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UHV AC transmission systems

Part 102: General system design

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The UK participation in its preparation was entrusted to Technical Committee GEL/8, Systems Aspects for Electrical Energy Supply.

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

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ISBN 978 0 539 04034 0

ICS 29.240.01; 29.240.10

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This Published Document was published under the authority of the Standards Policy and Strategy Committee on 31 August 2024.

Amendments/corrigenda issued since publication

Date	Text affected

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Full document details: PD IEC TS 63042-102:2021

IEC TS 63042-102

Edition 1.0 2021-08

TECHNICAL SPECIFICATION

colour inside

UHV AC transmission systems – Part 102: General system design

INTERNATIONAL ELECTROTECHNICAL COMMISSION

ICS 29.240.01; 29.240.10

ISBN 978-2-8322-1012-7

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UHV AC TRANSMISSION SYSTEMS –

Part 102: General system design

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

Draft	Report on voting
122/109/DTS	122/114/RVDTS

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

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

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

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INTRODUCTION

Large capacity power sources including large-scale renewable energy have recently been developed, but they are generally located far away from load centres. To meet the requirements for large capacity power transmission, some countries have introduced, or are considering introducing, ultra high voltage (UHV) transmission systems, overlaying these on the existing extra high voltage (EHV) systems.

The objective of UHV AC power system planning and design is to achieve both economic efficiency and high reliability, considering its impact on EHV systems.

Moreover, UHV AC transmission systems require comparatively large spaces, and the method of minimizing and optimizing the size and structure of UHV AC transmission lines and substation apparatus is another important issue.

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UHV AC TRANSMISSION SYSTEMS –

Part 102: General system design

1 Scope

This part of IEC 63042 specifies the procedure to plan and design UHV transmission projects and the items to be considered.

2 Normative references

There are no normative references in this document.

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
extra high voltage
EHV
voltages in the range of 345 000 V to 765 000 V

3.2
right-of-way
ROW
strip of land that is used to construct, operate, maintain and repair transmission line facilities

3.3
surge impedance loading
SIL
power delivered by a line to a purely resistive load equal in value to the surge impedance of that line

3.4
ultra high voltage
UHV
highest voltage exceeding 800 000 V

4 Objective and key issues of UHV AC transmission application

4.1 Objective

Recently, large capacity power sources including large-scale renewable energy have been developed, in most cases, far away from the load centres. To fully utilize these facilities, it is important to transmit power generated from these sources efficiently. Evacuation through extra high voltage (EHV) network enhancements would need more lines (right-of-way, ROW) and substations, increasing transmission losses and worsening fault current problems.

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UHV transmission systems are characterized by their large capacity over long distances and can provide a solution to address the above issues by minimizing ROW and switchyard requirements, effectively with fewer losses, improvement of fault current conditions, etc.

For example, the transmission surge impedance loading (SIL) capacity of a 1 100 kV transmission line can replace four to five 550 kV lines, the weight of the towers can be reduced by approximately 30 % and the weight of the wires by approximately 50 %. This can provide savings on the cost of construction of power lines and substations.

A UHV transmission system has many features such as:

- large capacity, long distance and high efficiency power transmission;
- decrease of ROW per unit GW required for transferring;
- improvement of fault current conditions and system stability;
- possible reduction of environmental impact;
- reduction of transmission losses.

4.2 Key application issues

UHV AC transmission systems are capable of transmitting large amounts of electric power.

However, if a failure occurs in a UHV AC system, the system influence can be severe from the viewpoints of reliability and overall security of the supply of the power system. In particular, the UHV AC transmission systems design should be considered to improve lightning and switching protection performance.

In UHV AC transmission systems, typical phenomena depend on the length of the transmission line. For the phenomenon due to the long transmission line, reactive power issues such as voltage rise due to the Ferranti effect and geometrical mean distance for increasing surge impedance loading (SIL) should be taken into consideration. For high voltage issues, it is also necessary to take into consideration secondary arc extinction, temporary over-voltage (TOV) at load shedding, and DC time constant of short-circuit currents.

In addition, size and cost of equipment are large and the system design should aim at minimizing visual impact, construction and maintenance costs and transmission losses, and increasing the network connectivity by forecasting generation and load scenarios.

The history of the development of UHV AC transmission technologies is given in Annex A.

5 Required studies on UHV AC system planning and design

5.1 General

Early strategic system planning is conducted to meet the load growth and power source development planning. Once it is determined that a new transmission line is required in the system, preliminary economic feasibility study and project design begin.

During the term of the project design, three primary decisions should be addressed in a transmission-line project at the conceptual stage: capacity, voltage, and route.

Furthermore, strategic planning, as it relates to the environmental authorizations process, is often overlooked or viewed as being of secondary importance. Early strategic planning for the project-specific environmental review process can avoid significant effects on a project's schedule, costs, and ultimate success.

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5.2 Required studies

The analytical studies can be divided into three types, corresponding to chronological phases of a project's planning, design, and implementation:

1) System planning study

   In the planning stages, wherever new lines are needed, the voltage and current ratings, and major auxiliary equipment such as shunt compensation, are determined. At this stage, system contingencies are considered. Further studies need to be carried out for various power demand and generation scenarios, typical ones including peak demand, off peak demand for various seasons (summer, winter, rainy season), to check adequacy of the proposed transmission system. The basic study is a power flow calculation for which positive sequence parameters are adequate.

2) System impact study or detailed system design study

   The impact of new planned transmission or generation on the power system should be evaluated by the system impact study. Based on the impact study, the high-level specification shall be determined. The system impact study may result in some adjustments, or mitigations applied to the system.

   Study topics include harmonic resonance, short-circuit currents, transient stability, voltage stability, and system relaying. The study tools include short-circuit, stability, and harmonic analysis programmes, and in some cases an electromagnetic transient analytical programme to explore resonant overvoltages. The modelling needs to vary from lumped parameter to distributed parameter, from positive sequence to three-phase unbalanced representation, and from direct current to a few kHz, depending on the subject. Models are often generic in early studies, later progressing to specific models for particular equipment.

3) Equipment and system design study

   Detailed protection and operating procedures for the switchgear, shunt compensation, and related equipment are established. The basic study tool is an electromagnetic transient analytical programme.

   Accurate frequency dependent models are preferable and sometimes necessary for many of these studies.

5.3 Required analysis tools

The main considerations are power flow, fault current, voltage control, dynamic stability and operational criteria that include reliability and system security.

Once the high-level specification (number and type of conductors, voltage level, current rating, and reactive power compensation) has been determined, a more detailed design phase follows to specify equipment, such as circuit-breakers, shunt reactors, and surge arresters. No foreseeable problem should affect the reliable and safe operation of the system.

The analysis tool by time-domain is shown in Figure 1.

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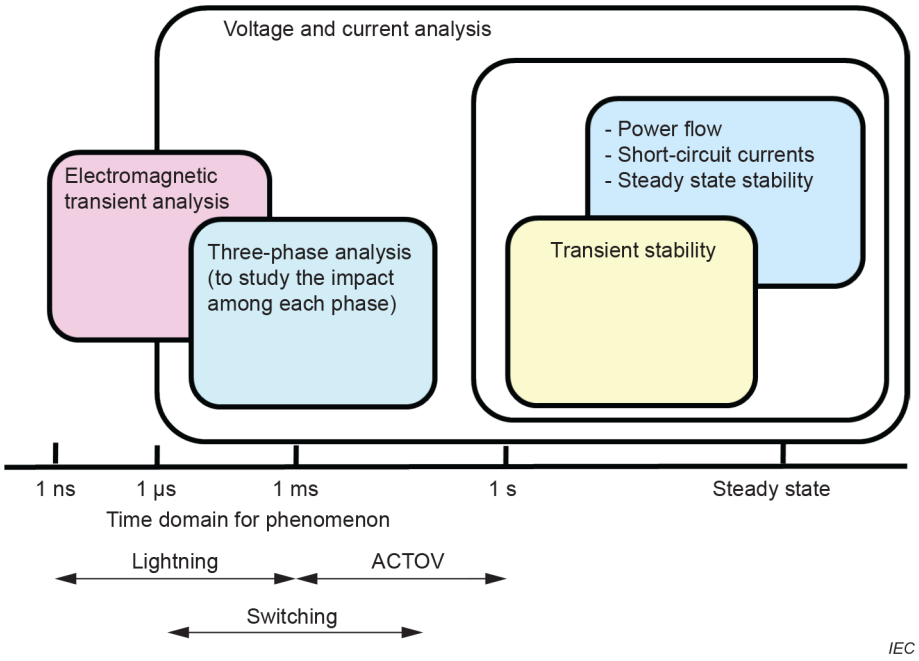

Figure 1 – Analysis tool by time domain

Line constants – a programme that calculates and represents electrical RLC parameters in a matrix form for a general system of tower and conductors, over a range of frequencies, and using either transposed or full unbalanced assumptions. This function may be bundled with another tool, or used separately.

Power flow – calculates steady-state voltages and currents based on a positive sequence model, with non-linear loads. The line model is symmetric and transposed. Power flow is the basic tool for transmission planning.

Short-circuit – a programme that solves voltage and current during faults, especially three-phase and single-phase-to-ground faults. The model is linear, symmetric, and assumes phase transposition. An auxiliary protection function simulates the response of relays to fault current and voltage.

Dynamics – a time-domain simulator based on numerical integration of differential equations. It differs from an electromagnetic transients programme (EMTP) as it focuses on (slower) electromechanical and control system transients, rather than electromagnetic transients. The models are sometimes linear and balanced. The programme usually includes eigenvalue analysis, or other functions for small-signal stability.

Harmonics – a frequency domain programme that solves voltage and current over a range of frequencies, using linear or non-linear load and source models, and balanced or unbalanced impedances. The frequency-scan function outputs driving point impedance, as obtained from the bus voltage for a unit current injection.

EMTP – a time-domain or transient simulator based on numerical integration of differential equations, including non-linear component models, unbalanced impedances, and frequency-dependent RLC parameters. An EMTP can also perform frequency scans, and may include an auxiliary programme of EMTP cable constants.

Electromagnetic field programme – a programme can compute electric and magnetic fields in the air and soil, as well as electric potentials, and the current distribution in the soil and in the conductors.

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6 UHV AC system planning

6.1 General

6.1.1 Introductory remarks

Generally, the planning study process includes the following steps. As UHV AC system planning has specific requirements, some considerations are necessary for each step.

Experiences relating to UHV AC transmission development are given in Annex B.

6.1.2 Transmission capacity considering routes and line types to use

In the planning and design of power grid, increasing the voltage level of the transmission line to UHV not only increases the transmission capacity, but also reduces the cost of the transmission system and increases the corridor utilization rate of the transmission line.

The economic transmission distance of UHV transmission lines can be as much as 1 000 km to 1 500 km or even longer. The single line transmission capacity with 8 bundled wires can reach 12 000 MW. In the selection of UHV transmission capacity, the economic benefits of the entire power grid should be considered, rather than being limited to the economic benefits of a transmission line project.

6.1.3 Reactive power management issues

In the planning of the power system, the planning of reactive power supply and reactive power compensation facilities shall be included. In the engineering design of UHV AC transmission, the design of reactive power supply and reactive power compensation facilities should be carried out.

An appropriate amount of reactive power supply should be planned and installed in the UHV AC system to meet the system voltage regulation requirements and reduce the unintended reactive power transfer between different network nodes.

A sufficient amount of reactive power supply with flexible adjustable capacity, as well as reserve capacity of reactive power should be maintained.

The configuration of reactive power compensation and equipment type selection should be technically and economically compared.

Planning and design of the reactive power compensator for a UHV AC system should meet the overvoltage limiting requirement of UHV AC transmission systems.

The process of configuring reactive power compensation for a UHV AC system is as follows:

Step 1

Identify the range of likely active power flow across the UHV line, calculate and analyse the characteristics of reactive power and voltage profiles along the UHV line, taking into account the charging reactive power produced by UHV AC lines and reactive power loss under different power flows.

Step 2

Select the UHV transformer tap position to avoid overvoltage under a range of operating conditions taking into account UHV substation location, number of transmission lines connected, and system operation mode.

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Step 3

Select the capacity and location of the UHV shunt reactor with consideration given to limiting temporary overvoltage and reducing secondary arc current, and balancing charging power of lines and flexibly controlling bus voltage.

Step 4

Identify the total and unit capacity of the compensator installed in the tertiary side of the transformer. The total capacity should be selected to reduce the reactive power exchange between different voltage levels and maintain bus voltage in an admissible range. When selecting the single bank capacity, the voltage fluctuation induced by switching of the single group capacitor or reactor within a reasonable range should be taken into consideration.

Step 5

Check if the dynamic reactive power reserve provided by generators is adequate within their reactive power capability range. If it is adequate, then the process stops, otherwise go back to Step 4.

Figure 2 shows the process of configuring reactive power compensation.

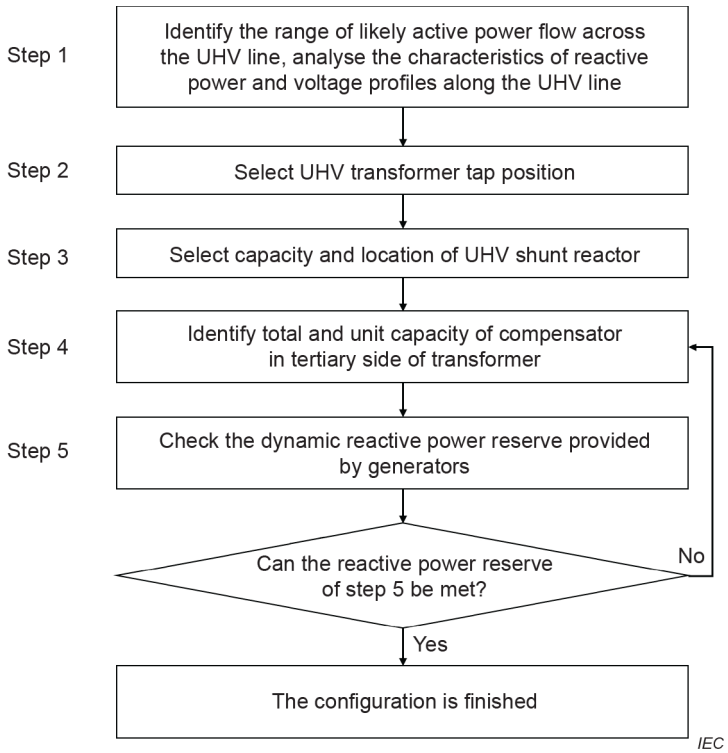

Figure 2 – Flowchart of reactive power compensation configuration

6.1.4 Environmental issues

The environmental impact of a power transmission project generally includes the impact on the ecological environment, electromagnetic fields, land occupation, visual landscape, etc. At present, the public's awareness of the quality of the environment in which they live has been strengthened, and more and more attention is paid to the environmental impact of power transmission projects. It is the responsibility of the users to ensure environment related laws and regulations in each country are complied with.

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During the UHV AC system planning and feasibility research, environmental issues should be included. A UHV AC transmission has the advantage of saving the total width of transmission corridors, as a result of its huge transmission capacity. However, because of its higher voltage and rated current, it may cause more serious electromagnetic fields and related problems, which include power frequency electric field, power frequency magnetic field, corona phenomenon, radio interference, audible noise. Corresponding countermeasures should be considered during the substation and transmission line design. Appropriate tests and measurements should be carried out to verify the effect of the countermeasure, during research and system commissioning.

6.2 Scenario for system planning

System planning mainly includes power load forecast, power source development planning and power grid planning. System planning is formulated considering the load growth demand, site selection of power source, and paths and networking with regard to how to connect the demand side and the supply side. Then power grid planning depends on the power development source planning. Construction of power plants requires several years but its prerequisite is that the corridors and required network enhancement are prepared.

In general, the construction period of a UHV transmission line may be comparatively longer than that of a lower voltage level and requires more restrictions. Therefore it is necessary to determine when and how to introduce UHV AC transmission systems based on the accumulated experiences and findings as well as demand forecast and then formulate planning scenarios to take account of the required construction period and the timing of power plants commissioning.

6.3 Scenario for network planning procedure

6.3.1 Power transmission capacity

Under steady-state balanced AC conditions, a power line can be represented by the simple π equivalent circuit shown in Figure 3.

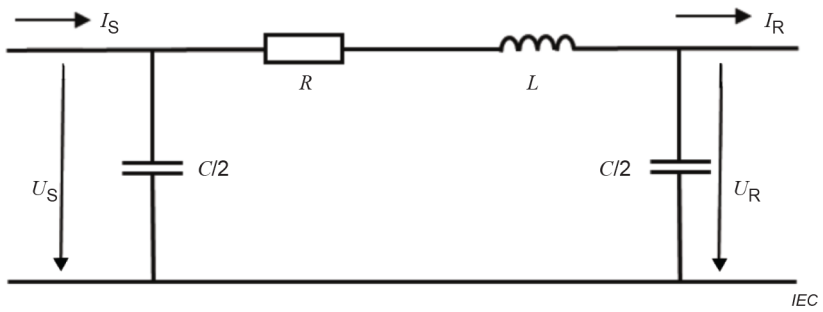

Figure 3 – π equivalent circuit

In Figure 3, the subscript "S" on the voltage and current applies to the sending-end and the subscript "R" to the voltage and current at the receiving-end of the line. R is the series resistance, L is the series inductance and C is the total shunt capacitance of the line.

NOTE Due to the fact that the corona loss of a UHV line is relatively small compared with other components, its conductance is ignored in the equivalent circuit model.

Shunt conductance provides a resistive path in parallel with both shunt capacitors. However, since the basic insulation for transmission lines is air, the shunt conductance is assumed to be zero and is ignored.

An analysis of a loaded line shows that, if line losses can be regarded as small in comparison with the power transferred by the line, the maximum power that the line can transmit is given by Equation (1):

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$$PL = U_S U_R \sin(\delta) / X \quad (1)$$

where:

PL is the power limit of the line, power transmission capacity;

U_S and U_R are the RMS values of the sending-end and receiving-end voltages, respectively;

X is the series reactance of the line;

δ is the phase difference between sending-end and receiving-end.

6.3.2 System voltage

The maximum power that a line can transmit is directly proportional to the product of sending-end and receiving-end voltages. Typically, in most transmission systems, sending-end and receiving-end voltages are more or less the same and hence the power limit is proportional to the square of the system voltage. Then higher voltages are used to increase the power to be transmitted. As the voltage increases, the change in reactance is generally small. Though increases in voltage require greater phase spacing and more insulation, wider rights-of-way, the relationship is not linear, and the economics of line design as well as the environmental impacts are, usually, in favour of increasing the voltage instead of placing additional parallel lines in the same right-of-way.

However, to upgrade the voltage, the insulation to ground and between phases has to be increased. In addition, the conductor surface gradient shall be maintained below certain levels to prevent the generation of audible noise and radio and television interference. Frequently these requirements lead to larger towers and conductors.

System voltage is described in IEC 60038 which shows two voltage levels (1 100 kV and 1 200 kV) so that the introduced voltage level should be selected to meet the individual network topology.

6.3.3 Route selection

Transmission-line routing is the selection of a corridor for a proposed line based on optimizing engineering, environmental, and economic criteria.

During the route selection process, there will be numerous tradeoffs between some of the factors listed previously. For example, a delta configuration tower may be desirable from an electric field standpoint and smaller right-of-way, but taller and difficult in terms of construction and with high costs.

It is clear that each major design factor needs to be evaluated from its impact on the environment. Sophisticated digital techniques, such as composite map with computer graphics, could visually indicate optimum and alternate transmission lines easily. In addition, there are specific circumstances for each area that need to be considered. For example, the geographical area under consideration may have restraints concerning population density, transportation line routes, preservation of natural habitats and areas of historical significance, that could prohibit or severely restrict any transmission line construction.

There will be trade-off between environmental concerns and economics involved in line delineation. With the soaring cost of land in some areas of the country, corridor length becomes a crucial issue. Another factor contributing to line routing costs is the clearing method itself. If the optimum line goes through surrounding vegetation, there might be additional cost to clearing and maintenance. Also, right-of-way, such as legal fees, should be considered.

Route selection should begin at an early stage in the strategic plan. This will allow for the optimum solution to be thoroughly documented, compared with alternatives, and presented in a convincing manner to governmental and private bodies as well as to the general public.

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6.3.4 Series compensation

The power limit is inversely proportional to the series reactance of the line. This reactance is directly related to the phase separation and the dimensions and configuration of the phase conductors as well as the line length. For a given length of line, the power limit can be increased by reducing the series reactance. This involves a reduction of phase spacing. However, considering the restriction of clearance of phase-to-phase, phase spacing cannot be reduced much.

For long lines, it is necessary to reduce the series inductance electrically by means of series capacitive compensation.

During the project planning and feasibility research, the reactance, rated current and location should be considered.

The reactance of a series capacitor is selected as a fixed percentage of the reactance of the transmission line. The percentage is selected from criteria like system power flow, stability, sub-synchronous resonance, etc. The cost of the equipment should also be considered. A 40 % series capacitive compensation degree has been used in some UHV AC projects.

The rated current of a series capacitor should be selected based on the research of continuous, emergency and swing current requirements of transmission lines. The cost is also an important issue.

Normally, series capacitors are installed at terminals of a transmission line in substations. If there is not enough space in substations, they can be installed at appropriate points of the line. However, power supply and other auxiliary equipment have to be equipped for these standalone series capacitor stations.

The electrical resonance produced by the series arrangement is always below power frequency so that resonance at power and harmonic frequencies will be avoided. In a series capacitor compensated transmission system connected with a thermal generator, sub-synchronous resonance risk shall be analysed carefully. Accordingly after analysing results, some specific suppression and protection technology and equipment may be necessary.

6.4 Required parameters

To formulate the feasibility plan, the assessment by both technical and economic aspects is required so that various analyses can be carried out. In such studies, it is important to use adequate parameters so that the referential or typical parameters are better prepared in advance.

The typical required data for the feasibility study are as follows:

– line data for power flow analysis (R, X /km positive sequence);
– line data for fault current analysis (positive sequence impedance, negative sequence impedance, zero sequence impedance/km);
– load data;
– transformer data (e.g. reactance, impedance, grounding method);
– generator data;
– generators' model for dynamic simulation (e.g. governor model, generator model);
– unit price of the transmission line and substation.

6.5 Transmission network (topology)

The transmission network should be well coordinated between transmission lines and devices in the substations and this depends on the individual system criteria, grid codes and guidelines

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as well as geographical characteristics. Adequate systems also depend on the system configuration of their subsystem. As a result, network requirements are dominated by such a topology.

Considering the expectation for UHV AC transmission systems, reliability and flexibility are key issues. In particular, how to maintain the reliability and increase flexibility for the integration of renewable energy generation is important.

At the beginning of the project and during the transition period, the coordination in voltage control and system operation between UHV and the lower voltage level should be considered.

In addition, the interaction is another consideration. As for the interaction between AC systems and DC transmission systems, it is necessary to consider how to decrease the impact when DC transmission systems malfunction and provide little impact to DC transmission systems when AC systems malfunction. As for DC-AC interaction, inter-tie should also be considered.

To introduce UHV AC transmission systems, it is important to consider such a transmission network topology as well as technical requirements.

6.6 Reliability

A feasibility plan should keep the system reliability to some degree. UHV AC transmission systems, in particular, require high reliability to avoid widespread influence of their system failures due to their characteristics.

As for the system reliability, the following aspects can be checked.

1) Overloading

   Most UHV AC transmission systems projects are targeted to deal with mass power to avoid failures spreading to whole systems.

   It is therefore necessary to set up a plan not to overload the facilities under the contingency. Generally single contingency (N - 1) is considered to check the overload situation but UHV AC transmission systems require high reliability so that targeted contingency should be considered according to the individual network topology.

2) Fault current levels

   Fault current level affects switchgear duty and electrical life time. Increased penetration in transmission systems can increase the prospective fault current levels.

3) Voltage stability

   UHV AC transmission systems provide more reactive power than EHV. Switched or variable shunt reactors associated with the system may provide more flexibility in reactive power control. However, the loss of these components shall be considered as a contingency in voltage stability analyses.

4) Dynamic stability

   Installation of higher voltage is favourable to angle stability. On the other hand, generally in UHV AC transmission systems, long distance transmission lines are used which worsen the angle stability. For due diligence, stability should be checked to determine whether a UHV installation has any significant impact on the transmission of a large amount of electric power.

5) Ferroresonance

   Ferroresonance is sensitive to the amount of capacitance isolated with a transformer and shunt reactor. Because of the long length and bundle wires of UHV AC transmission lines, the phase-to-phase and phase-to-ground capacitance of UHV AC are larger, which generates much capacitive reactive power. When a large amount of capacitive reactive power passes through the inductive components (e.g. transformers and transmission lines) of the system, the voltage will increase at the end of the line, which appears as "capacitive effect" or "ferroresonance" phenomenon. Transformers and long distance UHV transmission

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lines should not be switched together. To reduce the effect of "ferroresonance", a shunt reactor is generally selected to limit the overvoltage of the UHV AC transmission system. A shunt reactor generally connects between the middle or end of the UHV/EHV transmission line and the ground which is parallel to the grid for compensating capacitive current. The shunt reactor to compensate the capacitive charging power on the line may be a measure to reduce the increase of power frequency voltage.

6) Angle stability

Angular separation between adjacent buses is used to check reliability when carrying out system studies (steady state analysis) for transmission planning. The value below 30° is often used for the angular separation under the N - 1 contingency condition. Accordingly, the same is assessed while carrying out system studies.

7 UHV AC system design

7.1 General

In the design stage, one of the most important issues is how to counter overvoltage under various system conditions due to UHV system characteristics. To maintain the high reliability of UHV AC transmission systems, many kinds of analyses are required. The following items are typical issues:

1) voltage control and reactive power management;
2) overvoltage analysis and insulation coordination;
3) switching transients (energization, fault clearing, etc.);
4) influence of TOV and energy duty on arrester specifications;
5) lightning transients and arrester placement;
6) impact of auto-reclosing on system availability and reliability that could be considered in the planning study;
7) shunt reactor energization and zero-offset phenomenon when high compensation degrees are deployed.

7.2 Reactive power management

Reactive power compensation at the UHV side (primary side) refers to equipment that is directly connected to the UHV AC line or bus, including fixed capacitors and controllable shunt reactors. UHV shunt reactive power compensation is mainly used to compensate the charging reactive power of a UHV transmission line, limit temporary overvoltage and limit voltage to below the maximum operation voltage in transmission line energization. In addition, a shunt reactor with a neutral point reactor may be used to limit secondary arc current.

A shunt reactor connected to UHV transmission lines is used for reactive power compensation and overvoltage limiting. For substations with some short lines, the shunt reactor is normally connected to the bus, which is mainly used to compensate the charging reactive power of the UHV transmission line.

7.3 Reclosing schemes

The secondary arc is generally extinguished within several hundreds of milliseconds in a 550 kV system and below after the transient fault is cleared. Generally, single-phase auto-reclosing is widely used in EHV transmission lines, because of its advantage in increasing system stability.

In a UHV AC system, because higher voltage is induced electrostatically from the healthy phases, extinguishing the secondary arc might be more than several hundreds of milliseconds. To reclose in less than 1 s was evaluated as difficult without applying special measures.

There are two major methods, four-legged reactor and high speed earthing switches (HSESs), to realize the extinguishing of the secondary arc.

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