Earthing requirements for HVDC systems

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***Abstract*- Following the recent developments in the field of power electronic valves, High Voltage Direct Current (HVDC) systems have become more attractive in power systems, and are widely recognised as a suitable tool for future power systems, especially in bulk power transmission over long distances. Grounding electrodes are an important part with significant roles in the operation of the HVDC systems. In this paper, first a brief review of different types of HVDC configuration is presented. Essential requirements in the design and operation of the HVDC grounding system are then presented and discussed. In the relevant studies, environmental impacts of HVDC electrodes, e.g. step voltage, effect on the buried metallic structures, DC magnetic bias of power transformers and mitigation methods are highlighted. Finally, a basic modelling of different physical configurations of HVDC electrode resistance is performed.**

***Index Terms*- HVDC, Earthing system, Grounding electrode, Electrode design, Environmental impacts.**

I. INTRODUCTION

SINCE the first commercial implementation in 1954 in Sweden, HVDC systems have become very popular in modern power systems. Considering both technical and economic issues, HVDC systems are shown to be more advantageous for bulk power transmission over long distances than their counterpart HVAC systems. HVDC networks are also implemented to integrate electrical power of renewable energy sources and transfer to the mesh grids. In addition, they are an economic choice to link two networks separated by sea, and the only solution to synchronise two power systems of two different frequencies [1].

HVDC systems are classified into monopolar with earth/sea return, monopolar with metallic return and bipolar configurations [2]. All of the HVDC configurations need to be grounded through a suitable earthing electrode. In the monopolar configuration with metallic return, the earthing electrode provides a clamping neutral point or a reference potential point for the HVDC system. In the other two configurations, the earthing electrodes also provide an additional return path for the DC current [3]. Therefore, unlike earthing electrodes of HVAC networks, which are designed mainly for fault conditions and protection purposes, HVDC grounding systems are designed for normal operation of the system as well as fault conditions. Apart from the monopolar ground return mode, in which the grounding electrode are operating continuously with the rated current of the system, grounding electrodes of the other HVDC configurations might be, under maintenance or fault conditions, operating with high currents over a long time. Therefore, an appropriate grounding system is required to provide a safe and reliable operation for the HVDC system [4-5]. Many factors are involved in the design and operation of HVDC earthing systems, which determines the influence of the DC grounding current on the nearby and far away environment [5-9].

In this paper, an extensive review of the most important requirements for the construction of the earth electrodes for HVDC systems is presented. The main concepts of the HVDC grounding system including, different types of HVDC grounding electrodes, influence on the surrounding environment, electrode material and physical configurations of the electrodes are presented. Practical examples and experiences from the existing HVDC projects are also addressed. This could help to identify the areas where research and development is still required. It should be noted that earthing in HVDC is a wide area of research and, obviously, this paper cannot cover and discuss all of them in detail.

II. DIFFERENT CONFIGURATIONS OF HVDC SYSTEM

An HVDC transmission system is based on direct current and forms an asynchronous link between the sending and receiving ends of the system. An HVDC system comprises two converter stations and a DC overhead line (OHL) or cable. AC power is rectified to DC at the first converter station located at the sending end. DC power is transmitted through a DC OHL or cable, and then inverted to AC again at the second converter station at the receiving end. The main components of an HVDC system are shown in Fig 1.

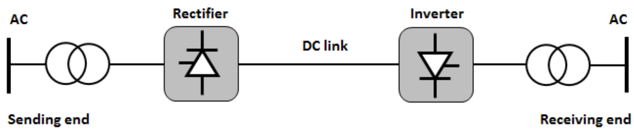

Fig 1 Main components of a HVDC system

HVDC systems are categorised based on the configuration of the converter stations and the transmission line (OHL or cables). Monopolar and bipolar configurations are used to transfer electric power over long distances, and back-to-back configuration is used to link two adjacent asynchronous power systems. Grounding system of the first two systems is more important and is discussed in this paper.

A. Monopolar configuration:

In the monopolar configuration, one converter is installed at each converter station and two conductors are required to interconnect the converter stations. In some applications, however, one HV conductor is installed as an OHL or cable and the ground or sea is implemented as a conductive path for

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the current return path. This configuration is known as "monopole with ground/sea return" which is the simplest and least expensive HVDC system [2]. In this configuration, the earth electrodes are required to operate with continuous full current rating. A schematic of this mode is shown in Fig 2.

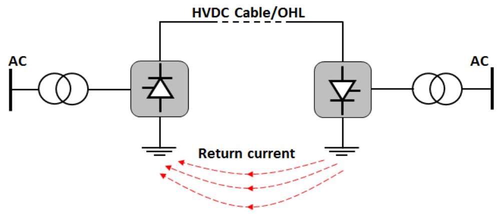
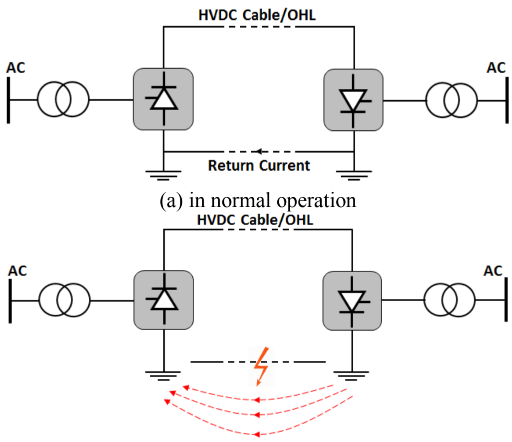


Fig 2 Monopolar configuration with ground/sea return

This configuration is an economic option, particularly for very long submarine cable links where only one cable would be required [10]. However, if one of the converters fails, the whole system will be completely lost. Furthermore, since a significant magnitude of DC current is injected into the ground, buried metallic structures can be susceptible to corrosion. The ground currents can also pass through the neutral point of transformers located in the vicinity of the HVDC electrode. In the case of a sea electrode, the DC current can also lead to chemical pollution in the water around the electrode [2].

To overcome the aforementioned problems, a metallic neutral or a low voltage cable is used as the current return path. Ground electrodes are, however, still required on both sides of the system to provide a clamping neutral point [2]. Such a configuration is known as "monopolar configuration with metallic return". A schematic diagram of this configuration is shown in Fig 3-a. Under normal operation, there is no current through the electrodes. However, in case of maintenance or a fault in the return conductor, the system is able to operate as a monopolar with earth/sea return, as shown in Fig 3-b.



(b) operating in ground return mode
Fig 3 Monopolar configuration with metallic return

This configuration is also implemented if the ground or sea condition is not suitable to use as the current return path, e.g. in heavily congested areas, fresh water cable crossings, or areas with high earth resistivity [11]. According to a study reported in [7], on the basis of economy, most of the existing monopolar HVDC systems in the world use ground/sea electrode return rather than metallic return.

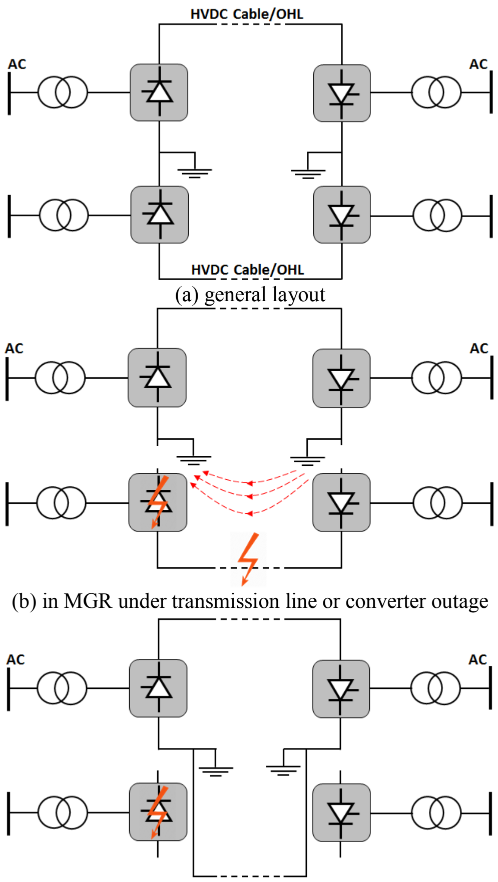
B. *Bipolar configuration:*

The bipolar configuration is the most common HVDC system in which each converter station consists of two converters which are operating with opposite polarity with respect to a common neutral point. The outputs of each converter station are connected either through a cable or an overhead line [12]. A schematic diagram of a bipolar configuration is shown in Fig 4-a. As can be seen from the figure, the bipolar configuration is a combination of two identical monopolar configurations, tied back-to-back, with common ground or sea return electrode [13]. During normal operation and under a balanced load, the current flowing between the neutral points is almost zero. However, in the case of unbalanced load between two poles, the path between the neutral points may carry a significant current either through the metallic return or via the earth/sea electrodes [2, 12]. If a fault occurs on one of the conductors of the transmission line, the affected pole can be isolated and the other pole is still able to operate under a monopolar configuration with earth/sea return, but with 50 % capacity, as shown in Fig 4-b. Furthermore, during maintenance or in case of an internal fault on one pole, the other pole is able to operate under a monopolar configuration, again with 50 % capacity. In this case, the earth/sea electrode or the line conductor of the faulty pole could be used as the return current path, as shown in Figs 4-b and 4-c, respectively. This is considered as the main advantage of the bipolar configuration.

Operating the bipolar system under monopolar configuration with an earth/sea return is time limited, because of the limits on conducting line current through the earth or sea and its undesirable consequences. This might lead to the shutdown of the whole HVDC system after a certain time [2].

III. Environmental Impact of DC current

When DC current is injected into the grounding electrodes between the converter stations, it creates high surface potential around the electrodes, especially in high resistivity areas. This potential depends on the ground resistance between the electrodes and the magnitude of the DC current injected into the ground. The surface potential is highest around the electrodes and falls gradually by increasing the distance from the grounding electrodes. As a result, surface potential varies at different distances from the grounding electrodes. This potential difference in the vicinity of the electrodes, known as step voltage, could endanger humans and livestock safety. It can also affect buried metallic structures, e.g. pipelines, railways, telecommunication systems, etc. and cause what is known as "stray current corrosion" [13]. It is also known that the neutral point of the power transformers located at AC substations in the vicinity of the HVDC electrodes could also be affected by the surface potential. Experience from the existing HVDC systems show that the area affected by the ground potential could reach out to a radius of tens of kilometres from the electrode [6], which depends on the current amplitude and properties of the current return medium. These issues are discussed in the following sections.



(a) general layout

(b) in MGR under transmission line or converter outage

(c) in MMR under converter outage

Fig 4 Bipolar configuration

A. Step voltage

Step voltage is an important factor in the design of HVDC grounding electrodes which depends on ground current, human body resistance, contact resistance between human body and soil resistivity. If the step voltage exceeds a certain magnitude, electric shock might occur. A low step voltage limit or annoyance threshold is defined to ensure human and livestock safety. The step voltage limit for human is calculated by the following expression [9]:

$$E_{step} = I_g(R + 2R_s) \quad (1)$$

where E_{step} is the step voltage in V, I_g is the maximum permissible body current in A, R is the human body resistance in Ω and R_s is the resistance between one foot and soil in Ω. According to a statistical investigation, over 95 % of 1028 subjects have a human body resistance greater than 1400 Ω and do not feel DC current of less than 5.3 mA. On the basis of this investigation, Equation (1) can be expressed as [9]:

$$E_{step} = 7.42 + 0.0318\rho_s \quad (2)$$

where ρ_s is the surface soil resistivity in Ωm. The maximum permissible step voltage during contingency conditions, such as maintenance of the earth electrodes, is limited to 70 V [9]. In the design of HVDC electrodes, the step voltage could also be quantified based on the electric field created by the grounding current. For land-based electrodes, an electric field of 13 V/m to 16.6 V/m is acceptable. For sea-based electrodes, the electric field is limited to 1.5 V/m to 2.5 V/m and 6.7 V/m in areas with large fish and small fish, respectively [14].

B. Effect of corrosion on buried metallic structures

Stray current corrosion is defined as "corrosion caused by direct current from an external source that travels through paths other than the intended circuit" [15]. Stray current and, hence, the level of the corrosion is highest when the structure is oriented in parallel with the external field [2]. Stray current corrosion occurs at locations where the current leaves the structures and flows into the ground. This phenomenon is also known as "cathodic corrosion". Except for aluminium and lead, no corrosion would takes place at the region where current enter the metallic structures [16].

In [17], it is indicated that a stray DC current of 1 A over one year results in a metal loss of 9 kg. Considering the significance of the corrosion rate (amount of metal loss in thickness per year), an anodic current density of 1 A/m^2 would result in a corrosion rate of 1.1 mm per year. Magg et al. [16] have experimentally proved that if the earth potential to remote earth is below 4 V, the effect of stray currents and, hence, corrosion could be neglected. However, depending on the soil resistivity, different levels of potential can be defined as the critical level.

Thunehed et al. [18] showed that the thickness and resistivity of different layers of the ground have a significant impact on the electric potential and, hence, level of the corrosion. They used a three layers ground model with different thickness and resistivity to investigate the distribution of electric field due to a DC current of 1000 A injected into an electrode at the ground surface. They found that low resistivity of the top layers can reduce the electric field near the surface, and low resistivity of the deep layer reduces the field at far distances. As a result, in the design of HVDC ground electrodes, it is necessary to ensure that the DC current penetrates deeply into the ground, which will result in lower potential rise around the electrodes. Therefore, in order to prevent stray-current corrosion on the metallic installations, areas with low resistivity at depth are preferred for grounding electrodes [18].

Consideration of DC stray current effects on metallic infrastructures can enhance the preliminary design and configuration of an HVDC system. For example, the Moyle interconnector, a ±400 kV HVDC link with a rated power of 500 MW between Northern Ireland and Scotland, was originally designed to operate in a monopolar ground return mode, but in order to reduce compass deviation and corrosion effects on nearby metallic pipelines, the design was changed to metallic return. Also, Basslink, a ±400 kV HVDC cable link with a rated power of 500 MW connecting the Australian mainland to Tasmania, is another example in which the preliminary design was based on a monopolar sea return, but in order to prevent corrosion effect on the metallic structures, the decision was changed to metallic return [7].

C. DC bias of power transformers in the AC substations

A DC component in the magnetising current of the transformer generates DC flux density in the transformer core which may cause magnetic saturation in the core. This phenomenon, known as "transformer DC magnetic bias" cause excessive core vibration, acoustic noise, high temperature and harmonic distortion in the transformer. This could lead to abnormal operation of the substations, power plants and power system in general [19]. The potential rise caused by DC return current through the ground can cause neutral points of the grounded transformers of the AC substations to have different potentials. Consequently, part of the DC current flowing between the two HVDC electrodes finds an alternative return path through the AC system via the grounded neutrals of the transformers [19], as shown schematically in Fig 5.

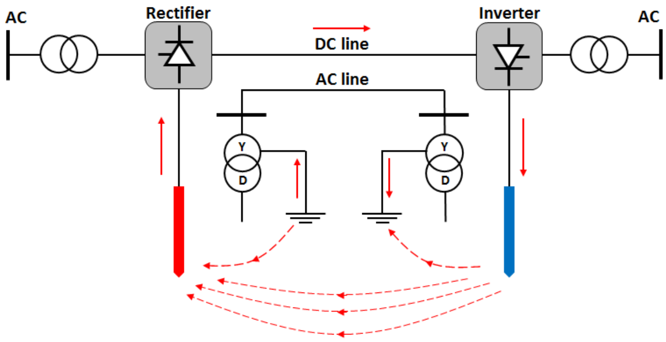


Fig 5 DC bias of AC transformers in the vicinity of a HVDC system

Factors affecting the degree of DC bias of the transformers include: (i) relative distance between the AC substations and HVDC grounding electrodes (ii) parameters of the AC transmission lines (iii) grounding systems of the power transformers and (iv) soil resistivity [20]. As a general rule, HVDC electrodes should be located a certain distance away from the converter stations and adjacent AC substations. A minimum distance of 3 km is recommended by Tykeson et al. [21]; but in IEC standard 62344 [9], it is recommended that the distance between the HVDC electrodes and any AC substation should not be less than 10 km. However, experiences from the real HVDC systems indicate different results; some of these are presented here.

Zhang et al. [20] have reported that, when a ±500 kV HVDC system uses ground as the return current path during planned services, power transformers in adjacent AC substations operate in abnormal conditions. DC current distribution in the AC transmission line and neutral point of the grounded transformer was measured at three AC substations, when a DC current of 1500 A was flowing from the HVDC grounding electrode. The measurement results indicated that, although the distance between substation "A" and the grounding electrode is more than 50 km, a DC current of 31.2 A flowed into the neutral point of the transformer. In contrast, at substation "B", which is closer to the grounding electrode, the DC current flowing through the transformer is only 13.4 A which is much smaller than that of substation "A" transformer. This implies that the DC current flowing through the neutral point of transformers cannot be determined by only the distance between the AC substations and the electrodes, but in fact it depends on the resistance of the ground path. The potential difference between the substations caused by the DC current is also a key factor and should be considered in the design of the grounding system of the HVDC system and AC substations.

Another consequence of DC magnetic bias of AC transformers is an increased level of acoustic noise from the transformer. A case-study has been undertaken by Wang et al. [22] on two main transformers at Ri Zhao and Huang Dao substations, adjacent to the Yinchuandong converter station of the ±660 kV, 4000 MW Ningdong-Shandong HVDC link. When the HVDC system is operated in monopolar earth return mode, a DC current of about 1000 A is circulated in the ground return path; and the power transformers at both AC substations were observed to undergo significant vibrations and noise. When the configuration of the HVDC system was changed to metallic return, vibrations and noise of both transformers were observed to return to normal levels. Location of the Yinchuandong converter station and Rizhao, and Huangdao substations are shown in Fig 6, and a summary of the results is shown in Table 1. The approximate distance between the Huang Dao and Ri Zhao substations, and the Yinchuandong converter station are 45 km and 100 km, respectively.

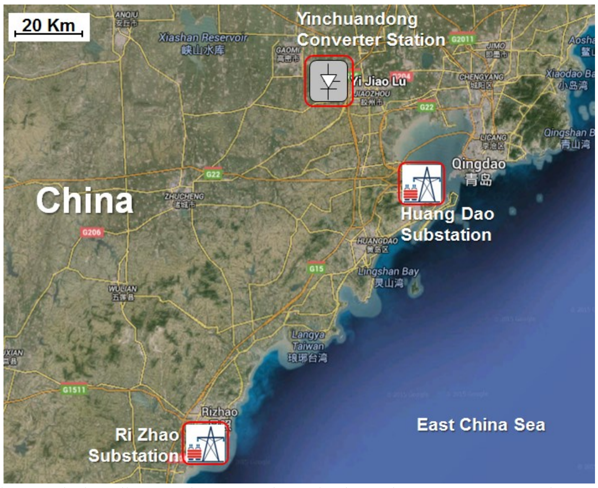


Fig 6 Relative distance between the Yinchuandong converter station and Ri Zhao, and Huang Dao AC substations

Table 1 Acoustic noise and direct current at the neutral point of transformers

Main transformer	DC current through neutral (A)	Transformer noise intensity (dB)	
		Normal operation	DC current through the neutral
Ri Zhao	13.9	78	95
Huang Dao	9.6	77	87

The results shows that a DC current of 13.9 A flows through the neutral point of the transformer at Rizhao substation which results in a 17 dB increment in the transformer noise. Similarly, a DC current of 9.6 A flows through the neutral point of the "transformer at Huangdao substation which causes a 10 dB increment in the transformer noise. Similar investigations have been performed by other researchers, as reported in [23, 24], and practical methods were described to limit or block DC bias of power transformers [23, 24, 25, 26].

Local soil resistivity and the AC network parameters are determinant factors in the selection of a suitable mitigation method. For example, a 5 Ω resistor was installed at the neutral point of "No. 1 main transformer" of the Chun-Chang substation to limit the DC bias of the transformer to 6 A, when the adjacent ±500 kV Gui-Guang HVDC system was operating in monopolar ground return mode with a nominal power of 750 MW. This method was found as an easy and economic method for this particular substation [24]. In high resistivity areas, however, a large resistor value is required to limit the DC bias of the transformers. Simulation results indicated that a DC resistance of more than 100 Ω was required to eliminate the DC bias of the main transformer in the Radisson substation in Quebec in Canada [26]. This can affect the original design performance of the transformer grounding system.

Reverse injecting current is also a practical method to mitigate the DC bias of transformers. In this method, a reverse DC current is injected into the transformer neutral point to reduce or eliminate the DC bias created by the ground current [20]. When applied to particular Chinese substations, the results showed that the DC bias of the transformer was reduced from 11 A to 2.2 A, which resulted in significant reduction in transformer noise and vibration [25]. Some other practical methods are also proposed, e.g. using a series capacitor in the neutral of the transformer as a blocking capacitor for the direct current, series compensation on AC transmission line and implementing sea electrode (when available) [25-26].

IV. ELECTRODE MATERIAL

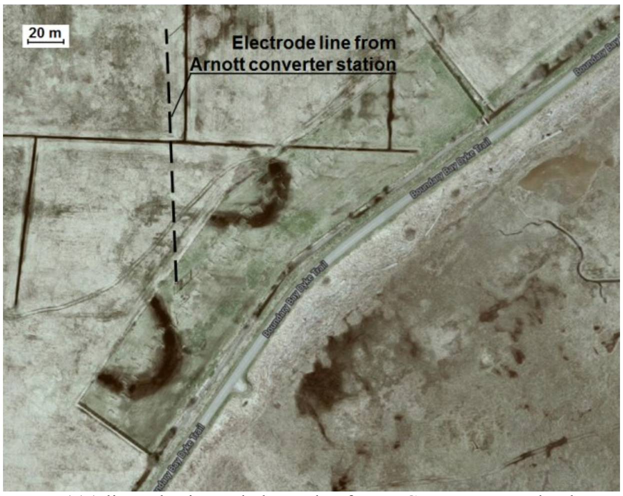
Electrolytic corrosion is usually one of the most important factors in the design of HVDC grounding electrodes which is related to the anodic and cathodic performance of the electrodes. Cathodic electrodes of HVDC systems are not influenced by corrosion and, hence, if the grounding electrode is implemented as a cathodic electrode only, the obvious electrode material to use is copper [2]. The Baltic cable between Germany and Sweden, the Fenno-Sakan link between Sweden and Finland, the Kontec link between Germany and Denmark and the Sacoi link in Italy are few examples that use copper conductors for cathodic electrodes.

In bipolar HVDC systems, power flow direction can be either way, and both electrodes at the sending and receiving ends of the HVDC system are designed to accommodate bidirectional current flow, i.e. the electrodes should be able to operate as anodic and cathodic electrodes. The main types of electrode material used for HVDC electrodes [2, 21]: titanium coated mesh electrodes, high silicon iron alloys electrode (SiCrFe) and carbon graphite electrode

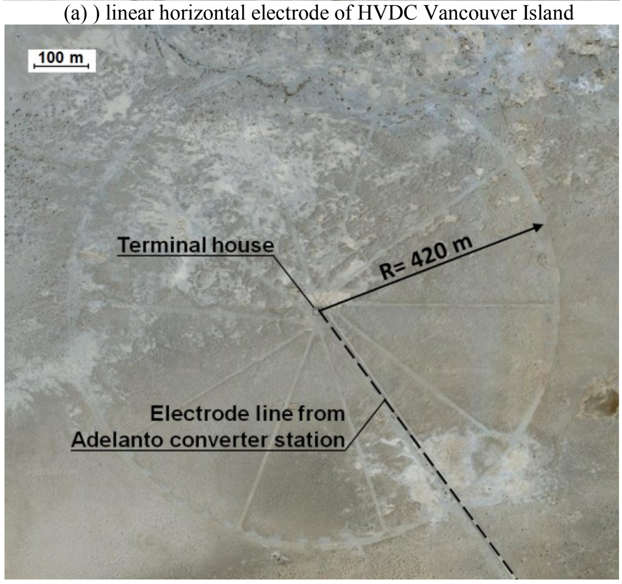
V. LAYOUT OF HVDC GROUNDING ELECTRODES

Apart from the inherent properties of the ground (or the soil medium in general), the geometry or layout of the grounding electrode is a significant factor to meet the criteria and requirements of an optimised performance of the grounding system. Typical physical layouts of HVDC grounding electrodes include: ring, star, linear horizontal and linear vertical electrodes also known as a deep-hole electrode [5, 14].

The selection of a particular electrode configuration depends on available land area, geographical location and electrical properties of the soil medium. Ring or star configurations are usually preferred when a wide area is available; while linear electrodes are chosen when a long and narrow strip of land is available [9]. These electrodes are usually buried at a depth of a few meters. Vertical electrodes, on the other hand, are not limited by space, since they are buried vertically in the ground and, hence, occupy less land. Vertical electrodes are an alternative when implementation of horizontal electrodes is not feasible, e.g. in areas with high resistivity in the top soil layer, vertical electrodes are preferred because using horizontal electrodes might result in high step voltage [14]. Two examples of horizontal electrode: land-based linear horizontal electrode of Vancouver Island and land-based ring electrode of the IPP HVDC line are shown in Figs 7-a and 7-b, respectively.



(a)) linear horizontal electrode of HVDC Vancouver Island



(b) ring electrode of IPP HVDC line
Fig 7 Examples of land-based horizontal electrode

For maintenance and inspection purposes, HVDC electrodes are generally divided into segments. The number and length of the segments should be chosen in such a way that if one segment needs to be removed, in case of maintenance or fault, the remaining electrode segments can still operate normally and safely under the nominal grounding current [9]. Regardless of the physical configuration, HVDC ground electrodes should provide a very low resistance to transfer high current to the ground continuously with a minimised power loss. Such a very low ground resistance requires a very large electrode dimension. The electrode resistance for three main types of HVDC electrodes, ring, horizontal linear and vertical linear are defined by following equations, respectively [14]:

$$R_e = \frac{\rho}{\pi^2 D} \ln \frac{4D}{\sqrt{dh}} \quad (3)$$

$$R_e = \frac{\rho}{\pi l}\left[\ln \frac{2l}{\sqrt{dh}} - 1\right] \quad (4)$$

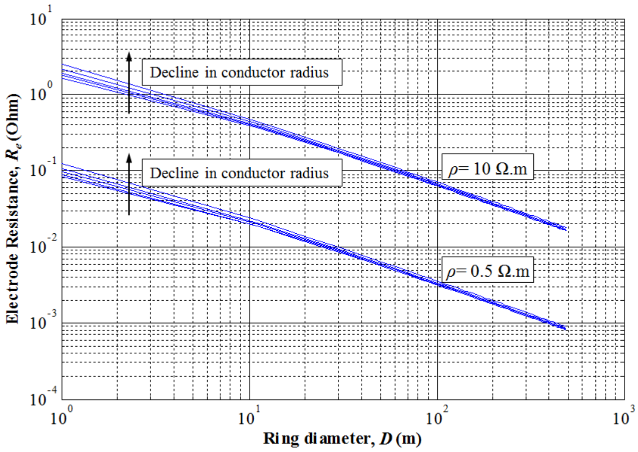
$$R_e = \frac{\rho}{2\pi l}\left[\ln \frac{4l}{d} - 1\right] \quad (5)$$

where R_e is the electrode resistance in Ω, ρ is the soil resistivity in Ωm, D is the diameter of the ring electrode in m, l is the total length of the conductor in m, d is the conductor diameter in m and h is the burial depth in m. Based on (3) to (5), resistance of a ring electrode versus its diameter, and resistances of linear horizontal and vertical electrodes versus electrode length at different conductor diameters and two soil resistivities, 0.5 Ωm and 10 Ωm were calculated. The results are shown in Figs 8-a to 8-c, respectively. In these calculations, a burial depth of 3 m was considered for the ring and linear horizontal electrodes. The radius of the conductor was changed from 2 mm up to 10 mm with length increments of 2 mm.

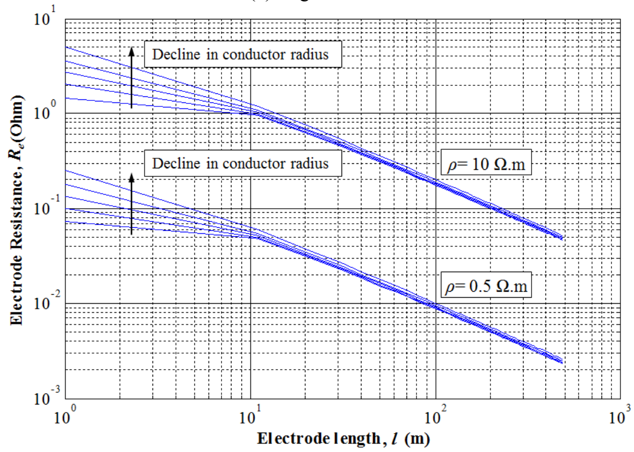
As expected, Fig 8 clearly indicates that a larger electrode dimension provides lower electrode resistance. Furthermore, for each particular electrode dimension, the ring and linear horizontal electrodes produce lower electrode resistance than the linear vertical electrode. However, the conductor diameter does not have a major impact on the electrode resistance because of the relatively large size of the electrode. Soil resistivity is also a principal factor in the determination of the resistance of the grounding electrodes. Therefore, using a ring electrode in a low resistivity area is a preferred option to obtain a low resistance electrode which is a key requirement for optimised performance of HVDC systems. This issue is strongly recommended in the literatures, specifically in [9].

SUMMARY

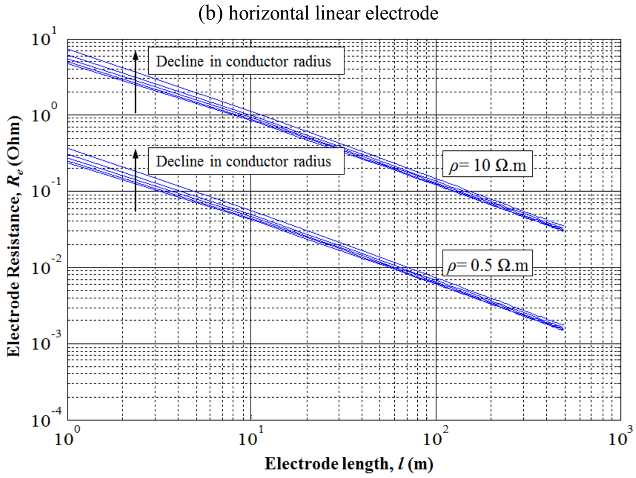
HVDC systems can be designed to operate in bipolar and monopolar modes. For the latter, either a metallic return or ground/sea return can be used. Depending on the HVDC mode, there are different requirements for the DC grounding systems. For monopolar ground/sea return systems, the DC earth electrodes must be designed to sustain continuous full load current, while for the other configurations, the earth/sea path may only be required to carry rated current for relatively short periods. HVDC systems with ground/sea return can introduce severe adverse effects on metallic structures and AC power systems in their vicinity. The affected area can extend to a radius of tens of kilometre around each electrode. The ground current affects the adjacent systems in two ways; (i) corrosion and (ii) DC bias of transformers of AC power systems.



(a) ring electrode



(b) horizontal linear electrode



(c) vertical linear electrode

Fig 8 Dependence of resistance on electrode dimensions and soil resistivity

The modelling and prediction of DC current flow in HVAC neutral-earth paths is difficult due to the complexity of the modelling process and the uncertainty in the soil resistivity conditions that determine the potential distributions across the neutral points of the power system. Current flows in the neutral earth path of transformers cause excessive vibration, noise, and voltage and current distortions. Mitigation methods include installation of neutral to ground resistors, neutral to ground capacitors and active reverse current injection schemes.

HVDC earth electrodes must be designed to limit the ground potential rise and voltage gradients in the vicinity of the electrodes to safe levels. This requires a low earth resistance and may be achieved using a very large area earthing system. Ring or star configurations with overall dimensions of several hundred metres may be used when land is available while long horizontal electrodes may be used if available land is restricted. Long vertical electrodes may also be used if land area is limited or if deep low resistivity ground can be penetrated.

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