Application of HVDC Technology in Medium Voltage Distribution Systems

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DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the degree of Master of Science in the University of KwaZulu-Natal, Durban. It has not been submitted before, for any degree or examination, at any other university.

Somasundran Chetty
December 2005

To my wife Chezlyn Cheryl and my son Ryan Caden

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LIST OF ABBREVIATIONS

AC	Alternating Current
CCC	Capacitor Commutated Converters
CP	Control and Protection
DC	Direct Current
EMI	Electromagnetic Interference
FACTS	Flexible Alternating Current Transmission Systems
FFC	Fundamental Frequency Commutation
HMI	Human Machine Interface
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
LAN	Local Area Network
MW	Megga Watt
OWS	Operator Work Stations
PCC	Phase Commutated Converter
PLL	Phase locked Loop
PPA	Power Purchase Agreement
PWM	Pulse Width Modulation
SCADA	Systematic Control and Data Acquisition
SCM	Station Control and Monitoring System
SSDC	Sub Synchronous Damping Controller
SVC	Static var Compensator
TCR	Thyristor-controlled Reactors
TFR	Transient Fault Recording
TSC	Thyristor-switched Capacitors
VCU	Valve Control Units
VSC	Voltage Source Converter

ABSTRACT

Approximately 60% of all South Africans do not have access to electricity from the national grid and 80% of the dwellings in the rural areas are not electrified. This is due to the fact that many rural South Africans, similar to other rural markets in the developing world, live in sparsely populated, widely dispersed villages, which cannot be reached within the grid electrification program. HVDC technology provides a viable option to transmit electricity to small distant loads.

The objective of the present study is to demonstrate the application of HVDC technology in a medium voltage distribution system, to provide electrical power to Kwa-Ximba, which is a small distant rural area, located in KwaZulu-Natal, South Africa. The proposed system generates electricity from a hydroelectric generation scheme namely Nagle Dam and transmits the excess power to Eskom's Catoridge-Georgedale sub-transmission network for system enhancement purposes. Extensive technical and economical analyses of the proposed system has been conducted. An HVAC system was also considered for the same purposes in order to make technical and economical comparisons between the use of a HVDC and a HVAC system. In addition, grid extension from Eskom's Catoridge-Georgedale sub-transmission was considered to provide power to Kwa-Ximba without the use of a hydroelectric generation scheme. The proposed networks were therfeore (i) Network A:- Power supply to Kwa-Ximba, and the Catoridge-Georgedale sub-transmission network, from a hydroelectric generation scheme, using HVDC technology, (ii) Network B:- Power supply to Kwa-Ximba, and the Catoridge-Georgedale sub-transmission network, from a hydroelectric generation scheme, using HVAC technology and (iii) Network C:- Power supply to Kwa-Ximba by extending Eskom's existing AC Catoridge-Georgedale sub-transmission network with the hydroelectric generation scheme switched off. It is proposed that Nagle Dam, which is situated adjacent to Kwa-Ximba be used as a hydroelectric generation plant.

In order to determine the most efficient and cost effective use of generator sets, the flow rate, available hydraulic power and available electrical power from the year 2005

to the year 2032 were calculated. The increase in flow rate was based on an annual growth rate of 1.5% in water demand. The increase in electrical power demand for Kwa-Ximba was calculated for the next 29 years based on an annual growth rate of 1.8 %. Load flow analyses was conducted on the various power line and busbars that constitute each of the networks, in order to determine the effectiveness of each network.

In order to maintain flexibility in power generation, five sets of hydro electrical generators were chosen to give a combined power delivery of 20MW. The first three hydro electrical generators are rated at 5MW each, the fourth set rated at 3MW and the fifth set rated to deliver 2MW, (G1 to G5 operate 11 KV, 3 phase). The combination of generator sets in use (G1 to G5) will vary depending on the electrical power demand in any given year. Analyses of the predicted load flow pattern revealed that in the year 2005, Kwa-Ximba will receive 10.5 MW of power while 8.64 MW of power will be used to enhance the Eskom's Catoridge-Georgedale sub-transmission network, with a 4% spinning reserve. By the year 2014 power supply to the sub-transmission network will cease since Kwa-Ximba will be absorbing 12 .2 MW of power with a 17.5% spinning reserve. By the year 2032, Kwa-Ximba will absorb 17 MW of power with a spinning reserve of 14.63%.

The converter stations required for the HVDC transmission network (Network A) will be equipped with VSC and PWM technology and have a true power rating of a 20MW. This will be adequate to supply Kwa-Ximba's power demand right up until the year 2032 when the demand will be 17 MW. Converters will include IGBTs. Two 45 km long, 30 MW, 80 kV triple extruded polymetric HVDC cable will be buried 700mm below natural ground level. The Rectic Master software was used to select an appropriate overhead line for HVAC transmission (Networks B and C). An aluminium, wolf conductor was selected to transmit 20MW of active power.

Load flow analyses revealed that the HVDC link contributes positively to network stability by absorbing more reactive power than the HVAC link. The HVDC system absorbed a combined (Kwa-Ximba, Catoridge-Georgdale sub-transmission network) reactive power of 22.04 MVAr, as opposed to the HVAC transmission system where a combined reactive power 1.89 MVAr was absorbed from the connected network. This demonstrated that the HVDC link had the ability to absorb more reactive power from the Catoridge-Georgedale sub-transmission network, therefore contributing positively to the enhancement and stability of the sub-transmission network. Network A contributes more to system stability than Network B. It has also been shown that if Eskom's Catoridge-Georgedale sub-transmission network (Network C) is extended to supply electricity to Kwa-Ximba, this would result in system instability, in the long term. It is evident that Eskom would attain direct benefit from the installation of Newtork A, rather than Networks B and C.

The technical and environmental differences noted in the present study, between the HVDC and HVAC systems does not, however, justify the economics to install a HVDC system in order to supply power to Kwa-Ximba. Economical analyses revealed that the implementation of Network A would cost 64% more to install and result in a 75% less annual net profit than Network B. Network B would yield the highest annual net profit for the developer. From the developer's perspective, Network B will be the most feasible network to implement. However, from Eskom's perspective, Network A will be the most beneficial. Various recommendations have been made by the researcher that would benefit the community of Kwa-Ximba, Eskom and the developer in the long term.

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CHAPTER ONE

INTRODUCTION

1.1 Electrical energy

By the year 2020, worldwide gross installed power generation capacity is expected to double from today's 3000 GW to 6000 GW. In the next 20 years, power consumption in developing and emerging countries is expected to more than double, whereas in industrialized countries, it will increase only for about 40 %. Fast development and further extension of power systems can therefore be expected mainly in the areas of developing countries (Breuer and Lei, 2004)

The major part of this increase will take place in developing countries. Currently approximately 70% of power plants use fossil fuels to generate electricity. This share is expected to grow to more than 80% by the year 2020, due to high dependency in emerging markets of fossil fuels and their availability at relatively low cost. Schemes based on renewable resources will make a valuable addition to fossil fuels. However, in the period up to 2020 renewables will constitute a comparatively small part of the total. Therefore, higher efficiency in conventional power generation, power transmission and distribution will still be required, because the efficiency improvement potential may surpass the amount of energy generated by new renewables for quite some years. Some new technologies have been developed which are in the process of being implemented in traditional areas.

1.2 South Africa's energy supply

South Africa's gross domestic product (GDP) is the 26th highest in the world, but its primary energy consumption ranks 16th. The energy sector is critical to the South African economy, contributing about 15% of GDP and employing about 250 000 people. Its energy intensity is above average, with only 10 other countries having higher commercial primary energy intensities (South African Business Guidebook, 2003). This high-energy intensity is largely a result of the economy's structure, with large-scale, energy-intensive primary minerals benefiting industries and mining industries.

In addition, there is a heavy reliance on coal for generation of most of the electricity and a significant proportion of the liquid fuels consumed in the country. South Africa's industry has not generally used the latest in energy-efficient technologies, mainly as a result of relatively low energy costs. South Africa, which supplies two-thirds of Africa's electricity, is one of the four cheapest electricity producers in the world. Eskom is among the top five utilities in the world in terms of size and sale. Eskom is South Africa's primary electricity supplier. It is governed by the South African Electricity Council and a Management Board, established in terms of the Eskom Act of 1987. Eskom's 24 power stations, with a nominal capacity of 40 585 megawatts power, operate 365 days a year. It supplies approximately 95% of the country's electricity requirements, which equals more than half of the electricity generated on the African continent (www.eskom.co.za).

1.3 Electrical power systems in South Africa

1.3.1 Generating Stations

This change of focus from capital investment to service delivery means that South Africa is reaching the point where more generation capacity will be required, both on-grid and remote power supply. Currently, Eskom's national generating capacity is 39 GW. Their portfolio of generating plants include (i) 34 882 MW coal fired, 600 MW hydroelectric, 1930 MW nuclear and 342 MW gas turbine (oil fired). The two hydroelectric schemes namely Gariep (360 MW) and Vanderkloof (240 MW) have a dedicated purpose for hydroelectric generation only.

1.3.2 Transmission lines and distribution networks

There are 26 461 kilometres of transmission lines, which span the entire country and also carry power to neighbouring countries. The national electricity grid, connects the power stations and large urban and industrial areas, as well as all neighbouring states. Altogether there is approximately 240 000 km of transmission, primary distribution and reticulation lines. Extra high voltage (765 kV) transmission lines are operated at high altitude (www.eskom.co.za). Cahora Bassa is the largest hydroelectric scheme in southern Africa and is based on HVDC transmision. In 1994 the installed capacity in Mozambique was 2 400 MW of which 91 % was hydroelectric. The system includes two converter stations, one at Songo in Mozambique and the other at Apollo in South Africa. There are two parallel lines between these two stations, covering 1 400 km. These HVDC lines work at 533 kV and in Mozambique territory only have about 4 200 towers (Eskom news, 2000).

1.4. Electricity supply to rural areas in South Africa

There are numerous impoverished communities in South Africa where living conditions are dire and connection to the electrical grid is a far off dream. The bulk of the rural population still has no access to services such as electricity, drinking water or sewage and sanitation.

The first matter to consider when discussing the use of electricity by rural households is to what extent these households have access to grid electricity. About two-thirds of households in South Africa (66%), and almost half (46%) of rural households, had been connected to the grid by the end of 1999 (Kotzé, 2001). This can be compared with an estimated 44% of households, and 12% of rural households, which had been electrified at the end of 1994 (Thom *et al.*, 1995). To address this problem, the National Electrification Forum (NEF) has devised a strategy to accelerate grid extensions and provide electricity. In the six years from 1994 to 1999 between 400,000 and 500,000 new connections were made annually as part of the accelerated national electrification programme, in accordance with the Reconstruction and Development Programme (RDP) targets agreed upon between the government and the electricity industry (Thom, 2000).

Current, electricity tariffs are proving to be unaffordable to a vast number of people. One study conducted through the Government's Human Sciences Research Council found that an estimated 10 million people have suffered water cutoffs and electricity disconnections under privatization, mostly because they could not afford increased rates (Bond, 2004).

1.5 Problem Definition

Since 1994, ESKOM has electrified approximately 1.8 million rural households via grid extensions. Those communities have benefited enormously, as the cross-subsidized programme has allowed each household a 20-amp grid connection, using a prepayment meter system, with no fixed monthly charge.

However the grid electrification programme has failed to reach all rural communities. Approximately 2 million rural households still do not have access to electricity and the subsequent opportunity to improve their quality of life. This is due to the fact that many rural South Africans, similar to other rural markets in the developing world, live in sparsely populated, widely dispersed villages, which cannot be reached within the budget of the grid electrification programme. Furthermore the cost per kilowatt-hour of electricity is perceived by many households to be too high. They thus continue to use traditional fuels such as wood, paraffin, gas and coal, for long-time cooking and space heating in winter. As a result, average consumption levels are low. Another problem that arises from the lack of sufficient energy to power, water treatment plants. This leads to a serious lack of clean drinking water in rural areas.

One of the worst affected areas in South Africa, is the province of is KwaZulu Natal, which has the largest population of all provinces. Despite the fact that it is the second highest contributor to the country's Gross Domestic Product, it has the highest unemployment rate and one of the lowest income rates per capita.

It is evident that the present means of transmitting electricity to small isolated rural locations is costly, inefficient and capital outlay for such projects is unlikely to be recovered . Such locations can be referred to as small distant loads. There is thus an urgent need to provide a more cost effective and sustainable means of providing power to small distant loads. This will aid in a more universal access to electricity which is a primary goal of South Africa's energy policy as identified in the Government's White Paper on Energy Policy.

1.5.1 Approach to solving the problem

It is proposed that the present problem can be alleviated by using renewable power generation plants such as hydroelectric plants (existing water sources located close to a rural location) generate power that can be transmitted via High Voltage Direct Current (HVDC) technology to small distant rural locations. In turn, excess capacity can be redirected to the main Alternating Current (AC) grid using HVDC technology for system enhancement.

HVDC transmission systems are proposed because they provide a more efficient and cost effective way of moving electricity over long distances. An HVDC system converts alternating current (AC) into direct current (DC) and which can be transmitted to a distant location, where it is converted back to AC and distributed to consumers. Advancement in the switching technology has broadened the scope for application of HVDC to Medium Voltage Direct Current (MVDC) and short links, including applications in distribution systems. HVDC technology was previously applied to MVDC installations such as the Gotland link (80kV) (Asplund *et al.*, 1998), the Directlink installation in South Australia (80kV) (Cook *et al.*, 1999) and the Tjaereborg installation in Demark(9kV) (Eriksson and Wensky, 2003). The Voltage Source Converter (VSC) concept for DC has made it feasible, in many cases, to connect remote locations to the main grid where cheap electricity is available.

In the present study a developmental plan for a HVDC transmission system from a renewable energy source namely Nagle Dam to the rural location Kwa-Ximaba, KwaZulu, Natal is established. The use of HVDC transmission to enhance the existing Catoridge-Georgedale sub-transmission network in KwaZulu-Natal is also established.

1.6 The scope of the study

HVDC technology provides a viable option to transmit electricity to small distant loads. Despite the advantages of this technology in improving the supply of electricity to distant rural locations, HVDC technology is not being used in MVDC applications in South Africa. The present study aims to address this issue and demonstrate the feasibility of applying HVDC technology in MVDC applications in the South African context. The proposed system will generate electricity from a renewable energy source (Nagle Dam) and will only use water that is intended for commercial use. Thus the purpose of the water will be two-fold (i) generating electricity and (ii) commercial use. This will minimise wastage of water. In the present study an HVDC transmission system for the rural location Kwa-Ximba a rural area in KwaZulu-Natal has been developed. A 20 MW hydro generating plant is sited adjacent to the Nagle dam, dam wall. The dam is sited in Kwa-Ximba. Catoridge is located 45km from the dam wall. The Georgedale network is sited approximately 30km from the Catoridge substation. The present study addresses part of the problem the local community is presently facing, by providing an adequate supply of electrical power to the dam site, sufficient power for a water treatment plant to be sited adjacent to the dam wall thereby minimizing operating costs. At present raw water is transported to Durban with aqueducts, it is treated in Durban and then distributed to the various bulk reticulation reservoirs. Perhaps, if the water could be treated at the dam site and then gravity fed to Durban, customers (local municipalities) that are located along the aqueduct may be supplied water along its route. In this case a water treatment plant will have to be built at the dam site. This will have a significant saving on pumping costs, since Kwa-Ximba is a higher lying area to Durban. At present all raw water is first transported to Durban, it is purified then pumped to locations that are of higher altitude than it self. The Water Treatment plant in Durban was built approximately 45 years ago.

This dam has been generating its own electricity since it was built during the Second World War. The hydro generating plant is rated at 315kVA and has an output Voltage of 400V. There are two generating sets installed and the plant is operated with one hydro generation plant on line and the other on standby. The power is presently being used to operate the dam. Due to location of the dam, Eskom was unable to extend its network to the dam. Limited available power at the dam has therefore led to the water treatment plant being sited in Durban, approximately 55 km away from the dam site. The water from this dam presently supplies water to Durban central and surrounding areas. The local community who lives close to the dam are deprived from having purified drinking water, sewage and basic sanitation services, medical services and electricity. In addition, the local communities are unable to find employment.

Modular, renewable energy power generation provides a cost-effective way to provide clean, affordable, and long lasting electricity solution to rural areas. Hydroelectric generation was chosen in the present study as it is an important source of renewable energy and provides significant flexibility in base loading, peaking, and energy storage applications. Whilst initial install capital costs are high, the inherent simplicity of hydroelectric plants coupled with a low operating and maintenance costs, long service life, and high reliability make them a very cost effective and flexible source of electricity generation. Especially valuable is the operating characteristic of fast response for startup, loading, unloading, and following of system load variations. Other useful features include the ability to start without the availability of power system voltage ("black start capacity"), ability to transfer rapidly from generation mode to synchronous condenser mode and pumped storage application (Ramakumar, 1998).

Hydro power stations convert water pressure into mechanical shaft power, which can be used to drive the electrical generator. The vertical difference between the upper reservoir and the level of the turbine is known as the head. The water falling through his head gains kinetic energy that in turn imparts it to the turbine blades, and electricity is generated. The best turbines can have hydraulic efficiencies in the range of 80 to over 90% (higher than most other prime movers), although this will reduce with size (Paish, 2002).

A hydro power plant has the ability to start up quickly and the advantage that no losses are incurred when at stand still. The installation costs of small hydro power plants ranges from $800-$2000 per kW installed. Small hydro schemes utilize both synchronous and asynchronous generators, therefore they could have two contrasting stability properties. Low head turbines tend to run more slowly and so either a gearbox or multipole generator is required (Jenkins *et al.*, 2000). The majority of hydro generators that are connected to distribution networks are directly connected with synchronous generators. However, there are a few cases of hydro generators utilizing induction generators. Hydro generators have to be fitted with a governor, which aid the damping of generators. The main features of a governor include:

- Speed control of the hydro turbine under different conditions of start up and load fluctuations.
- Fast response to load imposition and load rejection
- Shutting down inlet valve in case of over speed tripping

An additional control that is usually fitted with a hydro generator includes an Automatic voltage regulator (AVR). An AVR helps to maintain nominal voltages on the connected bus, as well as controlling the amount of active as well as reactive power that is injected into a network.

The proposed installation should prove to be technically feasible and financially viable with reasonable contingencies for revenue generation and capital investments costs. The power rating of the interconnectors was first determined. Thereafter the most economic design for the required power rating was optimized. This involved a balance between the operating voltage and current, based on cable cost, converter cost, number of poles and energy losses. In the present study the feasibility of using an HVAC system to transmit power from the hydroelectric generator to Kwa-Ximba was also investigated. This was done in order to do a comparative analysis between the HVDC and HVAC systems with regards to system stability and cost. Line extension from Eskom's existing AC Catoridge-Georgedale sub-transmission network with the hydroelectric generation scheme switched off was also considered in the present study.

The transmission system needs to be developed to be robust and fully functional in order to attract investor confidence to develop small to medium size industries to the

Kwa-Ximba rural location. In return, this will enable central government to build more schools, hospitals, clinics, develop roads, install street lights and provide more cost effective housing.

1.7 Hypothesis

HVDC technology can be used in a medium voltage distribution system to supply power from a hydroelectric generation scheme (Nagle Dam) to a small distant rural location, Kwa-Ximba, and the excess power transmitted to Eskom's Catoridge-Georgedale sub-transmission network for system enhancement.

1.8 Objectives

(i) To develop a hydroelectric generation scheme at Nagle Dam and determine and the scheme's present and predicted power output.

(ii) To develop a HVDC and a HVAC system to transmit power from the hydroelectric generation scheme (Nagle Dam) to Kwa-Ximba and transmit the excess power to Eskom's Catoridge-Georgedale sub-transmission network.

(iii) To develop a network extension system from the Catoridge-Georgedale sub- transmission network to provide electrical power to Kwa-Ximba, with the hydroelectric generation scheme switched off.

CHAPTER TWO

LITERATURE REVIEW

2.1 Electrical power

The development of the Electric Power Industry follows closely the increase of the demand on electrical energy (Sitnikov *et al.*, 2004). With the arrival of the electric light bulb in the homes and factories of late 19th century Europe and the USA, demand for electricity grew rapidly. New and efficient ways to generate and transmit electrical energy were being investigated.

Early electric power distribution schemes used direct current (DC) generators located near customer's loads. As electric power use became more widespread, the distances between loads and generating plant increased. Since the flow of current through the distribution wires resulted in a voltage drop, it became difficult to regulate the voltage at the extremities of distribution circuits. Higher voltages were used to reduce the resistive loss in the conductors for transmitting a given quantity of power.

2.2 High Voltage Alternating Current (HVAC)

AC came to dominate as a means of interconnection between generation plants and machinery. The principal advantage of AC is the possibility of using transformers to efficiently transform voltage used in power transmission. The ability to transform voltages is an important economic and technical consideration. A high voltage is useful for transmission since it reduces loss in the form of heat developed in the circuit conductors, while a low voltage is convenient for utilisation equipment such as lamps and motors. With the development of efficient AC machines, such as the induction motor, AC transmission became the norm (Asplund *et al.*, 2003).

The ability of AC to be effectively transformed in voltage a number of times during transmission led it to become, and remain, the dominant means of electrical power transmission. As the AC systems grew and power increasingly was being generated far from where most of its consumers lived and worked, long overhead lines were built, over which AC at ever-higher voltages flowed. To bridge expanses of water, submarine cables were developed.

Medium voltage direct current (MVDC) transmission can be used to bridge greater distances with low voltage and low power. MVDC can be considered as in-line compensation in the sense that it consists of a DC link with a voltage source converter (VSC) connected at either end (Povh, 2000)

2.3 High Voltage Direct Current (HVDC)

In the second half of the past century, High Voltage DC Transmission (HVDC) has been introduced, offering new dimensions for long distance transmission. This development started with the transmission of power in an order of magnitude of a few hundred megawatts and was continuously increased to transmission ratings up to 3 - 4 GW over long distances by just one bipolar line. By these developments, HVDC became a mature and reliable technology. Almost 50 GW HVDC transmission capacities have been installed worldwide up to now, transmission distances over 1 000 to 2 000 km or even more are possible with overhead lines. Transmission power of up to 600 - 800 MW over distances of about 300 km has already been realized (Breuer and Lei, 2004). Although direct current had been beaten at the starting gate in the race to develop an efficient transmission system, engineers had never completely given up the idea of using DC. Attempts were still being made to build a high-voltage transmission system with series-connected DC generators and, at the receiving end, series-connected DC motors all on the same shaft. This worked, but it was not commercially successful (Asplund *et al.*, 2003). HVDC technology has become a mature technology over the past 50 years and reliably transmits power over long distances with very low losses. Present HVDC-transmission technology was developed during a period from the end of the twenties and resulted in the first commercial transmission system, Gotland, in 1954.

Since then there has been a lot of development and refinements of HVDC technology such as the development of thyristor valves, lowering of losses, more advanced control and protection, lower harmonics and lower audible sound.

Currently HVDC technology is used to transmit electricity over long distances by overhead transmission lines or submarine cables. It is also used to interconnect separate power systems. In cases where traditional alternating current (AC) connections can not be used in a high voltage direct current (HVDC) system, electric power is taken from one point in a three-phase AC network, converted to DC in a converter station, transmitted to the receiving point by an overhead line or cable and then converted back to AC at the inverter station and injected into the receiving AC network. Typically, an HVDC transmission has a rated power of more than 100 MW and many are in the 1 000 – 3 000 MW range. HVDC Transmissions are used for transmission of power over long or very long distances, because it then becomes economically attractive over conventional AC lines.

With an HVDC system, the power flow can be controlled rapidly and accurately as to both the power level and the direction. This possibility is often used in order to improve the performance and efficiency of the connected AC networks. The present technology has, however, some inherent weaknesses, which to some extent limit the use of HVDC as the means to overcome these weaknesses are relatively expensive. The most important weaknesses are the need for rotating machines in the receiving network and the risk of commutation failure, which means that for some cycles there is no transmission of power. HVDC has exceeded all market expectations (Cook *et al.*, 1999).

2.3.1 Commercial HVDC transmission developments

The world's first commercial HVDC transmission link, was built in the Baltic sea between the Swedish mainland and the island of Gotland in 1954 (Asplund *et al.*, 2003). This project resulted in further development of the mercury arc valve and high-voltage DC cable, and also initiated design work on other components for the converter stations. Among the equipment that benefited from the increased efforts were transformers, reactors, switchgear and the protection and control equipment.

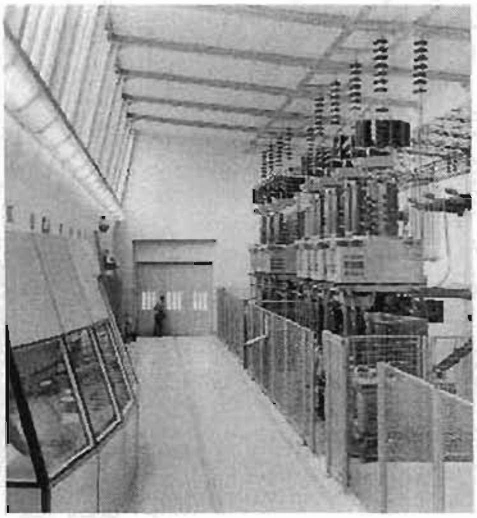


Fig. 2.1 Mercury-arc valves in the first Gotland link in 1954 (Asplund *et al.*, 2003)

Only some of the existing AC system technology could be applied to the new DC system. New technology was therefore necessary. Subsequently, a concept was developed for the Gotland system. This proved to be so successful that it has remained basically unchanged right down to the present time. Since Gotland is an island and the power link was across water, it was also necessary to manufacture a submarine cable that could carry DC. It was seen that the 'classic' cable with mass impregnated paper insulation that had been in use since 1895 for operation at 10 kV AC had potential for further development. Soon, this cable was being developed for 100 kV DC. The 96 km submarine cable for the first Gotland HVDC link – Gotland 1 – was laid in 1953 between Västervik on the Swedish mainland and Ygne, Gotland (Green, 2004).

The Gotland HVDC transmission link had a rating of 20 MW, 200 A and 100 kV. Fifty years on, HVDC technology has evolved considerably and plays an important role in electricity networks all over the world. The first link between Gotland and the Swedish mainland was a 20 MW, 150 kV link. Around 70 000 MW of HVDC transmission capacity is now installed around the world in more than 90 projects (Green, 2004). Although the development of mercury arc valves was essential to the success of the first HVDC link, the technology had limitations. The invention of the thyristor in 1957 presented new opportunities, however, and in 1967 one of the mercury arc valves at Gotland was replaced with a thyristor valve. After a year-long trial, a complete thyristor valve group was installed in each converter station, representing the first time that thyristor valves were used in a commercial HVDC link. This development allowed the link's voltage to be increased to 150 kV and its transmission capacity to 30 MW.

The original Gotland link was to see 28 years of successful service before being finally decommissioned in 1986. Two new links for higher power supply have meanwhile been built between the island and the Swedish mainland, one in 1983 and the other in 1987.

The first HVDC connection across the English Channel went into service in 1961 between the British nuclear power station Lydd and the French static inverter station Echingen. This scheme equipped with mercury steam valves used, in order to keep the disturbances of the magnetic compasses of the ships as small as possible, a bipolar cable with a length of 64 kilometers, which was operated symmetrically with a voltage of 100kV and a maximum current of 800 ampere. The maximum transmission power of this facility was therefore 160 megawatts. Because this installation did not meet the increasing requirements any longer, it was replaced in 1986 by a new HVDC line between France and Great Britain consisting of two bipolar submarine cables with a length of 72 kilometers. This line can transfer at an operating voltage of 270kV a maximum power of 2000 megawatts (Goodrich and Anderson, 2001).

During the 1960s several HVDC links were built. The eastern and western sections of Japan have been interconnected since 1965 through a HVDC frequency converting station located at Sakuma with a converting capacity of 300 MW. Two 125 kV, 37.5 MW three-phase bridge thyristor converters were installed at the Sakuma Testing Station in 1970 and have established confidence in the design of thyristor valves for hvdc power transmission (Horichui and Kato, 1974).

A HVDC link which was commissioned in 1965 connects the power systems of New Zealand's North and South Islands. On average 80 per cent of New Zealand's electricity energy production is from hydroelectric sources, most of which is produced in the South Island. However, the North Island accounts for almost two thirds of the total electricity energy demand and has a peak load almost twice that of the South Island. The capacity of the link is 1040 MW and it operates at voltages of 270 kV and 350 kV. In 1991 the HVDC was upgraded to 1 240MW (Gleadow *et al.*, 1991).

In contrast to most other installations for HVDC transmission the HVDC Italy-Corsica-Sardinia system is a multipoint system making possible the energy exchange between several static inverter stations. The sysem is used for the exchange of electric energy between Italy, Corsica and Sardinia. It was developed in 1965. It consists of three overhead line sections, one on the Italian mainland with a length of 50km, one on Corsica with a length of 167km and one on Sardinia with a length of 87km. In addition to this, there are two submarine cable sections, 103 km (between Italy and Corsica) and 15 km (between Sardinia and Corsica). Until the 1990s mercury steam electric rectifiers were used, which have now been replaced by thyristors. In 1992 a second pole was taken in service, which can transfer 300MW at a voltage of 200kV (Mazzoldi *et al.*, 1989).

Although many of these projects have since been replaced or upgraded with thyristor valves, some are still in operation today, after 30 to 35 years of service. Today, conventional HVDC technology is proving its worth in projects such as the Three Gorges links in China, which evacuate power to major load centres in Guangdong and Shanghai. The 850-kilometer power link came into commercial operation in 2003. HVDC has been used in projects such as the Cross Sound Cable link in the USA, which was instrumental in restoring power quickly to consumers after the blackout of August 2003 (Green, 2004).

2.4 HVDC transmission system configuration

A common configuration for interconnecting two unsynchronised grids is the back to back HVDC link. With the back to back link the AC to DC converters are housed in the same building. Station to station links, where two inverter/rectifier stations are connected by means of a dedicated HVDC link is also commonly used. Station to station configuations are used in connecting unsynchronised grids, long distance power transmission, and in undersea cables. The use of three or more stations is reffered to as multiterminal HVDC power transmission and is rarer than the other two configurations,. This is due to the high cost of the inverting/rectifying stations. The configuration of multiple terminals can be series, parallel, or a mixture of series and parallel.

2.4.1 Monopole and bipole systems

HVDC interconnections as either monopole or bipolar systems. A monopole system has a single, high voltage conductor and usually uses the earth or sea to prove the return path for the current by means of an electrode return. A single set of AC/DC converters is required (one converter pole at each end). Bipole systems transmit power through two high voltage conductors of opposite polarity. Two sets of AC/DC converters are required at each end.
The size of the monopole system is more limited than that of a bipolar system. This is because the largest practical size for a DC cable is 2 500 mm^2 which limits the current that can be carried. Therefore to transmit more power than a 2 500 mm^2 can handle two cables are required, and bipole systems become more attractive for their operational advantages as costs become comparable with monopole systems. These factors limit underground cables to a maximum of 700-800 MW.

Bipole systems offer several advantages over monopole system. The bipole system can carry twice as much power as a monopolar link, typically 3 000 MW. The current is the same, but the potential difference between the wires is doubled. Furthermore bipole systems continue to operate despite a fault in one of the wires or in one module of the converter equipment, by using the earth as a backup return path. Bipole systems also eliminate the need for elctrodes which offers a more enviromentally friendly solution. The cost difference of producing monopolar and bipolar cables is less than might otherwise be imagined (Woodford, 1998). Multi-terminal HVDC links, connecting more than two points, are possible but rare. An example is the 2000 MW Hydro Québec system opened in 1992.

2.4.2 Rectifying and Inverting Components

No equivalent of the transformer exists for direct current, so the manipulation of DC voltages is considerably more complex. The introduction of the fully-static mercury arc valve in 1954 marked the beginning of the modem era of HVDC transmission. However, this technology presented some difficulties in predicting the behavior of the valves themselves. Power transmission by the use of mercury arc valves was much more complicated than transmitting power by using rotating electrical machines and transformers. While electrical machines and transformers can be designed with great precision with the aid of mathematically formulated physical laws, the design of the mercury-arc valve must be based to a large degree on empirically acquired knowledge. When trying out higher voltages, one is confronted by specific physical challenges. In a power line or high-voltage apparatus raising the voltage is met by increasing the insulation clearances. In the mercury vapour atmosphere of the mercury-arc valves it does not help at all to increase the spacing between the electrodes. Also, mercury valves could not always absorb the reverse voltage, arc-backs occurred. They also required regular maintenance where absolute cleanliness was critical.

In 1957 a host of new opportunities were presented by the invention of thyristor valves, which eventually replaced mercury arc valves. The thyristor valve was first used in HVDC systems in the 1960s.

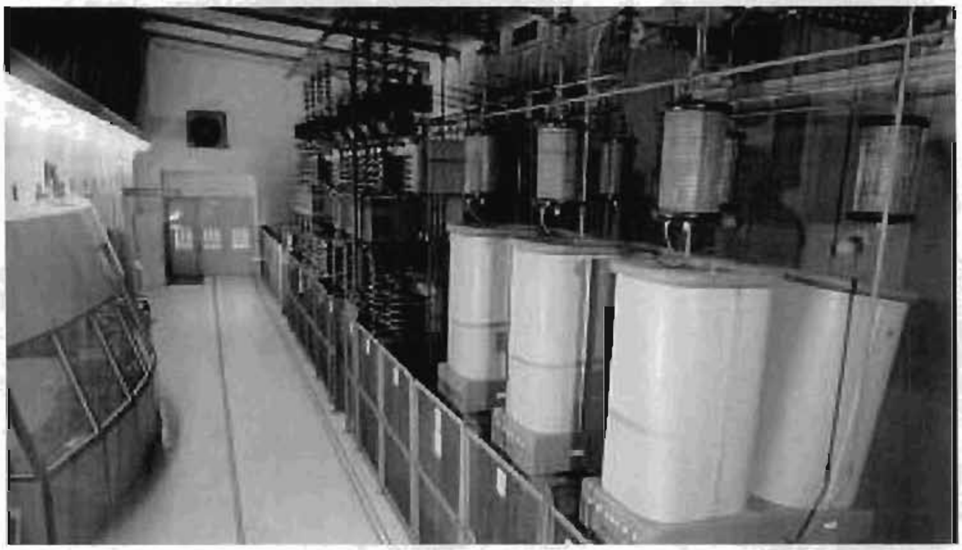


Fig. 2.2 The world's first thyristor valves (Asplund *et al.*, 2003)

With the advent of thyristor valves it became possible to simplify the converter stations, and semiconductors have been used in all subsequent HVDC links. Asea Brown Boveri teamed up with Siemens and AEG in the mid-1970s to build the 1920-MW Cahora Bassa HVDC link between Mozambique and South Africa. The same group then went on to build the 2000-MW Nelson River 2 link in Canada. This was the first project to employ water-cooled valves.

Because the voltages in HVDC systems, around 500 kV in some cases, exceed the breakdown voltages of the semiconductor devices, HVDC converters are built using large numbers of semiconductors in series. The low-voltage control circuits used to switch the thyristors on and off need to be isolated from the high voltages present on the transmission lines. This is usually done optically. In a hybrid control system, the low-voltage control electronics sends light pulses along optical fibres to the high-side control electronics. Another system, called direct light triggering, dispenses with the high-side electronics, instead using light pulses from the control electronics to switch light-triggered thyristors (LTTs). The use of LTTs reduces the number of componenets in the thyristor valve by 60% which results in increased reliability and aviablibity of the trasnmission system (Ammon, 2000).

Rectification and inversion use essentially the same machinery. Many substations are set up in such a way that they can act as both rectifiers and inverters. At the AC end a set of transformers, often three physically separate single-phase transformers, isolate the station from the AC supply, to provide a local earth, and to ensure the correct eventual DC voltage. The output of these transformers is then connected to a bridge rectifier of a number of valves. The basic configuration uses six valves, connecting each of the three phases to each of the DC rails. However, with a phase change only every sixty degrees, considerable harmonics remain on the DC rails. An enhancement of this configuration uses twelve valves (often known as a twelve-pulse system). The AC is split into two separate three phase supplies before transformation. One of the sets of supplies is then configured to have a gamma secondary, the other a delta secondary, establishing a thirty degree phase difference between each of the sets of three phases. With twelve valves connecting each of the two sets of three phases to the two DC rails, there is a phase change every thirty degrees, and harmonics are considerably reduced.

In addition to the conversion transformers and valve-sets, various passive resistive and reactive components help eliminate harmonics on the DC rails.

2.5 Voltage Source Converters (VSC)

Phase Commutated Converter (PCC) technology was originally used as HVDC converters (Asplund, 1998). PCC is now almost totally replaced by VSC (Voltage Source Converter) technology. The fundamental difference between these two technologies is that VSCs need components that can switch off the current and not only switch it on, as is the case in PCCs. In a VSC, the current can be switched off without the need for a network to commutate against.

2.5.1 Voltage Source Converter (VSC) and Integrated Gate Bipolar Transistor (IGBT)

In recent years, voltage source converter technology has made great progress through the development of high power self-turn off type semiconductor devices. The ratings for converters of this type in practical application has already reached as high as 100MVA and above (Susuki, 2001). In HVDC-applications it could also be of interest to use VSC Technology in order to supply "dead" networks, that is areas which lack rotating machines or does not have enough power in the rotating machines (too low short circuit power) (Eriksson, 1998).

The advantages of using VSC for DC transmission include the following (i) Independent control of active and reactive power, (ii) operation against isolated AC networks with no generation of their own, (iii) can operate at any short circuit ratio, (iv) limited need of filters, (v) no converter transformers and (vi) can connect isolated generators to the grid or to other isolated loads (Asplund *et al.*, 1997a; Asplund *et al.*, 1997b; Axelsson *et al.*, 1999; Grunbaum *et al.*, 1999, Hammad *et al.*, 1989).

The VSC convertor has a simple and straightforward circuit solution. VSC-based HVDC transmission utilizes several important technological developments: (i) high voltage valves with series-connected IGBTs, (ii) Compact, dry, high-voltage DC capacitors (iii) high capacity control system and (iv) solid dielectric DC cable.

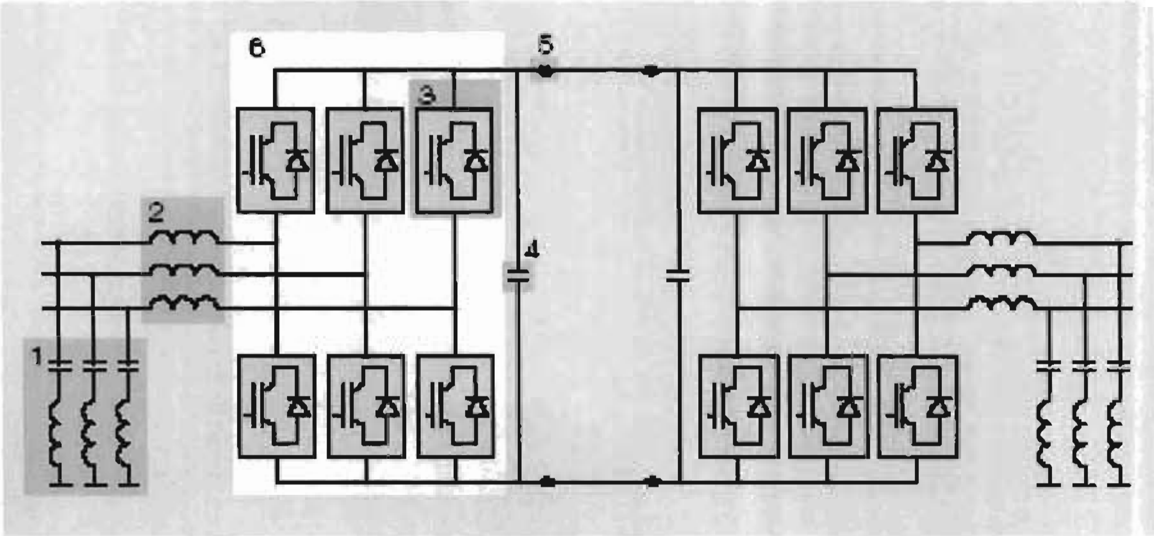


Fig. 2.3 Typical HVDC transmission link with voltage source converters (Asplund *et al.*, 1998)

Key:

1. Filter
2. Converter reactor
3. Converter valve
4. Commutation capacitor
5. Connection to cable
6. Converter

This provides for a compact and robust mechanical design, by which the convertor equipment is placed in simple module type housings. A VSC convertor station with ratings up to 20 MW and below 30 kV occupies an area less than approximately 250 square meters. The modular design gives the opportunity to preinstall the equipment at the factory and run highly complete tests before shipment.

The technical simplifications such as small filters, no or simplified transformers, less switching equipment and simple civil works contribute to small footprint and easy handling. The plant production process is based on a set of standardized sizes with module drawings ready on the shelf. The need for engineering will thereby be limited and for a normal project basically all equipment will be defined from start. The simple circuit solution makes it possible to design a station, that does not need stops for regular scheduled maintenance. The scheduled maintenance could be limited to checking of movable equipment such as pumps and fans for cooling, resins for cooling water quality and batteries. Auto monitoring of status so that faults will be automatically detected and alerted (Stendius and Eriksson, 1999)

IGBTs were introduced in the 1980s. IGBTs were designed for power applications. It is a device which combines MOS gate control and bipolar current flow mechanisms, featuring high current, high voltage operation and high input impedance at the same time. The IGBT is a cross between the bipolar and MOSFET transistors. The IGBT has the output switching and conduction characteristics of a bipolar transistor but is voltage-controlled like a MOSFET. In general, this means it has the advantages of high-current handling capability of a bipolar with the ease of control of a MOSFET (Pathak, 2001).

The power required to control the IGBT is very low, compared to the power requirements of Phase Commutated Thyristor Valves. This makes series connection possible with good voltage distribution even at switching frequencies in the kHz range. The voltage of the IGBTs components has recently reached 2.5 kV and higher voltages are expected due to the fast development of IGBTs (Linder, 2003).

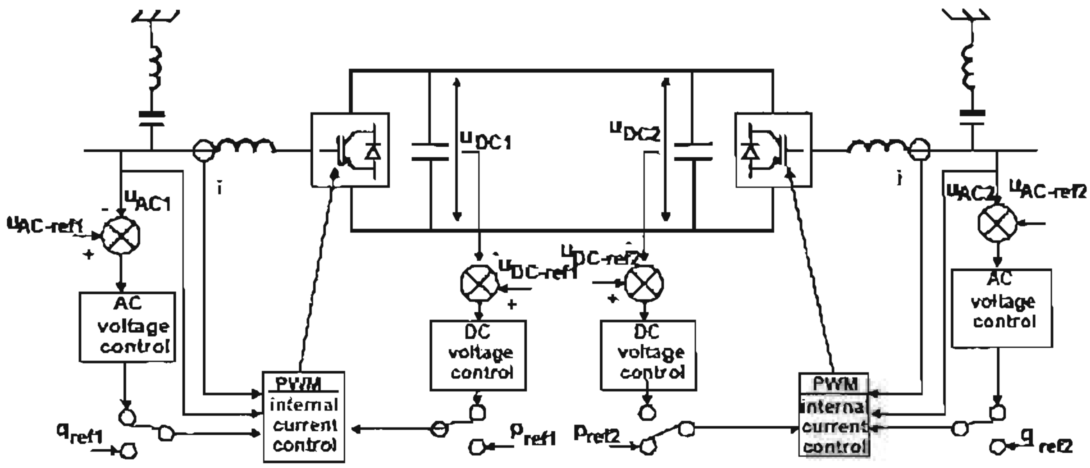
The main advantages of converters with IGBTs are high impedance gate which require low energy to switch the device high switching frequency due to short switching times and by that low switching losses. The objective for the DC capacitor is primarily to provide a low inductive path for the turned off current and an energy storage to be able to control the power flow. The capacitor also reduces the harmonics on the DC side. The converter generates characteristic harmonics related to the switching frequency. The harmonic currents are blocked by the converter reactor and then the harmonic contents on the ac bus voltage is reduced by a high-pass filter. The fundamental frequency voltage across the reactor defines the power flow between the AC and DC sides (Chokawala *et al.*, 2001).

A special gate unit and voltage divider across each IGBT maintain an even voltage distribution across the series connected IGBTs. The gate unit not only maintains proper voltage sharing within the valve during normal switching conditions but also during system disturbances and fault conditions. A reliable short circuit failure mode exists for individual IGBTs within each valve position. Depending on the converter rating, series-connected IGBT valves are arranged in either a three-phase, two-level or three-level bridge. In three-level converters, IGBT valves may also be used in place of diodes for neutral point clamping. Each IGBT position is individually controlled and monitored via fiber optics and equipped with integrated antiparallel, free-wheeling diodes. Each IGBT has a rated voltage of 2.5 kV with rated currents up to 1500 A. Each VSC station is built up with modular valve housings which are constructed to shield electromagnetic interference (EMI). The valves are cooled with circulating water and water to air heat exchangers. PWM switching frequencies for the VSC typically range between 1-2 kHz depending on the converter topology, system frequency and specific application. Each VSC is effectively mid-point grounded and coupled to the AC bus via phase reactors and a power transformer with intermediary shunt AC filters. The AC filters are tuned to multiples of the switching frequency. This arrangement minimizes harmonic content and avoids dc voltage stresses in the transformer which allows use of a standard AC power transformer for matching the AC network voltage to the converter AC voltage necessary to produce the desired DC transmission voltage. DC capacitors are used across the dc side of the VSC. For transmission applications there may also be DC filters and a zero-sequence blocking reactor. The filters and zero sequence reactor are used to mitigate interference on any metallic telephone circuits that run adjacent to the DC cables. The total capacitance of the pole to ground DC capacitors vary with the application. DC capacitance is higher for VSC used for flicker mitigation (Asplund, 2000).

2.5.2 VSC using PWM Technology

All power electronic converters operate using a switching process, whereby the required output voltage or current is made up of a series of pulses, which are switched through from the input by a modulation process and then filtered to create a smooth average result. The most effective strategy for controlling a converter in this way is called "Pulse Width Modulation" (PWM), which has been the subject of intense and continuing research for over 30 years.

With the introduction of high switching frequency components such as IGBTs it becomes advantageous to build VSCs using PWM Technology. PWM is a powerful technique for controlling analogue circuits with a processor's digital outputs. PWM is employed in a wide variety of applications, ranging from measurement and communications to power control and conversion (Barr, 2001). In the PWM bridge switching very fast between two fixed voltages creates the AC-voltage. The desired fundamental frequency voltage is formed through low pass filtering of the high frequency pulse modulated voltage. With PWM it is possible to create any phase angle or amplitude (up to a certain limit) by changing the PWM pattern, which can be done almost instantaneously. Hereby PWM offers the possibility to control both active and reactive power independently. This makes the PWM VSC a close to ideal component in the transmission network.



$$P = \frac{U_{ac}U_{v}\ \sin\delta}{X}$$

$$Q = \frac{U_{ac}(U_{ac} - U_{v}.\cos(\delta))}{X}$$

Fig. 2.4 Control of VSC based transmission (Bahrman *et al*., 2002) ;

P – Active power; Q – Reactive power

From a system point of view it acts as a motor or generator without mass that can control active and reactive power almost instantaneously. Furthermore, it does not contribute to the short circuit power as the AC current can be controlled (Asplund *et al*., 1997a). If the available switching components can only switch with low frequency. Fundamental Frequency Commutation (FFC) will probably be the right technology. If higher switching frequency components are available it is possible to use PWM Technology. With PWM, only one converter is needed and the AC voltage is created by switching very fast between two fixed voltages. After low pass filtering the desired fundamental frequency voltage is created. In this case the transformer arrangement is very simple and it is not even necessary to have a transformer for the functioning of the converter (Bahrman *et al*., 2003).

The AC-voltage is created by switching very fast between two fixed voltages. Low pass filtering of the high frequency pulse modulated voltage is used to create the desired fundamental frequency voltage.

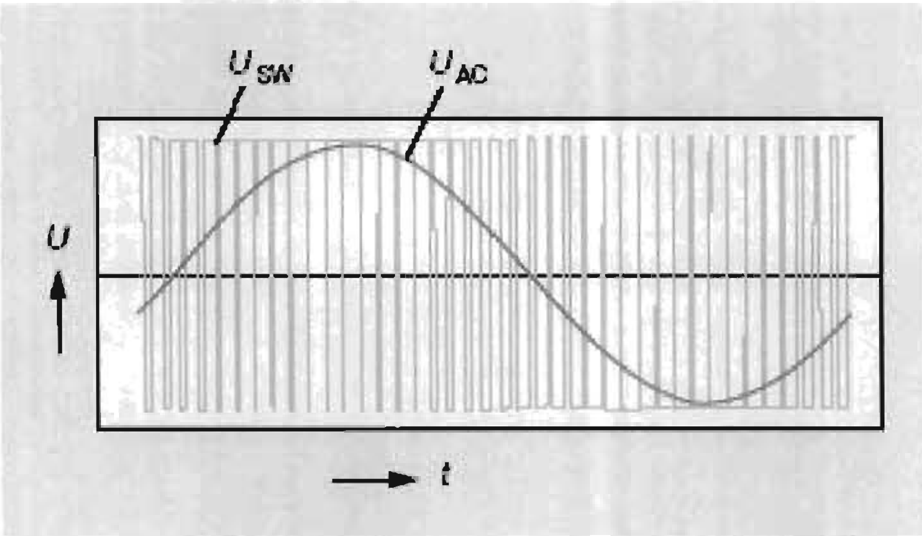


Fig. 2.5 PWM pattern and the fundamental frequency voltage in a Voltage Source Converter
T - Time; U - Voltage; UAC - AC voltage; USW - Converter PWM voltage (Eriksson *et al.*, 1998)

Reactive power generation and consumption of an HVDC converter can be used for compensating the needs of the connected network within the rating of a converter. As the rating of the converters is based on maximum currents and voltages the reactive power capabilities of a converter can be traded against the active power capability. The combined active /reactive power capabilities can most easily be seen in a P-Q diagram (positive Q is fed to the AC network).

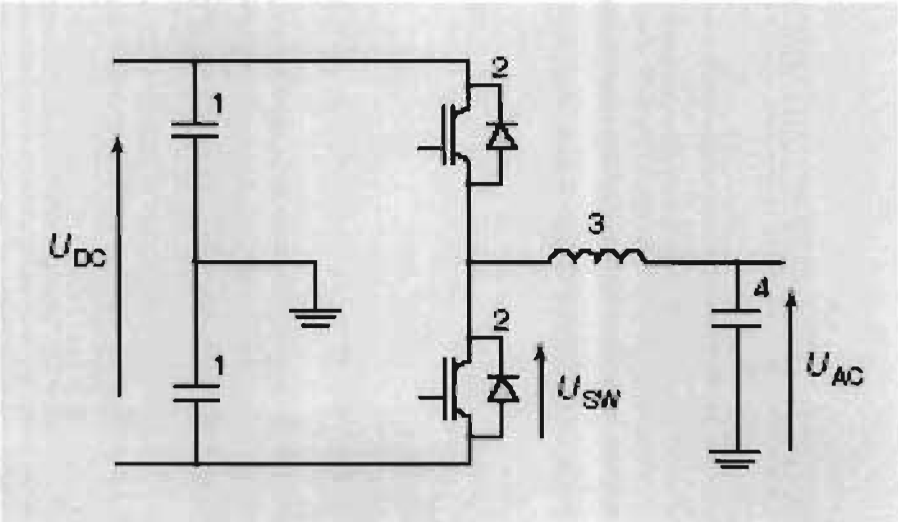
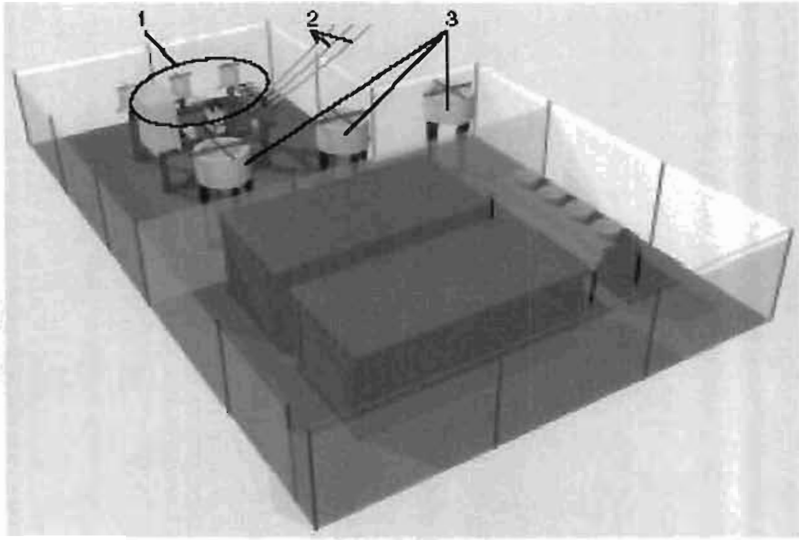


Fig. 2.6 Voltage Source Converter using PWM, UAC - AC voltage; UDC - DC voltage; USW - Converter PWM voltage, 1 - DC capacitor, 2- IGBT valve, 3 -Converter reactor, 4 – Filter (Eriksson *et al.*, 1998)

No reactive power compensation equipment is needed at the station, only an AC-filter is installed. While the transmitted active power is kept constant the reactive power controller can automatically control the voltage in the AC–network (Eriksson *et al.*, 1998).

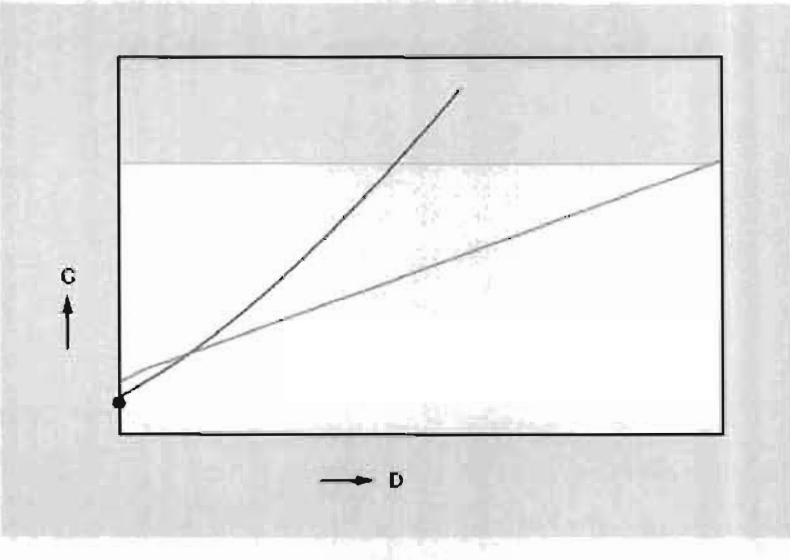
2.5.2.1 Typical layout of a 20-MW converter station



Key:

1. AC filter
2. AC connection
3. Converter reactors

Fig 2.7 Model of a typical layout of a 20-MW converter station (Asplund *et al.*, 1998)



Key:

C - Cost per kWh
D - Distance from AC grid
Beige - Local diesel generation
Blue AC plus overhead line
Red HVDC Light with cable
Green Energy cost for AC grid

Fig. 2.8 Comparison of typical costs for AC and DC transmission and local diesel generation (basis: 20 MW) (Asplund *et al.*, 1998)

The cost for HVDC land cables are typically lower than for AC cables. In two of the projects performed the cables have been ploughed into the ground instead of laying in excavated cable trenches. This has reduced the installation costs substantially.

2.6 HVDC cables

The primary function of cables is to carry energy reliably between source and utilisation equipment. In carrying this energy there are heat losses generated in the cables that must be dissipated. The ability to dissipate these losses depends on how the cables are installed and this affects their ratings.

Underground cables are used in power distribution networks in cities and densely populated areas. Cable technology has developed greatly in the last few decades. Cables are usually more expensive than overhead lines at all supply voltages with a cost ratio of about 20,8 and 2 at 400, 32, and 11KV respectively (King and Halfter, 1982).

Until now, cables used for HVDC transmission and distributions have been paper-insulated cables, low-pressure oil filled cables (LPOF) or Mass Impregnated non-Draining Cables (MIND). Low-pressure oil filled cables need auxiliary equipment to maintain the oil pressure and cannot be easily installed. There are also environmental oil spill concerns that are associated with low-pressure oil filled cables. Mass impregnated non-draining cables have limitations in the operating conductor temperature. Paper insulated cables are not feasible for aerial cables because of their sensitivity of repeated bending (Eriksson, 2001).

In HVDC there has been a change of technology going from paper insulated cables to extruded cables, mostly the new cables have insulated extruded polymer. The insulation system is triple extruded. The conductor screen, the insulation and the insulation screen are extruded simultaneously.

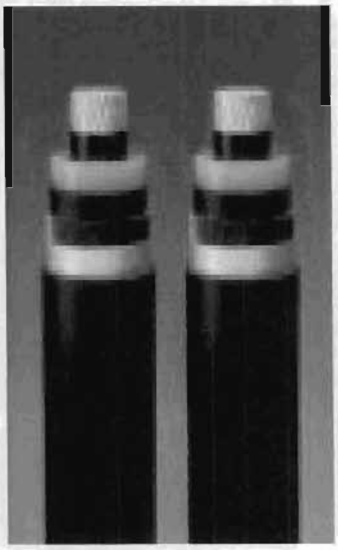


Fig. 2.9 Triple extruded HVDC cable (100 – 150kV) (Stendius and Eriksson, 1999)

The cable is rated for 100 - 150 kV, with a current carrying capacity of less than 1 200 amps. The cable weighs between 1 – 6.5 kg/m. The copper conductors are screened and wrapped with an overall sheath made of HDPE type material.

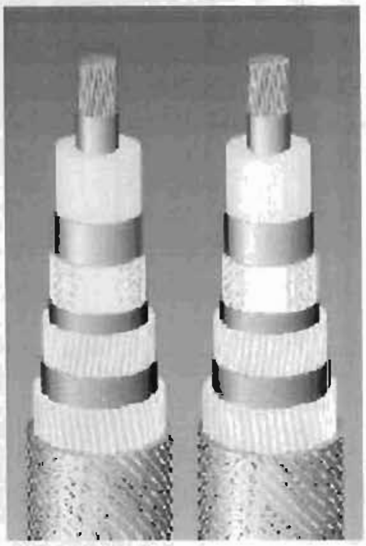


Fig. 2.10 Copper conductor with triple extruded insulation system rated for 80 – 100 kV HVDC application *viz.* conductor screen, HVDC polymer insulation, insulation screen
Armouring - Lead sheath, steel wire armour, cross wire steel armour (Asplund *et al.*, 2000)

The above cables are robust and can be installed by using a cost effective ploughing method of installation.

The preference of extruded cables for applications in HVDC is now becoming a market trend. Cross-linked polyethylene (XLPE) cables are not suited for HVDC applications due to the existence of space charges in the insulation leading to uncontrolled local high electric fields causing dielectric breakdowns. Another reason has been uneven stress distribution due to temperature dependent resistivity causing overstress in the outer part of the installation.

The first HVDC submarine mass impregnated non-draining cables were, 100km long and was installed in 1954 between the Swedish mainland and Gotland, showed no ageing after 32 years of operation. A long-term test on HVDC light cable with terminations has been conducted for a period of 250 days. The purpose was to qualify the cable for a rated voltage of 123kV DC. The test voltage of 210kV DC (Eriksson *et al.*, 1998).

Contrary to the case with AC transmission, distance is not the factor that determines the line voltage. The only limit is the cost of the line losses, which may be lowered by choosing a cable with a conductor with a larger cross section. Thus, the cost of a pair of DC cables is linear with distance. A DC cable connection could be more cost efficient than even a medium distance AC overhead line, or local generating units such as diesel generators. The converter stations can be used in different grid configurations. A single station can connect a DC load or generating unit, such as a photo-voltaic power plant, with an AC grid. Two converter stations and a pair of cables make a point-to point dc transmission with AC connections at each end. Three or more converter stations make up a DC grid that can be connected to one or more points in the AC grid or to different AC grids.

HVDC cable development work with the objective to type test an extruded HVDC cable, was initiated a couple of years ago. It has now resulted in an extruded cable for HVDC that is an important part of the HVDC concept and opens new opportunities for future power transmission and distribution.

The robustness opens for new cable applications, (1) direct ploughing of underground cables, (2) insulated aerial cables and (3) submarine cables for severe conditions.

Fig. 2.11 Ploughing of the HVDC Light Cable (Mattesson *et al.*, 2004)

Fig. 2.12 Low cost installation with ploughing (Cook *et al.*, 1999)

2.6.1 Magnetic field of HVDC bipole

HVDC cables are operated in bipolar mode, one cable with positive polarity and one cable with negative polarity. HVDC single core cables are installed close in bipolar pairs with antiparallel currents and thus eliminating the magnetic fields. A classic monopolar HVDC cable scheme with a current of 1000 A gives a magnetic field of the magnitude 20 micro Tesla at a distance of 10 meters. This is about half the magnitude of the natural magnetic field from earth. With bipolar HVDC cables the magnetic field is reduced to less than 0.2 micro Tesla.

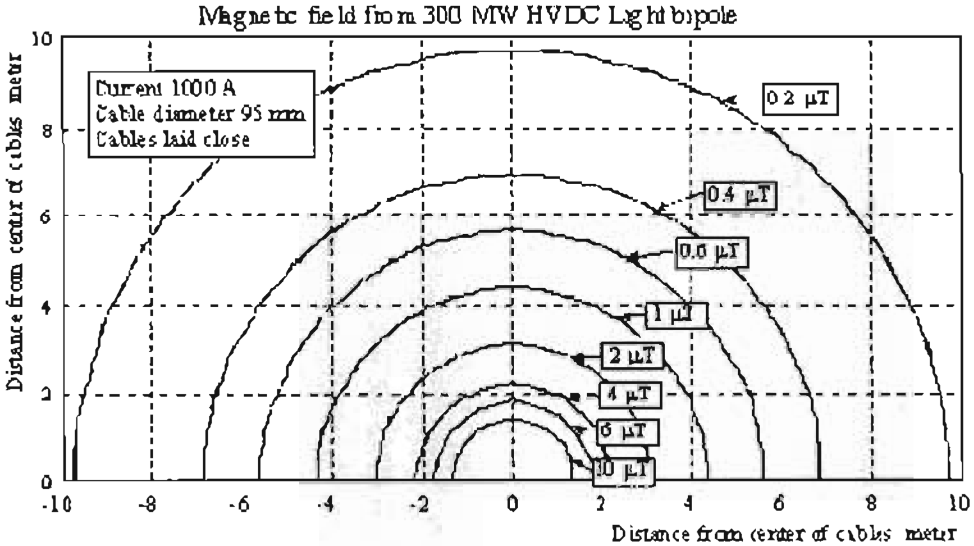


Fig. 2.13 Iso-Tesla curves for 300 MW HVDC submarine and land cables (Asplund *et al.*, 2000)

As the converter station ratings increased, so too did the powers and voltage levels for which the HVDC cables had to be built. The most powerful HVDC submarine cables to date are rated 600 MW at 450 kV. The longest of these are the 230 km cable for the Baltic Cable link between Sweden and Germany, and the 260 km cable for the SwePol link between Sweden and Poland. The HVDC extruded cable is the outcome of a comprehensive development program, where space charge accumulation, resistivity and electrical breakdown strength were identified as the most important material properties when selecting the insulation system. The selected material gives cables with high mechanical strength, high flexibility and low weight. Extruded HVDC cables systems in bipolar configuration have both technical and environmental advantages. The cables are small yet robust and can be installed by ploughing, making the installation fast and economical.

2.6.2 Application of HVDC marine and land cable

HVDC cables with insulation of extruded polymer and specifically adapted for direct voltage. On March 10, 1997 power was transmitted on the worlds first Voltage Source HVDC transmission between Hellsjön and Grängesberg in central Sweden. Two and a half years of excellent operation experience has shown, that the technology is mature. Four commercial transmissions are under design, manufacturing and commissioning. Especially in cases, where AC transmission is difficult from environmental, technical or economical point of view HVDC offers an environmentally friendly solution, which makes the permission process simpler.

2.7 Impact of HVDC on the environment

The HVDC is an environmentally friendly solution which makes the permitting process fast and smooth. The stations are small and compact which minimizes the visual impact. The current, flowing in a pair of cables, generates no electromagnetic field since the cables are installed close to each other. The cables can be buried in existing right of ways such as rail ways, roads or under an existing over-head line. Thus the impact on the environment is reduced to an absolute minimum.

In general, it is getting increasingly difficult to build overhead lines. Overhead lines change the landscape, and the construction of new lines is often met by public resentment and political resistance. People are often concerned about the possible health hazards of living close to overhead lines. In addition, a right-of-way for a high voltage line occupies valuable land. The process of obtaining permissions for building new overhead lines is also becoming time-consuming and expensive. Laying an underground cable is a much easier process than building an overhead line.

A cable does not change the landscape and it does not need a wide right-of-way. Cables are rarely met with any public opposition, and the electromagnetic field from a DC cable pair is very low. A pair of HVDC cables can be ploughed into the ground. Despite their large power capacity, they can be put in place with the same equipment as ordinary, AC high voltage distribution cables. Thus, HVDC is ideally suited for feeding power into growing metropolitan areas from a suburban substation.

Connecting to small scale, renewable power generation plants to the main AC grid is now economically feasible due to HVDC technology. Remote locations such as islands, mining districts and drilling platforms can be supplied with power from the main grid using the same technology. This eliminates the need for inefficient, polluting local generation diesel units. Underground cables replace overhead lines at no cost penalty. HVDC also has control capabilities that are not present in AC systems.

AC transmission and distribution technology has made it possible to locate generating plants in optimum locations, and to utilise them efficiently. This has also resulted in great environmental gains. Thermal plants have been located where they can be supplied with fuel through an efficient transportation system, thereby reducing waste and pollution. Hydro plants have been located where the hydro resources can be used at the greatest advantage. Large generating plants have meant fewer overhead lines than a multitude of smaller generating plants would have required.

However, today's AC transmission and distribution systems are, at least in principle, based on ideas that haven't changed much since a hundred years ago to generate power, step up the voltage with transformers, transmit power, step down the voltage and distribute power. Despite their proven advantages, it is difficult and expensive to adapt AC transmission and distribution systems to the numerous small scale generating plants that are being built, or to the increasingly complex and variable production and load demands.

Environmental concerns and regulations also put heavy restrictions on building new right-of-ways and on small-scale, fossil fuelled generating plants, such as diesel generating plants. These new trends require networks that are flexible. The networks must be able to cope with large variations in load and frequent changes in production patterns, with tougher environmental regulations. Also, in such flexible networks, the power flow and the voltages require precise control in order to make the grids stable and economical.

A DC link, connecting two such networks, can be used for combining the generation capacities of both networks. Cheap surplus power from one network can replace peak power generation in the other. This will result in both reduced pollution levels and increased fuel economy. The power exchange between the networks is also very easy to measure accurately.

HVDC technology saves the environment by replacing remote fossil fuelled diesel generators with cost-efficient transmission of power from efficient and clean, large-scale generation production units. The efficiency of a modern, large scale, thermal generating plant is usually 25 percent higher than that for a modern, small or moderate scale diesel generator plant. Vice versa, HVDC provides a convenient and cost-effective way for connecting renewable and non-polluting energy sources as wind power farms and photovoltaic power plants to a main grid. The HVDC technology in itself has strong environmental benefits.

Since bipolar HVDC transmissions systems, do not inject any currents into the ground, the risk of stray currents in the ground causing disturbance to communication systems or causing corrosion on gas or oil pipelines is minimized.

Overall, transmission by HVDC saves the environment by: - (1) replacing local fossil-fueled generation with transmission from main AC-grid, (2) connecting small scale renewable power to main AC –grid, (3) cables instead of OH transmission lines, (4) virtually no magnetic field and (5) no ground currents because with bipolar transmission.

CHAPTER THREE

METHODS OF ANALYSES AND RESULTS

The objective of the study is to consider line possibility of providing power to the rural location, Kwa-Ximba from a hydroelectric generation scheme and transmit the excess power to Eskom's Catoridge-Georgedale sub-transmission network for system enhancement. Currently the Catoridge-Georgedale network obtains power from Eskom's national grid.

The following networks have been proposed in order to in order to provide Kwa-Ximba and Eskom's Catoridge-Georgedale sub-transmission network with power.

(i) **Network A**

Power supply to Kwa-Ximba, and the Catoridge-Georgedale sub-transmission network, from a hydroelectric generation scheme, using HVDC technology.

(ii) **Network B**

Power supply to Kwa-Ximba, and the Catoridge-Georgedale sub-transmission network, from a hydroelectric generation scheme, using HVAC technology.

(iii) **Network C**

Power supply to Kwa-Ximba by extending Eskom's existing AC Catoridge-Georgedale sub-transmission network with the hydroelectric generation scheme switched off.

Network A (HVDC system) was considered as an option in order to determine the viability of using an HVDC system to supply electricity to Kwa-Ximba from the hydroelectric generation scheme situated at Nagle Dam and use the excess power to enhance Eskom's Catoridge-Georgedale sub-transmission network. Network B (HVAC system) was considered in order to make technical and economical comparisons between using an HVDC or HVAC system for the same purpose. Network C was considered to determine if merely extending Eskom's existing network to Kwa-Ximba will be more viable than using a hydroelectric scheme.

The first aim of the study was to develop the hydroelectric generation scheme at Nagle Dam. The magnitude of the electrical power that can be generated from the hydroelectric scheme was determined by the effective head of the Nagle Dam wall and the change in flow rate per annum (due to changes in water demand). In order to determine the most efficient and cost effective use of generator sets, the flow rate, available hydraulic power and available electrical power from the year 2006 to the year 2034 was calculated. The increase in flow rate was based on an annual growth rate of 1.5% in water demand. The increase in electrical power demand for Kwa-Ximba was calculated for the next 28 years based on an annual growth rate of 1.8 %. The annual growth rates were obtained from the Town Planning Department of eThekweni Municipality.

Eskom's present infrastructure at the Catoridge-Georgedale sub-transmission network was investigated. There is no existing electrical infrastructure at Kwa-Ximba. In order to supply power to the location, basic infrastructure was proposed for Kwa-Ximba. This infrastructure was common to all three networks, in the present study, and included reticulation cables, transformers overhead lines and underground cables.

Thereafter each proposed network was technically analyzed and detailed in network drawings. For Network A, HVDC cables, converter stations, additional transformers, power lines (AC) and busbars were selected. For Network B, a HVAC overhead line was selected. The hydroelectric scheme was used to generate power which was directly transmitted to Kwa-Ximba and the Catoridge-Georgedale sub-transmission network. For Network C, the hydroelectric generation scheme was switched off and the present Catoridge-Georgedale sub-transmission network was extended to Kwa-

Ximba. The Rectic Master software (2003) was used to optimize the selection the appropriate infrastructure for each Network.

Technical analyses was conducted on each network via load flow analyses. Load flow analyses were conducted on the various networks, using the same power lines and busbars that constitute each of the Networks. This was done in order to determine effectiveness of each network. The Digsilent Powerfactory v13.1 (Build 249) software program was used for load flow analyses.

Economical analysis was also conducted to determine the (i) cost of each network and (ii) the annual net profit that can be derived from each network. Finally the technical and economical merits and demerits of each network were discussed.

3.1. Development of the hydroelectric generation scheme at Nagle Dam

3.1.1 Present and predicted power output

There are currently two existing turbine-generating plants at Nagle Dam, which are rated at 315 kVA each. They are being used by Umgeni Water to provide power to the dam for maintenance and operations purposes. The power generated is proportional to the flow rate and the effective head. However, a high effective head is more desirable to increase power output because it reduces the required flow rate and hence the cross sectional area of the penstock. The height of Nagle Dam wall is 63 m. The present flow rate is 42.88m^3/s. The available hydro power output of the proposed hydroelectric generation scheme based on the present flow rate (for the year 2005) is calculated as follows:

$P_{hydraulic} = \rho gHQ$...(1)

Where,

$P_{hydraulic}$ = available hydraulic power (W)

ρ = density of water (1000kg/m^3)

g = acceleration due to gravity (9.81m/s^2)

Q = flow rate (m^3/s)

H = effective head (m)

Available hydro power output for 2005 based on the present flow rate of $42.88m^3/s$:

Substituting:-

H = effective head of dam wall = 63m

and Q = 42.88m3/s into (1)

Hence: Hydraulic power available to drive hydroelectric generation scheme for year 2005 = 26.50MW

However, due to losses in the generation system the actual electrical power output has to be calculated.

$P_{electrical} = \rho g H Q \eta_{overall}$..(2)

Where,

$P_{electrical}$ = electrical output power (W)

η = overall efficiency (efficiency of turbine plus efficiency of alternator)

Electrical power output for 2005 based on the present flow rate of $42.88m^3/s$:

Substituting:

Efficiency of turbine = 83%

Efficiency of alternator = 90%

Hence: Electrical power generated for year 2005 = 19.7MW

The available hydraulic power for Nagle Dam for 2005 is thus 26.50MW and the electrical power output is 19.7MW, due to generation losses in the system. Supplying power to the Kwa-Ximba rural area will inevitably result in a growth in the rural community. The development of small to medium industries is envisaged. This will lead to an increase job creation and a decrease in migration to urban areas. These factors will contribute to an increase in water demand by Kwa-Ximba, Durban and surrounding areas. As water demand increases so will the flow rate increase accordingly. Proportional to the increase of flow will be an increase in the potential of power generation. It is, therefore, also necessary to calculate the available hydro power capacity and electrical power output for the future. This will ensure that the proper selection of electrical equipment that can handle or easily be upgraded to handle the increase in electrical demand in the next five years. The Town Planning Department of eTekweni Municipality estimates that the present power demand to develop Kwa-Ximba is 10MW. The Town Planners further estimate an average growth of 1.8% electrical power demand per annum and an average growth rate of 1.5% water demand per annum for Durban (based on interview with Mr D. Thaver from the Town Planning Department of eThekweni Municipality, 2005). Table 3.1 shows the available hydro power and electrical power based on an increase in flow rate of 1.5% projected for the next 29 years.

The increase in flow rate for Kwa-Ximba and eTekweni Municipality was calculated for the next 29 years using the following equation:-

$$P = P_o.e^{a(t-to)} \qquad \text{...(3)}$$

a = average per unit growth rate = 1.5 %

P = demand in year t

P_o = is the given demand in year t_o.

Table 3.1 Flow rate, available hydro power and available electrical power from 2005 to 2034 (based on water demand projections provided by the eTekweni Municipality)

Year	Flow (m^3/s) with a annual growth of 1.5%	Available hydraulic power (MW)	Available electrical power (MW)
2005	42.88	26.50	19.7
2006	43.52	26.89	19.99
2007	44.17	27.3	20.29
2008	44.84	27.7	20.6
2009	45.51	28.13	20.9
2010	46.2	28.55	21.2
2011	46.89	28.98	21.54
2012	47.59	29.41	21.86
2013	48.3	29.85	22.19
2014	49.02	30.3	22.5
2015	49.76	30.75	22.86
2016	50.51	31.22	23.2
2017	51.27	31.68	23.55
2018	52.04	32.16	23.91
2019	52.82	32.64	24.26
2020	53.6	33.13	24.63
2021	54.4	33.63	25
2022	55.23	34.13	25.37
2023	56.06	34.64	25.75
2024	56.9	35.164	26.14
2025	57.7	35.69	26.53
2026	58.62	36.23	26.93
2027	59.5	36.77	27.33
2028	60.4	37.322	27.75
2029	61.3	37.88	28.16
2030	62.2	38.45	28.58
2031	63.15	39.03	29
2032	64.1	39.6	29.4
2033	65.06	40.19	29.84
2034	66.04	40.8	30.29

3.1.2 Present and predicted electrical power demand

The electrical power demand for the next 29 years is forecasted in order to match the infrastructure required for the hydroelectric generation scheme with the growth in electrical power demand. The electrical demand at Kwa-Ximba is predicted increase at a fixed rate of 1.8% annually. It is essential that the power generation equipment be effectively used, in order to keep operating costs as low as possible. In order to maintain flexibility in power generation, it is recommended that five sets of hydro electrical generators be purchased to give a combined power delivery of 20MW. Table 3.2 describes the five generator sets. The first three hydro electrical generators should be rated at 5MW each, the fourth set should be rated at 3MW and the fifth set should be rated to deliver 2MW.

Table 3.2 Description of generator sets

Generator set no.	Power (MW)	Voltage
G1	5	11 kV, 3 phase
G2	5	11 kV, 3 phase
G3	5	11 kV, 3 phase
G4	3	11 kV, 3 phase
G5	2	11 kV, 3 phase

The power demand over the next 29 years will determine which combination of generator sets are required to operate at various times. Table 3.3 shows the predicted load pattern from 2005 to 2034. The increase in electrical power demand for Kwa-Ximba was calculated for the next 29 years by using equation (3) and substituting *a = average per unit growth rate = 1.8 %*. It was essential to calculate the future load pattern for Kwa-Ximba in order to optimise the infrastructure required for each network.

Table 3.3 **Predicted load pattern from 2005 to 2034 based on the present study**

Year	Estimated electrical power demand by Kwa-Ximba (MW)	Estimated power delivery to Catoridge-Georgedale Sub-transmission network	Estimated spinning reserve at hydro generation plant (%)	Generators sets in operation	Electrical power demand on hydro-generation scheme (MW)
2005	10 56	8.64	4	1 – 5	20
2006	10.75	8.45	4	1 - 5	20
2007	10.944	8.25	4	1 - 5	20
2008	11.14	8.06	4	1 – 5	20
2009	11.341	7.859	4	1 – 5	20
2010	11.545	7.655	4	1 – 5	20
2011	11.753	7.447	4	1 – 5	20
2012	11.965	7.235	4	1 – 5	20
2013	12.18	6.901	4 5	1 – 5	20
2014	12.399	0.00	17.3	1, 2, 3	15
2015	12.622	0.00	15.8	1, 2, 3	15
2016	12.85	0.00	14.3	1, 2, 3	15
2017	13.08	0.00	12.8	1, 2, 3	15
2018	13.316	0.00	11.23	1, 2, 3	15
2019	13.556	0.00	20.25	1, 2, 3, 5	17
2020	13.8	0.00	18.8	1, 2, 3,5	17
2021	14.048	0.00	17.36	1, 2, 3,5	17
2022	14.301	0.00	15.87	1, 2, 3,5	17
2023	14.56	0.00	14.35	1, 2, 3.5	17
2024	14.82	0.00	17.67	1, 2, 3, 4	18
2025	15.087	0.00	16 183	1, 2, 3, 4	18
2026	15.36	0.00	14.67	1, 2, 3, 4	18
2027	15.636	0.00	13 133	1, 2, 3, 4	18
2028	15.917	0.00	20.4	1 – 5	20
2029	16.204	0.00	18.89	1 – 5	20
2030	16.495	0.00	17.5	1 – 5	20
2031	16.79	0.00	16.05	1 – 5	20
2032	17.074	0.00	14.63	1 – 5	20
2033	17.402	0.00	12.99	1 -5	20
2034	17.715	0.00	11.425	1 -5	20

Note: Power supply to Eskom's Catoridge-Georgedale sub-transmission network is terminated by the year 2014.

Table 3.3 shows that from the year 2005 to 2013, the hydroelectric generation plant will be able to supply Kwa-Ximba as well as Eskom's Catoridge-Georgedale sub-transmission network with electrical power and still have a spinning reserve of 4 to 4.5%. However, after the year 2013 it will no longer be feasible, from a technical and operating cost perspective. to supply the Catoridge-Georgedale sub-transmission network with electrical power. This is due to the fact that the supply to Eskom will be less than 5MW. It is therefore recommended that by year 2014, power supply to Eskom cease. The relatively low spinning reserve of 4% was selected until the year 2012. This is due to the fact that the hydroelectric generation sets will be highly efficient in their operation due to them being in service for less than eight years. Furthermore, until the year 2013 the hydroelectric generation scheme is connected to the Eskom network, so if there is a need for power in excess of the allowed spinning reserve, power can be easily drawn from the Catoridge-Georgedale sub-transmission network. Beyond the year 2013 the hydroelectric generation scheme will cease to supply power to the Eskom network and thus the spinning reserve will increase by 17.3%.

It is necessary for the existing two 315 kVA turbine generating plants, at Nagle Dam be decommissioned as they are too small to be used for the intended commercial purpose. The available hydro power capacity of Nagle Dam is calculated to be 19.7MW (Table 3.1) for the year 2005. It is therefore recommended that the hydroelectric generation scheme be sized at 20MW and be installed adjacent to the dam wall. This requires all five generators sets (G1 to G5) to be on line to deliver 20 MW of power. The delivery of 20 MW of power will accommodate the increase in power demand by Kwa-Ximba up until the year 2013 (Table 3.3) and deliver power to the sub-transmission network with an initial spinning reserve of 4 to 4.5%. The power supply to the Catoridge Georgedale sub-transmission network will decrease proportionally up until the year 2013.

From the years 2014 to 2018, the average electrical power demand by Kwa-Ximba is 12. 85 MW (Table 3.3). At this stage the hydroelectric generator sets will be combined to give an electrical power of 15MW. This means that only the first three generator sets of 5MW each (G1 to G3) will be on line and set four and five will be off line. In the year 2014 the spinning reserve will be 17.3% but will decrease to

11.23% by the year 2018. In the year 2019 the combination of generators sets in operation will change again, in order to ensure an adequate spinning reserve as well as deliver the required electrical power to Kwa-Ximba, with reasonable security on the supply from the hydroelectric generation scheme.

The average electrical power demand by Kwa-Ximba from the years 2019 to 2023 is 14.05 MW (Table 3.3). In order to make efficient use of the generator sets, G1,G2, G3, and G5 will be on line, resulting in an electrical power output of 17 MW. This will result in a 20.25% spinning reserve in 2019, but will decrease to 14.35% by the year 2023.

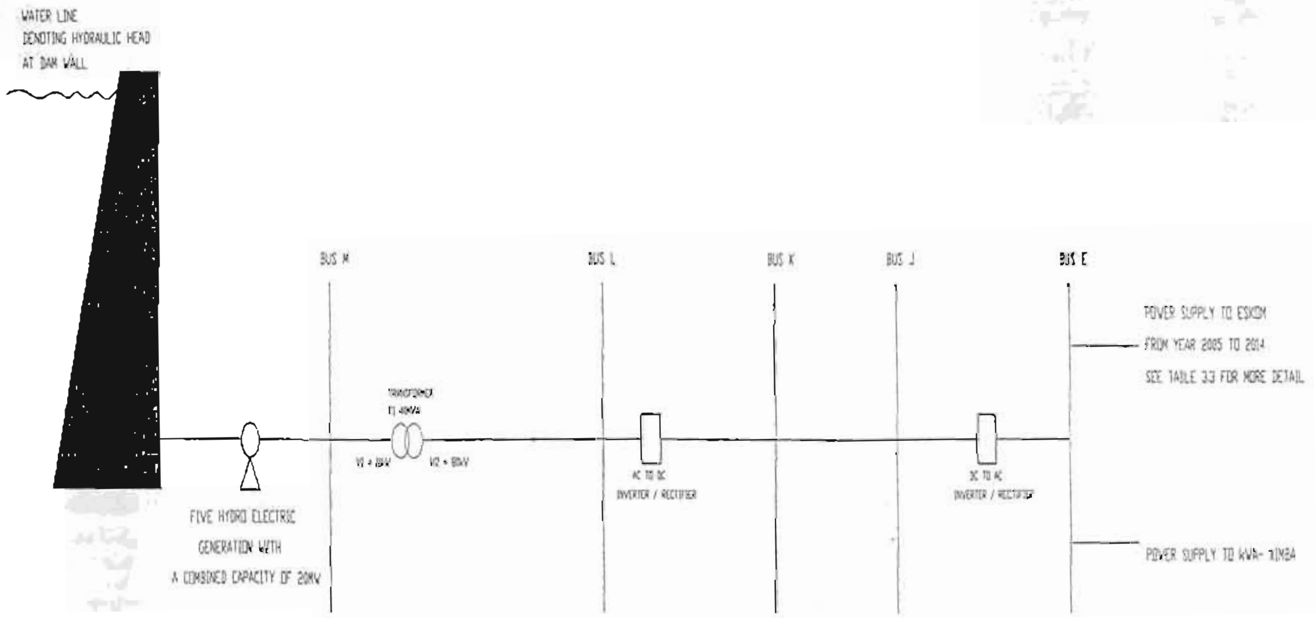
It will be necessary to bring generator sets G1, G2, G3, and G4 on line and switch off G5 from the years 2024 to 2027. This combination of generators sets will deliver an electrical power output of 18 MW, which will adequately cover the average of 15.23 MW (Table 3.3) required during this time period. The spinning reserve will be 17.67% in the year 2024.

The average demand in electrical power from the year 2029 to 2032 is 16.5 MW. This demand makes it necessary to bring all five generators sets on line to deliver a power output of 20 MW. By the year 2028 the spinning reserve will be 20.28%.

The hydroelectric generation scheme will be equipped with the structures necessary to channel and regulate the flow of water to the turbines. These structures will include the open channel spillway. This will enable the conversion of hydraulic energy to electrical energy. The main components of the hydro power plant will be separated into (i) the main inlet valve and turbine, (ii) the generator and (iii) the electrical control equipment and unit auxiliaries.

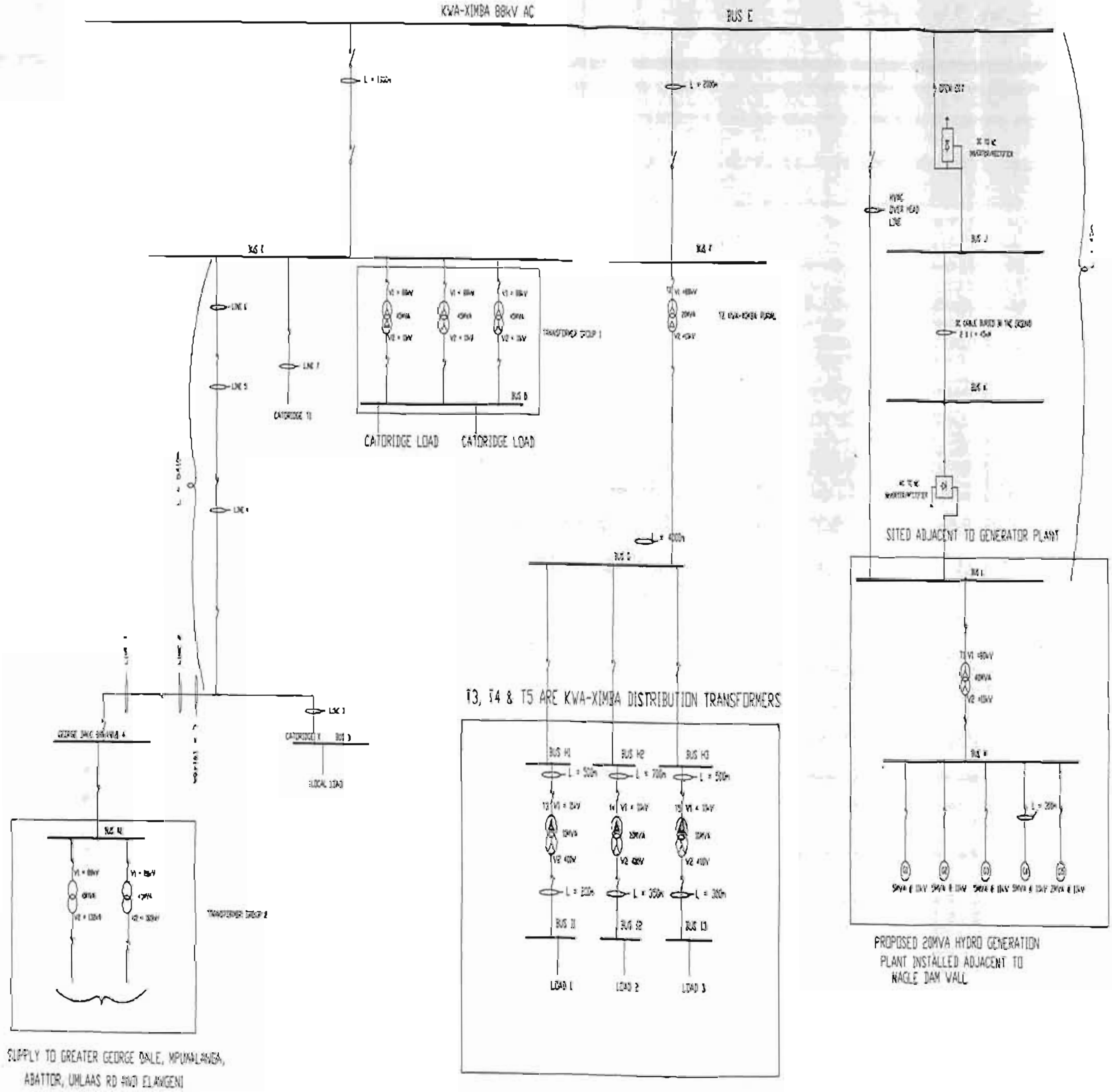
3.2 The existing Catoridge-Georgedale sub-transmission network

The existing Catoridge-Georgedale sub-transmission network is detailed in Drawings 1, 2, 3, 4 and 5. The section of the network extending from Catoridge to Georgedale is studied. An audit of the pre-existing infrastructure at the Catoridge-Georgedale sub-



ONE LINE DIAGRAM OF
INSTALLATION UNDER STUDY

DRAWING No. 01



PROPOSED ELECTRFICATION SCHEME FOR
KWA-XIMBA RURAL DISTRICT

DRAWING No. 04 = HVDC CCT ON LINE
DRAWING No. 03 = HVDC CCT OFF LINE
DRAWING No. 05 = HVAC OVERHEAD LINE INSTALLED
DRAWING No. 06 = HYDRO GENERATION PLANT ELECTRICALLY ISOLATED

Drawing No. 02

transmission network was undertaken. Tables 3.4 shows the technical details for the transformers located at the Catoridge substation (Group 1) and at the Georgedale substation (Group 2). Transformer group 1 (substation) is located at Catoridge. The primary side voltage is 88 kV and secondary side voltage is 11 kV. Transformer group 2 (substation) is located at Georgdale. The primary side voltage is 132 kV and the secondary side voltage is 88 kV.

Table 3.4 Details of the pre-existing transformers at the Catoridge-Georgedale sub-transmission network (Eskom Mkodeni KwaZulu-Natal database)

ITEMS	TRANSFORMER GROUP 1	TRANSFORMER 12 GROUP 2
Transformer location	Cato Ridge	Georgedale
Operating voltage	88/11kV	132/88kV
In folder	2 – Winding- PSSE	2 – Winding- PSSE
Technology	Three Phase Transformer	Three Phase Transformer
Rated power (MVA)	45	45
Nominal frequency (Hz)	50	50
HV. rtd. Volt (kV)	88	132
LV. rtd. Volt (kV)	11	88
Shc Volt (Z_1) %	8.67	10
Re (Shc Volt) (R_1) %	0.3468	0.4
HV Vector group	Y	YN
LV Vector group	Z	YN
Phase shift (30°)	11	1
Name	Yz11	Ynyn1
Uko (Z_0) %	0.78897	8.5
Shc Res.0 (R_0) %	0.0315588	0.34
Neutral tap	2	5
Min. tap	1	1
Max. tap	9	17

Table 3.5 shows the details and characteristics of the pre-existing overhead lines at the Catoridge-Georgedale sub-transmission network, operating under normal conditions. It must be noted that overhead Lines 1 to 7 operate at 88 kV. The operating parameters of the pre-existing transformers and power lines were considered in the study of each network.

Table 3.5 Details of the pre-existing power lines at the Catoridge-Georgedale sub-transmission network

Line No.	NAME	TYPE	LENGTH (km)	DERATING FACTOR	RATED CURRENT (kA)	Z_1 (ohm)	R_1 (ohm)	X_1 (ohm)	R_0 (ohm)	X_0 (ohm)
L1	GRGD-XT1-GRGDL-88-88kV-L1	ZEROIMPE	0.8	1	4	0.000001	0	0.000001	0	0.0000001
L2	CATOR-XT-GRGD-XT1-88kV-L3	126C7C3	5.31	1	0.313	2.62859	1.229507	2.323316	2.438454	6.143426
L3	CATOR-XT-CATOR-8-X-88KV-L3	124C	2.14	1	0.204	1.408585	1.052332	0.9363271	1.537897	2.474223
L4	CATOR-T-CATOR-XT-88kV-L3B	126C7C3	3.57	1	0.313	1.767244	0.8266178	1.562003	1.639413	4.130326
L5	CATOR-T-CATOR-XT-88kV-L3A	126W2C3	0.92	1	0.47	0.2775879	0.09119335	0.2621809	0.3006531	0.9240453
L6	CATOR88-CATOR-T-88kV-L3	ZEROIMPE	0.7	1	4	0.000001	0	0.000001	0	0.0000001
L7	New proposed Eskom Line	126W2C3	0.7	1	0.74	5.129341	1.685094	4.844646	5.555546	17.07475

3.3 Basic electrical infrastructure required for Kwa-Ximba

This is a green field project. There is presently no basic electrical infrastructure at Kwa-Ximba. All infrastructure proposed below will be new. The following infrastructure are common required for all the three networks.

3.3.1 Reticulation cables

In order to develop the electrical infrastructure for Kwa-Ximba it is necessary to install reticulation cables. The reticulation cables are referred to as Cables 1, 2, and 3 (Drawing Nos. 2, 3, 4 and 5). The cables will operate at 11kV and will be fed from Bus G to Bus H. These cables are required to be installed 700mm below natural ground level as detailed in the South African National Standards, The selection, handling and installation of power cables of rating not exceeding 33kV (SANS 10198-11). The same cable type will also be used to connect between Buses H_1, H_2 and H_3 to the primary side of Transformers T3, T4 and T5. The Rectic Master software was used to select the appropriate cable. For simulation purposes the following parameters were selected. A fixed magnitude of 5 MVA of apparent power was each assigned Load Centres 1, 2 and 3, which are fed from Bus I1, I2 and I3 respectively. This therefore translates that the Lump Parameter Method of Analyses was used to select the 11 kV cables within the proposed electrification scheme for Kwa-Ximba rural district. This was done by determining the maximum predictable power that Load Centres 1, 2 and 3 will be required to deliver in its later years of existence. In addition, Transformer T2 which is installed between Buses F and G was selected to have an installed spare power capacity of 125%

The resultant values from the simulations are shown in Figure 3.1. A standard length of 5km with a current carrying capacity of 271A/ph was considered for simulation purposes. It must be noted that the actual distances between (i) the 11 kV AC Bus H1 and Transformer T3 (ii) the 11 kV AC Bus H2 and Transformer T4 and (iii) the 11 kV AC Bus H3 and Transformer T5 are 500 m, 700m and 500m respectively (Refer to Drawing No. 2). The reason for using a standard length of 5km with a current carrying capacity of 271A/ph in the simulation is to ensure design flexibility with respect to (i) that a standard cable size was selected and (ii) that any potential alterations to the reticulation system up to 5 km in length is feasible.

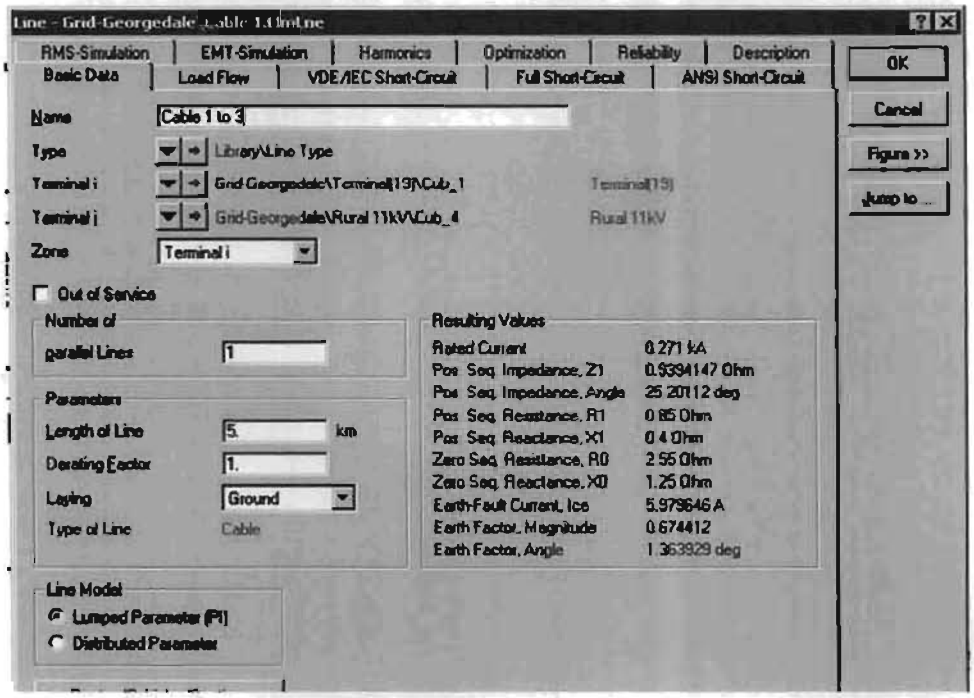


Fig. 3.1 Selection of the 11 kV (AC) cables between Bus G and Bus H_1 to H_3 and Transformers T3 to T5 for the Kwa-Ximba rural scheme

This resulted in the selection The following characteristic values were noted (See Drawing No. 2 for sub circuit entitled Proposed Electrification scheme for Kwa-Ximba Rural District)

(a) Positive sequence:-

(i) Cable impedance Z' was 0.9394147 ohm, (ii) impedance angle was 25.20112 degrees (iii) resistance R' was 0.85 ohm and (iv) cable reactance X' was 0.4 ohm.

(b) Zero sequence:-

(i) Cable resistance R_0' was 2.55 ohm and (ii) cable reactance X_0' was 1.25 ohm

(c) Earth fault current

(i) The earth fault current was recorded to be 5.979646A, (ii) the magnitude of earth factor was 0.674412 and (iii) the earth factor angle was 1.363929 degrees.

3.3.2 Overhead line (Line 8)

In order for the three proposed networks, in the current study, to operate, an additional line traversing between Catoridge 88 kV (AC) Bus C and Kwa-Ximba 88 kV (AC) Bus E will have to be installed. This additional line will be referred to as Line 8. The selection of Line 8 was made by using the Rectic Master 2003 software (Fig 3.2). Line 8 will be a 120mm^2 MV Cu PILC is modeled with the line length of 1.7 km long with a current carrying capacity of 271A/ph and an Operating Voltage of 88kV, for simulation purposes. The following characteristic values were noted:-

(a) Positive sequence:-

(i) Resistance R' was 0.17 ohm/km and (iv) cable reactance X' was 0.08 ohm/km.

(b) Zero sequence:-

(i) Cable resistance R_0' was 0.51 ohm/km and (ii) cable reactance X_0' was 0.25 ohm/km

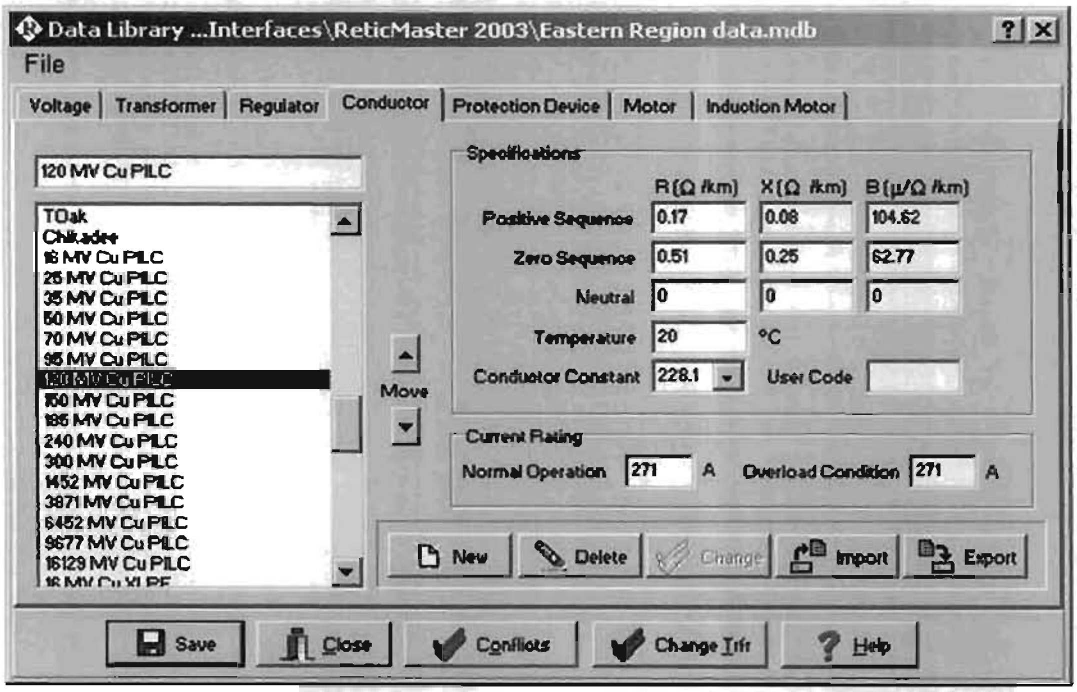


Fig. 3.2 Selection of Line 8 using the Rectic Master 2003 software

3.4 Specific infrastructure required for the various networks

All network simulations are based on the power demand for the year 2005, in which all generator sets are in operation and delivering a total of 20 MW of electrical power.

3.4.1 Network A

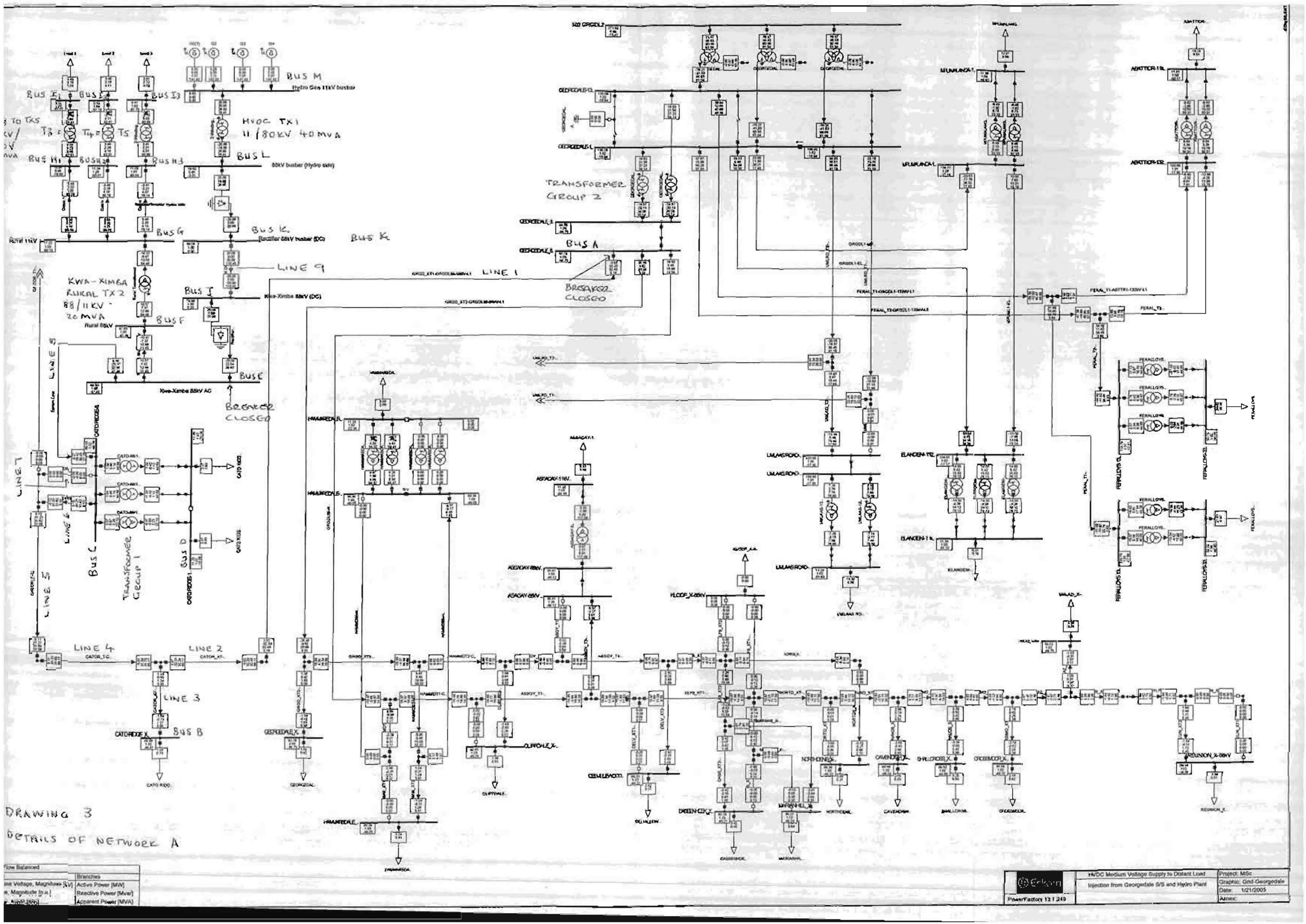
Drawings 1, 2 and 3 are diagrams depicting Network A. Drawings 1 and 2 details the dam wall, the five hydroelectric generator sets, Transformer T1, Bus L, AC to DC inverter/ rectifier, Bus K, 45 km HVDC line, Bus J, DC to AC inverter/rectifier to 88 kV (AC) Bus E located at Kwa-Ximba is shown. Network A will extend from the dam wall to Bus E located at Kwa-Ximba. Drawing 3 shows Network A in greater detail.

In Network A, the hydroelectric generation scheme runs in parallel with the Eskom sub-transmission network. The use of HVDC technology in Network A requires the installation of new electrical equipment. Such electrical equipment includes the hydroelectric generation scheme, additional transformers, power lines, busbars as well as converter stations and HVDC cables.

3.4.1.1 Optimization of generator usage to meet electrical power demand

Although five generator sets have been recommended for the hydroelectric generation scheme to meet the staggered load demand between the years 2005 and 2034, only four generator sets were modelled using the Rectic Master software. This was done in order to reduce operating costs by introducing more flexibility in the hydroelectric generation scheme to meet changes in load pattern.

Each generator is rated to deliver 11kV, not exceeding 105% of nominal voltage. The four generators that have been modelled are rated to deliver a combined active power of 20 MW (5MW each), and a combined reactive power of 3.75MVAr at 50Hz. Under simulation conditions the following power limits were recorded.



BUS M
Hydro Gen 11kV busbar
HVDC TX1
11/80kV 40MVA
BUS L
80kV busbar (Hydro side)
BUS K
Rectifier 88kV busbar (DC)
LINE 9
BUS J
Kwa-Ximba 88kV (DC)
BUS E
Kwa-Ximba 88kV AC
BREAKER CLOSED
KWA-XIMBA RURAL TX2
88/11KV - 20 MVA
Rural 88kV
BUS F
BUS G
Rural 11kV
BUS H1
BUS H2
BUS H3
BUS I1
BUS I2
BUS I3
T3
T4
T5
LINE 8
LINE 7
LINE 6
LINE 5
LINE 4
LINE 2
LINE 3
BUS B
BUS C
BUS D
TRANSFORMER GROUP 1
TRANSFORMER GROUP 2
BUS A
LINE 1
BREAKER CLOSED
DRAWING 3
DETAILS OF NETWORK A
Flow Balanced
Branches
Active Power [MW]
Reactive Power [Mvar]
Apparent Power [MVA]
HVDC Medium Voltage Supply to Distant Load
Injection from Georgedale S/S and Hydro Plant
Project: MSc
Graphic: Grid-Georgedale
Date: 1/21/2005
Annex:
PowerFactory 13.1.240

(1) Active power limits range between 0 to 6MW.

(2) Minimum reactive power ranges between –1 to –6.25MVAr,

(3) Maximum reactive power ranges between 1 to 6.26MVAr.

Figures 3.3 and 3.4. details the method of configuration and the power limits of the generators when simulated under normal operating conditions.

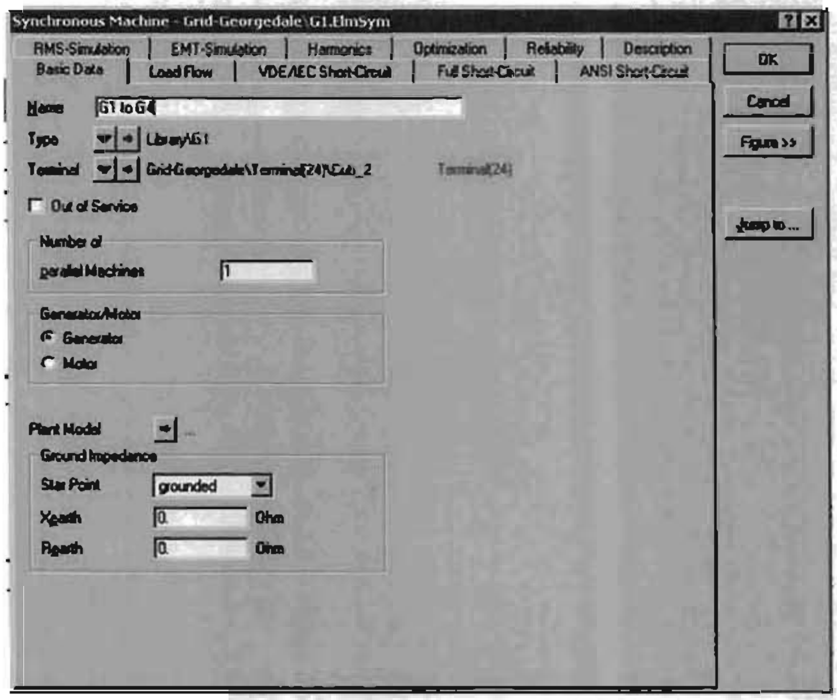


Fig. 3.3 Hydroelectric synchronous generators installed adjacent to dam wall, with a combined output of 20 MW (Applicable to Networks A and B)

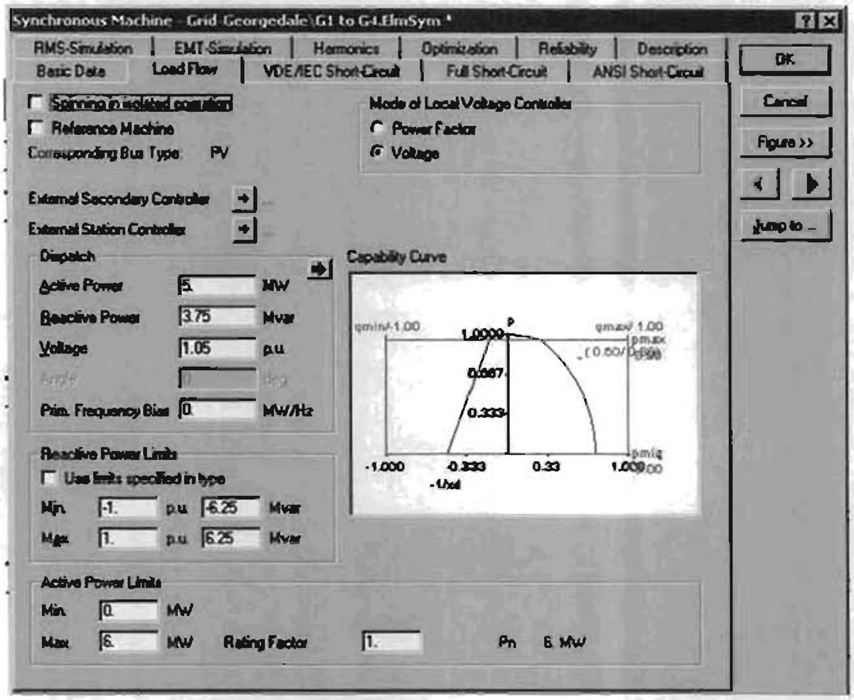


Fig. 3.4 Values of dispatch power and the generator capability curve (Applicable to Networks A and B

Brush less exciters will control the generating voltage as well as the amount of reactive power that is generated by the generator.

The four hydroelectric generators (rated at 11kV) will supply power to Transformer T_1, 11–80kV, 40 MVA (Drawing 2 and 3). At Bus L, the 80kV will be converted from AC to DC using converter stations. At the 88kV (AC) Bus E, power will be transmitted to 88kV (AC) Bus F which is Kwa-Ximba and also to the 88kV (AC) Bus C which is the Catoridge-Georgdale Bus, via Line 8. Transformer T1 will have its star point grounded for both HV and LV sides (Fig. 3.5).

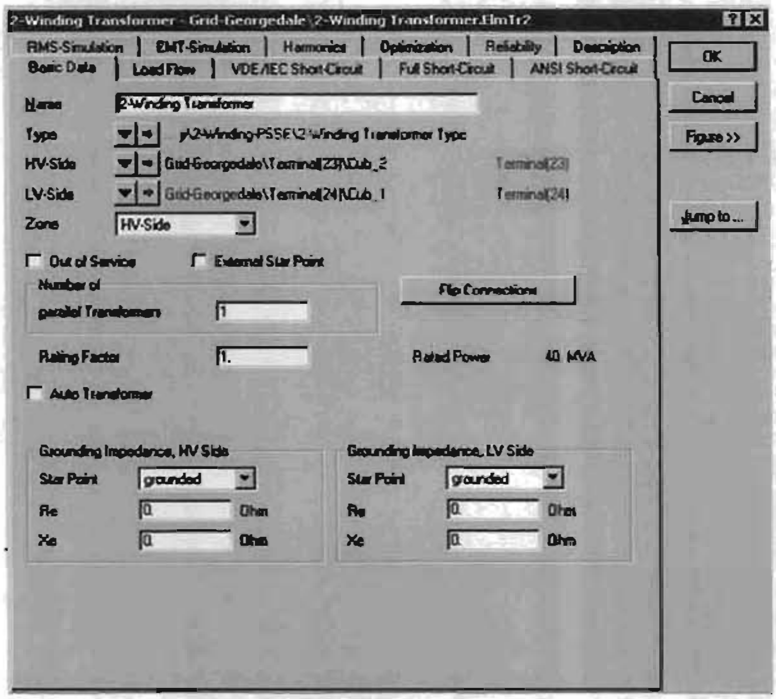


Fig. 3.5 **40 MVA, HVDC transformer T1 11/80kV, transformer installed adjacent to the hydro generation plant (Applicable to Networks A and B)**

In the present study the converter stations and the HVDC interconnected bipolar cable system is selected to operate at 80 kV (DC). The inverter station will be adjusted such that it delivers 88 kV (AC) onto Bus E. This is because the closest section of the Eskom network to Kwa-Ximba district is the Catoridge 88 kV AC Bus C, which is located 700m away from Kwa-Ximba district. In order to maintain low capital costs and obviate the need for a 30 MVA 3 phase oil filled transformer the operating voltage of the HVDC line was selected to be 88 kV. Furthermore the 88 kV line was selected since it matches with the smallest standard converter available. See converter station details in section 3.4.1.2.

3.4.1.2 Converter stations

In the present study, Network A, two Voltage Source Converters (VSC) equipped with PWM technology will be used. PWM will enable the converter to control active and reactive power independently, at the Kwa-Ximba 88 kV AC Bus E which lies between the Kwa-Ximba district and the Catoridge 88 kV AC Bus C (See drawing no.

3, Network A). In addition, VSC with PWM does not contribute to short circuit power since the AC current can be controlled.

Voltage source converters equipped with PWM converters are available from various vendors in different sizes. For the purpose of this study, converter stations with an active power rating of 20 MW each are required. The power rating of 20 MW will be adequate to supply Kwa-Ximba's power demand right up to the year 2032 when the demand will be 17.074 MW. Therefore the selection of these converters is based on requirements specific to the electrical demand of Kwa-Ximba in the next 30 years.

The converters are 3-level, using IGBT positions in place of diodes for the neutral-point clamping. The IGBT positions are based on IGBT and diode pack, divided into sub-modules to enable different current ratings using the same physical dimensions. The converter DC voltage operates at ±150 kV, but the selected PWM pattern switches the valves on and off only between + or –150 kV and 0 V, thus keeping the switching amplitude between +80 kV to –80 kV which matches the power profile of the Eskom network at Catoridge Bus C and Kwa-Ximba Bus E.

The switching frequency is 1260 Hz (21st harmonic). These parameters will only contribute to half the losses of a large 2 level converter, without contributing an to increase in harmonics.

The converter is connected to the 200 kV AC filter bus by water cooled phase reactors (L4) (Fig. 3.6). At this point three shunt filters, tuned to the 21st, 41st, and 25th harmonics are connected via breakers. The breakers are equipped with synchronous closing functionality. The power line carrier (PLC) filtering equipment (components L1, L2, L3, C1, C2 C3 and C4) is installed on the secondary side of the converter transformer.

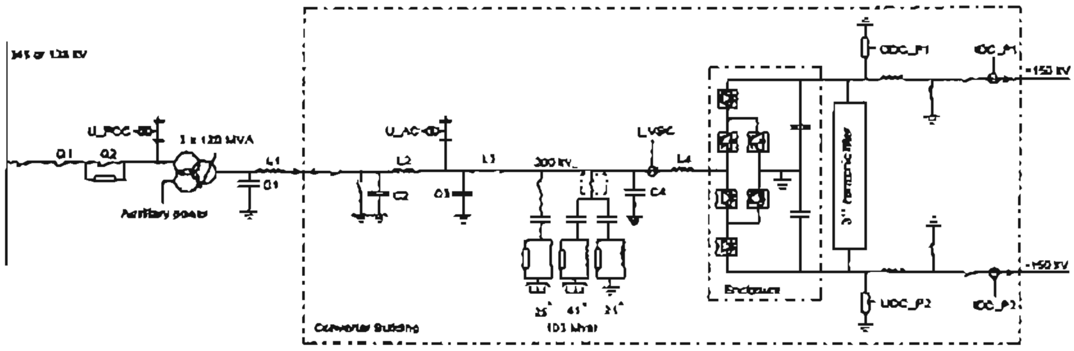


Fig 3.6. Converter Station Single-line Diagram (adapted from Railing *et al.*, 2004)

Standard AC transformers are used to match the AC network voltages of 88 kV to the converter AC voltage. The incoming breaker is equipped with pre-insertion resistors. They are used to minimize the transients when the converters are energized. A third harmonic filter is installed on the DC side of the converter. This is used to remove the third harmonic component.

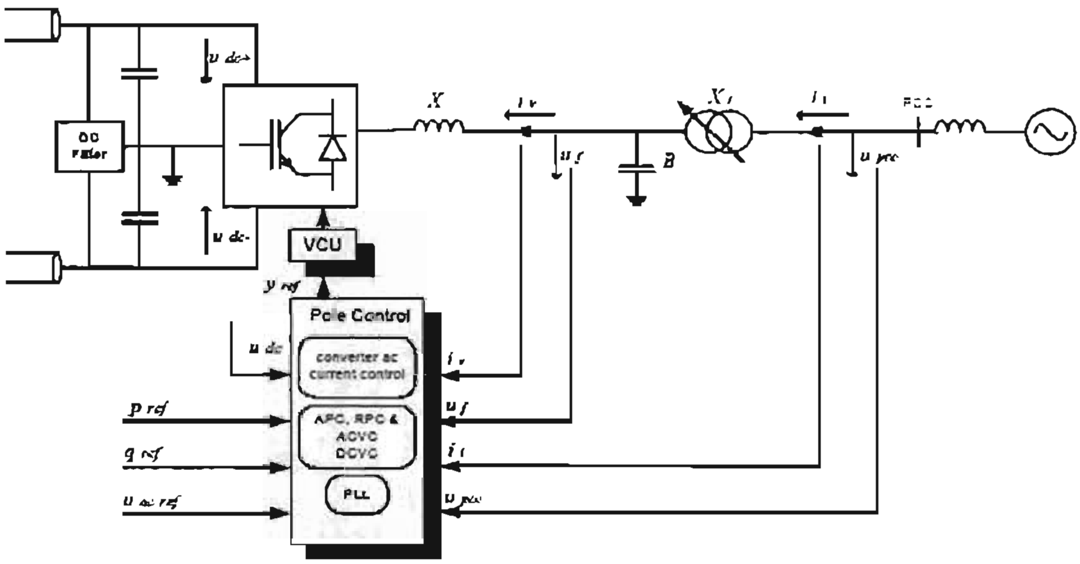
3.4.1.2.1. Control and Protection

The IGBT valves are cooled with a glycol/water mixture and installed in modular valve housings. Control equipment and equipment used for cooling water treatment are located within the converter building. The control and protection is built with telecommunication between the stations to enable fast runback for specific network disturbances. The existing telecommunication system in Kwa-Ximba, has to be upgraded in order to meet with control and protection requirements of the converter.

To ensure reliability between the two converters that are installed 45km apart between Bus L (adjacent to the Nagle Dam hydroelectric generation scheme) and Bus J the control system is duplicated with one control system active and the other in standby. Each control system consists of pole control and protection, and valve control units (VCU). The standby control system receives the on/off switching signals from the pole control and executes the switching orders to the valves.

The main objective of the control system is to control the transferred active and reactive power independently (See Drawing no, 3 Network A). The ability to control reactive power may be used either to keep the reactive power exchange or the AC voltage constant at the point of common coupling (PCC). This is done independently of the DC voltage or active power control modes. The converter voltage at the converter terminals is determined by factors such as the (i) calculated reference voltage, (ii) available DC voltage, (iii) harmonic generation and (iv) currents in the valves.

The converter current is controlled by the pole control, which consists of a state feedback controller (Fig. 3.7). The active and reactive currents are controlled independently. The controller is synchronized to the fundamental network voltage using a phase-locked loop (PLL). The DC voltage, active power, reactive power and AC voltage controls are able to calculate the reference currents to the converter current control. In steady state, one converter operates in DC voltage control (the converter installed at Bus L) and the other in active power control (the converter is installed adjacent to Bus E).



Key:-

DCVC - DC voltage control

APC - active power control

RPC - reactive power control

ACVC - AC voltage control

The control is synchronized to the network fundamental voltage using a phase locked loop, PLL

Fig. 3.7 Control f the converter station (Railing *et al.*,2004)

The converter protections operate independently of the control systems. All primary measuring units, cabling and computer boards are separated between control and protection. This ensures that a fault in one control measurement device does not affect the protection system.

Third-harmonic modulation: A zero sequence third-harmonic component is added to the sinusoidal reference voltage to reduce the peak AC converter voltage in order that, with the same DC voltage, an approximately 15 % increased AC-side fundamental-frequency voltage is available from the VSC.

DC voltage balance control: The three-level converter is mid-point grounded and balancing of the DC pole voltages is needed to prevent any ground current circulation. Certain space vectors are used in the modulation to balance the bridge.

Low order harmonic suppression: Minor non-linearities in the valve switching create low-order harmonics. To prevent their amplification, the converter is equipped with a controller to act on the PWM pattern in order to minimize the low order (5th and 7th) harmonic currents at the PCC. The PCC voltage levels at these harmonics are hardly affected by converter operation and there is very little contribution from these frequencies.

AC voltage control: This control feature includes a slope (droop), similar to the voltage regulators on generators. The reactive power capability is dependent on the active power transfer. A strong network may limit the possibility of reaching the AC voltage set point due to the reactive power limit. The use of a slope mitigates this issue and has the additional advantage of avoiding hunting between the converter AC voltage control and similar controls on the hydroelectric generation scheme installed at Nagle Dam.

Sub-synchronous damping control: A sub-synchronous damping controller (SSDC) is used to ensure that sub-synchronous oscillations are not amplified by the converter control. The angular frequency deviation given by a PLL is band-pass filtered to extract the sensitive frequency range. This signal issued in the SSDC and the limited output signal is added to the current orders. The SSDC is an integral part of the control system and cannot be turned off. It is active in the entire sensitive frequency range.

Table 3.6 shows technical details for the main components of the proposed converter stations.

Table 3.6 Converter station details

Description of HVDC scheme	Requirement
Type of transmission	Underground, triple extruded polymetric cables (bipole)
Distance between converter stations	45 km
Number of poles	Two
Neutral path	Metallic ground return
DC side switching between poles	Required
AC nominal voltage	88 Kv
DC nominal voltage	80 kV
Nominal Frequency	50 Hz
Nominal power rating (at inverter output terminals)	20 MW
Maximum power for continuous operation	23MW

3.4.1.3 Selection of HVDC cables (Line 9)

A 45 km long, 30 MW, 80 kV HVDC cable will be buried 700mm below natural ground level. This HVDC cable is referred to as Line 9 (Drawing 2 and 3). This depth is in accordance to the South African Bureau of Standards (SABS 051) specification. A rating of 30 MW for HVDC cables is selected in order to offer flexibility when upgrading the hydroelectric generation scheme and converter stations in the year 2034.

The cables will be made of extruded polymer and the insulation will be triple extruded together with the conductor screen and the insulation screen. The cables will be operated in bipolar mode, one cable with positive polarity and one cable with negative polarity. The cables will be installed close in a bipolar pair with anti-parallel currents and thus eliminating magnetic fields.

The 30 MW, 80 kV HVDC cables will be used with a diameter of 140 mm. The cable will be made up of four sections, which will be laid individually and joined by the laying barge. Both the high-voltage and return cables will run underground. The cable network will use only existing rights-of-way and will not require new rights-of-way. It will be buried alongside established rural (dirt) roads and traverse through non-perennial rivers.

Table 3.7 Summary of infrastructure required for Network A (refer to single line diagram, Drawing No. 2)

INFRASTRUCTURE	DETAILS
G1 to G4	Four 11 kV, 5 MW hydroelectric power turbine generator sets
Bus M	11kV (AC) bus will be fed from the five hydroelectric generators rated at 5 MVA each
Transformer T1	Rated at 40 MVA, 11 – 80 kV (AC), will be installed downstream of Bus M adjacent to dam wall
Bus L	88 kV (AC) bus will be fed from Transformer T1 and supply 20 MW of power to the rectifier unit. The 88 kV rectifier unit will supply DC power rated at 80kV to Bus K. Bus L will be located adjacent to Transformer T1, which will be installed in close proximity to the dam wall.
Bus K	A 45 000m long, 80 kV triple extruded polymetric cable will supply power from Bus K to Bus J.
HVDC power cable Line 9	The system will be configured in bipolar mode. One cable with positive polarity and the other with negative polarity.
Bus J	Will be located at Kwa-Ximba rural location 45 000m away from the hydroelectric generation scheme. Will be fed from Bus K with a 80 kV

triple extruded polymetric cable. Will Supply 20 MW of power to the inverter.

Bus E	The 88 kV (AC) Bus E, will be located at Kwa-Ximba. The 20 MW rectifier unit will supply 88 kV to Bus E and will be in close proximity to Bus J. There will be three lines connected to Bus E (i) the line leading from the 20 MW inverter to Bus E (ii) the line leading from Bus E to Bus F and (iii) line 8 leading from bus E to Bus C.
Bus F	The 88 kV (AC) Bus F will be installed approximately 2 000m from Bus E. The load side of Bus F will be connected to the primary side of Transformer T2, which will be rated at 20 MVA.
Transformer T2	Transformer T2 will be installed approximately 500m from Bus F and rated at 20 MVA, 88 to 11 kV, three phase oil-filled transformer.
Bus G	The 11kV (AC) Bus G will be located 300m away from Transformer T2 . Three load cables will be connected to Bus G. Cables 1,2 and 3 will be approximately 4 000m in length. Cable 1 will supply power from Bus G to Bus H1, Cable 2 will supply power from Bus G to Bus H2 and Cable 3 from Bus G to Bus H3.
Bus H_1	11kV (AC) Bus H_1 will be located approximately 500m away from Transformer T3.
Bus H_2	11kV (AC) Bus H_2 will be located approximately 700m away from Transformer T4
Bus H_3	11kV (AC) Bus H_3 will be located approximately 350m away from Transformer T5
Transformer T3	Transformer T3 will be installed approximately 200m from Bus I_1. Transformer T3 is rated at 10 MVA, 11 kV to 400 V. Bus I_1 will be fed from Transformer T2
Transformer T4	Transformer T4 will be installed approximately 350m from Bus I_2 and rated at 10 MVA, 11 kV to 400 V. Bus I_2 will be fed from Transformer T2.
Transformer T5	Transformer T5 will be installed approximately 300m from Bus I_3 and

rated at 10 MVA, 11 kV to 400 V. Bus I_3 will be fed from Transformer T2

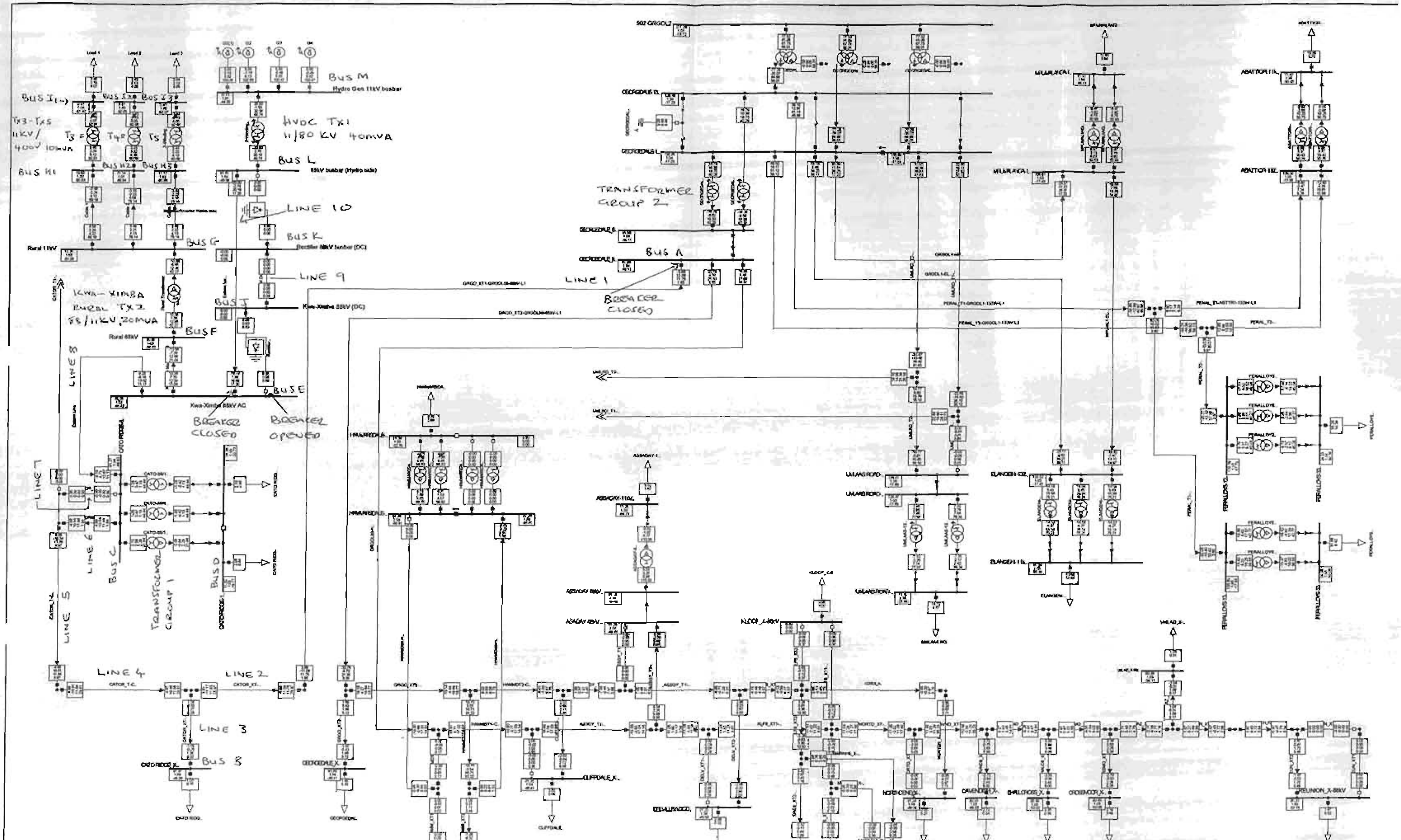
Bus I_1	Bus I_1 will be fed from Transformer T3, supply to Kwa-ximba load centre No. 1
Bus I_2	Bus I_2 will be fed from Transformer T4, supply to Kwa-ximba load centre No. 2
Bus I_3	Bus I_3 will be fed from Transformer T5, supply to Kwa-ximba load centre No. 3
Line 8	Will connect 88kV (AC) Kwa-Ximba Bus E to 88kV (AC) Catoridge Bus C. Line 8 is 17km long.
Bus C	Catoridge Bus C will be installed 17km from Bus E. This part of the installation belongs to Eskom.

3.4.2 Network B

Drawing 1 and 2 also depicts Network B from the dam wall up to 80 kV (AC) Bus L. From Bus L, Line 10 which is an overhead HVAC line will extend to the 88 kV (AC) Kwa-Ximba Bus E. Drawing 4 shows Network B in greater detail. The purpose and the operation of the hydroelectric generation scheme will remain unchanged. The optimisation of the use of the generators is the same as in Network A.

3.4.2.1 Selection of overhead line (Line 10)

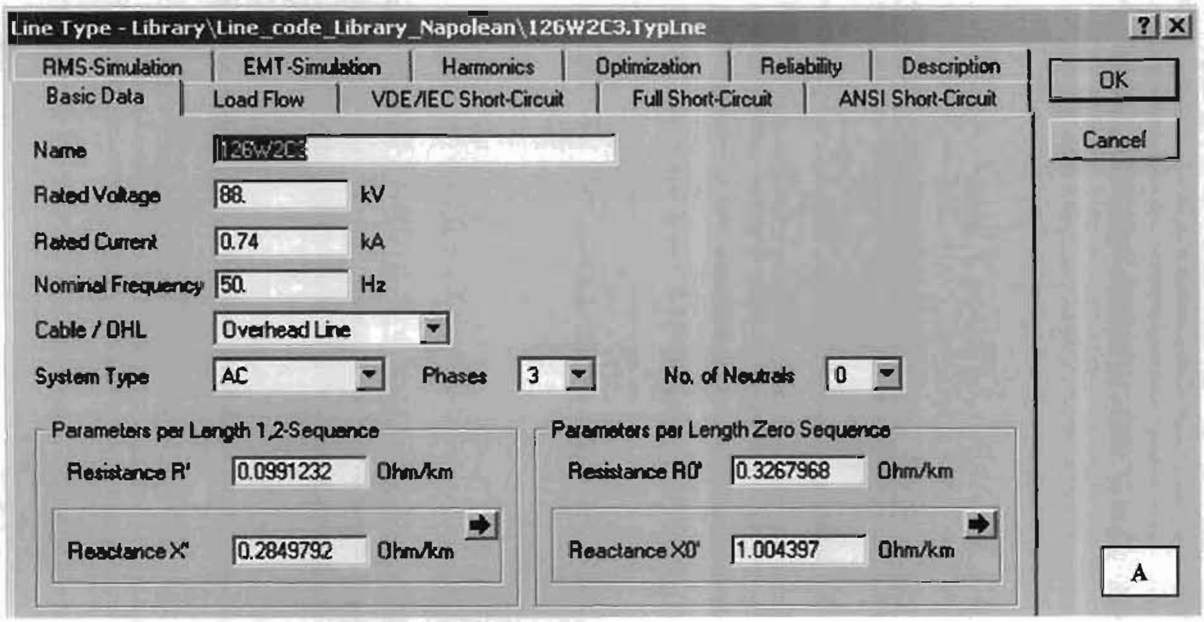
The Rectic Master software was used to select an appropriate overhead line for HVAC transmission (Fig. 3.8 A and B). This overhead line is referred to as Line 10. An aluminum, wolf conductor was selected to transmit a load demand of 20MW of active power. Since this overhead line has no take off's along its length, it traverses simply between Bus L and E with a length of 45km, the line was modeled using the lumped parameter method.



DRAWING 4

DETAILS OF NETWORK B

Load Flow Balanced	
Nodes	Branches
Line-Line Voltage, Magnitude [kV]	Active Power [MW]
Voltage, Magnitude [p.u.]	Reactive Power [Mvar]
Voltage, Angle [deg]	Apparent Power [MVA]



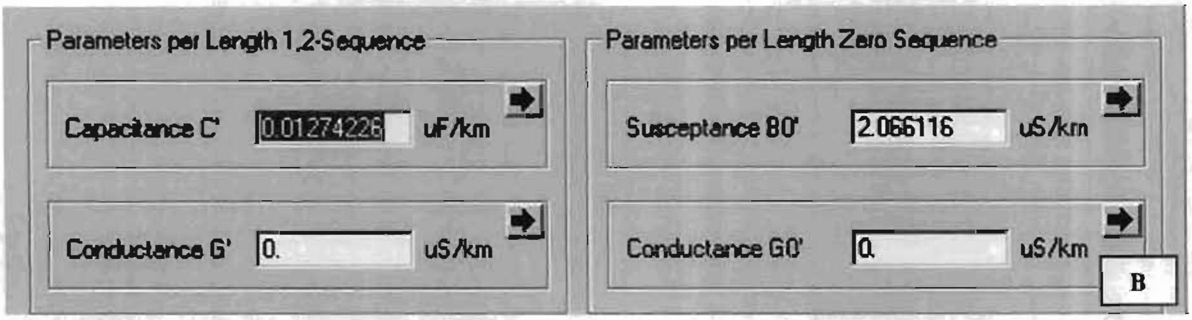


Fig. 3.8 A and B Selection of 88 kV (AC) overhead line between Bus L and Bus E

The following characteristics values were noted when operated under simulation conditions:-

(a) Positive sequence:-

(i) Cable resistance R' was 0.0991232 ohm/km, (ii) cable reactance X' was 0.2849792ohm/km, (iii) Capacitance C' was 0.01274226uF/km and (iv) conductance G' was 0 micro sec/km.

(b) Zero sequence:-

(i) Cable resistance R_0' was 0.3267968 ohm/km, (ii) cable reactance X_0' was 1.004397ohm/km, (iii) Susceptance B_0' was 2.066116u sec/km and (iv) conductance G_0' was 0 micro sec/km.

(c) Earth fault current

(i) The earth fault current was recorded to be 14.17132A, (ii) the magnitude of earth factor was 0.8336309 and (iii) the earth factor angle was 1.618033 degrees (Fig. 3.9)

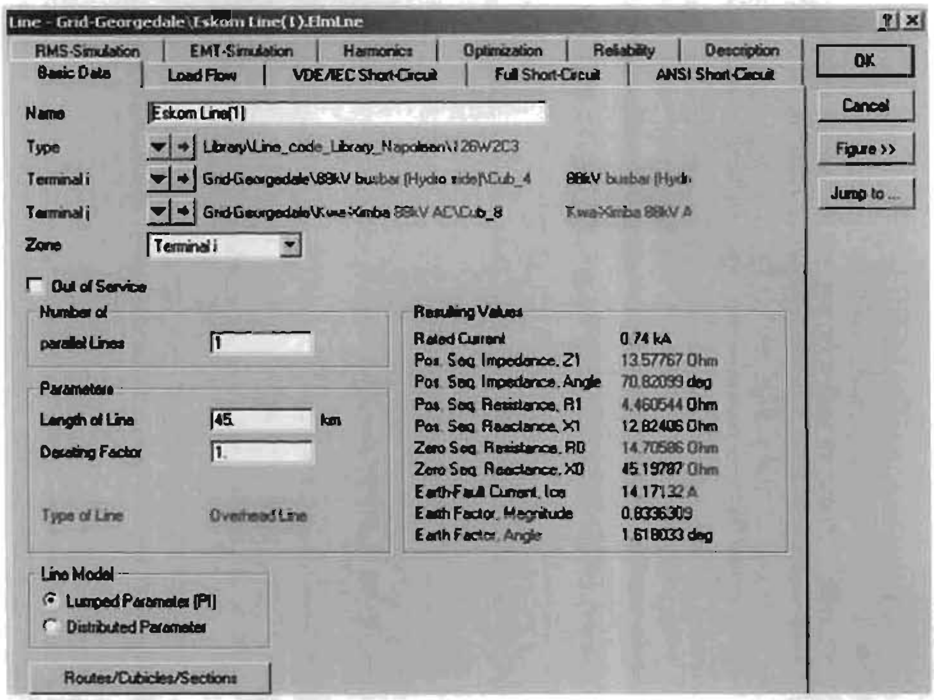


Fig. 3.9. AC line (Line 10) extension between 88 kV (AC) Bus L and 88 kV (AC) Bus E detailing earth fault conditions

The three phase 50Hz, overhead line will operate at 88kV with a maximum rated current of 740A/ph. Under normal operating conditions, Transformer T1 will deliver 20 MW of active power and absorb 2.78 MVAr of reactive power. However, at Bus E where Line 10 terminates, an active power delivery of 19.79 MW will occur and 1.89 MVAr of reactive power will be absorbed. It is therefore concluded that Line 10 adds 0.89 MVAr of reactive power to the installation under normal operating conditions.

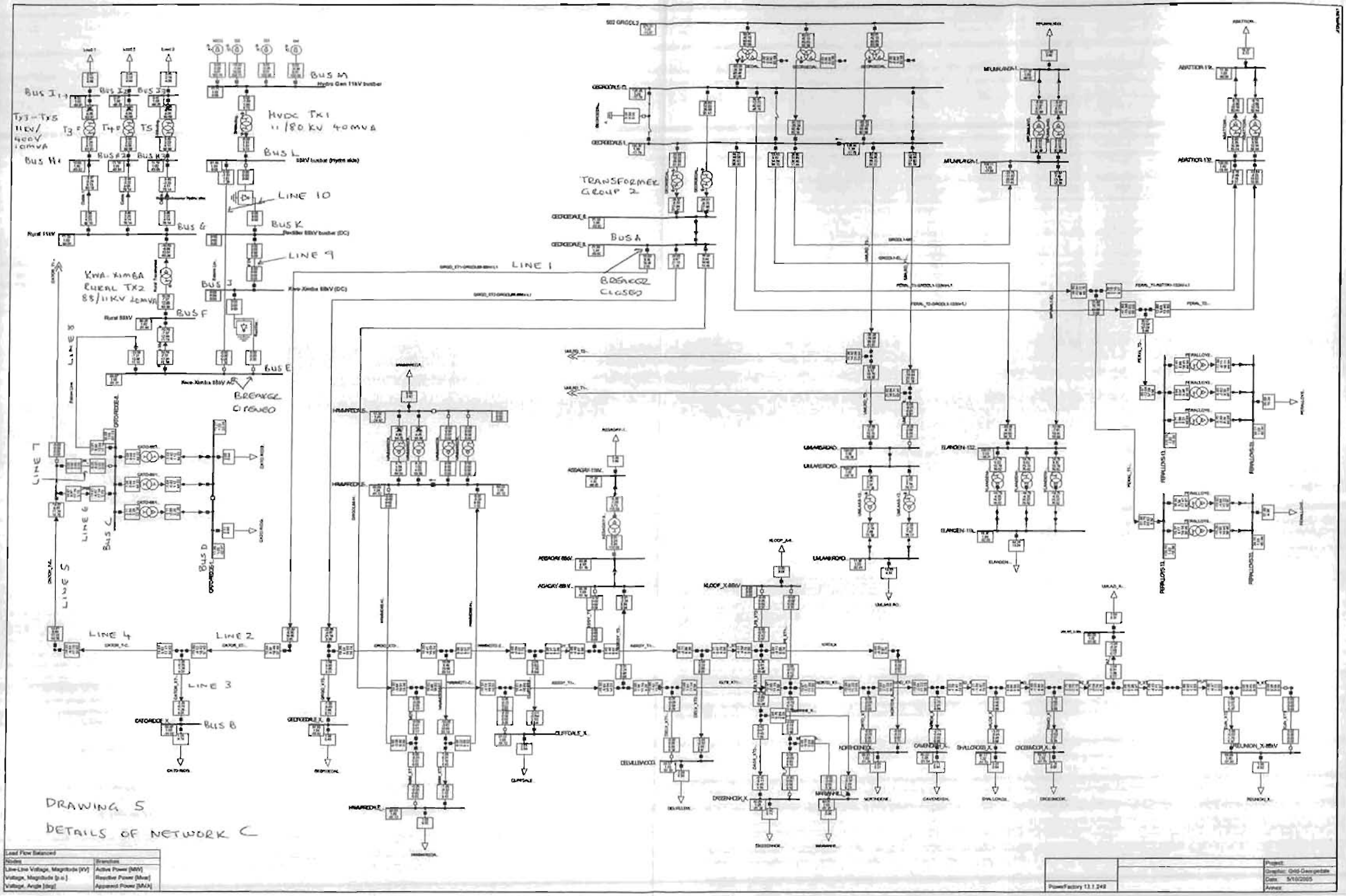
The generators will supply power to Transformer T1, which is located adjacent to the dam wall, T1 will supply power to Bus L. Line 10 will transfer power from Bus L to Bus E (Refer to Table 3.8).

Table 3.8 Summary of infrastructure for Network B

INFRASTRUCTURE	DETAILS
G1 to G4	Four 11 kV, 5 MW hydroelectric power turbine generator sets
Bus M	11kV (AC) bus will be fed from the four hydroelectric generators rated at 5 MVA each
Transformer T1	Rated at 40 MVA, 11 – 80 kV (AC), will be installed downstream of Bus M adjacent to dam wall
Bus L	88 kV (AC) bus will be fed from Transformer T1 and supplies 20 MW of power to Line 9.
Line 10	88 kV (AC) overhead line extension from the 88 kV (AC) Bus E to 88 kV (AC) Bus L
Bus E	The 88 kV (AC) Bus E, will be located at Kwa-Ximba. There are three lines connected to Bus E (i) line 10 leading from the Bus L to Bus E (ii) the 88 kV- 3 phase line leading from Bus E to Bus F and (iii) line 8 leading from Bus E to Bus C.

3.4.3 Network C

Drawing 5 shows Network C in detail. In Network C, the option of extending Eskom's existing AC Catoridge-Georgedale sub-transmission network to provide power to Kwa-Ximba, with the hydro generation scheme switched off, is studied. Line 8, which will connect the 88 kV (AC) Bus C to 88 kV (AC) Bus E in order to provide power to Kwa-Ximba. All branches and nodes downstream from this point of the network remains the same as in Network A (Drawing 3).


Bus M
Hydro Gen 11kV busbar
HVDC TX1
11/80 kV 40MVA
Bus L
LINE 10
Bus K
LINE 9
Bus J
Bus I1
Bus I2
Bus I3
T3-T5
11kV/
400V
10MVA
T3
T4
T5
Bus H1
Bus H2
Bus H3
Bus G
Rural 11kV
KWA-XIMBA
RURAL TX2
88/11kV 20MVA
Bus F
Rural 88kV
LINE 8
Bus E
Kwa-Ximba 88kV AC
BREAKER
OPENED
LINE 7
LINE 6
Bus C
Bus D
LINE 5
LINE 4
LINE 2
LINE 3
Bus B
TRANSFORMER
GROUP 2
BUS A
LINE 1
BREAKER
CLOSED
DRAWING 5
DETAILS OF NETWORK C
Load Flow Balanced
Nodes
Line-Line Voltage, Magnitude [kV]
Voltage, Magnitude [p.u.]
Voltage, Angle [deg]
Branches
Active Power [MW]
Reactive Power [Mvar]
Apparent Power [MVA]
PowerFactory 13.1.248
Project:
Graphic: Grid-Georgedale
Date: 5/10/2005
Annex:

3.5 Load flow analyses to determine viability of each Network

Load flow analyses was conducted on the various power lines and busbars that constitute each of the networks, in order to determine the effectiveness of each network.

3.5.1 Method of analyses

The Digsilent Powerfactory v13.1 (Build 249) software program from Eskom's Transmission Optimization Department, mKondeni, Pietermaritzburg, KwaZulu-Natal, was used to determine power flow of the various networks described in each option.

In each of the networks the typical operating parameters were simulated and recorded under normal operating conditions, using the software. Reactive power transfer depends mainly on the voltage magnitude. It is transmitted from the higher voltage magnitude side to the lower voltage magnitude. This is only true under normal operating conditions. Active power on the other hand, depends mainly on the angle by which the sending end voltage leads the receiving end voltage. The direction of active and reactive power flow is represented by the positive or negative (-ve) symbols (Drawing 3, 4 and 5).

In the case of active power flow the positive numeric value (+ve symbol is not shown) indicates that active power is leaving the node. The negative (-ve) symbol indicates that active power is entering the node it is immediately connected to.

In the case of reactive power flow the positive numeric value (+ve symbol is not shown) indicates that reactive power is entering the node it is immediately connected to and the negative (-ve) symbol indicates that reactive power is leaving the node it is immediately connected to.

Drawings 2, 3, 4 and 5 show the layout of Kwa-Ximba. The loads centres 1,2 and 3 at Kwa-Ximba are assumed to be 3.4 MW each. Therefore, it is assumed that the power flow through Buses H_1, H_2, H_3, I_1, I_2 and I_3 will be similar. Therefore in Tables 3.9 to

3.13, only Buses H_1 and I_1 will be explained. Analyses were conducted on the various nodes and branches for the following sections of the sub-transmission network (i) Catoridge, (ii) Georgedale. The objective was to determine the voltage and voltage angle at each bus (node), and the real and reactive power flow at each line (link) of each network.

In each network, load flow analyses was conducted to determine the effectiveness of transmission at the following locations:- (See Drawings3, 4 and 5).

(i) Between the hydroelectric generation plant feeding power into Bus M (adjacent to Dam wall) through to and Bus E, 88 kV bus located at Kwa-Ximba,

(ii) The Kwa-Ximba 88kV AC Bus (Bus E), feeding power into the Kwa-Ximba rural location via the 88kV Bus (Bus F) through to Bus I, which is located in close proximity to the load centers and

(iii) Hydro generating plant feeding power into the 88kV Catoridge Bus C, via Line 8.

3.5.2 Load flow analyses for Network A

The hydroelectric generation scheme, using HVDC technology is operated in parallel to the existing Catoridge-Georgedale sub-transmission network. The following values were recorded under normal operating conditions when simulated (Table 3.9). Also see Drawing 3.

Table 3.9 Load flow analyses for Network A

Bus Name	Bus Voltage (kV)	Voltage Angle at node in deg	Active power in branch (MW)	Reactive power in branch (MVAr)
A	90.78	-48.75	-3.82	32.20
B	89.99	-48.41	-1.04	-0.73
C (Line 8)	89.43	-48.14	-9.27	29.42
C (Line 6)	89.43	-48.14	5.12	-31.21
D	11.23	-19.06	-2.07	-0.83
E	88.00	-47.45	-20.05	22.04
F	87.93	-47.48	-10.57	-7.37
G	11.22	-80.13	-10.57	-6.57
H1	10.87	-79.90	-3.44	-2.22
H2	11.04	-80.01	-3.49	-2.26
H3	11.08	-80.04	-3.41	-2.21
I1	0.41	-81.01	-3.44	-2.43
I2	0.42	-81.10	-3.49	-2.46
I3	0.41	-81.15	-3.41	-2.42
J	79.95	0.00	20.05	20.00
K	80.0	0.00	20.06	0.00
L	79.80	-3.01	20.06	-18.00
M	9.93	0.00	20.06	20.00

(a) Catoridge substation Bus C, via Line 8

Table 3.9 shows the voltage at Bus E was 88.00 kV with a voltage angle of 47.45 degrees lagging and the voltage at Bus C was 89.43kV with a voltage angle of 48.14 degrees lagging. Active power to the magnitude of 9.27MW was transferred from the hydroelectric generation scheme to Bus C. A reactive power value of 29.42MVAr was transferred from Bus C to Bus E.

(b) Kwa-Ximba District (Bus F)

The voltage at Bus F was 87.93kV with a voltage angle of 47.48 degrees lagging. Bus F was then compared to Bus E and a magnitude of 10.57 MW of active power was absorbed from Bus E and 7.37 MVAr of reactive power was directed towards Bus E.

It is therefore noted that Bus F serves as the power bus to Bus G and H and I through Bus E.

(c) Catoridge Traction (Bus B)

The voltage at Bus B was 89.99kV with a voltage angle of 48.41 degrees lagging. Consequently the voltage at Bus A was 90.78kV with a voltage angle of 48.75 degrees lagging. In addition, Bus B was compared to Bus A and C. An active power of 1.04 MW was absorbed from Bus C and in exchange 0.73MVAr of reactive power was transferred from Bus B to Bus A, when measured from this node. Bus A has a higher voltage than Bus C and B.

d) Georgedale 88 kV (AC) Bus A

An active power entry of 3.82 MW into Bus A was recorded and 32.20MVAr of reactive power was transferred towards Bus B through Lines 1 and 2. Lines 1 and 2 are connected.

3.5.3 Load flow analyses for Network B

The hydroelectric generation scheme, using HVAC technology is operated in parallel to the existing Catoridge-Georgedale sub-transmission network. The following values were recorded under normal operating conditions when simulated (Table 3.10). Also see Drawing 4.

Table 3.10 Load flow analyses of Network B

Bus Name	Bus Voltage (kV)	Voltage Angle at node in deg	Active power in branch (MW)	Reactive power in branch (MVAr)
A	91.66	-49.11	-3.89	11.09
B	91.41	-48.96	-1.06	-0.75
C (Line 8)	91.27	-48.83	-9.19	8.73
C (Line 6)	91.27	-48.83	4.99	-10.54
D	11.32	-19.77	2.08	0.84
E	90.96	-48.42	-19.7905	1.8905
F	90.89	-48.45	-10.56	-7.35
G	11.33	-84.04	-10.56	-6.68
H1	10.96	-80.83	-3.47	-2.24
H2	11.14	-80.94	-3.34	-2.22
H3	11.17	-80.96	-3.33	-2.22
I1	0.41	-81.92	-3.46	-2.75
I2	0.41	-82.05	-3.43	-2.73
I3	0.41	-82.07	-3.44	-2.73
J	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00
L	91.51	-48.59	20	-2.78
M	11.11	-44.20	20.00	-1.93

(a) Kwa-Ximba (Bus E)

Table 3.10 shows the voltage at Bus L was 91.51V with a voltage angle of 48.59 degrees lagging. The voltage at Bus E was 90.96kV and a voltage angle of 48.42 degrees lagging was recorded. Active power (AC) with a magnitude of 19.79 MW was transferred from the hydroelectric generation scheme Bus L to Bus E. A reactive power value of 1.89 MVAr was transferred towards Bus L. Bus L absorbed a total of 2.78 MVAr of reactive power.

Comparison of power flow between Bus E to Bus L with Networks A and B (Refer to Table 3.11)

The HVDC hydroelectric generation scheme as detailed in Network A, managed to absorb more reactive power from Bus E, than in Network B. In Network A, Bus E delivered 22.04 MVAr of reactive power to the HVDC hydroelectric generation scheme. In Network B, Bus E delivered 1.89MVAr of reactive power to the HVAC hydroelectric generation scheme. A noticeable improvement between the two networks is 91.42 %, in favor of the HVDC hydroelectric generation scheme.

(b) Catoridge Bus C, via Line 8

The voltage at bus C was recorded to be 91.27 kV with a voltage angle of 48.83 degrees lagging and the voltage at Bus E was 90.96 kV with a voltage angle of 48.42 degrees lagging. Active power (AC) with a magnitude of 9.19 MW was transferred from the hydroelectric generation scheme Bus L to E and to Bus C. Active power with a magnitude of 10.56 MW was absorbed from Bus L to E to Bus F. A reactive power value of 8.73 MVAr was transferred towards the Bus E from Bus C.

Comparison of power flow between Bus C to Bus E (via Line 8) with Networks A and B (Refer to Table 3.11)

In Network A, Bus C absorbed 9.27 MW of active power from the HVDC hydro power system. Reactive power magnitude of 29.42 MVAr was transferred towards the HVDC system detailed in Network A and in Network B, Bus C absorbed 9.19 MW of active power from the HVAC system and 8.73 MVAr of reactive power was transferred towards the HVAC system. Bus C in Network A absorbed 0.863 % more active power from the HVDC system compared to Network B at the same node. In addition, at the same node in Network A, Bus C transferred 236.9 %more reactive power to the HVDC power system than in Network B. Comparatively, Network A contributes more positively to network stability than Network B.

(c) Kwa-Ximba Rural (Bus F)

The voltage at Bus F was 90.89 kV with a voltage angle of 48.45 degrees lagging and was compared to Bus E. A magnitude of 10.56 MW of active power was absorbed from Bus E and 7.35 MVAr of reactive power was directed towards Bus E.

Comparison of power flow between Bus F to Bus E with Networks A and B (Refer to Table 3.11)

Bus F absorbed 10.57 MW of active power from Bus E and 7.37 MVAr of reactive power was transferred from Bus F to Bus E as detailed in Network A. In Network B, Bus F absorbed 10.56 MW of active power from Bus E and 7.35 MVAr reactive power was transferred to Bus E. Bus F in Network A absorbed 0.095 % more active power, than in Network B at the same node under the same load conditions.

(d) Catoridge Traction (Bus B)

The voltage at Bus B was 91.41 kV with a voltage angle of 48.96 degrees lagging was recorded. Consequently the voltage at Bus A was 91.66 kV and a voltage angle of 49.11 degrees lagging was recorded. In addition, Bus B was compared to Bus A and C. An active power of 1.06 MW was absorbed from Bus C and in exchange 0.75MVAr of reactive power was transferred towards Bus A, which has a higher voltage than Bus C and B.

Comparison of power flow at Bus B with Networks A and B (Refer to Table 3.11)

Bus B absorbed 1.04 MW of active power and 0.73 MVAr of reactive power from HVDC system detailed in Network A and in Network B, Bus B absorbed 1.06 MW of active power from the HVAC system and 0.75 MVAr of reactive power from Bus A. Bus B in Network A absorbed 1.923 % less active power to Bus C than in Network B at the same node under the same load conditions.

(e) Georgedale 88 kV (AC) Bus A

An active power entry of 3.89 MW into Bus A was recorded and 11.09 MVAr of reactive power was transferred towards Bus B through Lines 1 and 2. Lines 1 and 2 are connected.

Table 3.11 shows a comparison of the changes in load flow, that would exist under normal operating conditions, for Networks A and B.

Table 3.11 Comparison of load flows at various points in Network A and B

Network	Bus name	Active power in branch (MW)	Reactive power in branch (MVAr)
A	A	-3.82	32.20
B	A	-3.89	11.09
A	B	-1.04	-0.73
B	B	-1.06	-0.75
A	C	-9.27	29.42
B	C	-9.19	8.73
A	D	-2.07	-0.83
B	D	2.08	0.84
A	E	-20.05	22.04
B	E	-19.79	1.89
A	F	-10.57	-7.37
B	F	-10.56	-7.35

3.5.4 Load flow analyses for Network C

Network C involves power supply to Kwa-Ximba by extending Eskom's existing AC Catoridge-Georgedale sub-transmission network with the hydroelectric generation scheme switched off. Buses J, K, L and M are de-energised. The following values were recorded under normal operating conditions when simulated (Table 3.12). Also see Drawing 5.

Table 3.12 Load flow analyses for Network C

Bus Name	Bus Voltage (kV)	Voltage Angle at node in deg	Active power in branch (MW)	Reactive power in branch (MVAr)
A	91.33	-50.82	15.94	9.3
B	90.86	-51.00	-1.05	-0.74
C(Line8)	90.55	-51.13	10.61	6.86
C(Line6)	90.55	-51.13	-14.81	-8.67
D	11.38	-22.07	2.11	0.85
E(Line8)	89.97	-51.41	-10.58	-7.31
F	89.90	-51.44	-10.58	-7.31
G	11.33	-84.04	-10.58	-6.68
H1	10.98	-83.82	-3.47	-2.24
H2	11.16	-83.93	-3.44	-2.22
H3	11.19	-83.95	-3.45	-2.23
I1	0.42	-84.91	-3.47	-2.15
I2	0.41	-85.03	-3.44	-2.13
I3	0.41	-85.05	-3.45	-2.14
J	0.00	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00
L	0.00	0.00	0.00	0.00
M	0.00	0.00	0.00	0.00

(a) Kwa-Ximba (Bus F)

Table 3.12 shows the voltage at Bus F was 89.90 kV with a voltage angle of 51.44 degrees lagging and the voltage at Bus E was 89.97 kV with a voltage angle of 51.41 degrees lagging. An active power magnitude of 10.58 MW was transferred to Bus E from Bus F. A reactive power value of 7.31 MVAr was transferred from Bus F to Bus E.

Comparison of power flow between Bus F to E with Networks A and C
(Refer to Table 3.13)

The amount of reactive power delivered from Bus F to Bus E was 7.37 MVAr. This value of active and reactive power transfer between the same two nodes remained unchanged when compared to network A.

(b) Catoridge Bus C (Line 8)

The voltage at Bus C was 90.55 kV with a voltage angle of 51.13 degrees lagging and the voltage at Bus E was 89.97kV with a voltage angle of 51.41 degrees lagging. An active power (AC) with a magnitude of 10.61 MW was transferred from Bus C to Bus E and 6.86 MVAr of reactive power flowed from Bus E to Bus C.

Comparison of power flow between Bus C to E (via Line 8) with Networks A and C (Refer to Table 3.13)

In Network A, Bus C absorbed 9.27 MW of active power from the HVDC hydro generation system. A reactive power magnitude of 29.42 MVAr was delivered to Bus E i.e. the HVDC system detailed in Network A. In Network C, Bus C delivered 10.61 MW of active power to Bus E. A reactive power magnitude of 6.86 MVAr was absorbed from Bus E. Bus C in Network C absorbed 14.455 % more active power, and transferred 328.86 % more reactive power than in Network A at the same node. This signifies that the HVDC power system as detailed in Network A has a positive effect of reducing reactive power from the pre-existing sub transmission network and renders a more efficient means of power flow.

Comparison of power flow between Bus C to E (via Line 8) with Networks B and C (Refer to Table 3.14)

In Network B, Bus C absorbed 9.19 MW of active power from the HVAC hydro generation system. A reactive power magnitude of 8.73 MVAr was delivered to Bus E which is the HVAC system detailed in Network B. In Network C, Bus C delivered 10.61 MW of active power to Bus E. A reactive power magnitude of 6.86 MVAr was transferred from Bus E to Bus C. In Network C, 13.38% more active power flows through this specific node when compared to Network B. This condition therefore contributes to a higher heat value at this node.
When comparing Network B to C it was noted, the direction of power flow was in opposite directions. In Network C, the hydroelectric plant is switched off.

(c) Catoridge Traction (Bus B)

The voltage at Bus B was 90.86kV and a voltage angle of 51.00 degrees lagging was recorded. Consequently the voltage at Bus A was 91.33 kV with a voltage angle of 50.82 degrees lagging was recorded. In addition, Bus B was compared to Bus A and C. The voltage angle at Bus C is higher than that of Bus A and Bus B. An active power of 1.05 MW is transferred from Bus A to Bus B and in exchange, 0.74 MVAr of reactive power was transferred towards Bus C. Bus A has a higher voltage level than Bus C and B.

Comparison of power flow at Bus B with Networks A and C (Refer to Table 3.13)

In Network A, Bus B absorbed 1.04 MW of active power from the HVDC system and in exchange it delivered 0.73 MVAr of reactive power to Bus A. Bus A has a higher voltage magnitude than Bus C and Bus B. In Network C, Bus B absorbed 1.05 MW of active power from Bus A and delivered 0.74 MVAr of reactive power to Bus A. Bus B in Network C absorbed 0.96 % more active power from Bus A and delivered 1.36 % less reactive power to Bus A in Network C.

Comparison of power flow at Bus B with Networks B and C (Refer to Table 3.14)

Network B, Bus B absorbed 1.06 MW of active power and in exchange it delivered 0.75 MVAr of reactive power to Bus A. Bus A has a higher voltage magnitude than bus C and Bus B. In Network C, Bus B absorbed 1.05 MW of active power from Bus A and delivered 0.74 MVAr of reactive power to Bus A. In this instance the direction of power flow remained the same. The change in active and reactive power flow is negligible.

(d) Georgedale 88 kV (AC) Bus A

An active power 15.94 MW was delivered from Bus A towards the direction of the following Buses:- B, C, D, E and F. A reactive power magnitude of 9.3 MVAr was absorbed by Bus A. A bus voltage of 91.33 kV and a voltage angle of 50.82 degrees lagging was recorded. Buses A to I are connected as a spur feed and the changes in bus voltage, voltage angle, and the flow of active and reactive power denotes typical characteristics of a spur feeder system.

Comparison of power flow at Bus A with Networks B and C
(Refer to Table 3.14)

The direction of power flow was in opposite direction to each of the above networks under study. In Network B, Bus A received 3.89MW of active power from the HVAC hydroelectric generator scheme and delivered 11.09MVAr of reactive power towards the same scheme. However, in Network C, Bus A was the supply bus to Bus B, C, D, E through to Bus I1, I2 and I3. The magnitude of reactive power flow was reduced by 16.14% when compared to Network B

Table 3.13 shows a comparison of the changes in load flow, that would exist under normal operating conditions, for Networks A and C.

Table 3.13 Comparison of load flow at various points in Networks A and C

Network option	Bus name	Active Power in branch (MW)	Reactive Power in branch (MVAr)
A	A	-3.82	32.20
C	A	15.94	9.3
A	B	-1.04	-0.73
C	B	-1.05	-0.74
A	C	-9.27	29.42
C	C	10.61	6.86
A	D	-2.07	-0.83
C	D	2.11	0.85
A	E	-20.05	22.04
C	E	-10.58	-7.31
A	F	-10.57	-7.37
C	F	-10.57	-7.37

Table 3.14 details a comparison of active and reactive power flow (load flows) at various nodes in Network B and Network C under normal operating conditions. In addition Table 3.10 and 3.12 details a comparison in bus voltage and the voltage angle at each node and active and reactive power flows. In general, at Network C the Bus voltages and voltage angles operated at a lower magnitude.

Table3.14 Comparison of load flows at various points in Network B and C

Network	Bus name	Active power in branch (MW)	Reactive power in branch (MVAr)
B	A	-3.89	11.09
C	A	15.94	9.3
B	B	-1.06	-0.75
C	B	-1.05	-0.74
B	C	-9.19	8.73
C	C	10.61	6.86
B	D	2.08	0.84
C	D	2.11	0.85
B	E	-19.79	1.89
C	E	-10.58	-7.31
B	F	-10.56	-7.35
C	F	-10.57	-7.37

3.8 Economic analyses for each Network

The cost of each network has been analysed. Costs include (a) system studies, (b) electrical and civil design, (c) supply of equipment to site, (d) civil works, (e) installation of electrical and mechanical equipment, (f) commissioning, (g) training of operators and maintenance personnel, (h) spare parts and (i) documentation. Further economic analyses include the annual (i) the income generated from the sale of the power to Kwa-Ximba and the Catoridge-Georgedale sub–transmission network (ii) the total anticipated expenses and (iii) the annual net profit for each network.

3.8.1 Network A

A cost analysis has been compiled for Network A to determine (i) the cost of the hydroelectric generation scheme (Table 3.15) and (ii) the cost of basic electrical infrastructure that needs to be installed in the district of Kwa-Ximba (Table 3.16). The purpose of which is to determine how feasible it would be, from a business perspective, to develop a scheme of this nature.

Table 3.15 shows detailed comparisons between the costs of 20 MW, 30 MW and 50 MW converter stations and hydroelectric generator sets as well as associated costs for the hydroelectric generation scheme. The 20 MW converter station and the 20 MW, 11 kV, 3 phase, 3 wire hydroelectric generator sets proved to be the cheapest alternative. Moreover, the 20 MW hydroelectric generator adequately meets with the demand forecast for the next thirty years (refer to Table 3.3). The 20 MW converter station and the 20 MW hydroelectric generator set were therefore chosen for the hydroelectric generation scheme, in the present study.

Table 3.15 Cost analysis for the hydroelectric generation scheme for Network A

Converter Stations	**20MW**	**30 MW**	**50 MW**
Valves	R6 440 000	11 013 100	16 686 500
Converter transformers	R6 352 000	8 810 480	13 349 200
Freight insurance	R1 610 000	2 753 280	4 171 630
Engineering	R3 220 000	5 506 550	8 343 250
Erection, commissioning	R2 576 000	4 405 240	6 674 600
Other equipment	R3 220 000	5 506 550	8 343 250
Control	R2 254 000	3 854 590	5 840 280
AC filters	R3 220 000	5 506 550	8 343 250
Civil works, buildings	R4 508 000	7 709 170	11 680 600
	R33 400 000	55 065 500	83 432 560
Hydroelectric generator sets			
20MW, 11kV, 3 phase 3 wire	R9 500 000		
30MW, 11kV, 3 phase 3 wire		14 250 000	
50MW, 11kV, 3 phase 3 wire			23 750 000
HVDC triple extruded @ 45km (bipole) cable	R1 200 000	R1 200 000	R1 200 000
Transformer T1 11 /88kV 20 MVA	R1 350 000	R1 350 000	R1 350 000
Civil costs	R6 363 000	R 10 061 170	R 15 362 558
Installation costs	R 5 454 000	R 8 623 860	R 13 167 907
Testing and Commissioning	R 3 636 000	R 5 749 240	R 8 778 605
	R15 453 000	R 24 434 270	R 37 309 070
Cost of hydroelectric generation scheme	**R 60 903 000**	**R 96 299 770**	**R 147 041 630**

The costs of the various converter stations and the two 45 km triple extruded polymetric HVDC cables were obtained from Rashwan, 2005.

The cost of hydroelectric generator sets were obtained from Dragu *et al.*, 2000.

The cost of transformers were obtained from Peer Review, 2004.

All cost assumptions exclude Value Added Tax (VAT)

As mentioned previously Kwa-Ximba does not have any existing electrical infrastructure. The basic electrical infrastructure that is required to be installed and the costs involved are detailed in Table 3.16.

Table 3.16 Cost of basic electrical infrastructure required to be installed at Kwa-Ximba for power rating not exceeding 20 MW for Network A

Description	Cost
Transformer T2 11 /88kV 20 MVA	R1 350 000
Transformer T3 11 /400V 10 MVA	R1 012 000
Transformer T4 11 /400V 10 MVA	R1 012 000
Transformer T5 11 /400V 10 MVA	R1 012 000
95 mm^2 X 3c aluminium conductor/ XPLE insulated 11 kV cable	R380 000
	R4 766 000
Civil costs – Trenching and backfilling	R667 450
Installation costs	R572 100
Testing and Commissioning	R381 400
	R 1 620 950
Cost of basic electrical infrastructure	**R6 386 950**

The cost of transformers were obtained from Peer Review, 2004

The cost of the XPLE insulated 11 kV cable was obtained from www.esru.strath.ac.uk

All cost assumptions exclude Value Added Tax (VAT)

The cost of installing a 20MW hydroelectric generation scheme is R60 903 000.00 (Table 3.15) and the cost of basic electrical infrastructure for Kwa-Ximba (Table 3.16) is R6 388 450. The total cost of Network A is thus **R67 291 450.** The potential developer for this project is Umgeni Water. It is proposed that they raise the capital sum of R67 291 450.00 at a commercial bank in the form of a bank loan. If the repayment period is extended over twenty years at an annual bank interest rate of 8.55% the annual repayment value will be R7 296 660. With regards to operation and maintenance costs, an allowance of 3 - 5% of infrastructure cost is usually set aside for this purpose, per annum (Hauth *et al.*, 1997). A conservative approach was adopted in the present study by selecting a value of 5% per annum, which amounts to R3 364 572 (Table 3.17).

Table 3.17 Total anticipated expenses per annum for Network A

Expense	Amount	
Principle loan value	R67 291 450	
Annual loan repayment at 8.55% over 20 years		R7 296 660
Operating and Maintenance cost @ 5% per annum		R3 364 572
Total anticipated expenses per annum		**R10 661 232**

The total anticipated expenses of R10 661 232 per annum has to be weighted against the income that will be generated from the sale of power to Kwa-Ximba and Eskom's Catoridge-Georgedale sub-transmission network. The (i) anticipated absorbed power per month, (ii) demand charge, (iii) energy charge and (iv) fixed charge was considered for each site for the year 2005 in order to calculate net income per annum (Table 3.18).

It is envisaged that Eskom will buy power from the developer, which is Umgeni Water at the same cost at which it supplies power. However due to the influences that economies of scale have on businesses in the real world, Eskom may choose to pay more or less for the power it would import from the hydroelectric generation scheme. This may be influenced by the net positive impact it would have on its sub-transmission network especially in cases where it is required to operate within the thermal limits of its present network. Since Lines 8, 9 and 10 (Drawing No. 4) will not always operate at peak load, the load duration must also be considered when setting a tariff. For this reason a de-rating factor that takes into account line usage, duration and losses over a period of one year is used. In the present analysis the de-rating factor is assumed to be 0.4. The factor of 0.4 will decrease once the connected load at Kwa-Ximba increases. The main contributing factor will be an increase in small to medium size industry and household connections. Power quality, easy access and affordability will be the drivers that will reduce the factor allowed in present study into future years.

Table 3.18 Income generated from Kwa-Ximba and Eskom's Catoridge – Georgedale sub-transmission network per annum based on the year 2005

Description	Kwa-Ximba	Cato Ridge – Georgedale sub-transmission network
Anticipated absorbed power per month	10.56MW	5MW
Power supply per annum (in hours)	8760h/annum	8760h/annum
Demand charge	R34.54/kVA	R34.54/kVA
Energy charge	22.79c/kWh	22.79c/kWh
Fixed charge	R115.12/month	R115.12/month
Income generated per annum	**R 8 814 131**	**R4 166 889**

The tariffs were obtained from Eskom's Electricity Tariff structure for 2005/6. The tariffs are applicable to bulk consumer low voltage. The tariff associated with (i) demand charge, (ii) energy charge and (iii) fixed charge have been assumed to be the same for this study over all three proposed networks.

The total income is thus R8 814 131 + R4 166 889 = R12 981 020 per annum.

Total income – total anticipated expenses (per annum) = R12 981 020- R10 661 232 = R2 319 788 per annum. **The annual net profit for Network A is thus R2 319 788.**

3.8.2 Network B

Table 3.19 Cost of the hydroelectric generation scheme in Network B

Item	Cost
Hydroelectric generator sets 20MW, 11kV, 3 phase 3 wire	R9 500 000
Transformer T1 11 /88kV 20 MVA	R1 350 000
20 MW 88 kV overhead line extension over a distance of 45,7 km	R2 285 000
Civil costs	R1 838 900
Installation costs	R1 576 200
Testing and Commissioning	R1 050 800
	R4 465 900
Cost of the hydroelectric generation scheme	**R 17 600 900**

The cost of overhead line extension was obtained from the NER Journal, 2000
All cost assumptions exclude Value Added Tax (VAT)

The cost of the hydroelectric generation scheme for Network B is R 17 600 900 (Table 3.19) and the cost of basic electrical infrastructure at Kwa-Ximba is R6 386 950 (Table 3.16, same as in Network A). The total cost for Network B is thus **R23 987 850.** If the developer raises a bank loan for this amount over a 20-year term, at an annual bank interest rate of 8.55%, the annual repayment value will be R2 497 048 (Table 3.20).

Table 3.20 Total anticipated expenses per annum for Network B

Expense	Amount	
Principle loan value	R23 987 850	
Annual loan repayment at 8.55% over 20 years		R2 497 048
Operating and Maintenance cost @ 5% per annum		R1 199 392
Total anticipated expenses per annum		**R3 696 440**

The total income generated from supplying power to Kwa-Ximba and the Catoridge-Georgedale sub-transmission network is assumed to be the same as in Network A (Table 3.18). Therefore:-

Total income – total anticipated expenses (per annum) = R12 981 020 - R3 696 440

The annual net profit on Network B is thus R9 284 580.

3.8.3 Network C

Table 3.21 Cost of Line extension to Kwa-Ximba including basic electrical infrastructure at Kwa-Xiimba

Item	Cost
20 MW 88 kV overhead line extension over a distance of 700m	R 350 000
Basic electrical infrastructure at Kwa-Xiimba (From Table 3.15)	R6 386 950
Civil costs	R49 000
Installation costs	R42 000
Testing and Commissioning	R28 000
	R119 000
Total cost of Network C	**R6 855 950**

The cost of grid extension was obtained from the NER Journal, 2000

All cost assumptions exclude Value Added Tax (VAT)

If the developer raises a bank loan for the amount of **R6 855 950** over a 20-year term, at an annual bank interest rate of 8.55%, the annual repayment value will be R713 679 over the next 20 years (Table 3.22).

Table 3.22 Total anticipated expenses per annum for Network C

Expense	Amount	
Principle loan value	R6 855 950	
Annual repayment at 8.55% over 20 years		R713 679
Operating and Maintenance cost @ 5% per annum		R342 797
Total anticipated expenses per annum		**R1 056 476**

The income generated will be only from the sale of power to Kwa-Ximba. This will amount to R 8 814 131 per annum. Therefore:-

Total income – total anticipated expenses (per annum) = R 8 814 131 - R1 056 476

The annual net profit on Network C is thus R 7 757 655.

Table 3.23 details the annual net profit for each network.

Table 3.23 Total cost and annual net profit for each network

Network	Total Cost	Annual net profit
A	R67 291 450	R2 319 788
B	R23 987 850	R9 284 580
C	R 6 855 950	R 7 757 655

From an economical perspective, Network B, is the most lucrative and from a technical perspective, Network A contributes the most to system stability for the Catoridge-Georgdale sub-transmission network. The financial benefits have to be weighted against the technical benefits of the networks. This will be discussed in the following chapter.

CHAPTER FOUR

DISCUSSION OF RESULTS

Three networks have been described to consider the possibility of supplying the rural location of Kwa-Ximba with power from a hydroelectric generation scheme, and transmit the excess capacity to Eskom's Catoridge-Georgedale sub-transmission network, for system enhancement purposes. Network A involves supplying power to Kwa-Ximba, and the Catoridge-Georgedale sub-transmission network, from the hydroelectric generation scheme, using HVDC technology. It must be noted that there are no previous reports detailing the use of HVDC in a medium voltage application, in power supply in South Africa. Network B also involves supplying power to Kwa-Ximba and the sub-transmission network from the hydroelectric generation scheme, however, via a HVAC transmission overhead line.

The overall purpose of connecting to the Eskom network is to demonstrate the impact it would have on the network under normal operating conditions, the transient and dynamic stability of the Catoridge-Georgedale sub-transmission network. The present study revealed that the hydroelectric generation plant is able to operate at its full rated capacity in Networks A and B. The study also demonstrated that the use of a HVDC system (Network A) has more technical advantages in overall power system enhancement than an HVAC system (Network B). Comparisons between the load flows of Networks A and B under normal operating conditions has revealed the following:- In Network A:- (i) Bus F, consumes 0.094 % more active power and delivers 0.272 % more reactive power, (ii) Bus E, consumes 1.314 % more active power and delivers 1066.14 % more reactive power, (iii) Bus C, consumes 0.87 % more active power and delivers 236.99 % more reactive power, (iv) Bus D, consumes 0.483 % more active power and delivers 1.19 % less reactive power, (v) Bus B, consumes 1.887 % less active power and delivers 2.667 % more reactive power, (vi) Bus A, consumes 1.799 % less active power and delivers 190.35 % more reactive power, when compared to Network B.

It is evident that, Network A confers more stability to Eskom's network and contributes more positively to overall system enhancement than the HVAC system. Overall, Network A absorbs 1065.8 % more reactive power from the network when compared to Network B. The power flow to Kwa-Ximba was made constant when Networks A, B and C were operated.

Comparisons between the load flows of Networks A and C under normal operating conditions has revealed the following:- In Network C:- (i) the power flow from Bus E to F was constant, (ii) Bus E, consumes 89.51 % less active power and delivers 2.01% less reactive power, (iii) Bus C, consumes 12.215 % more active power and delivers 328.86 % less reactive power, (iv) Bus D, consumes 1.896% more active power and delivers 2.354 % more reactive power, (v) Bus B, consumes 0.952 % more active power and delivers 1.352 % more reactive power, (vi) Bus A, consumes 76.00 % more active power and delivers 246.24 % less reactive power, when compared to Network A.

It is therefore evident that if Eskom had to extend their Catoridge-Georgedale sub-transmission network to Kwa-Ximba, the extension will place a high burden on the existing sub-transmission network. This is evident by the increase in active power demand at Bus A, C and E. Undoubtedly Network C, places risk from a network security and stability perspective due to the increase in load of the transmission lines. Beyond the year 2032 the power demand by Kwa-Ximba will exceed 20MW, resulting in a substantial risk to network security. Therefore in the long term it is beneficial to have the hydroelectric generation scheme installed to avoid excess loading on the network. If the hydroelectric generation scheme is used to provide power to Kwa-Ximba and Catoridge-Georgedale, system stability will be considerably enhanced.

When Network B was compared to Network C, it was noted that Network C operated with a higher load condition. This was clearly demonstrated with the recording of higher active power magnitude. In Network B the hydroelectric generation scheme ran in parallel to the Catoridge-Georgedale sub-transmission network. The hydroelectric generation scheme was able to absorb, marginally more reactive power from the sub-transmission network than Network C. This was demonstrated at Bus A.

Overall, the present study has shown that Eskom will benefit directly from the implementation of Network A, rather than Networks B and C with regards to system stability of their Catoridge-Georgedale sub-transmision network. The HVDC network is able to operate more efficiently by minimising system losses. The magnitude of reactive power also reduced significantly. This results in the network having an increased capacity to deliver active power. This therefore contributed to better line utilisation when the various nodes were analysed.

The HVDC transmission by virtue of its control system will not impact on the short circuit level of the transmission system. Blackouts in the Kwa-Ximba installation can be prevented by enabling cascaded outages from limiting the impact of multiple faults. In the present study, 30 MVA, 80 kV cables are used. The use of DC cable transmission will obviate many of the problems associated with AC cable transmissions e.g. no extra current is required for charging of the cable to its operating voltage level as in the case of AC cable transmission. With HVDC cable transmission such physical characteristics have no impact on power flow, voltage profile or transmission distance.

If HVAC and not HVDC transmission is used, new rights of way for overhead lines will have to be obtained. Legislation guarding environmental concerns is extremely high in South Africa. Concessions for new right-of ways may be hard to achieve and may also be a serious obstacle with regards to environmental impact and the distribution of electrical energy. From an environmental point of view, underground triple extruded polymetric HVDC cables would be more viable. Extruded DC cables are easier to install compared to the XLPE HVAC cables since no cross bonding is needed to reduce screen losses, i.e. link boxes and surge voltage limiters are not needed in HVDC cable systems.

Long distance HVAC transmission with overhead lines require an increase in voltage with increasing distance from a broad perspective. Long distances, as in the case with distant rural areas in South Africa, this can become technically impossible or economically too costly. For example, the installation of HVAC lines in locations in the Natal Midlands along the Drakensberg mountain range can prove to be very costly and challenging. This is because these locations are sparsely populated and many of them are sited in mountainous areas. The extruded HVDC cables to be used in the present development are very effective with regard to direct voltage capacity and thereby gives possibilities for high power compared to a similar HVAC cable. The underground cables will minimize environmental, aesthetic and commercial impacts. Furthermore, underground cables will minimise the profile of wiring and pylons for the given power transmission capacity. Based on recent studies these HVDC cables needs less space than an HVAC overhead line and can carry more power than an HVAC cable and is therefore many times the only practical solution.

Economical analyses in the present study reveals that the installation of Network A will cost 64% more than Network B and 89.81 % more than Network C. Network B will result in the highest annual net profit per annum (Table 3.23). The implementation of either Network A or C will translate to a loss of opportunity profit amounting to R6 964 792 (in the case of Network A) and R1 526 925 (in the case of Network C) per annum to the developer. The loss of opportunity profit by the developer needs to be measured against the technical benefits that Network A has on Eskom's Catoridge-Georgedale sub-transmission network. The undertaking to install Network A hinges on Eskom's commitment to improve the power transfer efficiency, at the sections of the of the present sub-transmission network as detailed in study. It is recommended that Eskom conduct a cost benefit analysis based on their long-term transmission and business objectives to identify and quantify the benefits of contributing financially to the installation of Network A. The financial contribution can take the form of (i) paying the developer a higher tariff in the form of a subsidy or (ii) contributing a percentage towards the difference in capital costs for Network A and B which amounts to R 43 303 600. The other alternative is for the developer to implement Network B, which involves the installation of the hydroelectric generation scheme and basic infrastructure for Kwa-Ximba, as an immediate solution. At later stage Eskom can install the HVDC converter stations, HVDC transmission cables and pay the associated HVDC transmission costs when the costs of HVDC converters and cables become more competitive and market related. It would be incumbent upon Eskom to fund this installation since they would benefit directly from the installation over the long term.

With regards to environmental impact HVDC transmission is also more viable than HVAC transmission. Society is becoming more aware of the need for environmentally friendly solutions for the generation and transmission of electricity. Maximising performance can lead to a negative environmental impact. Therefore there is a need to balance performance with minimal negative environmental impact.

With the immediate environmental benefits of HVDC technology, obtaining the necessary permits will be relatively easy. As opposed to obtaining permits for overhead transmission line, using underground cables for transmission will not create any permitting problems and the out-come is predictable and timeous. Tougher environmental concerns are placing heavy restrictions on right-of-ways for building new overhead transmission lines and for the construction of new generating plants. In the present study, existing rights-of-ways will be used, which will ease the permit procedure.

Furthermore, both the 20 MW converter stations are modular and flexible in design. They are designed to be as compact as possible in order not to have a negative impact on the environment.

A HVDC system also alleviates the problems associated with magnetic fields. Whenever electricity is transmitted through a conductor, it generates a magnetic field around it. With HVDC transmission, the field is of the same type as the earth's natural magnetic field. This is completely different to the AC fields normally produced, for example, around overhead lines. The electromagnetic field from a DC cable is very low and cancels each other out. Any radiated field is thus a static field as opposed to the power frequency fields radiated from HVAC cables. Also, since the HVDC transmission system used in the present study is bipolar they do not transmit any currents into the ground, which can disturb communication systems or cause corrosion to oil pipelines belonging to Petronet and water pipelines belonging to Umgeni Water. Measurements have shown that the magnetic field around the cable at a distance of six meters is equal in strength to the earth's natural magnetic field, while at a distance of 60 meters its intensity drops to just one tenth of that field.

The use of a VSC combined with extruded HVDC cables will also save the environment by replacing burning of gas and fossil fuelled local diesel generators, with a non polluting, small scale hydroelectric generation scheme, namely Nagle Dam. The hydroelectric generation scheme will have a limited visual impact and the noise made by the plant's turbines and generators can be minimised through insulation equipment. An HVDC cable connection could be a better choice than building a local power plant based on fossil fuels in the Kwa-Ximba area. Also, the pollution and noise produced when the diesel fuel is transported will be completely eliminated by a hydroelectric generation scheme.

The present study has shown that a VSC based HVDC transmission offers more power stability than the HVAC alternative. The HVDC system also exhibits more control capabilities and is more environmentally friendly than the HVAC alternative. HVDC transmission also makes it feasible to use remote generation sites thus taking full advantage of local renewable energy sources. However, the exorbitant cost of an HVDC transmission will only be justified if the power generated was of a higher magnitude and covered a longer transmission distance. The costs associated with an HVDC technology will be the main obstacle in using renewable energy sources and HVDC transmission in supplying small distant rural areas with power. HVAC still provides a cheaper alternative but is accompanied by many more technical problems as described above.

Network C involved supplying power to Kwa-Ximba by extending Eskom's existing AC Catoridge-Georgedale sub-transmission network with the hydroelectric generation scheme switched off. Eskom's network power quality is functional and stable. It is therefore able to handle an increase in electrical demand of 10.56 MW for the year 2006 resulting from the network extension.

The study demonstrates that the use of a small-scale local hydroelectric generation scheme is technically more feasible option to transmit power to Kwa-Ximba than extending the Catoridge-Georgedale sub-transmission network. It not only maximizes the use of a renewable energy source namely Nagle Dam. Network eextension will involve cable extensions, system adjustments like frequency controls and generation reserve. These adjustments could lead to problems with load flow, system oscillations and inter-area oscillations.

The use of the hydroelectric generation scheme also has the capability of reducing potential bottlenecks in the Catoridge-Georgedale network. The increase in demand on the Catoridge-Georgedale sub-transmission network will impact negatively on the short circuit capacity of existing switchgear equipment and other network components. Enhancement of the transmission systems and the control of load-flow will be essential to maintain the network's security. The use of a hydroelectric generation scheme will also provide a cost effective solution in providing power in the long term, in that the water that is used to turn the turbines will not be wasted but sold to people living in the Durban area.

The power demand for Kwa-Ximba was determined only by the real demand as stipulated by Rural Development planners stationed at the Town Planning Offices of the Ethekweni City Council. The electrical power output of 19.7 MW of the hydroelectric generation scheme, for the year 2005, is based on the present flow rate of $42.88m^3/s$. It is imperative that the existing two 315 KVA turbine generating plants at Nagle Dam be replaced. They are not only undersized for the intended commercial application but they are also very old. They have been in operation since 1945 and spare parts for them are obsolete. They will be replaced with five 11 kV generators, three 5MW generators, one 3MW generator and one 2MW generator. The total electrical output power will be 20 MW. The constant increase in power demand by Kwa-Ximba will result in a gradual decease in the amount of power being sold to Eskom for system enhancement. The maximum magnitude of power that can be supplied to Eskom will be 8.64 MW in the year 2005 and will gradually decrease until the year 2014 when power supply to Eskom's Catoridge-Georgedale sub-transmission network will be terminated. The cost of purchasing less than 5MW of power against the benefit of obtaining system enhancement in a large sub-transmission network is not feasible.

Since power supply to the Eskom's sub-transmission network is terminated in the year 2014 and the power demand by Kwa-Ximba is only 12.399 MW with a 17.3% spinning reserve, it will not be necessary to have all five generator sets on line. Generator sets 4 and 5 will be switched off, with 1, 2 and 3 delivering a total of 15 MW. This situation remains feasible until the year 2018.

It is imperative that the most appropriate and cost effective utilisation is made of the generators by combining different sets depending on power demand and spinning reserve. As time progresses the spinning reserve is continually decreasing as a result of an increasing power demand by Kwa-Ximba. It will thus become necessary to bring generator set 5 back on line, in the year 2019 in order to increase the total electrical output power to 17 MW. This combination of generators will allow Kwa-Ximba an average of 14.05 MW from the years 2019 to 2023 with an adequate spinning reserve. In the year 2024, generator set 5 will be switched off and generator set 4 brought on line, resulting in a total of 18 MW of electrical power. By the year 2028 all five generators will be back on line delivering a total output power of 20 MW.

The converter station in Network A is adequately rated to operate at 20 MVA and the HVDC cables are rated to operate at 30 MVA. Beyond the year 2032 it is envisaged that the hydroelectric scheme be upgraded by adding more generator sets and the converters station be upgraded to a 30 MVA operating capacity. The HVDC cables will not require replacement since its operating capacity is already 30 MVA. If Network B is used, it is still necessary to upgrade the hydroelectric scheme in the year 2032.

Should the sale of power to Kwa-Ximba increase significantly, the network will be expanded. This expansion project will be termed as a phase two project. The network will be extended to other locations with in the district of Kwa-Ximba. It would make business sense to operate the hydroelectric generation scheme at full load with a spinning reserve of 10% within the smallest possible time frame, in order to achieve the best possible Return On Investment (ROI). The possibility of this happening within phase one of the project undertaking is remote, however, phase two where the area of supply is extended makes this highly probable.

The present study can be compared to the Directlink HVDC transmission network which is an 180 MW underground HVDC transmission which connects New South Wales and Queensland electricity grids in Australia (Asplund, 2000). It also makes use of HVDC transmission in a medium voltage application. The Directlink transmission is composed by three HVDC independent links of 60 MVA each operating at 80 kV. The six underground cables are 59 km each. Directlink allows power to be traded between the two states for the first time.

Electricity is a basic necessity and access to it has a wide range of positive developmental benefits for communities. Increased usage of electricity improves the level of welfare, decreases health expenditures and improves opportunities for low-income families, and women in particular. Poor communities should have access to electricity, and should be enabled to afford it without sacrificing other basic necessities. Investors will inevitably be attracted to Kwa-Ximba since it has a high growth potential from an infrastructure development perspective and a high presence of job seekers. On the other hand, the local community will be able to find jobs close to their homes.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

The present study demonstrates that a HVDC transmission system can be efficiently applied to a medium voltage distribution network, from a technical perspective. The installation of a HVDC transmission link from the hydroelectric generation scheme, installed adjacent to the dam wall, to Kwa-Ximba and the Catoridge-Georgedale network has proven to be more feasible than an HVAC transmission link from a technical and environmental perspective.

Even though the magnitude of power generated and the transmission distance was relatively small, the HVDC transmission link contributes positively to network stability by absorbing more reactive power than the HVAC link. With the HVDC system the link absorbed a combined (Kwa-Ximba, Catoridge-Georgdeale sub-transmission network) reactive power of 22.04 MVAr, as opposed to the HVAC transmission link where a combined (Kwa-Ximba, Catoridge-Georgdeale sub-transmission network) reactive power 1.89 MVAr was absorbed. This demonstrates, the HVDC link has the ability to absorb more reactive power from the Catoridge-Georgdedale sub-transmission network, therefore contributing positively to sub-transmission network enhancement. It is also evident that the HVDC link will not contribute to short circuit power.

The HVDC system offers enough flexibility to provide the estimated 17.715 MW of power to the Kwa-Ximba district by the year 2034 with a 11.4% spinning reserve. The excess power will be transmitted to Eskom for system enhancement. The power transmitted to Eskom will diminish proportionally per year until 2014 when the supply to Eskom terminates. This is due to (i) increased power demand by Kwa-Ximba due to growth factor of 1.8% per annum, (ii) the size of the 20 MVA converter stations limit the amount of power that can be generated and (iii) the flow through the turbine is limited to 49.02m^3/s due to the maximum flow allowed through the 20 MVA turbine.

Other benefits of using an HVDC system rather than a HVAC system for the current project include extremely fast control of power flow which implies stability improvements, not only for the HVDC link but also for the surrounding AC network. The environmental impact for HVDC is also much smaller and existing rights-of way will be used. Furthermore, HVDC transmission has less negative environmental impact than an HVAC transmission system.

However, the technical and environmental differences noted between the HVDC (Network A) and HVAC (Network B) systems do not justify the economics to install a HVDC system in order to supply power to Kwa-Ximba. The cost to install a HVDC system would be 64 % more than the cost to install a HVAC system. Furthermore the developer will make 75 % less in opportunity profit if they implemented Network A and not B. The developer's interest in this project would essentially be two fold (i) to provide basic services to Kwa-Ximba and (ii) to obtain the highest possible return on investment. The implementation of Network B will adequately meet these objectives. However, Eskom does not benefit in terms of system enhancement from Network B as they would from Network A. It is therefore in Eskom's best interest to contribute towards the installation costs of the HVDC network, as the HVDC transmission would enhance their Catoridge-Georgdale sub-transmission network. One should also bear in mind that the study was conducted on the predicted present day (network not yet installed) electricity demand on the Catoridge-Georgdale sub-transmission network. In future when the load demand increases significantly the benefits associated with Network A would be more prominent to Eskom. It is therefore recommended that Eskom (i) pay the developer a higher tariff in the form of a subsidy or (ii) contribute a percentage towards the difference in capital costs for Network A and B now or (iii) completely fund the installation of HVDC equipment and associated HVDC transmission costs at a later stage when the cost of converters and cables are more competitive.

Whichever network is chosen, the community of Kwa-Ximba ultimately will be the main beneficiaries. They will acquire (i) electricity, (ii) potable water, (iii) sewage and sanitation services. This will ultimately lead to financial and social autonomy from state coffers and non-governmental organisations.

Also, HVDC can easily meet the changing requirements brought about by deregulation. The traditional electricity sector in South Africa involves the major utility Eskom having a power supply monopoly on a national level. The key drivers for deregulation in South Africa are global competitiveness, a quest for local industrial development through cost-effective services, equitable and sustainable power supplies and the social empowerment of communities through the eradication of poverty. The present Electricity Distribution Industry (EDI) is made up of Eskom Distribution and about 368 municipal distributors. HVDC technology allows the deregulated electricity market to develop with very little technical constraints. It enables fast and accurate control of the power transmitted, enhanced power quality and allows the converter to be located where it is most needed. Furthermore, power quality can be improved as the HVDC terminals can control reactive power between stations.

Extending the Catoridge-Georgedale network to supply power to Kwa-Ximba, with the hydroelectric generation switched off is technically not the most feasible option, despite the lower costs involved. It places undue burden on the sub-transmission network. Had the magnitude of the load been greater e.g. in the region of 60 MVA then the increased loading would have been noticed.

The use of Nagle Dam provides several advantages (i) It provides a reasonable amount of energy at the point of demand which is Kwa-Ximba, (ii) is a stand-alone power sources, (iii) is environmentally friendly (iv) the components have a long life span with little degradation and (iv) relatively unskilled workers can carry out operation and maintenance plans.

This will greatly impact in reversing the urban migration trend by installing sustainable power sources that are essential to the economic health of the rural areas. The feasibility of using wind could be a future development. Wind can also be used as an energy source. If alternative energy resources such as hydroelectric and wind power, are to be used to satisfy the energy needs in rural locations, they have to be designed in order to provide energy to meet an ever-increasing demand at affordable prices as in the present study.

The present study is in alignment with the aims and objectives of New Economic Partnership for Africa's Development (Nepad), Sadec and National Electrification Forum (NEF), which aims to uplift the African continent through investment. Nepad intends to use energy as a launching pad for Africa into the global economy. Against this, and despite the rich and diverse sources of energy on the continent, per capita consumption of energy in Africa is the lowest in the world, making energy poverty the root cause of underdevelopment.

Access, affordability, and efficiency are the characteristics by which any strategy that will put Africa's energy economy to a path of sustainable development must be judged. Since there is a high rate of poverty and low population density in rural areas, relying on grid solutions for lights on is a sure course for lights off. In fact, the energy needs of rural Africa are decentralised. Meeting the energy needs of rural populations requires the exploration of renewable energy sources. In contrast, the Nepad action plan prioritises the centralisation of power supply, the opposite of the decentralised energy needs of rural masses. Driven by profits, privatised utilities have no incentive to extend networks to rural areas, unless government subsidies make up for the financial losses and provide an attractive margin of profit. It is worth noting that the neo-liberal policies from which Nepad draws its viability is at odds with subsidies. In fact, governments are compelled to shirk their social responsibilities thereby leaving rural populations permanently unconnected to the grid.

In today's economic environment it is important to find the most cost effective solution in terms of technical performance when planning new networks or upgrading existing networks. Distribution remains the major challenge to providing all of South Africa with electricity. As democratization moves forward, attempts are being made to make use of renewable energy sources and extend power to supply small distant rural locations.

According to (NER Journal, 2000) it presently costs nearly R 50 000 per km of grid extension, with the average cost of connecting a household to the grid being R 3000. These costs are fully subsidized considering the fact that electricity sales in rural areas barely cover the operating costs borne by the utility. There is clearly a need for low cost electrification. The Department of Minerals and Energy issued a call for proposals in the field of non-grid rural electrification (www.polity.org.za). HVDC provides a basis for supplying cost effective, reliable and efficient electrical transmission and will aid in achieving the objective of electricity to all, by 2010.

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