



## **Caprivi Link HVDC Interconnector: Site selection, geophysical investigations, interference impacts and design of the earth electrodes**

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### **SUMMARY**

The Caprivi Link HVDC Scheme in Namibia, connecting the Zambezi 330 kV substation close to Katima Mulilo in the Caprivi Strip to the Gerus 400 kV substation in the centre of Namibia has been designed for both metallic return and earth return when operating in monopolar mode. A future bipole extension is planned.

The paper gives an overview of the scheme, the various operating configurations and the advantages of using earth return in monopolar mode. The paper outlines the approach followed and methodology utilised to select suitable sites for earth electrodes. The criteria considered important for the selection of earth electrode sites are described. An overview is provided of the geophysical investigations and studies undertaken to select suitable sites for earth electrodes. Interference investigations carried out to determine the possible effects of earth electrode operation are described. The design criteria and the preliminary design of the earth electrodes are described.

### **KEYWORDS**

Earth electrodes – Site selection - Geophysical investigations - Interference investigations - Design criteria

## 1. INTRODUCTION

The Caprivi Link Interconnector will provide an HVDC link between the Namibian and Zambian/Zimbabwean electricity networks. This will provide NamPower, the Namibian electricity utility access to power resources in those countries that are mainly hydro based, and ensure a low power loss and reliable power transfer capability between the east and west of the Southern African Power Pool (SAPP).

The final configuration of the Caprivi Link Interconnector will be a 600MW bipole scheme operating at  $\pm 350\text{kV}$  dc and utilising VSC technology. The converter stations are located at Zambezi 330 kV substation close to Katima Mulilo in the Caprivi Strip to the Gerus 400 kV substation in the centre of Namibia and are connected by 952km of overhead line. See figure 1.

The scheme will be constructed in two phases:

- Phase 1: 300MW monopolar scheme with earth and metallic return.
- Phase 2: Upgrade the 300MW monopolar scheme to a 600MW bipolar scheme.

Both poles of the dc line will be constructed in Phase 1 and earth electrodes will be constructed about 30km from each converter station. The scheme has been designed for operation in the following configurations in monopolar mode:

- Metallic return utilising the second pole of the dc line as the metallic return conductor
- Earth return with a single dc line pole conductor
- Earth return with paralleled dc line pole conductors

The advantages of operation with earth return are reduced losses, especially with paralleled dc line pole conductors and operational flexibility in monopolar configuration. The scheme has an overload rating in monopolar mode of 350MW.

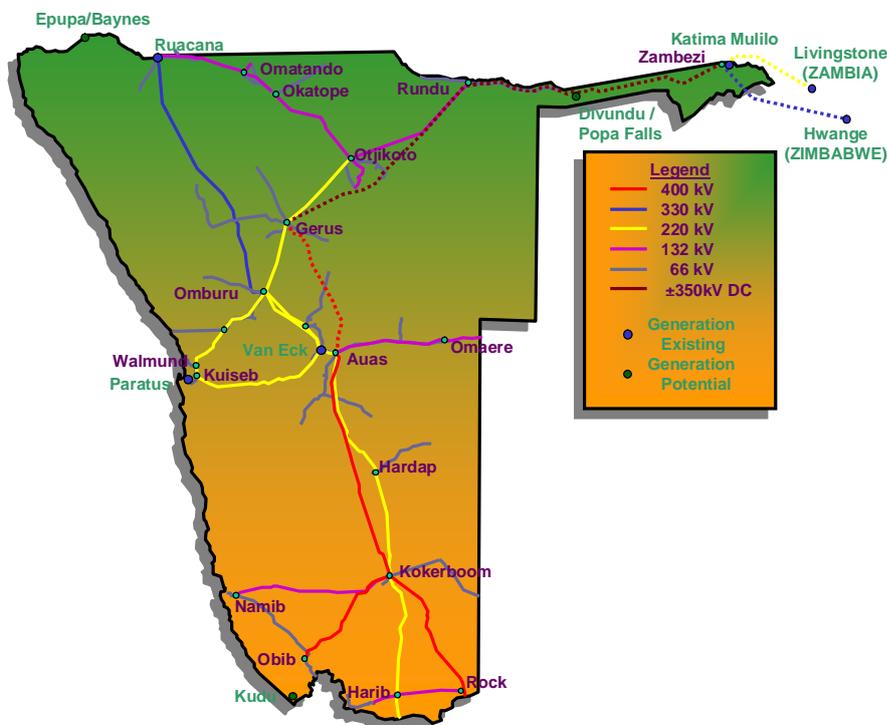


Figure 1: Geographical Location of Termination Points for the Caprivi Link Interconnector

## **2. SITE SELECTION FOR EARTH ELECTRODES**

The number and variety of criteria which must be taken into consideration in the selection of an electrode site mean that it is generally difficult to find a suitable site which meets all the applicable requirements. A number of different sites may need to be investigated and an iterative approach may need to be followed to select a suitable site.

### **2.1 Ground characteristics**

The most important requirement for the construction of an earth electrode relates to the ground characteristics. The most important of these characteristics is the electrical conductivity of the soil. As a good (low resistance) connection to deep earth is required both the surface soil conditions and the conditions several hundred metres and even kilometres deep are important. The soil conditions up to several kilometres away from the electrode also need to be considered to determine the surface effects.

Other important parameters of the ground that need to be considered are:

- Thermal conductivity
- Thermal capacitance
- Porosity (water and gas permeability)
- Penetration of moisture and influx of water

### **2.2 Buried and earthed metallic structures within the area of influence**

Buried and earthed metallic structures are subject to corrosion by direct current flowing in the ground. The important factors are not only distance from the electrode but also size/length of the object and the position of the object in relation to the principal direction of current. Surveys should be undertaken to identify objects within the area of influence.

### **2.3 Electrical infrastructure within the area of influence**

The location of overhead transmission and distribution lines, underground cables and electrical substations in the vicinity of the earth electrode should be determined. The earth electrode should also be located sufficiently distant from the HVDC converter stations to ensure that the return direct currents do not cause saturation of HVDC converter transformers.

### **2.4 Environmental/land use/landowner considerations**

Environmental impact assessments will need to be carried out to determine the effects of the electrodes on the environment. Present and future land use considerations also need to be considered e.g. recreational areas, town development, mining activities. The construction of an earth electrode is likely to constrain future some types of land use in the vicinity of the electrode.

### **2.5 Accessibility**

Vehicular and equipment access for construction of the electrode needs to be considered. During the subsequent operation of the HVDC scheme the electrode sites need to be accessible for inspection and maintenance purposes.

The above considerations were used to identify areas that may be suitable for earth electrode sites approximately 30km away from the converter stations located at Gerus and Zambezi.

### **3. GEOPHYSICAL INVESTIGATIONS AND STUDIES FOR SITE SELECTION**

The resistivity of the host material for an earth electrode is important, both for electrode functionality and for the minimisation of environmental impact due to the injected current. High resistivity close to the electrode will create losses and the function of the electrode might become obstructed by electro-osmosis and heating due to strong electrical fields. High resistivity away from the electrode, both laterally and towards depth, will result in high potentials and strong electric fields that can have an effect on infrastructure. It is therefore important to obtain information about the resistivity distribution in the ground also on a regional scale.

#### **3.1 Available geophysical methods**

Geophysical surveying is common in exploration for minerals and groundwater and also in geological pre-investigations related to infra-structure projects. Several methods are available but they are all based on the assumption that different geological units can be mapped based on their physical properties.

The resistivity of the ground can be measured by either galvanic or inductive methods. Galvanic measurements mean that a low-frequency current is injected into the ground with the help of two electrodes. The resulting electric potential difference between two points is measured with the help of two other electrodes. The size and depth extent of the investigated volume depends upon the configuration of the electrodes. Large electrode separation will yield information from deeper levels. Galvanic methods are robust and the survey data are usually fairly straightforward to model and interpret. However, really deep investigations become difficult since they require very large electrode separations. Measurements can also be difficult in dry terrain where galvanic contact with the ground is poor.

A magnetic ac field created by a coil or a cable loop is utilised in inductive measurements of ground resistivity. Secondary eddy currents will occur in conductive material in the ground due to induction. Those currents will produce a secondary magnetic ac field that can be picked up with e.g. a receiver coil. The magnitude and phase of the secondary field will be a function of the resistivity distribution in the subsurface. The investigation depth is a function of the skin effect and hence the measurement frequency. Low frequency fields will yield information from deep levels. It is possible to perform inductive surveys from e.g. a helicopter since no contact with the ground is necessary. A special type of inductive measurements (Magnetotellurics) makes use of naturally occurring ac fields. Very low frequencies can be measured in magnetotellurics and the resistivity down to several tens of km can be estimated.

Other geophysical methods can also be considered. In some cases the resistivity parameters of certain geological units might be known, at least within certain limits. Magnetic, gravity or seismic methods can then be used to map the three-dimensional distribution of the units. Airborne magnetic measurements are cheap and data are often acquired during basic geological mapping programs. Magnetic data are e.g. available from the Geological Survey of Namibia.

#### **3.2 Compilation of geological information**

The geological and geophysical investigations started with a desktop study where available information was compiled. Groundwater investigations, including a helicopter-borne geophysical survey, had been carried out in the Caprivi area. The geophysical survey identified a site with saline near-surface ground-water in porous sand that was considered as a suitable site for the Zambezi electrode.

The Gerus area is dominated by crystalline bedrock with thin and dry overburden. Graphite-bearing layers are fairly abundant in a geological unit that occurs around Gerus [1]. Graphitic rock was

considered as suitable to host an electrode. Only one locality of graphite was however specifically identified in official publications and this place was considered unsuitable as an electrode site for other than geological reasons.

### **3.3 Geophysical surveys**

Reconnaissance geophysical lines, both ground and helicopter-borne, were surveyed with inductive equipment around Gerus with the aim of locating areas with graphitic bedrock. Several such areas were identified. One of these was located in a logistically favourable position and fairly close to existing overhead line servitude, and it was therefore selected for further investigations.

Detailed geophysical measurements were carried out at both the Zambezi and the Gerus site. Galvanic resistivity measurements were carried out at the electrode site at Zambezi. This gave information about the resistivity of the sandy material that will host the electrode and the depth to groundwater. Shallow groundwater was considered necessary for the electrode design and knowledge about the resistivity was necessary in order to estimate the allowable current density from the electrode. Information about the resistivity above the ground-water table was also acquired. This will enable estimates of e.g. step-voltages in the area of the electrode site.

Inductive measurements were carried out at the Gerus electrode site so that the exact position of graphite-bearing sub-vertical layers could be determined. A so called slingram system was used, where a portable magnetic ac transmitter was carried along traverses and the secondary field was measured at a fixed distance from the transmitter. Several thin, steeply dipping conductive layers were identified. Positions of boreholes to test these layers have been identified at the time of writing. The positions of the layers must be known accurately in order to be able to penetrate them with electrode boreholes.

Information about the resistivity in the earth's crust was acquired through magnetotelluric measurements performed within the SAMTEX experiment. SAMTEX is a cooperative research programme involving research organisations and mining companies [2]. The objective is to characterize the earth's crust in southern Africa, which has bearing for e.g. diamond exploration. The magnetotelluric measurements have provided resistivity estimates from the surface down to several tens of km depth at both Zambezi and Gerus, although with rather poor spatial resolution. Fairly conductive rock was identified for the middle and lower crust (> 10 km depth) in both areas.

### **3.4 Prediction of electrical fields**

Geological information, historical geophysical data, helicopter-borne and ground geophysical data were compiled into three-dimensional models of earth resistivity for both electrode areas. Somewhat conservative estimates of the resistivity were used for the different geological units. The accuracy of the models can be assumed to be quite good close to the electrode sites where detailed investigations have been carried out. The models are of a more conceptual nature in other areas and towards large depths. One model for the Gerus electrode is shown in Figure 2. The size of the model is 27x27x20 km. A finite-difference program was used to calculate the electric potential caused by a hypothetical electrode that injects current into the models. Such predictions were then used as input for interference investigations. An example of modelling results can be shown in Figure 3. The map shows iso-potential contours for a current injection of 1000A (350MW) at the electrode around the proposed electrode site in the Gerus area for the geophysical model that can be considered as the most likely. The contour interval is 1 V. The town Otjiwarongo is located in the north-eastern part of the map at a potential of 2 V. The sub-station Gerus is located just north of the map area. The effects of changing different model parameters have been tested. The potential at distances larger than a few km from the electrode is mainly dependent upon the resistivity of the middle and lower part of the earth's crust, i.e. at depths of more than 10 km below the surface.

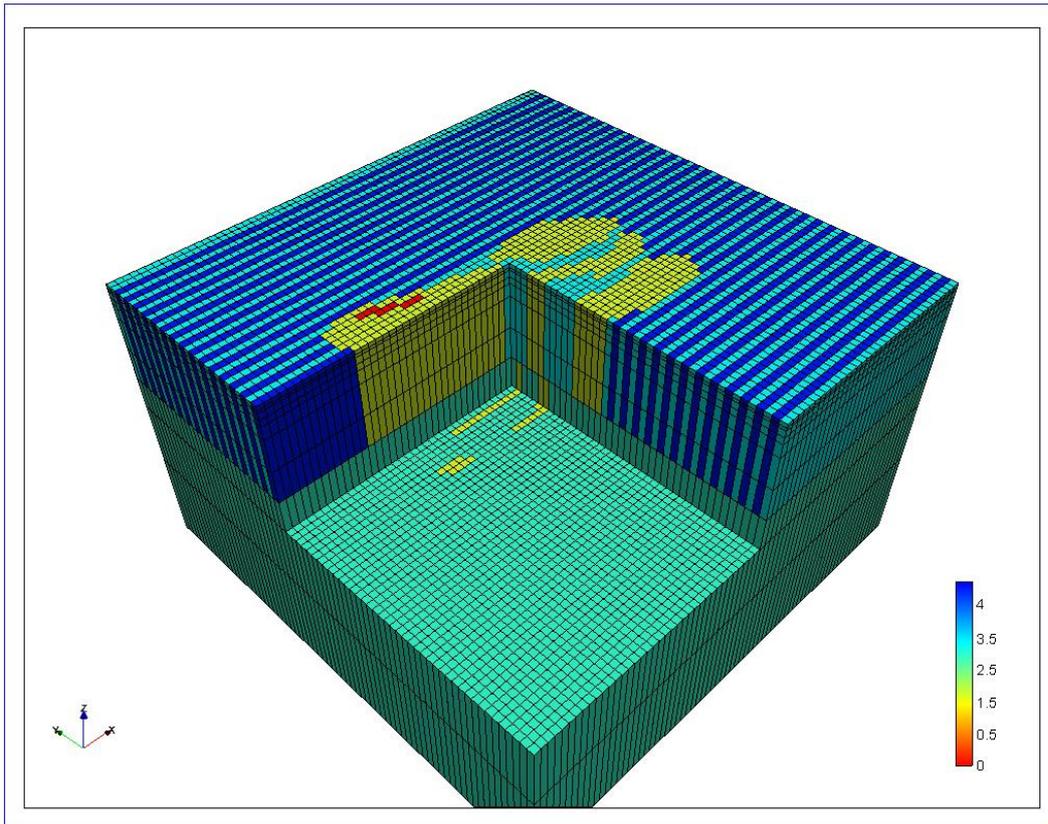


Figure 2: Example of a three-dimensional resistivity model that was used to predict the electric potential due to an earth electrode in the Gerus area. The colour scale shows the logarithm of resistivity in units of  $\Omega\text{m}$ .

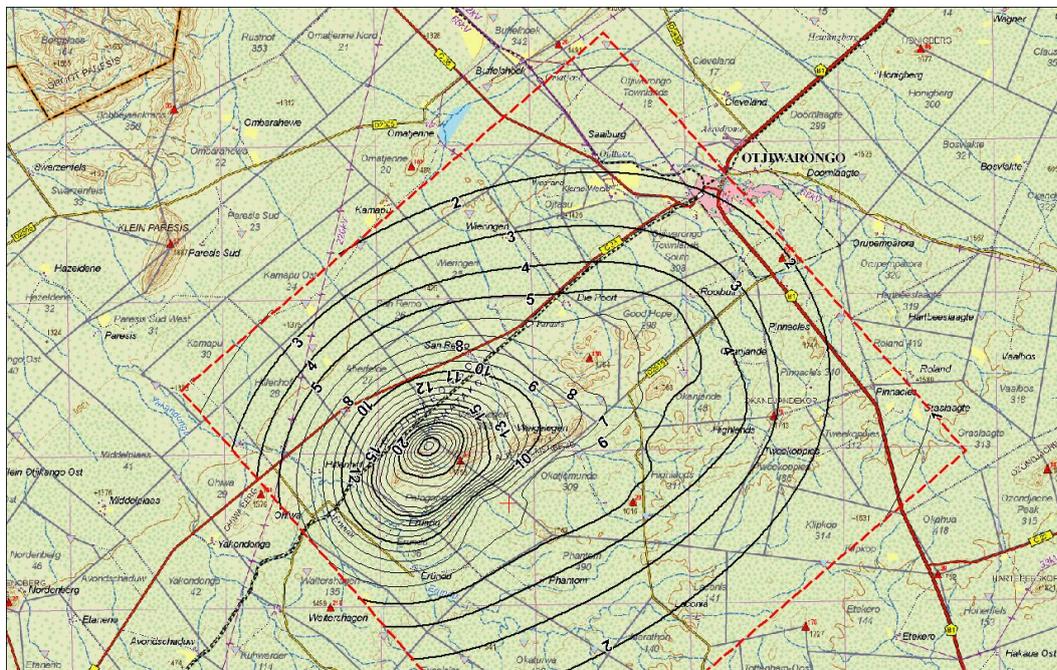


Figure 3: Map showing contours of predicted electric potential due to 1000 A of current injected into the ground at the electrode site at Gerus according to the model that is considered as most likely.

## **4. INTERFERENCE INVESTIGATIONS**

The electric field around the electrode can cause stray current influence on buried or immersed metallic structures. The main concern is the risk of increased corrosion but also other forms of interference have to be considered such as transformer saturation and disturbances in the telephone network. The electrical field in the vicinity of the electrode may also have an impact on humans and animals.

The primary method to avoid interference is to provide sufficient distance between the location of the earth electrode and critical structures. The influence area shall not reach densely populated areas. It is only in the close vicinity of the electrode that the design of the electrode influences the magnitude of the electric field. At a distance of a few km the design has no influence at all and geological parameters take over.

In the field of stray current interference it is common to talk about a so called “critical influence area”. This area is not a well defined distance from a specific HVDC electrode. In some cases the influence area is best defined as the distance from the electrode to a point where the ground potential has a specific value compared to remote earth. In other cases the magnitude of the field strength is more relevant to use.

### **4.1 Effects on metallic structures**

Stray current corrosion occurs in spots where the dc current leaves the metallic construction. (Aluminium and lead can however also be influenced by entering dc currents).

In principle all buried metallic structures can be exposed to stray current corrosion from HVDC electrodes. The extent of the structure, the longitudinal resistance, the quality of the coating system and the local top soil resistivity are the most important factors determining the magnitude of impact in each case. The structures most vulnerable to be attacked are pipelines having a good coating system. High current densities and therefore corrosion rates can occur in areas of damaged coating. From previous projects the experience has been that only these types of pipelines are influenced when the voltage to remote earth is below 4V. In practice this means that if large networks have the nearest earthing point at lower voltages than 4 V, interference is not likely to be expected.

For smaller items especially if poorly coated, the field strength is more important. Depending on the resistivity of the soil surrounding the structure different magnitudes of potential differences can be accepted. Recommendations of maximum allowed interference (change of potential on the structure) are stated in for example EN 50162 [3]. Based on these criteria's it is possible to determine critical length of a structure exposed to a specific field strength.

### **4.2 Effects on electrical infrastructure**

If a dc potential difference exists between the transformer neutrals in two transformer stations, a dc current will pass in parallel of the transformer to the remote transformer neutral and thus have an effect on the transformer saturation. In general, banks of single-phase and 5 limbed transformers are seriously affected by dc currents in the transformer neutrals. Transformer with 3 limbs can tolerate much higher dc currents due to a low magnetic resistance. It is only transformers having a directly earthed starpoint of the winding system that passes dc current through the windings. Delta-connected windings can not be affected by passing dc current. Voltage differences above 10 V will cause problems. Electrical networks are extensive and all transformers located at higher potentials than 10 V to remote earth should be investigated. The dc current going through the transformer can be decreased by installing capacitors, injecting a dc current opposing the one flowing in the neutral or by increasing the earth resistance of the transformer earthing by using a separate earthing rod for the transformer.

### **4.3 Effects on humans and animals**

The highest field strength and therefore the greatest risk for humans and animals is in the direct vicinity of the electrode. Current entering the body must not exceed 5 mA. The body resistance can be set to 1000 Ω. Maximum acceptable step voltage is influenced by the soil resistivity (ρ).

$$U_{\text{step}} = 5 + 0,03 \cdot \rho \text{ (V)}$$

Assuming very low soil resistivity the step voltage should not exceed 5V/m.

#### 4.4 Impact study

The impact study was performed in several steps. Based on the principal information given above and the calculated electrical field a "critical influence area" was selected for each type of structure. By contacting infrastructure owners and performing field surveys potentially influenced structures were determined. Data was collected on site and interference calculations performed thereafter. The aim of these calculations was to place each mapped structure into one of the categories below:

1. Structures where protective measures must be installed prior to start of operation.
2. Structures on which interference can not be ruled out.
3. Structures on which interference can be ruled out.

Structures belonging to the first category are those where even short time of interference would have unacceptable consequences either due to the magnitude of interference or due to the sensitivity of the structure itself. For structures placed in category 2 measurements are to be done after the HVDC scheme is in operation. For structures in category 3 no measurements are needed.

In Zambezi very limited geological data was available at the time of the impact survey. Therefore the extent of the electric field was uncertain. As a consequence quite an extensive area was investigated for structures being potentially influenced. When relevant geological data was collected and modelling performed it became obvious that the expected level of interference was extremely low. The nearest buried structure, an earthing in the village Kasheshe, 5,7 km from the electrode is positioned on a predicted voltage of 2,8 V. The field strength in the closest town, Katima Mulilo, is estimated to be below 50 mV/km, and no problems are anticipated.

The first investigated site for an electrode at Gerus resulted in a calculated potential of 11 V in the town Otjiwarongo. Mitigations would have been necessary on municipal networks as well as power lines. By moving the electrode to a new site, the interference situation was greatly improved. Preliminary calculations show insignificant increase in corrosion on the unelectrified railway. Mitigations are however needed on an adjacent 220 kV power line. Current will be picked up by the tower footing earths, be transported in the shield wire, giving out leaking current on tower earths located further away or vice versa. The current will not pass transformers at substations and saturation will not be a problem. Mitigations proposed are local cathodic protection or isolation of the shield wire from the tower structures for a certain distance. Mitigations will also be necessary on the Single Wire Earth Return (SWER) lines supplying the local farmers with electricity. These single wire systems return the current via earth. Both increased corrosion on earths and saturation of transformers are expected.

Apart from the interference issues identified above which can be mitigated, the electrode sites chosen for the Zambezi and Gerus electrodes were found to be suitable. Once the electrodes have been constructed and are used for earth return monitoring programs should be established to measure actual interferences and confirm these are below acceptable limits.

## 5. ELECTRODE DESIGN CRITERIA AND PRELIMINARY DESIGNS

### 5.1 Design criteria for Gerus and Zambezi earth electrodes

- The earth electrode shall be rated for 350 MW (984A) in monopolar operation (350MW overload condition) in both power directions;
- The earth electrode shall be sectionalised into a sufficient number of sub-elements in order to allow for repair of a sub-element without reducing the power capability of 300 MW (867A);
- The electrode station shall meet applicable safety regulations regarding step voltages, i.e., the ground around the earth electrode shall be able to be accessed without restrictions during operation;
- Resistance to remote earth of 0.2  $\Omega$ ;
- Current density of 0.5 to 1 A/m<sup>2</sup> on coke surface depending on the type of soil;
- Maximum temperature of the electrode shall be 60°C;
- The life of the earth electrode shall be at least 30 years assuming 200 MW continuous power transfer.

At the time of writing of the paper only the preliminary designs for the earth electrodes had been completed. These will be described below.

### 5.2 Anode and cathode

Depending on the direction of power flow one of the two earth electrodes of Caprivi Link will operate as anode while the other will operate as cathode. The dc current leaves the anode and enters to the cathode. Electrode materials used in anodic operation suffer from electrochemical corrosion because of the ionic current flow from anode into surrounding electrolytic media.

The first phase of the project is a monopole operating at – 350 kV dc with the normal power direction from Zambezi to Gerus. Consequently the Zambezi earth electrode mostly will work as anode and the Gerus earth electrode as cathode. When scheme is expanded to a bipole, the normal operation will be balanced bipolar operation with much less use of the earth electrodes to transmit high current.

### 5.3 Zambezi earth electrode

A proposed site south of Mpacha airport at the town of Katima Mulilo with sandy soil and ground water close to the surface is suitable for an electrode. Two types of earth electrodes have been evaluated for this site: horizontal ring electrode and vertical borehole type. The type that will be chosen will depend on practical considerations such as ease of installation and costs. Each of these electrode types is described below.

#### 5.3.1 Horizontal ring electrode

A ring electrode should be buried at a depth of 3-4 m below the ground water table, in a trench of coke. The dc current will be distributed to 16 segments from the centre of the ring, where the electrode line enters. The current capability should be maintained even if one of these segments fails. The material of current distributor in the electrode should be silicon iron, which is normally used in cathodic protection systems. The material of the electrode itself should be calcined petroleum coke. The benefit of using coke is that the active surface is increased and the corrosion of the silicon iron anodes is reduced.

For the conceptual design of the earth electrode, a current density of 0.5 A/m<sup>2</sup> and a quadratic profile of the electrode of 0.5 m \* 0.5 m have been assumed, of which 50 % is assumed to be able to transfer current (the lower parts and half of the sides). Taking the consumption of coke over the lifetime of the

electrode into consideration the required electrode length is 2262m or a circle with the diameter of 720 m.

The current density of  $0.5 \text{ A/m}^2$  above is required for a soil with clay to avoid the electro-osmosis phenomena which dries the electrode in anodic operation. For sandy soil, the current density can be higher and the ring electrode smaller. However, the contact resistance for an electrode buried in soil with sand is higher compared to an electrode buried in soil with clay, resulting in higher step voltages and a need to expand the ring electrode.

#### **5.3.1.1 Step voltage**

The step voltage has been calculated with the FEM-program Comsol using as input data resistivity of soil layers at different depths. The electrode has conservatively been assumed to be installed at a depth of 2.5 m. The resistivity of the top soil is  $1000 - 3000 \Omega\text{m}$ . This top soil layers have a seasonal difference. Consequently the threshold value of the step voltage should be  $5 \text{ V/m} + 1000 \cdot 0,03 \text{ V/m}$  which equals  $35 \text{ V/m}$ . The voltage gradient calculations resulted in a maximum step voltage of  $2.3 \text{ V/m}$  at an outage of one sub-element, which provides a safety factor of 15.

#### **5.3.1.2 Heat generation**

The heat generated by the dc current is calculated as the product of current density and field strength, expressed as  $\text{W/m}^3$ . This calculation has also been performed in FEM-program Comsol. No convective cooling was assumed and the upper surface was isolated. A uniform heat conductivity of  $1 \text{ W/m.K}$  and a soil temperature of  $10 \text{ }^\circ\text{C}$  were assumed.

A local heating source has been added, namely heat generated due to the electrochemical reactions taking place at the electrode. The electrode reactions require a certain potential drop over the interface. The interface can be compared with a diode that must have its voltage drop in order to be conducting. The magnitude of this voltage drop across the interface is likely to be in the electrochemical scale for water. With a coke bed in moist soil as interface the potential drop is likely to be 1-2 V.

The calculations resulted in a maximum surface temperature of the earth electrode of  $30 \text{ }^\circ\text{C}$ .

#### **5.3.2 Vertical-type electrode or deep well electrode**

An alternative to horizontal ring electrode is the vertical bore hole electrode type with the active electrode placed below the water table and down to about 100m depth depending on diameter of the bore hole. For Zambezi 40 bore holes with a diameter of 350mm and to a depth of 44m have been proposed. The sub electrodes consist of a chain of silicon iron with chromium anodes (chromium added in case of existence of salt water) embedded in coke.

This type of electrode will chosen when the horizontal type is expensive to install or not feasible, for example at conditions with high resistivity of the top soil layer or if there is a risk of harmful interferences at the site area.

A comparison between the horizontal and vertical earth electrode type for the Zambezi earth electrode station resulted in the following:

- The vertical earth electrode is much less susceptible to seasonal variations of moisture and temperature, e.g. variation of ground water table, which are very important to the overall performance of the earth electrode.
- The vertical earth electrode is easier to sectionalise, according to the requirement to be able disconnect one section of the electrode and still maintain full operation capability.
- The boiling point of water increases with the depth, which permits higher operation temperatures for the vertical earth electrode type

- It is more difficult to maintain the sub-electrodes of the vertical type and to fill the bore holes with coke at installation.

The conclusion was that the vertical earth electrode was more suitable for the Zambezi site and was chosen.

#### **5.4 Gerus electrode**

The conditions for earth electrodes are unfavourable at Gerus since the bedrock mainly consists of crystalline bedrock with very high resistivity. However, the existence of embedded graphite bedrocks provides a possibility to install vertical earth electrodes which are to be bored into the graphite bedrocks. Consequently at Gerus earth electrode station, several boreholes will be drilled into the graphite bedrock, each with a chain of silicon iron with chromium anodes (chromium added in case of existence of salt water) embedded in coke or a tube of metallic material “glued” to the borehole walls by a semiconducting material. The number, depth and location of the borehole electrodes were determined by the shape of the graphite bedrock and the requirement of a sufficient contact area.

A current density of more than  $1.0A/m^2$  on the surface of the coke may be sufficient as Gerus will most of the time be working as cathode, resulting in an effective length of 789m, with a current of 867A (300MW). The number of holes is 10, depth, total depth including 5m with high resistivity at the surface layer is 78m, and a total of 10 disconnectors with one open for maintenance and distance between the holes shall at least be same as the depth of the bore hole. This gives a length of 913m or a diameter of 291m.

#### **5.5 Electrode station design**

The electrode stations will consist of the following parts or systems:

- Earth electrode including current distribution system;
- Outdoor disconnectors on the incoming lines for isolation of the station;
- Indoor sectionalising switchgear;
- Monitoring system;
- Auxiliary power system.

#### **5.6 Monitoring system**

The condition of the electrode station in terms of important parameters will be monitored continuously by a computerized control system, and the status will be transferred to the converter stations via optical fibre. The following measurement and status signals are monitored:

- Soil temperature at the earth electrode segments;
- DC currents through the current distribution cables to the earth electrode segments;
- DC currents through the electrode lines;
- Status of auxiliary power supply.

### **5. CONCLUSION**

The paper has provided an overview of the methodology followed to select suitable earth electrode sites for the Caprivi Link. The criteria important for the selection of earth electrode sites have been outlined. An overview of the use of geophysical methods to find suitable sites for electrodes has been given and geophysical investigations and studies undertaken have been described. The investigations necessary to determine possible interferences on buried or immersed metallic structures and other infrastructure due to the electric field around the electrode have been described. The design criteria

and preliminary design for the Caprivi Link earth electrodes have been described. Once the electrodes have been constructed and are used for earth return monitoring programs should be established to measure actual interferences and confirm these are below acceptable limits.

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