# INVESTIGATIONS INTO THE UPGRADING OF TRANSMISSION LINES FROM HVAC TO HVDC


**by**

**Pathmanathan Naidoo**
**(BEng Electrical, MBA, PrEng**
**SMIEEE, SMSAIEE, MIET)**

**Student Registration Number: 861864146**


A thesis submitted in fulfillment of the requirements for the degree

of

**Master of Science in Electrical Engineering**

in the


School of Electrical, Electronic and Computer Engineering
Faculty of Engineering
University of KwaZulu-Natal
South Africa


Date of Submission: September 2007

Supervisors

Professor N. M. Ijumba (PhD, PrEng, CEng)
Dr. D. Muftic (PrEng)

# Abstract

Emanating from the proceedings of CIGRE 2004, a new idea for higher power transmission by recycling and up rating high voltage alternating current transmission lines for high voltage direct current application was presented at the HVDC working group session. To date, there is no known application of the idea. Globally, transmission congestion, power transfer bottlenecks with restricted and limited power transfers and unobtainable servitudes challenge electric power utilities. The literature review shows that since the early sixties, several authors have studied this proposal. However, no applications were done. Admittedly, early HVDC technology was troubled by problems with multi-terminal designs, external insulation breakdown in the presence of DC stress and mercury valve rectifiers struggled with arc backs. To date, power electronic and external insulation technology has grown and matured for confident application both in point to point and multi-terminal application. The economic costs of introducing the DC technology are also more affordable given reducing prices due to higher volume of purchases.

With promising developments in insulation and power electronic technology and driven by South Africa's surging growth in the consumption of electrical energy; the subject of upgrading HVAC transmission for HVDC application is revisited. For the research, the emphasis is beyond FACTS and towards a solution that could develop into a new supergrid that could overlay the existing national grid. Thus, the solution is prepared specifically for the case of recycling existing assets for higher power transfers. The working environment is defined by the difficulty in acquiring new powerline servitudes, transmission congestion in complex networks, the need for electrical islands within complex interconnections, and the need for enhanced power system stability and to promote new ancillary services energy management.

The focus of this research study was to determine the technical feasibility of upgrading of existing HVAC circuits for HVDC application. It is assumed that the transmission line will remain as is in structure, layout and mechanical design. The changing of external line insulators using live line technology is an accepted modification to the original HVAC line, if required.

From the study, we conclude that not all HVAC lines are recommended for upgrade to HVDC. We introduce boundary conditions as a first step towards checking on the suitability of the proposed upgrade from HVAC to HVDC mode. Emanating from this study, the first paper published introduced the initial boundary conditions as being only those lines where the "unused gap" between surge impedance loading and conductor current carrying capability is appreciable and large; generally three to four times surge impedance loading.

In the case where the unused gap is the smallest or negligible, then we do nothing. In between, where the unused gap is about two to three times the surge impedance loading, then we can consider active or passive compensation using the HVAC FACTS technology options as proposed by EPRI.

Having determined the candidate transmission line configuration for the proposed upgrade to HVDC application, we select the DC operating voltage as based on the voltage withstand capability of external insulation for varying environmental conditions. In addition, the DC voltage will generate allowable electrical fields and corona effects within and outside the transmission servitude. The optimum DC operating voltage would satisfy the conditions of minimum transmission power losses and volt drop for the case of maximum power transfers; within the limits of electrical fields and corona effects.

## Declaration

The research work presented in this submission is my own work. The study was conducted full time in 2005, 2006 and 2007. Three papers were peer reviewed, presented to international conferences and published in the conference proceedings. The co-authors included my supervisors and work colleagues who contributed to the study.

PNaidoo

Signed: P Naidoo

Date: 1 September 2007

## Acknowledgement

The creative idea emanated from the student participation at the B4 Study Committee proceedings of CIGRE 2004, held in Paris, France. The initial idea was delivered by Mr. Lionel Barthold and involved the upgrade of a three phase alternating current transmission line to that of a tripole for direct current application. Mr. Barthold's advice and assistance in the research work is greatly appreciated and acknowledged.

The support of my direct supervisors Professor Nelson Ijumba, Adjunct Professor Tony (A C) Britten and Dr Dzevad Muftic is much appreciated. The continuous encouragement from the numerous technical discussions with mentors Dr Adel Hammad, Dr Ani Gole, Dr Teddy Puttgen, Dr Andy Eriksson, Dr Ron Harley, Dr Pregarasen Pillay, Dr Ram Adapa, Dr Aty Edris, Dr Norman Macleod, Dr Gunnar Aspin, Mr Peter Lips, Mr Dennis Woodford and Dr Dido Diseko has provided confidence that the technology and the application thereof is now mature. The comments and contributions from original equipment manufacturers, the laboratory and administrative staff of the UKZN HVDC Centre and fellow students and work colleagues are acknowledged. With time, selected universal application will follow. The added HVDC converter technology at sending and receiving ends is considered a black box in this research assignment.

P. Naidoo

# Abbreviations

| | |
|---|---|
| AC | Alternating Current |
| AGC | Automatic Generation Control |
| BPC | Botswana Power Corporation |
| CCCC | Conductor Current Carrying Capability |
| CIGRE | International Council on Large Electric Systems |
| DC | Direct Current |
| EHVAC | Extra High Voltage Alternating Current |
| EHVDC | Extra High Voltage Direct Current |
| ENE | Empresa Nacional de Electricidade of Angola |
| EPDM | Ethylene propylene diene monomer |
| ESKOM | Eskom Holdings LTD. Of South Africa |
| FACTS | Flexible Alternating Current Transmission Systems |
| HVAC | High Voltage Alternating Current |
| HVDC | High Voltage Direct Current |
| MOTRACO | Mozambique Transmission Company |
| MTTF | Mean Time to Failure |
| MTTR | Mean Time to Repair |
| NAMPOWER | Namibia Power Corporation |
| SIL | Surge Impedance Loading |
| SNEL | Societe Nationale D Electricite of Democratic Republic of Congo |
| UHVAC | Ultra High Voltage Alternating Current |
| UHVDC | Ultra High Voltage Direct Current |
| UPTG | Unused power transfer gap between CCCC and SIL |
| Uprating | Uprating of a transmission line is the increase in its transmission capacity |
| Upgrading | Upgrading of a transmission line means improvement of its structural reliability |
| | [Uprating and Upgrading definitions proposed by Cigre WG B2.06] |
| WESTCOR | Western Power Corridor |

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# Chapter 1: Introduction

## 1. 1 Background

Uncompensated high voltage power transmission is most inefficient, as most of the installed conductor current carrying capability remains unutilized. The conductor generally forms the largest material cost contributor for any power line. To overcome the constraints of alternating current technologies, flexible alternating current technology systems (FACTS) were introduced as compensation. Given the number of alternating current circuits in service world wide; the number of FACTS devices deployed is negligible. There either exists ignorance or reluctance to employment or alternatively performance experiences have not been favourable or the technology is in its early introductory phase and usage would grow with time. For the moment, large volumes of conductors deployed on the various transmission lines remain unemployed. Hence, the study investigation proposal is to go beyond FACTS, to select the most under-utilised transmission lines for recycle and upgrade for HVDC application. With the introduction of HVDC, some of the positive gains include higher point to point power transfers, increased asset efficiency, lower power losses, enhanced interconnected power system transient and dynamic stability. These substantial gains and benefits are realised without any new lines or new servitudes or compensators. The higher power transfers and power loss savings would greatly support the additional costs of the DC rectifiers and inverters; which in itself by virtue of increasing volumes installed, is now more affordable at lower prices [1].

The strategy is to up rate and convert an existing HVAC circuit to an HVDC circuit so as to yield greater power transfer by fully utilising the installed phase conductor current carrying capability was shared and discussed by the members of the CIGRE Study Committee B4, at the 2004 proceedings of CIGRE held in Paris, France [2]. Here the study committee working group members reported on the tri-pole proposal of reconfiguring a three-phase transmission line for two-pole DC application. One phase of the conventional AC line is configured as the positive pole, another phase as the negative pole and the remaining third phase to be periodically swapped between positive and negative poles; to yield almost 2,5 times the power transfer capability of the conventional HVAC line. The schematic diagram of the proposal is given in figure 1-1.

The common understanding is that under direct current application, the alternating current skin effect of the conductor reduces to zero. The only resistance to current flow is the phase conductor DC series resistance. This benefit is further supported by the absence of alternating current line charging and inductive voltage drop effects. The compound result is lower transmission losses, higher power transfers and lower voltage drops for longer distance transmission [3].

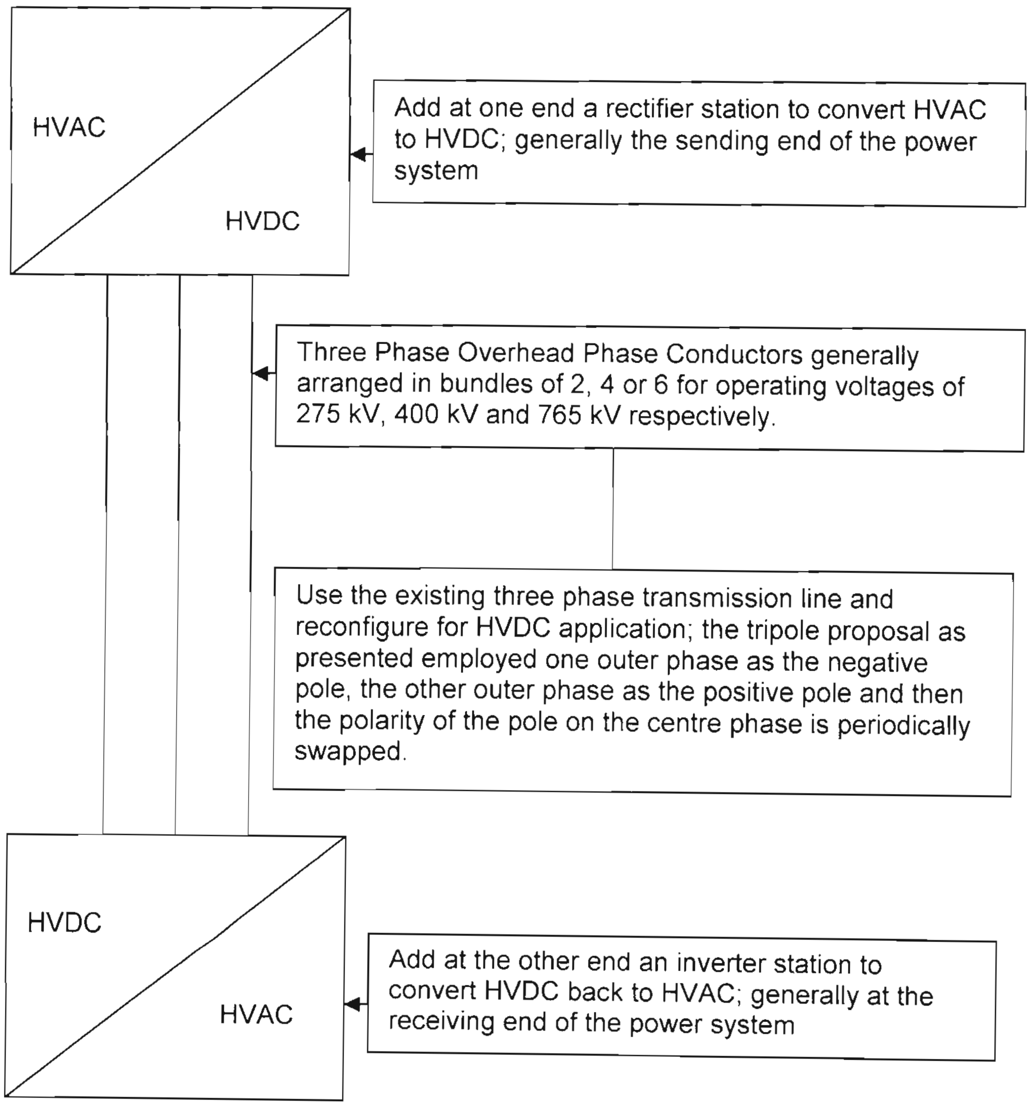


**Figure 1-1: Schematic of the Proposal for the Study Thesis**

Even this idea at CIGRE 2004 was not a new proposal. As early as 1966, Kennedy [4] presented his findings to the first International IEE HVDC Conference held at the University of

Manchester. Kennedy showed that for the upgrade from AC to DC, the break even power level for recycling AC to DC is largely a function of DC terminal costs and AC line costs. The subject of DC reliability was not discussed as Kennedy had inadequate reliability data from the few commissioned DC schemes. A summary of HVDC schemes commissioned from 1954 to date is given in Appendix A.

At the same meeting, Smedsfelt et al [5], reported on the operational performance and service experience with the Konti-Skan and Gotland HVDC projects and Gunn [6] reported on the commissioning and early operating experience with the New Zealand HVDC Inter-Island transmission scheme. Both papers noted that external insulation failures and valve arc backs have been experienced. The great majority of arc backs occurred on starting up valve groups. The first constraint to HVDC application was the poor performance of the technology; hence the reluctance to convert HVAC to HVDC.

Over the last two decades, much progress occurred on improving the power electronic technology. In a 1990 publication, K.R. Padiyar [7], reported on the step change in power electronic valve reliability when the technology progressed from mercury arc valves to that of thyristor valves. One of the first thyristor valves were commissioned on the Cahora Bassa – Apollo scheme in Southern Africa. To date, these thyristor valves continue to operate and excellent performance is sustained. In 2003, ABB special publication on the Three Gorges project [8] reported on the commissioning of the Three Gorges – Changzhou project. This 3000 MW bipole of 890km operating at +/- 500 kV cost US$ 340 m to build. Six more similar schemes are scheduled at Three Gorges to evacuate the 22,4 GW of hydro generation. A latest development from China is that China Southern is now constructing the first extra high voltage DC transmission system at 800 kV [8].

For the case of external insulation, the material technology has progressed from standard glass discs to that of composite silicone rubber technology. The silicone rubber has the hydrophobic capability that attenuates leakage current development during the wetting of polluted surfaces. Several HVDC circuits have been fitted with this new technology insulation. From in service operating experience, both material and circuits have returned excellent performance for some two-decade under AC stress and some one-decade under DC stress.

To date, the common issues of DC unreliability have been addressed. For all practical purposes, a DC scheme will be of equal to or higher than equivalent performance to that of an AC scheme. The comparison of performance between HVAC and HVDC technology is provided in Appendix B, primarily for the case of Eskom South Africa but supported with some international data from CIGRE Study Committee Proceedings. The power electronic technology has progressed even further and voltage source converters based on integrated gate bipolar transistor (IGBT) technology is now available for transmitting about 700 MW at voltages as high as 900 kV [1]. The HVDC schemes are now affordable and comparable to that of the HVAC design [1].

With present day economic and performance factors favouring HVDC, the idea to investigate HVAC upgrade to HVDC has merit. The key motivation remains the massive step change in point to point power transfers that can be achieved. This is all based on employing the unused installed phase conductor current carrying capability. The additional costs involve the end stations (rectifier and inverter) and possibly re-insulation of the phase conductors of the transmission line. In the final power system planning decision, the alternatives would need to be economically weighed. The objective of this study is to determine how the existing transmission line could be reconfigured from HVAC technology to that of HVDC application whilst retaining full structural integrity.

## 1.2 Study Objective

With specific reference to South and Southern Africa, we note the surge in energy consumption that is following the economic renaissance of the Southern African Development Community, the African Union and ultimately continental Africa [9]. The healthy economic growth is spurred by the improving state of nations in the Southern African Development Community. The positive growth is further compounded by erosion in Eskom's excess generation capacity and new generating and transmission capacity expansion plans are required. The maximum system demand has peaked at 38 GW whilst installed capability is at 41 GW; approximately. The first option selected is to return to service the old mothballed power stations; to be followed by brown field expansion of existing baseload thermal power stations; to be followed by new nuclear, new thermals and imported hydro to form the baseload pool of electrical energy for South Africa. In all cases, more power has to be transported from the power station nodes to the load centres.

A review of the Eskom National Grid structure shows the locality of the multiple bundle conductor transmission lines. All these lines emanate from key power station nodes and terminate close to major load centres.

For example, starting with brownfield expansion, Eskom has plans to extend the capacity of existing thermal power stations. One proposal is to expand the Matimba Thermal Power Station; by an additional 4200 MW in two stages of 2100 MW per stage. The new generation is planned alongside the existing 3600 MW capacity. A known constraint is the acquisition of additional power line servitudes to evacuate the increased power generation. The real estate area surrounding Matimba Power Station is emerging as prime investment for environmentally sensitive international investors.

Presently, eight 400 kV HVAC lines emanate from the existing 3600 MW Matimba Power Station. The national control recorded power flows from Matimba Power Station and associated substations are provided in Appendix C. The 400 kV lines are of quad zebra phase conductor design, suspended by V string glass insulators and arranged in a horizontal configuration. Each 400 kV line has a surge impedance load transfer capability of 672 MW. Thus for the additional load evacuation, as a steady state minimum, another 7 by 400 kV lines or 3 by 765 kV lines would be required. With advanced power electronic technology; cost effective higher current thyristors could present an economic argument for upgrading an existing HVAC transmission circuit for HVDC application in lieu of additional conventional HVAC transmission lines and substations. The HVDC application could be further developed.

In the case of Eskom South Africa, the national grid is planned and designed to the classic (N-1) contingency criteria. Thus, between national grid nodes, two transmission lines are generally built in separate and parallel servitudes. For selected transmission paths, one thought is to promote one transmission line as the positive pole and the second parallel line as the negative pole. Eskom's 533 kV DC lines on the Cahorra Bassa – Apollo scheme operate as a bipole with individual poles in separate servitudes. The vast air gap separating the positive and negative poles has greatly contributed to the successful performance of the scheme.

The Eskom national grid consists of 27 169 km of HVAC transmission lines arranged in voltages of 132 kV to 765 kV. In addition, one HVDC link exists. This is the Cahora Bassa

Apollo scheme of length 1414-km, operating voltage of 533 kV, for power transfers of 1920 MW. The bulk of the transmission system operates at 400 kV AC and there exists 15 318 km of lines in service. The next bulk level of transmission operates at 275 kV and there exists 7383km of lines in service. From 275 kV to 765 kV, all the lines are designed as in single circuit with a horizontal tower bridge configuration. The tower bridge structure was prepared for the statutory allowable electrical clearances between phase conductor and earth.

From in service operating experience, the acquisition of new power line servitudes is becoming more difficult as the value of the real estate escalates. South Africa has become an attractive destination for international investors who appreciate the abundance of open country containing wildlife, bird, fauna and flora. This new resident is more opposed to the introduction of new power lines and the "not in my backyard syndrome as experienced in the developed world" continues to take trend in South and Southern Africa. This constraint is understandable but makes more difficult the environmental impact assessment of new lines and the overall acquisition of new servitudes. The option to upgrade and recycle existing power lines becomes more attractive.

Preliminary discussions with my supervisors showed that the study proposal had merit with multiple benefits. We concluded that we look beyond FACTS as developed by EPRI and Hingorani [11] and that we develop the HVAC to HVDC recycle strategy in order to;

- Address the problem of limited availability of new servitudes;
- Address transmission congestion and bottlenecks in complex networks;
- Recycle existing assets for greater power transfers;
- Introduce electrical islands within complex interconnections;
- Enhance power system stability; and
- Promote ancillary services energy management.

We know that we can get more out of the installed phase conductors. The conductors can be driven to their full thermal current carrying design and line template levels. The key questions are whether we introduce additional enhancements or add more problems? DC external insulation is known to be problematic; we know the solutions for external insulation under HVAC technology; could the same solution be applied to HVDC technology? What performance do we expect out of DC? How would DC impact on the power flows; on stability and on generation torsional interaction?. How would DC impact on the electric fields and corona effects? HVAC electric fields and conductor surface gradients are known and within environmental limits for the given operating voltage. An initial response to the many questions is that the performance under HVAC operating will be similar or equivalent to the performance under HVDC operating. The high speed DC control computers and the rapid switching capability of the thyristors will support both rapid frequency and rapid voltage control as both active and reactive power management is within the control computers capability.

The geographical maps showing the interconnected power system of South Africa and Southern Africa are presented in Appendix D. The experience gained on the grid master power controller [GPMC] at Songo on the Apollo – Cahora Bassa 533 kV HVDC system has yielded very stable control operations for the case of a very weak HVAC circuit in parallel with a very strong HVDC. Electric fields and corona effects under DC conditions can be checked computationally and where practical, experimentally.

With reference to the power system maps presented in Appendix D, the six bundle 765 kV transmission line links the Mpumulanga Power Generation node with the heavy mining loads in the Free State. The six-bundle carrying capability at 800 kV DC is in the order of 6000 MW. The four bundle 400 kV links the Matimba Power Station node with the heavy mining loads in the Carltonville area and then provides a continuity path to Apollo, to Kendal, to Majuba, to Venus in the KwaZulu Natal load centre. With one 400 kV line configured as a positive pole and another 400 kV line configured as a negative pole, then three DC circuits can be prepared with each circuit consisting of 4 conductors in parallel. At a DC nominal voltage of 400 kV, 4 GW of power transfer is possible. This is almost six times the AC surge impedance loading of the line.

Preliminary study of the national grid paths shows that the megawatt transmission path could upgrade to that of gigawatt transmission paths under HVDC application. This could form the start of a super grid overlay onto the existing national grid.

### 1.3 Application of HVDC Technology

The conversion of selected high voltage alternating current circuits for high voltage direct current employment so as to yield greater power transfers is generally debated as an option in power system planning scenarios. To date, no operating scheme exists in South Africa or internationally.

The focus of this research study is to determine the technical feasibility of upgrading of existing HVAC circuits for HVDC application. It is assumed that the transmission line will remain as is in structure, layout and mechanical design. If required, the changing of external line insulators using live line technology is an accepted modification to the original HVAC line. It will be expected for the study to set the boundary conditions for the upgrade proposal, to highlight the technical limits for the HVDC on HVAC application and to highlight the technical and economic opportunities that could contribute to the further development of the initial idea.

Introducing HVDC technology into an existing HVAC interconnected power system has far reaching technical benefits for the overall power system. Physically, the technology supports the limited availability of power line servitudes; contributing a much smaller footprint than a conventional HVAC circuit. Reconfiguring existing assets for higher power transfers can alleviate transmission congestion and bottlenecks in interconnected power networks. The technology promotes a greater flexibility in power system control and operation, directly contributing to enhanced power system stability performance. These benefits are all technically and economically quantifiable and can be explored later in a separate study.

If the initial idea of converting one HVAC line for HVDC application is successful, then we can continue to grow the applications such that we create a new "supergrid" overlay from and onto the existing national grid. In South Africa, multiple extensions to existing baseload thermal plants are planned. Long term favourable coal contracts and or adequate water supply are supporting such development. Higher power transfers using existing circuits will grow in appeal and the initial idea has tremendous value for Eskom and other regional and international power transmission companies.

For Africa, the continued challenge is the large distances between power generation opportunities and power consumption load centres. HVDC transmission can accommodate and move bulk power, 3000 – 6000 MW, over appreciable distances of, 3000 – 6000 km; in many cases being the only choice when the task is not practical for HVAC transmission technology.

Given the student's two decades of planning, design, operating and maintenance experience with Eskom across the divisions of Generation, Transmission and Distribution, it was known that the phase conductors that comprise the distribution and transmission circuits are not employed to their full thermal current carrying capability. The phase conductors generally comprise the greater part of the total material cost of the line and the unused installed capability is inefficient. This inefficiency is generally due to the charging currents and inductive voltage drops associated with alternating current technology. Several studies using compensation technology showed improvements in power transfer capability but the gap between power transferred and power that could be transferred always existed. The idea of using DC technology and of dropping behind the issues of conductor skin effect, charging effect, inductive effects and system frequency is appealing. This initial appeal is further strengthened by the numerous benefits of DC transmission. The benefits are many and could grow to exceed the main constraint of economic costs of the HVDC terminal equipment. With several working discussions in India, China and original equipment manufacturers, we are confident that the increasing DC technology demand from India's Power Grid and China's State Grid will influence the economic cost towards affordability, making available the technology for greater global application.

The first pass technical study for the great Western Corridor Project has called for two conventional 800 kV, 3000 MW schemes for the extra long distance transmission from the Democratic Republic of Congo, through Angola, Namibia, and Botswana and onto South Africa [10]. When power transfers are low, the DC operating voltage can be as low as 500 kV for the 3000 km distance.

The first HVDC scheme was commissioned in 1954 in Gotland, Sweden. With some ten years of operating experience, Smedsfelt et al [2] investigated the operating performance of Gotland in Sweden and recorded that the rate of arc backs was very high in the first year of operation, but decreased thereafter. In 1963, one of the converter transformers was inspected after being subjected to 950 arc-backs and no abnormality was observed. In 1965, valves were opened and cleaned and found to be in acceptable condition.

Padiyar [5] reports that eleven schemes were commissioned with mercury arc valve from 1954 to 1977; including the large Pacific Intertie (US 1970, 1600 MW at 400 kV) and Nelson River Bipole 1 (Canada 1973-1977, 1620 MW at 450 kV). Since those early days, the power electronic technology progressed from mercury arc to that of thyristor valves. By 1990, an additional 52 schemes were co mmissioned and operated globally [5]. Some of the larger schemes included:

Eskom's Cahorra Bassa – Apollo (Mozambique – South Africa 1977, 1414km, 533 kV 1920MW)

Itaipu (Brazil 1985 –1987 800km, 600kV, 6300MW)

Intermountain (US, 1987, 794km, 500 kV 1600MW)

Liberty Mead (US, 1989/1990, 400km, 500 kV, 2200 MW)

Nelson River Bipole 3 (Canada, 1992/1997 930km, 500 kV, 2000MW)

Quebec-New England (Canada/US 1986/92, 450 kV, 2070 MW)

With new electricity markets and downswing in transmission investments, there was a lull in the 1990's. The next boost began with China's Three Gorges project and now multiple 500 kV, 3000 MW, approximately 1000km HVDC bipoles are being commissioned successfully in 28 months from order at a cost of US$360m [6]. This boost from China has positively supported the cost-effective development of higher current and higher voltage power electronic technology. With more acceptable DC terminal equipment costs and given the established AC line, the work of Kennedy [1] suggests that a techno-economical case could exist for converting selected HVAC to HVDC transmission for higher power transfers.

### 1.4 Proposed Research Hypothesis

The research hypothesis proposed is that a given physical powerline can be rearranged to become a DC pole or bipole. The (N –1) planning criterion has provided, in general, two powerlines in parallel servitudes for interconnecting two nodes of a power system. Thus, we have various options for uprating and converting the HVAC powerlines between the two HVAC nodes. The motivation for up rate and conversion is to transfer higher powers between the participating nodes. In the case of Eskom South Africa, this motivation has particular relevance given the proposed brownfield expansion of existing baseload thermal power stations to meet rising customer demands.

One option is to configure one line as the positive pole and the second parallel line as the negative pole. Here all three phase conductors of a line will be bonded together to form the single pole. This option would provide the largest collection of phase conductors for DC use. Another option would be to arrange the DC as multiple circuits; operated independently from each other. In this case, each phase conductor will be configured as a pole of the DC circuit; resulting in a maximum of three DC circuits, operated in bi-pole. No metallic earth return is provided; normal earth return is an option for monopole operation. In the case of environmental pressures for normal earth return, the option exists for two DC circuits to be prepared; with each line being configured as a bipole with the centre phase arranged as in metallic earth return. From HVAC to HVDC, an optional upgrade is shown in figure 1-3.

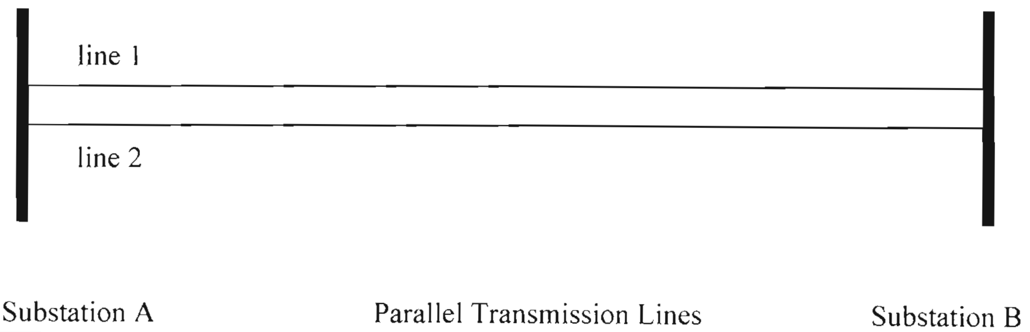


**Figure 1-3 (a): HVAC Transmission Line**

**Optional Upgrade to HVDC**

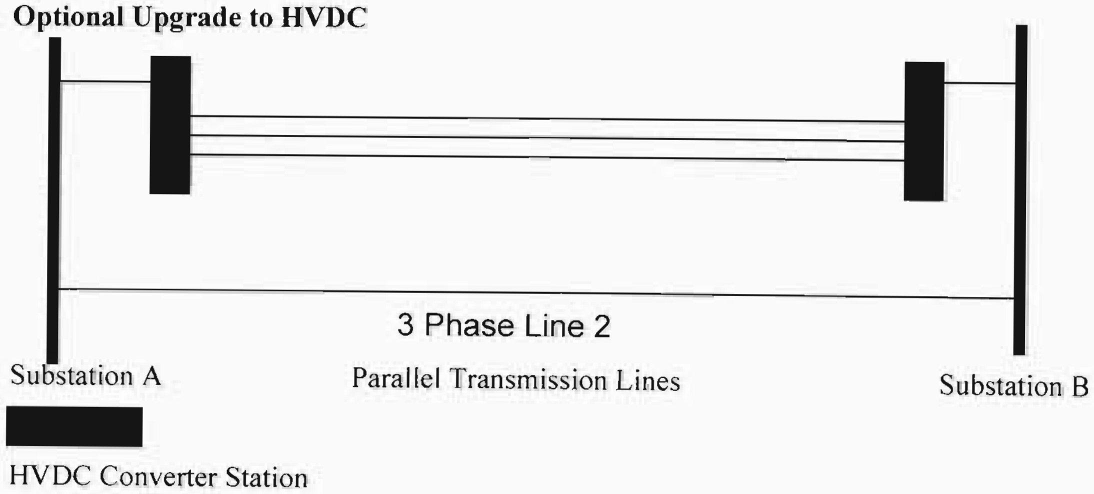


**Fig 1.3 (b): HVAC in service and parallel to one Converted HVDC Transmission Line**

## 1.5 Brief Overview of the Thesis

This research study is focussed on the conversion of an existing HVAC transmission line for HVDC application. The study covers in depth the electrical effects to the transmission line when upgraded and converted for HVDC use. The terminal converter stations of rectification and inversion are considered a black box.

The research study includes a detailed literature review, electric field modelling and calculations for various proposed configurations and the selection of the best design for maximum power transfers from point to point. Voltage drop and power losses are monitored and optimised for the best fit of operating DC voltage when the AC line is converted to DC operation.

The study results are collated, analysed and recommendation are tabled. Further, additional research work is recommended when selected design parameters are stretched for maximum gains.

# Chapter 2: Literature Review

## 2.1 Introduction

Kundur [12] notes that the famous Thomas Edison commissioned the first complete electric power system in 1882. This was the Pearl Street substation in New York City. The power system was of DC design; a steam engine driven DC generator was connected to 59 customers by 110-volt underground cable. The distribution covered a 1,5km radius of load consisting mainly of incandescent lamps. This simple power system was engineered at many other sites across the world, including Kimberley in South Africa and then London in the United Kingdom. The first challenge to the DC power system was the increasing loading as in customer demand for more lighting. This had a two-fold effect; the increasing current produced larger volt drops and increased the energy losses from source to load. The whole power system was constrained to a maximum allowable load with no room for additional expansion. Around the same period, the French, working with alternating current systems, invented voltage transformation. This invention introduced for the first time the flexibility of moving power at a different voltage other than what was available at generation. This advantage promoted alternating current developments and introduced higher voltages for higher efficiencies for power transmitted. Table 2-1 provides a listing of the operating voltages employed in South Africa.

**Table 2-1: Summary of Operating Voltages in South Africa**

| Generation | Transmission | | Distribution | | Customer Consumption |
|---|---|---|---|---|---|
| | HV | EHV | Main | Reticulation | |
| 11 kV | 88 kV* | 275 kV | 33 kV | 11 kV | 3.3 kV |
| 22 kV | 132 kV * | 400 kV | 66 kV | 22 kV | 380 volts 3 phase |
| | 220 kV | 765 kV | | | 220 volts 1 phase |
| Main generation voltage 22 kV | Main Transmission System voltage 400 kV | | also included as Distribution Main Voltages; main distribution voltage 132 | | Main Consumption Voltage is 380 Volts 3 phase and 220 volts for single-phase |

| | | | |
|---|---|---|---|
| | | kV main reticulation voltage 22 kV | customers. |

From Table 2-1, we note the voltage transformation range is generally from 22 kV to 400 kV to 132 kV and back to 22 kV and onto consumption. This flexibility in the use of higher voltages in the power delivery process afforded economical power delivery over longer distances; ensuring acceptable power losses and voltage drops.

However, HVAC systems have their own limiting characteristics. Arrillaga [3] notes that a benchmark of comparison for the power transfer capability is the natural load or surge impedance load (SIL) of a transmission line. In the power delivery process, the power transfer capability of a transmission line is the most important characteristic that defines the highest amount of power that can be economically transmitted along the line without exceeding the designed limits.

The natural load or surge impedance load (SIL) is given by equation 1.

$$SIL = U^2 / Zc \qquad (1)$$

U = the operating voltage;

Zc = the characteristic impedance = $\sqrt{(L / C)}$

L = inductance and C= Capacitance of the transmission line per unit length.

In order to transmit large blocks of power over long distances, transmission lines with increasing higher levels of SIL are required. This can be achieved by either increasing the operating voltage U or by decreasing the characteristic impedance Zc. Generally Zc is limited to a narrow band of 250 to 400 ohms and for higher SIL, the only option is to still further increase the operating voltage [3].

From Kundur's [12] recall of electric power transmission history to Arrillaga's [3] suggested benchmark for power transfer capability; we note that the original challenge of providing higher power transfers continues to persist. This is a constant challenge given the continuously increasing customer demand for electrical energy. New strategies for enhanced power transfers are required. This challenge sustains the motivation for this investigations and research exercise.

In 1991, Hingorani [11] introduced FACTS, the Flexible AC Transmission System as the technology to control power flows on transmission routes and to allow secure loading of transmission lines to their full thermal capability. Hingorani [11] clearly realised that a gap exists between power transfer capability and phase conductor thermal current carrying capability. This is the very gap that we plan to employ but under DC conditions whereas Hingorani sustained his investigations under AC conditions with greater emphasis on rapid control using power electronics. Hingorani [11] clearly noted that given mechanical control (protection or operator opened circuit breakers and on load transformer tap changing as examples), from a dynamic, transient or steady state condition; the power system is really uncontrolled. At a price, the power system operates given the large built in inefficiencies. Hingorani [11] realised that with faster control, power and voltage stability can be assured and thus the system can be driven harder within the unutilized existing power system gaps. A menu of controllers, such as static var compensator, dynamic load breaks and thyristor controlled series compensator were later developed and successfully utilized.

With reference to HVDC, Hingorani [11] notes that the full transmission capability can be achieved and maintained for the full thermal rating of the line. This is because with the converters, power is electronically controlled. However, due to costs and expensive technology, HVDC widespread use is not considered except for special application such as long distance bulk power transfer or the need for asynchronous interconnection. The results from Ewart et al [13] first pass studies further supports the fundamental benefits of FACTS and the study team recalls that FACTS concepts are similar to HVDC. Using HVDC as reference and with HVDC terminal equipment costs being justified by the reduced costs of the DC line, the power system can be controlled so as to provide significant enhancement for the AC system into which the DC is embedded [3]. This research work for converting HVAC to HVDC can be considered a continuation of Hingorani's efforts as introduced in 1991 at EPRI, USA.

## 2.2 Comparison of AC and DC Power Transfer and Voltage Control Characteristics.

The source is Arrillaga [3], published by IEE Power Engineering Series and Padiyar [7]. The economics of transmission, the technical performance and reliability of transmission determine the relative merits of AC and DC technologies. A major feature of power systems is the continuous expansion that is necessitated by increasing customer demand. HVDC provides a strategic solution for the existing power system infrastructure and goes beyond FACTS in terms of power transfer capability over longer distances. For the GW bulk power transfer business, HVDC leads and is more suited to the handling, switching and controlling of the higher powers and currents at higher speeds, also at lower power losses.

For a new DC scheme, it is noted that DC requires less servitude, less number of conductors, simpler towers and provides lower power losses and these do contribute to savings. The one drawback is the high terminal costs. For a longer distance and or a higher power transfer, the net cost of DC is lower than that of AC and this sets the scene for DC application. In our study, the emphasis is on using the existing HVAC transmission line but for higher power transfers in the GW range. On conclusion of the technical analysis, an economic analysis should follow and provide guidelines or additional boundary conditions for application. In addition to the linear analysis comparing AC to DC, it must also include the other significant benefits of DC transmission technology.

DC transmission overcomes some of the challenges of AC transmission; the first being stability limitations and the second being voltage control. DC provides an asynchronous interconnection and overcomes many of the AC limitations. These would need to be quantified and included in as additional boundary conditions.

In addition, under DC conditions, frequency, inductance and capacitance have no role and falls off. The converters require large quantities of reactive power and the AC filters and additional shunt capacitors provide for this. With weak AC systems, the AC voltage regulation with varying load conditions may require the use of a rotating synchronous condenser or a static var compensator. With DC, dynamic and transient stability is controlled. The AC system is decoupled and power flow is rapidly controlled between the operating pools. For a given conductor, only thermal considerations and ohmic losses may limit the size and the power carrying capability of a DC line. Academically, DC lines can thus carry substantially more power than AC lines.

In AC transmission, voltage control is complicated by the varying impact of line charging and inductive voltage drops. At a given power transfer corresponding to the surge impedance loading of the line, the voltage profile is flat and steady; otherwise it varies with line loading. To maintain constant voltages at the terminal ends, reactive power compensation is required. With DC, no compensation is required.

With HVDC control of sending end rectifier and receiving end inverter voltages, the power flow along the entire length of the transmission path can be accurately maintained for the full thermal rating of the line. For a given conductor, only thermal considerations and ohmic losses may limit the size and the power carrying capability of a DC line. DC lines can thus carry substantially more power than AC lines.

Finally, in AC interconnections (synchronous interconnections), there occurs an increase in fault level with increasing interconnections. With increasing interconnections, disturbances are transmitted from one system to another and the potential for large power oscillations exist. The power islands need to be controlled; the AGC of the islands have to be co-ordinated using tie line power and frequency signals. DC application promotes an asynchronous interconnection; it avoids all the above problems.

The brief comparison of DC and AC transmission supports the initial supremacy of direct current as a transmission channel and its revival is time dependent. The two main factors promoting the disadvantage of DC over AC include the following:

- the higher cost of terminal and control equipment; and
- the additional cost and need for AC and DC filters for absorbing the harmonics generated by the power electronics.

The disadvantage is purely economic and for certain levels of power transfer and or distance of power transfer, there would exist a break even point when DC is more economic than AC.

For the case of converting and upgrading existing HVAC power lines for HVDC application, the line is given. Hence, the breakeven point of distance or capital costs as compared to HVAC is much earlier. For the case of 765kV terminal equipment, the costs are high and comparable to that of a converter station. It must also be noted that AC has a limited distance for economic and possible transmission whereas DC has a greater tolerance, higher reliability and capability for longer distance transmission.

For the case of DC power transfer reliability, the statistical performance data provided in table 2-2 was reported by Padiyar [7]. When compared to 400 kV line faults and power transformer failures, one is tempted to note that DC affords a higher reliability than equivalent AC. This has been the common experience on both the Inga – Kolwezi 500 kV and the Cahora – Bassa 533 kV schemes in Southern Africa. For the last three years, the Three Gorges HVDC schemes have recorded zero failures for plant and equipment.

**Table 2-2: HVDC Outage Statistics [7]**

| Power Equipment | MTTF (Years) | MTTR (hours) |
|---|---|---|
| Thyristor Group | 13.7 | 6.1 |
| Converter Transformer | 16.1 | 1700.0 |
| Smoothing Reactor | 76.8 | 1700.0 |
| DC Filter | 19.7 | 7.9 |
| AC Filter | 12.6 | 9.3 |
| Master Control | 25.0 | 6.9 |
| Pole Control | 9.0 | 8.6 |
| Pole of Line | 1.25/100 km | 1.5 |
| DC Line Switch | 147.2 | 7.8 |

## 2.3 External Insulation of DC Power Systems

Emanating from the preliminary reading, we record that the key focus areas for the research study would include the evaluation and recommendations of the existing transmission line external insulation, to determine analytically and or experimentally the allowable range of operating voltages; to determine the electric field effects under the selected DC potential and to propose the boundary conditions for promoting the uprating of HVAC transmission lines to HVDC for higher power transfers. In support of the study, we undertake a detailed literature review to understand the behaviour of external insulation under DC stress.

### 2.3.1 Understanding Contamination accumulation under HVDC potential

In the case of DC external insulation, Guile and Paterson [14] have noted that DC promotes the electrostatic precipitation of atmospheric dirt, thereby causing the DC leakage path across the surface to be longer than that required for an equivalent peak ac line to earth voltage. This could limit the DC voltage and impose a higher current rating for a given conductor arrangement. Kundur [12] has also reported that electrostatic precipitation of atmospheric dirt has caused many DC systems to fail even in the early stages of commissioning. Similar was reported by Smedsfelt et al [5] for the Konti Skan – Gotland Project. Aside from the electrical breakdown, the high leakage currents would also promote corrosion of the metallic parts of cap and pin insulators.

It is known that external insulation performance [15] is dependent on

a. operating voltage ( AC/DC)
b. environmental pollution
c. environmental wetting; and
d. insulation material characteristics

The performance of insulators under DC conditions is known to be more onerous than under AC conditions due to the electrostatic precipitation of atmospheric dirt and pollutants. The opinion of severity will vary; from 1,5 to 2 times; up to 5 times; again very dependent on the type of insulator employed [15].

In the late seventies, Cheng and Wu [16] led a joint EPRI and University of Southern California team in systematic field and laboratory testing to study the problem of flashover of contaminated insulators under HVDC conditions. The objective of the study was to understand the mechanisms responsible for DC flashover. The study team noted that contamination flashover of insulators is a complex process involving a diverse collection of parameters from the operating environment, the characteristics of the insulation material, surface wetting and applied voltages. Further, the early experiences at the Sylmar Converter Station, the southern terminal station of the 1440 MW, +/- 400 kV Pacific HVDC Intertie in the US, had shown more severe insulator flashover problems than comparable AC transmission systems. This was attributed to the following factors:

- The process of contaminant accumulation and build up is much more under DC stress than equivalent AC stress; and
- The absence of current and voltage zeroes in a DC transmission system further complicates the flashover process as there is no opportunity for self recovery once leakage current growth is initiated.

At the Sylmar Converter Station, the Los Angeles Department of Water and Power constructed a field test facility for the study team [16]. The facility consisted of nine-insulator string assemblies', with 24 to 27 discs per insulator string. Nine assemblies were energised with the system DC voltage and two insulator string assemblies were left un-energised as control samples. A weather station was commissioned to provide continuous recording of rain, temperature, humidity, wind velocity and direction. For two years, in monthly intervals, sampling of the natural contaminants from the insulator string assemblies was conducted. The process involved removing the string from the rack, washing down the insulator surface with deionised water; washing separately the top and bottom sides of the insulator disks and then chemically testing the collected water plus contaminant samples. In the final stage, sample insulator strings were subjected to individual and composite ion electrolytes and tested under DC voltage. The study results were recorded as follows:

- The bottom surface of the disc provided consistent samples of contaminants as this side was less disturbed by weather effects
- In the chemical analysis, nitrate salts accounted for more than 50% of the total salts. The sulphates followed this. An interesting observation was that NaCl accounted for less than 10% of total salts. NaCl was only pronounced when additional samples were collected in the immediate vicinity of the marine coast. The study team cautions the use of NaCl as the only contaminant for laboratory study.
- In the study of the contaminants, seven salts were identified. Led by the nitrates, NaNO3, Ca(NO3)2, Mg(NO3)2, followed by the sulphates MgSO4 and then the chlorides NaCl and CaCl2. During DC voltage testing of electrolyte on insulator surface, the salts produced different colour arcs; orange in the case of sodium salts, purple in the case of calcium salts and pink in the case of magnesium salts. The difference in colour suggested that there exist cations in the plasma column during arcing; these cations tend to lower the flashover voltage, as they are more readily ionizable than air. This finding provided a first conclusion that the lower the ionisation potential of the ions, the lower will be the flashover voltage. The study team also observed that the effect of ionisation potential is greater for positive polarity than at negative polarity.
- The solubility of ions could have a similar impact. The environmental pollutant is composed of both soluble and insoluble particles; insoluble particles would contribute to local corona enhancement while soluble particles will render the electrolyte more conductive, thus resulting in a lower flashover voltage.
- Finally, the study team noted that the flashover voltage of the composite electrolyte was the sum of the flashover voltages for the individual ion electrolytes. Thus in any general operating environment, one or many of the ions would be present and given sufficient quantity of accumulated contaminants; the process of breakdown will commence. DC and

the precipitation of atmospheric dirt would make external insulation susceptible to breakdown.

### 2.3.2 Is the external insulation breakdown controllable when surface wetting occurs?

The ABB special publication on the Three Gorges Project DC Transmission [8] refers:

- With the DC scheme nominal voltage at +/- 500 kV, the operating voltage can be lowered to +/- 350 kV to maintain transmission even when the DC withstand strength is reduced during external insulation pollution or during adverse weather conditions. This operating feature is unique to DC and provides for design flexibility. This can be a design strategy and should be included in the converter station engineering.
- Another unique feature of the design is that most of the DC equipment is located indoors within controlled atmospheres. This design option also allows for pre-assembly within a defined factory environment; thereby contributing to smarter project management and shorter lead-time for delivery and commissioning. The last major DC scheme at Itaipu took greater than 60 months (5 years) to build whereas at Three Gorges, the Longquan to Changzhou 890-km link was completed in 32 months. The later Jingzhou to Huizhou 975-km link took 28 months to complete. The next link is scheduled for 24 months. Thus the design arrangement of indoor engineering has value both in time to commission plus lower operating and maintenance requirements.

### 2.3.3 Re-insulation of existing glass disc insulators with composite (polymeric) insulators could contribute to preventing flashovers?

In upgrading from AC to DC, we loose the AC phase to earth voltage magnitude (400 kV: P-E Voltage = 231 kV) and introduce the full peak voltage magnitude that will be continuously present across the insulator string assembly (400 kV: V peak = 400kV). It is for this prime reason, the existing AC glass disc insulators will present a limiting condition for the selected higher DC operating voltage and re-insulation with composite (polymeric) insulators is an option.

The hydrophobic property of silicone promotes the surface beading of water that arises from environmental wetting thereby continuously attenuating the growth and development of leakage currents. This property of the material has demonstrated sterling performance (zero electrical fault incidents) under AC application with up to two decades on in service duty on Eskom's coastal 400 and 275 kV transmission lines [17]. Al Hamoudi et al [18] report similar results in their trial in service application of silicone rubber insulators since May 1996 in Saudi Arabia. The Saudi Electric Company has several high voltage transmission lines in close proximity to the coast; marine pollutants combined with desert sand pollutants required the non-composite insulators to be washed regularly. With the use of silicone rubber, no washing was required and no electrical or mechanical breakdown had occurred.

In a study on the effect of water droplet corona on silicone rubber insulators under HVDC potential, Ijumba et al [19] had shown that both positive and negative corona can lead to temporal loss of hydrophobicity. This is dependent on the size of the water droplets, polarity and duration of exposure to corona discharges. Once hydrophobicity is lost, surface wetting will produce a growth in leakage currents leading to the formation of dry band discharges. It is known that silicone rubber has the ability to recover hydrophobicity due to the diffusion of low molecular weight polymer chains from the bulk of the material and due to the continuous re-orientation of the hydrophobic groups at the insulator surface.

Given the continual recovery of silicone rubber hydrophobicity, dry band formations have not been noticeable on inspected in service insulators for 400 kV and 275 kV a.c. transmission lines. Hence, the growth in leakage currents is continuously arrested leading to no insulation breakdown or flashover as report back from two decades of in service under a.c. conditions. A similar expectation exists for DC as evident from sample insulators installed on the Cahora Bassa 533 kV DC lines.

One design strategy to prevent breakdown would be to limit the growth in leakage current when insulator surface wetting occurs. We note from the early Sylmar Pacific Intertie Study [16], that we have no control on the accumulation and build up of contamination and DC will collect all that exists in the atmosphere. To limit the growth in leakage current when insulator surface wetting occurs, we would need to make the specific creepage of external insulation as large as is practicable either by using longer length insulator string assemblies or larger diameter discs or both or by selecting a hydrophobic insulation material. Note that glass and porcelain when new do have hydrophobic capability whereas composites are continuously hydrophobic. A further complication for the upgrade of existing AC lines to DC is the fixed connecting length of the insulator string assembly given the defined tower bridge window structure. Longer length string assemblies are not practicable. We have the choice to introduce either toughened larger disc special DC glass insulators or composite (silicone rubber) insulators.

From the CIGRE Study Report [15], we note that the most common material used historically in HVDC insulators is porcelain. The primary reason for this choice is a design life of 40 years. Silicone rubber insulation material is a relatively new introduction in the DC environment and has worked very well to date. From experience, Cigre Study Committee members quoted the results at Dorsey and Sylmar converter stations [15]. At Dorsey, Manitoba Hydro changed a 500 kV porcelain wall bushing to a 22mm/kV-creepage-silicone rubber bushing. At Sylmar Converter Station, a 400 kV porcelain wall bushing was replaced by a 23-mm/kV-silicone rubber bushing. There had occurred several flashovers on the porcelain bushings whilst the silicone rubber bushing had zero failures for several years of operation.

### 2.3.4 Will the new insulation material technology introduce additional complexities?

In further work on composite insulators, CIGRE Working Group B2.03 has published guidelines on the use of corona rings to control the electrical field along the length of the insulator [20]. It is known that the voltage distribution along any insulator string (glass, porcelain, and composite) is not linear. The presence of electric field activity is noted at both the live and ground ends of the insulator; at different intensities. In dry conditions, the highest electrical field is near the high voltage end of the insulator. If uncontrolled, the high electrical fields could lead to corona; causing both radio interference and possible accelerated ageing of the housing material of composite insulators. CIGRE thus recommends that the electrical field be controlled along the entire length of the insulator string by the use of corona rings; either at the high voltage end only or at both ends of the insulator. The results of experimental and software modelling of composite insulators yielded the following conclusions [20]:

- to attenuate excessive local electrical discharges, insulators should be fitted with corona rings; corona rings are only effective for AC unless there is zero leakage current;
- the design of the corona rings is the responsibility of the manufacturers;
- the tower window and string configuration will also influence the electric field; these should be included in the modelling and experimental verification; and
- to consider including a factor of safety to cover future environmental impacts such as corrosion of the corona rings.

With reference to manufacturers specifications for composite insulators [21], we note that the applicable IEC standards of IEC60815 of 1986, guide for the selection of insulators in respect of polluted conditions and IEC61109 of 1992, composite insulators of a.c. overhead lines with a nominal voltage greater than 1000V are generally provided. There exists no separate standard for DC composite insulators and this area will require further work. Further note that in terms of composite insulators, all the current specifications are based on the classical theory of creepage expressed in mm/kV and the ratio of shed spacing to shed projection; ideally should be unity for maximum inter-shed clearances. In the absence of sufficient in service experience of composite insulators under HVDC potential, the first reaction is to maximise the insulator specific creepage for a given connecting length.

Sediver of France have recently published their data schedules for composite insulators for voltages of 15 kV up to 765 kV, mechanical strength of 40 kN up to 600 kN. The covering material is "Armoursil" silicone rubber which minimises leakage current and prevents arcing even in polluted and salt water environments. The key strategy in pollution management is to continuously attenuate leakage currents by the action of material hydrophobicity. The effects of pollution accumulation and that of surface wetting are uncontrollable variables and these will vary with the conditions of the environment. It is for this reason that silicone rubber is the motivated material for use; either for AC or DC application.

### 2.3.5 What about longer term ageing effects of composite insulators under HVDC potential?

Vasudev et al [22] have conducted performance tests of polymeric insulators for the case of accelerated ageing under both AC and DC voltages. Tests were conducted on both silicone rubber and EPDM material using the methods and procedures as defined in IEC specifications for composite insulators. The test procedures involved surface conductance measurements, tracking and erosion testing on sample material and ageing studies on full-length insulators under low and high conductivity fog for both AC and DC voltages. The results published are as follows:

- under fog conditions, the size of the water droplets on the polymer material influenced performance; fog produced at 7 mg/cm2 gives the lowest flashover voltage and higher surface conductivity;

- for both AC and DC voltages, tracking and erosion of the polymer material is higher under lower severity pollution than higher severity pollution;
- positive polarity DC voltage causes more damage to the polymer material as compared to the negative polarity DC voltage;
- positive polarity DC is more severe under pollution ageing for the EPDM as compared to silicone rubber.
- under AC voltages and DC negative polarity voltage, both silicone rubber and EPDM performed well. This was valid also for the case of higher severity of pollution;
- under negative polarity voltages and for the case of accelerated ageing, no tracking or erosion was observed on the surface of the material; and
- analytical studies on the material before and after ageing showed that the higher severity pollution does not degrade the polymer material.

A secondary constraint is that of the cap and pin erosion caused by ion migration under DC stress which will eventually lead to mechanical failure. Muralidhara et al [23] have demonstrated a process of conducting the ion migration tests for insulators subjected to DC voltages as suggested in IEC 1325 of 1995.

## 2.4 Electrical and Corona Effects

### 2.4.1 Introduction

Electric and magnetic field effects together with corona effects define the operating environment of any transmission line. EPRI [24] define electrical effects of a transmission line as being the overlapping contribution of field effects and corona effects. The applied voltage on the line produces the electric field whilst the current produces the magnetic field.

Corona is caused when the voltage gradient on the surface of the conductors exceeds the breakdown strength of the air surrounding the conductors. This causes partial ionisation of the surrounding air and causes power loss, radio and television interference, audible noise and space charge fields. Space charge fields are unique to DC. Corona losses, radio and television interference and audible noise is common to AC and DC. Padiyar [7] records that in general, electric and corona effects tend to be less significant on DC conductors than AC conductors. This is due to the absence of the time varying characteristic of the DC line current. However, local experience on the Cahora Bassa 533 kV DC line has shown that corona generation on the insulated shield wire is very high and can disrupt amplitude modulated power line carrier communications [25].

Corona is generated when the conductor surface gradient exceeds the ionisation onset gradient of the conductor. As the voltage is increased, partial discharges are produced at a faster rate, until at a critical field, a steady glow is obtained. The onset gradient for a DC system at which ionisation begins for dry air is given by Peek's formula.

$E_c = 30\ m\ \delta\ [1 + 0.308/\sqrt{r\delta}]$ kV/cm ..........................................................equation 2

Where $\delta$ = relative air density; m = conductor roughness factor, $0 < m < 1$, r = conductor radius in cm; $\delta = p/760 \times 293/(273 + \Theta)$; where p = atmospheric pressure in mm Hg; $\Theta$ = ambient temperatures in deg Celsius.

The corona ionisation takes place in a zone which is a very thin circumferential layer surrounding the conductor surface. Within this zone, the high electric field strength causes high velocity particles to collide with the air molecules. Electrons are removed from the atoms of the air molecules and are accelerated towards the positive conductor or away from the negative conductor. These high velocity electrons collide with other air molecules, releasing additional electrons in an avalanche process.

Space charge fields involves the movement of ions both in still air and directionally biased under wind conditions. Space charge fields cause an increase in the voltage gradient at ground level. Thus, the total electric field at ground level consists of the sum of electrostatic field and space charge field. The North Dakota Public Service Commission regulated the total electric field [24]. EPRI [24] records state that the public service commission required that the 400 kV DC "CU (name of the DC scheme)" line be designed and operated such that the total electric field does not exceed 33 kV/m as measured at ground level. The total electric field was defined as the combination of the electrostatic field (12 kV/m) and the electric field produced by ions (21 kV/m) from the corona emanating from the conductors. The 33kV/m limit was determined from two bounds: 32kV/m was the total maximum estimated electric field for monopolar operation; and that persons wearing commercial footwear seldom experience any sensation even in DC electric fields of 40 kV/m. Note that the electrostatic field can be calculated, but the space charge field will depend on the local environmental factors, which is variable and can statistically be 2 to 3 times higher than the electrostatic field. This is the prime reason for detailed investigations when the DC operating voltage is raised to 800 kV.

In comparison to AC circuits, ions produced during one half cycle are captured during the second half cycle by the polarity reversal on the conductor [7]. The net effect is the increase in the diameter of the ionisation zone as the surface gradient above the critical level increases. The ions are trapped in the ionisation zone and ion drift is negligible. It is this effect, when subject to added particles from servitude fires, that causes a further increase in the diameter of the ionisation zone which eventually leads to air gap breakdown either between phases or between phase to earth for overhead transmission lines. However, under DC potential, ion drift occurs and is not captured as that which occurs in AC circuits. The ion drift is also wind sensitive. Ion drift in the presence of servitude fires should form the subject for further research and investigations with the hypothesis that DC should have a higher resistance to air gap breakdown than that of AC in the presence of servitude fires.

Further, in the case of AC, the time varying electric field will capacitively induce currents in humans, animals and objects directly beneath the phase conductors. It is for this reason, a maximum of 10 kV/m electric field level directly beneath the conductors and 5 kV/m at the edge of the servitude was selected by Eskom for the design and operation of AC transmission lines. In the case of DC, such induction is not present. Hence, higher levels of electric fields could be allowable. In the case of magnetic fields, the current flowing produces the field. Work done by EPRI [24] has shown that the earth's magnetic field of 50 μT contributes to partial cancellation of the line generated magnetic field; causing a reduction in the field underneath the transmission line. For DC lines, currents of 1000 A and 2000 A are common and at a height of 4m above ground, the magnetic field generated is roughly equal to the earth's magnetic field [24].

For the case of corona power loss, Morris and Maruvada [26] have shown that in the case of rain, DC losses increase by a factor of 10:1 as compared to that of AC where losses increase by a factor of 50:1. In addition, their work has also shown that for a given voltage, positive and negative polarity losses are almost equal and for the case of DC, losses usually increase with wind velocity in the range of 0 to 10 m/sec. Other factors, such as humidity, conductors surface condition, rain, wind direction, etc are also important.

Radio interference is due mainly due to the positive polarity conductor whereby the plume discharges and streamers are randomly distributed and form more persistent discharges. Under rain conditions, DC radio interference reduces whereas it increases for the case of AC [7]. DC television interference is due to the ion currents and at distances greater than 25m from the pole conductor, there is no interference [7]. For the case of audible noise, the positive polarity conductor dominates. Under rain, there exists a reduction for the case of DC as compared to higher values for AC.

In summary, we note from the literature review that the environmental electrical and corona effects are less onerous under DC than under AC conditions. The influencing variables would be height above ground and width of servitude; in all cases DC having an edge over AC, except for the unique space charge ion effect. With increasing operating voltages to higher levels of 800 kV, a different scenario could emerge, as all the effects are extremely sensitive to voltage magnitude.

Maruvada's [27] work on corona performance of high voltage transmission lines concluded that it is essential that experimental studies be conducted to evaluate the corona performance of both the AC and the proposed DC transmission line. This is due to the large number of factors influencing corona effects and the complex nature of corona performance. Maruvada [27] recommends that the initial theoretical calculations should be followed by experimental design. With sufficient long-term data, statistical trending and analysis can be performed. For the inclusion of seasonal variations, data collection over a year is recommended.

Operating AC and DC transmission lines, supported by test lines of 100 to 300m and indoor/outdoor corona cages can be employed to determine corona performance. Corona performance measurements on operating HVAC and HVDC transmission lines will support the development of the methods of prediction as well as checking the validity of the empirical methods and assumptions for fair weather conditions. The three principal parameters which define corona performance are corona loss (CL), audible noise (AN) and radio interference (RI). On an operating line, corona loss will be difficult to measure; recommend that a corona cage be employed. The operating line exists, hence best value is achieved provided that the line is available and the test source is mobile and available. Availability is generally a constraint, hence, test lines and corona cages are required.

Test lines also have limitations; a three-phase line is more expensive and in the case of radio interference, it is difficult to analyse the data. The extrapolation of short line data for long line prediction is also a constraint. For the case of DC bipolar operation, both positive and negative test polarities is required to correctly deliver the space charge effect in the inter-electrode region of a DC transmission line. The two influencing factors for test lines is that they must be sufficiently long to simulate fair weather corona performance and be long enough to permit radio interference measurements at frequencies within the amplitude modulated radio broadcast frequency band. A corona cage, either indoor or outdoor, is the most practical, easy to construct and control and the most value especially to determine worst case design levels in the case of foul weather conditions.

In a purpose built cage at the HVDC Centre of the University of KwaZuluNatal, Sibilant [28] showed that a large margin does exist between corona onset voltage and breakdown voltage as no flashover occurred even when the voltage was increased to more than twice the inception voltage. In similar studies at the University, Moyo [25] showed that corona current is generated in insulated shield wires even when no voltage source was directly applied on the shield wire itself. The presence of the shield wire in close proximity to the charged conductor allowed electrostatic induction to produce the electrical connection for corona current to flow. This arrangement of the corona cage or insulated earthwire can be considered for tapping of small corona currents. Typical applications include on route charging of telecommunications repeaters, for small lighting loads as in rural community electrification and even to serve as a charging current amongst other renewable rural electrification energy sources employed on route of a transmission line.

In the case of HVAC transmission line conversion to HVDC application, the window of the tower bridge is fixed and thus the insulator connecting length will directly determine the diameter (radius) of the corona cage. This is based on actual operating dimensions. For the measurement of corona power loss, all the current flowing through the air gap is due to corona. Hence we can measure the current between the insulated cage and ground and equate this to corona current.

## 2.5 Discussion on Literature Findings

The proposal to convert and upgrade selected existing HVAC transmission lines for HVDC application will necessitate the re-insulation of the HVAC transmission line. The existing glass disc insulators will experience ion migration and stem corrosion under DC potential; in addition to electrostatic precipitation of atmospheric dirt on the glass disc surface. On wetting, breakdown is likely. Based on the literature review and the experience to date, it is recommended that the transmission line be re-insulated using either silicone rubber composite or DC toughened glass coated with silicone rubber. The insulator will need to be specified and designed to fit in the given insulator connecting length of the existing towers. This work can be done live line in advance and will not affect the availability or performance of the transmission line. The costs associated with this recommendation are minimal when compared to the costs of a new transmission line; or three to four new transmission lines. The functional specification for external insulation can be defined for DC operating conditions and is to be included in the next chapter.

Electric field and corona effects would need to be determined by calculation, to be later verified by experimentation. It is expected that DC does provide a less onerous outcome as compared to conventional AC operating voltages. This benefit could support a strategy to lift the DC operating voltage to higher levels. This expectation needs to be checked experimentally prior to motivation for application. On the reverse, the presence of the overhead earth wire in the electric field path of the DC poles could cause severe corona onset on the earth wire; further compounded if the earth wire carries a circuit of the telecommunications power line carrier. Power line carriers are generally of amplitude modulation technology and this makes them more susceptible to signal to noise failures. Here the electrical noise would be the earth wire going into severe corona due to the high pole voltages.

Based on operating experience, Table 2 - 3 provides recommended operating levels for the case of converting and uprating HVAC lines for HVDC application.

**Table 2-3: Recommended HVDC Operating Levels as based on Literature Review and Eskom Operating experience.**

| Category | Recommended Operating Level |
|---|---|
| Maximum surface gradient on the pole conductor bundle | +/- 25 kV/cm |
| Maximum surface gradient on the overhead earth wire under normal bipolar operation with or without power line carrier circuits | +/- 10 kV/cm |
| Fair weather audible noise | Average Value 42 dBA at a midspan distance of 40 m recorded 1.8m above ground. |
| Ion Current Density at ground level | +/- 300 nA/per square meter. |

The recommended operating levels, source Eskom Line Design Standards, would further be checked and debated during this research. A key recommendation is to promote further longer term research to gather greater operating level confidence. The non time varying characteristic of DC needs to be exploited.

From the work of Arrillaga [3], it is stated that transmission lines of higher SIL could be achieved by either increasing the operating voltage U or decreasing the characteristic impedance Zc as given in equation 1. Given the limited range of Zc, Arrillaga reports of 250 to 400 ohms, the only alternative option for HVAC transmission is to increase the operating voltage U. Extra high voltage 800 kV has been successfully engineered and State Grid of China plan to go further to 1000 kV.

Increasing voltage will have merit but equally will be the challenge of shunt reactive power compensation for light load conditions and series capacitor compensation for inductive voltage drops; probably thyristor controlled. Compensation will support higher power transfers but the unused gap between conductor current carrying capability and surge impedance loading will exist and will be the greater when voltages are higher. State Grid of China's 1000 kV design employs an eight-bundle conductor configuration. The arguments for HVAC and HVDC will continue with a hybrid technical and economic flavour. This research study was directed totally at the opportunity to employ the unused current carrying gap of existing bundled conductor transmission lines by using HVDC technology.

The converter station layout is now standard amongst all manufacturers. The many benefits of DC should be cost evaluated and included into the financial evaluation for this project. The converter stations can also be erected prior to application. This strategy supports the modularity design; to upgrade as required.

Further research and development of power electronic technology is promoting the employment of bi-directional valves. The work at the Electric Power Research Institute in Palo Alto California has promising results with this new development [30]. Conventional AC to DC converters use thyristor valves that conduct current in one direction only. If converters were built with bi-directional valves, valves made up of anti-parallel connected thyristors, the result would be both economic and operational benefits. The basic research programme in progress will identify design requirements of bi-directional valves for HVDC tapping and conversion of HVAC to HVDC tripole operation.

The following specific practical applications of interest are being undertaken at EPRI [30].

1. Conversion of an existing 345 kV HVAC transmission line to a HVDC tri-pole system so as to increase the power transfer capability without increasing the short circuit duty at the receiving station.
2. Conversion of a single circuit 287 kV HVAC transmission line to an HVDC tri-polar line with substantial increased power flow capacity.
3. Conversion of one circuit of a double circuit 115 kV HVAC line to HVDC tri-polar transmission, increasing power flow on that circuit while leaving the remaining HVAC line to serve the distributed loads.
4. Tapping of the Pacific HVDC Intertie with bi-directional valves so that power flow reversal into and out of the tap can be easily achieved without the use of mechanical breakers.

This ongoing research work at EPRI augurs well for the ongoing research work at Eskom as presented in this research thesis. In the case of the current research dissertation, we have limited our scope of research to just the bipolar design for horizontal configuration lattice tower transmission lines; where the outer phases are the DC poles of positive and negative and the centre phase is configured as metallic earth return. This arrangement represents the greatest proportion of in service transmission lines and is more representative for South and Southern African conditions.

# Chapter 3: Research Design and Methodology

## 3.1 Introduction

The proposal is to upgrade existing HVAC transmission lines to HVDC for higher power transfers. Here we employ the existing installed phase conductors as DC pole current carrying conductors. The original transmission line continues to exist but is now operated as an HVDC bipole circuit. From the given mechanical and electrical specification of the HVAC transmission line, our task is to determine the equivalent specification when operated as an HVDC bipole circuit. The research methodology best suited to this study includes the case study supported by literature review findings, theoretical calculations, and experimental investigations. For the case of laboratory experimentation, the constraints would be small scale modelling given limited DC voltage source, but the upside is repeatability of tests to yield a greater confidence of proposals for the upgrade exercise. For the case of commercial application of the outcomes from this research study, it is recommended that full-scale tests be conducted at a suitable international test facility having bipolar voltages up to 1200 kV and test current ratings of 1 amp.

For the transmission line upgrade to HVDC, we are required to determine the following parameters for submission to Power System Planning for inclusion in power flow studies, fault level calculations and power stability analysis under contingency conditions.

a.) the sending end rectifier operating voltage
b.) the receiving end inverter operating voltage
c.) the proposed power transfers, power losses and voltage drop from sending to receiving ends.

The operating voltage selection is a key task. The higher the operating DC voltage, the lower the transmission power loss. The lower the DC operating voltage, the lower the electrical fields and corona effects. One is an economic preference whilst the other an environmental preference. In all cases, we would need to set the lower and upper operating boundaries for safe and reliable bulk power transmission.

## 3.2 Development of the Hypothesis

**3.2.1 Existing Infrastructure:** The South African (Eskom) national grid is composed primarily of single circuit 275 kV and 400 kV transmission lines with a small but growing population of 765 kV transmission lines. The phases are arranged in a horizontal configuration with two overhead earthwires for lightning protection. It is known that the current carrying capability of the installed phase conductors far exceed the surge impedance loading level and this gap between the two parameters represents the opportunity for promoting higher power transfers using HVDC technology.

The South African National Grid is planned and designed to an (N-1) contingency capability; thus affording one circuit to be made available for upgrade and conversion to HVDC. The upgrade and conversion work can be conducted whilst the HVAC circuits continue to operate; once the HVDC is fully commissioned; the switchover can occur. It is further noted that a flip-flop switch over back to HVAC is possible and will form part of the design feature for this proposal. Such flip-flop capability will assist during periods of planned maintenance of the HVDC scheme, but admittedly, at a lower load transfer capability. On introduction of the HVDC design, a further (N-1) contingency capability will be introduced by monopolar operation using the metallic earth return.

**3.2.2 Limiting Conditions**: Clearly, it is not proposed that all HVAC circuits become candidates for upgrade and conversion to HVDC. The introductory study and literature review have shown that the initial boundary conditions for admittance of a line for upgrade and conversion will be based on the magnitude of the unused power transfer gap (UPTG) between SIL and CCCC. This conclusion was published in two peer reviewed international conferences and accepted technically [30, 31]. In summary, we have:

Unused power transfer gap is small (equal to SIL) – do nothing

Unused power transfer gap is appreciable and of magnitude 1 to 2 times SIL – employ FACTS technology

Unused power transfer gap is large and of magnitude 3 to 4 times SIL – ideal candidate for upgrade to HVDC

At this stage, we introduce from Hingorani and Gyugyi [32] and their perspective on HVDC and FACTS. "Both HVDC and FACTS are complementary power electronic based technologies; having different value added contributions to the AC network. HVDC is not a grid network technology; but uses transmission to connect two nodes of an AC grid network. Here transmission could be a underground or submarine cables, overhead transmission lines or just a busbar as in a conventional back to back scheme for interconnecting different AC frequency networks. For both FACTS and HVDC application, the market potential within the AC network is on a value added basis. For both technologies, power control, voltage control and stability control exists; whereas HVDC can go onto provide lower power losses, independent frequency and control and for new lines, a lower line cost as compared to equivalent AC. Capital costs for power transfer throughput are the only key decision selector for power transfers in the MW range, favouring FACTS over HVDC; whereas in the multiple GW range and over longer distances, HVDC leads FACTS technically and economically." This perspective from Hingorani and Gyugyi [32] concurs with the proposed boundary condition.

From the proceedings of the three international conferences [30, 31, and 37] on ACDC Transmission, it was clear that the development of the HVDC solution would yield additional strategic and economic benefits. These include:

- The difficulty and high costs for acquiring new power line servitudes;
- The substantial savings that can be achieved if existing assets can be upgraded for higher power transfers;
- The rising need to introduce HVDC technology to address transmission congestion and bottlenecks in existing complex networks
- The rising need to introduce HVDC technology to create electrical islands for the controllability of large and complex AC networks.
- To promote and enhance power system stability by using the HVDC controllers in parallel with HVAC operations

- To support the growing ancillary services energy management requirements by making available regulation using the DC controllers.

For the final limiting conditions, table 3-1 introduces the statutory occupational health and safety act regulations as defined for South Africa. Emanating from the Occupational Health and Safety Act No85 of 1993, the study notes the following final boundary conditions that would apply to the HVAC and HVDC configured transmission lines [33].

**Table: 3-1: Electrical Machinery Regulations for Power Line Clearances**

| Maximum Voltage for which insulation is designed | Minimum safety clearance in meters | Minimum clearance in meters above ground and outside townships | Minimum clearance in meters above ground and inside townships | Minimum clearance in meters to roads, railway and tramways | Minimum clearance in meters to communi cation lines | Minimum clearance in meters to buildings, poles and structures |
|---|---|---|---|---|---|---|
| 300 kV rms. phase to phase | 2,35m | 7,2m | 7,2m | 8,4m | 2,9m | 4,7m |
| 420 kV rms. phase to phase | 3,2m | 8,1m | 8,1m | 9,3m | 3,8m | 5,6m |
| 800 kV rms. phase to phase | 5,5m | 10,4m | 10,4m | 11,6m | 6,1m | 8,5m |
| 533 kV DC maximum voltage to earth | 3,7m | 8,6m | 8,6m | 9,8m | 4,3m | 6,1m |

The proposed research hypothesis is presented in Figure 3-1.

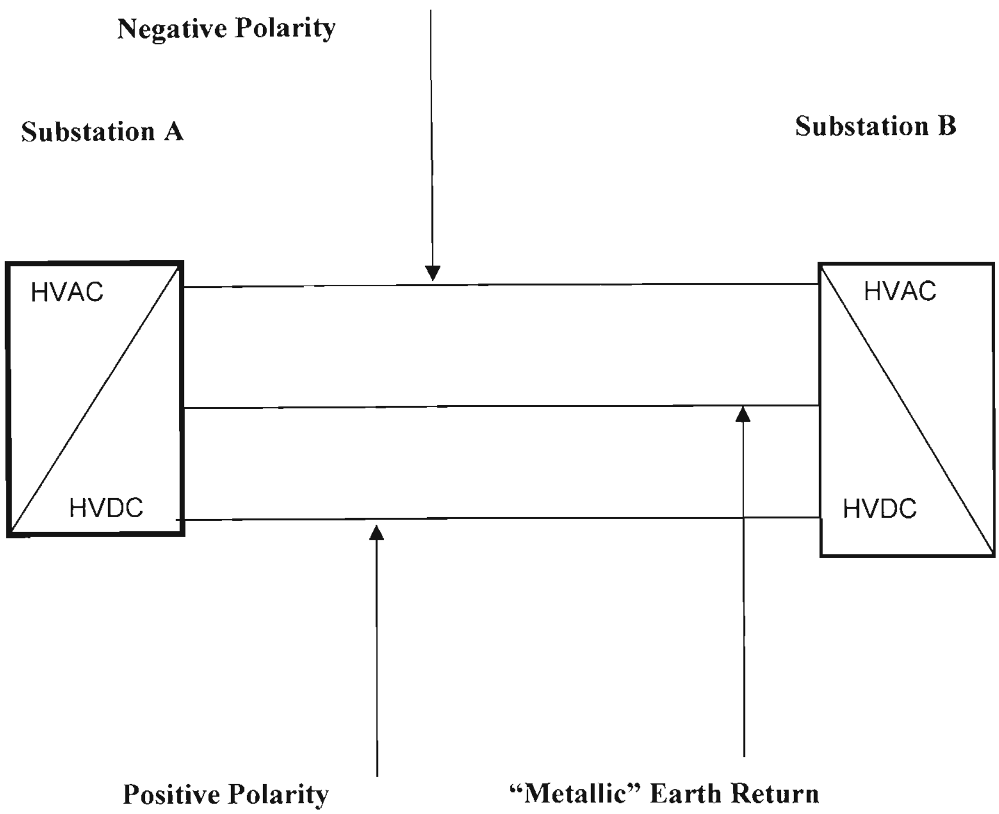


**Figure 3-1: Proposed Upgrade and Conversion of a three phase HVAC transmission line to HVDC**

In summary, the physical transmission line remains as is in structure for both HVAC and HVDC application; the additions being the inverter and rectifier converter stations and the change in external insulation, if required.

## 3.3 Research Methodology

### 3.3.1 Proposed Research Methodology for Selecting Candidate Transmission Lines for Upgrade from HVAC to HVDC

The South African National Grid collection of transmission lines was surveyed for all electrical and mechanical quantities of relevance to power transfer capability. The data included line lengths, characteristic impedance, surge impedance loading, phase conductor characteristics and thermal ratings. The data and patterns were analysed and three candidate transmission lines were selected for the study of upgrading and conversion to HVDC. These three candidate transmission lines are presented in Appendix E. In general, the research methodology is defined in steps 1 to 3, as presented in flowcharts, figures 3-2, 3-3 and 3-4.

**Step 1:** This involves the selection of a candidate transmission line for the upgrade. This is done by comparing the surge impedance load (SIL) and the conductor current carrying capability (CCCC) so as to determine the unused power transfer gap (UPTG). If the UPTG is almost equal to the SIL, then we do nothing and change the selected candidate transmission line. If the UPTG is equal to two times the SIL, then we should consider another methodology for achieving higher power transfers; such as the application of FACTS devices, for example, shunt capacitors, series capacitors or static var compensators. If the UPTG is greater than two times the SIL, say three or four times the SIL, then the selected candidate transmission line would be ideal for HVDC application.

**Step 2:** Review the external insulation and access suitability for DC application. For the given connecting length, establish the specific creepage and the pollution profile of the length of the transmission line. When subjected to surface wetting such as dew or light rain, predict the leakage current that would flow, the reliability or robustness of the insulation and the performance of the transmission line. If unacceptable, promote the re-insulation of the transmission line using suitable manufacturer specified external insulators for DC application. Select the DC operating voltage.

**Step 3:** Check the electric fields and corona effects for the selected DC operating voltage. If acceptable, proceed and determine the power transfers, the power losses and the line voltage drop. For enhanced efficiency, continue to increase the DC operating voltage whilst continuously checking the resulting electric field and corona effects for acceptable performance. The upper operating voltage limit achieved will be constrained by the allowable electric fields and corona effects. The flowcharts for steps 1,2 and 3 follows:

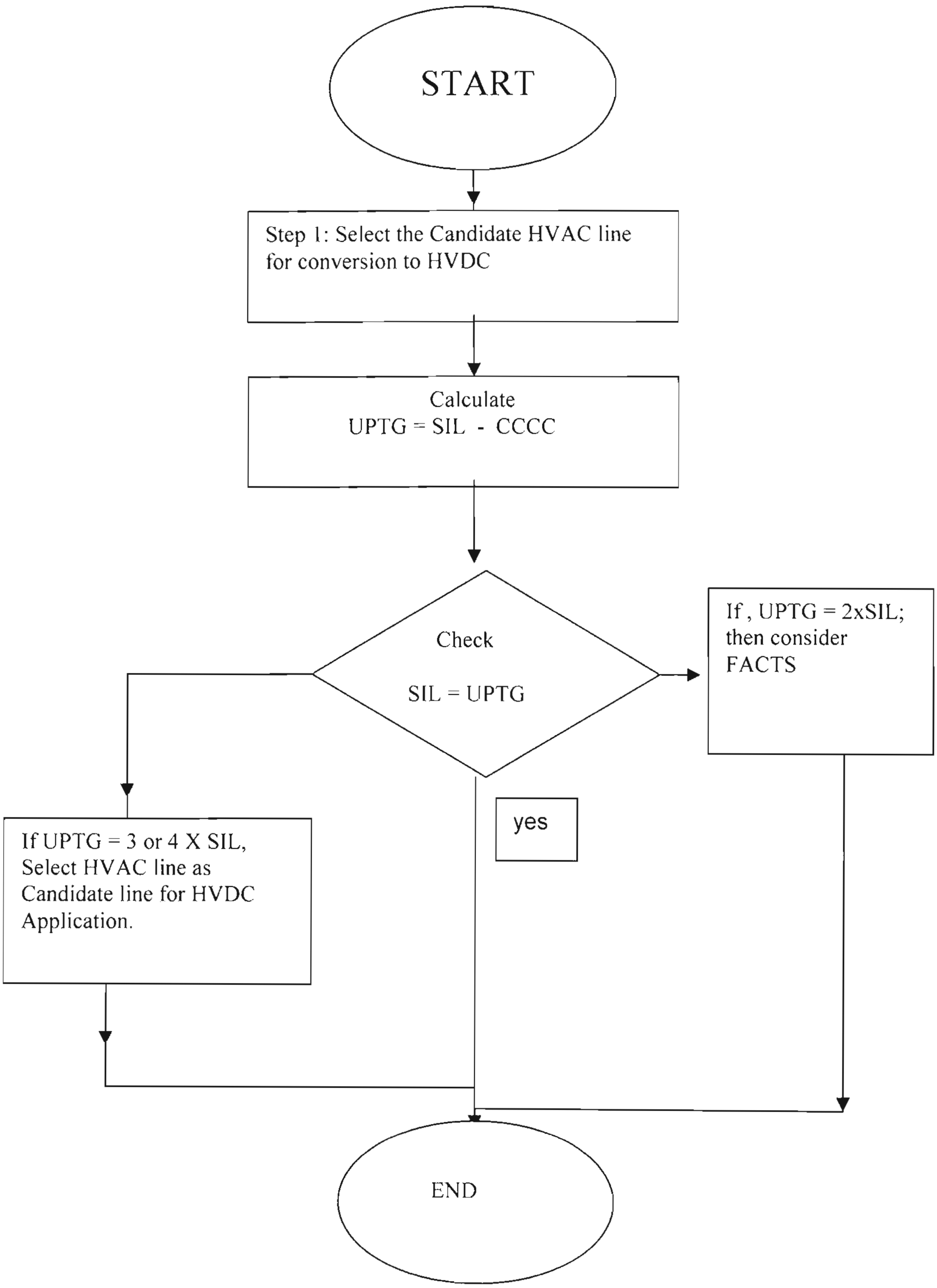


**Figure 3.2: Flowchart for Step 1: Selection of Candidate HVAC Transmission Line for Conversion to HVDC**

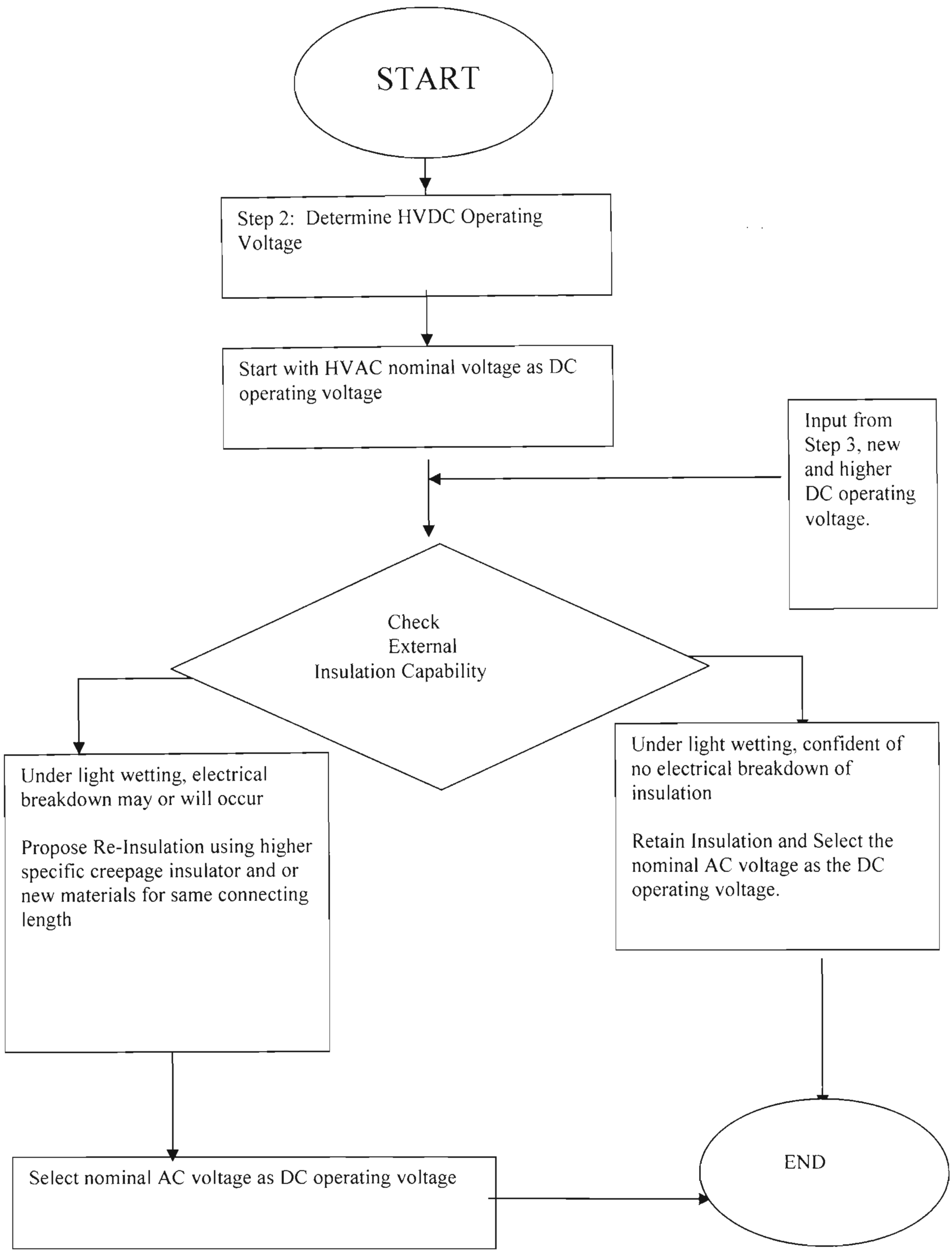


**Figure 3.3: Flowchart for Step 2: To Determine HVDC System Operating Voltage**

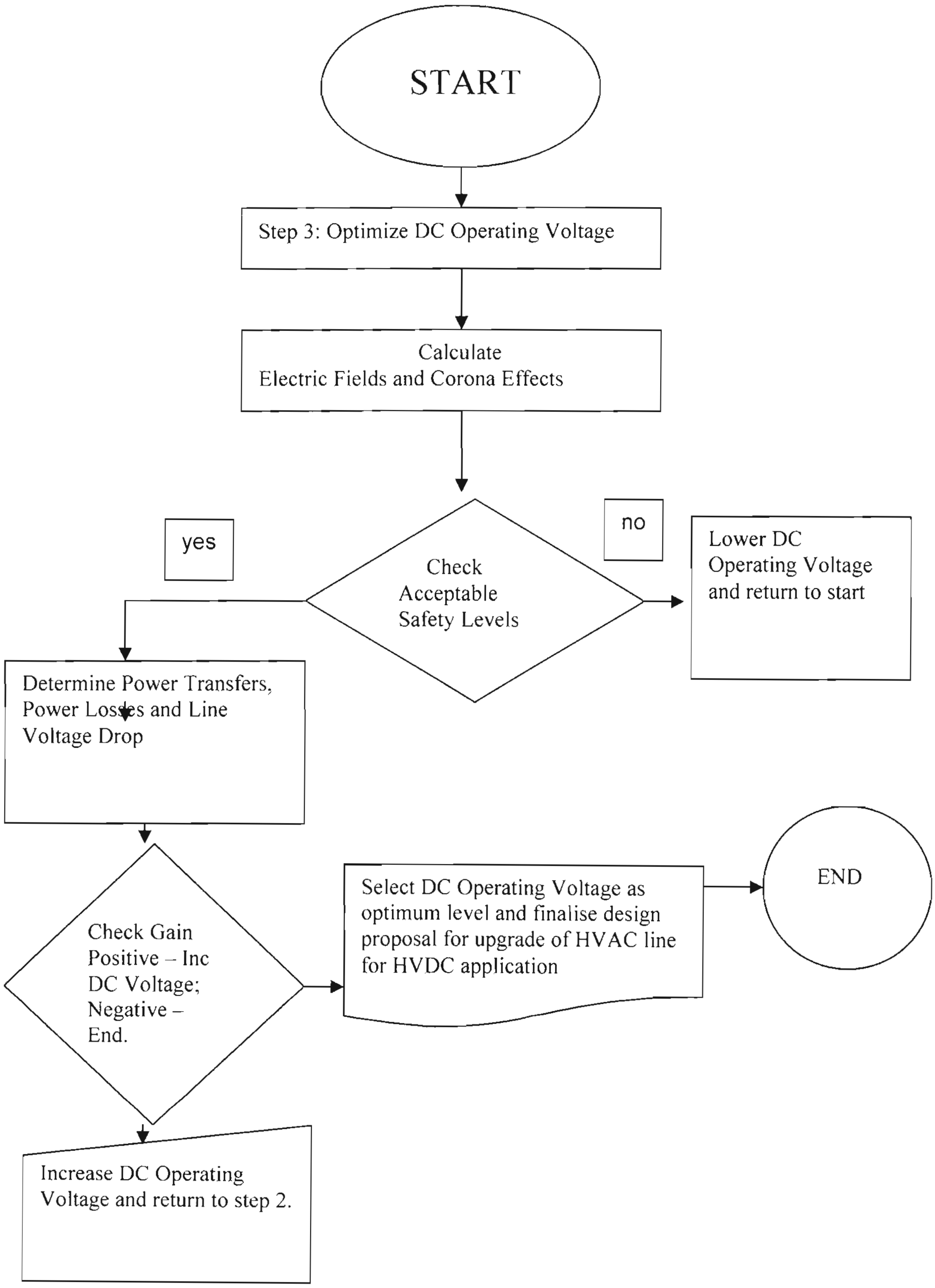


**Figure 3.4: Flowchart for Step 3: Optimization of HVDC Operating Voltage with due respect to Electric Fields and Corona Effects**

This concludes the flowchart of activities for the upgrade from HVAC to HVDC application.

### 3.3.2 Proposed Research Methodology to Determine the Power Transfer Characteristics of Candidate Transmission Lines

Employing the case study methodology for different operating transmission voltages of 275 kV, 400 kV and 765 kV; the power transfer characteristics when upgraded from HVAC to HVDC was determined. Power losses were also considered in relation to power transfers and operating distances. This is the simplest approach given that we are working with upgrading existing transmission lines where all the dimensions are given. The case study procedures for three selected transmission line voltages are given:

**Case Study 1: 275 kV Transmission Line with Twin Zebra Phase Conductors**

The cross section of the line is given in figure 3-5. The line electrical characteristics are:

DC Resistance at 20 deg C: 0.0674 ohms/km
Nominal Current Rating of Zebra Conductor: 860 amps
Selected HVAC to HVDC Configuration: Single Line Bipole with metallic earth return

| | | | |
|---|---|---|---|
| | **O** | **O** | overhead earthwires |
| **OO** | **OO** | **OO** | twin phase conductors |
| Positive Pole | "Metallic" Earth Return | Negative Pole | |

Ground Plane

**Figure 3-5: Cross Section of a 275 kV Transmission Line**

**Calculated Results**

Twin Bundle nominal current rating = 2 x 860 amps = 1720 amps = current per pole

Total Resistance per pole I/R = I/R1 + I/R2 = 1/0.0674 + 1/ 0.0674

R = 0,0337 ohms/km

Table 3-2-1 provides the power transfer results for various operating voltages, table 3-2-3 details the power loss as a function of distance whilst table 3-2-3 shows the percentage power loss for power transferred per pole.

**Table 3 – 2 - 1: Power Transferred for Various Operating Voltages**

| Operating Voltage kV | Power Transfer per pole MW | Power Transfer per Bipole MW |
|---|---|---|
| 50 | 86 | 172 |
| 100 | 172 | 344 |
| 150 | 258 | 516 |
| 200 | 344 | 688 |
| 250 | 430 | 860 |
| 300 | 516 | 1032 |
| 350 | 602 | 1204 |

**Table 3 – 2 - 2: Power Loss as a function of Transmission Distance**

| Transmission Distance km | Power Loss Per Pole MW |
|---|---|
| 100 | 10 |
| 200 | 20 |
| 300 | 30 |
| 400 | 40 |
| 500 | 50 |
| 1000 | 100 |

**Table 3 – 2 – 3: Determination of Power Loss as a Percentage of Power Transferred per pole**

| **Km** | **50 kV** | **100 kV** | **150 kV** | **200 kV** | **250 kV** | **300 kV** | **350 kV** |
|---|---|---|---|---|---|---|---|
| | **86 MW** | **172MW** | **258MW** | **344MW** | **430MW** | **516MW** | **602MW** |
| | | | | | | | |
| 100 | 12% | *6%* | *4%* | *3%* | *2,3%* | *1,9%* | *1,7%* |
| 200 | 23% | 11,6% | *7,8%* | *5,8%* | *4,7%* | *3,9%* | *3,3%* |
| 300 | 35% | 17,5% | 11,6% | *8,7%* | *7%* | *5,8%* | *4,9%* |
| 400 | 46,5% | 23,2% | 15,5% | 11,6% | *9,3%* | *7,8%* | *6,6%* |
| 500 | 58,1% | 29% | 19,49% | 14,5% | 11,6% | *9,7%* | *8,3%* |
| 1000 | - | 58% | 38,8% | 29% | 23,3% | 19,4% | 16,6% |

Setting the usable range to be power losses less than 10%, we get:

On average of 300 km transmission distance,
200 kV DC operating voltage = 688 MW per bipole
250 kV DC operating voltage = 860 MW per bipole
300 kV DC operating voltage = 1032 MW per bipole.

At 400 km transmission distance,
250 kV operating voltage = 860 MW per bipole
300 kV operating voltage = 1032 MW per bipole

At 500 km transmission distance,
300 kV operating voltage = 1032 MW per bipole.

The higher operating voltage is suitable for lower power losses. For the 275 kV structure, try and obtain a 300 kV DC operating voltage; second choice would be 250 kV operating voltage. The 300 kV DC voltage is the most efficient and can accommodate longer transmission distances.

**Case Study 2: 400 kV Transmission Line with Quad Zebra Phase Conductors**

The cross section of the 400 kV line is given in figure 3-6. The electrical characteristics for the line are:

DC Resistance at 20 deg C: 0.0674 ohms/km per quad zebra

Nominal Current Rating of Zebra Conductor: 860 amps x 4 = 3440 amps.

Selected HVAC to HVDC Configuration: Single Line Bipole with metallic earth return

| | |
|---|---|
| Four Bundle nominal current rating | = 4 x 860 amps = 3440 amps = current per pole |
| Total Resistance per pole | $1/R = 1/R1 + 1/R2 + 1/R3 + 1/R4 = 4/0.0674$ |
| | R = 0,01685 ohms/km |

| | | | |
|---|---|---|---|
| O | | O | overhead earthwires |
| **OO**<br>**OO** | **OO**<br>**OO** | **OO**<br>**OO** | quad phase conductors |
| Positive Pole | "Metallic" Earth Return | Negative Pole | |

Ground Plane

**Figure 3-6: Cross Section of a 400 kV Transmission Line**

**Calculated Results**

Table 3-3-1 provides the power transfer for various operating voltages, table 3-3-2 details the power loss as a function of distance whilst table 3-3-3 shows the percentage power loss for power transferred per pole.

**Table 3-3-1: Power Transferred for Various Operating Voltages**

| Operating Voltage kV | Power Transfer per pole MW | Power Transfer per Bipole MW |
|---|---|---|
| 100 | 344 | 688 |
| 200 | 688 | 1376 |
| 300 | 1032 | 2064 |
| 400 | 1376 | 2752 |
| 500 | 1720 | 3440 |
| 600 | 2064 | 4128 |

**Table 3-3-2: Power Loss as a function of Transmission Distance**

| Transmission Distance km | Power Loss Per Pole MW |
|---|---|
| 200 | 40 |
| 400 | 80 |
| 600 | 120 |
| 800 | 160 |
| 1000 | 200 |
| 1200 | 240 |

**Table 3-3-3: Determination of Power Loss as a Percentage of Power Transferred per pole**

| Km | 100 kV | 200 kV | 300 kV | 400 kV | 500 kV | 600 kV |
|---|---|---|---|---|---|---|
| | **344 MW** | **688 MW** | **1032 MW** | **1376 MW** | **1720 MW** | **2069 MW** |
| 200 | 11,6% | **5,8%** | **3,99%** | **2,9%** | **2,3%** | **1,9%** |
| 400 | 23% | 11,6% | **7,8%** | **5,8%** | **4,7%** | **3,9%** |
| 600 | 34,8% | 17,4% | 11,6% | **8,7%** | **6,9%** | ***5,8%*** |
| 800 | 46,5% | 23,3% | 15,5% | 11,6% | **9,3%** | *7,8%* |
| 1000 | 58,1% | 29,1% | 19,4% | 14,5% | 11,6% | ***9,9%*** |
| 1200 | 70 % | 35% | 23% | 17,4% | 14% | 11,6% |

Setting the usable range to be power losses less than 10%, we get:

On average of 400 km transmission distance,
300 kV DC operating voltage = 1032 MW per pole = 2064 per bipole

At 600 km transmission distance,
400 kV Dc operating voltage = 1376 MW per pole = 2752 MW per bipole

At 800 km transmission distance,
500 kV DC operating voltage = 1720 MW per pole = 3440 MW per bipole

Incidentally, the Three Gorges 980km; 500 kV HVDC carries 3000 MW per bipole. Once again, we note that the higher operating voltage is suitable for lower power losses. For the 400 kV structure, try and obtain a 400 kV DC operating voltage; second choice would be 300 kV for short length lines or 500 kV for long length lines.

**Case Study 3: 765 kV Transmission Line with Six Bundle Zebra Phase Conductors**

The cross section of the 765kV line is given in figure 3-7. The electrical characteristics are as follows:

DC Resistance at 20 deg C: 0.0674 ohms/km
Nominal Current Rating of Zebra Conductor: 860 amps
Selected HVAC to HVDC Configuration: Single Line Bipole with metallic earth return.

Six Bundle Nominal Current rating = 6 x 860 amps = 5160 amps = current per pole
Total Resistance per pole I/R = I/R1 + I/R2 + 1/R3+ 1/R4+ 1/R5+ 1/R6 = 6/0,0674 = 0,01123 ohms/km

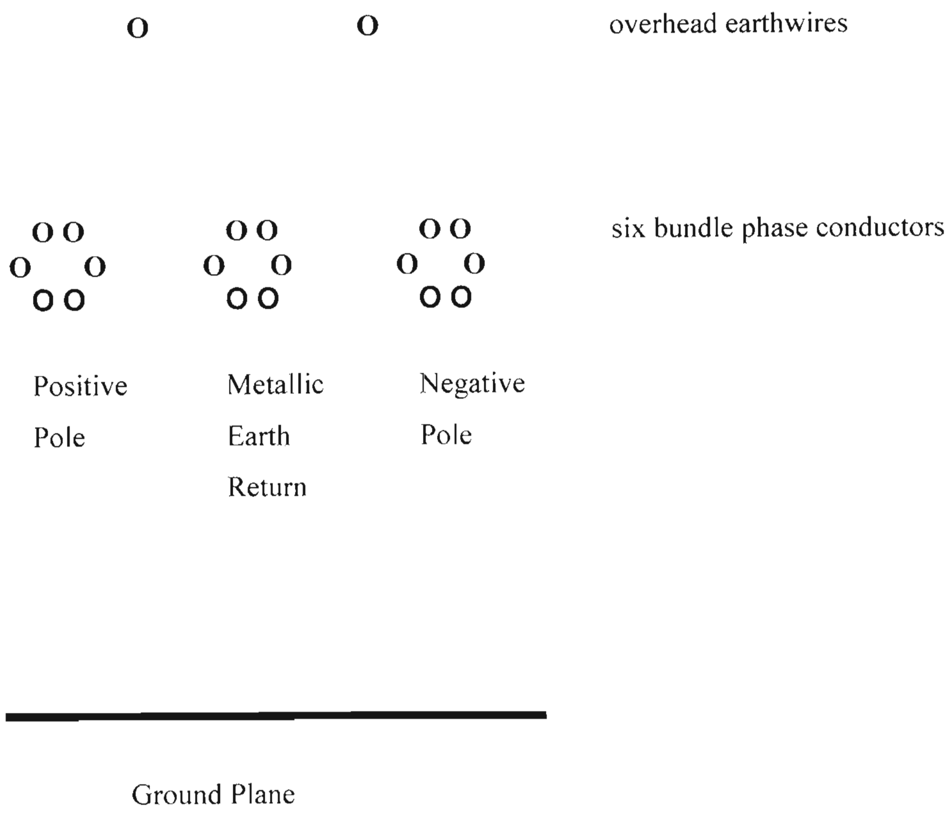


**Figure 3-7: Cross Section of a 765 kV Transmission Line**

**Calculated Results**

Table 3-4-1 provides the power transfer for various operating voltages, table 3-4-2 details the power loss as a function of distance whilst table 3-4-3 shows the percentage power loss for power transferred per pole.

**Table 3-4-1: Power Transferred for Various Operating Voltages**

| **Operating Voltage kV** | **Power Transfer per pole MW** | **Power Transfer per Bipole MW** |
|---|---|---|
| 400 | 2064 | 4128 |
| 500 | 2580 | 5160 |
| 600 | 3096 | 6192 |
| 700 | 3612 | 7224 |
| 800 | 4128 | 8256 |
| 900 | 4644 | 9288 |

**Table 3-4-2: Power Loss as a function of Transmission Distance**

| Transmission Distance km | Power Loss Per Pole MW |
|---|---|
| 400 | 120 |
| 800 | 240 |
| 1200 | 360 |
| 1600 | 480 |
| 2000 | 600 |
| 2400 | 720 |

**Table 3-4-3: Determination of Power Loss as a Percentage of Power Transferred per pole**

| Km | 400kV | 500kV | 600 kV | 700 kV | 800 kV | 900 kV |
|---|---|---|---|---|---|---|
| | **2064 MW** | **2580 MW** | **3096 MW** | **3612 MW** | **4128 MW** | **4644 MW** |
| 400 | ***5,8%*** | ***4.65%*** | ***3,9%*** | ***3,3%*** | ***2,9%*** | ***2,6%*** |
| 800 | 11,6% | ***9,3%*** | ***7,8%*** | ***6,6%*** | ***5,8%*** | ***5,1%*** |
| 1200 | 17,4% | 14% | 11,6% | ***10%*** | ***8,7%*** | ***7,7%*** |
| 1600 | 23,3% | 18,6% | 15,5% | 13,2% | 11,6% | 10,3% |
| 2000 | 29% | 23,2% | 19,4% | 16,6% | 14,5% | 12,9% |
| 2400 | 35% | 27,9% | 23,3% | 19,9% | 17,4% | 15,5% |

Setting the usable range to be power losses less than 10%, we get:

On average of 1200 km transmission distance,

600 kV DC operating voltage = 3GW per pole; 6 GW per bipole

Losses = 360 MW

800 kV DC is recommended.

Losses = 189 MW

For the higher transmission distances, the conductor bundle would need to be optimised; to accommodate 800 kV DC operating voltage but with power transfers limited to 3 GW per bipole; 1,5 GW per monopole; or if system operating reserves allow; to 4 GW per bipole and 2 GW per monopole.

### 3.3.3 Additional Theoretical Analysis and Mathematical Calculations:

In support of the case study research methodology, additional theoretical analysis for external insulation considerations and mathematical calculations for electrical field and corona effects are proposed.

From the literature review, it is clear that external insulation breakdown in the case of HVDC voltage stress is more onerous than under HVAC voltage stress. Early reports from the recently commissioned 500 kV HVDC on the Three Gorges 22,4 GW scheme in China shows that external insulation breakdown does occur and at problem sites, silicone rubber composite insulators are being installed in lieu of DC glass. Based on operating guidelines and at times of external insulation breakdown, the pole is not lost but continues to operate at a lower voltage (350 kV) for the duration of the wetting, generally early mornings and late evenings. For this thesis, it is recommended that detailed investigations be conducted on the re-insulation of the transmission line using silicone rubber composites or factory coated DC glass with silicone rubber insulation. It is known that the hydrophobic property of silicone supports the formation of water droplets at time of surface wetting and thus attenuates any growth in leakage current. For the re-insulation exercise, the constraint will be insulator-connecting length as the tower window dimensions are fixed. For the fixed connecting length, the strategy will be to maximise all the electrical insulation parameters such as creepage and ratio of shed spacing to shed projection.

The unknown factor in the case of silicone rubber composites or DC glass coated silicone rubber is the issue of ageing under continuous DC voltage stress. It is proposed that sample insulators be sourced and subjected to continuous DC voltage stress in the HVDC laboratory at the University of Kwa Zulu Natal. It is further proposed that this work continue into time even when this research assignment is complete.

Employing both DC and AC stress, and using the BPA version 3 field and corona effects software program and the EPRI transmission line field and corona effects program, the various parameters for electrical fields and corona effects for the various cases under study is determined.

The following input parameters is standardised for all the case studies.

- Set the altitude to be 1200m above sea level.
- Set the AC loading on the transmission lines to be as follows: 765 kV - 2400 MVA; 400 kV - 675 MVA and 275 kV – 450 MVA.
- Set the total servitude right of way to be as follows: 275 kV – 47m; 400 kV – 47/54m; 765 kV – 80m and 533 kV DC – 30m.
- Set the allowable AC limits to be as follows: electric field - within servitude 10 kV/m - at edge of servitude 5 kV/m, magnetic field within servitude - 1000 mG; audible noise L50 wet – 53,1 dBA and radio interference L 50 wet @ 500 kHz – 72 dBA. There is no limit for dry noise.
- In IEC standard terms, the conductors employed are as follows: zebra = 428 A1/S1A 54/7; tern is 404 A1/S1A 45/7 and dinosaur is 662 A1/S1A 54.19.

For the selected case studies, all the transmission lines to be studied are of horizontal configuration. For the upgrade to HVDC, the two outer phase conductors are configured as the bipoles of the HVDC scheme; one pole at positive polarity and the other pole at negative polarity. The centre phase conductor is configured as the metallic earth return; thus affording the DC scheme to be operated in monopole configuration at half power rating of the bipole. A later engineering option could be to configure this centre phase as the tripole.

### 3.4 Discussion on Laboratory Experimentation

Laboratory experimentation provides the distinct advantage of repeatability of tests for given operating conditions. The resulting results are of greater confidence. The existing laboratory facilities at the university is of small scale type and suitable for small air gap studies. For the large air gaps and high operating voltages; the facilities are not suitable.

Investigations by experimentation are supported but limited due to the unavailability of high DC test voltages at acceptable test currents. The laboratory facility at the university has a Cockcroft Walton DC generator, rated 500 kV with a 250 kV, 7,5 milli amp output. The 250 kV limit is introduced given the low ceiling of the indoor test chamber. To overcome this constraint, it was proposed that the DC generator be railed outdoors to create an outdoor laboratory under excellent weather conditions for full scale testing at 500 kV. This proposal was not supported given the low current output of the generator, the unsuitability of the generator for large air gap repeatable studies and the need for simultaneous positive and negative polarity test voltages. In the case of insulator ageing studies, a permanent high voltage DC source with a high-test current capability would be required.

In consultation with the university facilities planning, it was concluded that further expansion of the HVDC laboratory be deferred until the study into the new proposed Science Park is concluded. This decision impacts on the experimental work for this research, allowing only for small-scale experimentation supported by mostly theoretical analysis and mathematical calculations. The laboratory constraint is considered acceptable for the present day study requirements, as adequate analytical packages are available for a theoretical analysis of the given transmission line structures. In the case of greenfields study and the need to optimise all the design parameters, then the laboratory studies will be critical. The design of the experiments, summarised in table 3-2, is presented for full scale laboratory studies for later implementation when test facilities become available.

### 3.4.1 The Proposed Design of Experiments for a full scale outdoor 1200 kV HVDC Laboratory

Here we have to prepare the tower windows for the case of "Large Air Gaps". For the 400 kV tower configuration, the electrode to electrode horizontal spacing = 8.5m, whereas the electrode to ground spacing = 8.1m. The insulator connecting length = 4.3m. The quad zebra bundle configuration has the characteristics of higher corona inception voltage and reduced corona effects at lower voltages. These characteristics require the application of at least the full operating voltage as the test voltage for acceptable results. Higher test voltages would also be necessary for selected experiments. Also, in-migrating from HVAC to HVDC, the much smaller AC line to earth voltage is lost and under DC, the full peak voltage sustains continuously. Thus the higher "peak voltage" is required continuously for a full-scale application and analysis. From the brief discussion, it is clear that the test voltage be equal to the proposed operating voltage.

**Table 3-5: Design of Experiments for Evaluating Electrically an HVDC Transmission Line**

| Category | Electrical Effects | Area of Interest |
|---|---|---|
| Corona Effects | Corona Power Loss, Radio Interference, TV Interference, and Audible Noise | Boundary of Servitude, at a height of 1,8m above ground. |
| Space Charge Fields | Ion Density | Boundary of Servitude |
| Air Gap Critical Withstand Level | Impulse Only; Impulse with HVDC Bias | For the given tower window configurations |
| Horizontal Layout of Positive and Negative Electrodes | Positive Corona Effects<br>Space Charge Effects | Under the poles and at the boundary of the servitude. |
| Repeat Experiments | Fair Weather Conditions<br>Sea Level and 1800m altitude<br>Rain and Mist (water spray)<br>Servitude Fires (smoke generator with large particles)<br>Bird Streamers (egg yolk) | Under the poles and at the boundary of the servitude. |

# Chapter 4: Analysis and Discussion of Results

## 4.1 Presentation of Results

The case study methodology shows that for 275 kV HVAC lines, a DC operating voltage from 250 to 300 kV is acceptable; for 400 kV HVAC lines, a DC operating voltage of 300 to 500 kV would be acceptable; and for 765 kV HVAC lines, a DC operating voltage from 600 kV to 900 kV would be acceptable. In all cases, the nominal HVAC voltage as HVDC operating voltage is more than adequate. This equivalence of voltages if selected would promote similar performances for both HVAC and HVDC application. In later power flow studies, power losses and voltage drops can be checked. Given short to medium length transmission line lengths, power losses and voltage drops should be acceptable. This chapter collates and checks the results on the power transfers, power flows, power losses and DC voltage drop; to be followed by results on electrical fields and corona effects.

### 4.1.1 Tower Structural Analysis

From table 3-1, on comparing the allowable clearances for 533 kV DC to 420 kV rms. HVAC, the first observation is that there exists a 0,5m difference in clearance for all the defined categories of minimum clearance in meters. Based on this observation, we assume a linear relationship between voltage and clearance; then the allowable DC operating voltage when the HVAC is upgraded to HVDC would be:

485 kV for minimum safety clearance
445 kV for minimum clearance above ground inside and outside townships
442 kV for minimum clearance to roads, railway and tramways
475 kV for minimum clearance to communication lines
457 kV for minimum clearance to buildings, poles and structures

The maximum allowable operating voltage is thus 442 kV based on the assumption of a linear relationship between 420 kV rms. HVAC and 533 kV HVDC. The statutory regulations do not expand on the DC portfolio of voltages. This is valid given no past need. As we go into the future, both HVDC and EHVDC – UHVDC would mature as technology for application and thus further theoretical and experimental studies would be required for setting statutory levels. In this research and using the simple linear analysis, it is clear that for the given fixed transmission lines, we would need to work with DC voltages as in AC maximum rms. There is not much room for higher operating voltages although this should be explored. Thus for the three cases of 275 kV, 400 kV and 800 kV HVAC; the equivalent DC operating voltages will be 250 kV, 400 kV and 800 kV, respectively. This is a first pass conclusion based on allowable statutory clearances.

### 4.1.2 Surge Impedance Loading (SIL), Conductor current carrying capability (CCCC) and Unused Power Transfer Gap (UPTG) for candidate lines under study.

The survey of SIL, CCCC and UPTG for 400 kV and 765 kV lines for the case of quad bundle and higher coupled with distance greater than 100km is given in table 4-1.

**Table 4-1: MVA Rating for 400 kV and 765 kV Transmission lines greater than 100km in length, having 4 or more conductors per phase**

| Line Name | Conductor Type | Line Length km | Normal MVA rating | Emergency MVA rating | SIL MVA Rating |
|---|---|---|---|---|---|
| Bacchus / Proteus | Wolf | 249 | 1025 | 1330 | 628 |
| Delphi / Neptune | Wolf | 148 | 1025 | 1330 | 624 |
| Delphi / Poseidon | Wolf | 155 | 1025 | 1330 | 625 |
| Droerivier / Proteus | Wolf | 226 | 1025 | 1330 | 628 |
| Grassridge / Poseidon | Wolf | 116 | 1025 | 1330 | 624 |
| Kendal / Minerva | Zebra | 96 | 1796 | 2383 | 645 |
| Kendal / Tutuka | Zebra | 109 | 1796 | 2383 | 661 |
| Majuba | Zebra | 218 | 1796 | 2383 | 665 |

| | | | | | |
|---|---|---|---|---|---|
| / Venus1 | | | | | |
| Majuba / Venus 2 | Zebra | 234 | 1796 | 2383 | 665 |
| Matimba / Midas 1 | Zebra | 336 | 1796 | 2383 | 672 |
| Matimba / Pluto | Zebra | 342 | 1796 | 2383 | 671 |
| Alpha / Beta 1 765 | Zebra 6x | 436 | 5152 | 6837 | 2364 |
| Alpha / Beta 2 765 | Zebra 6X | 434 | 5152 | 6837 | 2364 |
| Beta/Hydr a 765 kV | Zebra 6x | 282,5 | 5152 | 6837 | 2364 |

From the sample provided, the unused gap between surge impedance loading and conductor bundle normal MVA rating is clearly evident. This is the unused gap that we wish to exploit by using direct current power transmission. Further, the magnitude of the unused gap is marginal for the wolf conductor bundle and appreciable for the zebra conductor bundle. Thus, the zebra conductor bundle becomes the ideal choice for candidate line for upgrade and conversion to DC transmission rather than the wolf conductor bundle configuration.

{For the case of the Eskom National Grid, all the wolf lines are located in the Eastern and Southern Cape and are more suited to power distribution rather than for bulk power transmission. The first supergrid leg can commence from Matimba to Pluto to Minerva to Kendal to Tutuka to Majuba to Venus; linking Northern Thermals with Kwa Zulu Natal Loads; the second leg of the supergrid can be sourced from one part of the 765 kV HVAC.}

### 4.1.3 Calculation of Unused Power Transfer Gap (UPTG): Case Study of Matimba – Midas – Pluto 400 kV HVAC Transmission lines.

Conductor = Zebra

DC resistance at 20 deg. C = 0,0674 ohms/km

Nominal Current Rating = 860 amps

Transmission Distance = 400 km

**Option 1: Convert 1 x 400 kV line as positive pole and another 400 kV line as negative pole.**

This option provides a 12-bundle configuration for each pole.

Equivalent resistance R: 400 km x 0,0674 ohms/km in 12 parallel conductors = 26,96 ohms in 12 parallel conductors; thus 1/R = 12/26,96 ohms; R = 2,25 ohms

Current carrying capability: 4 x 860 x 3 = 10 320 amps per pole

Voltage Drop per pole = 23,22 kV

Power Loss per pole = 240 MW

Power Transfer @ 400 kV operating voltage = 4128 MW per pole

Power Electronic Thyristor capability = 3,5 kA; Parallel operation of 7 kA limited current transfer

Power Transfer @ 400 kV operating voltage = 2800 MW per pole.

**Option 2: Convert only one 400 kV line for HVDC application**

Transmission Distance = 342 km

Equivalent resistance R: 342 km x 0,0674 ohms/km in 4 parallel conductors = 23,05 ohms in 4 parallel conductors; thus 1/R = 4/23.05 ohms; R = 5,76 ohms

Current Carrying Capability: 4 x 860 = 3440 amps; well within the thyristor 3,5 kA rating.

Voltage Drop per pole = 19,81 kV

Power Loss per pole = 68 MW

Power Transfer @ 400 kV operating voltage = 1376 MW per pole

Total Power Transfer per bipole = 2752 MW

Total losses per bipole = 136 MW; 4,9 % of received power

Total sending end power = 2888 MW

Thus UPTG for the case of the Matimba – Pluto 400 kV HVAC line operated as 400 kV HVDC is:

Total power transferred = 2888 MW, SIL at 400 kV HVAC = 671 MVA and UPTG is in the order of almost 2,2 GW. This is a substantial quantity of energy and it employs existing assets.

Under single contingency; the DC scheme can operate as in monopole configuration, using the centre phase conductor as metallic earth return. This option provides no environmental impact and is an excellent solution. Under monopole operation; total power transferred will be 1376 MW; or driven up to 1500 MW if a 3000 MW DC converter is employed. The short duration overload on the conductors will be well within the emergency rating limits. The next level of contingency operation would be 750 MW based on the bridge layout. At Pluto substation, table 4-2 shows the following power distribution as recorded in August of 2005 and table 4-3 shows the probable distribution when the Matimba – Midas HVAC is upgraded to 400 kV HVDC. The national control substation logs are given in Appendix E.

**Table 4-2: Power Distribution at Pluto Substation as recorded in August 2005**

| Power Imports | Power Exports | Power Loading of Transformers |
|---|---|---|
| Matimba 282 MW | Midas 510 MW | Unit 1 , 300 MW |
| Apollo 883 MW | Hermes # 1 , 263 MW | Unit 2, 300 MW |
| Lulumisa 445 MW | Hermes # 2 , 256 MW | |
| Total 1610 MW | Total 1029 MW | Total 600 MW |

**Table 4-3: Probable Power Distribution at Pluto substation when Matimba – Midas upgraded to 400 kV HVDC.**

| Power Imports | Power Exports | Transformer Loads |
|---|---|---|
| Matimba Bipole 1 , 1376 MW<br>Matimba Bipole 2, 1376 MW | Midas 700 MW | Unit 1 , 300 MW |
| Apollo ( 550 MW) | Hermes # 1 . 300 MW | Unit 2, 300 MW |
| Lulumisa ( 300 MW) | Hermes # 2 , 300 MW | |
| Total 2752 MW | Total 1300 MW | Total 600 MW |

The total additional power generated at Matimba Extension is fully absorbed by the loads at Pluto and there exists adequate first and second contingency support if the DC goes monopole or even on the loss of multiple converter bridge configurations; leaving only one 750 MW unit in service. For a total loss in DC, there is minimum impact as Pluto imports the least from

Matimba. The proposal is practical and is an option for the Project Development of Matimba brownfields expansion of 3 x 700 MW thermal generators.

Extending the analysis to the 765 kV circuit (one line only is more than adequate); we have:

### 4.1.4 For the case of Alpha – Beta at 765 kV HVAC

Transmission Distance = 436 km

Equivalent resistance R: 436 km x 0,0674 ohms/km in 6 parallel conductors = 29,38 ohms in 6 parallel conductors; thus 1/R = 6/29,38 ohms; R = 4,9 ohms

Current Carrying Capability: 6 x 860 = 5160 amps; well within the parallel arrangement of the thyristor at 2 x 3,5 kA rating.

Voltage Drop per pole = 25,28 kV

Power Loss per pole = 130,5 MW

Power Transfer @ 400 kV operating voltage = 2064 MW per pole

Power Transfer @ 500 kV operating voltage = 2580 MW per pole; just above the SIL of 2364 MVA

Power Transfer @ 600 kV operating voltage = 3096 MW per pole

Power Transfer @ 700 kV operating voltage = 3612 MW per pole

Power Transfer @ 800 kV operating voltage = 4128 MW per pole

Total Power Transfer per bipole = 4128 MW @ 400 kV and up to 8256 MW @ 800 kV

Total losses per bipole = 261 MW; 6,3 % of received power @ 400kV; 3,2% of received power @ 800 kV

Total sending end power = 4389 MW @ 400 kV and 8517 MW @ 800 kV.

Assuming that the transmission distance is increased to 1200 km so as to represent the full distance from Alpha substation to Koeberg Nuclear station outside Cape Town; then the equivalent power transfers would be:

Transmission Distance = 1200 km

Equivalent resistance R: 1200 km x 0,0674 ohms/km in 6 parallel conductors = 80,88 ohms in 6 parallel conductors; thus 1/R = 6/80,88 ohms; R = 13,48 ohms

Current Carrying Capability: 6 x 860 = 5160 amps; well within the parallel arrangement of the thyristor at 2 x 3,5 kA rating.

Voltage Drop per pole = 69,6 kV

Power Loss per pole = 358,9 MW

*Power Transfer @ 400 kV operating voltage = 2064 MW per pole*

*Power Transfer @ 500 kV operating voltage = 2580 MW per pole; just above the SIL of 2364 MVA*

*Power Transfer @ 600 kV operating voltage = 3096 MW per pole*

*Power Transfer @ 700 kV operating voltage = 3612 MW per pole*

*Power Transfer @ 800 kV operating voltage = 4128 MW per pole*

**Total Power Transfer per bipole = 4128 MW @ 400 kV and up to 8256 MW @ 800 kV**
***The total power transfer per pole or bipole stays the same as that for the Alpha – Beta calculations.***

Total losses per bipole = 717,8 MW; 17,4 % of received power @ 400kV; 8,7% of received power @ 800 kV

Total sending end power per bipole = 4845,8 MW @ 400 kV and 8973.8 @ 800 kV.

Increasing DC transmission voltage has the effect of reducing the power loss as a percentage of received power. The current transferred is load dependent and the nominal capacity of the installed conductor capability was used for demonstration. The total load current to be transferred can be limited to that of contingency capability of total local generation or parts thereof such as 4 x 750 MW for a 3000 MW transfer scheme; 1500 MW per monopole operation. In this case, the load current at 800 kV would be 3750/2 amps per pole = 1875 amps; 312,5 amps per conductor capable of 860 amps. We either have too many conductors or we should increase the loading to 4000 MW. This will provide 4 x1000 MW converter blocks; to yield at 800 kV; 5000 amps per bipole; 2500 amps per pole; 416,6 amps per 860 amp zebra conductor. We need to lose 2 conductors, then loading increases to 625 per 860-amp zebra conductor and possibly drop the operating voltage to 600 kV. One option could be a 4 bundle operating at 600 kV; resulting in 833 amps on an 860 amp rated zebra conductor for a 4000 MW bipole. Power losses will be of magnitude 20,22 ohms x 3332 amps x 3332 amps = 224 MW; 5,6% on total received power of 4000 MW at 600 kV. At 800 kV and assuming that a 4 bundle conductor configuration would be adequate for electric field and corona effects; the loss percentage reduces to 3,1 % (126,4 MW).

From these simple calculations and analysis, it is clear that HVDC is the choice for GW power transmission at the higher operating voltage. The 1200-km distance is not a key parameter of interest; rather the emphasis is on power loss reduction by employing a higher operating voltage. The 765 kV HVAC line has acceptable dimensions and would easily convert and upgrade to HVDC. For the case of greenfields expansion, the line design can be greatly optimised and this should be a preferred solution for power transmission from Alpha Thermal to Koeberg Nuclear.

#### 4.1.5 For the case of brownfield upgrade of one 400 kV line from Grootvlei to Muldersvlei over 1200 km; we have:

Phase Conductor = twin dinosaur; DC resistance of 0.0437 ohms/km and a conductor current carrying capability of 1123 amps

Equivalent resistance R: 1200 km x 0,0437 ohms/km in 2 parallel conductors = 52,44 ohms in 2 parallel conductors; thus 1/R = 2/52,44 ohms; R = 26,22 ohms

Current Carrying Capability: 2 x 1123 = 2246 amps; well within the thyristor 3,5 kA rating.

Voltage Drop per pole = 58,89 kV

Power Loss per pole = 132,26 MW

Power Transfer @ 400 kV operating voltage = 898,4 MW per pole

Total Power Transfer per bipole = 1796,8 MW

Total losses per bipole = 264,52 MW; 14,7 % of received power

Total sending end power = 2061,32 MW

Losses are high and the load current should be restricted. If total power transfer is limited to 1200 MW; then load current = 1500 amps; power loss per pole = 59 MW; per bipole 118 MW; yielding 9,8% of received power. The voltage drop will be 39 kV; sending end voltage of 440 kV would be acceptable.

For this case, we recommend a transfer of 1200 MW at 400 kV HVDC as normal operating; having the capacity to go up to 1800 MW per bipole under emergency loading when power loss is not a critical parameter.

To complete the exercise for the 275 kV voltage category; we note the relatively short distances and the presence of 3 and 4 conductor bundles distributing bulk power especially in the greater Gauteng (major city area). For this category, power losses under AC and DC conditions will be evaluated and the option of using HVDC light could be considered. We could also trade off operating voltages for enhanced reliability such as zero faults for servitude induced air gap breakdown. For longer distances, with twin zebra phase conductors, conventional point to point transmission could be an option.

### 4.1.6 External Insulation Functional Specification

The general power line characteristics is as follows:

- The transmission line is of horizontal configuration having V string phase assemblies.
- In the case of 400 kV power lines, mostly tower type 520 B is employed.
- The quad zebra conductors have diamond spacers whilst the twin dinosaur conductors have standard preform line spacers.
- The suspension insulators are of glass cap and pin design
- The strain insulators are also of glass cap and pin design; arranged in twin horizontal bundles.

Table 4-4 shows the typical collection of line faults for the period 1993 to 2003. Table 4-5 provides the insulator string assembly details whilst table 4-6 provides the insulator specification. [33]

**Table 4-4: Matimba – Midas – Pluto 400 kV Line Performance - 1993 to 2003**

| Power Line | Bird Pollution | Lightning | Servitude Fires | Other |
|---|---|---|---|---|
| Matimba – Midas 400 kV | 21 | 35 | 22 | 10 |
| Matimba – Pluto 400 kV | 40 | 31 | 22 | 7 |

The installation of bird guards will attenuate this fault cause but lightning and servitude fires will continue to cause breakdown under DC potential. The Songo – Apollo 533 kV HVDC reports equivalent fault causes. For the period 1/10/2001 to 30/9/2005; the converter station published the following statistics:

External Insulation (Pollution): 42% (more on negative pole)

Servitude Fires : 40% (more on positive pole)

Lightning: 9%

Birds: 2%

Tree in Servitude: 1%

Unknown: 6%

In all cases the faults do not appear as voltage dip to customers or as downgraded quality of supply. There is no opening of the circuit to clear the fault; the power electronics commutates, reduces operating voltage and provides a self heal function whilst maintaining some energy delivery during the time of faulting. This benefit of HVDC technology needs further exploration.

**Table 4-5: Matimba – Midas – Pluto 400 kV Insulator String Assembly**

| Tower Type | Connecting Length (mm) | Creepage Distance (mm) | Specific Creepage at Um = 420kV | Glass Disk Type |
|---|---|---|---|---|
| 520 B, 520 E, Suspension V String | 3382 | 6992 | 16.7 mm/kV | 19 x U190BS |
| 518 H Suspension V String | 3315 | 7480 | 17.8 mm/kV | 17 x U300BS |
| 518C, 518 D Strain Twin Horizontal | 3510 | 7920 | 18.9 mm/kV | 18 x U300BS |

**Table 4-6: Glass Insulator Standard Specification**

| Insulator Type | Diameter mm | Connecting Length mm | Creepage Distance mm | Min Fail Load (kN) |
|---|---|---|---|---|
| U190BS | 279 | 178 | 368 | 190 |
| U300BS | 320 | 195 | 440 | 300 |

Under DC potential, the electrostatic precipitation of atmospheric dirt could be severe. The existing specific creepage of 16 to 18 mm/kV would be inadequate at a DC operating voltage of 400 to 500 kV. It is recommended that the insulators be changed. For the given connecting length of 3200 mm, it is recommended that silicone rubber composites be considered. In service experience has shown better performance than traditional glass or porcelain material insulation. A minimum specific creepage of 30 mm/kV at Um of 500 kV will be required. The new hybrid toughened DC glass coated with silicone rubber could also be considered.

Note that there exists no unique standard specification for DC insulators. On the 533 kV Cahora Bassa DC line, similar strength composite insulators are employed; connecting length of 4,11m having creepage length of 16 000mm, to yield a specific creepage of 30,02 mm/kV. The insulators continue in service with no failures to date.

The first design recommendation for external insulation is to employ silicone rubber (either as composite or as a hybrid when coated onto toughened DC glass) with the following minimum specifications:

- Minimum creepage of 30 mm/kV
- Ratio of shed spacing to shed projection to be 1.0

These are clearly extracts from traditional AC specifications. From the internal study [33], the following additional questions are submitted for further research and investigations:

1. The current IEC specifications apply to AC insulators. We need similar for DC composite and hybrid insulators.
2. How does DC polarity affect the insulator integrity over the longer term?
3. What are the ageing modes for the various materials subjected to DC potentials?
4. What is the relative performance of the various DC insulator deigns and non-ceramic materials available on the market?
5. Can we use the existing AC site severity tests and methodologies and apply equally to DC?

Some of the work done helps to understand the technology challenge.

Work done at the Keramische Werke Hermsdork by Streubel et al [34] has shown the following results with respect to shed design versus pollution type and severity. In areas subject to industrial pollution, smooth surface low inclination sheds promoting good self cleaning properties have shown the best results. In coastal areas and areas with the frequent occurrence of highly conductive industrial fog, insulators with high shed inclination (35 to 90 deg) should be selected. For desert regions, sheds should have a smooth surface and a horizontal profile;

aerodynamic shed shape. Finally, for areas with heavy and highly conductive icing, the sheds should be amply spaced and have a large overhang. The insulators tested were cap and pin insulators of anti fog type, ceramic long rod insulators with shed shapes for industrial, industrial fog and desert pollution and composite insulators for industrial pollution.

At China EPRI, Jianchao et al [35] found similar results with respect to shed designs. In addition, the work showed that DC withstand voltages are lower than AC withstand voltages. Further, there was a tendency for the DC/AC ratio be become smaller as the pollution severity increased. For the smooth type aerodynamic profile shed, it was found that although AC performance was the best, the opposite occurred under DC. Jianchao et al [35] recommended that the ranking of insulator performance due to AC technology could not be transferable to DC technology. All work was done based on standard glass disc cap and pin insulators with varying shed profiles.

With respect to efficiency of leakage distance, Jianchao et al [35] concluded that the DC partial arcs moved up the insulator string, bridging the sheds and remaining very stable as compared to equivalent AC. This breakdown process reduces the effective leakage distance. Electrostatic precipitation of atmospheric dirt close to and amongst the intershed spacing will also contribute to breakdown and improved arc stability.

The final conclusions of Jianchao et al [35] has shown that DC withstand voltages per unit leakage distance have been found to have good correlation with the maximum leakage currents, irrespective of pollution severities and insulator types. These characteristics, together with leakage current recordings at site, could provide suitable criteria for insulation design in polluted areas.

Work done at the Institut de Recherche d' Hydro – Quebec in Canada by Lambeth et al [36] have provided the following table, table 4-7, of requirements for leakage path lengths for AC and DC insulators as a function of pollution severity. The table does not make allowance for any increase in the deposits on DC insulators caused by electrostatic precipitation. This effect may double the pollution deposits found in equivalent AC insulation.

**Table 4-7 Requirements for leakage path lengths for AC and DC insulators as a function of pollution severity.**

| Pollution Severity | Approximate Severity Range | | Specific Leakage Path Length | | |
|---|---|---|---|---|---|
| | Salt fog salinity kg/m3 | Solid Layer ESDD mg/cm2 | AC cap and pin suspension mm/kV system | DC cap and pin suspension mm/kV | DC bushing mm/kV |
| Light | 2.5 – 10 | 0.01 – 0.04 | 16 | 27 | 40 |
| Medium | 10 – 40 | 0.04 – 0.12 | 20 | 40 | 60 |
| Heavy | 40 – 160 | 0.12 – 0.4 | 25 | 55 | (85) |
| Very Heavy | 160 | 0.32 – 1.3 | 32 | (80) | (120) |

Lambeth et al [36] concluded that although all HVDC outdoor insulators are susceptible to pollution flashover, the requirements for converter station insulators and wall bushings in particular are most onerous. Regular maintenance by hand washing and using of silicone grease have shown benefits.

On large-scale introduction of silicone rubber composite insulators onto AC networks, similar age and performance related questions were tabled. Since 1991 to date, the silicone rubber insulators have delivered zero electrical or mechanical breakdown and we expect this performance to continue into the future.

### 4.1.6 Electric Fields and Corona Effects

The collection of case study results for 275 kV, 400 kV and 765 kV Transmission Lines are provided in tables from 4-8 onwards.

**Table 4-8: Case Study 1: 275 kV Twin Zebra HVAC Transmission Line**

Phase Conductor Diameter = 28.62mm

Midspan height of phase conductors = 7,2m

Midspan height of earth wires = 13,5m

DC operating voltage = 500 kV

| **Category** | **Operating HVAC** | **Operating HVDC** |
|---|---|---|
| **Max Surface Gradient (kV/cm)** | 275 kV | 500 kV |
| R phase | 14.02 | 36,90 |
| W Phase | 14,63 | 8,08 |
| B Phase | 14,02 | -36.90 |
| Earthwire 1 | 4,44 | 20,15 |
| Earthwire 2 | 4,44 | 20,15 |
| | | |
| **Audible Noise**<br>L 50 wet (dBA) | 42,3 < 53,1 upper limit | 41,3 |
| L50 Fair (dBA) | 17,3 | 47,3 |
| | | |
| **Radio Noise @ 500 kHz** | | |
| L50 Wet dBA | 60,4 < 72 upper limit | 47,7 |
| L50 Fair dBA | 43,4 | 60,7 |
| | | |
| **Electric Field kV/m** | | |
| Within servitude | 7,9 < 10 upper limit | 27,3 |
| At edge of servitude | 1,4 < 5 upper limit | 5,4 |
| | | |
| **Magnetic Field (μT)** | 68,47 < 100 upper limit | 86,61 |

Here we note the following:

- The WET audible and radio noise levels are reduced under DC potential
- The levels for audible and radio noise are within the overall AC limits

- The magnetic fields are easily within the acceptable AC limit
- There exists a substantial increase in conductor surface gradient and electric field within the servitude when under DC potential.
- At the edge of the servitude, the DC field effect reduces to that of the acceptable AC limit
- Shield wire corona generation is very severe and may impact on powerline carrier systems. This finding concurs with Moyo's laboratory investigation [25] that showed corona current generation in the earthwire even when no voltage is applied on the shield wire itself. Moyo ascribed this effect to induction. Without shield wire – power line carrier systems, the bonding of the shield wire at every tower will reduce the overall earth wire induced currents.

**Table 4-9: Case Study 2: 400 kV Twin Dinosaur HVAC Transmission Line**

Phase Conductor Diameter = 35.94mm

Midspan height of phase conductors = 8,1m

Midspan height of earth wires = 18,3m

DC operating Voltage = 500 kV

| Category | Operating HVAC | Operating HVDC |
|---|---|---|
| **Maximum Surface Gradient (kV/cm)** | 400 kV | 500 kV |
| R phase | 15,43 | 29,53 |
| W phase | 16,11 | 5,33 |
| B Phase | 15,43 | -29,53 |
| Earthwire 1 | 4,24 | 16.56 |
| Earthwire 2 | 4,24 | 16.56 |
| | | |
| **Audible Noise** | dBA | dBA |
| L50 Wet | 51,3 < 53 | 35,4 |
| L50 Fair | 26,3 | 41,4 |
| | | |
| **Radio Noise @ 500 kHz** | dBA | dBA |
| L50 Wet | 65,3 < 72 | 39,4 |
| L50 Fair | 48,3 | 52,4 |

| | | |
|---|---|---|
| | | |
| **Electric Field kV/m** | | |
| Within servitude | 10,1 < 10 | 24,1 |
| At edge of servitude | 1,4 | 3,7 |
| **Magnetic Field** | 52,04 μT < 100 | 66,22 μT |

All the findings for case 1 remain. In addition, we note the effect of the larger diameter conductor. For the larger diameter conductor, we record some attenuation in the levels of conductor surface gradient and electric field.

**Table 4-10: Case Study 3: 400 kV Triple Tern HVAC Transmission Line**

Phase Conductor Diameter = 27,0mm

Midspan height of phase conductors = 9,3m

Midspan height of earth wires = 19,4m

DC operating Voltage = 500 kV

| Category | Operating HVAC | Operating HVDC |
|---|---|---|
| **Maximum Surface Gradient kV/cm** | 400 kV | 500 kV |
| R Phase | 15,73 | 28,87 |
| B Phase | 17,03 | 7,77 |
| W Phase | 15,73 | -28.87 |
| Earthwire 1 | 5.04 | 19,43 |
| Earthwire 2 | 5.04 | 19.43 |
| | | |
| **Audible Noise** | dBA | dBA |
| L50 Wet | 46,2 < 53,1 | 34,8 |
| L50 Fair | 21,2 | 40,8 |
| | | |
| **Radio Noise @ 500 kHz** | dBA | dBA |
| L50 Wet | 60.8 < 72 | 35,5 |

| | | |
|---|---|---|
| L50 Fair | 43,8 | 48,5 |
| | | |
| **Electric Field kV/m** | | |
| Within servitude | 8,7 < 10 | 21,7 |
| At edge of servitude | 1,3 < 5 | 3,7 |
| | | |
| **Magnetic Field** | 40,15 μT | 66,84 μT |

In case3 and with a higher bundle order; the attenuation benefits improve whilst all the findings for cases 1 and 2 sustains. A higher conductor bundle order supports a lower surface gradient profile and a lower electric field profile.

**Table 4-11: Case Study 4: 400 kV Triple and Quad Zebra HVAC Transmission Line**

Phase Conductor Diameter = 28,62mm

Midspan height of phase conductors = 8,1m

Midspan height of earth wires = 13,8m

DC operating Voltage = 500 kV

| **Category** | **Triple Zebra** | **Quad Zebra** | **Quad Zebra** |
|---|---|---|---|
| | **HVAC** | **HVAC** | **HVDC** |
| | **400 kV** | **400 kV** | **500 kV** |
| **Maximum Surface Gradient kV/cm** | | | |
| R Phase | 15,29 | 12,54 | 23,99 |
| W Phase | 15,93 | 13,43 | 6,01 |
| B Phase | 15,29 | 12,54 | -23.99 |
| Earthwire 1 | 8,55 | 9,28 | 28,02 |
| Earthwire 2 | 8,55 | 9,28 | 28,02 |
| | dBA | dBA | dBA |
| **Audible Noise** | 3 zebra | 4 zebra | 4 zebra DC |
| L50 Wet | 45,2 < 53,1 | 34,6 < 53,1 | 32,1 |
| L50 Fair | 20,2 | 9,6 | 38,1 |
| | | | |

| | | | |
|---|---|---|---|
| **Radio Noise @ 500 kHz** | dBA | dBA | dBA |
| L50 Wet | 59,5 < 72 | 48,2 < 72 | 28,5 |
| L50 Fair | 42,5 | 31,2 | 41,5 |
| | | | |
| **Electric Field kV/m** | | | |
| Within servitude | 10,3 | 8,9 | 27,2 |
| At Edge of servitude | 1,5 | 1,1 | 3,5 |
| | | | |
| **Magnetic Field** | 41,17μT | | 66,93 μT |

The higher conductor bundle order further attenuates the conductor surface gradient profile and also that of the electric field. Under DC, we record that the environmental electrical and corona effects are reduced when compared to AC. The only question we have is whether the DC field levels are acceptable.

**Table 4-12: Case Study 5: 765 kV six bundle zebra HVAC Transmission Line**

Phase Conductor Diameter = 28,62 mm

Midspan height of phase conductors = 15m

Midspan height of earth wires = 27,6m

DC operating Voltage = 500, 600 and 800 kV

| **Category** | **765 kV HVAC** | **@ 500 kV DC** | **@ 600 kV DC** | **@ 800 kV DC** |
|---|---|---|---|---|
| **Max Surface Gradient kV/cm** | | | | |
| R Phase | 16,33 | 15,73 | 18,88 | 25,17 |
| W Phase | 17,39 | 4,41 | 5,29 | 7,06 |
| B Phase | 16,33 | -15,73 | -18,88 | -25,17 |
| Earthwire1 | 11,95 | 21,76 | 26,12 | 34,82 |
| Earthwire 2 | 11,95 | 21,76 | 26,12 | 34,82 |
| | | | | |
| **Audible Noise** | dBA | dBA | dBA | dBA |
| L50 Wet | 54,7 | 18,8 | 25,6 | 36,4 |

| | | | | |
|---|---|---|---|---|
| L50 Fair | 29,7 | 24,8 | 31,6 | 42,4 |
| | | | | |
| **Radio Noise @ 500 kHz** | dBA | dBA | dBA | dBA |
| L50 Wet | 61,8 | 11,5 | 18,4 | 29,1 |
| L50 Fair | 44,8 | 24,5 | 31,4 | 42,1 |
| **Electric Field kV/m** | 765 kV HVAC | @ 500 kV DC | @ 600 kV DC | @ 800 kV DC |
| Within Servitude | 9,8 | 13,3 | 16,0 | 21,3 |
| Edge of servitude | 2.0 | 3.0 | 3,6 | 4,7 |
| | | | | |
| **Magnetic Field μT** | 55,59 | 83,13 | 83,13 | 83,13 |

With a higher order conductor bundle arrangement and high height above ground, we record very acceptable levels are achieved when the 765 kV line is upgraded to DC. Once again, for the case of conversion to DC, we need to find acceptable limits for the conductor maximum surface gradient (kV/cm) and for the electric fields (kV/m); both within and at the edge of the servitude need to be found. The Canadians do report very high number of unexplained flashovers in the presence of high conductor surface gradients. An interesting finding is that at the edge of the servitude, in all cases for upgrade to DC, the final attenuated electric field is less than the AC limit of 5 kV/m. The electric field profiles are provided in appendix F, with published paper under reference [37].

A very important point to note is the shield wire gradient. In all the DC upgrade cases, it is substantially higher than the AC equivalent. This may impact on the use of earth wire attached fibre optic cables or power line carrier systems.

**DC Biased Medium Air Gap Breakdown for Lightning Impulses**

In DC systems, we are afforded the benefit of no switching impulses given the absence of circuit breakers and links; where all operating is done swiftly and accurately with power electronic thyristor. However, the line is exposed to lightning and back flashover of the air gap from pole to either overhead earthwire or from pole to tower across the air gap created by insulator string assemblies. In these cases, we can model the critical air gap created by the insulator string assemblies as being of rod to plane configuration.

In general terms, the rod to plane air gap withstand capability is given as 2 kV/cm or 100 kV per 50cm or 200 kV/m and for the case of impulses, we have 20cm for every 100 kV [500 kV/m]. On the 400 kV structures, the recorded air gap clearance is approximately 3,2m. For the case of pure DC voltage, a 3,2m gap has a withstand capability of 640 kV and an impulse capability of 1,6 MV. If we add the pure impulse onto a DC biased conductor, we get for the case of the positive DC polarity a reduction in the impulse flashover voltage (lightning) and for the case of negative DC polarity, an increase in the impulse flashover voltage for given air gap lengths. We would need to demonstrate this experimentally; a constraint being the availability of testing facilities.

**DC Biased Long Air Gap Breakdown for Servitude Fires**

In the presence of servitude fires, the voltage gradient between pole and earth at various points on the line is given in table 4-13.

**Table 4-13: Calculated Voltage Gradients for a 400 kV DC Typical Line**

| Section Spacing | Voltage Gradient kV/m |
|---|---|
| Between pole and overhead earthwire = 7,65m | 52,28 kV/m |
| Between pole and ground at midspan = 8,4m | 47,62 kV/m |
| Between pole and metallic earth return= 8,5m | 47,06 kV/m |

**Space Charge Considerations**

The voltage gradient is large for all for three cases. For a lower probability of breakdown, we require voltage gradients less than 15-18 kV/m [38]. For this case, long air breakdown in the presence of servitude fires is expected and would be no different to that currently experienced with HVAC. In both cases, the solution to servitude fires is well within management control and no technical solution can be offered. The fires would need to be managed by vegetation clearing.

Servitude fire caused faults continue to occur on the Apollo – Cahorra Bassa 533 kV line; pole to earth and these faults do not present themselves as voltage dips to customer's load. Quality of supply is enhanced under DC technology. This whole chapter of faults, fault management and self-healing capability of DC requires further in depth research and investigations. This work would extend to lightning, fires, birds; all being the typical fault causes under AC technology.

### 4.2 Discussion of results with respect to the hypothesis

The study results concur with that from the literature review. The areas of further research pertain to the acceptable levels for maximum conductor surface gradients and for the prevailing DC electric fields including that of space charge effects. The corona effects of audible noise and radio interference are well within the acceptable AC limits. However, we note that the fair audible noise values appear very low as compared to similar calculations using the EPRI workstation program. In case 2, using the EPRI workstation, we get L50 Fair for 400 kV HVAC as 43,2 dBA as compared to the BPA low value of 26,3 dBA. In the same case, under 500 kV DC, the L50 Fair level from EPRI is 58,5 dBA as compared to BPA's 41,4 dBA. For all the other parameters, there exists good agreement between the EPRI and BPA programs. The low fair weather values are a known issue with the BPA program. It is recommended that the EPRI workstation be employed and that full-scale tests be performed to verify the calculated results.

Further, it is noted that the DC conductor surface gradient is much higher than the equivalent AC gradient and this could lead to higher levels of radio interference. For the twin dinosaur and quad zebra configurations at 500 kV DC, the BPA calculations show acceptable RI levels. Carl Axel Rosen et al [29] in a presentation to Eskom recommended maximum DC levels of 26 kV/cm for the conductor bundle gradient. This satisfies the quad zebra operation at 500 kV DC but is marginally lower for the twin dinosaur operating at 500 kV DC. EPRI [24] records that although surface gradient is a sensitive parameter for predicting radio interference, this is less so for DC lines than for AC lines. The Dallas test line with surface gradient of 28,05 kV/cm produced a RI level of 65 dBA and the Shiobara Test line with a surface gradient of 25 kV/cm produced a RI level of 57 dBA; both within the acceptable level of 72 dBA [24]. Typical maximum conductor surface gradients in kV/cm for some operating DC lines are given in table 4-14 [39].

**Table 4-14: Typical Maximum Conductor Surface Gradient (kV/cm) [39]**

| HVDC Scheme | Gradient kV/cm |
|---|---|
| Apollo – Cahora Bassa +/-533 kV | 20,6 |
| Inga – Shaba +/- 500 kV | 23,5 |
| Des – Cantons +/- 450 kV | 20,6 |
| Sylmar – Oregon +/- 500 kV | 25,5 |
| Henday – Dorsey +/- 500 kV | 27,4 |
| Adelanto – Mountain +/- 500 KV | 20,0 |
| Itaipu +/- 600 kV | 24,9 |

For the case of electric fields, Cigre Working Group SCB2 –05 (JWG17) [40] recommends a maximum of 40 kV/m for electric fields within the servitude. In all cases studied, the electric field reduces to very low acceptable levels at the edge of the servitude. This effect can be seen on all the profiles of the case studies as presented in Appendix F.

Nayak's [40] investigations, included in the Cigre Working Group report have provided the following typical values:

- Beneath a 500 kV HVDC line – 30 kV/m
- In front of a TV/VDU – 20 kV/m
- Walking on non conducting carpets – 500 kV/m
- German DIN standard – 40 kV/m ( 60 kV/m permitted for exposures up to 2 hours)
- Average threshold of detection to DC field – 45 kV/m
- +/- 600 kV Itaipu HVDC line design level – 40 kV/m
- +/- 500 kV Indian HVDC lines – 40 kV/m saturated conditions, 20 kV/m for normal fair weather and 27 kV/m for normal wet weather.
- For AC lines; (without space charge) – 10 kV/m

For both the twin dinosaur and the quad zebra 400 kV lines configured to operate at 500 kV DC, the electric field levels can be considered acceptable. The static electric field of DC is less onerous than the time varying electric field of AC. With DC, no induced effects are conveyed to humans and animals within the powerline servitude.

### 4.3 Expected impact of results

For the present, a new strategy and option is provided to power system planners for their study into increasing power transfers through critical power corridors. The boundary conditions introduced make selective application of the introduction of HVDC technology economical. The main costs of sending end rectification, receiving end inversion and new reinsulation of the transmission line for an almost 3 to 4 fold increase in power transfer with assured stability would be economically justified with recycled transmission line and servitude assets. These detailed economic benefits would need to be done for each specific case study. The longer the transmission distance, the greater would be the benefits.

### 4.4 Concluding highlights

The conversion proposals for 275 kV and 400 kV structures show excellent benefits in terms of higher power transfers. For the case of the 765 kV structures, the current design is very suitable for conversion to DC and 800 kV is recommended. At 800 kV, each 765 kV line could bulk transport some 6 GW over the 1200-km from Alpha to Omega.

The concluding highlight from the research study has shown the substantial increase in power transfers for the selected operating voltages and transmission line configurations. Equally important are the power loss savings and the stability enhancement emanating when DC is operated in parallel with HVAC circuits.

### 4.5 Implications for future study

The first pass investigations into electrical and corona effects for the upgrading of HVAC transmission lines for HVDC application are promising. Audible noise in fair weather requires further work; correlation of study results with local experimental work. It is recommended that the composite tower window consisting of both polarities separated by a metallic earth return be tested at full-scale for the full operating range for the DC voltage. For the tests, all the electrical and corona effects are to be recorded long term and compared to that predicted by both the literature review findings and that of computer based calculations. The test work should be extended to cover typical servitude caused transmission line faults.

This summary concurs with the work done by Lambeth, Maruvada and Dallaire at Hydro Quebec [36]. The corona generated electric field and ion environment in the vicinity of DC transmission lines is rather difficult to characterise either analytically or experimentally. Some presently applied analytical techniques apply under idealised conditions and cannot take into account the prevailing weather conditions, wind conditions and ion displacement and conductors operating near corona onset [41]. Long term experimental studies at full scale are required. More experimental and analytical studies are required to develop prediction methods and establish permissible levels.

A recommendation emanating in the conclusion of this research is to employ the lower level voltage of the allowable range of operating voltages as the DC nominal voltage. The key parameters at this lower level operating voltage are well within the acceptable range. Thus, if implemented, the commercial DC transmission lines could well serve as experimental lines for the collection of long term operating data and experience. This strategy could serve both purposes; allow more power transfers whilst simultaneously gathering important data and environmental effects. The strategy should be considered by power system planners.

# Chapter 5: Recommendations and Conclusion

Starting with the various boundary conditions for motivating uprating of HVAC transmission lines to HVDC application, we have the following summary as presented in the published papers of this thesis. This summary forms the basis for the recommendations emanating from this study and is presented in 5.1.

## 5.1 Summary of the Recommendations for the Uprating of HVAC Transmission Lines for HVDC Application

1. For HVAC transmission lines where the thermal capacity is close to the surge impedance loading, do nothing.
2. For HVAC transmission lines where the thermal capacities is higher than surge impedance loading but of smaller bundle order; add FACTS technologies for higher power transfers.
3. For HVAC transmission lines where the thermal capacities is much higher than surge impedance loading and of larger bundle orders such as quad or six bundle conductor, then promote uprating to HVDC application. For longer distances, the benefits would be the greatest in terms of line loss savings for higher bulk power transfers.
4. Promote re-insulation of the transmission line using new technology silicone rubber composites. For the limited connecting length between conductor and tower, adequate high creepage insulation is achievable.
5. Select the HVDC operating voltage such that all the electrical and corona field effects are within generally accepted limits as experienced locally and internationally.
6. The case of twin conductor bundle at 275 kV, quad conductor bundle at 400 kV and six conductor bundle at 765 kV was found to be the minimum boundary condition for promoting HVAC transmission line up rate to HVDC.
7. The best candidate line was found to be the 765 kV HVAC six bundle transmission line. This is the most inefficient transmission line design for HVAC application as most of the installed phase conductors remain unemployed for power transfer. The tower structure has adequate room to accommodate full 800 kV HVDC voltages. One 765 kV transmission line from the Mpumalanga Generation Source (Alpha Substation) should be up rated to 800 kV HVDC; terminating at Omega Substation outside Cape Town. The transmission distance of 1200 -1500 km is ideal for application and some 6000 MW can be safely transferred.

The use of bi-directional valves [42] can be considered and the power flows for the entire scheme can be engineered to be reversible.

8. The second best candidate is found to be the quad 400 kV HVAC transmission line. Here we can limit the DC operating voltage to 300 kV HVDC for short length lines (300km) and 400 kV for medium length lines (600 km) and achieve all the electrical effects to be within the acceptable range. Full 3000 MW is transferable by the bi-pole configuration with 1500 MW on monopole metallic earth return. This capacity fits in with the power system reserve requirements.

   For longer distances or smaller bundle orders; further investigation at full 500 kV operating voltage should be considered. The 500 kV HVDC does present much higher electrical field effects but in an area that could still be within acceptable environmental safety. Here full scale testing with varying environmental effects would be necessary to determine conditions of acceptability, safety and degree of confidence. For now, the 500 kV operating voltage is not recommended.

   The similar recommendation applies to the 275 kV twin conductor HVAC transmission line. Full operating voltage at 500 kV HVDC would be ideal and could cover much longer distances say up to 1000 – 1200 km. However, at 500 kV HVDC, we get much higher electrical field effects and again in an area that could be acceptable. The same full scale testing for the 500 kV HVDC case is proposed. For the present, 275 kV HVAC operating at 250 – 300 kV HVDC is recommended; for medium length power transfer distances of 600km. All the recommendations were published in conference proceedings. Copies of the papers produced under this study are provided in Appendix H.

## 5.2 Predicted Performance when HVAC Power Lines are Uprated for HVDC Application

From the research study, we can draw the following predicted conclusions when HVAC power lines are converted and up rated for HVDC application. The historical performance of the HVAC lines can be sourced from the utilities performance reports [43].

The predicted performance under HVDC operation will be as follows:

1. TV Interference – This will not be an issue as ion migration for distances beyond the servitude boundary will approach zero.

2. Positive Corona – this will contribute to radio interference; again at the edge of the servitude and beyond the levels calculated are very low and will be acceptable.
3. Audible Noise – again the contributor will be positive corona; this will be acceptable along the line route; higher levels could be at the converter station and will emanate from the converter transformers.
4. Pole to ground faults for the case of servitude fires will occur at mid-span; protection and converter control to be designed to manage these faults; self healing using voltage management could be a strategy. An outcome will be enhanced quality of supply as compared to AC systems.
5. Given the high electric fields in the air gap of the tower windows, it is expected that bird streamers will cause electrical faults. The installation of bird guards is recommended and should be included in the scope of the re-insulation proposal.
6. Silicone rubber insulators will deliver the higher creepage for the given connecting length; 30mm/kV affordable and is required. The hybrid toughened glass for DC application and coated with silicone rubber will make an ideal design for external insulation.

   Silicone rubber technology for external insulation is now an acceptable and recommended insulator for external insulation of DC systems. The technology has matured. Work done on silicone rubber insulators corona testing [44] and artificial contamination [45] testing under laboratory conditions show that the new DC silicone rubber operates well within the specified limits and was recommended for the uprating of the Pacific DC Intertie. To date, the installed insulators are performing well. Back at Eskom, a few samples of these insulators are operating with no incidents. In the case of radio interference tests, a 40 dB RIV level was recorded for the positive 550 kV pole voltage whilst a 32 dB RIV level was recorded for the negative 550 kV pole voltage. Visual corona extinction was achieved at +555 kV for the positive pole whilst -565 kV was recorded for the negative pole. In the case of the contamination tests, no flashover occurred for three consecutive tests. Here 515 kV was sustained for a salt deposit density (SDD) of 0.08 and for a non soluble contaminant deposit density (NSDD) of 0.48 mg/square cm.

Additional predictions include:

7. With SiR insulators or DC toughened glass, no added problems such as ion migration and thermal heating are expected under DC potential.

8. DC with impulse loading provides a higher air gap critical withstand level; impulses will be less onerous than equivalent AC.
9. The overhead earth-wires will help to attenuate and reduce the space charge field effects.

## 5.3 Proposal for Implementation

The national and regional grid diagrams are provided in appendix D. We have three proposals from this study.

1. Up rate one existing 275 kV circuit into KwaZulu Natal; starting in Northern Natal and terminating equally between Durban and Richards Bay: 400 km at 300 kV for 516 MW x 2 [1000 MW] power transfer.

2. Up rate one existing 400 kV circuit from Matimba Power Station to Midas Substation: 400 km at 400 kV for 1500 MW x 2 [3000 MW] power transfer.

3. Plan to up rate one existing 765 kV circuit from Alpha Substation to Omega Substation: 1200 km at 800 kV for 4128 x 2 MW [8256 MW] power transfer; consider bi-directional values for optional power transfer directions. This could form part of the next generation nuclear strategy; having the choice to move large bulk power in any direction depending on the contingency on hand.

For an estimate on expected costs of the proposal, we reference the last commissioned project in China.

The Three Gorges project has recently been commissioned in China. The first HVDC circuit built was a 500 kV, 3000 MW bipole. This was commissioned in 28 months at a cost of US$360m [8].
The 275 kV KwaZulu Natal conversion proposal is estimated to cost USD 200m; the 400 kV Matimba – Midas conversion proposal USD 400m and the 800 kV Alpha to Omega conversion proposal USD 600m. The cost data provided is a best guess and more accurate estimations would be required once the functional specifications are prepared.

The strength of the HVDC proposal is resident in the high current, high voltage capability of the power electronics. In addition, the reuse of existing assets to maximum capacity and the absence of additional servitudes need to be economically valued and added as net benefits emanating from the uprating exercise.

## 5.4 Recommendations for Further Study

Investigate and prepare IEC specifications for external insulation under DC potential. The work commenced by Vosloo et al [46] includes a comment on the need for a three times factor for the case of DC minimum specific creepage distance (mm/kV). This is attributed to the electrostatic catch and absence of zero crossings in the leakage currents for DC systems. However, service experience of composite insulators as reported in Cigre Electra publication No.161 [47] indicates that no such correction factor is justified. Thus, more work, under IEC leadership, is required for DC external insulation standards.

Integrating HVDC into an existing HVAC interconnected power system requires extensive planning and modelling for all cases of steady state stability, transient and dynamic stability. At China Southern in Guangzhou, we were invited to explore the power system planning laboratory; a collection of real time digital simulators supported by PSCAD [48,49] calculating tools. The RTDS was shown to be the ideal tool for the power system studies; preparing both the technical proposals and also the commissioning parameters for the new incoming HVDC. In the time period between the planning proposals to that of real time commissioning, the real time system is continuously monitored for behaviours that follow normal power system faults with and without the HVDC in service. This is powerful modelling and adds great confidence to the planning proposals.

## 5.5 Conclusion

The key constraint of this research work was the lack of full scale testing facilities for high voltages of direct current. We visited all the South African test facilities and found no high voltage DC capability. We called upon international partners; Electric Power Research Institute of Lennox, New York, USA; State Grid of China Electric Power Research Institute; Swedish Test and Research Institute of Ludvika, Sweden and Power Grid of India, New Delhi. In all cases we found either old facilities that were run down either in test equipment or measuring equipment or alternatively, new facilities are proposed and are currently under development. We opted to do some work at the EPRI facilities in the USA but this has not materialised as much refurbishment work is required prior to testing. The option to employ the STRI laboratory in Ludvika was also considered; this high cost of contractual work formed part of the motivation to seek our own testing capability; to be located both at the University of Kwa-Zulu Natal HVDC Centre and at the National Electrical Test and Research Facility of the South African Bureau of Standards. Aside from the full scale testing capability, the current laboratory Cockcroft Walton HVDC Generator was employed to do small air gap experimentation.

Extrapolating the small air gap experimentation results to that of large air gaps as in full scale testing showed no correlation. It was best to stop the extrapolation process and rather evaluate the results as per the small air gap model. The interesting finding is that the laboratory based corona cage concept can be extended to form part of the transmission line tower configuration such that the corona energy could be captured and routed to the base of the tower and either employed directly or in association with other renewable energy sources as a potential energy source for on route power supplies. On route power supplies such as repeaters for telecommunications circuits, small rural lighting loads such as schools and clinics, safety lighting at river or rail or road crossings etc could be practically achieved. This work is recommended for the proposed 800 kV HVDC transmission that is being planned for Continental Africa. Further reading on the state of the art for tapping power from HV transmission lines is given by Nicolae et al [50].

Finally in the development of the new full scale laboratory facilities at the HVDC Centre, it is recommended that adequate test sources be made available for simultaneous bipolar test and measurement and for high current capacity with high voltage capability to continuously test and measure impact on external insulation. The continuous exposure of external insulation to high DC voltages is necessary to promote the electrostatic precipitation of atmospheric dirt in the vicinity of the electrode and the insulator assembly.

For the dissertation on hand, the lack of the full scale testing is considered not critical given the availability of multiple software modules for calculating and repeating the calculations for each parameter under study. These software tools were from different sources and their results compared favourably with that measured during normal operating experiences even under

HVAC conditions. The calculations and results presented in both the appendix and the body of the report demonstrates the repeatability of the work done. In addition, under real operating conditions, the transmission lines experience a multitude of environmental variables and perform differently under the influence of the different variables. Thus both in service operating experience and full scale simulated laboratory results would form the ideal basis for further study and optimization of the design proposals. This solution would develop with time and experience. For the present day, the first pass study is adequate to commit a circuit or two for commercial operation; to start to gather the in field operating experience. A cautionary note for DC operations is to recommend that the transmission line be maintained employing live technology practices. In the case of the metallic earth return path; all the conductors in the bundle will carry induced currents and voltages and must be considered live at all times. In the case of insulator maintenance, full live technology tools and equipment must be employed at all times; maintaining the critical air gaps between conductor and tower body at all times. These air gaps will be under extreme electric field exposure and any disturbance either by bridging or by the addition of impurities could lead to air gap breakdown.

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## Appendices

## Appendix A: Summary of HVDC Schemes Commissioned from 1954 to Date

This summary shows typical HVDC schemes providing operating information such as power transfers, power transmission distance and operating voltages that could be considered in this research proposal . Table A1 provides a collection of early HVDC schemes as based on mercury valve technology. Table A2 provides a collection of HVDC schemes employing thyristor valve technology.

**Table A1: Early Collection of HVDC Schemes Based on Mercury Arc Valve Technology**

| CCt | HVDC System | Comm Date | Trans. Distance (km) | | | Rated Voltage kV | Rated Capacity (MW) |
|---|---|---|---|---|---|---|---|
| | | | O/H | Cable | Total | | |
| 1. | Gotland / Sweden | 54/70 | - | 96 | 96 | 150 | 30 |
| 2. | Cross Channel 1 (GB-F) | 61 | - | 65 | 65 | ±100 | 160 |
| 3. | Volgograd – Donbass | 62/65 | 470 | - | 470 | ±400 | 720 |
| 4. | Konti / Skan (DK – S) | 65 | 95 | 85 | 180 | 250 | 250 |
| 5. | Sakuma (Japan) | 65 | - | - | - | 125 | 300 |
| 6. | New Zealand (NZ) | 65 | 570 | 39 | 609 | ±250 | 600 |
| 7. | Sardinia / Italian | 67 | 292 | 121 | 413 | 200 | 200 |
| 8. | Vancouver Pole 1(Canada) | 68/69 | 41 | 33 | 74 | ±260 | 312 |
| 9. | Pacific Intertie (US) | 70 | 1362 | - | 1362 | ±400 | 1600 |
| 10. | Nelson River Bipole 1 (Canada) | 73/77 | 890 | - | 890 | ±450 | 1620 |
| 11. | Kingsnorth (GB) | 74 | 0 | 82 | 82 | ±266 | 640 |

**Table A2: Collection of HVDC Schemes employing Thyristor Valve Technology**

| CCT | HVDC System | Comm Date | Transmission Distance (km) O/H | Cable | Total | Rated Voltage (kV) | Rated Capacity (MW) |
|---|---|---|---|---|---|---|---|
| 12. | Eel River (CND) | 72 | - | - | - | 80 (2) | 320 |
| 13 | Shagerrak (DK-N) | 76/77 | 113 | 127 | 240 | ±250 | 500 |
| 14 | David A. Hanil (US) | 77 | - | - | - | 50 | 100 |
| 15 | Cahora Bassa / Apollo | 77/79 | 1414 | - | 1414 | ±533 | 1920 |
| 16 | Vancouver Pole 2 | 77/79 | 41 | 33 | 74 | -280 | 370 |
| 17 | Square Butte (US) | 77 | 749 | - | 749 | ±250 | 500 |
| 18 | Shin Shinano (Japan) | 77 | - | - | - | 125 (2) | 300 |
| 19 | Nelson River Bipole 2 | 78 | 930 | - | 930 | ±450 | 900 |
| 20 | Cu (Underwood/Minneapdis) US | 79 | 710 | 200 | 910 | ±400 | 1000 |
| 21 | Hokkaido / Houshu (J) | 79/80 | 124 | 44 | 158 | 250 | 300 |
| 22 | Acaray (PY – BR) | 81 | - | - | - | 26 | 50 |
| 23 | EPRI Compact Stri (US) | 81 | - | 0.6 | 0.6 | 100/400 | 100 |
| 24 | Vyborg (USSR – Finland) | 82 | - | - | - | ±85 (3) | 170 |
| 25 | Inga Shaba (DRC) | 82 | 1700 | 0 | 1700 | ±500 | 560 |
| 26 | Dumrohr (A) | 83 | - | - | - | ±145 | 550 |
| 27 | Gotland 2 Sweden | 83 | 7 | 91 | 98 | 150 | 130 |
| 28 | Eddy Co (USA) | 83 | - | - | - | 82 | 200 |
| 29 | Itaipu (BR) | 84 | 783/806 | - | 783/806 | ±300 | 1575 |
| 30 | Chateauguary (CDN) | 84 | - | - | - | 140 | 1000 |
| 31 | Itaipu (BR) | 85/87 | 783/806 | - | 783/806 | ±600 (2) | 6300 |
| 32 | Oklaunion (US) | 84 | - | - | - | 82 | 200 |
| 33 | Pacific Intertie (US) | 85 | - | - | - | ±500 | 400 |
| 34 | Wien Sud Ost (A) | 87 | - | - | - | 145 | 550 |
| 35 | Corsica Tap (F) | 86 | - | - | - | 200 | 50 |
| 36 | Greece – Bulgaria | | | | | | 300 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 37 | Madawaska (CND) | 85 | - | - | - | 144 | 350 |
| 38 | Miles City (US) | 85 | - | - | - | 82 | 200 |
| 39 | Walker Co. (US) | 85 | 256 | 0 | 256 | ±400 | 500/1500 |
| 40 | Cross Channel 2 (GB-F) | 85/86 | 0 | 72 | 72 | ±270 (2) | 2000 |
| 41 | Kanti Skan 2 (DKS) | 88/89 | 95 | 85 | 160 | 250 | 270 |
| 42 | Ekibastus Centre (USSR) | 85/88 | 2400 | - | 2400 | ±250 | 600 |
| 43 | Store Baelt (DK) | 89/90 | 35 | 30 | 55 | 280 | 350 |
| 44 | Skagerrak 2 (DK-N) | 88/89 | 113 | 127 | 240 | 300 | 320 |
| 45 | Inter mountain (US) | 87 | 794 | - | 794 | ±500 | 1600 |
| 46 | Liberty Mead (US) | 89/90 | 400 | - | 400 | ±364<br>±500 | 1600<br>2200 |
| 47 | Nelson River Bipole 3 (CDN) | 92/97 | 930 | - | -930 | ±500 | 2000 |
| 48 | Chicoasen (Mex) | 85/90 | 720 | - | 720 | ±500 | 900/1800 |
| 49 | Yukatan – Mexico City | | | | | | |
| 50 | Quebec – New England | 86/92 | 175/3 75 | - | 175/3 75 | ±450 | 690/2070 |
| 51 | Des Cantons – Camerford | 86 | 175 | - | 175 | ±450 | 690 |
| 52 | Sidney (US) | 86 | - | - | - | 56 | 200 |
| 53 | Blackwater (US) | 85 | - | - | - | 56 | 200 |
| 54 | Highgate (US) | 85 | - | - | - | 56 | 200 |
| 55 | Sacoi – 2 (Italy) | 89 | | | | 200 | 300 |
| 56 | Pacific Intertie 2 (US) | | | | | ±500 | 1100 |
| 57 | Gezhouba – Nan Qiao (China) | 87/91 | 1080 | - | 1080 | ±500 | 1200 |
| 58 | Rihand – Delhi (India) | 87 | 1000 | - | 1000 | ±500 | 1000 |
| 59 | Uruguaiana (BR – Argentina) | 86/87 | | | | | 50 |
| 60 | Cameford – Sandy Pond | 90 | 200 | | | | 1400 |
| 61 | Vindhyachal (India) | 88 | - | - | - | 70 | 250/x2 |
| 62 | Gotland 3 – Sweden | 89 | - | 98 | 98 | 150 | 130 |
| 63 | South Finland East Sweden | 89/90 | 35 | 185 | 220 | 350 | 420 |
| 64 | Kii Channel (Japan) | 2000 | | | | 250<br>500 (o) | 1400<br>1400 (o) |
| 65 | China – 3G Multiple 500 kV 3 GW Bipoles | 2003 | ±1000 | - | ±1000 | 500 | 3000 |

## Appendix B: Comparison of Performance, HVAC vs. HVDC Technology as seen by Eskom, South Africa.

### Transmission Line Performance

### Source of Information: Eskom Transmission System Performance Reports

On average, Eskom's 765 kV transmission lines experience one fault per year, generally fire or electrical storm induced. For the case of 800 kV HVDC, similar performance is predicted. For the case of 400 kV and 275 kV HVAC transmission lines, several faults occur. For the 12 month moving indictor and expressed as faults/100km, the performance of Eskom South Africa's 400 kV and 275 kV HVAC transmission lines is given in figures B1 to B3 respectively, with causes of faults presented in figures B2 and B4 respectively.

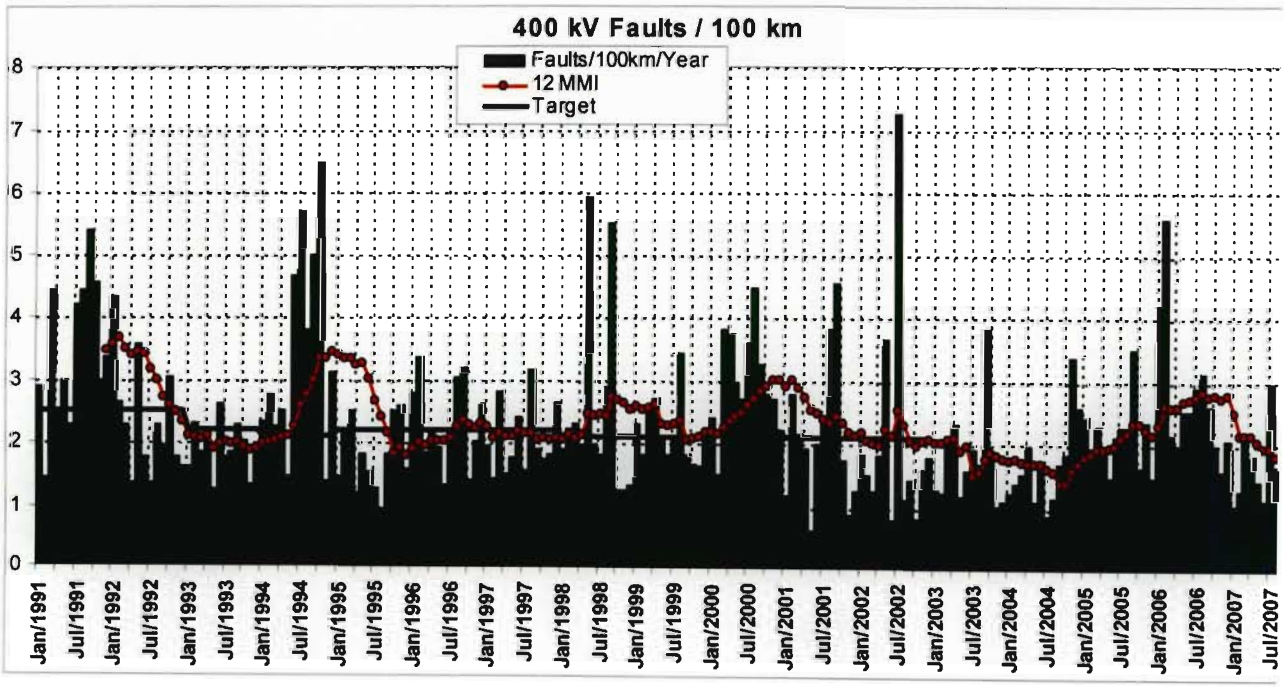



**Figure B1: 400 kV HVAC Transmission Line Performance expressed as faults/100km**

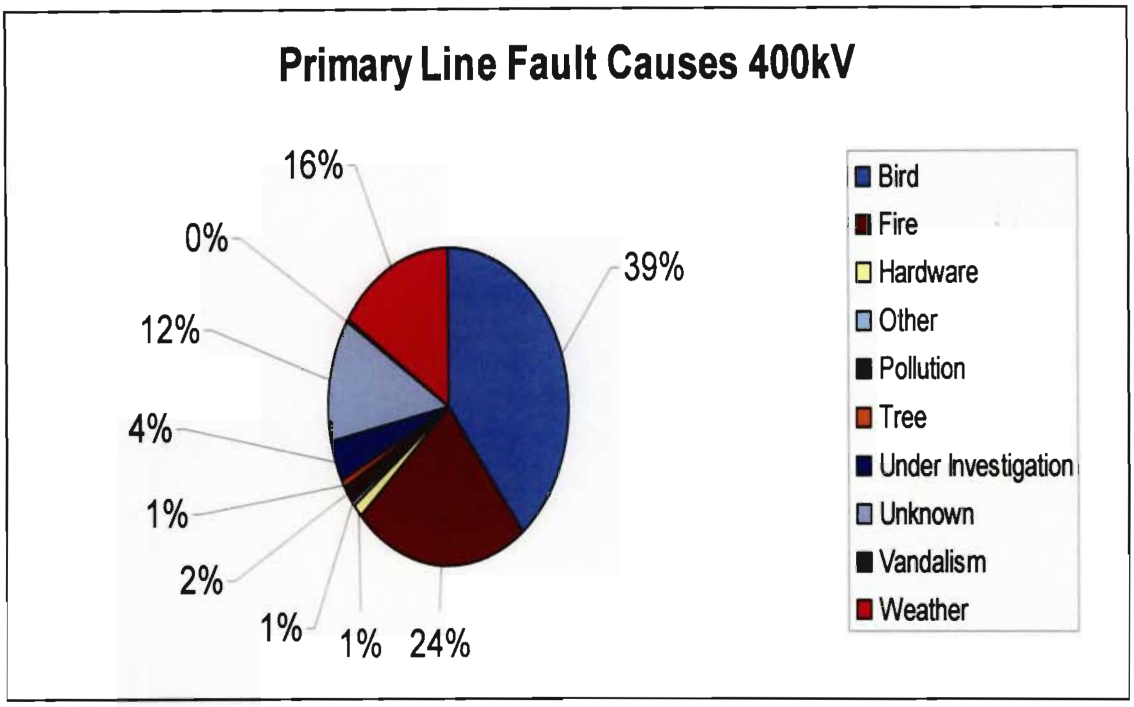



**Figure B2: Primary Line Fault Causes for 400 kV HVAC Transmission Lines**

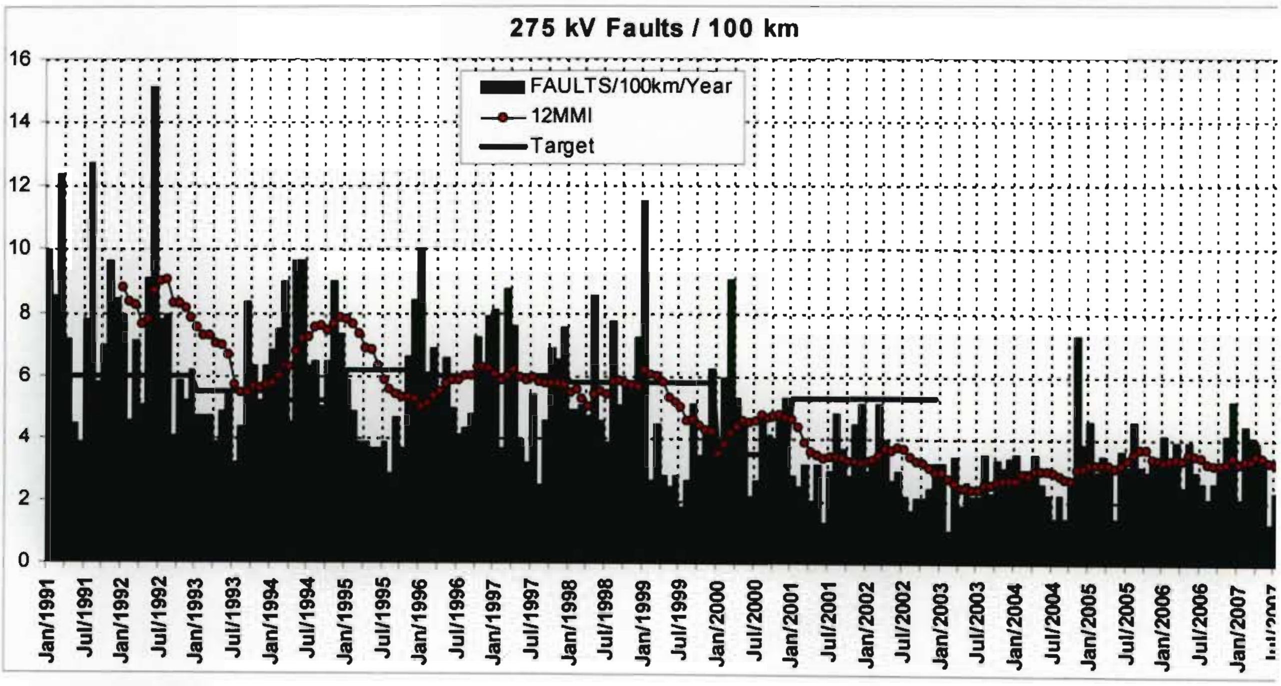



**Figure B3: 275 kV HVAC Transmission Line Faults expressed as faults/100 km**

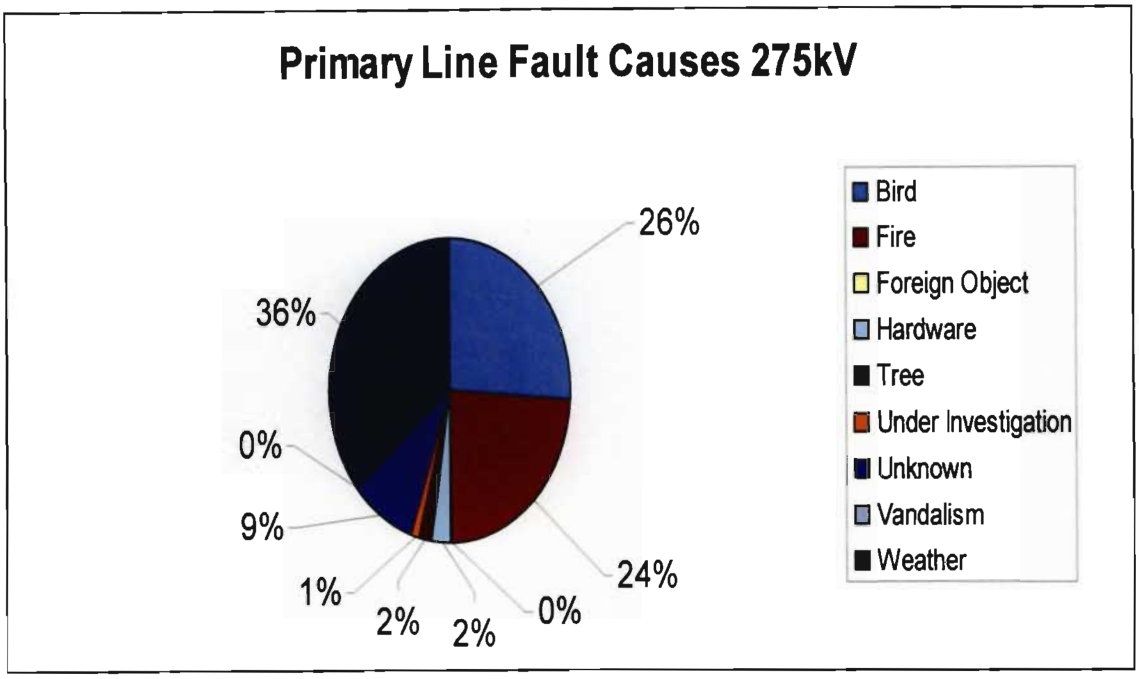



**Figure B4: Primary Line Fault Causes for 275 kV HVAC Transmission Lines**

The HVDC performance information is provided in figures B6 to B9 and tables BB1 to BB4 for the case of the 533 kV Apollo – Songo HVDC. This scheme links the South African National Grid with the Cahora Bassa Hydro Electric Power Station in Mozambique. The source of the information is the August 2007 Performance Report of Eskom Transmission [43].

**Table BB1: Frequency Performance**

| Frequency Incidents | Current Month 2007 | YTD |
|---|---|---|
| Apollo | 0 | 1 |
| Songo | 0 | 5 |
| | | |

| Load loss Range(MW) | APOLLO | | SONGO | |
|---|---|---|---|---|
| | Current Month 2007 | Year to Date | Current Month 2007 | Year to Date |
| 0-50 | 1 | 2 | 4 | 13 |
| 51-250 | 3 | 15 | 10 | 48 |
| 250 > | 3 | 5 | 5 | 34 |

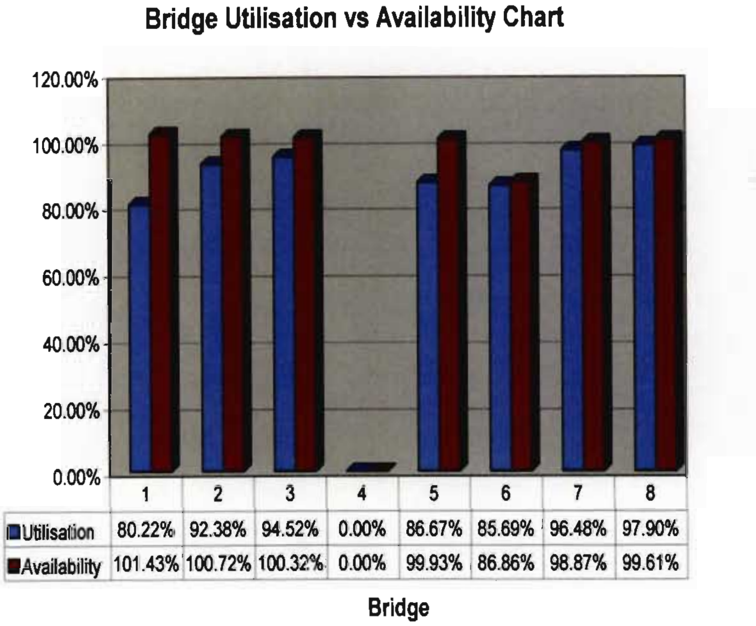



**Figure B6: Converter Bridge Performance**

**Table BB2: Converter Station Performance**

| Forced Outages | Current Month 2007 | Year to Date | Target |
|---|---|---|---|
| Converter Transformer | 0 | 0 | - |
| Smoothing Reactor | 0 | 0 | - |
| Circuit Breakers | 0 | 1 | - |
| Bridge Trips (Apollo) | 3 | 15 | 65 |
| Bridge Trips (Songo) | 1 | 71 | - |
| AC filters | 1 | 11 | 10 |
| Capacitor Banks | 0 | 1 | 5 |
| Pole (Apollo Related) | 0 | 1 | 6 |
| Pole ( Songo Related) | 0 | 6 | - |
| Station (Apollo Related) | 0 | 0 | 2 |
| Station ( Songo Related) | 0 | 0 | - |
| Line Faults ( Apollo related) | 9 | 17 | 12 |
| Line Faults ( Songo related) | 21 | 30 | - |
| Songo Generator faults | 2 | 11 | - |
| Unaccountable Faults | 3 | 11 | - |

## Table BB3: Causes for Plant and Equipment Failure

| Plant Affected | Date | MW Lost | Cause |
|---|---|---|---|
| 1. Filter no 2 | 05/08/2007 at 17h09 | | Filter no 2 tripped on step 3 alarm |
| 2. Bridge no 8 | 08/08/2007 at 00h40 | 320 | Bridge no 8 tripped on SCF on the blue phase |
| 3. Line no 1 | 12/08/2007 at 13h59 | 698 | Line 1 flashed 19km from Pietersburg towards songo (5th traveling wave ) resulting in loss of pole 1 (protection operated correctly). |
| 4. Line no 1 | 12/08/2007 at 13h59 | 105 | Line 1 flashed 8km from Pietersburg towards songo. |
| 5. Line no 1 | 26/08/2007 at 06h09 | 0 | Line 1 protection, 1st attempt TW. Distance calc 140km from Pietersburg towards Songo. |
| 6. Line no 1 | 26/08/2007 at 06h31 | 0 | Line 1 protection, 1st attempt TW. Distance calc 140km from Pietersburg towards Songo. |
| 7. Line no 1 | 26/08/2007 at 06h31 | 240 | Line 1 protection, 2nd attempt TW. Distance calc 151km from Pietersburg towards Songo resulted in Apollo Bridge 5 intertrip |
| 8. Line no 1 | 26/08/2007 at 07h58 | 50 | Line 1 protection, 1st attempt TW. Distance calc 140km from Pietersburg towards Songo. |
| 9. Bridge no 6 | 26/08/2007 at 10h35 | 315 | Bridge no 6 tripped by Valve Firing Monitoring |
| 10. Line no 1 | 27/08/2007 at 01h48 | 0 | Line 1 protection, 1st attempt TW. Distance calc 175km from Pietersburg towards Songo. |
| 11. Line no 1 | 27/08/2007 at 02h58 | 0 | Line 1 protection, 1st attempt TW. Distance calc 167km from Pietersburg towards Songo. |
| 12. Line no 1 | 27/08/2007 at 03h21 | 0 | Line 1 protection, 1st attempt TW. Distance calc 18km from Pietersburg towards Songo. |
| 13. Bridge no 1 | 31/08/2007 at 08h07 | 220 | Bridge no 1 tripped by B end E group alarm on white phase. |

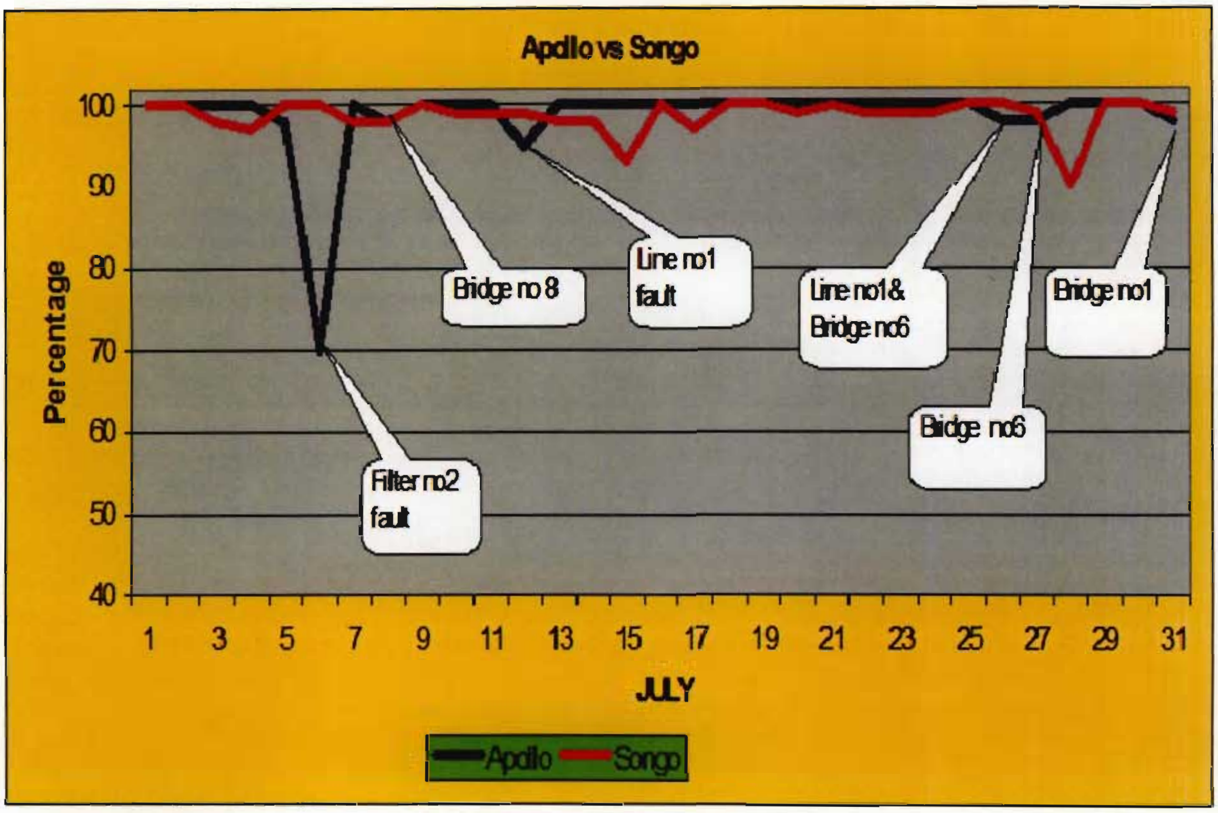



**Figure B7: Comparison of Converter Station Performance**

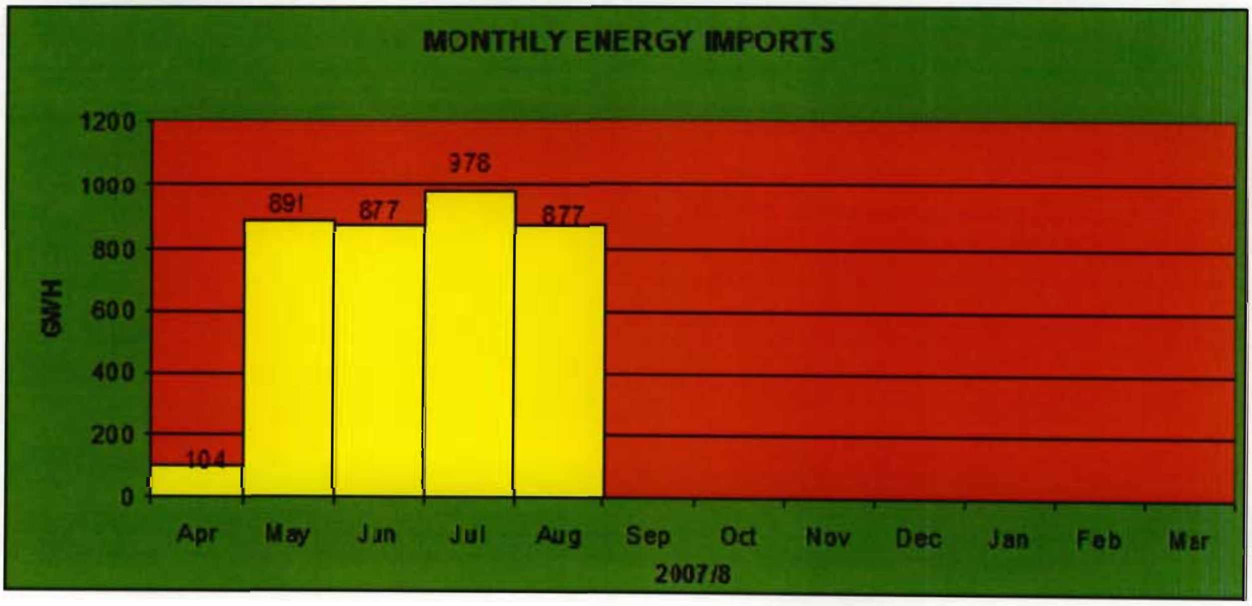



**Figure B8 : Monthly Energy Flows**

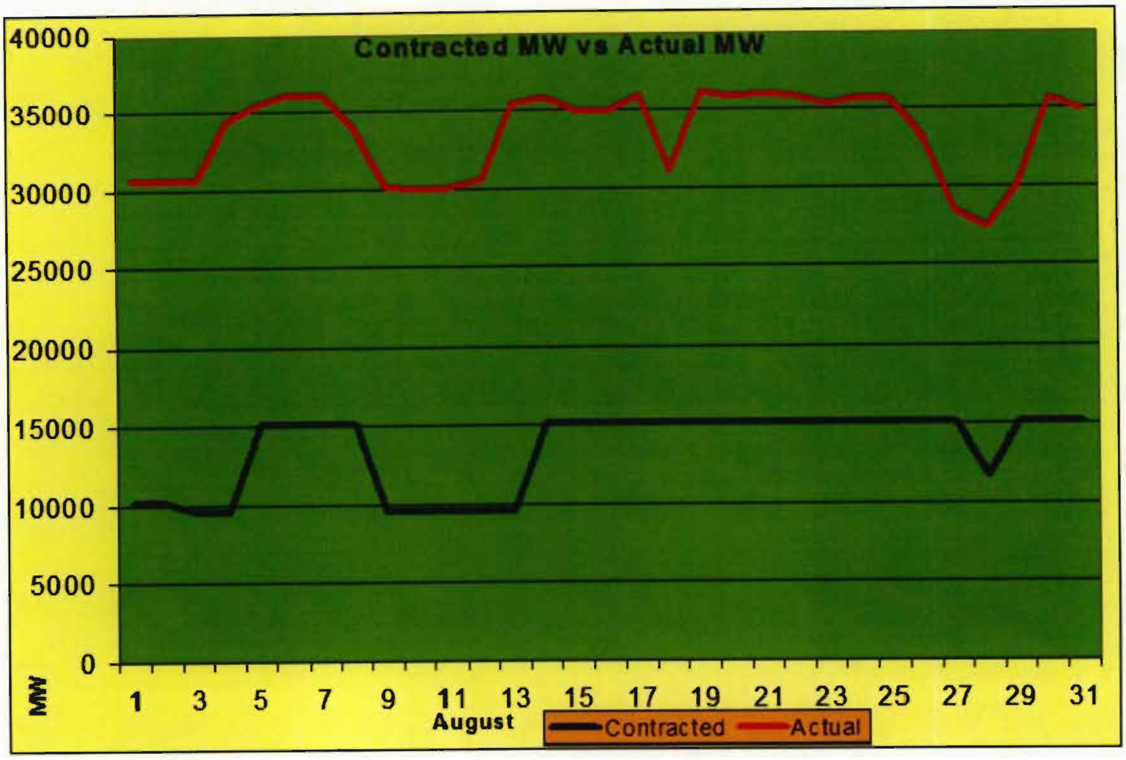



**Figure B9: Active Power Transferred in MW**

**Table BB4 : Calculated Converter Station Monthly and YTD Average Availability**

| Average availability as per contracted MW | August 2007 | YTD 2007/8 |
|---|---|---|
| Apollo | 99.50% | 99.00% |
| Songo | 97.10% | 98.50% |

The performance of the HVDC scheme operating over 1300 km across two countries shows the following characteristics:

1. High availabilities and infrequent disturbances
2. For line electrical faults, there is no corresponding voltage dip effect to customer's loads. Servitude fire caused faults continue to occur on the Apollo – Cahora Bassa 533 kV line; pole to earth and these faults do not present themselves as voltage dips to customer's load. The high speed thyristors located at both ends do not allow the build up of fault current and thus the associated voltage dip effect. Quality of supply delivered is thus enhanced under DC technology. This whole chapter of faults, fault management and

self-healing capability of DC requires further in depth research and investigations. This work would extend to lightning, fires, birds; all being the typical fault causes under AC technology.

Comparing HVAC technology to that of HVDC technology, we can conclude that the performance of both technologies is the same. Thus on conversion, we do not expect any worse performance than what is currently experienced.

## Appendix C

# Matimba – Midas – Pluto Case Study

# Recording of Power Flows on 29 August 2005

MATMB,SCADA[ONLINE]0,0 EKB 29-AUG-2005 06:56:37

T A4 D S I M

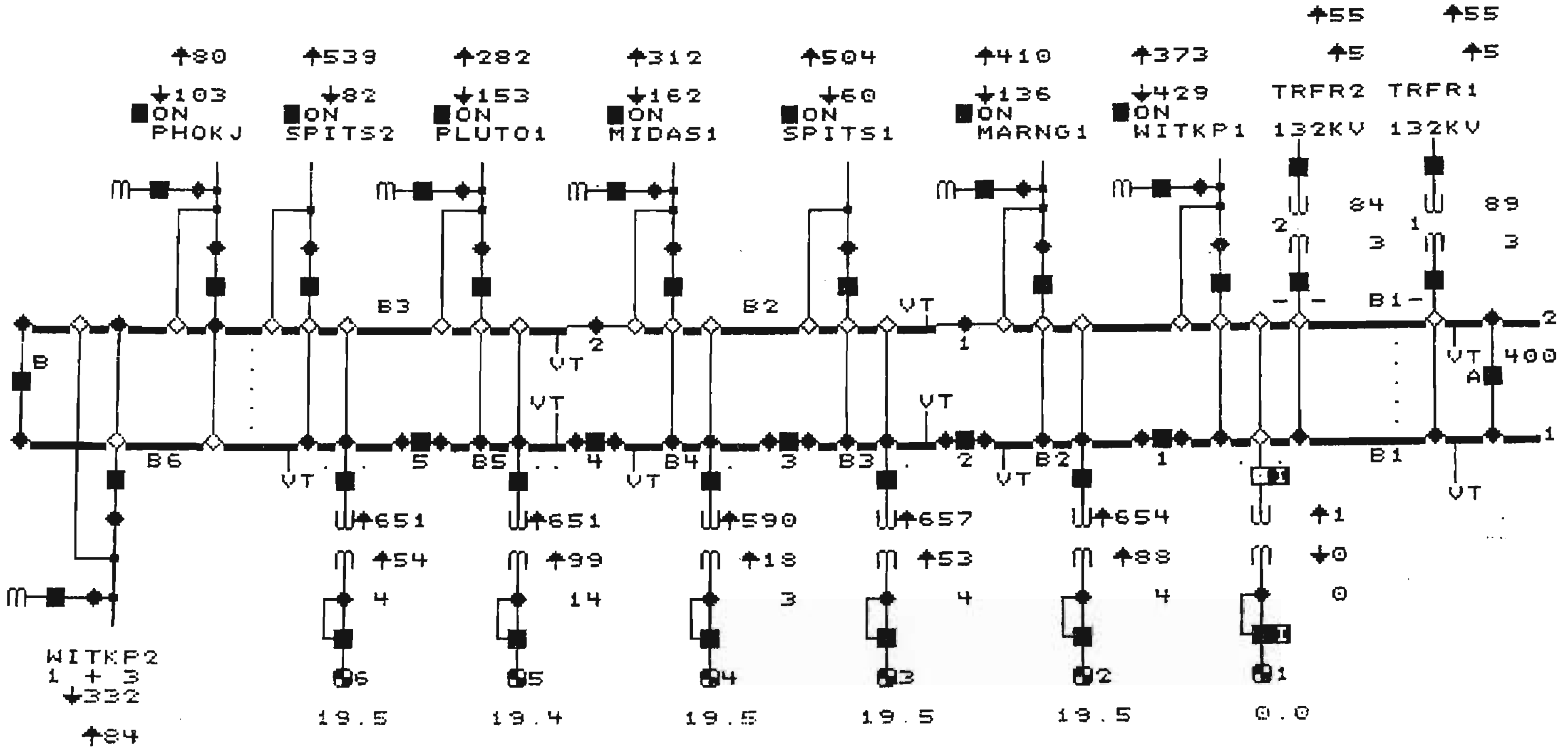
# MATIMBA (PRETORIA) (NORTH)

NCC TOC S/RESET B/Z TSS

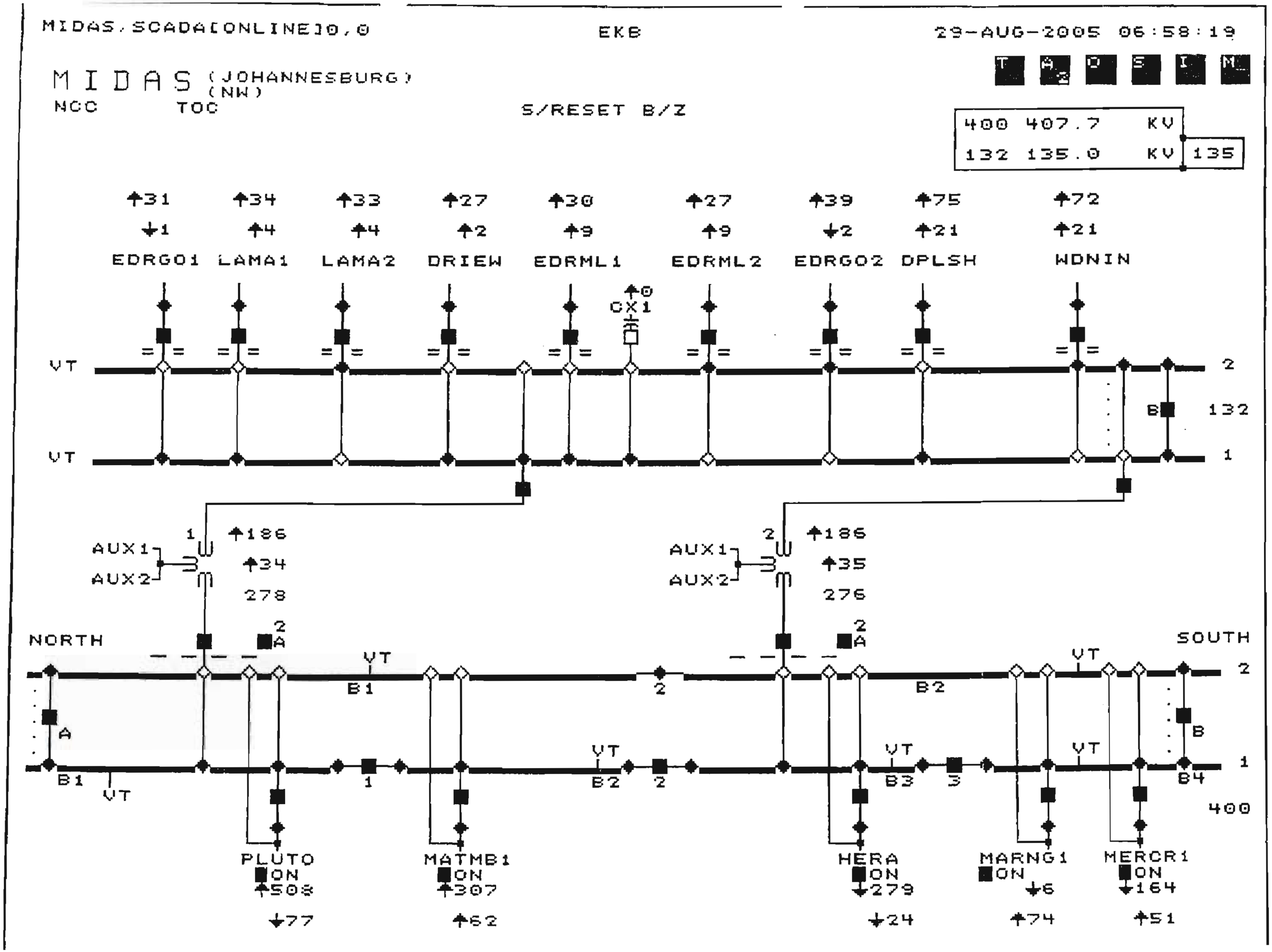
| | | | | | |
|---|---|---|---|---|---|
| 400CPLA-1 | 401.2 | KV | PHOKJ | 50.15 | HZ |
| 400CPLA-2 | 401.8 | KV | | | |
| 400CPLB-1 | 402.8 | KV | | | |
| 400CPLB-2 | 402.2 | KV | | | |

STAB
MARGIN 3870

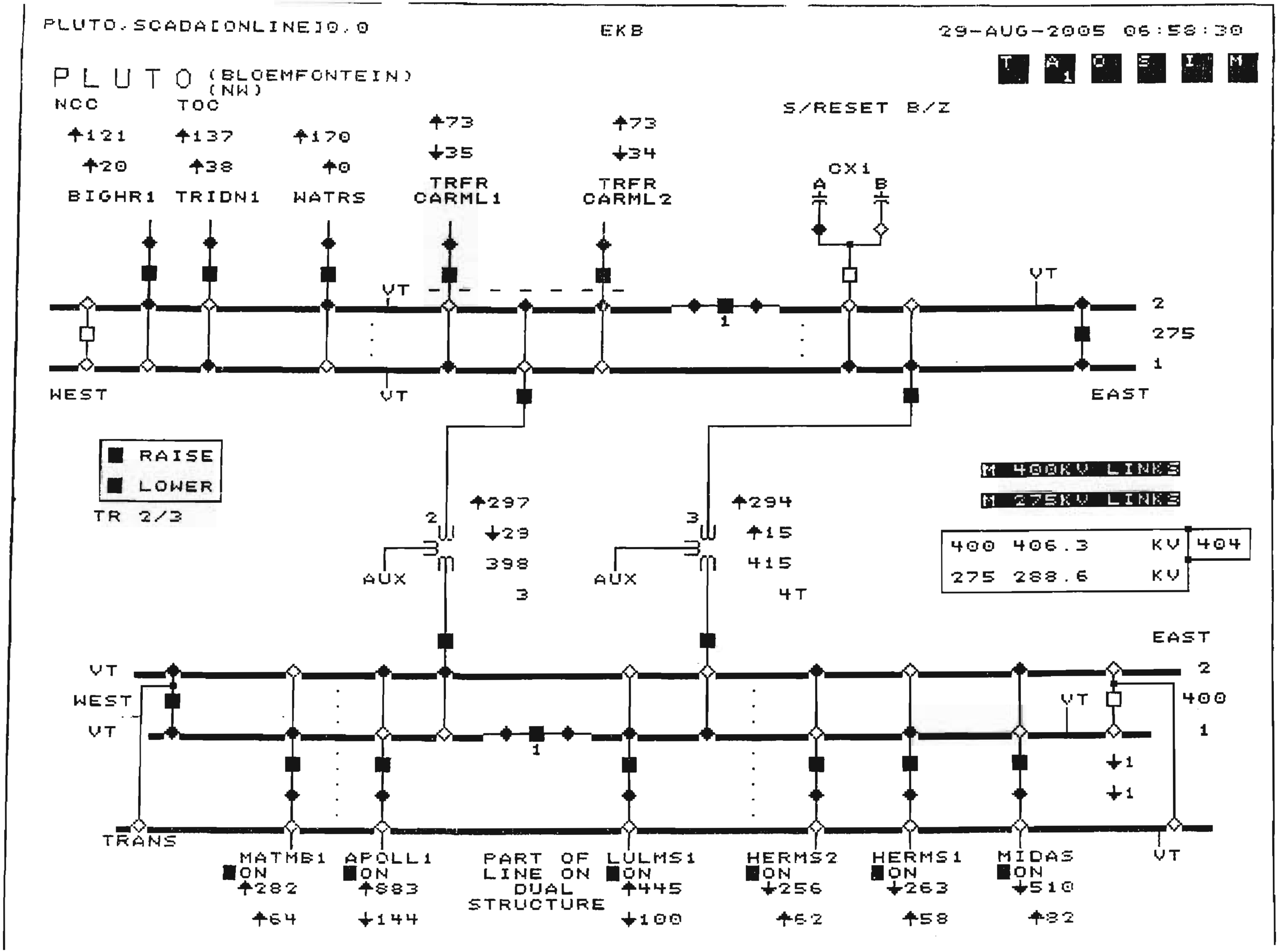
OUTPUT 2958




ARM 2

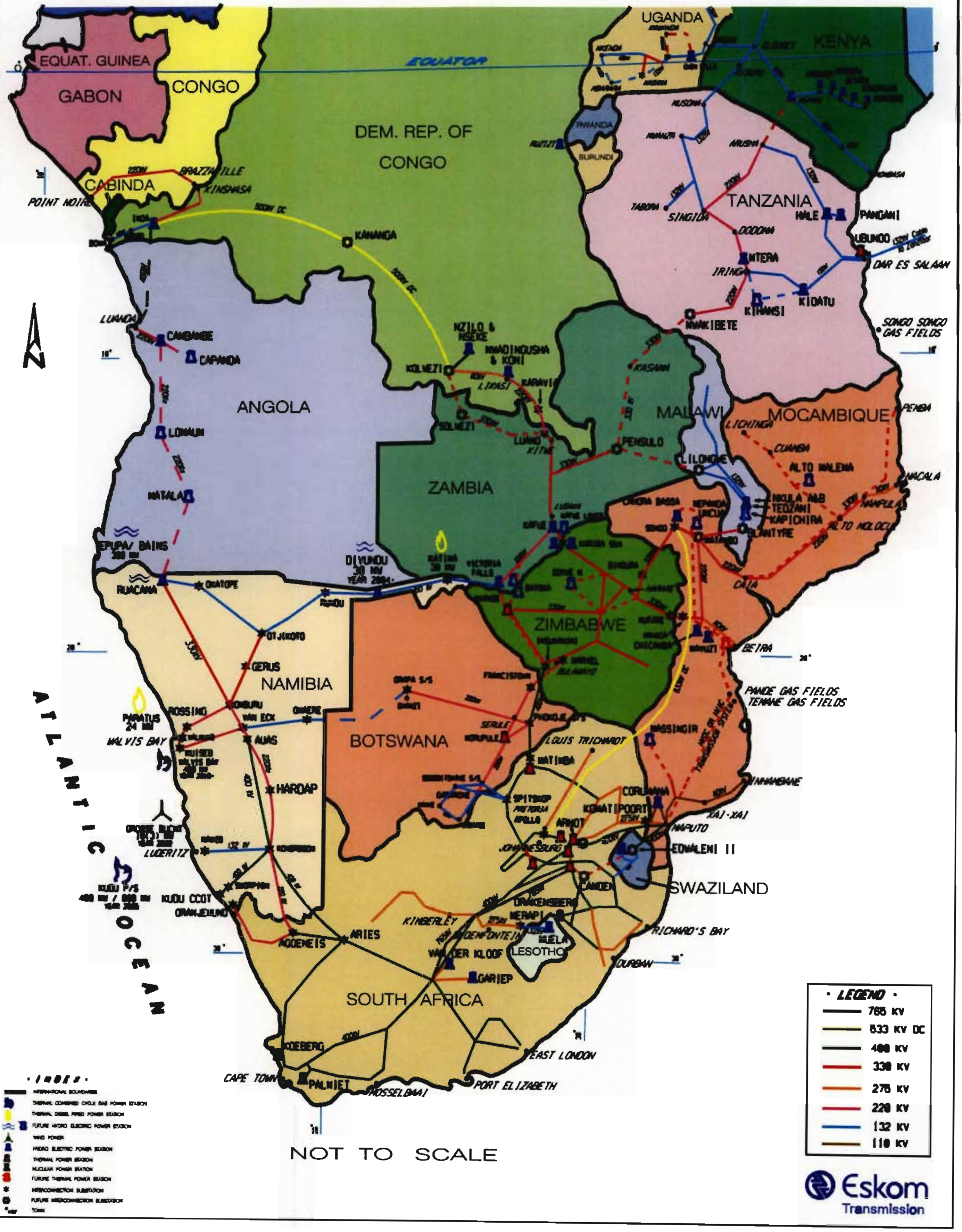


MIDAS.SCADA[ONLINE]0,0
EKB
29-AUG-2005 06:58:19
T A D S I M
MIDAS (JOHANNESBURG) (NW)
NCC TOC
S/RESET B/Z
400 407.7 KV
132 135.0 KV 135
↑31 ↓1 EDRGO1
↑34 ↑4 LAMA1
↑33 ↑4 LAMA2
↑27 ↑2 DRIEW
↑30 ↑9 EDRML1
↑0 CX1
↑27 ↑9 EDRML2
↑39 ↓2 EDRGO2
↑75 ↑21 DPLSH
↑72 ↑21 WDNIN
VT
VT
2
B
132
1
1 ↑186 ↑34 278
AUX1
AUX2
2 ↑186 ↑35 276
AUX1
AUX2
NORTH
SOUTH
2 A
2 A
VT
B1
2
B2
VT
2
A
B
B1
VT
1
VT
B2
2
VT
B3
3
VT
B4
1
400
PLUTO ON ↑508 ↓77
MATMB1 ON ↑307 ↑62
HERA ON ↓279 ↓24
MARNG1 ON ↓6 ↑74
MERCR1 ON ↓164 ↑51


PLUTO.SCADA[ONLINE]0.0
EKB
29-AUG-2005 06:58:30
T A 1 O S I M
PLUTO (BLOEMFONTEIN) (NW)
NCC
TOC
S/RESET B/Z
↑121 ↑20 BIGHR1
↑137 ↑38 TRIDN1
↑170 ↑0 WATRS
↑73 ↓35 TRFR CARML1
↑73 ↓34 TRFR CARML2
CX1
A
B
VT
2
275
1
WEST
EAST
RAISE
LOWER
TR 2/3
M 400KV LINKS
M 275KV LINKS
2
↑297 ↓29 398 3
3
↑294 ↑15 415 4T
AUX
AUX
400 406.3 KV 404
275 288.6 KV
EAST
2
400
1
WEST
VT
↓1
↓1
TRANS
MATMB1 ON ↑282 ↑64
APOLL1 ON ↑883 ↓144
PART OF LINE ON DUAL STRUCTURE
LULMS1 ON ↑445 ↓100
HERMS2 ON ↓256 ↑62
HERMS1 ON ↓263 ↑58
MIDAS ON ↓510 ↑82

# Appendix D: Geographical Maps showing the Interconnected Power System in South and Southern Africa

# AFRICA GRID PLAN – 2005
# EXISTING AND PROPOSED




NOT TO SCALE

## APPENDIX E: Candidate Transmission Line Tower General Arrangement

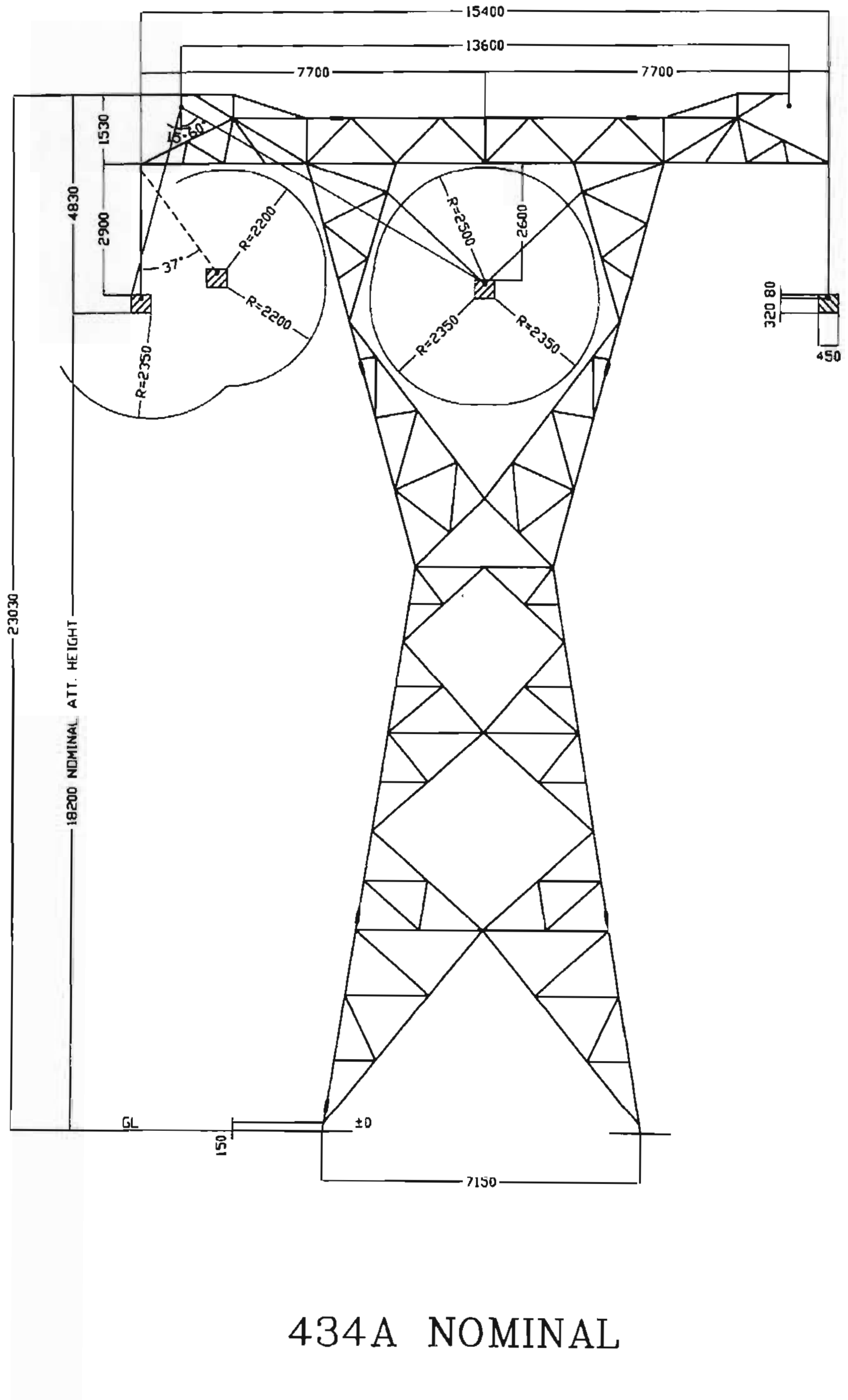
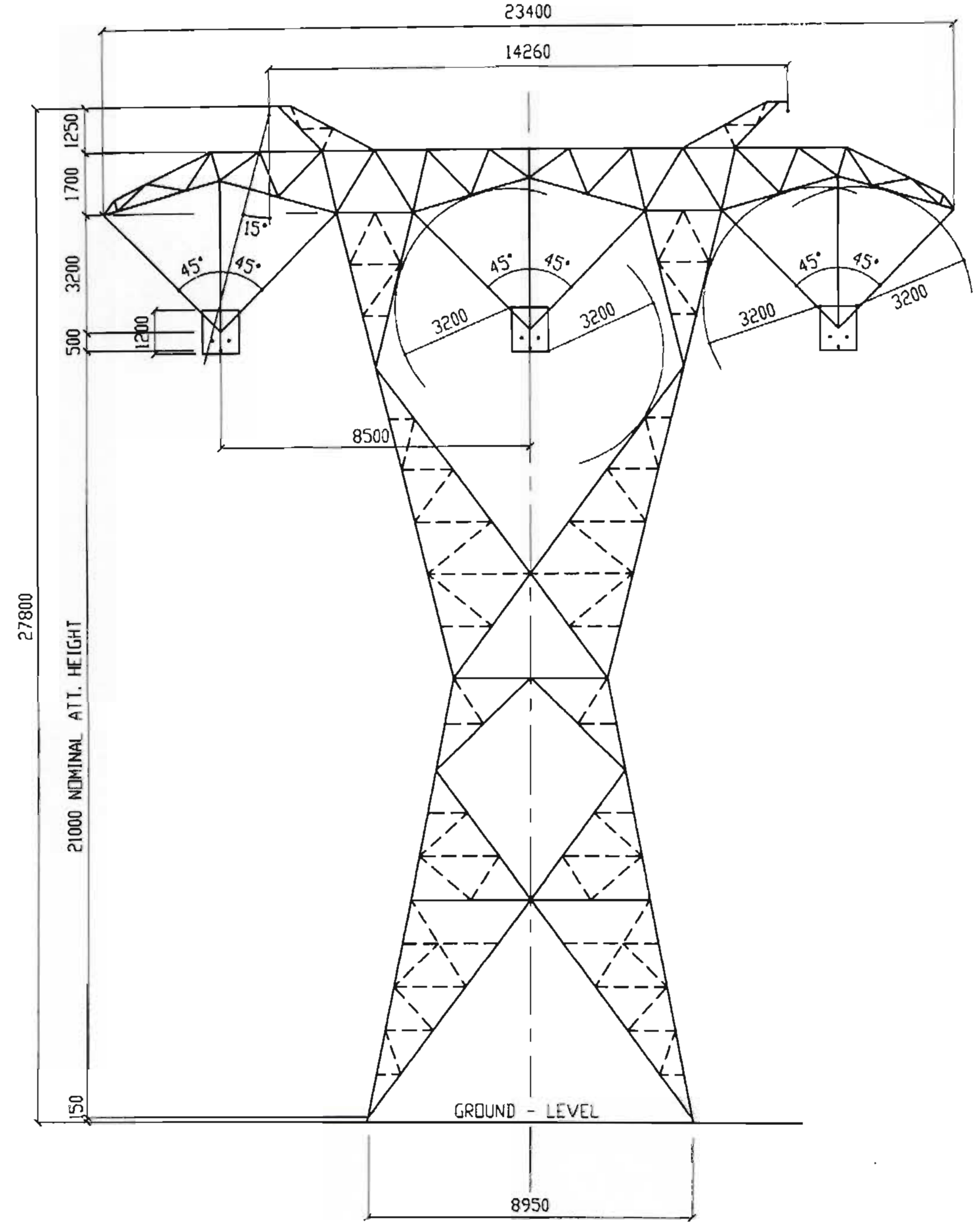
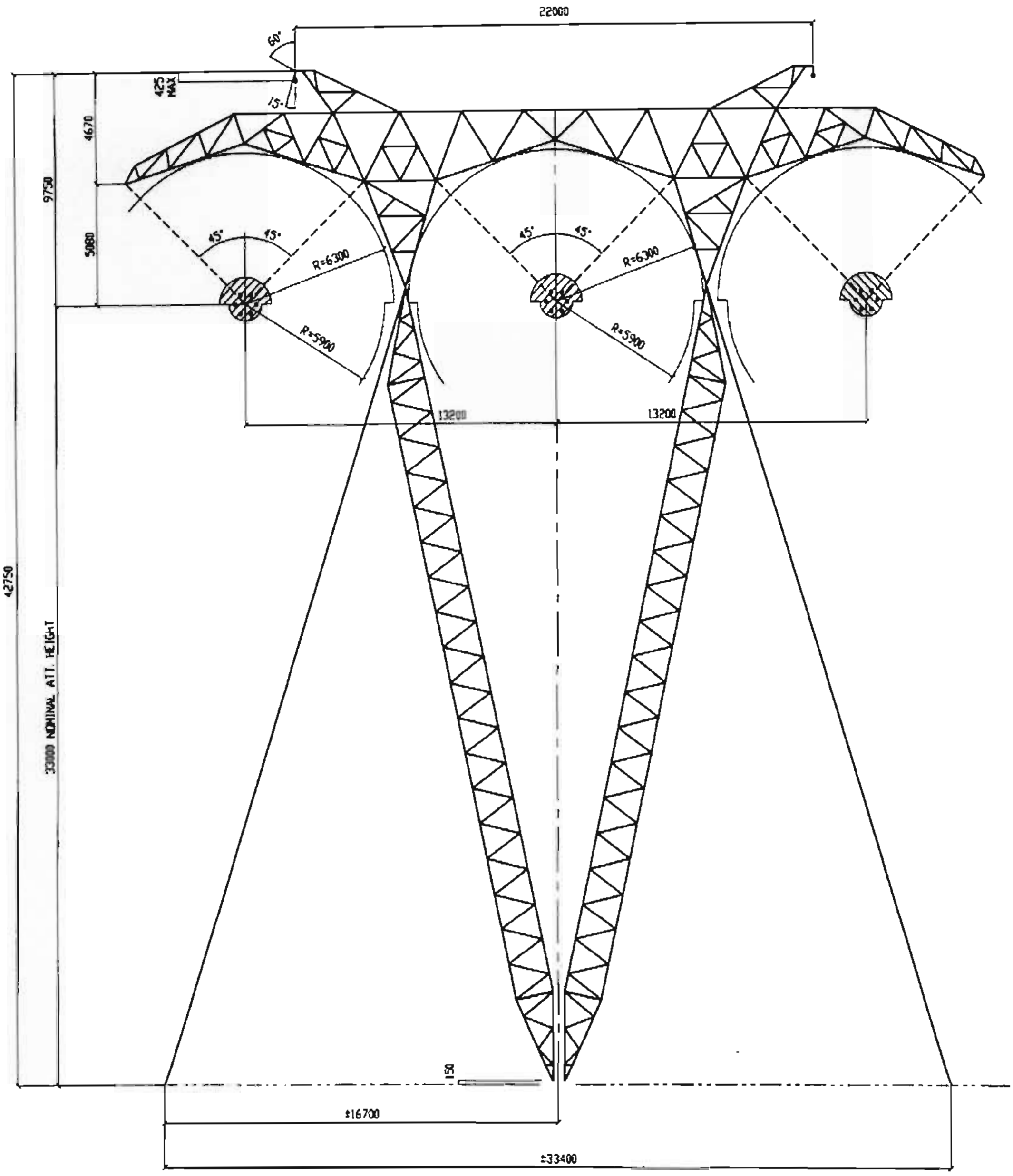



Figure E1: 275 kV Nominal Transmission Line Configuration: Suspension Tower




518H NOMINAL

**Figure E2: 400 kV Nominal Transmission Line Configuration: Suspension Tower**




703B NOMINAL

**Figure E3: 800 kV Nominal Transmission Line Configuration: Suspension Tower**

For all the given HVAC nominal voltage transmission line configurations, the overhead earthwires are generally steel (type 19/0.104) and in our selected cases, the phase conductors are Zebra, of diameter 28, 62 mm with bundle spacing of 380mm.

## Appendix F: Collection of Electric Field Profiles for the Multiple Case Studies

### General Notes from Eskom Design Practices

1. The maximum limit for AC electric fields under the line is 5 kV/m.

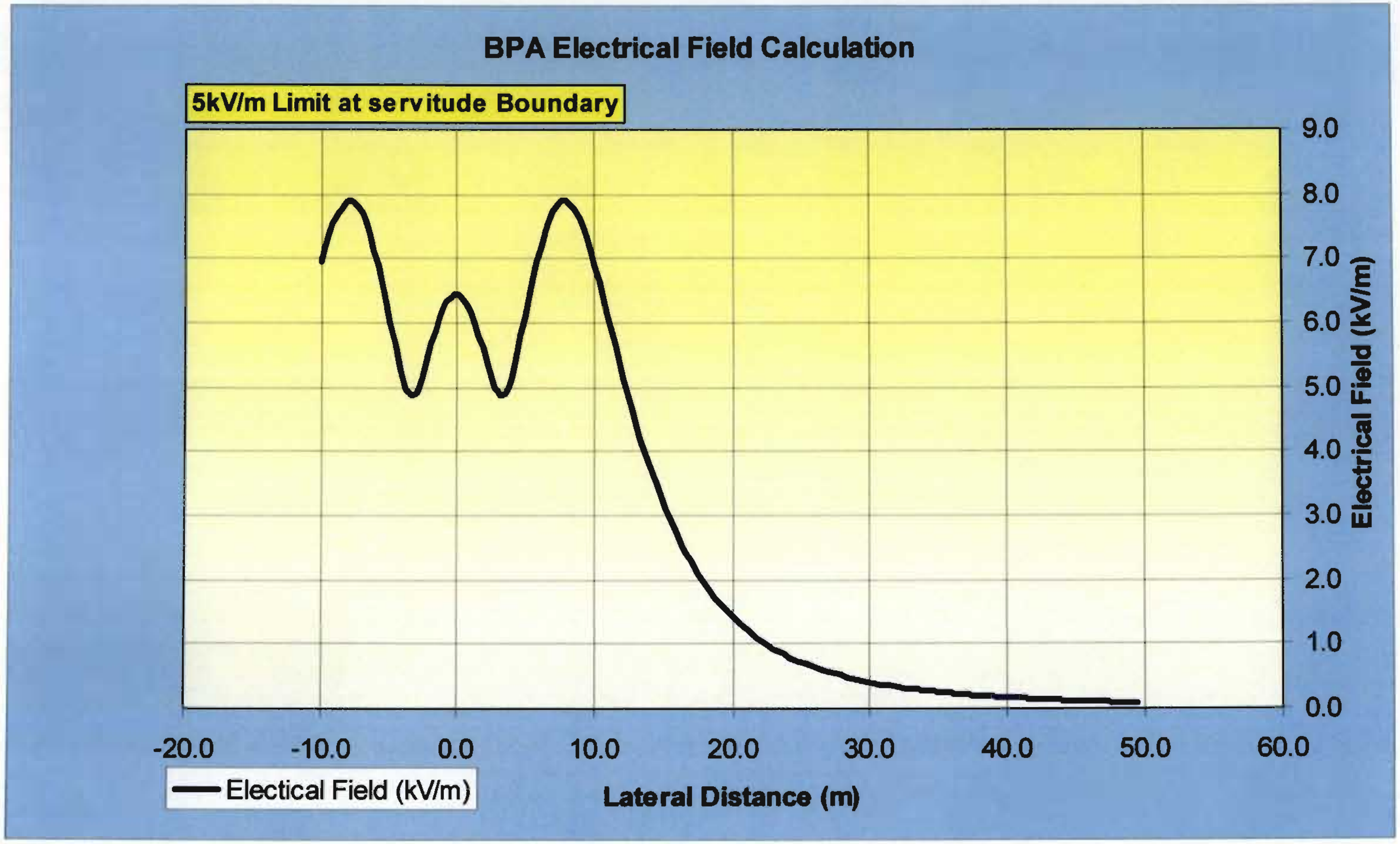
2. The corresponding maximum induced body current density is 2 mA/square meter.

3. Eskom has employed 10 kV/m as the electric field design limit. Dispensation is applied for.

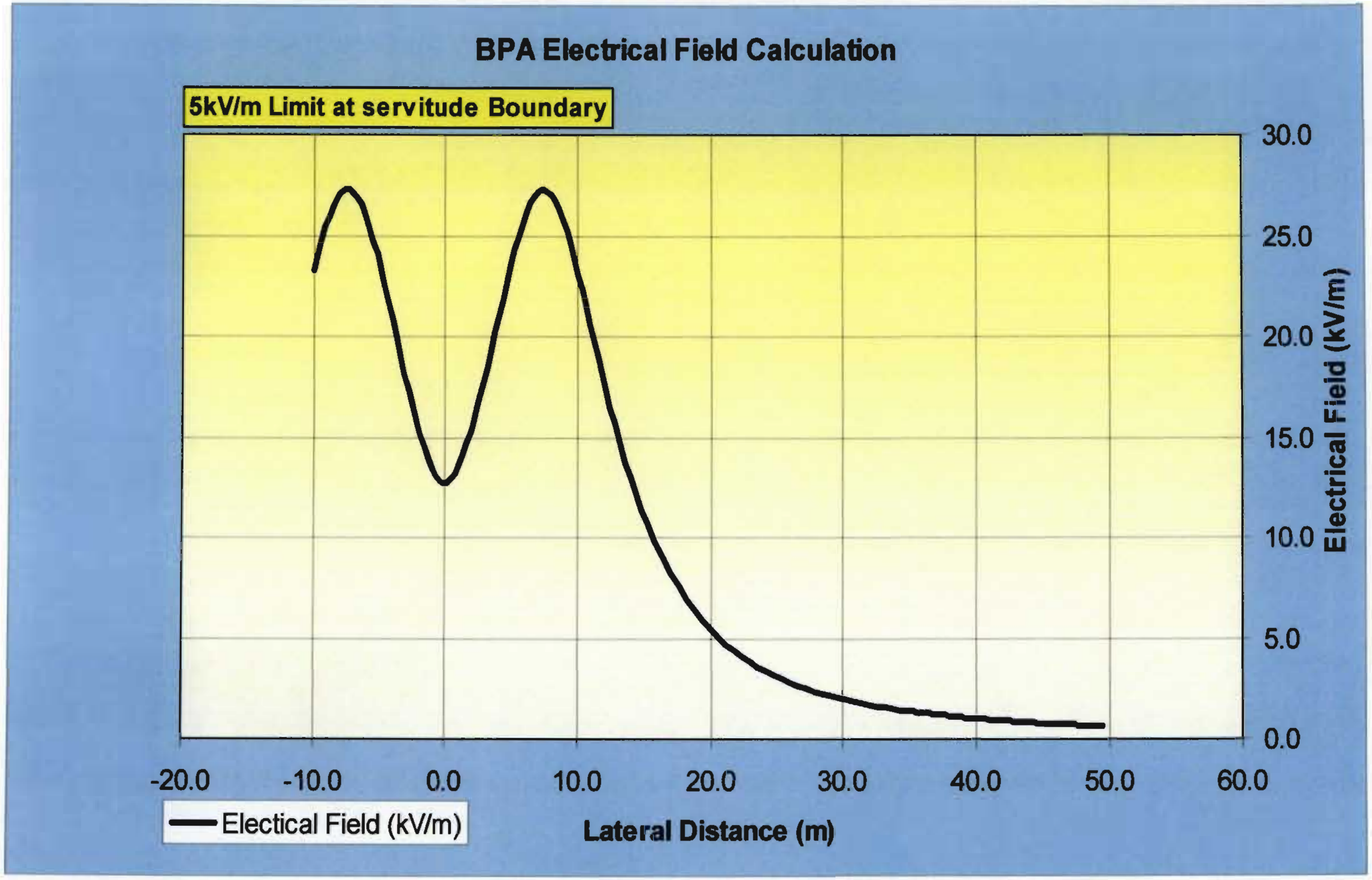
4. In the case of DC fields, the limit proposed is 25 kV/m. This is the combined electrostatic and space charge field.

## Source of Electric Field Plots: Canadian BPA Transmission Line Workstation

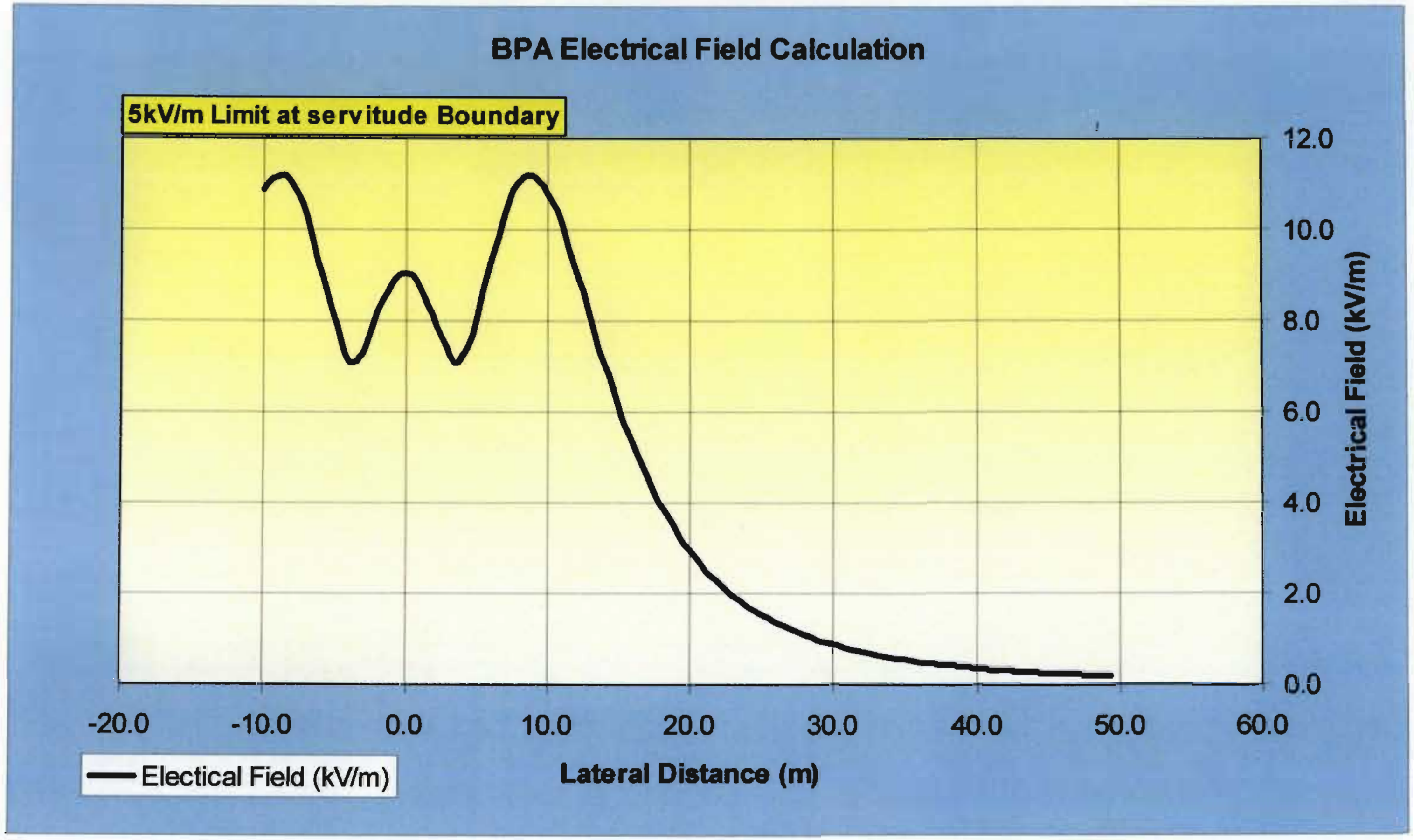
# 275 kV Twin Zebra Operating at 275 kV HVAC



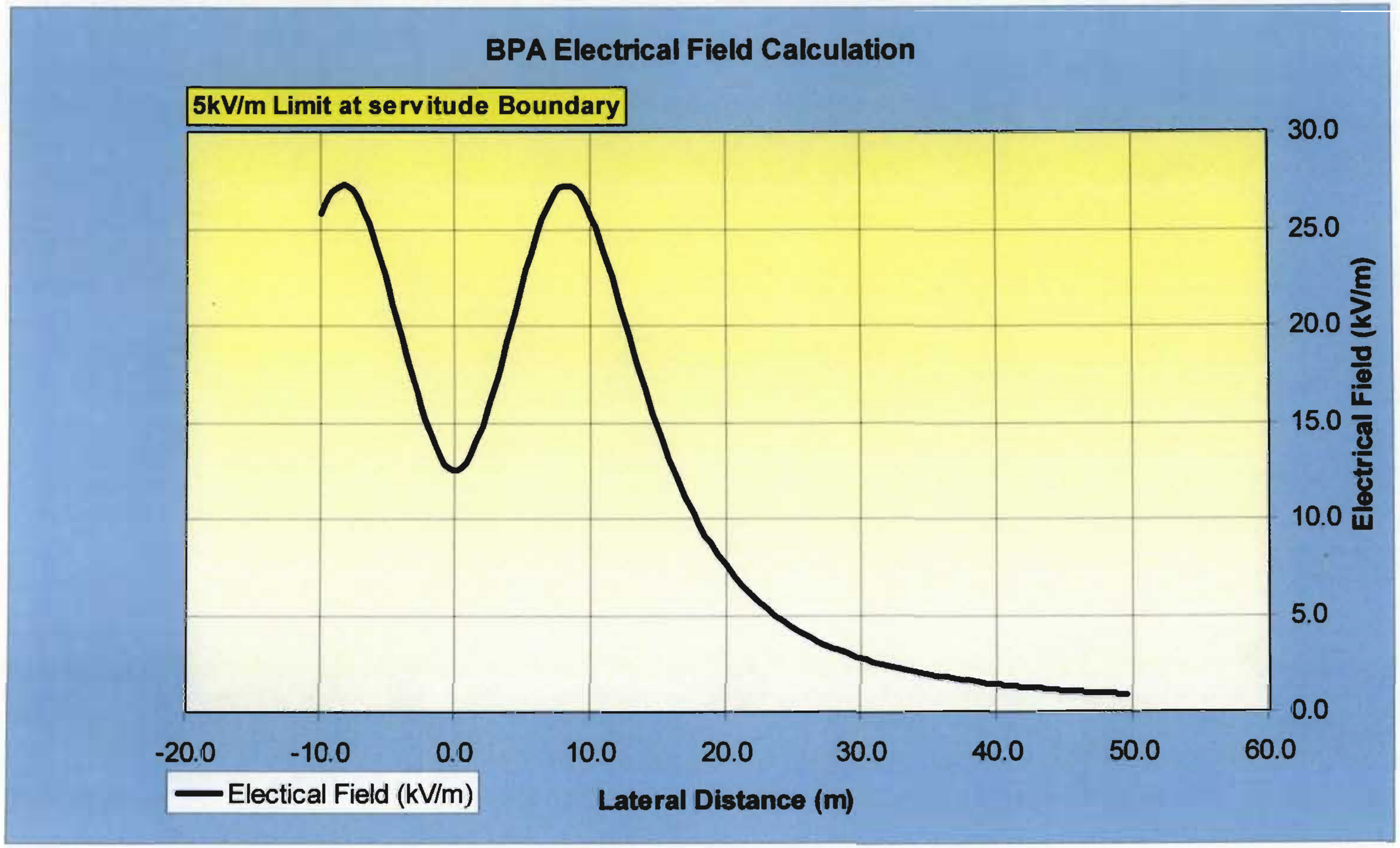
# 275 kV Twin Zebra Operating at 500 kV HVDC



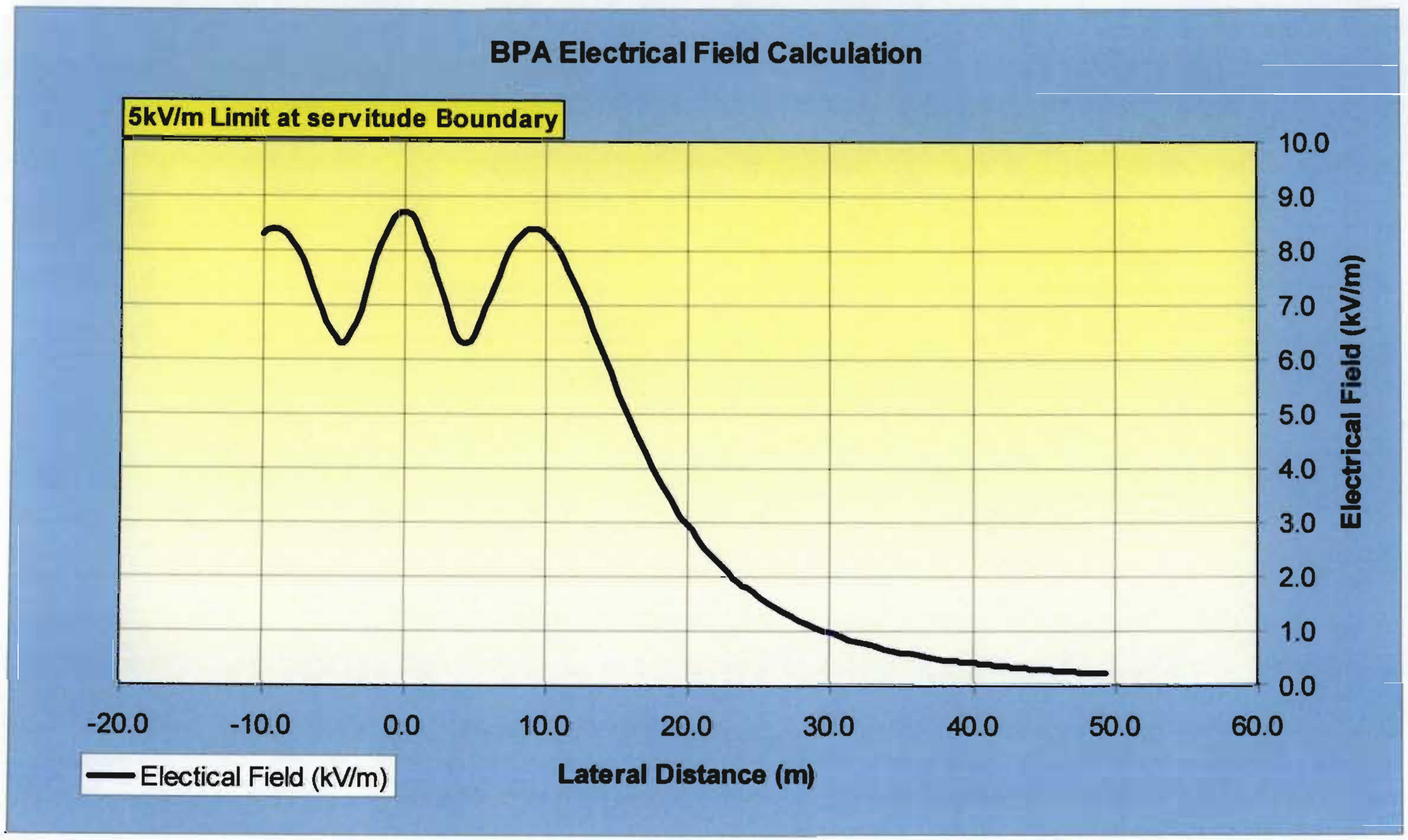
# 400 kV Quad Zebra operating at 400 kV HVAC



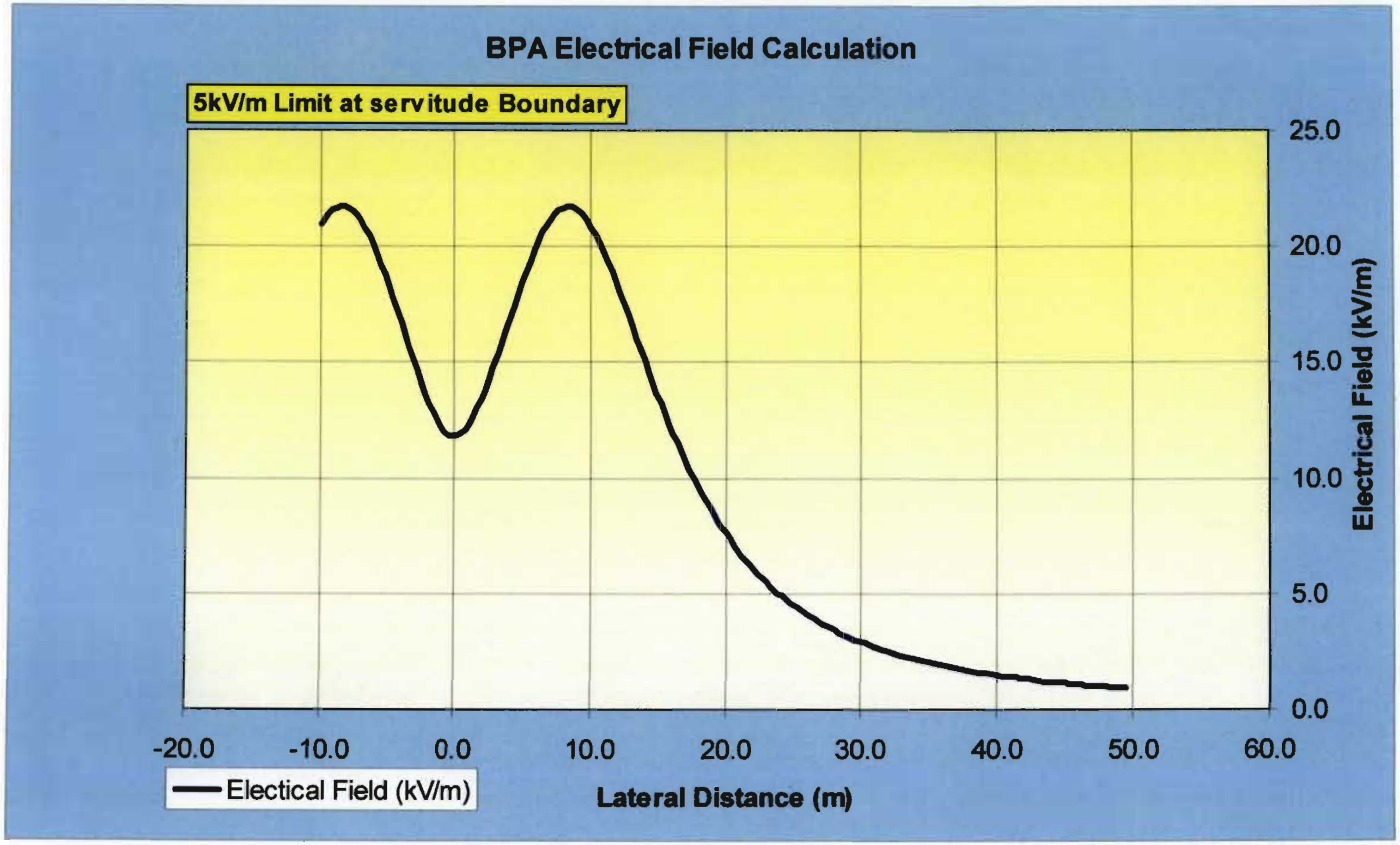
# 400 kV Quad Zebra operating at 500 kV HVDC



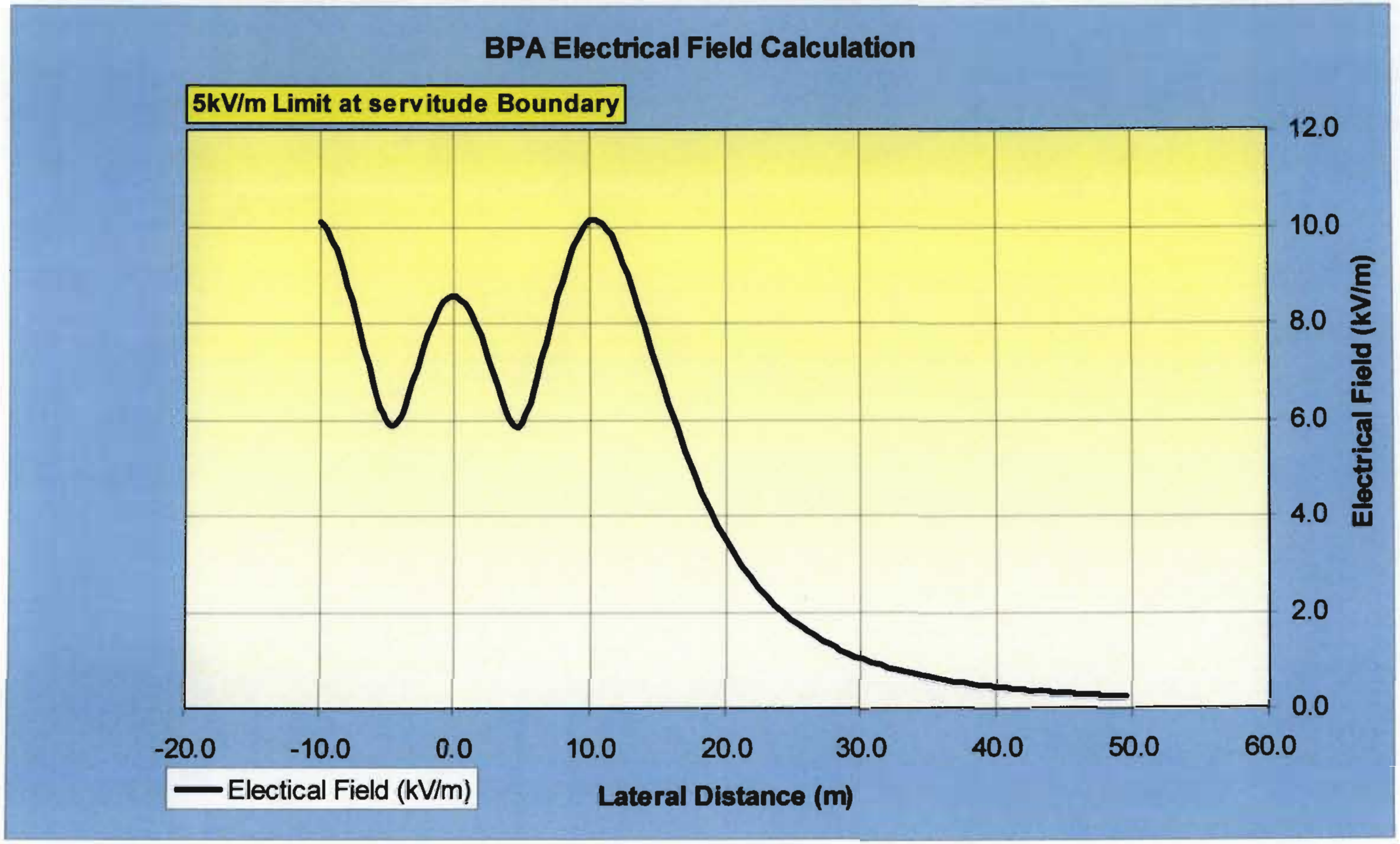
# 400 kV Triple Tern Operating at 400 kV HVAC



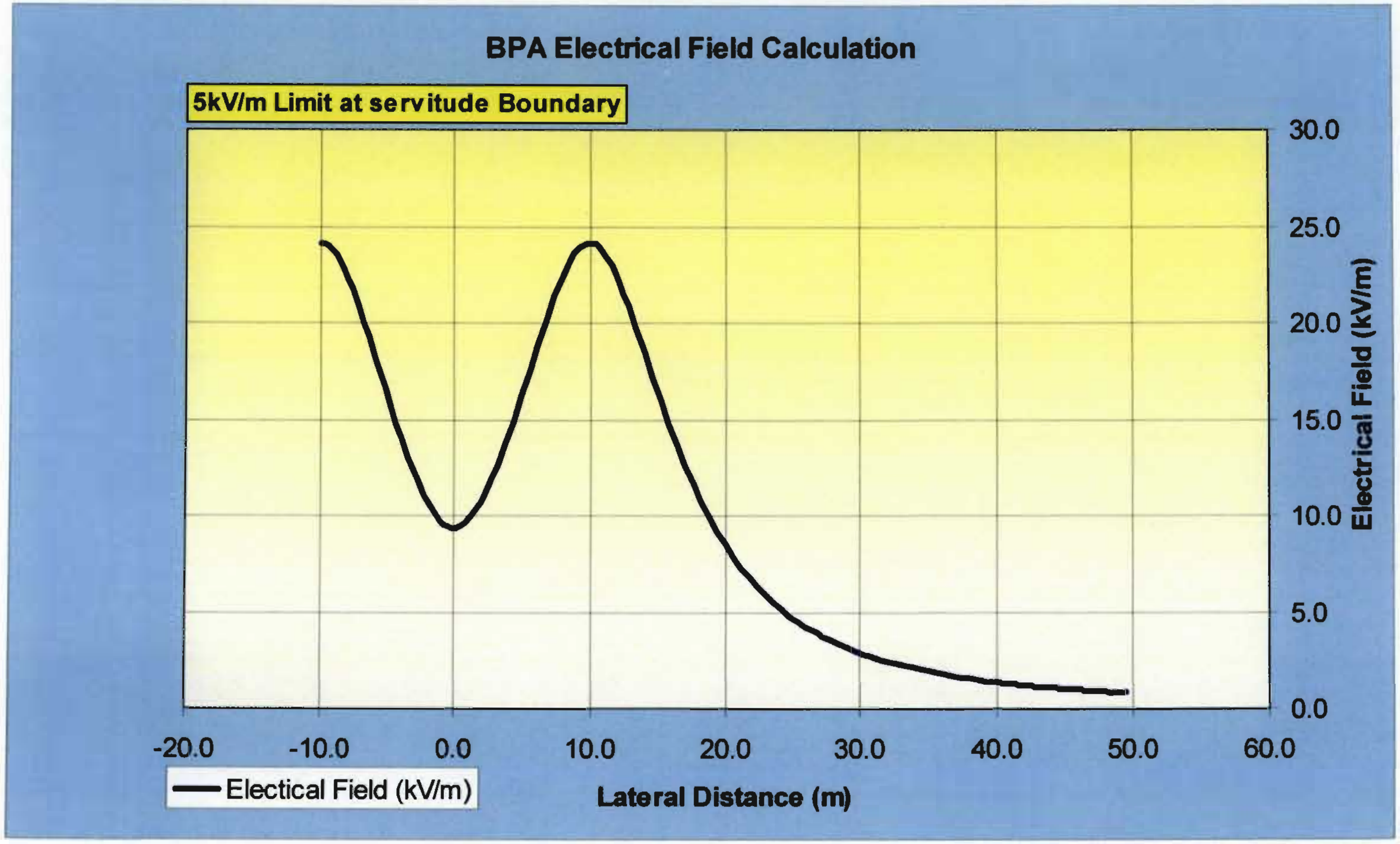
# 400 kV Triple Tern Operating at 500 kV HVDC



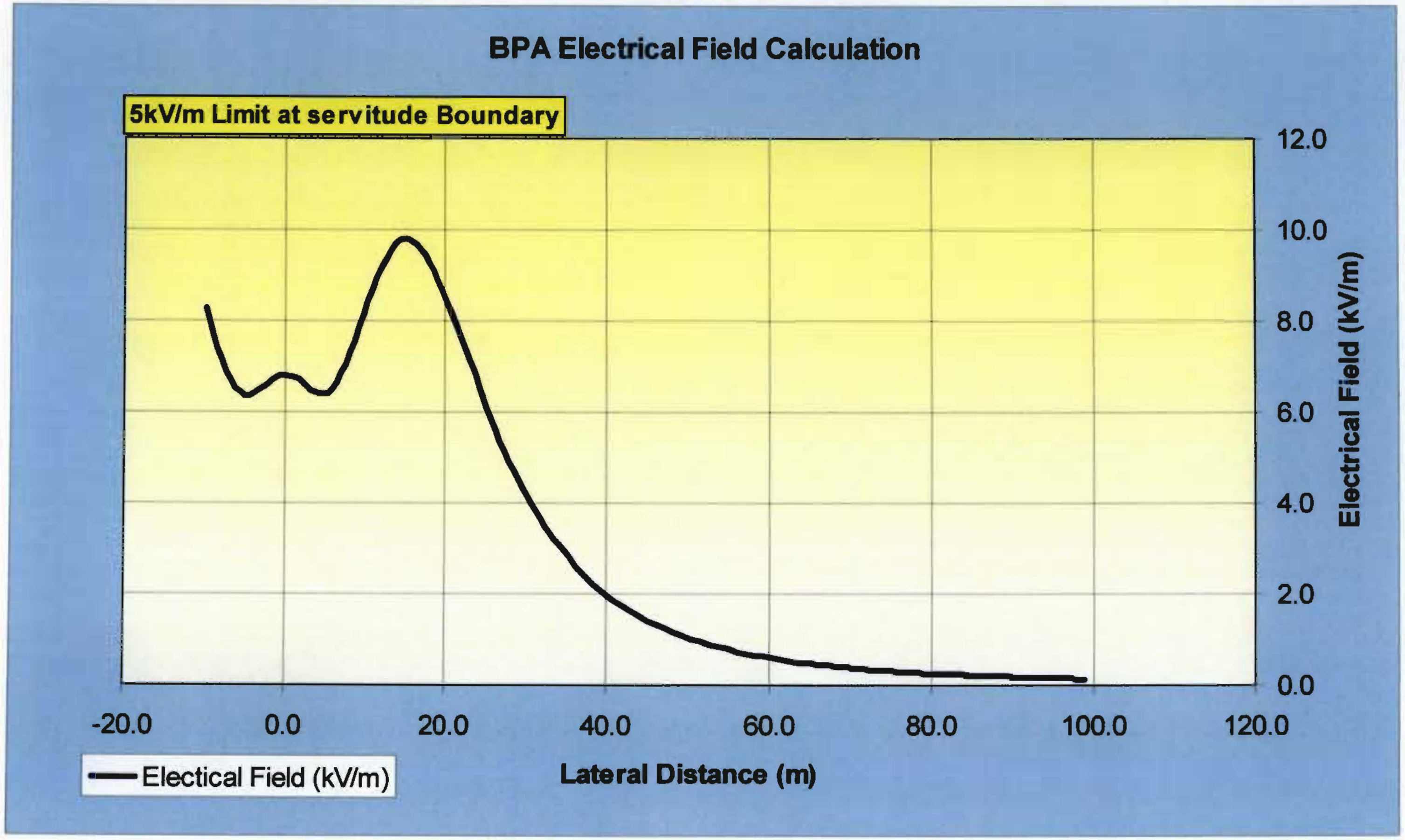
# 400 kV Twin Dino Operating at 400 kV HVAC



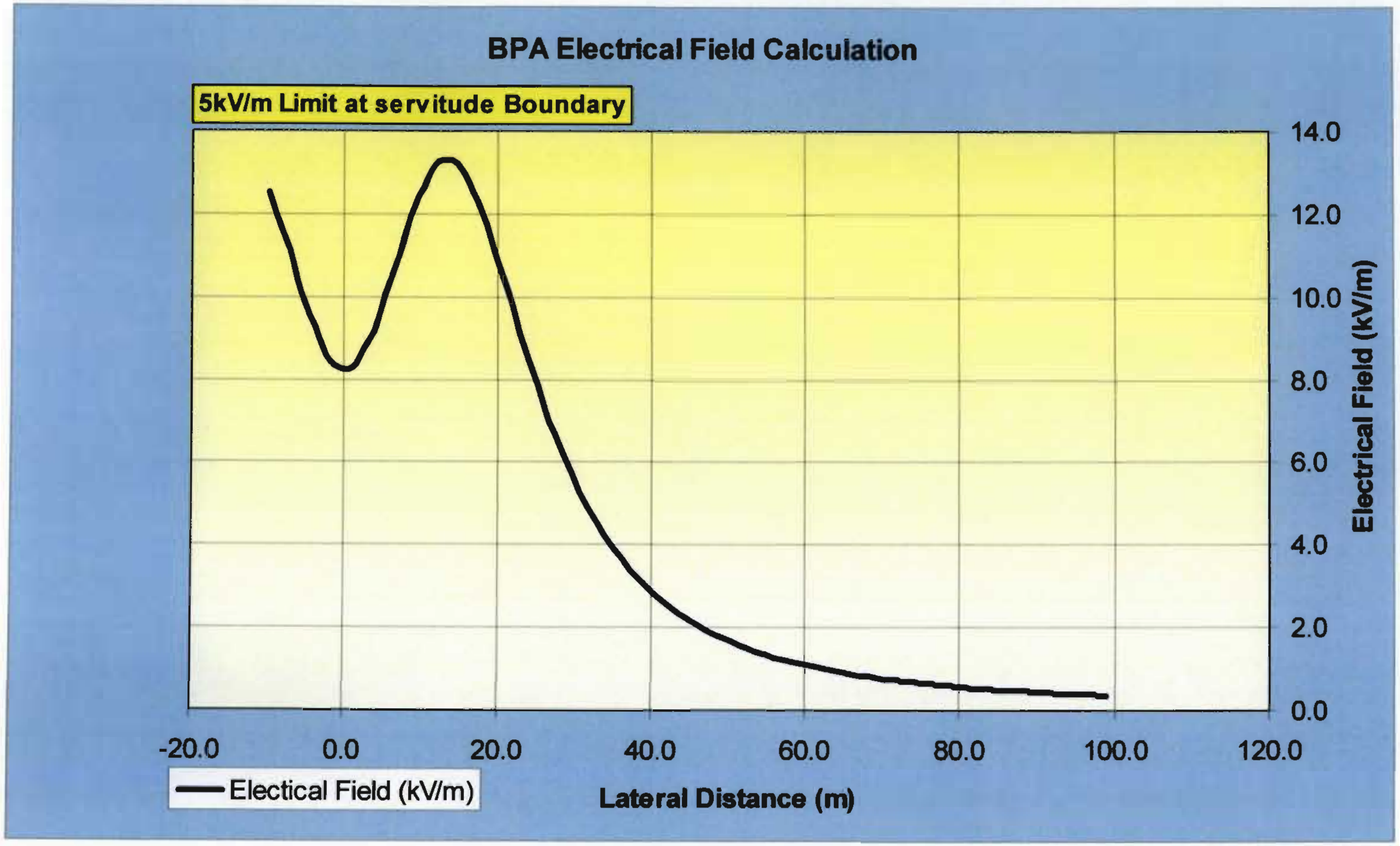
# 400 kV Twin Dino Operating at 500 kV HVDC



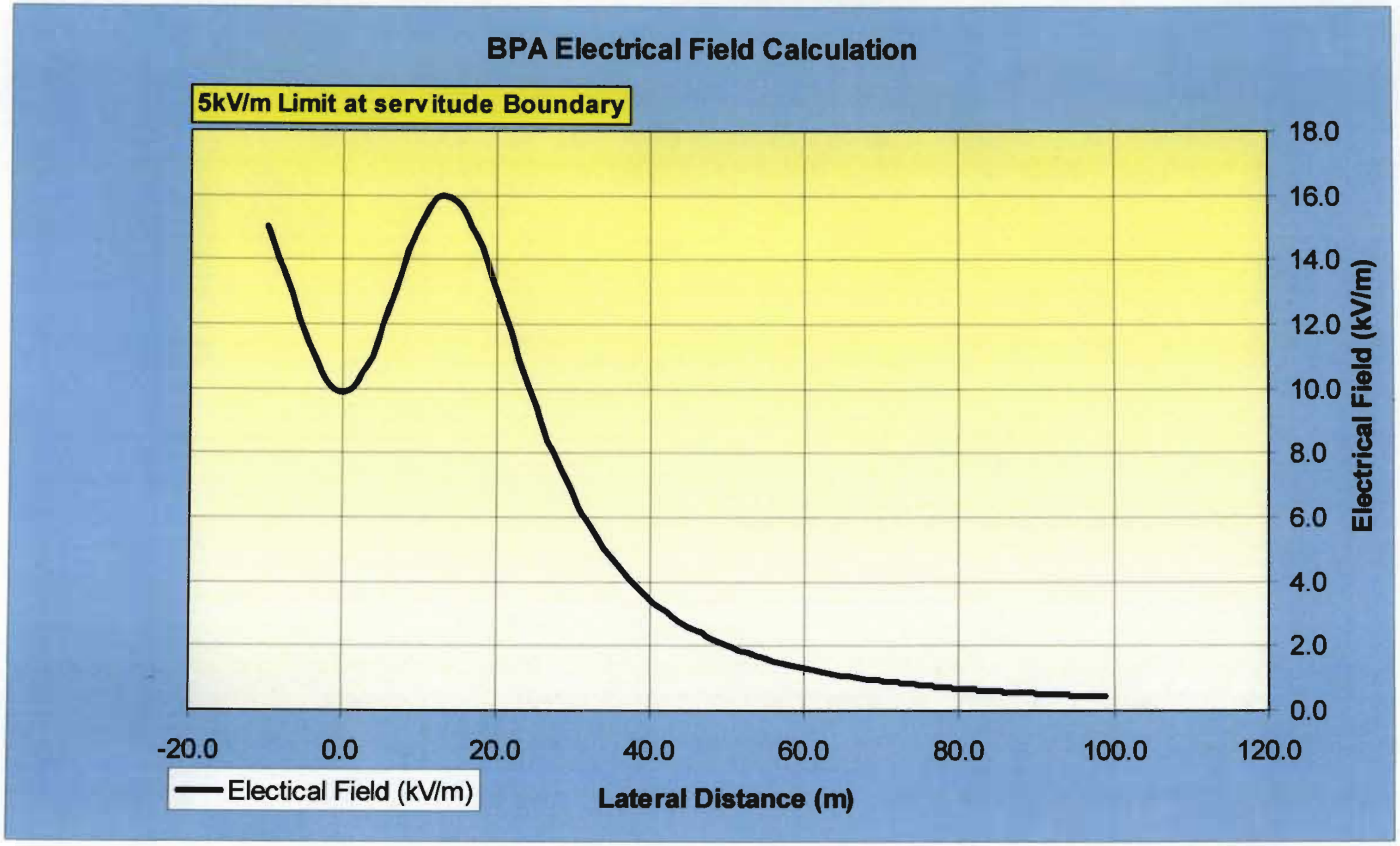
# 800 kV : Operating at 765 kV HVAC



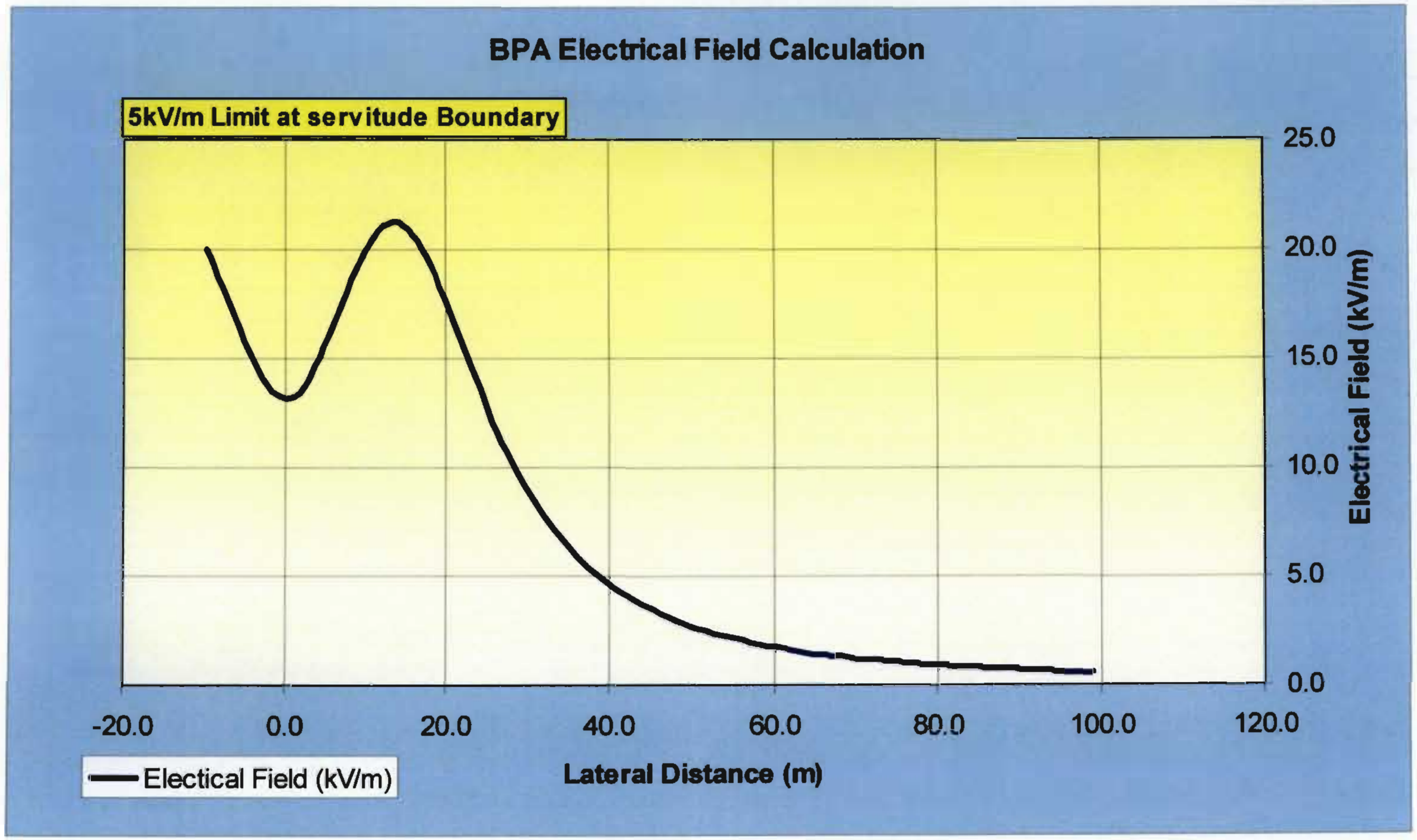
# 800 kV : Operating at 500 kV HVDC



# 800 kV : Operating at 600 kV HVDC



# 800 kV : Operating at 800 kV HVDC




Powergrid of India HVDC Limit 20 kV/m - 5000 km

## Appendix G: Copy of Conference Publications

Inaugural IEEE PES 2005 Conference and Exposition in Africa
Durban, South Africa, 11-15 July 2005

# Investigations into the Upgrading of Existing HVAC Power Transmission Circuits for Higher Power Transfers using HVDC Technology

P.Naidoo*, Dr. D Muftic**, Prof Dr N. Ijumba***
*Eskom, South Africa, **Trans Africa Projects, South Africa, ***University of KwaZulu Natal, South Africa
Eskom Transmission Division P O Box 1091, Johannesburg, South Africa, 2001
Phone: +27-11-800 4755, Fax: +27-11-800 3345, Email: pat.naidoo@eskom.co.za

***Abstract*** ***Cost effective higher current rated power electronic technology makes possible the conversion of high voltage alternating current circuits for high voltage direct current employment. This strategy is promoted so as to yield greater power transfers by using the same physical power line and installed conductor cross sectional area. This idea was shared and discussed by study committee B4 at the 2004 proceedings of Cigre in Paris, France. Here study committee working group members reported on the tri-pole proposal of using one phase of the conventional AC line as the positive pole, another phase as the negative pole and the remaining third phase to be periodically swapped between positive and negative poles; yielding almost 2,5 times the power transfer capability of the HVAC line. Along a similar path, the paper reports on Eskom's initial investigation into recycling two of the existing 400 kV lines emanating from Matimba Power Station. Additional 1800 MW thermal generation is planned alongside the existing 3600 MW power station. A known constraint is the acquisition of additional power line servitudes to evacuate the increased power generation. The real estate area surrounding Matimba Power Station is emerging as prime investment for environmentally sensitive international investors.***

## I. INTRODUCTION

Emanating from Matimba Power Station are several 400 kV lines generally operated in parallel to an N-1 contingency criteria. The N-1 contingency criterion allows one line to be removed temporarily out of service whilst maintaining transient and steady state system stability [1]. The 400 kV lines are of quad zebra conductor design on a horizontal configuration. The surge impedance load of the line is 672 MW.

For a higher power transfer capability utilising the existing transmission lines, an option under investigation is to configure one 400 kV line as the positive bipole and the neighbouring 400 kV line as the negative bipole. This would yield effectively 3 parallel HVDC circuits where each circuit consists of 4 conductors in parallel. The equivalent circuit conductor dc resistance is greatly reduced whilst current carrying capability is simultaneously quadrupled and trebled; the option of HVDC transmission appears attractive. Assuming a bipole operating voltage of 400 KV, the installed conductor cross sectional area can transfer some 3 to 4 GW of power. This is almost five to six times that of the AC surge impedance loading of the line.

The strategy of recycling is being developed and promoted for the case of limited availability of new power line servitudes, to overcome transmission congestion and bottlenecks in interconnected power networks; to recycle existing assets for greater power transfer efficiency, to promote bi-directional power transfer under different system operating conditions, to promote electrically separate power islands within a greater and growing interconnected power system thereby enhancing power system stability and controllability and to introduce the new technology HVDC control computers for rapid real time ancillary services energy management.

## II. THE NEED FOR RESEARCH IN THIS FIELD

The first complete electric power system was commissioned in 1882 by Thomas Edison at the Pearl Street Station in New York City [2]. This was a 110V, 1,5 km radius DC system supplying incandescent lamps and motor loads [2]. The first power transfer constraint engaged was that of increasing power loss and line voltage drops with increasing customer loads. In 1886, transformers were introduced and AC systems gathered momentum [2]. The key advantage was that different voltages could be employed for the different stages from generation to transmission to distribution to reticulation and eventually to consumption. For the case of increasing distance in transmission and distribution, the use of higher voltages was promoted. Power loss and line voltage drops continued to exist but at acceptable economic levels. With continued increase in customer loading and increasing transmission distances, the AC system natural or surge impedance load became the next constraint [3].

The surge impedance or natural load of an AC system transmission line is given by:

$$SIL = U*U / Zc \qquad (1)$$

Zc = characteristic or surge impedance of the transmission line [4]. These technical factors impose limits on the operation of a transmission line and this limits the power transfer capability. Maruvada [4] notes that for the case of thermal conductor rating, the power transfer limit can be up to 3 times SIL for distances up to 80km, for the case of voltage regulation limits, the power transfer limit is 1,3 to 3 times SIL with a distance range of 80 to 320 km and for the case of system stability and for distances greater than 320 km, the power transfer limit is less than 1,3 times SIL. Hence to transfer large blocks of power over long distances lines with increasing higher levels of surge impedance loading are required. To increase the SIL of equation 1, either the operating voltage U has to be increased or the characteristic impedance Zc has to be decreased.

The SIL survey of Eskom's 400 kV lines for the case of quad phase conductor bundle configuration and for distances of greater than 100km is given in table 1. We note that the quad zebra type phase conductor has the greatest lost opportunity for more power transfer.

Table 1: Survey of Eskom's 400 kV transmission line surge impedance loading for quad phase conductor bundle configuration and for distances greater than 100km.

| Line Name | Conductor Type | Line Length Km | SIL MVA |
|---|---|---|---|
| Bacchus to Proteus | Wolf | 249 | 628 |
| Delphi to Neptune | Wolf | 148 | 624 |
| Delphi to Poseidon | Wolf | 155 | 625 |
| Droerivier to Proteus | Wolf | 226 | 628 |
| Grassridge to Poseidon | Wolf | 116 | 624 |
| Kendal to Minerva | Zebra | (96) | 645 |
| Kendal to Tutuka | Zebra | 109 | 661 |
| Majuba to Venus 1 | Zebra | 218 | 665 |
| Majuba to Venus 2 | Zebra | 234 | 666 |
| Matimba to Midas | Zebra | 336 | 672 |
| Matimba to Pluto | Zebra | 342 | 671 |

From the table, all appears normal and within the expected design range. For Wolf conductor, the normal and emergency phase conductor bundle thermal power transfer ratings are 1025 MVA and 1330 MVA, respectively. To achieve higher than SIL power transfers, compensation from FACTS technologies would be adequate [5]. Now for the case of the Zebra phase conductor configuration, the gap is even larger; the normal and emergency thermal bundle conductor ratings are 1796 MVA and 2383 MVA respectively. Hence, at the normal levels, some 1,1 GW of power transfer opportunity is lost per transmission line. An interesting feature is that all the lines emanate from large thermal power stations (3600 MW) and the existing installed lines can carry a much higher loading for a few hundreds of kilometres into the load centres. This presents an opportunity to study the application of FACTS technologies [5] but noting the close electrical proximity of 600 MW turbo-generators.

The strategy to increase the operating voltage U for a higher surge impedance level is also limited. At 765kV uncompensated, the lost opportunity for power transfer increases greatly. The SIL result for Eskom's 765 kV lines is given in table 2.

Table 2: SIL of Eskom's Alpha to Beta 765 kV Transmission Lines. The phase conductor bundle is made up of 6 x zebra conductors

| Line Name | Line Length km | Normal MVA Rating | Emergency MVA Rating | SIL MVA |
|---|---|---|---|---|
| Alpha to Beta, 1 | 436 | 5152 | 6837 | 2364 |
| Alpha to Beta, 2 | 434 | 5152 | 6837 | 2364 |

It is clear that AC systems are also constrained for high power transfers and the initial 1882 Thomas Edison challenge continues to prevail. To date, AC systems have addressed adequately the issues of both increasing operating voltage and decreasing characteristic impedance [2,3,4]. The unused installed phase conductor cross sectional area is an asset that awaits application. Further application and new development of FACTS technologies is one option. Recycling the existing assets and servitudes by upgrading to HVDC is another. This paper promotes that DC systems offer an option to focus now on the installed phase conductor and to explore increased loading and higher power transfers for greater distances up to the conductors' thermal limits.

## III. THE 400 KV MATIMBA – MIDAS – PLUTO CASE STUDY

Midas and Pluto are electrically close and for all practical purposes, it can be considered as one site. The idea is to upgrade the Matimba – Midas 1 line to that of a positive bipole and the remaining Matimba – Pluto (Midas 2 line) to that of a negative bipole or to create three independent DC circuits from the given conductor assembly.

The idea to upgrade HVAC to HVDC emanated from the proceedings of the 2004 Cigre meeting held in Paris, France [6] where the current modulated tri-pole concept was presented. In the case of Eskom, the idea goes further to use the entire three phases for one bipole given the N-1 planning criteria introduced second line at transmission level. This is a design standard. In the event of the unavailability of the DC Converter stations, the lines could be returned to normal AC operation at reduced loading. Further, if multiple DC circuits are considered, then the loss of one DC circuit could be accommodated and planned for in the allocation of system reserves. The strategy of multiple DC circuits has merit and the economics thereof needs to direct further investigation.

Figure 1: Bipole Configuration for the Case of the Matimba – Midas – Pluto Power Corridor

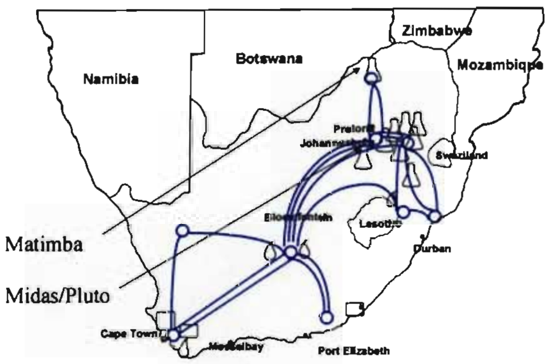
o o e/wire o o

oo oo oo R,W,B oo oo oo
oo oo oo oo oo oo

______________Ground Pane_________________

Figure 2: Map of South Africa showing location of Matimba Power Station and the load substations of Midas and Pluto on the Western side of Johannesburg.

Eskom System




*A. First Pass HVAC to HVDC Upgrade Proposal*

The strategy is to reemploy the phase conductors of the current AC line as DC poles; selecting the options as follows:

Option 1: Here all 3 phases are arranged as a pole of a DC bipole yielding effectively 12 parallel conductors per pole

\+ + + - - -

Or;
Option 2: From the same set of phase conductors; arrange for 3 independent DC bipoles with each pole having a quad bundle conductor arrangement.

\+ - + - + -

*B. First Pass Calculations for the HVAC to HVDC Upgrade Proposal*

Line Name: Matimba to Midas to Pluto

Terminal Stations: Matimba Rectifier Station

Midas – Pluto Inverter Station

Length: 400 km (monopolar)
800 km (bipolar)

Conductor : Zebra
DC Resistance at 20 Deg C = 0,0674 ohm/km
Nominal Current Rating = 860 Amps

For Option 1: 1 DC Bipole Circuit

Equivalent line resistance = 2,25 ohms
Nominal Current Rating of the 12 conductor arrangement is 10 320 Amps. If the thyristor circuits are designed to carry the full 12 conductor current capability; then at an operating voltage of 500 kV; we have:

Line losses = 240 MW per pole
Voltage Drop = 23,22 kV
Power Transfer = 5160 MW

If the power electronics is limiting and if we select 3,5 kA thyristors in parallel operation; then we have:

Line Losses = 110MW per pole
Voltage Drop = 15,75 kV
Power Transfer = 3500 MW

For Option 2, we have 3 independent DC bipoles each having a quad bundle conductor arrangement.

The equivalent line resistance is now 6,74 ohms.

Nominal Quad Bundle Current rating = 3440 amps.

Here, we can avoid parallel operation and select 3,5 kA thyristors for duty for each of the independent DC bipoles.

Then for a nominal line current of 3400 amps at 500 kV DC operating voltage; we have

Line losses = 77 MW
Voltage Drop = 23,19kV
Power Transfer = 1700 MW

Then for 3 independent DC bipoles, we have

Total Power Transfer = 5100 MW
Total Power Loss = 231MW

If the operating voltage is set at 400 kV, then we have

Total Power Transfer = 4080 MW
Total Power Loss =231MW

Under HVAC conditions; each line had a SIL of 672 MW; 1344 MW for both combined. From the simple first pass calculations, either for the 400 or the 500 kV operating voltage; we have a case of trebled power transfer or achieved an equivalent N-2 contingency with all factors being equal.

The planned extensions at Matimba Power Station of 1800 MW is easily accommodated by the HVAC to HVDC proposal; just about the total old and new Matimba output can be evacuated on the HVDC proposal. The proposal has the first pass merit for further study and the next step will involve the selection of the operating voltage.

### *C. The Next Step of Selecting the Operating Voltage*

Guile and Paterson [7] advises that the DC voltage causes electrostatic precipitation of atmospheric dirt on the surface of external insulation. Hence, for conventional glass or porcelain insulation, a higher leakage path is required for the equivalent DC voltage. Alternatively, the DC voltage would need to be reduced as compared to its equivalent peak AC voltage for the same insulator or external insulation connecting length. In the early stages of commissioning of HVDC schemes [8,9] electrostatic precipitation of atmospheric dirt was shown to be a cause for insulation failure. As a solution, silicone grease was employed with success. In lieu of greasing, New Zealand [9] also considered regular washing of insulation with varied success. Silicone based external insulation is an option and the re-insulation of the lines from the current glass discs would need to be investigated. Another motivation for re-insulation is that continuous high leakage currents would promote the corrosion of the metallic parts in the glass disc string. If re-insulation is considered, then the economic benefit of the difference in power transfer from 400 to 500 kV should be explored and banked. The choice of voltage would be dependent on the given insulator connecting length.

### *D. Recommended Further Investigations*

The tower window configuration should be checked for switching and lightning impulse levels given the presence of a continuous DC voltage. Conductor bundle corona power loss, audible noise and radio interference levels should be investigated under laboratory conditions for the selected operating voltage [4]. The quad bundle arrangement is an excellent initial and given condition. On conclusion of the technical work, the project is now ready for the business case evaluation and will be very dependent on the capital costs of the HVDC rectifier and inverter stations.

## IV. CONCLUSION

The proposal to upgrade HVAC to HVDC has merits and limitations. For HVAC lines where the thermal capacity is close to the surge impedance loading, then no additional benefit would arise. Similarly for those lines that have thermal capabilities higher than surge impedance loading but of smaller bundle configuration, then the employment of FACTS technologies would be more cost effective. For those circuits having quad or greater conductor bundle configurations, then the gap between thermal capacity and that of surge impedance loading is the largest and in these cases, the upgrade from HVAC to HVDC would have the greatest benefits. This poses a new challenge for extra high voltage AC transmission; do we employ FACTS technology such as thyristor series compensation or do we consider 765 kV upgrade to HVDC. This forms the subject of the next investigation after we have concluded with the Matimba proposal.

We also note that another 400km of quad 400 kV Eskom National Grid lines couple Kendal, Majuba and Tutuka Power Stations and the Pegasus and Venus load centres in Kwa Zulu Natal. This is another option to move 5000 MW of power deep into the load centre.

The proposal to convert HVAC to HVDC would have the greatest benefit in very large magnitude power systems such as those in North America, India and China. The asynchronous and no fault level increase attributes of HVDC together with existing servitudes will grow a giga-watt super-grid overlay on the existing mega-watt national grid.


## ACKNOWLEDGMENT

The authors wishes to thank the members of the Cigre B4 working group for the introductory idea, the HVDC Center of the University of Kwa Zulu Natal and Eskom for supporting and leading the research and investigations.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# Progress report on the investigations into the recycling of existing HVAC power transmission circuits for higher power transfers using HVDC technology

**P. Naidoo*, R.D. Estment*, D. Muftic**, N. Ijumba *****

*Eskom,South Africa, **Trans Africa Projects, South Africa, ***University of KwaZuluNatal, South Africa
pat.naidoo@eskom.co.za

**Keywords:** Power Transfers, AC and DC transmission technologies.

## Abstract

Cost effective higher current rated power electronic technology makes possible the economic conversion of an existing HVAC transmission circuit for HVDC employment. The objective is to use an existing transmission line and to operate the installed conductors to its full rated current carrying capacity. The paper reports on the boundary conditions for the proposal to upgrade HVAC to HVDC and the technical implications of introducing HVDC onto an existing HVAC tower and line configuration. In conclusion, a possible application of the proposal is presented. Here an existing 3600 MW thermal power station is being prepared for an additional 2100 MW of generation. System Planning promotes additional 400 kV or 765 kV HVAC transmission or to upgrade an existing 400 kV line for 500 kV DC application to yield a 3 GW power transfer capability.

## 1 Introduction

Upgrading high voltage AC transmission circuits to DC is promoted to use the full current carrying capability of the installed conductors so as to yield greater power transfers. This idea was shared and discussed by study committee B4 at the 2004 proceedings of Cigre in Paris, France. Study committee working group members reported on the tri-pole proposal of using one phase of the conventional AC line as the positive pole and another phase as the negative pole. The remaining third phase is then shared between the poles, periodically swapped between positive and negative poles. This upgrade results in almost 2,5 times the power transfer capability of the HVAC line [1].

Along a similar path, at the IEEE Power Engineering Society Inaugural Africa meeting held in July 2005, the study team reported on the large scale increase in power transfer when two of Eskom's 400 kV transmission lines are upgraded to three HVDC bipoles [2]. The HVAC 400 kV quad zebra phase conductor power transfer capability of 600 MW per line can increase to a substantial 1700 MW per DC bipole; to yield a total transfer of 5100 MW. This move from MW to GW signals that a super-grid could evolve from the existing HVAC transmission infrastructure and overlay the traditional National Grid.

The strategy of upgrading HVAC to HVDC is being developed and promoted for the case of;

- limited availability of new power line servitudes,
- to overcome transmission congestion and bottlenecks in large interconnected power networks;
- to recycle existing assets for greater power transfer efficiency,
- to promote bi-directional power transfer under different system operating conditions,
- to promote electrically separate and controllable power islands within a greater and growing interconnected power system
- to enhance power system stability and controllability,
- to introduce the new technology HVDC control computers for rapid real time ancillary services energy management.,
- etc.

As early as 1966, Kennedy [3] reported at the IEE Conference on High Voltage DC Transmission that his study results show that to a first approximation, the break even power level for AC to DC conversion is largely a function of DC terminal equipment costs and AC line costs. In this study, Kennedy did not consider the performance or the availability of the DC supply, as there was limited operating experience with inadequate reliability data from the few commissioned HVDC schemes.

At the same conference, Smedsfelt et al [4] reported on the operational performance and service experience with the Konti-Skan and Gotland HVDC project. The fault rate on the DC stabilised to be approximately the same as for AC alternatives but the issue of value arc backs persisted as the power electronic technology was still under development.

Much later, Padiyar [5] reported on the progression of the power electronic technology from mercury arc value to that of thyristor values. Most recently, The China Three Gorges project [6] reports excellent project and in service performance of HVDC technology. China is busy with several 500 kV, 3000 MW, and approximately 1000km

IEE 8th International Conference ACDC Power Transmission
March 2006, Savoy Place, London, UK

HVDC bipoles. The latest circuit was commissioned successfully in 28 months from order at a cost of US$360m [6]. Based on the Three Gorges Project as benchmark, the early work of Kennedy [3] suggests that a techno-economic case could exist for converting HVAC to HVDC transmission for higher power transfers. For the specific case of unavailability of servitudes for additional HVAC transmission lines, the HVAC to HVDC upgrade proposal gains the competitive edge over traditional solutions.

It is clear that for a successful engineering solution, the cost of the solution would need to be economically justifiable against conventional HVAC alternatives including the application of FACTS technology for higher power transfers. It is thus proposed that the HVDC upgrade proposal be technically developed and added to the existing menu of solutions available to power system planners. It is further proposed that the solution be developed specifically for the cases where additional transmission servitudes are difficult to obtain and where the **"unused power transfer gap"** between the installed conductor current rated capability and the surge impedance loading is the greatest [2]. Thus, prior to a detailed review of the technical merits of the proposal, the initial boundary condition for an HVAC circuit upgrade to HVDC should be considered.

## 2 The Initial Boundary Condition for an HVAC Circuit Upgrade to HVDC.

At the outset, it must be noted that the proposal to upgrade HVAC to HVDC is presented only for the case of special application where the **"unused power transfer gap"** on existing transmission lines is very large. This could be approximately 3 to 4 times the SIL. The added advantage is that the conductors are installed (ie. the DC line exists) but the installed capacity is partially utilised. The solution being developed for power system planners is for application in the giga-watt range rather than in the mega-watt range of power transfers. Further, the giga-watt category will contribute to a favourable outcome for the economic justification exercise.

The Eskom National Grid consists of 270 000km of HVAC transmission lines arranged in voltages of 132 kV, 220 kV, 275 kV, 400 kV and 765kV with 1414km of 533 kV HVDC from the Apollo - Cahora Bassa Scheme. From a detailed survey of all the national grid lines, their phase conductors, their rated current carrying capacity and their surge impedance loading (SIL), the following was found [2]:

- 400 kV lines with quad zebra bundle phase conductors and the 765 kV lines with the six bundle phase conductors have the greatest unused power transfer gap between installed current carrying capability versus power transfer surge impedance loading.
- In the case of the quad zebra 400 kV lines, the surge impedance load is on average 670 MVA as compared to the rated bundle current capability of 1796 MVA, normal limit, and 2383 MVA, emergency limit. In this case, 1,1GW of active power transfer is recorded as the lost opportunity per line.
- In the case of the six bundle zebra 765 kV lines, the surge impedance load is on average 2364 MVA as compared to the rated bundle current capability of 5152 MVA, normal limit, and 6837 MVA, emergency limit. In this case, 3GW of active power transfer is recorded as the lost opportunity per line.
- For all other transmission lines, the unused gap between phase conductor current capability and surge impedance loading was either small or negligible. For the latter, there is no case for upgrade to DC and where the gap is small, FACTS technology application would be suitable.

The theory of surge impedance loading of an AC transmission line indicates that to transfer larger blocks of load over long distances; higher levels of surge impedance loading will be required and this is obtained either by increasing the voltage or by decreasing the characteristic impedance of the line [7]. In addition, Maruvada [7] further notes that for the case

- of thermal conductor rating, the power transfer limit can be up to 3 times SIL for distances up to 80km,
- for the case of voltage regulation limits, the power transfer limit is 1,3 to 3 times SIL for distances from 80 to 320km and ,
- for the case of system stability and for distances greater than 320 km, the power transfer limit is less than 1,3 times the SIL.

HVDC technology has the advantage and can be designed for a specific voltage drop between sending and receiving ends. Distance is not a limiting factor and for all practical purposes, the power transfer limit can be designed to be up to 3 times the SIL. HVDC further has the advantage of not introducing greater power transmission inefficiency such as that noted when operating voltage is increased. The efficiency of 765 kV transmission is questionable as the unused conductor current rated capacity is the greatest. Phase conductors generally form the higher cost of materials for any power line. This area requires further research and investigation.

Decreasing characteristic impedance under controlled conditions as presented by Hingorani [8] could be considered a more efficient approach for achieving higher power transfers when the unused gap between installed conductor current rating and SIL is small. Hingorani [8] clearly realised the existence of the unused power transfer gap and that with faster control, power and voltage stability can be assured and thus higher power transfers can be achieved. Hingorani [8] further notes that with HVDC, full transmission capability can be achieved and maintained for the full thermal rating of the line as power is electronically controlled. Given the high cost of the HVDC terminal equipment, application is limited to special cases and thus the proposal to first establish the initial boundary condition. The research work in progress for converting selected HVAC circuits to HVDC can be considered a continuation of Hingorani's efforts as introduced under FACTS in 1991 at EPRI in the USA.

From Kundur's [9] recall of the history of electric power transmission (Pearl Street DC Substation 1882) to Arillage's [10] suggested benchmark for power transfer capability, it would appear that HVAC with FACTS is more suited for local power distribution rather than bulk power transmission. If that is accepted, then HVDC regains its 1882 position as a most appropriate technology for bulk power point to point transmission. This conclusion correlates with the growth in energy markets whereby several neighbouring countries and independent entities that can come together on a common power pool platform and an interconnected power system for energy trading and dispatch; not to be constrained by distance or congestion.

From the initial boundary condition analysis, we establish that the HVAC line under consideration for upgrade to HVDC is either the six bundle zebra 765 kV or the four bundle zebra 400 kV triple V glass disc configuration guyed and self supporting structures. This analysis included the survey done on Eskom's 270 000km collection of transmission line data.

With just these two selected circuits, the implications for Eskom, South Africa is enormous. Once located on the National Grid, we note that these circuits link very large thermal power stations to each other and onto very large load nodes. This makes for ideal bulk power point to point transmission. This comes with all the added benefits of lower transmission losses, higher (controlled) availability, reliability and performance and enhanced security and power system stability. A new giga-watt super-grid could evolve from and overlay the existing national grid. A first pass case study is explored to determine the technical viability of the upgrade proposal.

## 3. The Case Study for the 400 kV Quad Zebra Transmission Circuit.

Surging demand for electrical energy in South and Southern Africa has called for new capacity in power generation. One option being explored is to expand the existing Matimba Power Station from 3600 MW to 3600 + 2100 MW. Presently, we have 8 by 400 kV lines emanating from the power station. To evacuate the additional power, 4 by 400 kV lines or 2 by 765 kV lines are under review. Another option under development is to promote the upgrade of one of the HVAC 400 kV line for HVDC application; to evacuate some 3000MW of power.

Given

One physical power line with servitude. The tower type is 520/518 series. The line has glass disc cap and pin insulators, arranged in a V suspension and twin horizontal strain configuration holding quad zebra bundle phase conductors using diamond spacers. The phase conductors are spaced 8,5m horizontally. The phase conductor midspan height to ground is 8,1m and the radius of the conductor bundle to the tower structure is 3,2m.

### 3.1 External Insulation Analysis

The external insulation consists of cap and pin glass disc insulators of type U190BS and U300BS.

U190BS: 279mm diameter, creepage distance of 368mm
U300BS: 320mm diameter, creepage distance of 440mm

The tower types employed have the following insulation:

520 suspension: 19 U190BS – creepage distance of 6992mm
518 suspension: 17U300BS – Creepage distance of 7480mm
518 strain: 18U300BS – creepage distance of 7920mm

At Um 420kV, the specific creepage is 16,6; 17,8; 18,9 mm/kV for the three configurations. It is known that DC favours electrostatic precipitation of the atmospheric dirt and with wetting, insulation breakdown will occur at these specific creepage levels. It is also known that glass disc ion migration occurs under DC exposure and stem corrosion is severe. Re-insulation is required and a proposal is to consider the use of non-ceramic DC insulators of type silicone rubber. On the Apollo - Cahorra Bassa 533 kV line, non ceramic silicone rubber insulators are installed in a connecting length of 4,11m and with a creepage length of 16 000mm; yielding a specific creepage of 30.02mm/kV at 533 kV DC. These insulators have been supplied in accordance with IEC 61109-1992/1995-04 and IEC 60815/1986. The three-year performance to date has been zero electrical or mechanical faults.

In addition, Eskom's extensive work on 400 kV HVAC circuits involving 10 000's of non ceramic silicone rubber insulators in heavy coastal pollution corridors show excellent (zero electrical fault) performance now with some 20 years of operating experience. Silicone rubber insulators with a specific creepage of 30 mm/kV and a 1.0 ratio of shed spacing to shed projection will yield excellent performance under DC conditions. In an internal study conducted by Vosloo et al [11], it has been established that for the connecting length of 3315mm for the given tower configuration, a 31mm/kV-silicone rubber insulator at Um 500 kV DC would be possible. This first design specification is a contribution to the upgrade proposal. With the submission of the first functional design specification, the study team also submits the following questions for further review:

- IEC specifications pertain to AC insulators. What should we specify for DC non-ceramic insulators?
- What is the long-term effect of polarity? Will this differ from AC; from negative to positive or have no relevance?
- What are the ageing modes for various materials?
- What is the effect of DC on pollution catch and how will this effect overall insulator performance?
- What is the relative performance of the various DC insulator designs and non-ceramic materials available on the market?
- Can we use existing AC site severity assessment techniques and apply them for DC insulator selection?

- Can we use the Standard Test methods developed for AC pollution?

### 3.2 Corona Power Loss, Audible Noise and Radio Interference Analysis

Here the zebra conductor has a diameter of 28.62mm and the bundle has a sub conductor spacing of 380mm. Peek's law governing corona initiation on transmission line conductors provide a corona inception voltage of 34,9 kV at sea level and 29,7 kV at high altitude of 1500m.

Using Peek's formula and solving for the corona cage diameter, we obtain a diameter of 3865mm; say a cage of diameter 4m. On the tower; a radius of 3,2m separates the conductor bundle (rod) from the tower (plane). A further study intent is to experimentally measure the corona power loss by measuring the leakage current to the cage when the quad bundle is operated at 500 kV; positive and negative polarity.

Using the Bonneville Power Administration Corona and Field Effects Program version 3, the following corona effects results were calculated for the Apollo-Cahora Bassa 533 kV DC line (as reference) and for the planned upgrade of the 400 kV HVAC line to HVDC.

***Audible Noise Effects***

**533 kV Apollo – Cahora Bassa (limit is 53.1dB at edge of servitude)**

For all the scenarios, the calculated levels are within the operating limits.
At sea level at 600 operating voltage: L50 wet is 33,1 DBA; L50 dry is 39,1DBA.
At 1500m altitude at 399kV operating voltage: L50 wet is 22,9DBA and L50 dry is 28,9DBA.
At 1500 m altitude at 533 kV operating voltage: L50 wet is 30,8DBA and L50 dry is 36,8 DBA
At 1800m altitude at 533 kV operating voltage: L50 wet is 27,1 DBA and L50 dry is 33,1 DBA.

**400 kV HVAC Upgraded to HVDC all at 1500m altitude**

For all the scenarios, the calculated levels are within the operating limits and below that as compared to the 533 kV Cahora Bassa levels.

at 350kV operating voltage: L50 wet is 16,3 DBA; L50 dry is 22,3 DBA.
at 400kV operating voltage: L50 wet is 21,3 DBA and L50 dry is 27,3 DBA.
at 450 kV operating voltage : L50 wet is 25,7 DBA and L50 dry is 31,7 DBA
at 500 kV operating voltage: L50 wet is 29,6 DBA and L50 dry is 35,6 DBA.

Similarly, we calculated the radio interference levels and noted against limits of 72-dB wet and 50/60 dB dry at 500 kHz. For all the scenarios, all acceptable values are recorded for both the 533 kV DC and for the upgraded 400 kV AC to 500 kV DC. At 500 kV operating voltage of the upgraded 400 kV line, the wet RI level is 36,9 dB and the dry RI level is 49,9 dB.

Finally, the electric field gradient at the edge of the servitude for the case of 500 kV operating voltage is 4.049 kV/m within the operating limit of 5 kV/m continuous or 10 kV/m occupational. The similar result was recorded for the various study case scenarios.

### 3.3 Air Gap Critical Withstand Level under Composite Stresses

The air gap between conductor bundle and tower can be represented by a simple rod-plane configuration [5]. This would apply equally to the suspension and strain towers. This work is scheduled for experimental study in 2006. However, work done in 1984 and reported at Cigre [12] shows that the dielectric strength of air gaps and of clean and dry insulators, under continuous DC voltage, is close to 500 kV/m (streamer type discharge) and thus does not present any problem. Much lower flashover gradients are obtained on insulators under rain. Further, with the choice of silicone rubber, this conclusion may also vary or sustain. For this chapter, experimental work is planned and prepared for 2006; either at EPRI in the USA or CESI in Italy.

## 4 Conclusion

The first pass technical review shows that 500 kV operating voltage is possible for a DC bipole configuration using one set of phase conductors as the positive pole and another set of phase conductors as the negative pole. The remaining centre phase can be configured to be a metallic earth return or a tripole using current modulation as promoted by Barthold [1].

One quad zebra bundle conductor will have a nominal current capacity of 3440 amps (4 x 860 amps). At positive or negative 500 kV polarity, his equates to 1720 MW. The next task is to prepare the HVDC bipole configuration. This would be followed by circuit analysis such as HVDC in parallel with weak HVAC.

The initial foundations for the super-grid are in the planning phase and a first reaction is that the scheme be engineered to N-2 level of contingency including higher levels of system reserve. Traditionally, Eskom plans for the loss of one large thermal unit of 600 MW capacity and has set a reserve policy accordingly. The loss of Koeberg's nuclear 980 MW or Cahorra Bassa's 1200 MW are allowed for as in infrequent incidents and accommodated in frequency excursion limits.

If a 3 GW HVDC scheme is planned, then a monopole level could be 1500 MW with metallic earth return or forced to 750 MW with traditional earth return. These policy issues require clarity especially from regulatory pricing of transmission services.

## Acknowledgements

The study team acknowledges the continuous active support of Eskom, Trans Africa Projects and the University of Kwa Zulu Natal. In addition, the team is appreciative of comments and suggestions from Dr Barthold, Dr Vosloo, Associate Professor A C Britten and Rob Stephens of Cigre and Auther Burger of Trans Africa Projects.

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# Investigations into Electrical and Corona Effects for the Upgrade of HVAC Transmission Lines to HVDC

**P. Naidoo*, A.C. Britten*, W.L. Vosloo*, R. Stephen*, G. Sibilant*, D. Muftic**, A. Burger**, N.M. Ijumba*****

*Eskom, South Africa
** Trans Africa Projects, South Africa
*** University of KwaZulu-Natal, South Africa
pat.naidoo@eskom.co.za

**Keywords:** Electric Fields, Corona, Radio Interference, Audible Noise, HVAC and HVDC.

## Abstract

Cost effective higher current rated power electronic technology makes possible the economic conversion of an existing HVAC transmission line for HVDC employment. The large unused transmission line phase conductor current carrying capability promotes higher power transfers when operated at HVDC. This strategy introduces new electrical effects as we move away from alternating current to direct current conditions. In all cases, we record a substantial increase in electric field strength when AC is converted to DC. Equally, we record that DC environmental effects are less onerous than AC effects. It is found that height above ground is the primary parameter that influences the strength and magnitude of electric fields within the power line servitude. In all cases, the electric fields reduce substantially at the edge of the servitude. In all cases, the corona effects are well within the acceptable limits. The paper presents the results of several studies and reports on similar experiences internationally. In conclusion, we record that the proposed conversion from AC to DC is practical and a typical 400 kV AC line may be feasible to be operated DC at the upper voltage of 500 kV.

## 1 Introduction

The upgrading of HVAC transmission lines for HVDC application shows that the total installed phase conductor current carrying capability can be fully employed and this results in higher power transfers with lower losses [1,2]. This implies improved power transmission efficiency based on the use of existing assets. The approach is novel.

There will exist a lag in implementation as power system planners come up to speed with the understanding of DC technology. This lag in understanding is acceptable given that DC technology application also went into sleep mode during the last two decades; either due to reduced capital expansion as new market models were introduced or due to reliability concerns with multi-terminal engineering and external insulation breakdown. Most recently, China's Three Gorges Project, successfully re-introduced DC application on a large scale resulting in lower costs for the converter terminal equipment. all employing higher current and higher voltage rated power electronics. Silicone rubber insulation was also simultaneously introduced and this has totally attenuated the external insulation breakdown traditionally associated with glass and porcelain insulation in the presence of DC's accumulation of atmospheric dirt. Here the hydrophobic property of silicone prevents the build up and growth of insulation surface leakage current during surface wetting. With higher reliability and availability of the DC scheme, higher power handling capability and lower costs of the terminal converter equipment; DC applications will gather interest and over the next decade. As a result, several schemes could be commissioned on the Eskom National Grid and on the Southern African Power Pool Regional Grid.

For the present, we promote strategically, the continued research and investigations into the proposed upgrade of HVAC to HVDC. Several papers will emanate from this study which is jointly supervised by the University of KwaZulu Natal and Eskom. In this paper, we report on the change in electrical effects when moving from that of HVAC to that of HVDC. For the study, we employed the line models for 275 kV with twin zebra phase conductors. 400 kV line models with twin zebra twin dinosaurs' triple tern and quad zebra phase conductors followed this. Finally, we considered Eskom's 765 kV six bundle zebra phase conductor line model upgraded to 500kV DC, 600 kV DC and 800 kV DC. The research methodology employed was a computer-based calculation using the Bonneville Power Administration Corona and Field Effects program version 3.0; licensed to Eskom, South Africa. In all cases, the transmission line is maintained as an existing line, no changes were introduced and as reference, the HVAC electrical effects were calculated and recorded.

## 2 Literature Review of Electrical and Corona Effects under DC Potential

Electric and magnetic field effects together with corona effects define the operating environment of any transmission line. EPRI [3] define electrical effects of a transmission line as being the overlapping contribution of field effects and corona effects. The voltage of the line produces the electric field whilst the current conveyed produces the magnetic field.

Corona is caused when the voltage gradient on the surface of the conductors exceeds the breakdown strength of the air surrounding the conductors. This causes partial ionisation of the surrounding air and produces power loss, radio and television interference, audible noise and space charge fields. Space charge fields are unique to DC. Corona losses, radio and television interference and audible noise is common to AC and DC. Padiyar [4] records that in general, corona effects tend to be less significant on DC conductors than AC conductors. Local experience has shown that corona generation on the shield wire is very high and can disrupt the power line carrier system.

Space charge fields involves the movement of ions both in still air and directionally biased under wind conditions. Space charge fields cause an increase in the voltage gradient at ground level. Thus, the total electric field at ground level consists of the sum of electrostatic field and space charge field. The North Dakota Public Service Commission regulated the total electric field [3]. EPRI [3] records state that the public service commission required that the 400 kV DC "CU(name of the DC scheme)" line be designed and operated such that the total electric field does not exceed 33 kV/m as measured at ground level. The total electric field was defined as the combination of the electrostatic field ( 12 kV/m ) and the electric field produced by ions ( 21 kV/m) from the corona emanating from the conductors. The 33kV/m limit was determined from two bounds: 32kV/m was the total maximum estimated electric field for monopolar operation; and that persons wearing commercial footwear seldom experience any sensation even in DC electric fields of 40 kV/m.

Note that the electrostatic field can be calculated, but the space charge field will depend on the local environmental factors, which is variable and can statistically be 2 to 3 times higher than the electrostatic field. This is the prime reason for detailed investigations when the DC operating voltage is raised to 800 kV.

In comparison to AC circuits, ions produced during one half cycle are captured during the second half cycle by the polarity reversal on the conductor [4]. The net effect is the increase in the diameter of the ionisation zone as the surface gradient increases above the critical level. The ions are trapped in the ionisation zone and ion drift is negligible. It is this effect, when subject to added particles from servitude fires, that causes a further increase in the diameter of the ionisation zone which eventually leads to air gap breakdown either between phases or between phase to earth for overhead transmission lines. However, under DC potential, ion drift occurs and is not captured as that which occurs in AC circuits. The ion drift is also wind sensitive. Ion drift in the presence of servitude fires should form the subject for further research and investigations with the hypothesis that DC should have a higher resistance to air gap breakdown than that of AC in the presence of servitude fires.

Further, in the case of AC, the time varying electric field will capacitively induce currents in humans, animals and objects directly beneath the phase conductors. It is for this reason, a maximum of 10 kV/m electric field level directly beneath the conductors and 5 kV/m at the edge of the servitude is allowed for the design and operation of AC transmission lines. In the case of DC, such induction is not present. Hence, higher levels of electric fields could be allowable.

In the case of magnetic fields, the current flowing produces the field. Work done by EPRI [3] has shown that the earth's magnetic field of 500 milli-gauss contributes to partial cancellation of the line generated magnetic field; causing a reduction in the field underneath the transmission line. For DC lines, currents of 1000 A and 2000 A are common and at a height of 4m above ground, the magnetic field generated is roughly equal to the earth's magnetic field [3].

For the case of corona power loss, Morris and Maruvada [5] have shown that for the case of rain, DC losses increase by a factor of 10:1 as compared to that of AC where losses increase by a factor of 50:1. In addition, their work has also shown that for a given voltage, positive and negative polarity losses are almost equal and for the case of DC, losses usually increase with wind velocity in the range of 0 to 10 m/sec. Other factors, such as humidity, conductor surface condition, rain, wind direction, etc are also important.

Radio interference is due mainly due to the positive polarity conductor whereby the plume discharges and streamers are randomly distributed and form more persistent discharges. Under rain conditions, DC radio interference reduces whereas it increases for the case of AC [4]. DC television interference is due to the ion currents and at distances greater than 25m from the pole conductor, there is no interference [4].

For the case of audible noise, the positive polarity conductor dominates. Under rain, there exists a reduction for the case of DC as compared to higher values for AC.

In summary, we note from the literature review that the environmental electrical and corona effects are less onerous under DC than under AC conditions. The influencing variables would be height above ground and width of servitude; in all cases DC having an edge over AC, except for the unique space charge ion effect. With increasing operating voltages to higher levels of 800 kV, a different scenario could emerge, as all the effects are extremely sensitive to voltage magnitude.

## 3 Collection of Study Case Results for 275 kV, 400 kV and 765 kV Transmission Lines

The following input parameters were considered for all the case studies tabled.

- The altitude was set at 1200m above sea level.

- The AC loading on the transmission lines were set as follows: 765 kV - 2400 MVA; 400 kV - 675 MVA and 275 kV – 450 MVA.
- The total servitude right of way was set as follows: 275 kV – 47m; 400 kV – 47/54m; 765 kV – 80m and 533 kV DC – 30m.
- The allowable AC limits were set as follows: electric field - within servitude 10 kV/m - at edge of servitude 5 kV/m, magnetic field within servitude - 1000 mG; audible noise L50 wet – 53,1 dBA and radio interference L 50 wet @ 500 kHz – 72 dBA. There is no limit for dry noise.
- In IEC standard terms, the conductors employed are as follows: zebra = 428 A1/S1A 54/7; tern is 404 A1/S1A 45/7 and dinosaur is 662 A1/S1A 54.19.

For the selected case studies, all the transmission lines selected are of horizontal configuration. For the upgrade to HVDC, the two outer phase conductors are configured as the bipoles of the HVDC scheme; one pole at positive polarity and the other pole at negative polarity. The centre phase conductor is configured as the metallic earth return; thus affording the DC scheme to be operated in monopole configuration at half power rating of the bipole.

A later engineering option could be to configure this centre phase as the tripole.

**Table 1: Case Study 1: 275 kV Twin Zebra HVAC Transmission Line**

Phase Conductor Diameter = 28.62mm
Midspan height of phase conductors = 7,2m
Midspan height of earth wires = 13,5m
DC operating voltage = 500 kV

| Category | Operating HVAC | Operating HVDC |
|---|---|---|
| **Max Surface Gradient (kV/cm)** | 275 kV | 500 kV |
| R phase | 14.02 | 36,90 |
| W Phase | 14,63 | 8,08 |
| B Phase | 14,02 | -36.90 |
| Earthwire 1 | 4,44 | 20,15 |
| Earthwire 2 | 4,44 | 20,15 |
| | | |
| **Audible Noise** L 50 wet (dBA) | 42,3 < 53,1 upper limit | 41,3 |
| L50 Fair (dBA) | 17,3 | 47,3 |
| | | |
| **Radio Noise @ 500 kHz** | | |
| L50 Wet dBA | 60,4 < 72 upper limit | 47,7 |
| L50 Fair dBA | 43,4 | 60,7 |
| | | |
| **Electric Field kV/m** | | |
| Within servitude | 7,9 < 10 upper limit | 27,3 |
| At edge of servitude | 1,4 < 5 upper limit | 5,4 |
| | | |
| **Magnetic Field (mG)** | 684,7 < 1000 upper limit | 866,1 |

Here we note the following:

- The WET audible and radio noise levels are reduced under DC potential
- The levels for audible and radio noise are within the overall AC limits
- The magnetic fields are easily within the acceptable AC limit
- There exists a substantial increase in conductor surface gradient and electric field within the servitude when under DC potential.
- At the edge of the servitude, the DC field effect reduces to that of the acceptable AC limit
- Shield wire corona generation is very severe and may impact on powerline carrier systems.

**Table 2: Case Study 2: 400 kV Twin Dinosaur HVAC Transmission Line**

Phase Conductor Diameter = 35.94mm
Midspan height of phase conductors = 8,1m
Midspan height of earth wires = 18,3m
DC operating Voltage = 500 kV

| Category | Operating HVAC | Operating HVDC |
|---|---|---|
| **Maximum Surface Gradient (kV/cm)** | 400 kV | 500 kV |
| R phase | 15,43 | 29,53 |
| W phase | 16,11 | 5,33 |
| B Phase | 15,43 | -29,53 |
| Earthwire 1 | 4,24 | 16.56 |
| Earthwire 2 | 4,24 | 16.56 |
| | | |
| **Audible Noise** | | |
| L50 Wet dBA | 51,3 < 53 | 35,4 |
| L50 Fair dBA | 26,3 | 41,4 |
| | | |
| **Radio Noise @ 500 kHz** | | |
| L50 Wet dBA | 65,3 < 72 | 39,4 |
| L50 Fair dBA | 48,3 | 52,4 |
| | | |
| **Electric Field kV/m** | | |
| Within servitude | 10,1 < 10 | 24,1 |
| At edge of servitude | 1,4 | 3,7 |

| | | |
|---|---|---|
| **Magnetic Field** | 520,4 mG < 1000 | 662,2 mG |

All the findings for case 1 remain. In addition, we note the effect of the larger diameter conductor. For the larger diameter conductor, we record some attenuation in the levels of conductor surface gradient and electric field.

**Table 3: Case Study 3: 400 kV Triple Tern HVAC Transmission Line**

Phase Conductor Diameter = 27,0mm
Midspan height of phase conductors = 9,3m
Midspan height of earth wires = 19,4m
DC operating Voltage = 500 kV

| **Category** | **Operating HVAC** | **Operating HVDC** |
|---|---|---|
| **Maximum Surface Gradient kV/cm** | 400 kV | 500 kV |
| R Phase | 15,73 | 28,87 |
| B Phase | 17,03 | 7,77 |
| W Phase | 15,73 | -28.87 |
| Earthwire 1 | 5.04 | 19.43 |
| Earthwire 2 | 5.04 | 19.43 |
| | | |
| **Audible Noise** | | |
| L50 Wet dBA | 46,2 < 53,1 | 34,8 |
| L50 Fair dBA | 21,2 | 40,8 |
| | | |
| **Radio Noise @ 500 kHz** | | |
| L50 Wet dBA | 60.8 < 72 | 35,5 |
| L50 Fair dBA | 43,8 | 48,5 |
| | | |
| **Electric Field kV/m** | | |
| Within servitude | 8,7 < 10 | 21,7 |
| At edge of servitude | 1,3 < 5 | 3,7 |
| | | |
| **Magnetic Field** | 401,5 mG | 668,4 mG |

In case3 and with a higher bundle order; the attenuation benefits improve whilst all the findings for cases 1 and 2 sustains. A higher conductor bundle order supports a lower surface gradient profile and a lower electric field profile.

**Table 4: Case Study 4: 400 kV Triple and Quad Zebra HVAC Transmission Line**
Phase Conductor Diameter = 28,62mm
Midspan height of phase conductors = 8,1m
Midspan height of earth wires = 13,8m
DC operating Voltage = 500 kV

| **Category** | **Triple Zebra** | **Quad Zebra** | **Quad Zebra** |
|---|---|---|---|
| | **HVAC** | **HVAC** | **HVDC** |
| | **400 kV** | **400 kV** | **500 kV** |
| **Maximum Surface Gradient kV/cm** | | | |
| R Phase | 15,29 | 12,54 | 23,99 |
| W Phase | 15,93 | 13,43 | 6,01 |
| B Phase | 15,29 | 12,54 | -23.99 |
| Earthwire 1 | 8,55 | 9,28 | 28.02 |
| Earthwire 2 | 8,55 | 9,28 | 28,02 |
| | | | |
| **Audible Noise** | 3 zebra | 4 zebra | 4 zebra DC |
| L50 Wet dBA | 45,2 < 53,1 | 34,6 < 53,1 | 32,1 |
| L50 Fair dBA | 20,2 | 9,6 | 38,1 |
| | | | |
| **Radio Noise @ 500 kHz** | | | |
| L50 Wet dBA | 59,5 < 72 | 48,2 < 72 | 28,5 |
| L50 Fair dBA | 42,5 | 31,2 | 41,5 |
| | | | |
| **Electric Field kV/m** | | | |
| Within servitude | 10,3 | 8,9 | 27,2 |
| At Edge of servitude | 1,5 | 1,1 | 3,5 |
| | | | |
| **Magnetic Field mG** | 411,7 | | 669,3 |

The higher conductor bundle order further attenuates the conductor surface gradient profile and also that of the electric field. Under DC, we record that the environmental electrical and corona effects are reduced when compared to AC. The only question we have is whether the DC field levels are acceptable.

**Table 5: Case Study 5: 765 kV six bundle zebra HVAC Transmission Line**

Phase Conductor Diameter = 28,62 mm
Midspan height of phase conductors = 15m
Midspan height of earth wires = 27,6m
DC operating Voltage = 500, 600 and 800 kV

| **Category** | **765 kV HVAC** | **@ 500 kV DC** | **@ 600 kV DC** | **@ 800 kV DC** |
|---|---|---|---|---|
| **Max Surface Gradient kV/cm** | | | | |
| R Phase | 16,33 | 15,73 | 18,88 | 25,17 |
| W Phase | 17,39 | 4,41 | 5,29 | 7,06 |
| B Phase | 16,33 | -15,73 | -18,88 | -25,17 |

| | | | | |
|---|---|---|---|---|
| Earthwire 1 | 11,95 | 21,76 | 26,12 | 34,82 |
| Earthwire 2 | 11,95 | 21,76 | 26,12 | 34,82 |
| | | | | |
| **Audible Noise** | dBA | dBA | dBA | dBA |
| L50 Wet | 54,7 | 18,8 | 25,6 | 36,4 |
| L50 Fair | 29,7 | 24,8 | 31,6 | 42,4 |
| | | | | |
| **Radio Noise @ 500 kHz** | dBA | dBA | dBA | dBA |
| L50 Wet | 61,8 | 11,5 | 18,4 | 29,1 |
| L50 Fair | 44,8 | 24,5 | 31,4 | 42,1 |
| **Electric Field kV/m** | 765 kV HVAC | @ 500 kV DC | @ 600 kV DC | @ 800 kV DC |
| Within Servitude | 9,8 | 13,3 | 16,0 | 21,3 |
| Edge of servitude | 2.0 | 3.0 | 3,6 | 4,7 |
| | | | | |
| **Magnetic Field mG** | 555.9 | 831.3 | 831.3 | 831.3 |

With a higher order conductor bundle arrangement and high height above ground, we record very acceptable levels are achieved when the 765 kV line is upgraded to DC. Once again, for the case of conversion to DC, we need to find acceptable limits for the conductor maximum surface gradient (kV/cm) and for the electric fields (kV/m); both within and at the edge of the servitude need to be found. The Canadians do report very high number of unexplained flashovers in the presence of high conductor surface gradients. An interesting finding is that at the edge of the servitude, in all cases for upgrade to DC, the final attenuated electric field is less than the AC limit of 5 kV/m. Example electric field profiles are provided in figures 1 and 2.

A very important point to note is the shield wire gradient. In all the DC upgrade cases, it is substantially higher than the AC equivalent. This may impact on the use of earth wire attached fibre optic cables or power line carrier systems.

## 4 Analysis of Study Results

The study results concur in general with the literature review. The areas of further research pertain to the acceptable levels for maximum conductor surface gradients and for the prevailing DC electric fields including that of space charge effects. The corona effects of audible noise and radio interference are well within the acceptable AC limits. However, we note that the fair audible noise values appear very low as compared to similar calculations using the EPRI workstation programme. In case 2, using the EPRI workstation, we get L50 Fair for 400 kV HVAC as 43,2 dBA as compared to the BPA low value of 26,3 dBA. In the same case, under 500 kVDC, the L50 Fair level from EPRI is 58,5 dBA as compared to BPA's 41,4 dBA. For all the other parameters, there exists good agreement between the EPRI and BPA programmes. The low fair weather values are a known issue with the BPA programme. It is recommended that the EPRI workstation be employed and that full-scale tests be performed to verify the calculated results.

Further, it is noted that the DC conductor surface gradient is much higher than the equivalent AC gradient and this could lead to higher levels of radio interference. For the twin dinosaur and quad zebra configurations at 500 kV DC, the BPA calculations show acceptable RI levels. Carl Axel Rosen et al [6] in a presentation to Eskom recommended maximum DC levels of 26 kV/cm for the conductor bundle gradient. This satisfies the quad zebra operation at 500 kV DC but is marginally lower for the twin dinosaur operating at 500 kV DC. EPRI [3] records that although surface gradient is a sensitive parameter for predicting radio interference, this is less so for DC lines than for AC lines. The Dallas test line with surface gradient of 28,05 kV/cm produced a RI level of 65 dBA and the Shiobara Test line with a surface gradient of 25 kV/cm produced a RI level of 57 dBA; both within the acceptable level of 72 dBA [3]. Typical maximum conductor surface gradients in kV/cm for some operating DC lines are given in table 6 [7].

Table 6: Typical Maximum Conductor Surface Gradient (kV/cm) [7]

| HVDC Scheme | Gradient kV/cm |
|---|---|
| Apollo – Cahora Bassa +/- 533 kV | 20,6 |
| Inga – Shaba +/- 500 kV | 23,5 |
| Des – Cantons +/- 450 kV | 20,6 |
| Sylmar – Oregon +/- 500 kV | 25,5 |
| Henday – Dorsey +/- 500 kV | 27,4 |
| Adelanto – Mountain +/- 500 KV | 20,0 |
| Itaipu +/- 600 kV | 24,9 |

For the case of electric fields, Cigre Working Group SCB2 – 05 (JWG17) [8] recommends a maximum of 40 kV/m for electric fields within the servitude. In all cases studied, the electric field reduces to very low acceptable levels at the edge of the servitude. Example profiles are given in figures 1 and 2. Nayak's [9] investigations have provided the following typical values:

- Beneath a 500 kV HVDC line – 30 kV/m
- In front of a TV/VDU – 20 kV/m
- Walking on non conducting carpets – 500 kV/m
- German DIN standard – 40 kV/m ( 60 kV/m permitted for exposures up to 2 hours)
- Average threshold of detection to DC field – 45 kV/m
- +/- 600 kV Itaipu HVDC line design level – 40 kV/m

- +/- 500 kV Indian HVDC lines – 40 kV/m saturated conditions, 20 kV/m for normal fair weather and 27 kV/m for normal wet weather.
- For AC lines; (without space charge) – 10 kV/m

For both the twin dinosaur and the quad zebra 400 kV lines configured to operate at 500 kV DC, the electric field levels can be considered acceptable. The static electric field of DC is less onerous than the time varying electric field of AC. With DC no induced effects are conveyed to humans and animals within the powerline servitude.

## 5 Conclusion and Recommendation

The first pass investigations into electrical and corona effects for the upgrading of HVAC transmission lines for HVDC application are promising. Audible noise in fair weather requires further work; correlation of study results with local experimental work. It is recommended that the composite tower window consisting of both polarities separated by a metallic earth return be tested at full-scale for the full operating range for the DC voltage. For the tests, all the electrical and corona effects are to be recorded and compared to that predicted by both the literature review findings and that of computer based calculations. The test work should be extended to cover typical servitude caused transmission line faults. For the case of the 765 kV structures, the current design is very suitable for conversion to DC and 800 kV is recommended. At 800 kV, each 765 kV line could bulk transport some 6 GW over the 1200-km from Alpha to Omega.


## Acknowledgements

The study team acknowledges the continued support from Eskom and the University of Kwa-Zulu Natal in developing the final solution for upgrading transmission lines from HVAC to HVDC. The study calculations performed at Trans Africa Project by A. Burger and at Eskom TRI by G. Sibilant are also noted with appreciation.


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Figure 1: 400 kV Twin Dinosaur Transmission Line Operating at 500 kV HVDC (Grootvlei – Atlas / Muldersvlei – Koeberg )

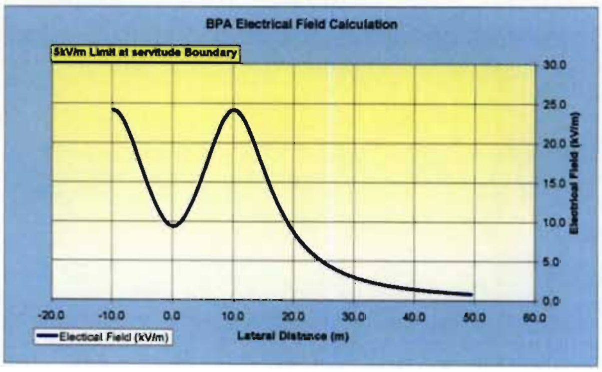


Figure 2: Quad Zebra 400 kV Transmission Line Operating at 500 kV HVDC ( Lines emanating from Matimba Power Station – Matimba /Midas/Pluto and also the 400 kV lines into Venus and Pegasus in Kwa Zulu Natal)