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TECHNICAL SPECIFICATION

colour inside

UHV AC transmission systems – Part 201: UHV AC substation design

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FOREWORD

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- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC TS 63042-201, which is a technical specification, has been prepared by IEC technical committee 122: UHV AC transmission systems.

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

Enquiry draft	Report on voting
122/64/DTS	122/71A/RVDTS

Full information on the voting for the approval of this technical specification can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 63042 series, published under the general title *UHV AC transmission systems*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://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- withdrawn,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.

A bilingual version of this publication may be issued at a later date.

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UHV AC TRANSMISSION SYSTEMS –

Part 201: UHV AC substation design

1 Scope

This part of 63042, which is a Technical Specification, provides common rules for the design of substations with the highest voltages of AC transmission systems exceeding 800 kV, so as to provide safety and proper functioning for the intended use.

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 60038:2009, *IEC standard voltages*

IEC 60044 (all parts), *Instrument transformers*

IEC 60059:1999, *IEC standard current ratings*
IEC 60059:1999/AMD1:2009

IEC 60071-1:2006, *Insulation co-ordination – Part 1: Definitions, principles and rules*
IEC 60071-1:2006/AMD1:2010

IEC 60071-2, *Insulation co-ordination – Part 2: Application guide*

IEC 60076 (all parts), *Power transformers*

IEC 60068-3-3, *Environmental testing – Part 3: Guidance – Seismic test methods for equipments*

IEC 60137, *Insulated bushings for alternating voltages above 1000 V*

IEC 60168, Tests on indoor and outdoor post insulators of ceramic material or glass for systems with nominal voltages greater than 1000 V

IEC 60196:2009, IEC standard frequencies

IEC 60255-26, *Measuring relays and protection equipment – Part 26: Electromagnetic compatibility requirements*

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

IEC 60721-2-4, *Classification of environmental conditions – Part 2-4: Environmental conditions appearing in nature – Solar radiation and temperature*

IEC TS 60815 (all parts), *Selection and dimensioning of high-voltage insulators intended for use in polluted conditions*

IEC 60865 (all parts), *Short-circuit currents*

IEC 60871 (all parts), *Shunt capacitors for a.c. power systems having a rated voltage above 1 000 V*

IEC 60909 (all parts), *Short-circuit currents in three-phase a.c. systems*

IEC TS 61463, *Bushings – Seismic qualification*

IEC 61850 (all parts), *Communication networks and systems for power utility automation*

IEC 61936-1:2010, *Power installations exceeding 1 kV a.c. – Part 1: Common rules*
IEC 61936-1:2010/AMD1:2014

IEC 62231, *Composite station post insulators for substations with AC voltages greater than 1 000 V up to 245 kV – Definitions, test methods and acceptance criteria*

IEC 62271-100, *High-voltage switchgear and controlgear – Part 100: Alternating current circuit-breakers*

IEC 62271-102, *High-voltage switchgear and controlgear – Part 102: Alternating current disconnectors and earthing switches*

IEC 62271-207, *High-voltage switchgear and controlgear – Part 207: Seismic qualification for gas-insulated switchgear assemblies for rated voltages above 52 kV*

IEC TR 62271-300, *High-voltage switchgear and controlgear – Part 300: Seismic qualification of alternating current circuit-breakers*

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
UHV AC
highest voltage of AC transmission system exceeding 800 kV

Note 1 to entry: UHV stands for "ultra high voltage".

3.2
high-voltage side of transformer
highest voltage among two or three voltages on each side of the main transformer

3.3
intermedium voltage side of transformer
second highest voltage among three voltages on each side of the main transformer

3.4
low-voltage side of transformer
lowest voltage among two or three voltages in the apparatus or installation

Note 1 to entry: In this document, the definition is modified as the lowest voltage among two or more voltages on each side of main transformer.

4 UHV AC substation requirement

4.1 General requirement

The UHV AC substation should withstand the electrical, mechanical, climatic and environmental influences anticipated on site.

In the design of the UHV AC substation, several factors should be taken into account: system demands, operation and maintenance requirements, construction requirements, site condition, environmental impact and economy.

To meet the requirements above, the design should also be performed in consideration of the following characteristics of the UHV AC substation:

- high importance of the UHV AC substation;
- high transmission capacity;
- high overvoltage;
- high secondary arc current;
- high electric and magnetic field strength;
- large dimension and weight of the UHV AC equipment;
- large dimension of the UHV AC substation.

A typical design of a UHV AC substation is shown in Figure 1.

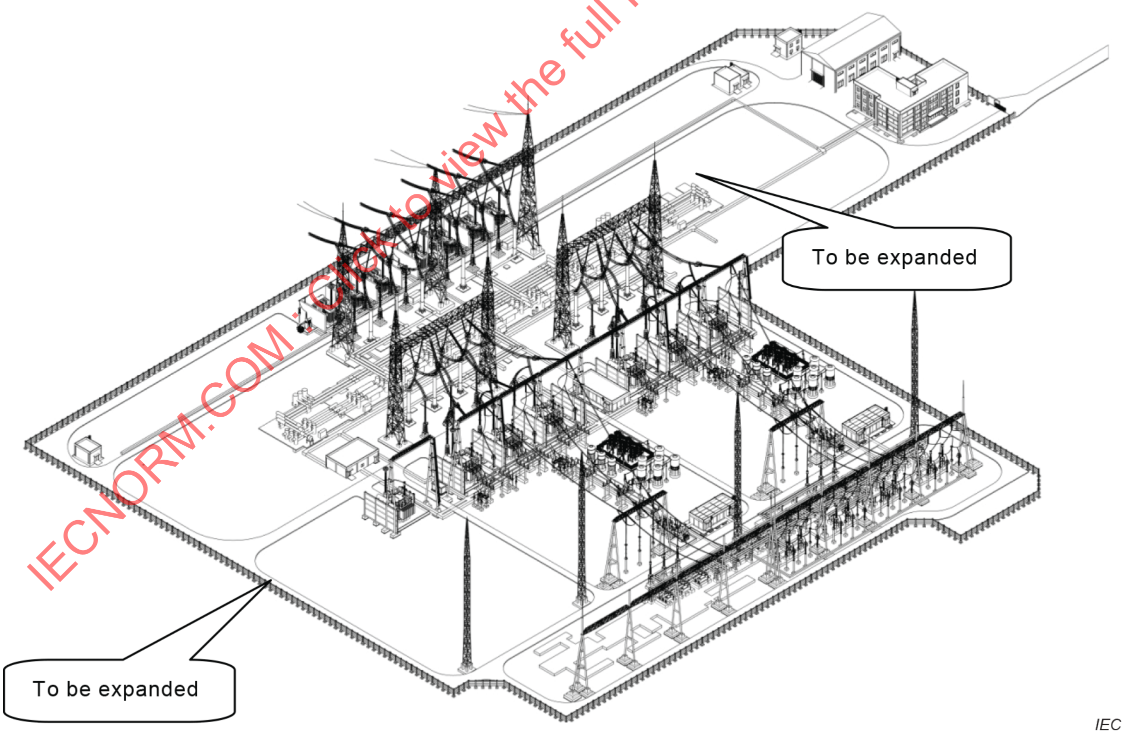


Figure 1 – Bird's-eye view of a typical UHV AC substation

4.2 System demands

The design of the UHV AC substation should meet the AC transmission system demands, including the following items:

a) reliability: the bus scheme and feeder connection, equipment and control protection system of the UHV AC substation should be adopted to meet the requirements of reliability, considering the importance of the UHV AC substation in the AC transmission systems.

b) availability: the selection of the bus scheme and feeder connection, the type and parameters of equipment, equipment layout, control protection and communication system should meet the demands of AC transmission system scale and parameters in the steady-state and transient-state and the possibility of extension (if required). Especially, the demands of the AC transmission system access should be taken into consideration in the design of equipment layout.

c) flexibility: the convenience of switching feeders such as a bank of transformers or a transmission line, switching devices such as circuit breakers, busbars and their relay protection devices in case of maintenance, and the transition from the initial bus scheme and feeder connection to the final bus scheme and feeder connection, should be taken into consideration in the design of bus scheme and feeder connection as well as equipment layout.

4.3 Operation and maintenance requirements

The UHV AC substation with high applied voltage and large dimension plays a significant role in AC transmission systems, which makes the operation and maintenance of these substations very severe. The design of the UHV AC substation should meet the requirements of operation and maintenance, including the following items:

a) The type of bus scheme and feeder connection and equipment should meet the requirements of operation and maintenance as much as possible on premise of meeting the system demands.

b) The design of the UHV AC substation should limit the safety distance and electric field strength to a permissible value in order to ensure the operator safety and to meet the requirements of a daily operation and maintenance, even though the applied voltage of the UHV AC substation is high.

c) The design of the earthing system should meet the requirements of a daily operation and maintenance. Especially, the step potential and touch potential of the earthing system should be limited to permissible value.

d) Control, protection and communication system should meet the requirements of the system architecture and operation mode of AC transmission systems.

4.4 Construction requirements

Large and heavy equipment complicates the construction of the UHV AC substation. The design of the UHV AC substation should meet the requirements of construction, including the following items:

a) The equipment layout and the distance between equipment should meet the requirements of transportation, lifting and installation of the equipment.

b) When selecting the UHV conductors, the effort involved in the structural design shall be taken into account, too, besides the electrical properties such as current-carrying capacity, thermal stability, corona effect, etc.

c) The transportation condition should meet the requirements for large equipment transport.

d) The construction measures should be adopted to meet the requirements of the UHV AC equipment's foundation. Structure construction should be used in order to avoid the temperature cracks generated by the hydration heat impact in mass concrete construction.

4.5 Site condition

The design of the UHV AC substation should meet the requirements of the site condition, including the following items:

a) Hydrological and geological condition. The UHV AC substation should be located in a stable geological region, and the hydrological and geological influence should be considered.

b) Meteorological condition. The type, parameters, and configuration of the UHV AC equipment and conductor should adapt to the meteorological condition such as temperature, humidity, atmospheric pressure, wind velocity, etc.

c) Seismic conditions. The UHV AC substation should avoid being located in a seismically unfavourable site, and electrical facilities should meet the anti-seismic requirements.

d) Altitude. The safety distance, current-carrying capacity of the conductor, and external insulation of the equipment should be corrected according to the altitude on site.

4.6 Environmental impact

The design of the UHV AC substation should reduce the environmental impact, including the following items:

a) Audible noise. The type, parameters, and configuration of the UHV AC equipment and conductor should limit the audible noise strength on the substation boundary that is specified by local regulations to a permissible value.

b) Electric and magnetic field. The type, parameters, and configuration of the UHV AC equipment and conductor should limit the electric and magnetic field strength to a permissible value.

c) Radio Interference. The type, parameters, and configuration of the UHV AC equipment and conductor should limit the radio interference strength to a permissible value.

d) The influence of the potential rising of the earthing system on the outside of the UHV AC substation. The potential rising of the earthing system should avoid being transferred to the outside of the UHV AC substation through metal pipes or cables in the design of the earthing system.

e) Carbon footprint. The design should limit the carbon footprint of the substation (e.g. reduce leakage of total volume of SF_6).

4.7 Economy

The design of the UHV AC substation should strike a balance between performance and cost based on the life-cycle cost analysis, on the premise of meeting functional requirements.

5 Bus scheme and feeder connection

5.1 General

The basic purpose of a chosen bus scheme and feeder connection is to facilitate the operational functions of a substation inside an electrical network. In the past, maintainability and accessibility of high-voltage equipment was very important due to the requirements for frequent maintenance. Different types of circuit breaker design and also the different types of operating mechanisms required regular maintenance with short intervals. These requirements meant that various configurations and arrangements of substations were developed to isolate the circuit breaker and current transformer in a complete bay for maintenance while ensuring availability of supply on adjacent equipment. Disconnectors were required to deal with safety requirements and provide physical isolation during long-term maintenance activities.

Because the latest development in switchgear is aimed at ever longer maintenance intervals, the importance of maintainability in the design of switchgear has changed. At the same time, today's society is getting more and more dependent on electric power supply for all its functions. This results in less tolerance towards quality of power supply issues and black-outs, which will require designers to put more emphasis on high security (i.e. fault tolerance) and availability requirements for substations, especially for UHV AC transmission systems as backbone system.

Summarizing, bus scheme and feeder connection of high voltage substations are strongly influenced by many factors such as operational requirements, security standards, availability, and maintainability, the need for sectionalizing, control and protection systems and regulations. The bus scheme and feeder connection of a UHV AC substation should be determined after comparison of technology and economy according to the importance of the substation in transmission system considering the factors mentioned above.

The configuration for a particular substation depends on its position within a network and also its relative importance.

Because of the generally high importance of UHV AC substations, the following configurations are preferred:

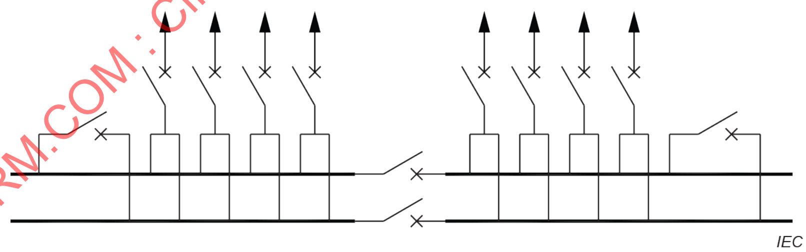
- double busbar (DB);
- one-and-a-half circuit breaker (OHCB);
- two-circuit breaker (2CB).

5.2 Scheme at high-voltage side of main transformer

The DB with a coupler bay as shown in Figure 2 is a substation in which the lines and transformers are connected to either of the two busbars by means of selector disconnectors.

The DB is particularly suitable for highly interconnected power networks in which switching flexibility is important and multiple supply routes are available. The coupler circuit breaker allows the possibility of keeping half of the station in service following a fault on the busbar, a busbar disconnector or any feeder circuit breaker. The configuration provides flexibility by allowing each circuit to be connected to either of the two busbars. It is also possible to move circuits from one busbar to the other while they are energized. Additional flexibility can be provided by adding sectionalised disconnectors into each busbar.

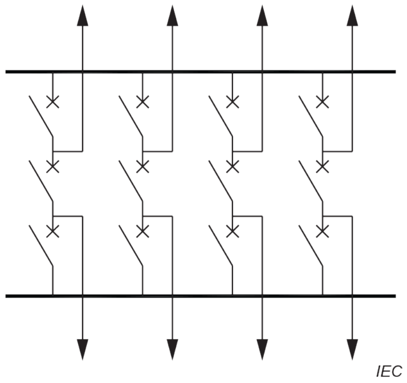
Using a bus section connection arrangement, a higher reliability is provided. This arrangement has the same characteristics and functionality of DB but it is recommended for use when there is a requirement to keep a high number of circuits in service during maintenance or repair of the circuit breaker or the busbar disconnectors.



NOTE The single line diagram only shows circuit breaker and busbar.

Figure 2 – Double busbar (DB) with or without bus section connection

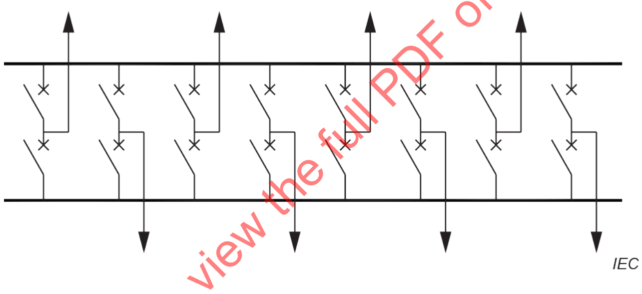
The OHCB as shown in Figure 3 is a double busbar substation where, for two circuits, three circuit-breakers are connected in series between the two busbars, the circuits being connected on each side of the central circuit-breaker. The OHCB is particularly suitable for substations handling large amounts of power, such as those associated with generating stations, and for networks which comprise mainly radial circuits with few mesh connections. The OHCB does not have any separate bus-coupler circuits. Each circuit breaker connecting is acting as a bus-coupler. The design of the bus zone and circuit breaker failure protection systems is simpler than the multiple busbar configurations with selector disconnectors as the systems do not need to select which circuit breakers to trip in response to a busbar fault or a circuit breaker fail situation.



NOTE The single line diagram only shows circuit breaker and busbar.

Figure 3 – One-and-a-half circuit breaker (OHCB)

The 2CB as shown in Figure 4 is a double busbar substation where the selectors are circuit-breakers. The 2CB is recommended for substations where the security of supply is particularly important. In addition, bus section connection in 2CB may strengthen the reliability of the substation. The 2CB is also more flexible than the OHCB. The configuration provides flexibility by allowing each circuit to be connected to either of the two busbars. It is also possible to move circuits from one busbar to the other while they are energized.



NOTE The single line diagram only shows circuit breaker and busbar.

Figure 4 – Two-circuit breaker (2CB)

5.3 Scheme at intermedium-voltage side of main transformer

The following configurations are preferred at the intermedium voltage side of main transformer:

- double busbar (DB);
- one-and-a-half circuit breaker (OHCB);
- two circuit breaker (2CB).

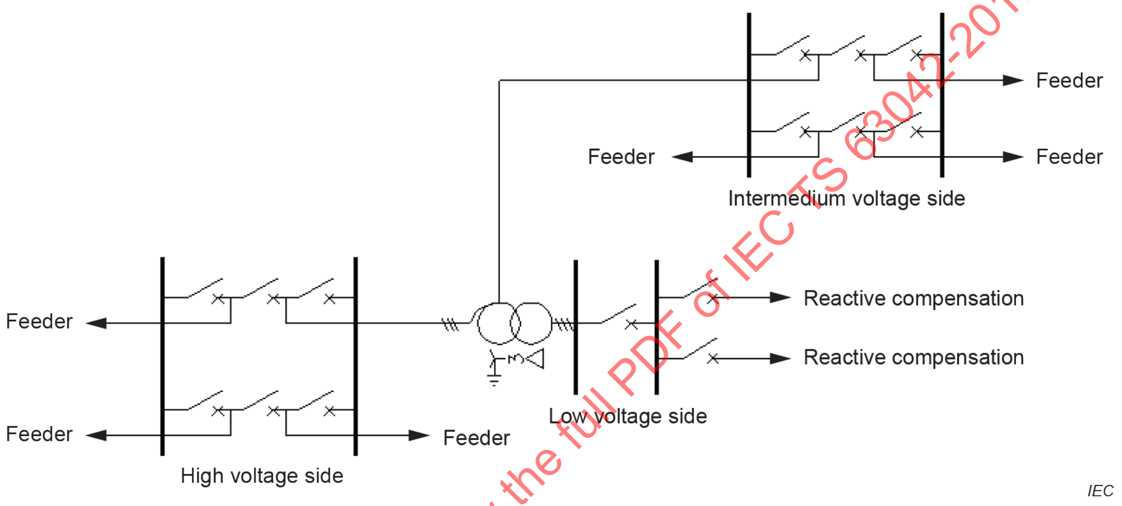
5.4 Scheme at low-voltage side of main transformer

The low-voltage side of main transformer and its rated voltage should be determined according to the following:

- system needs;
- transformer design and manufacturing;
- load configuration (including reactive compensation, feeders, etc.) at the low-voltage side of the main transformer.

If the low-voltage side of the main transformer will be connected to one or more feeders, single busbar layout with bus section connection may be employed. If the low-voltage side of the main transformer is connected to reactive compensation equipment only, the main transformer together with the busbar and connected equipment may be laid out as separate units.

According to load allocation at low voltage side of the main transformer and application of switchgear, a set or more of busbars can be installed at the low voltage side of each bank of transformers. To improve the power transmission reliability of the high-voltage and intermedium-voltage sides of the main transformer and reduce the influence of the low voltage side of the main transformer failure on the operation of the main transformer, each set of busbars may be connected with the low voltage side of the main transformer by a main circuit breaker. Figure 5 shows a typical diagram of a bus scheme and feeder connection.



NOTE The single line diagram only shows circuit breaker, busbar and transformer.

Figure 5 – Example diagram of a bus scheme and feeder connection

5.5 System neutral earthing mode of a UHV AC substation

A solid-earthed neutral system will result in a very high single-phase short circuit current and require immediate cut-off of lines or equipment, which will increase the operation times of the circuit breaker and reduce the power supply continuity. However, having reduced overvoltage and insulation level, it can lower the equipment cost, especially in HV, EHV and UHV grids, and produce significant economic benefits. When it is required to limit the short circuit current of a system, low impedance earthing can be employed.

The unearthed neutral mode allows running with a fault in cases of single-phase earthing and offers a good continuity of the power supply, in which case the earthing current is limited to the capacitive current of lines and equipment. But owing to the overvoltage, it requires a fairly high level of insulation.

High-voltage side and intermedium-voltage side of a main transformer in the UHV AC substation apply neutral solid-earthed mode or low-impedance earthing mode.

The system neutral earthing mode of the low voltage side of the main transformer should be determined according to the overvoltage, insulation level, power supply reliability and continuity, short circuit current, and protection configuration.

6 Selection of equipment and conductors

6.1 General

UHV AC equipment and conductors should be selected considering the system requirements and environmental conditions.

6.1.1 Voltage

See IEC 60038:2009, Table 5.

6.1.2 Rated current

See IEC 60059:1999 and IEC 60059:1999/AMD1:2009, Clause 3.

6.1.3 Rated frequency

See IEC 60196:2009, Clause 3.

6.2 Basic requirements

6.2.1 Electrical requirements

UHV AC equipment and conductors should be selected considering the following electrical requirement.

a) Short-circuit current

The equipment should be designed and installed to reliably withstand the thermal and mechanical effect caused by the short-circuit current in all kinds of short circuits, e.g.:

– three-phase;

– phase-to-phase;

– phase-to-earth;

– double phase-to-earth.

The peak factor for the rated peak withstand current is related to the DC time constant. The peak factor is higher in the case of UHV AC transmission systems owing to larger DC time constants.

IEC 60909 (all parts) and IEC 60865 (all parts) give the calculation method for the short-circuit current of the three-phase AC system and the effect of the short-circuit current respectively.

b) Overvoltage

The equipment should withstand the switching overvoltage and lightning overvoltage with insulation coordination and overvoltage protection. See Table 3 of IEC 60071-1:2006 and IEC 60071-1:2006/AMD1:2010 for values of rated insulation levels.

c) Electromagnetic interference

Radio interference with a frequency over 10 kHz mainly comes from the current, voltage mutation and corona discharge of the equipment or conductors. It can affect or impair the normal receiving of electromagnetic signal and operation of electrical and electronic equipment. Therefore, the electromagnetic fields generated by the equipment and conductors should be within an acceptable range, and the radio interference caused by the electromagnetic field should not exceed the required value. Because of UHV AC transmission systems, the voltage and current are high; therefore, the interference becomes severe in comparison to the other ratings. Under the highest operating phase voltage, the equipment and conductors should produce no visible corona on clear nights.

The limited value of electromagnetic interference and corona of UHV AC substation should not exceed the existing criteria.

NOTE See applicable limits set by the local regulatory authorities for the acceptable levels of electromagnetic field generated by the equipment and conductors and the maximum allowable radio interference.

6.2.2 Mechanical requirements

The mechanical strength of bushing and post insulator of equipment should be designed considering the effect of wind, ice and earthquake, electrodynamic action of short circuit current, as well as the combination of various loads. Annex A (see Table A.1) shows an example of load combination selection of UHV AC equipment. The safety factor of mechanical strength of bushing and post insulator should also be checked under the long-term and short-term load. The effect of wind and ice should be considered as a long-term load. The effect of earthquake and electrodynamic action should be considered as a short-term load.

When the equipment bushing is connected to bundled conductors, the effect of the conductor rigidity should be taken into consideration.

6.2.3 Environmental conditions

UHV AC equipment and conductors are typically located outdoors. They should be selected considering the influence of the following environmental conditions:

a) Ambient temperature

   The equipment and conductors should be able to operate under the specified highest and lowest ambient temperatures. In case ambient temperature is out of the range of specified values, the allowable current-carrying capacity should be subject to agreement between manufactures and users.

   The specified value of the highest and lowest ambient temperature refers to Subclause 4.4.2.2 of IEC 61936-1:2010.

b) Solar radiation intensity

   As the equipment will experience additional temperature rise under solar radiation, it should be able to withstand the highest solar radiation intensity at midday on sunny days specified if necessary during operation.

   Solar radiation level refers to IEC 60721-2-4.

c) Wind velocity

   The average maximum wind velocity for many years can be commonly determined according to the observational date of the 10 min mean wind velocity at the 10 m height from the open, plane terrain in locality, through the probability statistics, meanwhile, considering the relative air density. The design wind velocity should be corrected based on the actual installation height. For areas frequently hit by tropical cyclones (typhoon or hurricane) and strong wind, in addition to the purchase of customized equipment, effective protection measures should also be designed, such as lowering the installation height and enhancing the foundation.

d) Altitude

   When the altitude is not exceeding 1 000 m, the external insulation of equipment requires no correction. When the altitude is above 1 000 m, correction is required as specified in IEC 60071-2.

e) Ice and snow

   Measures such as increasing the effective creepage distance should be taken to prevent insulation flashover in areas exposed to heavy snow and ice. The ice-breaking capacity of the disconnector should satisfy the maximum ice coating thickness of the installation site.

f) Humidity

   The equipment selected should satisfy the requirement for the local maximum relative humidity. The specified value of humidity refers to IEC 61936-1.

   To withstand the effects of high humidity and condensation, a UHV AC equipment design for such conditions should be adopted. Condensation may be prevented by special design of the building or housing, by suitable ventilation and heating of the station or by use of a dehumidifying equipment.

g) Pollution

The damage caused by pollutants to electrical equipment in the polluted area depends on the conductivity, water absorption, adhesion, quantity and specific weight of pollutants, and the distance and meteorological conditions. See IEC TS 60815 (all parts) for classification of pollution and creepage distances of equipment under different conditions of pollution. Anti-pollution measures under serious pollution include increasing the effective creepage distance of external insulation, selecting electric porcelain with alternating sheds, large inclinations composite insulators with hydrophobic behaviour or other structures beneficial for pollution prevention.

h) Audible noise

The audible noise at the substation boundary should meet the local environmental protection regulations. See Annex B (Tables B.1, B.2, B.3 and B.4) for specification of UHV AC equipment and conductor.

If the equipment noise exceeds the limit, the following measures can be taken:

– use low-noise equipment;

– install a sound insulation barrier around the equipment;

– install a sound insulation barrier on substation walls;

– install a box-in sound insulation device on the equipment.

i) Earthquake

The earthquake mainly affects the equipment by seismic wave frequency and vibration acceleration. UHV AC equipment is higher, heavier and larger than EHV equipment. The natural frequency of equipment is typically close to that of the earthquake. Accordingly, measures should be taken to avoid resonant frequency and appropriately increasing the damping ratio of the equipment.

In verification of seismic performance for bushings and post insulators, the dynamic magnification factor of the whole structure, the apparatus, the ground conditions including foundation, the support, terminals (such as transformer bushing terminals) and connection fittings should be considered.

NOTE The ratio of vertical ground acceleration to horizontal acceleration is taken as 50 % in IEC 62271-207, 80 % in IEEE 693.

6.3 Transformer

The selection of UHV transformer should be taken into consideration as specified in IEC 60076 (all parts). And regarding higher voltage and capacity than EHV, some aspects such as the type, transportation and cooling mode of the UHV transformer should be given consideration.

Due to the high voltage and large capacity required for UHV AC substations, single phase oil-immersed transformers are recommended considering the transformer's manufacturing difficulty, reliability requirements, and transportation.

The autotransformer is recommended for main UHV transformers. The capacity of common winding in autotransformers should be checked according to the capacity of the system and reactive compensation configuration on the tertiary winding side of autotransformer.

Depending on the rated capacity, the ability of manufacturing and transportation, two-leg or three-leg main transformers may be employed.

As a UHV transformer is heavy in weight and large in size, it is necessary to take the transportation conditions into account. For transportation, the main UHV transformer may be disassembled and reassembled on site.

The main UHV transformer may use the oil forced air forced (OFAF) or oil directed air forced (ODAF) cooling mode to increase the cooling efficiency and ensure that the temperature of the transformer oil and winding meets the requirements.

The voltage of the transformer is regulated by using the tap changer to change the operation voltage ratio. The mode and range of voltage regulation are determined based on the voltage fluctuation range of the system and the requirement of system operation. If the system has a great voltage fluctuation and requires an on-load tap changer, the on-load regulation should be employed; otherwise, the off-circuit tap-changer should be employed.

The voltage regulation winding of the autotransformer may be installed at the end of the HV side winding, the end of the MV side winding or the neutral side. According to the manufacturing ability of the UHV transformer and tap, the neutral side regulation mode may be used.

If the UHV transformer employs the neutral voltage regulation, voltage deflection will occur on the LV side winding. When the voltage on HV side rises, it is required to reduce the number of common windings to stabilize the MV side voltage, which will raise the electrical potential of each winding, further saturate the iron core and increase the LV side voltage accordingly. In the case that the tertiary winding is connected with parallel compensation devices, the voltage change will be further raised, and the operation performance will deteriorate. Therefore, tertiary compensation windings should be added in the main transformer to control the voltage fluctuation range on the LV side.

6.4 UHV shunt reactor and neutral-earthing reactor

The selection of the UHV reactor should be taken into consideration as specified in IEC 60076 (all parts). Some aspects such as type, transportation and cooling mode of UHV shunt reactor should be given consideration.

As the capacity of UHV reactor is relatively large, the impact of electrodynamic force to the neutral earthing reactor during open-phase operation should be considered. The parameters of the neutral earthing reactor should be determined based on the requirements of secondary arc quenching acceleration and resonance overvoltage suppression combining of the power system operation. The insulation of the shunt reactor and neutral earthing reactor should be determined through the system overvoltage calculation.

Typically, the single-phase oil immersed iron core UHV reactor is recommended.

Considering the high rated capacity or transportation, the UHV shunt reactor can be of one leg or two leg type, and oil natural air natural (ONAN) or oil natural air forced (ONAF) should be employed for the UHV shunt reactor.

6.5 UHV switchgear

The developments in the design of high voltage devices and new switchgear components using different design principles with higher reliability or integrated functions mean that the reliable and efficient circuit configurations of the past may not be necessary and may result in onerous life-cycle-cost requirements for utilities. From a product point of view, new high voltage switchgear components are being developed based either on air-insulated technology (AIS) or on gas insulated technology (GIS) or on a combination of both, the so-called Mixed Technology Switchgear (MTS). In addition to the investment costs, life-cycle costs of high voltage substations should be considered for the selection of the technology.

In CIGRE TB 570, an evaluation of the applicability of the various characteristics to the three types of technologies AIS, MTS and GIS is given.

In recent years, environmental requirement aspects have become more relevant and important, and have to be considered when planning UHV AC substations. However, minimizing the impact on the environment of materials and practices used in a substation needs to be balanced with the requirement for equipment to be able to withstand severe environmental and climatic conditions.

6.6 UHV circuit breaker

Circuit breakers are used to connect or disconnect bays from a busbar and/or to connect different busbars or busbar sections. They are the most important element of high-voltage equipment, because they are able to control the power flow in the network and to break fault currents, i.e., to disconnect a faulty part of the network. Because of this important function, the reliability of a circuit breaker needs to be high. The circuit breaker type and design should be selected considering the actual project conditions and equipment manufacture and supply condition, as well as national policies for related industries, and technical/economical comparison. The technical requirement for circuit breakers should be determined after systematic study considering the characteristics of UHV AC transmission systems, based on IEC 62271-100.

UHV circuit breakers have more than one interrupter unit (typically 2 to 4) connected in series. The closing resistor can be positioned in parallel or in series to the interrupter units.

To suppress switching overvoltages, in addition to the surge arresters, pre-insertion closing and sometimes also opening resistors or point-on-wave switching could be applied. The effects of closing resistors are well-known and closing resistors are applied to most of the UHV AC transmission systems. The opening resistor can reduce the switching overvoltage and also have a considerable effect to reduce the amplitude of TRV oscillations. The effect has to be proven by simulation studies.

The values of closing and opening resistors should be taking into account the overvoltages generated by making and/or breaking operations and the insulation design of the transmission systems. The resistor values depend on the system aspects such as network configuration, and to which extent the switching surges are to be controlled.

The insertion time for the closing and/or opening resistors should be determined taking into account the switching overvoltage and insulation design of the transmission system. The insertion time of opening resistors should be set to be longer than the maximum arcing time of the main contacts and they should be inserted for a fixed period, typically around 30 ms, after opening of the main contacts.

6.7 UHV disconnector

A disconnector is a mechanical switching device which provides, in the open position, an isolating distance suitable to meet specified electrical withstand requirements. It is capable of opening and closing a circuit when either negligible current is broken or made, or when no significant change in the voltage across the terminals of each of the poles of the disconnector occurs. It is also capable of carrying currents under normal circuit conditions and carrying for a specified time currents under abnormal conditions such as those of short-circuit. Disconnectors are important to ensure adequate isolation safety conditions inside a substation, particularly during work or maintenance.

Disconnectors in multiple busbar substations need the capability to also switch commutating currents. Commutating currents appear when the load is switched from one busbar to the other due to the voltage drop over the current path. The voltage values are defined in IEC 62271-102.

During switching of disconnectors in gas-insulated switchgear a varying number of pre-strikes and re-strikes occur. Due to the very short duration of the voltage collapse of a few nanoseconds at the switching gap, travelling surges are generated in the GIS. The multiple refractions and reflections of these surges at impedance discontinuities within the enclosures create complex waveforms (very fast front overvoltages – VFFO).

VFFO in GIS are of greater concern at the highest rated voltages, for which the ratio of the lightning impulse withstand voltage (LIWV) to the system voltage is lower. Because the generated transients depend strongly on the specific configuration and on the superposition of travelling waves, it is not possible to give generally admitted values, valid for each case. An accurate simulation for each substation, especially in the UHV range, is necessary for the insulation coordination as a basis for the decision making about possible countermeasures. If the required VFFO withstand voltage is higher than LIWV, it is necessary to define measures reducing the risk of failures. There are two possibilities: an increase of the LIWV connected with additional costs or a mitigation of VFFO. The first choice is easy to realize, but cost-intensive. Nevertheless, in some cases, this solution has advantages. The second choice aims for mitigation of amplitudes of VFFO and finally for a reduction of the effect of VFFO on the equipment.

The damping of VFFO by integration of a damping resistor is a well proven technology. Generally, the mitigation effect of the damping resistor depends on the value of the resistance. Consequently, the resistance of a damping resistor could be chosen and defined according to the maximum calculated VFFO and the required mitigation effect. The damping resistor has to withstand the dielectric stress during striking. A flashover across the resistor may lead to high VFFO comparable to a disconnector without damping resistor and has to be avoided. A higher resistance value leads to a higher voltage stress across the damping resistor and can reach values in the range of 2 p.u. The absorption energy strongly depends on the load side capacitance and the voltage across the disconnector. The required capacity of thermal energy absorption for the resistor could be calculated by summing up all close-open operations containing a high number of strikes. Mostly the thermal absorption capability is defined to withstand the thermal stress for one close-open operation. The possibility to operate more than one close-open operation within some minutes which corresponds to the thermal time constant of the damping resistor is estimated to be very short.

The application of a slow-acting disconnector provides significant reduction of the VFFO, because of lower trapped charge voltages.

6.8 UHV earthing switch for maintenance

A mechanical switching device for earthing parts of a circuit, capable of withstanding for a specified time currents under abnormal conditions such as those of short circuit, but not required to carry current under normal conditions of the circuit. An earthing switch may have short-circuit making capacity.

Earthing switch for maintenance should earth de-energised parts so that work should be performed safely. As GIS is enclosed and the primary conductor is not accessible, each section should be provided with an earthing switch, which means that the number of earthing switches usually is higher than in AIS. The earthing switch in the incoming and outgoing feeders in a GIS normally is designed to be capable of closing onto, and withstanding for a specified time, the short-circuit current, a so-called high-speed earthing switch.

In the case of multiple configurations of overhead transmission lines, current may circulate in de-energized and earthed lines as a result of capacitive and inductive coupling with adjacent energized lines. Earthing switches applied to earth these lines should therefore be capable of switching induced currents.

6.9 High-speed earthing switch

In a UHV AC transmission system, the secondary arc does not extinguish in a short time for high induced voltages because the operating voltage level of UHV is very high and the charging capacity per unit length is also comparatively high. Therefore, a high-speed reclosing scheme should be employed to suppress the secondary arc with a four-legged reactor or high speed earthing switch (HSES).

HSES is often adopted at both ends of a relatively short transmission line. Alternatively, one HSES may be installed at a single end of an extremely short transmission line.

For double circuit systems with multi-phase auto-reclosing scheme, where four-legged reactors are not suitable, application of HSES is a useful and important means for the purpose of secondary arc extinction.

Interlocking is required between HSES and circuit breaker to avoid incorrect operation. Table A.2 of IEC 62271-112:2013 shows a comparison of a four-legged reactor and HSES with the following addition as shown in Table 1.

Table 1 – Comparison of a four-legged reactor and HSES

Equipment	Four-legged reactor		HSES
Connection	Direct connection with GIS	Line entrance side	Between CB and line side DS
Required equipment	Four-legged reactor, (Surge arrester with low protective level) Disconnector, Earthing switch.	Four-legged reactor, Surge arrester with low protective level	HSES

6.10 UHV current transformer

The selection of a UHV current transformer should be taken into consideration as specified in IEC 60044 (all parts).

Compared with the EHV system, the specification of a UHV current transformer is more strictly for the transient characteristics along with the increase of the DC component damping time constant of the short-circuit current. Requirements should be specified regarding the issue in the current transformer selection.

6.11 UHV voltage transformer

The selection of a UHV voltage transformer should be taken into consideration as specified in IEC 60044 (all parts).

In the case of being installed inside the GIS or MTS switchgear, the SF_6 gas insulated transformer with electromagnetic type or capacitive type can be employed, and in the case of choosing post type, the oil-immersed or SF_6 gas insulated transformer with capacitive type is typically employed.

The type of post capacitive voltage transformer is classified to stack-together structure and stack-separate structure. Selecting the suitable type for UHV capacitive voltage transformer mentioned above, the following aspects besides those for EHV capacitive voltage transformer should be considered:

NOTE Stack-together structure means that a capacitive voltage divider and an electromagnetic unit are placed in one cabinet. Stack-separate structure means that the capacitive voltage divider and the electromagnetic unit aren't placed in one cabinet.

- Low probability that the bottom capacitor of the capacitive voltage divider is affected by the operation temperature rise of the electromagnetic unit, which affects the measuring accuracy;
- Low probability of flashover discharge that occurs between the HV conductors led from capacitive voltage divider and the internal components or shell of electromagnetic unit;
- The convenience of separating the capacitive voltage divider from the intermediate transformer for commissioning or testing.

6.12 UHV surge arrester

The selection of UHV surge arrester refers to IEC 60099-4 and IEC 60099-5.

The surge arrester with low protective level should be used both on the line side and transformer side of UHV switchgear busbar. The surge arrester configuration for UHV switchgear busbar and shunt reactor circuit should be determined based on lightning overvoltage calculation or simulation test taking into account operation mode, shield angle of incoming transmission line section and other factors. The layout location and parameters of the surge arrester should meet the requirements of insulation coordination. As the duration of power frequency overvoltage can be limited, the permissive capability of arrester for power frequency overvoltage should be confirmed during the design stage. See Table 3 of IEC 60071-1:2006 for values of rated insulation levels.

6.13 Reactive power compensation device for low voltage side of UHV transformer

Reactive power compensation devices for tertiary winding of UHV transformer include the shunt capacitor and shunt reactor.

The selection of the shunt capacitor and shunt reactor should be taken into consideration as specified in IEC 60871 and IEC 60076 (all parts) respectively.

The sub-bank capacity of shunt capacitor or shunt reactor should be accommodated with the current capacity of the circuit breaker and should meet the requirement of busbar voltage fluctuation as breaker operation.

Also, the ratio of series reactance to parallel reactance should consider the effects of background harmonics.

The reactor can be dry type or oil-immersed type. If the dry type reactor is used and the single bank of shunt capacitor has a large capacity, the structure of windings in series can be used considering limitation of manufacturing ability and transportation. As all magnetic lines in the dry reactor winding will develop into circuits through air, the anti-magnetic space around reactor should be considered in case it will result in serious electromagnetic induction heating or electrodynamic force in the adjacent conductors (including the earthing conductor). All closed loop connection should be avoided at the magnetic conductive net, fence, support, foundation reinforcement, earthing conductor and secondary wiring.

6.14 UHV bushing

Generally, the UHV bushing is used to connect UHV equipment (main transformer, UHV reactor, UHV circuit breaker and UHV GIS) to overhead lines or UHV AC equipment.

The selection of UHV bushing should be taken into consideration as specified in IEC 60137. In terms of insulation structure, the UHV bushing is classified to the oil-immersed paper capacitance graded bushing and the gas-insulated bushing. The oil-immersed paper capacitance graded bushing should be used for the main transformer and UHV reactor, and the gas-insulated bushing should be used for UHV circuit breaker and UHV GIS.

In terms of material of external insulation, the UHV bushing is classified to porcelain bushing and composite bushing. The selection of porcelain bushing or composite bushing should be based on the pollution level, seismic intensity and other aspects of the substation.

6.15 UHV insulator

The selection of the UHV support insulator should be taken into consideration as specified in IEC 60168 for porcelain and IEC 62772 and IEC 62231 for composite insulators.

The selection of the UHV suspension insulator should be taken into consideration as specified in IEC TS 60815 (all parts).

The suspension insulator string of UHV AC substation should take a V-type string for lowering the gantry of UHV switchgear and reducing the wind-deviation impact of conductors. Also, if V-type string is taken, the deformation of long strings should take into account as selected the apparatus of grading ring and shield ring.

6.16 UHV conductor

6.16.1 General

UHV AC substation conductors are mainly used to connect the electrical device and transmit electrical power. Due to the high current flowing in the busbar, an appropriate conductor should be selected.

The design of the conductor and fittings of the UHV electrical equipment should consider the corona effect on any condition, especially on rainy days.

The design of the conductor of the UHV electrical equipment should consider the influence of the earthquake, calculate the force of the conductor, and select the flexible conductor according to the seismic intensity.

6.16.2 Conductor type

The types of UHV AC substation conductors should be determined according to their current-carrying capacity, thermal stability, mechanical characteristics, economy, site conditions, switchgear characteristics and so on. The conductors should be easy for installation and well adaptable to environmental conditions (high seismic performance, for instance).

In general, tabular conductors, flexible conductors and gas-insulated metal-enclosed conductors may be used in UHV AC substations. The advantages and disadvantages of conductors are shown as Table 2.

Table 2 – Comparison of conductors

Conductor type	Advantages	Disadvantages
Tubular busbars	The conductors have large current-carrying capacity, high corona inception voltage, good structural strength, simple installation fittings, convenient construction and wide adaptability.	The conductors have large stiffness, make the fittings and equipment have great stress during vibration.
Flexible conductors	The conductors have good flexibility, good anti-vibration performance, low cost, and low connection stress.	The conductors have larger phase-to-earth and phase-to-phase clearance is required due to their susceptibility to wind deflection and electromotive force, and higher structural strength is required due to their larger tensile force. In addition, multi-split flexible conductors are required for UHV AC substations because of high voltage level and corona, and are more complex in installation and construction.
Gas-insulated metal-enclosed conductors	The gas-insulated conductors are compact and have high corona inception voltage, no radio interference and electromagnetic issues.	Use of gas-insulated conductors should be decided based on technical and economic aspects.

6.16.3 Selection of current-carrying capacity (cross-section)

Current-carrying capacity should be appropriate to ensure the safe and stable operation of the conductor and equipment, and it should be determined according to the maximum operating current, short-circuit current, heat elimination conditions, etc. of the circuit. For outdoor bare conductors, the ambient temperature, solar radiation, wind speed, etc. should also be taken into account. The maximum continuously operating current should be seen as the operating current, and the possible maximum short-circuit current under various fault conditions as the short-circuit current. Meanwhile, thermal equilibrium and thermal stability should be considered.

6.16.4 Corona and radio interference

Special attention should be paid to the interference of corona and radio in the selection of outdoor bare conductors for UHV AC substations. The very high electric field on the surface of a conductor easily makes the surrounding air ionized and thus forms corona, which causes a corona discharge, increases the losses and brings radio interference and audible noise.

Since the mechanism of corona formation is extremely complex and related to many factors such as conductor shape, outside diameter, surface roughness, phase-ground distance, phase-phase distance, voltage level, contamination, weather conditions and so on, it is very hard to predict accurately whether corona will be formed on the conductor surface by means of any formula.

The same approach may be used in EHV substation about corona inception voltage measurement of bundle conductor in UHV AC substation. Normally, in order to reduce the corona losses, the radio interference level and audible noise, the corona inception voltage of bundle conductor of UHV AC substation should be high enough in a certain level in comparison to the operation voltage. An example of calculation of corona inception voltage of bundle conductor used in UHV AC substation is given in Annex C.

6.16.5 Mechanical strength

The mechanical properties of conductors may be undermined during operation due to their own gravity, wind load, ice load and instantaneous short-circuit forces in case of any failure. The mechanical strength of conductors for UHV AC substations should be checked according to their locations, environmental conditions and types. In order to ensure the safety of equipment, the stress should be checked during the earthquake according to the earthquake intensity demand of sites.

7 Equipment layout

7.1 General requirement of equipment layout

7.1.1 General

General requirements for power equipment layout in substation are introduced in IEC 61936-1. Special care for the design of UHV AC substations is described in 7.1.2.

7.1.2 Optimization of substation layout

To determine the equipment layout, the typical UHV AC substation should be designed considering the equipment function, maintainability and space reduction. The UHV AC substation layout is recommended to be compact and the following general rules are recommended for basic equipment layout:

- equipment is separately installed by unit and voltage, e.g. UHV switchgear unit, main transformer unit;
- share the space of equipment installation and disassembly in case of failure, and optimize equipment installation layout;
- shorten the length of busbars;
- minimize the roads as much as possible and utilize those roads for installation space such as parking and working space of towing cars or temporary location of equipment before installation;
- control the noise at the boundary to fulfil the requirements of local regulation;
- minimize the equipment in order to minimize the overall layout.

7.1.3 Seismic performance

Fundamental mechanical requirements of seismic loads are introduced in Subclause 4.3.9 of IEC 61936-1:2010 and IEC 61936-1:2010/AMD1:2014. As for UHV AC transmission systems, there are cases where UHV AC substations are constructed in areas where the earthquakes are expected. For these cases, a special care is necessary. The details of design for seismic performance are described in Subclause 7.8.

7.1.4 Construction, serviceability and reliability and failure response ability

General requirements for construction, serviceability and reliability and failure response ability of power equipment refer to 4.1.1, 7.1.1, 7.1.4, 7.4.1 and 7.4.2 of IEC 61936-1:2010. UHV AC equipment is normally large and heavy; therefore, UHV AC equipment should be disassembled into separate units for transportation along with consideration of on-site assembly in the UHV AC substation. The number of units assembled in the UHV AC substation should be minimized.

The procedures in case of equipment and/or system failures should be considered at the design stage. Careful consideration of these procedures is imperative in the design of UHV AC substations.

Outage area of substation in case of failure, maintenance or future expansion should be minimized. Examples of recommendations:

- multiple busbar to avoid whole busbar outage, or function of separation of outage area of busbar;
- gas compartment arrangement of depressurization to low pressure and vacuum evacuation for GIS and MTS;
- location of detachable busbar (expansion joint) for disassembly in case of failure;
- location of back-up (stand-by) equipment for replacement in case of necessity.

7.2 Minimum clearances

7.2.1 Normal environmental conditions

See Subclause 4.4.2 of IEC 61936-1:2010.

7.2.2 Minimum clearances in air-voltage range

See Subclause 5.4 and Table 2 of IEC 61936-1:2010 and IEC 61936-1:2010/AMD1:2014.

NOTE The minimum clearances in air given in Table 2 of IEC 61936-1:2010 apply for altitudes up to 1 000 m above sea level. For higher altitudes, see Subclause 4.4.3.2 of IEC 61936-1:2010.

The duration of the wave front is about a few hundred μs, such as the overvoltage in opening/closing transmission lines and earth fault. This switching overvoltage has much influence on the insulation design of towers and is particularly important for UHV AC transmission systems because of the saturation effects of the air insulation distance on the switching impulse strength. The flashover voltage of air-insulated gaps for switching overvoltage has a tendency to saturate. Therefore, an extremely high tower is required for air insulation. On the contrary, to reduce the construction cost of UHV AC transmission system, switching overvoltages can be reduced by adopting circuit breakers with closing and/or opening resistors and surge arresters with low protective levels.

7.3 Electromagnetic environment

7.3.1 Electrostatic induction mitigation design

See Subclause 4.2.7 of IEC 61936-1:2010 and IEC 61936-1:2010/AMD1:2014. The design of an installation should be such as to limit the electric and magnetic fields generated by energized equipment to an acceptable level for exposed people who are performing safety, operational and maintenance work. Further information is available from the International Commission on Non-Ionizing Radiation Protection (ICNIRP).

In a publication provided by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) named "ICNIRP Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz)-2010", guidelines are established for the protection of humans exposed to electric and magnetic fields in the low-frequency range of the electromagnetic spectrum from 1 Hz to 100 kHz. The main objective of this publication is to establish guidelines for limiting exposure to electric and magnetic fields (EMF) that will provide protection against all established adverse health effects. Accordingly, based on this publication, reference levels for occupational exposure to electric fields, which is defined as time-varying electric fields in unperturbed RMS to which a person may be exposed without an adverse effect and with acceptable safety factors, are 5 × 100/f kV m^{-1} (f in Hz) for 25 Hz to 300 Hz range, i.e. 10 kV/m for 50 Hz and 8,3 kV/m for 60 Hz respectively. On the other hand, reference levels for general public exposure to electric fields are half of those for occupational exposure.

Therefore, design criteria of ground electric fields generated by electrostatic induction should be less than 10 kV/m at 1,5 m from the ground, considering all the established adverse health effects, especially in the brain. If it is difficult to design less than 10 kV/m, the adoption of partial shield facilities should also be studied. As for the head region of aerial bushings and lower-part shields, it is necessary to configure those components at a ground height that complies with the above-mentioned permissible electric field.

The following other measures against electrostatic induction should also be considered during the design stage:

- placing any accessible equipment such as local control panels at a lower electric field;
- placing live parts of equipment or incoming leads at a higher location;
- other improvements in shield design to reduce the electric field.

7.3.2 Magnetic induction mitigation design

In accordance with "ICNIRP Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz)-2010", magnetic field strength 1,5 m above the ground should not be greater than 1 000 μT (50 Hz/60 Hz).

The reasonable measures against magnetic induction are shown as follows:

- secondary equipment such as local control panel may be located as far as possible away from dry-type air-core reactor;
- placing live parts of equipment or incoming leads at a higher location;
- reduce the exposure time on the area around dry-type air-core reactor.

7.3.3 Audible noise mitigation design

See Subclause 4.5.2 of IEC 61936-1:2010.

It is difficult to calculate or estimate the radio noise level because of the irregular shield of shielding rings of equipment in a UHV AC substation. Some effective suggestions to lower the radio noise level based on the engineering experience are provided here.

The shield ring design for bushings, V-shaped suspension insulators, etc. is based on the suppression of the audible noise level in busbars by lowering the corona discharge in an appropriate manner.

It is recommended that during the actual design stage, corona noise levels be below the criteria for the various connection parts between conductors and shield ring for bushing, V-shaped suspension insulator, etc.

The reasonable measures against audible noise are shown as follows:

- increased diameter of end shield (spherical shape) of disconnecting switch;
- enlarged conductor diameter of disconnecting switch;
- enlarged diameter of primary conductor of pull-down leads;
- enlarged conductor diameter for reducing the surface electric field strength;
- using a bundled conductor with more split numbers;
- placing incoming conductor at a higher location.

Audible noise caused by corona discharge under rainy condition should be considered, since the noise level under rainy condition is normally much higher than that under clear weather. An example of conductor design of a UHV AC substation under rainy conditions is given in Annex D.

7.4 Selection of switchgear equipment

For general requirements concerning the selection of power equipment including switchgear, see Subclause 6.1.1 of IEC 61936-1:2010. For UHV AC equipment, there are three types of switchgears: AIS type, MTS type and GIS type.

The technologies used in AIS, MTS and GIS have their own advantages. There is no recommended general solution for all users, the individual conditions of every case having a strong impact on the evaluation and leading to different conclusions. Typical examples of items to be considered in case of selection of AIS, MTS or GIS are as follows and examples of investigation for each item are introduced in Annex E.

- reliability;
- maintenance and operation;
- installation;
- layout;
- circumstance;
- construction cost;
- testing / commissioning.

The principal technologies of AIS, MTS and GIS used in UHV AC substation are shown in Table E.1.

Recently, there are cases to adopt MTS and GIS in a UHV AC substation. In these cases, the following matters should be considered:

- residual charge of main circuit effect against insulators used in MTS and GIS;
- induced surge effect to secondary circuit.

Selection of switchgear type of MTS or GIS is often made from the typical points of view as follows:

- number of live parts (i.e. bushings and busbars);
- anti-seismic performance;
- noise;
- electromagnetic circumstances;
- space of land;
- cost.

7.5 Switchgear Installations layout

7.5.1 General

For general requirements about power equipment installations, see Subclauses 7.1, 7.2 and 7.6 of IEC 61936-1:2010. The layout of switchgear in a UHV AC substation should be determined by function, performance, maintainability, construction and failure response in an integrated manner and not only for installation. As a basic layout, the following recommendations should be considered.

7.5.2 Location arrangement of switchgear

For general requirement of circuit arrangement of power equipment, see Subclause 7.1.1 of IEC 61936-1:2010. As for UHV AC substation, UHV and lower voltage switchgear should be installed in separate locations such as on opposite sides of transformers.

7.5.3 Basic arrangement of surge arresters

For general requirements of design and position of the surge arrester, see Subclause 6.2.5 of IEC 61936-1:2010. The arrangement of surge arresters should be determined through lightning surge and internal overvoltage analyses by varying system conditions including UHV switchgear, transformers and other equipment. The number of surge arresters in the UHV AC substation should be optimized and minimized by analyses. Surge protection and insulation coordination should be considered at the same stage as surge arrester analysis. The basic arrangement of surge arresters is recommended as follows:

- GIS: surge arrester should be located at the outgoing/incoming line, bank and main busbar;
- MTS: surge arrester should be located at the outgoing/incoming line and bank and, at the user's option, located in the main busbar;
- AIS: surge arrester should be located at the line and bank entrance.

7.5.4 Optimal gas-insulated busbar (GIB) layout and length

For general requirements of circuit arrangement for power equipment installations, see Subclause 7.1.1 of IEC 61936-1:2010 and IEC 61936-1:2010/AMD1:2014. UHV AC substation needs adequate large distance between neighbouring gantries for outgoing/incoming transmission lines and transformers. Therefore, location of gantries and transformers should be determined for optimal GIB layout and length.

7.5.5 Utilization of working space for substations

For a general requirement concerning aisles and access areas, see Subclause 7.1.4 of IEC 61936-1:2010.

a) GIS substation

Since UHV apparatus is large and heavy, space for installation of switchgear should be shared with the space for disassembly in case of failures in order to minimize the total area of the substation. For example, one unit of gas-insulated switchgear equipment such as circuit breaker, disconnector, earthing switch, excluding main busbars and GIB, is recommended to be connected in a linear configuration.

The following items should be considered with the layout of a UHV GIS substation:

– space for equipment needed for installation or disassembly, such as cranes;
– space for vertical or horizontal removal of disassembled equipment;
– space for working, like space for handling of bolts;
– maintenance space, such as space for opening of covers, or manholes;
– space for on-site test.

An example of crane location for installation or disassembly work is shown in

Figure 6.

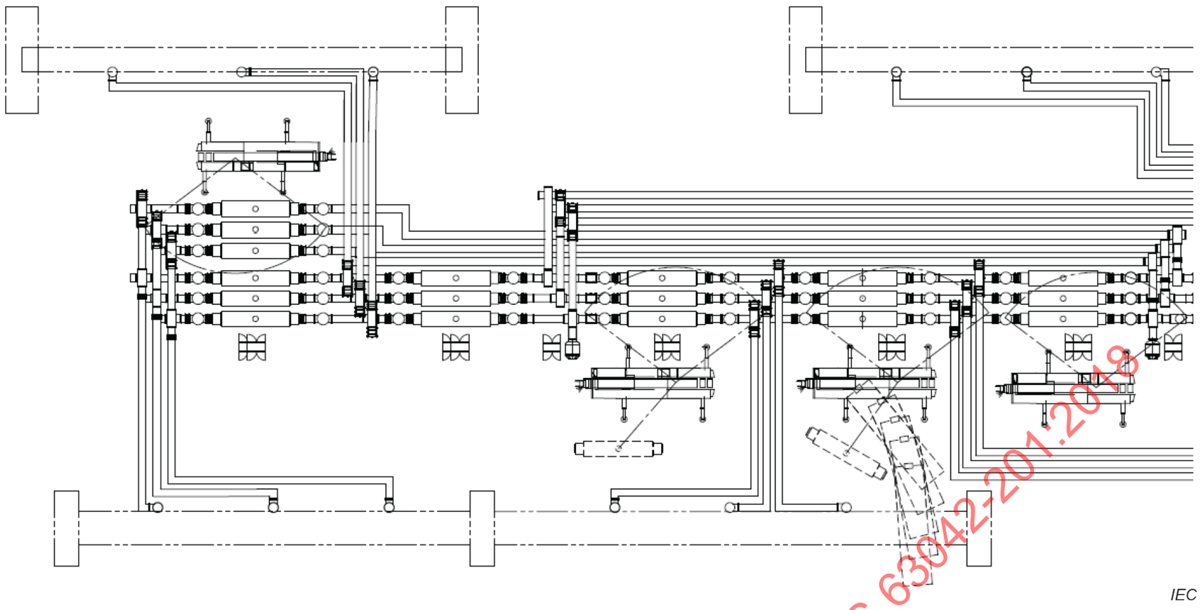


Figure 6 – Typical configuration of UHV gas-insulated switchgear and crane location

b) AIS substation

In case of AIS substations, generally sufficient space is available for installation and removal of any equipment due to the clearance requirement of UHV AC transmission systems. Roads between transformers, circuit breakers and disconnectors may be shared temporarily for assembly and disassembly, testing, or commissioning of equipment, in order to optimize land usage. While considering the layout, space for stationing on-site test equipment such as AC voltage test, impulse test etc. may also be considered.

7.6 Protection against direct lightning strike

For methods of protection against direct lightning strike, see Subclause 8.6 of IEC 61936-1:2010.

a) AIS or MTS substation

Overhead ground wires and/or lightning rods should be installed to shield against lightning in order to prevent a direct lightning strike to the main circuits of the substation.

b) GIS substation

Lightning protection facilities inside the lead-in transmission line of the GIS substation can be omitted for the following reasons:

- the conductive parts are shielded after the entrance of transmission line;
- facilities are not damaged because the energy of the direct lightning strike is extremely small even if it does occur;
- frequency of the direct lightning strike that makes backward flashover occur between GIS enclosures and main circuit conductors is extremely low (less than once per thousand years).

7.7 Earthing systems

7.7.1 General considerations

The earthing systems should be designed on the basis of compliance with IEC TS 60479-1 with the purpose of protecting the entire UHV AC substation.

For the design of earthing systems, see Subclause 10.3 of IEC 61936-1:2010 and IEC 61936-1:2010/AMD1:2014.

Considering that the earth fault current may be large in UHV AC transmission systems, the safety of operators and workers should be assured against the increase of touch and step voltages. The touch and step voltages should both be below a permissible level when an earth fault occurs inside or outside the substation.

When adopting GIS and MTS, the multiple-earthing method should be employed to reduce electromagnetic induced current in secondary circuits.

It is desirable to lay auxiliary earthing mesh under switchgear, whether substation equipment is GIS or MTS, to reduce the electromagnetic induced surge voltage in secondary circuits during an earth fault. There are also cases applied to AIS substation. In addition, the auxiliary earthing mesh material should be resistant to corrosion.

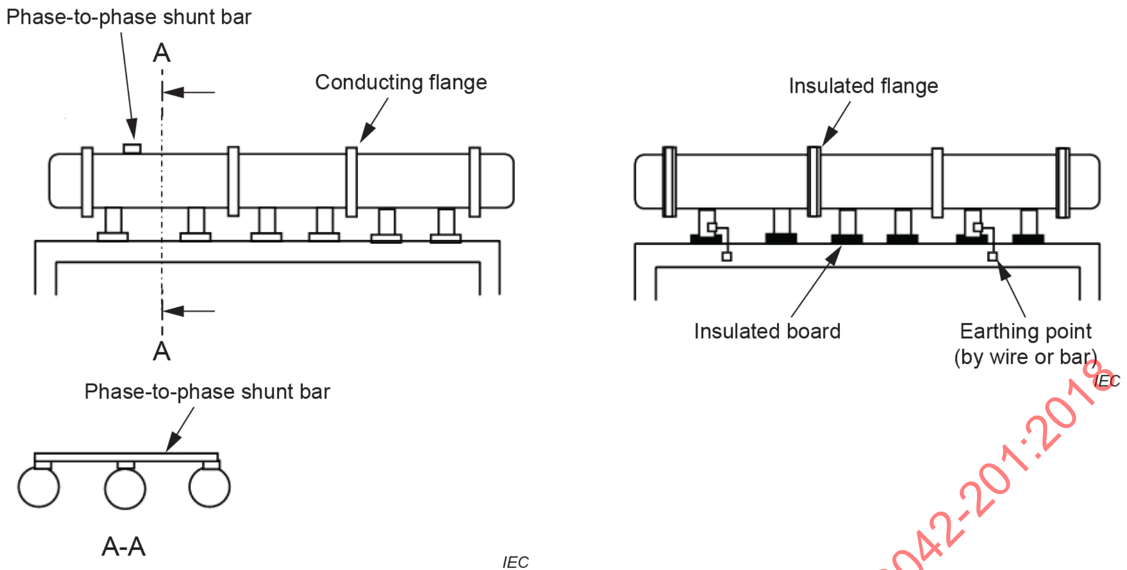
In case of MTS, the earthing current into auxiliary mesh becomes large and the appropriate earthing wire size should be considered. Interphase earthing wire can lead below the ground to realize the circuit connection.

7.7.2 Multiple point earthing method for GIS

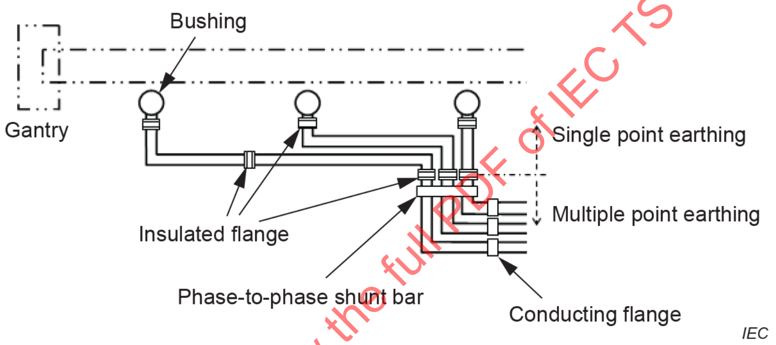
Multiple point earthing design is employed for GIS enclosures (see Figure 7). It should be adopted for the following reasons:

- suppression of induced surge from main circuit to secondary circuit;
- earthing is improved by multiplying the number of connections;
- reduction of eddy current heating of the supporting structure due to leakage flux;
- induced current from each enclosure sheath to the ground generated by multi-earthing method with adoption of a phase-to-phase shunt bar placed at the proper distance.

In case that it is difficult to install phase-to-phase shunt bars such as single point earthing parts, the single point earthing method should be employed. In that case, flashover may be avoided by installing insulated flanges between multi-earthing enclosures and bushing parts.



a) Multiple point earthing system b) Single point earthing system



c) Example of bushing parts using single point earthing system

Figure 7 – Earthing methods

7.8 Seismic design

7.8.1 General

Specifications for seismic performance of the equipment depend on the local regulations of each region, country, area, site, condition of basement, and foundation construction.

This means that the seismic criteria, qualification methods and levels, and performance requirements are standardized for a given equipment type.

Therefore, there are some differences in several guides and standards (see Tables F.1 and F.2 of Annex F).

These differences depend on the conditions and damage of past earthquakes in each region and it is very difficult to harmonize these standards.

7.8.2 Basic seismic design

For seismic design of UHV AC substation switchgear, see IEC 62271-207 and IEC TR 62271-300, and for the design of UHV AC substation transformer, see IEEE 693-2005.

For the consideration of seismic loads in seismic design, see Subclause 4.3.9 of IEC 61936-1:2010 and IEC 61936-1:2010/AMD1:2014.

In a region where earthquakes occur frequently, three qualification levels are recommended according to their frequency: low, moderate, and high.

For seismic design, the following flow chart and procedures in Figure 8 are recommended:

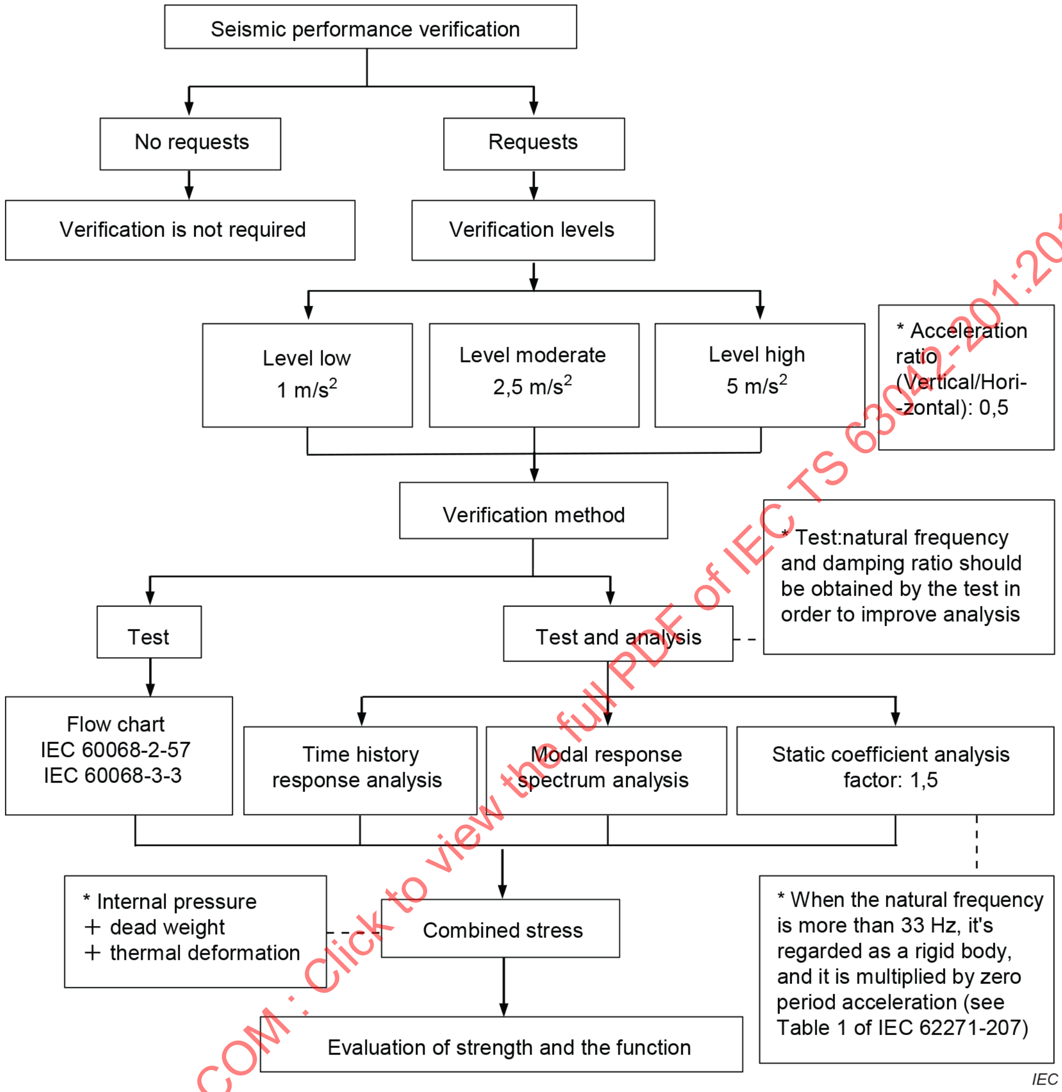


Figure 8 – Flow chart for seismic qualification

a) Gas bushing, surge arrester, oil-immersed transformer, VT, PD, MTS, GIS, and AIS exceeding 800 kV should be qualified for seismic performance before they are installed at a location where an earthquake can occur.

b) A series of seismic tests should be carried out with a full-scale model whenever possible. However, if it is impossible to conduct the seismic test with a full-scale model due to the size of the actual equipment, seismic analysis is often applied. In this case, mathematical models including a computer-simulation model or sub-set (partial model) which can meaningfully represent the whole system may be used to simulate the seismic performance.

7.8.3 Special seismic performance for UHV AC substation equipment

Seismic performance should be taken into account for large and heavy UHV AC equipment (especially porcelain/composite bushings, porcelain/composite surge arresters, voltage transformers, and supporting insulators).

For seismic considerations of UHV AC substation switchgear, see IEC 62271-207 for GIS and IEC TR 62271-300 for circuit-breakers.

From the point of view of the seismic strength, components made of porcelain materials are considered to be the weakest structures used in UHV AC substations.

a) UHV porcelain/composite bushing

   See IEC TS 61463.

b) Porcelain/composite surge arrester

   The appropriate dynamic amplification factor (e.g. 1,4 to 2,0) is considered for a porcelain/composite surge arrester mounted on a supporting structure for UHV AC equipment when tested or computed without a supporting structure.

c) Other considerations

   The following should be considered in the seismic design of the equipment:

   – rocking motion of foundation;
   – ensuring sufficient slack of connecting leads;
   – split foundations.

8 Control, protection and communication

8.1 General

The function and basic component of the control, protection and communication system of an UHV AC substation is the same as that of an EHV substation.

Because of the importance of the UHV AC substation, the interruption of the substation control system network will affect the safe operation of the substation. The control system network of UHV AC substations should be designed in double-set configuration.

When the UHV transformer is of the split type, that is, provided with the independent regulation transformer and compensation transformer tank (sharing the same tank), if the regulation transformer or compensation transformer has small inter-turn short circuit faults, the UHV transformer longitudinal differential protection designed for the whole transformer is hard to operate. Therefore, it is necessary to provide a separate main protection for the regulation transformer and compensation transformer.

The control, protection and communication system in a UHV AC substation should be configured considering both short-term and long-term needs and have both openness and compatibility.

8.2 Control system

The substation control system should use the networked, distributed and systematic hardware structure conforming to international standards. The computer storage and processing capacity should be able to satisfy the final requirement of a UHV AC substation.

The substation control system consists of two parts, station level and bay level. The station level, as the control, monitoring, measurement and management center of all electrical equipment in the station, serves to manage and control the bay level equipment and communicate with the remote control centre. It consists of a station computer, operator workstation, remote communication equipment, etc. which are connected to the network. The bay level consists of control units classified based on the voltage level and electrical bays. In case of a station level equipment or network failure, bay level equipment should be capable of monitoring and controlling the bay equipment locally and independently. The bay level equipment may be disconnected when the equipment in the bay is under maintenance.

The substation control system should have at least the functions of data acquisition and processing, switchgear and transformer tap control, synchronization for circuit breaker closing, event and alarm record, database management, graphical screen generation and display, measurement trend and energy record, remote communication, etc. The communication protocols of a substation control system should follow IEC 61850 (all parts).

8.3 Relay protection

8.3.1 General

Relay protection of UHV AC equipment generally includes UHV transformer protection, UHV busbar protection, UHV reactor protection, UHV line protection, UHV breaker failure protection, etc.

Relay protection of UHV AC equipment serves to ensure the safe operation of UHV AC equipment and the power grid and to improve power supply reliability of the power grid.

8.3.2 Duplicated configuration of UHV AC equipment relay protection

The configuration of UHV AC equipment relay protection should be considered based on its role and function. In general, UHV AC equipment has a large capacity and a high voltage, and is expensive to purchase and repair. Its safe operation is vital to the system stability as well as the safety and reliability of the substation; besides, because the principle and structure of UHV relay protection are relatively complicated and involve many factors, any UHV AC equipment damage or power loss of a substation due to failure or maloperation of protection will result in huge direct or indirect losses, which imposes higher requirements on the relay protection of the UHV AC equipment.

Therefore, to ensure the safety and continuous operation of UHV AC equipment and minimize the effect of fault and abnormal operation on UHV AC equipment and power systems, it is recommended to provide duplicated relay protections for UHV AC equipment all the time. When one set of protection devices fails, the other set should be able to provide a complete relay protection.

Based on the considerations above, duplicated configuration of UHV transformer protections, UHV busbar protections, UHV reactor protections and UHV line protections should be provided. The UHV breaker failure protection serves as the local back-up of the above protection, while the UHV transformer non-electrical protection and UHV reactor non-electrical protection serve as the supplementation of electrical protection. To simplify the protection configuration, it is recommended to provide only one set of such protections, which should operate on two tripping coils of the circuit breaker at the same time.

8.3.3 UHV transformer protection

UHV transformer protection should consider all kinds of UHV transformer and their operating conditions comprehensively.

a) Purpose of UHV transformer protection

   The UHV transformer should be provided with protection against phase-to-earth faults, phase-to-phase faults, winding inter-turn faults, overload, over-excitation, and non-electrical faults.

b) Configuration and function requirements for UHV transformer protection

   UHV transformer protection should include the main protection, the backup protection, non-electrical protection and the abnormal operation protection.

   The main protection of the UHV transformer should be provided with longitudinal differential protection, which serves to protect the transformer inside, bushing, and outgoing line up to CT.

The backup protection of the UHV transformer is used to protect the overcurrent and neutral overvoltage caused by external earthing and phase-to-phase short circuit and serves as backup protection against faults in adjacent components and the transformer.

The non-electrical protection of the UHV transformer generally covers the gas, low oil level, high temperature, high pressure, cooler fault, etc.

The abnormal operation protection covers the overload protection and over-excitation protection.

c) Configuration and function requirements for regulation transformer and compensation transformer protection

When the UHV transformer is of the split type, that is, provided with the independent regulation transformer and compensation transformer tank (sharing the same tank), theoretically internal faults of the regulation transformer and the compensation transformer should be within the longitudinal differential protection range of the UHV transformer.

But the analysis and results of related dynamic simulation tests of protection devices show that as the regulating transformer and compensator transformer has fewer turns than the main transformer, when the regulation transformer or compensation transformer has inter-turn short circuit faults, especially small inter-turn short circuit faults, the UHV transformer longitudinal differential protection designed for the whole transformer is hard to operate. Therefore, it is necessary to provide separate main protection for the regulation transformer and compensation transformer, that is, differential protection for the regulation transformer and differential protection for the compensation transformer.

Independent non-electrical protection should also be provided for the regulating transformer and compensator transformer, which covers the gas, low oil level, high temperature, high pressure, cooler fault, etc.

8.4 Communication

The communication equipment in the UHV AC substation should be configured according to the local dispatching system and the location of the substation in the grid, and adequate backup equipment should be reserved accordingly. The designation of the communication system of the UHV AC substation should satisfy the requirements of local technical standards.

8.5 Electromagnetic compatibility requirements for control and protection equipment

The UHV AC substation has a fairly complicated electromagnetic environment. The control and protection equipment should have sufficient anti-interference capacity. The main sources of electromagnetic interference are as follows:

- operation of HV disconnector and circuit breaker;
- lightning attack lines, structures or relay rooms;
- power system short-circuit fault;
- power frequency electromagnetic interference of HV lines;
- partial discharge (corona, creeping discharge);
- switch operation of the control and protection circuit;
- LV power supply, such as voltage fluctuation, voltage sag and short-time power failure, power frequency change, harmonic, etc.

It should be noted that the interference immunity concerns all equipment as a whole. Even though a single component, or a combination of components can pass the interference immunity test, coupling of further elements may lead to an increased value or a new mode of electromagnetic interference; eventually, the complete system may fail to meet the requirements of immunity.

Since there are multiple kinds of interference caused by switching surge, operation of HSES, VFFO and so on, the investigation on integrated countermeasures against various surges and overvoltages is desirable.

See IEC 60255-26 for other anti-interference requirements of UHV AC substation control and protection equipment.

9 DC and AC auxiliary power supply system

9.1 General

The function and basic component of a DC and AC power supply system of a UHV AC substation is the same as that of an EHV substation.

Because a UHV AC substation is large in size and contains a large number of control and protection components, a single DC power supply system may not be sufficient in terms of reliability and economy. Several DC power supply systems provided in the substation are recommended, each of which is an independent and complete power supply system located where the loads are relatively concentrated.

The AC/DC auxiliary power supply system should be designed based on the requirements of various loads for voltage fluctuation range and power supply capacity.

9.2 DC power supply system

The substation DC power supply system can employ the centralized configuration or distributed configuration. The centralized configuration means the whole substation has only one DC power supply system. This way is suitable for substations with a small size or concentrated DC loads. The distributed configuration means several DC power supply systems are provided in the substation, each of which is an independent and complete power supply system. This way is suitable for substations with a large size and multiple relay rooms. It is recommended to use distributed DC power supply systems in the UHV AC substation.

The DC power system voltage of a UHV AC substation should be determined appropriately based on electrical equipment type, rated capacity, power supply distance, installation site, etc.

As the main transformer, shunt reactor, UHV line, UHV busbar of UHV AC substation are all provided with duplicated protection and duplicated trip circuits of UHV circuit breaker are also required, the DC power supply system should be provided with two storage batteries for the sake of reliable power supply. The two storage batteries should be connected with two single busbars, between which the electric connection device should be provided. Under normal circumstances, the two storage batteries should run independently with no electrical connection, which helps to improve the power supply reliability of the DC system.

The number and capacity required of cells should be designated based on the DC power system voltage, the DC loads and the time of the power failure occurs at the substation.

It is recommended to provide two sets of charging devices for the two storage batteries of the UHV AC substation DC power supply system. To improve the reliability of a DC power supply system, a third set of charging devices can also be provided, which can charge either of the storage batteries through the electric switching device.

9.3 AC auxiliary power supply system

AC auxiliary power supply system needs to operate the total auxiliary load and play an important role to maintain any control function in the substation. The following should be considered:

a) Voltage, circuit configuration and control/protection method of the AC auxiliary supplies should be designed based on the bus scheme, selection of equipment, equipment scale of the substation, and reliability to be required.

b) The capability of load and auxiliary transformers should be designed to accommodate the final load determined during the planning stage.

c) The AC auxiliary circuit should be designed for economy, operation and maintenance.

d) An automatic changeover function should be provided in case of loss of power supply. Duplication of power supply is recommended.

e) Selection of a circuit system should be considered from economy.

9.4 AC uninterruptible power supply (UPS) system

As the host and network equipment of control system employs the duplicated configuration, the UPS host should also employ the duplicated configuration. In the duplicated configuration, two single busbars or a single busbar with bus section connection can be used for connection.

The UPS AC power source of a UHV AC substation should be provided by the auxiliary AC power system, and the DC power source should be provided by the auxiliary DC power system. It is not recommended to provide a special battery for UPS.

10 UHV gantry, support and foundation design

10.1 UHV gantry and support design

10.1.1 General

The structural type and calculation criteria of UHV gantry and support should be determined based on electrical layout, importance of the project and environmental conditions.

a) The basic design parameters of gantry and support, including design service life and importance factors of structure (importance factors are used to adjust the minimum design loads for UHV structures, depending on the risk to human life, health, and welfare associated with their damage or failure by nature of their occupancy or use) should conform to the latest international standard as well as regulations of the specific country.

b) According to the importance of UHV AC substation, the limit state design method based on the probability theory can be used in gantry and support calculation.

c) The gantry should prefer steel pipe or angle steel lattice column and steel pipe or angle steel lattice beam with good stress and aseismic performance. The structural type of the support should be consistent with the gantry. Steel pipe or angle steel lattice support should be preferred.

d) The allowable deflection of gantry and support in serviceability limit state should meet the requirements of safe operation of the electrical equipment.

10.1.2 Load and combination of loads

Load and combination of loads on UHV gantry and support should consider items as follows:

a) Load classification

   Load on the gantry and support can be divided into the following categories:

   – Static load: self-weight of structure, lines and fixed equipment on the gantry (including the insulator string, fitting, line trap and so on);

   – Dynamic load: wind load, ice load, load from the conductor, temporary load during erection and repair, thermal response, and seismic response.

b) Wind pressure and velocity

   The wind pressure and velocity used in gantry and support calculation should be consistent with the important factors and wind sensitivity of structure. The gantry and support should be designed considering the effect of wind vibration and wind vibration coefficient (height factor) should be determined according to the ground surface roughness and height above the ground.

c) Seismic response calculation

The seismic response calculation of gantry and support should be considered as follows:

– Gantry: Seismic response of the gantry should be calculated according to the finite element method. The analysis mode of the seismic response of gantry should be consistent with that of the static force effect; in intensity consideration, axial (tensile) force/bending moment as well as shear force are also necessary;

– Support: The support should be combined with the electrical equipment mounted on the support in calculating the seismic response according to the finite element method.

d) Load combination on gantry and support

Load combination on gantry and support should be determined as follows:

– The design of gantry and support should meet the load-bearing limit and the common operation limit respectively, and their structure should meet the requirements for overall stability and local stability.

– The strength limit state should be determined under three load cases, namely operation, erection, and maintenance. Under operation load case, gale, ice coating and wind, and thermal response should be combined respectively. In serviceability limit state, the erection load case of the gantry can be used as the basis for the calculation of gantry deformation; the quasi-permanent combination value of the wind under the gale load case can be taken as the loading condition for deformation calculation in serviceability limit state of the support.

– The combination of the seismic response should be considered for the gantry and support.

– The load combination factors of lines and lightning wires should conform to the currently valid international standard as well as regulations of specific country.

10.1.3 Detailing requirements

The design of UHV gantry and support should meet following requirements:

a) Appropriate measures should be taken for use of the continuous gantry structure in Figure 9, considering the thermal effect.

b) Different sections of the main member in the gantry and support should be connected with the flange or bolt to reduce the welding work at site.

c) The gantry column should be designed with the ladder, safety cage and other safety devices to facilitate maintenance personnel climbing up and down. The walkways and rail should be provided in the gantry beam for the sake of installation and maintenance.

d) Effective anti-corrosion measures should be taken according to the different atmospheric corrosion mediums for the gantry and support. Steel structures in common environmental conditions should be protected from corrosion by a hot-dip galvanizing or zinc spray.

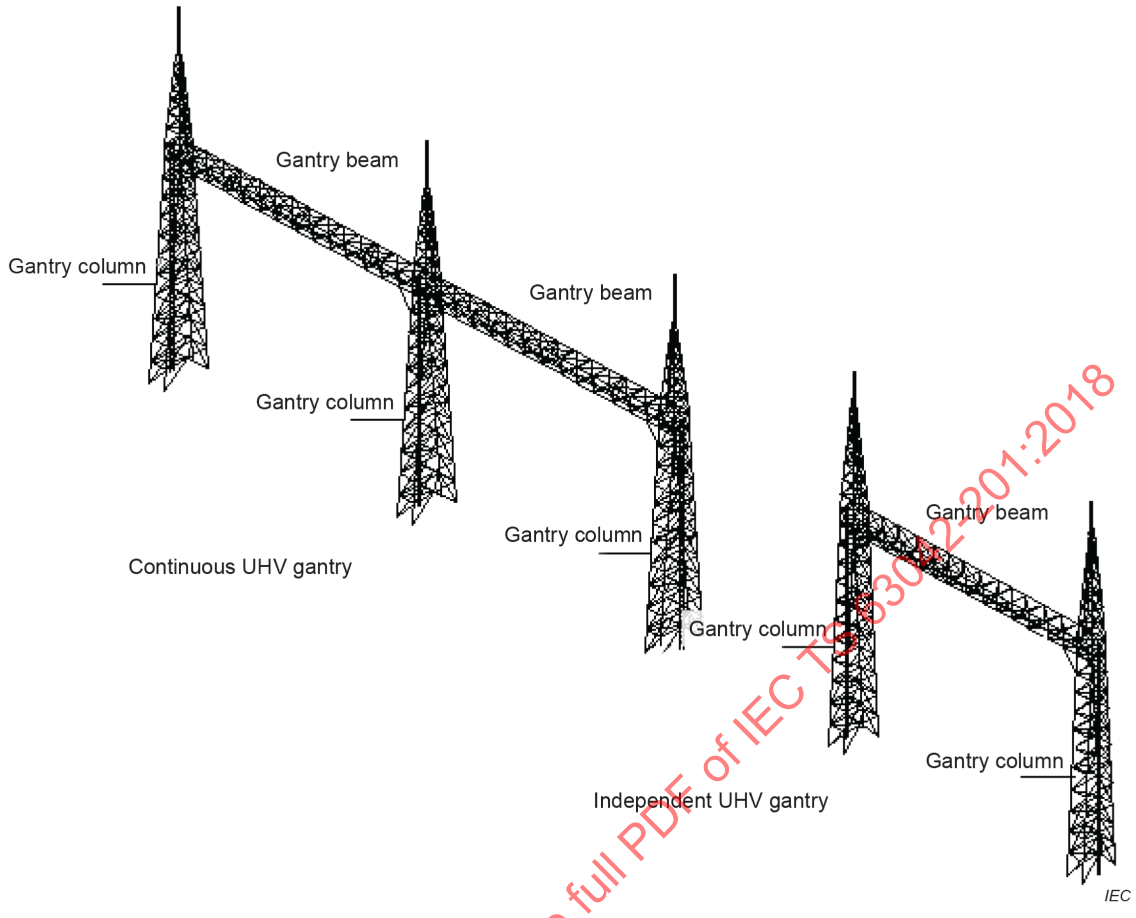


Figure 9 – Example of continuous UHV gantry and independent gantry

10.2 GIS or MTS foundation design

The spread foundation should be installed in the following ground:

- bearing force of ground can be expected;
- harmful settlements do not occur to a superstructure;
- groundwater level is relatively low.

Meanwhile, when installing in the ground where bearing force of ground cannot be expected, the pile foundation or the spread foundation by ground improvement should be installed.

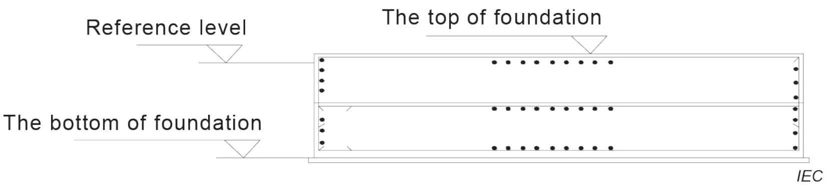
GIS or MTS foundation design should consider items as follows:

a) GIS should adopt the unified raft foundation, raft foundation with upper buttress, or unified box foundation. Within the GIS foundation plane, cable trenches, embedded iron parts, and earthing points are densely, complexly and irregularly set, so GIS foundation should use raft foundation with upper buttress preferentially. The examples of GIS foundation forms are as shown in Figure 10.

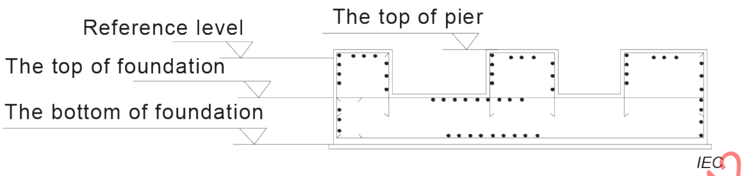
b) When the GIS foundation is too long, efforts should be made together with the equipment manufacturer to set an expansion joint or settlement joint at the corresponding position of the horizontal expansion joint and vertical expansion joint of gas-insulated busbars.

c) The temperature cracks generated by hydration heat impact in mass concrete construction should be prevented or controlled. The design should clearly specify the type of foundation concrete and type and quantity of additives; the surface should be provided with anti-crack reinforcement, and the foundation plate should be provided with post-cast belt.

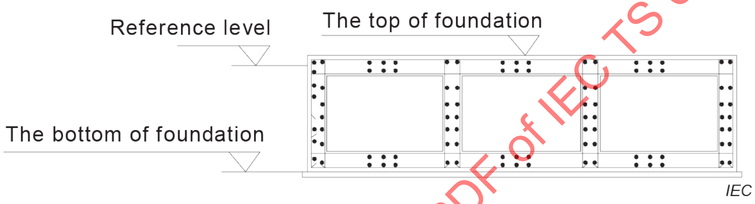
d) In order to monitor the settlement of the foundation in real time, the settlement observation point may be adopted in a position that is mutually visible.



a) Unified raft foundation



b) Raft foundation with upper buttress



c) Unified box foundation

Figure 10 – GIS foundation forms

Annex A
(informative)

Load combination of UHV AC equipment

The following Table A.1 is an example of load combination for UHV AC equipment.

Table A.1 – Example of load combination for UHV AC equipment

Circumstance	Wind velocity	Net weight	Download conductor weight	Ice weight	Short-circuit force	Seismic force
Normal	Wind speed with ice	√	√	√		
	Maximum wind speed	√	√			
Short circuit	50 % of the maximum wind speed, and not less than 15 m/s	√	√		√	
Earthquake	25 % of the maximum wind speed	√	√			Relevant seismic intensity

Annex B
(informative)

Specification of UHV AC equipment and conductor

Voltage specification, short-circuit current specification, noise specification, and surge arrester specification of UHV AC equipment and conductor are respectively given in Table B.1, Table B.2, Table B.3 and Table B.4.

Table B.1 – UHV voltage specification

Voltages in kV (r.m.s. value)

U_s	U_m
1 000	1 100
1 150	1 200

Key

U_S Nominal system voltage

U_m Highest voltage for equipment

Table B.2 – Specification of UHV short-circuit current

Highest voltage for equipment kV (r.m.s. value)	1 100	1 200
DC time constant ms	120	120
Peak factor	2,7	2,7

Table B.3 – Noise specification

Category	China	Japan	India
Highest voltage for equipment kV (r.m.s. value)	**1 100**	**1 100**	**1 200**
Transformer (continuous noise) dB(A)	75	65/70/75[a]	75
Shunt reactor (continuous noise) dB(A)	75	---	80
Outdoors SF_6 circuit breaker (non-continuous noise) dB(A)	110	---	110

[a] The noise limitation of 1 100 kV transformer in Japan depends on the location of the substation.

Table B.4 – Surge arrester specification applied in different countries

Category	China	Japan	India
Highest voltage for equipment kV (r.m.s. value)	1 100	1 100	1 200
Nominal system voltage kV (r.m.s. value)	1 000	1 000	1 150
Rated voltage kV (r.m.s. value)	828	826	850
Continuous operating voltage kV (r.m.s. value)	638	635	723
Nominal discharge current kA	20	20	20
Steep wave impulse residual voltage under 1/10 µs, 20 kA kV (peak value)	≤1 782	≤1 780 (under 1/2,5 µs)	-----
Lightning impulse residual voltage under 8/20 µs, 20 kA kV (peak value)	≤1 620	≤1 620	1 700
Switching impulse residual voltage under 30/60 µs, 2 kA kV (peak value)	≤1 460	≤1 400 (under 30/80 µs, 1 kA)	1 500
Reference voltage under direct-current 8 mA kV (peak value)	≥1 114	≥1 050 (under 12 mA)	-----

Annex C
(informative)

1 000 kV outdoor overhead flexible conductor for UHV AC substations in China

C.1 General

The first 1 000 kV UHV AC substation – Changzhi 1 000 kV substation – is taken as an example. It is preliminarily determined to use four-bundled conductors, and corona check is made on three types of four-bundled conductors – ACSR-1, ACSR-2, ACSR-3.

ACSR-1: four-bundle thermal resistant diameter-expanded hollow aluminium alloy wire, the diameter of sub-conductor is 70 mm and the aluminium conductor's cross-sectional area of the sub-conductor is 1 600 mm^2.

ACSR-2: four-bundle extra light steel reinforced aluminium wire, the diameter of the sub-conductor is 51 mm and the aluminium-conductor's cross-sectional area of the sub-conductor is 1 400 mm^2.

ACSR-3: four-bundle diameter-expanded hollow aluminium wire, the diameter of sub-conductor is 51 mm and the aluminium-conductor's cross-sectional area of the sub-conductor is 600 mm^2.

The ACSR-1 is finally selected and its bundle spacing and sub-span are optimized. The process is introduced as follows:

C.2 Environmental conditions

a) Ambient temperature

   maximum temperature: +37 °C

   minimum temperature: –27,2 °C

b) Ice coating thickness: 16 mm

c) Wind speed: Average maximum wind speed 31 m/s

d) Altitude: < 1 000 m

e) Site pollution severity class: d

C.3 Current-carrying capacity and thermal stability check

C.3.1 Current-carrying capacity check

Proximity effect of bundle conductor lead to a decrease of current-carrying capacity, the actual current-carrying capacity of bundle conductor can be calculated as follow

$$Z = 4\pi\lambda\left(\frac{d_0}{2}\right)^2 \frac{s}{\left(\frac{d_0}{2}\right)^2(\rho+1)} \qquad \text{(C.1)}$$

$$B=\left\{1-\left[1+\left(1+\frac{1}{4}Z^2\right)^{-\frac{1}{4}}+\frac{10}{20+Z^2}\right]\times\frac{Z^2 d_0}{\left(16+Z^2\right)d}\right\}^{-\frac{1}{2}} \tag{C.2}$$

$$I=nI_{xu}\frac{1}{\sqrt{B}} \tag{C.3}$$

where

B is the proximity effect coefficient;

S is the subconductor cross section (mm^2);

d_0 is the subconductor diameter (cm);

ρ is the twist ratio of subconductor;

n is the number of subconductors;

λ is the conductivity of subconductors;

d is the spacing of subconductors (cm);

I_{XU} is the subconductor current (A).

The actual current-carrying capacities of ACSR-1, ACSR-2 and ACSR-3 are listed in Table C.1

Table C.1 – Current-carrying capacity of bundle conductor

Category	ACSR-1	ACSR-2	ACSR-3
Proximity effect coefficient	1,064	1,226	1,163
Actual current-carrying capacity A	>10 000	5 533	3 695

C.3.2 Thermal stability check

Minimum cross-section for thermal stability is

$$A=I\frac{\sqrt{t}}{C} \tag{C.4}$$

where

A is the cross section (mm^2);

I is the fault current (kA, r.m.s. value);

t is the current duration (s);

C is thermal stability coefficient of conductor.

The remarkable thing is that the fault current should contain the DC component. For this UHV AC substation, I = 63 kA, t = 0,35 s, C = 87, and the A is 428,4 mm^2, which is far less than the cross-section of the listed three kinds conductor.

C.4 Determination of bundle spacing

C.4.1 General

Larger bundle spacing increases the equivalent radius and average capacitance of the conductor, the average electric field strength around the conductor thus increases and the maximum electric field strength has a tendency to increase. However, the increased bundle spacing decreases the additional influence coefficient of the electric fields around the sub-conductors, and the maximum electric field strength around the conductor thus has a tendency to decrease. If the former effect is greater than the latter, the electric field strength around the conductor increases; if the former effect is less than the latter, the electric field strength around the conductor decreases. As a result, it is necessary to determine the best bundle spacing so as to minimize the electric field strength around the conductor.

C.4.2 Calculation of maximum electric field strength around conductor

The potential coefficient matrix can be used to calculate the electric field strength E_m around a conductor:

$$E_m = \frac{\sqrt{2} C U_L}{2\pi \varepsilon r_0 \sqrt{3}} = 0{,}00147 \frac{C U_L}{r_0} \quad \text{(C.5)}$$

where

E_m is the maximum electric field strength (MV/m);

U_L is the line voltage (kV);

C is the phase conductor positive sequence capacitance (pF/m);

r_0 is the conductor radius (cm);

ε is the dielectric constant (F/m).

When three phase conductors are arranged horizontally in parallel, Maxwell's potential coefficient matrix can be used to accurately calculate the capacitance C of the middle conductor and thus determine the maximum electric field strength around the conductor accurately.

The relationship between the maximum electric field strength and the bundle spacing is calculated for the ACSR-1, ACSR-2 and ACSR-3 type steel core stranded aluminium conductors, and the results are shown in Figure C.1.

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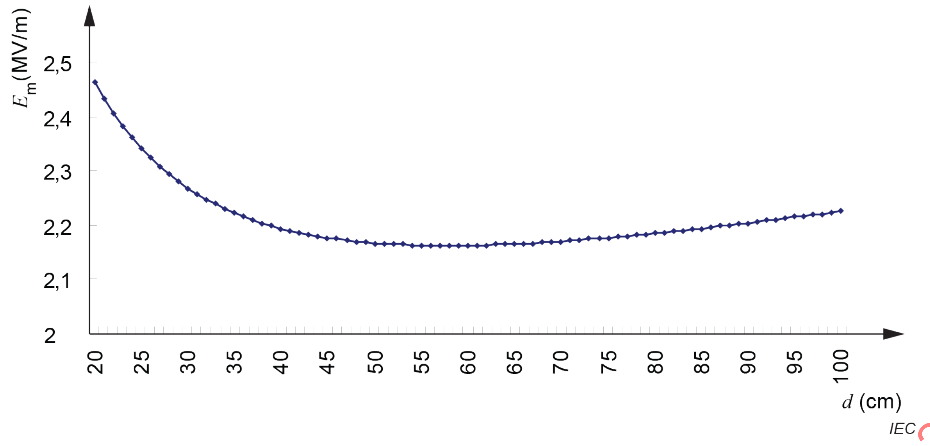
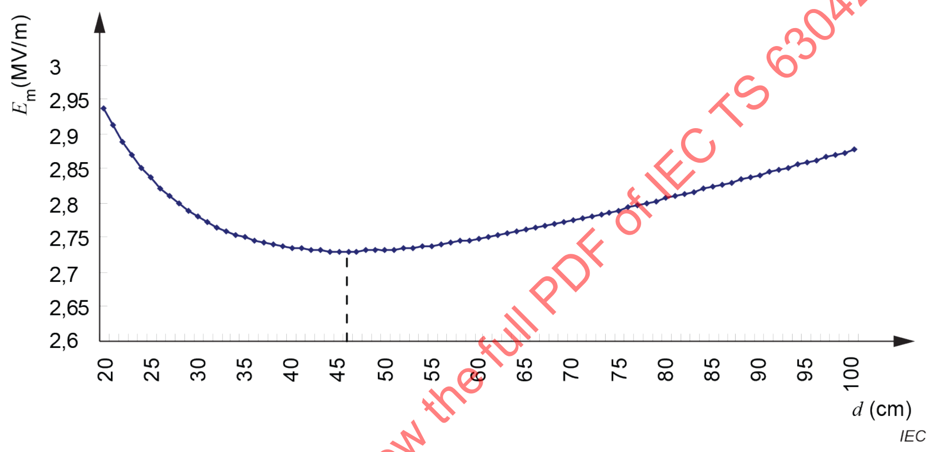


a) **ACSR-1 conductor**



b) **ACSR-2 and ACSR-3 conductors**

Figure C.1 – Relationship between maximum electric field strength and bundle spacing

According to the results, the ACSR-1 conductor with a bundle spacing of 60 cm has the minimum electric field strength.

C.5 Corona inception voltage

The corona inception voltage of a conductor should be greater than the maximum operating voltage at its corresponding installation position. The corona inception voltage of a split conductor can be calculated as follows:

$$U_0 = 84 m_1 m_2 K \delta^{\frac{2}{3}} \frac{n r_0}{K_0} \left(1 + \frac{0{,}301}{\sqrt{r_0 \delta}}\right) \lg \frac{a_{jj}}{r_d} \tag{C.6}$$

$$\delta = \frac{2{,}895\, p}{273 + t} \times 10^{-3} \tag{C.7}$$

$$K_0 = 1 + \frac{r_0}{d} 2(n-1) \sin\frac{\pi}{n} \tag{C.8}$$