective solutions. Technical and non-technical aspects are interdependent. To investigate the intrinsic land requirements for subtransmission systems boundary EMF, corona, noise, and accessibility must be reviewed. Environmental factors directly influence the technical performance of subtransmission lines. These environmental factors are solar radiations, air or soil temperature, thermal resistivity, humidity, altitude, wind, ice, soil properties, vegetation, topography, corrosion, and wildlife.

The factors outlined in this chapter are used to evaluate the enhancement options to increase the power transfer capabilities of subtransmission power systems. This chapter presented the fundamental topics. In the next chapter, these fundamental topics are applied to unrelated case studies, to determine the significance of specific solutions to increase power transfer.

CHAPTER 3 – Investigation and review

This chapter contains case studies to review and explain increased power transfer options applied in context. The fundamental topics of the previous chapter are applied in different case studies. Although all topics and fundamental principles cannot be covered and applied in a single case study, the case study research design aims to incorporate a wide variety of the subservient topics reviewed in the previous chapter.

Over and above the basic methods reviewed in the previous chapter to increase power transfer, this chapter will also investigate unorthodox approaches to strengthen the subtransmission system by increasing power transfer to a specific zone. The focus of increased power transfer remains on subtransmission lines, rather than terminal equipment.

Terminal equipment connects subtransmission lines to nodes. For terminal equipment, such as substations, the general performance indicators are functionality, operability, maintainability, and expandability. Although it comes at a cost, most substation challenges in terms of ratings and space can be solved by deploying HYB, CAIS, or GIS technology, occupying a smaller footprint than conventional AIS substations. The area required for a GIS substation can be less than 20% of the area required for a conventional substation, depending on the layout [45]. Space-saving can be further increased by building a GIS substation in multiple levels through vertical expansion (above ground and underground); medium voltage switchgear can be installed in a basement, power transformers at ground level, and GIS switchgear on the first-floor level. The cost of GIS has proven to become more competitive in recent years [18]. Substations are not considered in detail as part of this study.

As previously stated, alternatives to XLPE cable are not considered for underground applications. In addition to those reviewed in Chapter 2, Chapter 3 outlines unusual methods of increasing power transfer, such as specific overhead conductor applications, high surge impedance loading of lines, AC to DC conversion, Flexible AC Transmission Systems (FACTS), and high phase order lines.

The content of this chapter links to the preceding chapter as marked in Table 27:

Table 27: Chapter 2 and 3 linkage

	Practical considerations	Power system modelling	Techno-economic assessment	Overhead power lines	Underground cables
OHL conductor evaluation				×	
Surge impedance loading				×	×
AC/DC Conversion				×	
Case 1 - Strengthening and grid expansion	×	×	×	×	×
Case 2 - Rebuild and compact AC OHLs				×	
Case 3 - Subtransmission system reinforcement	×	×		×	×
Case 4 - Weak grid	×	×	×	×	

The next paragraph examines higher capacity OHL conductors and is followed by the previously mentioned unusual methods of increasing power transfer, before proceeding to case studies.

3.1 OHL conductor evaluation

High-temperature conductors can transfer more power with reduced sag when compared to conventional ACSR, due to a lower coefficient of thermal expansion as presented in paragraph 2.2.3.1 “General aspects of OHL conductor”.

Transmission line loading, considering sag calculations and high-temperature conductor technologies as investigated by Slegers [134], compares various types of high-temperature conductor with ACSR. The study shows the cost of high-temperature conductors may vary between 1.3 to 6.0 times the cost of ACSR. Mostly due to improved sag capabilities, it is proven that uprating of existing lines with high-temperature conductors will provide significantly higher power transfer capabilities than uprating with ACSR.

In 2012, Cigré published research completed by ESB International in Ireland titled “Introduction of high-temperature low sag conductors to the Irish transmission grid”. In this specific case, the study concluded that high-temperature low sag (HTLS) conductor plays an essential and cost-effective role in the uprating of existing power lines. However, it is noted that HTLS conductors present additional design and installation challenges in comparison to conventional conductors [135].

The review and evaluation process for a case by ESB International [135] considered ACSS, G(Z)TACR, (Z)TACIR, ACCC and ACCR under various criteria as possible conductors for uprating. The critical criteria for evaluation were primary and secondary technical merits, economic advantages, and risk mitigation. The review process, as described by Geary et al. in [135], can be generally applied to uprating projects.

A study by Kavanagh and Armstrong [83] showed that by using HTLS over ACSR for uprating, based on a peak load over 25 years, a 60% saving is achievable when taking into account the initial cost plus lifecycle losses. To fully benefit from HTLS with uprating, the initiation construction cost should be less than the lifecycle cost of losses after uprating. Figure 87 presents the total lifecycle cost for conductors considered in [135].

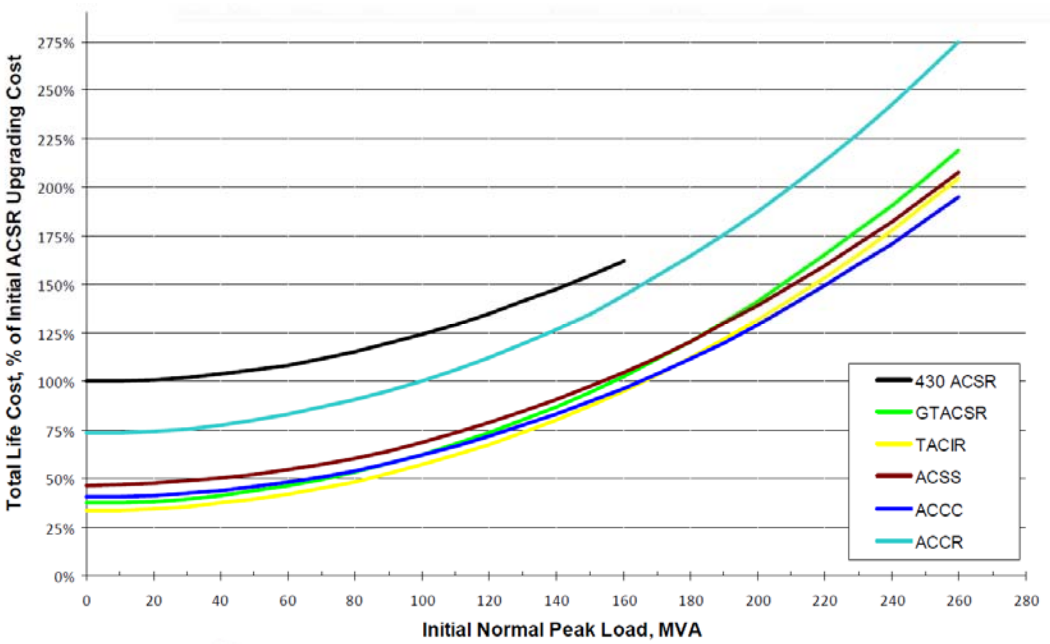


Figure 87: Conductors lifecycle cost [83]

When considering Figure 87, it can be concluded that for a specific peak load, the most cost-effective conductor for uprating of existing lines varies between TACIR and ACCC. Despite having sophisticated installation techniques, GTACSR was chosen due to technical reasons and its track record [83].

A reference case study by [46] concludes that the outcome of a single uprating study provides limited inference to other scenarios. However, the results that were obtained during the case study indicating the following guidelines [46]:

- Re-rating is a very low-cost option to increase power transfer capacity through theoretical uprating or re-tensioning. Re-rating can be a cost-effective first step approach to defer more expensive upgrades.

- Upgrading line voltage or possibly re-building a line with a heavier conductor can be more cost-effective than restringing with HTLS conductors if the network can sustain lengthy interruptions and the substation can accommodate a simple voltage upgrade.

- HTLS has expensive initial capital investment cost, but GZTACSR, ACCC and ZTACIR provide the best total increase in power transfer within the allowable existing infrastructure limits.

- Per MVA GZTACSR (Gap–type) was the most economic HTLS conductor for this case.

- The total cost of losses correlates to total resistive losses, most notably for increasing the rating of existing ACSR, the total investment cost aligns with other options because of the operation cost.

From the considerations in Chapter 2 and the results of [46], [75], [83], and [136], a feasible approach to uprating is:

(a) The theoretical increase of capacity such as a probabilistic rating;

(b) The increase in thermal capacity be means of rerating, attainable through conductor re-tensioning or mechanical changes. A variety of mechanical changes are possible such as insulated cross-arms, insulator change, tower reconfiguration, inter-catenary or intermediary suspenders, negative sag devices and general hardware changes;

(c) When the conductor's thermal capacity is saturated, investigate the increase of thermal capacity by rebuilding the line with a similar conductor, but in larger bundles;

(d) Finally, consider reconductoring with an HTLS conductor or rebuilding the line.

A complete rebuild is not always required to increase the number of subconductors. An increase in subconductors is achievable by effective hardware solutions and structural strengthening.

Next, even higher power transfer is achievable by moving conductor positions and formation, to achieve high surge impedance loaded lines.

3.2 Surge impedance loading

Surge impedance loading is indicative of the maximum thermal rating of an overhead power line. However, feeders are not terminated at their surge impedance loading; the actual loading varies between light and heavy load conditions. Furthermore, power line lengths are fractions of a power frequency wavelength required to change the phase angle of the voltage or current by 360° [53]. The surge impedance loading is a simple method of evaluating the power transfer capabilities of different lines by using the line voltage and the impedance. The voltage profile of an uncompensated and lossless line with a fixed sending end voltage is depicted below:

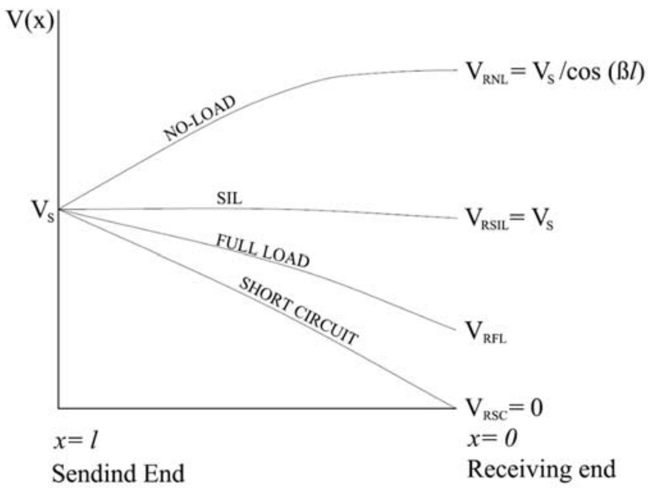


Figure 88: SIL Voltage profile [53]

V_s is the sending end voltage, l the line length, V_{RNL} is the receiving end voltage at no-load, $\beta = \omega\sqrt{LC}$ m^{-1}, V_{RSIL} - is the voltage when the line is terminated at its SIL, V_{RFL} is the receiving end voltage at full load and V_{RSC} is the receiving end voltage during a short circuit [53].

The surge impedance loading of a feeder line is determined by the following equation [137]:

$$SIL = \frac{V_{LL}^2}{Z_C} \quad \textbf{(60)}$$

Where SIL is the Surge impedance loading, V_{LL} the Line-to-line Voltage, and Z_c the feeder's characteristic impedance $\left(Z_C = \sqrt{X_L X_C} = \sqrt{\frac{X}{B}} = \sqrt{\frac{L}{C}}\right)$.

The characteristic impedance Z_C, is the square root of the series inductive reactance $(X = X_L = 2\pi f L)$ and shunt capacitive reactance $\left(B = {}^1/_{X_C} = {}^1/_{2\pi f C}\right)$ of the line multiplied.

The line configuration that will transfer the most power for a selected conductor can be determined by calculating the SIL. To increase power transfer capacity and achieve the highest SIL for a feeder, a decrease in inductance and an increase in capacitance will yield optimum results by reducing the characteristic line impedance.

When considering the voltage stability limit in the transmission line loading curve, the loadability curve can be extended as per Figure 89. The curve has been adjusted by compensating the line charging to zero.

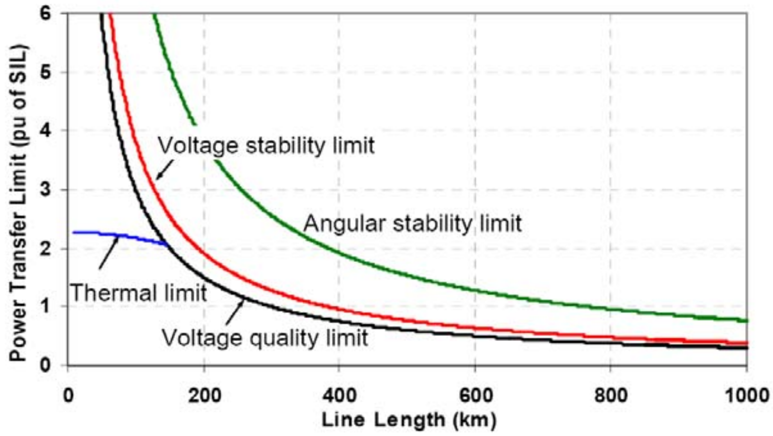


Figure 89: Extended power transfer limit [138]

For shorter subtransmission lines, the thermal limit of the line is the determining factor of the line power transfer capability.

The surge impedance of a line can be increased by reducing phase-to-phase separation, attempting to achieve a phase geometry as close as possible to a delta, increase the number of sub-conductors, and by increasing subconductor spacing. The OHL capacitance will also be increased by having the minimum allowable conductor ground clearance to assist with increasing the SIL.

From a case study at transmission voltages by Maphumulo, Stephen, and van Coller [137], high SIL (HSIL) OHL configurations achieve 29.2% reduction in inductive impedance, a 30.8% reduction in series resistance, and a 41.8% increase in susceptance. The change in reactive impedance increases the SIL of the specific line by 36.2%. Line losses are reduced by 34.5%.

By optimising sub-conductor spacing and geometry, the SIL of lines is further increased. According to Ghassemi [139], an increase of 40% above the base case is achieved by optimising conductor usage for high surge impedance loaded lines. An optimised location for six subconductors is shown in Figure 90:

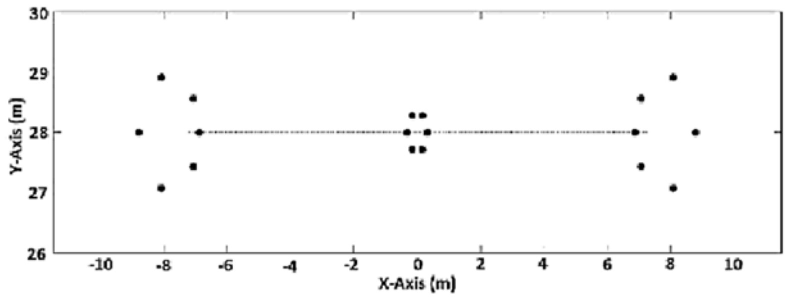


Figure 90: Optimised subconductor positions for HSIL lines [139]

Designing overhead power lines for HSIL offers a unique, cost-effective solution to accomplish maximum power transfer with subtransmission lines.

The 69 kV double circuit conversion to 138 kV, as shown in Figure 61 (page 93), sacrificed the n-1 criteria due to geometry constraints and the use of suspension insulators. The maximum power transfer capacity for the 69 kV to 138 kV conversion can be increased by more than four times that of the initial rating, without sacrificing the contingency. The capacity is increased and the contingency condition is not sacrificed by implementing a compact, low-profile, high-SIL design approach rather than standard cross-arms with suspension insulators. Such an increase is possible by doubling the voltage to 138 kV by using high strength post insulators, braced post insulators, or the smart use of hardware instead of suspension insulators, increasing the SIL by implementing an HSIL formation design, and increasing the current by more than double, by using ACCC trapezoidal wrap HTLS conductor. In short, the first substantial increase in capacity is by increasing the voltage (69 kV to 138 kV), the subsequent increases are achievable by compacting the line's phase geometry (HSIL), reinforcing or replacing the support structures, increasing the number of subconductors, and increasing the conductive area of conductors (cylindrical stranding replaced by trapezoidal wrap).

Through AC to DC conversion, overhead power line capacity can be increased beyond the yield provided by increasing voltage, using HTLS conductor, and designing for HSIL.

3.3 AC to DC Conversion

Most subtransmission systems are based on an AC design approach. Converting AC overhead power lines to DC can be implemented on existing AC infrastructure at similar phase-to-ground voltage clearance levels without significant adjustments to structures, but the cost of converter stations could render the conversion not economically feasible [48]. The relationship between AC voltage (V_{AC}) and DC voltage (V_{DC}) for comparable insulation levels is:

$$\frac{V_{AC}}{\sqrt{3}}\sqrt{2} \cong V_{DC} \quad \textbf{(61)}$$

The RMS current rating for DC is slightly higher (approximately 10%) than for AC due to the absence of frequency-dependent effects, furthermore, under heavily loaded conditions, an assumed 15% reactive losses in an AC system will be absent in a DC system with an estimated increase in power transfer of 180% when converting an AC system into DC [119].

AC-to-DC converter station cost can be reduced by using a monopole system with the earth as a return path, although this is economically attractive, there is a high risk of damaging underground services with a monopole system. A bipole DC system provides a power transfer increase of approximately 20% $\left({}^{2}/_{3} \times 1.8\right)$. Theoretically, for a tripole system, if pole one is positive with pole two and pole three negative, then pole one can be overloaded for a period with the overload transferred around poles employing bridges called the “hot potato system”, each pole/conductor sees the overload current for a third of the time [119].

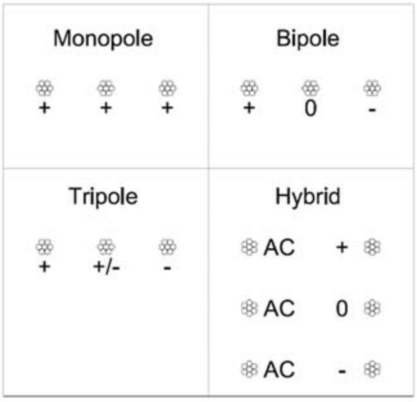


Figure 91: Possible AC/DC conversion arrangements [48]

No references could be found for DC subtransmission systems in South Africa. The high capital costs of converter stations and the additional losses with conversions makes this option unattractive in South Africa. In addition to HSIL, line parameters can also be adjusted to increase loading by using reactive compensation such as FACTS.

3.4 FACTS

Flexible AC Transmission Systems (FACTS) consist of static equipment and primarily power electronics, to enhance and control the power transfer of electrical grids by controlling one or more AC system parameters. Through series and shunt reactive compensation, FACTS can also reduce feeder losses. A parallel FACTS controller is a static var compensator (SVC) or a static compensator (Statcom). A series FACTS controller is a thyristor-controlled series capacitor (TCSC) or a static synchronous series compensator (SSSC), and a hybrid series and parallel compensator is a unified power flow controller (UPFL) [140]. Pilz [140] gives the maximum amount of active power that can be transmitted:

$$P = V_1 V_2 \, {}^{1}/_{X} \sin\delta \qquad \textbf{(62)}$$

Where P is the active power (W), V_1 and V_2 the voltage of the two nodes, X the reactive component between two nodes, and δ the phase angle between V_1 and V_2.

Care must be taken when applying this equation to sub-transmission systems. This equation is more applicable to transmission systems, where resistance can be neglected and where sending and receiving end voltages can be fully and independently controlled.

From equation (62), $V_1 V_2$ is adjusted by a parallel FACTS controller and X by a series FACTS controller. FACTS can control the following parameters as summarized in Table 28:

Table 28: Series and parallel FACTS controllers [140]

Parallel FACTS controller	Series FACTS controller.
Voltage control	Current control
Reactive power compensation	Reduction of transmission angle
Damping of oscillation	Damping of oscillation
Contribution to transient and dynamic voltage stability	Contribution to transient and dynamic voltage stability
Load balancing (decrease negative phase sequence)	Fault current limiting
Improvement of power quality	

3.5 Higher phase order lines

Higher phase order lines is an addition to compact lines for maximum power transfer by increasing the number of phases to more than three. This principle has been investigated for numerous years, but no reference to the construction of such lines in South Africa could be found, prototype 6- and 12-phase lines were built near Binghamton, New York. A practical application of a high phase-order line is the conversion of a double circuit line to a single circuit, six-phase line. If a single-circuit, six-phase line, is spread symmetrically around the peripheral of a circle, the resulting phase angles between should be 60 degrees. By increasing the number of phases, the conductor surface electrical field reduces, and the line can either be compacted, or the phase-to-ground voltage can be increased when compared to a double circuit line. By increasing the phase-to-ground voltage, the thermal rating increases linearly with the voltage, and the SIL increases with the square of the voltage [141].

Next, the available case studies are used to validate the antecedent fundamental concepts and appraisals.

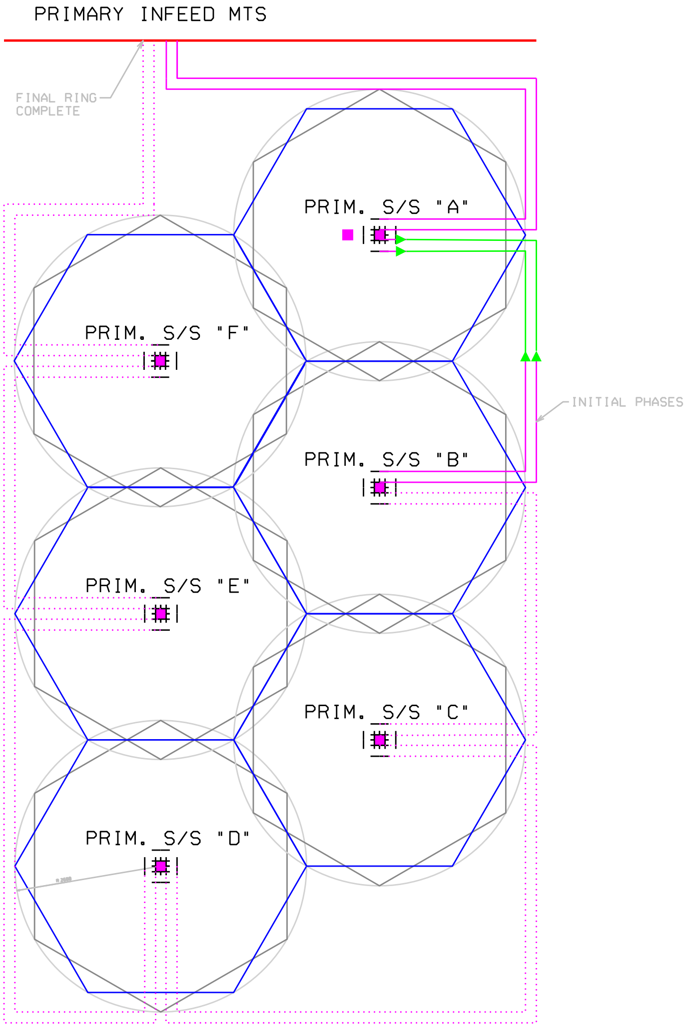
3.6 Case 1 – Strengthening and grid expansion

Case 1 considers the strengthening of a subtransmission system, together with the expansion of the subtransmission grid to unload existing infrastructure. The case involved the construction of a new MTS, and a new MTS infeed from another source, to unload existing transmission infrastructure. However, only the subtransmission aspects are considered as part of this study. For this subtransmission grid with an end-state voltage of 132 kV, an end-state capacity of 450 MVA must be available at any point within the subtransmission ring network. The 450 MVA rating per circuit is not difficult to achieve with overhead lines.

However, with buried cables, the cables' efficiency drastically decreases with an increase in conductor overall diameter, this is worsened by thermal coupling with more than one circuit.

3.6.1 Case 1 - Grid Planning

It is not uncommon for South African subtransmission grids to be subject to simultaneous outages. When possible, an n-2 contingency scenario can be designed to mitigate the risk of prolonged outages. A double circuit ring feeder with a double-busbar substation philosophy was applied with this case, to achieve an n-2 operational contingency. Another option to achieve an n-2 supply is a single circuit ring feeder system with interconnectors between substations. The case below shows that the initial planning of a subtransmission system can prevent possible future reliability and overloading problems before the event occurs.



The Main Transmission Station obtains a connection from the transmission grid at 275 kV, which is stepped down to 88 kV. In future, the 275 kV supply is upgradable to 400 kV, and the 88 kV network is upgradable to 132 kV.

During the initial phases, before the closing of the ring, the subtransmission system operates under an n-1 contingency with a rating of 150 MVA per feeder at 88 kV. Both circuits of the subtransmission ring feeder system have the same end-state thermal capacity of 225 MVA per circuit at 132 kV, individually loaded.

When the double circuit ring is complete, and the voltage is upgraded to 132 kV, the system will effectively comprise of two double circuit feeders per substation with a rating of 225 MVA per circuit. This allows for any two circuits to be out of operation without compromising supply to the remainder of the network and thus achieving the 450 MVA n-2 condition.

Figure 92: 450 MVA Subtransmission grid philosophy

Before implementing a grid planning philosophy, the property cost for the area under investigation must be considered.

3.6.2 Case 1 - Property cost

The property cost investigation is based on the Case 1 grid plan and actual load requirements. The double circuit subtransmission line is required to establish downstream capacity for ongoing development in the area and to reduce the load on other existing transmission level infrastructure. For this case, as shown in green on Figure 92, the section of the feeder between primary substation “a” and primary substation “b” was designed as a UGC, which transitions to an overhead line. The UGC section was implemented due to high property value in the area and constrained space where the typography did not suit an OHL. Portions of the UGC is installed in the shoulder of the road under the paved walkways, and within a servitude registered on the building restrictions between two neighbouring stands. The graph in Figure 93 shows the breakeven point between OHL and UGC for a property cost of R 473/m^2 at the time. The cable and overhead line costs given in Figure 93 are based on the actual costs after implementation.

Figure 93: Cable and overhead line cost vs property cost

For this specific feeder, the UGC cable infrastructure cost is roughly 4 times higher than the cost of the overhead line per kilometre. The OHL and UGC are designed for the same thermal rating. The property cost is for servitudes, and the transition yard costs are shared. The values illustrated will vary with time, based on inflation, exchange rates and indices.

Instead of registering a servitude for the entire route, the cost of the overhead power line section was reduced by using the median of a road for a portion of the OHL route. Likewise, the property cost for the cable portion was reduced by using the shoulder of the service roads adjacent to the planned provincial road.

To transfer the pre-determined capacity following the grid planning, and based on the selection between overhead or underground power transfers, the subtransmission feeder design must provide the required capacity.

3.6.3 Case 1- Thermal rating, corona, hardware, and practical considerations

The deterministic rating for Chickadee is 425 A, akin to a thermal capacity of 195 MVA. For the overhead line, a probabilistic rating of 560 A per Chickadee ACSR conductor provided the most cost-effective solution by using twin conductors, with a combined rating of 250 MVA, to ensure a thermal capacity of at least 225 MVA is provided. The twin conductor offers the added advantage of reducing the line losses when compared to a single conductor. At 132 kV, single Chickadee conductor has high surface voltage gradients. Therefore, Twin-Chickadee solves corona concerns. A vertical bundle reduced the line hardware cost and simplified the conductor stringing. Post insulators with higher than usual MDCL ratings provided a cost-effective alternative to braced post insulators.

The structures were designed fit for purpose. Monolithic steel poles provided a compact line while maintaining sufficient spacing between circuits to allow maintenance on one circuit while the other is energised. Due to limited space, the strain structures were self-supporting, and cross-arms were used to further reduce the double circuit angle-strain structures' footprint where needed.

The solution to this study was a new MTS infeed and "new-build" subtransmission feeders to de-load existing infrastructure. Bunting ACSR was a competitive alternative to Twin-Chickadee ACSR. However, Twin-Chickadee offered lower life-cycle cost and superior corona performance at 132 kV.

HTLS conductors and ACSR conductors operating at higher temperatures were considered, but the high capital investment cost did not justify the use of HTLS and the increased operating temperature raises the total operating cost of the line. HTLS conductors operated at higher temperatures are expected to be cost-competitive for restringing. Bear ACSR and Lisbon ACCC would transfer the required capacity at higher temperatures, in Table 29 the advantage of operation at a lower temperature is shown for a unity load cycle.

Table 29: Losses when operating conductor at high temperatures

Description	Lisbon ACCC	Twin-Chickadee ACSR	Bear
Aluminium area ratio	84.58%	72%	60.98%
Temperature to transfer 225 MVA	119°C	67°C	137°C
Current rating at 119°C	983 A	-	-
Current rating at 67°C	-	986 A	-
Current rating at 137°C	-	-	983 A
AC Resistance at 25°C	0.09099 Ω	0.0718 Ω (0.14354 Ω in parallel)	0.11181Ω
I^2R losses	360 kW	243 kW	465 kW
Total losses (20 years)	84 879 GWh	61746 GWh	107127 GWh

By using twin-conductor, in addition to reducing the surface voltage per phase, a much lower TOC is achieved. For lower load factors, the TOC saving will be less for the selected conductor. In terms of costs, the conductor's cost fraction is increased from approximately 9.67% to 17.64% of the CIC, by using twin conductor. The CIC is increased by almost 10% by using twin conductor and is recovered within the first year of operation.

The remainder of paragraph 3.6.3 defines the practical considerations to achieve maximum power transfer using underground cables.

At the time, UGCs with cross-sectional areas larger than 1000 mm^2 become even more costly than the already expensive cable installation. To transfer 225 MVA, the inter-phase spacing required for 100% load factor was too large to fit within the available space. Therefore, the spacing calculated for the 1000 mm^2, single-core, Aluminium, 132 kV cable, in flat formation, was based on a cyclic load, which yielded a sufficient transfer capacity. A FEM model yielded a capacity above 225 MVA. To achieve 225 MVA at 132 kV (984 A), per circuit, when applying the cyclic load and with the cable buried at 1.5 m with low thermal resistivity backfill, the inter-phase spacing and circuit spacing was determined. The results yielded an inter-phase spacing of 0.5 m and circuit centre-to-centre spacing of 3.4 m as illustrated by Figure 94. The spacing yielded thermal independence between phases and between circuits.

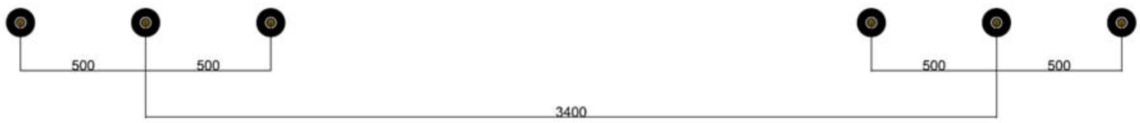


Figure 94: Cable spacing (independent horizontal arrangement)

The standard manufacturer catalogue rating, without derating factors or considering thermal interdependency between circuits, is 840 A in a flat formation, and 767 A in a trefoil formation. The catalogue ratings do not provide details of the bonding method to be considered. As shown in Figure 79, the method of sheath bonding influences cable ampacity. In addition to the bonding method, the sizing of the bonding leads must match the application. The bonding leads for this case were sized according to IEC 949:1990 for a maximum earth fault current of 40 kA:

$$I_{AD}^2 . t = K^2 S^2 \ln\left(\frac{\theta_f + \beta}{\theta_i + \beta}\right) \quad \textbf{(63)}$$

Where, I_{AD} is the rated RMS short circuit current (A), t the time duration (s), K and β the material constants, S the conductor cross-section area, and θ_f, and θ_i the final and initial temperature.

For a 40 kA phase-to-ground fault level, *K* = 4.119, 30 °C initial temperature and 250 °C final temperature, *β* = 234.5°C, for 3 seconds, the electrical equivalent copper area required is 366.8 mm^2. Therefore, a 400 mm^2 bonding lead was selected.

The design constructed divides the cable system into sections as per Table 30.

Table 30: Cable sections

MAJOR SECTION:	**2 km**		
	MINOR SECTION	MINOR SECTION	MINOR SECTION
CIRCUIT 1	0.67 km	0.67 km	0.67 km
CIRCUIT 2	0.67 km	0.67 km	0.67 km

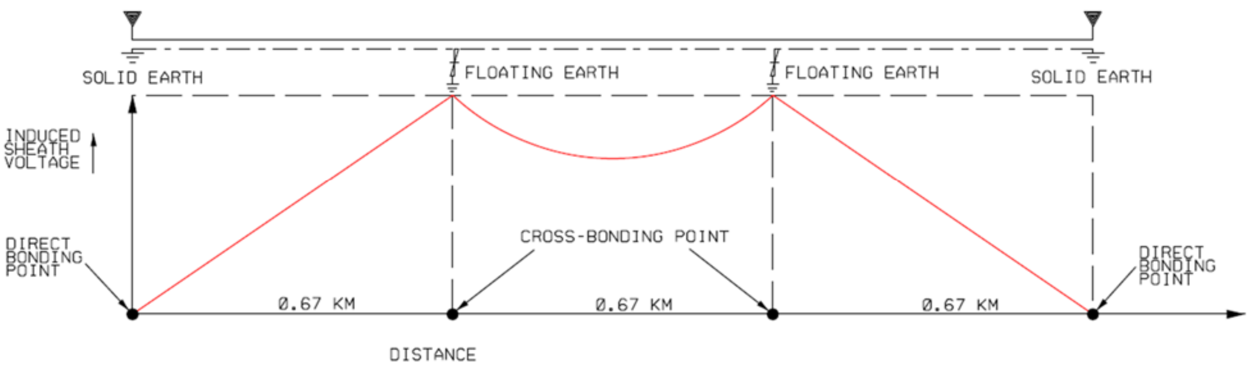


Figure 95: Cable system design – sheath cross bonding (proposed for concept design)

Given the short length of the cable and limited space at joint bays, there was no need to transpose cables due to only a small resultant voltage unbalance as shown in Figure 96. However, cross-bonding was implemented at joints to reduce induced sheath voltages.

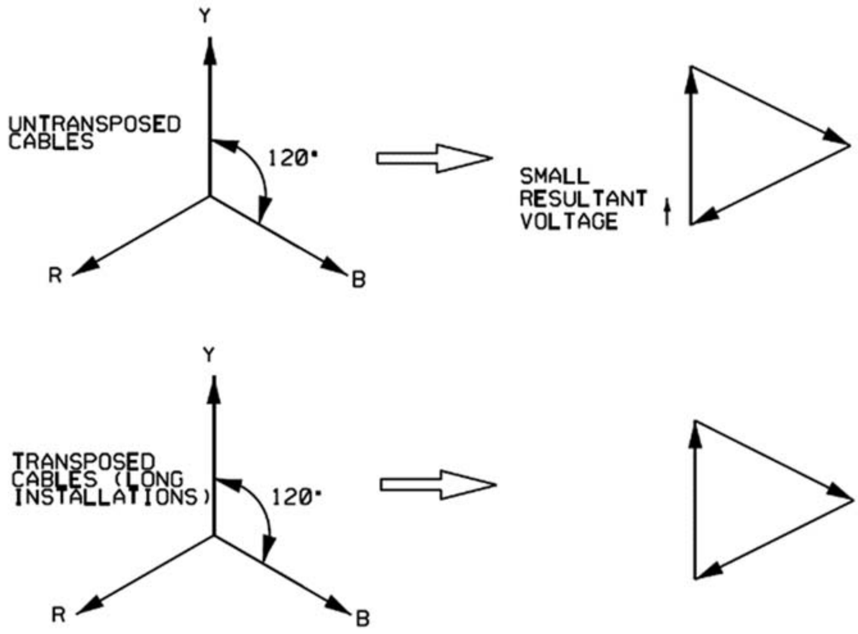


Figure 96: Transposition consideration for short cable lengths

The cable sheaths are bonded directly to earth at the cable sealing ends and cross-bonded with SVLs (floating earth) at the joint bays. Sheaths were bonded directly to earth at the cable sealing ends.

Provision was made for DTS to prevent a thermal runaway situation as occurred with the Auckland failure [3]. A distinct optical fibre cable was strapped to the centre phase of each circuit. In South Africa, although OPGW is commonly used, insulated cables incorporating fibre optics internally could not be found locally. The DTS monitoring is provided on top of the centre phase of each circuit, to measure the hottest external temperature on each circuit.

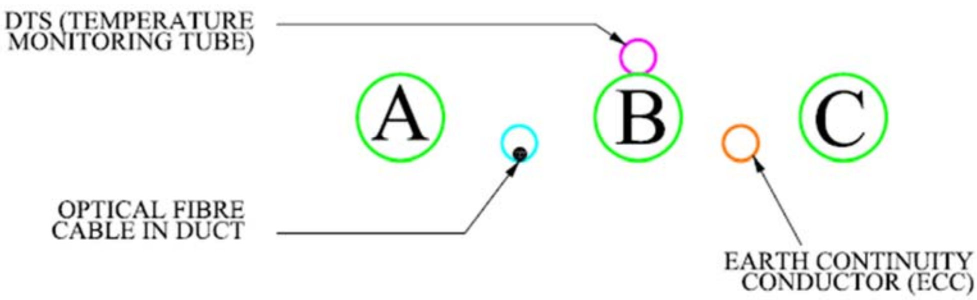


Figure 97: Circuit arrangement

Additional space is required at joint bays to retain thermal independency. Joints are staggered to save space, as shown in Figure 98.

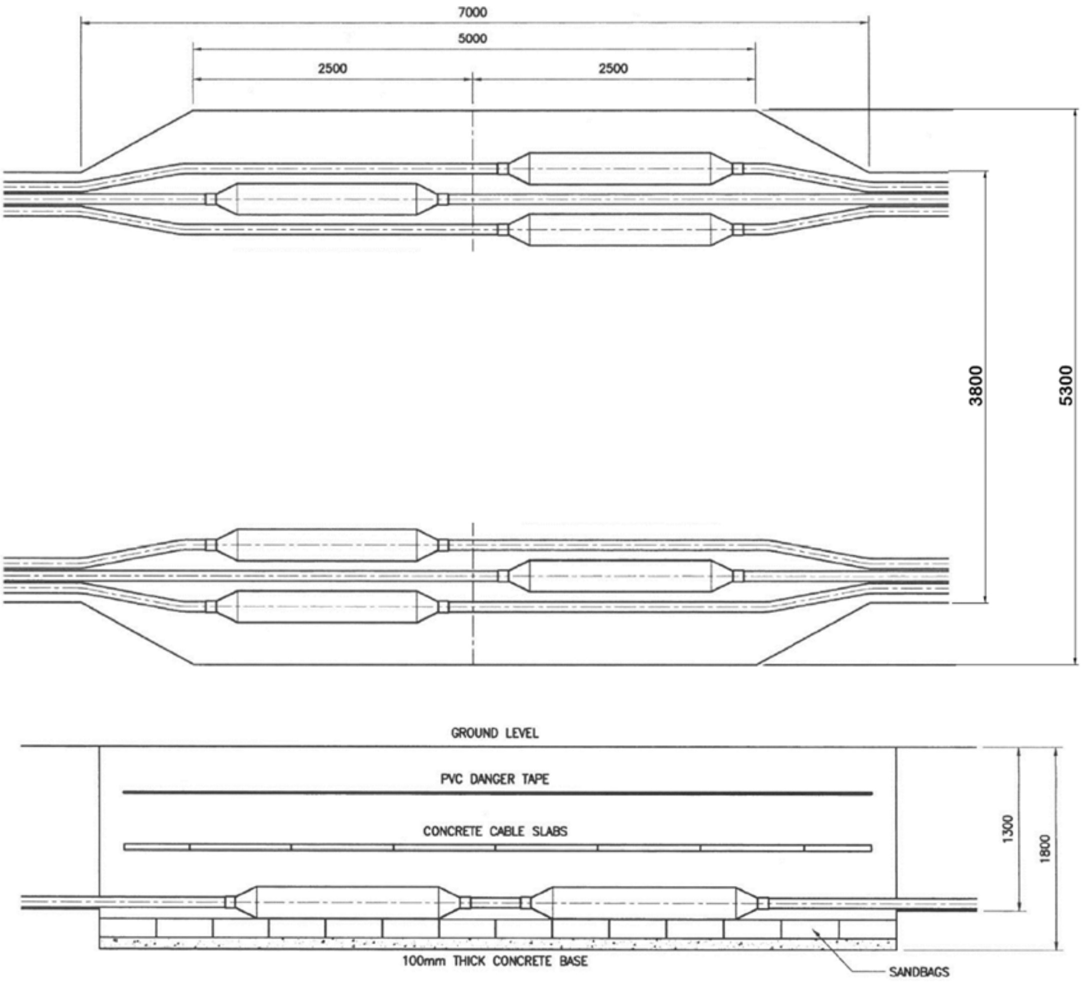


Figure 98: Joint bay layout

Link-box maintenance holes at joint bays were hardened as a theft deterrent. The maintenance hole lids were pre-cast, reinforced concrete, requiring a unique sling and a 1-tonne crane to remove the lids from the maintenance holes. The link-box layout is shown in Figure 99. The electrical design for the underground cable system is shown in Figure 100, which includes the section lengths, bonding, earthing, cross-linking, sheath-voltage limiters, earth continuity conductors, and surge arrestors.

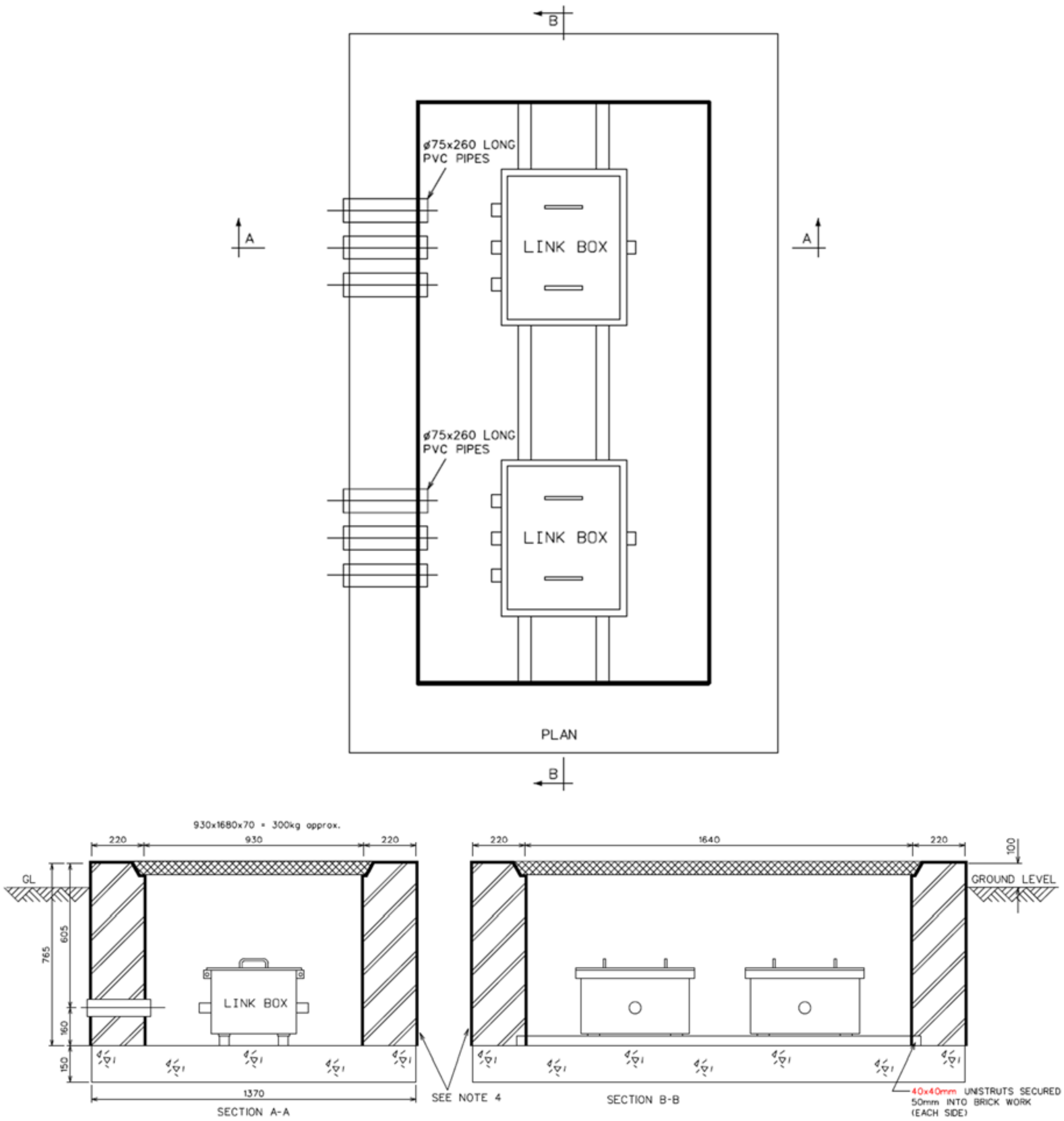


Figure 99: link box maintenance holes

MAJOR SECTION	2 km		
SECTION	MINOR SECTION	MINOR SECTION	MINOR SECTION
CIRCUIT 1	0.67 km	0.67 km	0.67 km
CIRCUIT 2	0.67 km	0.67 km	0.67 km

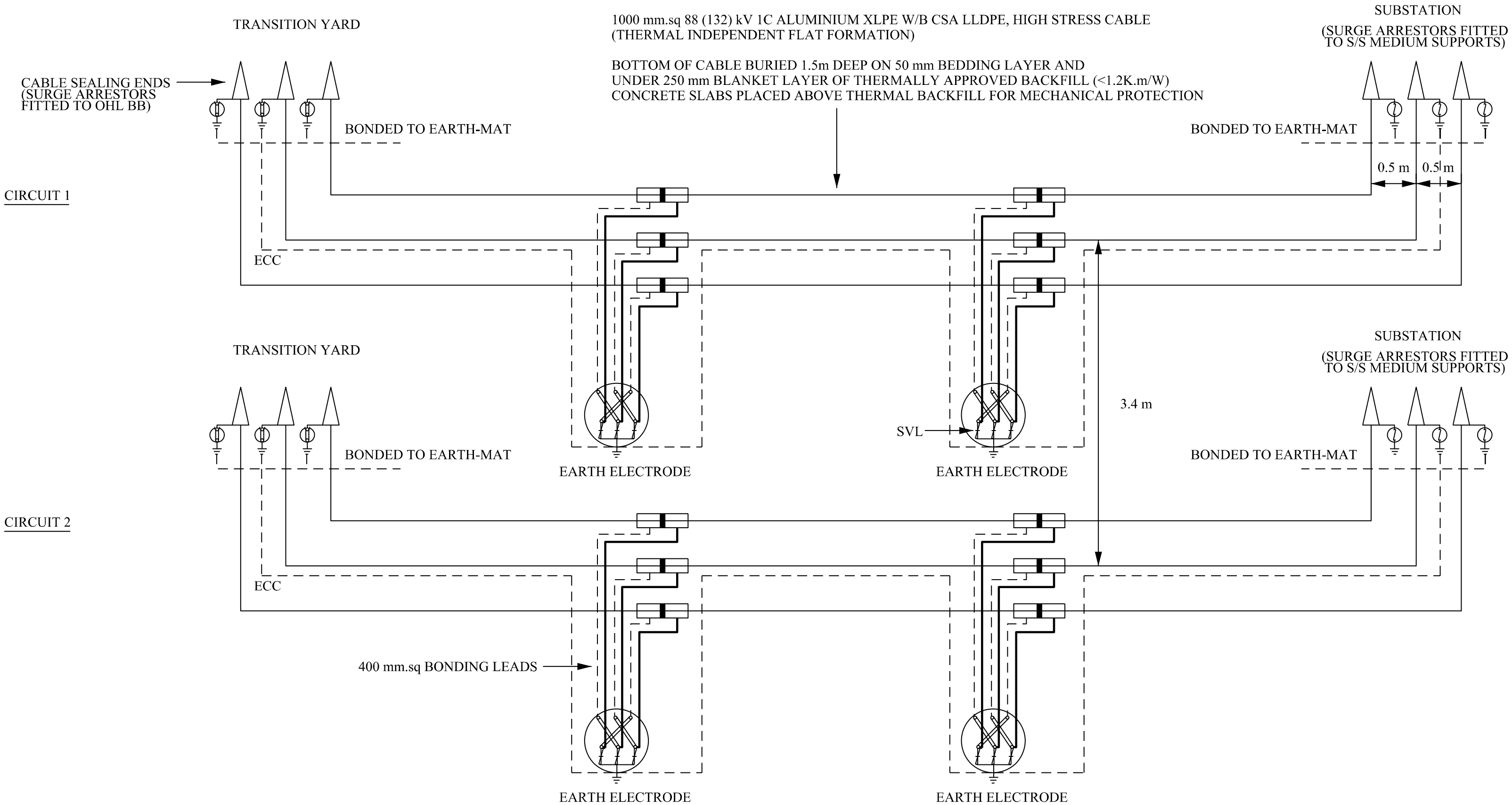


Figure 100: UGC installation design - electrical diagram

3.6.4 Case 1 summary and outcomes

Case 1 involved the establishment of electrical infrastructure into a greenfield area, and the greenfield area was zoned for high-density power requirements, within a metropolitan city. The following outcomes were achieved for this case:

- Effective grid planning can cater for load requirements over an extended period, supporting the importance of an electrical services master plan. The network can be capacitated in phases, starting with an n-1 supply ring, and an end-state n-2 double ring. Similarly, if the initial design allows, voltage levels can easily be increased from 88 kV to 132 kV or from 275 kV to 400 kV. To increase voltages, subtransmission transformers can easily be constructed with an internal change-over switch from 88 kV to 132 kV, other equipment should be designed for the highest voltage level with the implementation of the project.

- Non-technical aspects such as the space available and property cost play a key role with the selection of the technology type to be applied.

- For the full capacity transfer, a bundled overhead conductor was selected. For this new overhead power line, Twin-Chickadee ACSR offered the most cost-effective solution.

- The spacing and formation for thermal independency of the buried cable installation were determined through a FEM model, increasing the thermal rating by 29% (from 175 MVA per circuit to 225 MVA per circuit).

- A hybrid overhead power line to underground cable offered the most cost-effective and fit for purpose solution.

- Some of the technical aspects involved with an actual underground cable installation design were given. Buried cable projects at subtransmission levels are not regularly executed in South Africa.

The solution implemented started with the n-1 philosophy and unlocked prime-property for on-going developments. The n-2 double-ring solution will be the network's end-state configuration. The project was well executed and successfully delivers reliable power to an important economic node.

The next case is focused on an overhead power line rebuild, where a portion of the existing line route is constrained by space, due to an 11 kV distribution feeder constructed between the two existing subtransmission circuits.

3.7 Case 2 – Rebuild and compact AC OHLs

3.7.1 Case 2 – Background and problem

This case requires the complete demolishing of a section of the overhead power line, to be followed by a rebuild with a compact overhead power line. Fortunately, the existing infrastructure is not yet overloaded. However, the existing infrastructure will not be able to service the load in the near future, due to the 18 000-stand development to be supplied by Savanna City substation and the additional load by Jaguar substation in Lakeside (Vaal area). When the Savanna City substation load is added to the existing 88 kV subtransmission network without any upgrades or expansions, the contingency load ability for sections of the network is lost.

The supply to Savanna City forms part of an existing subtransmission ring supplying Seboka, Roshnee, Ironside and the future Jaguar substations, partially constructed with Tern-, Wolf-, and Panther ACSR, at templating temperature of 50 °C (various older lines in South Africa were rated at 50 °C).

With the addition of new substations, the existing subtransmission ring cannot sustain the load requirements. Although the specific subtransmission ring under investigation is rated at 50 °C, the rating was increased with the application of a probabilistic approach. Furthermore, the upstream Main Transmission Station (MTS), Snowdon, must reduce its load to the Vaal area, to avail capacity to other supply zones. The various changes at the subtransmission level results in a higher fault level throughout the subtransmission network. The shield wires for the entire ring must be upgraded to accommodate the end-state configuration's high fault levels.

The primary issue resolved with this case is the constrained space for a section of line required to strengthen the supply into a specific zone (Savanna City supply), while maintaining contingency of supply. Low-cost housing developments, such as Savanna City, cannot absorb the cost of an underground cable. Alternative routes are not available, resulting in that the ring supply must be routed as a double circuit for a portion of the ring. The new lines to Savanna City will belong to Eskom, who primarily use standard equipment for new infrastructure. However, the Eskom standard and mechanical load-tested, cylindrical poles and hardware are not suited for heavy conductors such as Tern ACSR.

To establish the bulk supply from Ironside to Savanna City and Jaguar substation, a portion of the Ironside to Roshnee overhead power line will be demolished. The demolished Panther ACSR section of the line allows space for the construction of a new Tern ACSR line, from Ironside to Savanna City. This results in a portion of the ring being upgraded to Tern ACSR. After that, the remainder of the ring is upgraded to Tern ACSR when Jaguar substation is constructed, and a new Tern ACSR line is constructed from Kookfontein MTS to Jaquar SS.

3.7.2 Case 2 – Compact rebuild, upgrade, and strengthening

To accommodate the anticipated future loads and for the transfer of the ring from Snowdon MTS to Kookfontein MTS, the preferred solution for the supply to Savanna City is a rebuild, OHL extensions, and upgrading the Panther ACSR sections of the subtransmission ring to Tern ACSR. A portion of the new overhead lines to Savanna City requires the rebuild of an existing section of line with a compact design, to optimise the use of available space, before the lines' extension through completely new routes.

Figure 101 is the end-state condition for the deloading of Snowdon MTS to Kookfonein MTS and shows each stage for the additions of Savanna City and Jaguar substations, adding load to the existing ring. Stage 1 includes a compact rebuild on a section of an existing Roshnee-Ironside line and an extension of the ring to Savanna City. Stage 2 requires the Panther ACSR section of the ring to be upgraded with Tern ACSR, and stage 3 is a new line from Kookfontein MTS to Jaguar Substation, an extension of the Tern ACSR ring from Savanna City SS to Jaguar SS, and upgrading of old shield wires. The stage 1 compact rebuild section is on the Roshnee-Ironside-Savanna Tee segment of the ring.

When stage 1 on Figure 101 is implemented, the Roshnee-Ironside-Savanna Tee OHL becomes overloaded on Panther ACSR, when the Kookfointein-Seboka line is off. The normal probabilistic rating for Panther ACSR is 441 A (templated at 50 °C for the old line). With the Kookfontein-Roshnee line off, the loading on the Roshnee-Ironside-Savanna Tee becomes 604 A (137% of the normal Panther rating at 50 °C). Therefore, stage 2 on Figure 101 must be implemented by the time that the Savanna City load reaches 25 MVA (42% of the substation's rated capacity). Thereafter, stage 3 on Figure 101 must be implemented when establishing Jaguar substation.

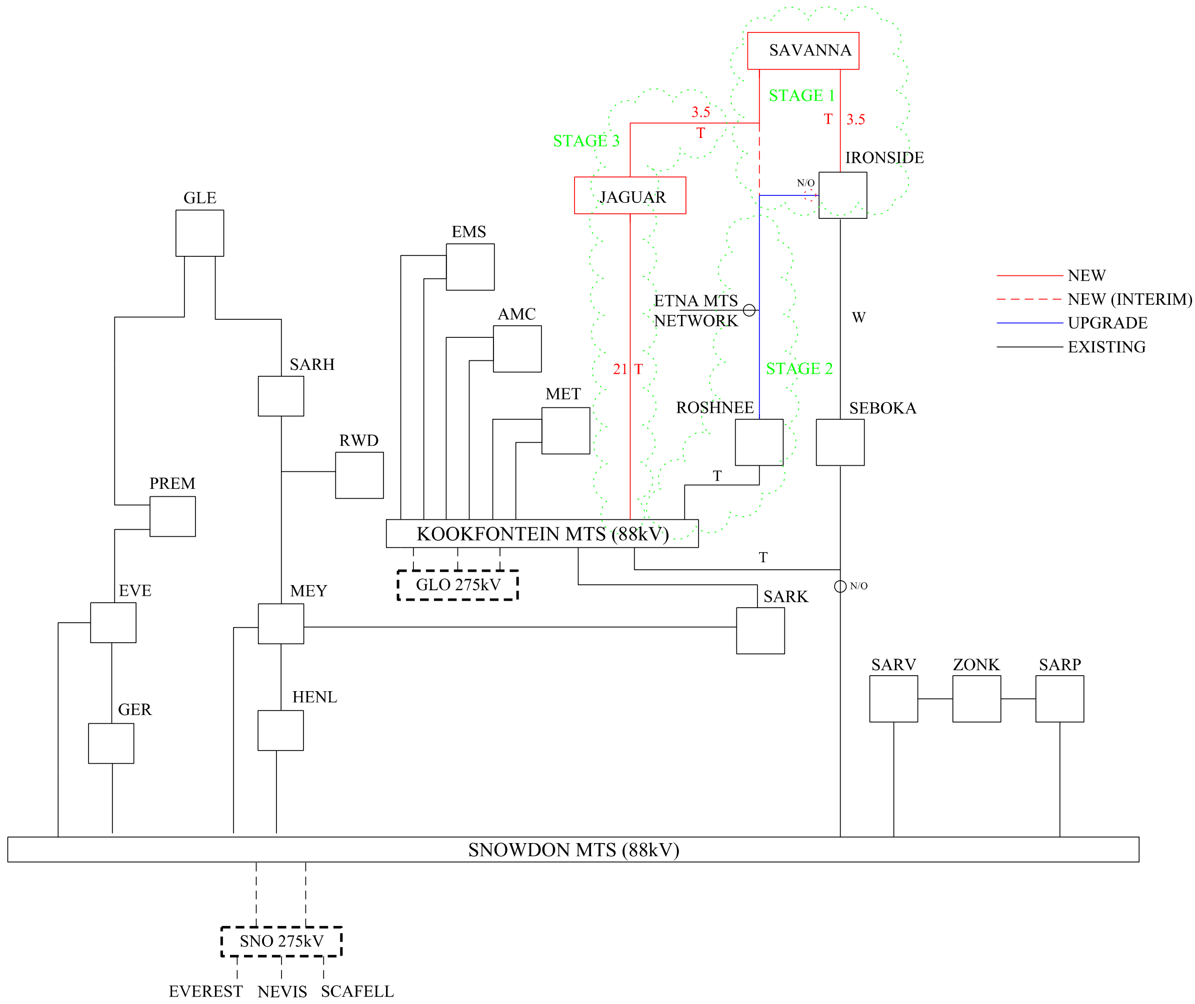


Figure 101: Kookfontein - Savanna SLD

Following the completion of stage 1 to stage 3 on Figure 101, the maximum anticipated loading on the ring becomes 84.76% on the Seboka-Ironside line, when the Kookfontein-Seboka line is off.

The preceding paragraphs give an overview of the overall 88 kV ring. The paragraphs to follow focus on the establishment of the Savanna City substation due for implementation in 2021. With all subtransmission grid configuration changes (anticipated by 2027), the single-phase fault level at Savanna City SS increases from 6.5 kA at 88 kV, to 12.24 kA at 88 kV. The high fault level of the final configuration was considered with the Savanna City 88 kV OHL line designs, resulting in the use of Wolf ACSR as shield wire to achieve an acceptable burn-off time (20 Ω minimum tower footing resistance).

As mentioned, one of the biggest challenges with the overhead lines to Savanna City substation was the availability of space to construct the lines. Therefore, compact solutions had to be considered. Part of compact designs and material selection is the pole designs and attachments to be used. Some support structure options are lattice steel structures, monolithic pre-stressed spun-concrete structures, monolithic symmetrical steel cylinders, “coffin” shaped steel cylinders (reduces intermediate longitudinal strength to ⅓ of the transverse strength), cross-braced double pole structures and double pole structures. Steel cylinder sections can be attached, either by overlapping compression or flange attachments. Flange attachments for sections are generally less cost-effective. For up to 150 kN tip load, self-supporting poles can be planted, for higher tip loads, flange-mounted pole foundations become more cost-effective. Foundation designs are done following the type of support structure selected.

Figure 102 shows the Ironside – Savanna design extract, where the double circuit overhead line transitions to two single circuits. A wooden pole distribution line transitioning to cable is also noticeable. A section of the feeder is designed as a compact double circuit overhead power line that replaces existing H-poles. Where space becomes available, the line transitions into two single circuits for the remainder of the ring feed (compact vs conservative designs). For the section of the new single circuit lines, a stroke of luck, or proper planning in 1937, provided two empty and available servitudes to be used.

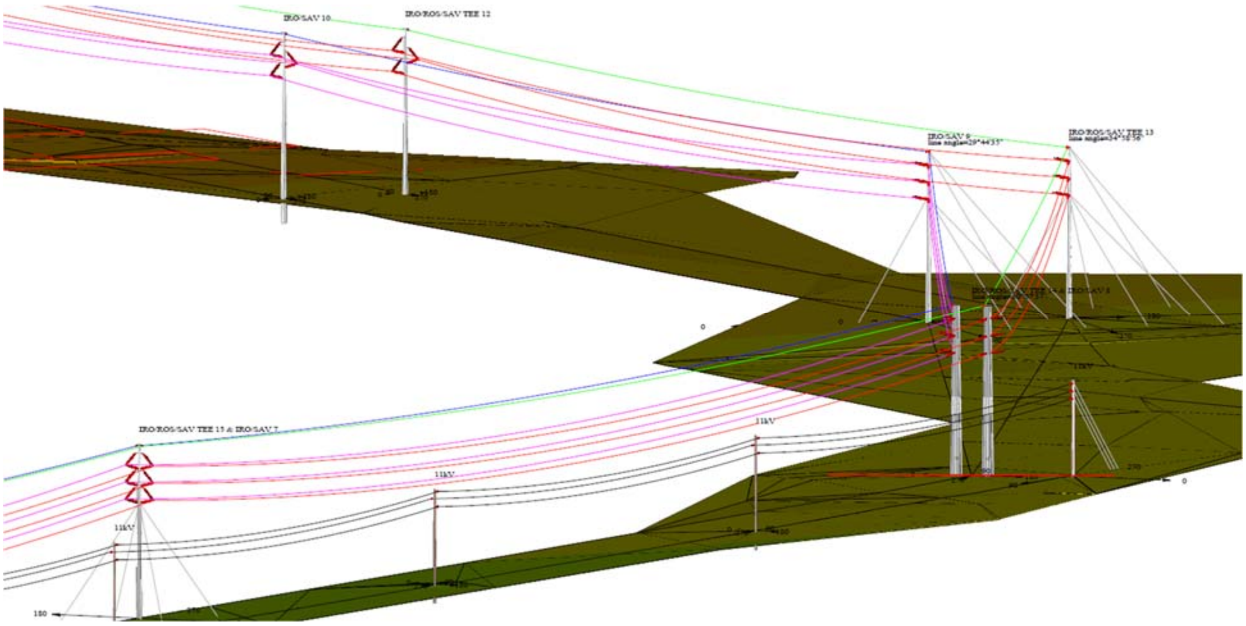


Figure 102: Ironside - Savanna PLS-CADD design

From the figures in Table 31,

Table 32, and Table 33, there are too many structure options to mention; however, these are the shortlisted structures for the Savanna to Ironside feeder (lattice structures not shortlisted due theft and space):

Table 31: Single circuit strain structures

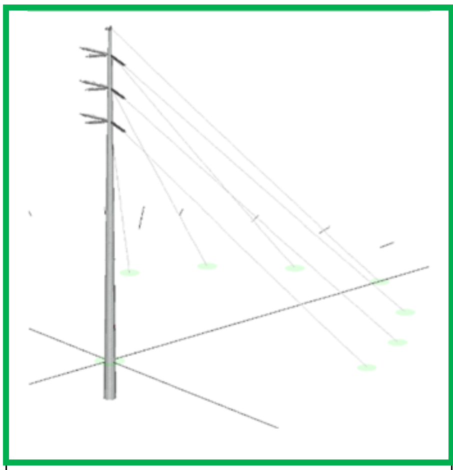
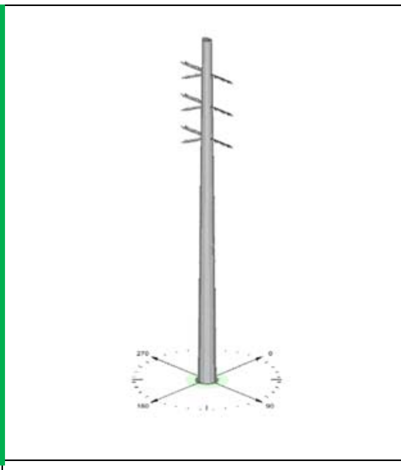
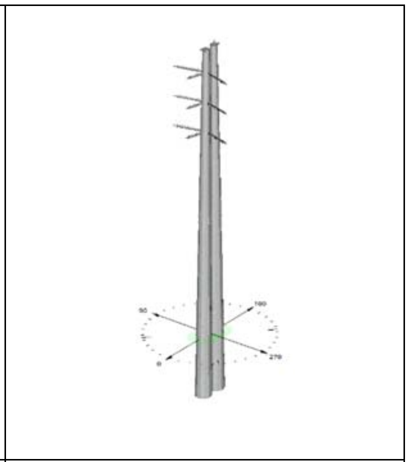
		
Stayed single circuit strain structure.	Monolithic self-supporting strain structure (planted or flange mounted).	Double cylinder self-supporting pole.
Cost-effective.	No stays, compact, foundations are large and costly. Flange-mounted outage times to tie into existing networks can be reduced.	No stays, compact, foundations are large and costly. Flange-mounted outage times to tie into existing networks can be reduced. More cost-effective than a monolithic pole, but longitudinal strength is reduced vs transverse tip load.

Table 32: Double circuit strain structures

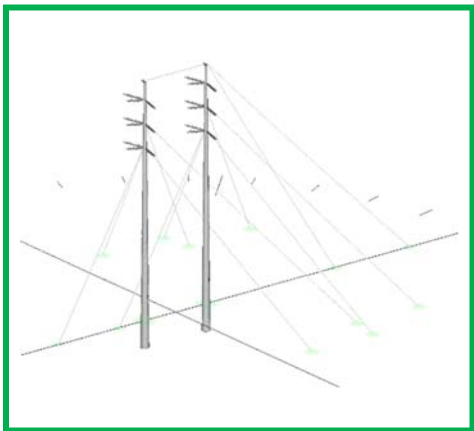
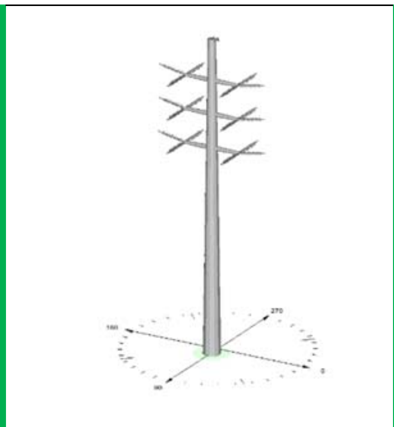
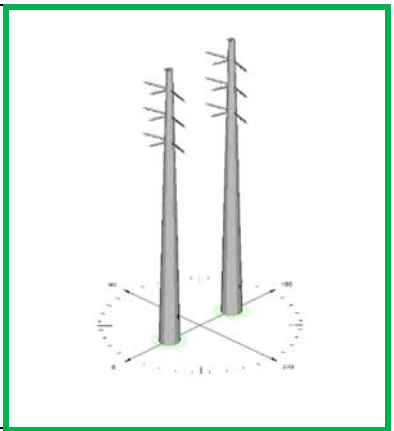
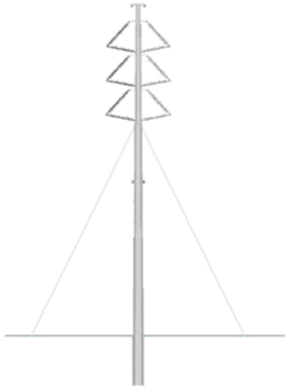
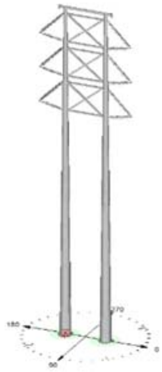
		
Stayed double circuit strain structures (compact)	Monolithic self-supporting structure	Two monolithic self-supporting poles
Cost-effective, consumes a lot of space, guy-anchors are subject to theft, 'busy'.	Neat, very compact, extensive foundation, expensive.	Neat, compact, extensive foundation, expensive, easier maintenance than a single pole.
(Bolt-cage flange type foundations allow for surface mounting of poles where needed i.e., high tip loads, or underneath existing overhead conductors)		

Table 33: Double circuit intermediate structures

		
Single pole, double-circuit intermediate structure (with 4 x stays due to heavy conductor).	Single pole, double-circuit intermediate structure	
Cost-effective, compact, stays can be omitted by strengthening the pole (stays are more cost-effective), bird-friendly when compared to stand-off post insulator without braces, insulators act like a collapsible cross for a broken conductor.	Bird-friendly structure, relatively compact, relatively cost-effective, bird-friendly, has insulator swing. Generally, a coffin-shaped cylinder with higher transverse strength, suspension insulator and cross-arm accommodate broken conductor conditions.	Bird-friendly, braces reduce the cost of two poles, costly, best for maintenance. Insulators act like a collapsible cross for a broken conductor condition.

Following a technical evaluation and design review, monolithic self-supporting poles per circuit were chosen for strainers where stays cannot be installed and stayed poles for the remainder of the angle strain structures. Where space permits, the design is for two single circuit lines, per Eskom policy.

For intermediate structures, two ahead and two backstays in an X-formation stabilises the structure in all directions. The stay angles had to be reduced due to limited space. By installing the stays to a standard and mechanical load-tested, cylindrical pole, the previous overstressed mechanical usage of the pole is reduced, which enables the installation of a larger and heavier conductor than which the pole was designed for. The "X" arrangement of the stays is for omnidirectional stability, for both maximum transverse wind and broken conductor conditions. Stay guards are used as a theft deterrent.

For constrained areas, a single-pole, double-circuit structure with braced post insulators and stays, was chosen. Post insulators are reinforced with braces due to the phase conductor weight (Tern ACSR). After the addition of the "X" stays, Figure 103 shows the braced post insulator has become the most strained components of the structure (stressed between 75% to 100%).

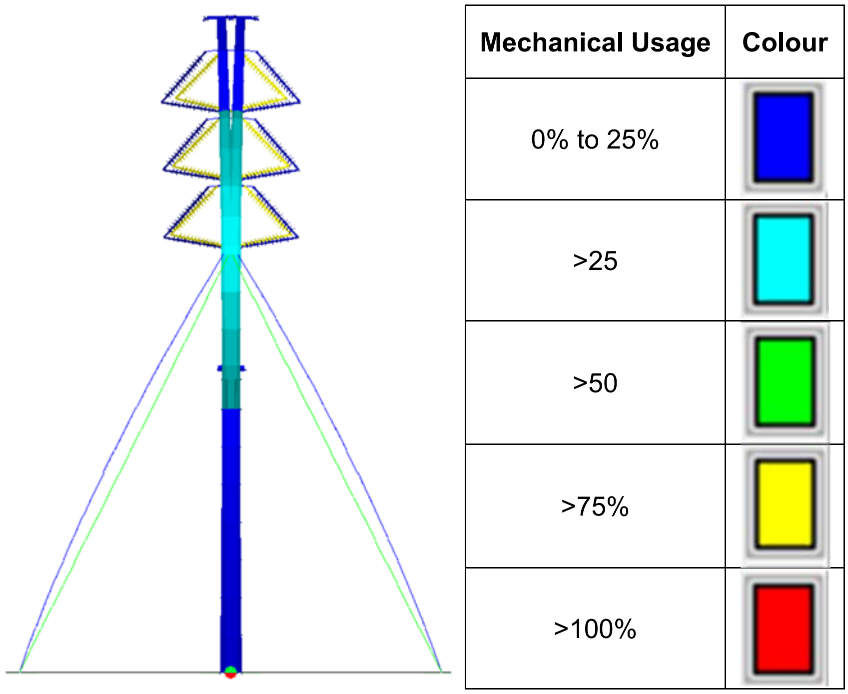


Figure 103: Self-supporting structure design

The percentage usage in Figure 103 depicts the structure's strength usage for its various components. The strength usage is calculated by comparing the actual structure loading to its maximum capacity. The strength usage considers normal stresses due to axial load, normal stress due to bending, shear stress due to shear force, shear stress due to torsion, and a strength factor for a safety margin.

Without modularity in structure design, a re-build would not be possible. The application of commonly used hardware such as guy anchors and braced post insulators increases the power transfer limit of a standard structure, by allowing the use of heavier and larger conductors. The last piece of hardware responsible for higher power transfer is the conductor itself. Conductor properties for Tern ACSR are shown in Table 34 [64].

Table 34: Conductor rating Tern ACSR (probabilistic) [64]

Temp (°C)	Rate A (A)	Rate B (A)	Rate C (A)
50	665	963	1509
60	792	1110	1678
70	894	1231	1817

Rate A is the normal rating for a healthy system, Rate B is an n-1 contingency rating that could last for days or weeks, and Rate C is a 15-minute time limited rating [64].

Although the Savanna City line is templated at 70°C, a 500 mm clearance buffer is allowed, the actual thermal rating for the line at unity load factor is 94 °C, based on the limiting span. The limitation is due to the fence of a planned retention pond. In Figure 104, the phase wires are shown for 70 °C, and the vertical limitation for the conductor temperature of 94 °C is indicated. Therefore, should the 894 A rating at 70 °C become insufficient during the line's service life, the line can be re-rated to 94 °C. Increasing the conductor temperature to above 94 °C will result in a clearance violation.

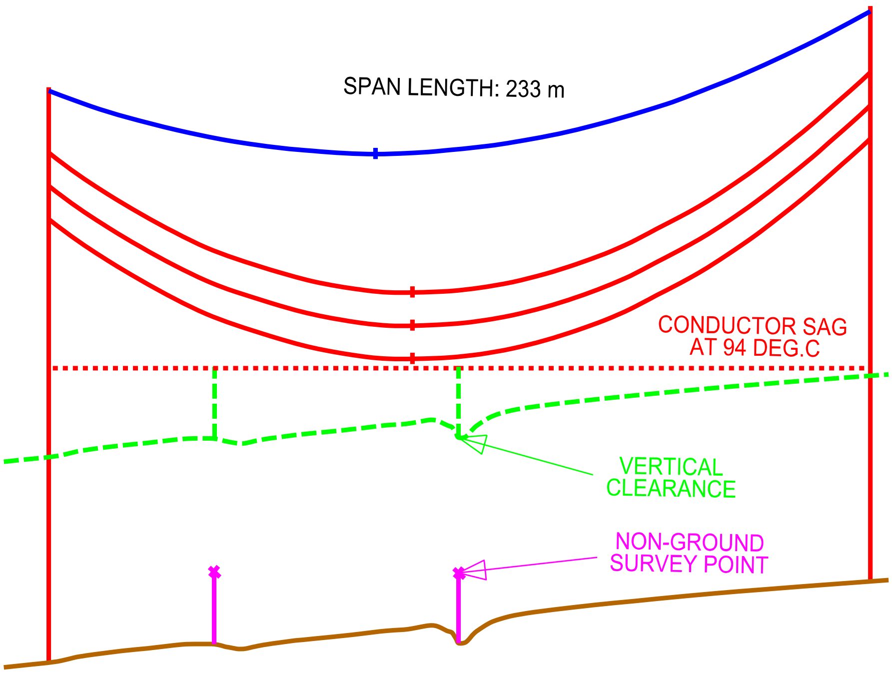


Figure 104: Limiting span for the line's thermal rating

The next case surrounds an old subtransmission grid, subjected to repeated failures, extensive blackouts periods and lengthy repair time.

3.7.3 Case 2 summary and outcomes

Case 2 involves a subtransmission overhead power line ring on the verge of losing its n-1 supply contingency and becoming excessively loaded. The possible alternatives were limited by constrained space and the mostly compulsory standard equipment required by the utility. The solution is based on stages as the increase of loading is anticipated. The Savanna City 88 kV overhead line design provides a compact, cost-effective, and reliable solution to the subtransmission ring's limitation:

- The solution comprises of a line rebuild, new overhead power lines, extension of an existing subtransmission ring, and upgrading of existing lines.

- A flange/surface mounted foundation design allows for the minimum outage time, by enabling foundation construction underneath energised overhead conductors (a single day outage is required to place the support structure and tie into existing conductors).

- By incorporating the substation into the specific ring, the electrical master plan for the area is partially executed.

- A compact, double-circuit, braced post insulator, "X" stayed line design is applied to use standard equipment far as possible, and drastically increases standard intermediate structure strength to allow the use of large conductors. The load case maximum usage for a 37 kN intermediate steel pole structure is reduced from 116% without stays, to 54% with stays for the same structure.

- The increased fault level is addressed for the line by a sufficient lower tower footing resistance and a high ampacity earth return (shield) wire.

- The line rating is increased from the 441 A Panther ACSR deterministic rating at 50 °C to the probabilistic 894 A Tern ACSR rating at 70 °C. The line can be uprated from 70 °C to 94 °C if additional capacity is required.

- The solution proposed was accepted by a forum of senior Eskom engineers for implementation. Implementation is anticipated for early 2021.

The next case revolves around an aged network, where the reliability of supply has deteriorated over a long service life.

3.8 Case 3 – Subtransmission system reinforcement

Case 3 investigates increased reliability and feeder re-rating to reinforce an aged subtransmission system that has had repeated failures, erratic power availability, and planned expansions.

This case is based on the 66 kV subtransmission network of Kroonstad, and some variations are made to the base case network. Part of the network consists of legacy oil-filled cables, which have plunged the town into complete darkness for extended periods, due to repeated cable failures. The 66 kV electrical network performance is reviewed, based on increased loading, and strengthening by replacing the legacy oil-filled cable. The contingency operational conditions are explored, to achieve better reliability of supply.

The first 66 kV network problem to be addressed, is the replacement of the 66 kV oil-filled cable from Main substation to South substation by an overhead power line. In Figure 105 the jagged "pink" line is the existing 66 kV oil-filled cable, to be replaced by the proposed new "turquoise" line, representing an OHL feeder. The overhead feeder meanders less than the cable, due to its ability to span across obstacles such as railway lines, eroded areas, rivers, and wetland buffers. For a UGC to overcome these obstacles, the UGC needs to follow the existing roads with levelled contours, which allow the use of existing infrastructure, for instance, bridges and subways to cross obstacles such as rivers and railway lines respectively. Directional drilling or pipe-jacking to cross obstacles with a cable can become extremely expensive.

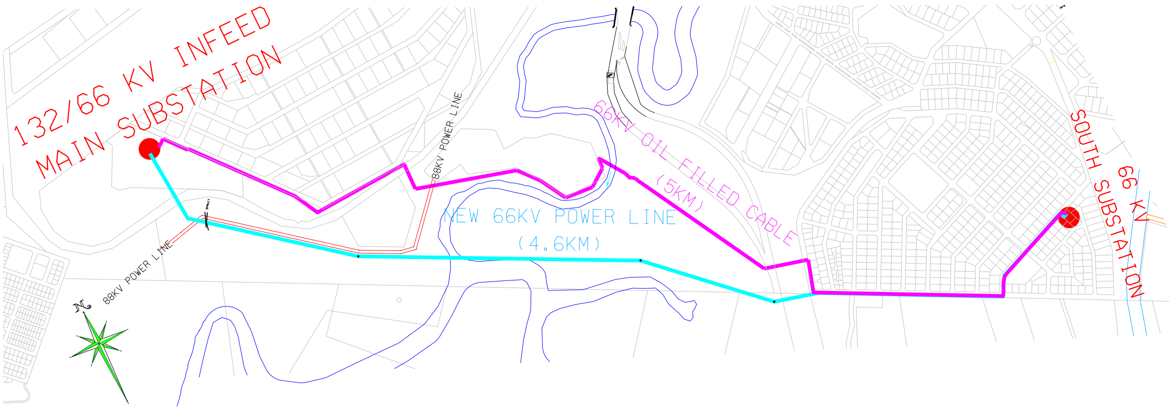


Figure 105: Kroonstad Main-South 66kV feeder routes

The existing 66 kV oil-filled cable (OFC) will be replaced by an OHL to increase power transfer and reliability. The UGC can remain operational while the OHL is constructed. Using buried cable as an addition or as a replacement to the existing cable was not selected due to the cost of a new cable, and the hindrance it would cause to residents during installation. The image in Figure 106 illustrates the planned alignment of the overhead line within the residential area; vegetation management is needed, although the line height was increased to accommodate trees and shrubs. The replacement of the 66 kV OFC with a new 66 kV XLPE UGC would be a severe disruption to residents at a much higher cost, and most vegetation would have to be removed to allow excavation and storage of excavated material.

Figure 106: Kroonstad 66 kV Oil-filled cable route overgrown with vegetation

Figure 107 shows a joint bay for the 66 kV oil-filled cable following an incident, a joint kit could not be found locally but had to be flown in from Cape Town.

Figure 107: 66 kV oil-filled cable repair - joint bay

The oil-filled cable must be replaced by the proposed Main to South 66 kV overhead power line in Kroonstad. As part of the line design, the restrictions and line position is determined by vertical clearance under maximum conductor temperature and horizontal clearance for maximum wind perpendicular to the conductor at maximum spans of 140 m. The clearance with short spans allows for the construction of the line within a widened road reserve, but the short spans increase the line cost. An 8 m restriction from the power line centre to stand boundaries was determined and applied. A delta configuration and compact design were chosen to allow for space-saving and a higher line rating.

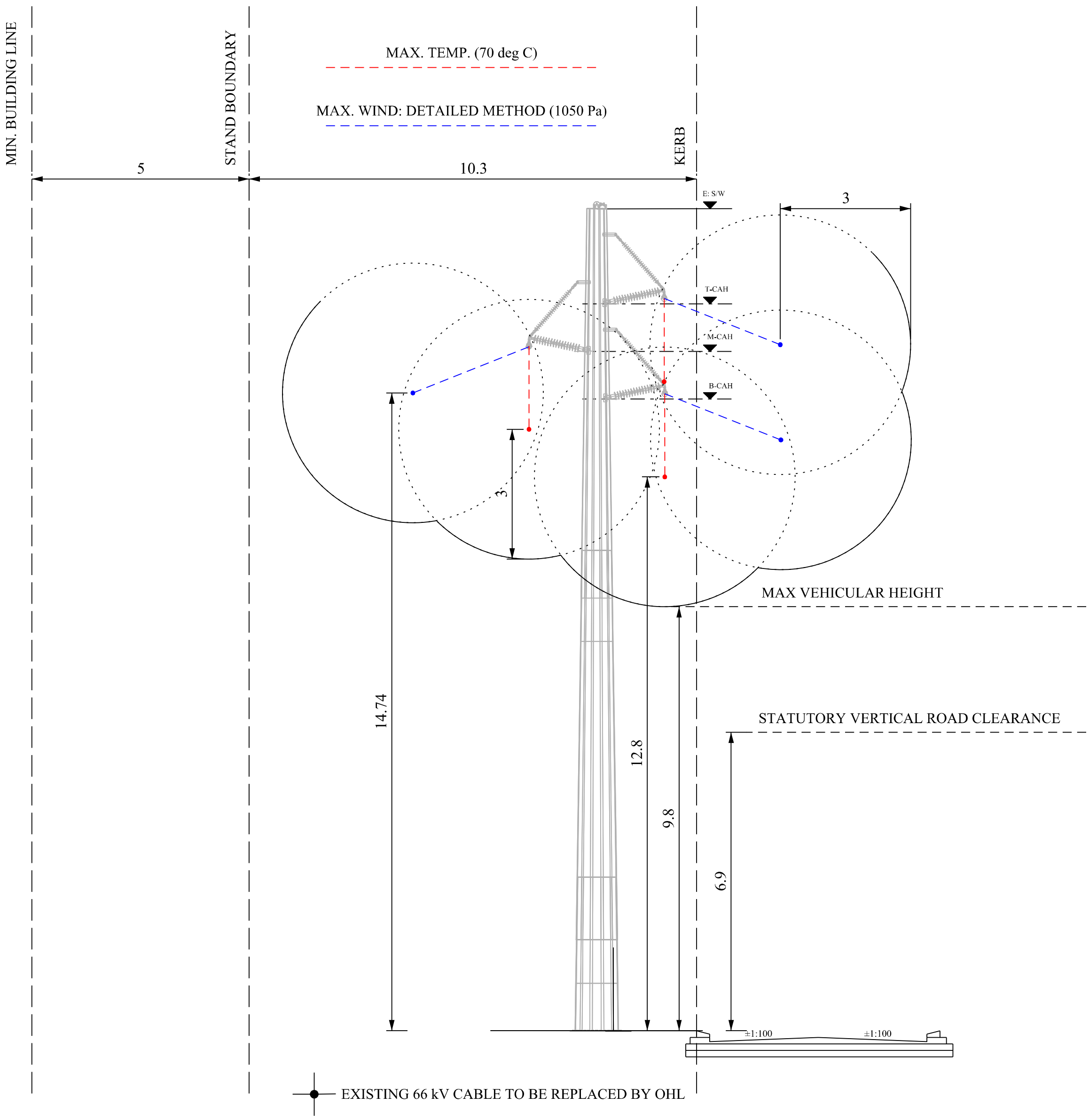


Figure 108: Compact line clearance tree for a 140 m, 66 kV span

The Main to South feeder is not the only buried cable forming part of the Kroonstad 66 kV subtransmission network. In other areas of the network 'newer' XLPE cables are installed. For constrained sections of buried XLPE cable, the rerating of the existing XLPE cables were investigated.

3.8.1 Case 3 - Cable rerating

Next, the existing 66 kV XLPE cables will be rerated to ensure that maximum capacity can be transferred during emergency conditions. The rerated current is used to adjust the respective feeders' protection settings, to allow the cables to operate at higher currents without tripping the feeder on overload.

The graph in Figure 109 is based on measurements taken averaged per hour for ten-minute average reading intervals. Measurements were taken during peak load winter months, and the daily load cycle with the highest peaks was selected. Most daily load cycles for the measurement period resembled the average profile below, but sometimes with a much higher morning peak. This load cycle is applied when rerating the existing 66 kV XLPE feeders.

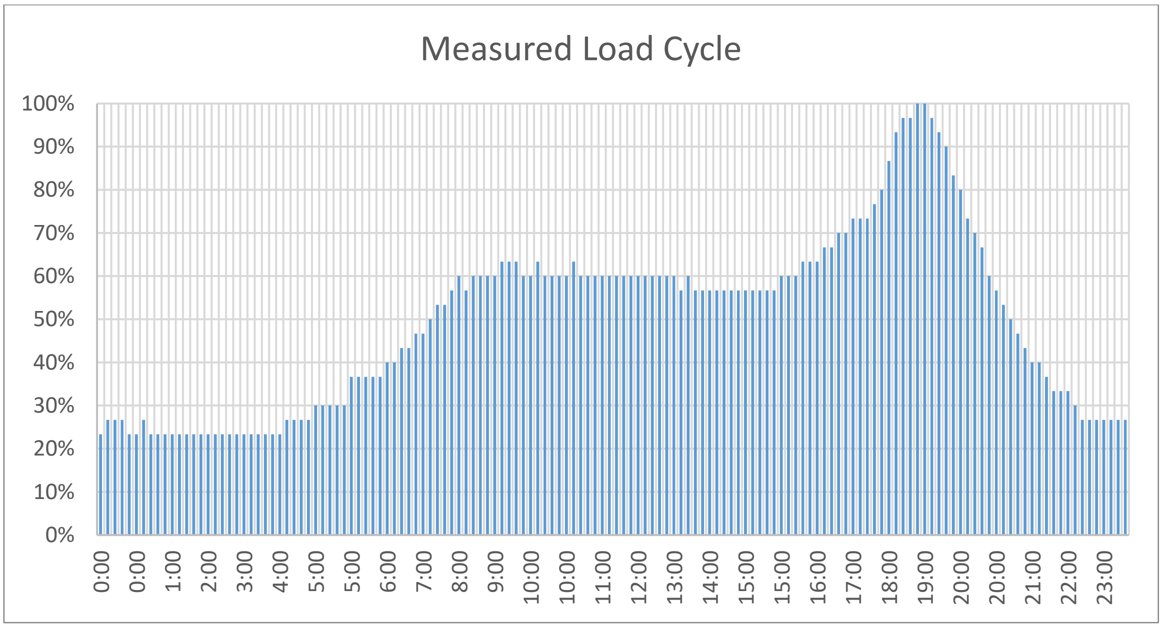


Figure 109: Measured daily load profile

For three, 300 mm^2 Cu, 66 kV, single-core, lead sheath, Cu wire screened, PVC-HDPE sheathed cables in trefoil, buried and backfilled at 1.5 m, the steady-state rating at 100% load factor, calculated according to IEC 60871-1-1 of 2014, is 430 A.

When using thermal backfill with a soil thermal resistivity of 1.2°C/m/W, at an ambient soil temperature of 16.7°C, the thermal rating is increased to 523 A, at a maximum cable operating temperature of 90 °C, again, by using IEC 60871-1-1 of 2014 or the Neher-McGrath method.

When applying Figure 109's load cycle, the peak current is increased to 728 A for the specific load cycle. This proves an increased rating, or rerating, of approximately 40%, resolving that for contingency conditions, the cables' standard datasheet rating can be "overloaded" to a certain extent.

The accuracy of the re-rating can be increased by using a FEM approach with historical meteorological conditions, if available. It is shown that through theoretical rerating, the required line capacity can be achieved in some cases. The rerated lines will assist with distributing power, particularly during emergency conditions. The next paragraph will investigate how to improve the reliability of supply for this 66 kV subtransmission system.

3.8.2 Case 3 - 66 kV Subtransmission system

This paragraph will address the contingency conditions of the 66 kV subtransmission system.

In addition to the 66 kV oil-filled cable from Main substation, South substation obtains a second supply from newer 66 kV XLPE feeder cables via North-East Substation, to form a ring supply. The 66 kV oil-filled cable between Main substation and South substation is no longer reliable, as a result of repetitive failures, difficulty in the repairing of the cable in case of failure, and reaching the end of its expected service life. The oil-filled cable to South Substation has passed its reliable life span, being installed in the 1970s. The drainage following puncturing of the 66 kV oil-filled cable is also a high risk for environmental contamination, especially where it passes over the Vals river. The oil-filled cable has leaked oil into the Vals river in the past. The Kroonstad 66 kV network configuration is shown in Figure 110.

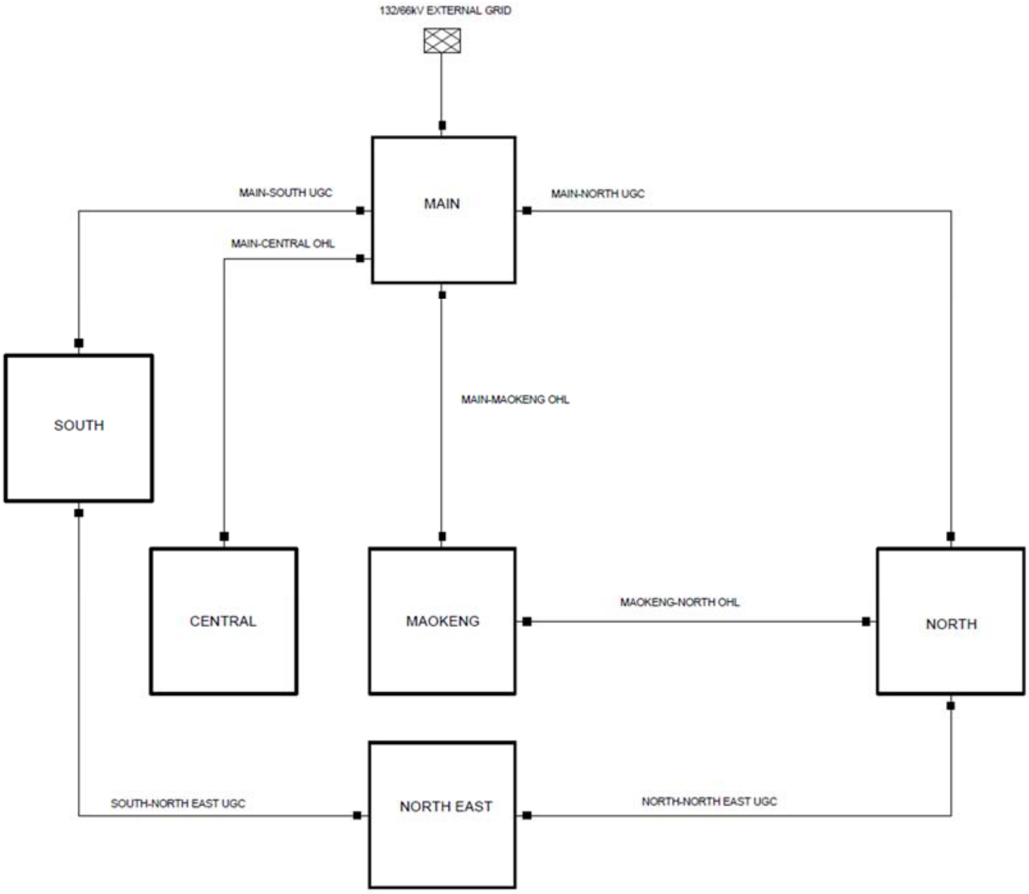


Figure 110: Kroonstad 66 kV overview

To address the reliability of supply, a new overhead power line was constructed from Main substation to Maokeng substation. The Main to Maokeng 66 kV line now serves as the primary supply, and the initial North to Maokeng 66 kV line, becomes the secondary or backup supply for an n-1 supply condition. The Main to Maokeng to North line now serves as an essential backup to the Main to North cable.

After adding anticipated future loads, a contingency analysis was performed on the network. The n-1 contingency analysis results in the following network concerns:

- The Central Substation is on a radial supply, and
- If the Main-North UGC cable is taken out of service, the Main-South UGC cable, which already has vulnerable reliability, becomes heavily loaded.

Additional capacity is required through the Main to South feeder, to loop Central substation in-and-out between South substation and North East substation. This will address the reliability problems with the Main to South feeder by deloading the feeder. The loop-in-loop-out will also address the radial supply to Central substation.

In addition to the above-mentioned strengthening of the grid, a planned future substation must be considered and is added using a loop-in-loop-out between North substation and Maokeng substation, to provide power to developable areas according to the spatial development framework. The additional substation increases network loading by 21%.

As reviewed under 2.1.1 “Grid planning”, there are frequent simultaneous feeder outages in South Africa, provoking an n-2 level of reliability approach. The worst-case consequences of such an n-2 contingency analysis are listed below:

(a) Main SS to Maokeng SS OHL (101% loading based on deterministic rating)

(b) North SS to North East SS UGC (102% loading based on a steady-state unity load factor rating)

(c) Main SS to Central SS OHL (105% loading based on deterministic rating)

(d) Central SS to North East SS UGC (125% loading based on a steady-state unity load factor rating)

(e) Main SS to North SS UGC (135% loading based on a steady-state unity load factor rating)

From the above list (a) to (e), the UGC cable rating needs to increase by 35% from 433 A to 585 A and the OHL rating 23% from 425 A to 523 A for the standard conductor sizes used.

When applying a probabilistic rating to Chickadee ACSR, the rating is increased from 425 A to 559 A under normal operating conditions, and unity load factor. The increase is equal to 15.3 MVA at a voltage level of 66 kV. Under n-2 contingency conditions and with a unity load factor, the “Main to Central” and “Main to Maokeng” line loadings are both decreased to below a

100% loading, when applying a probabilistic line rating approach as opposed to a deterministic approach.

By calculating the IEC emergency rating for a 300 mm^2 XLPE Copper cable in trefoil, the datasheet rating is increased from 430 A to 523 A for unity load factor. This emergency rating reduces the "Main to North" maximum n-2 loading from 135% to 84.7%.

However, the emergency rating only reduces the "Main to North" and "Central to North East" maximum n-2 loading from 135% to 111%, and from 125% to 103% respectively. If needed, with a DTS system and RTTR, it is plausible that the loading for the previously mentioned two results can be reduced to below 100%. However, no data is available for validation of an actual RTTR. With the average daily load cycle, applied as per Figure 109, the Neher-McGrath permissible peak of the cyclic load is 685 A.

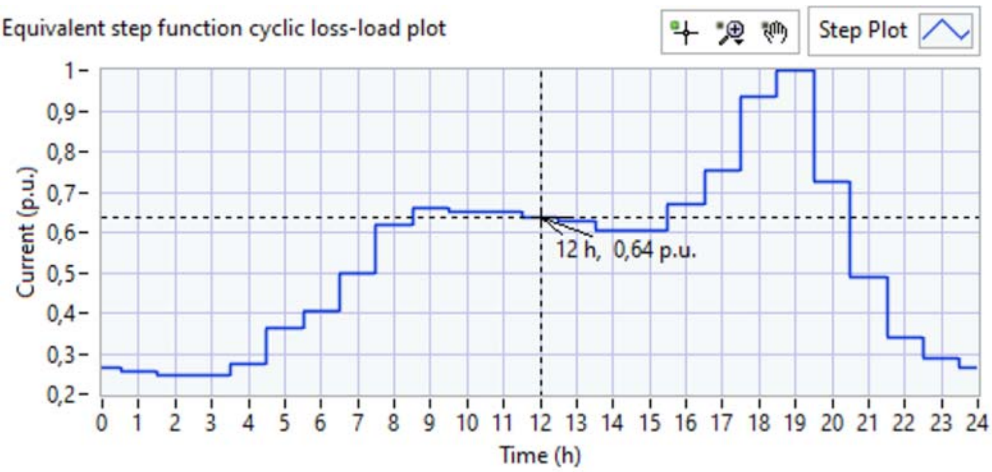


Figure 111: Permissible peak current of 685 A (cyclic rating factor M=1.31)

Based on the permissible peak current for a cyclic load approach, the overloading of the "Main to North" and "Central to North East" UGCs in the network model will depend on the load profile. For a load factor of one, the mentioned UGCs will be overloaded. However, overloading is an unlikely result when applying cyclic loads.

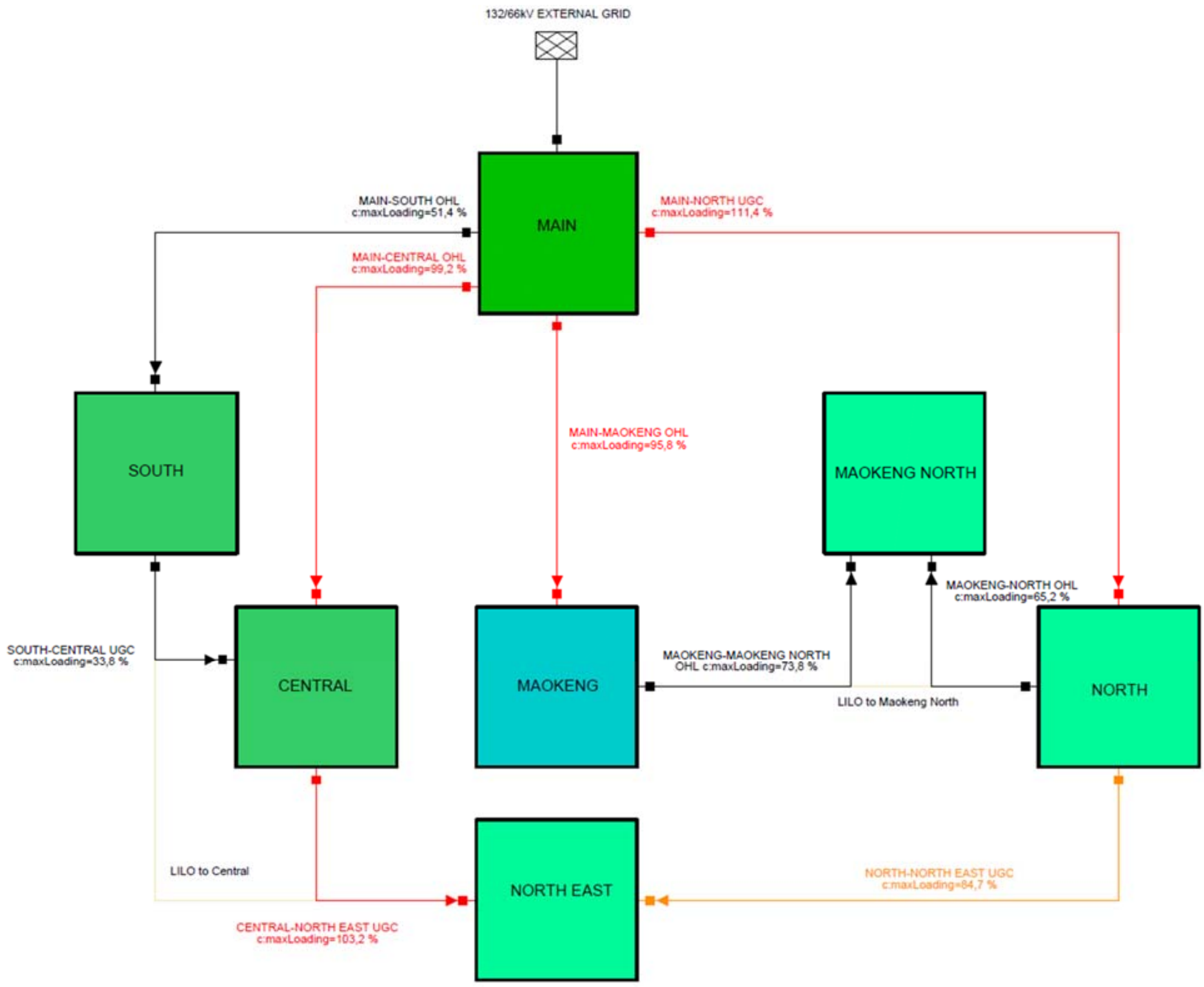


Figure 112: Contingency analysis results with uprated feeders (n-2)

Based on Figure 112's "n-2" contingency analysis results, reinforcing old networks through grid planning, increasing reliability by using contingency analysis, and theoretical rerating of feeders to increase power transfer is feasible.

3.8.3 Case 3 summary and outcomes

The primary issue addressed by this case is the reinforcement of an unreliable supply and increasing of the subtransmission grid capacity.

The design for the overhead power line from Main substation to South substation that will serve as a replacement to the oil-filled cable was concluded and approved for implementation. Construction has started but is slow to progress due to funding constraints. Similarly, the design for the loop-in-loop-out of cables to Central substation is approved, two cable feeder bays are constructed at Central substation, but the remainder has not been implemented due to limited funding.

The outcomes of this study show:

- The use of favourable soil conditions showed an increase of 22% on the buried cable's rating.
- When rating the cable with a cyclic load, the cable's rating is increased by 39% over and above the 22% increase. Therefore, with thermal backfill, favourable soil conditions, and when applying a cyclic load, the rating of the cable is effectively increased by 69%.
- A lot of capacity can be added to existing subtransmission lines using detailed theoretical analysis.
- For Chickadee ACSR the rating is increased from a deterministic thermal limit of 425 A to a probabilistic thermal limit of 559 A under normal operating conditions and a unity load factor.
- The 300 mm^2 Copper XLPE cable's thermal rating is increased from 430 A to 523 A for a unity load factor. The thermal limit is then raised by applying a cyclic load resulting in a thermal limit of 685 A under the maximum permissible operating temperature for XLPE of 90 °C.

The study was limited by not having sufficient data to determine a real-time thermal rating.

The next case study considers a weak network with low fault levels, where multiple actions are required to provide additional capacity to a specific point within the network.

3.9 Case 4 – Weak grid

This case is based on an interconnected cross-border electrical grid with multiple supply sources, operated by two independent utility companies. Confidentiality prevents the disclosure of actual substation names and geographic locations. At a specific point of delivery (POD) within the network, additional capacity is required for mining activities. To provide the capacity at the POD through the weak grid results in low voltages, or too large voltage drops, at various positions on the network. The electrical grid comprises multiple voltage levels, with a cogeneration power station supplementing the two infeeds. The capacity can only be made available to the POD by interconnecting different voltages, and by adding reactive compensation at a strategic position. All feasible options to increase power transfer requires reactive compensation.

3.9.1 Case 4 - Existing network

The POD for the consumer labelled “X-Ray” in Figure 115, requires additional power to the extent that the existing 88 kV supply must be upgraded. The existing load at “X-ray” is 13 MVA (power factor of 0.85 compensated by 2.8 Mvar to a 0.94 pf), the load is anticipated to increase from 13 MVA to 35 MVA, and finally reach 48 MVA. The existing external infeed cannot provide the additional capacity required without implicating voltage levels. The actual voltage at the POD is approximately 0.94 per unit (p.u.). Based on the voltage measured at the POD, the external grid infeed voltage level is 1.03 p.u. (0.09 p.u. voltage drop). Therefore, the voltage at the external grid infeed will be regulated at 1.03 p.u. for the network emulations. Table 35 provides the existing voltage levels used in the simulated network base case.

Table 35: Existing network voltage level (no-load)

Location in network	Voltage (per unit)
Existing infeed point	1.03
88 kV Substation at the POD (86 km)	0.937
POD distribution side at 11 kV (88 km)	0.98

Rerating, uprating, or dynamic rating of the existing infrastructure does not provide sufficient stable capacity for the increased load demand. The existing network and external grid infeed can only support the present load, due to the network being operated very close to its thermal limit and its voltage limit, whilst the fault level is relatively low.

If the existing subtransmission system is supported by reactive compensation, the existing grid capacity can be increased by 18%. However, at the increased capacity, transformers are overloaded by a similar percentage. With the key power consumers operating almost 24 hours a day, with a very flat load profile, overloading of transformers creates a high risk of failure for this operating condition.

Various power supply alternatives using infrastructure upgrades were identified, which was analysed extensively to establish whether the alternatives can transfer sufficient supply capacity for the new load requirements at the customer. Only the customer load was increased whilst performing a P-V analysis of the network. The maximum capacity for each alternative considered was determined by gradually increasing the loading to the point at which the infrastructure’s thermal capacities are exceeded or when a voltage collapse occurs anywhere in the network. Various criteria must be adhered to while investigating options, to maintain system stability.

3.9.2 Case 4 - Subtransmission system stability criteria

To maintain stability on the subtransmission network, the following criteria set the operating parameter limits for the alternatives considered:

- A minimum of 0.9 p.u. voltage at any busbar (lowered from the general value of 0.95 p.u.);
- The minimum voltage level for subtransmission networks to be maintained as close as possible to 0.95 p.u.;
- The maximum voltage at any busbar 1.05 p.u.;
- Equipment loading to 100% of the respective thermal limits;
- A minimum fault current to load current ratio of 7:1;
- The customer power factor must be regulated to 0.98 or better.

Figure 113 gives the voltage profile of the existing network, from the infeed point up to the POD at both 88 kV and 11 kV.

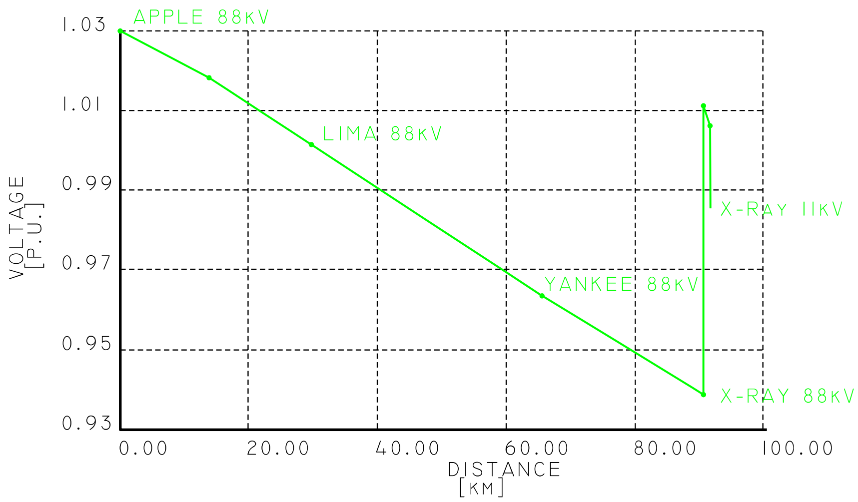


Figure 113: Existing network voltage profile

Numerous options were investigated for an increased load at the POD without causing a voltage collapse or without overloading equipment. Due to the variety and number of alternatives considered, only viable options are shown, and only the chosen option will be detailed.

3.9.3 Case 4- Alternatives

From the viable options listed in Table 36, alternative 2A was identified as the best long term technical solution. However, the additional revenue generated by increasing the supply by 42 MVA did not justify the associated cost, alternative 1C then became the preferred interim solution and was approved for implementation by two utilities, the mine, and the mine design engineering company. Option 1C was selected due to being both having the lowest CIC, and being the most cost-effective (R/MVA). The shortfall in capacity can be re-evaluated in the future based on the economic environment at that time. The viable options with cost, at the base date, and power transfer ability are listed in Table 36.

Table 36: Viable case options

OPTION	DESCRIPTION	COST	POWER TRANSFER	SUPPLY
1C	New 132 kV S/C OHL from India to Lima, and equip Lima with 2 x 40 MVA 132/88 kV transformers (to interlink external grid supplies).	R90 million	22 MVA	Standard (n)
2A	New 132 kV D/C OHL from India to X-Ray. New 3 x 20 MVA 132/11 kV substation at X-Ray. Retain the existing 88 kV supply.	R237 million	42 MVA	Premium (n-1)
2C	New 132 kV D/C OHL from India to X-Ray. New 2 x 20 MVA 132/88 kV transformers at X-Ray. Use existing 88/33 kV infrastructure and expand 33 kV infrastructure at the POD to accommodate the additional load.	R265 million	35 MVA	Standard (n)
2D	Similar to 1C but with 3 x 132/88/11 kV transformers at the POD (X-Ray). Decommission all 33 kV infrastructure at X-Ray.	R260 million	40 MVA	Standard (n)

All of the options in Table 36 provide for reactive compensation at the consumer and other strategic locations in the grid to achieve the additional power transfer as stipulated in Table 36 . The network diagram is shown in Figure 115.

Table 37: Estimated solution cost

DESCRIPTION	COST
Additional 132 kV GIS switch bay at India.	R6.75 million
13 km, 132 kV power line from India to Lima.	R20.0 million
Establish 132 kV substation at Lima with 2 x 40 MVA 132/88 kV transformers	R44.25 million
24 Mvar capacitive compensation at Pappa	R8.5 million
Subtotal	**R79.5 million**
Engineering costs	R5.5 million
Contingency allowance 5%	R4.25 million
Estimated Cost (Excluding VAT)	**R89.25 million**
Exclude any external grid infrastructure cost by the transmission system operator (i.e. upstream transmission strengthening and additional upstream transmission transformer capacity)	

Without the reactive compensation at Pappa, the network voltage falls below 0.9 p.u. at multiply instances throughout the network. If the load is increased from 22 MVA to 24 MVA at the POD, the voltage goes below 0.9 p.u. at Pappa. The option chosen remains a weak and unfirm solution, but the additional capacity that cannot be provided from the existing infeed is made available by interlinking two infeeds.

Figure 114 provides the voltage profile after implementing Option 1C with the additional load of 22 MVA at the POD and 24 Mvar reactive compensation at Pappa. Pappa is not shown on the voltage profile due to being situated on a different feeder than X-Ray. Pappa is situated on the Alpha external grid supply and with Option 1C X-Ray is situated on the Apple external grid supply. For option 1C the existing external grid source, “Apple”, is interconnected to another external grid supply “Alpha”. The Apple and Alpha external supplies are interconnected through Bravo, Charlie, Delta, Foxtrot, India, and Lima. The 33 kV, 88 kV and 132 kV grids are interconnected at Lima, which slightly increases the voltage at Apple from 1.03 to 1.04 per unit.

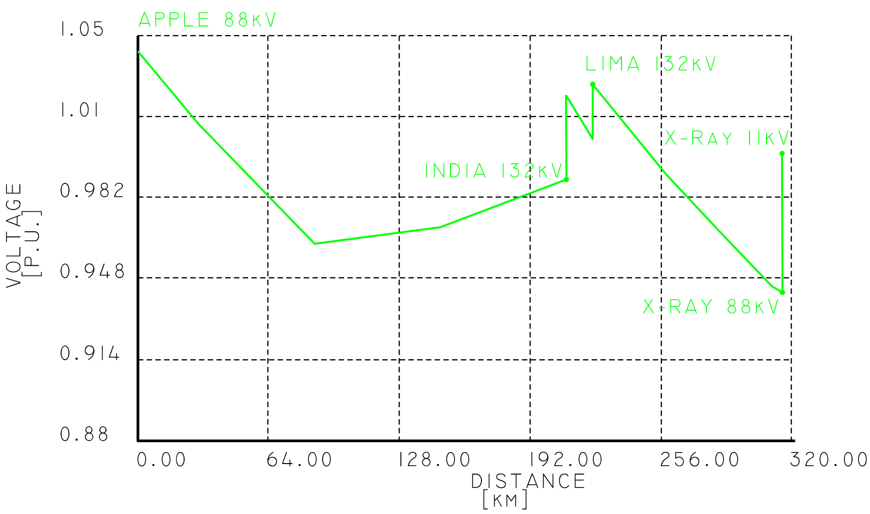


Figure 114: Voltage profile after implementing Option 1C

Even though the interim additional load can be provided by implementing Option 1C, the low fault-levels still imposes constraints on the network. When starting a 1 MW motor direct online at 11 kV, the 11 kV busbar at X-ray will have a 7% voltage dip. Therefore, motor sizes must be limited as far as possible, up to 200 kW motors can be started direct online, but larger motors will require soft-starters, or variable speed drives.

On the next page, Figure 115 gives an overview of the electrical network for Option 1C. The three external grids are located at Alpha, Apple, and Zulu. Embedded generation is located at India.

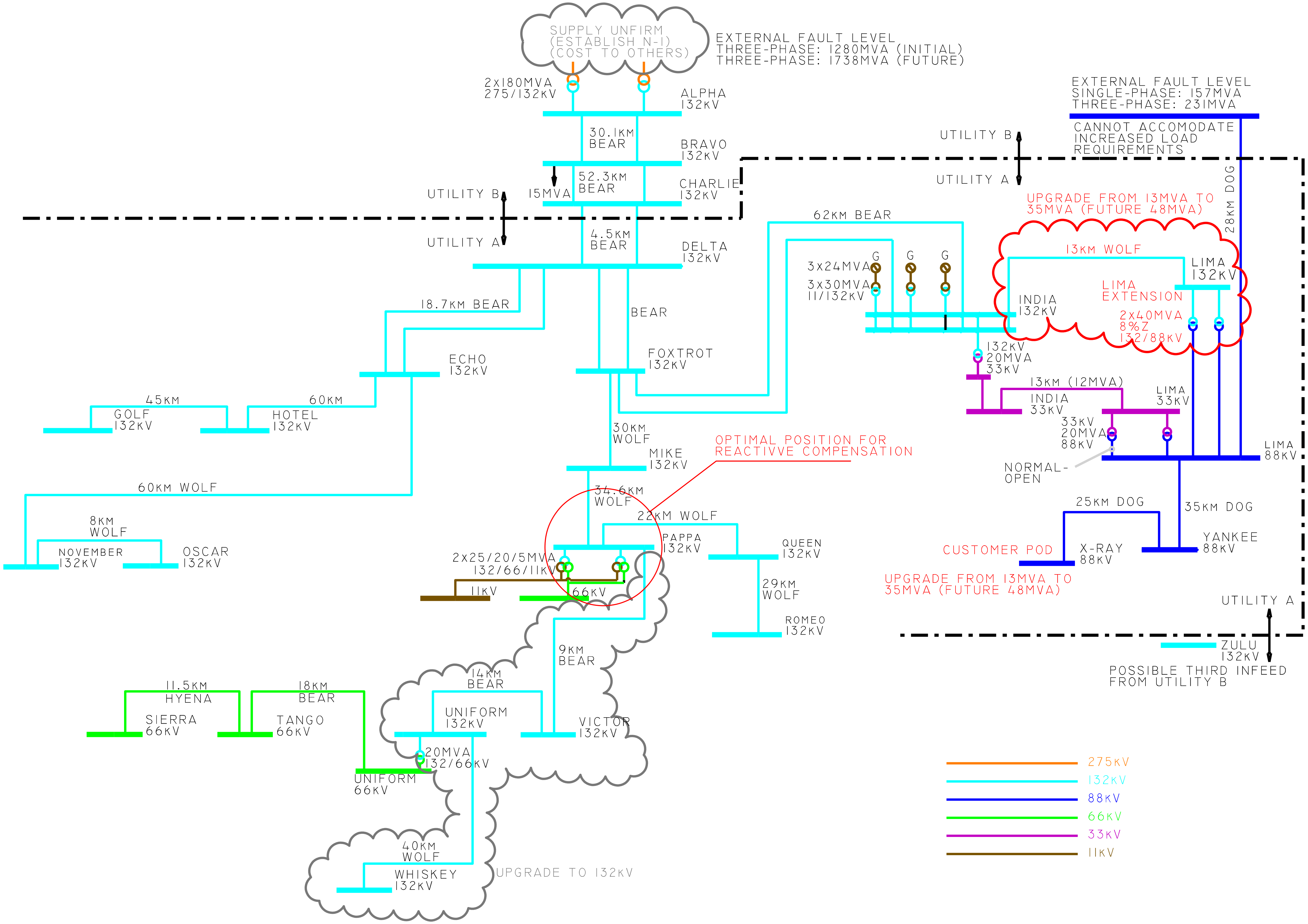


Figure 115: Option 1C subtransmission system

3.9.1 Case 4 summary and outcome

For the original grid at the POD (X-Ray), the primary strain on the infrastructure is a "weak" source with low fault levels. In this case, the subtransmission line is long (almost 100 km), resulting in voltage drop becoming an operational constraint.

Restringing the existing supply and increasing the supply voltage does not provide satisfactory solutions. The only viable solutions were the options where the supply is strengthened by incorporating an infeed at a higher voltage. In addition to the external 132 kV supply, the internal 132 kV network is equipped with a 72 MVA power station. By changing the existing substation "Lima" to a multi-ratio substation, the 33 kV, 88 kV and 132 kV supplies can be interlinked and strengthens the grid. Option 1C offers a power transfer increase of 22 MVA at less than half the cost of other viable options.

Other system configuration options incorporated reactive compensation at various positions in the grid, however, the results still showed constraints such as low fault levels, high voltage drops in other sections of the network, insufficient capacity on the existing infeed, operating near thermal limits, and exceeding allowable loads on existing equipment.

Although Option 1C was out to tender, it was never implemented due to a fall in the price of the commodity that is being mined.

3.10 General summary

This paragraph briefly reviews and summarises the general topics and conclusions from chapter 2 and 3.

At subtransmission level for a South African utility, FACTS devices, DC power systems, and high-phase order feeders have no proven references, but are possible methods of increasing power transfer or strengthening of subtransmission grids.

The investigations and review proved the theoretical increase of standard cable ratings by achieving thermal independence between phases and between circuits. The increase in power transfer through theoretic rerating of overhead power lines was proven. It was also shown how reactive compensation stabilises the grid voltage in weak grids.

Case 1 proved that although cable installations remain more expensive when compared to overhead lines, for high property values cable installations can be more cost-effective due to the smaller servitude required. Table 38 provides a cost comparison overview:

Table 38: UGC vs OHL cost ratio [127]

Voltage (kV)	Cost ratio (Installation cost)	Cost ratio (Lifetime cost)
20*	1.2 to 1.5	1
66	3	1.5
132	5.7	2.6

**not a standard South African voltage (20 kV is based on International data*

Although Table 38 is from an international source, the result at 132 kV correlates with the cost ratio of Case 1 between the overhead power line and underground cable.

For the subtransmission feeder line's loadability, due to their short lengths, the lines' thermal rating is ascertained as the limiting factor [138]. Changing from a deterministic to probabilistic approach postpones the need for an upgrade of numerous OHLs by increasing the thermal design limit. By following a probabilistic approach, existing OHL infrastructure can be re-rated for an increased power transfer capacity of 20% to 25% and real-time monitoring can add an estimated 25% further increase in capacity [142]. The thermal rating can also be increased by re-tensioning the line, or by using negative sag devices and equipment.

Cable and OHL feeder ratings can be increased by employing DTS and RTTR, to determine the allowable loading on the feeder at any given time.

All the above are methods of re-rating existing infrastructure. An ideal solution is to determine the maximum thermal rating of a feeder, implement the relevant solutions to uprate feeders where necessary, and apply on-line temperature monitoring to manage the asset.

The practical usage of space on the support structures can be leveraged to increase power transfer. Vertical space has fewer limitations than the ground footprint of subtransmission feeder lines. Compact AC OHL designs also increase lines' SIL.

Multi-circuit lines with multiple voltages on a shared structure can be considered. Multi-circuit lines take up vertical space for the same footprint of a double-circuit structure. The picture in Figure 116 is from China, and sufficient dry and open land is not available to accommodate all feeders from an MTS.

Figure 116: Multi-circuit lines

Based on the load profiling section of grid planning in the literature review, it is noteworthy that decentralised cogeneration connected at distribution (MV) voltage levels, can assist with de-loading of the subtransmission feeder systems. Therefore, decentralised cogeneration is a method of ameliorating constrained subtransmission feeders without increasing the transfer capacity of such a feeder.

Given the frequency of outages in South Africa and the associated repair time, the implementation of n-2 contingency operational scenarios assists with reliability and reduces the higher emergency thermal ratings generally required for n-1 grid designs. Effective grid planning can achieve an initial n-1 contingency, and upon completion of a double circuit ring (end-state), an n-2 contingency can be established.

With an increase in the capacity supplied to a specific area, the fault levels of infrastructure must be considered, and possible complications must be solved where necessary.

Over and above technical and engineering aspects, practical considerations must be considered when increasing power transfer capabilities. The explicit requirements for these factors, such as climate, environmental, legislation, standards, and socio-economic constraints, varies between cases and must, therefore, must be addressed based on merits for each case.

It is prevalent that at voltages such as 132 kV and higher, higher surface voltage gradients on bare conductors causes audible nuisance noise if not addressed. When increasing power transfer, specifically on overhead lines, attention must be given to how increased voltage levels or current implicates the lines' performance in terms of the corona.

Cable designs and overhead conductor designs are subject to fundamental physics; only material types, composition and geometry can be varied to achieve the specific characteristics required for a feeder to increase the power transfer capacity. The technical aspects investigated the main conductive part of a feeder and are fundamental to determining the thermal capacity of a feeder. These aspects investigated shows that power transfer capacity is highly dependent on a feeder's impedance characteristics, resistivity, frequency, voltage, the conductor dimension, stranding, geometry and temperature. Each aspect mentioned is subject to different external influences that affect the dynamics of the conductor. Temperature, for instance, is influenced by solar radiation, convective cooling by wind velocity and direction, the absorptivity of the conductor, seasonal changes, humidity, soil conditions and time.

Certain aspects are more dependent on frequency than others when calculating overhead power line and cable parameters. Therefore, to ensure accurate results, the effects of frequency on overhead line and cable impedances should be considered.

The use of computer-aided software simplifies the calculation of power line parameters, which are used in simulation models of electrical grids. The basic principles for calculating parameters for overhead power lines and underground cables are fundamentally similar.

There is significance in the study research methodology, which is a qualitative descriptive approach, following case study research design and a cross-sectional time frame. This method of research not often used in postgraduate engineering studies. The dissertation does not only review direct methods of increasing power transfer but considers influential factors to a large extent.

3.10.1 Proven solutions: power system uprating through re-stringing

In Johannesburg around 2010, the demand was exceeding the capacity of City Power infrastructure established in the 1930s and 1950s. At the time, infrastructure upgrades in Johannesburg were fast-tracked for the 2010 Soccer World Cup held in South Africa. Roughly 400 km of ACCC Lisbon conductor was used to restring 88 kV OHLs to increase feeder capacity. The live-stringing techniques were implemented to limit outages [143].

The technology change increased the subtransmission feeder ratings from between 60 MVA to 100 MVA, to an increased thermal rating of approximately 200 MVA [144].

City Power of Johannesburg's situation focussed on alternative conductor technologies not conventionally used in South Africa, including high temperature, low sag conductors, such as ACSS, ACCR or ACCC, which are options to replace conventional ACSR. The City Power project successfully proved that HTLS conductors offer a viable solution to alleviate limitations on constrained and longstanding feeders.

From the North-West University, Pieter van Staden and Prof. Jan de Kock undertook experimental research into the thermal uprating of transmission lines and substation equipment. Their research proved that certain existing Eskom 275 kV transmission lines were designed conservatively and still operate significantly below the conductor temperatures that the line can accommodate, therefore, it is possible to unlock spare thermal capacity on heavily loaded overhead power lines [145].

In the next and final chapter, the conclusion and recommendation based on this study are given.

CHAPTER 4 – Conclusion and recommendation

This chapter deals with the study's conclusion and possible recommendations, based on the initial research questions. For the conclusion to reflect on verification and validation, the two concepts are kept distinct. The study's method of verification is through peer review, result comparison, comparison to existing and previous research, and critical evaluation of topics, theory, and ideas. Verification is done throughout the study as part of the chapters proceeding the conclusion. On the other hand, validation forms an integral part of the conclusion, to determine if the correct philosophical research questions were asked, and to determine the answer to the respective questions.

Before continuing to the conclusion, the validation of the research questions is assessed.

4.1 Validation

For validation of the research, the philosophical questions asked are considered and reflected upon. The initial research question asked as part of the problem statement were:

(a) What are the available options when the demand arises to increase the electrical energy transfer into a specific area or to increase the electrical energy transfer capabilities of existing subtransmission infrastructure?

Fundamentally, this question determined the options considered to ameliorate the subtransmission system by increasing power transfer. A variety of options to increase power transfer were investigated in detail, and include rerating, uprating, rebuild, strengthening, compensating, compacting, and unconventional approaches.

(b) Which methods are available for system upgrading, system refurbishment, system strengthening or uprating?

In addition to the options available to ameliorate the subtransmission system by increasing power transfer, the 'how-to' was considered. Methods are case dependant as shown with the investigations and reviews, no universal solution or recipe exists. However, the logical approach is to follow a low-cost to expensive approach, which generally starts with a theoretical approach and the minimum amount of hardware and equipment. At the expensive end, the last resort is new infeeds and complete rebuilds.

(c) What is the comparison of equipment ratings, in reality, to theoretical approaches and limitations set by industry standards?

The link between theoretical work and a real-life context was drawn. A historical deterministic approach placed a considerable limitation on subtransmission line capacity. Therefore, theoretical approaches can either be the limitation or a solution. Based on reference studies, the theoretical principles correlate with the real-life application thereof. The disadvantage of theoretical applications is that assumptions or parameters might not always be an exact correlation to the real-life context. As a result, the last step of a theoretical approach is to merge theory with real-life context. This can be done actively using approaches such as real-time thermal ratings or passively using equipment such as SLiM devices on overhead power lines.

(d) Is a practical and holistic approach applied and necessary to cater for planning aspects, and integrating technologies, when enhancing subtransmission power systems?

Distinctive solutions may not provide a sufficient solution to certain constraints, based on the complexity of the problem. However, a combination of solutions and a holistic perspective can provide a satisfactory outcome to the problem. From the investigations, it can be resolved that problems rapidly escalate and that due to subtransmission infrastructure forming part of a system, an atomistic approach may not always provide the best solution from a systems perspective.

(e) Are possible creative or unorthodox solutions considered?

Boundaries are necessary, but a sound solution can be found outside the proverbial "box". Although the actual implementation of creative solutions is limited, the options available were investigated. As power systems are modernised, expansion and constraints become more severe, it is anticipated that more and more untraditional solutions will be implemented to increase power transfer. It is anticipated that in future direct current subtransmission systems will be established, more high-surge impedance loading lines will be designed, flexible AC transmission systems will be implemented at subtransmission level, and even high phase order lines can become a reality.

This dissertation ascertains the restrictive conditions associated with power transfer in subtransmission systems, and as part of the reviews, a wide variety of solutions are presented to ameliorate the subtransmission systems' restrictions. The physics applied as part of this study used mathematical constructions to provide abstractions of the natural conditions of conductors and the modelling of both the restrictive conditions, as well as possible solutions. Emulations were based on factual data and information gathered over an extended period, the results were verified through literature, comparison to physical tests performed by others, and by correlations to actual performance.

The power transfer limitation is a constraint present to a notable degree on power systems, which explicitly includes subtransmission power systems. Various research has addressed some limitations through a single solution approach. This dissertation is original in considering both subtransmission overhead power lines and underground cables, not only either-or. In addition to the extended subject matter that considers both above- and underground subtransmission line installations, a significant variety of technical aspects set the basis from where solutions are developed. Scientific approaches are applied to technical aspects such as the mechanical loading of support structures, heat transfer, conductor mechanics associated with catenaries, material sciences, electro-magnetism, economics, and practical industry-related considerations.

Through the case studies, it was shown that solutions to a significant variety of existing problems are provided. The results reveal that a single solution approach will repeatedly solve a specific problem. However, the context of subtransmission systems in operations is that of a hybrid arrangement, partly consisting of interconnected subtransmission lines involving various topologies. These hybrid arrangements consist of overhead power lines, underground cables and substations in hybrid mesh, star, bus, and ring topologies. Due to the contextual application, a systems approach was followed, rather than a very specific application defined by sets of battery limits.

The study is validated by the contextual application thereof.

4.2 Conclusion

In the accumulating previous chapters, a problem is defined, the relevant literature is studied, and fundamental topics are considered as the subservient narrative to ideas and solutions for the defined problem. After that, some concepts and ideas are applied to actual real-life problems, which includes the solutions to the respective problems. Finally, the problem defined was validated based on the context of this dissertation.

Based on the above, whilst considering the appropriate limitations, it is concluded that subtransmission power systems can be ameliorated through increased power transfer, achievable by:

(a) Theoretical approaches to increase line ratings, such as applying probabilistic ratings instead of deterministic ratings, using finite element method models, and by applying measured information such as the most severe load profile recorded to determine a cyclic rating;

(b) Uprating or rerating lines through dynamic temperature sensing, real-time thermal rating, negative sag devices, inter-catenary suspenders, inter-phase insulators, insulated cross-arms, restringing with larger conductors, restringing with high-temperature low sag conductors, reinforcing or strengthening of support structures, repurposing structures for higher voltages, and the smart use of hardware;

(c) Establishing new external grid infeed(s), interlinking of external grid infeeds, increasing reliability of supply from n to n-1 or to n-2, and deloading of existing infrastructure the avail capacity;

(d) Reactive compensation, high surge impedance line designs, compact line designs, conversion from alternating current to direct current, the implementation of flexible alternating current transmission systems, and high phase order lines;

(e) Although not investigated in detail, small-scale embedded generation can provide invaluable assistance with reducing the load on incapacitated grids, if the SSEG offers base-load generation or generation during peak hours i.e., small-scale hydro generation, or hybrid photovoltaic plants and gas turbine generation.

The electrical and thermal resistance, capacitive and inductive reactance associated with a feeder, ultimately determines the maximum capacity of the specific feeder. Although not much can be done to improve the series resistance of a conductor, the conductor geometry, phase geometry and insulation significantly influence the capacitive and inductive reactance of a feeder.

The outcomes throughout this study are highly dependent on the context. The description of the study content was intended to be rich enough to be applied in full to other cases, and provide traditional and non-conventional solutions to ordinary constrained subtransmission feeder system problems. Various options to increase power transfer in subtransmission systems were explored. This study described that the power transfer rating of a feeder is not the only denominator when investigating methods to increase power transfer. Electrical grid dynamics, operation, and planning are key factors that contribute to successfully increasing the amount of electrical energy that can be transferred from one location to another. Amelioration solutions presented explained various constraints, but no “one size fits all” solution exists. However, the first step to increase feeder power transfer is a theoretical rerating approach. After that, uprating can be achieved through innovative solutions. The last resorts are complete upgrades or rebuilds and establishing new infeed sources.

Subtransmission grid planning is essential to network operations and financial planning, the determining of depreciated values and condition monitoring can be used to ascertain replacement dates of equipment to prevent infrastructure failures from implicating network reliability.

4.2.1 Limitations

This study was limited by not having data for DTS and RTTR systems. All the types of technology available in the industry could not be reviewed in detail, and not all could be applied to case scenarios. However, the most common technologies, considerations and methods were applied to real problems to present the outcome in the specific paradigm context.

4.2.2 Explanation of the complex phenomenon

The thermal rerating and uprating of feeders were recognised as cost-effective measures to gain maximum benefit from the delayed thermal response phenomenon of conductors and defer expensive infrastructure capital investment costs.

4.2.3 Exploring new ideas

Increasing the thermal ability of UGC has limited scope. However, numerous innovative solutions were presented to increase power transfer for OHLs, over and above theoretical re-rating and dynamic ratings. These solutions include the smart use of hardware (V-insulators and braced insulators, negative sag devices, inter-catenary suspenders, mid-span insulators, and insulated cross-arms), the strengthening of existing structures, BOLD structures, the use of CHS for lattice towers, HSIL designs, HTLS conductors, AC/DC conversion, FACTS, the reward of detail planning, and the effective use of the property.

4.3 Recommendation for further study

Future studies recommended involves the development of a model to log feeder and auxiliary data for extended periods, to develop an as-operated maximum feeder rating. If the measured data is available for all operational scenarios at a specific location, together with meteorological and environmental records, it is plausible to develop very accurate feeder ratings for every operational scenario based on the feeder location. This extends to the probabilistic statistical approach, where ratings are determined throughout the entire utility. The recommended statistical rating would be a location and history-based thermal rating (LHTR). This will provide an inexpensive alternative for existing feeders where an RTTR is not available.

Due to the thermal time delay with increasing load flows, the cyclic rating of feeders can be developed into a rating factor, similar to derating factors for the installation condition (duct, in-ground, or air), depth of burial, spacing, soil thermal resistivity, ambient temperature, soil temperature, and formation. The rating factor for cyclic loading can typically be referenced to the anticipated load factor.

As stated by [146], further research is needed into the validity and accuracy of overhead line parameters obtained through algorithms developed by [55], and alternative approximations. Differences in the line impedance calculations results can lead to maloperation of numerical relays, Troskie [146] calculated a 26.97% discrepancy in zero-sequence resistance between two software models. However, other sources claim better accuracy with approximations. As shown with this study, feeder parameters' accuracy also implicates the accuracy of load flow studies, resulting in possible incorrect thermal ratings and economic analysis of feeder systems.

The use of CHS structures and HSIL designs in South Africa provides an opportunity to change the South African OHL landscape. The use of CHS towers will enable the benefit of using vertical space more efficiently by constructing multiple circuit structures. If implemented, linesman must be upskilled to achieve proper installation and maintenance principles. With multiple circuits, n-2 conditions can be achieved on a single structure in a ring configuration, allowing for upgrades to be implemented without total shutdowns while maintaining at least n-1 conditions during upgrades. The challenges with terminating the lines to substations must be investigated.

Additional topics for further research proposed by the research examiners:

- Improving the reliability of the subtransmission system through capital expenditure on both feeders (OHL and cables). Utilise both a network model and substation models and consider techniques such as contingency enumeration and Monte Carlo simulation.

- Improving the reliability of subtransmission systems through operational expenditure. This is through better maintenance and network operation. Also with contingency enumeration and Monte Carlo simulation.

- The implications of voltage slide.
- When evaluating the transfer capability of a network that shows voltage instability some care needs to be applied with the analysis i.e., proper voltage stability is required so a mere load-flow study or a motor starting study may not confirm the performance of the entire power system properly. For example, special care needs to be taken with the load model and real voltage collapse will only be clear after tap-changer reaction.

Bibliography

[1] W. Smith, Principles of Material Sciences and Engineering, New York: McGraw Hill, 1996.

[2] U. Nkalo and E. Agwu, “Review of the impact of electricity supply on economic growth: a Nigerian case study,” IOSR Journal of Electrical and Electronics Engineering, vol. 14, no. 1, pp. 28-34, 2019.

[3] M. Johnston, “A crisis recalled: The power cuts that plunged the Auckland CBD in darkness for five weeks,” New Zealand Herald, 16 04 2018. [Online]. Available: https://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=12033654. [Accessed 18 01 2019].

[4] D. Stern, P. Burke and S. Bruns, “The Impact of Electricity on Economic Development: A Macroeconomic Perspective,” *EEG State-of-Knowledge Paper Series,* vol. Paper No.:1.1, pp. 1-42, 2016.

[5] N. Jordaan, “Times Live,” Sunday Times, 30 08 2019. [Online]. Available: https://www.timeslive.co.za/news/south-africa/2019-08-30-steel-thieves-down-fordsburg-power-pylons/#:~:text=An%20electricity%20pylon%20was%20brought,Johannesburg%2C%20on%20August%2030%202019.&text=%22Eskom%20is%20concerned%20about%20the,tower%20in%20the%2. [Accessed 23 08 2020].

[6] NERSA, “NERSA>Electricity>Compliance Monitoring,” [Online]. Available: http://www.nersa.org.za/#. [Accessed 08 06 2019].

[7] Z. Csereklyei, M. del Mar Rubio Varas and D. Stern, “Energy and Economic Growth: The Stylized Facts,” *Energy Journal,* vol. 37, no. 2, pp. 223-255, 2016.

[8] P. Burke, “The National-Level Energy Ladder and Its Carbon Implications,” *Environment and Development Economics,* vol. 18, no. 4, pp. 484-503, 2013.

[9] P. Burke and Z. Csereklyei, “Understanding the Energy-GDP Elasticity: A Sectoral Approach,” *Energy Economics,* vol. 59, pp. 199-210, 2016.

[10] H. Smith, M. Lorusso and F. MacKillop, “Powering the City in the Global South: Increasing Energy Access for all in a Context of Urbanisation and Changing

Governance," *EEG State-of-Knowledge Paper Series,* vol. Paper no.:3.3, pp. 1-20, 2017.

[11] H. Joffe, "Eskom keeps the lights on while achieving strong financial performance," *Energize,* pp. 6-7, 07 2011.

[12] ESKOM SOC, "Integrated results 2019: Integrated report, p179," Eskom (https://www.eskom.co.za/IR2019/Pages/default.aspx), Johannesburg, 31 March 2019.

[13] STATS SA, "Mid-year population estimates," Statistics South Africa, Pretoria, 2018.

[14] CTC Global, *ACCC Conductor news,* Irvine: Private communication, 2012.

[15] M. Engbrecht, "Methods of maintenance on high voltage fluid-filled cables," *Energize - Transmission Section,* pp. 31-34, 10 2008.

[16] M. Lyon, *Upgrading of Vulcania South Substation for City of Ekurhuleni,* Brakpan: Private communication, 2019.

[17] J. Voigt, *Refurbishment of Fordsburg Substation,* Johannesburg: Private communication, 2012.

[18] M. Lyon, *Refurbishment of Central B and Bree Street Substations for City Power,* Johannesburg: Private communication, 2015.

[19] S. Peens, Interviewee, *New Sebenza Substation.* [Interview]. 10 2017.

[20] L. Greeff, Interviewee, *Kroonstad power failures.* [Interview]. 2011-2019.

[21] M. Lyon, *Refurbishment of Unibijl Substation due to failure (Tender number 67/2007),* Vanderbijlpark: Private communication, 2007.

[22] I. Pandelani, Interviewee, *Town Substation failure.* [Interview]. March 2019.

[23] I. Pandelani, Interviewee, *Cross-member theft of lattice structure.* [Interview]. 10 December 2018.

[24] M. Lyon, *Premier FMCG Application for increase in bulk electrical supply,* Pretoria: Private communication, 2019.

[25] Google, "Google Earth Pro," Google LLC, 2019.

[26] J. Nieuwenhuis, "Introducing qualitative research," in *First steps in research*, Pretoria, Van Schaik, 2010, pp. 47-68.

[27] J. Nieuwenhuis, "Qualitative research designs and data gathering techniques," in *First steps in research*, Pretoria, Van Schaik, 2010, pp. 70-97.

[28] SABS, *SANS1019 Standard voltages, currents and insulation levels for electricity supply,* Pretoria: The South African Bureau of Standards, 2014.

[29] J. Nieuwenhuis, "Analysing qualitative data," in *First steps in research*, Pretoria, Van Schaik, 2010, pp. 99-122.

[30] V. Janesick, "The choreography of qualitative design," in *Handbook of qualitative research*, Thousand Oaks, 2000, pp. 379-399.

[31] C. Baylis and B. Hardy, Transmission and Distribution Electrical Engineering, Fourth Edition, Oxford: Elsevier, 2012.

[32] Study Committee 37, "Summary on planning methods for sub-transmission systems," *Electra,* vol. 138, no. October 1991, pp. 147-167, 1991.

[33] Pacific Northwest National Laboratory, "Valuation of Electric Power System Services and Technology," US Department of Energy, Oak Ridge, 2016.

[34] M. Reta-Hernandez, "Transmission line parameters," in Electric power generation, transmission and distribution, Taylor & Francis Group LLC, 2006.

[35] Q. Chen, D. Lin, L. Lin, S. Liu and M. Xiao, "Research on Economical Power Supply Radius and Transformer Capacity for Substations in Distribution Network," in *International Conference on Power, Energy Engineering and Management (PEEM 2016)*, Guangzhou, 2016.

[36] R. Stephen and K. Yeomans, "Statistical signatures for the determination of transmission safety," *Elektron, Official Journal of the South African Institute for Electrical Engineers,* no. November/December, pp. 5-10, 1993.

[37] Cigré WG22.12, “The thermal behaviour of overhead conductors – Section 3: Mathematical model for evaluation of conductor temperature in the unsteady state,” *Electra,* vol. 174, no. October, pp. 59-69, 1997.

[38] J. Alberts and J. de Kock, *Impact of energy efficiency and renewable energy on electricity master planning and design parameters,* Potchefstroom: North-West University, 2017.

[39] World Bank, “South Africa GDP,” Trading Economics, 2019. [Online]. Available: https://tradingeconomics.com/south-africa/gdp. [Accessed 20 06 2019].

[40] Stats SA, “Four facts about our provincial economies,” Statistics South Africa, 29 03 2019. [Online]. Available: http://www.statssa.gov.za/?p=12056. [Accessed 06 04 2019].

[41] Stats SA, “2020 Mid-year population estimates,” Statistics South Africa, 09 07 2020. [Online]. Available: http://www.statssa.gov.za/?p=13453. [Accessed 30 07 2020].

[42] Public Service Commission of Wisconsin, “Underground Electric Transmission Lines,” [Online]. Available: https://psc.wi.gov/Documents/Brochures/Under%20Ground%20Transmission.pdf. [Accessed 08 01 2019].

[43] SABS, SANS10280-1 Overhead power lines for conditions, Pretoria: South African Bureau of Standards, 2013.

[44] Eskom DGL:34-600 / 240-125383428, *Building line restrictions, servitude widths, line separations and clearances from power lines,* Johannesburg: ESKOM, 2017.

[45] K. Weltmann, “GIS versus non-GIS - a value based comparison,” ABB, Zuerich/Switzerland, 2001.

[46] G. Landwehr and P. Marais, “Practical comparison of power line uprating and upgrading results,” *Cigré Science & Engineering,* vol. 5, no. June 2016, pp. 50-56, 2016.

[47] A. Fews, D. Henshaw, R. Wildling and P. Keitch, “Corona ions from power lines and increased exposure to,” *International Journal of Radiation Biology,* vol. 75, no. 12, pp. 1523-1531, 1999.

[48] Cigré, Overhead lines - a Cigré green book, Cigré, Paris, France, 2014.

[49] Cigré working group 36.01, “074 Electric Power Transmission and the Environment - Fields, Noise and Interference,” Cigré, Paris, France, 1991.

[50] Eskom, The planning, design & construction of overhead power lines, Johannesburg: Crown Publications cc., 2010.

[51] L. Lukic, M. L. D. Djapic and A. Petrovic, “Aspects of design of power transformers for noise reduction,” in *23rd National Conference & 4th International Conference Noise and Vibration*, Kragujevac, Serbia, 2012.

[52] J. D. Glover, M. S. Sarma and T. J. Overbye, Power System Analysis and Design, 4^{th} ed., Stamford: Cengage Learning, 2008.

[53] SABS, SABS10103-2008: The measurement and rating of environmental noise with respect to annoyance and speech communication, Pretoria, South Africa: South African Bureau of Standards, 2008.

[54] H. W. Dommel, Electromagnetic transient program reference manual, Portland: Bonneville Power Administration, 1986.

[55] DigSilent GmbH, “Technical Reference Documentation: Overhead Line Models,” DigSilent GmbH, Gomaringen, 2017.

[56] G. Moses, “The purpose of electrical insulation,” IEEE, Chicago, 1960.

[57] Cigré Working Group B2.63, *792 Compact AC overhead lines,* Cigré, Paris, France, 2020-02.

[58] R. Blodgett and R. Fisher, “A New Corona- and Heat-Resistant Cable Insulation Based on Ethylene Propylene Rubber,” *IEEE Transactions on Power Apparatus and Systems,* vol. 82, no. 69, pp. 980-990, 1963.

[59] Cigré Working Group B2.43, *601 Guide for thermal rating calculations of overhead lines,* Cigré, Paris, France, 2014.

[60] S. Uski-Joutsenvuo and R. Pasonen, “Maximising power line transmission capability by employing dynamic line ratings - technical survey and applicability in Finland,” VTT, Finland, 2013.

[61] IEEE, *IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors (IEEE Std 738-2012),* New York: IEEE, 2013.

[62] P. Van Staden and J. De Kock, “The practical comparison of conductor operating temperatures against IEEE and CIGRE ampacity calculations,” in *IEEE PES PowerAfrica 2012 Conference and Exposition*, Johannesburg, 2012.

[63] Eskom SOC, “Standard: determination of conductor ratings in Eskom (240-100176272),” Eskom, Johannesburg, South Africa, 2015.

[64] A. Burger, Interviewee, *Eskom conductor ratings and corona studies (Eskom Tx).* [Interview]. 03 09 2012.

[65] P. Van Staden and J. De Kock, “The practical comparison of conductor operating temperatures against IEEE and CIGRE ampacity calculations,” in *IEEE PES PowerAfrica 2012 Conference and Exposition*, Johannesburg, 2012.

[66] Cigré Working Group 22.12, “207 Thermal behaviour of overhead conductors,” Cigré, Paris, France, 2002-08.

[67] K. Rozmiarek, *Overhead line design principles training,* Vanderbijlpark: Private communication, 2018.

[68] M. Bockarjova and G. Andersson, “Transmission Line Conductor Temperature Impact on State Estimation Accuracy,” IEEE, Lausanne, Switzerland, 2007.

[69] Cigré Working Group B1.07, *338 Statistics of AC underground cables in power networks,* Cigré, Paris, France, 2007.

[70] Cigré Working Group B1.11, *606 Upgrading & Uprating of Existing Cable Systems,* Cigré, Paris, France, 2015.

[71] SANS 60853-2:2011, *Calculation of the cyclic and emergency current rating of cables, Part 2: Cyclic rating of cables greater than 18/30 (36) kV and emergency ratings for cables of all voltages,* Pretoria: SABS, 2011.

[72] Cigré Working Group B2.12, *29 Guide for selection of weather parameters for bare overhead conductor ratings,* Cigré, Paris, France, 2006.

[73] CBi Electric: African cables, “HV XLPE Cable Data Sheet,” CBi Electric, Vereeniging, 2018.

[74] Cigré W.G. 22.12, “Probabilistic determination of conductor current ratings,” *Electra,* vol. 164, no. February, pp. 102-119, 1996.

[75] etap, “etap cable-thermal-analysis-software,” 2019. [Online]. Available: https://etap.com/cable-thermal-analysis-software/cable-steady-state-temperature-calculation. [Accessed 25 11 2019].

[76] DNV KEMA, *In-house cable courses at CBi African Cables: Ampacity and engineering aspects of power cables,* Vereeniging: Private communication, 2013.

[77] P. Wang, H. Ma, G. Liu, Z. Han, D. Guo, T. Xu and L. Kang, “Dynamic Thermal Analysis of High-Voltage Power Cable Insulation for Cable Dynamic Thermal Rating,” *IEEE Access,* vol. 7, no. April, pp. 56095-56106, 2019.

[78] K. Xiao, “Accurate Simulations of Thermal Field of Operational Conductors,” in *IOP Conference Series: Materials Science and Engineering*, 2017.

[79] K. e. a. Xiao, “Accurate Simulations of Thermal Field of Operational Conductors,” in *IOP Conference Series: Materials Science and Engineering*, Busan, 2017.

[80] Cigré Working Group B1.45, *756 Thermal monitoring of cable circuits and grid operators’ use of dynamic rating systems,* Cigré, Paris, France, 2019.

[81] Cigré Working Group B2.55, *763 Conductors for the uprating of existing overhead lines,* Paris: Cigré, 2019.

[82] T. Kavanagh and O. Armstrong, “An evaluation of High-Temperature Low Sag Conductors for Uprating the 220kV Transmission Network in Ireland,” in *International Universities Power Engineering Conference (UPEC)*, Cardiff, Wales, 2010.

[83] E. Bosze and D. Bryant, Interviewees, *CTC ACCC Training.* [Interview]. 08 2012.

[84] W. Thue, Electrical Power Cable Engineering, CRC Press, 2011.

[85] S. Singh, Electric Power Generation, Transmission and Distribution, 2nd Edition ed., New Delhi: Asoke K. Ghosh, 2008.

[86] H. Shabani and V. B, “A probabilistic approach for optimal power cable ampacity computation by considering uncertainty of parameters and economic constraints,” *Electrical Power and Energy Systems 106,* pp. 432-443, 2019.

[87] P. De Arizon, “A comparison of numerical algorithms for determining electrical resistance and reactance using subdivision of the cable conductors,” the University of British Columbia 2010-05-22T17:40:37Z 2010-05-22T17:40:37Z 1984 2010-05-22T17:40:37Z, Venezuela, 1984.

[88] F. Lui and R. Findlay, “Investigation of mechanical properties of single-layer ACSR based on an Integrated Model,” Elsevier, Zhejiang & Ontario, 2007.

[89] European EMTP-ATP users group, “EMTP Theory Book - Electromagnetic Transients Program Rule Book,” Bonneville Power Administration, Portland Oregon, 1982.

[90] D. Kusiak, T. Szczegielniak, P. Jablonski and Z. Piatek, “An improved solution for the skin and proximity effect in a tubular screen,” in *International Conference on Computational Problems of Electrical Engineering (CPEE)*, Banská Štiavnica, Slovak Republic, 2018.

[91] Cigré Working Group B2.12, *345 Alternating current (AC) resistance of helically stranded conductors,* Cigré, Paris, France, 2008.

[92] K. Ferkal, M. Poloujadoff and E. Dorison, “Proximity effect and eddy current losses in insulated cables,” *IEEE Transactions on Power Delivery,* vol. 11, no. 3, July, pp. 1171-1178, 1996.

[93] D. Chatzipetros and J. Pilgrim, “Impact of Proximity Effects on Sheath Losses in Trefoil Cable Arrangements,” *IEEE Transactions on Power Delivery,* no. 30 January, pp. 1-1, 2019.

[94] V. Morgan, “The Current Distribution, Resistance and Internal Inductance of Linear Power System Conductors - A Review of Explicit Equations,” IEEE, 2013.

[95] W. Moutassem and G. Anders, “Calculation of the Eddy Current and Hysteresis Losses in Sheathed Cables Inside a Steel Pipe,” *IEEE TRANSACTIONS ON POWER DELIVERY,* vol. 25, no. No. 4, pp. 2054-2063, 2010.

[96] A. Pabla, Electric Power Distribution, Sixth edition, New York: McGraw Hill, 2011.

[97] IEC60287-1-1:2006, *Electric cables - Calculation of the current rating - Part 1-1: Current rating equations (100 % load factor) and calculation of losses - General,* Geneva: IEC, 2006.

[98] C. Spezia, “Electrical Power Systems Engineering,” Mathsoft Engineering and Education, 2004.

[99] S. Islam and F. Islam, “Impact of Temperature, Wind Flow, Solar Radiation, Skin Effect and Proximity Effect on Overhead Conductor,” *Global Journal of researches in engineering, Electrical and electronics engineering,* vol. 12, no. 1, 2012.

[100] IEC, *IEC60287-1-1:2014 Electric cables - Calculation of the current rating Part 1-1: Current rating equations (100% load factor) and calculation of losses - General,* IEC, 2014.

[101] C. Fortescue, “Method of symmetrical coordinates applied to the solution of polyphase networks,” in *34th Annual Convention of the American Institute of Electrical Engineers*, Atlantic City, America, 1918.

[102] DigSilent GmBH, “Technical Reference Documentation: Cable System,” DigSilent GmBH, Gomaringen, 2017.

[103] H. Beauty and S. Santoso, Handbook of electric power calculations, New York: McGraw-Hill, 2001.

[104] A. Ametani, “A general formulation of impedance and admittance of cables,” *IEEE Transactions on Power Apparatus and Systems,* Vols. PAS-99, no. 3, pp. 902-910, 1980.

[105] R. Ebrahimi, A. Babaee and M. Hoseynpoor, “Evaluation and Calculation of Overhead Line Impedance in Distribution Networks,” *Australian Journal of Basic and Applied Sciences,* vol. 5, no. 8, pp. 1278-1284, 2011.

[106] C. JR, “Wave Propagation Overhead Wires with Ground Return,” *Bell System Technical Journal,* vol. 5, pp. 539-554, 1926.

[107] R. Rivas, “Section 9 - Overhead transmission lines and underground cables,” in *Handbook of Electric Power Calculations, Third Edition*, New York, McGraw-Hill, 2001, pp. 9.1-9.33.

[108] H. Dommel, “Overhead Line Parameters from Handbook Formulas and Computer Programs,” *IEEE Transactions on Power Apparatus and Systems,* Vols. PAS-104, no. 2, pp. 366-372, 1985.

[109] D. C, “"Calcul Approché des Paramètres Primaires et Secondaires d’Une Ligne de Transport, Valeurs Homopolaires (“Approximate Calculation of Primary and Secondary Transmission Line Parameters, Zero Sequence Values”, in French)”,” *EDF Bulletin de la Direction des Études et Reserches,* vol. Serie B—Réseaux Électriques, no. Matériels Électriques No. 1., pp. 53-62, 1969.

[110] ““Approache Complète de la Propagation Multifilaire en Haute Fréquence par Utilisation des Matrices Complexes, (“Complete Approach to Multiconductor Propagation at High Frequency with Complex Matrices,” in french)”,” *EDF Bulletin de la Direction des Études et Reserches,* vol. Serie B—Réseaux Électriques, no. Matériels Électriques No. 3/4., pp. 5-20, 1976.

[111] A. Deri, G. Tavan, A. Semlyen and C. A, “The Complex Ground Return Plane, a Simplified Model for Homogeneous and Multi-layer Earth Return,” *IEEE Transactions on Power Apparatus and Systems,* Vols. PAS-100, no. August, pp. 3686-3693, 1981.

[112] W. Kersting and G. RK, “The application of Carson's equations to steady-state analysis of distribution feeders,” in *IEEE PES Power Systems Conference and Exposition*, 2011.

[113] M. Cenky, *Elektrické parametre vonkajších elektrických vedení VVN a ZVN a ich vplyv na potrebu transpozície vedenia,* Bratislave: Slovenska technicka univerzita v Bratislave, 2015.

[114] M. Cenky, J. Bendik and Z. Eleschova, “Advanced methods for computation of electrical parameters for overhead transmission lines,” *Journal of Electrical Engineering,* vol. 2, no. 68, pp. 133-147, 2017.

[115] Institut fur Experimtelle Kernphysik, Comparison of Advanced High Power Underground Cable Designs, Karlsruhe: Gesellschaft für kernforschung, 1975.

[116] M. Lauer, "European Commission," [Online]. Available: https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/thermalnet_methodology_guideline_on_techno_economic_assessment.pdf. [Accessed 05 2017].

[117] Y. Yang, M. Darwish, M. Moghadam, L.-C. C, G. O'Brien and D. Quennell, "Power Cable Cost-Benefit Analysis: A Critical," in *53rd International Universities Power Engineering Conference (UPEC)*, Glasgow, 2018.

[118] Cigré Working Group B2/C1.19, *425 Increasing Capacity of Overhead Transmission Lines,* Cigré, Paris, France, 2010.

[119] I. Ferreira, *Dissertation: Designing power line towers using circular hollow sections,* Potchefstroom: NWU, 2013.

[120] A. Eric, P. Miller and E. Decima, "Breakthrough Overhead Line Design (BOLD) - Transmission Line Design Considerations," BOLD & AEP, Columbus, Ohio, 2016.

[121] K-line insulators limited, *Distribution silicone insulators catalogue,* Toronto: K-line insulators limited, 2018-11.

[122] C. Henderson, "Uprating of high voltage overhead transmission lines using intermediary catenary suspenders," in *Cigré 8th Southern Africa Regional Conference*, Cape Town, 2017.

[123] R. Adapa, M. Shirmohamadi and R. Gray, "SLiM (Sagging Line Mitigator) – Mitigating Excess Sag in Overhead Transmission Lines," in *Inaugural IEEE PES 2005 Conference and Exposition in Africa*, Durban, South Africa, 11-15 July 2005.

[124] Shirmohamadi, *Sag compensating device for suspended lines,* Google Patents, 2002.

[125] Cigré Woring Group B2.51, *638 Guide to Overall Line Design,* Cigré, Paris, France, 2015.

[126] H. Orton, “Virginia Register of Regulations,” 2019. [Online]. Available: http://dls.virginia.gov/commission/pdf/overheadorunderground.pdf. [Accessed 03 07 2019].

[127] M. Rycroft, “Effects of MV and HV cable capacitance on operational limits,” *EEPublishers - Energize,* pp. 32-34, August 2018.

[128] T. Vrana and O. Mo, “Optimal Operation Voltage for Maximal Power Transfer Capability on Very Long HVAC Cables,” in *Elsevier: 13th Deep Sea Offshore Wind R&D Conference*, Trondheim, Norway, 2016.

[129] J. Cooper, “Ampacity and sheath bonding,” in *ICC 2003 Fall Educational Session*, 2003.

[130] CBi African Cables, *F2MC_300_068,* Vereeniging: CBI African Cables, 2006.

[131] J. Ruiz, A. Garcia and X. Morera, “Circulating sheath currents in flat formation underground power lines,” ResearchGate, Spain, 2007.

[132] Brugg Cables, “High Voltage XLPE Cable systems - Technical user guide”.

[133] J. Slegers, “Transmission Line Loading,” IOWA STATE UNIVERSITY, 18 10 2011. [Online]. Available: http://home.eng.iastate.edu/~jdm/wind/TransmissionLineLoadingDesignCriteriaAndHTS.pdf. [Accessed 23 10 2020].

[134] R. Geary, T. Condon, T. Kavanagh, O. Armstrong and J. Doyle, “Introduction of high-temperature low sag conductors to the Irish transmission grid,” Cigré 2012 Technical Programme, Paris, France, 2012.

[135] M. Ntuli, N. Mbuli, L. Motsoeneng, R. Xezile and J. Pretorius, “Increasing the Capacity of Transmission Lines via Current Uprating: An Updated Review of Benefits, Considerations and Developments,” in *Australasian Universities Power Engineering Conference (AUPEC)*, Brisbane, Australia, 2016.

[136] T. Maphumulo, R. Stephen and J. Van Coller, “Consideration to use high SIL lines versus series compensation in high voltage power transmission lines,” in *The 20th International Symposium on High Voltage Engineering*, Buenos Aires, Argentina, 2017.

[137] J. Hao and W. Xu, “Extended Transmission Line Loadability Curve by Including Voltage Stability Constraints,” IEEE, Alberta, 2008.

[138] M. Ghassemi, “High Surge Impedance Loading (HSIL) Lines: A Review Identifying Opportunities, Challenges, and Future Research Needs,” *IEEE TRANSACTIONS ON POWER DELIVERY,* vol. 34, no. 5, pp. 1909-1924, October 2019.

[139] G. Pilz, “FACTS Planning, Technology Selection and Specification,” in *9th Cigré Southern Africa Regional Conference*, Johannesburg, 2019.

[140] D. Fink and H. Beaty, Standard handbook for electrical engineers, New York: McGraw-Hill, 1993.

[141] R. Vajeth, A. Burger, L. Wilson and D. Mufitc, “Tutorial 8 Power transfer capacity of overhead lines,” in *IEEE PES PowerAfrica 2012*, Johannesburg, 2012.

[142] Quanta Energized Services, “www.quantaenergized.com,” 2012. [Online]. Available: http://www.quantaenergized.com/project/574-2/. [Accessed 2017].

[143] P. O’Halloran, “Live-line transmission lines upgrade projects: First-in-Africa project,” in *AMEU*, Johannesburg, 2011.

[144] P. Van Staden, “Thermal up-rating of transmission lines and substation equipment,” North-West University, Potchefstroom, 2013.

[145] H. Troskie, “Research into Specific Numerical Protection Maloperations,” North-West University, Potchefstroom, 2012.

Appendix 1 – CIGRE article

The article's inclusion starts on the next page.

10th CIGRE Southern Africa
Regional Conference
2nd – 4th November 2021
Johannesburg, South Africa

Subtransmission overhead power line amelioration through increased power transfer: A review

M. LYON[1], J.A. DE KOCK[2]
North-West University[1,2]
South Africa[1,2]
marnus@lyon.co.za[1], jan.dekock@nwu.ac.za[2]
Orcid: 0000-0001-6907-8461[1], 0000-0002-5485-0647[2]

SUMMARY

Power transfer limitation is a constraint present to a notable degree on power systems, including subtransmission overhead power lines. Subtransmission in a Southern African context is power transmitted at the standard nominal voltage levels for high voltage systems of 66 kV, 88 kV and 132 kV. Often subtransmission systems are hybrid arrangements that consist of overhead power lines, underground cables and substations in hybrid mesh, star, bus, and ring topologies. This review considered only subtransmission overhead lines. The subject matter considers various technical aspects, from where solutions are evaluated for power transfer limitations. The review combined fundamental characteristics with different approaches. Amelioration solutions were presented for various constraints, but no "one size fits all" solution exists. However, it was found that the first step to increased power transfer on a subtransmission line should follow a theoretical re-rating approach. After that, uprating can be achieved through innovative solutions such as new hardware, component upgrades, structure strengthening and restringing. The last resorts are complete upgrades or re-builds and establishing new external grid infeed sources.

KEYWORDS

Overhead powerline, subtransmission, power distribution.

marnus@lyon.co.za

1. INTRODUCTION

Electrical energy is the heartbeat of a country's economy. Therefore, an unreliable supply and distribution of electrical energy negatively impact economic expectations [1]. Electrical energy is the third most crucial production factor in economic models, other than capital and labour [1].

The assessments throughout this review are highly dependent on the context. The aim was to examine and understand options and methods through literature and case studies to upgrade or strengthen overhead subtransmission lines where supply reliability was compromised or insufficient power transfer capacity was available. Although power system reliability and power system transfer improvement can be related, the concepts differ significantly and can be unrelated. The study was solution-focused, which excluded investigating the intrinsic reasons that gave rise to the specific problems. This paper presents a review of the solutions to be considered for enhancing overhead subtransmission feeders' power transfer capacity.

All opportunities cannot be reviewed in detail as part of this article. An overview is given of theoretical enhancements, followed by hardware use, structure design, surge impedance loading, AC to DC conversion, flexible AC transmission systems, and higher phase order lines.

2. THEORETICAL ENHANCEMENT

Regulatory requirements are practical aspects that greatly influence the investigations into the refurbishment of existing subtransmission systems or the planning of new subtransmission systems and must be considered. Various NRS, SANS, IEC, ASCE, ANSI, ISO, IEEE, BS and other South African and international standards cover power system designs and equipment performance. The legal and regulatory requirements should always be taken into consideration when investigating possible solutions.

The electrical resistance, thermal resistance, capacitive reactance, and inductive reactance associated with a feeder ultimately determine the feeder's maximum capacity. Although not much can be done to improve the series resistance without selecting alternative material or increasing the cross-sectional area of the conductor, the conductor geometry, phase geometry, and insulation significantly influence a feeder's capacitive and inductive reactance and allow an opportunity to optimise power transfer. By varying the engineering approaches, the line thermal rating can theoretically be increased.

2.1. Thermal Rating

The conductor thermal rating establishes the thermal range wherein a subtransmission feeder can be operated without implicating safety precautions or inflicting damage to infrastructure. Various methods and approaches exist to determine thermal ratings or feeder ampacity for OHL's, such as:

- The deterministic method for OHL rating (assumes worst-case cooling) [2] [3];
- A probabilistic method for OHL rating (statistical chance approach) [4];
- The finite element models for stochastic environmental conditions, and
- The dynamic rating systems (DTS) or real-time (variable) thermal rating (RTTR).

The above methods apply to the re-rating of existing infrastructure. By comparing the measured conductor temperature to ampacity calculations, Van Staden confirmed the correlation between measured ampacity, the IEEE ampacity calculations and the Cigré ampacity calculations [5].

For the subtransmission lines, which typically run over short distances, the thermal limit of the line is the determining factor of the line power transfer capability [6]. The thermal limitation for a strung overhead conductor is the maximum allowable thermal expansion to maintain statutory clearances, annealing temperatures, or the thermal limits of composite cores.

With the basic power system model and feeder thermal rating, investigations can be launched to consider the available options for increased power transfer.

The chart from Figure 1 depicts the increase obtained in current rating for four Aluminium Conductor Steel Reinforced (ASCR) conductor sizes by varying from a deterministic approach to a probabilistic approach:

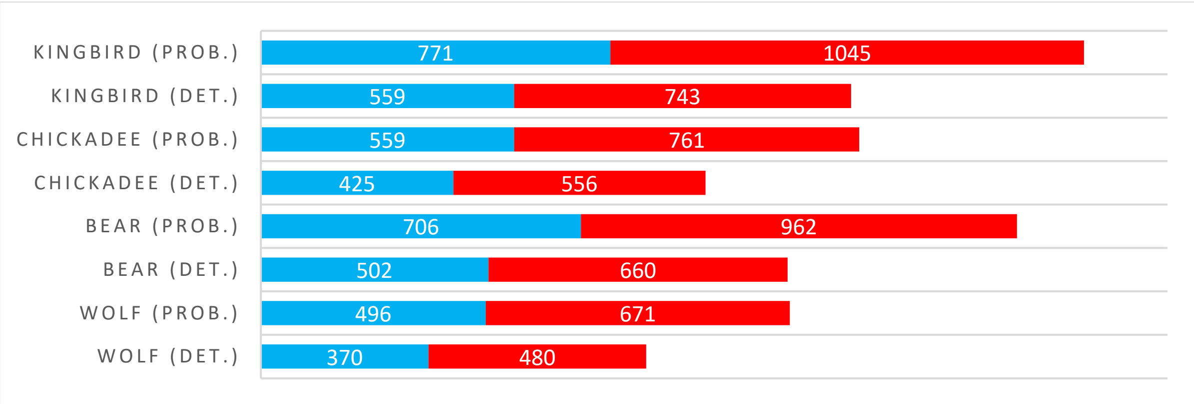


Figure 1: ACSR deterministic and probabilistic ratings at 70°C [7]

In Figure 1, the first part per conductor of the stacked-bar chart is the normal conductor rating (in blue). The second part is the emergency conductor rating (in red).

3. OVERHEAD POWER LINE CONDUCTORS

Technological advances saw the birth of composite conductors with alternative materials to steel. The changes in conductor technologies allow the increased conductor ampacity and improve mechanical characteristics [8]. Substitute conductors to AAAC (all aluminium alloy conductor) and ACSR, such as ACSS (aluminium conductor steel supported), GZTACSR (Gap-type thermally upgraded ACSR), and ZTACIR/AA (Super thermal-resistant aluminium alloy conductor Aluminium-clad invar reinforced), were introduced in the 1970s and 1980s. The early 2000s introduced hybrid composite conductors such as ACCR (aluminium conductor composite reinforced) and ACCC (aluminium conductor composite core). Conductors such as ACCR or ACCC with low thermal expansions are used for high-temperature applications [8]. These conductors are referred to as HTLS (high-temperature low sag) conductors. Some conductors are stranded with trapezoidal wraps to increase the conductive cross-sectional area when compared to cylindrical strands.

The ideal conductor core development characteristics are high mechanical strength, high modulus of elasticity, low thermal expansion, lightweight, low electrical resistance, high resistance to vibration, high strength, and high heat tolerance. The experimental results of the graph below compare sag for a 70 m span, based on Drake size conductors [9].

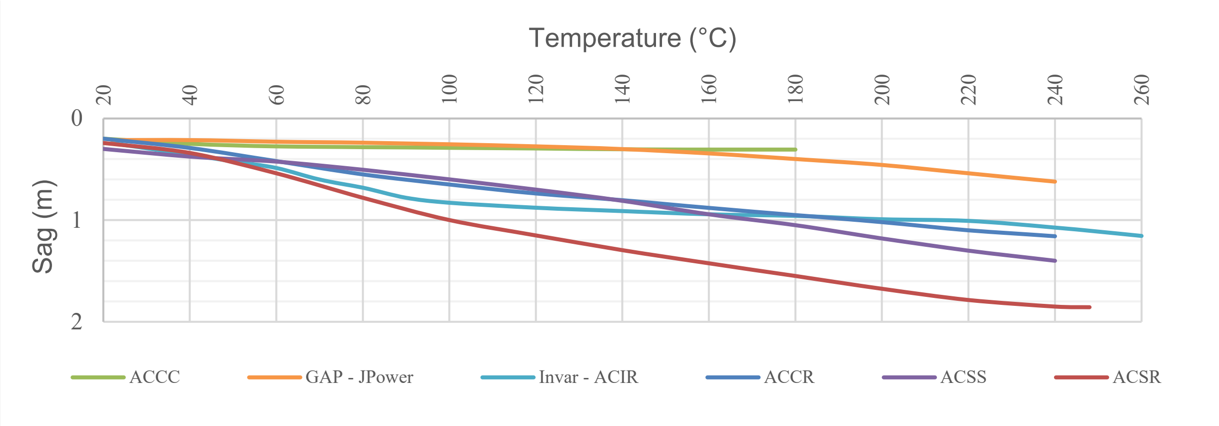


Figure 2: Temperature vs sag for various conductors [9]

For the reconductoring of an ACSR line, the sag limit or templating temperature would typically be set to 100 ºC when using ACCC (max. operating temperature of 180 ºC).

A comparison by Landwehr and Marais concludes that the outcome of a single uprating study provides limited inference to other scenarios. However, the results indicate the following guidelines [10]:

- Re-rating is a very low-cost option to increase power transfer capacity through theoretical uprating or re-tensioning. Re-rating can be a cost-effective first step approach to defer more expensive upgrades.
- Upgrading line voltage or possibly re-building a line with a heavier conductor can be more cost-effective than restringing with HTLS conductors if the network can sustain lengthy interruptions and the substation can accommodate a simple voltage upgrade.
- HTLS has an expensive initial capital investment cost. Still, GZTACSR, ACCC and ZTACIR provide the best total increase in power transfer within the allowable existing infrastructure limits.
- Per MVA, GZTACSR was the most economic HTLS conductor for the specific case.
- The total cost of losses correlates to total resistive losses, most notably for increasing the rating of existing ACSR. The total investment cost aligns with other options because of the operational cost.

A study by Kavanagh and Armstrong [11] showed that using HTLS over ACSR for uprating, based on a peak load over 25 years, a 60% saving is achievable when considering the initial cost, plus lifecycle losses. To fully benefit from HTLS with uprating, the initial construction cost should be less than the lifecycle cost of losses after uprating.

4. HARDWARE

By effectively using hardware, line ratings can be increased. The following hardware applications create an opportunity to increase power transfer:

- Insulated cross-arms;
- Insulator changes and mid-span interphase insulators;
- Tower reconfiguration and strengthening;
- Inter-catenary or intermediary suspenders;
- Negative sag devices;
- Re-dressing and strengthening of structures, and
- Phase geometry alterations to achieve HSIL.

Sagging line mitigation devices (SLiM) introduces a negative sag into a catenary by passively compensating for sag caused by increased conductor temperatures. The working principle of a SLiM device is to mimic, but reverse, the axial thermal expansion of a catenary. The thermal expansion within the actuator of the SLiM device is amplified by hardware such as levers, cogs, and gears [12].

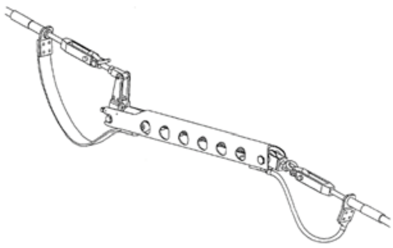


Figure 3: US patent image of a SLiM device [12]

Braced insulators or multiple insulators such as V-string insulators offer increased mechanical strength and better geometric stability when compared with single-post insulators or single-suspension insulators. The increase in mechanical strength allows longer spans, additional sub-conductors or heavier conductors. Rigid insulators eliminate plenty of conductor swing, allowing for compact line designs and voltage upgrades on the same structure.

Insulated cross-arms can be used to replace suspension insulators and to increase ground clearance. By increasing ground clearance, the thermal rating of the overhead line can be improved, or the line voltage can be upgraded.

Photograph 1: Insulated cross-arm on H-pole [13]

The typical length of a 132 kV long-rod insulator is 1480 mm from the ball to the socket. By applying an insulated cross-arm, the allowable sag is conservatively increased from 6.87 m to 8.03 m over the 270 m span, with a corresponding templating temperature increase from 70 °C to 110 °C. Although clearance is maintained at the higher operating temperature, the effect of the higher temperature on losses, the conductor, and fittings must be thoroughly considered.
The line voltage can be increased on existing lines, and geometry can be compacted using midspan inter-phase insulators. The installation of insulators between the phase conductors is possible using "live-line" techniques [13].

Another method of inexpensively increasing ground clearance is the use of intermediary catenary suspenders. Intermediary suspenders or inter-catenary suspenders (suspension insulators) are connected from the earth conductor to phase conductors, enacting an opposing force to the weight of the phase conductor. With the conductor being supported by the overhead earth wire, with a high steel content, most of the conductors' weight is transferred from the conductor to the steel shield wire, resulting in the temperature effect on sagging of the conductor becoming less influential. The conductor current can be estimated to be increased by 40% at a tension increase of 15% to 17 % above every-day tensions (EDT) [14], with a minimal cost implication. Figure 4 illustrates the increased clearance by intermediary suspenders, allowing for higher operating temperatures.

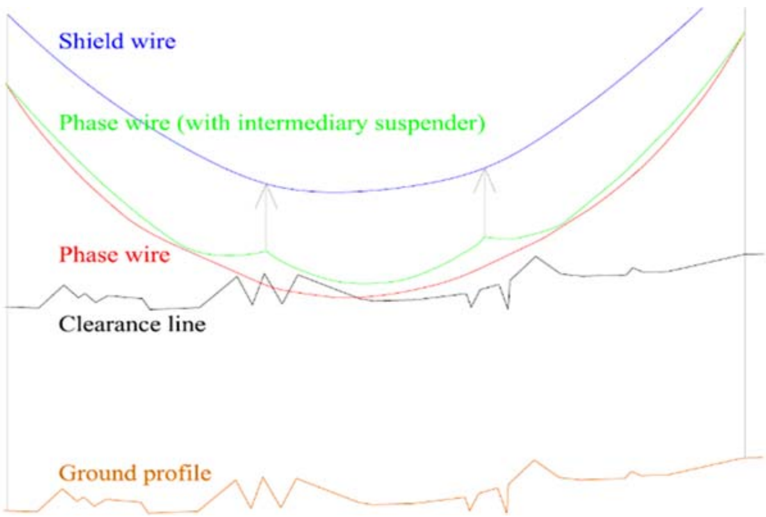


Figure 4: Inter-catenary suspenders [14]

5. STRUCTURE DESIGN

When re-building or restringing existing lattice towers, or when building new lines with the use of a heavier conductor than what the tower was initially designed for, a viable option to be considered is to increase the number of cross members to strengthen the tower.

Increased power transfer can be achieved by adding additional circuits to double-circuit structure footprints and will be possible using Circular Hollow Section (CHS) towers. From a basic analysis by Ferreira [15], it is concluded that CHS provides additional mechanical loading capabilities of 1.22 times more than angular members. When considering the limitation for class 3 compression, CHS is 11.7 times stronger than angle members. Furthermore, CHS structures showcase superior withstand capabilities compared to other cross-sections in compression, at a weight of 2.3 times less than conventional angle members with equivalent compression resistance [15]. The structures are challenging to climb, which holds maintenance challenges but acts as a theft deterrent measure. CHS further reduces wind loading on structures due to its reduced drag coefficient. A disadvantage of CHS is the increased material connection costs. The economics of full-scale structures has not been tested in the industry. However, it is expected that the manufacturing cost will be higher for CHS towers, but the overall cost, including installation and maintenance, is significantly less [15].

6. SURGE IMPEDANCE LOADING

Surge impedance loading (SIL) is a simple method to determine the maximum ampacity of subtransmission lines. Power line lengths are fractions of the power frequency wavelength required to change the phase of the voltage or current by 360º [16]. Therefore subtransmission lines are not terminated at their SIL. The SIL evaluates different lines' maximum power transfer capabilities by using the line voltage and characteristic impedance.

The SIL of an overhead line can be varied using reactive compensation such as shunt line reactors, series capacitor banks and by changing the wire geometry and spacing. Therefore, the SIL can be increased by changing conductor geometry into compact delta configurations, adding sub-conductors, and increasing inter sub-conductor spacing [17]. From a case study at transmission voltages by Maphumulo, Stephen and van Coller, high SIL (HSIL) OHL configurations achieve a 29.2% reduction in inductive impedance, a 30.8% reduction in series resistance, and a 41.8% increase in susceptance [17]. The change in reactive impedance increases the SIL of the specific line by 36.2%. Line losses are reduced by 34.5%. By optimising sub-conductor spacing and geometry, the SIL of lines is also increased. According to Ghassemi, an increase of 40% above the base case is achieved by optimising conductor usage for HSIL lines [18]. Designing OHLs for HSIL offers a unique, cost-effective solution to accomplish maximum power transfer with subtransmission lines.

For effective land use by minimising conductor blowout, BOLD™ (Breakthrough Overhead Line Design) and AEP (American Electric Power) pioneered an optimised design of HSIL compact delta structures through a non-conventional approach, as shown in Figure 5. The approach requires exceptional attention to galloping criteria, rolling clearances, structure geometry, and the optimising of conductor diameter, the number of subconductors and bundle spacing. The advantages include an increased SIL due to the reduced inductance and increased capacitance of delta-configured lines, a reduction in servitude widths and better aesthetics. However, the use of hardware is increased, and the compact nature of the design may present some additional challenges during maintenance. The "rotation" of the delta, when compared to a "flat delta" geometry, has the added benefit of not having any conductors of the same circuit in the same horizontal plane to not negatively impact the allowable clashing span and retain the compact nature and efficiency advantages of a delta configuration [19]. The approach allows for a 345 kV tubular structure to be constructed on the same footprint and servitude of a conventional 138 kV lattice structure.

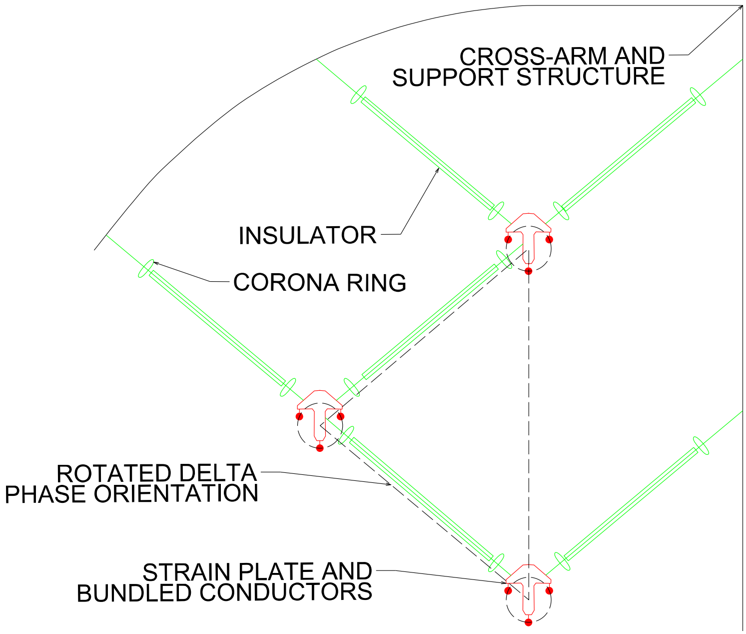


Figure 5: Compact rotated-delta phase geometry [19]

7. AC TO DC CONVERSIONS

Most subtransmission systems are based on an AC design approach. Converting AC OHLs to DC can be implemented on existing AC infrastructure at similar phase-to-earth voltage clearance levels without significant structural adjustments. However, the cost of converter stations results that AC to DC conversions is not economically feasible [8]. The relationship between AC voltage (V_{AC}) and DC voltage (V_{DC}) for comparable insulation levels is:

$$\frac{V_{AC}}{\sqrt{3}}\sqrt{2} \cong V_{DC} \quad (1)$$

The RMS current rating for DC is slightly higher (approximately 10%) than for AC due to the absence of frequency-dependent effects, furthermore, under heavily loaded conditions, an assumed 15% reactive losses in an AC system will be absent in a DC system with an estimated increase in power transfer of 180% when converting an AC system into a DC system [20].

The cost of AC to DC converter station can be reduced using a monopole system with the earth as a return path. Although this is economically attractive, there is a high risk of damaging underground services with a monopole system. A bipole DC system provides a power transfer increase of approximately 20% $\left({}^{2}/_{3} \times 1.8\right)$. Theoretically, for a tripole system, if pole 1 is positive with pole 2 and pole 3 negative, then pole 1 can be overloaded for a period with the overload transferred around poles employing bridges called the "hot potato system", each pole sees the overload current for a third of the time. [20]

No references could be found of DC subtransmission systems in Southern Africa. In addition to HSIL, line parameters can also be adjusted to increase loading by using reactive compensation such as Flexible AC Transmission Systems (FACTS).

8. FLEXIBLE AC TRANSMISSION SYSTEMS (FACTS)

FACTS consist of static equipment and primarily power electronics to enhance and control the power transfer of electrical grids by controlling one or more AC system parameters. Through series and shunt reactive compensation, FACTS can also reduce feeder losses. A parallel FACTS controller is a static var compensator (SVC) or a static compensator (Statcom). A series FACTS controller is a thyristor controlled series capacitor (TCSC) or a static synchronous series compensator (SSSC), and a hybrid series and parallel compensator is a unified power flow controller (UPFL) [21]. Pilz [21] gives the maximum amount of active power that can be transmitted as:

$$P = V_1 V_2 \, {}^{1}/_{X} \sin \delta \qquad (2)$$

Where P is active power (W), V_1 and V_2 the voltage between two nodes, X the reactive component between two nodes, and δ the phase angle between V_1 and V_2.

From equation (2), $V_1 V_2$ is adjusted by a parallel FACTS controller and X by a series FACTS controller (see Table 1).

Table 1: Series and parallel FACTS controllers [21]

PARALLEL FACTS CONTROLLER	SERIES FACTS CONTROLLER.
Voltage control	Current control
Reactive power compensation	Reduction of transmission angle
Damping of oscillation	Damping of oscillation
Contribution to transient and dynamic voltage stability	Contribution to transient and dynamic voltage stability
Load balancing (decrease negative phase sequence)	Fault current limiting
Improvement of power quality	

9. HIGHER PHASE ORDER LINES

Higher phase order lines is an addition to compact lines for maximum power transfer by increasing the number of phases to more than three. This principle has been investigated for numerous years. Still, no reference to the construction of such lines in Southern Africa could be found. Prototype 6- and 12-phase lines were built near Binghamton, New York. A practical application of a high phase-order line is the conversion of a double circuit line to a single circuit, six-phase line. Suppose a single-circuit, six-phase line, is spread symmetrically around the peripheral of a circle. In that case, the resulting phase angles between phases should be 60º. By increasing the number of phases, the conductor surface electrical field reduces. The line can either be compacted, or the phase-to-earth voltage can be increased compared to a double circuit line. By increasing the phase-to-earth voltage, the thermal rating increases linearly with the voltage, and the SIL increases with the square of the voltage [22]. Terminal equipment at substations must be customised to accommodate higher phase order lines due to standard three-phase equipment not providing adequate functionality for measurements, protection, switching and power transformation. Three criteria must be met for six-phase lines to be cost-competitive when compared to conventional technologies [23]:

(a) The line length must be long enough for the savings from the reduced losses to justify the capital expenditure associated with line construction;
(b) Terminal equipment must be kept to the minimum,
(c) Voltages must be high enough to attain benefits from corona effects, land usage, and field levels.

Based on the above, higher phase order lines will be more competitive at transmission voltage levels as opposed to subtransmission.

10. CONCLUSION

Whilst considering the appropriate limitations, it is concluded that subtransmission power systems can be ameliorated through increased power transfer. Increased power transfer is achievable by:

(a) Theoretical approaches to increase line ratings, such as applying probabilistic ratings instead of deterministic ratings, using finite element method models, and by applying measured information such as the most severe load profile recorded to determine a cyclic rating;
(b) Uprating or re-rating lines through dynamic temperature sensing, real-time thermal rating, negative sag devices, inter-catenary suspenders, inter-phase insulators, insulated cross-arms, restringing with larger conductors, restringing with high-temperature low sag conductors, reinforcing or strengthening of support structures, repurposing structures for higher voltages, and the smart use of hardware;
(c) Establishing new external grid infeed(s), interlinking of external grid infeeds, increasing reliability of supply from n to n-1 or n-2, and deloading of existing infrastructure the avail capacity;
(d) Reactive compensation, high surge impedance line designs, compact line designs, conversion from alternating current to direct current, the implementation of flexible alternating current transmission systems, and high phase order lines;
(e) Although not investigated in detail, small-scale embedded generation can provide invaluable assistance with reducing the load on constrained grids, if the SSEG offers base-load generation or generation during peak hours, i.e., small-scale hydro generation or hybrid photovoltaic plants and gas turbine generation.

The outcomes throughout this review are highly dependent on the context. Various methods are described to increase subtransmission system performance by increasing the power transfer. Power transfer can be achieved with new and existing feeders, whether overhead, underground or a combination of both. No "one size fits all" solution exists for constrained areas, and each case must be investigated based on its own merits. Once capacity deficiencies are identified, the first step in obtaining a solution will be theoretical, such as network modelling, re-rating, uprating and dynamic ratings, which includes investigating possible changes in network configurations and network planning to de-load grid sections or transfer load between grid sections. Re-rating and real-time rating can increase loadability from 25% to 50%. If no solution is obtained, refurbishment and new infrastructure come into play.

11. BIBLIOGRAPHY

[1] U. Nkalo and E. Agwu, “Review of the impact of electricity supply on economic growth: a Nigerian case study,” *IOSR Journal of Electrical and Electronics Engineering,* vol. 14, no. 1, pp. 28-34, 2019.

[2] Cigré Working Group B2.12, *29 Guide for selection of weather parameters for bare overhead conductor ratings,* PARIS: Cigré, 2006.

[3] Cigré Working Group 22.12, “207 Thermal behaviour of overhead conductors,” Cigré, Paris, 2002-08.

[4] Cigré W.G. 22.12, “Probabilistic determination of conductor current ratings,” *Electra,* vol. 164, no. February, pp. 102-119, 1996.

[5] P. van Staden and J. de Kock, “The practical comparison of conductor operating temperatures against IEEE and CIGRE ampacity calculations,” in *IEEE PES PowerAfrica 2012 Conference and Exposition*, Johannesburg, 2012.

[6] J. Hao and W. Xu, “Extended Transmission Line Loadability Curve by Including Voltage Stability Constraints,” IEEE, Alberta, 2008.

[7] K. Rozmiarek, *Overhead line design principles training,* Vanderbijlpark: Private communication, 2018.

[8] Cigré, Overhead lines - a cigré green book, Paris: Cigré, 2014.

[9] E. Bosze and D. Bryant, Interviewees, *CTC ACCC Training.* [Interview]. 08 2012.

[10] G. Landwehr and P. Marais, “Practical comparison of powerline uprating and upgrading results,” *Cigré Science & Engineering,* vol. 5, no. June 2016, pp. 50-56, 2016.

[11] T. Kavanagh and O. Armstrong, “An evaluation of High Temperature Low Sag Conductors for Uprating the 220kV Transmission Network in Ireland,” in *International Universities Power Engineering Conference (UPEC)*, Cardiff, Wales, 2010.

[12] R. Adapa, M. Shirmohamadi and R. Gray, “SLiM (Sagging Line Mitigator) – Mitigating Excess Sag in Overhead Transmission Lines,” in *Inaugural IEEE PES 2005 Conference and Exposition in Africa*, Durban, South Africa, 11-15 July 2005.

[13] K-line insulators limited, *Distribution silicone insulators catalogue,* Toronto: K-line insulators limited, 2018-11.

[14] C. Henderson, “Uprating of high voltage overhead transmission lines using intermediary catenary suspenders,” in *Cigré 8th Southern Africa Regional Conference*, Cape Town, 2017.

[15] I. Ferreira, *Dissertation: Designing power line towers using circular hollow sections,* Potchefstroom: NWU, 2013.

[16] J. D. Glover, M. S. Sarma and T. J. Overbye, Power System Analysis and Design, 4th ed., Stamford: Cengage Learning, 2008.

[17] T. Maphumulo, R. Stephen and J. Van Coller, “Consideration to use high SIL lines versus series compensation in high voltage power transmission lines,” in *The 20th International Symposium on High Voltage Engineering*, Buenos Aires, Argentina, 2017.

[18] M. Ghassemi, “High Surge Impedance Loading (HSIL) Lines: A Review Identifying Opportunities, Challenges, and Future Research Needs,” *IEEE TRANSACTIONS ON POWER DELIVERY,* vol. 34, no. 5, pp. 1909-1924, OCTOBER 2019.

[19] A. Eric, P. Miller and E. Decima, “Breakthrough Overhead Line Design (BOLD) - Transmission Line Design Considerations,” BOLD & AEP, Columbus, Ohio, 2016.

[20] Cigré Working Group B2/C1.19, *425 Increasing Capacity of Overhead Transmission Lines,* Paris: Cigré, 2010.

[21] G. Pilz, “FACTS Planning, Technology Selection and Specification,” in *9TH Cigré Southern Africa Regional Conference*, Johannesburg, 2019.

[22] D. Fink and H. Beaty, Standard handbook for electrical engineers, New York: McGraw-Hill, 1993.

[23] J. Bortnik, *Transmission Line Compaction Using High Phase Order Transmission, Master of Science in Engineering Dissertation,* Johannesburg: University of the Witwatersrand, 1998.