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INTERNATIONAL STANDARD

colour inside

Design of earth electrode stations for high-voltage direct current (HVDC) links – General guidelines

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COMMISSION

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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DESIGN OF EARTH ELECTRODE STATIONS FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) LINKS – GENERAL GUIDELINES

FOREWORD

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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC TS 62344:2013. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC TS 62344 has been prepared by IEC technical committee 115: High Voltage Direct Current (HVDC) transmission for DC voltages above 100 kV. It is a Technical Specification.

This second edition cancels and replaces the first edition published in 2013. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- Changed the requirement of earthing resistance limit for short-time unipolar earth system in 5.1.3.
- Corrected the coefficient before ρ_s from 0,015 9 to 0,008 in touch voltage limit calculation formula (3) in 5.1.5.
- Deleted the analytical calculation formulas of earthing resistance for sea and shore electrodes in 6.1.3.
- Changed the current density limit from 100 A/m^2 to 40 A/m^2 ~ 50 A/m^2 for the sea electrodes that are not accessible to human beings or to marine fauna in 6.1.7.
- Extended some detailed technical requirements for the measurement of ground/water soil parameters in 6.2.5.
- Reformulated the types and characteristics of electrode element material for sea and shore electrodes in 6.3.2.
- Added an informative Annex B: Earth electrode design process.
- Added an informative Annex C: Test results of human body resistance.
- Deleted the formula for calculating the average soil resistivity using harmonic mean when processing the measurement data in D.2.6 of Annex D.
- Extended some detailed technical requirements of electrode online monitoring system in Annex H.
- CIGRE 675:2017 is added to the bibliography.
- Terminology and way of expressions are modified using more commonly used terms in the HVDC electrode design industries and English speaking countries, so as to make the readers understand the content more easily.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
115/276/DTS	115/293/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

The high-voltage DC earth electrode is an important part of the DC power transmission system. It takes on the task of guiding the current into the earth under the monopolar ~~metallic~~ earth return operation mode, and the unbalanced current under the bipolar operation mode. Further, it secures and provides the reference potential of ~~valve~~ converter neutral point under the bipolar/ monopolar operation mode, to protect the safe operation of the valves.

DC earth electrodes include land electrodes, sea electrodes, and shore electrodes. Today, there are around tens of DC electrodes in the world. Their influence on the nearby and far away environment is produced when there is DC current continuously leaking into the earth through DC earth electrodes.

Their influence on the surrounding environment includes:

a) influence on humans, mainly due to step voltage, touch voltage and transferred voltage;

b) influence on the electrode itself, mainly reflected by ~~earth~~ ground temperature rise and corrosion on the electrode;

c) influence on nearby ponds and organisms in the sea;

d) influence on the AC power system, mainly reflected by the DC voltage excursion of transformer neutral point;

e) influence on buried metallic objects, mainly revealed by the corrosion of buried metallic pipelines, AC grounding grids, tower foundations for power transmission lines and armoured cables, etc.

A great deal of experience has been accumulated in the research and design work in many countries, and relevant national standards or enterprise standards have been developed. The aim of this document is to develop the design guide for DC earth electrodes, on the site selection, material selection, shape, buried depth, adoption of equipment and connection styles, etc. It ~~could~~ can be referred to by the ~~specialized employees~~ electrode design engineers in different countries, to ensure the safe operation of earth electrode under different modes, control the influence on the environment nearby and the environment far away to the acceptable level, and to reasonably decrease engineering costs.

To ensure this document is more scientific, precise and practical, ~~IEC/PAS 62344:2007 is referred to, and~~ some research results obtained in recent years are adopted.

DESIGN OF EARTH ELECTRODE STATIONS FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) LINKS – GENERAL GUIDELINES

1 Scope

This document applies to the design of earth electrode stations for high-voltage direct current (HVDC) links. It is intended to provide necessary guidelines, limits, and precautions to be followed during the design of earth electrodes to ensure safety of personnel and earth electrodes, and ~~prevent~~ reduce any significant impacts~~ they may exert~~ on DC power transmission systems and the surrounding environment.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC~~/TS~~ 60479-1, *Effects of current on human beings and livestock – Part 1: General aspects*

IEC TS 61201, *Use of conventional touch voltage limits – Application guide*

IEC 61936-1, *Power installations exceeding 1 kV AC and 1,5 kV DC – Part 1:~~ Common rules~~* AC

IEC TS 61936-2, *Power installations exceeding 1 kV a.c. and 1,5 kV d.c. – Part 2: d.c.*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
earth (ground) electrode
~~**ground electrode** (US)~~
~~structure with a conductor or a group of conductors embedded in the soil or immersed in sea water, directly or surrounded with a specific conductive medium~~

~~EXAMPLE Coke, providing an electric connection to the earth, for transmission of d.c. current from a d.c. system.~~

conductive part that is in electric contact with local earth, directly or through an intermediate conductive medium

[SOURCE: IEC 60050-195:~~1998~~2021, 195-02-01]

3.2
land electrode
earth electrode buried in the ground~~ more than 1 km away from the coastline~~ above the high tide water level and located away from the shore and not influenced by water bodies

3.3
shore electrode

3.3.1
beach electrode
~~electrode located on the beach inside the waterline (usually less than 1 km away from the waterline), and the active part of the electrode makes contact with the soil or with underground water, but not directly with seawater or pond electrodes~~

electrode located on the shore above the low tide water level, where the active part of the electrode is in contact with the soil or with underground water, but not directly with seawater

Note 1 to entry: Compared with land electrode, beach electrode is relatively close to the shore and is influenced by water bodies.

3.3.2
pond electrode
~~electrode usually placed outside but within 100 m of the waterline, having electrodes directly in contact with sea water, within a small area which is usually protected against waves and possible ice damage by a breakwater~~

electrode located on the seashore below the low tide water level, where the active part is directly in contact with seawater, within a small area which is protected by a breakwater against waves and possible ice damage or damage from other floating debris

3.4
sea electrode
electrode located away from the shoreline ~~at a distance deeper than 100 m into the sea~~ in a body of seawater

3.5
electrode station
whole ~~system~~ facility which ~~guides~~ transfers current from/to electrode line to/from the earth or sea water, usually including the feeding cable, towers, switchgear, fencing and any necessary auxiliary equipment in addition to the electrode itself

3.6
common or shared earth electrode
earth electrode system, which is composed of a single earth electrode or multiple earth electrodes in parallel, shared by multiple converter stations

~~Note 1 to entry: It mainly consists of earth electrodes and intertie lines between sub- earth electrodes in different electrode sites.~~

3.7
electrode site
site where the earth electrode is located

3.8
electrode line
overhead line or underground cable used to connect the neutral bus in a converter station to the earth electrode station

3.9
~~**feeding rod**~~
electrode element
earthing conductor buried underground or in the sea for guiding earthing current into the surrounding medium (soil or sea water)

~~Note 1 to entry: They are the most important devices in an earth electrode station.~~

3.10
feeding cable
cable used to guide current from current-guiding wire to ~~feeding rods~~ electrode elements

3.11
current-guiding wire
main branch used to conduct current from electrode line (or bus) to feeding cables

3.12
current guiding system
system used to guide the current from electrode line to feeding rods electrode elements

Note 1 to entry: It consists of current-guiding wire(s), disconnecting switches, feeding cables and connections.

3.13
jumper cable
cable used to connect two feeding rods electrode elements placed at some distance from each other

EXAMPLE At two sides of a channel. The cable that connects the two electrode elements on either side of a trench when the electrode has to cross the trench.

3.14
earth return operation mode
operation mode in the HVDC power transmission system, using DC lines and earth (or sea water) as the current loop

3.15
earth return system
series set of devices designed and built specifically for earth return operation mode

Note 1 to entry: It mainly consists of the electrode line, earth electrode, current guiding system, and other auxiliary facilities.

3.16
rated current under monopolar mode
current of a converter station at rated power in monopolar (operation) mode

3.16
system rated current
nominal rated current of one converter pole of the HVDC system

3.17
maximum short-time overload current
maximum current for which the associated d.c. system(s) is designed for monopolar operation for longer than several minutes that can be sustained in monopolar operation condition of DC system for a defined time interval (generally between 10 s and 2 h)

3.18
maximum transient overcurrent
average maximum current flowing through the earth electrode for a few seconds (generally less than 10 s) when a system disturbance occurs

3.19
unbalanced current
difference of current between two poles during operation of a bipolar DC system

Note 1 to entry: For symmetrical balanced bipolar operation mode, the unbalance current flowing can be controlled automatically by the control system within about 1 % of the rated current.

Note 2 to entry: For asymmetrical unbalanced bipolar operation mode, the current flowing through the earth electrode is the difference in currents between the two poles.

3.20
cathode
electrode capable of emitting negative charge carriers to and/or receiving positive charge carriers from the medium of lower conductivity

Note 1 to entry: The direction of electric current is from the medium of lower conductivity, through the cathode, to the external circuit.

Note 2 to entry: In some cases (e.g. electrochemical cells), the term "cathode" is applied to one or another electrode, depending on the electric operating condition of the device. In other cases (e.g. electronic tubes and semiconductor devices), the term "cathode" is assigned to a specific electrode.

[SOURCE: IEC 60050-151:2001, 151-13-03]

3.21
anode
electrode capable of emitting positive charge carriers to and/or receiving negative charge carriers from the medium of lower conductivity

Note 1 to entry: The direction of electric current is from the external circuit, through the anode, to the medium of lower conductivity.

Note 2 to entry: In some cases (e.g. electrochemical cells), the term "anode" is applied to one or another electrode, depending on the electric operating condition of the device. In other cases (e.g. electronic tubes and semiconductor devices), the term "anode" is assigned to a specific electrode.

[SOURCE: IEC 60050-151:2001, 151-13-02]

3.22
current-releasing density

~~**3.22.1**~~
~~**current-releasing density per unit length**~~

~~current released to earth from a unit length of feeding rod (in A/m)~~

~~**3.22.2**~~
~~**current-releasing density per unit area**~~

~~current released to earth from a unit area of coke surface (in A/m^2)~~

3.22.1
linear current density
current released to earth from a unit length of electrode element

Note 1 to entry: It is expressed in A/m.

3.22.2
surface current density
current released to earth from a unit area of the coke-soil interface

Note 1 to entry: It is expressed in A/m^2.

3.23
designed lifespan
designed operational lifespan of the earth electrode, typically of the same order as the operational lifespan of the converter station

3.24
corrosion lifespan
time integral of current when an earth electrode runs as an anode, such as monopolar operation and bipolar operation with unbalanced current, during its designed lifespan

Note 1 to entry: It is expressed in the unit of ampere hour (Ah).

3.25
thermal time constant
time required for the temperature of the soil ~~to reach the steady state temperature at the initial rate of rise of temperature~~ immediately adjacent to the active elements of an electrode to reach 63,2 % of the steady state temperature rise at a given current

~~Note 1 to entry: In practice the soil temperature rises nonlinearly when earthing current is released into earth through an electrode, see Annex F.~~

3.26
earthing resistance
resistance between an earth electrode and remote earth ~~at an infinite distance~~ with zero potential

3.27
step voltage
~~voltage between two points on the Earth's surface that are 1 m distant from each other, which is considered to be the stride length of a person~~

~~[SOURCE: IEC 60050-195:1998, 195-05-12]~~

difference in surface potential experienced by a person or animal bridging a distance between two feet without contacting any other grounded object

Note 1 to entry: For a human the distance between the two contact points on the earth is normally taken as 1 m.

3.28
touch voltage
potential difference between ~~a grounded metallic structure and any point on the earth 1 m from the structure~~ the surface potential at the point where a person is standing and the potential of a grounded structure touched by him

3.29
transferred voltage
~~potential difference applied to a person when this person stands on the ground near the earth electrode and touches a conductor grounded at a remote site, or when this person stands on the ground far away from the earth electrode and touches a conductor grounded near the electrode site~~

special case of the touch voltage where a voltage is transferred into/out of a point near the electrode site from/to a remote point far away from the electrode site

3.30
insulated metallic structures
metallic structures buried in the ground ~~near an earth~~ within the electrode interference area and coated with insulating material to isolate the structure from earth

3.31
bare metallic structures
metallic structures buried in the ground ~~near an earth~~ within the electrode interference area and not coated with insulating material

3.32
coefficient of uneven current density distribution
ratio of maximum current-releasing density at any specific point of an earth electrode, to the average current-releasing density of that earth electrode

Note 1 to entry: This parameter reflects the uniformity of current released from the earth electrode to the surrounding medium and is a dimensionless quantity.

3.33
equivalent earthing current
ratio of time integral of current of an earth electrode operated as a cathode or anode to its designed lifespan

Note 1 to entry: It is used to analyse the corrosion impact on underground metallic objects in the vicinity of the electrode.

4 System conditions

4.1 General principles

The system conditions to be considered during earth electrode design mainly include the amplitude and duration of the current relating to the earth electrode, and designed lifespan and polarity.

4.2 System parameters related to earth electrode design

4.2.1 Amplitude and duration of the current

The operation current and duration of DC earth return operation systems should normally be specified in local regulations, bid documents, or specifications. In the absence of such documents that can be used as a reliable source, the following values may be used as a reference during design:

a) the amplitude of earth electrode rated current is equal to the HVDC system rated current (I_N). The maximum duration of this current corresponds to that of the monopolar earth return operation mode of the earth electrode. The duration of rated current can be continuous or of defined length. A typical defined length for a bipolar system~~,~~ is the interval from the time when the monopolar system is put into service to the time when the bipolar system is put into service~~ is typically used~~;

b) the amplitude of the maximum short-time overload current is typically 1,1~1,3 I_N. The maximum duration of this current is generally the time allowed for operation at maximum overload current~~ after~~ with the redundant cooling equipment~~ is put into~~ in service;

c) the amplitude of the maximum transient overcurrent is determined through system stability calculation, typically in the range of 1,25~1,5 I_N. The maximum duration is generally a few or less than 1 s;

d) the amplitude of bipolar unbalanced current is the difference of the operating currents of two poles. For DC power transmission systems with two symmetrically operated poles, the value is very small relative to I_N, e.g. 1 % of I_N. The duration is the same as the bipolar operation time of the~~ earth electrode~~ HVDC system.

4.2.2 Polarity

Polarity of the earth electrode~~ shall comply~~ should be selected to be consistent with system operation and environment protection requirements. For anode type earth electrodes, the corrosion of earth electrode material~~ shall~~ should be~~ taken into account~~ considered.

If there are any long buried metallic structure~~ near~~ within the~~ earth~~ electrode interference area, corrosion at the~~ far~~ distal end of the metallic structures should also be~~ taken into account~~ considered. For cathode type earth electrodes, the focus should be on the corrosion impact on proximal end of buried metallic structures~~ near~~ within the~~ earth~~ electrode interference area. Should the cathode type earth electrode be a sea electrode, the impact of compound sediments near the earth electrode is also a concern.

For earth electrodes with reversible polarity, in addition to the above issues relating to cathode and anode type earth electrodes, attention shall be paid to safe operation with reversible polarity. The earth electrodes for bipolar and asymmetrical monopolar VSC systems~~ are often~~ should be designed with reversible polarity.

4.2.3 Designed lifespan

The design of an earth electrode should generally allow construction and operation of associated converters in a series of steps. The designed lifespan~~ shall~~ should not be~~ the same as~~ less than that of the converter station using this earth electrode. Where no specific lifespan is specified, the minimum designed lifespan of an earth electrode should be 30 years or more.

Within the designed lifespan of an earth electrode, loss of earth electrode material caused by corrosion shall not affect its normal operation. During calculation of earth electrode corrosion during a lifespan, the following aspects~~ shall~~ should be~~ taken into account~~ considered:

a) monopolar system: for an LCC monopolar system (or a bipolar system with one pole built and put into operation at an earlier stage), the polarity of the earth electrodes can be determined by the system planning studies.~~ Where no specific requirements are stated, the design shall be based on the anode type of the earth electrode~~ For a VSC asymmetric monopolar system (or bipolar system consisting of asymmetric monopole converters), the design of both (all) electrodes needs to allow for polarity reversals and anodic operation, as the system changes power direction by changing the current direction rather than changing voltage polarity;

b) bipolar system operated in monopolar mode: after a bipolar system is put into service, the situation where one pole is out of service for repair or maintenance and the other pole (healthy pole) is operated using earth as the circuit return, shall be considered. In this case, the ampere hours during operation as an anode shall be calculated based on data provided by the system planning studies;

c) bipolar operation: during bipolar operation, the ampere hours of unbalanced current during operation as an anode shall should be selected calculated.

4.2.4 Common earth electrodes

For a common earth electrode(s) shared by multiple converter stations, the worst case which should be taken into account considered is where monopolar earth return operation mode occurs simultaneously at more than one converter station with the same polarity. Calculation of earthing current of the earth electrode(s) should consider the probability of superposition of currents from different converter stations. Usually, higher requests of electrode sites are demanded when common electrodes are under design. So compared with ordinary electrodes, common electrodes usually demand higher requirements for electrode site conditions.

The designed lifespan of a common earth electrode shall be determined as the interval from the time when the first converter station is put into operation to the time when the last converter station is put out of use.

The polarity of the common earth electrode is determined by summing the directions and amplitudes of the currents from all the converter stations that share it.

5 Design of land electrode stations

5.1 Main technical parameters

5.1.1 General principles

The design of the land electrode shall ensure its safe and reliable operation throughout its lifespan and under different earthing current conditions including rated current, maximum overload current, and maximum transient overcurrent. Different technical parameters such as temperature rise of the earth electrode, earthing resistance, step voltage, touch voltage and transferred voltage shall be controlled within the specified range by appropriate choices of electrode shape and buried depth. It is important to note that the change of electrode shape or burial depth does not affect the electric field strength further than 1 km to 2 km away from the electrode.

For a common earth electrode(s) or multiple earth electrodes within a short distance of each other, the situation of long time simultaneous and continuous operation of DC systems with the same polarity under earth return operation mode shall be avoided as much as possible. In addition, the effect of one circuit operated in monopolar earth return mode on the neutral voltage shift of other bipolar systems should be considered.

Calculation of characteristics of earth electrodes shall be performed with programs. See Annex E for the calculation principles.

Calculation of parameters and performance of earth electrodes should be done with computer software. See Annex G for the calculation principles.

5.1.2 Temperature rise

Under all circumstances, the maximum temperature of any point of the earth electrode shall be lower than the boiling point of water at the local altitude. For example, at an elevation of 0 m, the maximum allowed temperature is 100 °C. The temperature rise calculation method is listed in Annex F described in Annex G.

5.1.3 Earthing resistance

The determination of earthing resistance for the electrode shall consider two aspects:

a) the ground temperature rise of soil;

b) touch and step voltage rise locally at the electrode station.

For an earth electrode in any operation mode which ~~gives~~ involves a large earthing current, if the duration of the current is longer than the thermal time constant of the electrode (see ~~Annex F~~ Annex G for the calculation method), which is typically the case for rated current flowing into the earth for a long time, the maximum permissible earthing resistance is typically dependent on the permissible temperature rise, which should be in accordance with Formula (1):

$$R_e \le \frac{1}{I_d}\sqrt{2\lambda_m \frac{\rho^2{}_e}{\rho_m}(\theta_{max} - \theta_c)} \qquad (1)$$

where

R_e is the earthing resistance between the earth electrode and remote earth ~~at an infinite distance~~ with a zero potential (Ω);

I_d is the ~~a certain~~ earthing current which flows into the earth for a long time (A);

λ_m is the thermal conductivity of the soil where the earth electrode is buried (W/(m·°C));

θ_{max} is the maximum allowed ~~soil~~ ground temperature (°C);

θ_c is the maximum natural ground temperature ~~of soil~~ (°C);

ρ_m is the resistivity of the soil where the earth electrode is buried (Ω·m);

ρ_e is the general equivalent earth resistivity at the electrode site (Ω·m~~, see B.2.6 for the calculation method~~).

~~$$R_{e\,max} \le \frac{1}{I_d}\sqrt{2\lambda \frac{\rho^2{}_e}{\rho_m}\mathrm{dfac}(\theta_{max} - \theta_c)} \qquad (2)$$~~

~~where~~

~~dfac is the heat dissipation factor, typically in the range 5~10. In the absence of an accurate value, 5 is recommended.~~

If the duration of the current is shorter than the thermal time constant of the electrode, the maximum permissible earthing resistance could be increased significantly than that determined by Formula (1) from the point view of ground heating. In this case, the area of the coke-soil interface and current density at the interface is usually used to control the ground temperature rise instead of earth resistance (see 5.5.3).

5.1.4 Step voltage

The step voltage of any ground point that can be accessed by the public shall not exceed the safety limits defined for humans and livestock. According to tests conducted on 1 028 subjects, over 95 % of the subjects have a foot to foot human body resistance greater than 1 400 Ω (see Annex C), which is slightly different from the hand to hand human body resistance given by IEC 60479-1, and over 95 % of the subjects have no strong feeling at a DC current of 5,3 mA. Based on these test results and in consideration of different amplitudes and durations of DC system earthing currents, the maximum allowed step voltage of any point on the ground can be determined with Formula (2) under maximum short-time overload current of one pole.

~~$$E_{tp} = 7{,}42 + 0{,}0159\,\rho_s \qquad (4)$$~~

$$E_{sp} = 7{,}42 + 0{,}03\,\rho_s \qquad (2)$$

where

E_{sp} is the permissible step voltage (V);

ρ_s is the resistivity of surface soil (Ω·m).

During contingency conditions, such as maintenance of the earth electrodes (1/8 or more parts of earth electrodes are out of service), according to IEC TS 61201 and IEC 60479-1, the maximum permissible step voltage (E_{sp}) shall be less than 70 V. Under such conditions, the electrode shall be fenced to prevent access by the public and animals, and maintenance staff shall be advised of the hazards and should take adequate precautions.

For common earth electrodes or multiple earth electrodes with a short distance, to lower the step voltage, the situation where two DC systems run simultaneously with the same polarity under earth return operation mode shall be avoided as much as possible. However, the case of these systems running in short-time (e.g. < 30 min) earth return operation mode with the same polarity due to accidents (e.g. equipment failures or human errors or lightning strikes, etc.) should be considered during design. Considering that it is small probability, the maximum allowed ground step voltage for common earth electrodes can be increased appropriately with reference to Formula (2) in this case, on the premise that the ~~secondary~~ impacts on the surrounding facilities have been evaluated and the maximum permissible step voltage is lower than that in contingency conditions.

If any point on the ground fails to meet the above requirement for maximum step voltage, mitigation measures shall be taken.

5.1.5 Touch voltage

For earthed metallic structures that can be accessed by the public, the touch voltage of any point on the site ground shall not exceed E_{tp} obtained from Formula (3) under maximum short-time overload current of one pole.

~~$$E_{tp} = 7{,}42 + 0{,}0159\,\rho_s \quad (4)$$~~

$$E_{tp} = 7{,}42 + 0{,}008\,\rho_s \quad (3)$$

where

E_{tp} is the permissible touch voltage (V).

For earthed metallic structures that cannot be accessed by the public, the maximum permissible touch voltage of any point on the site ~~ground~~ should be less than 70 V in general.

5.1.6 Current density

For land electrodes that are likely to run as anodes for a long time, the current density at the ~~contact between coke and soil~~ coke-soil interface should be limited to prevent electro-osmosis (moving of water by the electric field). For anode-type earth electrodes that run in monopolar mode for a long time and are in fine particle (clay) soil, the permissible average current density at the ~~surface of coke and soil~~ coke-soil interface should be limited to 0,5 A/m^2 to 1 A/m^2 at the rated current of one pole. For specified outage conditions (e.g. 30 % electrodes out of service), the current density may be higher as allowed by soil conditions.

~~For earth electrodes that run in bipolar mode for long periods or are in soil with high water content~~ In the case of a coarse-grained soil with large pore size and where the active portion of the electrode is below the water table, an average current density of 2 A/m^2 or higher may be the permissible value under rated current of one pole.

5.1.7 Field intensity in fish ponds

For earth electrodes near fish ponds, the field intensity of any point in the water should not exceed 15 V/m when operating at ~~rated~~ maximum short-time overload current.

For common earth electrodes or multiple earth electrodes within a short distance of each other, the case of systems running in short-time (e.g. < 30 min) earth return operation mode with the same polarity should be considered during design.

5.2 Electrode site selection and parameter measurement

5.2.1 General principles

Selection of the electrode site is a critical step ~~during~~ in the beginning of the earth electrode design, and also a complicated process, during which technical and economic comparison is required to select a safe, reliable, economically feasible, and environment-friendly site.

Local environmental impacts (see Clause 4) and remote environmental impacts (see Clause 7) should be focused on during selection of the electrode site. ~~Survey, measurement, and calculations are all necessary in this step. To reduce the impact of earth current on the environment, sea or shore electrodes should be considered first if possible. The common earth electrode solution can be adopted as a priority if system operation conditions are met.~~ Multiple geophysical and geotechnical surveys, geoelectric modelling, electrode pre-design and performance calculations (electrical and thermal) are all necessary in this step. To reduce the impact of earthing current on the environment, the sites which have lower resistivity in deep ground should be considered as the first candidate if possible. If the electrode will serve as ground return for more than one HVDC system with converter stations in the close vicinity, it is recommended to consider the common earth electrode solution if it can meet all the system operation conditions. Split earth electrodes or compact earth electrodes can be used if the technical and economic feasibility has been demonstrated.

5.2.2 Data collection survey

~~To find~~ For the evaluation of a suitable electrode site, a survey within a radius of at least 10 km should be conducted to obtain the natural conditions in the neighbourhood of the prospective electrode site~~, which~~. The survey data should at least include the landform and terrain, geological structure, hydrological-meteorological conditions, and ocean tide (for shore electrodes or sea electrodes), and a technical assessment should be carried out based on Annex D.

In addition, local development plans should be acquired from the local government or other relevant authority. For complete assessment of the electrode site under investigation, information should at least cover existing and planned power facilities (such as substations and lines), buried metal pipes, armoured or earthed cables, and railway lines.

~~It is recommended that the collection information about extra high-voltage a.c. power facilities should cover a larger range, e.g. within 50 km of the electrode site.~~

Depending on the tectonic setting of the area, it is recommended to collect information of extra high-voltage AC power facilities in a larger range, e.g. located within 50 km ~ 100 km or more of the electrode site. A high-resistivity terrain will require a wider geographical survey than a low-resistivity terrain.

5.2.3 Distance from converter station (substation)

~~During the determination of the electrode site~~ In the site selection process, the impact of the earth electrodes on surrounding converter stations and AC substations shall be ~~calculated~~ quantified. See Annex K for the calculation method. If calculation and analysis are not possible, the distance from the electrode site to any converter station or ~~220 kV or higher~~ high voltage AC substation should be no less than 10 km in general to ~~decrease~~ minimize the risk of DC current flow into the Y grounded windings of the AC transformers, and the minimum distance from the electrode site to any aerial power line with earth wire should be ~~greater~~ larger than 5 km to ~~decrease~~ reduce the risk of corrosion of tower grounding ~~devices~~ and foundation. If for some reason it is impossible to ~~keep outside~~ maintain these distances, measures should be taken to mitigate the effect, such as DC current-blocking devices in series with transformer neutral and ground (see Clause 7), or insulation between earth wires and the towers.

5.2.4 Environment conditions, terrain and landform

The electrode site should be ~~placed~~ located far away from cities and densely populated ~~towns and be located~~ residential areas, on a reasonably flat area, without ground erosions and rocks outcropping, and avoiding lowlands, without risk of flood erosion or long-time flood submersion. In addition, the location should be in an open space to provide a wide and conductive current-releasing area and to facilitate making the necessary connections.

~~5.2.5 Terrain and landform~~

~~The electrode site shall provide a wide and conductive current-releasing area. In particular, the resistivity of the soil around the electrode site is preferably less than 100 Ω·m. The soil should be damp but without any water-logging.~~

~~5.2.6 Measurement of soil parameters~~

~~During the design of earth electrodes, the main physical parameters of the soil on the electrode site including the soil resistivity model, soil thermal conductivity, thermal capacity, maximum environmental temperature, humidity, and ground water table (see Annex B for detailed measurement methods and technical requirements) should be measured.~~

~~5.2.7 Geological exploration~~

~~For one to two predetermined electrode sites, the drilling method is used to explore the soil type and cover layer thickness on the electrode site. The exploration should be carried out in a range not less than the size of the earth electrode and up to the depth of the bedrock, if it is not too deep.~~

5.2.5 Geophysical and geological surveys

In the beginning of the design of earth electrodes, the main physical parameters of the soil on the electrode site including the soil resistivity model, soil thermal conductivity, volume thermal capacity, maximum ambient temperature, humidity, and ground water table (see Annex D for detailed surveying methods and technical requirements) should be surveyed.

For the selected electrode sites, test holes shall be drilled for a direct survey of the shallow ground structure and for the determination of the structure of the sedimentary cover within the electrode site. The exploration should be carried out in a range not less than the size of the earth electrode and up to the depth of the bedrock, or the expected depth of the electrode. In the case of a vertical or deep well electrode, a survey method of well profiling that measures the resistivity of the well walls directly by means of a probe that is lowered down to the well could be used for the direct access of the shallow ground geoelectric structure. This data shall be used for the calibration of the shallow ground layers of the final geoelectric model for the electrode site.

5.2.6 Topographical map

1:1 000 or 1:2 000 topographic maps should be drawn based on ~~measurement results~~ a field survey. The measurement range should be defined in such a way to ~~ensure optimal layout~~ allow for the optimization of earth electrode~~s~~ layout.

5.2.7 Values selected during design

In general, reasonable values shall be selected for soil parameters based on actual ~~measurements~~ surveys through analysis, calculation and sorting:

- the reliability of the measurements should be higher than 95 %. For N effective values measured at the same place (X_1, X_2, …, X_N) , the average (X_p) and standard deviation (σ) can be calculated with:

$$X_p = \frac{1}{N}\sum_{1}^{N} X_n \tag{4}$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{1}^{N}(X_n - X_p)^2} \tag{5}$$

The value of soil parameters can be calculated with:

$$X = X_p + 1{,}96 \times k \times \sigma \tag{6}$$

where

k = +1 for soil resistivity and temperature, and

k = –1 for thermal conductivity and volume thermal capacity.

- in case of uneven distribution of a soil parameter on the electrode site, the electrode site calculation model can be simplified appropriately on an equivalent basis for convenient calculation, but the characteristic parameters such as earth electrode current-releasing density, maximum temperature, maximum step voltage, earthing resistance, potential rise and its distribution shall not be significantly affected. As a general rule, a layered 2D horizontal site model can be used if the electrode site lies in a plain area, and a 3D site model could be more precise if the site lies in an area with complex terrain such as mountain, coast or river;
- values selected for soil resistivity during the design should consider the influence of unfavourable seasons, which means the season coefficient should be applied after calculation with Formula (6).

5.3 Earth electrode and associated components

5.3.1 General principles for material selection

Feeding rod Electrode element material should be selected through technical and economical comparisons based on engineering and market conditions. The selection shall respect be based on the following principles: good conductive property, good resistance to erosion corrosion and to ground aggressivity (pH, chloride content, etc.), easy mechanical processing, no toxic or negative effect, and cost-effectiveness.

5.3.2 Selection of feeding rods electrode elements and characteristics

Feeding rods Electrode elements used for DC earth electrodes should be preferably made of iron, high-silicon cast iron, high-silicon chromium iron, or graphite.

If the pH value of soil and ground water is between 3 and 11 and the content of $Cl^{-}+SO_4^{2-}$ ions is less than 500 mg/l, for anode type land electrodes with a service life shorter than 40 × 10^6 Ah, the feeding rods electrode elements should be made of iron.

If the corrosion lifespan of the electrodes is longer than 40 × 10^6 Ah or the soil has a pH value less than 3, the feeding rods electrode elements should be high-silicon cast (chromium) iron or graphite.

If high-silicon cast iron or high-silicon chromium iron is used for feeding rods electrode elements, the final products should be equipped with feeding cable.

The carbon content in iron should be less than 0,5 %. Graphite should preferably be treated by submersion in linseed oil. The chemical composition of high-silicon cast iron and high-silicon chromium iron should correspond to the values listed in Table 1.

Table 1 – Composition of iron-silicon alloy electrode

Chemical composition	High-silicon cast iron %	High-silicon chromium iron %
Silicon (Si)	14,25~15,25	14,25~15,25
Manganese (Mn)	<0,5	≤0,5
Carbon (C)	<1,4	<1,4
Phosphorous (P)	<0,25	<0,25
Sulfur (S)	<0,1	<0,1
Chromium (Cr)	0	4~5
Iron (Fe)	>82,5	>77,5

5.3.3 Chemical and physical properties of petroleum coke

The chemical composition of the petroleum coke after calcination should correspond to the values listed in Table 2.

Table 2 – Chemical composition of the petroleum coke after calcination

Substance	Proportion %
Carbon	≥95
Water	≤0,1
Volatile components	≤0,5
Sulphur	≤1
Iron	≤0,04
Silicon	≤0,06
Ash and others	≤1

The physical properties of petroleum coke products used for DC earth electrodes should correspond to the values listed in Table 3.

Table 3 – Physical properties of petroleum coke used for earth electrodes

Properties	Values
Resistivity (at a volume weight of 1,1 g/cm^3)	<0,3 Ω·m
Volume weight	0,9~1,1 g/cm^3
Specific gravity	2 g/cm^3
Space ratio	45 %~55 %
Volume thermal capacity	>1,0 J/(cm^3 °C)

5.3.4 Current-guiding system

The earth current should be guided from electrode line to the current-guiding wire, disconnecting switchgear, feeding cables and connections in turn before it reaches different ~~feeding rods~~ electrode elements (more details in 5.6).

5.3.5 Bus

The current is ~~shunted~~ distributed by the bus, which can be of either the strain or rigid types. Strain bus is typically composed of an aluminium ~~clad~~ conductor steel reinforced ~~aluminium conductor~~, and rigid bus is typically composed of aluminium pipe or copper bar.

5.3.6 Electrode line and its monitoring device

The design of electrode line can be seen in Annex E. In some systems, electrode line monitoring (capacitor/reactor) devices are connected at the electrode end of the electrode line, to monitor integrity of the electrode line. The technical requirements of such devices are typically determined during converter station design. Their arrangement shall be considered during the design of the current guiding system.

5.4 Electrode arrangement

5.4.1 General principles

The arrangement of land electrode ~~feeding rods~~ elements can be classified as horizontal (trench) and vertical (well) type, which shall be selected through technical and economic comparison based on distribution of soil resistivity and terrain conditions. Generally, if the resistivity of deep soil (deeper than 10 m below ground) is significantly lower than that of the surface or if the ground water table is deep, a vertical well arrangement ~~should preferably~~ might be used, otherwise horizontal trench arrangement ~~should preferably~~ might be used.

5.4.2 Filling coke

Horizontal earth electrodes should preferably use square or rectangular sections or other suitable shapes according to the surrounding situation, and vertical earth electrodes should use circular sections. The ~~feeding rod~~ electrode element in the center is surrounded by filling coke, as shown in Figure 1. The recommended density of the reinforced filling coke should be between 1 000 kg/m^3 and 1 100 kg/m^3. The density for vertical electrodes should be higher in the case of water-filled bore holes.

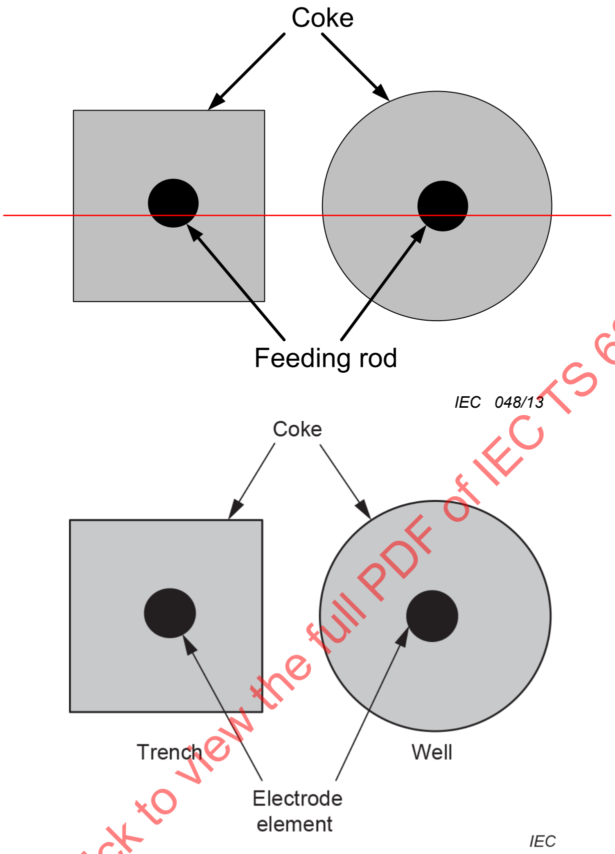


Figure 1 – Electrode cross-section

5.4.3 Selection of earth electrode shape

~~Selection of the shape of earth electrodes should respect the following rules:~~

~~a) the distribution of current-releasing density shall be as uniform as possible;~~

~~b) the average coefficient of uneven current distribution should be less than 10 %;~~

~~c) the maximum coefficient of uneven current distribution should be less than 100 %.~~

~~To this end, the following principles should be kept in mind during the selection or determination of the shape of the land electrodes:~~

The shape of the electrode shall be selected to achieve better current distribution and balance as suggested below:

– if the electrode site ~~allows~~ is flat and wide enough, first choose a horizontal single circular arrangement. If this proves to be unsuitable, next choose a double concentric circular arrangement, with the ratio of diameters of internal circle to external circle between 0,7 and 0,85. If circular earth electrodes are not possible due to limited site conditions, the electrode arrangement should be as circular as possible, maximising the curvature radius at curved parts;

– in case of rough terrain (such as ravine or loch), ~~star shape or~~ horizontal linear arrangement ~~should~~ could be used. In this case, ~~the number of branches is generally no higher than 6, and~~ a properly sized ~~current-sharing~~ electrode of circled loop ~~should~~ can be installed at the end (often with the highest current-releasing density) to reduce current-releasing density at the end. If the soil resistivity at depths ranging from tens to hundreds of meters is very low, vertical or deep well electrode is also a good choice;

- ~~if the temperature rise and step voltage or current density are critical factors, the concentric arrangement with multiple circles should be used, but the number of concentric circles should not exceed 3;~~
- for horizontal multiple circles electrodes, the number of concentric circles is recommended not to exceed 3, in order to reduce the shielding effect and improve the utilization efficiency of electrodes;
- ~~symmetric arrangement should be adopted as much~~ the electrodes should be arranged as symmetrically as possible to facilitate the layout of the current guiding system, improve current shunt uniformity and reliability of the current guiding system, and reduce construction cost of the current guiding system.

5.4.4 Earth electrode corridor (right of way)

If earth electrodes lie near any low-lying areas such as a trench, ditch or pond, and the burial depth of the earth electrodes is less than that of the trench, ditch or pond, the distance from the earth electrodes to its edge should generally be no less than 10 m.

5.4.5 Distance between sub-electrodes in the arrangement

In case of vertical arrangement of the earth electrode ~~feeding rods~~ elements, the distance between sub-electrodes should generally comply with Formula (7), as shown in Figure 2.

$$D = \eta L \tag{7}$$

where

D is the distance between sub-electrodes in vertical arrangement (m);

L is the length of the sub-electrodes in vertical arrangement (m);

η is the coefficient, 0,8~1,0.

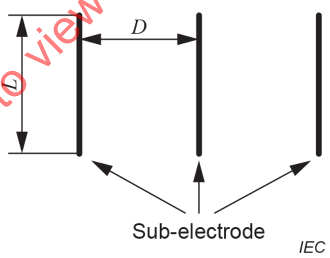


Figure 2 – Vertical arrangement

If earth electrode ~~feeding rods~~ elements are horizontally arranged in a discrete way, as shown in Figure 4 b) sub-electrodes should have a distances less than 2 m to achieve a uniform current distribution at the coke-soil interface.

5.4.6 Burial depth of the earth electrodes

Optimal burial depth of earth electrodes should be selected through technical and economic comparison based on the following principles:

a) step voltage ~~control~~. If the electrode length is horizontally arranged, ~~and the soil resistivity is uniform,~~ the minimum burial depth of the earth electrodes can be ~~calculated~~ estimated with Formula (8) approximately.

$$h = \frac{\rho_s \tau}{2\pi E_{sp}} \tag{8}$$

where

h is the minimum burial depth of the earth electrode (m);

ρ_s is the average shallow soil resistivity of soil (Ω·m);

τ is the earth electrode current-releasing density, calculated with earthing current divided by total length of electrode (A/m);

E_{sp} is the maximum permissible step voltage (V/m);

b) the earth electrode should be buried in soil with low resistivity, good thermal performance, and high moisture, and shall not be buried in rock, sand and gravel layers, or dry soil with high resistivity;

c) after the above conditions have been satisfied, the burial depth of the earth electrode should be minimized to reduce earthwork;

d) if farming is allowed on top of the area where the electrode is buried, the earth electrodes shall not be buried at a shallow depth to avoid artificial damage due to farming and machine-aided cultivation and impact of atmospheric temperature on the operation performance of electrodes. In general, earth electrodes should be buried to a depth exceeding 1,5 m.

5.4.7 Segmentation of earth electrodes

DC earth electrode feeding rods elements shall be divided into segments for better inspection and maintenance. The number of feeding rod electrode element segments shall be limited to avoid impact on current distribution and prevent a complicated current guiding system. Sub-electrode length shall be selected in such a way that other segments can still run safely and reliably at the specified maximum earthing current when one of these segments is put out of use (for maintenance).

5.5 Minimum size of earth electrode

5.5.1 General principles

Minimum sizes of earth electrodes refer to total earth electrode length, the side length of the coke section and the feeding rod electrode element diameter when the thermal stability or step voltage conditions are met. The principles for determining these three important dimensions include at least the following:

- at constant rated current, the highest temperature at any part of the earth electrodes shall not exceed the boiling point of water;
- at the maximum short-time overload current, the maximum step voltage at any point on the ground soil surface shall not exceed the allowed value;
- during at the end of the designed lifespan, the feeding rods electrode elements shall still meet current-carrying requirements after the corrosion is considered.

5.5.2 Total earth electrode length

In general, the length of the earth electrode (or floor occupied area) should be determined based on heating conditions (see 5.1.2 and 5.1.3), checked against the value allowed by maximum step voltage (see 5.1.4) and current density at the surface of the coke column coke-soil interface (see 5.1.6), and finalized through optimization of the earth electrode material consumption.

5.5.3 Side length of coke section Area of the surface of the coke-soil interface

For earth electrodes running in earth return mode, if the thermal time constant is greater than the duration of the rated current, the side length area of the coke section coke-soil interface at any point (P) of the electrode may be conservatively calculated by Formula (9) to ensure that the highest temperature at any point (P) will not exceed the permissible value.

$$S_p \geq k \cdot \rho_m \cdot \tau_p \sqrt{\frac{T_0}{16\rho_p C_p(\theta_{mp} - \theta_c)}} \qquad (10)$$

$$S_p \geq k^2 \times \rho_m{}^2 \times \tau_p{}^2 \frac{T_0}{16\rho_p C_p(\theta_{mp} - \theta_c)} \quad (9)$$

where

S_p is ~~the side length of coke section~~ the area of the coke-soil interface at point P (m);

k is the matching coefficient, in the range of 0,9~1,1; see ~~Annex F~~ Annex G;

τ_p is the linear current ~~releasing~~ density at point P (A/m);

ρ_p is the soil resistivity at point P (Ω·m);

C_p is the soil volume thermal capacity at point P (J/(m^3 °C));

ρ_m is the resistivity of the soil burial layer (Ω·m);

θ_c is the highest natural ambient temperature of the soil at any time in the year (°C);

θ_{mp} is the maximum permitted temperature of the earth electrode (°C);

T_0 is the duration of the rated current (s).

For earth electrodes running in anode mode for a long time, the maximum surface current density at ~~soil contact surface~~ the coke-soil interface should meet the recommendations in 5.1.6.

5.5.4 Diameter of ~~feeding rods~~ electrode elements

To ensure that the ~~feeding rods~~ electrode elements have sufficient current-carrying capacity, expected lifespan and permitted temperature rise, the sizes of ~~feeding rods~~ electrode elements should comply with both Formulae (10) and (11).

$$\Phi_p \geq \sqrt{\frac{4k_1 k_2 \rho_p \tau_p F V_f + \pi\phi^2 \rho_m g I_d \times 10^{-3}}{\pi \rho_m g I_d \times 10^{-3}}} \quad (10)$$

~~$$\Phi_p \geq \frac{4S_p \rho_p C_p}{\pi \rho_p C} \times 10^3$$~~

$$\Phi_p \geq \frac{4S_p}{\pi}\sqrt{\frac{\rho_c C_p}{\rho_p C}} \times 10^3 \quad (11)$$

where

S_p is the side length of coke section at point P (m), see Formula (9);

Φ_p is the equivalent diameter of the ~~feeding rod~~ electrode element at point P (mm);

k_1 is the protection coefficient, which is ratio of unit area ion current in the coke to the total current, k_1 = 0,1~0,6;

k_2 is the electric corrosion accumulation effect coefficient, see Table 4;

F is the service life of the anode (A·h);

V_f is the electric corrosion rate of ~~feeding rod~~ electrode element material in the soil (kg/(A·h)), see Table 4;

φ is the remaining equivalent diameter of the ~~feeding rod~~ electrode element when the total operation time of the earth electrode reaches the designed lifespan (mm);

g is the ~~specific~~ density of the ~~feeding rod~~ electrode element material (g/cm^3), see Table 4;

ρ_c is the coke resistivity (Ω·m);

C is the coke volume thermal capacity (J/(m^3·°C));

I_d is the rated current (A).

Others are the same as Formula (9).

Table 4 – Electric corrosion characteristics of different materials

Material	~~Specific~~ Density, g g/cm^3	Corrosion rate, V_f kg/(A·h)	Accumulation effect coefficient, k_2
Iron (steel)	7,86	0,001 039	3,0
High-silicon cast iron	7,03	0,000 228	2,0/3,0 (in sea water)
High-silicon chromium iron	7,02	0,000 114	2,0
Graphite	2,1	0,000 114	>3,0

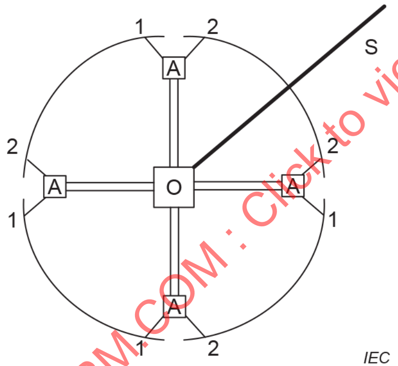
5.6 Current guiding system

5.6.1 General principles

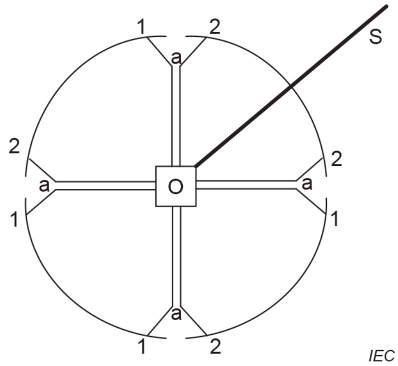
Generally, electrode lines from converter stations should first (or via electrode line monitoring reactors) be connected to the bus, and then the current should be guided to the current-guiding wire, disconnecting switchgear, feeding cables and connections in turn before it reaches different ~~feeding rods~~ electrode elements. The current guiding system should be designed in such a way that the current flowing through branches of the same level is equal or roughly equal.

5.6.2 Placement of the current-guiding wire

The current-guiding wire can be overhead wire or underground cable. The placement of such wire should generally match the electrode shape to achieve good current sharing characteristics. In general, for symmetrically arranged earth electrodes, the current-guiding wire should also be arranged symmetrically, e.g. Figure 3a) or Figure 3b).



a) Overhead conductor is adopted



b) Underground cable is adopted

Key

O central tower
A branch tower
a location where the feeding cables branch.
S-O electrode line
A-O current-guiding wire (where overhead conductors are used) between central tower and branch tower.
a-O current-guiding wire (where underground cables are used) between central tower and electrode.
a-1, a-2 feeding cables
A-1, A-2 feeding cables

Figure 3 – Placement of the current-guiding wire

5.6.3 Connection of current-guiding wire

To facilitate maintenance or commissioning, the current-guiding wire and feeding cable shall be bolted on the ground or connected with outdoor disconnecting switch, as per IEC 61936-1 and IEC TS 61936-2. If a disconnecting switch is adopted, the disconnecting switches should be installed on the current-guiding wire support structures. To ensure human safety, disconnecting switches shall be fenced off or placed at a sufficient ~~distance~~ height above ground.

5.6.4 Selection of current-guiding wire cross-section

The current-guiding wire cross-section should be selected based on the calculation results of the current in different branches, and in such a way that safe operation of other current-guiding wires is not affected under any earthing current operation conditions or when any electrode segment is out of use (due to damage or for the purpose of maintenance).

If cable is used as current-guiding wire, see 5.6.10.

5.6.5 Insulation of the current-guiding wire

Because the operation voltage on the earth electrode bus is very low (typically no higher than 10 kV even under transient conditions), the operation voltage on the bus is generally not a factor controlling the insulation level of the current-guiding wire.

If the current-guiding wire uses overhead line, the possibility of short-circuited insulator discs should be considered. Usually insulator strings with lightning impulse withstand level of at least 125 kV or at least two fully rated DC suspension insulators are used as the insulation between the conductors and tower structure.

If cable is used as current-guiding wire, see 5.6.11.

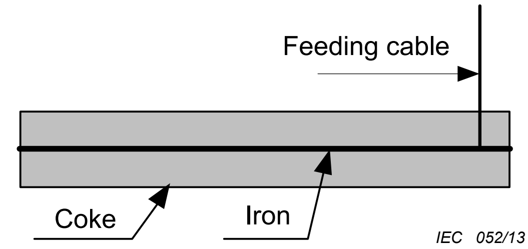
5.6.6 Disconnecting switch

To facilitate commissioning or maintenance, disconnecting switches should be installed in each group of sub-electrodes. The rated current of the disconnecting switches shall be no less than the maximum current that may occur in the corresponding circuit. The rated voltage should be no less than 10 kV.

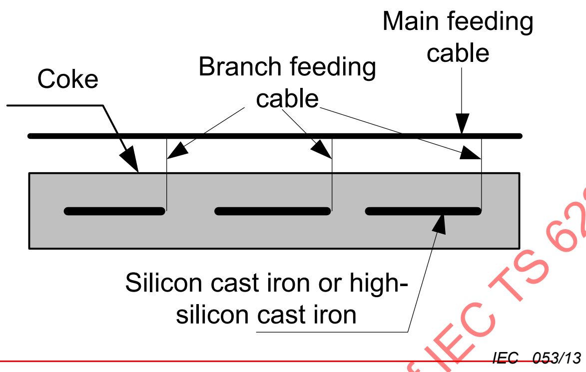
5.6.7 Connection of the feeding cable

Each electrode segment shall be connected to feeding cables.

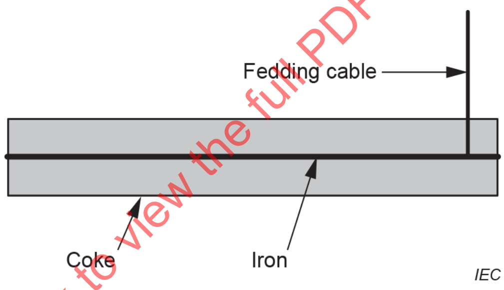
If the ~~feeding rod~~ electrode element is made of high-conductivity iron, ~~a feeding rod~~ an electrode element can be connected to the current-guiding wire directly by one feeding cable, as shown in Figure 4a). If the ~~feeding rod~~ electrode element is made of poor-conductivity material such as high-silicon cast iron or high-silicon chromium iron, an individual feeding cable is used to connect each ~~feeding rod~~ electrode element and the main feeding cable, which connects the current-guiding wire, as shown in Figure 4b).



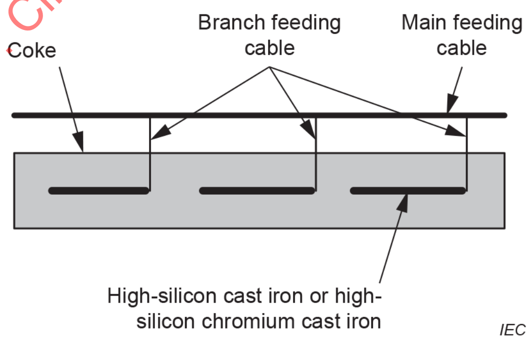
~~a) Iron used for feeding rod~~



~~b) Silicon cast iron or high-silicon cast iron used for feeding rod~~



a) Iron used for electrode element



b) High-silicon cast iron or high-silicon chromium cast iron used for electrode element

Figure 4 – Feeding cable

5.6.8 Connection of jumper cables

To reduce the step voltage, each sub-electrode shall be continuous as much as possible. The electrode may be ~~disconnected~~ interrupted if it has to cross low-lying areas such as trenches, ponds, or ditches, provided the electrical connections between the two segments are ensured. Two jumper cables are typically used to join ~~disconnected~~ separate electrode segments.

5.6.9 Selection of cable structure

Feeding cables and jumper cables should preferably use single core copper conductors with insulation, e.g. Kynar or XLPE, to facilitate construction, operation and maintenance and to reduce the cost. For cable buried directly in soil, single core copper conductor cable with double insulation may be used.

5.6.10 Selection of cable cross-section

The current-carrying cross-section of feeding cables and jumper cables (or cable-type current-guiding wire) shall be selected based on the calculation results of the current with adequate margin in different branches, and in such a way that safe operation of a cable is not affected under any earthing current operation conditions or when the other cable is out of use (due to damage or for the purpose of maintenance).

When selecting the cross-section of underground cable conductors, the maximum allowed current-carrying capacity of the cable shall be calibrated based on the environmental conditions of the soil (such as the parameters of maximum ambient temperature, soil thermal conductivity, volume thermal capacity, and cable distance). In addition, the insulation cover shall provide good thermal stability.

5.6.11 Selection of cable insulation

The insulation of current guiding system cables can be generally grouped into two levels:

- for feeding cable and jumper cable (or cable-type current-guiding wire), the insulation level should be generally no less than 6 kV and should preferably have a metal sheath to prevent moisture absorption into the cable;
- for branch feeding cables connected to high-silicon cast iron or high-silicon chromium iron sub-electrodes, the insulation level should be generally no less than 750 V and should preferably have double insulation.

5.6.12 Cable welding position

For ~~a feeding rod~~ an electrode element made of iron (steel), during connection between feeding cable and ~~feeding rod~~ electrode element and between jumper cable and ~~feeding rod~~ electrode element, the recommended welding position should be more than 5 m away from ends of the electrode (~~feeding rod~~ electrode element).

5.6.13 Welding

For connections and splices between underground cable and ~~feeding rods~~ electrode elements, exothermic welding, arc welding or hydraulic compressed connections should be used. ~~Pressure welding or~~ Bolt connection is prohibited.

The welding shall be firm and tight. The welding contact resistance shall not exceed that of the material of the same length with original specifications.

5.6.14 Mechanical protection for cable

All underground cables shall be effectively protected. The cable should be fixed on a cable bracket and be protected by a properly sized PVC plastic pipe at the place where the feeding cable enters the ground. For current-guiding wires, feeding cables or jumper cables that are directly buried in soil, sand should be filled around them, with cement panels laid directly over the cable to protect it against damages caused by external forces. For branch feeding cables connected to high-silicon cast iron or high-silicon chromium iron sub-electrodes, compatible PVC plastic pipes should be used as shields.

All underground cable joints and welding points exposed to soil shall be sealed reliably with epoxy resin.

5.7 Auxiliary facilities

5.7.1 Online monitoring

To determine or monitor the operation status of earth electrodes, monitoring devices that can detect current distribution, temperature and humidity of the earth electrodes ~~shall~~ can be installed at the location of the current-feeding cable. Alternatively, installation ~~shall~~ can be done in a manner such that portable instruments can be used. Common detection devices can be ~~connected via detection~~ installed in monitoring pits and wells. An online monitoring system can also be set up if necessary required. See Annex I for operation principle detailed information of this system.

The current distribution detection device shall at least be able to detect current flowing through different feeding cables. The detection well or sensor should be preferably placed at the access point of the feeding cable or the location where high current-releasing density or high temperature rise occurs may occur.

A main and redundant power supply system which may include the combination of local AC supply, solar panel, batteries or diesel generator may be installed for the electrode monitoring and control.

5.7.2 Soil treatment Moisture replenishment

If required, water-filling devices should be installed for horizontal (trench) type earth electrodes to reduce soil resistivity and prevent soil from drying out. During design, suitable water filling methods such as seepage wells can be selected based on site conditions.

5.7.3 Exhaust equipment

To facilitate release of gas generated during operation of the earth electrodes and maintain good operation characteristics of the earth electrodes, earth electrodes, especially deep well type and shore type electrodes, are typically shall be equipped with exhaust equipment.

5.7.4 Fence

If the step voltage or touch voltage exceeds safe limits, a wall or fence shall be erected, carrying distinguishing marks to prevent or warn unauthorized people attempting to enter the site.

The fence should be preferably made of insulating materials such as brick, wood. If non-insulating material is used, small independent earthing devices should be installed, and the fence should be discontinuous segmented using insulators to avoid large transferred voltages.

5.7.5 Marker

A marker should be erected at a proper place right over the earth electrode if required.

Markers should be placed at proper locations above the perimeter of the electrode if required.

6 Design of sea electrode station and shore electrode station

6.1 Main technical parameters

6.1.1 General

Design of the sea electrodes or the shore electrodes should ensure their safe and reliable operations throughout their life cycles and under different earthing current conditions including rated current, maximum short-time overload current, and maximum transient overcurrent. Different technical parameters such as earthing resistance, voltage gradient in water, step voltage, touch voltage and transferred voltage should be within the specified range.

6.1.2 Temperature rise

The temperature rise is not a dimensioning factor for sea electrodes and pond electrodes with adequate water exchange, and it is not required to do this calculation.

For beach electrode stations, the basic principle is that the maximum temperature of any point of the earth electrode shall be lower than the boiling point of water under all circumstances. The temperature calculation can be conducted by transformation of Formula (2), in which the value of λ will be about 2,5 W/m·°C for soil and seabed and dfac may be 10 since the soil in the electrode area is saturated with water close to the surface.

6.1.3 Earthing resistance

The requirement for earthing resistance of sea and shore electrodes are the same as for land electrode (see 5.1.3).

Since the resistivity layers of sea and shore electrodes are not horizontal, the formula to calculate the resistance to remote earth is more complicated than for electrodes with horizontal layers (see Figure 5). In this case, calculation should be performed with computer programs.

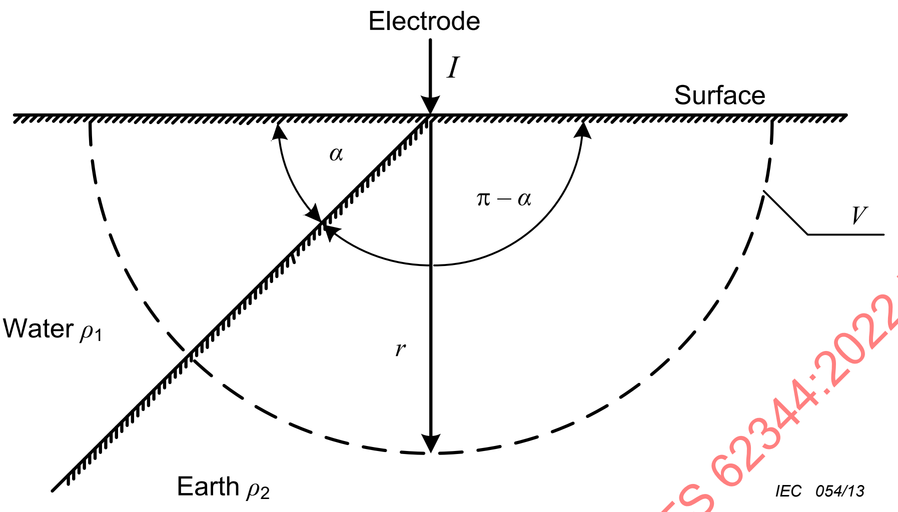


Figure 5 – Resistivity layers with sea or shore electrodes

The potential V of the equipotential sphere with radius r (m), for the parameters as defined in Figure 5 is given by Equation (13) for homogenous soil, and the earthing resistance can be obtained by V/I.

$$V = \frac{I}{2r\left(\frac{\alpha}{\rho_1} + \frac{\pi - \alpha}{\rho_2}\right)} \tag{13}$$

As the equipotentials are spheres, the potential varies as 1/r, therefore an apparent resistivity ρ_α can be evaluated from the last equation simply by:

$$\rho_\alpha = \frac{\pi}{\left(\frac{\alpha}{\rho_1} + \frac{\pi - \alpha}{\rho_2}\right)} \tag{14}$$

And used with the formula for homogenous soil:

$$V = \frac{\rho_\alpha \cdot I}{2\pi r} \tag{15}$$

For the best results, calculation should be performed with computer programs.

6.1.4 Step voltage

The step voltage of any ground point shall not exceed the safety limits defined for humans and livestock (see 5.1.4).

Step voltages tend to be of a high level in beach stations if the electrode is buried at a moderate depth. The fence will often be damaged if the station area is at risk of possible high tides, waves and/or ice. If it is preferred to avoid fencing, the total station shall be made larger, or buried at a greater depth.

6.1.5 Touch voltage

For earthed metallic structures that can be accessed by the public, the touch voltage of any point on the site ground shall not exceed the safety limits defined for humans under the maximum short-time overload current of one pole (see 5.1.5).

6.1.6 Voltage gradient in water

The voltage gradient in water shall not exceed 1,25 V/m to 2 V/m in areas accessible to humans or marine fauna.

6.1.7 Current density

The recommended average current density in sea water for sea electrodes and pond electrodes is 6 A/m^2 to 10 A/m^2 in order to ensure a suitable gradient of 1,25 V/m to 2 V/m close to the electrode (at a sea water resistivity of 0,2 Ω·m). The anode should be shielded from fish, as fish are attracted to the anode and not the cathode. If the sea electrodes or pond electrodes are functioning in an environment open to free water but not accessible to human beings or to marine fauna, the average current density can be raised to a value up to ~~100~~ 40 A/m^2~ 50 A/m^2.

For beach electrodes, in addition to electro-osmosis, Cl_2 generation should also be considered since it is not good for the ~~electrode~~ environment. For water saturated beach electrodes, the recommended current density on the surface of the coke is 7 A/m^2.

6.2 Electrode site selection and parameter measurement

6.2.1 General principles

Selection of the electrode site is a critical step during earth electrode design, and a complicated process, during which technical and economic comparison is required to select a safe, reliable, economically feasible, and environment-friendly site.

The following factors shall be considered when candidate sea electrode sites are compared and selected: distance to converter station, substations, pipelines, cables, etc., salinity of the sea water, slope of the seabed, resistivity on the shore, and uniformity of the seabed.

6.2.2 Data collection survey

To ~~find~~ verify a ~~suitable~~ possible electrode site, a survey within a radius of at least 10 km should be conducted to determine the natural conditions in the neighbourhood of the electrode site under investigation, which should at least include the landform and terrain, geological structure, ocean tide and currents in the sea. The survey shall show that the seabed is without clay so that the electrode does not sink.

Besides, in order to conduct environmental impacts evaluation, the surrounding facilities near the electrode site should also be surveyed, such as the existing and planned power facilities (substations and lines), buried metal pipes, armoured or earthed cables, railway lines, fishing areas, vacation beaches, cathodic protection system for marine metallic structures, etc. Coastal areas are often characterised by a layer of fresh water, rising to a higher level than the nearby sea and a deeper layer of salt water, penetrating from the sea. If a distinct interface between freshwater and saline water exists, survey should be done to determine which depth is the best for the active part of an electrode station. If the current is emitted in the freshwater layer, anodic operation will evolve only oxygen, not chlorine. If the electrode is close to, but still above, the interface, the salt-water layer will absorb the current very effectively, within a short horizontal distance. If low resistance to remote earth and decrease of loss are the goals, the electrodes shall be placed in the saline strata, but some evolution of chlorine will be the result.

6.2.3 Distance from converter station (substation)

During the determination of the electrode site and during the commissioning of the electrode station, the impact of earth electrodes on surrounding converter stations and AC substations shall be calculated or measured.

6.2.4 Environment conditions

The electrode site should be placed far away from populated areas, such as vacation beaches if possible, to reduce public concern about earth electrode.

~~6.2.5 Measurement of soil parameters~~

~~The measurement of soil parameters shall meet the following requirements:~~

a) the Wenner or Schlumberger methods may be used for earth resistivity surveys at shallow depths. The magnetotelluric (MT) method shall be used for areas with greater depths (see Annex B);

b) the salinity of the sea-water shall be measured.

In electrolytic processes there will always be a chemical action, because the materials in the soil ground/seawater (more precisely the substances diluted in the ground/seawater) will be decomposed and/or built up to new chemical substances, see Annex L.

In an anodic process in ground water of very low or zero salinity, O_2 (oxygen) is produced and emanates, which is generally not seen as a problem since the atmosphere partly consists of O_2. With increasing salinity, the evolution of Cl_2 (chlorine) will take over, which is a kind of toxic gas. However, there will still be, even in salinities up to sea water level, a substantial evolution of O_2. The sum of evolved gases respects Faraday's law of electrolysis, which says that the mass of decomposed material is proportional to the electric charge, i.e. the number of ampere hours.

6.2.5 Measurement of ground/water parameters

The measurement of ground/water parameters shall meet the following requirements:

a) For beach/pond electrodes, the resistivity of seawater and shallow soil on the beach should be measured. The former can be measured by a liquid conductivity tester, and the latter can be conducted by the Wenner or Schlumberger methods as used in land electrode, but the effect of seawater on the apparent resistivity measurement results shall be considered in soil model inversion analysis. Besides, the seawater depth and seabed slope near the electrode should also be tested or surveyed which may use the method of sonar or echo-sounding. If required, the deep soil resistivity could be measured by the magnetotelluric (MT) method (see Annex D), which is used to evaluate the impact on the surrounding facilities on land.

b) For sea electrodes, the factors like sea currents, sea-bottom roughness and sea-bottom soil conditions should be investigated. Morphological and geological investigations can include side-scan sonar, sub-bottom profilers and echo-sounders. Bottom conditions should also be investigated by divers and/or with under water vessels and documented by camera. The resistivity of seawater and soil of sea-bottom can be measured by seawater/soil sampling. Resistivity measurements are possible for sea electrodes, at least in shallow water areas, however more complicated than on land. The resistivity may also be measured on undisturbed soil samples from the seabed.

c) The salinity of the seawater shall be measured in order to analyse gas evolution rates.

6.3 Earth electrode and associated components

6.3.1 General principles for material selection

The material shall be selected through technical and economical comparisons based on engineering and market conditions. The selection shall respect the following principles: low dissolution rate as well as low chlorine emission rate in anodic regime, low toxic or other negative effects, and cost-effectiveness.

6.3.2 Common feeding rods electrode elements and characteristics

Feeding rods Electrode elements used for sea electrodes or shore electrodes should be preferably made of high-silicon chromium iron, or graphite embedded in coke. The carbon content in iron should be less than 0,5 %. Graphite should preferably be treated by submersion in linseed oil. The chemical composition of high-silicon chromium iron should correspond to the values listed in Table 1.

Other material that can be used directly in sea water without embedment in coke are:

a) platinised titanium or niobium (Pt/Ti or Pt/Nb);

b) magnetite;

c) bare copper conductors (for cathodic operation only);

d) mixed metal oxides (MMO).

~~Platinised titanium is also well-known (for anodes) and may also be used as the cathode, depending on the manufacturer. The material is as an expanded mesh of titanium, of which the filaments are about 0,5 mm × 2 mm, all interconnected in about 20 mm × 50 mm meshes. The titanium is covered by a special thin (5 µm -20 µm) layer of metals, resistant to anodic corrosion. The expanded network is delivered in subelectrodes each covering 1,22 m × 16,5 m.~~

Platinised titanium or niobium are also well-known electrode material for anodes, the most widely available shapes of which are wires, meshes and rods, depending on the manufacturer. But they are not very suitable for cathodic operation.

Magnetite, Fe_3O_4, is commonly used for cathodic protection purposes. The electrodes are usually produced in rod-form, 0,06 m in diameter, 0,72 m in length and other sizes as well. The resistivity of magnetite is about 5×10^{-5} Ω·m –10×10^{-5} Ω·m. A disadvantage of this material is that it is brittle and not easy to manufacture.

Bare copper is ~~good choice~~ an electrode material fit for cathodic ~~electrodes~~ operation only, as anodic operation will lead it to quickly corrode itself. A reason for this choice is the possibility of establishing reliable clamp connections by compression or by welding, which will withstand the environmental conditions of the seawater.

Mixed metal oxides (MMO) electrode is developed to prevent the corrosion during chlorine production by coating the titanium with special mixed metal oxides (coating thickness in the range of 5 µm to 20 µm). It can be used both in anodic and in cathodic operations. But in cathodic operations the dispersed current density shall be limited to be much lower than that in anodic operation. This is due to the adsorption of the hydrogen developed in cathodic operation by the crystal structure of titanium, and subsequent formation of titanium hydride, which is brittle and leads to net damage.

6.3.3 Chemical properties of petroleum coke

See 5.3.3.

6.3.4 Current-guiding system

See 6.5.

6.3.5 Bus

See 5.3.5.

6.3.6 Electrode line monitoring device

See 5.3.6.

6.4 Electrode arrangement

6.4.1 General principles

The arrangement of sea electrode ~~feeding rods~~ elements can be classified as horizontal embedded in coke (see Figure 5) or placed in cages directly on the bottom of the sea. If nets are used, these shall be placed on sea bottom and covered by gravel or cement sacks.

The arrangement of shore electrode ~~feeding rods~~ elements can be classified as vertical embedded in coke (beach type) or placed directly in seawater (pond type), see Annex M.

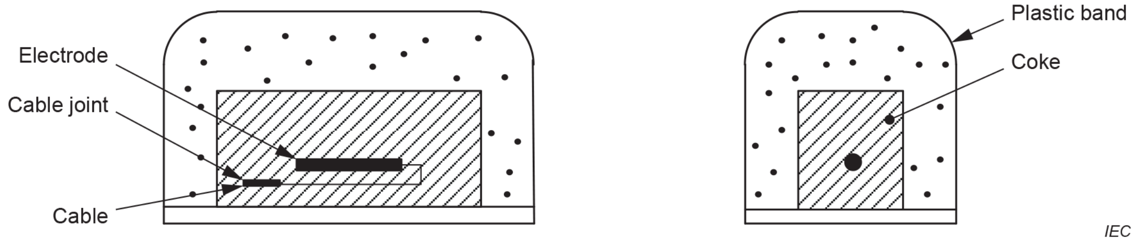


Figure 5 – Sea electrode

6.4.2 Filling coke

For sea electrodes and shore electrodes, the filling of coke, if used, should be performed on the shore. Fabric shall be used to keep the coke in place. The sub electrode is then placed on the seabed, covered by gravel or cement sacks.

For beach electrodes, the sub electrode is then placed in the bore holes made on the shore.

6.4.3 Selection of earth electrode shape

The physical layout of the electrode should be as round as possible. With a net type electrode (anodes) the ends form a curve approximately to half circles against the coast. See Figure 6. This is to ensure the best possible current sharing among sub-electrodes, because the influence of current density on the production of Cl_2 makes it important that all sub-electrodes carry an equally low part of the current. For shore electrodes, if the shore is narrow, an elliptical or linear shape electrode may be used.

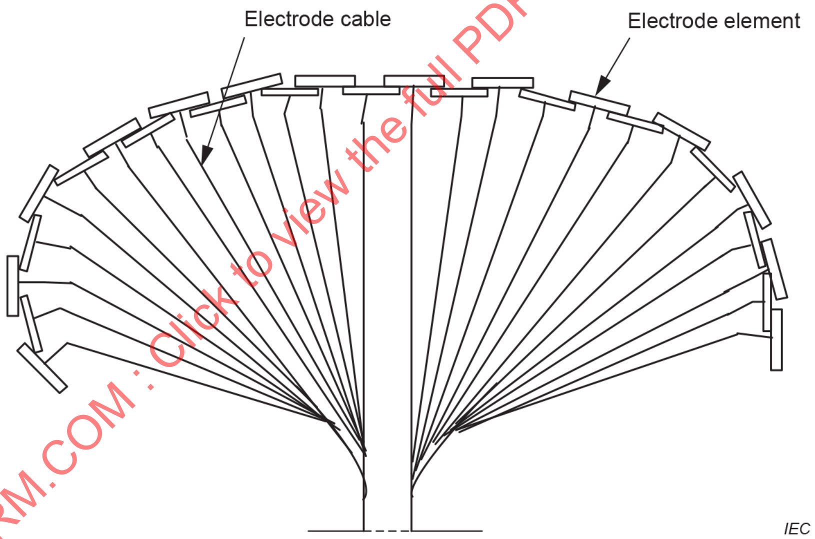


Figure 6 – Sea bottom electrode with titanium nets

6.4.4 Segmentation of earth electrodes

DC earth electrode sub sections shall be divided into a few segments for better inspection and maintenance. The number of sub sections shall be limited to avoid impact on current distribution and avoid the need for a complicated current guiding system. Subsections shall be performed so one part of the electrode can be taken out for maintenance or repair without resulting in unacceptably high potentials in water or ground close to the section out of service.

If the total electrode is composed of a number of sub-electrodes (which is preferred), then two different "philosophies" shall be considered:

a) the sub-electrodes are placed such that they are easily accessible for inspection/repair. This normally requires a small depth of burial and generally applies only to horizontal sub-electrodes;

b) the sub-electrodes are inaccessible when installed, with the idea that they are of a disposable (throwaway) type, which is left underground when damaged, if they are too difficult to salvage. A new substitution electrode is arranged close to the damaged one. ~~This philosophy is relevant to vertical electrodes, buried at large depths.~~

6.5 Current-guiding system

6.5.1 Placement of the current-guiding wire

For sea electrodes and pond electrodes, the busbar and other equipment, should preferably be placed in a cabin at some distance (e.g. more than 500 m) from the electrode area, at a safe level above sea surface. The current guiding wires between the busbar in the cabin and the sub-electrodes, or subparts, shall preferably be made as individual smaller cables, or mutually insulated sub-conductors in large cables. The extra (and equal) resistance in each sub-conductor will tend to equalize the current sharing among sub-electrodes. If not, series resistors can be used.

For beach electrodes, see 5.6.2.

6.5.2 Connection of current-guiding system

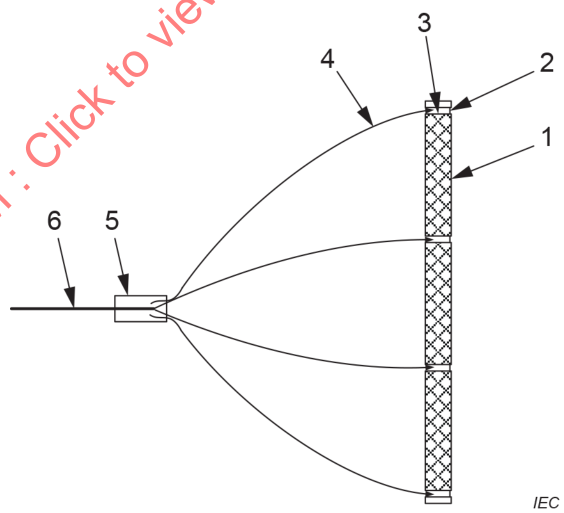
For beach electrodes, see 5.6.3.

For sea electrodes and pond electrodes, each electrode segment shall be connected to feeding cables, and feeding cables shall be connected to current guiding wires (in cable-type), see Figure 7.

~~The cables to the electrode element shall be made by the manufacturer of the electrode element. The feeding cable shall have a watertight heat-shrink joint to the element.~~

The connection of the feeding cable to each electrode elements shall be done by its supplier. The feeding cable shall have a watertight heat-shrink or epoxy resin joint to the element.

All cables, connection points and joints intended for anodic operation shall be well insulated since a direct contact with the water results in heavy electrolytic corrosion. The insulation shall, in addition, resist high electrode temperatures, mechanical stress during installation and various aggressive chemical elements in the environment.



Key

1 Electrode of titanium net, 1,22 m × 16,5 m

2 Connection plate of titanium

3 Watertight heat-shrink joint

4 Electrode cable (feeding cable), copper conductor 10 mm^2

5 Watertight heat-shrink joint

6 Electrode cable (current guiding wire), copper 35 mm^2

Figure 7 – Titanium net

6.5.3 Selection of cable cross-section

See 5.6.10.

6.5.4 Insulation of the current-guiding system

See 5.6.5 and 5.6.11.

6.5.5 Selection of cable structure

Feeding cable should preferably use single core copper conductor with insulation, e.g. Kynar or XLPE, to facilitate construction, operation and maintenance and to reduce the cost. For cable buried directly in the seabed, single core copper conductor cable with double insulation may be used.

6.5.6 Mechanical protection for cable

See 5.6.14.

6.6 Auxiliary facilities

To determine or monitor operation status of earth electrodes, monitoring devices that can detect current distribution of the earth electrodes shall be installed at the location of current-feeding cables (see 5.7.1).

Exhaust equipment should be considered for exhaust of Cl_2 (see 5.7.3).

7 Impact on surrounding facilities and mitigation measures

7.1 Impact on insulated metallic structures and mitigation measures

7.1.1 General principles

Touch voltage on any insulated metal structure buried near earth electrodes caused by ground return current shall not affect safety and health of people in contact with the metal structure, and possible corrosion shall not affect normal operation of the structures.

7.1.2 Relevant limits

For underground metal pipes insulated by surrounding cement or asphalt, the voltage between the pipe and surrounding soil shall be within the range from –1,5 V to –0,85 V at the equivalent earthing current. If this is not the case, proper precautions should be taken.

For pipes equipped with a cathodic protection system, the voltage to earth on the pipes caused by earth electrode earthing current shall not exceed the capability of the cathodic protection system.

At normal rated current, the touch voltage of a metal structure shall not exceed 70 V. If this is not the case, proper precautions should be taken.

7.1.3 Mitigation measures

For insulated metal pipes buried in ground with a voltage exceeding the limit, common precautions include addition or reinforcement of cathodic protection capabilities, addition of pipe anti-corrosion coating, and separating a pipe into segments and connecting them with insulative materials.

7.2 Impact on bare metallic structures

7.2.1 General principles

Impact of current field of DC earthing current on any buried bare metallic structure, such as touch voltage and corrosion, shall not affect the ~~normal behavior~~ safety of people in contact with the metallic structure and safe normal operation of the metal structure.

7.2.2 Relevant limits

To protect personal safety, the touch voltage of any metal structure shall not exceed the value defined in 5.1.5. If this is not the case, proper precautions should be taken.

During analysis of corrosion effects of the earth electrodes on surrounding bare metallic structures, the current density at the surface of any buried metal structure exposed to soil should not exceed 1 μA/cm^2 at the equivalent earthing current, and the corrosion shall not affect normal operation of the metal structure. See Annex J for the calculation method.

7.2.3 Mitigation measures

The distance between earth electrodes and surrounding bare metal structures should be as large as possible. If the minimum distance between earth electrodes and underground bare metal structures, such as buried bare metallic pipes, is less than 10 km, or if the length of the underground metallic structure is longer than the distance, the adverse effects of DC earthing current of the earth electrodes on the structure shall be ~~calculated~~ evaluated.

In case of excessive current flowing out of a bare metal pipe exposed to soil, corresponding anti-corrosion measures such as insulation coating or cathodic protection shall be taken for the metal pipe. ~~A commonly used precaution is an insulation coating or cathodic protection.~~ The insulation coating is usually made of concrete, asphalt, enamel, or resin, and polyvinyl fluoride is the best choice. Cathodic protection is typically achieved in two ways: primary battery cathodic protection or external DC power supply cathodic protection.

7.3 Impact on the power system (power transformer, grounding network, and surrounding towers)

7.3.1 General principles

Rise of earth potential on an AC system near the earth electrodes resulting from the earthing current is likely to cause DC component in neutral-grounded transformers and consequently DC biasing (see Annex A). The schematic diagram of impact of the DC earth electrodes on AC systems is shown in Figure 8.

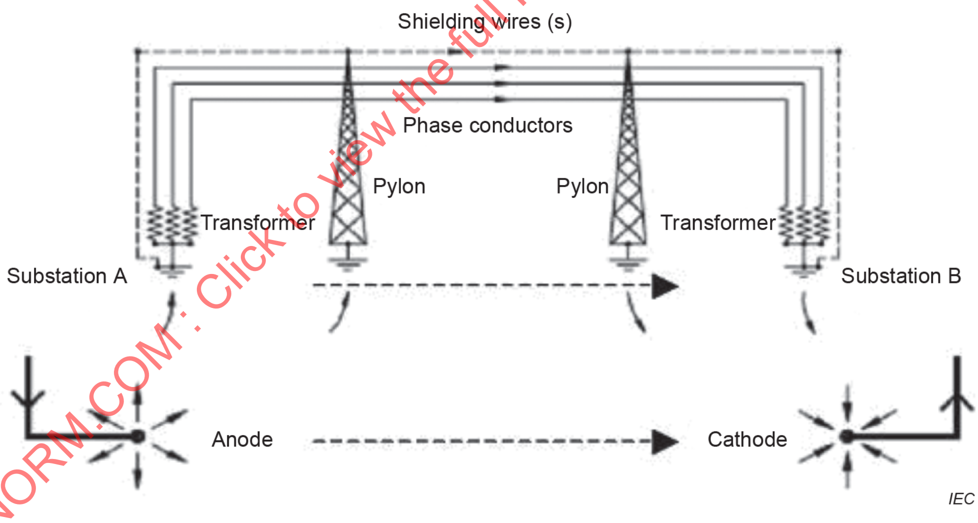


Figure 8 – Impact of earth electrodes on AC systems (transformer, grounding network, tower)

7.3.2 Relevant limits

The permissible DC current for windings of each transformer phase, if actual values are not known, can be as follows: 0,3 % of rated current for a single-phase transformer, 0,5 % of rated current for a three-phase five-legged transformer, or 0,7 % of rated current for a three-phase three-legged transformer.

7.3.3 Mitigation measures

If the earth electrode DC current flowing through the transformer windings is higher than the above limit, proper current-limiting or DC current-blocking measures shall be taken. The two main methods are:

a) DC current-blocking capacitor;

b) a small resistor connected in series with transformer neutral and ground.

7.4 Impact on electrified railway

If the earth electrodes lie near an electrified railway, simulative calculation should be performed to analyse issues concerning touch voltage on communication cables and signal cables of the railway caused by the earth electrode earthing current, DC current flowing through the traction transformer, and corrosion of earthing devices. Under rated current, the touch voltage between any point on the communication and signal cable and the common machine control room should not exceed 70 V, the consequent corrosion of earthing devices shall not affect their normal operation, and the DC current flowing through the traction transformer in the traction station shall be within the allowed range (usually higher than those of general AC transformers).

7.5 Other facilities (such as greenhouses and water pipes)

If the earth electrodes lie near facilities such as greenhouse or earthed metallic water pipes, the touch voltage and transferred voltage generated on them shall be considered. Impact of the touch voltage and transferred voltage can be reduced by earthing or removal or relocation of these facilities.

If the earth electrodes lie near a seismic station, simulative calculation and measurement should be performed to evaluate the potential difference between observation electrodes and magnetic flux density caused by the electrode lines and DC transmission lines. Measures such as adjusting the direction, or the length of the seismic station observation electrodes can be taken.

Annex A
(informative)

Basic concepts of earth electrodes

A.1 Basic concepts

Earth electrodes play a very important role in the operation of DC power transmission systems. Firstly, they can ~~supply power to the system for a long time to improve system operation reliability~~ provide a transmission path for the load current under monopolar earth return operation mode when one of the poles of a DC transmission system fails or is overhauled. Secondly, they ~~can hold~~ provide the ground reference for the neutral potential at the converter station ~~(rectifying valve)~~ to avoid equipment damage due to unbalanced voltage to earth of the two poles. Hence the design of earth electrodes is critical during the design and construction of the whole DC power transmission system.

A.2 Operation mode

A.2.1 General

An HVDC power transmission system typically consists of three parts: rectifier station, DC current line, and inverter station, as shown in Figure A.1.

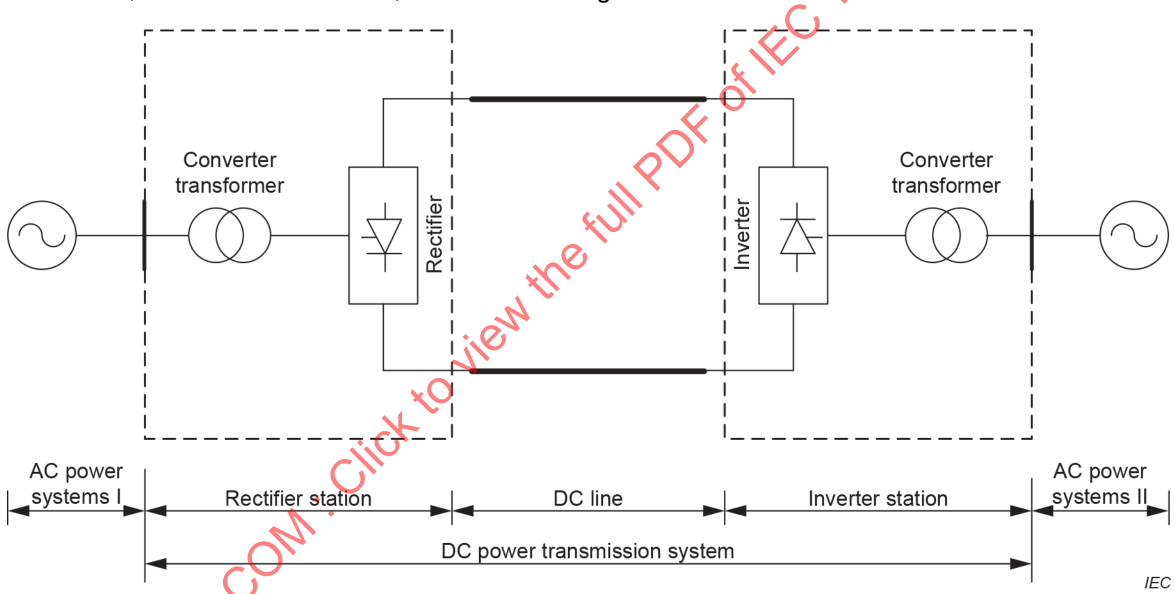


Figure A.1 – HVDC power transmission system structure

Depending on the number of nodes connected to AC systems, DC power transmission systems can be grouped into two-terminal and multiple-terminal systems. Two-terminal DC power transmission systems can be further classified into three ~~types~~ configurations: ~~monopolar type, bipolar type and back-to-back type~~ monopole, bipole and back-to-back.

A.2.2 Monopolar system

A.2.2.1 General

The monopolar system as shown in Figure A.2 is typically operated with ~~the positive~~ only one pole connected to earth. ~~This type of d.c. system actually has only one negative pole, and due to this it is called a monopolar system. The advantage of a monopolar system operated in negative pole mode lies in the fact that it is less likely to be affected by lightning strikes and produces less radio disturbance caused by corona than the positive pole operation mode. The monopolar systems can be further classified into single-pole earth (seawater) return mode and monopolar metallic return mode.~~ The monopole DC system usually operates in negative pole mode, as it is less likely to be affected by lightning strikes and produces less radio disturbance caused by corona than the positive pole operation mode. The monopolar systems can be operated in two modes, ground return via ground electrodes or dedicated metallic return as shown in Figure A.2 and Figure A.3, respectively.

NOTE The terms "positive pole" and "negative pole" relate to the voltage polarity of that pole under the operating condition when power is being transmitted in the direction for which the HVDC project was primarily designed. For HVDC projects that are designed to be bi-directional, it is not possible to distinguish between the terms "positive pole" and "negative pole".

A.2.2.2 Monopolar earth (sea water) return mode

This is a DC power transmission system with an overhead conductor or cable and using earth or sea water as the return ~~circuit~~ path. ~~It is also called a one-line one-earth system.~~

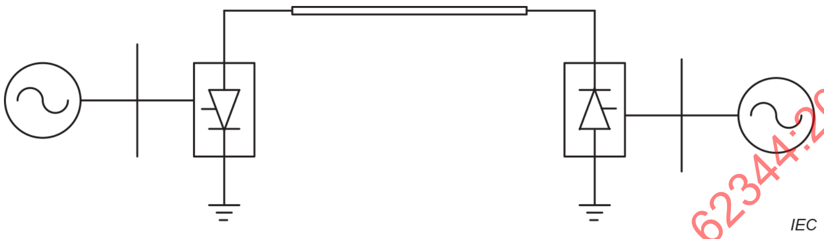


Figure A.2 – Schematic diagram of ~~the structure of~~ ~~a~~ monopolar earth/ ~~(~~sea water~~)~~ return system

A power transmission system adopting monopolar earth/ ~~(~~sea water~~)~~ return mode can save investment in lines. However, electrochemical corrosion may occur in underground metal facilities ~~at places where the system passes by~~ located within the interference radius of the ground electrodes, and nearby communication and magnetic compass may be disturbed. This operation mode is applied in many systems, including the Gotland Island DC system in Sweden and the Sardinia-Corsica-Italy DC system.

A.2.2.3 Monopolar with dedicated metallic return mode

~~This is also called a monopolar two-line system. It is a monopolar line system using~~ Monopolar system with dedicated metallic return uses a low insulation conductor earthed at one end as the return circuit, as shown in Figure A.3. ~~It should be noted that~~ The earth reference shown in Figure A.3 conducts no DC current and does not need to be designed as an earth electrode.

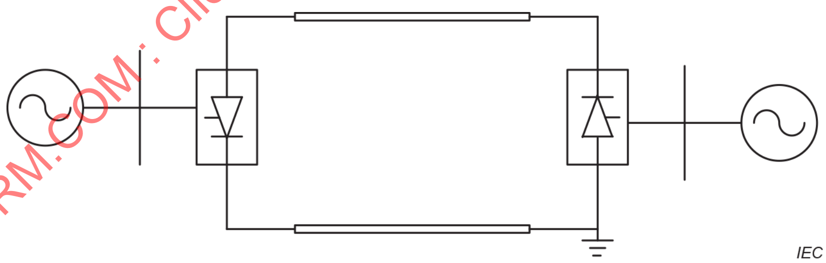


Figure A.3 – Schematic diagram of ~~the structure of~~ monopolar dedicated metallic return system

A.2.3 Bipolar system

A.2.3.1 General

As shown in Figure A.4, the bipolar line mode requires two conductors of different polarities (positive and negative pole). Bipolar systems can be further classified into three types: ~~bipolar neutral grounded at both ends, bipolar neutral grounded at one end, and bipolar neutral line~~ bipolar earth (sea water) system, rigid DC current bipolar system, and bipolar dedicated metallic return system.

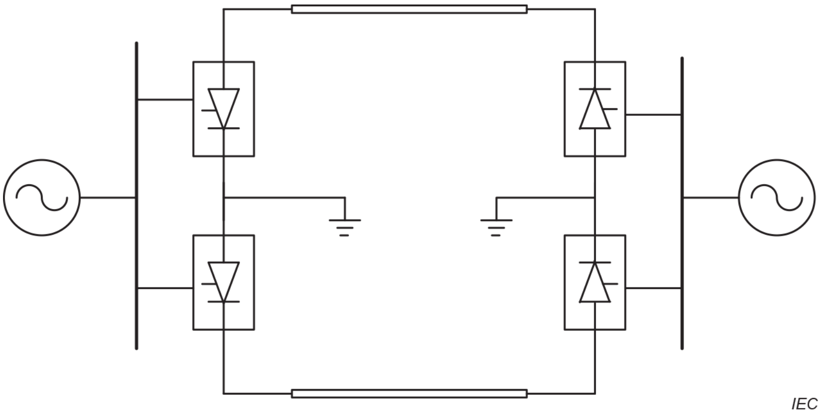


Figure A.4 – Schematic diagram of ~~the structure of bipolar neutral grounded at both ends~~ bipolar earth/sea water system

A.2.3.2 Bipolar ~~neutral grounded at both ends~~ earth (sea water) return mode

The mode of bipolar ~~neutral grounded at both ends~~ earth/sea water system is shown in Figure A.4. Both the neutral of the rectifier station and that of the inverter station are grounded in this mode. It can be regarded as a system formed by two superimposed ~~one-line one-ground~~ monopolar systems. Unbalanced current flows through the return circuit during normal operation. If this current is low (e.g. symmetrically operated bipolar system), corrosion on underground metallic equipment is significantly reduced. Besides, in case of failure of any pole, the functional pole can still use earth or sea water as the current return circuit and thus maintain 50 % of total power transmission.

A.2.3.3 ~~Bipolar neutral grounded at one end~~ Rigid DC current bipolar mode

The mode of rigid DC current bipolar ~~neutral grounded at one end~~ system is shown in Figure A.5. In this mode, the system is not grounded at the ~~converter~~ rectifier station end and thus avoids ~~corrosion~~ ground interference as it only happens in the ~~mode of~~ bipolar ~~neutral grounded at both ends~~ earth/sea water mode. It should be noted that the earth reference shown on Figure A.5 conducts no DC current and does not need to be designed as an earth electrode. The disadvantage of this mode is that the operation is not possible when a failure occurs on one line. It also requires the currents in the two poles to be exactly equal, since there is no return path for any unbalance current. ~~Technically, it is possible to use this operation mode; however, no actual project has adopted this scheme.~~

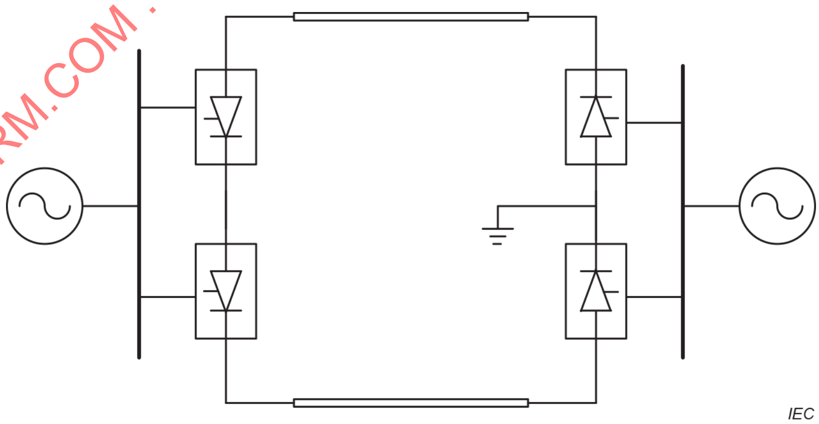


Figure A.5 – Schematic diagram of ~~the structure of bipolar neutral grounded at one end~~ rigid bipolar system

A.2.3.4 Bipolar ~~neutral line~~ with dedicated metallic return mode

The mode of bipolar ~~neutral line~~ with dedicated metallic return is shown in Figure A.6. In this mode, in addition to conductors for positive and negative pole, a conductor is used as the neutral line between two converter station neutral points and grounded at one end. This mode not only eliminates the drawbacks due to earth or sea water being used as the current return circuit, but also allows continuous monopolar operation. In this mode, the earth reference shown in Figure A.6 conducts no DC current and does not need to be designed as an earth electrode.

Construction of DC power transmission systems typically require a bipolar system to be built in different phases. One pole is often built before the other and operated as a monopolar system to achieve benefits at an early stage. The ± 500 kV Geshang DC project and Tianguang DC project in China were both constructed in this way.

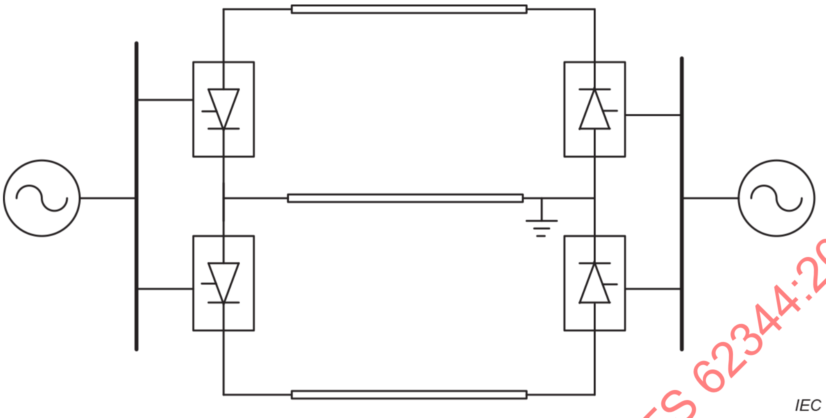


Figure A.6 – Schematic diagram of ~~the structure of bipolar neutral line~~ bipolar dedicated metallic return system

A.2.4 Symmetric unbalanced system

A balanced bipolar system consists of two completely identical monopolar systems, which are typically built and put into operation in stages, which means the second monopolar system is built and put into operation shortly after the first one is put into service. If this is not the case and the second monopolar system is built at a late stage according to planning, advancement of relevant technologies in the transition period can lead to different transmission power and voltage rating between these two systems. For instance, the Konti-Skan DC system consists of two monopolar systems with different transmission powers, which share a pair of reversible converter stations. The Skagerrak DC system was planned to be a balanced bipolar system at the beginning, but ~~now has three~~ later a 3rd monopolar system~~s~~ was added to this project. The power transmission direction of the third monopolar system is opposite to that of the bipolar system built at an early stage. ~~The converter station is therefore in an unbalanced operation mode.~~ And a 4th (VSC) pole had just been added to the Skagerrak project in 2014.

A.2.5 Back-to-back converter station

~~This type of d.c. system that has no d.c. power transmission lines and combines the rectifier station and inverter station together is called back-to-back converter station. Due to the absence of power transmission lines, the d.c. system can select a lower voltage rating, reducing the total investment of the work.~~ Back-to-back converter station is a DC system without DC power transmission lines and with both rectifier and inverter converter stations in the same switchyard. “Back–to-back” converter stations are now widely used with the main purpose of limiting increase of short-circuit current during the interconnection of electric grids, improving the reliability of grid under operation, and serving as a frequency conversion station during the interconnection of grids with different frequencies. Back–to-back converter stations do not require earth electrodes.

A.3 Dangerous impact and accumulated impact

A.3.1 General

The safety risks of DC grounding systems mainly involve electric shock due to touch voltage, transferred voltage and step voltage, among which electric shock due to step voltage should receive more attention. ~~The accumulative effects of d.c. grounding systems mainly involve corrosion of the earth electrodes themselves and nearby metallic structures.~~

A.3.2 Safety risks of DC earth electrode

A.3.2.1 General

The concept of touch voltage, transferred voltage and step voltage are shown in Figure A.7.

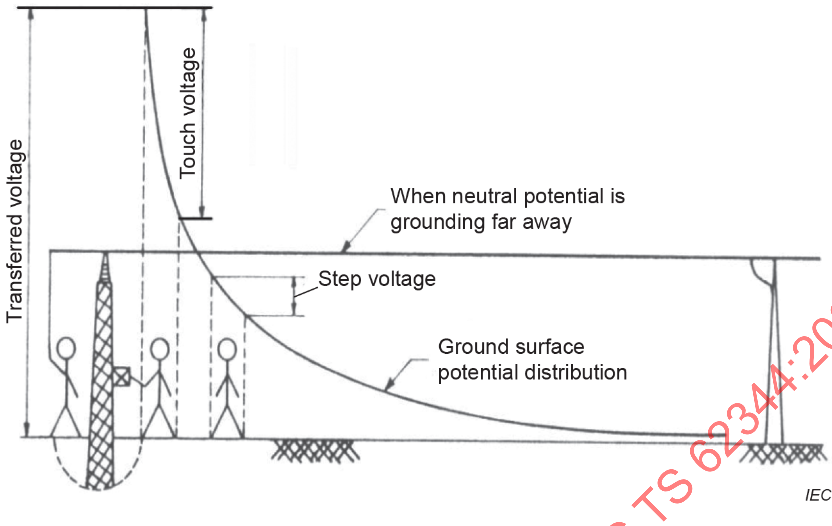


Figure A.7 – Schematic diagram of touch voltage and step voltage

A.3.2.2 Step voltage limit

The step voltage limit is an important basis for the design of earth electrodes. When the step voltage caused by earth electrode current in the ground exceeds a certain value, electric shock due to step voltage may occur it may cause annoyance to people or animal around the electrode. On the other hand, too low a value for step voltage will increase the total cost of the system. Hence the selection of a reasonable step voltage in the neighbourhood of the earth electrodes is significant for ensuring personal safety and lowering system costs.

What really poses safety hazards to people is the current flowing through the human body. Hence the step voltage limit depends on physical conditions and the footsteps of people. Impact of step voltage is more significant at lower sensing current, lower human body resistance, lower contact resistance between the human body and the soil, and longer footstep. A low step voltage limit should be defined to ensure personal safety.

The step voltage limit for the human body is calculated with:

$$U = I_g (R + 2R_s) \tag{A.1}$$

where

U is the step voltage limit (V),

I_g is the minimum current (A) sensed by a human body,

R is the human body resistance (Ω), and

R_s is the contact resistance (Ω) between one foot and the soil.

According to tests conducted on 1 028 subjects, over 95 % of the subjects have a foot to foot human body resistance greater than 1 400 Ω (see Annex C), which is slightly different from the hand to hand human body resistance given by IEC 60479-1, and over 95 % of the subjects do not feel anything at a DC current of 5,3 mA. Based on these test results and considering the different amplitudes and durations of DC system earthing currents, the maximum allowed step voltage of any point on the ground can be determined with Formula (2) under maximum short-time overload current of one pole.

Designing earth electrodes based on step voltage limits can ensure the safety of people walking near earth electrodes. For earth electrodes failing to meet the step voltage limit, an isolation wall should be erected in corresponding areas to prevent people from entering these areas and ~~suffering from~~ being exposed to electric shock.

A.3.2.3 Typical distribution of DC earth electrode step voltage

Present-day DC earth electrodes are often closed loops, the circular configuration being the best option.

a) Typical single circular DC earth electrode

A single circular DC earth electrode structure is shown in Figure A.8, and distribution of step voltage is shown in Figure A.9 and Figure A.10.

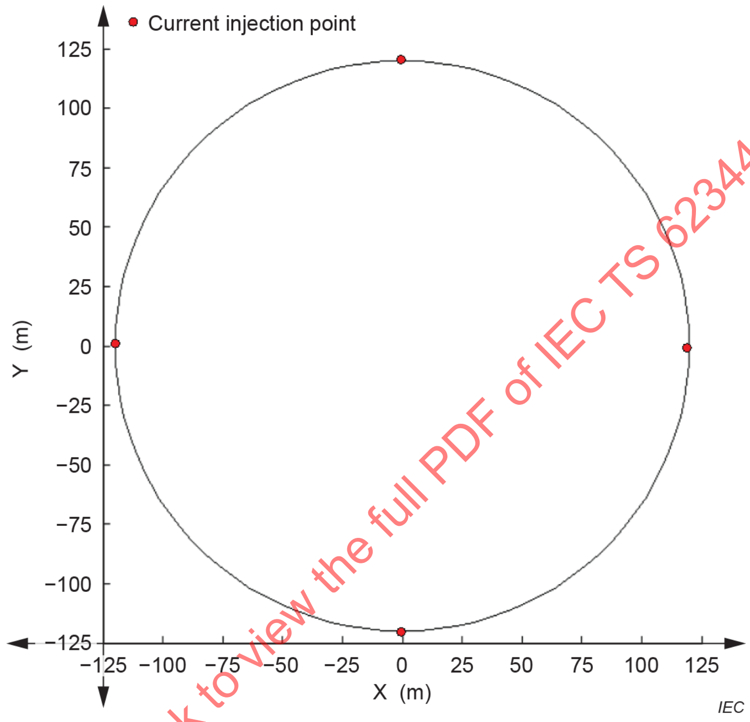


Figure A.8 – Schematic diagram of single circular earth electrode

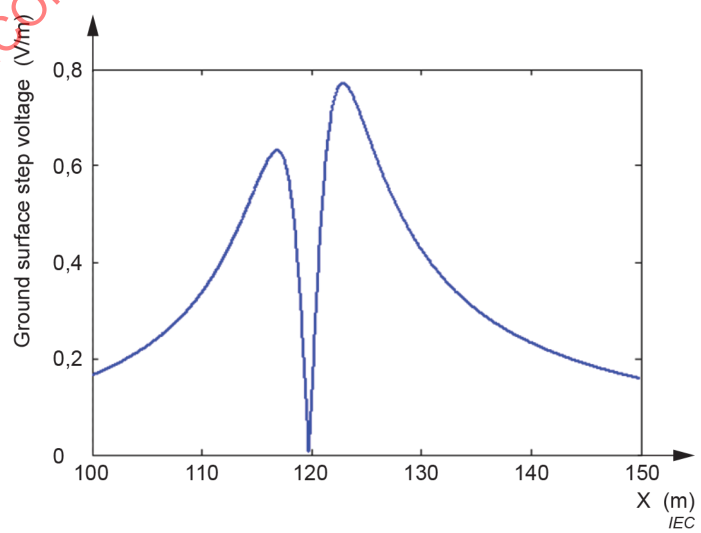


Figure A.9 – Axial distribution of step voltage of single circular earth electrode

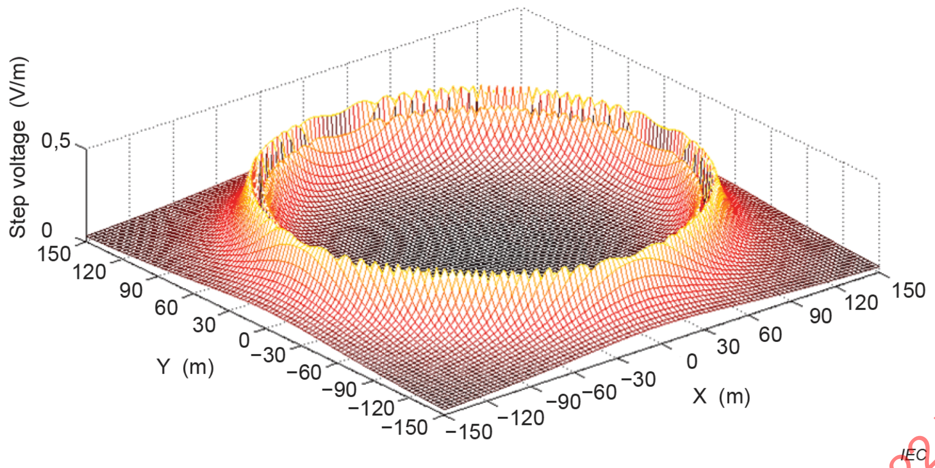


Figure A.10 – 3-D distribution of step voltage of single circular earth electrode

b) Typical double circular DC earth electrode

A double circular DC earth electrode structure is shown in Figure A.11, and distribution of step voltage is shown in Figure A.12 and Figure A.13.

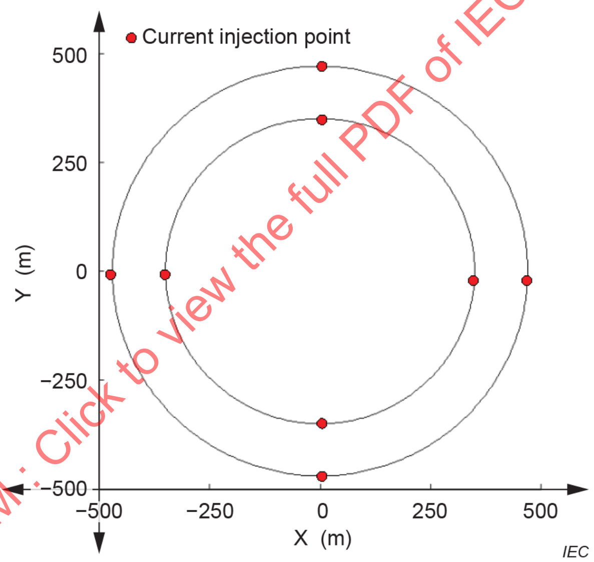


Figure A.11 – Schematic diagram of double circular earth electrode

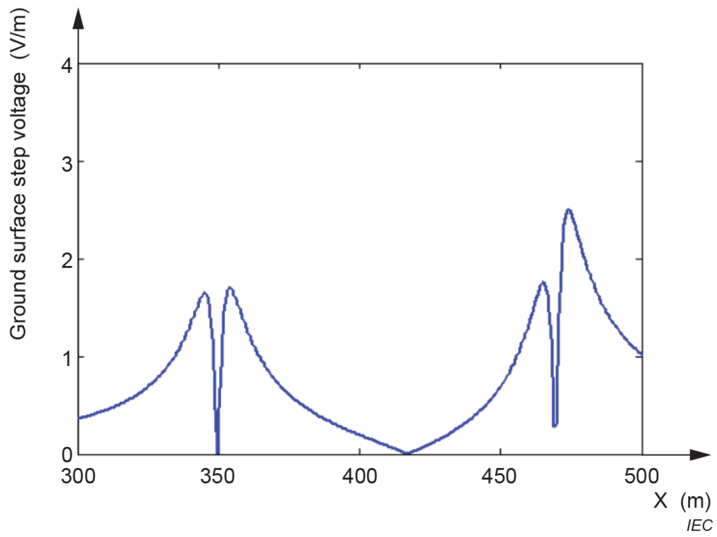


Figure A.12 – Axial distribution of step voltage of double circular earth electrode

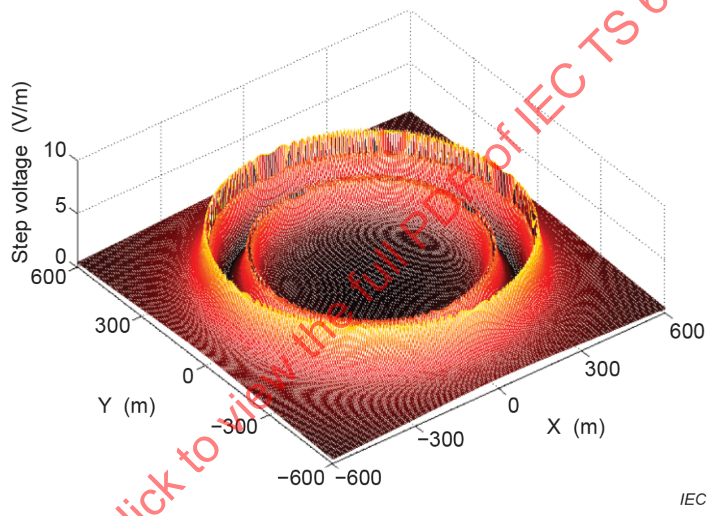


Figure A.13 – 3-D distribution of step voltage of double circular earth electrode

c) Typical triple circular DC earth electrode

A triple circular DC earth electrode structure is shown in Figure A.14, and distribution of step voltage is shown in Figure A.15 and Figure A.16.

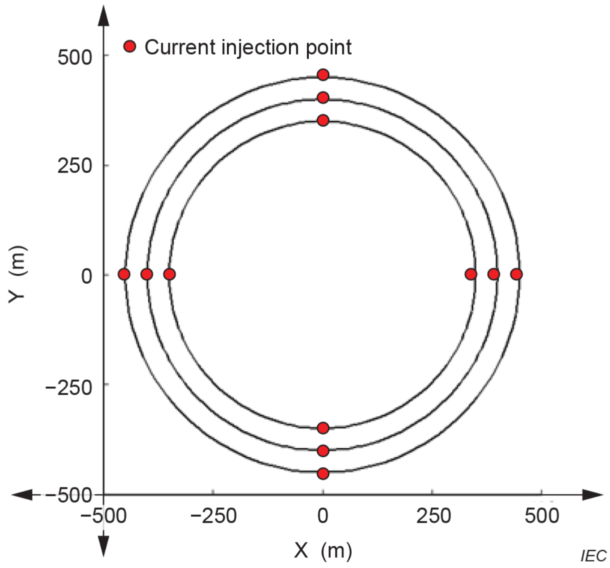


Figure A.14 – Schematic diagram of triple circular earth electrode

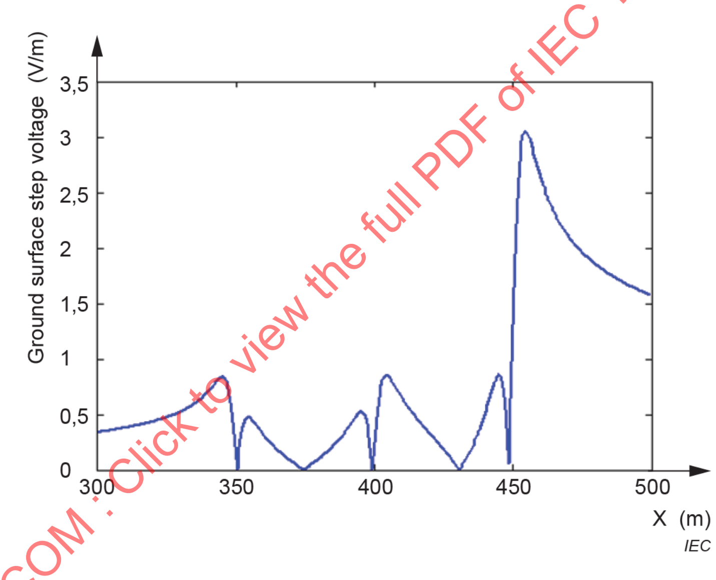


Figure A.15 – Axial distribution of step voltage of triple circular earth electrode

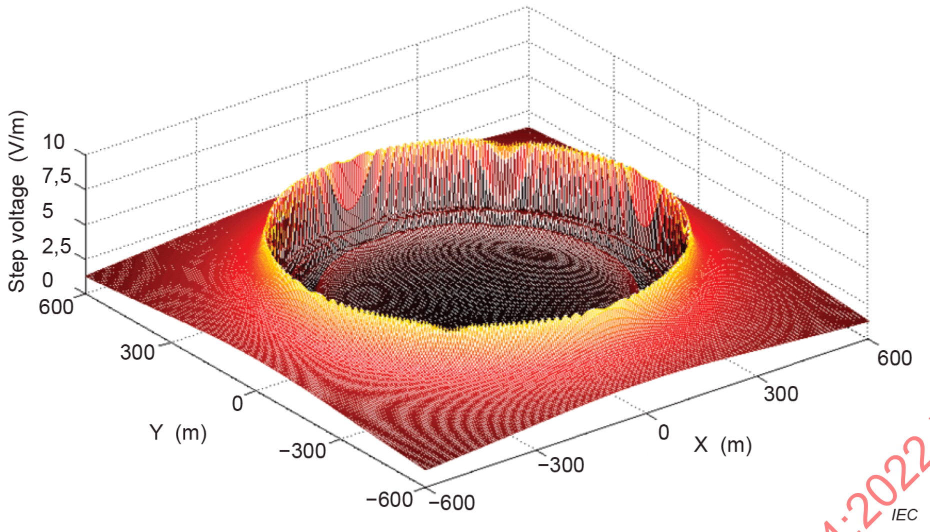


Figure A.16 – 3-D distribution of step voltage of triple circular earth electrode

A.3.3 Accumulated effect of DC earth electrodes

The accumulated effect of earth electrodes mainly involves electrochemical corrosion of metal conductors due to DC current. During system operation, the earth serves as a giant electrolyte tank, and the DC earth electrodes of the converter station at the two ends serve as two electrodes in this electrolyte tank. The process of electrolysis and dissipation continues at the anode according to Faraday's laws of electrolysis, leading to electrochemical corrosion of the DC earth electrodes themselves. As the time elapses, the total ampere hours of the earth electrodes in operation continue to increase, causing more serious corrosion of the buried metal conductors. The corrosion of earth electrodes therefore has a typical accumulated effect over time.

One important aspect of well-designed earth electrodes is the ability to ensure safe operation of electrodes throughout the designed service life, despite the corrosion during operation of these electrodes. On the other hand, investment in earth electrode construction should be minimized.

For DC earth electrodes, the issue of electrolysis corrosion remains a major challenge as a high current, of the order of kA, is likely to flow through them for a long time.

When a DC power transmission system is operated using earth as the return circuit, the current will flow from the ~~grounded anode to soil~~ anode electrode to the ground, and, at the other end of the DC line a corresponding current will flow back from the ground to the cathode ~~to the lines~~. ~~Flow of current in soil is mostly made possible by electrolyte in the soil.~~ The current flow on the ground is mostly made possible by the weak electrolyte formed by the ground waters.

Low-carbon steel (iron) is now a commonly used anode material as it is widely available and low in price. The electrolysis corrosion process is explained below by using an iron anode as an example.

Chemical Formulas near the anode:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \tag{A.2}$$

$$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2 \tag{A.3}$$

$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3 \tag{A.4}$$

Fe^{2+} ions generated during electrolysis will enter the electrolyte from the anode to react with OH^{-} ions there, generating ferrous hydroxide, $Fe(OH)_2$. Ferric hydroxide, $Fe(OH)_3$, is the product of further oxidation (a reddish-brown unconsolidated material). This process will continue to consume anode metal. Consumption of metal anode during electrolysis can be calculated below based on Faraday's laws:

$$m = \frac{A_m}{KF} It \tag{A.5}$$

where

m is the consumption of metal material (g);

A_m is the molar mass of the metal (g/mol);

K is the metal valency, dimensionless;

F is Faraday's electrolytic constant, 9,648 53 × 10^4 C/mol;

I is the current flowing through the metal (A);

t is the current flowing time (s).

As the molar mass and valency of iron are 55,86 g/mol and 2 respectively (ferrous ions with valence 2 are generated during electrolysis), for each ampere of current flowing through the iron anode, the annual consumption of the anode can be calculated as follows:

$$m = \frac{55{,}86}{2 \times 9{,}648\,53 \times 10^4} \times 1 \times 365 \times 24 \times 60 \times 60 = 9\,128{,}86 \quad [\text{g}] \tag{A.6}$$

In case of bipolar connection, suppose the rated current of each pole is 1 kA, the unbalanced current in normal conditions is 30 A, and the monopolar operation rate is 1 %, then the annual consumption of the iron anode can be as high as:

$$m = 9\,128{,}86 \times (30 \times 0{,}99 + 1\,000 \times 0{,}01) = 3{,}62 \times 10^5 \quad [\text{g}] \quad = 362 \quad [\text{kg}] \tag{A.7}$$

~~It can be seen that~~ The anode material is significantly corroded due to electrolysis. If the earth electrode has a designed life of 30 years, which means 40 % of earth electrodes can be consumed after 30 years, earth electrodes will require 27,15 tons of steel.

~~Anti-~~ Corrosion of the earth electrodes is an issue that cannot be overlooked during design of earth electrodes. The solutions are typically selected from the perspectives of anode material selection, structure and shape optimization~~, and proper anti-corrosion measures, such as anti-corrosion coating and cathode protection~~.

A.4 Impact on an AC grid

A.4.1 General

In general by far the most difficult problems that may arise in the performance of ground return mode of operation, concerns the influence on AC power systems. Such problems would likely be due to the resistivity profile of the ground over vast areas around the electrode and the relative location of infrastructures like AC substations and the configuration of electrical power systems.

The necessary and effective protection for ground DC ~~excitation~~ bias of transformers is to locate the electrode station at a certain distance from any vulnerable substation, including the converter station.

A.4.2 DC current path to AC system

A.4.2.1 General

The basic cause of effects of HVDC transmission in ground return mode on to the AC system is due to potentials at the ~~gradient of ground potential rise~~ soil surface caused by the return of DC current through the ground. The main paths that DC current follows into AC system include the shielding wire(s) and the grounded star point of AC transformer(s).

A.4.2.2 Shielding wire

~~When the shielding wires are continuous, part of the picked-up current follows these wires. Intermediate towers close to the anode pick up further fractions of current, while towers close to the cathode discharge corresponding fractions. The principal risk is corrosion of the anodic part.~~

When the electrode operates as an anode type, the shielding wires of the towers close to the electrode will pick up part of the electrode current and discharge it to the towers at the distal end. On the contrary, if the electrode operates as a cathode type, the towers at the distal end will absorb current from the surrounding soil and discharge it to the towers close to the electrode. Under these circumstances, it may result in risk of corrosion to the grounding devices of the towers discharging current.

A.4.2.3 Grounded star point of AC transformer

Due to the ~~earth~~ soil surface potential gradient, DC current enters the grounded star point of AC transformer A, follows the high-voltage phases to transformer B and leaves through the star point connection and ground grid of substation B. The transformers most affected by DC current will be in the vicinity of either electrode stations as the ground potential gradient is steep only in the vicinity of electrode stations.

A.4.3 DC magnetic bias of AC transformer

A.4.3.1 General

The DC component through the transformer windings provokes a constant magnetising of the core, which, superimposed on the symmetrical AC magnetising, lets the flux vary in an unbalanced way, which in one flux direction may lead to saturation of the core. Both YY and YD type of transformers will have flux offset by the ground potential rise. As the transformer operates in the nonlinear portion of its magnetizing curve, the magnetizing current will consist of a series of harmonic currents. The wave form of the current is ~~destroyed~~ distorted mainly due to a rise in the content of the second harmonics. Generally there will also be a rise of several other positive, negative and zero sequence harmonics, particularly 3rd harmonic current.

The vulnerability to DC magnetizing varies for different core types. Monophase transformers with magnetic return equal in area to the wound leg are strongly affected. Three-phase, five-legged transformers also react to some degree. Three-phase, three-legged transformers will withstand a high level of DC current excitation.

A.4.3.2 Three-phase, three-legged transformer

The tank of the three-legged transformer, for zero sequence flux, acts like a single turn secondary winding and large currents may be induced in the tank causing vibration and overheating.

A.4.3.3 Three-phase, five-legged transformer

In three-phase, five-legged transformers, the return legs carrying more DC flux are more likely to saturate than the phase legs. Once the outer legs are saturated, the transformer for further excitation acts almost like a three-legged transformer.

A.4.3.4 Reactor

Reactors with magnetic cores, for compensation purposes, are not at all exposed to DC saturation. This statement is valid regardless if the reactors are monophase or three-phase, with three- or five-legged cores.

A.4.3.5 Saturation time constant

The rise of the harmonics in the transformers with saturation depends on the time constant of the circuit through which the DC current would circulate. Generally, this time constant is of several seconds and full harmonic current peaks due to saturation are not reached until almost a minute after the rise of ground potential. Within this time it is generally possible to transfer the system to metallic return configuration.

A.4.3.6 Saturation analysis

When analysing the possibility of saturation, the grid composition is usually much more complicated. A detailed resistance network containing the different stations, the mutual interconnection between stations and the resistance in transformers should be set up, and the flow in the different branches calculated.

Generally speaking, the problem of saturation is not very serious for most of small grid transformers (<200 MVA), as they are normally three-phase, three-legged. Attention will be drawn to large ~~monophase~~ single phase units and to large three-phase units, which are often five-legged to reduce height in order to facilitate transportation.

Annex B
(informative)

Earth electrode design process

B.1 Site selection process

Site selection of earth electrode starts with a desktop study and then is followed by geographic survey and data acquisition, electrode pre-design, preliminary interference studies, and preparation of site selection reports.

The flow chart of earth electrode site selection process is shown in Figure B.1.

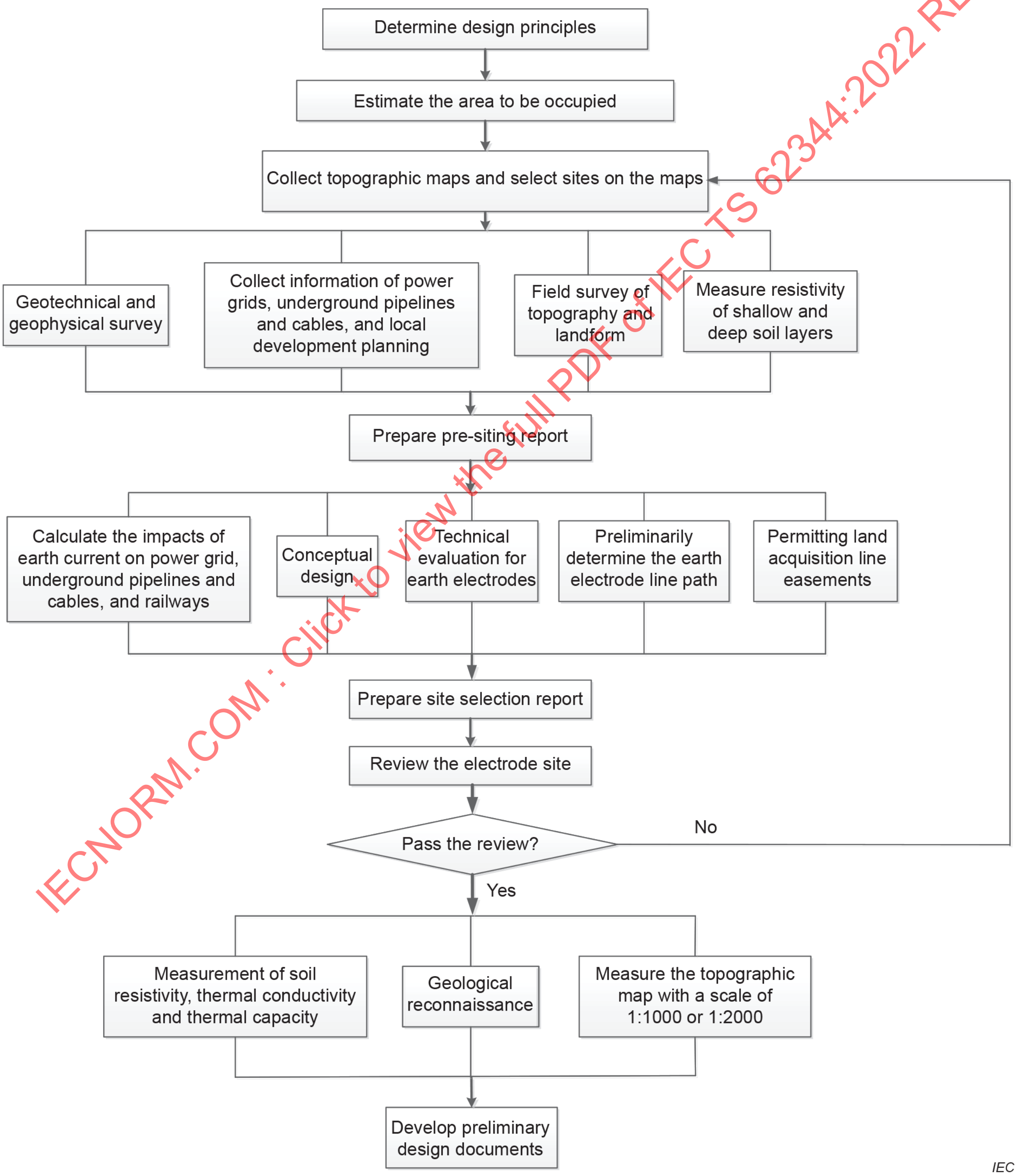


Figure B.1 – Flow chart of earth electrode site selection process

B.2 Earth electrode design process

a) Specify the system conditions for design of earth electrode, with the definition of the current versus time for each operational condition – continuous unbalance current, monopolar current during annual maintenance of one pole at maximum current, overload current, and rated current of earth electrode, plus any assumed long time operation in monopolar operation to determine the service life of earth electrode elements;

b) Developed a desktop survey, which will consider the relevant aspects for the selection of the candidate sites to be surveyed (geography, geology and so on). After the selection of the candidate sites, they should be inspected and surveyed. The owners of the lands should be previously contacted because it they do not agree to allow for the surveys in their lands the site should be discarded;

c) Conduct geotechnical and geophysical surveys at the selected sites that are being considered as candidate sites for the electrode, followed by the construction of the geoelectric models of the soil each site, to be used for the preliminary electrode design;

d) Determine the type of earth electrode based on electrode site conditions, site constraints, areas, soil resistivity model, thermal parameters (thermal conductivity and capacity), and other parameters;

e) Determine the material of earth electrode considering factors such as the magnitude of earth current of earth electrode, service life of earth electrode, and corrosiveness of groundwater, as well as engineering application and costs of various materials;

f) Determine the major design parameters of earth electrode. The dimensional parameters, such as the electrode size, burial depth and cross-sectional area of coke, should be determined based on the available area of the electrode site and comprehensively considering technical parameters such as the electrode resistance, step voltage, current density, and ground temperature rise. The impact of construction difficulty and project cost should also be taken into consideration;

g) Design of the current-guiding system of earth electrode. In design of the current-guiding system of earth electrode, the electrode should be sectionalized if the owner has specified that operation shall be possible with outage of a given portion of the electrode in case of maintenance. It should be designed based on the calculation results of the electrode current and potential distribution; the cross-sectional area of current-guiding cables should be determined based on the magnitude of current in each section of electrode;

h) Design of auxiliary facilities. Seepage wells and monitoring wells can be designed for earth electrode, and online monitoring system can also be provided if specified by the owner.

The flow chart of earth electrode design process is shown in Figure B.2.

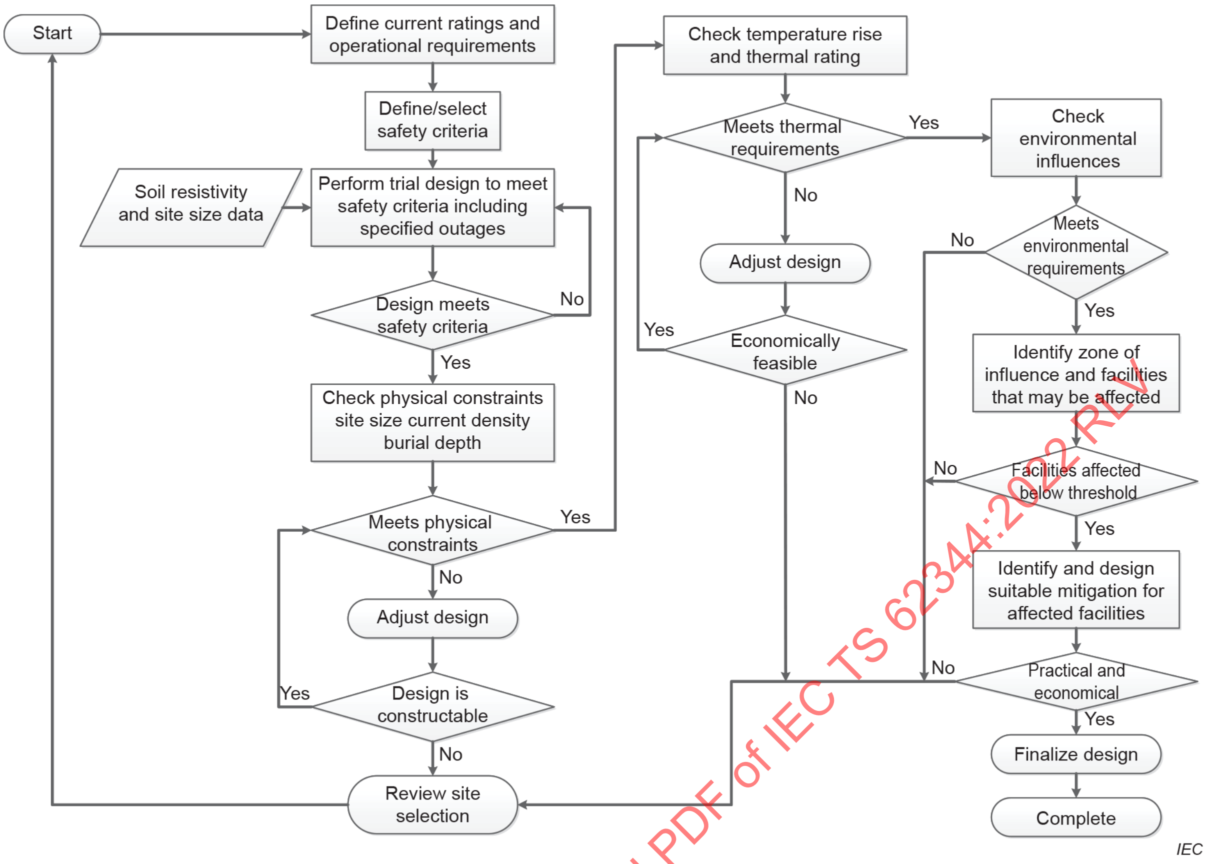


Figure B.2 – Flow chart of earth electrode process

Annex C
(informative)

Test results of human body resistance

C.1 Basic information of test subjects

A total of 1 028 test subjects including 589 farmers, 278 college students and 161 scientific workers are selected to test the human body resistance. Among them, there are 631 males and 397 females, presenting a ratio of about 1,59:1. The test subjects are 12~75 years old, 140 cm~186 cm in height and 27 kg~95 kg in weight. All the test subjects were healthy, and their heart rate was stable and normal when participating in the test.

The age, height and weight distribution of the test samples are shown in Figure C.1, Figure C.2 and Figure C.3 respectively. For all samples, the average height of males was 170,01 cm, with an average weight of 63,50 kg, and the average height of females was 157,98 cm, with an average weight of 55,31 kg.

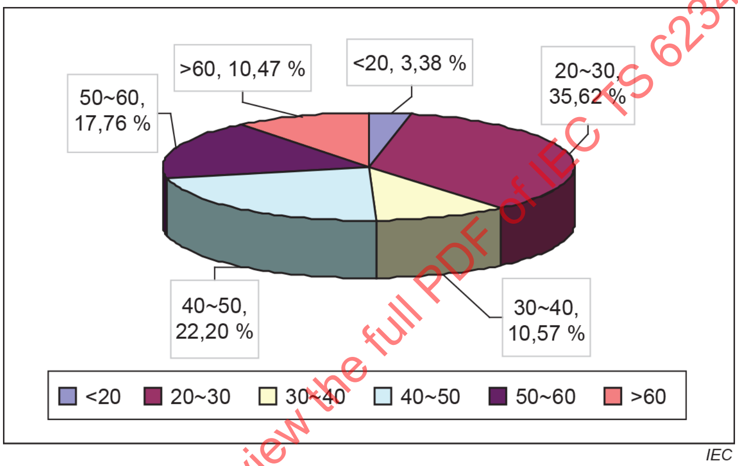


Figure C.1 – Age distribution of test samples

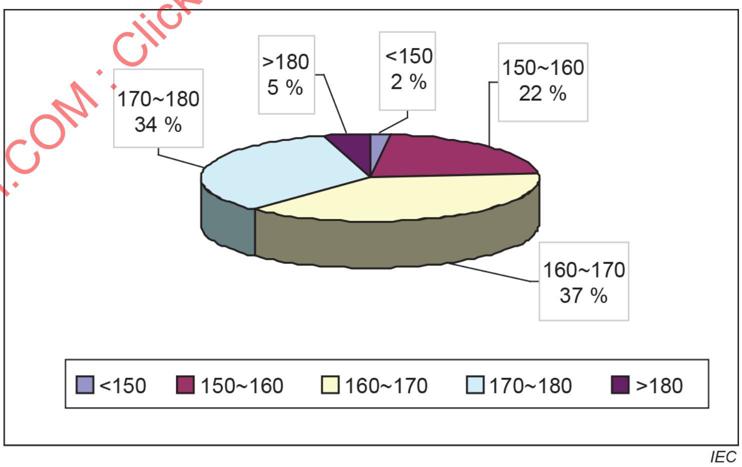


Figure C.2 – Height distribution of test samples

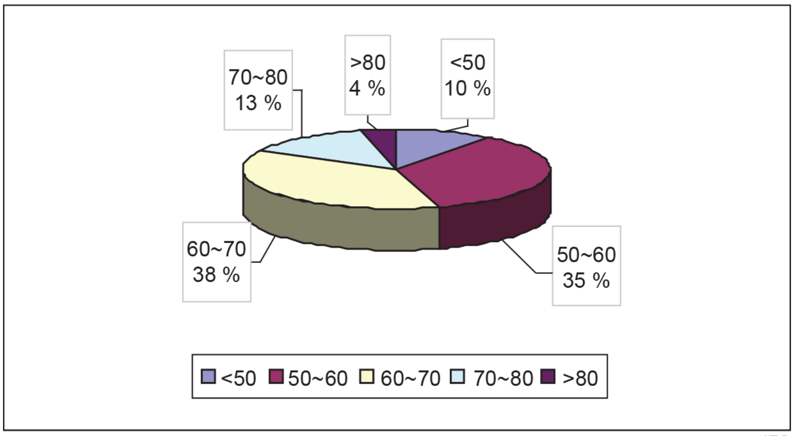


Figure C.3 – Weight distribution of test samples

C.2 Test method

The human body resistance is measured by using the ammeter and the voltmeter. Use an adjustable DC power supply to apply voltage to two copper plates immersed in 10 % salt water (with a resistivity of 1,53 Ω·m) in a test tank and let the test subject stand barefoot on these two copper plates. The depth of salt water is about 3 mm~5 mm such that the copper plates is just immersed into the water and the soles of the test subject are in full contact with the salt water. This will minimize the impact of the contact resistance between the two feet of the human body and the surface of the copper plates on the measurement. Under this condition, use an ammeter to measure the current flowing through the human body, and use a voltmeter to measure the voltage between the two copper plates, then calculate the human body resistance by Ohm's law. The pulse and blood pressure of the test subjects are monitored throughout the whole test process.

The schematic diagram of the test circuit is shown in Figure C.4.

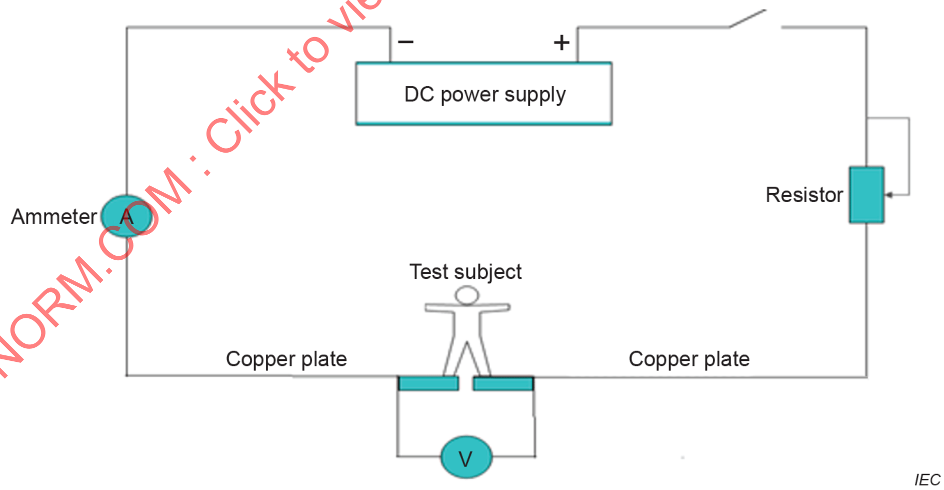


Figure C.4 – Schematic diagram of test circuit

C.3 Test results

The foot-to-foot human body resistance is recorded under the perception current (when the sample subject starts to have sensation). The statistical information of test subjects and test results are given in Table C.1.

A total of 945 sets of valid data were obtained from 243 students (25,7 %), 156 scientific workers (16,5 %) and 546 farmers (57,8 %). The statistics show that the average foot-to-foot body resistance is 2 550 Ω. Specifically, the distribution of human body resistance is: 1 000 Ω ~1 100 Ω accounted for 0,42 %, 1 100 Ω ~1 200 Ω accounted for 0,85 %, 1 200 Ω ~1 300 Ω accounted for 1,06 %, 1 300 Ω ~1 500 Ω accounted for 4,66 %, and larger than 1 500 Ω accounted for 93,01 %.

Table C.1 – Statistical test results (foot-to-foot body resistance)

Place of test	No. of subjects			Foot-to-foot human body resistance Ω		
	Total	Male	Female	Minimum	Maximum	Average
College A	58	52	1	1 181	4 900	2 360
College B(1)	98	82	16	1 355	6 366	2 707
College B(2)	53	51	2	1 422	5 121	2 680
College C	39	28	11	1 567	5 131	2 992
Village A	39	14	25	1 530	5 668	3 140
Village B(1)	132	59	73	1 133	6 497	2 549
Village B(2)	74	33	41	1 140	4 412	2 416
Town C	57	42	15	1 047	6 114	2 878
Town D	19	18	1	1 100	5 116	2 789
Town E	24	20	4	1 433	3 681	2 280
Village F	69	12	57	1 236	4 096	2 470
Town G	58	36	22	1 416	4 012	2 366
Previous data	225	150	75	1 021	8 477	2 370
Total	**945**	**597**	**348**	**1 021**	**8 477**	**2 550**

Figure C.5 shows the histogram of foot-to-foot human body resistance distribution by occupation, and Figure C.6 shows the cumulative probability distribution curve of foot-to-foot body resistance by occupation. The statistical results show that among the test subjects, the measured foot-to-foot body resistance from farmers is a bit larger than that obtained from other occupations.

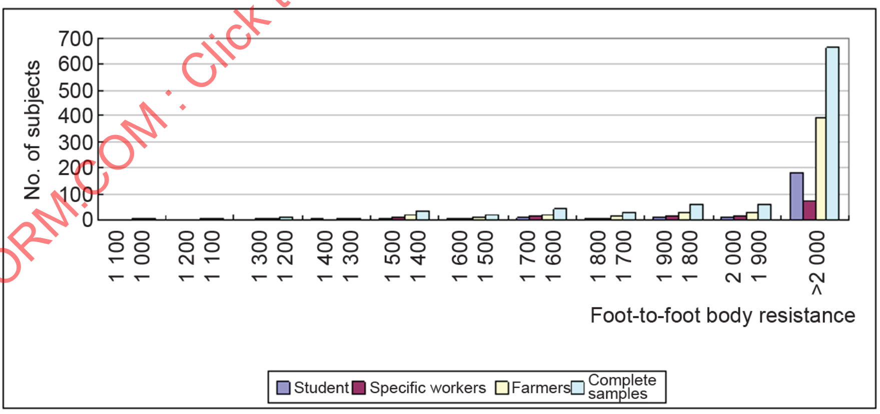


Figure C.5 – Histogram of foot-to-foot human body resistance distribution

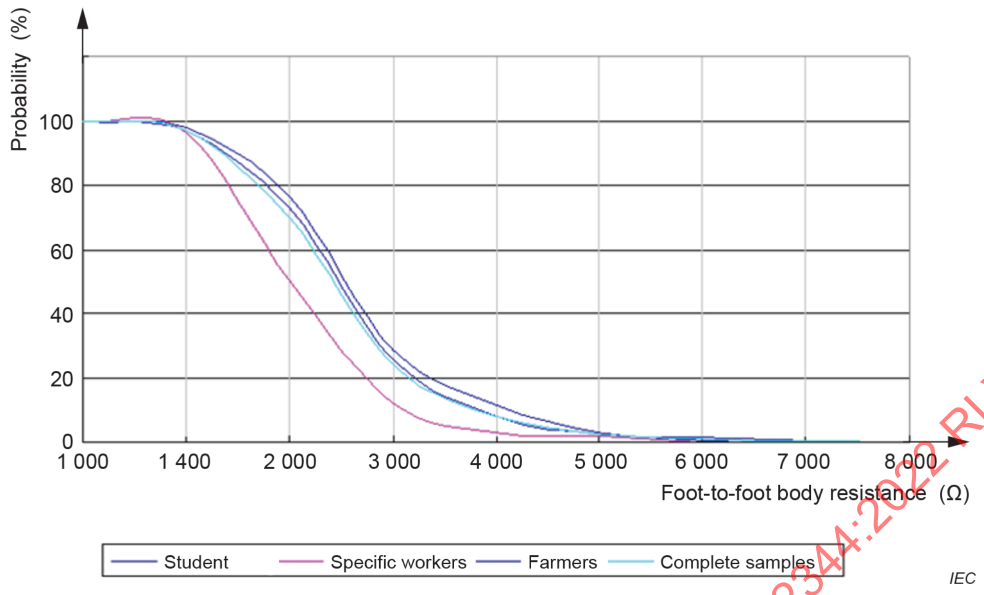


Figure C.6 – Cumulative probability distribution of foot-to-foot body resistance by occupation

The foot-to-foot human body resistance with probability greater than 90 % in Figure C.6 and the cumulative probability are listed in Table C.2.

According to the statistics, the foot-to-foot human body resistance of 95 % of the test subjects is larger than 1 467 Ω. Therefore, when calculating the step voltage limit of earth electrode, it is safe to take the human body resistance as 1 400 Ω.

Table C.2 – Cumulative probability distribution of foot-to-foot human body resistance

Probability of human body resistance which is larger than a certain value %	Foot-to-foot resistance Ω
98	1 290
97	1 398
96	1 447
95	1 467
93	1 502
90	1 609

Annex D
(informative)

Soil parameter measurement method

D.1 General requirements

During the design of earth electrodes, the main physical parameters of the soil on the electrode site should be measured in order to determine the ~~electrical parameter~~ geoelectric model of the site, thermal properties of soil and evaluate the impact of the earth electrodes on the environment. The main physical parameters of soil include soil resistivity, soil volume thermal capacity, soil thermal conductivity, soil highest natural temperature, soil moisture, and groundwater table.

Common soil (rock) / Water resistivity values are listed in Table D.1. Soil volume thermal capacity values are listed in Table D.2. Soil thermal conductivity values are listed in Table D.3. Due to the importance of these 3 parameters, they ~~shall~~ should be measured at the electrode sites, especially for the soil resistivity. Some measurement methods of soil resistivity are listed in Clause ~~B.2~~ C.2.

Table D.1 – Soil (rock) / Water resistivity

Substance	Soil (rock) / Water name	Resistivity Ω·m	Remarks
Water	Rainwater	$>10^3$	Related to the ~~content of conductive substances~~ number of ions in the water
	River water	$10\sim10^2$	
	Sea water	$5\times10^{-2}\sim1$	
	Ground water	$10^{-1}\sim3\times10^2$	
	Ice	$10^4\sim10^8$	
Soil	Clay, silty clay	$10\sim10^3$	Related to the ~~content of water and conductive substances~~ number of ions in the soil water
	Silt		
	Wet sand		
	Dry sand, pebble	$10^3\sim10^5$	
Sandstone	Argillaceous shale	$20\sim10^3$	
	Tight sandstone		
	Red sandstone	$10\sim10^2$	
Limestone	Muddy limestone	$50\sim8\times10^2$	
	Limestone	$3\times10^2\sim10^4$	
Rock	Granite	$2\times10^2\sim10^5$	Highly related to the moisture content
	Granodiorite	$5\times10^2\sim10^5$	
	Diorite		
	Basalt		
	Gabbro		
	Porphyrite		
	Peridotite		
	Schist	$2\times10^2\sim10^4$	
	Gneiss	$2\times10^2\sim2\times10^4$	
	Dolomite	$10^2\sim10^4$	
	Carbonate rock	$10^4\sim10^8$	

Substance	Soil (rock) / Water name	Resistivity Ω·m	Remarks
Mineral	Gypsum	10^2~10^8	
	Copper pyrite	10^{-4}~10^{-1}	Related to the minerals and moisture content
	Magnetite	10^{-4}~10^3	
	Hematite	1~10^5	
	Quartz	>10^6	
	Mica	>10^8	

Table D.2 – Soil volume thermal capacity

Soil type	Volume thermal capacity J/(m^3·°C) × 10^6		
	Dry	50 % wet saturation	100 % wet saturation
Sand	1,26	2,13	3,01
Clay	1,00	2,22	3,43
Humus	0,63	2,18	3,77

Table D.3 – Soil thermal conductivity

Soil type	Thermal conductivity W/(m·°C)	
	Dry	Wet
Sand	0,27	1,85
With silt and clay	0,43	1,90
Soil with fine sand	0,33	2,3
Silt soil	0,37	0,88
Clay with sand	0,42	1,95
Volcanic soil	0,13	0,62
Black agricultural soil (frozen)	0,18	1,13
Brown natural soil (frozen)	0,08	1,20
Yellow-brown natural soil (frozen)	0,10	0,82
Gravel with sand and silt	0,55	2,55
Ice (0 °C)		2,22

D.2 Measurement of resistivity of ~~surface soil~~ shallow ground

D.2.1 Measurement method of resistivity

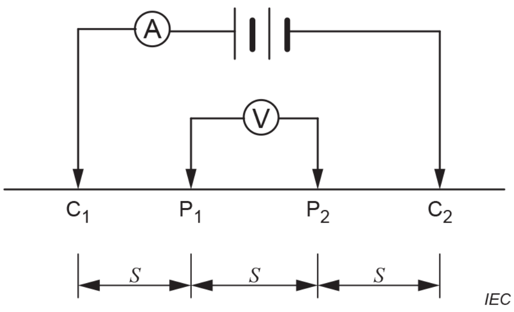
D.2.1.1 General

~~The resistivity of the soil surface should be measured with a field geophysical survey method to ensure the accuracy of the results. Among the most frequently used geophysical survey methods in current measurements are Wenner, Schlumberger and dipole-dipole methods.~~

The resistivity of the shallow ground can be done by a field survey with the electroresistivity method. Among the most frequently used arrangements of the electroresistivity method, it can be mentioned the Wenner, Schlumberger and dipole-dipole.

D.2.1.2 Wenner method

The equivalent circuit for this measurement ~~method~~ arrangement is shown in Figure D.1. The apparent resistivity can be calculated with Formula (D.1).



Key

S ~~pole distance~~ potential probe spacing (m)

V voltage meter

A current meter

P_1, P_2 ~~voltage pole~~ potential probe

C_1, C_2 current ~~pole~~ probe

Figure D.1 – Equivalent circuit of Wenner method

$$\rho_S = 2\pi S \frac{U}{I} \tag{D.1}$$

where

I is the measurement result of current meter (A);

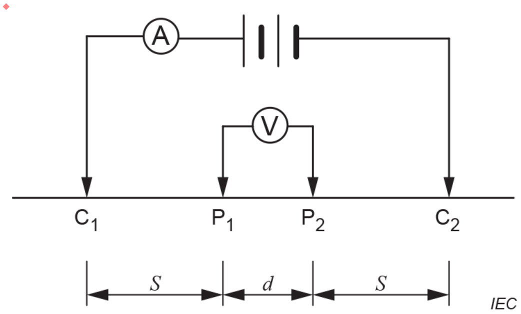
ρ_S is the apparent resistivity of earth (Ω·m);

S is the ~~pole distance~~ potential probes spacing (m);

U is the measurement result of voltage meter (V).

D.2.1.3 Schlumberger method

The equivalent circuit for this measurement ~~method~~ arrangement is shown in Figure D.2. The apparent resistivity can be calculated with Formula (D.2).



Key

S ~~pole distance~~ spacing between the adjacent current probe and potential probe (m)

d ~~distance between voltage poles~~ potential probes spacing

V voltage meter

A current meter

P_1, P_2 ~~voltage pole~~ potential probe

C_1, C_2 current ~~pole~~ probe

Figure D.2 – Equivalent circuit of Schlumberger method

$$\rho_s = \pi \frac{S(S+d)}{d} \frac{U}{I} \tag{D.2}$$

where

ρ_s is the apparent resistivity of earth (Ω·m);

S is the ~~distance between current poles and voltage poles~~ spacing between the adjacent current probe and potential probe (m);

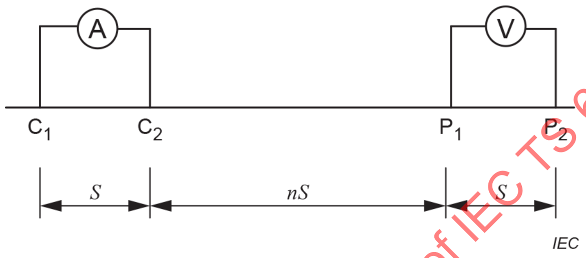
d is the ~~distance between voltage poles~~ potential probes spacing (m);

U is the reading of voltage meter (V);

I is the reading of ammeter (A).

D.2.1.4 Dipole-dipole method

The equivalent circuit for this measurement ~~method~~ arrangement is shown in Figure D.3. The apparent resistivity can be calculated with Formula (D.3). It is especially useful for measuring lateral resistivity changes and has been increasingly used in geotechnical applications.



Key

S ~~distance between current poles (voltage poles)~~ spacing between current probes (potential probes) (m)

nS ~~distance between the adjacent current pole and voltage pole~~ spacing between the adjacent current probe and potential probe (m)

V voltage meter

A current meter

P_1, P_2 ~~voltage pole~~ potential probe

C_1, C_2 current ~~pole~~ probe

Figure D.3 – Equivalent circuit of dipole-dipole method

$$\rho_s = \pi S \times n(n+1)(n+2)\frac{U}{I} \tag{D.3}$$

where

ρ_s is the apparent resistivity of earth (Ω·m);

S is the ~~distance between current poles (voltage poles)~~ spacing between current probes (potential probes) (m);

n is the ratio of ~~distance between the adjacent current pole and voltage pole, and distance between current poles~~ spacing between the adjacent current probe and potential probe, and current probes spacing;

U is the reading of voltage meter (V);

I is the reading of ammeter (A).

D.2.2 Measurement requirements

~~The measurement is made with d.c. power supply and d.c. meters.~~

~~During measurement, the meter accuracy, error and data should be calibrated properly.~~

The survey should be done either directly using a DC resistivity meter, or indirectly using a combination of a DC power supply, a DC ammeter and a DC voltmeter.

The resistivity should be measured at different measurement points (center location of current ~~poles~~ probes) and with different alignments of measuring probes. Measurement points generally have a uniform distribution at the electrode site. Because information of shallow layers will be obtained usually when ~~pole distance~~ probes spacing is short, measurements with short ~~pole distance~~ probes spacing should be conducted at more measurement points due to the importance of resistivity model of shallow layers. Table D.4 provides an example for resistivity measurement.

Table D.4 – Number of measurement points with different ~~pole distances~~ potential probes spacing

~~Pole distance~~ Potential probes spacing m	2	5	10	15	20	30	50	70	100	150	200	300	500	700	1 000
Number of measurement points point/km^2	49					36				25		16		9	4

~~If the voltage probe pole distance is longer than 300 m, measures should be taken (such as increasing testing current or using compensation) to reduce the impact of disturbance current in soil on the measurement results and achieve an error not exceeding 5 %, and measurement wires should be deployed in two directions that are vertical to each other.~~

If the potential probes spacing (P_1P_2) is wider than 300 m, measures should be taken (such as lowering the current probes resistances to increase testing current) to reduce the impact of disturbance current in soil on the measurement results.

D.2.3 Measurement range

The soil resistivity measurement range should be larger than the area of the earth electrode. The ~~pole distance~~ potential probes spacing (P_1P_2) should be no shorter than ~~1 000 m~~ the maximum diagonal distance of electrode.

D.2.4 Data accuracy

For those electrode sites where stray DC currents may exist, to ensure accurate results, during soil resistivity measurement, two groups of data should be read by switching the power supply connection polarity of the same measurement point at the same measurement depth (~~pole distance~~ potential probes spacing). Repeat the measurement if the difference between both data groups is higher than 5 %.

D.2.5 Seasonal coefficient

The seasonal coefficient of soil resistivity should be considered. At the place where the earth electrode is buried, a few representative permanent marks should be erected so that measurement of soil resistivity can be performed at the same place during the dry season (when the soil is dry) if possible.

D.2.6 Processing of measurement data

~~With the above measurement method, the apparent resistivity at different depths of different segments on the electrode site can be achieved. Formula (B.4) is used for processing the equivalent apparent resistivity measured at the same depth.~~

$$\rho_m = \frac{N}{\sum_{n=1}^{N} \frac{1}{\rho_n}} \qquad \text{(B.4)}$$

~~where~~

~~N is the number of soil segments;~~

~~ρ_m is the equivalent apparent resistivity measured at the same depth (Ω·m);~~

ρ_n is the apparent resistivity at the same measurement depth (Ω·m).

Based on Formula (B.3), a group of data concerning the variance of equivalent apparent resistivity depending on the depth on the electrode site can be achieved. Calculation is then made with this data with soil layering software to achieve a surface electrical property model on the electrode site.

After the conclusion of the shallow resistivity survey, an apparent resistivity curve can be obtained by averaging the apparent resistivity values of the same spacing.

This average apparent resistivity curve can be then used for the inversion process to achieve a surface electrical property model on the electrode site.

D.3 Measurement of resistivity of deep soil (MT method)

During the creation of the electrical parameter model for the electrode site, the earth resistivity needs to be measured from the surface to a depth (range) of tens of kilometers below the ground surface. Normal geophysical survey methods The electroresistivity method do not apply to the measurement of earth resistivity at a deep level. The magnetotelluric method (MT method) widely used in mine exploration tectonic studies and for oil survey should be adopted, which makes it easier to measure the earth resistivity at a deep level.

This is an electromagnetic measurement method based on the MT induction principle using alternating electromagnetic field as the natural field source. The MT method applies the electromagnetic induction principle using alternating electromagnetic field as the natural fluctuation of the earth's magnetic field. In the MT method, two horizontal components of the electric field that are perpendicular to each other (Ex and Ey) as well as three components of the magnetic field that are perpendicular to each other (Hx, Hy and Hz) are recorded successively simultaneously at the same point and same time. The wave impedance (Z) at the point can be calculated by means of the ratio of orthogonal measured fields Z = E/H. When the MT field is distributed uniformly along all directions and horizontally layered, the impedance Z = E/H. After transformation, variation of Earth crust apparent resistivity with the period T can be determined (apparent resistivity and phase curves) and expressed with $\rho_a = 0,2|Z|^2$.

This method uses the skin effect principle and treats the skin effect depth as the exploration depth:

$$H = \sqrt{\frac{\rho}{\pi f \mu}} \tag{D.4}$$

where

H is the exploration depth (m);

ρ is the apparent resistivity (Ω·m);

f is the frequency, can be as low as 0,000 1 (Hz);

μ is the soil permeability (H/m).

By changing the frequency, values of apparent resistivity at different exploration depth can be achieved, which are then processed by the computer (software) to obtain a deep-level electrical parameter model of the electrode site.

By means of a conversion from period domain to frequency domain (with a Fourier transform of the time-series data), values of apparent resistivity at different exploration depth can be calculated, which are then processed by the computer (software) to obtain the deep geoelectric model at the electrode site.

As the MT method makes use of the inductive coupling effect of alternating electromagnetic fields, it can penetrate high-resistance layers that can hardly be penetrated by DC exploration. Hence as long as if a suitable frequency band is selected, the MT method can detect the variance of underground electrical properties at a depth from a few hundred metres to a few hundred kilometres. Due to these features, the MT method has become a very effective method in exploration of minerals such as petroleum, especially during the evaluation of electrical properties of deep layers.

D.4 Measurement of soil volume thermal capacity

The volume thermal capacity of the soil layer where the electrode is buried should be measured. The volume thermal capacity of the soil is defined as the energy required for raising the temperature of unit volume of soil by one degree Celsius. The soil volume thermal capacity is typically measured with a heat-insulating calorimeter in a lab. The measurement method can use either continuous heat sources or intermittent heat sources.

With the intermittent heat source method, the sample in an insulation jacket is heated intermittently at a constant power. Curves of temperature variation over time are drawn to derive a relation between enthalpy and temperature and corresponding specific heat capacity of the sample. As the enthalpy in the sample is uniformly distributed due to intermittent heating, this method is often used for high-precision measurement.

With the continuous heat source method, the sample is continuously heated in an insulation jacket at a constant power. The specific heat capacity can be calculated based on the temperature rise and enthalpy of the sample after it has been heated for a while. The volume thermal capacity is the product of the specific heat capacity and density.

Samples delivered to the lab should be collected from each typical deep soil layer on the selected electrode site. The original conditions and moisture of the soil should be maintained during sampling. The number of samples should not be lower than the total number of soil types on the site and should be no less than 10. The samples should be undisturbed, which means that the original density and moisture should be preserved. The samples should be collected at the previewed depth of the electrode burial.

D.5 Measurement of soil thermal conductivity

The thermal conductivity of the soil layer where the electrode is buried should be measured. The thermal conductivity refers to the heat transferred every second when the temperature difference between two ends of unit length and area of soil is 1 °C. Measurement of thermal conductivity can be performed in a lab or on the site.

For measurement of thermal conductivity in a lab, samples need to be obtained and delivered. Requirements for samples delivered to the lab for such measurements are the same as those for samples used for volume thermal capacity measurements. Two methods are available for measurement of soil thermal conductivity. With the first method, soil samples are placed in two round metal plates with known thermal conductivity with one end being heated. A set of thermocouples are used to measure temperature at both ends, and a sensing device is used to measure the heat flux of the sample. After heat flux is measured for a period of time, for example 10 min to 2 h, the thermal conductivity is obtained by multiplying the heat flux through the meter with the sample thickness and then dividing the product by temperature difference. With the second method, the soil sample is produced into round thin pieces (e.g. with a diameter of about 8 mm and a thickness of about 1 mm). After the sample surface is heated by laser instantaneously, the thermal diffusion coefficient is obtained based on the temperature rise on the back of the sample. Next, the soil thermal conductivity is achieved by multiplying the thermal diffusion coefficient with a specific heat capacity and density. As the original conditions of soil and consequently measurement results are changed during this process, site measurement is usually used instead.

Site measurement can also be made with the static or instantaneous method. With the static method, a buried ball is heated until uniformly distributed heat flux can be achieved. As this process often lasts for a few days, it is often impractical. With the instantaneous method, a ~~cylinder measurement pole~~ needle or probe equipped with heater and temperature measurement components is inserted into soil at a desired depth. The heater supplies heat suddenly and the heat is transferred into the soil at a constant rate. In the meanwhile, the temperature rise at the contact between the measurement pole and the soil is monitored to determine the correlation between soil temperature rise and heat output over time. Thermal conductance theory is then ~~used~~ applied based on this data to calculate thermal conductivity. Generally, this method only requires 1 h.

D.6 Measurement of maximum natural temperature of soil

The best way to determine the maximum natural temperature of soil is on-site measurement or acquisition of relevant data in at least two recent years, from the meteorological authority. During the measurement of soil temperature, a thermistor thermometer should be adopted, and other considerations include measurement points with different geological conditions as well as highest temperature in summer and lowest temperature in winter at different depths. The minimum measurement depth should not be less than the depth of the buried earth electrode. In areas without terrestrial heat source and with distinct seasons, the maximum natural temperature of soil can be calculated as the maximum ground temperature over the year, minus 10 °C, and the minimum natural temperature of soil can be calculated as minimum ground temperature over the year, plus 10 °C.

D.7 Measurement of soil moisture and groundwater table

For an electrode site in a wet low-lying area, measurements should be made to find the parameters such as soil moisture and permanent groundwater table. The electrode site groundwater table can be obtained by consulting hydrological and geological maps or field investigation. To measure soil moisture, soil samples are often taken on the site and delivered to the lab, where the weight loss method is used to measure and find the moisture content of soil. The water table is usually measured in field, with geotechnical soundings (SPT) and with the drilling of monitoring wells distributed along the site area.

D.8 Measurement of soil chemical characteristics

For land electrodes near the sea and those in outback saline and alkaline land, soil parameters such as content of Cl^-, SO_4^{2-} ions and pH value should be measured to determine soil corrosiveness. Measurement of soil chemical characteristics is typically completed by taking soil and water samples on the site and testing them in a lab.

D.9 Geological exploration

The drilling method is used to find the soil types on the electrode site and thickness of cover ~~soil~~ sediments. The exploration range should match the ~~layout~~ previewed area and depth of the earth electrodes. The exploration should reach the depth of bedrock if it is shallower than 100 m depth.

D.10 Topographical map

1:1 000 or 1:2 000 topographic maps are drawn during measurement. The measurement range should match the layout of earth electrodes.

Annex E
(informative)

Electrode line design

E.1 Overview

The power lines used to connect DC converter station neutral buses and DC earth electrode current guiding systems are typically called electrode lines, which serve the main purposes of guiding the converter station earthing current out of the station and to the DC earth electrode, preventing both the corrosion of the grounding metal system in the converter station and rise of earth potential in the converter station, and avoiding magnetic saturation of the transformer and its effect in the station. Electrode line is an important part of the whole DC power transmission system. When the DC power transmission system runs in monopolar earth return mode, the current flowing through the electrode lines is equal to that in the DC lines. The electrode lines feature high rated current, low operation voltage, and, for some types of DC systems, short operation time at rated current.

The rated current of electrode lines is that of the DC power transmission system, which depends on the rated power transmission capacity and the rated voltage of this system. The rated current of a DC power transmission system is typically between a few hundred and a few thousand amperes.

The operation voltage of electrode lines is the voltage drop on the earth electrode and electrode lines caused by the current flowing through electrode lines. This voltage is related to factors such as the current flowing through electrode lines, line length, conductor resistance, and earth electrode earthing resistance. When a rated current flows through electrode lines, the operation voltage at the converter station end of electrode line is usually no higher than 10 kV, and at the earth electrode end is usually no higher than 1 kV. The operation voltage is even lower if the current flowing is a bipolar balanced current.

For a bipolar balanced DC power transmission system, the operation duration of electrode lines at rated current is the time for the bipolar balanced DC power transmission system to run in monopolar earth return mode, which is typically no longer than one year, or even as short as a couple of days.

For a monopolar earth return DC power transmission system, the operation duration of electrode lines at rated current is the operation duration of the DC power transmission system.

E.2 Main design principles

The main principles for electrode line design are the following:

a) design of electrode lines should comply with system operation requirements to ensure safe, reliable, and cost-effective operation, facilitate construction, operation and maintenance, save resources, and protect the environment;

b) determination of meteorological conditions should be based on calculation and analysis using the data provided by meteorological stations near the project lines and collected through meteorological field surveys. Wind pressure maps can be consulted, and the operation experiences of existing power lines can be drawn on. The design standards of similar DC power transmission systems with appropriately reduced voltage levels can be used as a reference;

c) selection of electrode line routes, safety factors for conductors, earth wires and electric power fittings, and design of tower and infrastructure can use DC line design standards of similar DC power transmission systems with appropriately reduced voltage levels as a reference;

d) conductors should be selected by giving full consideration to operation characteristics of electrode lines and making comparisons based on rated current, terrain in areas where the lines are deployed, ice-coating, and wind speed;

e) insulation coordination of electrode lines should be designed in such a way as to ensure reliable operation in different conditions including normal operation voltage, lightning overvoltage, and live-line operation.

~~f) the distance of electrode line conductors to earth and distance between conductors at crossings can be determined according to design standards of 110 kV a.c. lines in principle.~~

E.3 Selection and layout of conductor and earth wire

E.3.1 Selection of conductor

For the electrode lines of bipolar balanced DC power transmission systems, in consideration of short operation time at rated current, low operation voltage, and typically short lines, selection of cross-section of conductors should preferably be selected based on the current-carrying capacity allowed for heating.

For the electrode lines of monopolar earth return DC power transmission systems, selection of the cross-section of conductors should consider economic current density and is typically the same as that of DC line conductors.

During the selection of electrode line conductors, there is no need to consider electric field effects such as ground electric field intensity and ion current density or check corona effects such as corona loss, radio disturbance and audible noise. Combination of electrode line conductors should follow the principles of minimising the number of branches, easy deployment, and high reliability.

The conductor types should be determined through technical and economic comparison of conditions such as terrain in areas where the lines are deployed, ice coating and wind speed.

E.3.2 Selection of earth wire

The earth wire, if applied, should meet electrical and mechanical requirements during operation. Galvanized steel wire strand or aluminium clad steel wire strand is usually chosen for this purpose.

E.3.3 Layout of conductor and earth wire

For the sake of monitoring and protection of current-carrying capacity and lines, multiple sub-conductors with the same potential are often used for electrode lines. If potential is the only consideration, different sub-conductors can be bundled without insulation. However, because electrode line fault monitoring devices often use high-frequency pulses to detect line failures, the electrode line sub-conductors need to be grouped into two mutually insulated bundles. In addition, for single-circuit electrode lines, separating the electrode line sub-conductors into two groups and deploying them on two sides of a tower can reduce the mechanical stresses on the tower and hence reduce the weight of the tower. For the above-mentioned reasons, electrode line conductors are typically separated into two groups and deployed symmetrically on two sides of the tower. Since the two conductor groups have the same potential, the horizontal distance between conductors in the middle of the span length can be determined based on the following principle: The two groups of sub-conductors will not collide with each other when they don’t swing simultaneously in strong wind.

Considering the short distance between two groups of sub-conductors of electrode lines, electrode lines only need one earth wire, which can be placed on top of the tower.

E.4 Insulation coordination and earthing for lightning protection

~~C.4.1 Minimum gap between live parts and tower components~~

~~The minimum gap between live parts and tower components can be determined by consulting design standards for 35 kV a.c. lines.~~

E.4.1 Type and number of insulators

Given the low operation voltage of electrode lines, one piece of insulator will be enough from the perspective of electrical properties. However, due to the importance of electrode lines and the possibility of a short-circuited insulator, at least 2 pieces of insulators are used in most occasions. As far as the type of electrode line insulator is concerned, DC insulator should be selected.

E.4.2 Arcing horn gap

To prevent the insulators from being burnt by continuing DC current when the electrode line insulator string is broken through by lightning, the insulator string is often equipped with an arcing horn. The gap of the arcing horn should be designed in such a way to effectively protect the insulators after electrode lines are hit by lightning. In general, the gap should be less than 0,85 times the effective length of insulator string, and should not exceed the gap under lightning overvoltage. Also, the arcing horn gap should be able to quench the arc effectively within a short time so as to interrupt continuing DC current.

E.4.3 Earthing for lightning protection

As the insulation level of electrode lines is very low, installation of an earth wire will not significantly reduce the probability of the lines being hit by lightning. Typically, an earth wire is not necessarily used for a whole electrode line. To protect converter station equipment, an earth wire can be installed within a radius of 2 km to 3 km of the converter station.

In segments where the earth wires are installed, the distance between earth wires in the middle of the span length is dependent on the span length, and should generally be no shorter than 0,001 2 × L + 1 m (L representing the span length). The conductor protective angle of the earth wire at the tower head should not be larger than 30°.

The tower should be grounded at the base. The power frequency earthing resistance of the tower can be determined based on relevant requirements for AC lines.

E.5 Other considerations

To prevent earth electrode earth current from flowing between the bases of towers near the electrode site and causing electric corrosion of the tower bases, the bases of towers within a radius of 2 km to 3 km of the electrode site should be insulated from earth for most part and grounded with one point. The earth wires within a radius of 10 km of the site should also be insulated from earth. Base insulation is usually provided by bitumen and glass cloth (2 layers of bitumen and 3 layers of glass cloth) that wrap around the bases. The earthing resistance of tower bases should be higher than 500.

Annex F
(informative)

Assessment of measurement method

F.1 General guidance

Upon completion of earth electrode installation, acceptance tests and system commissioning tests should be carried out before the system is put into operation. During acceptance tests, the main characteristic parameters of the earth electrode station should be measured including the current distribution of the current guiding wire, earth electrode earthing resistance, and maximum step voltage, etc. The tests are intended to check compliance of the earth electrode station with design specifications and provide a basis for determining if the system is ready for commissioning tests. During system commissioning tests, in addition to checking the above main characteristic parameters of the earth electrode body with system earthing current, some other parameters should be measured including ground potential distribution near the electrode and electrode temperature rise if the system commissioning process allows the current to flow through the earth electrode continuously for a long time so as to provide basis for evaluation of impact on environment and thermal properties of the earth electrode during its operation. Data concerning the earth electrode obtained in the above tests can be used as the background parameters for operation of the earth electrode, and also as reference for evaluation of operation conditions of the earth electrode in the future.

F.2 Experiment (testing) items

F.2.1 Visual inspection of the earth electrode

F.2.1.1 Inspection of the construction records of the earth electrode

Check compliance of the earth electrode cross-section area and burial depth with design specifications. Check tightness and reliability of the welding between different ~~feeding rods~~ electrode elements and between ~~feeding rods~~ electrode elements and cables as well as insulation sealing.

F.2.1.2 On-site inspection of the earth electrode site

Clear facilities that may affect normal operation of the earth electrode. Repair sites ~~destroyed~~ damaged during construction. Check compliance of the layout and installation sizes of the earth electrode with design specifications.

F.2.1.3 Inspection of current guiding system

Check that the wiring of current guiding system and installation of its accessories are correct, complete and reliable. Check that the distance between conductors and earth (tower) is correct.

F.2.1.4 Insulation inspection

Check good insulation from earth of the earth electrode current-guiding construction and its base (with the earthing part disconnected).

F.2.1.5 Inspection of water penetration (filling) and detection devices

Check compliance of layout and installation of water penetration (filling) and detection devices with design specifications.

F.2.1.6 Inspection of safety precautions

Check safety marks and precautions. Ensure that the marks are intact, clear and readable.

F.2.2 Current guiding system current distribution measurement

The current distribution of the current guiding system can be measured in acceptance tests or in the system commissioning or in both.

During the acceptance test, a DC current no lower than 10 A should be injected into different electrode segments and the earth electrode (as a whole) to measure the current flowing through different branches in the current guiding system. This operation is intended to check compliance of design, construction and installation of the earth electrode and current guiding system with safety operation requirements. Any issue discovered should be addressed promptly:

a) inspection of welding quality. Inject a DC current into each electrode segment through the current guiding wire connected to the electrode segment, and measure the current in different feeding cables on the electrode segment under test. Where a tested branch has two or more parallel feeding cables, the current in these cables should be measured separately. The quality of welding on the feeding cables and ~~feeding rods~~ electrode elements of an electrode segment is satisfactory if the current of different feeding cables is roughly the same (which is related to soil resistivity);
b) inspection of current distribution properties. Disconnect the electrode line ~~with~~ from the converter station or disconnect the current guiding wires ~~with~~ from the electrode line, and inject a DC current into the earth electrode at the disconnection point. Measure the current in different current guiding wires. The tested current flowing through different current guiding wires multiplied by the scale factor (rated current / total testing current) should be roughly equal to the design value. If the current flowing through any current guiding wire exceeds the design limit, the design of the current guiding system should be modified.

These two tests can also be conducted together.

During system commissioning, inject a continuous current no lower than 50 % of the rated current into the earth electrode. Measure the current flowing through different branches of the current guiding system in normal operation conditions and during line disconnection to further check compliance of the design of the current guiding system with specifications.

F.2.3 Measurement of earthing resistance

Earthing resistance of the earth electrode should be measured with current injection method, namely current meter – voltage meter method. Use of portable earthing resistance meters is prohibited. The measurement of earthing resistance can be measured in acceptance tests or in system commissioning or in both.

An external DC testing power supply is adopted during acceptance tests, and the earthing current flowing through the earth electrode in monopolar earth return operation mode is utilized during system commissioning.

A current injection loop and a voltage measurement loop are necessary in the test. Usually the two conductors of the electrode line, provided that they are insulated from each other, can be used as the current line and potential line respectively during tests for convenience. Manual wiring is also an option.

One end of the current injection loop is connected to the earth electrode directly or through electrode line, and the other is grounded at least 10 km away from the earth electrode, usually connected with the grounding network of the converter station or tower grounding, of which the grounding resistance is typically less than 5 Ω. If the electrode is located in a high-resistivity terrain, the remote grounding should be located further than 10 km proposed.

One end of the voltage measurement loop is connected to the earth electrode at the electrode site, and the other end, called reference pole, is grounded at least 10 km away from the earth electrode. The reference pole should be 10 km away from the current pole to be sure that the potential of the reference pole is about zero. Cu-$CuSO_4$ reference electrode ~~or Angle steel bars with a size no smaller than 50×5 mm^2 and a length of 1,5 m~~ can be used as the reference pole.

During acceptance tests, the background voltage U_0 between the earth electrode and the reference pole should be measured before measurement with the injected current. The real voltage is obtained by eliminating the background voltage and the earthing resistance, which is the ratio of the real voltage to the injected current, can be calculated. It is usually not conducted during system commissioning.

F.2.4 Measurement of step voltage on the ground and potential gradient in water near the earth electrode

The measurement of step voltage on the ground and potential gradient in water can be measured in acceptance tests or in system commissioning or in both.

A ~~self-contained~~ DC power supply or the DC system earth electrode earthing current can serve as the power supply for generating ground potential around the earth electrode.

The measurement should be conducted in every location where the step voltage is likely to be high, usually determined by simulation results, or the previous measurement of the current distribution between the section feeders of the electrode. The section with the highest current share will be the one that probably will present the highest potential gradients at soil surface. At the location where the direction of the step voltage is not clear, the measurement should be performed in two directions that are perpendicular to each other so as to achieve the amplitude and direction of the potential gradient through the addition of vectors. The highest measured step voltage and highest potential gradient in water should not exceed the design limit.

Step voltage can be measured either with the potential method or the voltage method. With the potential method, one of a pair of reference electrodes is fixed on the ground surface above the buried earth electrode. The other reference electrode is moved at 1 m interval and the change in potential of the moving electrode is measured as step voltage, using the first reference electrode as the potential reference. With the step voltage method, the distance between the two reference electrodes is fixed to 1 m and both are moved simultaneously in the radial direction.

~~During acceptance tests, the background voltage U_0 between the two electrodes should be measured before measurements with the injected current. The real step voltage is obtained by eliminating the background voltage.~~ During acceptance tests, the tested results should be multiplied by the scale factor (rated current divided by the total testing current).

The potential difference between the two reference electrodes in a pair should be less than 10 mV. The potential meter should be able to provide effective readings. The multimeter for the measurement of these potentials should have a high internal impedance.

F.2.5 Measurement of touch voltage

The measurement of touch voltage can be done in acceptance tests or during the system commissioning or both.

The touch voltage measurement should be carried out on grounded metal structures near the earth electrode, such as earth electrode current-guiding towers, metal greenhouses, metal water taps and also in irrigation systems. The measured maximum touch voltage should not exceed the design limit.

The touch voltage is measured with a digital multimeter and a $Cu\text{-}CuSO_4$ reference electrode. During measurement, one of the voltage probes of the multimeter is connected to the metal construction and the other voltage probe is connected to the reference electrode, and the reference electrode is inserted into a point on the ground 1 m horizontally away from the metal construction.

During acceptance tests, the background voltage U_0 should be measured before measurement with the injected current. The real touch voltage is obtained by eliminating the background voltage. The tested results should be multiplied by the scale factor (rated current divided by the total testing current).

In the case of a large metal construction the measurements should be made at different positions to achieve the maximum touch voltage.

F.2.6 Measurement of ~~ground~~ soil surface potential ~~distribution~~ profile

Potential rise (~~curve~~ profile) is an important characteristic parameter of the earth electrode, which can be used as the basis for evaluating the impact of earth current on the environment. The measurement of ~~touch voltage~~ soil surface potential profile can be done in acceptance tests or during system commissioning or both.

The measurement method and measurement requirements are almost the same as those in the earthing resistance measurement. The difference is that the voltage probe connected to the earth electrode is fixed during the earthing resistance measurements, whereas it is a moving probe during ground surface potential distribution measurements. The probe moves from the earth electrode to the reference pole to obtain a potential distribution ~~curve~~ profile.

F.2.7 Measurement of earth electrode temperature rise

If the system allows the current to flow through the earth electrode continuously for a long time during commissioning, the temperature rise of the earth electrode should be measured to evaluate thermal properties of the earth electrode during operation.

During testing, the temperature rise in the earth electrode and surrounding soil should be measured. The measurement should be carried out both before and after energization. Tests before energization should be conducted in the hottest season if possible. In tests after energization, the earthing current should remain constant until the measured temperature reaches a stable level.

At least 6 measurement locations, where the current flowing density or current releasing density is large, should be selected. The measurement of the soil temperature should be on the surface of the backfilled coke column. Given the limitations of site conditions, the maximum measurement depth in soil temperature measurements can be the burial depth of the earth electrode in general.

Temperature is measured in °C with a precision of ± 0,5 °C. Soil temperature should preferably be measured with a portable thermistor thermometer. Or, alternatively, a mercury or alcohol capillothermometer can be adopted for this purpose. If a mercury thermometer is used and placed in a long testing tube, proper measures should be taken to ensure that the thermometer can measure the temperature at the specified depth and will not be affected by a change of ground atmospheric temperature.

At least one temperature survey should be done in the water of a monitoring well, at the top, the middle and at the bottom of the well. Also the depth of the water table should be monitored.

Annex G
(informative)

Earth electrode electrical parameter calculation method

G.1 General

This annex describes the numerical calculation methods for the electrical parameters of earth electrodes in complicated soil conditions.

In case of uneven distribution of a soil parameter on the electrode site, the electrode site calculation model can be simplified appropriately on an equivalent basis for convenient calculation, but the characteristic parameters such as earth electrode current-releasing density, maximum temperature, maximum step voltage, earthing resistance, potential rise and its distribution should not be significantly affected. As a general rule, a layered 2D horizontal site model can be used if the electrode site lies in a sedimentary area, and a 3D site model could be more precise if the site lies in an area with complex terrain such as mountain, coast or river, but in the case of a 3D modelling, a much wider geophysical survey is required.

For a DC earth electrode buried in complicated soil conditions, the numerical calculation method is suggested for analysis. The recommended calculation methods include network method, moment method and finite element method. The network method can be used for estimation of simple earth electrode model. The moment method can be used for soil structures in which a 2D horizontal multi-layer model can be created. The finite element method can be used for ~~other~~ 3D complicated situations.

G.2 Network method calculation model for DC earth electrode

The earth electrode unit in ground network can be represented by a ‘π’ shape equivalent circuit formed by unit length of resistance (R_0) and conductance (G_0), as shown in Figure G.1.

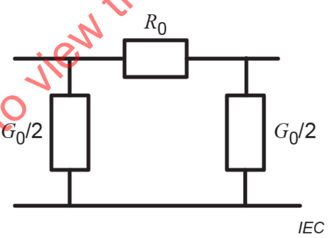


Figure G.1 – π shape equivalent circuit of an individual earth electrode unit

On this basis, an earth electrode can be represented by a network composed of multiple unit earth electrode models as shown in Figure G.1. This means that an earth electrode can be divided into a number of small ‘π’ shape equivalent circuits, and in this way the earthing resistance of the earth electrode can be achieved by means of external excitation.

The above earth electrode unit models and solutions can be completed with time domain software such as EMTP, etc., which simplifies the calculation.

G.3 Moment method calculation model for DC earth electrodes

To find the solution of the constant current field of an earth electrode with the moment method, the leakage currents of conductors are used as the basic variables. The deduction process using leakage current to describe earthing characteristics of DC earth electrodes is mainly based on two basic physical laws: the potential continuity law and Ohm’s law. With these two laws, the mathematical description of leakage current characteristics can be determined. After the specific presentation of characteristics of earth electrode leakage current has been determined, the earth electrode potential rise and ground potential distribution can be calculated with Green’s function in multiple soil layers and mathematical relations.

The specific steps are described below.

a) apply Ohm's law to the earth electrode conductor shown in Figure G.2 and perform a linear integration along the conductor axis to achieve Formula (G.1):

$$Il = vUS$$
$$IR = U \tag{G.1}$$

where

I is the axial current of the conductor,

S is the conductor cross-section area,

l is the conductor axial length,

v is the medium conductivity,

R is the DC resistance of the earth electrode,

U is the potential difference of any segment in the conductor;

b) based on the potential continuity Formula, as shown in Figure G.3, build the axial potential difference Formula (G.2) for the internal surface of the conductor and its external surface in contact with the surrounding medium:

$$U^{\mathrm{e}} = U^{\mathrm{i}} \tag{G.2}$$

where

U^{e} is the potential of the external surface of the conductor,

U^{i} is the potential of the internal surface of the conductor;

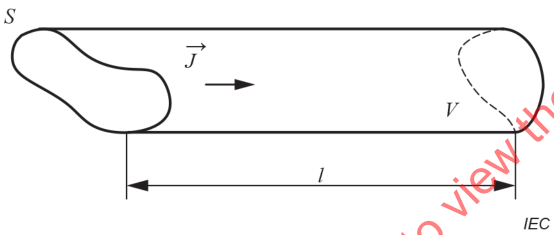


Figure G.2 – Ohm's law applied to cylinder conductor

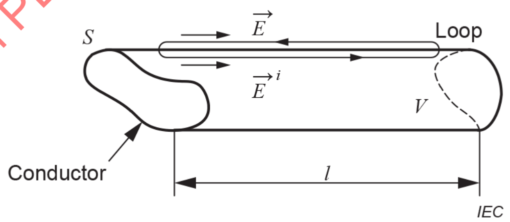


Figure G.3 – Continuity of axial component of the electric field in the soil and in the conductor

c) express the potential difference inside and outside the conductor as a function of leakage current on the surface of the conductors to construct the Formulas to be solved.

To describe the earthing characteristics of the earth electrode as a function of leakage current, first divide the earth electrode into several conductor segments in space, as shown in Figure G.4. For any conductor segment, by using the number n conductor as an example, create Formula (G.3) based on potential continuity Formula (G.2).

$$R_n I_n = \sum_m t_{nm}(I_{m\text{–leak}}) \tag{G.3}$$

where

$I_{m\text{-leak}}$ is the leakage current of the number m conductor segment,

t_{nm} is the function to associate the leakage current of leakage current of number m conductor and potential difference of outer surface of number n conductor;

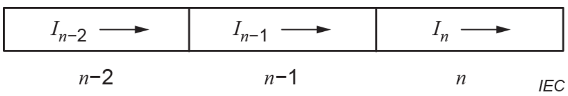


Figure G.4 – Spatial division of the earth electrode

The solution of this function requires the use of point current source Green function in layered soil.

Formula (G.3) can be expressed in a matrix form:

$$RI = t(I_{\text{leak}}) \tag{G.4}$$

where

R is the diagonal matrix containing elements of axial DC resistance of different conductor segments;

I_{leak} is the leakage current vector of different conductor segments;

I is the axial current vector of different conductor segments.

For the circuit network formed by grounding network conductors shown in Figure G.5, each conductor segment has only two end points due to spatial division. Assume that the two end points of number n conductor are n^- and n^+, and φ_n, φ_{n-1}, …, and φ_{n-k} are the middle point potential of number n, number n–1, …, and number n–k conductor segments respectively.

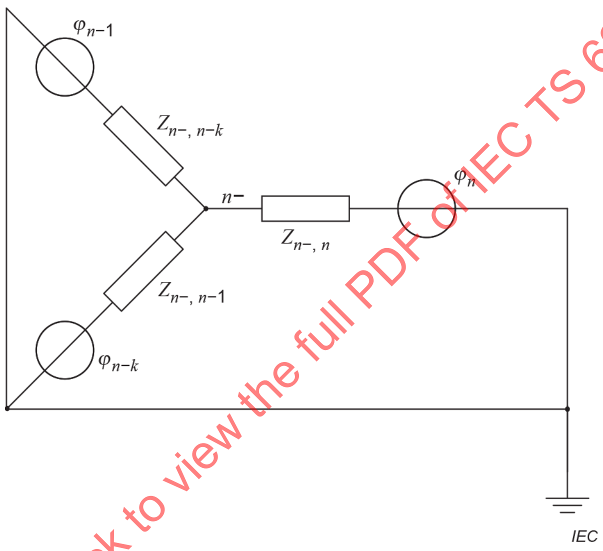


Figure G.5 – Network for solving axis current

d) use the node voltage method to solve the network and achieve the current I_{n-} flowing from axis of number n– node to number n conductor:

$$I_{n^-} = f_{n^-}(R,\varphi) = f_{n^-}(R,I_{\text{leak}}) \tag{G.5}$$

where

φ is the middle point potential vector of different conductor segments,

~~F~~ f is the relations between I and R and I_{leak}.

Based on Kirchhoff's current law, the current released from number n conductor to the earth is:

$$I_{n\text{–leak}} = I_{n^-} - I_{n^+} = f_{n^-}(R,I_{\text{leak}}) - f_{n^+}(R,I_{\text{leak}}) \tag{G.6}$$

If any current is injected into number n conductor segment, the relation between axial current and leakage current is:

$$I_{n\text{–leak}} = I_{n^-} - I_{n^+} + I_e = f_{n^-}(R,I_{\text{leak}}) - f_{n^+}(R,I_{\text{leak}}) + I_e \tag{G.7}$$

e) make the above calculation for different conductor segments to achieve Formulas for n axial currents and n leakage currents.

$$I = F(R, I_{\text{leak}}, I_e) \tag{G.8}$$

where

I_e is the excitation vector,

F is the matrix composed of f;

f) put Formula (G.8) into Formula (G.4) to achieve:

$$[R][F(R, I_{\text{leak}}, I_e)] = [t(I_{\text{leak}})] \tag{G.9}$$

g) solve Formula (G.9) to achieve the distribution of leakage current of the earth electrode. Use Green's function of the layered soil to obtain potential of any spatial point. In this way, the earthing resistance of the earth electrode and ground potential distribution can be easily obtained.

During the deduction of the arithmetical relation concerning the distribution of earth electrode leakage current, one important concept is the potential distribution resulting from the point current source, i.e. Green's function of point current source, as shown in Figure G.6. With the point current source, the potential distribution in layered medium can be expressed below.

In a reactive region:

$$\nabla^2 \phi = 0 \tag{G.10}$$

In an active region:

$$\nabla^2 \varphi = -\rho_l I \delta(R - z_0) \tag{G.11}$$

where

I is the current amplitude of the point current source,

ρ_l is the resistivity of number l soil,

δ is the Dirac function,

R is the field point vector, and

z_0 is the and source point vector.

The solution of potential function φ_l in active layers can be expressed as follows:

$$\varphi_l = \varphi_l' + \frac{\rho_l I}{4\pi |(R - z_0)|} \tag{G.12}$$

The first part (φ_l') of Formula (G.12) satisfies the Laplace Formula (G.10) in the reactive region. The second part of Formula (G.12) is a component specific to the active layers.

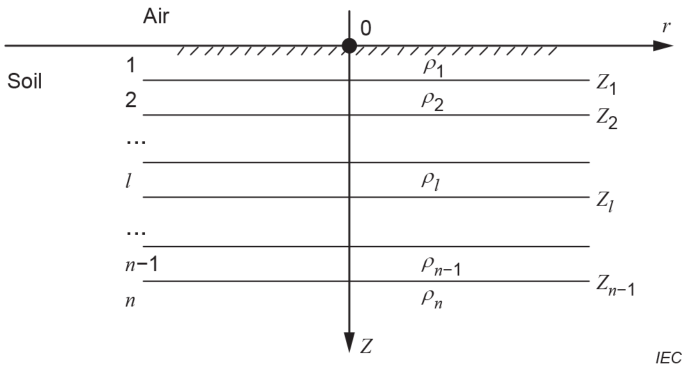


Figure G.6 – Horizontally layered soil

Taking horizontally layered soil as an example, the second part of Formula (G.12) can be expressed below using Lipsitzch integration:

$$\frac{\rho_l I}{4\pi\left|(R-z_0)\right|}=\frac{\rho_l I}{4\pi}\int_0^{\infty} J_0(\lambda r)e^{-\lambda\left|z-z'\right|}d\lambda \qquad \text{(G.13)}$$

where $J_0(\lambda r)$ is a zero-order Bessel function of the first kind.

For reactive layers (number l layer as an example), the potential function expression that satisfies Formula (G.11) is:

$$\phi_l=\frac{I\rho_l}{4\pi}\left[\int_0^{\infty}\alpha_l'(\lambda)J_0(\lambda r)\mathrm{e}^{-\lambda(z-z')}\mathrm{d}\lambda+\int_0^{\infty}\beta_l'(\lambda)J_0(\lambda r)\mathrm{e}^{\lambda(z-z')}\mathrm{d}\lambda\right] \qquad \text{(G.14)}$$

where α_l' and β_l' are coefficients to be determined.

The potential layers (number l layer as an example) is:

$$\begin{aligned}\phi_l=&\frac{I\rho_l}{4\pi}\int_0^{\infty}J_0(\lambda\gamma)e^{-\lambda\left|z-z'\right|}d\lambda+\frac{I\rho_l}{4\pi}\int_0^{\infty}\alpha_l'(\lambda)J_0(\lambda\gamma)e^{-\lambda(z-z')}d\lambda\\&+\frac{I\rho_l}{4\pi}\int_0^{\infty}\beta_l'(\lambda)J_0(\lambda\gamma)e^{\lambda(z-z')}\mathrm{d}\lambda\end{aligned} \qquad \text{(G.15)}$$

α_l' and β_l' in Formula (G.14) and Formula (G.15) are coefficients to be determined. The solution of these Formulas requires boundary conditions of soil layers. For a conductive medium with a structure of n layers of soil, the boundary conditions of soil layers are described below:

$$\begin{aligned}&\varphi_1=\varphi_2,\frac{1}{\rho_1}\frac{\partial\varphi_1}{\partial z}=\frac{1}{\rho_2}\frac{\partial\varphi_2}{\partial z},z=z_1\\&\cdots\cdots\\&\varphi_2=\varphi_3,\frac{1}{\rho_2}\frac{\partial\varphi_2}{\partial z}=\frac{1}{\rho_3}\frac{\partial\varphi_3}{\partial z},z=z_2\\&\cdots\cdots\\&\varphi_i=\varphi_{i+1},\frac{1}{\rho_i}\frac{\partial\varphi_i}{\partial z}=\frac{1}{\rho_{i+1}}\frac{\partial\varphi_{i+1}}{\partial z},z=z\\&\cdots\cdots\\&\varphi_{n-1}=\varphi_n,\frac{1}{\rho_{n-1}}\frac{\partial\varphi_{n-1}}{\partial z}=\frac{1}{\rho_n}\frac{\partial\varphi_n}{\partial z},z=z_{n-1}\end{aligned} \qquad \text{(G.16)}$$

$$\begin{aligned}&\frac{\partial\phi_1}{\partial z}=0,z=0\\&\phi_n=0,z=\infty\end{aligned} \qquad \text{(G.17)}$$

h) put Formulas (G.16) and (G.17) into boundary conditions of different soil layers to obtain the expression for coefficients α_l' and β_l'.

G.4 Finite element method calculation model for DC earth electrodes

For complicated soil models in which Green's function cannot be determined, the finite element method is required for calculation and analysis. Assume that V represents the solution domain of the earth electrode current field, and S is the boundary. The potential distribution within the field domain can be expressed as $\varphi(x,y,z)$. To solve this model using the finite element method, first divide the soil domain V (field domain) containing the earth electrode into several regular units. Tetrahedron units are typically used for the division of the domain V, and the boundary S is substituted by triangles. Define e as the index number of the tetrahedron units. Suppose the total number of tetrahedron units is M, then e =1, 2, ..., M. The vertexes of number e units are called nodes, and are represented by the numbers 1, 2, 3, and 4, as shown in Figure G.7.

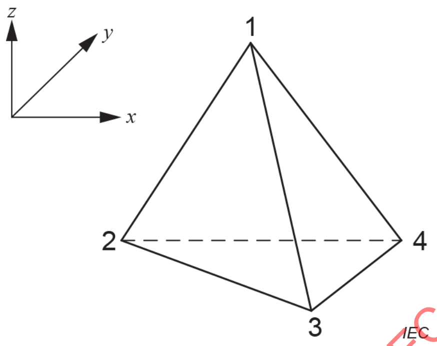


Figure G.7 – Geometrical structure of a tetrahedron unit

After the division of the field domain V, based on the principle of minimum potential energy, in Cartesian coordinates, the variation expression describing the DC current field in unit e can be written as:

$$F(\varphi^e) = -\int_V \gamma^e \left\{ \left(\frac{\partial \varphi^e}{\partial x} \right)^2 + \left(\frac{\partial \varphi^e}{\partial y} \right)^2 + \left(\frac{\partial \varphi^e}{\partial z} \right)^2 + \varphi^e J_V \right\} dV - 2\int_{S_2} \varphi^e J_{s2} dS \qquad \text{(G.18)}$$

where

S is the current density on the given face,

J_{s2} is the second type boundary face, and

J_{v} is the body current density.

The field distribution characteristics $\varphi(x,y,z)$ within unit e can be expressed with known polynomial $\varphi^e(x,y,z)$ approximately as:

$$\varphi^e(x,y,z) = N_1{}^e \varphi_1{}^e + N_2{}^e \varphi_2{}^e + N_3{}^e \varphi_3{}^e + N_4{}^e \varphi_4{}^e \qquad \text{(G.19)}$$

where $N_i{}^e$(i=1,2,3,4) is the shape function of the tetrahedron, which is expressed as:

$$N_i{}^e(x,y,z) = \frac{1}{6\Delta}\left(a_i{}^e + b_i{}^e x + c_i{}^e y + d_i{}^e z\right), \quad (i = 1,2,3,4) \qquad \text{(G.20)}$$

where Δ, as determined below, is the volume of unit e, and the coefficients $a_i{}^e$, $b_i{}^e$, $c_i{}^e$, $d_i{}^e$ (i=1,2,3,4) are determined based on the node coordinates.

$$\Delta = \frac{1}{6}\begin{vmatrix} 1 & 1 & 1 & 1 \\ x_1{}^e & x_2{}^e & x_3{}^e & x_4{}^e \\ y_1{}^e & y_2{}^e & y_3{}^e & y_4{}^e \\ z_1{}^e & z_2{}^e & z_3{}^e & z_4{}^e \end{vmatrix}$$

The approximate field distribution of the tetrahedron $\varphi^e(x,y,z)$ can therefore be achieved and expressed as the following matrix:

$$\varphi^e(x,y,z) = \left[N_1{}^e, N_2{}^e, N_3{}^e, N_4{}^e\right]\begin{Bmatrix}\varphi_1{}^e \\ \varphi_2{}^e \\ \varphi_3{}^e \\ \varphi_4{}^e\end{Bmatrix} = [N]_e\{\varphi\}_e \tag{G.21}$$

Substitute the interpolation function $\varphi^e(x,y,z)$ into the variation Formula (G.18) describing unit e, and use the minimum first variation conditions to achieve Formula (G.22):

$$\begin{aligned}\frac{\partial F(\varphi^e)}{\partial \varphi_i{}^e} &= 0 \\ &= -\sum_{j=1}^{4}\int_{V^e}\gamma^e\left\{\frac{\partial N_i{}^e}{\partial x}\partial\frac{\partial N_j{}^e}{\delta x}+\frac{\partial N_i{}^e}{\partial y}\partial\frac{\partial N_j{}^e}{\delta y}+\frac{\partial N_i{}^e}{\partial z}\partial\frac{\partial N_j{}^e}{\delta z}+N_j{}^e J_v\right\}\varphi_j{}^e dV \\ &\quad -2\int_{S_2{}^e} N_i{}^e J_{s2} dS\end{aligned} \tag{G.22}$$

which can be expressed as a matrix:

$$\left[\frac{\partial F(\varphi^e)}{\partial \varphi_i{}^e}\right] = \left[K^e\right]\left[\varphi^e\right] - \left[f^e\right] = 0 \tag{G.23}$$

At this point, the algebraic Formula describing field distribution characteristics in unit e can be obtained:

$$\left[K^e\right]\left[\varphi^e\right] = \left[f^e\right] \tag{G.24}$$

where

$$\left[K^e\right] = \begin{bmatrix}K_{11}{}^e & K_{12}{}^e & K_{13}{}^e & K_{14}{}^e \\ K_{21}{}^e & K_{22}{}^e & K_{23}{}^e & K_{24}{}^e \\ K_{31}{}^e & K_{32}{}^e & K_{33}{}^e & K_{34}{}^e \\ K_{41}{}^e & K_{42}{}^e & K_{43}{}^e & K_{44}{}^e\end{bmatrix}, \quad \left[f^e\right] = \begin{bmatrix}f_1{}^e \\ f_2{}^e \\ f_3{}^e \\ f_4{}^e\end{bmatrix}, \quad \left[\varphi^e\right] = \begin{bmatrix}\varphi_1{}^e \\ \varphi_2{}^e \\ \varphi_3{}^e \\ \varphi_4{}^e\end{bmatrix}.$$

Merge the above Formulas to be solved in all units in field domain V to achieve the algebraic Formula describing the whole field domain V:

$$[K][\varphi] = [f] \tag{G.25}$$

where

$[K]$ is the stiffness matrix $[K] = \begin{bmatrix}K_{11} & K_{12} & K_{13} & \cdots & K_{1n} \\ K_{21} & K_{22} & K_{23} & \cdots & K_{2n} \\ K_{31} & K_{32} & K_{33} & \cdots & K_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ K_{n1} & K_{n2} & K_{n3} & \cdots & K_{nn}\end{bmatrix}$;

[*f*] is the excitation vector $[f]=\begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ \vdots \\ f_n \end{bmatrix}$;

[*φ*] is the node potential vector $[\varphi]=\begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \vdots \\ \varphi_n \end{bmatrix}$.

By solving Formula (G.25), the node potential distribution in field domain V and consequently the ground potential distribution of the area where the earth electrode is located can be obtained. On this basis, the distribution of step voltage of the earth electrode can be calculated.

G.5 Calculation of earthing resistance, step voltage, touch voltage, electric field intensity and current density

G.5.1 General

For the network method and moment method, after finding the distribution of current on the earth electrode, the potential on the earth electrode and any spatial point can be calculated by using Formulae (G.14) or (G.15). For the finite element method, the potential on the earth electrode and any spatial point are obtained directly.

The earthing resistance, step voltage, touch voltage, electric field intensity, current density can be deduced by using the potential on the earth electrode and any spatial point.

G.5.2 Calculation of earthing resistance

By dividing the potential on the segment that is injecting current into the earth electrode by the injecting current, the earthing resistance can be found.

G.5.3 Calculation of step voltage

The step voltage of any point P on the ground surface is calculated using the following method:

a) calculation of the ground surface potential V_p on point P;

b) calculation of the ground surface potential V_{p1}, V_{p2}, …, V_{p8} on the points P_1, P_2, …,P_8 which are uniform distribution on the circumference on the ground surface of 1m away from point P;

c) calculation of the potential difference DV_{p1}, DV_{p2}, …, DV_{p8}, of V_p and V_{p1}, V_{p2}, …,V_{p8}. The maximum value is the step voltage of point P.

G.5.4 Calculation of touch voltage

The touch voltage of any point P on ground surface is calculated using the following method:

a) calculation of the potential V_p of the earthing point P of specific projecting metallic structure;

b) calculation of the ground surface potential V_{p1}, V_{p2}, …,V_{p8} on the points P_1, P_2,…,P_8 which are uniform distribution on the circumference on the ground surface 1 m away from the projecting metallic structure;

c) calculation of the potential difference DV_{p1}, DV_{p2}, …, DV_{p8}, of V_p and V_{p1}, V_{p2}, …, V_{p8}. The maximum value is the touch voltage of point P.

G.5.5 Calculation of electric field intensity

Electric field intensity of any point P on ground surface is calculated using the following method:

a) for the network method and moment method, calculate the derivation of Formula (G.14) or Formula (G.15) with respect to x, y, z respectively. Substituted into the conductor current and the coordinates of P to obtain the electric field intensity E_x, E_y, E_z of point P;

b) for the finite element method, calculate the potential V_p, V_{px}, V_{py}, V_{pz} of these four points $P(x_0, y_0, z_0)$, $P_x(x_0 + Dx, y_0, z_0)$, $P_x(x_0, y_0 + Dy, z_0)$, $P_x(x_0, y_0, z_0 + Dz)$, where Dx, Dy, Dz are in the range 0,001 m to 0,01 m. Then $E_x = (V_{px} - V_p)/Dx$; $E_y = (V_{py} - V_p)/Dy$, $E_z = (V_{pz} - V_p)/Dz$. This method can also be used in network method and moment method.

G.5.6 Calculation of current density

Divide the electric field strength at any point by the soil resistivity at this point can be the current density.

G.6 Application description

G.6.1 Original parameters

The original parameters that need to be prepared for calculating grounding electrical parameters of a DC earth electrode and calculation results are the following:

a) geometrical sizes of the earth electrode;
b) spatial location of the earth electrode in soil;
c) electric conductivity and magnetic permeability of the earth electrode conductor;
d) geometrical sizes of the coke (if any) wrapping around the earth electrode;
e) earthing current and current injection point in operation conditions;
f) thickness and electric conductivity of different soil layers for horizontally layered soil structure;
g) distribution of electric conductivity of the soil within a radius equal to ten times the maximum distance between any two points on the earth electrode for complicated soil structure.

G.6.2 Example using the moment method

This subclause presents a simple example using the moment method to analyse horizontally layered soil.

In the double-circle earth electrode, the radius of the external circle and the internal circle is 300 m and 210 m respectively. The earth electrode ~~feeding rods~~ elements for internal and external circles are Φ 50 high-silicon iron bars (with relative magnetic permeability of 636 and resistivity of 2 × 10^{-7} Ω·m). The cross-section of the coke bed is a 0,6 m × 0,6 m square. Both the internal circle and external circle of the earth electrode have a burial depth of 4 m. The structure is shown in Figure G.8.

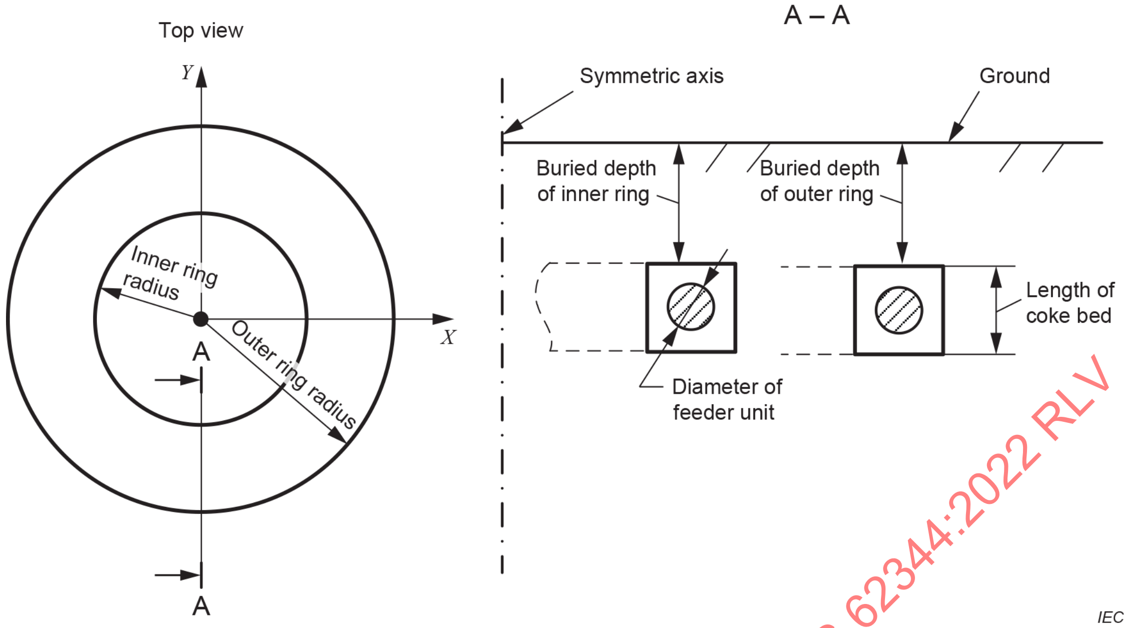


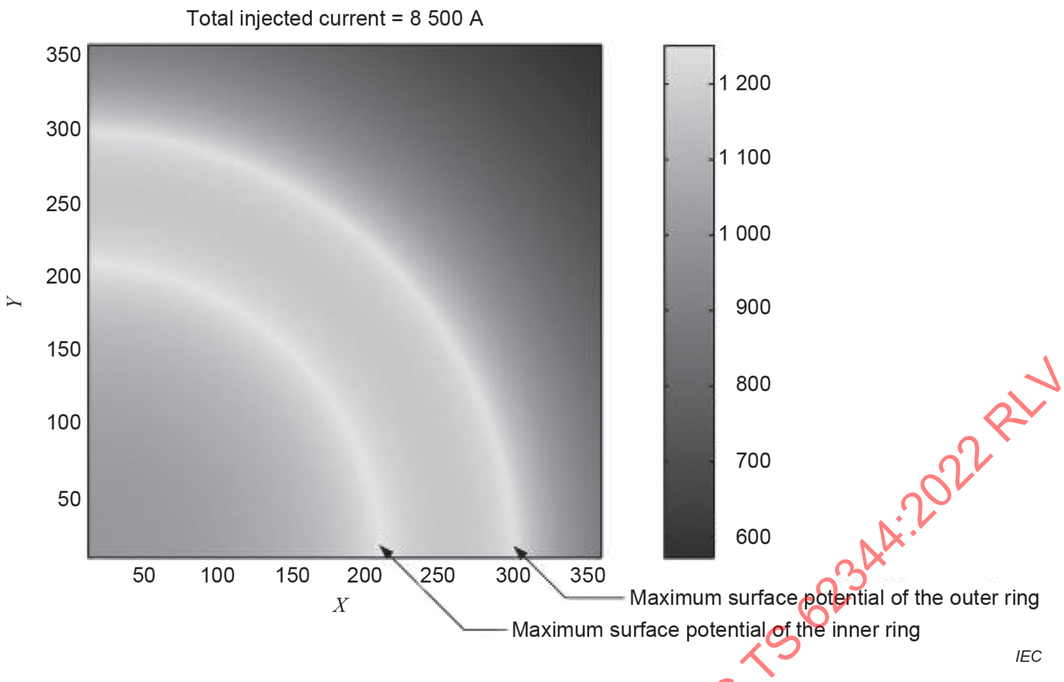
Figure G.8 – Structure of a double-circle DC earth electrode

The soil layers are shown in Table G.1.

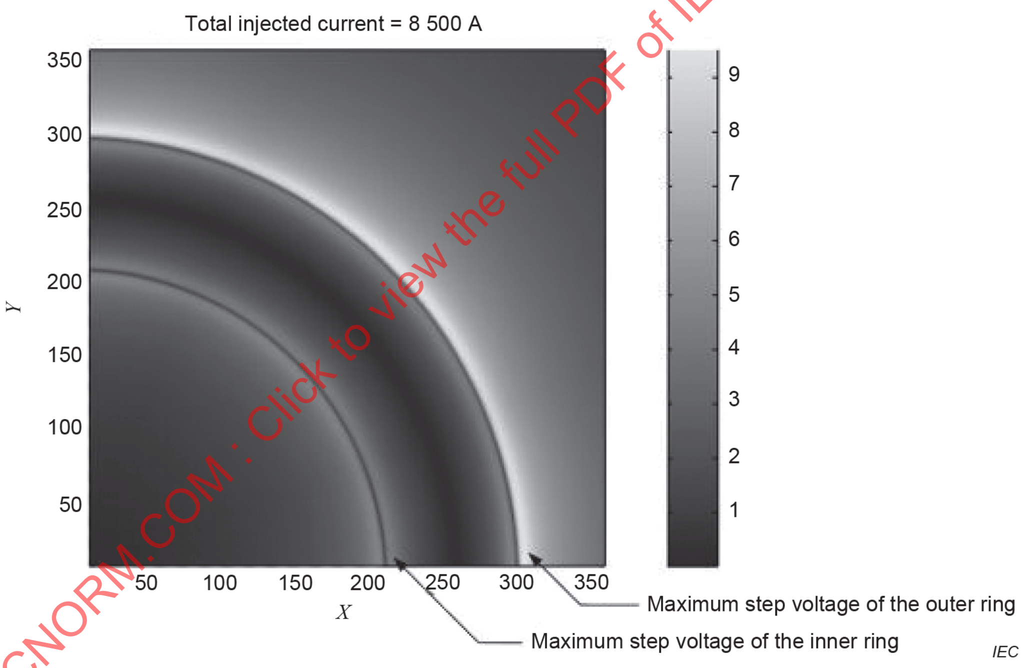
Table G.1 – Model of soil with two layers

No.	Thickness m	Resistivity Ω·m
1	10	50
2	∞	200

The earthing current is 1 kA. The ground potential and step voltage of the earth electrode site are shown in Figure G.9.



a) **Surface potential distribution**



b) **Step voltage distribution**

Figure G.9 – Ground potential and step voltage distribution of a double-circle earth electrode

Annex H
(informative)

Thermal time constant

When a DC current flows through an earth electrode and enters the ground continuously, the temperature of the soil on the electrode site will rise slowly. Based on the thermal dynamic's theory, the soil temperature at any point near the earth electrode can be depicted with Formula (H.1) or Figure H.1.

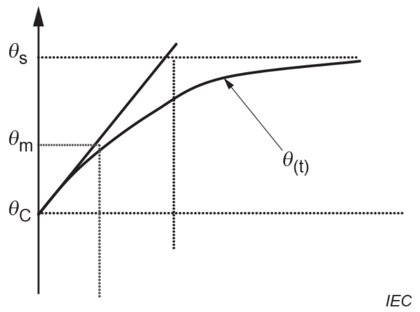


Figure H.1 – Earth electrode temperature rise characteristics

$$\theta(t) = (\theta_S - \theta_C)(1 - e^{-k\frac{t}{\tau}}) + \theta_C \qquad \text{(H.1)}$$

where

$\theta(t)$ is the temperature of soil at any time t (°C);

θ_s is the stable temperature of the soil on the earth electrode site if DC current flows continuously (°C);

θ_c is the environment (t = 0) temperature (°C);

τ is the earth electrode thermal time constant (s);

k is a coefficient related to soil properties and environment conditions, which should be typically determined through test.

The time constant is the time for the earth electrode temperature to reach 63,2 % of the stable level at ~~the initial rise rate~~ a given current, and is dependent on soil parameters (resistivity, thermal conductivity, and volume thermal capacity).

In a uniform current field, the earth electrode thermal time constant can be calculated with Formula (H.2).

$$\tau = \frac{C}{2\lambda}\left(\frac{R_e \times A}{\rho}\right)^2 \qquad \text{(H.2)}$$

where

τ is the thermal time constant (s);

R_e is the earth electrode earthing resistance (Ω);

A is the coke surface area (m^2);

ρ is the soil resistivity (Ω·m);

C is the soil volume thermal capacity (J/(m^3·°C));

λ is the soil thermal conductivity (W/(m·°C)).

The maximum temperature of the earth electrode ~~shall~~ should not exceed the boiling point of water. In case where the maximum temperature of an earth electrode is higher than water boiling point, the operation duration or amplitude of earth electrode current ~~shall~~ should be less.

Annex I
(informative)

Online monitoring system

I.1 Schematic diagram of online monitoring system

With an online monitoring system installed for earth electrodes, data concerning earth electrode current distribution, earth electrode temperature, humidity, and current density can be easily detected in the control room of the converter station so that the operation conditions of the earth electrode can be found in real time.

The operation principle of the earth electrode online monitoring system is shown in Figure I.1.

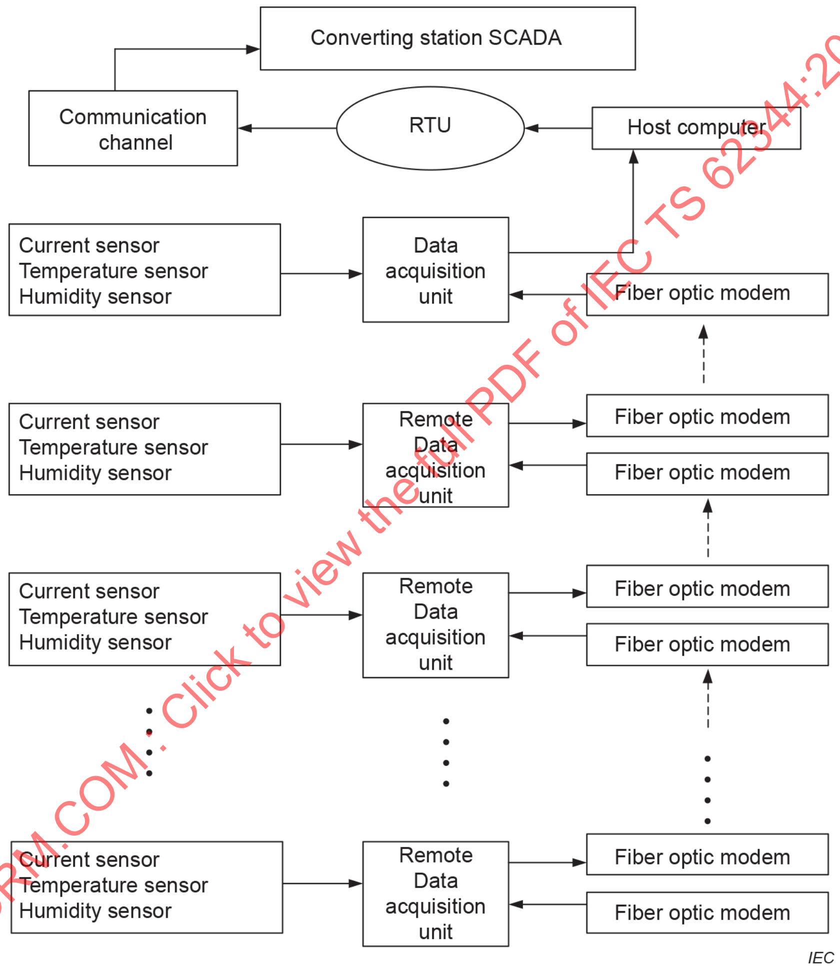


Figure I.1 – Schematic diagram of earth electrode online monitoring system

I.2 Composition of online monitoring system

The online earth electrode monitoring system should be composed of the electrode site monitoring equipment, the workstation equipment in the converter station, communication equipment, as well as auxiliary power supply.

The electrode site monitoring system should be composed of infrared temperature measuring system, image and security monitoring system, and current distribution of current-guiding cable monitoring system, and may also be equipped with the monitoring system for water level monitoring well and for soil temperature and humidity on an as-needed basis.

The workstation equipment of the online earth electrode monitoring system should be configured in combination with the background equipment of the auxiliary control system in converter station.

The communication equipment of the online earth electrode monitoring system serves to transmit monitored data and video information from the electrode site to the converter station, for which purpose OPGW communication or wireless communication can be adopted.

The auxiliary power supply of the online earth electrode monitoring system should be connected to an external power supply, or a power supply of new energy sources, such as solar energy. The DC power supply system and UPS system can be provided for the online earth electrode monitoring system according to the equipment load demand. The capacity of the auxiliary power transformer, batteries and UPS should meet the load demand.

The power supply, measurement interfaces and communication equipment of the earth electrode monitoring system can be centrally arranged in prefabricated cabin or conventional relay room according to equipment configuration.

Annex J
(informative)

Calculation method for corrosion of nearby metal structures caused by earth electrodes

J.1 Consumption of metal structure due to corrosion

The consumption of metal anode due to electrolysis can be calculated based on Faraday's law of electrolysis:

$$m = \frac{A_r \mathrm{m_c}}{\mathrm{e}K} \int_{t_1}^{t_2} i \mathrm{d}t \tag{J.1}$$

$$m = \frac{\mathrm{A_m}}{K\mathrm{F}} \int_{t_1}^{t_2} i \mathrm{d}t \tag{J.2}$$

$$m = Z \int_{t_1}^{t_2} i \mathrm{d}t \tag{J.3}$$

where

m is the consumption of metal material during the time from t_1 to t_2 (g);

A_r is the relative atomic mass of metal, dimensionless;

$\mathrm{m_c}$ is the atomic mass constant, which is equal to 1/12 of a carbon-12 atom, 1,660 40 × 10^{-24} g;

e is the electron charge, 1,602 18 × 10^{-19} C;

K is the metal valency, dimensionless;

i is the current flowing through the metal (A);

$\mathrm{A_m}$ is the metal molar mass (g/mol), which is equal to relative atomic mass A;

F is Faraday's electrolytic constant, 9,648 53 × 10^4 C/mol;

Z is the electro-chemical equivalent (g/mol).

For DC current, the integration term is changed to product of current and time.

J.2 Estimate of leakage current in metal pipes

The current flowing through metal pipes is the basis for calculating the consumption of metal structures due to corrosion. The current density through metal pipes can be estimated with the following method. However, numerical calculation is recommended if possible.

As shown in Figure J.1, the soil is simplified as a uniform medium, and the earth electrode is simplified as a point current source. The potential at a certain point P on a metal pipe can be approximated as:

$$V = \frac{I_0 \rho}{2\pi (x^2 + y^2)^{1/2}} \tag{J.4}$$

where

V is the potential of point P on the metal pipe (V);

I_0 is the Earth electrode equivalent earthing current;

ρ is the soil resistivity (Ω·m);

x is the distance from point P to the near end of the metal pipe (m);

y is the distance from near end of the metal pipe to the earth electrode (m).

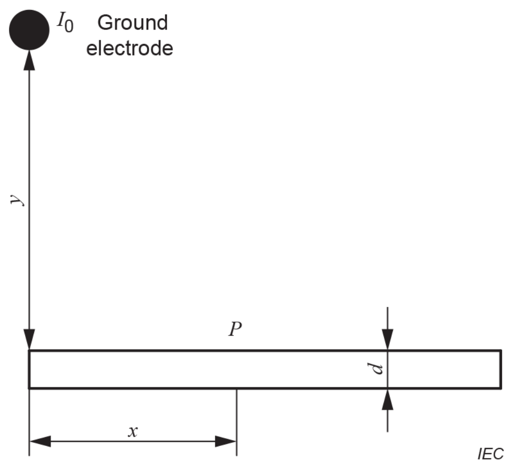


Figure J.1 – Calculation of current flowing through a metal pipe

The leakage current density at point P of the metal pipe can be approximated as:

$$j = \frac{I_0 \rho}{2\pi^2 d R_l} \frac{2x^2 - y^2}{(x^2 + y^2)^{5/2}} \quad \text{(J.5)}$$

where

j is the leakage current density at point P of the metal pipe (A/m^2). If $j > 0$, the current flows out of the metal pipe, otherwise it flows into the metal pipe;

d is the diameter of the metal pipe (m);

R_l is the resistance of unit length of the metal pipe (Ω/m).

J.3 Calculation of the leakage current of the metal pipe

To obtain more accurate current density through metal pipes, corresponding numeric calculation methods are required. The numeric calculation method described in Annex G is recommended. While the earth electrode is considered, the metal pipes are included in the calculation model to calculate metal pipe leakage current with a higher accuracy. The calculated results are usually greater than those estimated by the method proposed in Clause J.2.

Annex K
(informative)

Calculation method for DC current flowing through AC transformer neutral near earth electrodes

In the DC power transmission system earth return operation mode, a DC current of one thousand amperes or even a few thousand amperes is likely to flow from the earth electrode to the earth. This large DC current will lead to potential distribution in the soil, which will affect nearby AC systems. The existence of DC potential distribution will cause a DC current flowing through transformers with directly grounded neutral in AC systems. Excessive DC current flowing into (and out of) transformers with directly grounded neutral can result in serious DC magnetic bias of the transformers. This annex describes the method for calculating DC current flowing into (and out of) transformers with directly grounded neutral.

When a DC power transmission system runs using earth as the circuit, the current flows from the DC earth electrode to earth. The current field caused by such current results in significantly different ground potential in a wide range. Since AC substations have different ground potential, a potential difference exists between them. When the neutral of a substation transformer is grounded, a DC current will flow through AC systems. Hence, for the ground resistance network formed by power transmission lines and transformers, the ground potential of different substations is equal to the voltage source connected to them, as shown in Figure K.1.

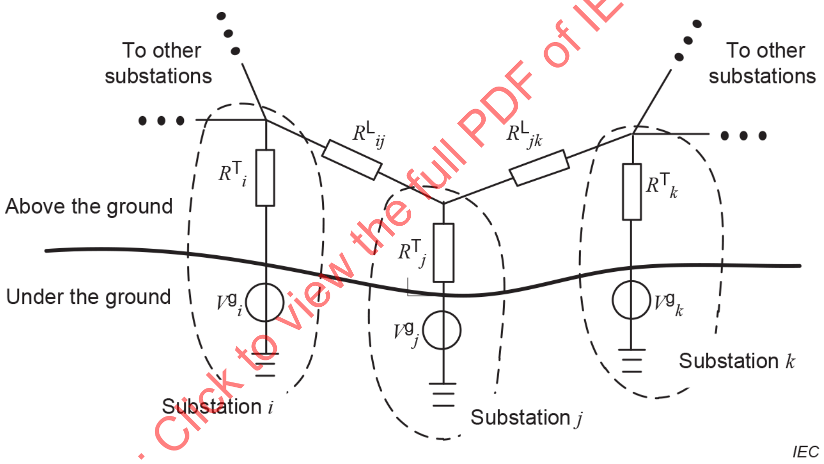


Figure K.1 – Schematic diagram of ground resistance network and underground voltage source

In Figure K.1, R^L_{ij} and R^L_{jk} are the DC resistances of line ij and line jk respectively. The value of the resistance is equal to the DC parallel resistance of all the sub-conductors in all three phases of the different circuits of the corresponding line. R^T_i, R^T_j and R^T_k represent the effective DC resistance of transformers with grounded neutral in corresponding substations. V^g_i, V^g_j and V^g_k represent the ground potential of different substations. The above parameters can be achieved with the calculation method described in ~~Annex E~~ Annex F. As all currents flowing into the earth will create a potential in the earth, if the grounding system has n grounding networks, the potential of these grounding networks can be expressed as Formula (K.1) with a matrix.

$$V = RI \tag{K.1}$$

where V contains the potential of n grounding networks, and I contains the earthing current from n grounding networks. The diagonal elements R_{ii} and non-diagonal elements in R represent the self-resistance of number I grounding network and mutual resistance between number I grounding network and number k grounding network respectively. As the ground potential at the substations is caused by both the DC current from DC earth electrode and that from all substations to earth, the ground potential of any substation in Formula (K.1) can be expressed as the form in Formula (K.2).

$$V_i^{\mathrm{g}} = R_{i\mathrm{d}} I_{\mathrm{d}} + R_i^{\mathrm{g}} I_i + \sum_{s \neq i} R_{i\mathrm{s}} I_{\mathrm{s}} \tag{K.2}$$

where I_{d}, I_i and I_{s} represent DC electrode earthing current, DC current flowing through number i substation and DC current flowing through number s substation respectively. $R^{\mathrm{g}}{}_i$ represents the earthing resistance of number i substation. $R_{i\mathrm{d}}$ and $R_{i\mathrm{s}}$ are the transfer resistance between the DC electrode and number i substation and that between number s substation and number i substation respectively.

During the analysis of the DC current distribution in Figure J.1, calculations concerning the transfer resistance are required. In fact, the distance between different substations is much longer than the edge length of the substations and the DC current flowing through the substations is much lower than that flowing from the DC electrode to the earth. The ground potential at each substation is therefore absolutely dominated by DC current flowing from the DC electrode to the earth and from the substation itself. Also, the ground potential resulting from the DC current flowing from other substations to earth is negligible. As a result, the transfer impedance between substations can be ignored. Consequently, Formula (K.2) is simplified as Formula (K.3):

$$V_i^{\mathrm{g}} \approx R_{i\mathrm{d}} I_{\mathrm{d}} + R_i^{\mathrm{g}} I_i \tag{K.3}$$

where

$V^{\mathrm{d}}{}_i = R_{i\mathrm{d}} I_{\mathrm{d}}$, and

$V^{\mathrm{d}}{}_i$ represents the ground potential caused by the DC electrode earthing current at the corresponding substation.

It is approximately equal to the ground potential of this substation when the neutral of the transformers is not grounded. Hence, the underground part of each substation can be seen as a voltage source with an electric potential equal to the ground potential caused by the DC electrode earthing current in that substation and with an internal resistance equal to the earthing resistance of that substation. When the neutral of the transformers is grounded, a DC current flows through the substations. In this case, the actual ground potential of the different substations can be calculated with Formula (K.3). Formula (K.3) can be expressed as Formula (K.4) with a matrix.

$$V = V_{\mathrm{d}} - RI \tag{K.4}$$

Due to this, during the analysis of the DC distribution of the AC systems, the circuit model shown in Figure K.2 can be used. After obtaining the ground potential (V_{d}) generated by the DC electrode earthing current at the corresponding substation, the node voltage Formulas can be listed for the circuit network illustrated in Figure K.2, as shown in Formula (K.5).

$$I = GV \tag{K.5}$$

where

G is an $n \times n$ admittance matrix.

The matrix element G_{ij} can be calculated based on DC resistances of different lines and those of windings per phase of the different transformers.

Putting Formula (K.5) into Formula (K.4) gives the distribution of DC current in an AC system as shown in Formula (K.6), or grounding network potential of the substation as shown in Formula (K.7).

$$I = \left[E + GR\right]^{-1} GV_{\mathrm{d}} \tag{K.6}$$

$$V = [E + RG]^{-1} V_\mathrm{d} \tag{K.7}$$

where E is the unit matrix and superscript –1 indicates the inverse matrix.

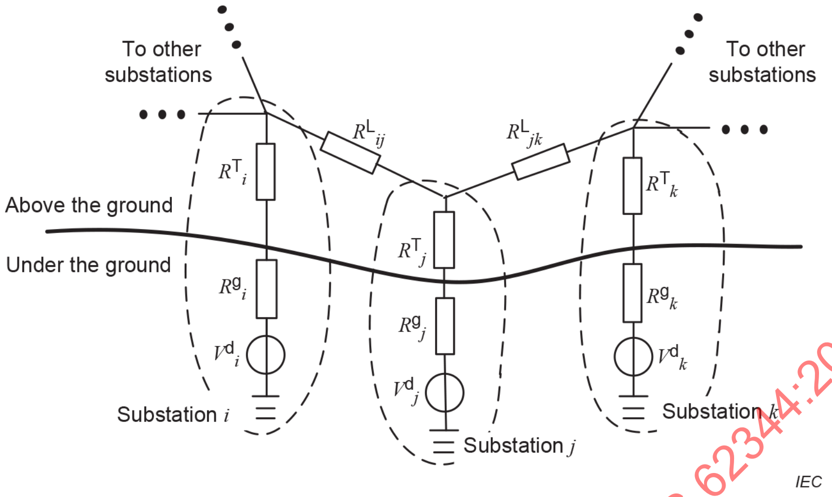


Figure K.2 – Circuit model for the analysis of DC distribution of AC systems

Annex L
(informative)

Chemical ~~aspects~~ processes in sea electrodes

Chlorine (Cl_2) is evolved from electrodes in contact with seawater. However, if Cl is evolved at a low rate it will not form gaseous Cl_2, but will form hypochlorite ions, which are considered much less harmful, because they react with the buffer content of carbonate in normal water.

The buffer effect of carbonate is ineffective, either in the case of forceful evolution of Cl by high current density or if the electrolyte liquid is not exchanged. Lack of exchange of the liquid may be the case with deep vertical electrodes, especially if the vertical solution has been chosen because of saline strata underground. The need for ventilation of gases is also mostly discussed for deep vertical electrodes.

The anodic reaction of HVDC electrodes means that, although not generally discussed, the anode itself has to be noble, that is, it shall not lose any significant amount of itself. In this sense, graphite, coke, SiCrFe and titanium are noble chemicals. If the electrode is non-noble, such as Al, Zn, Mg or Fe, it will lose metallic ions which will participate in the anodic chemical process. If an anode was made by just ramming down a number of coarse sectional steels, to a large, but still practical depth, then the evolved gases, oxygen and/or chlorine will react with the anode material to form substances like Fe_2O_3 (i.e. common rust), $FeCl_2$ or related chemicals, and no gas is expected to be released.

Of course such an electrode is corroded at a rate of 1,042 kg/(kA·h). However, if the intention or license of operation limits the electrode to a short time duty, an electrode of this simplified type will last for many years. Deep non-noble metallic rods electrodes will also be corroded from the bottom, because the current density is expected to be largest at the bottom ends of the vertical electrodes.

By the cathodic process H_2 (hydrogen) is evolved in gaseous form. This hydrogen is partly dissolved in the water, finally to a saturated concentration, if there is little or no exchange of electrolyte close to the cathode. The part of hydrogen not dissolved can be assumed to be released to the atmosphere, which has a natural content of H_2 of about 0,5 ppm (parts per million). If there is only little exchange of water by the cathode, the strong base NaOH (sodium hydroxide) will concentrate around the cathode.

It is well-known from sea electrodes running only in cathodic mode that the cathodic process involves chalk-like substances being deposited on the electrode surface. These deposits are not harmful to the electrode surface, but may involve local extra resistance and then heating. If this heating is too accentuated, the deposit may even be blasted off due to steam explosions inside the deposit.

Changes between anodic and cathodic direction of current may be a problem for certain materials. Running as an anode the surface of the electrode develops an acid environment, and is polarized according to that, while a cathode develops a chemically basic environment, also involving polarisation. The sum of polarisation voltages in a pair of electrodes can easily reach about 2 V, which represents a voltage drop, corresponding to a loss.

When a polarised pair of reversible electrodes is reversed, the polarisation, starting with the "wrong" direction, will diminish the total voltage drop, until opposite chemical conditions have been established by the electrodes.

~~Materials like coke and graphite withstand current reversals well, while high silicon iron is indicated as less suited, because a layer of SiO_2 on the surface bursts. Likewise, titanium and coated titanium, which withstand the harsh anodic condition extremely well, will not withstand cathodic conditions. A warning has even been expressed against very low current densities and the combination of ripple and low current density. Even titanium electrodes can work with both current directions.~~

Materials like coke and graphite withstand current reversals well, while high silicon iron is less tolerant, because a layer of SiO_2 on the surface can burst and cause pitting. However, if sufficient material is installed, some pitting that occurs may not significantly affect service life of the electrode. Platinised titanium and mixed metal oxides (MMO) can withstand the harsh anodic condition extremely well, but they are not very suitable for reversible operation under large earthing current, because they can only withstand very low dispersed current density in anodic operation.

Annex M
(informative)

Simple introduction of shore electrodes

M.1 General

Shore electrodes are most common for monopolar operation with sea cables. Shore electrodes may be divided into two groups: beach electrodes and pond electrodes.

M.2 Beach electrodes

Beach electrodes are located on the beach inside the waterline, and the active part of the electrode makes contact with the soil or with underground water but not directly with seawater. See Figure M.1.

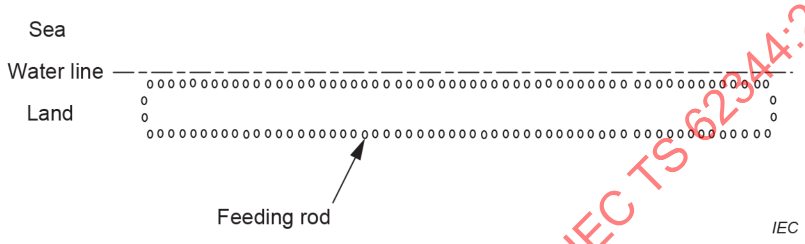


Figure M.1 – Top view of shore electrode, beach type

M.3 Pond electrodes

Pond electrodes have electrodes directly in contact with seawater, within a small area which most often is protected against waves and possible ice damage by a breakwater. Either the breakwater or the bottom of the pond or both ~~shall~~ should be able to conduct current. If the breakwater is built of rocks or boulders which are assumed to be insulating, then the flow of current through the breakwater follows the water-filled interstices. See Figure M.2.

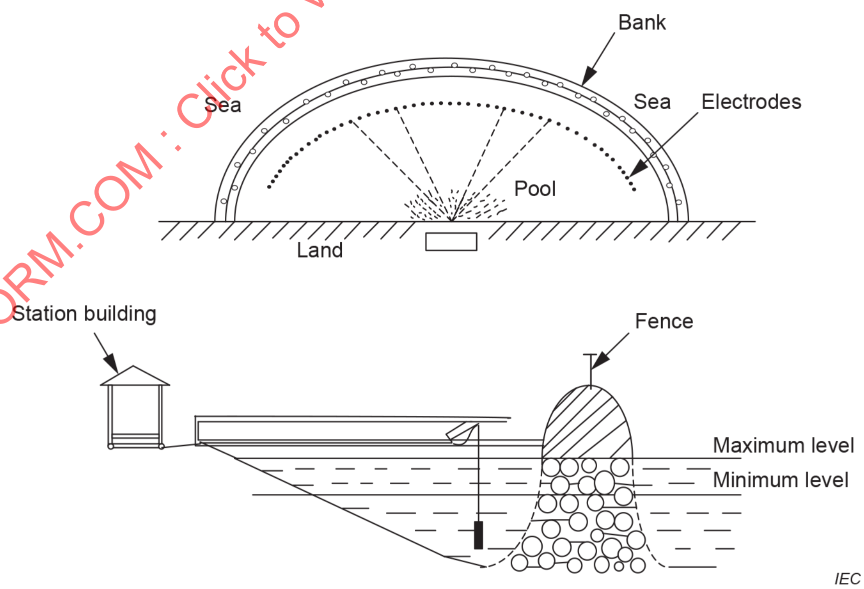


Figure M.2 – Shore electrode, pond type

Shore electrodes differ from sea electrodes in a practical but important way: they are (normally) accessible by cars and persons from land, which makes maintenance easy, while access to a sea electrode demands use of boats, cranes, divers, etc.

Pond stations are advantageous for several reasons:

a) they generally need a small area, 6 000 m^2 to 10 000 m^2;

b) the electrodes are very easy to supervise or to inspect directly, by lifting them out of the water. The voltage of the lifted-out sub-electrode with respect to surrounding objects when the remaining sub-electrodes are still working ~~shall~~ should be determined. If the voltage is sufficiently low to be harmless for skilled staff, disconnecting switches for each sub-electrode may be avoided;

c) although there is only limited information on costs for different types of electrodes, it is assumed that pond stations are generally less expensive than sea electrodes.

Pond electrodes are characterised by their location, on the shore, but with the current transmitted directly to the sea water. Normally closed breakwater protects the site, and at the same time prevents the access of large marine life. The access of unauthorized persons is normally prevented by fences and signs.

It is an inherent trait for this type of electrode that the current density can reach very high values. The magnitudes of current densities are not greater than generally recommended for these materials, but two problems ~~shall~~ should be considered.

Firstly, the gradients and "step" voltages inside the pond may reach high values as on the surface of the sub-conductors the voltage gradients are of a magnitude of 100 V/m to 150 V/m.

A second problem is the fairly high selectivity for evolution of Cl_2 instead of O_2, which may be unacceptable in some cases.

Regarding the configuration (geometric arrangement) there will be possibilities as already described for other types, such as linear, ring, etc. As a practical consideration, a timber construction could carry the suspended electrodes, which leads to a preference for a double linear configuration, suspended on both sides of a timber bridge.

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TECHNICAL SPECIFICATION

colour inside

Design of earth electrode stations for high-voltage direct current (HVDC) links – General guidelines

IEC TS 62344:2022-05(en)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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DESIGN OF EARTH ELECTRODE STATIONS FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) LINKS – GENERAL GUIDELINES

FOREWORD

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This second edition cancels and replaces the first edition published in 2013. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

– Changed the requirement of earthing resistance limit for short-time unipolar earth system in 5.1.3.
– Corrected the coefficient before ρ_s from 0,015 9 to 0,008 in touch voltage limit calculation formula (3) in 5.1.5.
– Deleted the analytical calculation formulas of earthing resistance for sea and shore electrodes in 6.1.3.
– Changed the current density limit from 100 A/m^2 to 40 A/m^2 ~ 50 A/m^2 for the sea electrodes that are not accessible to human beings or to marine fauna in 6.1.7.

– Extended some detailed technical requirements for the measurement of ground/water soil parameters in 6.2.5.
– Reformulated the types and characteristics of electrode element material for sea and shore electrodes in 6.3.2.
– Added an informative Annex B: Earth electrode design process.
– Added an informative Annex C: Test results of human body resistance.
– Deleted the formula for calculating the average soil resistivity using harmonic mean when processing the measurement data in D.2.6 of Annex D.
– Extended some detailed technical requirements of electrode online monitoring system in Annex H.
– CIGRE 675:2017 is added to the bibliography.
– Terminology and way of expressions are modified using more commonly used terms in the HVDC electrode design industries and English speaking countries, so as to make the readers understand the content more easily.

The text of this Technical Specification is based on the following documents:

Draft	Report on voting
115/276/DTS	115/293/RVDTS

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

The high-voltage DC earth electrode is an important part of the DC power transmission system. It takes on the task of guiding the current into the earth under the monopolar earth return operation mode, and the unbalanced current under the bipolar operation mode. Further, it secures and provides the reference potential of converter neutral point under the bipolar/ monopolar operation mode, to protect the safe operation of the valves.

DC earth electrodes include land electrodes, sea electrodes, and shore electrodes. Today, there are around tens of DC electrodes in the world. Their influence on the nearby and far away environment is produced when there is DC current continuously leaking into the earth through DC earth electrodes.

Their influence on the surrounding environment includes:

a) influence on humans, mainly due to step voltage, touch voltage and transferred voltage;
b) influence on the electrode itself, mainly reflected by ground temperature rise and corrosion on the electrode;
c) influence on nearby ponds and organisms in the sea;
d) influence on the AC power system, mainly reflected by the DC voltage excursion of transformer neutral point;
e) influence on buried metallic objects, mainly revealed by the corrosion of buried metallic pipelines, AC grounding grids, tower foundations for power transmission lines and armoured cables, etc.

A great deal of experience has been accumulated in the research and design work in many countries, and relevant national standards or enterprise standards have been developed. The aim of this document is to develop the design guide for DC earth electrodes, on the site selection, material selection, shape, buried depth, adoption of equipment and connection styles, etc. It can be referred to by the electrode design engineers in different countries, to ensure the safe operation of earth electrode under different modes, control the influence on the environment nearby and the environment far away to the acceptable level, and to reasonably decrease engineering costs.

To ensure this document is more scientific, precise and practical, some research results obtained in recent years are adopted.

DESIGN OF EARTH ELECTRODE STATIONS FOR HIGH-VOLTAGE DIRECT CURRENT (HVDC) LINKS – GENERAL GUIDELINES

1 Scope

This document applies to the design of earth electrode stations for high-voltage direct current (HVDC) links. It is intended to provide necessary guidelines, limits, and precautions to be followed during the design of earth electrodes to ensure safety of personnel and earth electrodes, and reduce any significant impacts on DC power transmission systems and the surrounding environment.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60479-1, *Effects of current on human beings and livestock – Part 1: General aspects*

IEC TS 61201, *Use of conventional touch voltage limits – Application guide*

IEC 61936-1, *Power installations exceeding 1 kV AC and 1,5 kV DC – Part 1:* AC

IEC TS 61936-2, *Power installations exceeding 1 kV a.c. and 1,5 kV d.c. – Part 2: d.c.*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
earth (ground) electrode
conductive part that is in electric contact with local earth, directly or through an intermediate conductive medium

[SOURCE: IEC 60050-195:2021, 195-02-01]

3.2
land electrode
earth electrode buried in the ground above the high tide water level and located away from the shore and not influenced by water bodies

3.3
shore electrode

3.3.1
beach electrode
electrode located on the shore above the low tide water level, where the active part of the electrode is in contact with the soil or with underground water, but not directly with seawater

Note 1 to entry: Compared with land electrode, beach electrode is relatively close to the shore and is influenced by water bodies.

3.3.2
pond electrode
electrode located on the seashore below the low tide water level, where the active part is directly in contact with seawater, within a small area which is protected by a breakwater against waves and possible ice damage or damage from other floating debris

3.4
sea electrode
electrode located away from the shoreline in a body of seawater

3.5
electrode station
whole facility which transfers current from/to electrode line to/from the earth or sea water, usually including the feeding cable, towers, switchgear, fencing and any necessary auxiliary equipment in addition to the electrode itself

3.6
common or shared earth electrode
earth electrode system, which is composed of a single earth electrode or multiple earth electrodes in parallel, shared by multiple converter stations

3.7
electrode site
site where the earth electrode is located

3.8
electrode line
overhead line or underground cable used to connect the neutral bus in a converter station to the earth electrode station

3.9
electrode element
earthing conductor buried underground or in the sea for guiding earthing current into the surrounding medium (soil or sea water)

3.10
feeding cable
cable used to guide current from current-guiding wire to electrode elements

3.11
current-guiding wire
main branch used to conduct current from electrode line (or bus) to feeding cables

3.12
current guiding system
system used to guide the current from electrode line to electrode elements

Note 1 to entry: It consists of current-guiding wire(s), disconnecting switches, feeding cables and connections.

3.13
jumper cable
cable used to connect two electrode elements placed at some distance from each other

EXAMPLE The cable that connects the two electrode elements on either side of a trench when the electrode has to cross the trench.

3.14
earth return operation mode
operation mode in the HVDC power transmission system, using DC lines and earth (or sea water) as the current loop

3.15
earth return system
set of devices designed and built specifically for earth return operation mode

Note 1 to entry: It mainly consists of the electrode line, earth electrode, current guiding system, and other auxiliary facilities.

3.16
system rated current
nominal rated current of one converter pole of the HVDC system

3.17
maximum short-time overload current
maximum current that can be sustained in monopolar operation condition of DC system for a defined time interval (generally between 10 s and 2 h)

3.18
maximum transient overcurrent
average maximum current flowing through the earth electrode for a few seconds (generally less than 10 s) when a system disturbance occurs

3.19
unbalanced current
difference of current between two poles during operation of a bipolar DC system

Note 1 to entry: For balanced bipolar operation mode, the unbalance current flowing can be controlled automatically by the control system within about 1 % of the rated current.

Note 2 to entry: For unbalanced bipolar operation mode, the current flowing through the earth electrode is the difference in currents between the two poles.

3.20
cathode
electrode capable of emitting negative charge carriers to and/or receiving positive charge carriers from the medium of lower conductivity

Note 1 to entry: The direction of electric current is from the medium of lower conductivity, through the cathode, to the external circuit.

Note 2 to entry: In some cases (e.g. electrochemical cells), the term "cathode" is applied to one or another electrode, depending on the electric operating condition of the device. In other cases (e.g. electronic tubes and semiconductor devices), the term "cathode" is assigned to a specific electrode.

[SOURCE: IEC 60050-151:2001, 151-13-03]

3.21
anode
electrode capable of emitting positive charge carriers to and/or receiving negative charge carriers from the medium of lower conductivity

Note 1 to entry: The direction of electric current is from the external circuit, through the anode, to the medium of lower conductivity.

Note 2 to entry: In some cases (e.g. electrochemical cells), the term "anode" is applied to one or another electrode, depending on the electric operating condition of the device. In other cases (e.g. electronic tubes and semiconductor devices), the term "anode" is assigned to a specific electrode.

[SOURCE: IEC 60050-151:2001, 151-13-02]

3.22
current-releasing density

3.22.1
linear current density
current released to earth from a unit length of electrode element

Note 1 to entry: It is expressed in A/m.

3.22.2
surface current density
current released to earth from a unit area of the coke-soil interface

Note 1 to entry: It is expressed in A/m^2.

3.23
designed lifespan
designed operational lifespan of the earth electrode, typically of the same order as the operational lifespan of the converter station

3.24
corrosion lifespan
time integral of current when an earth electrode runs as an anode, such as monopolar operation and bipolar operation with unbalanced current, during its designed lifespan

Note 1 to entry: It is expressed in the unit of ampere hour (Ah).

3.25
thermal time constant
time required for the temperature of the soil immediately adjacent to the active elements of an electrode to reach 63,2 % of the steady state temperature rise at a given current

3.26
earthing resistance
resistance between an earth electrode and remote earth with zero potential

3.27
step voltage
difference in surface potential experienced by a person or animal bridging a distance between two feet without contacting any other grounded object

Note 1 to entry: For a human the distance between the two contact points on the earth is normally taken as 1 m.

3.28
touch voltage
potential difference between the surface potential at the point where a person is standing and the potential of a grounded structure touched by him

3.29
transferred voltage
special case of the touch voltage where a voltage is transferred into/out of a point near the electrode site from/to a remote point far away from the electrode site

3.30
insulated metallic structures
metallic structures buried in the ground within the electrode interference area and coated with insulating material to isolate the structure from earth

3.31
bare metallic structures
metallic structures buried in the ground within the electrode interference area and not coated with insulating material

3.32
coefficient of uneven current density distribution
ratio of maximum current-releasing density at any specific point of an earth electrode, to the average current-releasing density of that earth electrode

Note 1 to entry: This parameter reflects the uniformity of current released from the earth electrode to the surrounding medium and is a dimensionless quantity.

3.33
equivalent earthing current
ratio of time integral of current of an earth electrode operated as a cathode or anode to its designed lifespan

Note 1 to entry: It is used to analyse the corrosion impact on underground metallic objects in the vicinity of the electrode.

4 System conditions

4.1 General principles

The system conditions to be considered during earth electrode design mainly include the amplitude and duration of the current relating to the earth electrode, and designed lifespan and polarity.

4.2 System parameters related to earth electrode design

4.2.1 Amplitude and duration of the current

The operation current and duration of DC earth return operation systems should normally be specified in local regulations, bid documents, or specifications. In the absence of such documents that can be used as a reliable source, the following values may be used as a reference during design:

a) the amplitude of earth electrode rated current is equal to the HVDC system rated current (I_N). The maximum duration of this current corresponds to that of the monopolar earth return operation mode of the earth electrode. The duration of rated current can be continuous or of defined length. A typical defined length for a bipolar system is the interval from the time when the monopolar system is put into service to the time when the bipolar system is put into service;

b) the amplitude of the maximum short-time overload current is typically 1,1~1,3 I_N. The maximum duration of this current is generally the time allowed for operation at maximum overload current with the redundant cooling equipment in service;

c) the amplitude of the maximum transient overcurrent is determined through system stability calculation, typically in the range of 1,25~1,5 I_N. The maximum duration is generally a few or less than 1 s;

d) the amplitude of bipolar unbalanced current is the difference of the operating currents of two poles. For DC power transmission systems with two symmetrically operated poles, the value is very small relative to I_N, e.g. 1 % of I_N. The duration is the same as the bipolar operation time of the HVDC system.

4.2.2 Polarity

Polarity of the earth electrode should be selected to be consistent with system operation and environment protection requirements. For anode type earth electrodes, the corrosion of earth electrode material should be considered.

If there are any long buried metallic structure within the electrode interference area, corrosion at the distal end of the metallic structures should also be considered. For cathode type earth electrodes, the focus should be on the corrosion impact on proximal end of buried metallic structures within the electrode interference area. Should the cathode type earth electrode be a sea electrode, the impact of compound sediments near the earth electrode is also a concern.

For earth electrodes with reversible polarity, in addition to the above issues relating to cathode and anode type earth electrodes, attention shall be paid to safe operation with reversible polarity. The earth electrodes for bipolar and asymmetrical monopolar VSC systems should be designed with reversible polarity.

4.2.3 Designed lifespan

The design of an earth electrode should generally allow construction and operation of associated converters in a series of steps. The designed lifespan should not be less than that of the converter station using this earth electrode. Where no specific lifespan is specified, the minimum designed lifespan of an earth electrode should be 30 years or more.

Within the designed lifespan of an earth electrode, loss of earth electrode material caused by corrosion shall not affect its normal operation. During calculation of earth electrode corrosion during a lifespan, the following aspects should be considered:

a) monopolar system: for an LCC monopolar system (or a bipolar system with one pole built and put into operation at an earlier stage), the polarity of the earth electrodes can be determined by the system planning studies. For a VSC asymmetric monopolar system (or bipolar system consisting of asymmetric monopole converters), the design of both (all) electrodes needs to allow for polarity reversals and anodic operation, as the system changes power direction by changing the current direction rather than changing voltage polarity;

b) bipolar system operated in monopolar mode: after a bipolar system is put into service, the situation where one pole is out of service for repair or maintenance and the other pole (healthy pole) is operated using earth return, shall be considered. In this case, the ampere hours during operation as an anode shall be calculated based on data provided by the system planning studies;

c) bipolar operation: during bipolar operation, the ampere hours of unbalanced current during operation as an anode should be calculated.

4.2.4 Common earth electrodes

For a common earth electrode(s) shared by multiple converter stations, the worst case which should be considered is where monopolar earth return operation mode occurs simultaneously at more than one converter station with the same polarity. Calculation of earthing current of the earth electrode(s) should consider the probability of superposition of currents from different converter stations. So compared with ordinary electrodes, common electrodes usually demand higher requirements for electrode site conditions.

The designed lifespan of a common earth electrode shall be determined as the interval from the time when the first converter station is put into operation to the time when the last converter station is put out of use.

The polarity of the common earth electrode is determined by summing the directions and amplitudes of the currents from all the converter stations that share it.

5 Design of land electrode stations

5.1 Main technical parameters

5.1.1 General principles

The design of the land electrode shall ensure its safe and reliable operation throughout its lifespan and under different earthing current conditions including rated current, maximum overload current, and maximum transient overcurrent. Different technical parameters such as temperature rise of the earth electrode, earthing resistance, step voltage, touch voltage and transferred voltage shall be controlled within the specified range by appropriate choices of electrode shape and buried depth. It is important to note that the change of electrode shape or burial depth does not affect the electric field strength further than 1 km to 2 km away from the electrode.

For a common earth electrode(s) or multiple earth electrodes within a short distance of each other, the situation of long time simultaneous and continuous operation of DC systems with the same polarity under earth return operation mode shall be avoided as much as possible. In addition, the effect of one circuit operated in monopolar earth return mode on the neutral voltage shift of other bipolar systems should be considered.

Calculation of parameters and performance of earth electrodes should be done with computer software. See Annex G for the calculation principles.

5.1.2 Temperature rise

Under all circumstances, the maximum temperature of any point of the earth electrode shall be lower than the boiling point of water at the local altitude. For example, at an elevation of 0 m, the maximum allowed temperature is 100 °C. The temperature rise calculation method is described in Annex G.

5.1.3 Earthing resistance

The determination of earthing resistance for the electrode shall consider two aspects:

a) the ground temperature rise;

b) touch and step voltage at the electrode station.

For an earth electrode in any operation mode which involves a large earthing current, if the duration of the current is longer than the thermal time constant of the electrode (see Annex G for the calculation method), which is typically the case for rated current flowing into the earth for a long time, the maximum permissible earthing resistance is typically dependent on the permissible temperature rise, which should be in accordance with Formula (1):

$$R_e \leq \frac{1}{I_d}\sqrt{2\lambda_m \frac{\rho^2{}_e}{\rho_m}(\theta_{max} - \theta_c)} \quad (1)$$

where

R_e is the earthing resistance between the earth electrode and remote earth with a zero potential (Ω);

I_d is the earthing current which flows into the earth for a long time (A);

λ_m is the thermal conductivity of the soil where the earth electrode is buried (W/(m·°C));

θ_{max} is the maximum allowed ground temperature (°C);

θ_c is the maximum natural ground temperature (°C);

ρ_m is the resistivity of the soil where the earth electrode is buried (Ω·m);

ρ_e is the general equivalent earth resistivity at the electrode site (Ω·m).

If the duration of the current is shorter than the thermal time constant of the electrode, the maximum permissible earthing resistance could be increased significantly than that determined by Formula (1) from the point view of ground heating. In this case, the area of the coke-soil interface and current density at the interface is usually used to control the ground temperature rise instead of earth resistance (see 5.5.3).

5.1.4 Step voltage

The step voltage of any ground point that can be accessed by the public shall not exceed the safety limits defined for humans and livestock. According to tests conducted on 1 028 subjects, over 95 % of the subjects have a foot to foot human body resistance greater than 1 400 Ω (see Annex C), which is slightly different from the hand to hand human body resistance given by IEC 60479-1, and over 95 % of the subjects have no strong feeling at a DC current of 5,3 mA. Based on these test results and in consideration of different amplitudes and durations of DC system earthing currents, the maximum allowed step voltage of any point on the ground can be determined with Formula (2) under maximum short-time overload current of one pole.

$$E_{sp} = 7{,}42 + 0{,}03\,\rho_s \quad (2)$$

where

E_{sp} is the permissible step voltage (V);

ρ_s is the resistivity of surface soil (Ω·m).

During contingency conditions, such as maintenance of the earth electrodes (1/8 or more parts of earth electrodes are out of service), according to IEC TS 61201 and IEC 60479-1, the maximum permissible step voltage (E_{sp}) shall be less than 70 V. Under such conditions, the electrode shall be fenced to prevent access by the public and animals, and maintenance staff shall be advised of the hazards and should take adequate precautions.

For common earth electrodes or multiple earth electrodes with a short distance, to lower the step voltage, the situation where two DC systems run simultaneously with the same polarity under earth return operation mode shall be avoided as much as possible. However, the case of these systems running in short-time (e.g. < 30 min) earth return operation mode with the same polarity due to accidents (e.g. equipment failures or human errors or lightning strikes, etc.) should be considered during design. Considering that it is small probability, the maximum allowed ground step voltage for common earth electrodes can be increased appropriately with reference to Formula (2) in this case, on the premise that the impacts on the surrounding facilities have been evaluated and the maximum permissible step voltage is lower than that in contingency conditions.

If any point on the ground fails to meet the above requirement for maximum step voltage, mitigation measures shall be taken.

5.1.5 Touch voltage

For earthed metallic structures that can be accessed by the public, the touch voltage of any point on the site ground shall not exceed E_{tp} obtained from Formula (3) under maximum short-time overload current of one pole.

$$E_{tp} = 7{,}42 + 0{,}008\,\rho_s \tag{3}$$

where

E_{tp} is the permissible touch voltage (V).

For earthed metallic structures that cannot be accessed by the public, the maximum permissible touch voltage of any point on the site should be less than 70 V in general.

5.1.6 Current density

For land electrodes that are likely to run as anodes for a long time, the current density at the coke-soil interface should be limited to prevent electro-osmosis (moving of water by the electric field). For anode-type earth electrodes that run in monopolar mode for a long time and are in fine particle (clay) soil, the permissible average current density at the coke-soil interface should be limited to 0,5 A/m^2 to 1 A/m^2 at the rated current of one pole. For specified outage conditions (e.g. 30 % electrodes out of service), the current density may be higher as allowed by soil conditions.

In the case of a coarse-grained soil with large pore size and where the active portion of the electrode is below the water table, an average current density of 2 A/m^2 or higher may be the permissible value under rated current of one pole.

5.1.7 Field intensity in fish ponds

For earth electrodes near fish ponds, the field intensity of any point in the water should not exceed 15 V/m when operating at maximum short-time overload current.

For common earth electrodes or multiple earth electrodes within a short distance of each other, the case of systems running in short-time (e.g. < 30 min) earth return operation mode with the same polarity should be considered during design.

5.2 Electrode site selection and parameter measurement

5.2.1 General principles

Selection of the electrode site is a critical step in the beginning of the earth electrode design, and also a complicated process, during which technical and economic comparison is required to select a safe, reliable, economically feasible, and environment-friendly site.

Local environmental impacts (see Clause 4) and remote environmental impacts (see Clause 7) should be focused on during selection of the electrode site. Multiple geophysical and geotechnical surveys, geoelectric modelling, electrode pre-design and performance calculations (electrical and thermal) are all necessary in this step. To reduce the impact of earthing current on the environment, the sites which have lower resistivity in deep ground should be considered as the first candidate if possible. If the electrode will serve as ground return for more than one HVDC system with converter stations in the close vicinity, it is recommended to consider the common earth electrode solution if it can meet all the system operation conditions. Split earth electrodes or compact earth electrodes can be used if the technical and economic feasibility has been demonstrated.

5.2.2 Data collection survey

For the evaluation of a suitable electrode site, a survey within a radius of at least 10 km should be conducted to obtain the natural conditions in the neighbourhood of the prospective electrode site. The survey data should at least include the landform and terrain, geological structure, hydrological-meteorological conditions, and ocean tide (for shore electrodes or sea electrodes), and a technical assessment should be carried out based on Annex D.

In addition, local development plans should be acquired from the local government or other relevant authority. For complete assessment of the electrode site under investigation, information should at least cover existing and planned power facilities (such as substations and lines), buried metal pipes, armoured or earthed cables, and railway lines.

Depending on the tectonic setting of the area, it is recommended to collect information of extra high-voltage AC power facilities in a larger range, e.g. located within 50 km ~ 100 km or more of the electrode site. A high-resistivity terrain will require a wider geographical survey than a low-resistivity terrain.

5.2.3 Distance from converter station (substation)

In the site selection process, the impact of the earth electrodes on surrounding converter stations and AC substations shall be quantified. See Annex K for the calculation method. If calculation and analysis are not possible, the distance from the electrode site to any converter station or high voltage AC substation should be no less than 10 km in general to minimize the risk of DC current flow into the Y grounded windings of the AC transformers, and the minimum distance from the electrode site to any aerial power line with earth wire should be larger than 5 km to reduce the risk of corrosion of tower grounding and foundation. If for some reason it is impossible to maintain these distances, measures should be taken to mitigate the effect, such as DC current-blocking devices in series with transformer neutral and ground (see Clause 7), or insulation between earth wires and the towers.

5.2.4 Environment conditions, terrain and landform

The electrode site should be located far away from cities and densely populated residential areas, on a reasonably flat area, without ground erosions and rocks outcropping, and avoiding lowlands, without risk of flood erosion or long-time flood submersion. In addition, the location should be in an open space to provide a wide and conductive current-releasing area and to facilitate making the necessary connections.

5.2.5 Geophysical and geological surveys

In the beginning of the design of earth electrodes, the main physical parameters of the soil on the electrode site including the soil resistivity model, soil thermal conductivity, volume thermal capacity, maximum ambient temperature, humidity, and ground water table (see Annex D for detailed surveying methods and technical requirements) should be surveyed.

For the selected electrode sites, test holes shall be drilled for a direct survey of the shallow ground structure and for the determination of the structure of the sedimentary cover within the electrode site. The exploration should be carried out in a range not less than the size of the earth electrode and up to the depth of the bedrock, or the expected depth of the electrode. In the case of a vertical or deep well electrode, a survey method of well profiling that measures the resistivity of the well walls directly by means of a probe that is lowered down to the well could be used for the direct access of the shallow ground geoelectric structure. This data shall be used for the calibration of the shallow ground layers of the final geoelectric model for the electrode site.

5.2.6 Topographical map

1:1 000 or 1:2 000 topographic maps should be drawn based on a field survey. The measurement range should be defined in such a way to allow for the optimization of earth electrode layout.

5.2.7 Values selected during design

In general, reasonable values shall be selected for soil parameters based on actual surveys through analysis, calculation and sorting:

- the reliability of the measurements should be higher than 95 %. For N effective values measured at the same place (X_1, X_2, ..., X_N) , the average (X_p) and standard deviation (σ) can be calculated with:

$$X_p = \frac{1}{N}\sum_{1}^{N} X_n \quad (4)$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{1}^{N}(X_n - X_p)^2} \quad (5)$$

The value of soil parameters can be calculated with:

$$X = X_p + 1{,}96 \times k \times \sigma \quad (6)$$

where

k = +1 for soil resistivity and temperature, and

k = –1 for thermal conductivity and volume thermal capacity.

- values selected for soil resistivity during the design should consider the influence of unfavourable seasons, which means the season coefficient should be applied after calculation with Formula (6).

5.3 Earth electrode and associated components

5.3.1 General principles for material selection

Electrode element material should be selected through technical and economical comparisons based on engineering and market conditions. The selection shall be based on the following principles: good conductive property, good resistance to corrosion and to ground aggressivity (pH, chloride content, etc.), easy mechanical processing, no toxic or negative effect, and cost-effectiveness.

5.3.2 Selection of electrode elements and characteristics

Electrode elements used for DC earth electrodes should be preferably made of iron, high-silicon cast iron, high-silicon chromium iron, or graphite.

If the pH value of soil and ground water is between 3 and 11 and the content of $Cl^-+SO_4^{2-}$ ions is less than 500 mg/l, for anode type land electrodes with a service life shorter than 40 × 10^6 Ah, the electrode elements should be made of iron.

If the corrosion lifespan of the electrodes is longer than 40 × 10^6 Ah or the soil has a pH value less than 3, the electrode elements should be high-silicon cast (chromium) iron or graphite.

If high-silicon cast iron or high-silicon chromium iron is used for electrode elements, the final products should be equipped with feeding cable.

The carbon content in iron should be less than 0,5 %. Graphite should preferably be treated by submersion in linseed oil. The chemical composition of high-silicon cast iron and high-silicon chromium iron should correspond to the values listed in Table 1.

Table 1 – Composition of iron-silicon alloy electrode

Chemical composition	High-silicon cast iron %	High-silicon chromium iron %
Silicon (Si)	14,25~15,25	14,25~15,25
Manganese (Mn)	<0,5	≤0,5
Carbon (C)	<1,4	<1,4
Phosphorous (P)	<0,25	<0,25
Sulfur (S)	<0,1	<0,1
Chromium (Cr)	0	4~5
Iron (Fe)	>82,5	>77,5

5.3.3 Chemical and physical properties of petroleum coke

The chemical composition of the petroleum coke after calcination should correspond to the values listed in Table 2.

Table 2 – Chemical composition of the petroleum coke after calcination

Substance	Proportion %
Carbon	≥95
Water	≤0,1
Volatile components	≤0,5
Sulphur	≤1
Iron	≤0,04
Silicon	≤0,06
Ash and others	≤1

The physical properties of petroleum coke products used for DC earth electrodes should correspond to the values listed in Table 3.

Table 3 – Physical properties of petroleum coke used for earth electrodes

Properties	Values
Resistivity (at a volume weight of 1,1 g/cm^3)	<0,3 Ω·m
Volume weight	0,9~1,1 g/cm^3
Specific gravity	2 g/cm^3
Space ratio	45 %~55 %
Volume thermal capacity	>1,0 J/(cm^3 °C)

5.3.4 Current-guiding system

The earth current should be guided from electrode line to the current-guiding wire, disconnecting switchgear, feeding cables and connections in turn before it reaches different electrode elements (more details in 5.6).

5.3.5 Bus

The current is distributed by the bus, which can be of either the strain or rigid types. Strain bus is typically composed of an aluminium conductor steel reinforced, and rigid bus is typically composed of aluminium pipe or copper bar.

5.3.6 Electrode line and its monitoring device

The design of electrode line can be seen in Annex E. In some systems, electrode line monitoring (capacitor/reactor) devices are connected at the electrode end of the electrode line, to monitor integrity of the electrode line. The technical requirements of such devices are typically determined during converter station design. Their arrangement shall be considered during the design of the current guiding system.

5.4 Electrode arrangement

5.4.1 General principles

The arrangement of land electrode elements can be classified as horizontal (trench) and vertical (well) type, which shall be selected through technical and economic comparison based on distribution of soil resistivity and terrain conditions. Generally, if the resistivity of deep soil (deeper than 10 m below ground) is significantly lower than that of the surface or if the ground water table is deep, a vertical well arrangement might be used, otherwise horizontal trench arrangement might be used.

5.4.2 Filling coke

Horizontal earth electrodes should preferably use square or rectangular sections or other suitable shapes according to the surrounding situation, and vertical earth electrodes should use circular sections. The electrode element in the center is surrounded by filling coke, as shown in Figure 1. The recommended density of the reinforced filling coke should be between 1 000 kg/m^3 and 1 100 kg/m^3. The density for vertical electrodes should be higher in the case of water-filled bore holes.

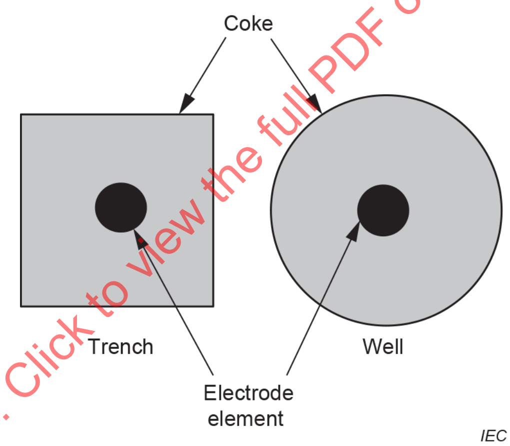


Figure 1 – Electrode cross-section

5.4.3 Selection of earth electrode shape

The shape of the electrode shall be selected to achieve better current distribution and balance as suggested below:

- if the electrode site is flat and wide enough, first choose a horizontal single circular arrangement. If this proves to be unsuitable, next choose a double concentric circular arrangement, with the ratio of diameters of internal circle to external circle between 0,7 and 0,85. If circular earth electrodes are not possible due to limited site conditions, the electrode arrangement should be as circular as possible, maximising the curvature radius at curved parts;
- in case of rough terrain (such as ravine or loch), horizontal linear arrangement could be used. In this case, a properly sized electrode of circled loop can be installed at the end (often with the highest current-releasing density) to reduce current-releasing density at the end. If the soil resistivity at depths ranging from tens to hundreds of meters is very low, vertical or deep well electrode is also a good choice;
- for horizontal multiple circles electrodes, the number of concentric circles is recommended not to exceed 3, in order to reduce the shielding effect and improve the utilization efficiency of electrodes;

– the electrodes should be arranged as symmetrically as possible to facilitate the layout of the current guiding system, improve current shunt uniformity and reliability of the current guiding system, and reduce construction cost of the current guiding system.

5.4.4 Earth electrode corridor (right of way)

If earth electrodes lie near any low-lying areas such as a trench, ditch or pond, and the burial depth of the earth electrodes is less than that of the trench, ditch or pond, the distance from the earth electrodes to its edge should generally be no less than 10 m.

5.4.5 Distance between sub-electrodes in the arrangement

In case of vertical arrangement of the earth electrode elements, the distance between sub-electrodes should generally comply with Formula (7), as shown in Figure 2.

$$D = \eta L \tag{7}$$

where

D is the distance between sub-electrodes in vertical arrangement (m);

L is the length of the sub-electrodes in vertical arrangement (m);

η is the coefficient, 0,8~1,0.

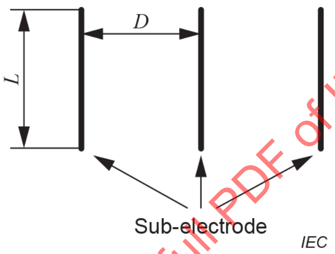


Figure 2 – Vertical arrangement

If earth electrode elements are horizontally arranged in a discrete way, as shown in Figure 4 b) sub-electrodes should have a distances less than 2 m to achieve a uniform current distribution at the coke-soil interface.

5.4.6 Burial depth of the earth electrodes

Optimal burial depth of earth electrodes should be selected through technical and economic comparison based on the following principles:

a) step voltage. If the electrode length is horizontally arranged, the minimum burial depth of the earth electrodes can be estimated with Formula (8) approximately.

$$h = \frac{\rho_s \tau}{2\pi E_{sp}} \tag{8}$$

where

h is the minimum burial depth of the earth electrode (m);

ρ_s is the average shallow soil resistivity (Ω·m);

τ is the earth electrode current-releasing density, calculated with earthing current divided by total length of electrode (A/m);

E_{sp} is the maximum permissible step voltage (V/m);

b) the earth electrode should not be buried in rock, sand and gravel layers;

c) after the above conditions have been satisfied, the burial depth of the earth electrode should be minimized to reduce earthwork;

d) if farming is allowed on top of the area where the electrode is buried, the earth electrodes shall not be buried at a shallow depth to avoid artificial damage due to farming and machine-aided cultivation and impact of atmospheric temperature on the operation performance of electrodes. In general, earth electrodes should be buried to a depth exceeding 1,5 m.

5.4.7 Segmentation of earth electrodes

DC earth electrode elements shall be divided into segments for better inspection and maintenance. The number of electrode element segments shall be limited to avoid impact on current distribution and prevent a complicated current guiding system. Sub-electrode length shall be selected in such a way that other segments can still run safely and reliably at the specified maximum earthing current when one of these segments is put out of use (for maintenance).

5.5 Minimum size of earth electrode

5.5.1 General principles

Minimum sizes of earth electrodes refer to total earth electrode length, the side length of the coke section and the electrode element diameter when the thermal stability or step voltage conditions are met. The principles for determining these three important dimensions include at least the following:

- at constant rated current, the highest temperature at any part of the earth electrodes shall not exceed the boiling point of water;
- at the maximum short-time overload current, the maximum step voltage at any point on the soil surface shall not exceed the allowed value;
- at the end of the designed lifespan, the electrode elements shall still meet current-carrying requirements after the corrosion is considered.

5.5.2 Total earth electrode length

In general, the length of the earth electrode (or occupied area) should be determined based on heating conditions (see 5.1.2 and 5.1.3), checked against the value allowed by maximum step voltage (see 5.1.4) and current density at the coke-soil interface (see 5.1.6), and finalized through optimization of the earth electrode material consumption.

5.5.3 Area of the surface of the coke-soil interface

For earth electrodes running in earth return mode, if the thermal time constant is greater than the duration of the rated current, the area of the coke-soil interface at any point (P) of the electrode may be conservatively calculated by Formula (9) to ensure that the highest temperature at any point (P) will not exceed the permissible value.

$$S_P \geq k^2 \times \rho_m{}^2 \times \tau_P{}^2 \frac{T_0}{16\rho_P C_P(\theta_{mp} - \theta_c)} \tag{9}$$

where

S_p is the area of the coke-soil interface at point P (m);

k is the matching coefficient, in the range of 0,9~1,1; see Annex G;

τ_p is the linear current density at point P (A/m);

ρ_p is the soil resistivity at point P (Ω·m);

C_p is the soil volume thermal capacity at point P (J/(m^3 °C));

ρ_m is the resistivity of the soil burial layer (Ω·m);

θ_c is the highest natural ambient temperature of the soil at any time in the year (°C);

θ_{mp} is the maximum permitted temperature of the earth electrode (°C);

T_0 is the duration of the rated current (s).

For earth electrodes running in anode mode for a long time, the maximum surface current density at the coke-soil interface should meet the recommendations in 5.1.6.

5.5.4 Diameter of electrode elements

To ensure that the electrode elements have sufficient current-carrying capacity, expected lifespan and permitted temperature rise, the sizes of electrode elements should comply with both Formulae (10) and (11).

$$\Phi_p \geq \sqrt{\frac{4k_1k_2\rho_p\tau_p FV_\mathrm{f} + \pi\phi^2\rho_m gI_\mathrm{d} \times 10^{-3}}{\pi\rho_m gI_\mathrm{d} \times 10^{-3}}} \qquad (10)$$

$$\Phi_p \geq \frac{4S_p}{\pi}\sqrt{\frac{\rho_c C_p}{\rho_p C}} \times 10^3 \qquad (11)$$

where

S_p is the side length of coke section at point P (m), see Formula (9);

Φ_p is the equivalent diameter of the electrode element at point P (mm);

k_1 is the protection coefficient, which is ratio of unit area ion current in the coke to the total current, k_1 = 0,1~0,6;

k_2 is the electric corrosion accumulation effect coefficient, see Table 4;

F is the service life of the anode (A·h);

V_f is the electric corrosion rate of electrode element material in the soil (kg/(A·h)), see Table 4;

φ is the remaining equivalent diameter of the electrode element when the total operation time of the earth electrode reaches the designed lifespan (mm);

g is the density of the electrode element material (g/cm^3), see Table 4;

ρ_c is the coke resistivity (Ω·m);

C is the coke volume thermal capacity (J/(m^3·°C));

I_d is the rated current (A).

Others are the same as Formula (9).

Table 4 – Electric corrosion characteristics of different materials

Material	Density, g g/cm^3	Corrosion rate, V_f kg/(A·h)	Accumulation effect coefficient, k_2
Iron (steel)	7,86	0,001 039	3,0
High-silicon cast iron	7,03	0,000 228	2,0/3,0 (in sea water)
High-silicon chromium iron	7,02	0,000 114	2,0
Graphite	2,1	0,000 114	>3,0

5.6 Current guiding system

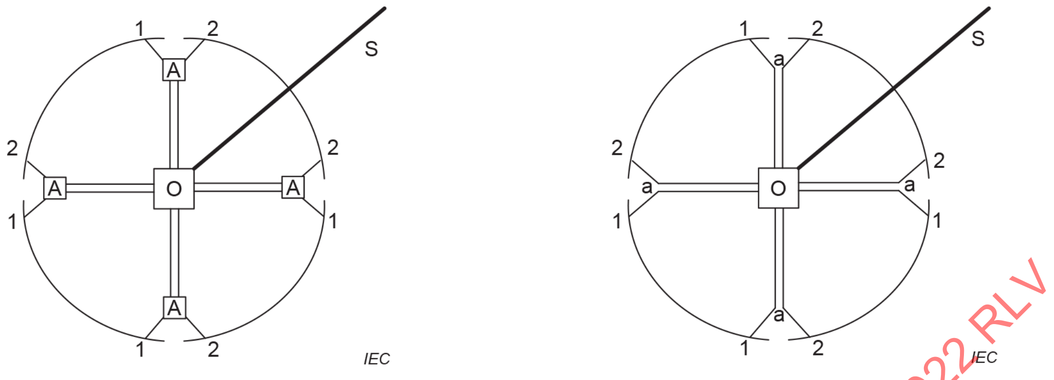
5.6.1 General principles

Generally, electrode lines from converter stations should first (or via electrode line monitoring reactors) be connected to the bus, and then the current should be guided to the current-guiding wire, disconnecting switchgear, feeding cables and connections in turn before it reaches different electrode elements. The current guiding system should be designed in such a way that the current flowing through branches of the same level is equal or roughly equal.

5.6.2 Placement of the current-guiding wire

The current-guiding wire can be overhead wire or underground cable. The placement of such wire should generally match the electrode shape to achieve good current sharing characteristics.

In general, for symmetrically arranged earth electrodes, the current-guiding wire should also be arranged symmetrically, e.g. Figure 3a) or Figure 3b).



a) Overhead conductor is adopted **b) Underground cable is adopted**

Key

O	central tower
A	branch tower
a	location where the feeding cables branch.
S-O	electrode line
A-O	current-guiding wire (where overhead conductors are used) between central tower and branch tower.
a-O	current-guiding wire (where underground cables are used) between central tower and electrode.
a-1, a-2	feeding cables
A-1, A-2	feeding cables

Figure 3 – Placement of the current-guiding wire

5.6.3 Connection of current-guiding wire

To facilitate maintenance or commissioning, the current-guiding wire and feeding cable shall be bolted on the ground or connected with outdoor disconnecting switch, as per IEC 61936-1 and IEC TS 61936-2. If a disconnecting switch is adopted, the disconnecting switches should be installed on the current-guiding wire support structures. To ensure human safety, disconnecting switches shall be fenced off or placed at a sufficient height above ground.

5.6.4 Selection of current-guiding wire cross-section

The current-guiding wire cross-section should be selected based on the calculation results of the current in different branches, and in such a way that safe operation of other current-guiding wires is not affected under any earthing current operation conditions or when any electrode segment is out of use (due to damage or for the purpose of maintenance).

If cable is used as current-guiding wire, see 5.6.10.

5.6.5 Insulation of the current-guiding wire

Because the operation voltage on the earth electrode bus is very low (typically no higher than 10 kV even under transient conditions), the operation voltage on the bus is generally not a factor controlling the insulation level of the current-guiding wire.

If the current-guiding wire uses overhead line, the possibility of short-circuited insulator discs should be considered. Usually insulator strings with lightning impulse withstand level of at least 125 kV or at least two fully rated DC suspension insulators are used as the insulation between the conductors and tower structure.

If cable is used as current-guiding wire, see 5.6.11.

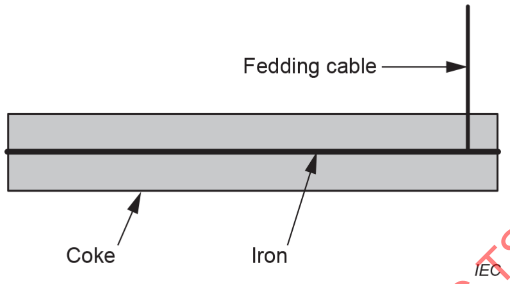
5.6.6 Disconnecting switch

To facilitate commissioning or maintenance, disconnecting switches should be installed in each group of sub-electrodes. The rated current of the disconnecting switches shall be no less than the maximum current that may occur in the corresponding circuit. The rated voltage should be no less than 10 kV.

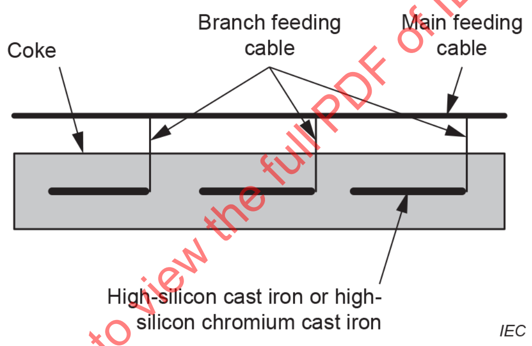
5.6.7 Connection of the feeding cable

Each electrode segment shall be connected to feeding cables.

If the electrode element is made of high-conductivity iron, an electrode element can be connected to the current-guiding wire directly by one feeding cable, as shown in Figure 4a). If the electrode element is made of poor-conductivity material such as high-silicon cast iron or high-silicon chromium iron, an individual feeding cable is used to connect each electrode element and the main feeding cable, which connects the current-guiding wire, as shown in Figure 4b).



a) Iron used for electrode element



b) High-silicon cast iron or high-silicon chromium cast iron used for electrode element

Figure 4 – Feeding cable

5.6.8 Connection of jumper cables

To reduce the step voltage, each sub-electrode shall be continuous as much as possible. The electrode may be interrupted if it has to cross low-lying areas such as trenches, ponds, or ditches, provided the electrical connections between the two segments are ensured. Two jumper cables are typically used to join separate electrode segments.

5.6.9 Selection of cable structure

Feeding cables and jumper cables should preferably use single core copper conductors with insulation, e.g. Kynar or XLPE, to facilitate construction, operation and maintenance and to reduce the cost. For cable buried directly in soil, single core copper conductor cable with double insulation may be used.

5.6.10 Selection of cable cross-section

The current-carrying cross-section of feeding cables and jumper cables (or cable-type current-guiding wire) shall be selected based on the calculation results of the current with adequate margin in different branches, and in such a way that safe operation of a cable is not affected under any earthing current operation conditions or when the other cable is out of use (due to damage or for the purpose of maintenance).

When selecting the cross-section of underground cable conductors, the maximum allowed current-carrying capacity of the cable shall be calibrated based on the environmental conditions of the soil (such as the parameters of maximum ambient temperature, soil thermal conductivity, volume thermal capacity, and cable distance). In addition, the insulation cover shall provide good thermal stability.

5.6.11 Selection of cable insulation

The insulation of current guiding system cables can be generally grouped into two levels:

- for feeding cable and jumper cable (or cable-type current-guiding wire), the insulation level should be generally no less than 6 kV and should preferably have a metal sheath to prevent moisture absorption into the cable;
- for branch feeding cables connected to high-silicon cast iron or high-silicon chromium iron sub-electrodes, the insulation level should be generally no less than 750 V and should preferably have double insulation.

5.6.12 Cable welding position

For an electrode element made of iron (steel), during connection between feeding cable and electrode element and between jumper cable and electrode element, the recommended welding position should be more than 5 m away from ends of the electrode (electrode element).

5.6.13 Welding

For connections and splices between underground cable and electrode elements, exothermic welding, arc welding or hydraulic compressed connections should be used. Bolt connection is prohibited.

The welding shall be firm and tight. The welding contact resistance shall not exceed that of the material of the same length with original specifications.

5.6.14 Mechanical protection for cable

All underground cables shall be effectively protected. The cable should be fixed on a cable bracket and be protected by a properly sized PVC plastic pipe at the place where the feeding cable enters the ground. For current-guiding wires, feeding cables or jumper cables that are directly buried in soil, sand should be filled around them, with cement panels laid directly over the cable to protect it against damages caused by external forces. For branch feeding cables connected to high-silicon cast iron or high-silicon chromium iron sub-electrodes, compatible PVC plastic pipes should be used as shields.

All underground cable joints and welding points exposed to soil shall be sealed reliably with epoxy resin.

5.7 Auxiliary facilities

5.7.1 Online monitoring

To determine or monitor the operation status of earth electrodes, monitoring devices that can detect current distribution, temperature and humidity of the earth electrodes can be installed at the location of the current-feeding cable. Alternatively, installation can be done in a manner such that portable instruments can be used. Common detection devices can be installed in monitoring pits and wells. An online monitoring system can also be set up if required. See Annex I for detailed information of this system.

The current distribution detection device shall at least be able to detect current flowing through different feeding cables. The detection well or sensor should be preferably placed at the access point of the feeding cable or the location where high current-releasing density or high temperature rise may occur.

A main and redundant power supply system which may include the combination of local AC supply, solar panel, batteries or diesel generator may be installed for the electrode monitoring and control.

5.7.2 Moisture replenishment

If required, water-filling devices should be installed for horizontal (trench) type earth electrodes to reduce soil resistivity and prevent soil from drying out. During design, suitable water filling methods such as seepage wells can be selected based on site conditions.

5.7.3 Exhaust equipment

To facilitate release of gas generated during operation of the earth electrodes and maintain good operation characteristics of the earth electrodes, earth electrodes, especially deep well type and shore type electrodes, shall be equipped with exhaust equipment.

5.7.4 Fence

If the step voltage or touch voltage exceeds safe limits, a wall or fence shall be erected, carrying distinguishing marks to prevent or warn unauthorized people attempting to enter the site.

The fence should be preferably made of insulating materials such as brick, wood. If non-insulating material is used, small independent earthing devices should be installed, and the fence should be segmented using insulators to avoid large transferred voltages.

5.7.5 Marker

Markers should be placed at proper locations above the perimeter of the electrode if required.

6 Design of sea electrode station and shore electrode station

6.1 Main technical parameters

6.1.1 General

Design of the sea electrodes or the shore electrodes should ensure their safe and reliable operations throughout their life cycles and under different earthing current conditions including rated current, maximum short-time overload current, and maximum transient overcurrent. Different technical parameters such as earthing resistance, voltage gradient in water, step voltage, touch voltage and transferred voltage should be within the specified range.

6.1.2 Temperature rise

The temperature rise is not a dimensioning factor for sea electrodes and pond electrodes with adequate water exchange, and it is not required to do this calculation.

For beach electrode stations, the basic principle is that the maximum temperature of any point of the earth electrode shall be lower than the boiling point of water under all circumstances.

6.1.3 Earthing resistance

The requirement for earthing resistance of sea and shore electrodes are the same as for land electrode (see 5.1.3).

Since the resistivity layers of sea and shore electrodes are not horizontal, the formula to calculate the resistance to remote earth is more complicated than for electrodes with horizontal layers. In this case, calculation should be performed with computer programs.

6.1.4 Step voltage

The step voltage of any ground point shall not exceed the safety limits defined for humans and livestock (see 5.1.4).

Step voltages tend to be of a high level in beach stations if the electrode is buried at a moderate depth. The fence will often be damaged if the station area is at risk of possible high tides, waves and/or ice. If it is preferred to avoid fencing, the total station shall be made larger, or buried at a greater depth.

6.1.5 Touch voltage

For earthed metallic structures that can be accessed by the public, the touch voltage of any point on the site ground shall not exceed the safety limits defined for humans under the maximum short-time overload current of one pole (see 5.1.5).

6.1.6 Voltage gradient in water

The voltage gradient in water shall not exceed 1,25 V/m to 2 V/m in areas accessible to humans or marine fauna.

6.1.7 Current density

The recommended average current density in sea water for sea electrodes and pond electrodes is 6 A/m^2 to 10 A/m^2 in order to ensure a suitable gradient of 1,25 V/m to 2 V/m close to the electrode (at a sea water resistivity of 0,2 Ω·m). The anode should be shielded from fish, as fish are attracted to the anode and not the cathode. If the sea electrodes or pond electrodes are functioning in an environment open to free water but not accessible to human beings or to marine fauna, the average current density can be raised to a value up to 40 A/m^2~ 50 A/m^2.

For beach electrodes, in addition to electro-osmosis, Cl_2 generation should also be considered since it is not good for the environment. For water saturated beach electrodes, the recommended current density on the surface of the coke is 7 A/m^2.

6.2 Electrode site selection and parameter measurement

6.2.1 General principles

Selection of the electrode site is a critical step during earth electrode design, and a complicated process, during which technical and economic comparison is required to select a safe, reliable, economically feasible, and environment-friendly site.

The following factors shall be considered when candidate sea electrode sites are compared and selected: distance to converter station, substations, pipelines, cables, etc., salinity of the sea water, slope of the seabed, resistivity on the shore, and uniformity of the seabed.

6.2.2 Data collection survey

To verify a possible electrode site, a survey within a radius of at least 10 km should be conducted to determine the natural conditions in the neighbourhood of the electrode site under investigation, which should at least include the landform and terrain, geological structure, ocean tide and currents in the sea. The survey shall show that the seabed is without clay so that the electrode does not sink.

Besides, in order to conduct environmental impacts evaluation, the surrounding facilities near the electrode site should also be surveyed, such as the existing and planned power facilities (substations and lines), buried metal pipes, armoured or earthed cables, railway lines, fishing areas, vacation beaches, cathodic protection system for marine metallic structures, etc. Coastal areas are often characterised by a layer of fresh water, rising to a higher level than the nearby sea and a deeper layer of salt water, penetrating from the sea. If a distinct interface between freshwater and saline water exists, survey should be done to determine which depth is the best for the active part of an electrode station. If the current is emitted in the freshwater layer, anodic operation will evolve only oxygen, not chlorine. If the electrode is close to, but still above, the interface, the salt-water layer will absorb the current very effectively, within a short horizontal distance. If low resistance to remote earth and decrease of loss are the goals, the electrodes shall be placed in the saline strata, but some evolution of chlorine will be the result.

6.2.3 Distance from converter station (substation)

During the determination of the electrode site and during the commissioning of the electrode station, the impact of earth electrodes on surrounding converter stations and AC substations shall be calculated or measured.

6.2.4 Environment conditions

The electrode site should be placed far away from populated areas, such as vacation beaches if possible, to reduce public concern about earth electrode.

In electrolytic processes there will always be a chemical action, because the materials in the ground/seawater (more precisely the substances diluted in the ground/seawater) will be decomposed and/or built up to new chemical substances, see Annex L.

In an anodic process in ground water of very low or zero salinity, O_2 (oxygen) is produced and emanates, which is generally not seen as a problem since the atmosphere partly consists of O_2. With increasing salinity, the evolution of Cl_2 (chlorine) will take over, which is a kind of toxic gas. However, there will still be, even in salinities up to sea water level, a substantial evolution of O_2. The sum of evolved gases respects Faraday's law of electrolysis, which says that the mass of decomposed material is proportional to the electric charge, i.e. the number of ampere hours.

6.2.5 Measurement of ground/water parameters

The measurement of ground/water parameters shall meet the following requirements:

a) For beach/pond electrodes, the resistivity of seawater and shallow soil on the beach should be measured. The former can be measured by a liquid conductivity tester, and the latter can be conducted by the Wenner or Schlumberger methods as used in land electrode, but the effect of seawater on the apparent resistivity measurement results shall be considered in soil model inversion analysis. Besides, the seawater depth and seabed slope near the electrode should also be tested or surveyed which may use the method of sonar or echo-sounding. If required, the deep soil resistivity could be measured by the magnetotelluric (MT) method (see Annex D), which is used to evaluate the impact on the surrounding facilities on land.

b) For sea electrodes, the factors like sea currents, sea-bottom roughness and sea-bottom soil conditions should be investigated. Morphological and geological investigations can include side-scan sonar, sub-bottom profilers and echo-sounders. Bottom conditions should also be investigated by divers and/or with under water vessels and documented by camera. The resistivity of seawater and soil of sea-bottom can be measured by seawater/soil sampling. Resistivity measurements are possible for sea electrodes, at least in shallow water areas, however more complicated than on land. The resistivity may also be measured on undisturbed soil samples from the seabed.

c) The salinity of the seawater shall be measured in order to analyse gas evolution rates.

6.3 Earth electrode and associated components

6.3.1 General principles for material selection

The material shall be selected through technical and economical comparisons based on engineering and market conditions. The selection shall respect the following principles: low dissolution rate as well as low chlorine emission rate in anodic regime, low toxic or other negative effects, and cost-effectiveness.

6.3.2 Common electrode elements and characteristics

Electrode elements used for sea electrodes or shore electrodes should be preferably made of high-silicon chromium iron, or graphite embedded in coke. The carbon content in iron should be less than 0,5 %. Graphite should preferably be treated by submersion in linseed oil. The chemical composition of high-silicon chromium iron should correspond to the values listed in Table 1.

Other material that can be used directly in sea water without embedment in coke are:

a) platinised titanium or niobium (Pt/Ti or Pt/Nb);

b) magnetite;

c) bare copper conductors (for cathodic operation only);

d) mixed metal oxides (MMO).

Platinised titanium or niobium are also well-known electrode material for anodes, the most widely available shapes of which are wires, meshes and rods, depending on the manufacturer. But they are not very suitable for cathodic operation.

Magnetite, Fe_3O_4, is commonly used for cathodic protection purposes. The electrodes are usually produced in rod-form, 0,06 m in diameter, 0,72 m in length and other sizes as well. The resistivity of magnetite is about 5×10^{-5} Ω·m –10×10^{-5} Ω·m. A disadvantage of this material is that it is brittle and not easy to manufacture.

Bare copper is an electrode material fit for cathodic operation only, as anodic operation will lead it to quickly corrode itself. A reason for this choice is the possibility of establishing reliable clamp connections by compression or by welding, which will withstand the environmental conditions of the seawater.

Mixed metal oxides (MMO) electrode is developed to prevent the corrosion during chlorine production by coating the titanium with special mixed metal oxides (coating thickness in the range of 5 µm to 20 µm). It can be used both in anodic and in cathodic operations. But in cathodic operations the dispersed current density shall be limited to be much lower than that in anodic operation. This is due to the adsorption of the hydrogen developed in cathodic operation by the crystal structure of titanium, and subsequent formation of titanium hydride, which is brittle and leads to net damage.

6.3.3 Chemical properties of petroleum coke

See 5.3.3.

6.3.4 Current-guiding system

See 6.5.

6.3.5 Bus

See 5.3.5.

6.3.6 Electrode line monitoring device

See 5.3.6.

6.4 Electrode arrangement

6.4.1 General principles

The arrangement of sea electrode elements can be classified as horizontal embedded in coke (see Figure 5) or placed in cages directly on the bottom of the sea. If nets are used, these shall be placed on sea bottom and covered by gravel or cement sacks.

The arrangement of shore electrode elements can be classified as vertical embedded in coke (beach type) or placed directly in seawater (pond type), see Annex M.

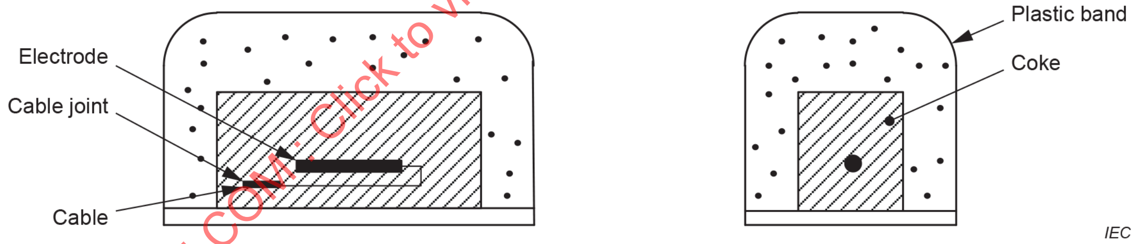


Figure 5 – Sea electrode

6.4.2 Filling coke

For sea electrodes and shore electrodes, the filling of coke, if used, should be performed on the shore. Fabric shall be used to keep the coke in place. The sub electrode is then placed on the seabed, covered by gravel or cement sacks.

For beach electrodes, the sub electrode is then placed in the bore holes made on the shore.

6.4.3 Selection of earth electrode shape

The physical layout of the electrode should be as round as possible. With a net type electrode (anodes) the ends form a curve approximately to half circles against the coast. See Figure 6. This is to ensure the best possible current sharing among sub-electrodes, because the influence of current density on the production of Cl_2 makes it important that all sub-electrodes carry an equally low part of the current. For shore electrodes, if the shore is narrow, an elliptical or linear shape electrode may be used.

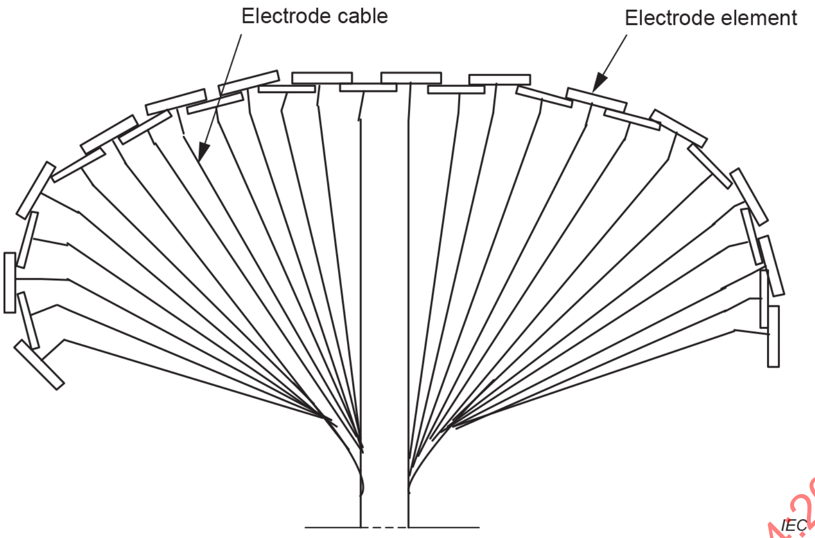


Figure 6 – Sea bottom electrode with titanium nets

6.4.4 Segmentation of earth electrodes

DC earth electrode sub sections shall be divided into a few segments for better inspection and maintenance. The number of sub sections shall be limited to avoid impact on current distribution and avoid the need for a complicated current guiding system. Subsections shall be performed so one part of the electrode can be taken out for maintenance or repair without resulting in unacceptably high potentials in water or ground close to the section out of service.

If the total electrode is composed of a number of sub-electrodes (which is preferred), then two different "philosophies" shall be considered:

a) the sub-electrodes are placed such that they are easily accessible for inspection/repair. This normally requires a small depth of burial and generally applies only to horizontal sub-electrodes;

b) the sub-electrodes are inaccessible when installed, with the idea that they are of a disposable (throwaway) type, which is left underground when damaged, if they are too difficult to salvage. A new substitution electrode is arranged close to the damaged one.

6.5 Current-guiding system

6.5.1 Placement of the current-guiding wire

For sea electrodes and pond electrodes, the busbar and other equipment, should preferably be placed in a cabin at some distance (e.g. more than 500 m) from the electrode area, at a safe level above sea surface. The current guiding wires between the busbar in the cabin and the sub-electrodes, or subparts, shall preferably be made as individual smaller cables, or mutually insulated sub-conductors in large cables. The extra (and equal) resistance in each sub-conductor will tend to equalize the current sharing among sub-electrodes. If not, series resistors can be used.

For beach electrodes, see 5.6.2.

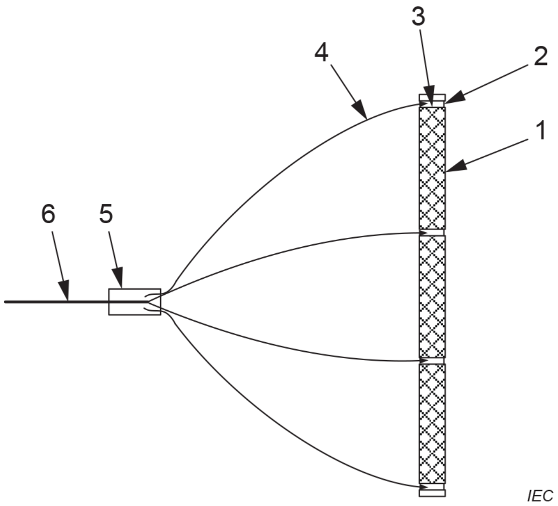
6.5.2 Connection of current-guiding system

For beach electrodes, see 5.6.3.

For sea electrodes and pond electrodes, each electrode segment shall be connected to feeding cables, and feeding cables shall be connected to current guiding wires (in cable-type), see Figure 7.

The connection of the feeding cable to each electrode elements shall be done by its supplier. The feeding cable shall have a watertight heat-shrink or epoxy resin joint to the element.

All cables, connection points and joints intended for anodic operation shall be well insulated since a direct contact with the water results in heavy electrolytic corrosion. The insulation shall, in addition, resist high electrode temperatures, mechanical stress during installation and various aggressive chemical elements in the environment.



Key

1 Electrode of titanium net, 1,22 m × 16,5 m
2 Connection plate of titanium
3 Watertight heat-shrink joint
4 Electrode cable (feeding cable), copper conductor 10 mm^2
5 Watertight heat-shrink joint
6 Electrode cable (current guiding wire), copper 35 mm^2

Figure 7 – Titanium net

6.5.3 Selection of cable cross-section

See 5.6.10.

6.5.4 Insulation of the current-guiding system

See 5.6.5 and 5.6.11.

6.5.5 Selection of cable structure

Feeding cable should preferably use single core copper conductor with insulation, e.g. Kynar or XLPE, to facilitate construction, operation and maintenance and to reduce the cost. For cable buried directly in the seabed, single core copper conductor cable with double insulation may be used.

6.5.6 Mechanical protection for cable

See 5.6.14.

6.6 Auxiliary facilities

To determine or monitor operation status of earth electrodes, monitoring devices that can detect current distribution of the earth electrodes shall be installed at the location of current-feeding cables (see 5.7.1).

Exhaust equipment should be considered for exhaust of Cl_2 (see 5.7.3).

7 Impact on surrounding facilities and mitigation measures

7.1 Impact on insulated metallic structures and mitigation measures

7.1.1 General principles

Touch voltage on any insulated metal structure buried near earth electrodes caused by ground return current shall not affect safety and health of people in contact with the metal structure, and possible corrosion shall not affect normal operation of the structures.

7.1.2 Relevant limits

For underground metal pipes insulated by surrounding cement or asphalt, the voltage between the pipe and surrounding soil shall be within the range from –1,5 V to –0,85 V at the equivalent earthing current. If this is not the case, proper precautions should be taken.

For pipes equipped with a cathodic protection system, the voltage to earth on the pipes caused by earth electrode earthing current shall not exceed the capability of the cathodic protection system.

At normal rated current, the touch voltage of a metal structure shall not exceed 70 V. If this is not the case, proper precautions should be taken.

7.1.3 Mitigation measures

For insulated metal pipes buried in ground with a voltage exceeding the limit, common precautions include addition or reinforcement of cathodic protection capabilities, addition of pipe anti-corrosion coating, and separating a pipe into segments and connecting them with insulative materials.

7.2 Impact on bare metallic structures

7.2.1 General principles

Impact of current field of DC earthing current on any buried bare metallic structure, such as touch voltage and corrosion, shall not affect the safety of people in contact with the metallic structure and safe normal operation of the metal structure.

7.2.2 Relevant limits

To protect personal safety, the touch voltage of any metal structure shall not exceed the value defined in 5.1.5. If this is not the case, proper precautions should be taken.

During analysis of corrosion effects of the earth electrodes on surrounding bare metallic structures, the current density at the surface of any buried metal structure exposed to soil should not exceed 1 μA/cm^2 at the equivalent earthing current, and the corrosion shall not affect normal operation of the metal structure. See Annex J for the calculation method.

7.2.3 Mitigation measures

The distance between earth electrodes and surrounding bare metal structures should be as large as possible. If the minimum distance between earth electrodes and underground bare metal structures, such as buried bare metallic pipes, is less than 10 km, or if the length of the underground metallic structure is longer than the distance, the adverse effects of DC earthing current of the earth electrodes on the structure shall be evaluated.

In case of excessive current flowing out of a bare metal pipe exposed to soil, corresponding anti-corrosion measures such as insulation coating or cathodic protection shall be taken for the metal pipe. The insulation coating is usually made of concrete, asphalt, enamel, or resin, and polyvinyl fluoride is the best choice. Cathodic protection is typically achieved in two ways: primary battery cathodic protection or external DC power supply cathodic protection.

7.3 Impact on the power system (power transformer, grounding network, and surrounding towers)

7.3.1 General principles

Rise of earth potential on an AC system near the earth electrodes resulting from the earthing current is likely to cause DC component in neutral-grounded transformers and consequently DC biasing (see Annex A). The schematic diagram of impact of the DC earth electrodes on AC systems is shown in Figure 8.

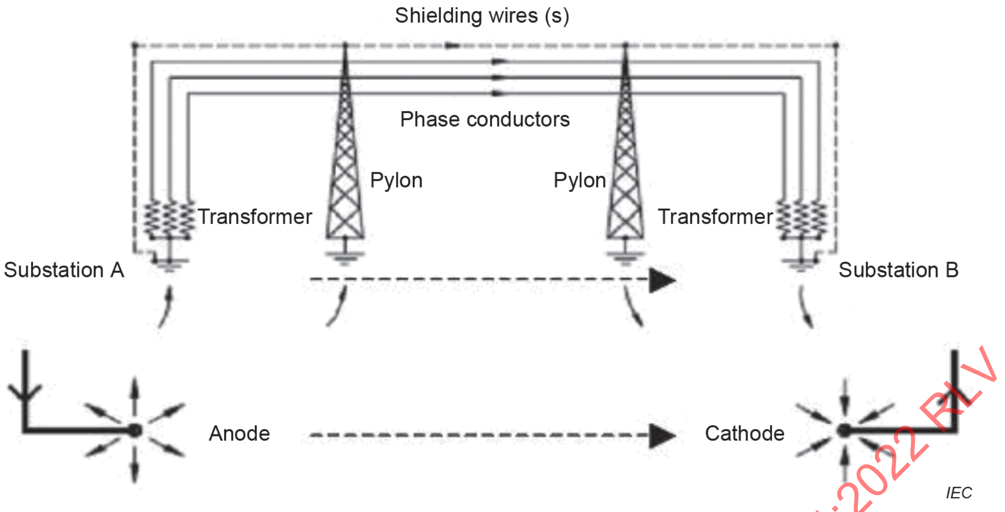


Figure 8 – Impact of earth electrodes on AC systems (transformer, grounding network, tower)

7.3.2 Relevant limits

The permissible DC current for windings of each transformer phase, if actual values are not known, can be as follows: 0,3 % of rated current for a single-phase transformer, 0,5 % of rated current for a three-phase five-legged transformer, or 0,7 % of rated current for a three-phase three-legged transformer.

7.3.3 Mitigation measures

If the earth electrode DC current flowing through the transformer windings is higher than the above limit, proper current-limiting or DC current-blocking measures shall be taken. The two main methods are:

a) DC current-blocking capacitor;

b) a small resistor connected in series with transformer neutral and ground.

7.4 Impact on electrified railway

If the earth electrodes lie near an electrified railway, simulative calculation should be performed to analyse issues concerning touch voltage on communication cables and signal cables of the railway caused by the earth electrode earthing current, DC current flowing through the traction transformer, and corrosion of earthing devices. Under rated current, the touch voltage between any point on the communication and signal cable and the common machine control room should not exceed 70 V, the consequent corrosion of earthing devices shall not affect their normal operation, and the DC current flowing through the traction transformer in the traction station shall be within the allowed range (usually higher than those of general AC transformers).

7.5 Other facilities (such as greenhouses and water pipes)

If the earth electrodes lie near facilities such as greenhouse or earthed metallic water pipes, the touch voltage and transferred voltage generated on them shall be considered. Impact of the touch voltage and transferred voltage can be reduced by earthing or removal or relocation of these facilities.

If the earth electrodes lie near a seismic station, simulative calculation and measurement should be performed to evaluate the potential difference between observation electrodes and magnetic flux density caused by the electrode lines and DC transmission lines. Measures such as adjusting the direction, or the length of the seismic station observation electrodes can be taken.

Annex A
(informative)

Basic concepts of earth electrodes

A.1 Basic concepts

Earth electrodes play a very important role in the operation of DC power transmission systems. Firstly, they can provide a transmission path for the load current under monopolar earth return operation mode when one of the poles of a DC transmission system fails or is overhauled. Secondly, they provide the ground reference for the neutral potential at the converter station to avoid equipment damage due to unbalanced voltage to earth of the two poles. Hence the design of earth electrodes is critical during the design and construction of the whole DC power transmission system.

A.2 Operation mode

A.2.1 General

An HVDC power transmission system typically consists of three parts: rectifier station, DC current line, and inverter station, as shown in Figure A.1.

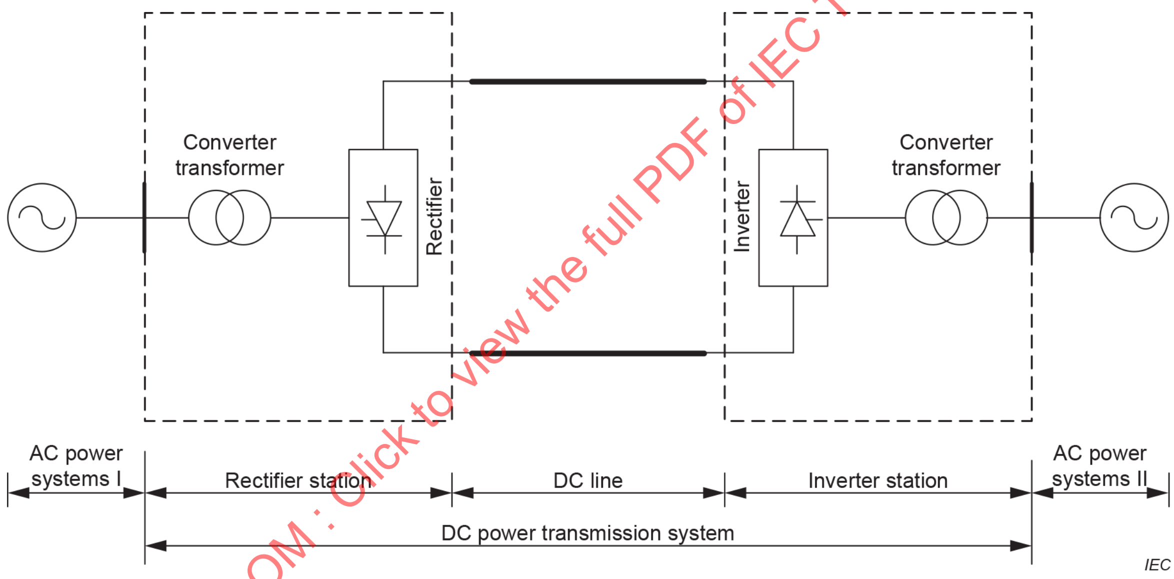


Figure A.1 – HVDC power transmission system structure

Depending on the number of nodes connected to AC systems, DC power transmission systems can be grouped into two-terminal and multiple-terminal systems. Two-terminal DC power transmission systems can be further classified into three configurations: monopole, bipole and back-to-back.

A.2.2 Monopolar system

A.2.2.1 General

The monopolar system as shown in Figure A.2 is typically operated with only one pole connected to earth. The monopole DC system usually operates in negative pole mode, as it is less likely to be affected by lightning strikes and produces less radio disturbance caused by corona than the positive pole operation mode. The monopolar systems can be operated in two modes, ground return via ground electrodes or dedicated metallic return as shown in Figure A.2 and Figure A.3, respectively.

NOTE The terms “positive pole” and “negative pole” relate to the voltage polarity of that pole under the operating condition when power is being transmitted in the direction for which the HVDC project was primarily designed. For HVDC projects that are designed to be bi-directional, it is not possible to distinguish between the terms “positive pole” and “negative pole”.

A.2.2.2 Monopolar earth (sea water) return mode

This is a DC power transmission system with an overhead conductor or cable and using earth or sea water as the return path.

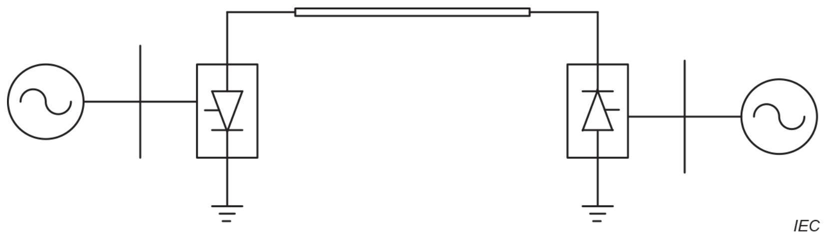


Figure A.2 – Schematic diagram of monopolar earth/sea water return system

A power transmission system adopting monopolar earth/sea water return mode can save investment in lines. However, electrochemical corrosion may occur in underground metal facilities located within the interference radius of the ground electrodes, and nearby communication and magnetic compass may be disturbed. This operation mode is applied in many systems, including the Gotland Island DC system in Sweden and the Sardinia-Corsica-Italy DC system.

A.2.2.3 Monopolar with dedicated metallic return mode

Monopolar system with dedicated metallic return uses a low insulation conductor earthed at one end as the return circuit, as shown in Figure A.3. The earth reference shown in Figure A.3 conducts no DC current and does not need to be designed as an earth electrode.

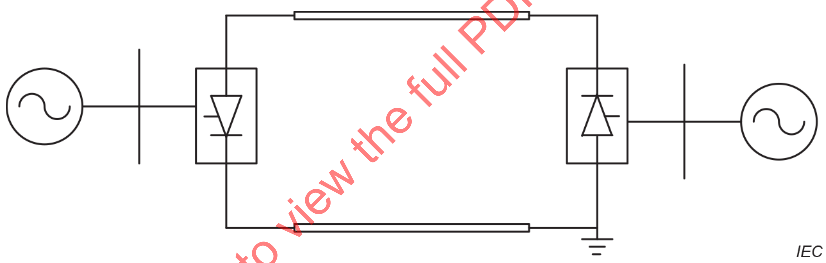


Figure A.3 – Schematic diagram of monopolar dedicated metallic return system

A.2.3 Bipolar system

A.2.3.1 General

As shown in Figure A.4, the bipolar line mode requires two conductors of different polarities (positive and negative pole). Bipolar systems can be further classified into three types: bipolar earth (sea water) system, rigid DC current bipolar system, and bipolar dedicated metallic return system.

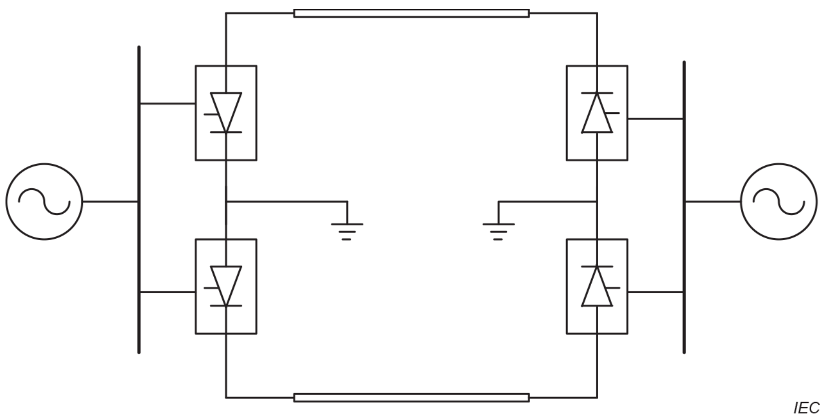


Figure A.4 – Schematic diagram of bipolar earth/sea water system

A.2.3.2 Bipolar earth (sea water) return mode

The mode of bipolar earth/sea water system is shown in Figure A.4. Both the neutral of the rectifier station and that of the inverter station are grounded in this mode. It can be regarded as a system formed by two superimposed monopolar systems. Unbalanced current flows through the return circuit during normal operation. If this current is low (e.g. symmetrically operated bipolar system), corrosion on underground metallic equipment is significantly reduced. Besides, in case of failure of any pole, the functional pole can still use earth or sea water as the current return circuit and thus maintain 50 % of total power transmission.

A.2.3.3 Rigid DC current bipolar mode

The mode of rigid DC current bipolar system is shown in Figure A.5. In this mode, the system is not grounded at the rectifier station end and thus avoids ground interference as it only happens in the bipolar earth/sea water mode. It should be noted that the earth reference shown on Figure A.5 conducts no DC current and does not need to be designed as an earth electrode. The disadvantage of this mode is that the operation is not possible when a failure occurs on one line. It also requires the currents in the two poles to be exactly equal, since there is no return path for any unbalance current.

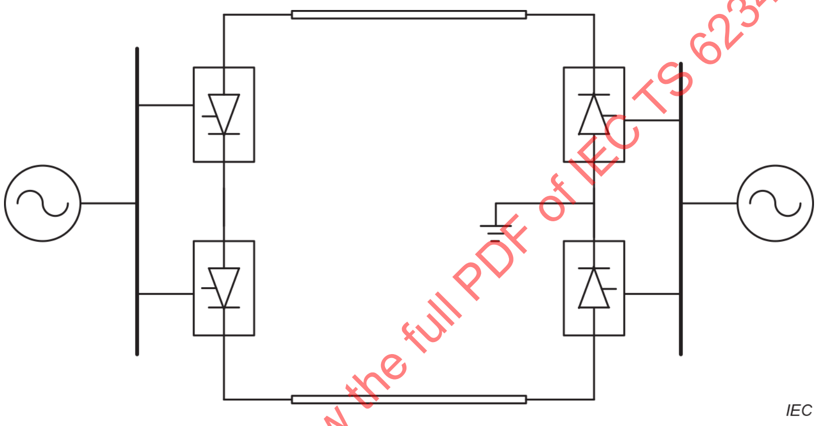


Figure A.5 – Schematic diagram of rigid bipolar system

A.2.3.4 Bipolar with dedicated metallic return mode

The mode of bipolar with dedicated metallic return is shown in Figure A.6. In this mode, in addition to conductors for positive and negative pole, a conductor is used as the neutral line between two converter station neutral points and grounded at one end. This mode not only eliminates the drawbacks due to earth or sea water being used as the current return circuit, but also allows continuous monopolar operation. In this mode, the earth reference shown in Figure A.6 conducts no DC current and does not need to be designed as an earth electrode.

Construction of DC power transmission systems typically require a bipolar system to be built in different phases. One pole is often built before the other and operated as a monopolar system to achieve benefits at an early stage. The ± 500 kV Geshang DC project and Tianguang DC project in China were both constructed in this way.

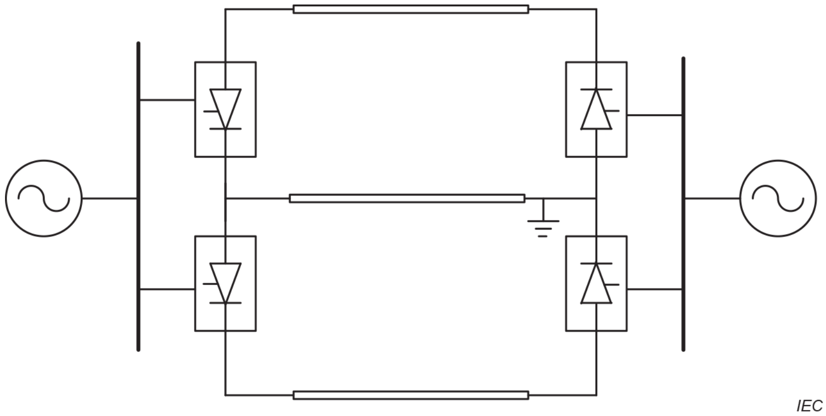


Figure A.6 – Schematic diagram of bipolar dedicated metallic return system

A.2.4 Symmetric unbalanced system

A balanced bipolar system consists of two completely identical monopolar systems, which are typically built and put into operation in stages, which means the second monopolar system is built and put into operation shortly after the first one is put into service. If this is not the case and the second monopolar system is built at a late stage according to planning, advancement of relevant technologies in the transition period can lead to different transmission power and voltage rating between these two systems. For instance, the Konti-Skan DC system consists of two monopolar systems with different transmission powers, which share a pair of reversible converter stations. The Skagerrak DC system was planned to be a balanced bipolar system at the beginning, but later a 3rd monopolar system was added to this project. The power transmission direction of the third monopolar system is opposite to that of the bipolar system built at an early stage. And a 4th (VSC) pole had just been added to the Skagerrak project in 2014.

A.2.5 Back-to-back converter station

Back-to-back converter station is a DC system without DC power transmission lines and with both rectifier and inverter converter stations in the same switchyard. “Back–to-back” converter stations are now widely used with the main purpose of limiting increase of short-circuit current during the interconnection of electric grids, improving the reliability of grid under operation, and serving as a frequency conversion station during the interconnection of grids with different frequencies. Back–to-back converter stations do not require earth electrodes.

A.3 Dangerous impact and accumulated impact

A.3.1 General

The safety risks of DC grounding systems mainly involve electric shock due to touch voltage, transferred voltage and step voltage, among which electric shock due to step voltage should receive more attention.

A.3.2 Safety risks of DC earth electrode

A.3.2.1 General

The concept of touch voltage, transferred voltage and step voltage are shown in Figure A.7.

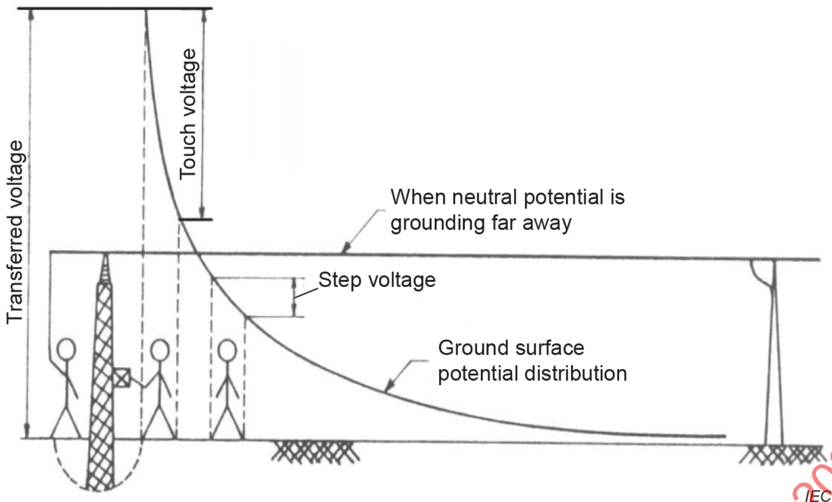


Figure A.7 – Schematic diagram of touch voltage and step voltage

A.3.2.2 Step voltage limit

The step voltage limit is an important basis for the design of earth electrodes. When the step voltage caused by earth electrode current in the ground exceeds a certain value, it may cause annoyance to people or animal around the electrode. On the other hand, too low a value for step voltage will increase the total cost of the system. Hence the selection of a reasonable step voltage in the neighbourhood of the earth electrodes is significant for ensuring personal safety and lowering system costs.

What really poses safety hazards to people is the current flowing through the human body. Hence the step voltage limit depends on physical conditions and the footsteps of people. Impact of step voltage is more significant at lower sensing current, lower human body resistance, lower contact resistance between the human body and the soil, and longer footstep. A low step voltage limit should be defined to ensure personal safety.

The step voltage limit for the human body is calculated with:

$$U = I_g(R + 2R_s) \quad \text{(A.1)}$$

where

U is the step voltage limit (V),

I_g is the minimum current (A) sensed by a human body,

R is the human body resistance (Ω), and

R_s is the contact resistance (Ω) between one foot and the soil.

According to tests conducted on 1 028 subjects, over 95 % of the subjects have a foot to foot human body resistance greater than 1 400 Ω (see Annex C), which is slightly different from the hand to hand human body resistance given by IEC 60479-1, and over 95 % of the subjects do not feel anything at a DC current of 5,3 mA. Based on these test results and considering the different amplitudes and durations of DC system earthing currents, the maximum allowed step voltage of any point on the ground can be determined with Formula (2) under maximum short-time overload current of one pole.

Designing earth electrodes based on step voltage limits can ensure the safety of people walking near earth electrodes. For earth electrodes failing to meet the step voltage limit, an isolation wall should be erected in corresponding areas to prevent people from entering these areas and being exposed to electric shock.

A.3.2.3 Typical distribution of DC earth electrode step voltage

Present-day DC earth electrodes are often closed loops, the circular configuration being the best option.

a) Typical single circular DC earth electrode

A single circular DC earth electrode structure is shown in Figure A.8, and distribution of step voltage is shown in Figure A.9 and Figure A.10.

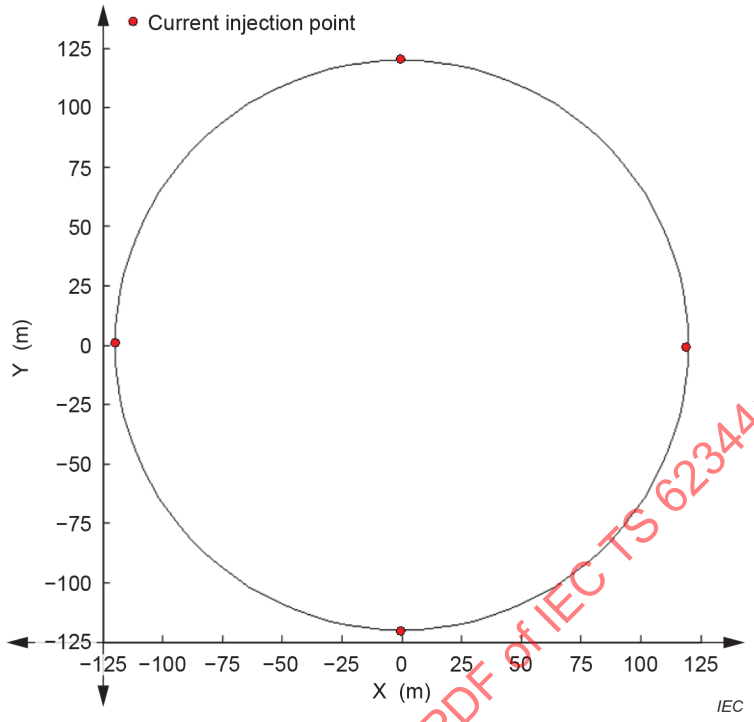


Figure A.8 – Schematic diagram of single circular earth electrode

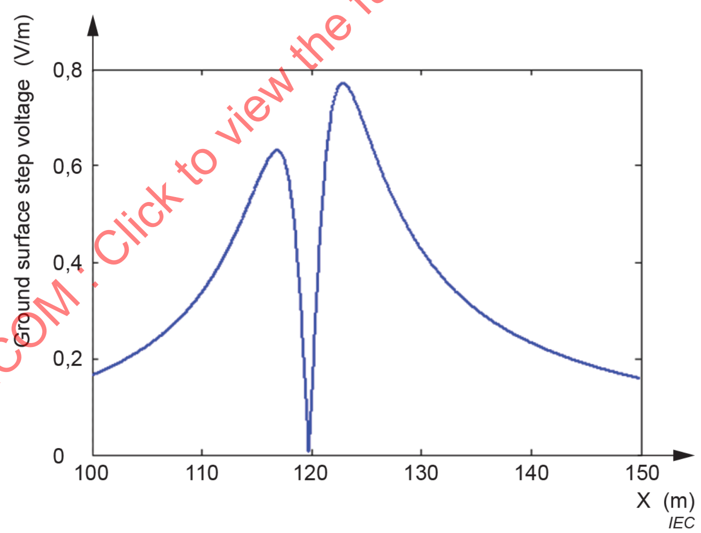


Figure A.9 – Axial distribution of step voltage of single circular earth electrode

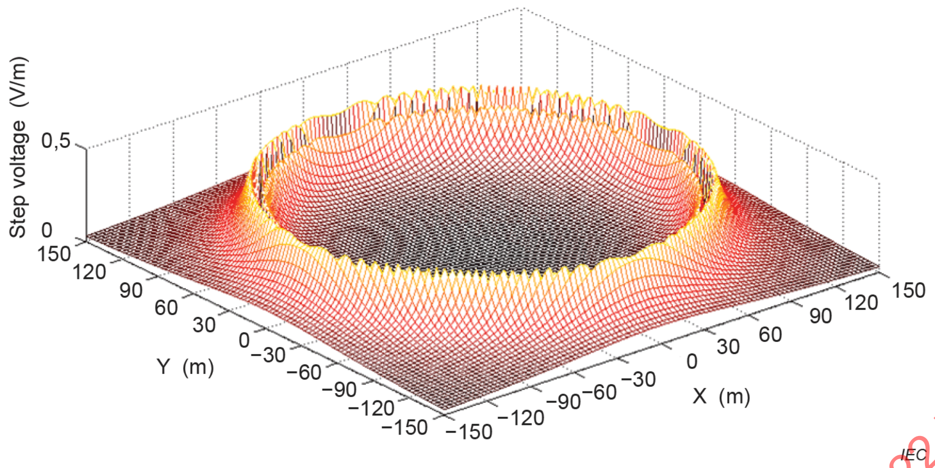


Figure A.10 – 3-D distribution of step voltage of single circular earth electrode

b) Typical double circular DC earth electrode

A double circular DC earth electrode structure is shown in Figure A.11, and distribution of step voltage is shown in Figure A.12 and Figure A.13.

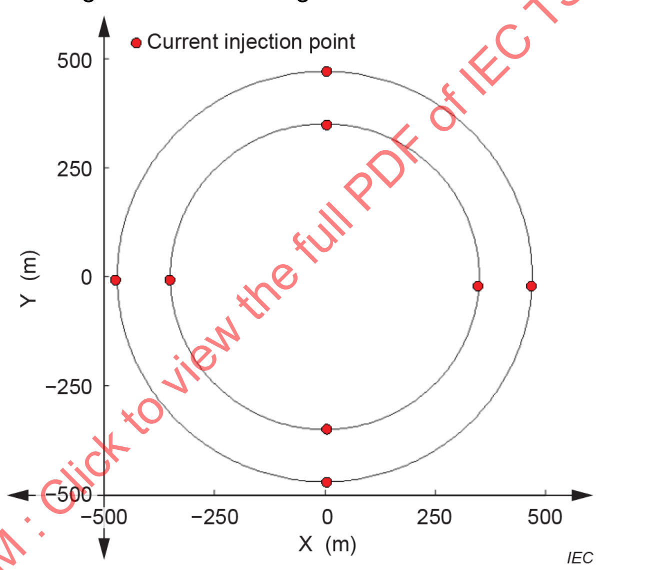


Figure A.11 – Schematic diagram of double circular earth electrode

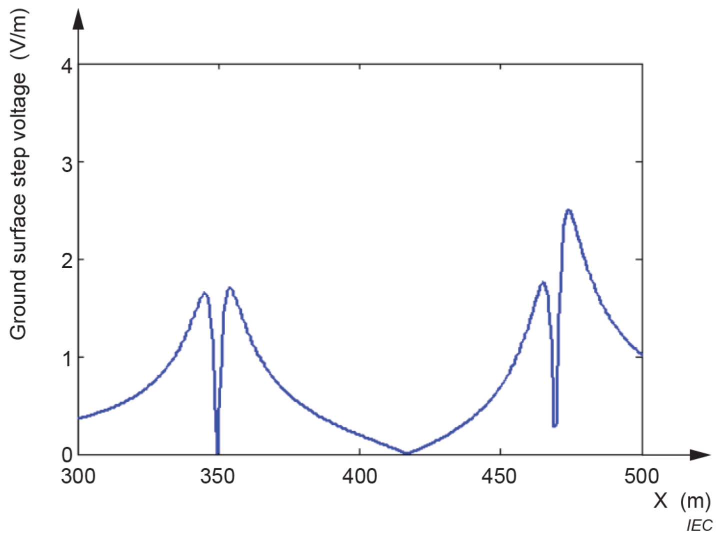


Figure A.12 – Axial distribution of step voltage of double circular earth electrode

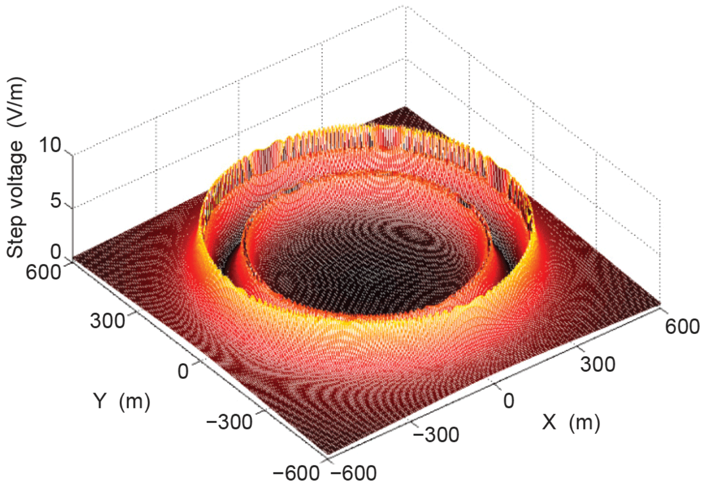


Figure A.13 – 3-D distribution of step voltage of double circular earth electrode

c) Typical triple circular DC earth electrode

A triple circular DC earth electrode structure is shown in Figure A.14, and distribution of step voltage is shown in Figure A.15 and Figure A.16.

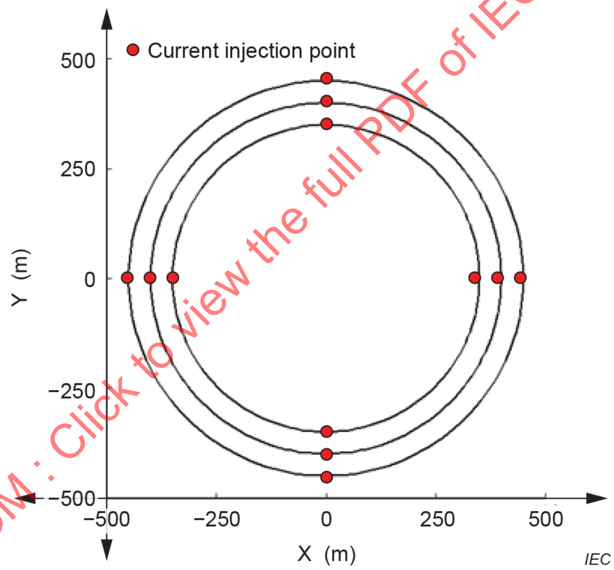


Figure A.14 – Schematic diagram of triple circular earth electrode

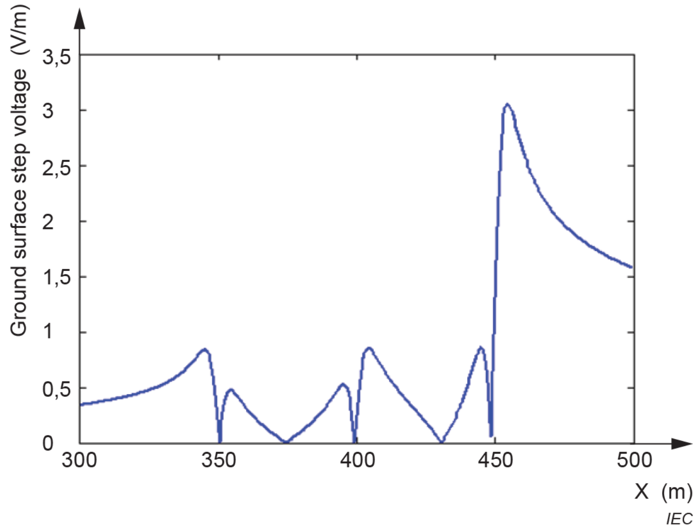


Figure A.15 – Axial distribution of step voltage of triple circular earth electrode

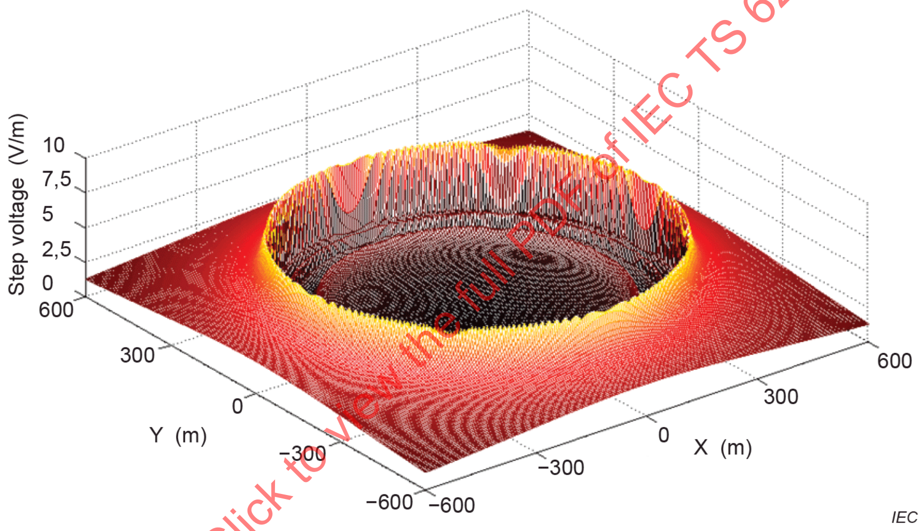


Figure A.16 – 3-D distribution of step voltage of triple circular earth electrode

A.3.3 Accumulated effect of DC earth electrodes

The accumulated effect of earth electrodes mainly involves electrochemical corrosion of metal conductors due to DC current. During system operation, the earth serves as a giant electrolyte tank, and the DC earth electrodes of the converter station at the two ends serve as two electrodes in this electrolyte tank. The process of electrolysis and dissipation continues at the anode according to Faraday's laws of electrolysis, leading to electrochemical corrosion of the DC earth electrodes themselves. As the time elapses, the total ampere hours of the earth electrodes in operation continue to increase, causing more serious corrosion of the buried metal conductors. The corrosion of earth electrodes therefore has a typical accumulated effect over time.

One important aspect of well-designed earth electrodes is the ability to ensure safe operation of electrodes throughout the designed service life, despite the corrosion during operation of these electrodes. On the other hand, investment in earth electrode construction should be minimized.

For DC earth electrodes, the issue of electrolysis corrosion remains a major challenge as a high current, of the order of kA, is likely to flow through them for a long time. When a DC power transmission system is operated using earth as the return circuit, the current will flow from the anode electrode to the ground and, at the other end of the DC line a corresponding current will flow back from the ground to the cathode. The current flow on the ground is mostly made possible by the weak electrolyte formed by the ground waters.

Low-carbon steel (iron) is now a commonly used anode material as it is widely available and low in price. The electrolysis corrosion process is explained below by using an iron anode as an example.

Chemical Formulas near the anode:

$$\mathrm{Fe} \rightarrow \mathrm{Fe}^{2+} + 2\mathrm{e}^{-} \quad \text{(A.2)}$$

$$\mathrm{Fe}^{2+} + 2\mathrm{OH}^{-} \rightarrow \mathrm{Fe(OH)}_2 \quad \text{(A.3)}$$

$$4\mathrm{Fe(OH)}_2 + 2\mathrm{H}_2\mathrm{O} + \mathrm{O}_2 \rightarrow 4\mathrm{Fe(OH)}_3 \quad \text{(A.4)}$$

Fe^{2+} ions generated during electrolysis will enter the electrolyte from the anode to react with OH^{-} ions there, generating ferrous hydroxide, $Fe(OH)_2$. Ferric hydroxide, $Fe(OH)_3$, is the product of further oxidation (a reddish-brown unconsolidated material). This process will continue to consume anode metal. Consumption of metal anode during electrolysis can be calculated below based on Faraday's laws:

$$m = \frac{A_\mathrm{m}}{KF} It \quad \text{(A.5)}$$

where

m is the consumption of metal material (g);

A_m is the molar mass of the metal (g/mol);

K is the metal valency, dimensionless;

F is Faraday's electrolytic constant, 9,648 53 × 10^4 C/mol;

I is the current flowing through the metal (A);

t is the current flowing time (s).

As the molar mass and valency of iron are 55,86 g/mol and 2 respectively (ferrous ions with valence 2 are generated during electrolysis), for each ampere of current flowing through the iron anode, the annual consumption of the anode can be calculated as follows:

$$m = \frac{55{,}86}{2 \times 9{,}648\,53 \times 10^4} \times 1 \times 365 \times 24 \times 60 \times 60 = 9\,128{,}86 \quad [\mathrm{g}] \quad \text{(A.6)}$$

In case of bipolar connection, suppose the rated current of each pole is 1 kA, the unbalanced current in normal conditions is 30 A, and the monopolar operation rate is 1 %, then the annual consumption of the iron anode can be as high as:

$$m = 9\,128{,}86 \times (30 \times 0{,}99 + 1\,000 \times 0{,}01) = 3{,}62 \times 10^5 \quad [\mathrm{g}] \quad = 362 \quad [\mathrm{kg}] \quad \text{(A.7)}$$

The anode material is significantly corroded due to electrolysis. If the earth electrode has a designed life of 30 years, which means 40 % of earth electrodes can be consumed after 30 years, earth electrodes will require 27,15 tons of steel.

Corrosion of the earth electrodes is an issue that cannot be overlooked during design of earth electrodes. The solutions are typically selected from the perspectives of anode material selection, structure and shape optimization.

A.4 Impact on an AC grid

A.4.1 General

In general by far the most difficult problems that may arise in the performance of ground return mode of operation, concerns the influence on AC power systems. Such problems would likely be due to the resistivity profile of the ground over vast areas around the electrode and the relative location of infrastructures like AC substations and the configuration of electrical power systems.

The necessary and effective protection for ground DC bias of transformers is to locate the electrode station at a certain distance from any vulnerable substation, including the converter station.

A.4.2 DC current path to AC system

A.4.2.1 General

The basic cause of effects of HVDC transmission in ground return mode on to the AC system is due to potentials at the soil surface caused by the return of DC current through the ground. The main paths that DC current follows into AC system include the shielding wire(s) and the grounded star point of AC transformer(s).

A.4.2.2 Shielding wire

When the electrode operates as an anode type, the shielding wires of the towers close to the electrode will pick up part of the electrode current and discharge it to the towers at the distal end. On the contrary, if the electrode operates as a cathode type, the towers at the distal end will absorb current from the surrounding soil and discharge it to the towers close to the electrode. Under these circumstances, it may result in risk of corrosion to the grounding devices of the towers discharging current.

A.4.2.3 Grounded star point of AC transformer

Due to the soil surface potential gradient, DC current enters the grounded star point of AC transformer A, follows the high-voltage phases to transformer B and leaves through the star point connection and ground grid of substation B. The transformers most affected by DC current will be in the vicinity of either electrode stations as the ground potential gradient is steep only in the vicinity of electrode stations.

A.4.3 DC magnetic bias of AC transformer

A.4.3.1 General

The DC component through the transformer windings provokes a constant magnetising of the core, which, superimposed on the symmetrical AC magnetising, lets the flux vary in an unbalanced way, which in one flux direction may lead to saturation of the core. Both YY and YD type of transformers will have flux offset by the ground potential rise. As the transformer operates in the nonlinear portion of its magnetizing curve, the magnetizing current will consist of a series of harmonic currents. The wave form of the current is distorted mainly due to a rise in the content of the second harmonics. Generally there will also be a rise of several other positive, negative and zero sequence harmonics, particularly 3rd harmonic current.

The vulnerability to DC magnetizing varies for different core types. Monophase transformers with magnetic return equal in area to the wound leg are strongly affected. Three-phase, five-legged transformers also react to some degree. Three-phase, three-legged transformers will withstand a high level of DC current excitation.

A.4.3.2 Three-phase, three-legged transformer

The tank of the three-legged transformer, for zero sequence flux, acts like a single turn secondary winding and large currents may be induced in the tank causing vibration and overheating.

A.4.3.3 Three-phase, five-legged transformer

In three-phase, five-legged transformers, the return legs carrying more DC flux are more likely to saturate than the phase legs. Once the outer legs are saturated, the transformer for further excitation acts almost like a three-legged transformer.

A.4.3.4 Reactor

Reactors with magnetic cores, for compensation purposes, are not at all exposed to DC saturation. This statement is valid regardless if the reactors are monophase or three-phase, with three- or five-legged cores.

A.4.3.5 Saturation time constant

The rise of the harmonics in the transformers with saturation depends on the time constant of the circuit through which the DC current would circulate. Generally, this time constant is of several seconds and full harmonic current peaks due to saturation are not reached until almost a minute after the rise of ground potential. Within this time it is generally possible to transfer the system to metallic return configuration.

A.4.3.6 Saturation analysis

When analysing the possibility of saturation, the grid composition is usually much more complicated. A detailed resistance network containing the different stations, the mutual interconnection between stations and the resistance in transformers should be set up, and the flow in the different branches calculated.

Generally speaking, the problem of saturation is not very serious for most of small grid transformers (<200 MVA), as they are normally three-phase, three-legged. Attention will be drawn to large single phase units and to large three-phase units, which are often five-legged to reduce height in order to facilitate transportation.

Annex B
(informative)

Earth electrode design process

B.1 Site selection process

Site selection of earth electrode starts with a desktop study and then is followed by geographic survey and data acquisition, electrode pre-design, preliminary interference studies, and preparation of site selection reports.

The flow chart of earth electrode site selection process is shown in Figure B.1.

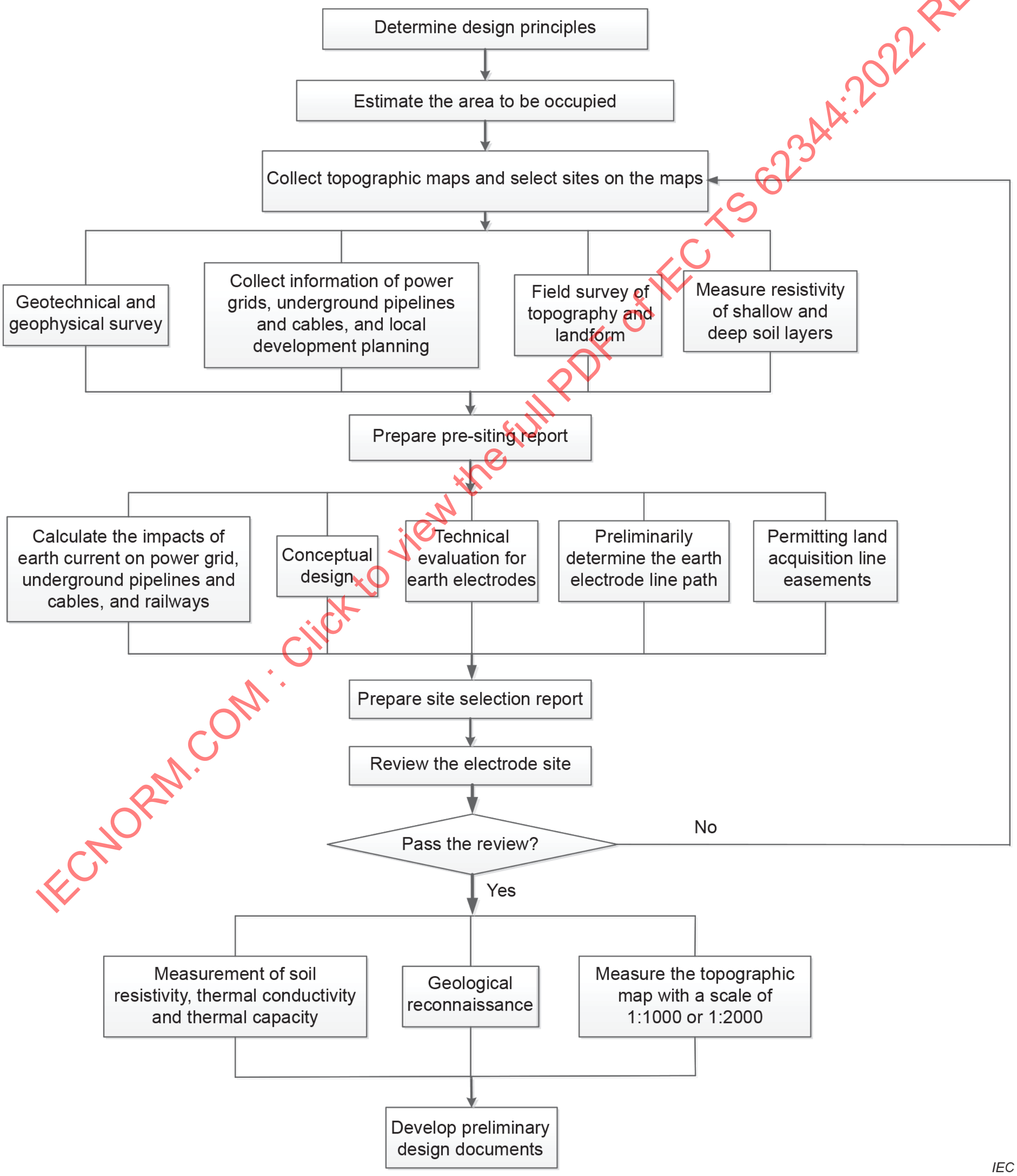


Figure B.1 – Flow chart of earth electrode site selection process

B.2 Earth electrode design process

a) Specify the system conditions for design of earth electrode, with the definition of the current versus time for each operational condition – continuous unbalance current, monopolar current during annual maintenance of one pole at maximum current, overload current, and rated current of earth electrode, plus any assumed long time operation in monopolar operation to determine the service life of earth electrode elements;

b) Developed a desktop survey, which will consider the relevant aspects for the selection of the candidate sites to be surveyed (geography, geology and so on). After the selection of the candidate sites, they should be inspected and surveyed. The owners of the lands should be previously contacted because it they do not agree to allow for the surveys in their lands the site should be discarded;

c) Conduct geotechnical and geophysical surveys at the selected sites that are being considered as candidate sites for the electrode, followed by the construction of the geoelectric models of the soil each site, to be used for the preliminary electrode design;

d) Determine the type of earth electrode based on electrode site conditions, site constraints, areas, soil resistivity model, thermal parameters (thermal conductivity and capacity), and other parameters;

e) Determine the material of earth electrode considering factors such as the magnitude of earth current of earth electrode, service life of earth electrode, and corrosiveness of groundwater, as well as engineering application and costs of various materials;

f) Determine the major design parameters of earth electrode. The dimensional parameters, such as the electrode size, burial depth and cross-sectional area of coke, should be determined based on the available area of the electrode site and comprehensively considering technical parameters such as the electrode resistance, step voltage, current density, and ground temperature rise. The impact of construction difficulty and project cost should also be taken into consideration;

g) Design of the current-guiding system of earth electrode. In design of the current-guiding system of earth electrode, the electrode should be sectionalized if the owner has specified that operation shall be possible with outage of a given portion of the electrode in case of maintenance. It should be designed based on the calculation results of the electrode current and potential distribution; the cross-sectional area of current-guiding cables should be determined based on the magnitude of current in each section of electrode;

h) Design of auxiliary facilities. Seepage wells and monitoring wells can be designed for earth electrode, and online monitoring system can also be provided if specified by the owner.

The flow chart of earth electrode design process is shown in Figure B.2.

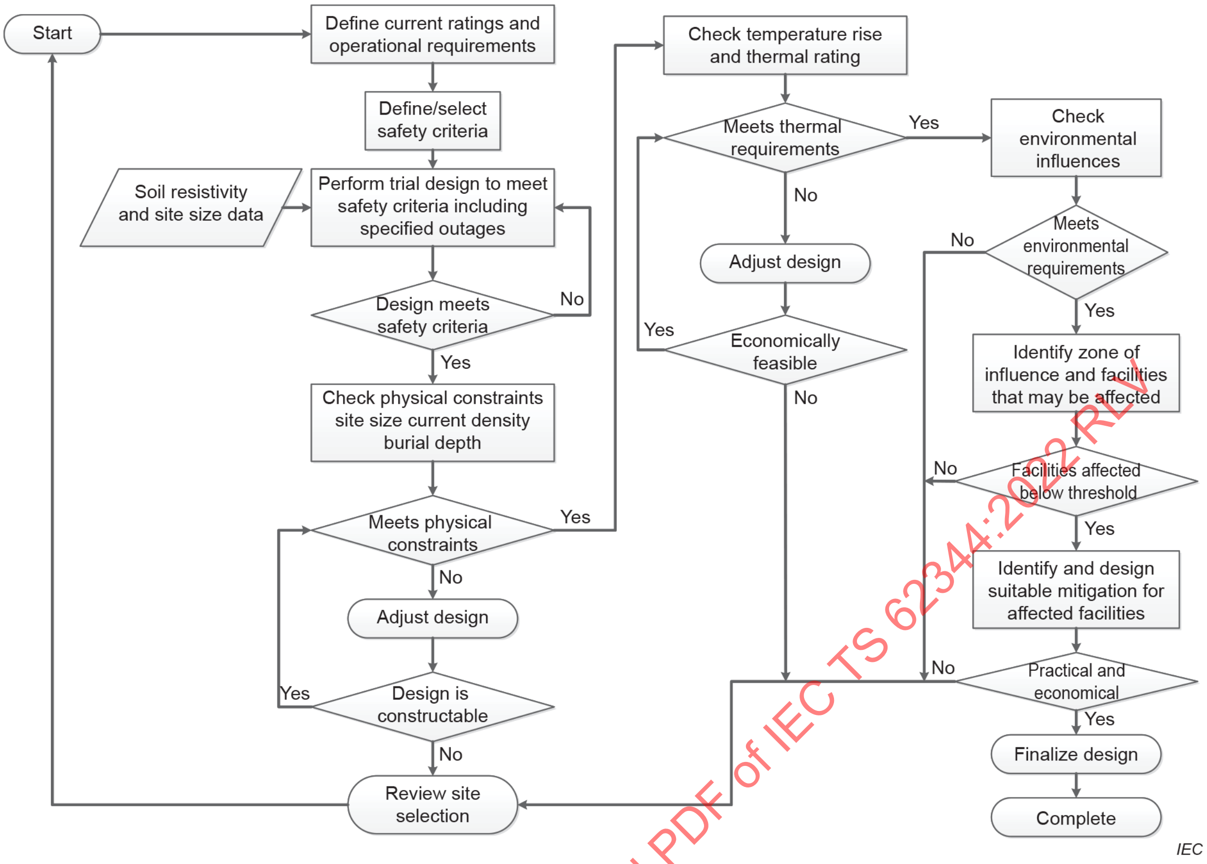


Figure B.2 – Flow chart of earth electrode process

Annex C
(informative)

Test results of human body resistance

C.1 Basic information of test subjects

A total of 1 028 test subjects including 589 farmers, 278 college students and 161 scientific workers are selected to test the human body resistance. Among them, there are 631 males and 397 females, presenting a ratio of about 1,59:1. The test subjects are 12~75 years old, 140 cm~186 cm in height and 27 kg~95 kg in weight. All the test subjects were healthy, and their heart rate was stable and normal when participating in the test.

The age, height and weight distribution of the test samples are shown in Figure C.1, Figure C.2 and Figure C.3 respectively. For all samples, the average height of males was 170,01 cm, with an average weight of 63,50 kg, and the average height of females was 157,98 cm, with an average weight of 55,31 kg.

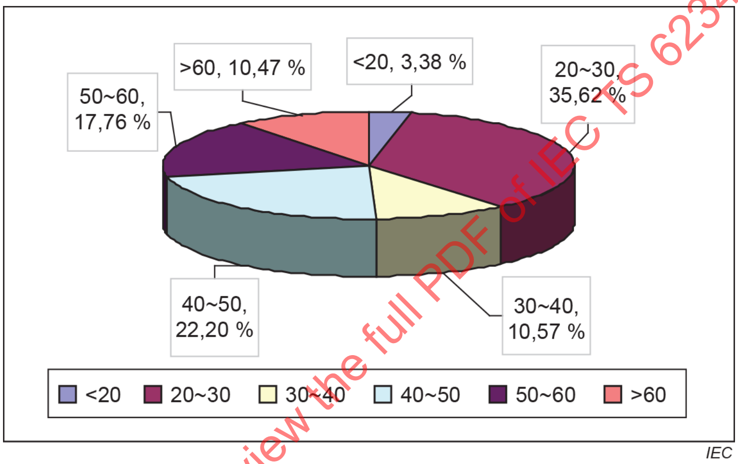


Figure C.1 – Age distribution of test samples

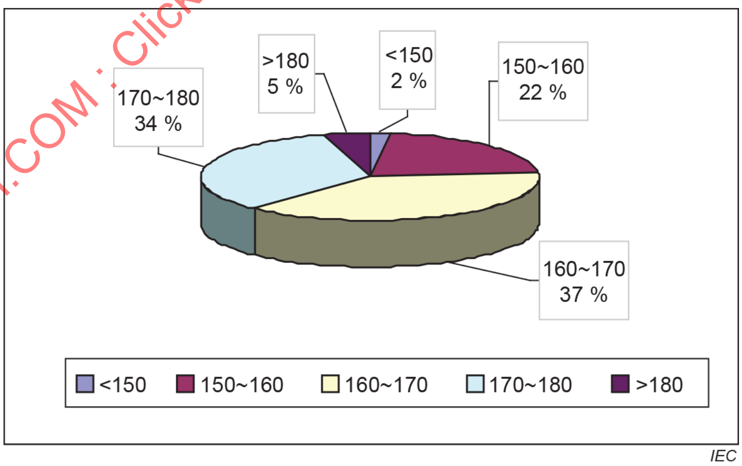


Figure C.2 – Height distribution of test samples

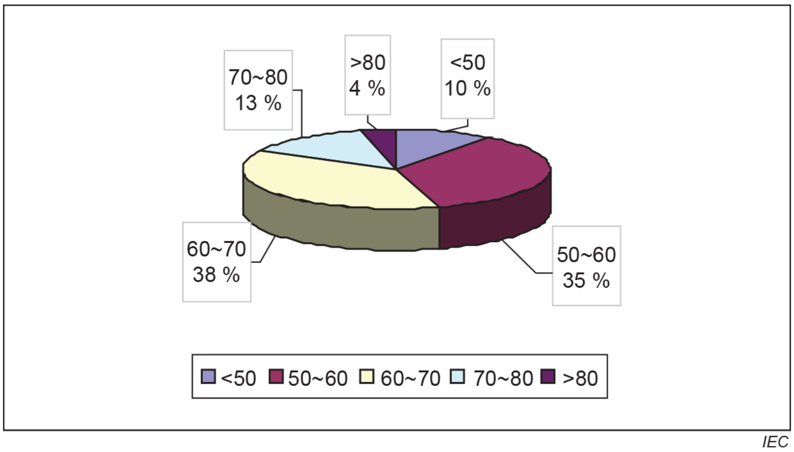


Figure C.3 – Weight distribution of test samples

C.2 Test method

The human body resistance is measured by using the ammeter and the voltmeter. Use an adjustable DC power supply to apply voltage to two copper plates immersed in 10 % salt water (with a resistivity of 1,53 Ω·m) in a test tank and let the test subject stand barefoot on these two copper plates. The depth of salt water is about 3 mm~5 mm such that the copper plates is just immersed into the water and the soles of the test subject are in full contact with the salt water. This will minimize the impact of the contact resistance between the two feet of the human body and the surface of the copper plates on the measurement. Under this condition, use an ammeter to measure the current flowing through the human body, and use a voltmeter to measure the voltage between the two copper plates, then calculate the human body resistance by Ohm's law. The pulse and blood pressure of the test subjects are monitored throughout the whole test process.

The schematic diagram of the test circuit is shown in Figure C.4.

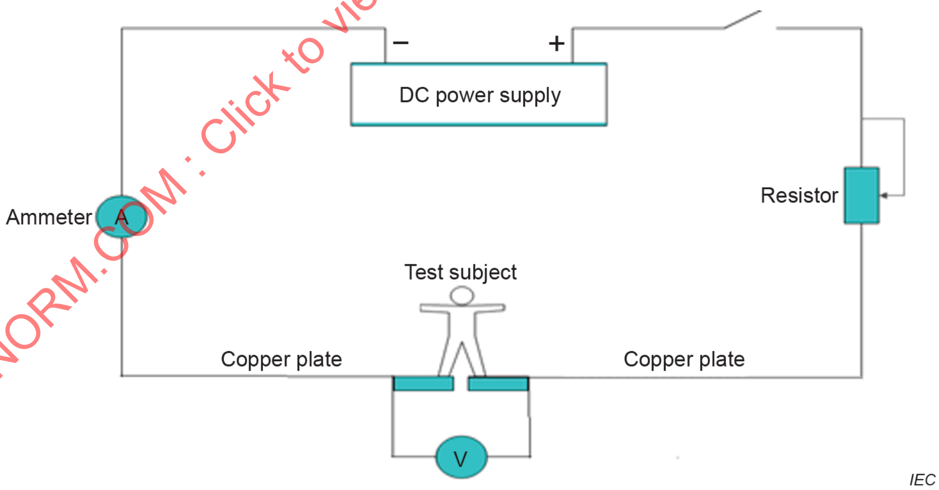


Figure C.4 – Schematic diagram of test circuit

C.3 Test results

The foot-to-foot human body resistance is recorded under the perception current (when the sample subject starts to have sensation). The statistical information of test subjects and test results are given in Table C.1.

A total of 945 sets of valid data were obtained from 243 students (25,7 %), 156 scientific workers (16,5 %) and 546 farmers (57,8 %). The statistics show that the average foot-to-foot body resistance is 2 550 Ω. Specifically, the distribution of human body resistance is: 1 000 Ω ~1 100 Ω accounted for 0,42 %, 1 100 Ω ~1 200 Ω accounted for 0,85 %, 1 200 Ω ~1 300 Ω accounted for 1,06 %, 1 300 Ω ~1 500 Ω accounted for 4,66 %, and larger than 1 500 Ω accounted for 93,01 %.

Table C.1 – Statistical test results (foot-to-foot body resistance)

Place of test	No. of subjects			Foot-to-foot human body resistance Ω		
	Total	**Male**	**Female**	**Minimum**	**Maximum**	**Average**
College A	58	52	1	1 181	4 900	2 360
College B(1)	98	82	16	1 355	6 366	2 707
College B(2)	53	51	2	1 422	5 121	2 680
College C	39	28	11	1 567	5 131	2 992
Village A	39	14	25	1 530	5 668	3 140
Village B(1)	132	59	73	1 133	6 497	2 549
Village B(2)	74	33	41	1 140	4 412	2 416
Town C	57	42	15	1 047	6 114	2 878
Town D	19	18	1	1 100	5 116	2 789
Town E	24	20	4	1 433	3 681	2 280
Village F	69	12	57	1 236	4 096	2 470
Town G	58	36	22	1 416	4 012	2 366
Previous data	225	150	75	1 021	8 477	2 370
Total	**945**	**597**	**348**	**1 021**	**8 477**	**2 550**

Figure C.5 shows the histogram of foot-to-foot human body resistance distribution by occupation, and Figure C.6 shows the cumulative probability distribution curve of foot-to-foot body resistance by occupation. The statistical results show that among the test subjects, the measured foot-to-foot body resistance from farmers is a bit larger than that obtained from other occupations.

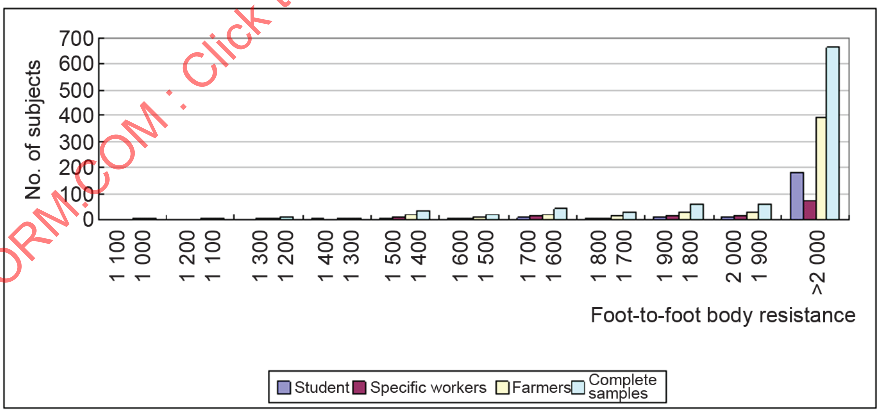


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Figure C.5 – Histogram of foot-to-foot human body resistance distribution