CONSIDERATION INTO USING HIGH SURGE IMPEDANCE LOADING (HSIL) LINES IN PLACE OF SERIES COMPENSATION ON HIGH VOLTAGE TRANSMISSION LINES

Qualification: Master of Science in Engineering by Research

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A dissertation submitted in fulfilment of the requirements for the degree of Master of Science in Engineering (research).

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DECLARATION

I declare that this dissertation is my own, unaided work. It is submitted for the degree of Master of Science in Engineering at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University. So far as I know the investigation into using High Surge Impedance Loading lines in place of series capacitor bank for conditions that prevail in Eskom has not been done before.

I also submitted the following publications that form part of the research that is presented in this dissertation.

Publication 1 – Poster

T. P. Maphumulo, R. Stephen and J. Van Coller, Consideration to use High Surge Impedance Loading lines (HSIL) in place of series compensation in high voltage transmission lines, 25th Southern African Universities Power Engineering Conference, Stellenbosch University, Stellenbosch South Africa, 30 January – 01 February 2017.

Publication 2 – Paper

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Publication 3 – Paper and Poster

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Publication 5 – Paper

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Publication 6 – Poster

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Publication 7 – Paper

T. P. Maphumulo, R. Stephen and J. Van Coller, Application and advantages of utilising HSIL methods (impedance matching) to improve the system performance (impedance matching), Power-Gen & DistribuTECH Africa, Sandton Convention Centre, Sandton South Africa, 17-19 July 2018.

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Tumisang Penelope Maphumulo Date

ABSTRACT

Long transmission lines have a large series inductive reactance (much greater than resistance) that consumes a substantial amount of reactive power when transferring real power. The reactive power deficit results in angular and voltage stability problems that limit the flow of real power. To reduce the real power flow restrictions, the series inductive reactance of long lines must be reduced. The conventional method used to increase the stability and voltage limits on long lines is to add series capacitors. However due to the increase in servitude acquisition difficulties, statutory requirements and environmental considerations, Eskom is exploring other methods to increase power transfer on both new and existing Main Transmission System (MTS) assets without using series compensation.

The pursuit for cost effective methods to counter voltage collapse and stability problems has led to the consideration to use HSIL methods instead of series capacitors on long transmission lines in Eskom. Series capacitors are self-regulating devices that increase the production of reactive power as the real power transferred on the line increases, thus series capacitors reduce reactive power consumption, control voltage and improve the system stability. Series capacitors achieve this by reducing the line’s series inductive reactance and the electrical length. The same concept applies when High Surge Impedance Loading (HSIL) methods are implemented (the series inductive reactance is reduced). Series capacitors perform this function effectively and efficiently. However, since they are additional elements on the line, they have a number of disadvantages: substantial increase in the investment costs (expensive), extra maintenance, reduction in network reliability (planned and unplanned outages), sub-synchronous resonance and complex protection settings. All these disadvantages can be removed if HSIL line design methods are found to be comparable with the installation of series compensation on long transmission lines. Added benefits to eliminating the series capacitor bank are the reduced environmental impact and an improvement in the system reliability since outages related to maintenance of the series capacitor bank will be eliminated.

The results show that HSIL methods do increase the Surge Impedance Loading (SIL) of transmission lines. The increase in SIL is achieved by altering the line’s configuration which in turn alters the R, X and B values. When evaluating what HSIL methods achieve in terms of reducing the series inductive reactance which is the same objective that is achieved by installing series capacitors, the results indicate that HSIL lines are a viable alternative to installing series capacitors on conventional lines. When the conventional 3 x Tern horizontal configuration is compared with the proposed delta HSIL configuration that utilizes 4 x Tern (Increasing the number of sub-conductors in the bundle – method 2) with 12 m as the phase-to-phase spacing (compacting the phases – method 1) and 1 500 mm as the sub-conductor spacing (expanding the bundle – method 3), the series inductive reactance is reduced by 26.56% and the SIL is increased by 36.20%. When the existing perfect inverted delta HSIL tower (528A) is optimized the resulting configuration is a 4 x IEC 450 sub-conductor bundle with 740 mm as the

sub-conductor spacing where the series inductive reactance is reduced by 26.91% and the SIL is increased by 35.88%. Both these configurations clearly prove that HSIL methods are a workable alternative to the installation of series capacitors. The elimination of the series capacitor bank is network specific. Additionally, HSIL methods are effective for impedance matching to improve load sharing in parallel lines.

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LIST OF SYMBOLS

Symbol	Explanation	Units
I	Current	A
V	Voltage	kV
V_{max}	Maximum Voltage	kV
S	Apparent power	MVA
P	Real power	MW
Q	Reactive power	MVar
R'	Resistance	Ω/m
L'	Series inductance per unit length	H/m
X'_L	Inductive reactance per unit length	Ω/m
C'	Shunt capacitance per unit length	F/m
X'_C	Capacitive reactance per unit length	Ω/m
Z	Impedance	Ω
Y	Admittance (1/Z)	S
G	Conductance	S
B	Susceptance (1/X_C)	S
I_a	Active current (in phase with the network voltage)	A
I_r	Reactive current (lagging – inductive load) or leading – capacitive load).	A
I_t	Apparent current	A
E_{max}	Maximum sub-conductor surface gradient	kVrms/cm
E_{ave}	Average sub-conductor surface gradient	kVrms/cm
E_C	Corona inception gradient	kVrms/cm
n	Number of sub-conductors in the bundle	
r	Sub-conductor radius	cm
R	Conductor bundle radius	cm
Q	Conductor charge per unit length	C/m
ε_o	Permittivity of free space	8.85×10^{-12} F/m
m	Surface roughness factor	
δ	Relative air density	

DEFINITIONS AND ABBREVIATIONS

AC	Alternating current
HV	High Voltage
HVAC	High Voltage Alternating Current
SIL	Surge Impedance Loading
HSIL	High Surge Impedance Loading
Km	Kilometer
Short lines	Lines that are less than 100 km
Medium lines	Lines that are between 100 km and 200 km
Long lines	Lines that are greater than 200 km
RI	Radio Interference
AN	Audible Noise
ICNIRP	International Commission for Non Ionizing Radiation Protection
BPA	Bonneville Power Administration
ATP	Alternative Transients Program
PSS/E	Power System Simulations for Engineers
VSAT	Voltage Security Assessment Tool
MTS	Main Transmission System
High Altitude	1 800 m
Low Altitude	1 100 m
LES	Line Engineering Services
System Planning	The Eskom department that plans the transmission network
RXB	R, X and B values of the line (line parameters)

1. INTRODUCTION

1.1 Background

Due to the fact that generating stations in South Africa are far from the loads, Eskom is faced with the challenge of power flow along transmission lines being limited by series impedance rather than thermal rating [1] [2] [3]. Thermal rating (ampacity) is a critical factor to consider when designing short lines; while SIL (natural capacity) is the dominating factor when designing long lines [2] [3] [4] [5].

As shown in Figure 1-1, when comparing the transmission line's ampacity to natural capacity, the line's thermal limit is generally higher than the natural capacity [2] [5] [6] [7]. Thermal over-exposure results in conductor permanent elongation (creep) and loss of strength (annealing), thus the thermal limit is a concern when addressing premature aging of conducting components as well as maintaining minimum electrical safety clearances and it is not part of this research [6] [8] [9]. This research investigates the SIL, which is a concern on long lines.

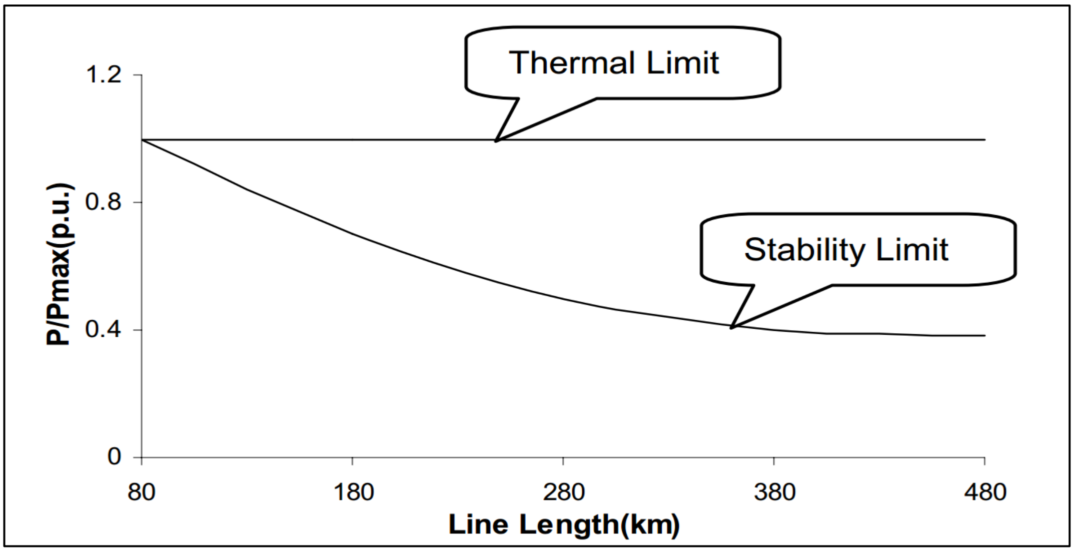

Figure 1-1: Thermal limit and stability limit versus line length [2]

1.2 Problem statement

Eskom is exploring ways to build cost effective, more reliable and efficient transmission systems. This is a result of the high cost and low returns of power line infrastructure as well as the difficulty of acquiring servitudes. The majority of loads in South Africa are far from generation centers thus Eskom's network is dominated by long transmission lines. Long transmission lines of length greater than 200 km consume a substantial amount of reactive power when transferring real power to the end users. The consequence of a deficit of reactive power is voltage collapse [2]. A commonly used method to mitigate voltage collapse is reactive power compensation [2] [4] [6]. Some of the common compensation methods include but are not limited to series capacitors, shunt capacitors, line shunt reactors and static Var compensators. Of these methods only the series capacitor presents an opportunity to save costs that are related to compensation devices when HSIL lines are considered [10] [11] [12].

This research seeks to find a way to reduce the amount of series compensation that is required, as an option to provide electricity at a lower cost. The cost saving that is anticipated necessitates an investigation into whether an increase in SIL of a power line through the use of HSIL methods can eliminate the need to install series capacitors on long 400 kV lines in Eskom.

The null hypothesis is whether an increase in the SIL of a power line through the use of HSIL methods can eliminate the need to install series capacitors in Eskom's long 400 kV lines.

1.3 Research questions

Flow of active power can be increased by reducing the series inductive reactance of the line [1] [2] [3]. HSIL theory shows that SIL can be increased by compacting the phases, expanding the bundle, increasing the number of sub-conductors in the bundle, a combination of the above methods and lastly by increasing the voltage [1] [2] [3] [4] [9] [12] [13] [14]. Although higher voltage levels increase the SIL substantially, it also increases costs due to larger clearances, wider servitudes, bigger structures and larger bundles to overcome electrical performance requirements [4] [9] [11]. Thus the method of increasing voltage does not present an opportunity for a cost effective solution when compared to the conventional solution [4] [11]. As a result the option of increasing the voltage is not considered in this research.

The main aim of this research is to optimize the existing 400 kV servitude width and towers. Focusing on the optimization of the existing parameters will ensure a solution whose cost will be comparable to costs of the existing towers. The HSIL lines will be investigated on the existing Eskom network. The research seeks to provide answers to the following questions:

1. Which HSIL methods are more attractive for increasing the SIL of long lines?
2. How sensitive is the electrical performance of a line when HSIL methods are applied?
3. How significant is the change in SIL and line parameters when HSIL methods are applied?
4. Can an increase in the SIL of long lines eliminate or reduce the need to install series capacitors?
5. What are the effects and benefits of HSIL lines when compared against the traditional existing lines with compensation?
6. How significant is the cost saving if HSIL lines are applied to the selected cases?
7. What is the impact on operational flexibility?

2. LITERATURE REVIEW OF THE APPLICATION OF HSIL METHODS AND IMPACT ON COMPENSATION, SIL AND ELECTRICAL PERFORMANCE

Series and shunt Var compensation devices are used to modify the natural electrical characteristics of a power system; the series compensation varies the series inductive reactance of a line while the shunt compensation modifies the load impedance [4] [10] [15] [16]. Shunt line reactors sink excessive capacitive reactive power to prevent Ferranti voltages under lightly loaded conditions or when the line is energized [15] [16]. Series capacitors reduce the transmission line inductive reactance and reduce the electrical length [15] [16].

Only the series capacitors present an opportunity to save costs that are related to compensation devices when HSIL lines are considered. Series capacitors make the line electrically shorter and the same principle applies when HSIL theory / methods are implemented [4] [10] [11] [12].

HSIL theory shows that the Surge Impedance Loading (SIL) of a line can be increased by altering the line's configuration; this is achieved by [1] [2] [3] [4] [12] [13] [14] :

- Decreasing the distance between phases (phase compaction) which increases the flux cancellation between the phase conductors which reduces the flux linkage of the phase conductors and hence reduces the series inductance of the phase conductors [3] [6] [11] [17] [18] [19],
- Increasing the sub-conductor spacing of the bundle (bundle expansion) which reduces the flux linkage of each sub-conductor and hence reduces the series inductance of the phase conductors [3] [6] [7] [11] [17] [18] [19] [20].
- Increasing the number of sub-conductors in the bundle which reduces the current in each sub-conductor which reduces the flux linkage of each sub-conductor and hence reduces the series inductance of the phase conductor [3] [6] [7] [11] [17] [18] [19].
- Decreasing the inductive reactance of the line by increasing the number of sub-conductors and the sub-conductor spacing or geometric mean radius (GMR) and decreasing the phase spacing or geometric mean distance (GMD) to increase the capacitance of the line [1] [3] [11] [12] [18] [19] [21].
- Decreasing the self impedance (Z_s) by using larger conductor types [2] [3] [4] [7] [18].
- Increasing the mutual impedance (Z_m) by decreasing the distance between the phases [1] [2] [3] [6] [7] [18].

Below is a list of papers that report the findings of the HSIL methods that have been implemented in Brazil, China and India:

- In 1998 Brazilian authors presented a paper on increasing the capacity of existing lines through the application of the bundle expansion HSIL method [18]. The focus was on electrical studies, bundle optimization, engineering aspects and costs for application on 230 kV and 500 kV lines. The results confirmed that the bundle expansion method increases the SIL, results in a better voltage profile and better current distribution between circuits despite the different aluminum cross-sectional area because the series inductive reactance is reduced by 26% [18]. Due to the 15% increase in SIL the compensation that was scheduled previously could be postponed [18].

- In 1999 two Brazilian papers reported on the results of phase-to-phase insulation electrical strength laboratory tests, radio-interference measurements, corona loss measurements, overvoltage studies and experiments combined with theoretical studies of the electric and magnetic fields with the objective of finding the optimized HSIL configuration when the phases are compacted, the number of sub-conductors in the bundle is increased and the bundle is expanded [12] [19]. The results showed that upgrades could be delayed due to an increase of the transmission capability of the existing lines and HSIL lines require the installation of line shunt reactors to mitigate against overvoltages [12] [19].
- In 2003 a Chinese paper reported the results from comparing several conductor configurations for a 500 kV compact line (inverted delta) [22]. These configurations were also compared against the conventional line. The results showed that to increase SIL, the number of sub-conductor in the bundle should be increased, the sub-conductor spacing should be increased and the phase spacing should be decreased. The proposed configuration increases SIL by 34% when compared to the conventional configuration [22].
- In 2006 an Indian papers represented a mathematical model for increasing the SIL level of a quadruple bundle on a 400 kV single circuit line towards its thermal limit [2]. The model analyzed the sensitivity of SIL to bundle spacing and bundle configuration on both a horizontal and compact delta configuration [2]. The study considered the impact of HSIL methods on series and shunt compensation. The results showed that bundle expansion combined with phase compaction can increase the SIL towards the thermal rating and a non-symmetrical bundle achieves higher margins than a symmetrical bundle. In this study the bundle expansion method increases SIL by 22% and when combined with phase compaction method SIL is was increased by 33% [2].
- In 2007 a Brazilian paper reported the results from analyzing the impact of bundle expansion on overvoltages when the line and transformer is energized, the load is rejected and when three phases reclose plus evaluate the impact on compensation levels of a 500 kV system [23]. The results showed that the bundle expansion method reduced inductance by 15% and SIL increased by 20% when compared to the standard bundle. As a result the sizes and number of line shunt reactors increased [23]. The conclusion reached was that the bundle expansion method results in

higher overvoltages during switching surges thus bigger line shunt reactors are required.

- In 2008 a Brazilian paper reported the results of increasing the SIL of 230 kV and 500 kV overhead lines by exploiting the phase compaction and bundle expansion HSIL methods. Focus was on the mechanical designs (tower types) [1]. The study considered the combination of HSIL methods with series capacitors. The results showed that the combination of phase compaction and bundle expansion implemented on a single-mast guyed structure yielded a 20% increase in transmission capacity and reduced the tower cost by 25% [1].
- In 2012 a Chinese paper presented an optimized multi-objective (MTO) model that was developed with aim of enhancing SIL and natural transmission power per unit cross-sectional area (SILP) [20]. The research was done to optimize conductors configuration of a 1 000 kV single circuit AC compact line and the finite element was used and compared with results from an analytical methods. The model focused on electromagnetic levels and SIL [20].
- In 2015 an Indian papers represented the methods can be used to increasing the SIL level of a 400 kV AC transmission line [3]. This was done through various single circuit configurations [3]. The investigated aspects where phase-to-phase spacing, bundle spacing, conductor diameter, number of sub-conductors in the bundle, phase to ground clearance and phase conductor configuration. The sensitivity of SIL to the different configurations was analyzed using a model that was developed on Matlab software. The results show that to increase SIL, the phase-to-phase spacing must be decreased, bundle spacing must be increased, conductor diameter must be increased, number of sub-conductors in the bundle must be increased, phase to ground clearance must be decreased and the phases conductor should be configured as a delta [3]. The results showed that HSIL methods can increase the SIL towards the thermal rating without application of additional equipment on the line.
- In 2015 a Brazilian paper reported on the results of evaluating of HSIL methods for six different 500 kV transmission lines projects with four sub-conductors in the bundle. Focus was on the impact of the bundle expansion and phase compaction on positive sequence, zero sequence impedance, electric field on the conductors’ surface, the electric and magnetic fields at ground level [6]. The results showed that the positive sequence impedances of each configuration were very close but there were major differences in the zero sequence impedance which indicates that there will be different responses to unbalanced conditions and switching transients [6].
- In 2015 a Brazilian paper reported on the advantages of utilizing an optimized phase conductor configuration to increase the capacity of transmission lines instead of increasing the maximum operation temperature, increasing the size of the conductors or utilizing multiple conductors per phase. The focus was on developing a computational tool

using the adaptive deep-cut ellipsoidal algorithm to calculate and minimize the intensity of electric fields at ground level [24]. Case 1 was a 345 kV line with two conductors in the bundle and Case 2 was a 500 kV line with 3 conductors in the bundle. The results show that the optimized configuration is one where the distance between the phases is decreased (phases compaction) and the distance between the conductors of one phase are increased (bundle expansion) [24].
- In 2016 an Indian paper reported the results of optimizing the bundle spacing and bundle configurations to increase the SIL of a single and double circuit 765 kV transmission line. Focus was on the effect of increasing bundle spacing and bundle configuration on the SIL level. The results show that increasing the bundle spacing and asymmetrical bundles increases SIL [20] [7].

Previous research also proved the following:

- Asymmetrical expanded bundles achieve higher SIL levels than the symmetrical expanded bundle [2] [3] [20] [22].
- Asymmetrical phase configurations achieve higher SIL levels that the horizontal phase configuration [3].
- The delta configuration generates higher RI at the center than at the edge of the servitude and asymmetrical expanded bundles lead to equalization and optimization of the electric field distribution around all sub-conductors [6] [12] [17] [19] [25] [22].
- The delta configuration eliminates the need to transpose the line because the spacing between the phases is symmetrical thus voltage drop is equal among the spaces [3].
- The sub-conductor surface gradient can be reduced by increasing the phase spacing, increasing the number of sub-conductors per phase, selecting larger sub-conductor sizes and utilizing smooth sub-conductor surfaces [3] [7] [19] [20] [22] [26].
- The electric field between the phases can be equalized and decreased by rearranging the phases or by increasing the number the number of conductors per phase [22] [24] [27].
- The electrostatic and electromagnetic unbalance factors can be reduced by using an inverted delta configuration (symmetrical arrangement). The unbalance is significantly reduced thus line transposition may not be necessary [22].
- The sub-span oscillation can be reduced by using expanded bundle geometry, thus the required number of spacer dumpers is reduced when compared to a conventional line [20].
- HSIL lines generate more reactive power than conventional lines, as such a line shunt reactor maybe necessary to mitigate overvoltage under no load and low load conditions [2] [23].

3. SIL THEORY

3.1 Line model

The line parameters of balanced three-phase transmission lines can be represented by a simple lumped parameter PI equivalent single-phase circuit as shown in Figure 3-1, where [5] [6] [11] [17]:

P = Transmitted power (MW)

V_s = Sending-end rms line voltage (kV)

V_r = Receiving-end rms line voltage (kV)

C' = Shunt capacitance per unit length (F/m)

$X'_L = 2\pi f L'$ = Series Inductive reactance per unit length (Ω/m)

R' = Resistance per unit length (Ω/m)

Z = Impedance of the line (Ω)

l = line length (m)

X_L consumes reactive power that leads to a voltage drop and steady-state stability problems on long transmission lines [2] [3] [6]. Eskom utilizes reactive power compensation to increase the voltage and stability limits on long lines [2] [15] [17] [16]. The different types of reactive power compensation devices will be addressed in Section 3.9.

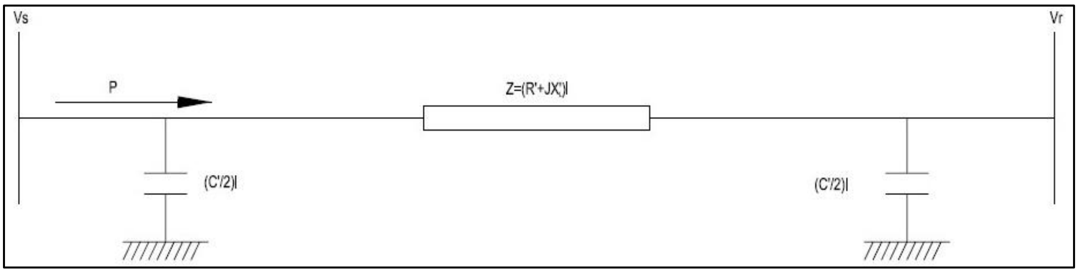

Figure 3-1: Simplified diagram for a transmission line in electric systems [6]

The maximum power that can be transmitted by the line is commonly known as the steady-state stability limit and is given by equation 3-1 [1] [2] [3] [4] [11] [17] [18] [19] [21]:

$$P = \frac{V_s V_r}{X} sin\,\emptyset \tag{3-1}$$

Where:

P = Maximum power (MW)

V_s = Sending-end rms line voltage (kV)

V_r = Receiving-end rms line voltage (kV)

X = Series reactance (Ω)

Ø = Electrical phase shift (degrees or radians)

The transfer capability or loadability of transmission lines is limited by the following criteria:

1. Limitation of power losses and conductor heating ($P = I^2R$) which is commonly referred to as the thermal limit [2] [5] [9] [18] [28]. The thermal limit is a constraint on short lines and is increased by decreasing the resistance of the conductor/s. Conductor resistance is decreased by increasing the cross-sectional area of the conductors or increasing the number of sub-conductors per phase [3] [4] [5] [8]. These losses are also affected by the permissible conductor temperature, ambient conditions and other environmental factors [2] [3] [4] [11] [17] [21].

2. Limitation of voltage drop along a line which is commonly referred to as the voltage drop limit [2] [5] [9] [11] [17]. The voltage drop is a constraint on medium and long lines and the voltage drop is reduced by decreasing the resistance and series inductance of a line [1] [3] [5] [6] [15] [16] [18] [19] [20].

3. System stability which is commonly referred to as the line stability limit [5] [9] [28]. Steady stability limit is a constraint on long lines and is improved by decreasing the series inductance of a line [2] [5] [19] [20]. Stability is classified into two of types: steady-state stability and transient stability [3] [4] [15] [16].

3.2 Definition of the SIL

The SIL is the amount of active power that, when transmitted along the line, causes the consumption of reactive power ($\mathrm{I}^2\omega\mathrm{L}$) by the line inductance to equal the amount of reactive power generated ($\mathrm{V}^2\omega\mathrm{C}$) by the capacitance of the same line [1] [2] [3] [6] [11] [20] [21] [22].

When a line is loaded to its SIL the ratio of the receiving-end voltage to receiving-end current is equal to the line's surge impedance (Z_C) represented by equation (3-3) [16]. Thus a line that is loaded to its SIL has no net reactive power flow and the voltage profile along the line is relatively flat [2] [10]. A line that is loaded above its SIL will absorb net reactive power and behaves like a shunt reactor, thus it depresses the voltage at the receiving-end [2] [3] [10] [11] [20]. A line that is loaded below its SIL supplies net reactive power and behaves like a shunt capacitor resulting in a rise in receiving-end voltage [2] [3] [10] [11] [20].

The SIL for a given line voltage level depends on the conductor type, conductor cross-sectional area, number of sub-conductors, the geometry of the bundle of each phase, sub-conductor spacing and the distance between the phases [1] [2] [3] [4] [6] [7] [11] [12] [18] [19] [20] [22].

Surge Impedance Loading (SIL), Surge Impedance (Z_C) and Impedance (Z) of a lossless (series resistance and shunt conductance are assumed to be zero) transmission line are defined by equations 3-2, 3-3 and 3-4:

$$\mathrm{SIL} = \frac{V^2{}_{LL}}{\mathrm{Z_C}} \quad (\mathrm{MW}) \tag{3-2}$$

Where:

$\mathrm{V_{LL}}$ = Receiving-end rms line voltage (kV)

Z_C = Surge Impedance of the line (Ω)

Where:

$$Z_C = \sqrt{\frac{L\prime}{C\prime}} \quad (\Omega) \tag{3-3}$$

Where:

L' = Series inductance per unit length (H/m)

C' = Shunt capacitance per unit length (F/m)

And impedance is

$$\mathrm{Z} = \frac{V}{\mathrm{I}} \quad (\Omega) \tag{3-4}$$

Where:

V = Line voltage (V)

I = Line current (A)

3.3 Line parameters

The parameters that define the limit of the amount of power that a line can transmit are R (resistance), X_L (series inductive reactance) and B (shunt capacitive reactance). To maximize the transfer capacity, the line must have low R, low X_L and high B ($1/X_C$) [2] [3] [6] [11] [21]. As per equation 3-3, the surge impedance Z_C depends on the series inductance and shunt capacitance of a line per unit length.

The inductive reactance and capacitive reactance of a line per unit length is given by equation 3-5 and 3-6 [6] [18]:

$$X'_L = 2\pi f L' = \omega L' \qquad (\Omega/m) \tag{3-5}$$

$$X'_C = 1/2\pi f C' = 1/\omega C' \qquad (\Omega/m) \tag{3-6}$$

Where

f = Power frequency (Hz)

L' = Inductance per unit length (H/m)

C' = Capacitance per unit length (F/m)

ω = Radians

To reduce the inductive reactance of the line, the number of sub-conductors and the sub-conductor spacing or geometric mean radius (GMR) should be increased and the phase spacing or geometric mean distance (GMD) should be decreased [1] [3] [11] [12] [18] [19] [21]. To increase the capacitance of the line, the phase spacing should be decreased [1] [3] [11] [12] [18] [19] [21]. Inductance for a fully transposed line is given by equation 3-7 and capacitance for a three phase system can be calculated as shown in Section 2.6.2 of the "The planning, design and construction of overhead power lines – 132 kV and above" book and Section 2.4 of the "Guide to Overall Line Design" [2] [17] [11] [21]:

$$L' = 2 \times 10^{-7} \ln\left(\frac{GMD}{GMR}\right) \qquad \text{(H/m)} \tag{3-7}$$

Where

$$GMR = \sqrt[n]{n\, r\, R^{n-1}} \qquad (m)$$

$$GMD = \sqrt[3]{d_{12}\, d_{13}\, d_{23}} \qquad (m)$$

Where

r = 0.7788 x radius of the conductor (m)

R = radius of the conductor bundle in (m)

n = number of subconductors in the bundle

d_{12}, d_{13} and d_{23} = phase spacing (m)

3.4 Symmetrical components

For steady state and transient studies, the symmetrical component zero sequence impedance (Z_0) and positive sequence impedance (Z_1) are used [11] [17]. Z_1 assumes that the sum of currents in the phases is zero and the earth return effects are negligible and can be related to Z_s and Z_m by equation (3-8) [1] [3] [6]:

$$Z_1 = Z_s - Z_m \tag{3-8}$$

Z_1 = Positive sequence (Ω)

Z_s = Self impedance (Ω)

Z_m = Mutual impedance (Ω)

As explained in Section 3.2 by Equation 3-2, a line that has smaller positive sequence impedance per unit length will have a higher capacity for the same length reference [3] [6] [18]. The zero sequence impedance considers the effect of the earth return path and is used for transient studies (switching, faults, etc.) and unbalanced (dynamic) conditions [6] [11] [17]. Z_0 can be related to Z_s and Z_m by equation 3-9 [6]:

$$Z_0 = Z_s + 2\,Z_m \tag{3-9}$$

Z_s depends on the conductor type and the geometry of the bundle of each phase. The bigger the sub-conductor spacing the smaller the line's self impedance [2] [3] [4] [18]. Z_m depends on the distance between the phases and the smaller the phase spacing the higher the line's mutual impedance [1] [2] [3] [6] [18].

This research is concerned with the analysis of steady-state balanced conditions and load flow studies that analyze voltage control. Thus positive sequence values are used for the line impedance. Transient studies where impedance varies with frequency plus the effect of HSIL lines on transient overvoltages are not covered in this research [14] [23].

3.5 Non-ionizing field effects

Power frequency (Eskom utilizes 50 Hz) electric and magnetic fields beneath the line are a function of tower configuration and are directly proportional to line voltage and load current [11] [17] [26] [29]. Magnetic fields depend on the current flow and the line's X_L [2] [11] [17]. Magnetic fields are measured in micro tesla (μT) [17] [25]. Electric fields are determined by the line voltage and minimum distance from the conductor-to-ground [11] [17] [19] [23]. Electric fields are measured in kilovolts per meter (kV/m) [2] [17].

Electric fields are higher at mid-span due to the lowest conductor height and can be reduced by increasing the conductors height from ground or by compacting the phases [1] [2] [6] [30]. When electric fields are higher they lead to an increase in corona activity which generates higher levels of audible noise (AN) [6] [26] [31].

Research has shown that the delta configuration generates higher RI at the center than at the edge of the servitude and asymmetrical expanded bundles lead to equalization and optimization of the electric field distribution around all sub-conductors [6] [12] [17] [19] [25].

Table 3-1 outlines the non-ionizing field effect limits for public exposure that Eskom complies with and they are the guideline of ICNIRP (1998) [17] [30] [32].

Table 3-1: Non-ionizing field effect limits

Max Electric Field at the servitude boundary at V_{max} = 420 kV	≤ 5 kV/m
Max Electric Field in the servitude at V_{max} = 420 kV	≤ 10 kV/m
Max Magnetic Field at the servitude boundary	≤ 500 μT

3.6 Ionizing field effects

Corona is caused by a partial breakdown (ionization) of the air around the energized components of the transmission line [11] [17] [31]. It occurs when the surface gradient of a sub-conductor exceeds the corona inception gradient of a sub-conductor [11] [17] [31].

The maximum sub-conductor surface gradient for a conductor bundle above the earth plane is given by equation 3-10 [11] [17] [22] [31]:

$$\mathrm{E_{max}} = E_{ave}\left(1 + (\mathrm{n} - 1)\frac{\mathrm{r}}{\mathrm{R}}\right) \tag{3-10}$$

Where:

$$E_{ave} = \frac{Q}{2\pi\varepsilon_o\, nr} \tag{3-11}$$

Where:

E_{max} = maximum rms sub-conductor surface gradient (kVrms/cm)

E_{ave} = average rms sub-conductor surface gradient (kVrms/cm)

n = number of sub-conductors in the bundle

r = sub-conductor radius (cm)

R = conductor bundle radius (cm)

Q = conductor charge (Coulombs/m)

ε_o = permittivity of free space = 8.85×10^{-12} (Farad/m)

Equations 3-10 and 3-11 were developed by Markt and Mengele [31]. They provide a simple method for calculating the sub-conductor surface gradient and the error is below 2% when applied to practical line configurations with four sub-conductors and less [30] [31]. A number of assumptions are made to simplify the electric field calculations:

- Each conductor is at the same height above ground [17] [31].
- The sub-conductors are equipotential surfaces with a known potential applied [17] [31].
- Total charge on the bundle is distributed evenly amongst the sub-conductors and thus the electric field distribution around each sub-conductor is identical [17] [31].

- The ground is assumed to be at zero potential and its impact is accounted for by imaging all conductors in the ground plane [17] [31].

The corona inception gradient for AC lines is given by equation 3-12:

$$E_C = 21m\delta\left(1 + \frac{0.308}{\sqrt{r\delta}}\right) \tag{3-12}$$

Where:

E_C = Corona inception gradient (kVrms/cm)

m = Surface roughness factor (0.76 is used in the simulations)

r = Sub-conductor radius (cm)

δ = Relative air density

Corona discharges on the sub-conductor and hardware generate audible noise, radio interference, corona power losses and ozone [17]. Corona increases with an increase in altitude (reduced air density), wet conditions (rain, fog, snow etc.), an increase in wind speed and an increase in voltage level [19] [17] [22] [26]. The sub-conductor surface gradient can be reduced by increasing the phase spacing, increasing the number of sub-conductors per phase, selecting larger sub-conductor sizes and utilizing smooth sub-conductor surfaces [19] [22] [26].

Table 3-2 outlines the ionizing field effect limits for public exposure that Eskom complies with and they are the guideline of ICNIRP (1998) [17] [30] [32].

Table 3-2: Ionizing field effect (corona) limits

L50 Wet Audible Noise at the servitude boundary	≤ 53.1 dBA
L50 Radio Noise at the servitude boundary	≤ 72 dBu
Surface Gradient Margin	≥ 4.5%
Required Roughness factor for the % margin	0.5 – 0.8

3.7 Compensation methods

Reactive power compensation is an important consideration for increasing the line's natural capacity, improving the quality of supply, improving the system performance and reducing the cost of electricity [1] [9] [10] [15] [16] [28]. All electrical systems and equipment that use AC consist of two categories of power, namely active power ($P = VI \cos \emptyset$) measured in MW and reactive power ($Q = VI \sin \emptyset$) measured in MVar. Active power is used to produce work and reactive power is associated with the electric and magnetic fields [15] [33].

For active and reactive power, the components are shown in Figure 3-2 [33].

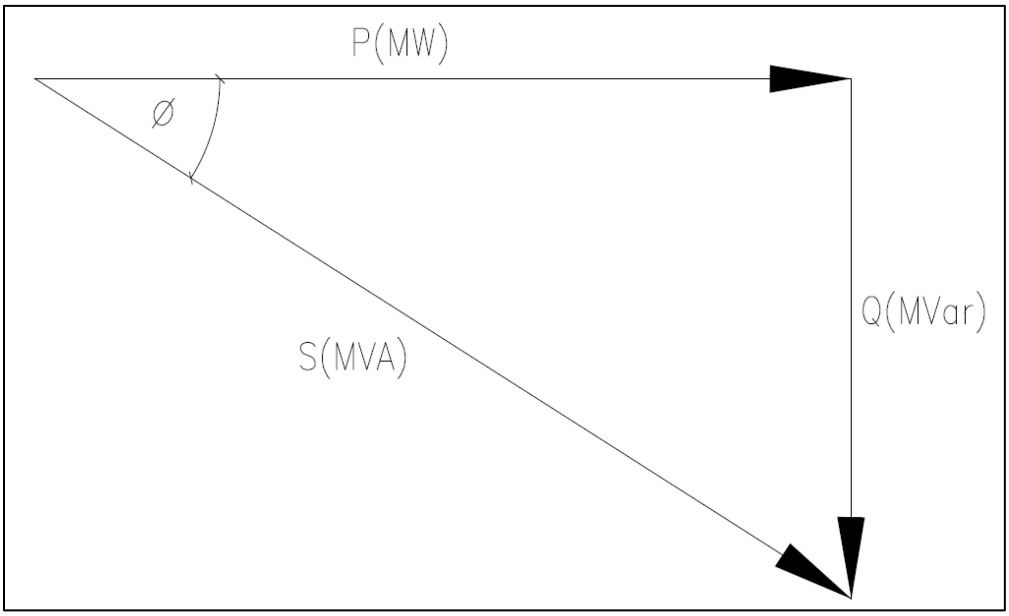

Figure 3-2: Vector composition of active, reactive and apparent power

Where

∅ = phase displacement (degrees)

S = apparent power (MVA)

P = active power (MW)

Q = reactive power (MVar)

Using current as an example, active current is in phase with the network voltage, reactive current is phase shifted by 90° in relation to the active current, either lagging it (inductive load) or leading it (capacitive load) and apparent current is the resulting current which flows from the source to the load and is phase shifted by an angle ∅ in relation to the active current or to the voltage [11] [17] [33]. This same explanation also applies to active and reactive power. In the case of no harmonics, cos ∅ is equal to the power factor (PF) [11] [17] [33]. The power factor of the fundamental components can also be defined by equation 3-13;

$$PF = \cos \emptyset = P/S = (W / VA) \qquad (3\text{-}13)$$

In the power system most loads are inductive thus they absorb reactive power and result in a lagging power factor [10] [15] [16]. To boost the power factor to as close as possible to 1, capacitors can be installed at the load end [10] [33]. Generating the reactive power close to the load as opposed to supplying it from the generators reduces losses and the sizes of conductors required to transport the power to the loads [10].

Series and shunt Var compensation devices are used to modify the natural electrical characteristics of a power system; the series compensation varies the series inductive reactance of a line while the shunt compensation modifies the load impedance [4] [10] [15] [16]. The advantages of reactive power compensation are: reduced reactive energy consumption, a reduction of active power losses, an increase of active power carried at constant apparent current and a reduction in voltage drop [4] [10] [15] [16]. All these factors lead to an improvement of system power factor thus smaller conductors are used for transmitting the same power which results in a more efficient and economical transmission system and a more stable system [2] [4] [10].

Some of the common compensation methods include but are not limited to series capacitors, shunt capacitors, line shunt reactors and static Var compensators [9] [10] [15] [16]. The different types, their function, application, advantages and disadvantages are listed in Table 3-3. All devices increase the transfer capacity of the system in one form or another.

Table 3-3: Types of compensation devices used by utilities [10] [11] [15] [16]

Compensation device	**Function**	**Application**	**Advantages**	**Disadvantages**
Series capacitors	Make the line electrically shorter by reducing the total inductive reactance of the line.	Installed on long lines to decrease the line's series impedance.	- Increases the SIL by reducing the X. - Reduces the voltage drop. - Reduces the phase shift thus improving the system stability. - Reduces the active power losses. - Self-regulating. - Have significant short-time overload capacity.	- Capacitors may get damaged under short circuit conditions. - Sub-synchronous resonance problems. - Complex protection co-ordination. - Shunt reactors may be required for lightly loaded conditions.
Busbar shunt capacitors	Compensate reactive power that is consumed by the load (increases voltage).	Installed on the busbar to increase voltage under peak loads and n-1 conditions (contingency).	- Prevents under voltage during peak loads. - Improves power factor. - Reduces the reactive current flowing to the load.	- Increases the phase shift which leads to poor system stability. - Affects synchronous machines. - Resonance.
Line shunt reactors	Absorb reactive power (reduce voltage).	Installed on lines to control Ferranti voltages.	- Prevent overvoltages when the line is switched in.	Manual switching in and out by the network operator.
Static Var compensators (SVCs)	Regulate the grid voltage.	Installed on high power outgoing transmission lines and feeders to increase the transmission capacity. Provide for temporary overvoltages	- Dynamic, fast-acting and automated impedance matching device. - Regulate voltage after load loss. - Improvement of power factor, transmission efficiency and system stability.	- Very expensive - Create harmonics thus filters are required. - Instability occurs once the SVC reaches its boost limit (limit is the critical (collapse) voltage).

Of these methods, only series capacitors present an opportunity to save costs that are related to compensation devices when HSIL lines are considered. Series capacitors make the line electrically shorter by reducing the total series inductive reactance of the line and the same principle applies when the number of sub-conductors is increased, the phases are compacted and the conductor bundles are expanded [4] [10] [11] [12]. Series capacitors are very effective and efficient in increasing the transfer capacity of power lines. However since they are additional elements on the line, series capacitors have a number of disadvantages: substantial increase in the investment costs (expensive), extra maintenance, reduction in network reliability (planned and unplanned outages), sub-synchronous resonance and complex protection settings [2] [6] [11] [10] [16]. All these disadvantages can be removed if HSIL line design methods are found to be comparable with series capacitors on long transmission lines. An added benefit is the reduced environmental impact and an improvement in the system reliability since outages related to maintenance of the series capacitor will be eliminated [2].

3.8 SIL of a series compensated line

Utilities around the world utilize two types of passive series reactive power compensation devices, series capacitors and shunt line reactors. Compensation devices produce or sink reactive power at any location in the power system. Series capacitors are self-regulating devices that increase the production of capacitive reactive power as the real power transferred along the line increases. Thus series capacitors reduce reactive power absorption (I^2X_L), control voltage and improve the system stability [15] [16]. This is achieved by reducing the transmission line inductive reactance (X_L) and the electrical length [15] [16]. Shunt line reactors sink excessive capacitive reactive power to prevent Ferranti voltages under lightly loaded conditions or when the line is energized [15] [16]. The resulting SIL for a series and shunt compensated line can be represented by the equation 3-14 [16].

$$\mathrm{SIL} = V^2 \sqrt{\frac{(B.l)-B_{LR}}{(X_L.l)-X_{SC}}} \tag{3-14}$$

Where:

V = Receiving-end rms line voltage (kV)

B = 1/X_C = $2\pi f\mathrm{C}$ = Susceptance (S)

B_{LR} = $1/\omega L$ = Admittance of shunt line reactor (S)

X_{SC} = $(1/\omega\mathrm{C})$ = Impedance of Series capacitor bank (Ω)

X_L = Series Inductive reactance ($2\pi f L$) (Ω)

l = line length (m)

3.9 HSIL methods

HSIL theory shows that the SIL of power lines can be increased by

(1) Reducing the distance between phases (phase compaction) which increases the flux cancellation between the phase conductors which reduces the flux linkage of the phase conductors and hence reduces the series inductance of the phase conductors [3] [6] [11] [17] [18] [19],

(2) Increasing the sub-conductor spacing of the bundle (bundle expansion) which reduces the flux linkage of each sub-conductor and hence reduces the series inductance of the phase conductors [3] [6] [11] [17] [18] [19]

(3) Increasing the number of sub-conductors in the bundle which reduces the current in each sub-conductor which reduces the flux linkage of each sub-conductor and hence reduces the series inductance of the phase conductor [3] [6] [11] [17] [18] [19].

Tables 3-4 summarize the different methods, effect of the modification on SIL and effect on existing towers [1] [3] [4] [6] [12] [13] [19] [20] [22].

Table 3-4: HSIL methods that are used to increase the SIL of a transmission line

Technique	**Implementation**	**Effect on Z ($Z_1 = Z_s - Z_m$)**	**Effect on existing designs**
Phase compaction	Decreasing the distance between the phases increases the SIL by increasing the phase coupling.	Increases the Z_m thus reduce the Z_1.	New tower design e.g. delta.
Bundle expansion	Increasing the distance between the sub-conductors increases the SIL by decreasing the sub-conductor coupling.	Reduces the Z_s thus it reduces the Z_1.	New / non-standard hardware design.
Increasing the number of sub-conductors	Increasing the bundle size increases the SIL by reducing the self-inductance.	Reduces the Z_s thus it reduces the Z_1.	New tower and hardware.
Combination: Phase compaction and expanded bundle	Increases the SIL by increasing the phase coupling and decreasing the sub-conductor coupling.	Reduces the Z_s and increases the Z_m thus it reduces the Z_1.	New tower and hardware.

With lines being high cost with low returns, the main advantage of expanding the bundle is that it can increase the SIL of a line using the existing towers. Research shows that asymmetrical expanded bundles achieve higher SIL than the symmetrical expanded bundle [2] [3]. However, the non-standard hardware required for this technique brings about uncertainties with regards to mechanical interaction under wind, load, short-circuit and live-line maintenance. The symmetrical expanded bundle technique will be explored; however, its effect on vibrations, swing behavior and construction needs to be studied further and is not covered in this research.

3.10 Voltage stability or voltage collapse

Voltage stability problems have become a serious concern in the planning and operating of the electric power system. Voltage instability and collapse can result in major system failures [34]. There are several causes of voltage stability problems, ranging from but not limited to generator control to transmission network reactive power compensation (system operations) to distribution network design to the load characteristics [34]. The transmission of reactive power is governed by the voltage magnitude and it flows from the sending-end (higher voltage) to the receiving-end (lower voltage) [5] [11] [15] [17] [34]. The reactive power at receiving-end is represented by equation 3-15 [34].

$$Q_R = \frac{V_R V_S \cos\emptyset - V_R^2}{X_L} \tag{3-15}$$

Where:

Q_R = reactive power at receiving-end (MVar)

V_S = Sending-end rms line voltage (kV)

V_R = Receiving-end rms line voltage (kV)

X_L = transmission line series inductive reactance (Ω)

∅ = electrical phase shift (degrees or radians)

If we assume a lossless system, the maximum power transfer occurs at an electrical phase shift of 90°. However, to warrant steady-state rotor angle stability, the electrical phase shift throughout the transmission network is normally kept below 44° [34].

Voltage stability is the ability to transfer reactive power during steady-state operating conditions [34]. As such, voltage instability normally occurs during abnormal conditions such as high power transfer / high angle and emergency conditions (high stress). When the system is highly loaded, the line drains the reactive power from the sending-end [34]. The deficit in reactive power requires an additional source in order to maintain satisfactory voltage levels at the receiving-end [5]. Series and shunt capacitors are used as the source of additional reactive power. Series capacitors vary the series inductive reactance of a line while the shunt capacitors modify the load impedance [4] [10] [15] [16] [34].

4. RESEARCH METHODOLOGY

4.1 Summary

HSIL methods increase the Surge Impedance Loading (SIL) of a line by altering the line's configuration which affects the ionizing and non-ionizing field effects of the line. Bonneville Power Administration (BPA) software is used to analyze the electric and magnetic fields and Alternative Transients Program (ATP) software is used to calculate the line parameters and SIL of the proposed configurations. The Motraco network (two 400 kV lines) is selected as a case study. The PSS/E and VSAT software packages were used to evaluate the effects of replacing the existing series compensated lines with HSIL lines.

4.2 Proposed HSIL line configurations

4.2.1 New HSIL configuration – high altitude (inland)

Increasing the SIL of a line through the application of HSIL techniques can reduce power flow restrictions relating to voltage drop and steady-state instability. HSIL methods increase the SIL through altering the line's configuration which significantly affects the electrical performance of the line. Thus the choice of suitable HSIL methods needs a detailed analysis, with special consideration of the ionizing and non-ionizing field effects. This analysis is done so to propose HSIL configurations that comply with the ionizing and non-ionizing field limits as set by the ICNIRP. The study is limited to application on long 400 kV transmission lines in Eskom's network and for high altitudes (1 800 m) that prevail in much of South Africa.

Table 4-1 shows the sub-conductor bundle spacings and phase configurations that are selected for the investigation of HSIL methods. To evaluate the impact of phase compaction, three configurations are selected: flat as configured on the 517A and 518H towers, a shallow delta as configured on the 529A tower and a perfect inverted delta as configured on the 528A tower, with phase-to-phase spacing of 8.2 m, 8.5 m, 7.5 m and 7.0 m respectively as shown in Appendix 1. The method of increasing the number of sub-conductors per phase is assessed using two sub-conductor bundle sizes: 3 x Tern and 4 x Tern. To evaluate the impact of expanding the bundle, 450 mm, 690 mm, 1 000 mm and 1 500 mm sub-conductor spacings are selected. Four sub-conductor spacing are selected so to investigate the impact of expanding a bundle as a technique and its effect when combined with compacting the phases. For practical reasons, the sub-conductor spacing is only expanded at mid-span while the standard spacing of 450 mm is maintained at the towers.

A total of twenty-four configurations are proposed, twelve with a 3 x Tern sub-conductor bundle and twelve with a 4 x Tern sub-conductor bundle. The base case is the flat configuration (517A) with 3 x Tern spaced 450 mm apart as illustrated on Figure 4-1.

The tern conductor is selected as it is typical on 400 kV lines in Eskom. It has stranding and wire diameter of 45 / 3,38 mm + 7/2,25 mm with a total steel diameter of 6,75 mm and overall diameter of 27,00 mm. The total cross-sectional area is 431,60 mm^2 with a total weight of 1340 kg/km with ultimate tensile strength of 98700 Newton and DC resistance at 20°C of 0,0718 Ω/km [35].

Table 4-1: The proposed HSIL methods: three configurations, two conductor bundles and four sub-conductor spacings

Method 1: Phase Compaction (Phase-to-Phase Spacing, PS in Figure 4-1)	Method 2: Conductor Bundle	Method 3: Expanded Bundle (mm) (Sub-conductor Spacing, SCS in Figure 4-1)	Phase-to-Phase Spacing (m) (PS Figure 4-1)		
			Phase 1	Phase 2	Phase 3
Case 1: Flat (517A)	3 x Tern	450, 690, 1 000 and 1 500	-8,20	0,00	8,20
Case 2: Flat (518H)	4 x Tern	450, 690, 1 000 and 1 500	-8,50	0,00	8,50
Case 3: Shallow delta (529A)	3 x Tern 4 x Tern	450, 690, 1 000 and 1 500	-7,00	0,00	7,00
Case 4: Perfect inverted delta (528A)	3 x Tern 4 x Tern	450, 690, 1 000 and 1 500	-3,50	0,00	3,50

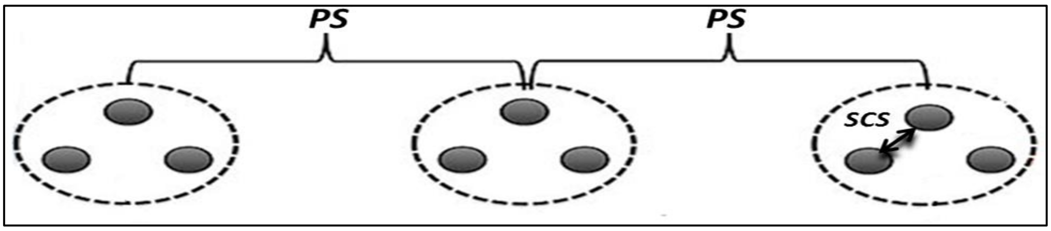

Figure 4-1: Flat configuration with three sub-conductors (3 x Tern) per phase with phase-to-phase spacing of 8.2 m (PS) with a symmetrically sub-conductor spacing of 450 mm (SCS)

The Bonneville Power Administration (BPA) software was used to calculate and compare the ionizing and non-ionizing field effects of the proposed configurations. The compared parameters were electric fields (kV/m) and magnetic fields (µT) for non-ionizing field effects while the ionizing field effects are L50 wet audible noise (dBA), L50 radio noise (dBu), and surface gradient margin (> 4.5%). Simulations are done at 1.8 m above ground level with a minimum conductor height above ground (midspan) of 10 m, servitude width of 55 m and an altitude of 1 800 m. A roughness factor of 0.76 was used for the conductor and soil resistivity of 700 Ω-m. All simulations were done with a rain rate of 25 mm/hr (wet weather conditions) because moisture enhances corona for dry weather conditions by a factor of up to 3 [11]. As shown in Table 3-1 and Table 3-2 the ionizing and non-ionizing field effect limits that Eskom complies with are as set by the ICNIRP guideline [30]. The Alternate Transients Program (ATP) software was used to calculate and compare the line parameters (R, X and B values) and SIL. Table 4-1 shows the inputs for the BPA and ATP software.

Figure 4-2, Figure 4-3 and Figure 4-4 illustrate some of the proposed HSIL configurations. The HSIL configuration with the largest increase in SIL is then used to evaluate if HSIL methods can eliminate the need for series capacitors on long transmission lines. The Power System Simulation for Engineers (PSS/E) software package was used to compare power transfer (PV plots) plus line and system losses of the as-built lines with series capacitors against HSIL lines.

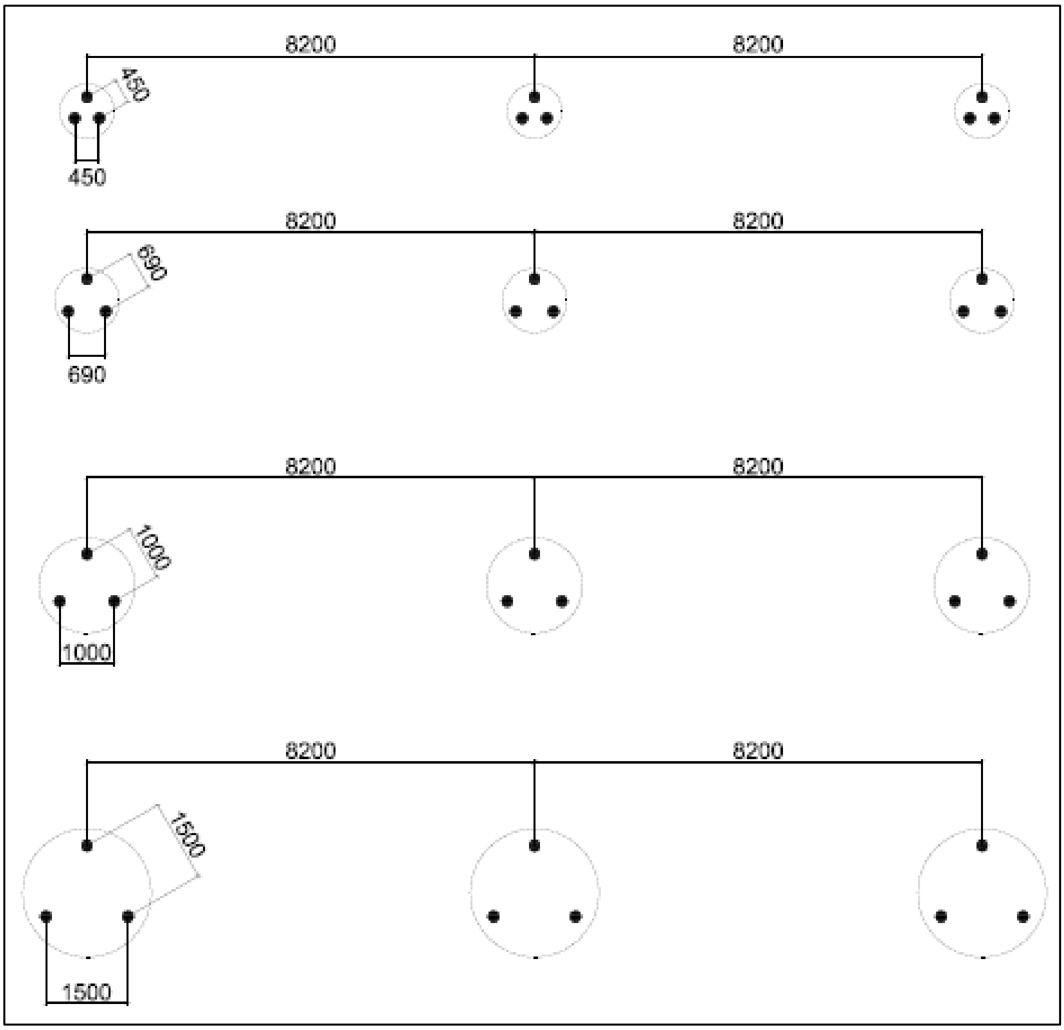

Figure 4-2: Illustration of Case 1: 3 x Tern on the flat configuration (517A)

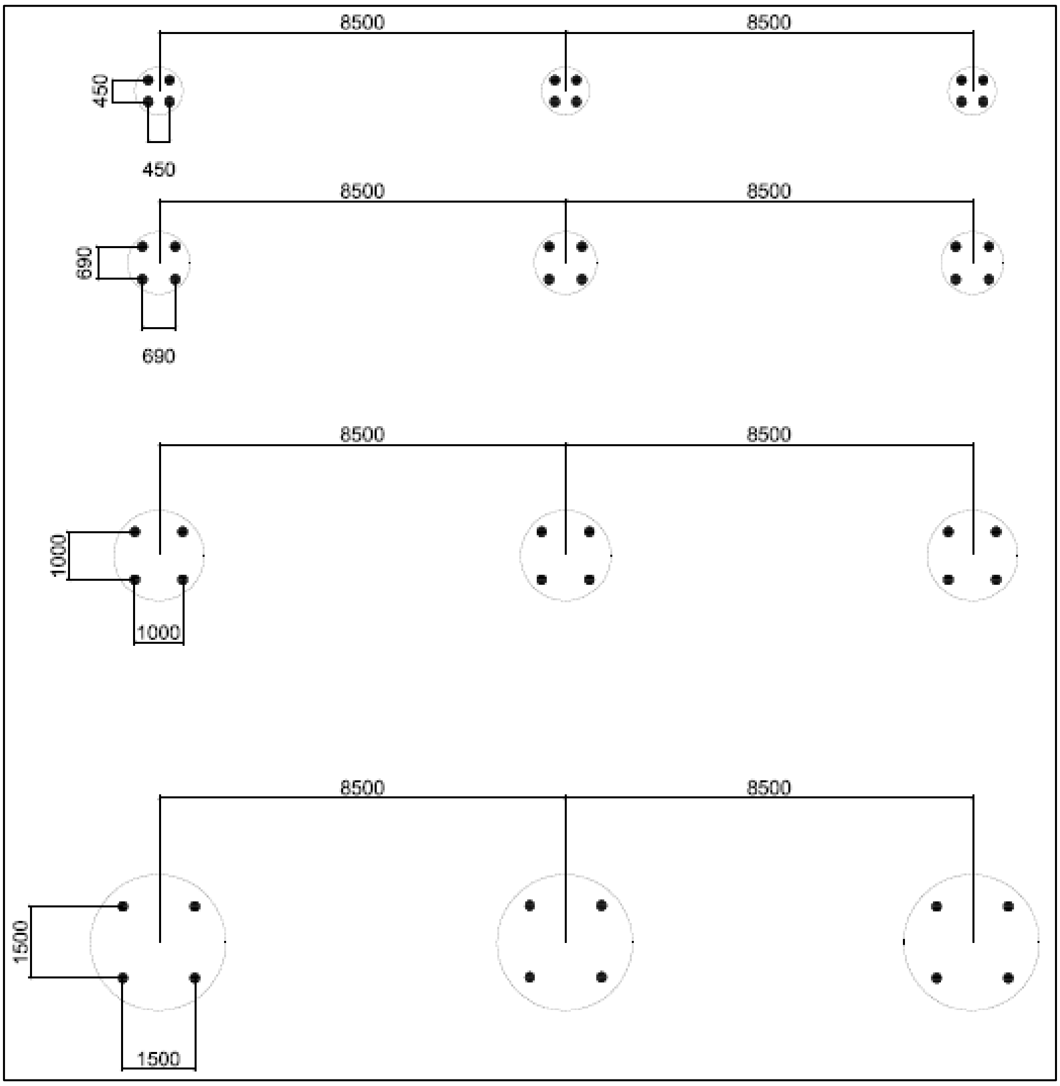

Figure 4-3: Illustration of Case 2: 4 x Tern on the flat configuration (518H)

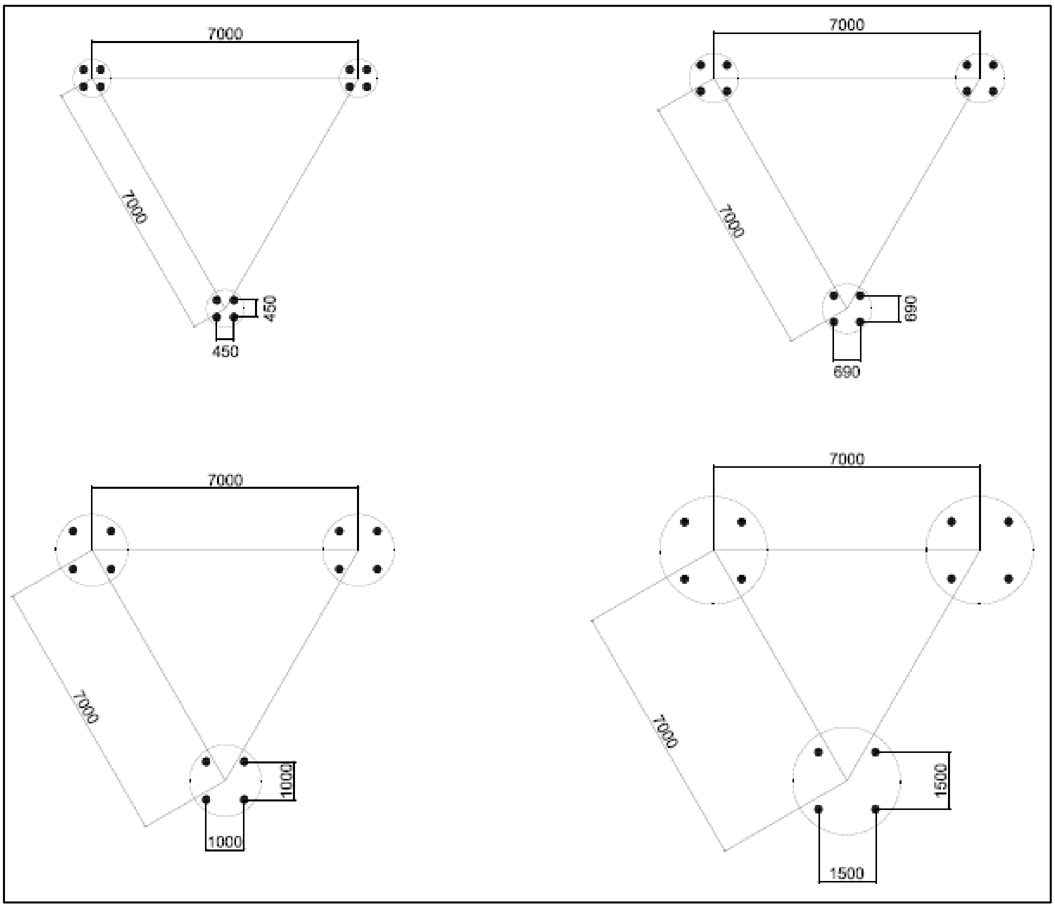

Figure 4-4: Illustration of Case 4: 4 x Tern on the perfect inverted delta configuration (528A)

4.2.2 New HSIL configuration – low altitude (coastal)

The main study is done at a high altitude of 1 800 m since these conditions prevail in South Africa. However simulations done at high altitude are classified as a worst case scenario when corona performance is considered. Thus the proposed high altitude HSIL configuration from Section 4.2.1 is subjected to an electrical performance analysis at an altitude of 1 100m. At high altitudes the phase-to-phase spacing that is required for non-compliance to corona limits will be substantially larger than the one that would be required at lower altitudes. The low altitude HSIL configuration will save costs related to tower steel (smaller tower) and servitude (narrower width).

4.2.3 Optimization of the existing HSIL configurations

The search for new techniques and technologies that can be used to increase the amount of power that can be transferred per corridor (MW/m^2) and reduce the total investment cost (Rands/MW) of power lines has led to the design of the existing 528A cross-rope suspension tower, where the phase compaction HSIL method is implemented. The phase conductor geometry is a perfect inverted delta.

In order to optimize this existing HSIL tower, the sub-conductor spacing is increased to implement the bundle expansion HSIL method. The ionizing and non-ionizing field effect limits are used as the overruling criteria for how far the bundle can be expanded. The recommended sub-conductor spacing is then simulated with thirteen different conductor bundles. The ionizing and non-ionizing field effects, SIL and line parameters of each bundle are compared with the aim of selecting the bundle with the most benefits for the line and the system as a whole. Table 4-2 shows the inputs for the BPA and ATP software.

The superior bundle is then used to do reactive power loss comparison (PQ Plots) and load flow studies to determine if the HSIL configuration can increase the SIL to levels were the series capacitor that is installed on the selected existing line can be eliminated. Simulations are done using the PSS/E and Voltage Security Assessment Tool (VSAT) software.

Table 4-2: Inputs to the BPA and ATP software

Tower Type	**Conductor Bundle size**	**Sub-conductor Spacing (mm)**	**Phase conductor horizontal position (perfect inverted delta)**		
			Phase 1	**Phase 2**	**Phase 3**
Inverted delta (528A)	2, 3, 4 & 6	690 up to 750	-3,50 m	0,00 m	3,50 m

4.3 The impedance matching case study

In 2009 Line Engineering Services (LES) designed a 230 km 400 kV line with the predicted average normal load of 480 MVA, maximum normal load of 564 MVA and the maximum contingency load of 644 MVA. The RXB values that the System Planner used to do the system analysis significantly deviated from the RXB values that the Line Designer recommended as the preferred line configuration.

Table 4-3 shows the RXB values from the System Planner and those that resulted from the conductor optimization study. The conductor optimization exercise indicated that a 3 x Tern sub-conductor bundle with 450 mm as the sub-conductor spacing be used on the 529A tower for altitudes that are below 1 000m and the 529C tower can be used for altitudes that are above 1 000 m. As shown in Table 4-4 the designed RXB values deviate from the planning RXB values by more than the acceptable difference of 5%. A deviation of more than 5% from the system planning RXB values can result in an infringement of the statutory requirements and the system stability limits which can have catastrophic impact of the existing network.

The proposed mitigating measure was to do an impedance matching exercise in order to identify which sub-conductor bundle, sub-conductor bundle spacing, conductor type and tower type can be used to achieve the desired system planning RXB values. The first phase of permutations was conducted with the existing towers and inputs for the analysis are shown in Table 4-5. The second phase of permutations was done using the proposed new HSIL configurations from Table 4-1. A percentage difference in comparison with the system planning RXB values is computed from the first phase. The objective is to identify the configuration that gives the least variance from the desired system planning RXB values. The winning sub-conductor bundle and sub-conductor bundle spacing is then used for the second phase permutations. Then a percentage difference in the RXB values from the HSIL configuration is computed to evaluate whether the HSIL configurations can supersede the configuration that is identified from the first phase. A total of 25 combinations were simulated in phase one and a total of 12 combinations were simulated in phase two.

Table 4-3: System Planning RXB values compared with the designed RXB values

Tower Type	**Sub-conductor Bundle size**	**Sub-conductor Spacing (mm)**	**Positive Sequence Line Impedances (pu/km obtained using 100 MVA as base)**		
			R (pu x 10^{-5})	**X (pu x10^{-4})**	**B (pu x10^{-2})**
529A	3 x Tern	450	1.53	1.66	0.689
529C	3 x Tern	450	1.56	1.83	0.628
Unknown	Unknown	Unknown	1.15	1.51	0.763

Table 4-4: Percentage difference in the RXB values of the selected configurations when compared to the System Planning RXB values

Tower Type and conductor bundle size	**Positive Sequence Line Impedances (pu)**					
	R (pu)	**% change in R**	**X (pu)**	**% change in X**	**B (pu)**	**% change in B**
529A and 3 x Tern	0.0035	24.36%	0.038	9.45%	1.585	-10.78%
529C and 3 x Tern	0.0035	25.93%	0.042	17.76%	1.444	-21.54%

Table 4-5: Inputs for calculating the RXB values for phase 1

Case No.	**Tower type**	**Proposed Bundle**	**Sub-conductor spacing (mm)**	**Altitude (m)**
1	529A	3 x Tern	450	1 000
2	529C	3 x Tern	450	1 500
3	529A	4 x IEC 315	380	1 500
4	529A	3 x IEC 450	450	1 500
5	529C	2 x Bersfort	570	1 500
6	529C	2 x IEC 800	570	1 500
7	529A	4 x Tern	450	1 500
8	529A	3 x Bersfort	570	1 500
9	529A	3 x IEC 800	570	1 500
10	525A	3 x Tern	450	1 500

11	525A	3 x Tern	570	1 500
12	525A	3 x Tern	450	1 500
13	525A	3 x Tern	570	1 500
14	525A	3 x Tern	380	1 500
15	525A	3 x Tern	380	1 500
16	529A	3 x Tern	570	1 500
17	529A	3 x Tern	380	1 500
18	529C	3 x Tern	380	1 500
19	529C	3 x Tern	570	1 500
20	525A	3 x Tern	690	1 500
21	525A	3 x Tern	690	1 500
22	528A	3 x Tern	380	1 500
23	528A	3 x Tern	450	1 500
24	529A	4 x IEC 315	570	1 500
25	529A	3 x Bersfort	570	1 500

4.4 The proposed system analysis case study

The investigation is limited to the existing 400 kV transmission lines in the Eskom transmission system.

4.4.1 Network analysis

Ideal transmission lines for the application of HSIL methods are lines that are longer than 200 km, have a high and constant load factor (not varying between peak and light load), operate at or above their SIL under system healthy conditions and have series capacitors installed. Using this criterion, the best suited network is the existing Motraco network with two 400 kV lines that supply a constant load of 1143.9 MW.

Table 4-6 shows the characteristic data of the existing lines in the Motraco network. Figure 4-5 shows the single line diagram of the selected network. The top dotted line shows the existing 284 km Arnot – Maputo 400 kV line that is built with a 3 x Tern conductor while the green line below shows the 284 km HSIL Arnot – Maputo 400 kV line that is proposed with a 4 x Tern conductor. The bottom dotted line shows the existing 277 km Camden – Maputo 400 kV line that is built with a 3 x Tern conductor while the green line shows the 277 km HSIL Camden – Maputo 400 kV line that is proposed with a 4 x Tern conductor.

Table 4-6: Parameters for the existing 400 kV lines in the Motraco network

Line Name (400 kV)	Conductor Bundle	Series Capacitor (pu x 10^{-2})	R (pu x 10^{-3})	X (pu x10^{-2})	B (pu)
Arnot – Maputo	3 x Tern	2.765	4.88	5.068	1.82
Camden – Maputo	3 x Tern	1.778	4.76	4.942	1.77

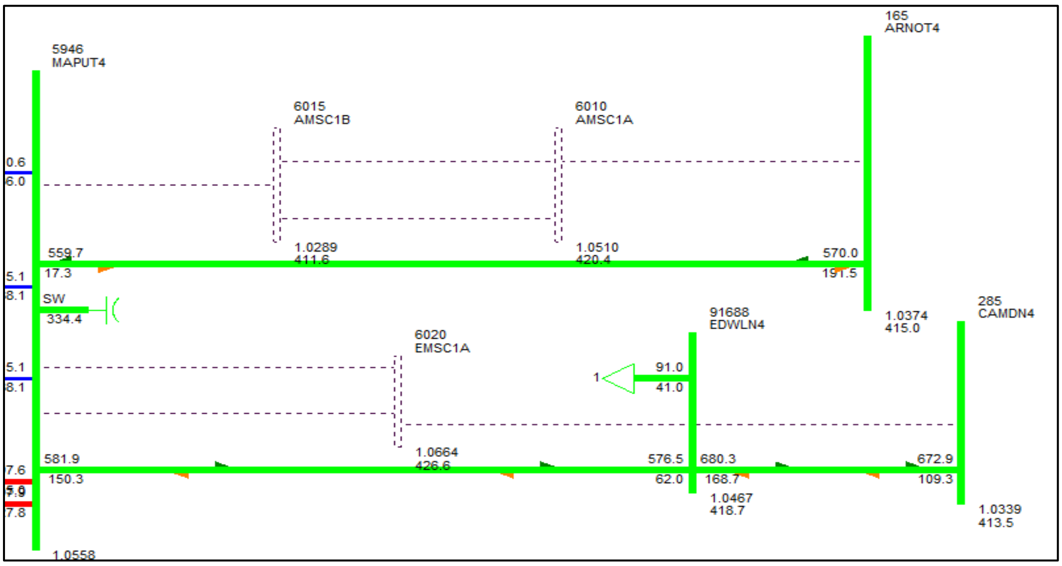

Figure 4-5: Motraco network with the as-built lines switched off and HSIL lines switched on

4.4.2 Single line analysis

The Arnot – Maputo 400 kV line was selected as a case study for a single line analysis and comparison. The as-built parameters of the Arnot – Maputo line are as shown in Table 4-7. The series capacitor on the existing Arnot – Maputo line is installed in the middle of the line. Consequently the line is divided into two sections that are 142 km each. To analyze and compare the reactive power absorption of the existing line against the HSIL line, four scenarios are simulated as stated in the cases below:

- Case i is the existing line from Arnot to the series capacitor,
- Case ii is the existing line from the series capacitor to Maputo,
- Case iii is the proposed HSIL line without a series capacitor and
- Case iv is a summation of the as-built line parameters (R and B of the two sections are added and X_C is subtracted from X_L).

Table 4-7: Parameters for the existing Arnot – Maputo 400 kV lines

Line Name (400 kV)	**Line Length (km)**	**Conductor Bundle**	**Series Capacitor (pu x 10^{-2})**	**R**	**X**	**B**
				(pu x 10^{-3})	**(pu x10^{-2})**	**(pu)**
Arnot – Maputo	284	3 x Tern	2.765	4.88	5.068	1.823

5. RESULTS

5.1 Summary

The results are divided into two sections: the ionizing (corona) field effects which are AN L50 wet and RI L50 wet and the non-ionizing field effects which are the electric fields and magnetic fields.

5.2 Ionizing (corona) field effects

5.2.1 Audible noise

5.2.1.1 New HSIL configuration – high altitudes (inland)

The selection of suitable HSIL methods is initially focused on phase compaction and bundle expansion methods because they present an opportunity of a HSIL configuration that will have costs that are comparable to the existing 400 kV towers. Table 5-1 shows the results for the proposed configurations analyzed with a 3 x Tern conductor bundle. When the proposed phase compaction and bundle expansion methods are applied, the 3 x Tern conductor bundle does not comply with the ionizing (corona) field effects at an altitude of 1 800 m (highlighted in red). These results are expected because corona increases with an increase in altitude. At high altitudes the air density and pressure decrease and as a consequence the corona inception voltage is reduced [17]. The maximum altitude where the margin of corona inception gradient over the maximum surface gradient is above 4.5 %. The observation made from column 2 (bundle separation) of Table 5-1 is that the sub-conductor spacings of 1 000 mm and 1 500 mm are not feasible with a 3 x Tern conductor bundle because the maximum altitudes are significantly below the required 1 800 m.

Table 5-1: Results for a 3 x Tern bundle

Case	Tower and Bundle Separation (mm)	Altitude (m)	AN L50 Wet at servitude boundary (Limit: 53.1 dBA)	Electric Field at servitude boundary (Limit: 5 kV/m)	Max Electric Field in servitude (Limit: 10 kV/m)	RI L50 Wet at servitude boundary (Limit: 72 dBu)	Margin % of Corona Inception gradient over max surface gradient
1st.	517A & 450	1 300	46.10	1.415	7.39	61.4	5.17%
2nd.	517A & 690	900	46.90	1.515	7.90	62.0	5.27%
3rd.	517A & 1 000	600	48.50	1.614	8.41	63.4	4.56%
4th.	517A & 1 500	100	50.00	1.780	7.73	65.1	2.84%
5th.	529A & 450	900	46.30	1.209	5.35	60.8	5.57%
6th.	529A & 690	500	47.20	1.296	5.72	61.8	5.18%
7th.	529A & 1 000	100	48.60	1.383	6.09	63.3	5.06%
8th.	529A & 1 500	100	52.30	1.492	6.55	67.2	-2.42%
9th.	528A & 450	1 000	47.90	0.655	6.32	63.8	4.66%
10th.	528A & 690	600	48.80	0.705	6.84	64.7	4.48%
11th.	528A & 1 000	200	50.20	0.757	7.37	66.0	4.60%
12th.	528A & 1 500	100	53.50	0.822	8.06	69.3	-1.58%

The conductor surface gradient can also be reduced by increasing the number of sub-conductors from 3 x Tern to 4 x Tern (method 2).

The results shown in Table 5-1 and 5-2, indicate that 4 x Tern is the minimum sub-conductor bundle size that can be considered when the sub-conductor bundle spacing is expanded, the phases are compacted and the combination of expanding the bundle and compacting the phase is applied at an altitude of 1 800 m.

The application of both methods evaluated with 4 x Tern on the existing towers is only feasible for a bundle spacing up to 690 mm on the 528A and 529A towers while the 518H tower is feasible up to 1 000 mm. The bundle spacings of 1 000 mm on the 529A and 528A towers and 1 500 mm on all existing towers do not comply with the corona limits (highlighted in red). This is addressed by increasing the phase-to-phase spacing until the margin of corona inception gradient over maximum surface gradient is above 4.5% (highlighted in green). The 518H / flat configuration (case 4m) is increased from 8.5 m to 11 m, 529A / shallow delta (case 8d) is increased from 7 m to 10 m and the 528A / perfect delta (case 12i) is increased from 7 m to 12 m (highlighted in yellow). These results are acceptable as they are in line with the literature that states that the conductor surface gradient can be reduced by increasing the number of sub-conductors per phase and increasing the phase-to-phase spacing.

The results in Table 5-2 suggest that in order to implement the bundle expansion method the existing towers need to be modified by increasing the phase-to-phase spacing. The phase-to-phase modification does not only aid non-compliance to corona limits but it also ensures compliance with the minimum phase-to-phase clearance of 4.8 m, when the bundle sub-conductor spacing is expanded to 1 000 mm and 1 500 mm. This parameter is derived from SABS 10280 [36].

Table 5-2: Results for a 4 x Tern bundle (high altitude)

Case No	Configuration and sub-conductor spacing (mm)	Phase Spacing (m)	AN L50 Wet at servitude boundary (Limit: 53.1 dBA)	Electric Field at servitude boundary (Limit: 5 kV/m)	Max Electric Field in servitude (Limit: 10 kV/m)	RI L50 Wet at servitude boundary (Limit: 72 dBu)	Margin % of Corona Inception gradient over max surface gradient	Min Ground Clearance (m)
1	518H with 450 mm	8.5	41.6	1.602	8.19	54.0	17.90%	10.0
2	518H with 690 mm	8.5	44.3	1.743	8.91	56.5	11.53%	10.0
3	518H with 1 000 mm	8.5	47.6	1.888	9.63	59.6	5.69%	10.0
4a	518H with 1 500 mm	8.5	51.9	2.122	9.01	64.3	-3.46%	11.0
4b	Modified 518H with 1 500 mm	8.5	51.2	2.130	5.22	66.0	-3.18%	15.0
4c	Modified 518H with 1 500 mm	8.5	50.6	1.894	3.08	67.2	-3.18%	20.0
4d	Modified 518H with 1 500 mm	9.5	50.4	2.354	10.90	63.2	0.13%	10.0
4e	Modified 518H with 1 500 mm	9.5	49.3	2.366	5.47	63.9	0.91%	15.0
4f	Modified 518H with 1 500 mm	9.5	48.6	2.071	3.25	65.0	0.97%	20.0
4g	Modified 518H with 1 500 mm	10.5	49.1	2.662	11.17	62.9	3.43%	10.0
4h	Modified 518H with 1 500 mm	10.5	47.6	2.616	5.68	62.4	4.52%	15.0
4i	Modified 518H with 1 500 mm	10.5	46.9	2.252	3.40	63.1	4.71%	20.0

Case No	Configuration and Sub-conductor spacing (mm)	Phase Spacing (m)	AN L50 Wet at servitude boundary (Limit: 53.1 dBA)	Electric Field at servitude boundary (Limit: 5 kV/m)	Max Electric Field in servitude (Limit: 10 kV/m)	RI L50 Wet at servitude boundary (Limit: 72 dBu)	Margin % of Corona Inception gradient over max surface gradient	Min Ground Clearance (m)
4j	Modified 518H with 1 500 mm	10	49.7	2.496	11.07	63.0	1.88%	10.0
4k	Modified 518H with 1 500 mm	10	48.4	2.482	5.57	62.9	2.80%	15.0
4l	Modified 518H with 1 500 mm	10	47.7	2.155	3.32	64.0	2.93%	20.0
4m	Modified 518H with 1 500 mm	11	48.5	2.832	11.34	62.8	4.97%	10.0
4n	Modified 518H with 1 500 mm	11	48.2	2.849	10.49	62.7	5.16%	10.5
4o	Modified 518H with 1 500 mm	11	48.0	2.860	9.73	62.7	5.36%	11.0
4p	Modified 518H with 1 500 mm	11.5	47.9	3.007	11.44	62.8	6.35%	10.0
5	529A with 450 mm	7	43.7	1.330	5.86	55.4	11.70%	10.0
6	529A with 690 mm	7	46.6	1.450	6.37	58.6	5.10%	10.0
7a	529A with 1 000 mm	7	50.3	1.572	6.89	62.4	-0.98%	10.0
7b	529A with 1 000 mm	7	49.5	1.550	3.55	64.5	-0.30%	15.0
7c	529A with 1 000 mm	7	49.0	1.354	2.12	65.6	-0.16%	20.0

Case No	Configuration and Sub-conductor spacing (mm)	Phase Spacing (m)	AN L50 Wet at servitude boundary (Limit: 53.1 dBA)	Electric Field at servitude boundary (Limit: 5 kV/m)	Max Electric Field in servitude (Limit: 10 kV/m)	RI L50 Wet at servitude boundary (Limit: 72 dBu)	Margin % of Corona Inception gradient over max surface gradient	Min Ground Clearance (m)
7d	529C with 1 000 mm	10	43.6	2.171	9.15	57.2	12.49%	10.0
8a	529A with 1 500 mm	7	55.2	1.736	7.56	67.6	-10.35%	10.0
8b	529A with 1 500 mm	7	54.5	1.708	3.89	69.7	-9.73%	15.0
8c	529A with 1 500 mm	7	53.9	1.488	2.33	70.8	-9.59%	20.0
8d	529C with 1 500 mm	10	47.8	2.369	10.12	60.9	3.50%	10.0
8e	529C with 1 500 mm	10	47.4	2.303	8.54	60.9	4.26%	11.0
8f	529C with 1 500 mm	10	47.3	2.267	7.88	60.9	4.65%	11.5
9	528A with 450 mm	7	44.9	0.720	7.03	57.9	12.20%	10.0
10	528A with 690 mm	7	47.9	0.800	7.78	60.8	5.90%	10.0
11a	528A with 1 000 mm	7	51.5	0.870	8.57	64.3	0.07%	10.0
11b	528A with 1 000 mm	7	50.7	0.743	4.21	65.2	2.31%	15.0
11c	528A with 1 000 mm	7	50.1	0.633	2.51	65.4	3.43%	20.0

Case No	Configuration and Sub-conductor spacing (mm)	Phase Spacing (m)	AN L50 Wet at servitude boundary (Limit: 53.1 dBA)	Electric Field at servitude boundary (Limit: 5 kV/m)	Max Electric Field in servitude (Limit: 10 kV/m)	RI L50 Wet at servitude boundary (Limit: 72 dBu)	Margin % of Corona Inception gradient over max surface gradient	Min Ground Clearance (m)
11d	Modified 528A with 1 000 mm	10	46.1	1.081	9.47	59.7	9.72%	10.0
12a	528A with 1 500 mm	7	56.4	0.970	9.63	69.2	-9.05%	10.0
12b	528A with 1 500 mm	7	55.5	0.830	4.71	70.0	-6.80%	15.0
12c	528A with 1 500 mm	7	55.5	0.830	4.71	70.0	-6.80%	15.0
12d	528A with 1 500 mm	7	54.9	0.707	2.80	70.2	-5.71%	20.0
12e	Modified 528A with 1 500 mm	10	50.4	1.191	10.53	63.9	0.85%	10.0
12f	Modified 528A with 1 500 mm	10	49.2	0.976	5.32	64.2	4.26%	15.0
12g	Modified 528A with 1 500 mm	10	49.1	0.937	4.74	64.2	4.71%	16.0
12h	Modified 528A with 1 500 mm	10	48.9	0.904	4.28	64.2	5.10%	17.0
12i	Modified 528A with 1 500 mm	12	47.9	1.278	10.95	61.7	5.23%	10.0
12j	Modified 528A with 1 500 mm	12	47.7	1.250	10.13	61.8	5.82%	10.5
12k	Modified 528A with 1 500 mm	12	47.5	1.223	9.40	61.8	6.35%	11.0

5.2.1.1.1 Impact on the existing HSIL tower

The HSIL configuration that has the highest increase in SIL from Table 5-2 is case 12k, where the phase-to-phase spacing is increased from 7 m to 12 m in order to satisfy the corona limits. As shown on Figure 5-1 and 5-2, the 5 m increase in the phase-to-phase spacing of the existing 528A tower results in a ± 4.5 m increase in the guywire foot print and the mast heights of the existing tower. The 4.5 m increase in the mast height translates into an increase in steel of approximately 300 kg/mast which is approximately R 7000/mast and R 14000/tower.

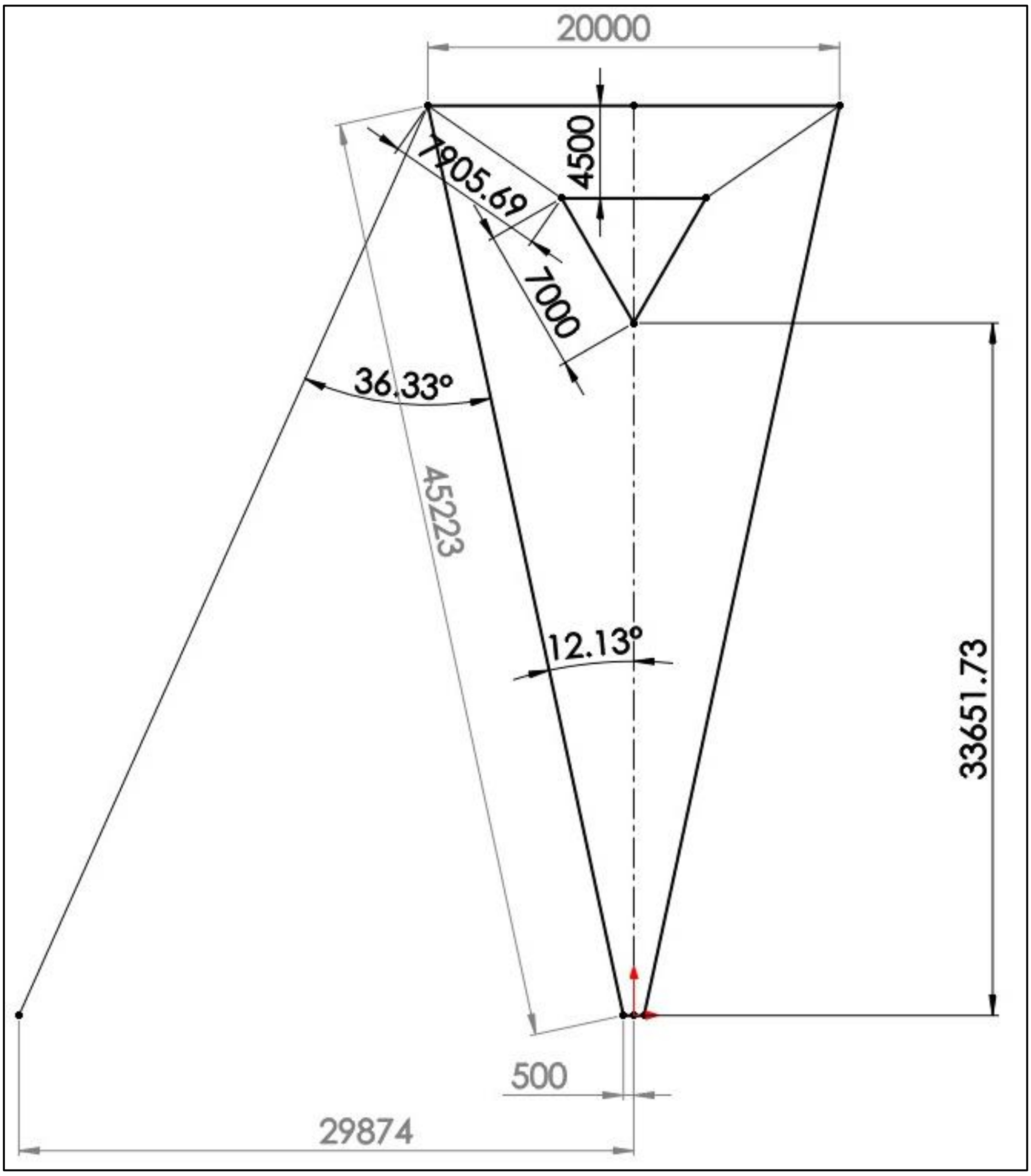

Figure 5-1: The existing HSIL tower (528A)

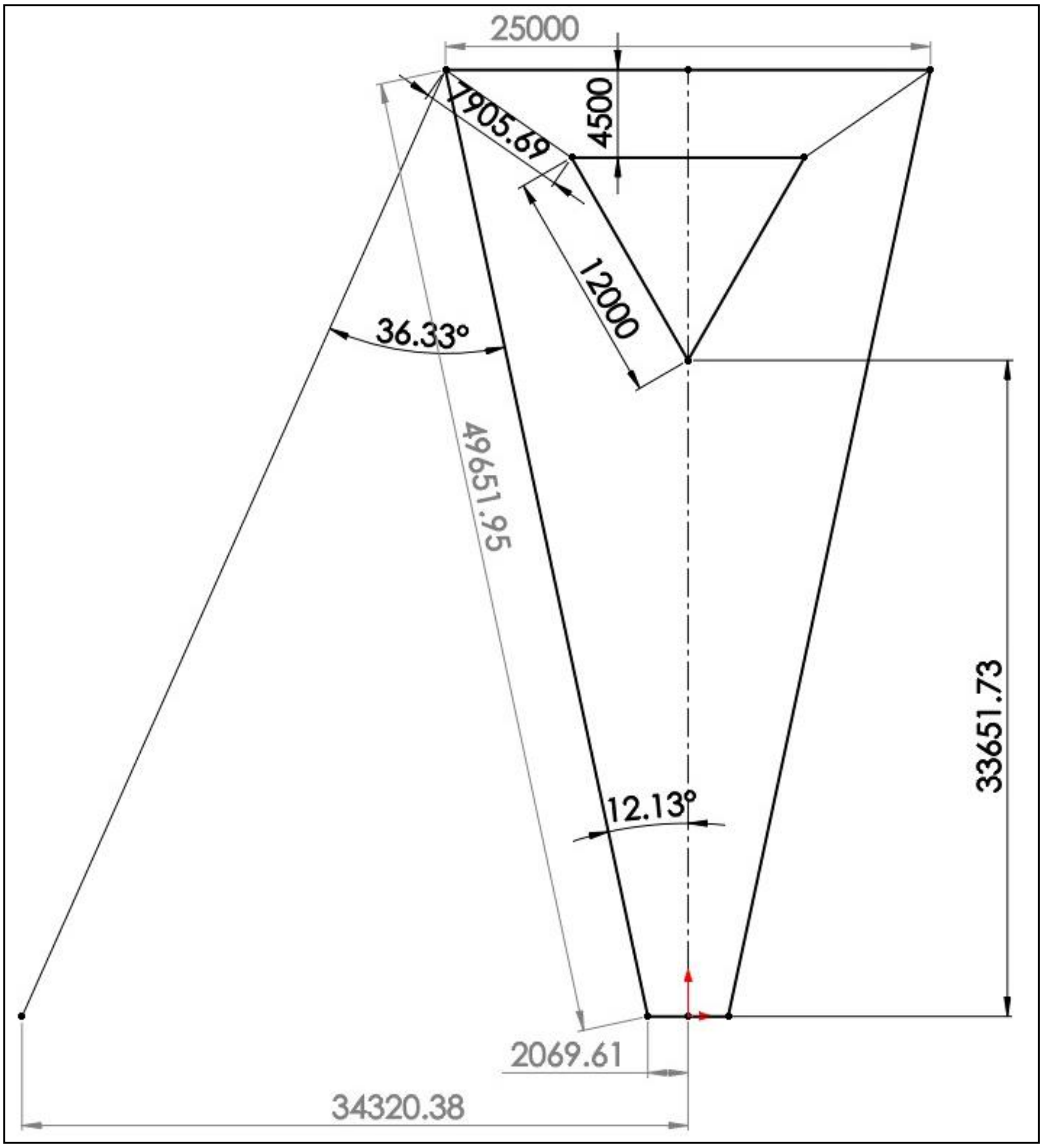

Figure 5-2: The proposed HSIL tower (modified 528A)

5.2.1.2 New HSIL configuration – low altitudes (coastal)

The combination of expanding the bundle and compacting the phases is implemented with a 4 x Tern sub-conductor bundle at an altitude of 1 100 m. The results shown in Table 5-3 indicate that in order to satisfy the corona limits the phase-to-phase spacing only needs to be increased by 2 m unlike the high altitude tower where the required phase-to-phase spacing is increased by 5 m. The resulting phase-to-phase spacing is 9 m (case 4a) unlike the 12 m phase-to-phase spacing that is required at an altitude of 1 800 m.

Table 5-3: Results for a 4 x Tern bundle (low altitude)

Case No	Configuration and Bundle Separation (mm)	Phase Spacing (m)	AN L50 Wet at servitude boundary (Limit: 53.1 dBA)	Electric Field at servitude boundary (Limit: 5 kV/m)	Max Electric Field in servitude (Limit: 10 kV/m)	RI L50 Wet at servitude boundary (Limit: 72 dBu)	Margin % of Corona Inception gradient over max surface gradient	Min Ground Clearance (m)
1	528A with 1 500 mm	12	45.2	1.223	9.40	59.4	15.35%	10.0
2	528A with 1 500 mm	11	46.9	1.175	10.78	60.9	10.64%	10.0
3	528A with 1 500 mm	10	48.2	1.137	10.55	62.0	8.07%	10.0
4	528A with 1 500 mm	9	49.8	1.093	10.28	63.2	5.01%	10.0
4a	528A with 1 500 mm	9	49.7	1.074	9.48	63.3	5.43%	10.5
4b	528A with 1 500 mm	9	49.5	1.055	8.77	63.4	5.86%	11.0
5	528A with 1 500 mm	8	51.7	1.035	9.98	64.9	1.54%	10.0
6	528A with 1 500 mm	7	54.0	0.970	9.63	66.8	-2.66%	10.0

5.2.1.3 Optimization of the existing HSIL configurations

The initial ionizing and non-ionizing field effect studies were simulated with 4 x Tern as the conductor bundle. The Tern conductor is selected as it is widely used in the Eskom Main Transmission System (MTS). In order to optimize the existing HSIL tower (528A), the sub-conductor spacing is increased to implement the bundle expansion HSIL method. The field effect limits are used as the overruling criteria for how far the bundle can be expanded.

The results in Table 5-4 indicate that the existing tower can only be used with a sub-conductor bundle that is expanded up to 740 mm without exceeding the ionizing field effect limits.

The second phase field effect studies were simulated with varying bundle sizes that consist of different conductor types and different conductor sizes. A total of thirteen bundles were simulated. As shown in Table 5-5 cases 2, 4, 6 and 8 exceed the corona limits at an altitude of 1 800 m (highlighted in red). As such only nine of the thirteen cases are considered for further studies.

Based on the results shown in Table 5-5, the 4 x Tern bundle ranks first when cost versus electrical performance is prioritized. However, since this study is done at high altitudes 4 x IEC 450 is preferred as it exhibits healthier margins for the inception of corona for a 9.6% increase in the conductor diameter. The cost of the IEC 450 conductor is R 48 280 per km while the Tern conductor is R 37 500 per km. Thus, the selection of the IEC 450 conductor over the Tern conductor translates into an increase of R 10 780 per km when compared to the 4 x Tern bundle.

5.2.2 Radio noise

The results shown in Table 5-2, 5-3 and 5-4 indicate that increasing the sub-conductor bundle spacing increases the radio interference, increasing the phase-to-phase spacing decreases the radio interference and decreasing the phase-to-phase spacing increases the radio interference. The radio interference levels of the proposed HSIL configurations are below the limit of 72 dBu.

Table 5-4: BPA results for expanding a 4 x Tern bundle on the existing 528A tower

Case	Bundle Separation (mm)	Phase Spacing (m)	AN L50 Wet at servitude boundary (Limit: 53.1 dBA)	Electric Field at servitude boundary (Limit: 5 kV/m)	Max Electric Field in servitude (Limit: 10 kV/m)	RI L50 Wet at servitude boundary (Limit: 72 dBu)	Margin % of Corona Inception gradient over max surface gradient
A	690	7	47.9	0.796	7.78	60.8	5.88%
B	700	7	48.0	0.798	7.81	60.9	5.62%
C	710	7	48.2	0.801	7.84	61.1	5.35%
D	720	7	48.3	0.803	7.86	61.2	5.08%
E	730	7	48.4	0.806	7.89	61.3	4.89%
F	740	7	48.5	0.809	7.92	61.4	4.62%
G	750	7	48.6	0.811	7.95	61.5	4.36%

Table 5-5: BPA results for 740 mm bundle spacing simulated with the proposed 13 bundles

Case No	Conductor Bundle	Conductor Diameter (mm)	AN L50 Wet at servitude boundary (Limit: 53.1 dBA)	Electric Field at servitude boundary (Limit: 5 kV/m)	Max Electric Field in servitude (Limit: 10 kV/m)	RI L50 Wet at servitude boundary (Limit: 72 dBu)	Margin % of Corona Inception gradient over max surface gradient
1	4 x Tern	27.00	48.5	0.809	7.92	61.4	4.62%
2	4 x IEC 315	24.70	51.0	0.801	7.84	64.7	-4.36%
3	6 x IEC 315	24.70	45.3	0.969	9.61	54.3	16.29%
4	4 x IEC 400	27.90	48.6	0.808	7.92	61.5	4.34%
5	4 x IEC 450	29.60	47.4	0.812	7.95	60.0	8.83%
6	3 x IEC 500	31.20	51.1	0.722	7.01	66.3	-2.07%
7	4 x IEC 500	31.20	46.3	0.816	7.99	58.5	13.30%
8	3 x IEC 560	33.00	50.00	0.7	7.049	64.80	1.94%
9	4 x IEC 560	33.00	45.3	0.819	8.03	57.1	17.89%
10	3 x IEC 630	35.00	48.8	0.730	7.09	63.2	6.52%
11	3 x IEC 710	37.20	47.7	0.734	7.14	61.7	11.31%
12	3 x IEC 800	39.50	46.8	0.737	7.17	60.5	15.06%
13	3 x Bersfort	35.58	47.9	0.733	7.13	61.9	10.51%

5.3 Non-ionizing field effects

5.3.1 Electric field

5.3.1.1 New HSIL configuration – high altitudes (inland)

Column 6 (max electric field in servitude) of Table 5-2 shows the configurations that violate the electric field limit of 10 kV/m within the servitude (highlighted in orange). To satisfy the electric field limit, the ground / midspan clearance is increased. The 518H tower (case 4o) is increased from 10 m to 11 m. For the 529C tower (case 8f) the clearance is increased from 10 m to 11.5 m. For the modified 528A tower (case 12k) the clearance is increased from 10 m to 11 m (highlighted in blue).

5.3.1.2 New HSIL configuration – low altitudes (coastal)

Column 6 (max electric field in servitude) of Table 5-3 shows that the 9 m phase-to-phase configuration exceeds the electric field limit of 10 kV/m within the servitude (highlighted in orange). To satisfy the electric field limit, the ground clearance for the modified 528A tower (case 4) is increased from 10 m to 10.5 m (highlighted in blue).

5.3.1.3 Optimization of the existing HSIL tower

Since this analysis entails the optimization of the existing HSIL tower (528A), the non-ionizing field effect limits are within the limits as per the original design.

5.3.2 Magnetic field

The line MVA rating of 650 MVA is used for all simulations. The highest magnetic field level from all simulations was 20.3 uT and it is well within the limit of 500 uT per 1 kA at the servitude boundary. Thus no reduction is required.

5.4 Line parameters

5.4.1 New HSIL configuration – high altitudes (inland)

Table 5-6 shows the SIL and line parameters of the HSIL configurations that satisfy the electrical performance requirements from Table 5-2. Case 1 shows the conventional configuration with SIL of 680 MW. Case 9 shows the phase compaction technique with SIL of 754 MW. Case 4o shows the expanded bundle technique with SIL of 821 MW. Case 12k shows the combination of phase compaction and expanded bundle with SIL of 849 MW. The highest increase in SIL is achieved with the combination of phase compaction and bundle expansion (case 12k), where the SIL is increased by 24.78% when compared to the conventional 4 x Tern configuration labelled case 1. The second highest increase is realized using the expanded bundle technique (case 4o) where SIL is increased by 20.67%, while phase compaction achieves an SIL increase of 10.81% (case 9). These results resemble previous research because the highest increase in SIL is achieved with the combination of the phase compaction and the bundle expansion method. The HSIL configuration with the highest increase in SIL (case 12k) also achieves a 19.92% reduction in X and a 24.69% increase in B. The reduced X value implies that the line and system losses of the HSIL line will be lower than those of a conventional line.

Table 5-6: ATP results for the cases that satisfy the ionizing (corona) and non-ionizing field requirements

Case No.	**SIL (MW)**	**% Increase in SIL**	**Positive Sequence Line Impedances (pu/km obtained using 100 MVA as base)**					**MVar Charging**
			R (pu x 10^{-5})	**X (pu x10^{-4})**	**% Change in X**	**B (pu x10^{-3})**	**% Change in B**	**MVar/km**
1	680	0.00	1.149	1.576	0.00	7.3043	0.00%	0.730
2	741	9.00	1.150	1.45	8.01	7.9825	9.29%	0.798
3	805	18.28	1.152	1.34	14.99	8.686	18.92%	0.868
4o	821	20.67	1.165	1.321	16.19	8.914	22.04%	0.891
5	710	4.44	1.152	1.506	4.48	7.6113	4.20%	0.761
6	778	14.32	1.153	1.379	12.50	8.3529	14.36%	0.835
7d	748	9.94	1.186	1.438	8.78	8.053	10.25%	0.805
8f	818	20.23	1.188	1.318	16.41	8.8262	20.84%	0.882
9	754	10.81	1.156	1.409	10.63	8.0151	9.73%	0.801
10	829	21.91	1.158	1.282	18.66	8.8304	20.89%	0.883
11d	813	19.49	1.170	1.313	16.72	8.6848	18.90%	0.868
12k	849	24.78	1.187	1.262	19.92	9.1074	24.69%	0.910

5.4.2 Optimization of the existing HSIL tower

The preferred sub-conductor bundle size and conductor type is 4 x IEC 450 and it is selected using the ionizing (corona) field effect performance. As shown in Table 5-7 the selection of IEC 450 over Tern is further supported by the fact that its SIL is 3.6 MW higher, R is 10.13% lower, X is 0.43% lower and B is 0.44% higher. When this configuration is compared to the conventional 3 x Tern configuration, R is reduced by 31.54%, X is reduced by 26.91%, B is increased by 34.94% and SIL is increased by 35.58%. Thus a line built with this bundle will give superior performance on the line and the system as a whole.

Table 5-7: ATP results for the proposed 13 sub-conductor bundles

Case No.	Proposed Bundle	Surge Impedance Loading (MW)	Positive Sequence Line Impedances (pu/km obtained using 100 MVA as base)			MVar Charging
			R (pu x 10^{-5})	X (pu x10^{-4})	B (pu x10^{-2})	MVar/km
1	4 x Tern	843.7	1.158	1.261	0.898	0.898
3	6 x IEC 315	1017.2	0.990	1.045	1.082	1.082
5	4 x IEC 450	847.3	1.041	1.256	0.901	0.901
7	4 x IEC 500	851.1	0.942	1.250	0.905	0.905
9	4 x IEC 560	854.8	0.847	1.245	0.910	0.910
10	3 x IEC 630	758.4	1.005	1.404	0.808	0.808
11	2 x IEC 710	762.8	0.900	1.396	0.812	0.81
12	3 x IEC 800	766.3	0.806	1.390	0.816	0.816
13	3 x Bersfort	762.2	0.925	1.397	0.812	0.812

5.4.3 The impedance matching case study

Table 5-8 shows the RXB values for the conductor optimization recommended configurations: a 3 x Tern sub-conductor bundle with 450 mm sub-conductor spacing on the 529A and 529C towers plus the RXB values that result from the permutation that are outlined in Table 4-5.

Table 5-8: ATP results for the selected sub-conductor bundle in order to match the system planning RXB values

Case No.	Proposed Bundle	Sub-conductor spacing (mm)	Surge Impedance Loading (MW)	Positive Sequence Line Impedances (pu/km obtained using 100 MVA as base)		
				R (pu x 10^{-5})	X (pu x10^{-4})	B (pu x10^{-2})
1	3 x Tern	450	643.88	1.530	1.662	0.689
2	3 x Tern	450	585.83	1.562	1.830	0.628
3	4 x IEC 315	380	682.63	1.459	1.567	0.730
4	3 x IEC 450	450	647.20	1.373	1.655	0.693
5	2 x Bersfort	570	544.17	1.405	1.972	0.584
6	2 x IEC 800	570	547.73	1.226	1.961	0.588

Case No.	Proposed Bundle	Sub-conductor spacing (mm)	Surge Impedance Loading (MW)	Positive Sequence Line Impedances (pu/km obtained using 100 MVA as base)		
				R (pu x 10^{-5})	X (pu x10^{-4})	B (pu x10^{-2})
7	4 x Tern	450	711.51	1.151	1.505	0.762
8	3 x Bersfort	570	686.18	0.919	1.563	0.736
9	3 x IEC 800	570	689.52	0.801	1.555	0.739
10	3 x Tern	450	621.44	1.531	1.720	0.664
11	3 x Tern	570	645.08	1.531	1.658	0.690
12	3 x Tern	450	636.44	1.528	1.676	0.679
13	3 x Tern	570	661.28	1.528	1.614	0.706
14	3 x Tern	380	605.49	1.531	1.764	0.646
15	3 x Tern	380	619.63	1.528	1.721	0.660
16	3 x Tern	570	669.54	1.530	1.600	0.717
17	3 x Tern	380	626.72	1.529	1.706	0.670
18	3 x Tern	380	571.64	1.562	1.874	0.612
19	3 x Tern	570	606.90	1.562	1.768	0.651
20	3 x Tern	690	663.50	1.531	1.608	0.712
21	3 x Tern	690	682.93	1.528	1.564	0.729
22	3 x Tern	380	685.51	1.527	1.550	0.728
23	3 x Tern	450	706.02	1.527	1.506	0.750
24	4 x IEC 315	570	740.80	1.460	1.448	0.794
25	3 x Bersfort	570	686.18	0.919	1.563	0.736

Table 5-9 shows the percentage difference between the twenty five combinations compared with the RXB values that the System Planner used to complete the system analysis studies. The results indicate that a 4 x Tern sub-conductor bundle with 450 mm used as sub-conductor spacing on the 529A tower (highlighted in bold) is the configuration that has the least change from the RXB values that were used when the line was planned. A percentage difference of -0.05% is achieved for R, 0.05% is achieved for X and -0.14% is achieved for B. Before a conclusion about the most probable configuration is drawn, the leading sub-conductor bundle (4 x Tern with 450 mm) is paired with the HSIL configurations that meet the electrical performance requirements from Table 5.2 and the RXB values are shown in Table 5-6. This check is done to assert if this configuration is the best match or HSIL configurations can supersede this configuration that utilizes the existing 529A tower.

Table 5-9: Percentage difference between the RXB values of the selected configurations when compared to the System Planning RXB values

Case No.	**Positive Sequence Line Impedances (pu)**					
	R (pu)	**% change in R**	**X (pu)**	**% change in X**	**B (pu)**	**% change in B**
1	0.0035	24.36%	0.0382	9.45%	1.585	-10.78%
2	0.0035	25.93%	0.0420	17.76%	1.444	-21.54%
3	0.0033	20.70%	0.0360	4.00%	1.680	-4.49%
4	0.0031	15.73%	0.0380	9.06%	1.594	-10.11%
5	0.0032	17.65%	0.0453	23.69%	1.343	-30.70%
6	0.0028	5.67%	0.0451	23.26%	1.353	-29.73%
7	**0.0026**	**-0.50%**	**0.0346**	**0.05%**	**1.753**	**-0.14%**
8	0.0021	-25.85%	0.0359	3.71%	1.692	-3.72%
9	0.0018	-44.44%	0.0357	3.26%	1.701	-3.21%
10	0.0035	24.41%	0.0395	12.50%	1.528	-14.91%
11	0.0035	24.43%	0.0381	9.23%	1.587	-10.64%
12	0.0035	24.26%	0.0385	10.24%	1.562	-12.40%
13	0.0035	24.28%	0.0371	6.79%	1.624	-8.11%
14	0.0035	24.41%	0.0405	14.70%	1.487	-18.01%
15	0.0035	24.26%	0.0395	12.55%	1.519	-15.53%
16	0.0035	24.37%	0.0368	5.94%	1.649	-6.42%
17	0.0035	24.35%	0.0392	11.80%	1.541	-13.89%
18	0.0035	25.93%	0.0431	19.70%	1.408	-24.64%
19	0.0035	25.94%	0.0406	14.88%	1.498	-17.22%
20	0.0035	24.44%	0.0369	6.40%	1.638	-7.14%
21	0.0035	24.29%	0.0359	3.80%	1.678	-4.61%
22	0.0035	24.21%	0.0356	2.91%	1.675	-4.79%
23	0.0035	24.22%	0.0346	0.05%	1.726	-1.70%
24	0.0033	20.76%	0.0333	-3.95%	1.827	3.93%
25	0.0021	-25.85%	0.0359	3.71%	1.692	-3.72%

Table 5-10 shows the percentage difference between the twelve HSIL combinations (Table 5-6) compared with the RXB values that the System Planner used. Again the results indicate that a 4 x Tern with 450 mm sub-conductor spacing on the existing 529A tower (highlighted in bold) is the configuration that has the least deviation from the RXB values that were used when the line was planned. A percentage difference of -0.046% is achieved for R, 0.04% is achieved for X and -0.30% is achieved for B.

Table 5-10: Percentage difference in the RXB values when the HSIL configurations in Table 5-6 are compared to the System Planning RXB values

Case No.	Positive Sequence Line Impedances (pu)					
	R (pu)	**% change in R**	**X (pu)**	**% change in X**	**B (pu)**	**% change in B**
1	0.0026	-0.65%	0.0362	4.52%	1.679	-4.52%
2	0.0026	-0.57%	0.0333	-3.80%	1.835	4.36%
3	0.0026	-0.43%	0.03082	-12.32%	1.997	12.11%
4o	0.0026	0.67%	0.0303	-13.93%	2.050	14.36%
5	**0.0026**	**-0.46%**	**0.0346**	**0.04%**	**1.750**	**-0.30%**
6	0.0026	-0.34%	0.0317	-9.12%	1.921	8.60%
7d	0.0027	2.44%	0.0330	-4.67%	1.852	5.20%
8f	0.0027	2.64%	0.0303	-14.22%	2.030	13.50%
9	0.0026	-0.05%	0.0324	-6.84%	1.843	4.75%
10	0.0026	0.07%	0.0294	-17.38%	2.030	13.54%
11d	0.0026	1.09%	0.0301	-14.65%	1.997	12.10%
12k	0.0027	2.55%	0.0290	-19.24%	2.094	16.17%

5.5 Impact on the line and system losses (new HSIL configuration)

The HSIL configuration that was used, to evaluate the impact of HSIL lines on system operations was Case 12k in Table 5-2 and the configuration is shown as in Figure 5-3.

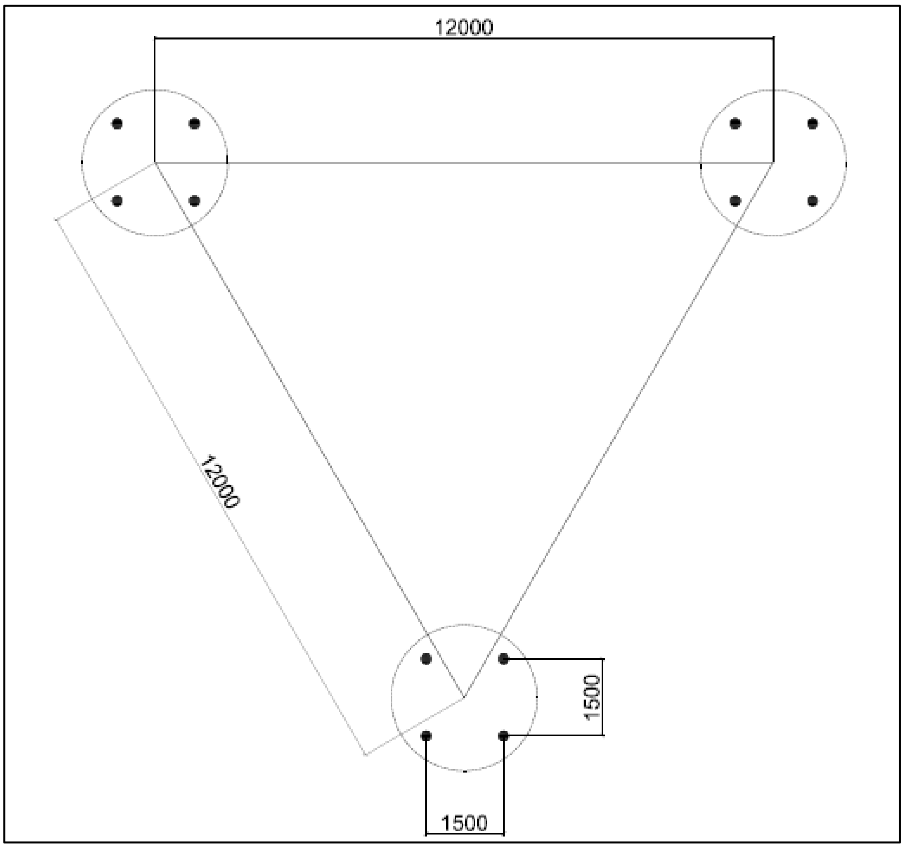

Figure 5-3: Illustration of Case 12k: 4 x Tern on the perfect inverted delta configuration (modified 528A)

As shown in Table 5-11 the existing Arnot – Maputo 400 kV line is compensated by 54.5% and the existing Camden – Maputo 400 kV is compensated by 35.9%. Both the existing lines are built with a 3 x Tern sub-conductor bundle with 450 mm as the sub-conductor spacing. When the as-built configuration is compared with a HSIL configuration, X is reduced by 29.2%, R is reduced by 30.8% and B is enhanced by 41.8%. As stated in Section 3.3 a lower R and X and higher B will increase the transfer capacity of the line. The line losses in the existing lines are 35.3 MW, while the line losses in the HSIL lines are 23.1 MW. This is equivalent to a 34.5% reduction in line losses.

Table 5-11: Parameters for the existing lines and HSIL lines

Line Name (400 kV)	Series Capacitor (pu x 10^{-2})	R (pu x 10^{-3})	X (pu x10^{-2})	B (pu)
Arnot – Maputo	2.76	4.88	5.068	1.823
Camden – Maputo	1.7	4.76	4.942	1.777
HSIL Arnot – Maputo	-	3.37	3.585	2.586
HSIL Camden – Maputo	-	3.28	3.496	2.522

5.6 PV plots (new HSIL configuration)

The HSIL configuration that was analyzed from Table 5-2 is case 12k because it achieves the highest increase in SIL. As shown in Figure 5-3 this HSIL configuration is a perfect inverted delta with 12 m as the phase-to-phase spacing and 1 500 mm as the sub-conductor spacing on a 4 x Tern sub-conductor bundle.

The Motraco network was selected as a case study because the lines are longer than 200 km, supply a constant load of 1143.9 MW, operate at their SIL under system healthy conditions and have series capacitors installed. Power System Simulations for Engineers (PSS/E) was used to compare the power transfer of the existing (as-built) lines with series capacitors against HSIL lines.

The results shown in Table 5-12 and Figure 5-4 indicate that the HSIL lines result in higher voltage levels than the existing lines with series capacitors. This is a result of the increase in the shunt capacitive susceptance of the line. The HSIL lines result in 1.056 Vpu which is above the allowable maximum of 1.05 Vpu. When a 100 MVar line shunt reactor is simulated on the Arnot – Maputo 400 kV line only, the resulting voltage is 1.053 Vpu under system healthy conditions thus the second iteration is to simulate a 100 MVar line shunt reactor on both lines. This results in 1.032 Vpu under system healthy conditions; however under contingency conditions both lines experienced voltage levels that are below the statutory limit of 0.95 Vpu with voltage collapse on the Arnot – Maputo 400 kV line and 0.936 Vpu on the Camden – Maputo 400 kV line. This is due to the removal of capacitance when one line is disconnected. The third iteration is to simulate a 100 MVar line shunt reactor on the Camden – Maputo 400 kV line only and this results in 1.034 Vpu under system healthy conditions; however under contingency conditions both lines experienced voltage levels that are below 0.95 Vpu with 0.916 Vpu on the Arnot – Maputo 400 kV and 0.936 Vpu on the Camden – Maputo 400 kV. Once again it is due to the removal of capacitance when one line is disconnected.

The observation made for the Motraco network is that a shunt line reactor on the Camden – Maputo 400 kV line results in low voltages under contingency conditions, thus it cannot be considered as a mitigation measure to reduce the excessive reactive power that is generated by the HSIL lines. The fourth iteration is to simulate a 200 MVar line shunt reactor on the Arnot – Maputo 400 kV line. The 200 MVar line shunt reactor on the Arnot – Maputo 400 kV line is the recommended mitigation measure because the voltage level is reduced to the allowable limit of 1.05 Vpu on the Maputo busbar under system healthy conditions and under contingency conditions Arnot – Maputo 400 kV line results in 0.949 Vpu while Camden – Maputo 400 kV line results in 0.978 Vpu.

The results in Figure 5-4 and Table 5.12 indicate that for the Motraco network, HSIL lines are comparable under system healthy conditions. As shown in Figure 5-5 under contingency conditions the HSIL Arnot – Maputo 400 kV transfers 12.2% less power than the existing line. The power that is transferred by the HSIL Arnot – Maputo 400 kV line is 6.1% less than the load that is currently connected to the as-built network. As illustrated in Figure 5-6 under contingency conditions the HSIL Camden – Maputo 400 kV line transfers 2.7% less power than the existing line. The power that is transferred by the HSIL Camden – Maputo 400 kV line is 3% less than the load that is currently connected to the as-built network.

The conclusion drawn from Table 5-13 is that the HSIL lines result in higher voltage levels than the existing lines however under contingency conditions the HSIL lines are not comparable with the existing lines that have series capacitors installed. This is expected because the HSIL lines reduce the series inductive reactance by 29.2% while the series capacitors reduce the series inductive reactance by 54.5% on the Arnot – Maputo 400 kV line and by 35.9% on the Camden – Maputo 400 kV line. For the Motraco network, the HSIL lines can only eliminate the need for series capacitors under system healthy conditions. Under contingency conditions the transfer capacity of the lines in the Motraco network does not meet the load demand (case specific). It is critical to note that the conclusion is case specific and cannot be used as a blanket statement.

Table 5-12: Power transfer comparison into the Motraco network (system healthy)

Line Description	Voltage at Base Load (Vpu)	Line Loading (MW)	Power Transfer at 0.95 Vpu (MW)
Existing	1.015	1287	1712
HSIL	1.056	1239	1738

Table 5-13: Power transfer comparison under N-1 contingency conditions (one line in service)

Line Description	Voltage at Base Load (Vpu)	Line Loading (MW)	Power Transfer at 0.95 Vpu (MW)
As-built Arnot – Maputo	0.925	1222	-
HSIL Arnot – Maputo	0.989	1073	1105
As-built Camden – Maputo	0.956	1140	1157
HSIL Camden – Maputo	0.978	1109	1163

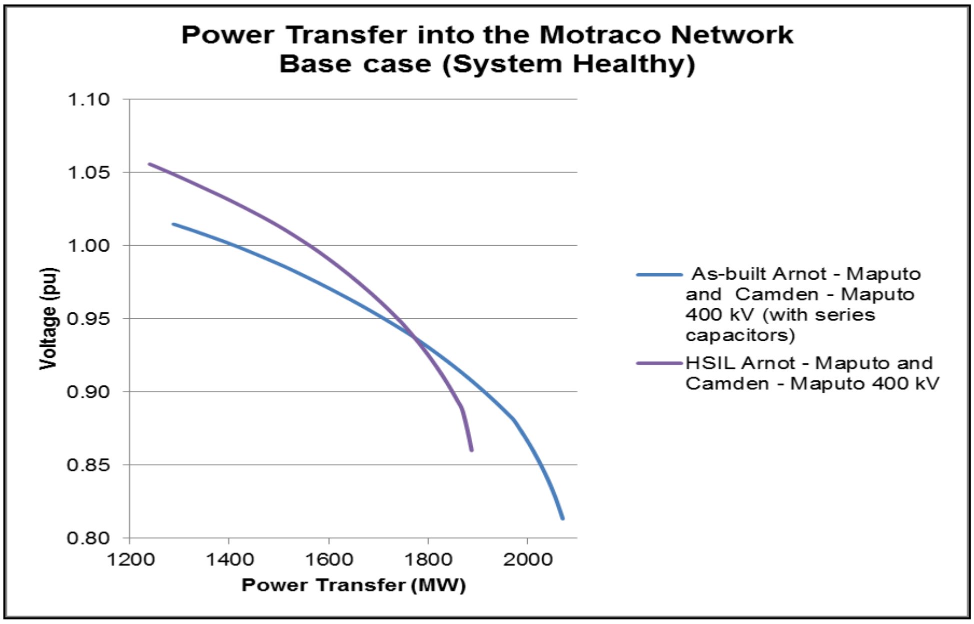

Figure 5-4: Power transfer comparison into the Motraco network (system healthy)

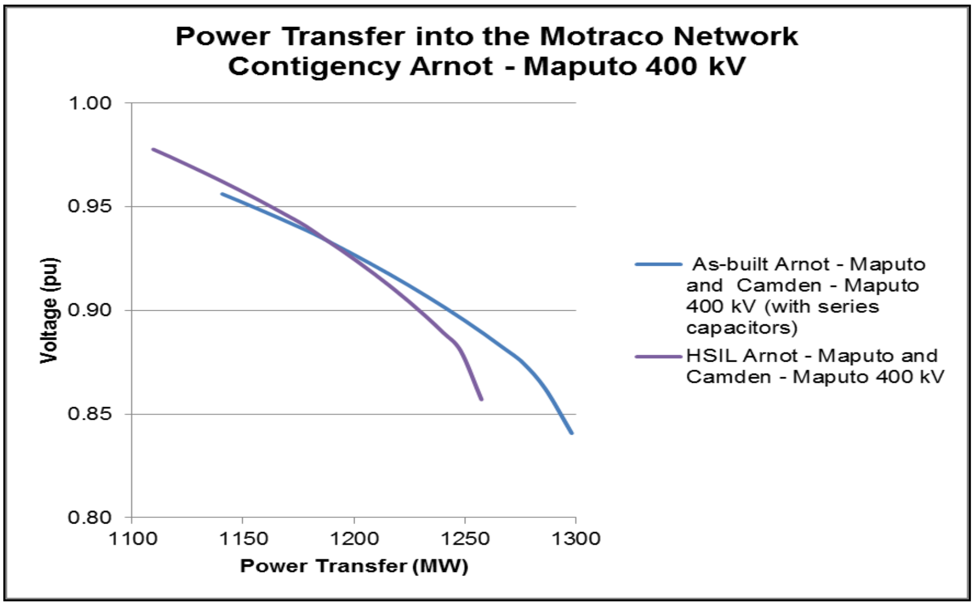

Figure 5-5: Power transfer comparison into the Motraco network (Camden – Maputo 400 kV).

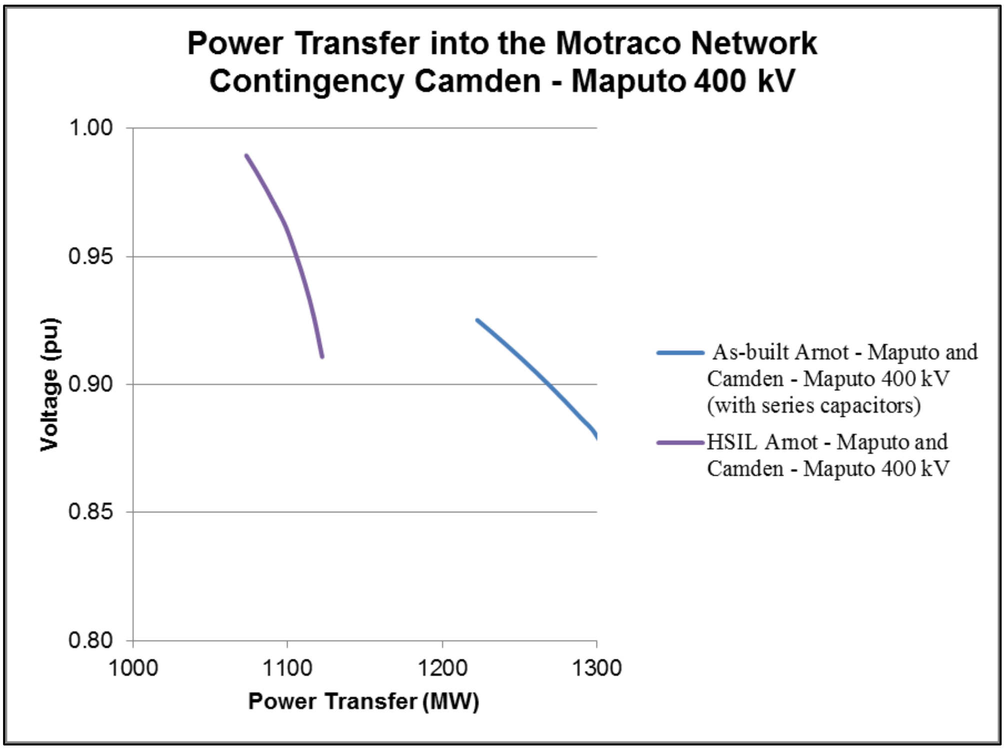

Figure 5-6: Power transfer comparison into the Motraco network (Arnot – Maputo 400 kV).

5.7 PQ plots (optimization of the existing HSIL tower)

Table 5-14 shows the parameters of the 4 x IEC 450 sub-conductor bundle (case 5) that is used to analyze and compare the reactive power consumption of the existing line against the HSIL line. Case i represents the existing line from Arnot to the series capacitor, Case ii represents the existing line from the series capacitor to Maputo, Case iii represent the proposed 4 x IEC 450 HSIL line and Case iv represents a summation of the as-built line parameters (R and B of the two sections are added and for X the X_C is subtracted from X_L).

Table 5-14: Parameters for the existing line and the HSIL line

Case No	Series Capacitor (pu x 10^{-2})	R (pu x10^{-3})	X (pu x10^{-2})	B (pu)
i.	-	2.44	2.534	0.9117
ii.	2.765	2.44	2.534	0.9117
iii.	-	2.95	3.567	2.5615
iv.	-	4.88	2.303	1.8234

Figure 5-7 shows the results for Case i, Figure 5-8 shows the results for Case ii, Figure 5-9 shows the results for Case iii and Figure 5-10 shows the results for Case iv. Ranking the results in terms of SIL, Case iv comes first with 920 MW, while Case iii is second with 882 MW, Case i is third with 627 MW. Case iv is a theoretical winner because in real operation, compensation does not operate as per the proposed summation. This is simulated to demonstrate the impact of X on reactive power consumption. In real life, the series capacitor operates as illustrated on Figure 5-8, where the series capacitor supplies additional reactive power to boost the voltage level at the receiving end. Figure 5-8 clearly shows this because the transfer level is 38 MVar above the SIL reference line while Case i and iii are below which implies that the lines are supplying 73 MVar and 256 MVar respectively. The results shown in Figure 5-7 to 5-9 indicate that HSIL methods are indeed effective in increasing the transfer capacity of power lines. The voltage level of the HSIL line clearly shows that HISL methods do increase the natural capacity of the line because the HSIL line has the healthiest voltage level both at initial and at maximum power transfer.

As per the results shown in Table 5-15, the capacitive reactive power generated by the HSIL line is increased by a factor of 3.5, when compared to the conventional line (73 MVar versus 256 MVar). At maximum power transfer this translates to a reactive power requirement that is 33% less than the conventional line.

Table 5-15: Power transfer comparison for the four cases

Case No	**Voltage (pu)**	**MW_{INI}**	**$MVar_{INI}$**	**Voltage (pu)**	**MW_{MAX}**	**$MVar_{MAX}$**
i.	1.120	26	- 73	0.911	1250	323
ii.	1.120	23	38	0.911	1211	418
iii.	1.198	39	-256	0.949	1094	205
iv.	1.139	30	-175	0.921	1297	232

The transfers were initially increased in steps of 16 MW in search of the stability limit. After the system became unstable with the last 16 MW step, the step size is reduced in order to reach the peak of the QP curve. A fine-tuning process is started to determine the limit within the cut-off step size of 4 MW. This caused discontinuation in the plots. The change/reduction in step size is easily recognizable in Figures 5-7, 5-8 and 5-10.

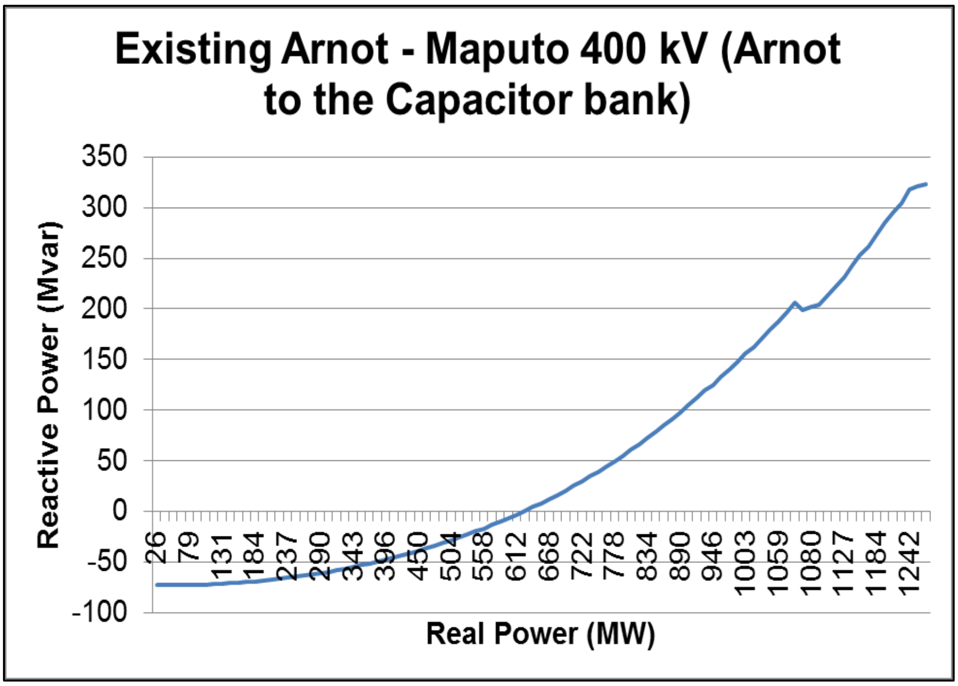

Figure 5-7: QP plot for Case i

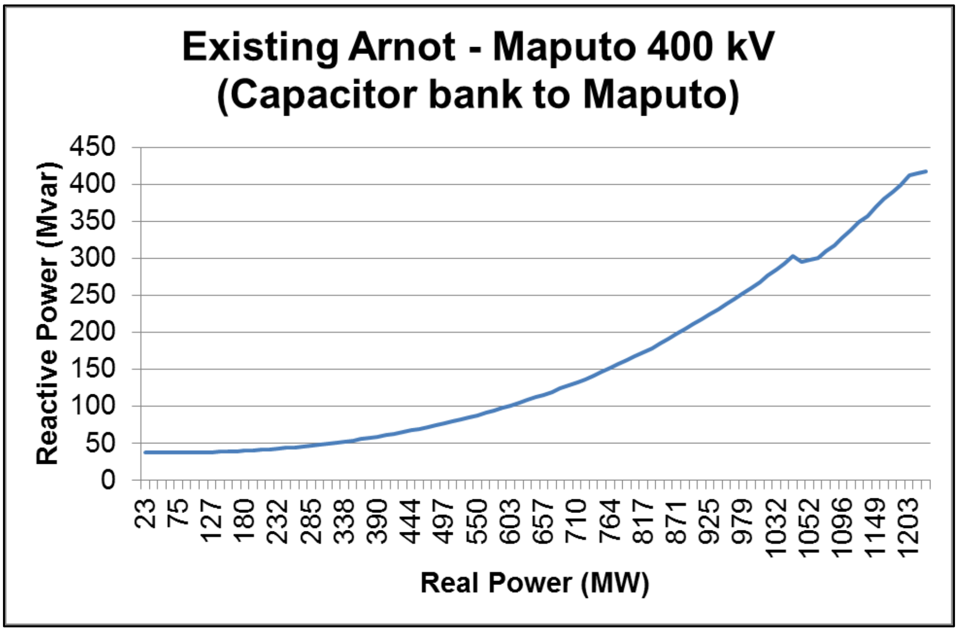

Figure 5-8: QP plot for Case ii

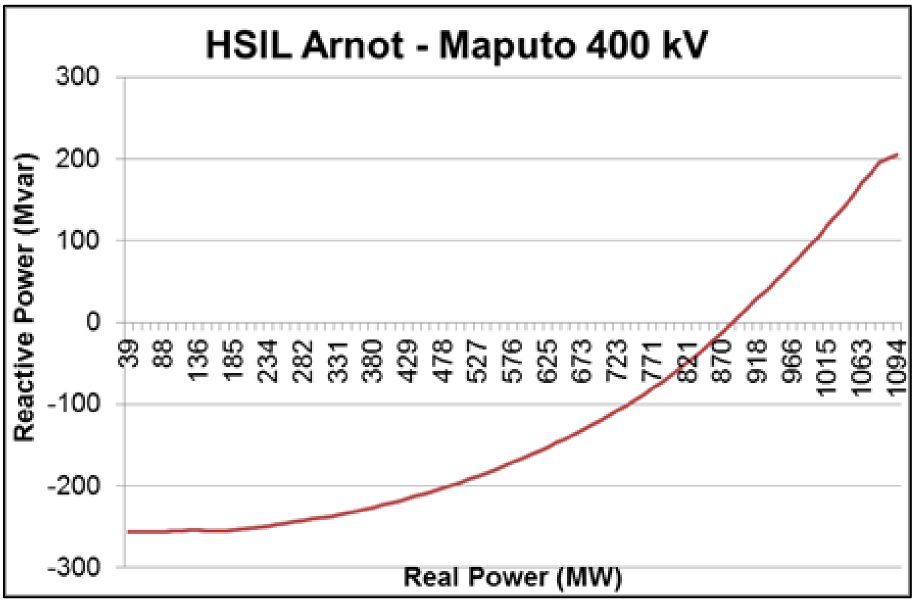

Figure 5-9: QP plot for Case iii

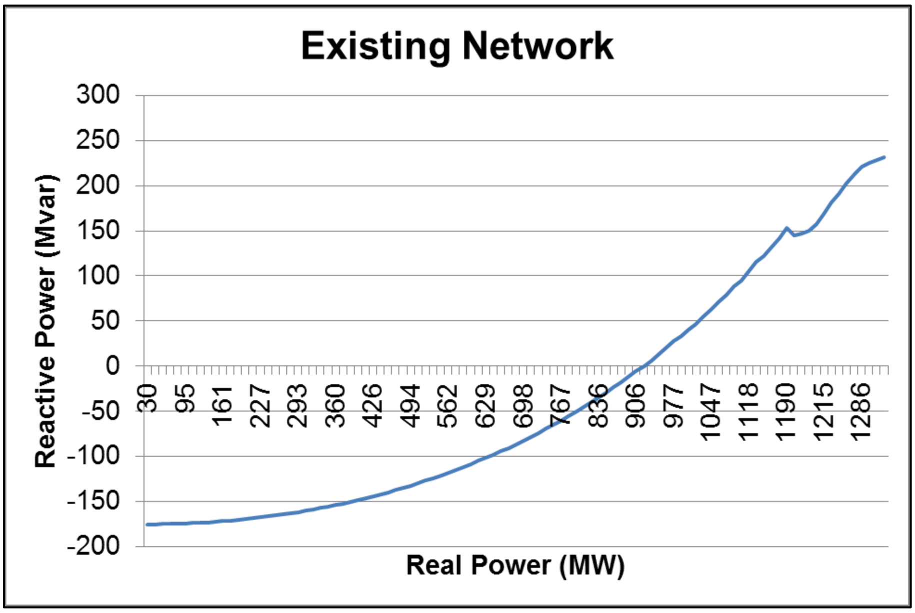

Figure 5-10: QP plot for Case iv

5.8 Series capacitor sizing (optimization of the existing HSIL tower)

The aim of this analysis was to determine if HSIL lines can increase the SIL to levels where the series capacitor can be eliminated. This evaluation is done by combining the HSIL line parameters with the series capacitor. The line parameters are as shown in Table 5-16.

Table 5-16: Parameters for the HSIL line paired with the series capacitor

Series Capacitor (pu x 10^{-2})	R (pu x 10^{-3})	X (pu x 10^{-3})	B (pu)
2.76	2.95	3.56	2.56

The capacitor size is then reduced until voltage levels reached the statutory limit of 0.95 Vpu. Figure 5-11 shows the impact of reducing the series capacitor in conjunction with a 100 MVar shunt line reactor. Figure 5-12 shows the results in conjunction with a 50 MVar shunt line reactor. What is deduced from Figure 5-11 and Table 5-17 is that the series capacitor can be reduced from 0.0276 pu to 0.00165 pu without infringing on the voltage limits of 0.95 Vpu. A capacitor of 0.00165 pu is negligible because it translates to 5.97% of the original capacitor size which is equivalent to 3.25% compensation on the existing Arnot – Maputo 400 kV. Thus the HSIL line does eliminate the need to install the series capacitor. Figure 5-12 and Table 5-18 undoubtedly indicate that the series capacitor can be eliminated when the voltage level is 0.9666 Vpu. As shown in Appendix 2, the cost saving from eliminating the series capacitor is estimated at $ 8 500 000 as per a preliminary quote received from GE. From these results one could conclude that the series capacitor can be removed when a 50 MVar line reactor is used. However this statement cannot be made until the line configuration is tested for Ferranti effect voltages. Ferranti effect is an over-voltage phenomena that occurs when long lines are energized or when lightly loaded and no shunt reactors are present.

Table 5-17: Capacitor sizing with a 100 MVar line reactor

Series Capacitor Size (pu)	**Voltage (V) (pu)**
0.0276	1.000
0.0256	0.999
0.0236	0.997
0.0216	0.994
0.0196	0.991
0.0176	0.987
0.0156	0.982
0.0136	0.977
0.0116	0.972
0.0096	0.969
0.0076	0.963
0.0056	0.958
0.0036	0.957
0.0016	0.951
-0.0003	0.948
-0.0023	0.940
-0.0043	0.936
-0.0063	0.924

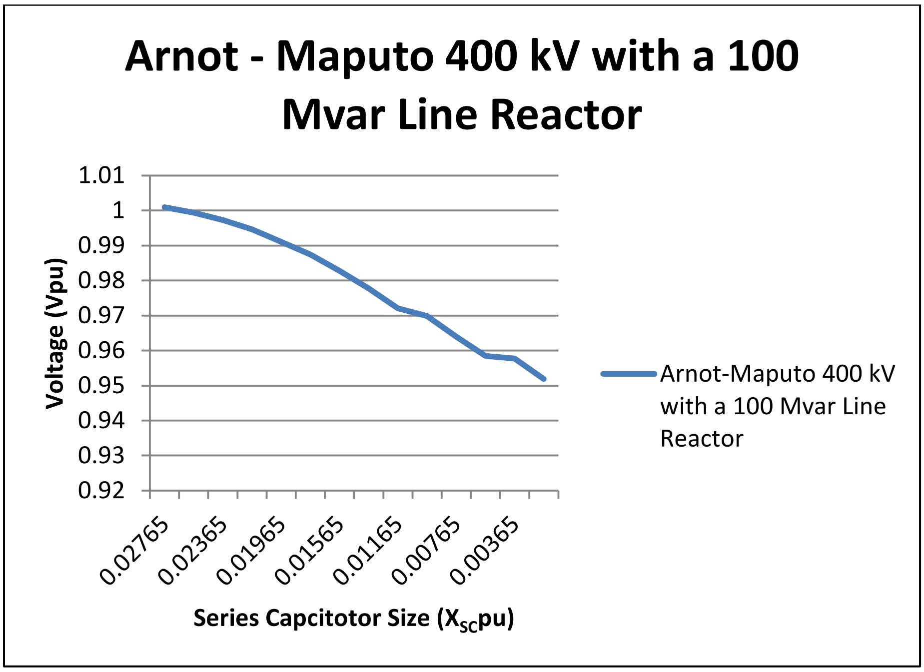

Figure 5-11: Series capacitor sizing with a 100 MVar line reactor

Table 5-18: Series capacitor sizing with a 50 MVar line reactor

Series Capacitor Size (pu)	Voltage (Vpu)
0.0276	1.003
0.0256	1.002
0.0236	1.006
0.0216	1.005
0.0196	1.003
0.0176	1.000
0.0156	0.997
0.0136	0.993
0.0116	0.988
0.0096	0.983
0.0076	0.978
0.0056	0.976
0.0036	0.970
0.0016	0.965
-0.0003	0.966
-0.0023	0.959
-0.0043	0.957
-0.0063	0.949

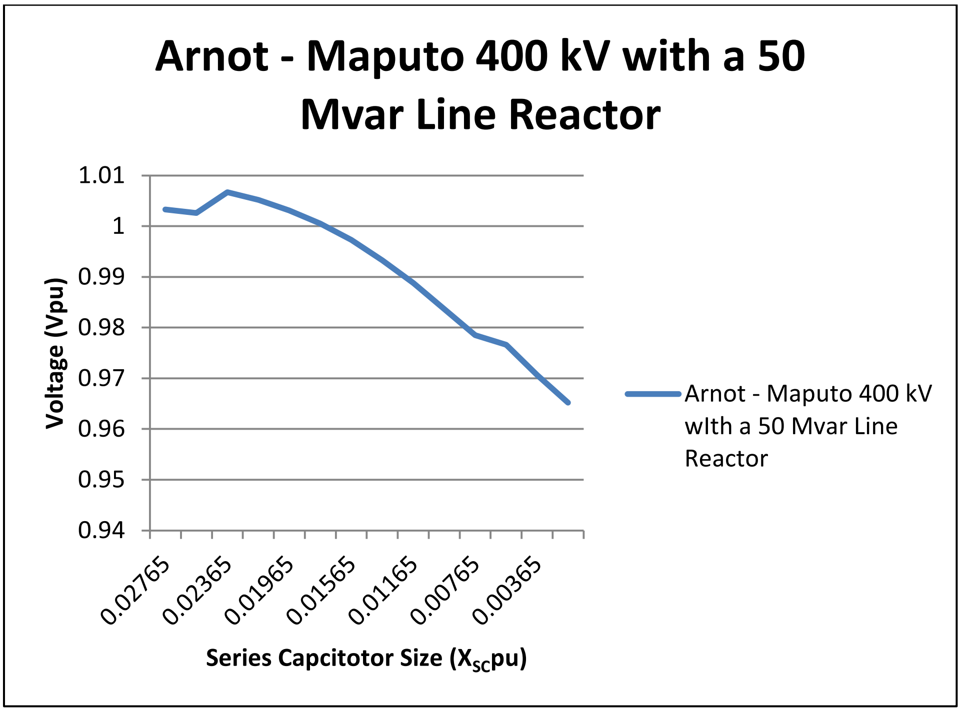

Figure 5-12: Series capacitor bank sizing with a 50 MVar line reactor

5.9 Shunt line reactor sizing (optimization of the existing HSIL tower)

The first phase capacitor sizing simulations were done with the as-built 100 MVar line reactor. The second phase analysis was done with a 50 MVar line reactor. This iteration gives insight into the impact of HSIL on the sizing of line shunt reactors because they form part of shunt compensation on long transmission lines that suffer from Ferranti effect voltages under low load or no load conditions.

The lines were tested for the Ferranti effect and the results shown in Figure 5-13 indicate that the 50 MVar shunt line reactor is not adequate to mitigate Ferranti effect voltages, because the voltage level is 1.07 Vpu during a no-load condition which is above the limit of 1.05 Vpu. Ferranti effect voltages were then checked with a 100 MVar line reactor and as shown in Figure 5-14, the voltage level is exactly the same as the limit of 1.05 Vpu. Thus the existing line reactor cannot be reduced or eliminated.

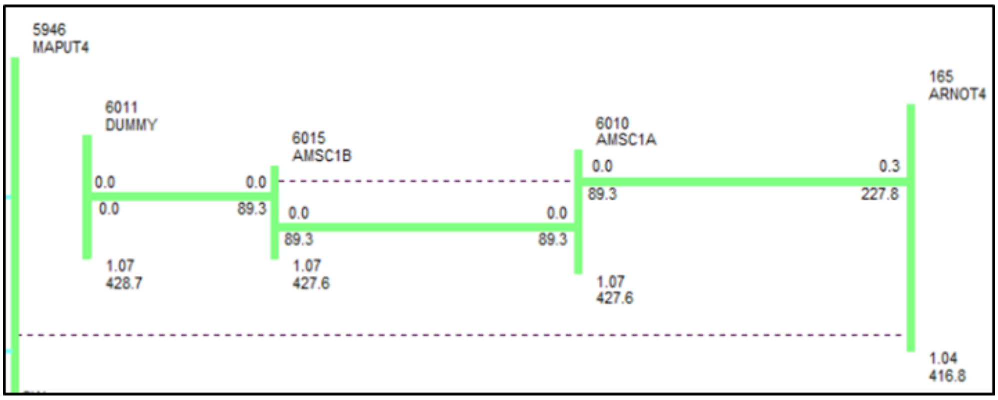

Figure 5-13: Shunt line reactor sizing with a 50 MVar line reactor

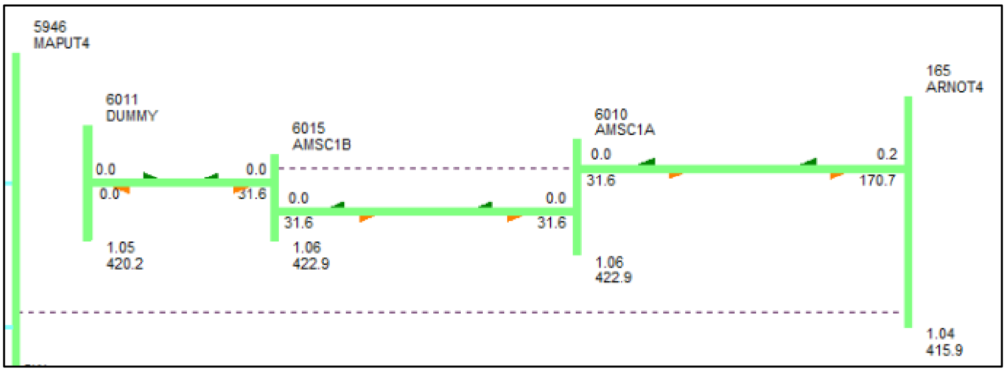

Figure 5-14: Shunt line reactor sizing with a 100 MVar line reactor

6. CONCLUSION AND RECOMMENDATIONS

6.1 Summary

The results indicate that the SIL of power transmission lines can be increased by changing the line’s configuration by applying HSIL methods. HSIL methods do not only reduce series inductive reactance of the line but they also increase the line’s natural shunt capacitive reactance. The increase in the capacitive reactive power leads to excess reactive power that leads to overvoltages / Ferranti effect. To mitigate Ferranti effect voltages the HSIL lines require the installation of line shunt reactors to sink the excess reactive power during no load and light load conditions

HSIL methods are also found to be effective for impedance matching which can be used to achieve improved load sharing in parallel lines and correct mismatches between the planning and designed line parameters.

The advantage of the phase compaction method which results in the horizontal configuration being converted into a perfect inverted delta configuration eliminates the need to transpose the line to aid voltage unbalance because the voltage drop throughout the line is equal between the phases.

6.2 New HSIL configuration – high altitudes (inland)

The conclusion drawn from the results shown in Table 5-1 and Table 5-2 is that a minimum bundle size of 4 x Tern is required in order to implement HSIL methods. The 529A and 528A towers are workable for sub-conductor spacings up to 690 mm while the 518H tower is workable up to 1 000 m when simulated with a 4 x Tern conductor bundle. The sub-conductor spacings of 1 000 mm on the 529A and 528A plus 1 500 mm on all existing towers do not comply with corona and electric field limits. To satisfy corona limits the number of sub-conductors and the phase-to-phase spacing is increased. To satisfy electric field limits the ground clearance is increased. Table 6-1 shows the sub-conductor spacing and phase configurations that are required to comply with the ionizing and non-ionizing limits as observed by Eskom if HSIL methods are considered.

The largest increase in SIL is achieved with case 12k where a combination of increasing the number of sub-conductors in the bundle, compacting the phases and expanding the sub-conductor spacing is implemented. The configuration is as shown in Figure 4.4, where:

- SIL is increased by 36.2%, X is reduced by 29.2% and B is increased by 41.8% when compared with the 1st case in Table 5-1 (3 x Tern on a 517A).
- SIL is increased by 24.8%, X is reduced by 19.92% and B is increased by 24.68% when compared with case 1 in Table 5-2 (4 x Tern on a 518H).

- X is reduced by 29.2%, R is reduced by 30.8% and B is increased by 41.8% when compared to the selected Motraco network that illustrated by Table 4-6 and Figure 4-5.
- R is reduced by 30.8% when compared to the existing Motraco network (Figure 4-5) which results in a 34.5% reduction in line losses and 1.6% reduction in system losses.

Table 6-1: The proposed configuration for implementing HSIL methods.

Case No.	Tower Type	Bundle Separation (mm)	HSIL Technique	SIL (MW)	Phase Spacing (m)	Min Ground Clearance (m)
1st.	517A 3 x Tern	450	Conventional	623.6	8.2	10
1	518H 4 x Tern	450	Conventional	680.7	8.5	10
4o	Modified 518H 4 x Tern	1 500	Expanded bundle	821.4	11	11.0
9	528A 4 x Tern	450	Phase compaction	754.3	7	10.0
12k	Modified 528A 4 x Tern	1 500	Combination of both	849.4	12	11.0

The results shown in Table 5-12 and 5-13 plus Figure 5-4, 5-5 and 5-6 indicate that for the Motraco network (case specific) the HSIL lines are comparable to the installation of a series capacitors under system healthy conditions. A 200 MVar line reactor is required on the Arnot – Maputo 400 kV to reduce the high voltage level of 1.056 Vpu to levels that are above the maximum allowable limit of 1.05 Vpu and are not comparable under contingency conditions (case specific) as they do not meet the load demand for the Motraco network.

6.3 Optimization of the existing HSIL tower

The aim of this investigation was to find an alternative method that is cost effective in increasing the power transfer capability of long transmission lines. To minimize the impact of other line related costs (e.g. servitude, tower steel, etc.) HSIL methods are implemented on the existing 528A compact cross-rope tower.

The HSIL configuration that is recommended from Table 5-7 is a 4 x IEC 450 sub-conductor bundle that has 740 mm as the sub-conductor spacing. The results shown Table 5-15, 5-17 plus 5-18 and Figure 5-9, 5-11 plus 5-12 indicate that the series capacitor that is installed on the existing Arnot – Maputo 400 kV line can be eliminated if the SIL of a line is increased through the use of HSIL methods. This statement is applicable to long transmission lines that supply loads with high load factors and require series capacitors.

The results also indicate that a 100 MVar shunt line reactor that is installed on the existing line is still required to prevent the Ferranti effect voltages during no load and low load conditions, especially when the line is initially energized.

6.4 The impedance matching case study

The results shown in Table 5-9 and 5-10 indicate that a 4 x Tern sub-conductor bundle with 450 mm sub-conductor spacing on the existing 529A tower (highlighted in bold) is the configuration that yields RXB values that match the RXB values that were used when the line was planned. In both phase one and phase two analyses the 4 x Tern with 450 mm sub-conductor spacing on the 529A tower had the least percentage change from the RXB values that were used by the System Planner.

The results indicate that a desired impedance value with the variance of ±5% can be achieved if as many as possible configurations are created between the available conductor types, available conductor sizes, varying the sub-conductor bundle size, varying the sub-conductor spacing, varying the phase-to-phase spacing and varying the phase configuration (flat, horizontal, shallow delta or perfect delta).

The impedance matching concept combined with HSIL methods can also be effective in achieving enhanced load sharing in parallel lines. Especially in cases where the new line is built parallel to an existing line that has series capacitors installed.

6.5 Research results

6.5.1 Summary

The research work was to determine whether an increase in the SIL of a line through the use of HSIL methods can eliminate the need to install series capacitors in Eskom’s long 400 kV lines. The research was conducted in four main phases. The first phase entailed the recommendation of HSIL configurations that meet the ionizing and non-ionizing field effect limits. The second phase entailed the calculation of RXB values and SIL to evaluate if HSIL methods do indeed increase the natural capacity of transmission lines. The third phase consisted of a single line and a network analysis using the RXB values from phase two; this was done to assess the impact of HSIL configurations on the system statutory requirements and system operation. The case study was selected from the existing 400 kV lines that are longer than 200 km and have series capacitors installed. The fourth phase consisted of an impedance matching case study and the main aim was to show that a desired impedance value can be achieved through different combinations of the conductor types, conductor sizes, sub-conductor bundle sizes and phase-to-phase spacing. The impedance matching case study is done to prove that different line configurations can be used to achieve the desired line impedance to improve load sharing on parallel lines and aid mismatches between the designed line parameters and the parameters that are used during the system planning stage.

6.5.2 Answers to the research questions

Question 1: Which HSIL methods are more attractive for increasing the SIL of long lines?

Table 4-2 shows the HSIL methods that are found to be attractive for conditions that prevail in Eskom. The suitable HSIL methods are compacting the phases, increasing the number of sub-conductors in the bundle and expanding the sub-conductor bundle.

Question 2: How sensitive is the electrical performance of a line when HSIL methods are applied?

The results in Table 5-1 and 5-2 indicate that 4 x Tern is the minimum sub-conductor bundle size that is required to implement the three attractive HSIL methods, more especially when a combination of the three HSIL methods is applied at an altitude of 1 800 m. The bundle expansion methods resulted in non-compliance to corona limits and this is alleviated by increasing the phase-to-phase spacing. An increase in the phase-to-phase spacing resulted in a non-compliance in the electric fields limit and this is mitigated by increasing the minimum distance to ground (midspan clearance). HSIL configurations that comply with the electrical performance requirements are case 2, 3, 4o, 6, 7d, 8f, 10, 11d and 12k in Table 5-2, case 4a in Table 5-3 and case 1, 3, 5, 6, 9, 10, 11, 12 and 13 in Table 5-5.

Question 3: How significant is the change in SIL and line parameters when HSIL methods are applied?

Table 5-6, case 4a in Table 5-3 and case 1, 3, 5, 6, 9, 10, 11, 12 and 13 in Table 5-5 show the HSIL configurations that comply with the ionizing and non-ionizing field effects limits. The results in Table 5-6 indicate that the biggest increase in SIL is achieved with a combination of all three HSIL methods. The proposed HSIL configuration is case 12k in Table 5-2 and the proposed geometry is shown in Figure 5-3, where the SIL is increased by 36.20%, series inductive reactance (X) is reduced by 26.56% and B is increased 41.8 % when compared to the conventional 3 x Tern configuration that is used on the selected Motraco network. Case 5 from Table 5-5 also shows that the X is reduced by 26.91% and the SIL is increased by 35.88% and B is increased 34.95%.

Question 4: Can an increase in the SIL of long lines eliminate or reduce the need to install series compensation?

Table 5-15, Figure 5-7 compared with Figure 5-9, Table 5-17 and Table 5-18 indicate that HSIL configurations can replace the installation of series capacitors.

Question 5: What are the effects and benefits of HSIL lines when compared with the traditional existing lines with compensation?

HSIL configurations increase the shunt capacitive susceptance of the line which results in excess reactive power when the HSIL lines are compared to the conventional lines with series compensation. Figure 5-13 and 5-14 indicate that the 100 MVar shunt line reactor that is currently installed on the conventional line with series compensated still needs to be present on the HSIL line.

The benefit of the phase compaction method which results in the conventional horizontal configuration being converted into a perfect inverted delta configuration is that it eliminates the need to transpose the line in order to aid voltage unbalance because the voltage drop throughout the line is equal between phases.

Question 6: How significant is the cost saving if HSIL lines are applied to the selected cases?

Figure 5-11 and 5-12 plus Table 5-17 and 5-18 indicate that the series capacitor bank can be eliminated if the existing HSIL tower (528A) with 7 m as phase-to-phase spacing configured as a perfect inverted delta is optimized by expanding the sub-conductor bundle spacing from 450 mm to 740 mm and 4 x 450 IEC sub-conductor bundle is used instead of Tern conductor. As shown in Appendix 2, the capital cost saving from eliminating the series capacitor bank is estimated at $ 8 500 000 USD as per a preliminary quote received from GE.

Question 7: What is the impact on operational flexibility?

As shown in Section 5.6, Figure 5-13 and 5-14 HSIL configurations result in an increase in capacitive reactive power when compared to the conventional configurations. The excess capacitive reactive power results in voltage levels that are above the statutory limit of ±5% (overvoltage) when the line has no load or is lightly loaded. To mitigate the Ferranti effect voltages, the line shunt reactors that are currently installed on the existing lines still need to be present on the HSIL lines.

7. FUTURE WORK

The following aspects need to be investigated further;

- Mechanical interaction and vibration behavior of expanded bundle symmetrical and asymmetrical bundles.
- The effects of HSIL lines on the zero sequence impedance (switching over voltages) and system protection (settings and protection co-ordination).
- A study of attachment points for the interphase spacers on conductors, so to avoid additional stress that will cause conductor bending and damage.
- Effect of unbalanced winds for conductor swing angle.
- Flashover due to non-synchronous swing on long span.
- Improved load sharing between parallel lines during the system planning phase.
- Challenges with manufacturing hardware.
- Challenges with construction machinery and construction methods.

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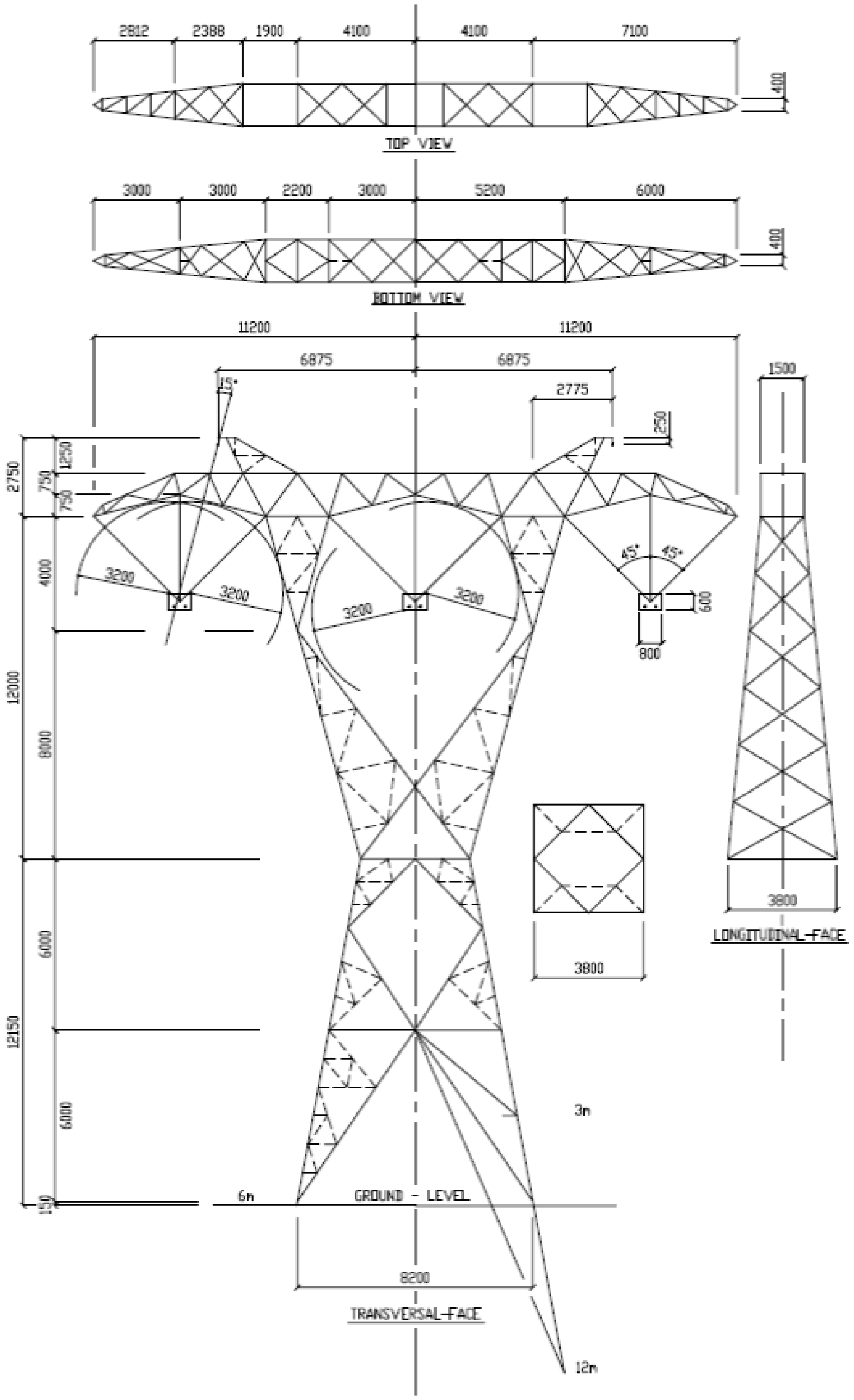
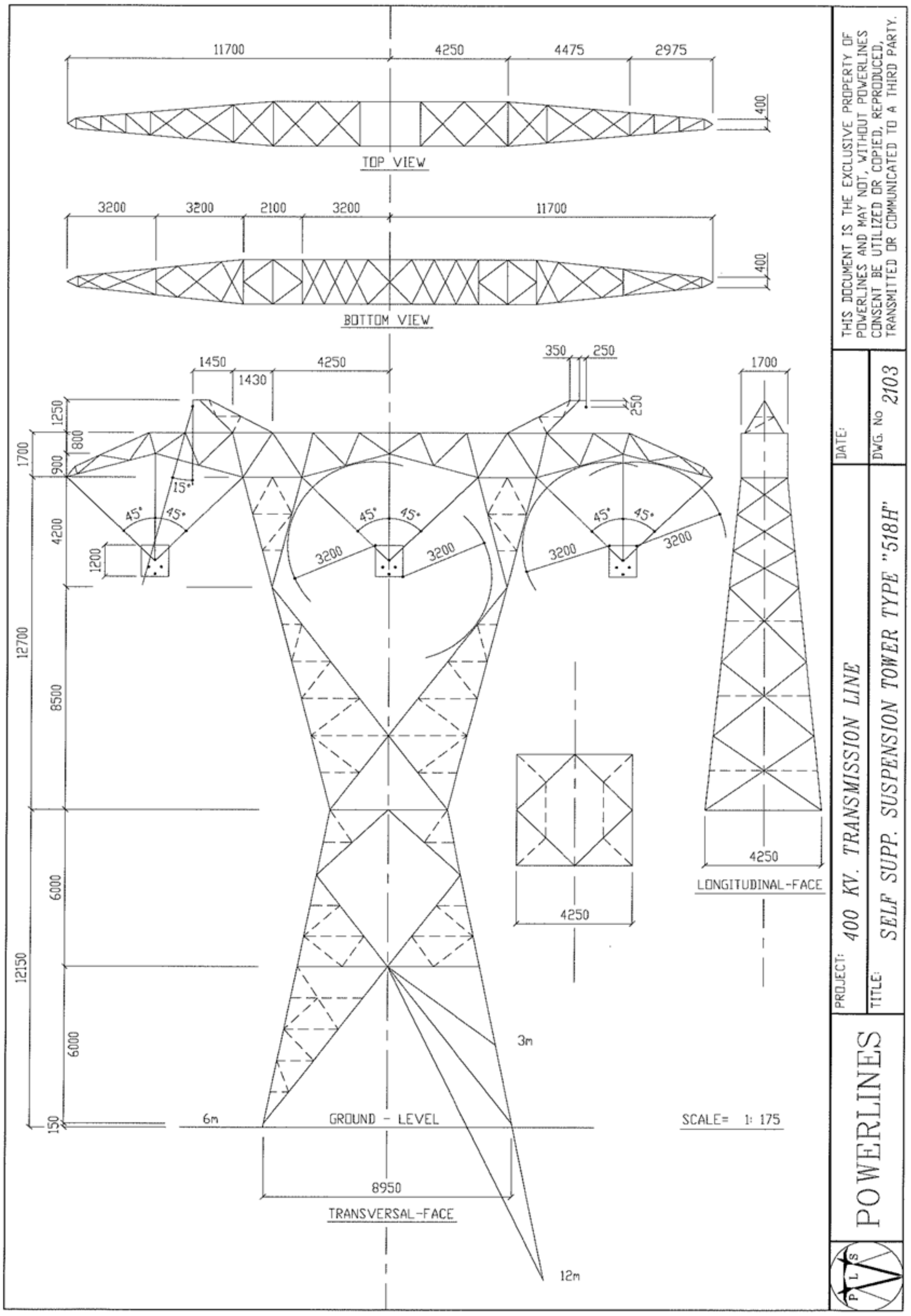
9. APPENDICES

9.1 APPENDX 1 - TOWER OUTLINE DRAWINGS



400 kV TRANSMISSION LINE
SELF SUPP. SUSPENSION TOWER TYPE "517A"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BOTTOM VIEW
TRANSVERSAL-FACE
LONGITUDINAL-FACE
GROUND - LEVEL
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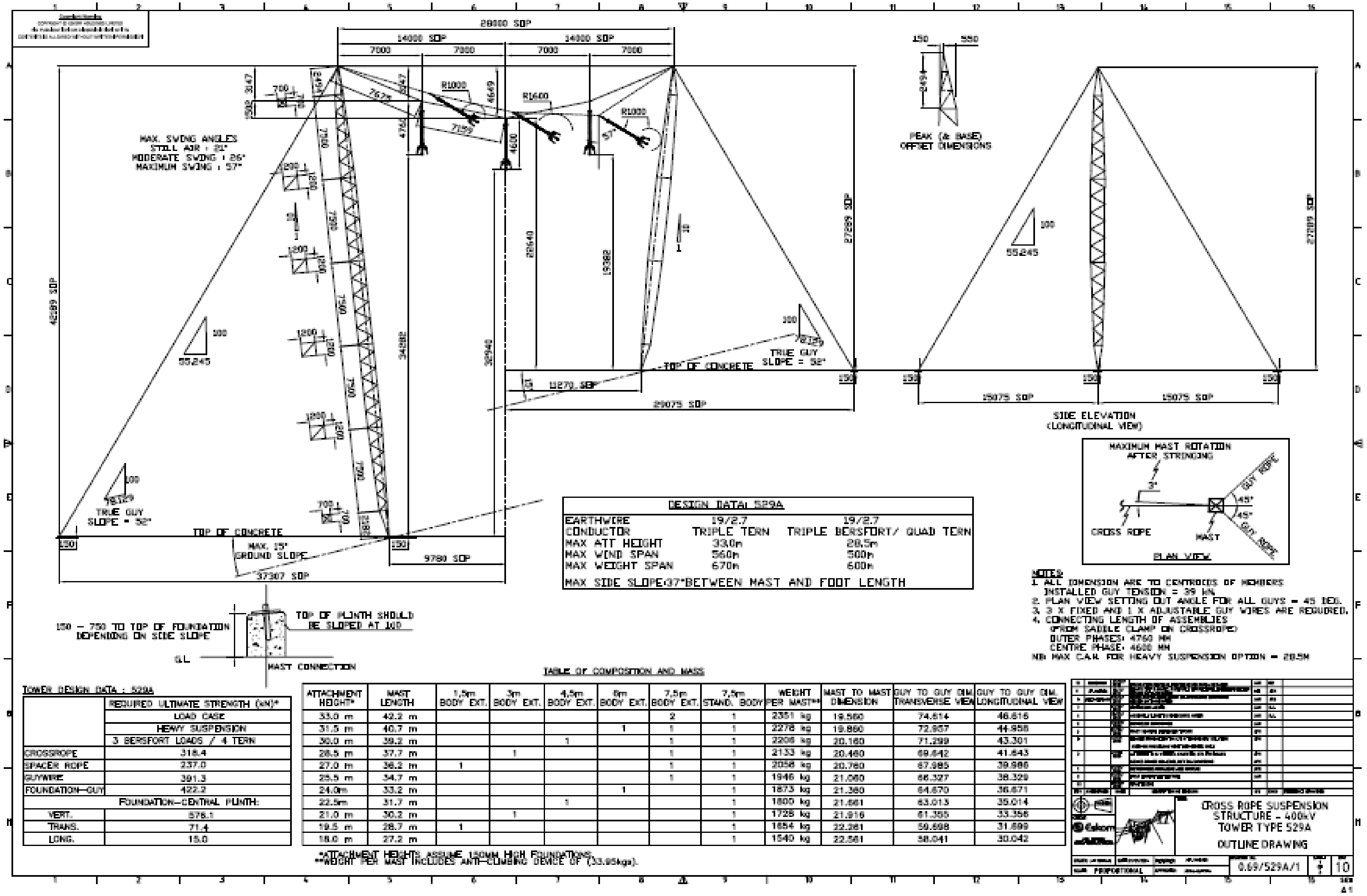


DESIGN DATA: 529A

EARTHWIRE	19/2.7	19/2.7
CONDUCTOR	TRIPLE TERN	TRIPLE BERSFORT/ QUAD TERN
MAX ATT HEIGHT	33.0m	28.5m
MAX WIND SPAN	560m	500m
MAX WEIGHT SPAN	670m	600m

MAX SIDE SLOPE:37°BETWEEN MAST AND FOOT LENGTH

NOTES:
1. ALL DIMENSION ARE TO CENTROIDS OF MEMBERS
INSTALLED GUY TENSION = 39 kN
2. PLAN VIEW SETTING OUT ANGLE FOR ALL GUYS = 45 DEG.
3. 3 X FIXED AND 1 X ADJUSTABLE GUY WIRES ARE REQUIRED.
4. CONNECTING LENGTH OF ASSEMBLIES
(FROM SADDLE CLAMP ON CROSSROPE)
OUTER PHASES: 4760 MM
CENTRE PHASE: 4600 MM
NB: MAX C.A.H. FOR HEAVY SUSPENSION OPTION = 28.5M

TOWER DESIGN DATA : 529A

	REQUIRED ULTIMATE STRENGTH (kN)*
	LOAD CASE
	HEAVY SUSPENSION
	3 BERSFORT LOADS / 4 TERN
CROSSROPE	318.4
SPACER ROPE	237.0
GUYWIRE	391.3
FOUNDATION—GUY	422.2
FOUNDATION—CENTRAL PLINTH:	
VERT.	576.1
TRANS.	71.4
LONG.	15.0

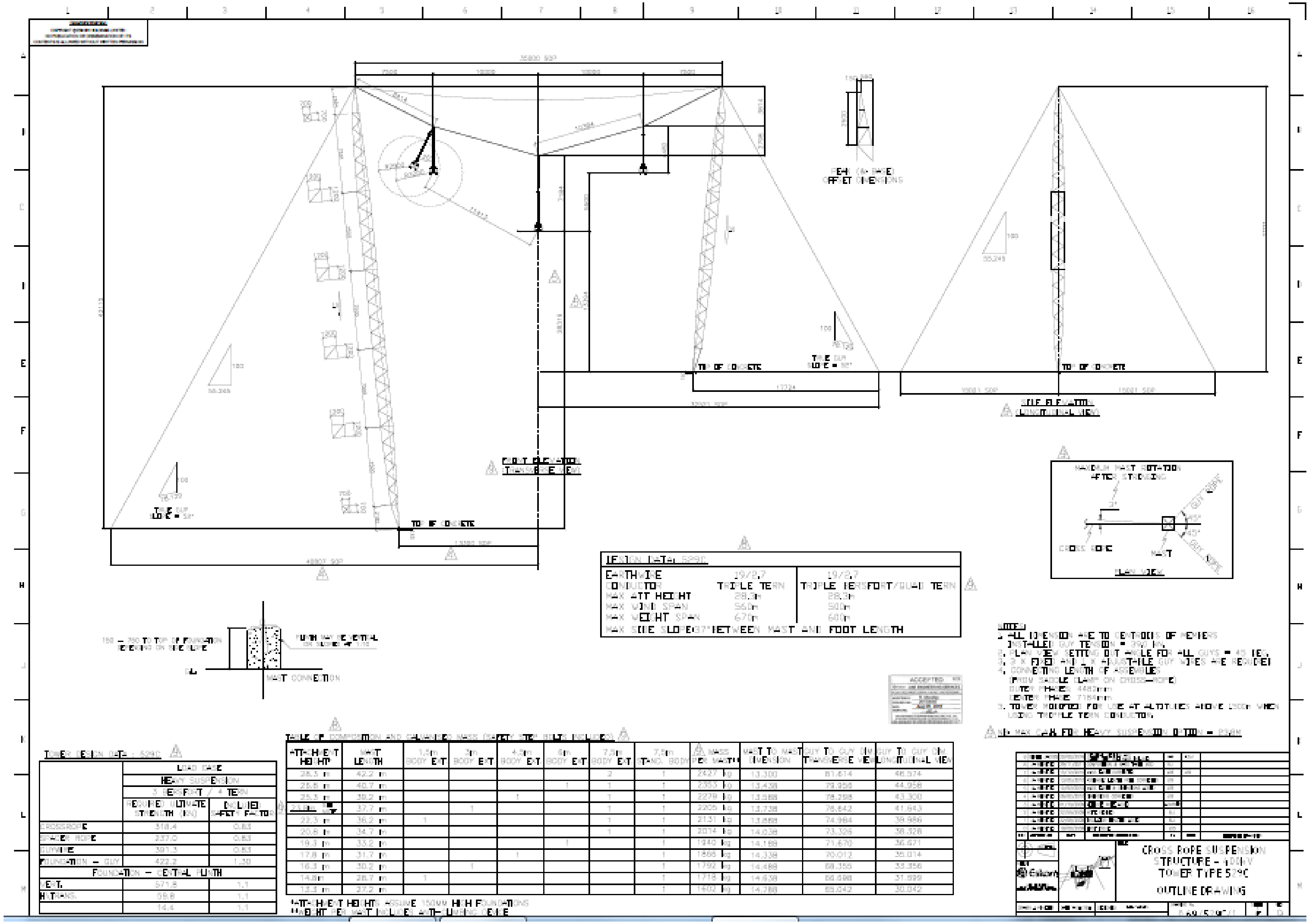
TABLE OF COMPOSITION AND MASS

ATTACHMENT HEIGHT*	MAST LENGTH	1,5m BODY EXT.	3m BODY EXT.	4,5m BODY EXT.	6m BODY EXT.	7,5m BODY EXT.	7,5m STAND. BODY	WEIGHT PER MAST**	MAST TO MAST DIMENSION	GUY TO GUY DIM. TRANSVERSE VIEW	GUY TO GUY DIM. LONGITUDINAL VIEW
33.0 m	42.2 m					2	1	2351 kg	19.560	74.614	46.616
31.5 m	40.7 m				1	1	1	2276 kg	19.860	72.957	44.958
30.0 m	39.2 m			1		1	1	2206 kg	20.160	71.299	43.301
28.5 m	37.7 m		1			1	1	2133 kg	20.460	69.642	41.643
27.0 m	36.2 m	1				1	1	2058 kg	20.760	67.985	39.986
25.5 m	34.7 m					1	1	1946 kg	21.060	66.327	38.329
24.0m	33.2 m				1		1	1873 kg	21.360	64.670	36.671
22.5m	31.7 m			1			1	1800 kg	21.661	63.013	35.014
21.0 m	30.2 m		1				1	1728 kg	21.916	61.355	33.356
19.5 m	28.7 m	1					1	1654 kg	22.261	59.698	31.699
18.0 m	27.2 m						1	1540 kg	22.561	58.041	30.042

*ATTACHMENT HEIGHTS ASSUME 150MM HIGH FOUNDATIONS.
**WEIGHT PER MAST INCLUDES ANTI—CLIMBING DEVICE OF (33.95kgs).

CROSS ROPE SUSPENSION
STRUCTURE - 400kV
TOWER TYPE 529A
OUTLINE DRAWING

0.69/529A/1
10



DESIGN DATA: 529C

EARTHWIRE	19/2.7	19/2.7
CONDUCTOR	TRIPLE TERN	TRIPLE BERSFORT/QUAD TERN
MAX ATT HEIGHT	28.3m	28.3m
MAX WIND SPAN	560m	500m
MAX WEIGHT SPAN	670m	600m

MAX SIDE SLOPE 37° BETWEEN MAST AND FOOT LENGTH

NOTES:
1. ALL DIMENSION ARE TO CENTROIDS OF MEMBERS
INSTALLED GUY TENSION = 390 kN.
2. PLAN VIEW SETTING OUT ANGLE FOR ALL GUYS = 45 DEG.
3. 2 X FIXED AND 1 X ADJUSTABLE GUY WIRES ARE REQUIRED
4. CONNECTING LENGTH OF ASSEMBLIES
(FROM SADDLE CLAMP ON CROSS–ROPE)
OUTER PHASES: 4483mm
CENTER PHASE: 7184mm
5. TOWER MODIFIED FOR USE AT ALTITUDES ABOVE 1300m WHEN USING TRIPPLE TERN CONDUCTOR.

NB: MAX CAH FOR HEAVY SUSPENSION OPTION = 2500M

TOWER DESIGN DATA : 529C

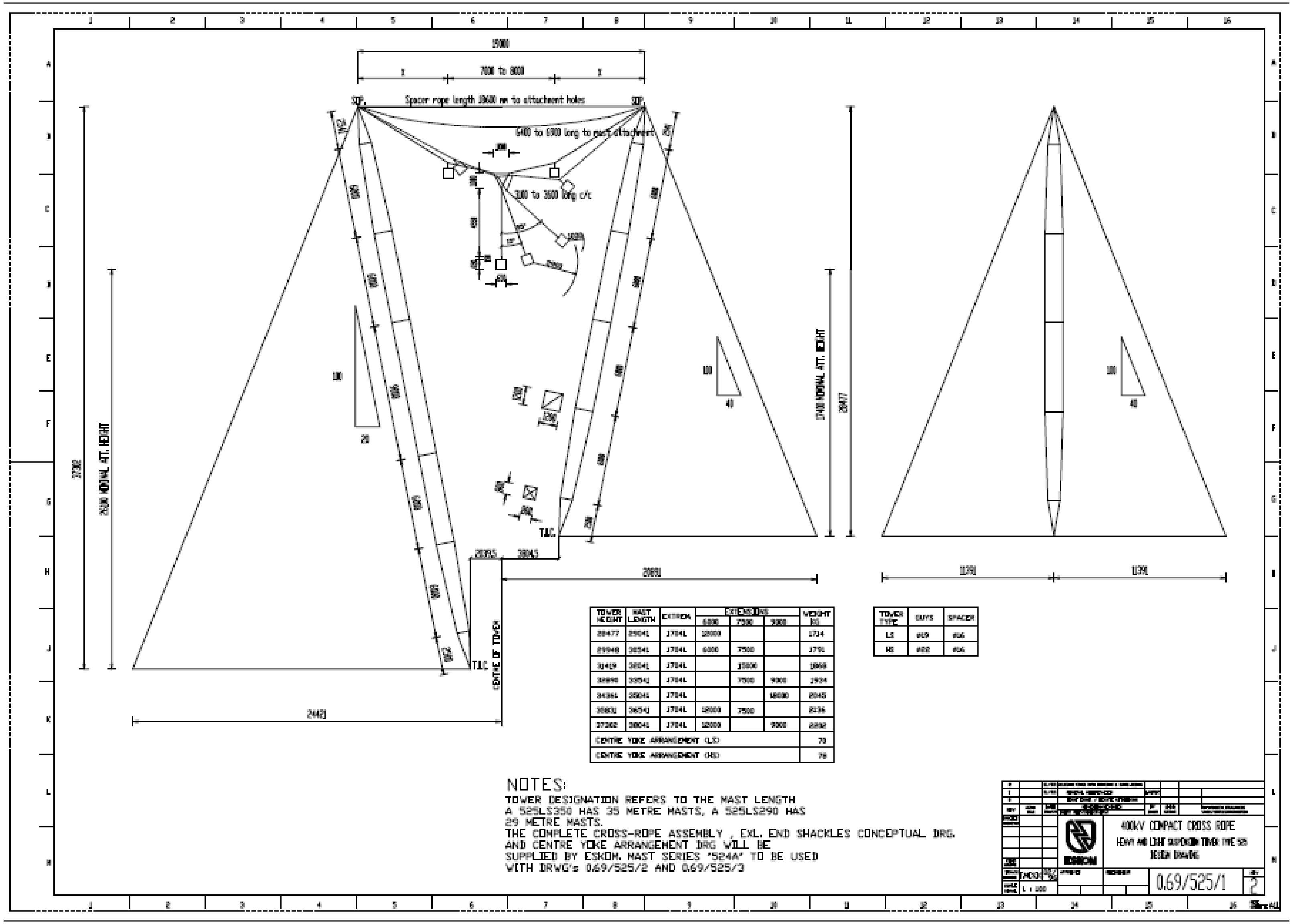
	LOAD CASE	
	HEAVY SUSPENSION	
	3 BERSFORT / 4 TERN	
	REQUIRED ULTIMATE STRENGTH (kN)	INCLUDED SAFETY FACTOR
CROSSROPE	318.4	0.83
SPACER ROPE	237.0	0.83
GUYWIRE	391.3	0.83
FOUNDATION – GUY	422.2	1.30
FOUNDATION – CENTRAL PLINTH		
VERT.	571.8	1.1
H\TRANS.	59.8	1.1
	14.4	1.1

TABLE OF COMPOSITION AND GALVANISED MASS (SAFETY STEP BOLTS INCLUDED)

*ATTACHMENT HEIGHT	MAST LENGTH	1.5m BODY EXT	3m BODY EXT	4.5m BODY EXT	6m BODY EXT	7.5m BODY EXT	7.5m STAND. BODY	MASS PER MAST**	MAST TO MAST DIMENSION	GUY TO GUY DIM TRANSVERSE VIEW	GUY TO GUY DIM LONGITUDINAL VIEW
28.3 m	42.2 m					2	1	2427 kg	13.300	81.614	46.574
26.8 m	40.7 m				1	1	1	2353 kg	13.438	79.956	44.958
25.3 m	39.2 m			1		1	1	2279 kg	13.588	78.298	43.300
23.8m	37.7 m		1			1	1	2205 kg	13.738	76.642	41.643
22.3 m	36.2 m	1				1	1	2131 kg	13.888	74.984	39.986
20.8 m	34.7 m					1	1	2014 kg	14.038	73.326	38.328
19.3 m	33.2 m				1		1	1940 kg	14.188	71.670	36.671
17.8 m	31.7 m			1			1	1866 kg	14.338	70.012	35.014
16.3 m	30.2 m		1				1	1792 kg	14.488	68.355	33.356
14.8m	28.7 m	1					1	1718 kg	14.638	66.698	31.699
13.3 m	27.2 m						1	1602 kg	14.788	65.042	30.042

*ATTACHMENT HEIGHTS ASSUME 150MM HIGH FOUNDATIONS
**WEIGHT PER MAST INCLUDES ANTI-CLIMBING DEVICE

CROSS ROPE SUSPENSION
STRUCTURE – 400kV
TOWER TYPE 529C
OUTLINE DRAWING



TOWER HEIGHT	MAST LENGTH	EXTREMA	EXTENSIONS			WEIGHT (KG)
			6000	7500	9000	
28477	29041	1704L	12000			1714
29948	30541	1704L	6000	7500		1791
31419	32041	1704L		15000		1868
32890	33541	1704L		7500	9000	1934
34361	35041	1704L			18000	2045
35831	36541	1704L	12000	7500		2136
37302	38041	1704L	12000		9000	2202
CENTRE YOKE ARRANGEMENT (LS)						73
CENTRE YOKE ARRANGEMENT (HS)						78

TOWER TYPE	GUYS	SPACER
LS	#19	#66
HS	#22	#66

NOTES:
TOWER DESIGNATION REFERS TO THE MAST LENGTH
A 525LS350 HAS 35 METRE MASTS, A 525LS290 HAS
29 METRE MASTS.
THE COMPLETE CROSS-ROPE ASSEMBLY , EXL. END SHACKLES CONCEPTUAL DRG.
AND CENTRE YOKE ARRANGEMENT DRG WILL BE
SUPPLIED BY ESKOM. MAST SERIES "524A" TO BE USED
WITH DRWG's 0.69/525/2 AND 0.69/525/3

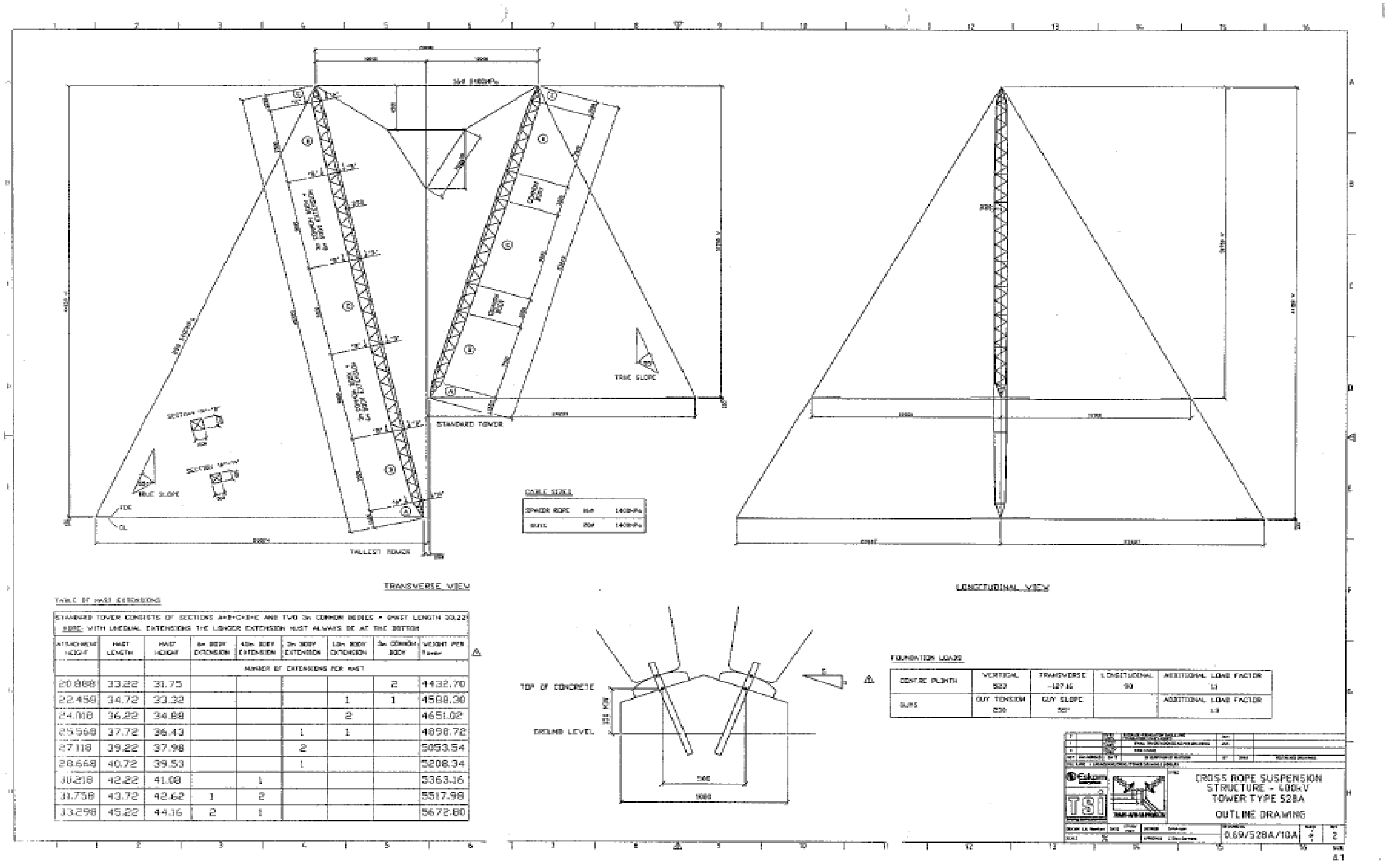


TABLE OF MAST EXTENSIONS

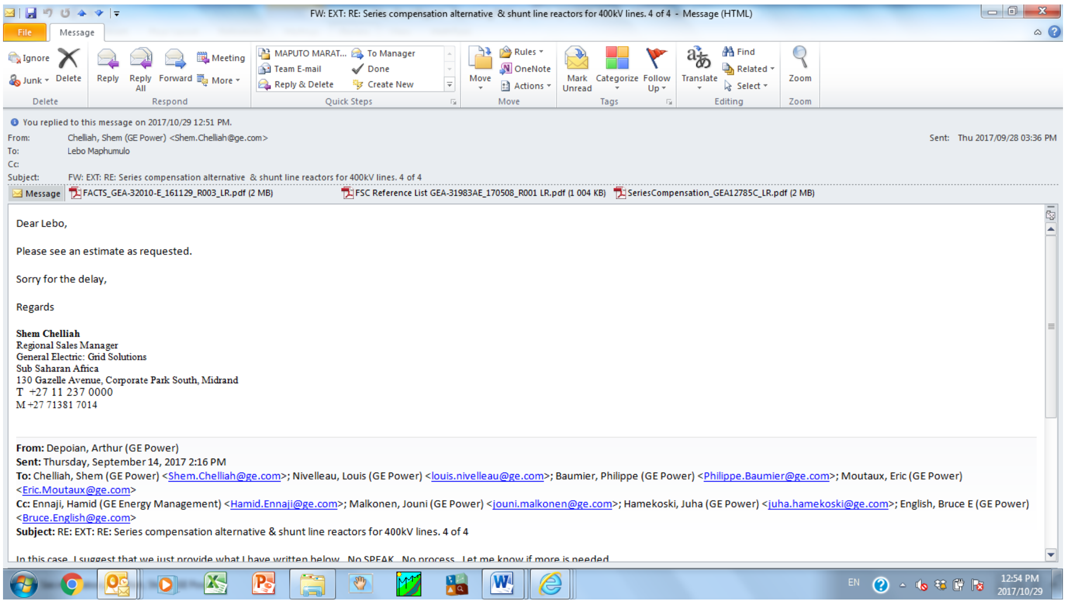
STANDARD TOWER CONSISTS OF SECTIONS A+B+C+B+C AND TWO 3m COMMON BODIES = MAST LENGTH 33.22
NOTE: WITH UNEQUAL EXTENSIONS THE LONGER EXTENSION MUST ALWAYS BE AT THE BOTTOM

ATTACHMENT HEIGHT	MAST LENGTH	MAST HEIGHT	6m BODY EXTENSION	4.5m BODY EXTENSION	3m BODY EXTENSION	1.5m BODY EXTENSION	3m COMMON BODY	WEIGHT PER Tower
			NUMBER OF EXTENSIONS PER MAST					
20.888	33.22	31.75					2	4432.70
22.458	34.72	33.32				1	1	4588.30
24.008	36.22	34.88				2		4651.02
25.568	37.72	36.43			1	1		4898.72
27.118	39.22	37.98			2			5053.54
28.668	40.72	39.53			1			5208.34
30.218	42.22	41.08		1				5363.16
31.758	43.72	42.62	1	2				5517.98
33.298	45.22	44.16	2	1				5672.80

FOUNDATION LOADS

CENTRE PLINTH	VERTICAL 520	TRANSVERSE -127.15	LONGITUDINAL 90	ADDITIONAL LOAD FACTOR 1.1
GUYS	GUY TENSION 230	GUY SLOPE 58°		ADDITIONAL LOAD FACTOR 1.3

9.2 APPENDIX 2 – SERIES CAPACITOR COST ESTIMATION



You replied to this message on 2017/10/29 12:51 PM.

From: Chelliah, Shem (GE Power) <Shem.Chelliah@ge.com>
Sent: Thu 2017/09/28 03:36 PM
To: Lebo Maphumulo
Cc:
Subject: FW: EXT: RE: Series compensation alternative & shunt line reactors for 400kV lines. 4 of 4

Message | FACTS_GEA-32010-E_161129_R003_LR.pdf (2 MB) | FSC Reference List GEA-31983AE_170508_R001 LR.pdf (1 004 KB) | SeriesCompensation_GEA12785C_LR.pdf (2 MB)

Dear Lebo,

Please see an estimate as requested.

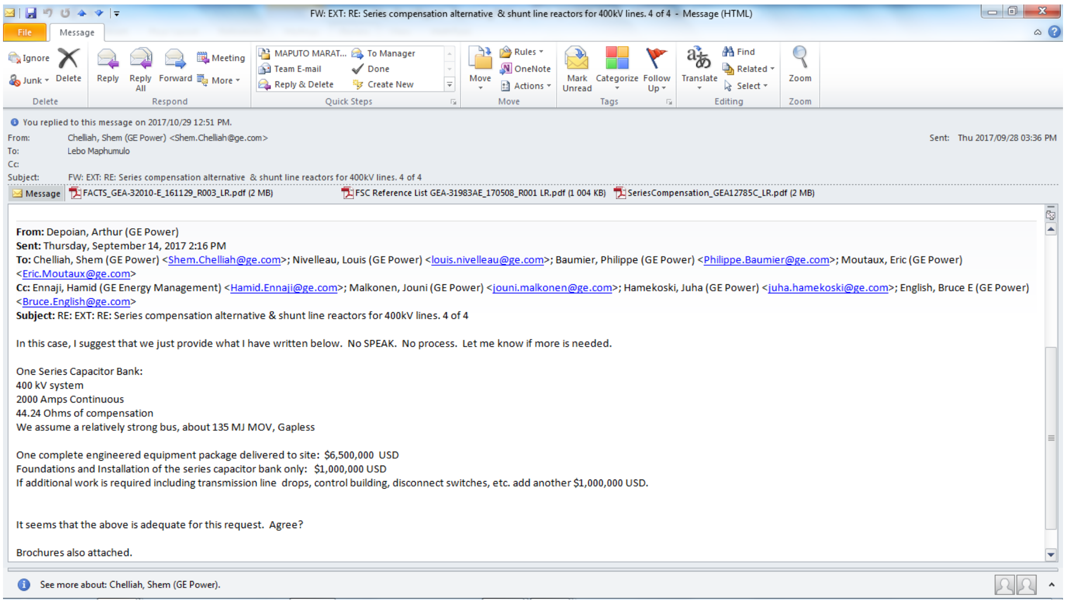
Sorry for the delay,

Regards

Shem Chelliah
Regional Sales Manager
General Electric: Grid Solutions
Sub Saharan Africa
130 Gazelle Avenue, Corporate Park South, Midrand
T +27 11 237 0000
M +27 71381 7014

From: Depoian, Arthur (GE Power)
Sent: Thursday, September 14, 2017 2:16 PM
To: Chelliah, Shem (GE Power) <Shem.Chelliah@ge.com>; Nivelleau, Louis (GE Power) <louis.nivelleau@ge.com>; Baumier, Philippe (GE Power) <Philippe.Baumier@ge.com>; Moutaux, Eric (GE Power) <Eric.Moutaux@ge.com>
Cc: Ennaji, Hamid (GE Energy Management) <Hamid.Ennaji@ge.com>; Malkonen, Jouni (GE Power) <jouni.malkonen@ge.com>; Hamekoski, Juha (GE Power) <juha.hamekoski@ge.com>; English, Bruce E (GE Power) <Bruce.English@ge.com>
Subject: RE: EXT: RE: Series compensation alternative & shunt line reactors for 400kV lines. 4 of 4

In this case, I suggest that we just provide what I have written below. No SPEAK. No process. Let me know if more is needed.



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Message | FACTS_GEA-32010-E_161129_R003_LR.pdf (2 MB) | FSC Reference List GEA-31983AE_170508_R001 LR.pdf (1 004 KB) | SeriesCompensation_GEA12785C_LR.pdf (2 MB)

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Sent: Thursday, September 14, 2017 2:16 PM
To: Chelliah, Shem (GE Power) <Shem.Chelliah@ge.com>; Nivelleau, Louis (GE Power) <louis.nivelleau@ge.com>; Baumier, Philippe (GE Power) <Philippe.Baumier@ge.com>; Moutaux, Eric (GE Power) <Eric.Moutaux@ge.com>
Cc: Ennaji, Hamid (GE Energy Management) <Hamid.Ennaji@ge.com>; Malkonen, Jouni (GE Power) <jouni.malkonen@ge.com>; Hamekoski, Juha (GE Power) <juha.hamekoski@ge.com>; English, Bruce E (GE Power) <Bruce.English@ge.com>
Subject: RE: EXT: RE: Series compensation alternative & shunt line reactors for 400kV lines. 4 of 4

In this case, I suggest that we just provide what I have written below. No SPEAK. No process. Let me know if more is needed.

One Series Capacitor Bank:
400 kV system
2000 Amps Continuous
44.24 Ohms of compensation
We assume a relatively strong bus, about 135 MJ MOV, Gapless

One complete engineered equipment package delivered to site: $6,500,000 USD
Foundations and Installation of the series capacitor bank only: $1,000,000 USD
If additional work is required including transmission line drops, control building, disconnect switches, etc. add another $1,000,000 USD.

It seems that the above is adequate for this request. Agree?

Brochures also attached.

See more about: Chelliah, Shem (GE Power).

Dear Lebo,

Please see an estimate as requested.

Sorry for the delay,

Regards

Shem Chelliah
Regional Sales Manager

General Electric: Grid Solutions

Sub Saharan Africa

130 Gazelle Avenue, Corporate Park South, Midrand
T +27 11 237 0000
M +27 71381 7014

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Art