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TECHNICAL SPECIFICATION

colour inside

UHV AC transmission systems –
Part 102: General system design

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

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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.

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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.

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.

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.

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.

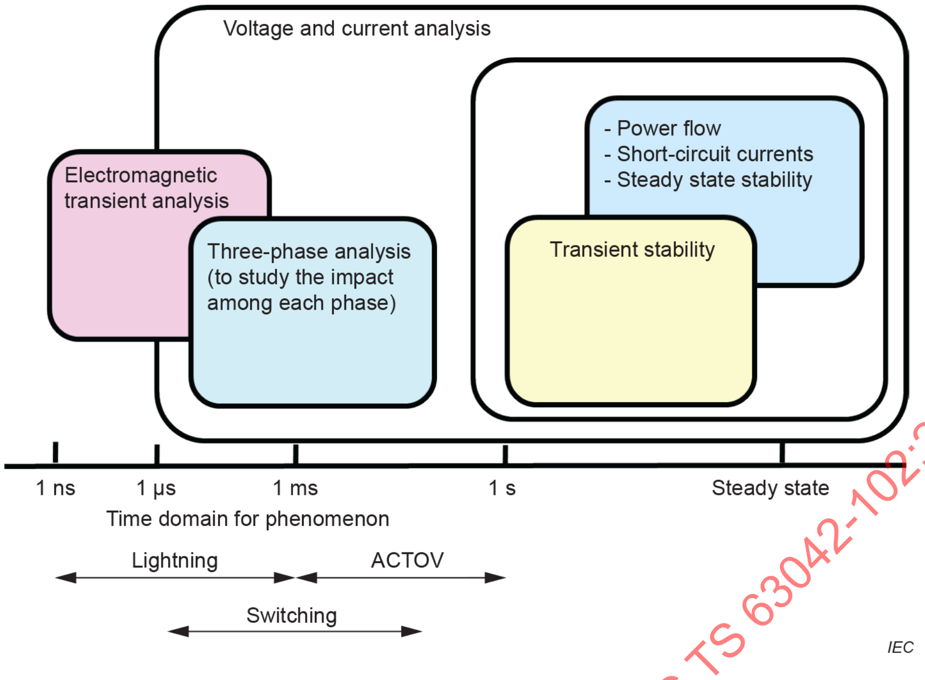


Figure 1 – Analysis tool by time domain

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.

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.

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.

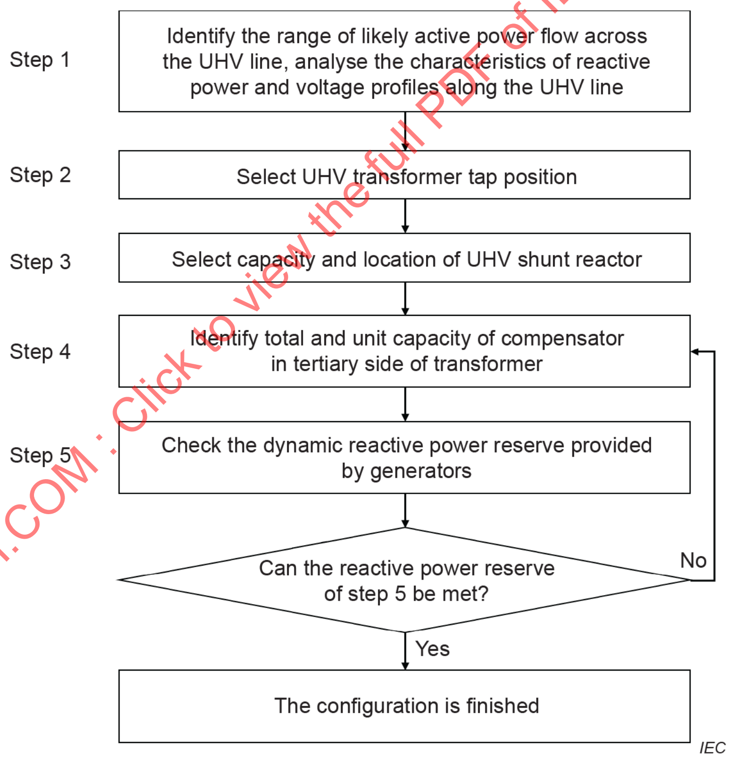


Figure 2 – Flowchart of reactive power compensation configuration

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.

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.

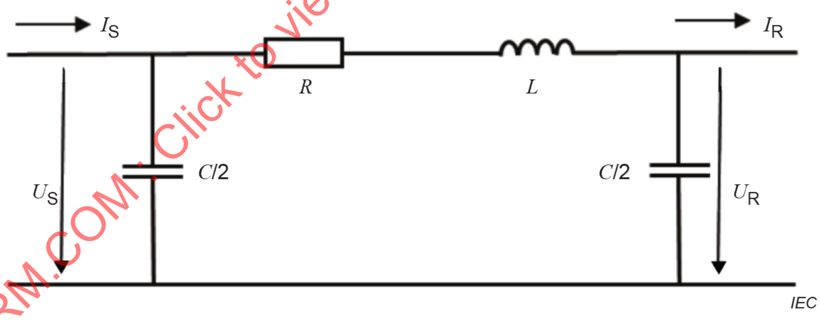


Figure 3 – π equivalent circuit

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):

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

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.

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 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 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.

For a UHV transmission line with shunt reactor compensation, four-legged reactors can be used to decrease secondary arc current and recovery voltage, and help extinguish the secondary arc.

The use of an HSES is one of the solutions, which immediately extinguishes the secondary arc of the faulted phase grounded by the closing operation of the HSES.

In addition, the multi-phase-reclosing system is one of the most effective technologies to minimize the possibility of losing both circuits on the double-circuit transmission line.

In the case where the multi-phase-reclosing system is adopted, a four-legged reactor or an HSES should be used.

1) Four-legged reactor

   The circuit of a four-legged reactor is shown in Figure 4. "X_L" is the three-phase shunt reactance which are used to compensate the capacitive charging current of the transmission line.

   "X_N" is the neutral earthing reactance which is connected between earth and the neutral point of the three phases "X_L". The reactance "X_N" should be appropriately chosen, as it works together with "X_L" to adequately compensate the phase-to-phase capacitive reactance of the transmission line.

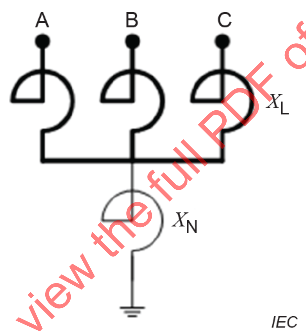


Figure 4 – Four-legged reactor

2) High speed earthing switch (HSES)

   The HSES of the faulted line closes after the fault has been cleared to extinguish the secondary arc forcibly, and then quickly opens for system restoration.

   An HSES is designed with high reliability both mechanically and electrically so that its malfunction will not cause a fatal failure of the entire power system. The reclosing scheme is shown in Figure 5 and the specification is shown in Table 1.

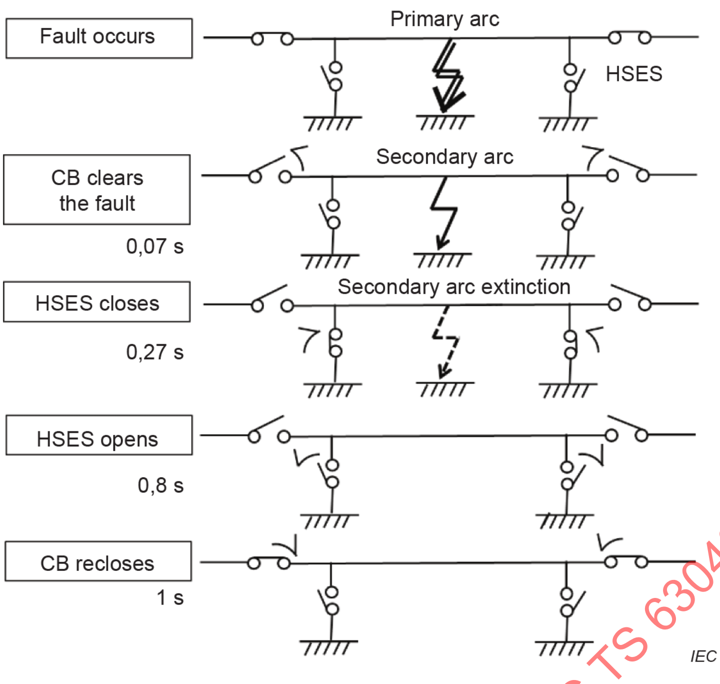


Figure 5 – One typical reclosing sequence of high speed earthing switches (HSESs)

Table 1 – Specification of reclosing scheme

Type	Secondary arc extinction
HSES	150 A for 4 s

For a very short UHV line, such as 20 km or less, which is typically used to connect an adjacent power plant or a convertor station with a substation, an HSES is not necessary due to very small secondary arc current.

For a short UHV line with a length of several tens of kilometres, increasing the dead time of auto-reclosing to 1 s to 2 s is an economical measure.

7.4 Delayed current zero phenomenon

In UHV AC transmission systems, the time constant of the transient DC component is longer and its magnitude is larger than in lower voltage systems because of large charging in MVA, multi-bundle conductors with small resistance, and the closeness to power sources.

An eight-conductor phase wire is introduced to suppress partial discharge on the transmission line to a low level. Since it lowers line resistance, it increases the time constant of the DC component in the short-circuit currents to longer than 45 ms, the IEC standard value.

In a UHV AC transmission system, the delayed current zero phenomenon occurs more easily than in a lower voltage system because of the large charging MVA and the small line resistance. This means that the fault current may not cross zero within several cycles, and the occurrence of this phenomenon may cause damage to circuit-breakers and influence the performance of the power system.

This phenomenon is most likely to occur in a line-to-line short-circuit as its frequency of occurrence is higher in a double-circuit line than in a single-circuit line. A circuit-breaker is required to clear the fault current even if lightning multiple-stroke currents invade it.

7.5 Protection and control system

When DC transmission lines operate in the network, the planning and design of the UHV AC line should consider their mutual influence and follow the principle of coordinated development.

In the case where the UHV AC transmission line and UHV DC/HV DC transmission line exist in parallel, the AC transmission line should be able to bear the transfer of power after DC blocking.

The protection system is mainly introduced to maintain healthiness of the system and equipment, and minimize the influence of UHV AC transmission systems failures. Since the UHV AC system requires a high reliability, it is desirable to adopt protection systems with high performance of speed, accuracy, and reliability.

In particular, the following protection and safety control systems should be considered:

– transmission line protection relay;
– back-up protection of a transmission line;
– transformer protection relay;
– bus protection relay;
– reactive power control, etc.

The system protection and relay protection should be designed for different fault levels to ensure the system security and stability.

The first defence consists of fast and reliable relay protection and effective preventive control measures which ensure that the power grid maintains a stable operation and normal power supply when a common single fault (high probability of failure) occurs. Generally, it is the relay protection that can quickly and accurately remove the faulty component and offer protection against abnormal operation and quickly isolate faults without loss of load.

The second defence consists of emergency control measures such as stable control devices, generator tripping, and load shedding which are used to ensure that the grid can continue to operate in a stable manner in the event of a serious failure (low probability of failure). Generally, it is a safety automatic device that ensures safe operation of the power grid, allowing a small load loss, and avoiding component overload and grid instability.

The third defence consists of out-of-step splitting, frequency and voltage emergency control devices. When the power grid encounters multiple serious accidents with low probability and stability is impacted, one relies on these devices to prevent accidents from expanding and prevent large-scale power outages. All necessary measures shall be taken to avoid grid collapse.

7.6 Insulation design (cost effectiveness)

UHV technology is characterized by a stringent need to reduce as far as possible the sizes, weights, costs and environmental impacts of the overhead lines and substations, in order to get projects which are feasible from an economic, societal and technical point of view.

Figure 6 shows the overall concept to be adopted for insulation.

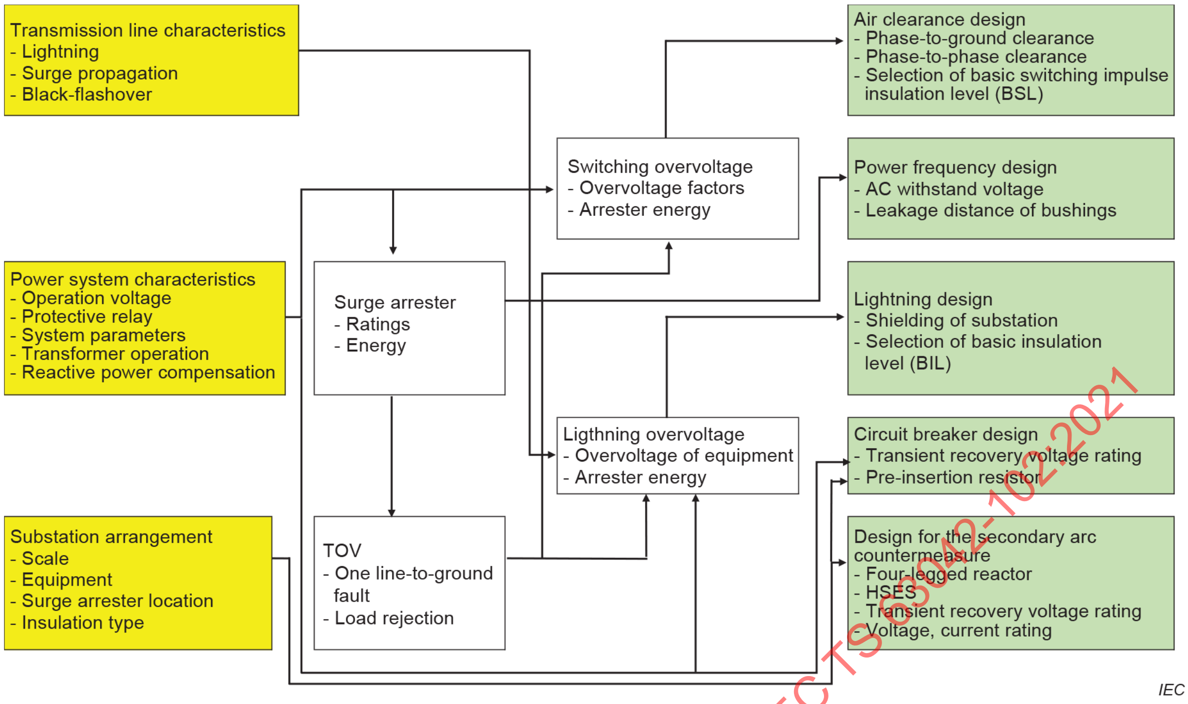


Figure 6 – Procedure for insulation design

A typical countermeasure used to reduce the insulation levels is the application of surge arresters. Closing resistors are used to control switching overvoltage (SOV) due to closing and re-closing of overhead transmission lines.

Switchable or controllable shunt reactors, fast protection schemes, single-phase auto-re-closing, three-phase auto-re-closing and four-legged shunt reactors are applied to achieve stable power supply when a fault occurs on the lines.

With respect to switching overvoltage generated in the healthy lines at the source side of the circuit-breaker (CB) when clearing a fault, it depends on the fault conditions and tends to be larger in multiphase line faults to ground such as two lines-to-ground fault and three lines-to-ground fault. The probability of the occurrence of these faults may be comparatively low in UHV AC transmission systems. As for the methods of technology to avoid successive breakdowns that may affect the availability of the whole system, opening resistors can be one option to reduce the opening SOV.

A summary of system technologies specific to UHV AC transmission systems is given in Annex C.

Annex A
(informative)

History of development of UHV AC transmission technologies

A.1 General

The history of UHV systems development is surprisingly long. In the 1970s, UHV studies were launched in several countries. The USA and Russia established the basic design and Italy resolved basic technical issues and developed several devices and basic ideas to counter UHV typical issues.

Japan developed UHV full components and tested them in the 1990s. China constructed a UHV transmission system and proceeded with its commercial operation since 2009.

India also strived to construct UHV systems with the highest voltage (1 200 kV).

The detailed history of each project is described below.

A.2 History of development in the USA

American Electric Power (AEP) started 800 kV transmission in 1969 and presently owns more than 3 400 km of nominal 765 kV lines and 24 major substations, integrating key generating plants with load centres throughout the eastern AEP system and providing interconnections with neighbouring utilities.

Bonneville Power Administration (BPA)'s 1 200 kV Transmission Line Test and Development Program was initiated in the mid-1970s to meet the need for economical transportation of large amounts of electric power over limited rights-of-way and with minimum power loss. In 1974, BPA authorized the construction of a three-phase, 1 200 kV prototype transmission line in order to investigate the technical, economic and environmental feasibility of transmitting electric power at this voltage. After the 1 200 kV test facility was completed in 1977, an extensive testing and evaluation programme was launched.

A.3 History of development in former USSR and Russia

Russia is extremely rich in natural resources. The main sources of energy were concentrated in the distant Asian part of Russia, whereas the population was concentrated mainly in the European and Southern parts, leaving vast spaces in the polar region and Siberia sparsely populated. Electric energy was used mainly for industrial purposes, domestic consumption per capita was small and distances to transport electric energy were large. A total of 900 km of 1 150 kV AC transmission line were operated for two years, as test voltage.

A.4 History of development in Italy

At the end of the 1960s, the electricity demand in Italy was still doubling every ten years. As this robust growth was foreseen to continue, the introduction of higher voltage level transmission lines would become appropriate for increasing the need of power transmission. Since Italy's existing EHV transmission grid was highly meshed, the connection of a large capacity link at 1 000 kV did not require large network reinforcements in the underlying voltage levels (400 kV and 220 kV) that would warrant security conditions, such as those stipulated in the Union for the Coordination of Transmission of Electricity (UTCE) in continental Europe, (see www.ucte.org) rules. Three kilometres of 1 000 kV AC transmission line of were operated for about 14 300 h over a period of three years.

A.5 History of development in Japan

In the middle of the 1970s when power demand was expected to increase steadily in Japan, some Japanese utilities predicted the difficulties that they would face in the future to secure sufficient land for a power plant in the area adjacent to the load centres. They recognized the necessity of long distance and large capacity transmission technology, which enables the power transmission of 10 GW over a total length or more than 400 km with a limited number of transmission corridors.

A 1 100 kV transmission route that links a nuclear power plant on the Sea of Japan to the metropolitan region (north–south route) and the other route linking power sources on the Pacific Ocean (east-west route) were completed by 1999. These transmission lines, double-circuit lines that ran 240 km from east to west and 190 km from north to south, a total of 430 km, are now operated at 550 kV.

In order to carefully establish technologies towards UHV upgrading, field-testing of UHV substation equipment has been carried out since 1996.

A.6 History of development in China

From 1990 to 2005 China's capacity grew at quite a steady rate around 8,6 % per year and by the end of 2005 the installed capacity attained 512 GW. Two-thirds of the coal reserves are located in the north and 80 % of the hydropower reserves are located in the west, while the biggest load centres are concentrated in eastern areas at distances in the range of 800 km to 3 000 km from primary sources locations. The UHV AC transmission system will form the backbone of the synchronized power system, replacing the weak 500 kV connections and enhancing the transfer of bulk power between regions and improving the system stability.

An initial 1 000 kV AC transmission pilot project over 600 km connecting the north and central China grid has been in operation since 2009. By June 2019, there were 10 843 km UHV AC transmission lines and 147 000 MVA UHV AC transformers were in operation, and they are very important parts of the backbone power grid. Furthermore, some new projects are being constructed and planned.

Except for conventional transformers and overhead transmission lines, many other important equipment are developed and used in UHV voltage level UHV transmission systems in China, such as UHV series capacitor, UHV transformer with OLTC, UHV controllable shunt reactor, UHV GIL.

A.7 History of development in India

India's power system is poised for accelerated growth. Peak demand is expected to increase to about 300 GW by 2027 from the present level of about 180 GW for which an installed capacity of about 620 GW is required. To meet the long-term power transfer requirement by 2027 and beyond, large transmission networks interconnecting the distant generating resources with load centres are being planned. Considering the serious difficulty of availability of right-of-way (ROW), it was considered prudent to adopt 1 200 kV AC as the next transmission voltage level in the country for the transfer of bulk power. Preliminary work on the 1 200 kV UHV AC system has already started. To develop 1 200 kV AC technology indigenously, a 1 200 kV test station was established in Bina, Madhya Pradesh in the central part of India under a public-private partnership (PPP) model. Based on the field testing and experience gained on the performance of 1 200 kV equipment, technical parameters were envisaged to be fine-tuned for a 1 200 kV AC transmission system. Further, India is developing a 1 200 kV corridor which includes a Wardha-Aurangabad 1 200 kV circuit (about 380 km) in parallel with EHV corridors. However, as there was initially less power transfer requirement over this corridor, it was proposed that the 1 200 kV line be operated at a 400 kV level.

Annex B
(informative)

Experiences relating to UHV AC transmission development

B.1 Project development in Italy

B.1.1 Background (including network development)

At the end of the 1960s, the electricity consumption in Italy was still doubling every 10 years. The robust growth experienced in the previous decades was faced with the building of plants of increasing size and with the periodic increase of network voltage levels, a new level being introduced roughly every 20 years.

A new higher voltage level would become appropriate in order to keep within acceptable limits the amount of land occupied by overhead lines and to economically deal with the increasing need of power transmission.

B.1.2 Demand analysis and scenario of application

Figure B.1 shows the trend of the demand situation in Italy.

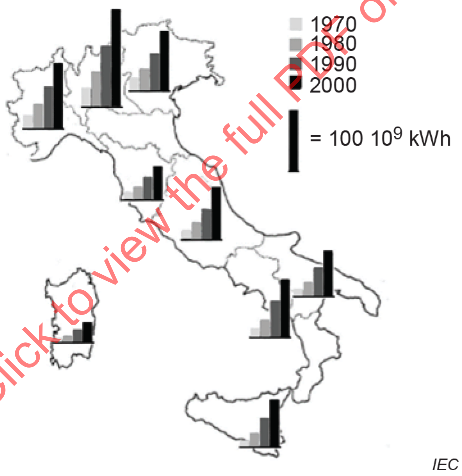


Figure B.1 – Demand situation in Italy

B.1.3 Project overview

It was assumed that the future network had to connect four new powerful generating centres, of the order of 4 000 MW each, to the main load area located at a distance of about 200 km to 250 km. A solution with two lines at 1 000 kV, having a surge impedance loading (SIL) of about 4 000 MW resulted in an economic and reliable solution.

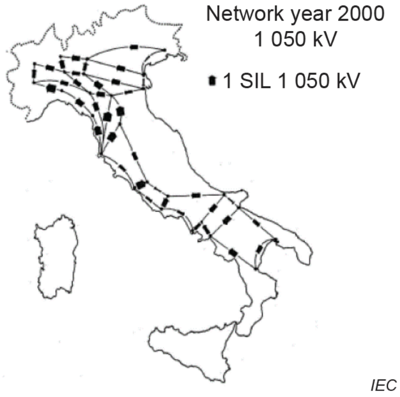


Figure B.2 – UHV transmission lines in Italy as originally planned in '70

The Italian 1 000 kV project was studied focusing on the following technical concerns:

- behaviour of air and surface insulation;
- electric field effects on conductors and accessories and related effects (corona loss, audible noise, radio interference and at ground);
- control of overvoltage;
- electrodynamic problems associated with short-circuit;
- effects of wind and ice on bundled conductors (vibration, sub-span galloping);
- additional losses in the conducting materials of transformers, cable, etc.;
- need to limit the extension of right-of-ways and the visual impact on the environment;
- withstand capability against earthquakes;
- testability of the large components;
- transportability (especially transformers).

Figure B.2 shows UHV transmission lines in Italy, as originally planned in '70 assuming an extremely high increase of the load demand expected for the year 2000.

B.1.4 UHV system planning

The system planning was conducted through the following four major fields.

a) Basic system outline for new UHV links:
   - which corridor?
   - how many circuits?
   - single or double-circuit line?
b) Reliability of new and impact on the whole power electric system especially when the first UHV links are commissioned.
c) Steady state analysis under normal and emergency conditions:
   - voltage profile;
   - reactive compensation requirement;
   - losses;
   - line energization.
d) Dynamic analysis with specific grid perturbations:
   - short-circuit currents;
   - transient stability;
   - voltage collapse;

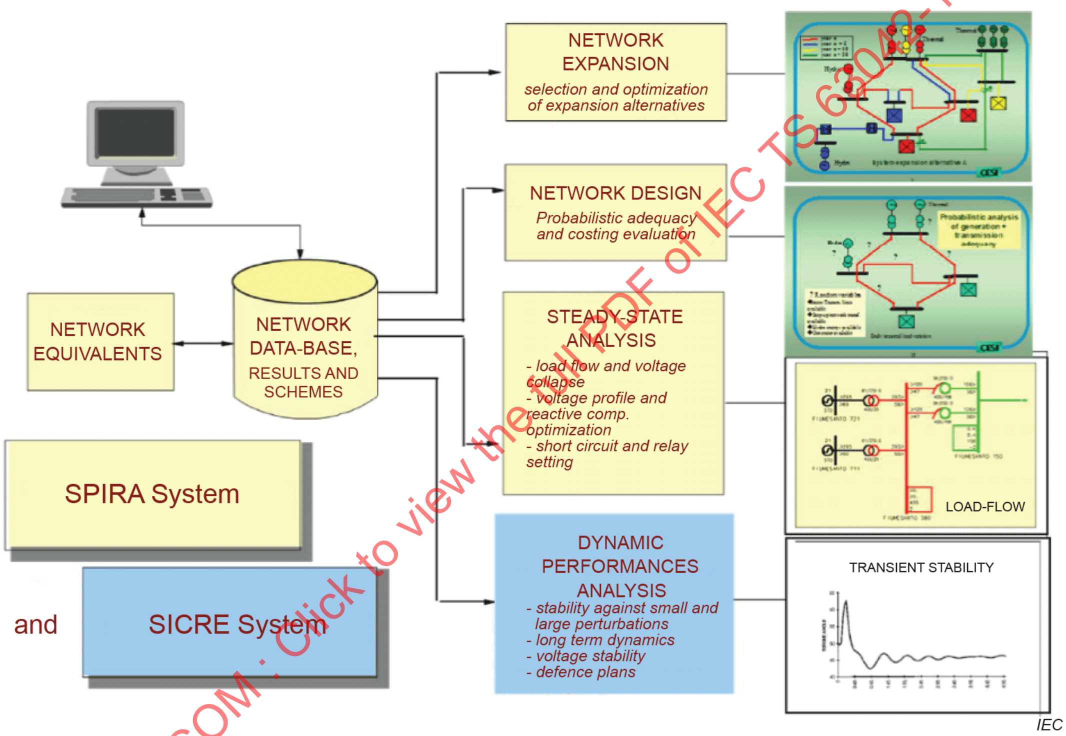
– overvoltage.

Owing to the relatively short overhead transmission line lengths and the meshed scheme with a strong 400 kV network underneath, no critical issue came out from the steady state and dynamic performance analysis of the system including the 1 000 kV network.

The planned 1 000 kV lines range from 50 km to 250 km long and have the following advantages:

- series compensation is not necessary;
- only shunt compensation is necessary, provided by reactors connected line side, for lines longer than approximately 50 km.

The SPIRA (simulator for steady-state analysis) system and SICRE (simulator for dynamic analysis) system are shown in Figure B.3.



NOTE SPIRA (simulator for steady-state analysis), SICRE (simulator for dynamic analysis), Comp. (Compensation).

Figure B.3 – SPIRA system and SICRE system

B.1.5 UHV system design

B.1.5.1 Transmission lines

For the overhead transmission line, the following guidelines were set

a) to minimize
   – visual impact,
   – geometrical mean distance for increasing SIL and transmission capacity,
   – EMF around the transmission line,
   – right-of-way and space occupation,
   – investment cost and operating cost (O&M and losses), and

b) to increase lightning performance.

B.1.5.2 UHV substations

For substation design, the following requirements should be considered:

- mitigating the fast transients generated by disconnecting switches' operation to meet the insulation coordination design;
- limiting the closing and opening switching surge to 1,7 p.u.;
- extinguishing the secondary arc by special countermeasures;
- low residual voltage for the lighting surge and the switching surge.

B.1.5.3 Preliminary system design

Following preliminary system design studies, the relationships shown in Figure B.4 were established.

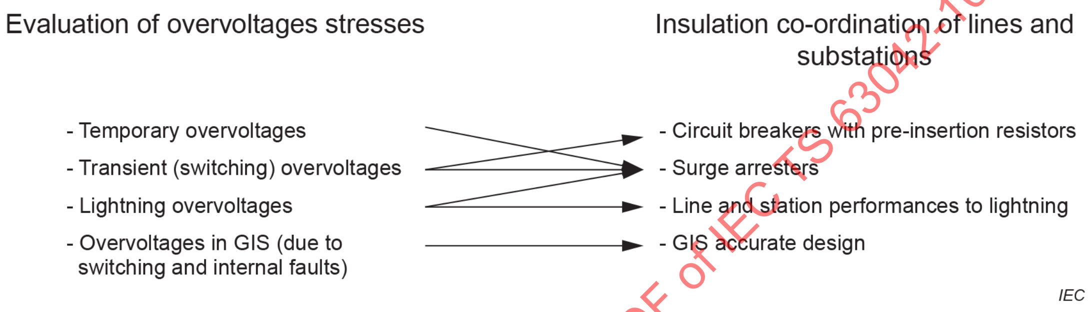


Figure B.4 – Preliminary system design

B.1.6 Laboratory and field tests

B.1.6.1 Main research

Field tests were conducted with the installation of full-scale equipment (see Figure B.5). The specifications of the test equipment are shown in Table B.1, Table B.2, and Table B.3.

The field test facility was energized from 1995 to 1996. During this period, no major faults were experienced. Only one minor fault was experienced on the auxiliary system of the cable refrigeration.

Figure B.5 – Field testing of UHV equipment

B.1.6.2 Facilities

Table B.1 – Specifications of 1 100 kV transformer

Rated power	400 MVA / 400 MVA / not determined
Rated voltages	1 050/√3 kV / 400/√3 kV / 12,2 kV
Rated lightning impulse withstand voltages	2 250 kV / 1 300 kV / 95 kV
Rated switching impulse withstand voltages	1 800 kV / consequent kV / consequent kV
1 h induced voltage test with partial discharge measurements	1,5 $U_m/\sqrt{3}$ (U_m = 1 050 kV)
Short-circuit voltage	15 %
Total weight with oil	355 t
Total weight without oil	275 t

NOTE All equipment and transformers were declared with a rated voltage = 1 050 kV, but the cable was declared with a rated voltage = 1 100 kV. The "highest voltage" was not declared formally, only the insulation levels (test values), in terms of lightning and switching impulse withstand voltages, and 1 h induced tests for transformers.

Table B.2 – Specifications of pilot plant (substation)

Rated voltages	1 050 kV
Lightning impulse withstand voltages	
To earth	2 250 kV
Across the open contacts of CB and disconnectors	2 250 kV + 606 kV
Switching impulse withstand voltages	
To earth	1 675 kV
Across the open contacts of CB and disconnectors	1 675 kV + 606 kV
Power frequency withstand voltage	
To earth	910 kV
Across the open contacts of CB and disconnectors	910 kV
Rated nominal current of:	
Switching devices	6 000 A
Busbars	8 000 A
Rated short-circuit breaking capacity	63 kA
Disconnector opening and closing resistance	110 Ω
Circuit-breaker opening and closing resistance	500 Ω

Table B.3 – Specifications of pilot plant (cable)

Rated voltages	1 100 kV
Type of construction	Oil-filled single pole
Type of insulation	Oil impregnated paper
Oil duct diameter	40 mm
Hydraulic pressure	1,3 Mpa
Conductor cross-section	1 250 mm^2
Insulation thickness	35 mm
Overall cable diameter	155 mm

B.1.6.3 Remarks and pending aspects

- Modern surge arresters and CB controlled switching could be extensively considered in order to control switching overvoltages, as an alternative to the use of CB switching resistors.
- High overvoltage caused by faults are generally present on moderately meshed configurations of a UHV system and may require line surge arresters in addition to those located in the substations.
- The requirements to ensure an appropriate extinction of the secondary arc can be a binding factor strongly limiting the maximum acceptable length of a UHV line without intermediate switching substations.
- A solution to secondary arc extinction within a short time (1 s) might be either the use of a high-speed grounding switch operated in synchronism with the circuit-breaker of a single-phase faulted line or a four-legged shunt compensating reactor equipped with a reactance at neutral point.
- As for the design of UHV substations, a hybrid air-insulated switchgear (AIS)-gas-insulated switchgear (GIS) solution may be the best compromise from a reliability viewpoint by virtue of their easiness in repair (lower mean time to repair (MTTR)) with respect to a full GIS substation.

B.2 Project development in China

B.2.1 Background

In China, there is a geographical mismatch between the distribution of energy resources and the development of productivity. Coal reserves, hydropower resources, wind power and solar resources are mainly located in the north, northwest and southwest of China, while the energy demand is concentrated in the eastern and central regions. Therefore, it is an inevitable choice for the country to develop a UHV power grid.

The advantages of UHV AC are its large capacity power transmission and wide coverage network construction. The development of UHV AC technology can ensure the large-scale and highly efficient development of renewable energy. The construction of UHV AC power grid in the load centre can provide important support for DC transmission and receive large capacity multi UHV DC links feed-in.

B.2.2 Project overview

From the beginning of 2005 to August 2006, government departments, State Grid Corporation of China (SGCC), relevant research institutes, design institutes, manufacturing enterprises, universities and colleges, industry associations and advisory bodies in China jointly carried out an evaluation of the necessity and feasibility of UHV power transmission projects and conducted comprehensive technical R&D.

Since then, a number of UHV AC projects have been planned, approved, constructed, commissioned and put into service. By June 2019, there were 10 843 km of UHV AC transmission lines and 147 000 MVA of UHV AC transformers were in operation. Furthermore, some new projects are being constructed and planned. See Figure B.6.

A single-line diagram of Changzhi-Nanyang-Jingmen UHV AC pilot project is given in Figure B.7. Parameters of substation and switching station are given in Table B.4 and transmission lines is given in Table B.5.

Figure B.6 – UHV AC transmission projects implemented in China

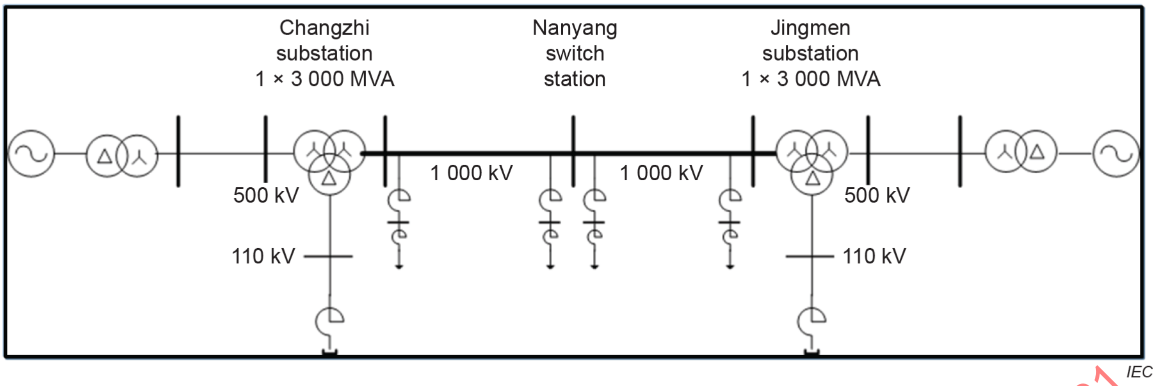


Figure B.7 – Single-line diagram of Changzhi-Nanyang-Jingmen UHV AC pilot project

Table B.4 – Parameters of substation and switching station of Changzhi-Nanyang-Jingmen UHV AC pilot project

Station Name	Jindongnan	Nanyang	Jingmen
Main transformer (MVA)	1 × 3 000	/	1 × 3 000
1 000 kV shunt reactor (Mvar)	1 × 960	2 × 720	1 × 600
110 kV shunt reactor (Mvar)	2 × 240	/	2 × 240
110 kV capacitor (Mvar)	4 × 210	/	4 × 210
Switchgear	GIS	HGIS (Hybrid GIS)	HGIS (Hybrid GIS)

Table B.5 – Parameters of transmission lines of Changzhi-Nanyang-Jingmen UHV AC pilot project

Line type	single circuit
Number of bundled sub-conductors	8
Conductor type	LGJ-500/35 ACSR-630/45
Length: Changzhi-Nanyang-Jingmen	640 km

B.2.3 Changzhi-Nanyang-Jingmen UHV AC extension project

In 2011, a new set of main transformers was built in the Jindongnan substation and Jingmen substation, respectively, and two new sets of 3 000 MVA UHV transformers in the Nanyang substation. The UHV series capacitors with the compensation degree of 40 % (each side is 20 %) are installed on the line from Jindongnan to Nanyang. A series capacitor with the compensation degree of 40 % is installed on the line from Nanyang to Jingmen, concentrated in Nanyang. Figure B.8 shows the artificial grounding test of UHV series capacitors in China.

The transmission capacity of this project was improved to 5 GW and fully verified at commission test in 2011.

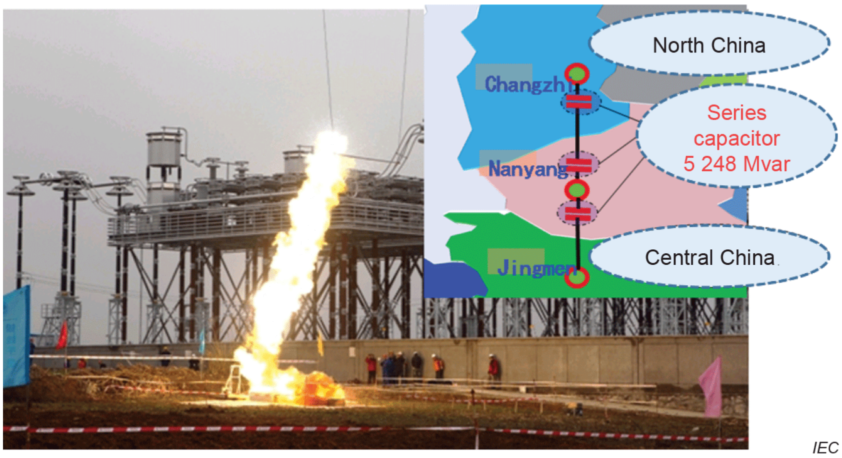


Figure B.8 – Artificial grounding test of UHV series capacitors in China

The Huainan-Zhebei-Shanghai project was the second UHV AC project. Double-circuit lines were firstly used in this project. This project starts from Huainan substation (Anhui Province), passes by Wannan substation (Anhui Province) and Zhebei substation (Zhejiang Province), and ends at Huxi substation (Shanghai), with a transformer capacity of 21 000 MWA and a total line length of 2 × 648 km (steel tube tower and double circuits on the same tower). The construction of the project started in October 2011 and it was put into operation in September 2013. A single-line diagram of Huainan-Zhebei-Shanghai double-circuit UHV AC project is given in Figure B.9.

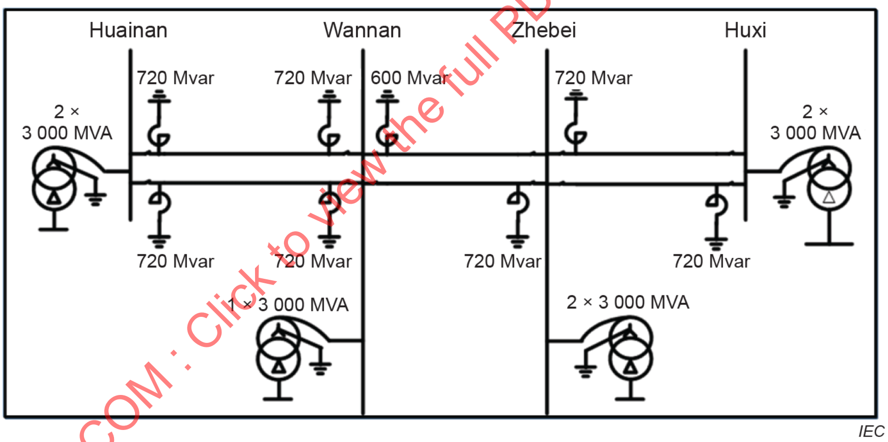
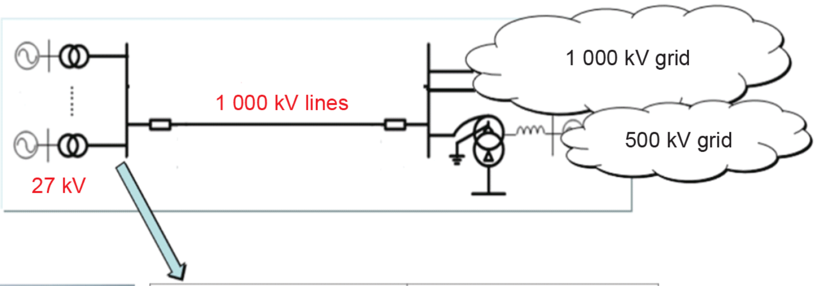


Figure B.9 – Single-line diagram of Huainan-Zhebei-Shanghai double-circuit UHV AC project

After the commissioning of this project, one unit of 1 000 MW generator in the Pingwei power plant was integrated to Huainan substation through a 1 000 kV line in 2015. The generator with a terminal voltage of 27 kV connects the UHV system through a 27 kV/1 000 kV step-up transformer. This is the first application of a UHV step-up transformer. The generator integrated into a UHV system through a UHV step-up transformer is given in Figure B.10.



Rated capacity (MVA)	1 200/1 200 (3 phases)
Rated voltage (kV)	1 100/√3/27
Impedance (%)	18

IEC

Figure B.10 – Generator integrated into a UHV system through a UHV step-up transformer

B.2.4 Overvoltage mitigation and insulation coordination

B.2.4.1 Main system parameters

The nominal voltage for UHV AC systems in China is 1 000 kV and the maximum voltage is 1 100 kV. The main system parameters are shown in Table B.6.

Table B.6 – Main system parameters of UHV AC projects in China

Parameters	Value
Nominal voltage	1 000 kV
Maximum voltage	1 100 kV
Rated frequency	50 Hz
Fault current	63 kA

B.2.4.2 Overvoltage and mitigation

In order to avoid the huge cost of insulation, the overvoltage in UHV AC is mitigated to reasonable levels. Series mitigation measures are applied, which include shunt reactor, MOV, and closing resistor.

B.2.4.3 Temporary overvoltage

Single-phase ground fault and load rejection of a transmission line are critical scenario causing temporary overvoltage.

Shunt reactors installed on the transmission line are very helpful to mitigate this type of overvoltage.

In UHV projects in China, the temporary overvoltage at the bus bar side of the circuit-breaker should be mitigated to below 1,3 p.u. and it should be less than 1,4 p.u. at the line side of the circuit-breaker.

B.2.4.4 Switching overvoltage

Ground fault and clearing, energizing, and single-phase-auto-reclosing of a transmission line are critical scenarios causing switching overvoltage.

Surge arresters are a basic switching mitigation method. The main parameters of a UHV arrester used in UHV projects in China are shown in Table B.7. Furthermore, closing resistors of circuit-breakers are used to suppress closing overvoltage.

Table B.7 – Main system parameters of UHV arrester

Parameters	Value
Rated voltage	828 kV
Continuous operating voltage	635 kV
Switching impulse residual voltage	≤ 1 460 kV at 2 kA (30/60 μs)
Lightning impulse residual voltage	≤ 1 620 kV at 20 kA (8/20 μs)

Shunt reactors installed at transmission lines can suppress temporary overvoltages (TOVs), which are the fundamental component of switching overvoltage. The usage of shunt reactors can help in switching overvoltage mitigation.

In UHV projects in China, the switching overvoltage in substations should be mitigated to below 1,6 p.u. and it should be less than 1,7 p.u. on transmission lines in most instances.

B.2.4.5 Lightning overvoltage

Lightning overvoltages in UHV transmission systems with overhead lines originate from line shielding failure and back-flashover. As in the case of EHV transmission lines, lightning flashover caused by shielding failure is the main reason for trip-outs of UHV transmission lines.

Lightning overvoltages may be limited through overhead ground wires, reducing tower foot resistance and surge arresters.

B.2.4.6 Very fast front overvoltages

Very fast front overvoltages (VFFOs) are caused by disconnector operations or faults within GIS.

As the withstand voltage for VFFO has not been standardized, the lightning impulse withstand voltage (LIWV) is referenced during the insulation coordination for VFFOs. The VFFO is proportional to the system voltage. In UHV systems, the ratio of the LIWV to the system nominal voltage is lower than that of the EHV system. The risk caused by VFFOs should therefore be taken into consideration in UHV substations.

In UHV projects in China, disconnectors with an inserting resistor are used for parts of substations to suppress VFFO.

B.2.5 Insulation coordination

B.2.5.1 Clearance of transmission line

The required minimum values of clearance under lightning overvoltage are listed in Table B.8. For single-circuit lines, clearance under lightning overvoltage does not control the size of the transmission tower window; therefore no requirement is specified in such a case. For the case of double-circuit line towers, in order to meet the requirements of lightning trip-out rate, sufficient clearance below the conductor bundle and the cross arm beneath are necessary.

Table B.8 – Required minimum value of clearance of the 1 100 kV transmission line

Voltage type	Transmission line type	Minimum clearance distance required m		
		Altitude 0 m to 500 m	**Altitude 500 m to 1 000 m**	**Altitude 1 000 m to 1 500 m**
Power frequency voltage and overvoltage	Single circuit	2,7	2,9	3,1
	Double circuit	2,7	2,9	3,1
Switching overvoltage	Single circuit [a]	Side-phase: 5,9 Centre-phase: 6,7/7,9	Side-phase: 6,2 Centre-phase: 7,2/8,0	Side-phase: 6,4 Centre-phase: 7,7/8,1
	Double circuit	6,0	6,2	6,4
Lightning overvoltage	Single circuit	No regulation		
	Double circuit [b]	6,7	7,1	7,6

[a] The value in front of the slash (/) is the gap distance between the centre-phase conductor and the oblique iron. The value behind the slash is the gap distance between the centre-phase conductor bundle and the upper cross arm.

[b] In mountain regions with intense lightning activities, the minimum clearance distance of lightning can be appropriately increased according to the actual conditions of the project.

To avoid oversize clearance of the line tower window, the safe distance for live line working is not to be taken as the controlling factor of line insulation clearance. The distance consisting of the safe distance of live line working plus the area of the worker's body movement (not less than 0,5 m), should not be greater than the clearance as determined by switching overvoltages.

B.2.5.2 Clearance of substation

The minimum clearance of substations (A) is classified into A1 (minimum clearance of phase-to-ground) and A2 (minimum clearance of phase-to-phase). A1 includes A1' (minimum clearance of phase-to-ground with windage yaw) and A1" (minimum clearance of phase-to-ground without windage yaw).

The minimum clearance of substations in the regions with an altitude not exceeding 1 000 m is shown in Table B.9.

Table B.9 – Minimum clearance of UHV substation (metres)

Voltage	A1		A2
	A1′	A1″	
Power frequency voltage and overvoltage	4,2		6,8
Switching overvoltage	6,8	7,5	10,1 (grading ring to grading ring) 9,2 (four split wires to four split wires) 11,3 (pipe bus bar to pipe bus bar)
Lightning overvoltage	5,0		5,5

B.2.5.3 Withstand voltage of UHV equipment

The withstand voltages of UHV equipment is shown in Table B.10

Table B.10 – Overvoltage withstand level of UHV AC projects in China

Equipment	Lightning impulse withstand voltage kV peak	Switching impulse withstand voltage kV peak	Power-frequency withstand voltage kV rms
Transformer and shunt reactor	2 250 (2 400: Chopping)	1 800	1 100 (5 min)
GIS	2 400	1 800	1 100 (1 min)
Insulator	2 550	1 800	1 100 (1 min)
Capacitive voltage transformer (CVT)	2 400	1 800	1 200 (5 min)
Bushing for transformer and shunt reactor	2 400 (2 760: chopping)	1 950	1 200 (5 min)
GIS bushing	2 400	1 800	1 100 (1 min)
Longitudinal insulation of switchgear	2 400 + 900	1 675 + 900	1 100 + 635 (1 min)

B.2.6 Laboratory and field tests

B.2.6.1 Test base

In order to support the technology research on UHV AC transmission technology, SGCC has established a UHV AC test base in the city of Wuhan in Hubei province (Figure B.11) and a UHV tower test base in the city of Bazhou in Hebei province (Figure B.12).

Figure B.11 –Hubei Wuhan UHV AC test base

Figure B.12 –Hebei Bazhou UHV tower test base

B.2.6.2 System commissioning test

Commissioning tests are a prerequisite for UHV AC projects before they are put into service.

For the first UHV AC project, the commissioning tests were carried out from December 2008 to January 2009. The main results were the following.

1) In voltage-raising experiments, all equipment, such as the Jingmen and Changzhi transformers, UHV AC lines and their shunt reactors, withstood the UHV full-voltage tests.
2) During the experiments, UHV transformers, circuit-breakers, UHV transmission lines, shunt reactors and low-voltage compensation devices withstood several switching impulse tests, and all the equipment remained reliable.

   During the whole experimental period, 24 switching no-load UHV transformers were carried out on the 500 kV side. The largest phase-to-ground overvoltage on the 1 000 kV side was 1,54 p.u. which is lower than the allowed voltage 1,6 p.u., and it was 1,48 p.u. on the 500 kV side which is lower than the allowed voltage 2,0 p.u.. The maximum inrush current was 4 816 A.

   During the three-phase and single-phase switching and artificial single-phase short-circuit grounding, the largest phase-to-ground switching overvoltage measured on the UHV bus side was 1,25 p.u. and on line terminal was 1,26 p.u., both far lower than the allowed voltage 1,6 p.u.

   During the switching of low-voltage reactors the maximum overvoltage was 166 kV and during the switching of low-voltage capacitors the maximum overvoltage was 171 kV. Both are much lower than insulation coordination claims.
3) The UHV system withstood the test of transmission power control, system dynamic disturbance, peak load experiment and artificial single-phase grounding test.

   During the power control test, the UHV system was stable. The power fluctuations were in the range of ±200 MW for most of the time.

   In the system dynamic disturbance experiment, Changzhi-Jinmen line's maximum active power fluctuation was 2 100 MW after the Three Gorges' 700 MW generator cut off, and the first fluctuation amplitude was approximately 625 MW. Its active power oscillation frequency was approximately 0,15 Hz. Its active power oscillation damping ratio was approximately 0,11, which corresponds to a strong damping system. UHV power grids have good dynamic operating characteristics and strong anti-disturbance ability.

   In accordance with the commissioning test plan, the UHV pilot project's maximum power flow was 2 829,5 MW, which meets the expectation.

   The results of artificial grounding tests show that four-legged reactors can effectively limit secondary arc, ensuring the success of single-phase reclosing. The pilot project's reclosing time is proper when it is in the range 0,7 s to 1 s.
4) The commissioning tests had comprehensive check and anti-disturbance experiments on protection and relay systems. Protecting actions met the designed logic and setting values accurately. The results show that the protection systems and auxiliary equipment were in good condition.
5) In the experiments, oil sample, and vibration of transformers and shunt reactors met the requirements of technical specifications. No abnormal temperature rising was found through infrared observations.
6) Electromagnetic environment measurement results met the requirements of China's State Environmental Protection Agency.

   In conclusion，functions and performance of equipment of the Changzhi-Nanyang-Jingmen UHV AC pilot project were verified and met the requirements. The UHV system's voltage and power were under control. This project is suitable for the transmission of power in accordance with its design, can withstand system dynamic disturbance and grounding faults. This project is respectful of aspects related to the electromagnetic environment.

B.3 Project development in India

B.3.1 Background (including network development)

India has witnessed exponential growth in the power sector in the past seven decades. The voltage level of the state-sector network grew from a 132 kV level during the 1950s and 1960s to 220 kV during the 1960s and 1970s. Subsequently, a 400 kV network was developed in many states in 1970s for bulk power transfer over long distances as part of a state grid. At the end of the 1980s, the approach was shifted to development of regional grids. Further, in the 1990s with the development of asynchronous connection (HVDC back to back) between the regional grids, exchange of a large regulated quantum of power was enabled between the regions. Regions were inter-connected synchronously through a 400 kV system in the mid 1990s whose capacities were continually strengthened over two decades. In December 2013, the southern grid was synchronized with the rest of all-India grid, i.e. the new grid through the Raichur-Solapur 765 kV line, thus leading to the formation of one synchronous National Grid (one grid – one nation – one frequency).

Since the advent of the current century, the focus on planning the generation and the transmission system in the country shifted from the orientation of regional self-sufficiency to the concept of optimum utilization of resources on an all-India basis realized through its strong national grid with EHV AC (765 kV), long distance UHV DC (800 kV) overlaying systems along with the integration of emerging technologies like flexible AC transmission system (FACTS), UHV AC, etc.

B.3.2 Demand analysis and scenario of application

As per future demand projections, the peak power requirement of India is expected to increase to about 300 GW by 2027. To meet the demand, about 620 GW generation capacity has been envisaged by 2027, which includes a significant amount of renewables.

The primary energy resources in India, coal and hydro potential, are unevenly distributed in the country and the majority is concentrated in the eastern and western parts of the country. Further load centres are also distantly located in the western and northern parts of the country. In order to meet the projected demand growth through the generation resources mentioned above, India still needs huge power corridors to transfer bulk power from resource locations to far off demand centres. Keeping the above in mind as well as other factors like economy of scale in setting up large size pit-head generating stations, conservation of right-of-way (ROW), long-term power transfer, etc. requires the development of high capacity long distance bulk power transmission systems between the resource points and the major load centres criss-crossing the country, in addition to the development of load centre based generating stations, if feasible.

To accomplish this though an 800 kV AC system, a huge but scarcely available ROW is required. To meet such long term power transfer requirements in the country, an overlaying super grid comprising a 1 200 kV UHV AC system is envisaged in India taking into consideration socio-economic challenges. However, development of UHV was always constrained due to the non-availability of standard parameters and limited application of technology in large countries like India, for which initiatives were taken by POWERGRID (Power Grid Corporation of India), the central transmission utility (CTU) of India.

B.3.3 Project overview

POWERGRID is giving special emphasis on the integration of new technological products and services for enhancing the performance of transmission systems as well as improving the quality of power supply infrastructure with the optimization of the cost of transmission. Keeping pace with the rapid development and growing demand of power, POWERGRID has adopted 800 kV technology on a large scale in addition to the implementation of a ±800 kV HVDC system.

B.3.4 Development of 1 200 kV national test station in India

UHV AC technology is still in a nascent stage and evolving continuously. POWERGRID, seeing the potential benefit which can be accrued with UHV AC technology, floated the idea for indigenous development of UHV AC technology. In October 2007, a discussion was held with Indian manufacturers about the possibilities and modalities to carry out research, development and demonstration in this area. On that basis, a unique model of public-private partnership (PPP) evolved, wherein it was decided that equipment would be developed by manufacturers indigenously while POWERGRID would provide the field bed for trial and testing of 1 200 kV equipment. Accordingly, POWERGRID, through unique collaborative efforts with leading Indian Manufacturer and the Central Electricity Authority (CEA), Central Power Research Institute (CPRI) indigenously set up a 1 200 kV National Test Station in Bina (Madhya Pradesh), India under a PPP model (see Figure B.13).

IEC

Figure B.13 – 1 200 kV national test station (India)

The objective for development of such a 1 200 kV national test station was:

- to meet the country's long term power transfer requirement especially considering socio-economic challenges like ever diminishing right-of-ways (ROW), etc.,
- provide the opportunity to Indian manufacturers to indigenously develop substation equipment especially when no international standards are available,
- carry out field testing of indigenously developed equipment based on which further development could be carried out,
- learn safety, quality and operational requirements of UHV system technology.

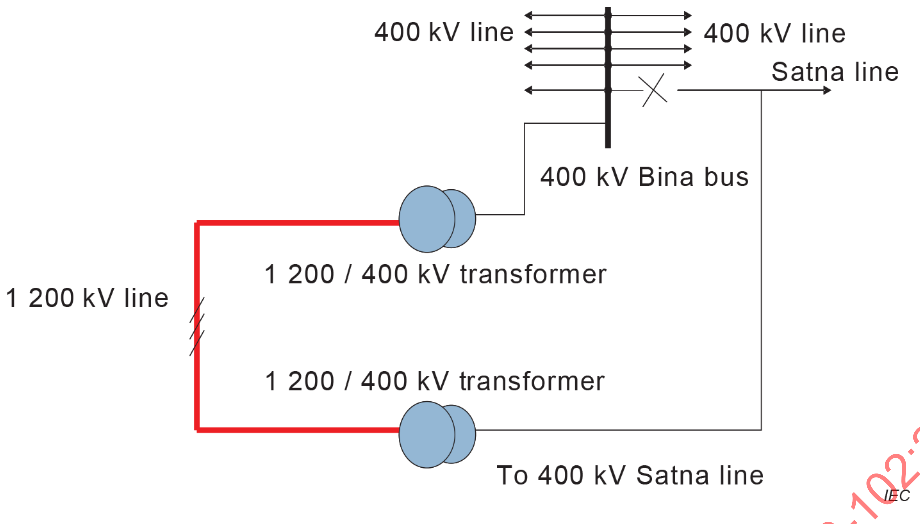


Figure B.14 – Power flow from Satna to Bina diverted via a 1 200 kV test station (India)

The test station consists of two 1 200 kV bays comprising 1 200 kV class equipment such as instrument transformers, circuit-breakers and surge arresters and two 1 000 MVA transformer banks each comprising three single-phase 400 kV/1 200 kV, 333 MVA auto transformers. In addition to the above substation equipment, two 1 200 kV AC test lines about 1 km long each (series interconnected single-circuit and double-circuit lines) were also constructed and charged through these two 1 200 kV Bays to study their performance by conducting measurements of various line parameters. In the existing 400 kV system through a loop-in loop-out (LILO) arrangement, power flow through 1 200 kV test station was established. A schematic diagram is shown in Figure B.14.

B.3.5 POWERGRID's 1 200 kV transmission system

In India, load centres are located in the western and northern parts of the country while generation pockets are located mainly in the eastern part. In order to facilitate power transfer from the eastern to the western parts of the country as well as to address right-of-way issues, high capacity East-West transmission corridors comprising 765 kV and 1 200 kV AC have been planned. Further, in the central part of India, Wardha is a gateway for power transfer towards the northern and western parts. In view of the above, a high capacity 765 kV transmission corridor has been planned up to Wardha from the eastern part, whereas beyond Wardha, a hybrid 1 200 kV and 765 kV transmission corridor i.e. Wardha – Aurangabad – Padghe has been planned towards the western part. The 1 200 kV corridor including the Wardha-Aurangabad 1 200 kV single circuit (about 380 km) is set up in parallel with four 765 kV lines. A schematic diagram depicting the 1 200 kV system in the western region power map is shown in Figure B.15. However, as there was initially less power transfer requirement over this corridor, it was proposed that the 1 200 kV line be operated at 400 kV, i.e. line insulation at 1 200 kV level with terminal equipment at 400 kV level. Subsequently, with the increased power transfer requirement, this corridor shall be charged at rated voltage.

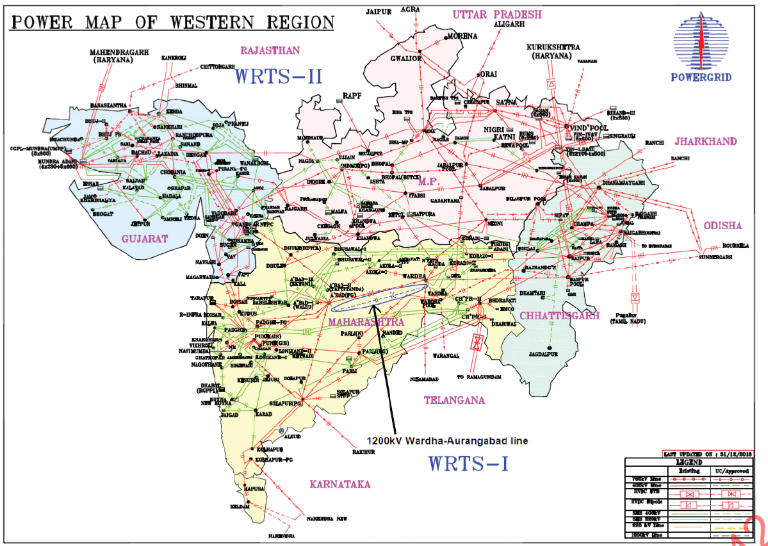


Figure B.15 – Schematic of 1 200 kV UHV AC line

B.3.6 UHV AC technology design – Insulation coordination

Insulation coordination is very important for the design of the 1 200 kV system from the point of view of lightning impulse withstand voltage level and switching impulse withstand voltage level for 1 200 kV equipment. To achieve necessary protective margins in accordance with respective standards, insulation coordination studies were carried out along with surge arrester parameters. Accordingly, lightning impulse withstand voltage level and switching impulse withstand voltage level were selected at 2 400 kV and 1 800 kV respectively. Details of the basic technical parameters for the 1 200 kV UHV AC system selected in India are given in Table B.11.

Table B.11 – Basic technical parameters for 1 200 kV UHV AC system selected in India

Sr.No.	Parameters	Value	Remarks
1	Rated voltage	1 200 kV	
2	Nominal voltage	1 150 kV	
3	Rated frequency	50 Hz	
4	Fault current	50 kA	
5	Lightning impulse voltage level	2 400 kV	Switchyard equipment
		2 250 kV	Transformers and reactors
		2 550 kV	Transformer and reactor bushings
6	Switching impulse voltage level	1 800 kV	Switchyard equipment and transformers
		1 950 kV	Bushings
7	1 min power frequency voltage	1 200 kV	

Surge arresters in a UHV system play a major role in controlling overvoltages, as parameters of various equipment will be decided considering the presence of surge arresters in the system to control the voltage stress that these equipment will experience under normal and contingency conditions. Economic and physical constraints necessitate such a requirement.

The surge arresters will require very high energy discharge capability considering stringent duties and sustained overvoltages in the UHV system. For the 1 200 kV system in India, the following V-I characteristics have been considered for metal oxide surge arrester (MOSA) for all designs (see Figure B.16).

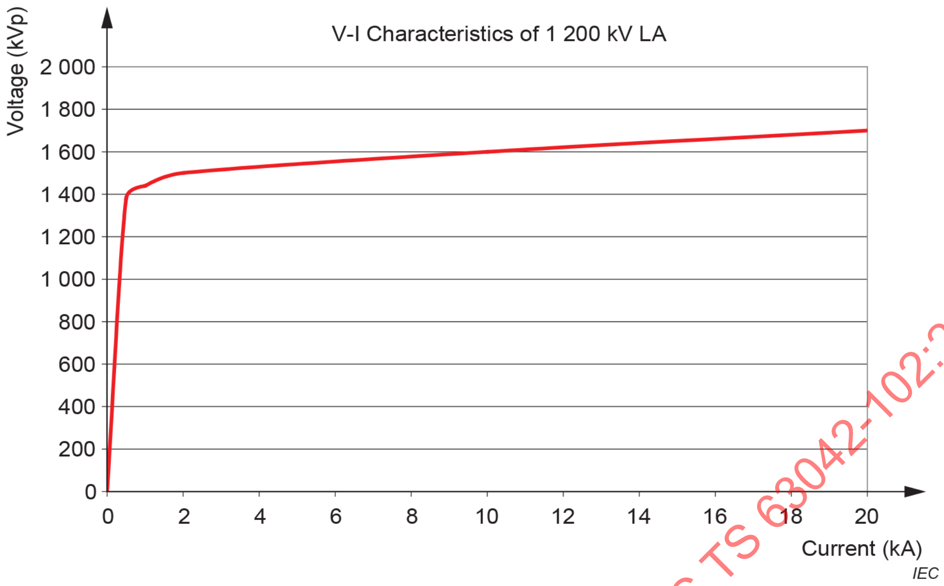


Figure B.16 – Typical V-I characteristic of 1 200 kV MOSA

B.3.7 Insulation design for substation

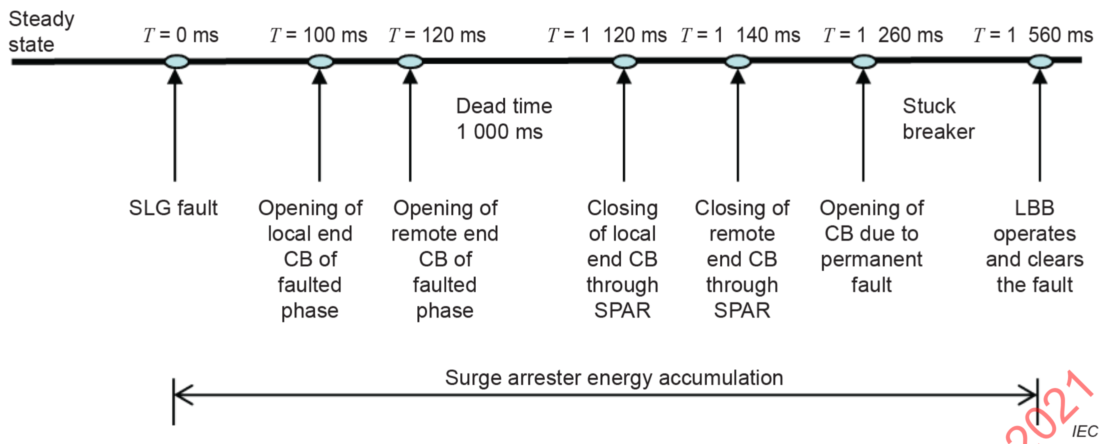
B.3.7.1 General

The location of surge arresters is very critical in order to contain voltage rise due to switching surges as well as lightning surges in a UHV AC system. For adequate protection of equipment against lightning surges, it was decided to locate surge arresters at the line entrance and near transformers/reactors. The values of switching impulse withstand voltage (SIWV) and lightning impulse withstand voltage (LIWV) are obtained considering adequate margin over the values of switching impulse protective level (SIPL) and lightning impulse protective level (LIPL) as obtained from the V-I characteristics of the surge arrester. The SIWV for 1 200 kV equipment has been considered as 1 800 kV with about 20 % protective margin. The LIWV has about 35 % protective margin for 1 200 kV equipment and about 25 % protective margin for 1 200 kV transformer and reactors.

B.3.7.2 TOV and energy absorption by surge arrester

For the determination of temporary overvoltages, studies were carried out on a fault duty cycle consisting of a single-line-to-ground fault followed by three-phase interruption at the receiving end. The studies were carried out with different source strengths and reactive compensation. The study results showed a TOV of 1,33 p.u. with a 10 000 MVA short-circuit level at the sending end. For the purpose of the insulation coordination study the value of TOV is taken as 1,4 p.u.

To determine the discharge capability of the surge arrester, the most severe condition of operation was considered. The series of events started with single-line-to-ground fault followed by the opening of local and remote end CB of the faulted phase. The single-phase autoreclosure became effective after a dead-time of 1 000 ms. However the reclosing was unsuccessful and the breaker could not be opened due to the struck breaker condition. The sequence of events is shown in Figure B.17.



NOTE: LBB (local breaker backup).

Figure B.17 – Sequence of events for calculation of surge arrester energy accumulation

The information for TOV and energy absorption by surge arrester is given in Table B.12.

Table B.12 – TOV and energy absorption by surge arrester

Overvoltage on healthy phase in case of ground fault		1,4 p.u.
Maximum TOV (p.u.) and its duration (s)		1,4 p.u., duration 1 s
Case and condition for studies		(corresponding to the energy absorption of 55 MJ)
Energy absorption of surge arrester (MJ)		1-Ph-ground fault followed by load rejection
Calculation method		EMTP/ATP
Power frequency test voltage for substation equipment		
Assumed overvoltage condition for power frequency test	**Transformer**	1 200 kV
	Other equipment	1 200 kV
Analysis programme		EMTP/ATP

B.4 Project development in Japan

B.4.1 Background (including network development)

In the middle of the 1970s when the power demand was expected to increase steadily in Japan, some Japanese utilities predicted the difficulties in the future to get sufficient land for a power plant in the area adjacent to the load centres. They recognized the necessity for long distance and large capacity transmission technology, which enables to transmit the power of over 10 GW over a total length of more than 400 km.

A 1 100 kV transmission route was completed by 1999. The north–south route connected a nuclear power plant on the Sea of Japan to the metropolitan area and the east–west route connected power sources on the Pacific Ocean to the metropolitan area. Double-circuit lines were adopted. The lines were 240 km long (east–west route) and 190 km long (north–south route), a total of 430 km, and were put into operation at 550 kV.

Field testing of UHV equipment has been carried out at the 550 kV Shin-Haruna substation since 1996.

B.4.2 Demand analysis and scenario of application

Figure B.18 shows the trend of peak demand in the supply area of the Tokyo Electric Power Company (TEPCO) from the 1950s to 2000s. Peak demand gradually increased until the early 1990s.

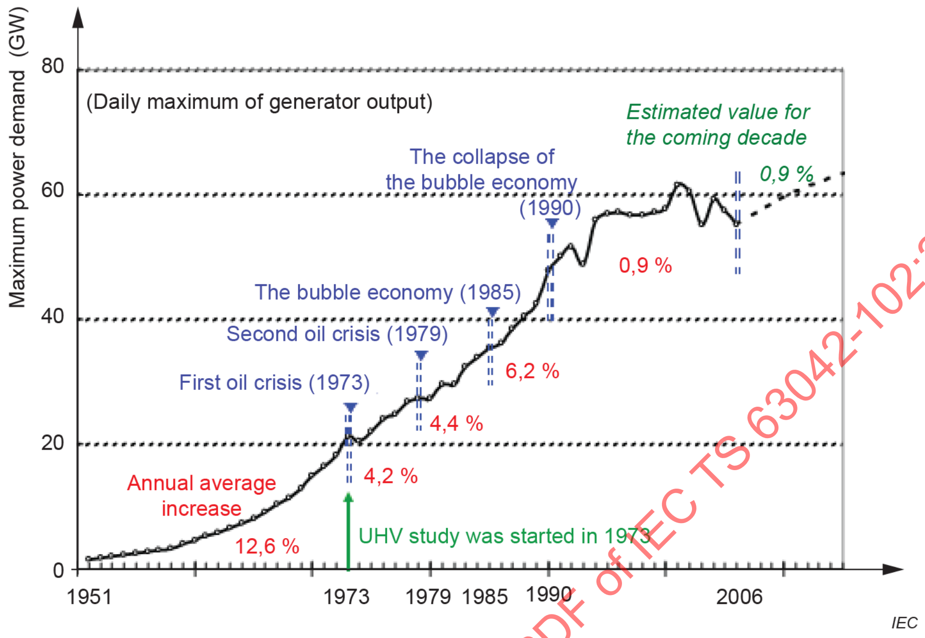


Figure B.18 – Trend of peak demand in Japan

B.4.3 Project overview

In the middle of the 1970s, TEPCO expanded the 550 kV network to respond to the rapid demand growth. However, it was anticipated that the existing 550 kV grid would not be able to accommodate the steady growth of the peak demand and increase in load flow from power plants in the north-east and north-west parts of the area. Therefore, further development of the transmission system was necessary. TEPCO decided to introduce UHV transmission lines with a capacity three to four times greater than the 550 kV line.

TEPCO started UHV research in 1973. The central electric power council, the consultative body for wide area operation in Japan, also started research on a new generation of electric transmission responding to future demand growth. At the end of its study, the council recommended the use of a UHV transmission line of 10 GW, 1 100 kV over 600 km to meet the future demand. Based on the recommendation, the UHV line was constructed and completed by 1999. The field test facilities have been energized since May 1996. Accumulated energized time reached 58 350 h by the end of March 2007.

According to the planned timetable, operation voltage would rise up to 1 100 kV in the mid 2020s. However, the plan was not implemented because demand did not increase as initially estimated.

UHV transmission line for each construction year in Japan is given in Figure B.19.

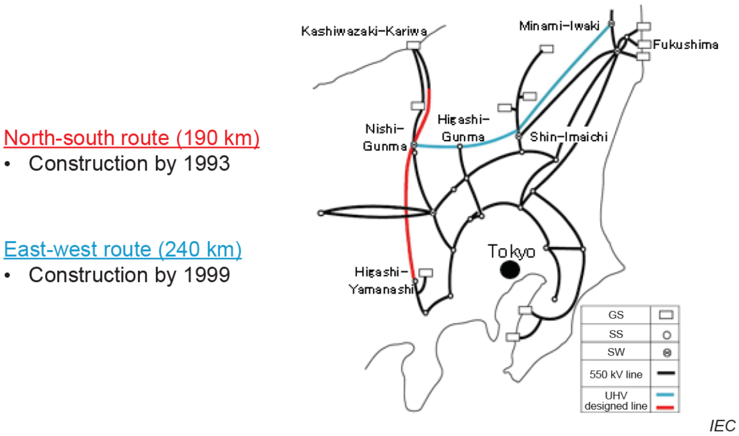


Figure B.19 – UHV transmission line for each construction year in Japan

B.4.4 UHV system planning

Power demand has more than doubled in the last 20 years. Since the middle of the 1970s, TEPCO has worked to expand the 550 kV network; however it is very difficult to secure multiple power transmission routes in Japan. In addition, countermeasures for short-circuit capacity problems were required in order to increase the number of 550 kV transmission lines.

Therefore, TEPCO decided to construct 1 100 kV transmission lines with a capacity three to four times greater than that of 550 kV transmission lines. In addition, the introduction of a UHV system can lead to the separation operation of 550 kV systems so that the fault current of 550 kV systems can be decreased. See Figure B.20.

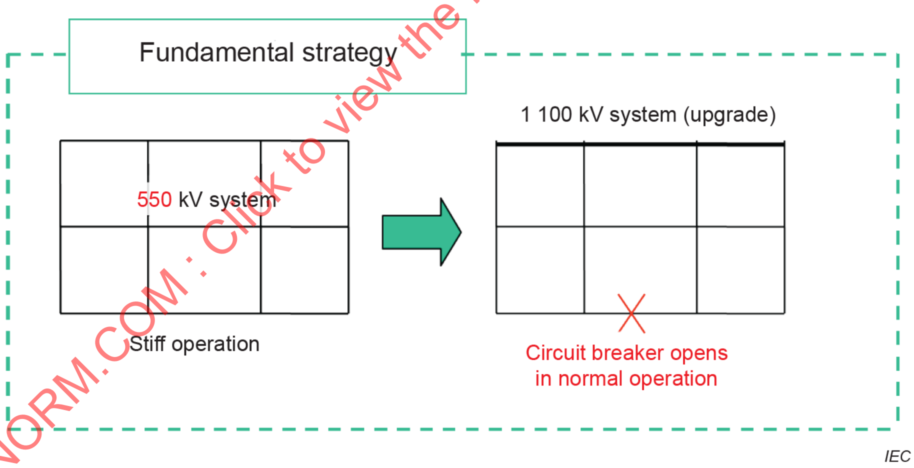


Figure B.20 – Concept for transmission capacity enhancement with short-circuit current restriction

B.4.5 UHV system design

B.4.5.1 Transmission lines

For UHV transmission system design, since the corridor passes through narrow and mountainous areas, a self-supporting double-circuit configuration turned out to be the most advantageous from the technical and economic viewpoints. The self-supporting double-circuit configuration is widely applied to other EHV lines in TEPCO. As for UHV transmission lines, the double-circuit type adopted was the first attempt in the world.

The predominant factors determining the air gap clearances of transmission lines are switching surges, which include closing, fault clearing surge caused by the operation of circuit-breakers and ground fault surge generated on sound phases.

Generally, there is no effective means of controlling the ground fault overvoltage level. It can only be reduced with the help of surge arresters near substations. On the other hand, closing overvoltage and fault clearing overvoltage can be controlled effectively by inserting resistors in the circuit-breakers. Considering these characteristics of switching overvoltages, TEPCO decided to set the ground fault overvoltage level as the phase-to-ground insulation level, and control closing and fault clearing overvoltages rationally below this level. Figure B.21 shows a more detailed sequence of the insulation coordination.

Thus, TEPCO succeeded in suppressing the phase-to-ground insulation level to 1,6 p.u. to 1,7 p.u., less than the 2,0 p.u. conventionally applied to 550 kV transmission lines. These efforts in air gap clearances design permitted the tower height, which would have been 143 m with the conventional 550 kV insulation technologies alone, to be reduced to 110 m. Figure B.22 shows the overview of the actually constructed UHV designed transmission lines.

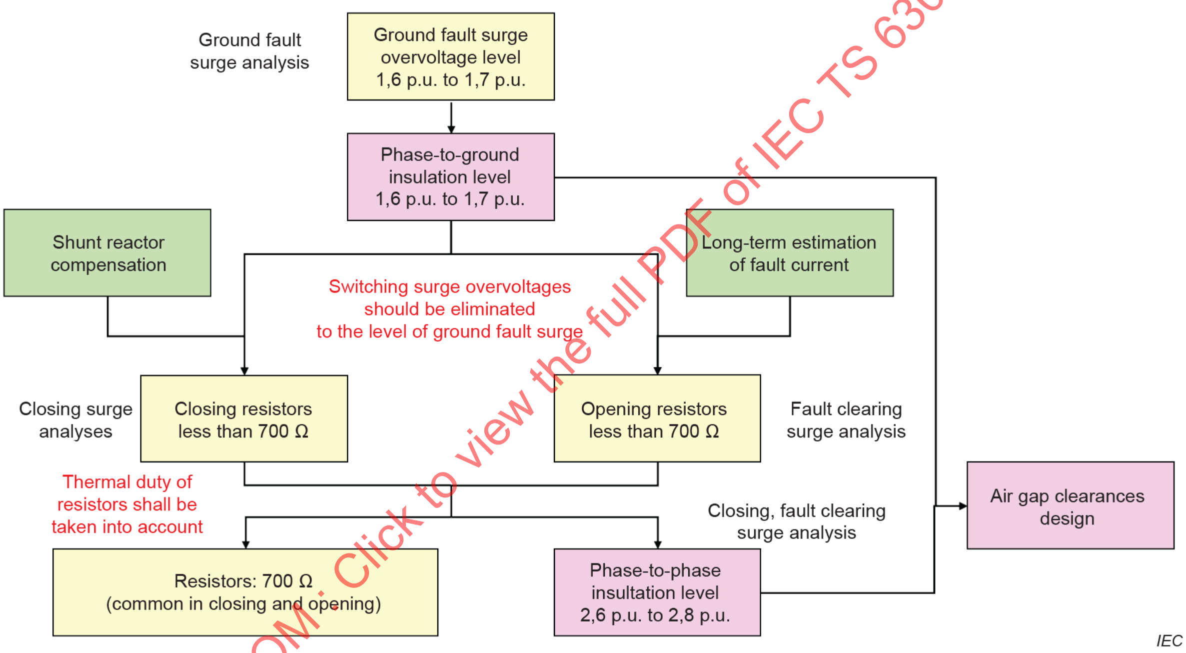
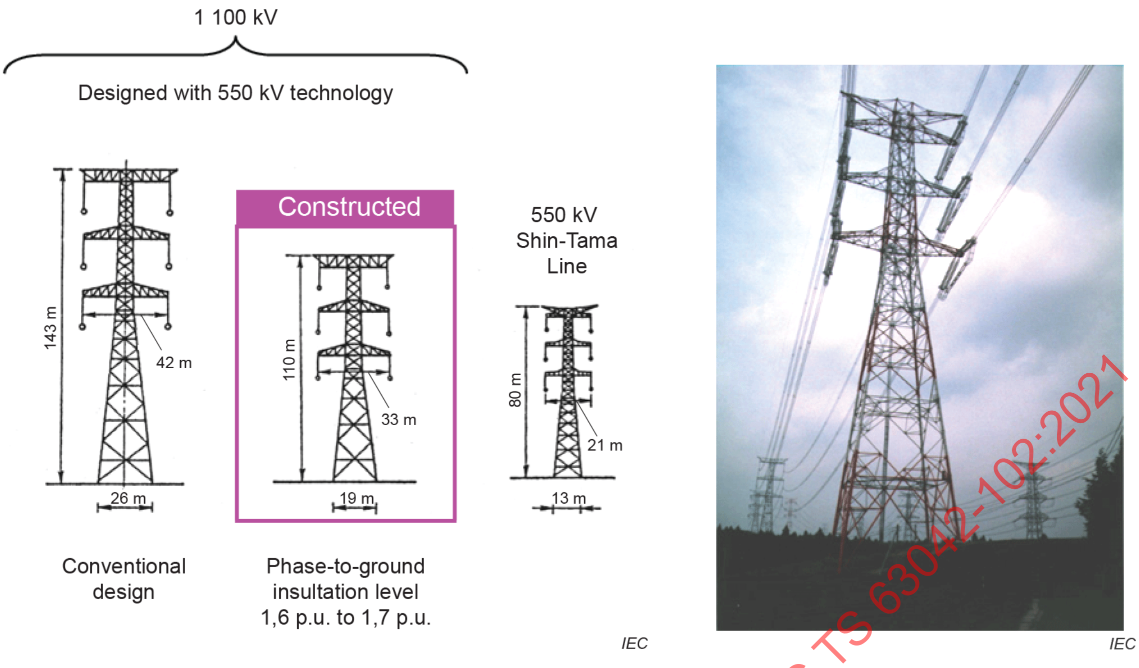


Figure B.21 – Insulation design sequence of 1 100 kV transmission lines' air gap clearances



a) Comparison of transmission tower designs **b) Constructed UHV line**

Figure B.22 – UHV designed transmission line in TEPCO

B.4.5.2 UHV substations

For substation design, size and weight reduction is emphasized to save costs with regard to site development, transportation, and the environmental burden, because the sites for prospective substations are in mountainous areas. Therefore, TEPCO decided to adopt GIS. The outline of a typical UHV substation is as follows:

- configuration: double bus four-bus-tie system;
- capacity of transformer: 3 000 MVA (composed of 1 000 MVA single-phase transformers);
- number of transformers: 4 to 6;
- number of transmission line circuits: 4 to 6.

B.4.5.3 Insulation design

TEPCO's insulation designs are described in Table B.13 and Table B.14.

Table B.13 – Requirement against large charging MVA

TOV	Resonance overvoltage	Time constant of DC component	Zero-offset phenomenon	Transient recovery voltage
1,15 p.u. (line) 1,1 p.u. (substation)	Line lengths are relatively short and shunt reactors are not installed.	150 ms	Not applicable	Suppressed by surge arrester and opening resistor.

Table B.14 – Specifications of substation insulation design

Disconnector overvoltage	Lightning impulse withstand voltage	Switching impulse withstand voltage
Resistor insertion (500 Ω)	2 250 kV (GIS) 1 950 kV (transformer)	1 550 kV (GIS) 1 425 kV (transformer)

B.4.6 Laboratory and field tests

B.4.6.1 Main research

Field tests were conducted by installing full-scale equipment. The specifications of test equipment are shown in Table B.15 and Table B.16 – Specifications of 1 100 kV GIS . The test facilities consist of three single-phase transformers, circuit-breakers, bus-bars, arresters and bushings. They are connected to the operating substation and energized at operating voltage. In the transformer, the current is flowed by the maximum tap difference. As for GIS, 100 % of the rated continuous current is flowed by using power CTs.

The field test facility has been energized since May 1996. During this period, the reliability of substation equipment, such as long-term reliability and performance against various overvoltage and characteristics of switchgear was verified. Figure B.23 shows field testing of UHV substation equipment since 1996.

Figure B.23 – Field testing of UHV substation equipment since 1996

B.4.6.2 Facilities

Specifications of 1 100 kV transformer are given in Table B.15 and specifications of 1 100 kV GIS are given in Table B.16.

Table B.15 – Specifications of 1 100 kV transformer

Item		Specification
Rated voltage	Primary	1 050/√3 kV
	Secondary	525/√3 kV
	Tertiary	147 kV
Rated capacity		3 000/3 MVA × 3
Tertiary capacity		1 200/3 MVA × 3
Primary tapping range		±7 % (27 taps)
Impedance		18 %
Test voltage	Lightning impulse	1 950 kV
	AC	1,5 E × 1 h + √3 E × 5 m + 1,5 E × 1 h
NOTE E = 1 100 kV/√3.		

Table B.16 – Specifications of 1 100 kV GIS

<table>
<tr><th colspan="3">Item</th><th>Specification</th><th colspan="2">Item</th><th>Specification</th></tr>
<tr><td rowspan="6">GIS</td><td colspan="2">Rated voltage</td><td>1 100 kV</td><td>GCB</td><td>Closing/Opening resistor</td><td>700 Ω</td></tr>
<tr><td colspan="2">Rated continuous current</td><td>8 000 A</td><td>DS</td><td>Surge suppression resistor</td><td>500 Ω</td></tr>
<tr><td colspan="2">Rated short-time withstand current</td><td>50 kA (2 s)</td><td rowspan="2">HSES</td><td>Electromagnetic induction</td><td>Breaking current
3 500 A RMS
TRV 600 kV peak</td></tr>
<tr><td rowspan="3">Test voltage</td><td>Lightning impulse</td><td>2 250 kV</td><td>Electrostatic induction</td><td>Breaking current
1 000 A rms
TRV 900 kV peak</td></tr>
<tr><td rowspan="2">AC</td><td rowspan="2">1,5 E × 30 m,
√3 E × 1 m,
1,5 E × 30 m</td><td rowspan="2">MOA</td><td>Rated voltage</td><td>826 kV</td></tr>
<tr><td>Residual voltage</td><td>1 620 kV
(at 20 kA)</td></tr>
<tr><td colspan="7">NOTE E = 1 100 kV/√3.</td></tr>
</table>

B.4.6.3 Test items

At the beginning of the field testing, there were issues such as oil flow electrification of the transformer and delay in the opening time of the main interrupter of the CB. The equipment design was improved to overcome these issues and ensure the long-term reliability of UHV equipment.

Basic data of 1 100 kV substation equipment was collected. Measurement items of the transformer and GIS are shown in Table B.17 and Table B.18. Accumulated energized time reached 77 807 h by the end of March 2019. The higher voltage operation (1,05 E: E = 1 100 kV/√3) was continued, and equivalent years under normal voltage was 146 years.

Table B.17 – Example of field test – Measurement items of transformer

Category	Test and measurement item
Energizing/Temperature rise test	· Characteristics change · Loading test (energizing condition)
Periodic measurements	· Inrush test · Static electrification test (oil charge density, neutral leakage current) · Dissolved gas analysis · Analysis insulation-oil characteristics · Vibration/noise measurement · Transient voltage measurement
On-line monitoring	· Dissolved gas analysis · Partial discharge

Table B.18 – Example of field test – Measurement items of GIS

Category	Test and measurement item
Energizing/Temperature rise test	• Characteristics change • Temperature and thermal behaviour measurement
Periodic measurements	• Arrester leakage current measurement • Surge measurement (DS operating surge, HSGS making surge, EMC) • Vibration/acceleration measurement • Operating time characteristics test • Accuracy measurement (optical PD, CT without iron core)
On-line monitoring	• Partial discharge • Gas pressure • GCB/DS/HSES operating time

Annex C
(informative)

Summary of system technologies specific to UHV AC transmission systems

C.1 Technologies used in China

C.1.1 Transformer

The transformer is one of the main equipments of a UHV AC system. The main parameters of a UHV AC typical transformer used in UHV AC projects in China are shown in Figure C.1Table C.1. Figure C.1 shows a UHV AC transformer.

Transformers with a capacity of 4 500 MVA (three phases) have also been developed, but have not been used in projects so far. On-load-tap-changer UHV transformers have been used in one project. 27 kV/1 100 kV 1 200 MVA two windings step-up transformers have also been developed and used in power plants, directly integrated into the UHV system.

Table C.1 – Main parameters of UHV AC typical transformer

Parameters	Value
Type	Single phase auto transformer
Rated capacity (three phases)	3 000 MVA / 3 000 MVA / 1 000 MVA
Rated voltage	1 050/√3 / 525/√3 / 110 kV
Tap	±1,25 × 4 % (525 kV side)
Rated frequency	50 Hz
Short impedance	P-S 18 % P-T 62 % S-T 40 %
NOTE P (primary), S (secondary) and T (tertiary).	

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Figure C.1 – UHV AC transformer

C.1.2 UHV shunt reactor and reactive compensation at tertiary side of transformer

Shunt reactors at the UHV side as shown in Figure C.2 and the reactor and capacitor at the tertiary side of the transformer as shown in Figure C.3 are used as the main method for reactive power management in a UHV AC transmission system. The Main parameters of UHV AC reactive power compensation equipment are shown in Table C.2.

Most shunt reactors are connected with a transmission line through the disconnector only. For these cases, the neutral point of three-phase shunt reactors is earthed through a reactor, which is used for secondary arc current control.

Table C.2 – Main parameters of UHV AC reactive power compensation equipment

Parameters	Rated voltage	Rated capacity (three phases)
UHV shunt reactor	1 100 kV	600 Mvar 720 Mvar 840 Mvar 960 Mvar
Reactor at tertiary side of transformer	105	240 Mvar
Capacitor at tertiary side of transformer	126	210 Mvar 240 Mvar

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Figure C.2 – UHV AC shunt reactor

Figure C.3 – Reactor and capacitor at tertiary side of UHV transformer

The controllable shunt reactor (CSR) can meet the requirement of limiting temporary overvoltage and self-adaptively balancing the charging power of the transmission line under light load and heavy load. Because of the large variation of reactive power requirement of the UHV system during power flow changing, a CSR is suitable for the reactive power compensation of a UHV system.

The UHV CSR was developed and tested before 2016. It was firstly applied in the Zhangbei-Xiongan (west of Beijing) project, which was constructed starting in 2018 and put into service in 2020. The main purpose of this project is the transmission of renewable power to the north China grid, including wind and PV generation. A CSR can meet the requirement of large fluctuation of reactive power, which comes from the large fluctuation of renewable power. During a transmission line load rejection or fault, it can change to maximum vars to suppress overvoltage or help with the extinction of secondary arc current.

C.1.3 Switchgear

Gas insulated switchgear is widely used in UHV substations. Besides GIS, air insulated UHV disconnectors are used for UHV series capacitors. The main parameters of UHV AC circuit-breaker are given in Table C.3. Gas insulated switchgear is shown in Figure C.4 and mixed technology switchgear is shown in Figure C.5. UHV air insulated disconnectors are shown in Figure C.6.

Table C.3 – Main parameters of UHV AC circuit-breaker

Parameters	Value
Rated voltage	1 100 kV
Rated current	6,3 kA
Rated short-circuit breaking current	63 kA
Time constant of DC component	120 ms