PD IEC TS 62344:2022

BSI Standards Publication

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

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Full document details: PD IEC TS 62344:2022

National foreword

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The UK participation in its preparation was entrusted to Technical Committee PEL/22, Power electronics.

A list of organizations represented on this committee can be obtained on request to its committee manager.

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Published by BSI Standards Limited 2023

ISBN 978 0 580 51635 1

ICS 29.240.99

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This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 January 2023.

Amendments/corrigenda issued since publication

Date	Text affected

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Full document details: PD IEC TS 62344:2022

IEC TS 62344

Edition 2.0 2022-05

TECHNICAL SPECIFICATION

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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.240.99

ISBN 978-2-8322-1035-2

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

FOREWORD

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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.

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– 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 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.

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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.

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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

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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.

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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.

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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

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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.

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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

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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.

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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:

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- 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.

- 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.

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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.

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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.

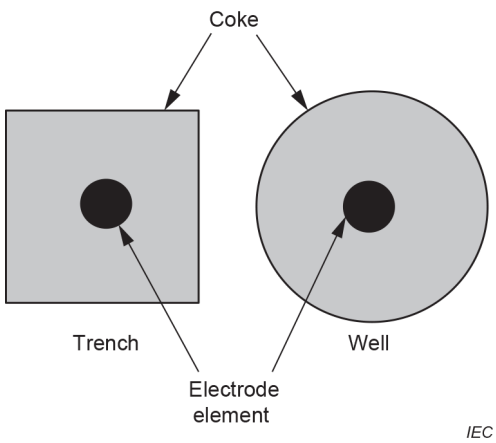

Figure 1 – Electrode cross-section

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;

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– 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.

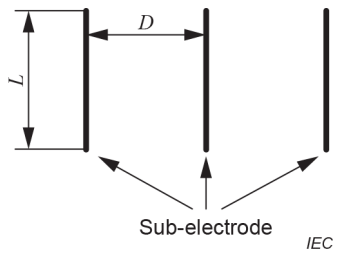

Figure 2 – Vertical arrangement

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-

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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.

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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).

$$\Phi_p \geq \sqrt{\frac{4k_1k_2\rho_p\tau_p FV_{\mathrm{f}} + \pi\phi^2\rho_m g I_{\mathrm{d}} \times 10^{-3}}{\pi\rho_m g I_{\mathrm{d}} \times 10^{-3}}} \tag{10}$$

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

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.

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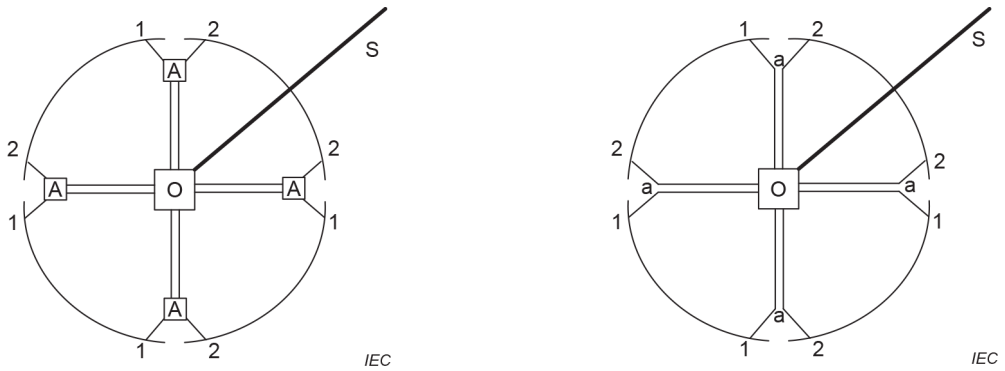
In general, for symmetrically arranged earth electrodes, the current-guiding wire should also be arranged symmetrically, e.g. Figure 3a) or Figure 3b).



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

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