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Technical requirements for substations exceeding 800 kV

Working Group
B3.22

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WG B3.22

TECHNICAL REQUIREMENTS FOR SUBSTATIONS EXCEEDING 800KV

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This document is prepared on behalf of CIGRE B3 and reports about the requirements of UHV Substation, Guideline of UHV substation planning, some consideration to construct UHV substation and operate UHV substation. WG B3.22 “TECHNICAL REQUIREMENTS FOR SUBSTATION EXCEEDING 800KV” has researched the technical issues concerning UHV substation and prepare some proposals for relevant CIGRE WGs and IEC TCs in future standard to cover the UHV substation system requirements based on the recent UHV experiences.

Abbreviations

1LG	**Single-phase line fault to ground**
2LG	**Two-phase line faults to ground**
3LG	**Three-phase line faults to ground**
ACSR	**Aluminum Conductor Steel Reinforced**
AEP	**American Electric Power (USA)**
AIS	**Air Insulated Switchgear**
AN	**Audible-Noise**
BPA	**Bonneville Power Administration (USA)**
CEPRI	**China Electric Power Research Institute (China)**
CESI	**Centro Elettrotecnico Sperimentale Italiano (Electrotechnical Testing Centre, Italy)**
CISPR	**International Special Committee on Radio Interference**
CRIEPI	**Central Research Institute of Electric Power Industry (Japan)**
CT	**Current Transformer**
CVT	**Capacitor Voltage Transformer**
DS	**Disconnector**
EHV	**Extra High Voltage**
EMI	**Electromagnetic Immunity**
EMTP	**Electro Magnetic Transient Program**
ES	**Earthing Switch**
ESDD	**Equivalent Salt Deposit Density**
FFO	**Fast Front Overvoltage**
GCB	**Gas Circuit Breaker**
GIS	**Gas Insulated Switchgear**
HSGS	**High Speed Grounding Switch**
IEC	**International Electrotechnical Commission**
KEPCO	**Korea Electric Power Corporation (Korea)**
LI	**Lightning Impulse**
LIPL	**Lightning Impulse Protection Level**
LIWV	**Lightning Impulse Withstand Voltage**
MOSA	**Metal Oxide Surge Arrester**
MOV	**Metal Oxide Varistor**
NCI	**Non-Ceramic Insulator**
PD	**Optical potential devices**
PIR	**Pre-Insertion Resistor**
RI	**Radio Interference**
RIV	**Radio Interference Voltage**
SA	**Surge Arresters**
SFO	**Slow-Front Overvoltage**
SiC	**Silicon Carbide**
SIPL	**Switching Impulse Protection Level**
SIWV	**Switching Impulse Withstand Voltage**

SPAR	**Single-Phase Rapid Auto-Reclosing**
SGCC	**State Grid Company of China**
TEPCO	**Tokyo Electric Power Company (Japan)**
TOV	**Temporary Overvoltage**
TPAR	**Three-Phase Rapid Auto-Reclosing**
TRV	**Transient Recovery Voltage**
UHV	**Ultra High Voltage (exceeding 800 kV)**
VFT	**Very Fast Transient**
VFTO	**Very Fast Transient Overvoltage**
VT	**Voltage Transformer**

1 UHV Substation specific matters

1.1 UHV substation specific requirements [1]

There are fundamental and specific requirements which need to be addressed and fulfilled in the design of UHV substations. Focusing on the large size of UHV substations, service area, network constraints and requirements, life cycle costs, and optimization of substation design, we identified the following eight important basic requirements, as shown in Fig.1.

Fig.1 Requirements of UHV Substation

(1) Reliability

This is one of the most important requirements, because UHV substations are generally designed to serve a large area and population, such as major cities or industrial areas. A typical UHV network may need to transfer tens of gigawatts of electricity to hundreds or thousands of kilometres of network. The failure of a UHV substation in such a network would create more serious problems for the overall network grid. in Fig.1.

Therefore, reliability of the UHV substation will directly affect the reliability of the overall network. In general from the viewpoint of UHV substation, Full GIS and Hybrid-GIS are suitable compared with AIS because the exposure parts of main circuits are limited in the case of GIS. But the Suitability of GIS / Hybrid GIS or AIS depends upon various factors like altitude, severity of pollution (coastal / industrial), land availability & cost, repairing cost, experience with technology etc.

(2) Safety and Disaster-prevention

Safety is an important issue because of the very high voltages involved. large insulation distances are required to maintain the required insulation. This affects the space requirements as well as safety aspects to ensure that the insulation distance is properly maintained. Any unsafe conditions may lead to accidents, which could have disastrous consequences due to the high voltage levels.

In general from the viewpoint of safety and disaster prevention, Full GIS and Hybrid-GIS are suitable compared with AIS. But in GIS large amount of SF_6 gas is necessary. In case of repairs, it is highly specialized work, expert labors are required to make the repairs.

(3) Environmental Harmony

As in the design of all substations, environmental harmony is important for substations to be accepted as part of the infrastructure of the surrounding areas. Proper environmental impact assessment studies will need to be conducted in advance to study the impact of UHV substations on the surrounding environment.

In general, from the viewpoint of environmental harmony, full GIS and Hybrid-GIS are suitable compared with AIS. But UHV of the AIS type substation is generally located outside cities and once the design takes care of electric and magnetic fields within acceptable limits, environmental harmony is still maintained in AIS.

Environmental harmony is usually examined at the planning or designing stage before the construction of UHV substation. An example of 3D-CAD landscape simulation of Jingmen UHV Hybrid-GIS substation in China is shown in Fig.2 As during the design of all substations, environmental harmony is very important for substations to be accepted as part of the infrastructure of the surrounding areas. Proper environmental impact assessment will need to be conducted in advance to studying the impact of UHV substations on the surrounding environment. Bird's eye view of Jingmen UHV Hybrid-GIS substation is shown in Fig.2.

Fig.2 Bird's eye view of Jingmen HGIS substation

(4) Operation and Maintenance

It is essential that the UHV substations be designed and constructed to allow suitable operation and maintenance. Recently, for substations up to 550 kV voltage class, there is tendency for utility companies to minimize the occurrence of open maintenance so that outage time will also be minimized. In the case of UHV substations, the technology is still new and it is difficult to manage outage time. In such circumstances, maintenance is an important aspect to be considered.

From the viewpoint of operation, maintenance and recovery time from the failure, the time is a little bit long for the Full GIS and Hybrid-GIS compared with AIS concerning outage-time. But we have to pay attention to the maintenance of UHV substation facilities and pylon. Table 1 shows the operational data for Russian 787-1200kV transmissions. There is no description concerning switching equipment.

Table 1 Operational data for Russian 787-1200 kV transmissions [2]

Equipment	Parameter	787 kV	1200 kV
Line	Failure rate, per 100 km-year	0.2	0.12
	Single –pole failures, %	98	100*
	Successful single-pole reclosures, %	52	**
	Successful single- and three pole reclosures in total, %	52	**
	Average restoration time, hrs, if reclosing was unsuccessful	5.8	10.5
Transformer	Outages, per phase-year	0.107	0.13
	Average restoration time, hrs	112	5,090*
Shunt reactor	Outages per phase-year	0.068	0.25*
	Average restoration time, hrs	198	23*

Notes: *- insufficient time of observation; **- devices for automatic reclosures and schemes of 4-legged reactors were not properly established during relatively short period of tests and operation; x-initial period of 'baby illnesses".

(5) Ease of Construction

UHV facilities should be designed for easy construction and erection. This is especially important as UHV equipment is large and tools for construction and erection, such as cranes, will thus be larger than normal. It is important to maintain uniform quality of construction in order to maintain reliability.

This matter correlates the transportation unit or shipping unit of UHV equipment.

(6) Economy

The cost of UHV substations is still considerably high compared to EHV substations, because the technology for UHV equipment is still new. Therefore, cost evaluation is an important aspect to consider in the decision to construct UHV substations. Total life cycle cost and optimization of the design considering the above requirements are part of the cost evaluation for UHV facilities.

GIS substations seem to be more costly than AIS however it depends upon many factors like availability of land, geographical condition, environmental condition, cost of labour, local laws etc. and varies countries to countries. Further scheme may be different in case of AIS (breaker & half) & GIS (double breaker) comparison may not be adequate. However in case of 400kV voltage level, it has been seen that the cost of GIS substation is around 2 times compared to AIS.

Usually, the cost of AIS substation is much lower than Full GIS and Hybrid GIS. But the cost of O&M per year and cost of installation of AIS substation is more expensive than those of GIS or HGIS substation, But in the case of UHV the cost of the required space is a major economic factor and depending on the availability of land advantage of AIS may not be obvious. In China AIS was tried to adopt in Nanyang switching station firstly, it was difficult to purchase the land for the extension work of this project, which will be 10 circuits transmission lines and 3 group main transformers. HGIS was adopted in Nanyang switching station after technical & economical comparison finally.

(7) Location

The choice of location for a UHV substation site will depend on many external factors, such as the cost of land, the strategic location of the substation site in relation to the network, etc. In determining the location, the condition of the site for substation construction and accessibility for transportation of UHV equipment should also be considered. Due to environmental concerns, the location of UHV substations is normally limited to mountain or desert areas, which may have limited access for transportation and delivery of equipment.

(8) Larger Size and Weight of Equipment

Due to the high voltage levels, the size and weight of UHV equipment is invariably larger than normal EHV equipment, which has an impact on the UHV substation design. On the other hand, it is also important to minimize the size of the UHV equipment so that the cost of the UHV substation is not increased drastically. From the viewpoint of the equipment and system requirements of a UHV substation, there are many different requirements compared with 550 kV systems. Fig.3 shows the equipment and system based on UHV system aspect and the measure.

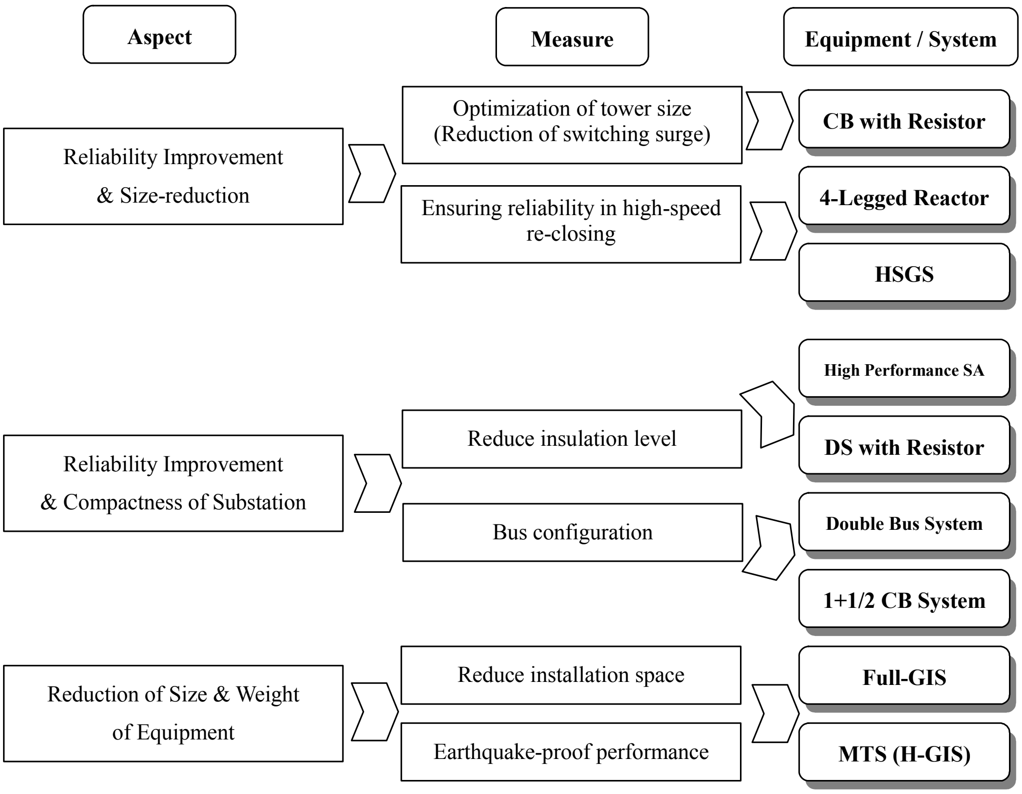


Fig.3 Requirements of UHV substation equipment and system

Based on Fig.1 and Fig.3, following items are necessary to be considered during UHV substation planning.

Environmental Impacts

- Environmental harmony
- Environmental assesement
- Effects on human body
- Electromagnetic environmental control

Electro-magnetic compatibility

Electrical specifications of UHV facilities

- Pollution
- Snow
- Ice
- Wind
- Rain

Mechanical specifications of UHV facilities

- Seismic requirements
- Snow
- Ice
- Wind

Transportation restriction

GIS Layout, Air-insulation distance

Cost of the substation construction and equipment

Maintenance and reliability

- Audible noise
- Corona
- Radio Interference voltage

1.2 Seismic requirements and design

Guide and standards relevant to seismic designs have been established and used as a basis for seismic specifications of substation equipment all over the world. There are several acceptance criteria of the seismic performance for substation equipment. From the viewpoint of seismic strength, a part with porcelain materials is considered as the weakest structure used for various substation equipments. Due to large and heavy construction of UHV substation, it is very important to secure the seismic performance of all UHV equipment (especially for a top of gas bushings with heavy porcelain, porcelain-housing surge arresters, and supporting insulators) in a region where an earthquake would expect to occur periodically. Table 2 shows typical seismic guide and standards.

Table 2 Typical seismic guide and standards

Standard (Guide) No.	Titles	Country
JEAG 5003-1998	Seismic Design Guide of Substation Equipment	Japan
GB/T 13540-92	Anti-seismic Characteristics Test for High-voltage Switchgear	China
IEEE Std 693-2005	IEEE Recommended Practice for Seismic Design of Substations	USA
IEC 62271-207	Seismic qualification for gas-insulated switchgear assemblies for rated voltages above 52kV	Europe
IEC 62271-300	High-voltage switchgear and control gear - Part 300: Seismic qualification of alternating current circuit-breakers	Europe
IEC 61463	Bushings –Seismic qualification	Europe
IEC 60068-3-3	Environmental testing Part 3: Guidance Seismic test methods for equipment	Europe

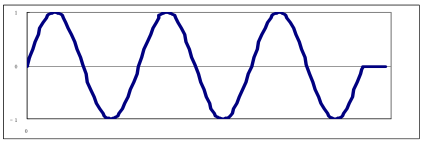
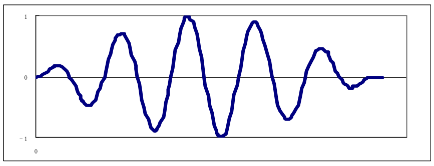
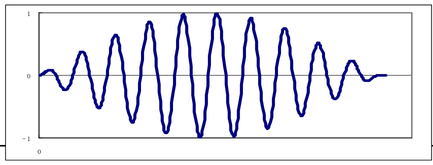
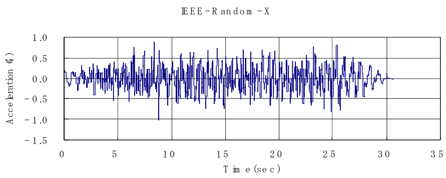
Since the configuration (height, width, and weight) of UHV equipment become large compared with 550kV substation equipment, the natural frequencies of the equipment have a high possibility to coincide with the predominant frequency of the earthquakes. In general the predominant frequency of past earthquake waveforms ranges from nearly 0.5Hz to 10Hz.

Table 3 shows the comparison of main items among the standards. There are some differences in several items. These differences depend on the conditions and damages of the past earthquakes in each country and it seems very difficult to harmonize these standards. There are two types of input waveforms; (a) equivalent sinusoidal waveform as resonant three cycles sine and 5 or 10 cycles sine beat and (b) artificial earthquake wave which satisfies RRS (Required Response Spectrum). The features of these waveforms are shown in Table 4. Analysis methods are classified into two types: a time-history method and a response spectrum method. Remarkable difference between both methods is whether time integration is necessary or not.

Table 3 Comparison of main items between standards

		JEAG 5003-1998	GB 50260-1996	IEC 62271-207, 300	IEEE 693-2005
Classification of Equipment		Overall	Overall	CB, Switchgear	Overall
Frequency range		0.5 to 10Hz	0.5 to 25Hz	0.1 to 25Hz	0.3 to 33Hz
Acceleration ratio (Vertical/Horizontal)		0.5	0.65	0.5	0.8
Test	Input acceleration(G)	0.3	0.4,0.2(Artificial) 0.3,0.15 (5cycle)	0.5,0.3,0.2	0.5,0.25,0.1
	Waveform	Resonant 3 cycles sine wave	Artificial earthquake wave or 5 cycles/beat	Artificial earthquake wave or 5 cycles/beat	Artificial earthquake wave, 10 cycles/beat
	Exciting Direction	One horizontal (Two axial if vertical is necessary)	Two axial	Two axial simultaneously	Basically three axial simultaneously
Analysis	Static	Specified	Specified	Specified	Specified
	Static coefficient	None	None	Specified	Specified
	Dynamic	Time-history: Input waveform is same as test	Time-history: Input waveform is same as test	Time-history Response spectrum	Response Spectrum
	Exciting direction	One horizontal (Two axial if vertical is necessary)	Two axial	Two axial	Basically three axial

Table 4 Input waveforms

Waveform		Merit and Demerit
3 cycles sine		[Merit] ・Waveform is simple ・It is easy to analyze and test because waveform is sinusoidal. ・These waveform is effective to the porcelain structures because the failure of brittle materials such as porcelain occurs at maximum acceleration. [Demerit] ・Inaptitude to structures which have several significant modes ・Inaptitude to functional check because duration time is short
5 cycles/beat		
10 cycles/beat		
Artificial earthquake		[Merit] ・Universality of time history waveform which satisfies RRS is high because RRS envelops responses of historical big earthquakes. ・The influence of predominant frequency components is small because the wave includes equally frequency components in the frequency domain considered. ・This wave is suitable for recreating the coupling movement of the multiple modes. [Demerit] ・It takes time.

For the purpose of conducting the equivalent and the convenient seismic tests, a quasi-resonant method with the resonant N cycle's sinusoidal waveforms was adopted as a standard input waveform in Japan. In the case of using a number of actual earthquake waveforms recorded on the ground surface (615 records), the acceleration response factor of a simplified single-degree-of-freedom model are plotted in Fig. 4.

The acceleration responses are evaluated and compared with the resonant two or three cycle sinusoidal wave inputs. It is noted that the response for the resonant two cycle's sinusoidal wave input covers the response for the most of the real earthquake waves recorded in the past. Accordingly, the resonant two cycles sinusoidal wave was adopted in combination with the severest horizontal acceleration of 0.3G as an equivalent vibration for the design force at the ground surface. Moreover, considering the influence of a foundation structure, connecting leads and so on, and 0.3G resonant three cycle's sine wave at the bottom end of the supporting structure was defined as standard input waveform.

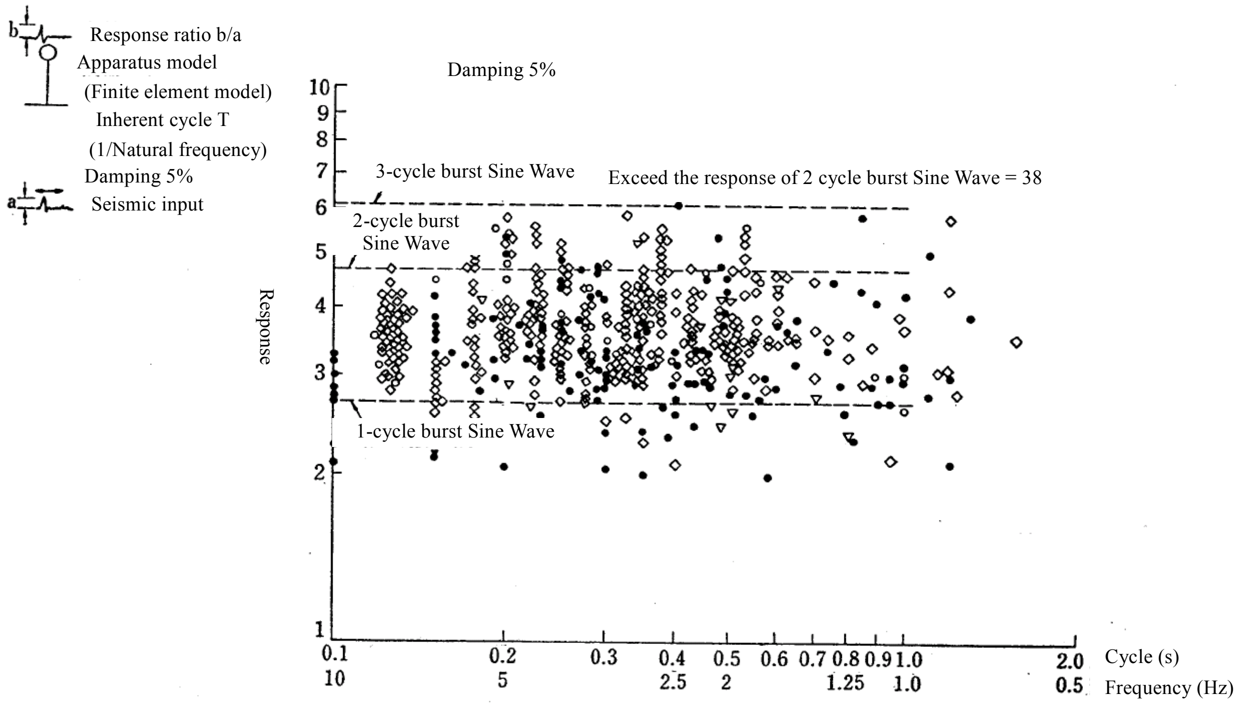
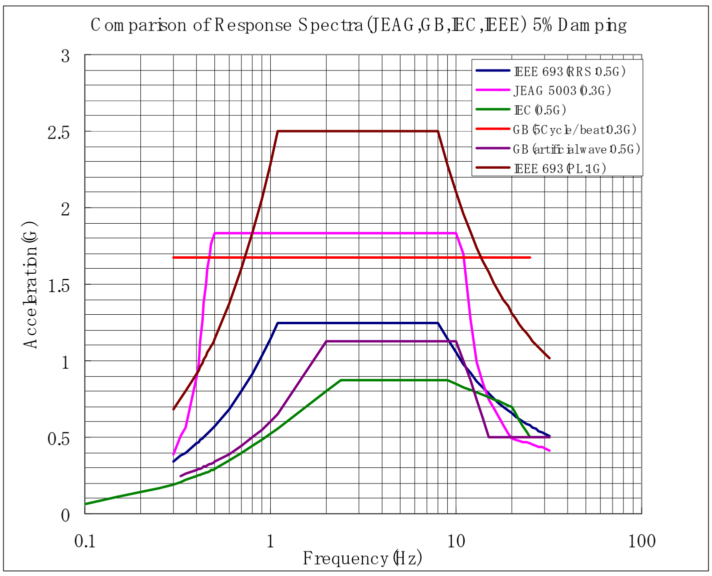


Fig. 4 Comparison of the response (Acceleration amplitude) to the past-earthquake wave forms input and one obtained in resonance sine N waves input

Fig. 5 shows a comparison of the response spectra of single degree of freedom system. It is possible to evaluate the severity of responses from this comparison chart. These charts are often used to calculate the responses of equipment by the response spectrum method.

However, when evaluating the seismic strength of equipment, allowable stresses of materials must be also considered using with this chart. In this figure, two types of response spectrum are plotted. Those are RRS (Required response Spectrum) and PL (Performance Level) curves specified in IEEE 693. The response of PL is twice of RRS and the level of PL is associated with a safety factor of 1.0.



It is clear that PL of IEEE 693 is the most severe waveform except for 0.5G ten cycles/beat waveforms specified for a CB and a GIS in accordance with IEEE 693. By the way, the magnification factor of 5 cycles/beat waveforms has a similar severity to the resonant three cycle's sine waveform.

Fig. 5 Comparison of the response spectra of single degree of freedom system

UHV substation equipments are required to posse high reliability from the viewpoint of electricity-supply due to the huge transmission electricity and a loss of the electricity supply would exert significant impacts on the social infrastructure and make a lot of problems. In order to avoid these situations, it is indispensable for the UHV substation equipment to secure enough seismic performance.

For seismic design, the following procedures should be highly recommended.

1) Gas bushing, Surge arrester, Oil-immersed transformer, VT, PD, Hybrid GIS, Full GIS and AIS exceeding 800kV should be verified seismic performance before they are installed at the place where the earthquake may occur.
2) A series of seismic tests should be carried out with full-scale model basically. However, in the case that it seems impossible to conduct the seismic test with full-scale model due to a large size of actual equipment, the seismic analysis is often applied. In this analysis, mathematical models including the computer-simulation model or sub-set (a partial model) which can meaningfully represent the whole system, could be used to simulate the seismic performance.
3) The severity of the acceleration and the waveform concerning in an input motion must be selected with the most appropriate testing waveform to UHV equipment. According to previous experiences, 0.3G (3m/s2) three cycles sine or 5 cycles sine beats waveform is recommended for the evaluation of seismic strength. A time history waveform is required for a functional test.

1.2.1 Special seismic consideration for UHV substation facilities

Seismic considerations have been taken into account for large-scale equipments, such as UHV substation equipment. The following subjects highlight the most important aspects of seismic design. Some countermeasures are also explained.

(a)Rocking motion of foundation

When the natural frequency of rocking motion coincides with that of the equipment, it is highly likely that high acceleration amplification for the equipment will be observed in the testing of the equipment.

(b)Ensuring sufficient slack of connecting leads

Sufficient slack of the connecting leads must be ensured to avoid an impulse force being exerted at the top of the equipment. In Japan, the required slack is specified being the greatest value of (1) 1.5 times the maximum theoretical relative displacement, (2) 5% of the straight distance between terminals of two neighbouring apparatuses, and (3) 70 mm in the case of 275 kV substation facilities.

Both flexible bundle line and pipe bus are adopted as the connecting lead in Chinese UHV substation, and flexible bundle line is primary and pipe bus is auxiliary when inevitable.

In India, connection between equipments is done generally through flexible conductor or rigid Al. tube. In case of connection between equipments through rigid Al tube, expansion type of connectors is selectively considered at one end to take care of expansion in the connections. While in flexible connections, provision of slacking in conductors is kept.

(c)Split foundations

When an installation of the equipment covers a wide area, such as GIS, split foundations are often adopted. When the vibration characteristics of each foundation differ, relative displacement will occur between the neighbouring two foundations. The equipment should be designed considering the relative displacement. Generally, an application of bellows for equipment is a common practice

(d)Soil conditions

In Japan, standard soil conditions are specified as $V_s \geqq 150$m/s or N value$\geqq 5$. The soil conditions are one of the important factors for defining an input motion. Particular attention must be paid to embankments. It has been reported that a large number of substations installed on the embankments have been damaged in past big earthquakes.

1.2.2 1100 kV gas bushing

(a) Structure and dimensions of bushing and base

The structure and dimensions of the Bushing and its base are shown in Fig. 6. All metal parts were made of aluminium, except the cylindrical pedestal and base, which were made of stainless steel.

(b) Analysis

In order to optimize the bushing design, a study group in Japan consisting of three equipment manufacturers and a bushing manufacturer, led by Tokyo Electric Power Company (TEPCO), cooperated in the seismic analysis of the bushings. Since it was already known that the critical point for mechanical strength is the root of the porcelain shell, the strength was evaluated on those terms. The analyzed values obtained with different bushing models are shown in Table 5.

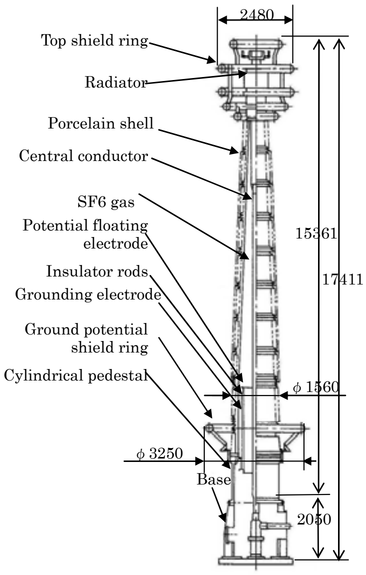


Fig. 6 Structure and dimensions of bushing and base (unit: mm)

Table 5 Seismic analysis of 1100 kV gas bushings

No.	Manufacturer/Analyzer	Specific frequency [Hz]	Bending stress at porcelain shell's root [N/mm^2]	Analysis method
1	Toshiba	4.35	11.3	Shell model
2	Japan AEPS	4.92	10.4	
3	MELCO	4.63	11.8	
4	NGK Insulators	4.86	11.1	Bar model

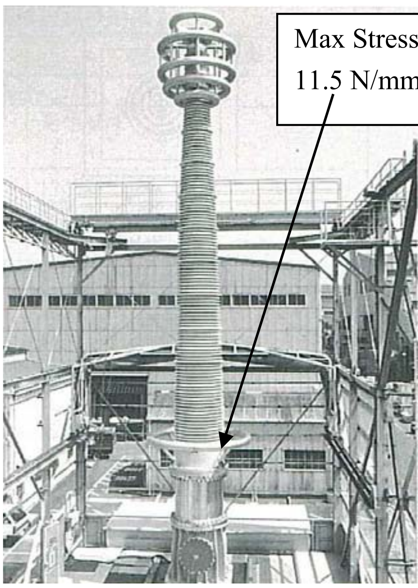


Fig. 7 The seismic test

(b) Test results and evaluation

As for UHV porcelain Bushing, seismic tests were conducted as shown in Fig. 7.

The measured maximum bending stress on the root of the porcelain shell was 11.5 N/mm^2, which agreed well with the predicted value, differing by only 3%. It was concluded that these manufacturers' seismic analyses were precise enough and could serve as reliable substitutes for actual tests in evaluating the bushings' seismic strength.

1.2.3 Porcelain surge arrester

The seismic performance of the UHV surge arrester was evaluated by numerical analysis. First, a finite element model was constructed, and its natural frequencies were extracted by Eigen-value analysis, as shown in Fig.8. Second, dynamic responses were calculated by modal analysis with horizontal ground input. In both China and Japan, the seismic design acceleration is defined in the form of a sinusoidal wave consisting of the resonant frequency of the equipment. A five-cycle sine beat is used in China, whereas a three-cycle burst sine is used in Japan. Their response spectra are shown in Fig.9 for amplitude of 0.3G and a damping ratio of 10%. The response levels were mostly the same at the resonant frequency.

The acceptance criteria are defined by means of allowable stress (or allowable bending moment), taking the brittleness of the porcelain into account. In China, the safety factor is prescribed on the basis of the minimum failure stress. Qualification is assumed if the safety factor is no less than 1.67.

In Japan, the allowable stress is prescribed including a statistic variance of three-sigma in bending strength. The safety factor is considered for a surge arrester with a supporting structure for the UHV equipment.

Finite element model 1st mode 1.6 Hz 2nd mode 8.6 Hz

Fig.8 Eigen-value analysis

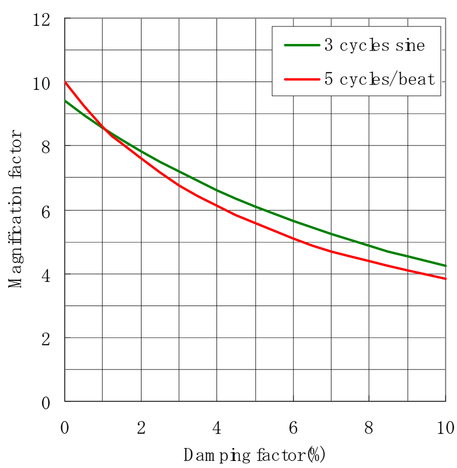


Fig.9 Response spectra of input waveform

The influence of the supporting structure also needs to be taken into account. The actual response of an arrester is amplified by its flexibility. In Japan, the acceptable safety factor of a surge arrester with a supporting structure is 2.0. In China, the magnification factor of 1.2 is commonly used. Thus, a total safety factor of 1.2 × 1.67 = 2.0 was used as an acceptance criterion for a surge arrester without a supporting structure.

Table 6 shows the responses of a UHV arrester with a ground acceleration of 0.3G in a 5-cycle sine beat at the resonant frequency. The safety factor of the porcelain insulator satisfied the acceptance criterion. The displacement of the top was large. Therefore, to avoid impulse force by the connecting lead during an earthquake, it is very important to ensure sufficient lead-length margins based on our experiences of damage observed in the Miyagioki earthquake and the Tanshan earthquake.

Table 6 Calculation results

	Value	Total Safety factor
Max. bending moment of insulator (kNm)	471	2.13
Acceleration at the top (m/s^2)	17.2	---
Displacement at the top (mm)	173.9	---

<Related IEC, IEEE standard>

There are a lot of standards concerning seismic qualification of substation facilities.

IEC 60068-2-6:1995, Environmental testing – Part 2: Tests – Test Fc: Vibration (sinusoidal)

IEC 60068-2-47:1982, Basic environmental testing procedures – Part 2: Tests – Mounting of components, equipment and other articles for dynamic tests including shock (Ea), bump (Eb),vibration (Fc and Fd) and steady-state acceleration (Ga) and guidance

IEC 60068-2-57:1989, Environmental testing – Part 2: Test methods – Test Ff: Vibration – Time-history method

IEC 60068-2-59:1990, Environmental testing – Part 2: Test methods – Test Fe: Vibration – Sine beat method

IEC 60068-3-3:1991, Environmental testing – Part 3: Guidance – Seismic test methods for Equipments

IEC 60694, Common specifications for high-voltage switchgear and controlgear standards

IEC 60137:1995, Insulated bushings for alternating voltages above 1 000 V

IEC 60721-2-6:1990, Classification of environmental conditions – Part 2: Environmental conditions appearing in nature – Earthquake vibration and shock

IEC 62271-2, High-voltage switchgear and controlgear – Part 2: Seismic qualification for rated voltages of 72.5kV and above

IEC 62271-203, High-voltage switchgear and controlgear – Part 203: Gas-insulated metal enclosed switchgear for rated voltages above 52 kV

IEC 61166:1993, High-voltage alternating current circuit-breakers - Guide for seismic qualification of high-voltage alternating current circuit-breakers

IEC 61264:1994, Ceramic pressurized hollow insulators for high-voltage switchgear and controlgear

ISO 2041:1990, Vibration and shock – Vocabulary

IEEE Standard 693-2005 "IEEE Recommended Practice for Seismic Design for Substations" is a newly revised document covering the seismic design and qualification of all types of electrical equipment found in power substations. This document is a revision of the IEEE Std 693-1997 "IEEE Recommended Practice for

Seismic Design of Substations" It simplifies the process of specifying seismic requirements by providing a single standard set of design recommendations for seismic qualification of each equipment type.

This means that the seismic criteria, qualification methods and levels, and performance requirements are standardized for a given equipment type. Three qualification levels are recommended: low, moderate, and high. The user determines which level the equipment is to be qualified to, and includes this as part of their specification. In this way the equipment manufacturer has a very clear understanding of what must be done to obtain the qualification. IEEE 693 does not allow calculations as the only means of qualification of bushings, but requires testing.

IEC Technical Report 1463 IEC 1463: 1996-07 "Bushings-Seismic qualification" is an IEC document covering the seismic qualification of power bushings, and is based on static coefficient calculations to compare the expected forces generated during a seismic event to the cantilever withstand capability of the bushing.

1.3 Pollution and anti-pollution design

1.3.1 Anti-pollution design approaches

To select suitable insulators from catalogues based on the system requirements and the environmental conditions, three approaches are recommended in IEC 60815-1[3]. Table 7 shows the data and decisions needed within each approach. The applicability of each approach depends on available data, time and economics involved in the project.

Table 7 The three approaches to insulator selection and dimensioning

	APPROACH 1 (Use past experience)	APPROACH 2 (Measure and test)	APPROACH 3 (Measure and design)
Method	• Use existing field or test station experience for the same site, a nearby site or a site with similar conditions.	• Measure or estimate site pollution severity. • Select candidate insulators using profile and creepage guidance hereafter. • Choose applicable laboratory test and test criteria. • Verify/adjust candidates	• Measure or estimate site pollution severity. • Use these data to choose type and size of insulation based on profile and creepage guidance hereafter.
Input Data	• System requirements. • Environmental conditions. • Insulator parameters. • Performance history.	• System requirements. • Environmental conditions. • Insulator parameters. • Time and resources available.	• System requirements • Environmental conditions. • Insulator parameters. • Time and resources available.
Decisions	• Does the existing insulation satisfy the project requirements and is it intended to use the same insulation design ? **YES** Use the same insulation design. **NO** Use different insulation design, materials or size. Use experience to pre-select the new solution or size	• Is there time to measure site pollution severity? **YES** Measure **NO** Estimate • Type of pollution determines the laboratory test method to be used • Site severity determines the test values	• Is there time to measure site pollution severity? **YES** Measure **NO** Estimate
Selection Process	• If necessary, use the profile and creepage guidance hereafter to adapt the parameters of the existing insulation to the new choice using approach 2 or 3.	• Select candidates • Test if pollution performance data is not available for candidates • If necessary, adjust selection/size according to the test results.	• Use the type of pollution and climate to select appropriate profiles using the guidance hereafter. • Use the pollution level and correction factors for profile design and material to size the insulation using the guidance hereafter.
Accuracy	• A selection with a good accuracy.	• A selection with an accuracy varying according to the degree of errors and/or shortcuts in the site severity evaluation and with the assumptions and/or limitations of the chosen laboratory test.	• A possibly over or under-dimensioned solution compared with approaches 1 or 2 • A selection with an accuracy varying according to the degree of errors and/or shortcuts in the site severity evaluation and the applicability of the selected correction factors.

The approach 2 is commonly employed for a new power substation such as 1100kV substation without field and test station experience. It can be done by the following steps:

Step 1 : The Site Pollution Severity (SPS): Equivalent Salt Deposit Density (ESDD) and Non Soluble Deposit Density (NSDD) are measured or estimated;

Step 2 : The chemical composition of the contaminant is analyzed and a correction is applied on the ESDD and the Salt Deposit Density (SDD), which is equal to the amount of sodium chloride (NaCl) in an artificial deposit on the same insulator surface, is acquired.

Step 3 : The artificial pollution tests are carried and the maximum withstand voltages of insulator or bushing with various SDD can be gained.

Step 4 : The regression analysis is used and the curve fitting or formula between the pollution flashover voltage and SDD is acquired;

Step 5 : The maximum withstand voltage under certain SDD is calculated, the specific creepage is acquired.

Step 6 : The necessary corrections are applied to the results including the corrections of NSDD, the average diameter, the non-uniform pollution distribution and so on. Then the dimension of insulator can be decided lastly.

1.3.2 Anti-pollution design experience of UHV in Japan

1.3.2.1 Pollution Performance of UHV gas bushing porcelain shell

In the case of 500kV or less porcelain concerning a withstand voltage, it was able to be evaluated for 500kV or less by the characteristic of the porcelain tube length (only porcelain). Fig. 10 shows the withstand voltage characteristics of the porcelain tube and the gas bushing.

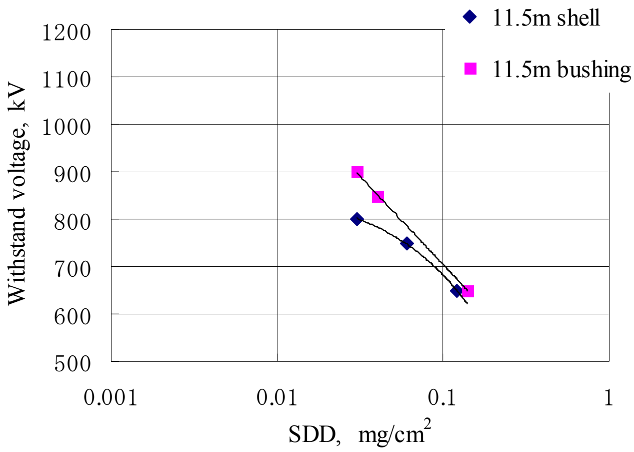


Fig. 10 Withstand voltage characteristics of UHV gas bushing and porcelain shell

The saturation tendency is seen in the withstand-voltage characteristic in the light pollution (less than 0.01mg/cm^2) but in the heavy pollution of 0.03mg/cm^2 or more as shown in Fig. 11 the voltage characteristic of the bushing and the porcelain tube unit doesn't show the saturation characteristics. The withstand voltage characteristic is thought to be decided by not the surface resistance but electric capacitive distribution around 0.01mg/cm^2 of the light pollution , though it is decided to be distributed in the porcelain tube surface resistance potential when 0.03mg/cm^2 or more polluted.

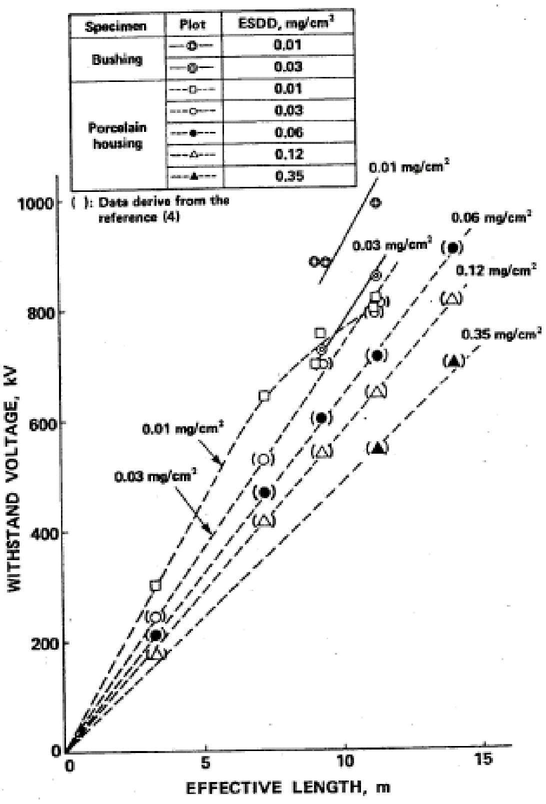


Fig. 11 Withstand voltage characteristics of UHV gas bushing under pollution conditions

The following design method is devised by thinking about the pollution affection for the porcelain tube and the bushing (UHV classes) in the effective length and the voltage characteristic of porcelain tubes and bushings.

1) The electric field concentrates on the upper part up in general, and the potential distribution deteriorates in the porcelain tube. On the other hand, the bushing concentrates on the lower side by the existence of an internal conductor the electric field and deteriorates the potential distribution. Therefore, when did the proportion of the effective length to the voltage performance by improving the potential distribution, it becomes it. Therefore, because the weight is very heavy, and the height of the bushing is also very high, the improvement of the potential distribution by the middle electrode is especially thought from respect of an earthquake-proof performance by the porcelain tube as for the UHV bushing though the adoption of the capacitor bushing structure is thought by the installation and the bushing of a high-pressure shield.

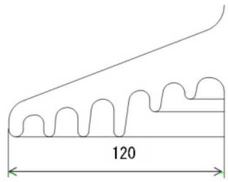
2) To attempt the improvement of the potential distribution, the installation of the best shield ring is needed for the pollution design of the porcelain tube and the insulator type arrestor.

Therefore, the potential distribution is an important matter in the insulator equipment of UHV according to the electric field control with an internal shield and an external shield.

1.3.2.2 1100 kV gas bushing

For a 1100 kV gas bushing having a longer length, a more compact design of the hollow insulator is essential from the viewpoints of enough seismic qualification design and its ease of transportation. Therefore, many kinds of shed shapes were subjected to pollution withstand tests and evaluated. Finally, the insulator design shown in Table 8 was selected for this application. The height of the bushing shell for the 1100 kV application was 11.5 m.

Table 8 Gas bushing insulator design

Overall length, m	11.5
Effective Length , m	10.62
Average Diameter, mm	1120
Creepage Distance, mm	46400
Shed pitch, mm	100
Shed Profile	

(1) Test Conditions

We found that when controlling the electric field strength with the internal potential floating electrode, the withstand voltage of the bushing was higher than that obtained on the hollow insulator shell only, as shown in Fig. 12.

In addition, since the non-uniformities of the pollution deposit distribution in the longitudinal and circumferential directions of the bushing, as well as the wet conditions in the longitudinal direction, affect the resistance distribution in the longitudinal direction, the electric field distribution of the bushing may also be affected.

The investigation results of the withstand voltage characteristics indicated that the effect of non-uniform pollution in the circumferential direction on the withstand voltage of the bushing could be represented with the average deposit density.

Furthermore, non-uniformities of the pollution deposit distribution and wet conditions in the longitudinal direction affect the electric field distribution of the bushing, causing a reduction in the withstand voltage of the bushing. However, if the electric field distribution of the bushing is correctly controlled with the potential floating electrode, such a reduction of the withstand voltage is not more than 5%, and the influence due to the reduction is minimized, as shown in Fig. 12.[4].

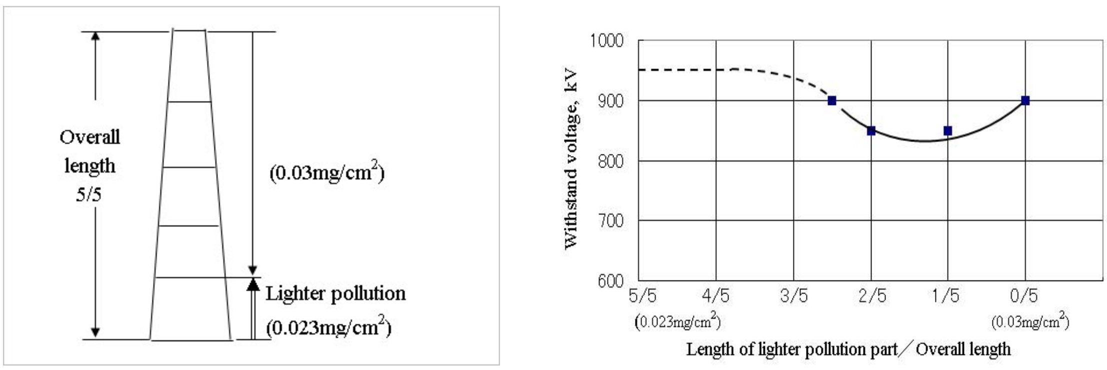


Fig. 12 Effect of longitudinal non-uniform pollution distribution on withstand voltage of bushing

1.3.3 Anti-pollution design experience of UHV in China

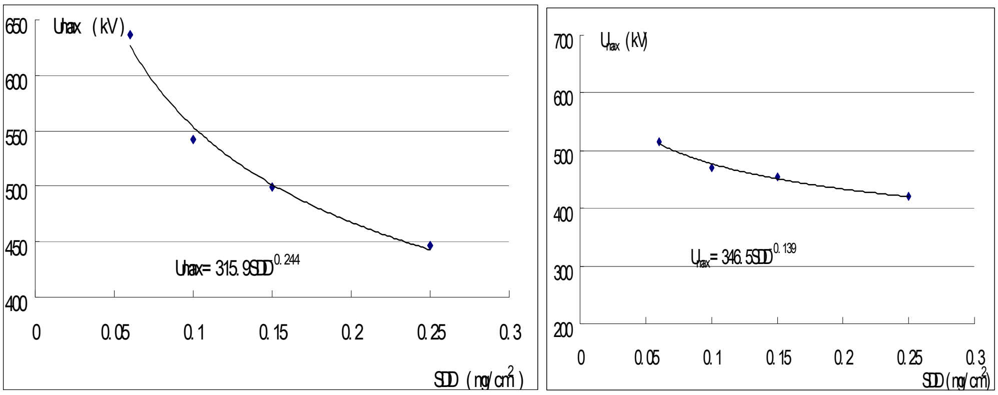
1.3.3.1 Pollution Performance of UHV Post Insulators and Bushings

Test was processed on a kind of 1000kV porcelain post insulator with 8.8m height. On the top of the post insulator, corona ring with an actual size was mounted. The total height of hollow insulator is 7520mm. The test arrangement is shown Fig. 13.

Fig. 13 The test arrangement of post insulator and hollow bushing shell

The solid layer method was used in the test, and the SDD used in the test were 0.06 mg/cm^2, 0.10 mg/cm^2, 0.15 mg/cm^2, 0.25 mg/cm^2.

The test results are shown in Fig. 14[5]



(a) Post insulator **(b) hollow bushing shell**

Fig. 14 Pollution performance of UHV post insulator and hollow bushing shell[5]

1.3.3.2 Correction for average diameter of insulator

A correction for average insulator diameter D_a shall be applied to the reference Unified Specific Creepage Distance (USCD)* according to Equation 1.

* USCD- The creepage distance of an insulator divided by the maximum operating voltage across the insulator (for a.c. systems usually Um/√3) It is generally expressed in mm/kV.

$$Corrected\ USCD = reference\ USCD \times K_{ad}$$ Equation 1

The D_a is defined as Equation 2, see also Fig. 15 for the meaning of different parameters.

$$D_a = (2D_t + D_{s1} + D_{s2}) / 4$$ Equation 2

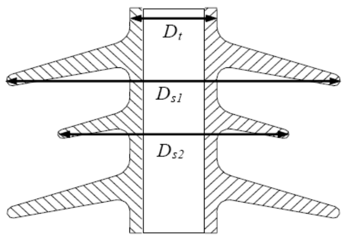


Fig. 15 The definition of average diameter.

For porcelain and glass insulators [6]
$K_{ad} = 1$, When D_a is smaller than 300mm.
$K_{ad} = 0.001D_a + 0.7$, When D_a is equal to or larger than 300 mm, see also Fig. 16.

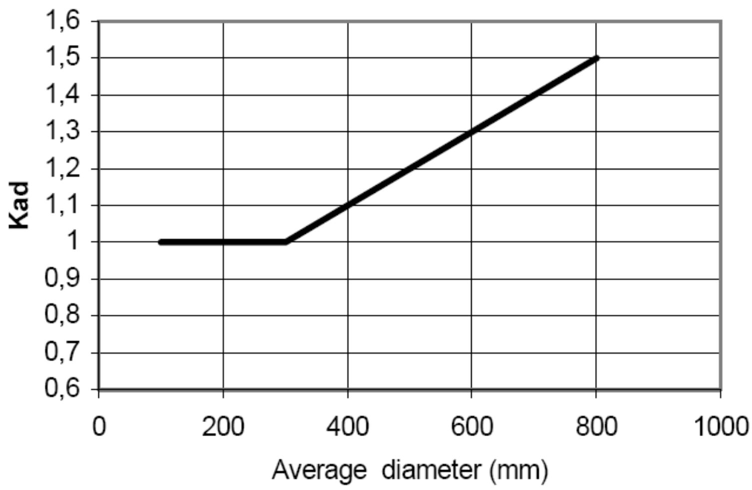


Fig. 16 K_{ad} as a function of average diameter of porcelain and glass insulator.

For polymer insulators [7]
$K_{ad} = 1$, When D_a is smaller than 300 mm.
When D_a is equal to or larger than 300 mm, the K_{ad} is according to Fig. 17[1]

[1] HTM - Hydrophobicity Transfer Materials

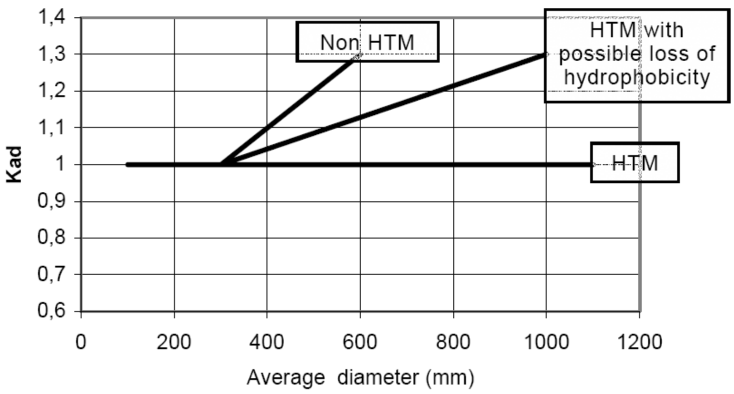


Fig. 17 K_{ad} as a function of average diameter of polymer insulator

1.3.3.3 NSDD Correction

The NSDD correction is according to the test results of suspension insulator string in China. The relationship between $U_{50\%}$ of insulator string (48 pieces of FC-400/205 glass insulator) and NSDD was negative exponential function, the exponent was 0.154[[5]].

1.3.3.4 Non-uniform Pollution distribution Correction

The pollution severity of natural polluted insulator was non-uniform, it means that the pollution flashover voltage from uniform test should be corrected.

The following formula for non-uniform pollution correction is used in outdoor insulation design of 1000kV UHV AC projects in China

$$K = 1 - N \ln(T / B) \qquad \text{Equation 3}$$

Where K : Correction coefficient; N : constant, about 0.055 [5ss], T / B : pollution severity ratio between the toper surface and the bottom surface.

1.4 Transportation restriction

1.4.1 General Consideration

Since the rated voltage of UHV substation equipment is more than twice as 500kV class or below, size of equipment may become larger. Therefore it is more important to consider transportation restriction for the design of equipment.

For the equipment like GIS, each component should be designed so as to be an optimum transportation unit considering assembling and testing at a factory or on site. In the meantime, for GCB as the largest component of GIS, height and weight of component must be considered including a vehicle of transportation.

1.4.2 Transportation Restriction for Transformers

Transformers are the largest equipment in size and weight among UHV substation equipment. Therefore transportation restriction must be taken into account on a design of UHV transformers.

<Example in Japan >

The UHV transformer specifications are double the voltage and power of the highest system voltage transformers (500kV) currently used in Japan. This must be transported under the same railway transport restrictions as the conventional transformers. The railway transport limit is 4.1m in height and 3.1m in width.

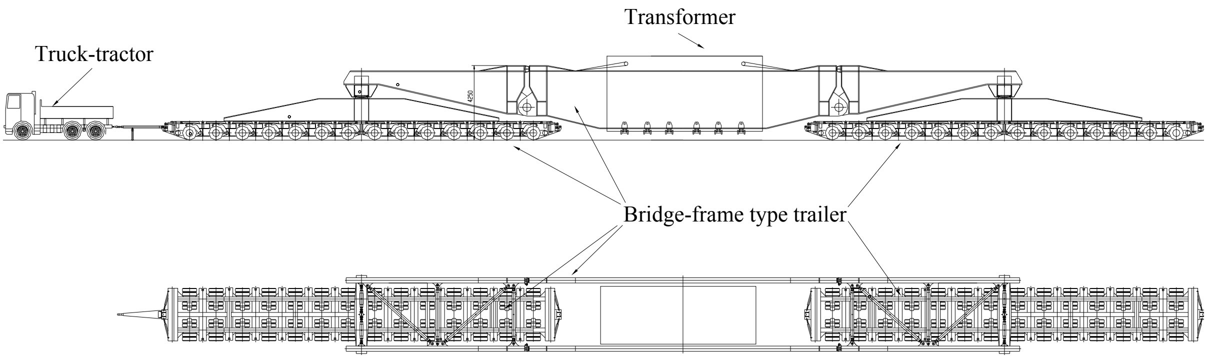
The capacity of UHV transformer is 3000MVA, so the single phase main tank was divided into 2 units according to the railway transport limit. One tank of 1/2 phase unit is transported to the nearest rail station of the site by railway, and is then loaded onto a special trailer for transport to the site. The shipping weight is approximately 200 tons. Fig. 18 shows the transportation of UHV transformer to the site in Japan. [8]

Fig. 18 Transportation of UHV transformer to the site in Japan

<Example in China>

The transportation size of transformers cannot exceed the allowable value of the tunnel, culvert and bridge. The transportation weight of transformers cannot exceed the withstand capacity of the bridge, road, vehicle, ship and so on.

Method and route of transportation for large equipment has been chosen by CPECC, China Power Engineering Consulting Group Corporation, which is the design institute of China UHV AC project. Under the consideration of safety and reliability, the transportation method has been optimized and cost has been reduced. Road transportation or a combination of road and waterway transportation for the large equipment will be chosen. Truck-tractor and bridge-frame type trailer will be used. The maximum transportation capability of the China highway is 450ton-total weight, including transportation vehicles, and 5m total height. So the transportation limits for the UHV transformer in China is 12m long, 4.15m wide, 4.9m high and 375 tons. In highway transportation, the ground slope could not exceed 15 degrees and the turning radius should be more than 28m. Several bridges on the transportation route have to be improved for UHVAC transformers' transportation.



Axle load (each weight /axle: 16 ton /axle)

Fig.19 Transportation of UHVAC transformer in China

<Example in India>

In India, as such there are no constraints for transportation of heavy transformers except in hilly areas in northern part. Generally transportation of EHV / UHV transformers are done through roads. So far HVDC converter transformer with length 10.63 m, width 4.82 m, height 5.0 m and weight 335 tonnes shall be transported by road. However, utilities always prefer for survey of transportation by the manufacturer to take care any strengthening of existing culverts, small bridge etc.

1.5 Electro-magnetic Field

1.5.1 Exposure to Electric, Magnetic and Electro-magnetic Fields

1.5.1.1 Guidelines

In the end of 1970's, concern for an adverse health effect of the public exposure to the electro-magnetic fields to the residents who live near transmission lines grew up, and study to evaluate the effect has been started by some organizations in cooperation with the Environmental Health Division of the World Health Organization (WHO). In 1998 the Guideline for Limiting Exposure to Time-Varying Electric, Magnetic, and Electromagnetic Fields (up to 300GHz) was published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP).

Meanwhile, the Institute of Electrical and Electronics Engineers (IEEE) issued the standards on the safety levels for human exposure to electromagnetic fields.

These guidelines and standards mainly consider the effects on the public. Therefore, it could be inappropriate to apply the general public exposure limits for the area inside substations, but the area near transmission lines or outside the wall of the substation.

Table 9 Reference levels for general public exposure

<table>
<tr><td></td><td></td><td>E-field (kV m^{-1})</td><td>B-field (μT)</td></tr>
<tr><td rowspan="2">ICNIRP Guidelines</td><td>General public</td><td>5 (50Hz)
4.2 (60Hz)</td><td>100 (50Hz)
83 (60Hz)</td></tr>
<tr><td>Adverse indirect effects can be excluded</td><td>Reference levels can be exceeded</td><td>Reference levels can be exceeded</td></tr>
<tr><td rowspan="2">IEEE C95.6 Standard</td><td>General public</td><td>5</td><td>904 (head and torso)
75800 (arms or legs)</td></tr>
<tr><td>Power line rights-of-way</td><td>10</td><td>—</td></tr>
</table>

For the area inside substation, the reference levels below are recommended as the occupational exposure in ICNIRP guidelines and IEEE Standard.

Table 10 Reference levels for occupational exposure

<table>
<tr><td colspan="2"></td><td>E-field (kV m^{-1})</td><td>B-field (μT)</td></tr>
<tr><td rowspan="2">ICNIRP Guidelines</td><td>Occupational exposure</td><td>10 (50Hz)
8.3 (60Hz)</td><td>500 (50Hz)
416 (60Hz)</td></tr>
<tr><td>Specific case</td><td>20</td><td>—</td></tr>
<tr><td rowspan="2">IEEE C95.6 Standard</td><td>Controlled environment</td><td>20</td><td>2710 (head and torso)
75800 (arms or legs)</td></tr>
<tr><td>not within reach of grounded conductor</td><td>>20</td><td>—</td></tr>
</table>

1.5.1.2 Electro-magnetic Fields in UHV Substations

The design levels of electric and magnetic fields in substations depend upon the countries and utilities, but many of those adopt the reference levels for occupational exposure in ICNIRP guidelines.

The actual levels of electric and magnetic fields are determined by the configuration of the substation, such as the height of live part of equipments, height of conductors and bundle diameter of conductors.

Papers B3-213[[9]] and B3-214[[10]] describe the electric field strength in AIS substations for 800 kV and 400 kV respectively. Both of papers show examples of measurement or calculation results, and indicate the electric field strength at some parts like GCB and DS exceeding that in ICNIRP guidelines. Fig.15 shows an example of measured electric field strength distribution higher than 10 kV/m in the 420/245 kV substation provided in the paper B3-214[[10]].

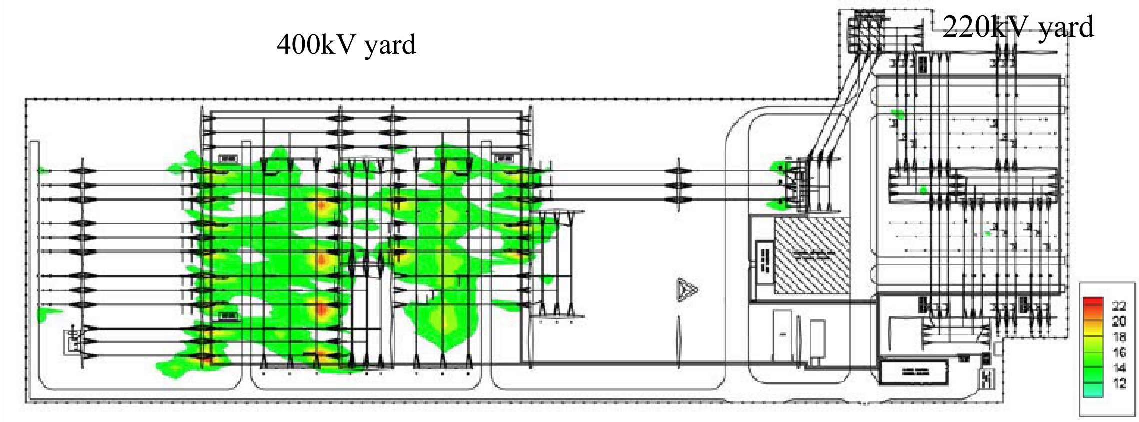


Fig. 20 Electrical Field Map with Values higher than 10kV/m

In case of UHV substations, electrical field strength becomes more critical to the substation design because of high voltage.

<Example in China>

Measurements were performed in the UHV test site, the set-up of the verification tests are shown in Fig. 21~ Fig. 24. 1100 kV SF6 porcelain type circuit breaker, disconnector and busbar of two types were tested respectively. The height of circuit breaker is 13.6m without underframe and 15.6m with underframe; the height of disconnector is 13m; one bus bar is pipe conductor with the diameter of 250mm, and the other bus bar is a four-bundle conductor with the bundle diameter of 848mm. The length of the two types of bus bars are 16m and 20m respectively, and the clearance of the lowest conductors from ground are 13m and 17m separately.

The RIV from circuit breaker, disconnector and bus bars are measured at routine sites.

The ground power frequency resultant electric field from disconnector and bus bars were measured. The measurement positions of AN (Audible Noise) from the bus bars locate at lateral distance of 0m (just under the bus bar), 15m and 20m from the tested bus bars.

The test results under operation voltage are shown as follows: the RIV from circuit breaker, double suspension insulator strings and bus bars are all lower than 55dBμV; the ground power frequency electric field from disconnector and bus bars are all lower than 15kV/m, it satisfies the design requirement; audible noise from the bus bars are 50dB approximately and no influence on environment outside the substation.
Electrical field design criteria of UHV substation in China is as follows.

<u>Inside the substation:</u>

1000kV CVT: the measurement value of power frequency electric field cannot exceed 10 kV/m at 1.5m above ground below the equipment under 1.1 Um/√3kV (According to equipment contract)
The electrostatic induction field inside the 1000kV outdoor substation equipments cannot exceed 10kV/m at 1.5m above ground. Some areas can be up to 15kV/m. (Final Preliminary Design Instruction)

<u>Outside the UHV substation:</u>

The limit of power frequency electric field is 4kV/m in residential area.

Transmission Lines: 7kV/m and 10kV/m in residential area and non-residential area respectively

Fig. 21 Electromagnetic field test set-up for UHV SF_6 circuit breaker

Fig. 22 Electromagnetic field test set-up for UHV double suspension insulator strings

Fig. 23 Electromagnetic field test set-up for 4-bundle conductor

Fig. 24 Electromagnetic field test set-up for UHV disconnector

<Example in Japan>

Measurements of electric field strength in the 1100kV Shin-Haruna pilot plant of Tokyo Electric Power Co. (TEPCO) were performed. TEPCO carried out full-scale field verification tests with 1100kV GIS and transformers from 1996, and various data were collected and long-term reliability was verified. A full GIS is selected for UHV substation, therefore the only air insulation high voltage part is entrance bushings and the lead to the towers.

TEPCO adopts 10kV/m as the design level in substations, which is the same as the reference level in the ICNIRP guideline.

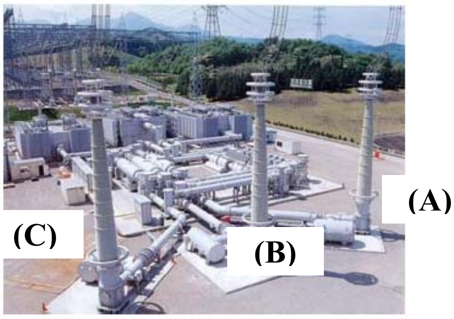
Measurement at factory

Measurements were performed by a prototype. The maximum electric field strength was 9.1kV/m at the point of 4.5m from the center of the bushing horizontally and 1.5m high from the ground level, which is less than the field t reference level 10kV/m in the guideline.

Measurement at test site

Measurements were also performed at the 1100kV pilot plant. Configuration around bushings in the pilot plant simulates the actual substation layouts. The height to the lower grading ring of the bushing is designed as 4.5m. Electric field distribution was measured around the bushings.

Voltages from the phases to the ground during measurement were 607 – 617kV. The highest value was 8.15kV/m at 1.5m above ground level near C-phase. This value is equivalent to 8.5kV/m with 635kV, which is less than the reference level 10kV/m.



Overview of 1100kV Pilot Plant

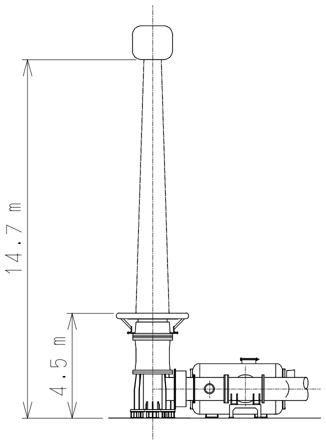


Fig. 25 Height of Bushing

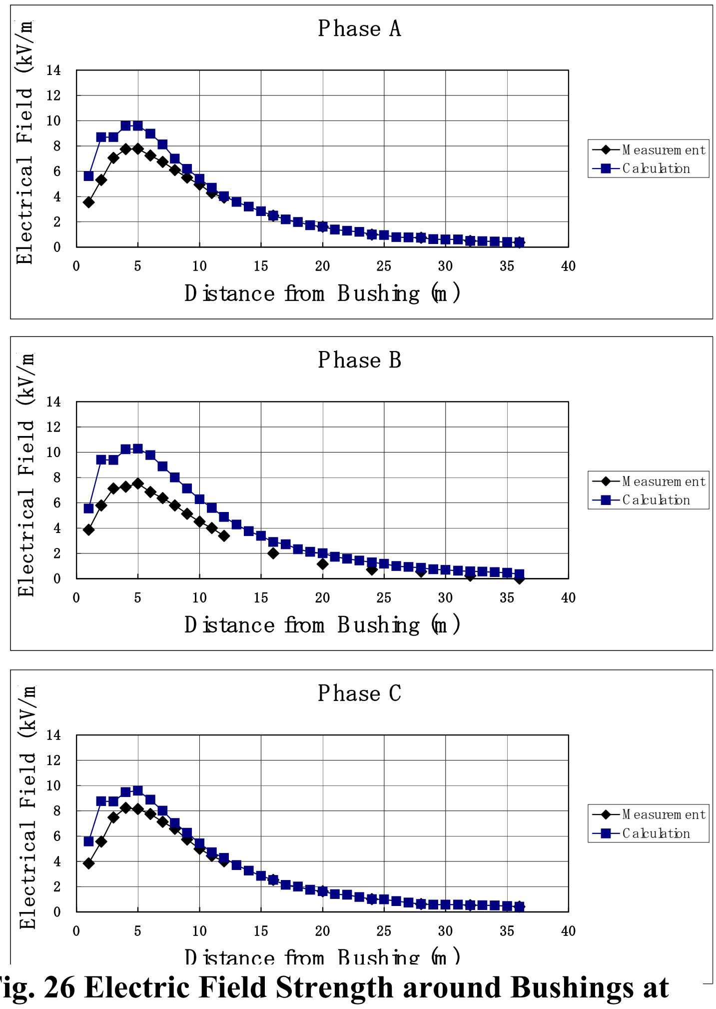


Fig. 26 Electric Field Strength around Bushings at 1.5m above ground Level

<Examples in India>

As per measurements of electric and magnetic fields done by POWERGRID's 765/400 kV Seoni substation (with first level of equipment connection with 4.5” IPS Al tube at 14 m, second bus bar level at 27 m and third cross over level at 39 m with quad bull ACSR conductor with 450 mm sub conductor spacing), the electric field values have been measured less than 10 kV / m at 1.8 m level and magnetic field values also have been measured in the range of 10 micro tesla only.

For 1200 kV substation also the same criteria i.e. electric field value of 10 kV/ m (max) at 1.8 m level and magnetic field 500 micro tesla (max) at 1.8 m level, is proposed to be adopted.

<Examples in South Africa>

Eskom has decided to adhere to the ICNIRP guidelines with regard to exposure levels for electromagnetic fields. In substations the occupational limit for electric fields is 10kV/m and this is Eskom's target design value. For Eskom’s latest 765kV AIS substation designs, the calculated value was below 10kV/m under the busbar and in the majority of the station. However, in some minor portions of the substation, especially under some equipment connections, the calculated value was approximately 13kV/m.

Whilst the ICNIRP basic occupational limit is 10kV/m, ICNIRP does go on to state, "For the specific case of occupational exposures at frequencies up to 100kHz, the derived electric fields can be increased by a factor of 2 under conditions in which adverse indirect effects from contact with electrically charged conductors can be excluded". This statement basically allows values up to 20kV/m in certain circumstances. In light of the above statement, as well as the fact that the actual measured values are usually lower than the calculated values, Eskom's substation design department has accepted the value of 13kV/m on a minor portion of the station.

1.6 Earthing system for UHV GIS, AIS, and H-GIS

The earthing system is important to guarantee a safe operation for UHV systems and protect human body and electrical equipment during operation and especially in case of a system failure. Therefore the design, the installation, the testing and the maintenance of the earthing system has to fulfill safety and protection criteria.

International standards are dealing with these aspects e.g. the IEC 61936 (IEEE 80) for electrical equipment for a voltage higher than 1 kV. This standard covers the requirements for UHV substations in general, but has to be complemented with dielectric values for safety criteria in UHV systems. Effects on passive parts due to voltage charging caused by the UHV system should be taken in consideration.

In AIS substation, power and control armored cables would shield the cables from any magnetic field or surges in secondary side in UHV substation. These armored cables should be properly earthed.

1.6.1 Step Voltage / Touch voltage (UHV substation)

The following definitions are listed in IEEE 80-2000.

(1) Ground potential rise (GPR): The maximum electrical potential that a substation grounding grid may attain relative to a distant grounding point assumed to be at the potential of remote earth. This voltage, GPR, is equal to the maximum grid current times the grid resistance with respect to remote earth.

(2)Mesh voltage: The maximum touch voltage within a mesh of a ground grid

(3)Metal-to-metal touch voltage: The difference in potential between metallic objects or structures within the substation site that may be bridged by direct hand-to-hand or hand-to-feet contact.

(4)Step voltage: The difference in surface potential experienced by a person bridging a distance of 1 m with the feet without contacting any other grounded object.

(5)Touch voltage: The potential difference between the ground potential rise (GPR) and the surface potential at the point where a person is standing while at the same time having a hand in contact with a grounded structure

Already step voltage and touch voltage for gas-insulated substations are examined as follows.

A person touching the outer sheath of a GIS might be exposed to voltages resulting from two basic fault conditions

a) An internal fault within the gas-insulated bus system, such as a flashover between the bus conductor and the inner wall of the enclosure.

b) A fault external to the GIS in which a fault current flows through the GIS bus and induces currents in the enclosures.

Because the person may stand on a grounded metal grating and the accidental circuit may involve a hand-to-hand and hand-to-feet current path, the analysis of GIS grounding necessitates consideration of metal-to-metal touch voltage

Most GIS manufacturers consider the enclosure properly designed and adequately grounded if the potential difference between individual enclosures, and the potential difference between an enclosure and other grounded structures, does not exceed 65–130 V during a fault.

Already clear equation to estimate these step voltage and touch voltage are described in the IEEE80-2000. This estimation method is effective, so it is important to keep same criteria In the case of UHV substation case.

For step voltage the limit is

$$E_{step} = \left(R_B + 2R_f\right) \cdot I_B$$

for body weight of 50kg

$$E_{step50} = \left(1000 + 6C_s \cdot \rho_s\right)\frac{0.116}{\sqrt{t_s}}$$

For touch voltage the limit is

$$E_{touch} = \left(R_B + \frac{R_f}{2}\right) I_B$$

for body weight of 50kg

$$E_{touch50} = \left(1000 + 1.5C_s\rho_s\right)\frac{0.116}{\sqrt{t}}$$

where

Estep is the step voltage in V
Etouch is the touch voltage in V
Cs is determined from Figure 11 or Equation (27) in IEEE80-2000.
rs is the resistivity of the surface material in Ω·m
ts is the duration of shock current in seconds
If no protective surface layer is used, then *Cs* =1 and ρ*s* = ρ.

The following empirical equation gives the value of Cs. The values of Cs obtained using following equation are within 5% of the values obtained with the analytical method (Thapar, Gerez, and Kejriwal [[11]]).

$$C_s = 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09}$$

<Indian Practice>

The permissible step and touch voltages so calculated as per above formula should be less than the actual calculated step and touch voltages. In addition to this, the earth mat resistance of the EHV AIS substation is kept within 1 ohm. Suitable measures to take care potential difference due to rise of voltage in the substation during fault condition (i.e fault current x fault duration) need to be taken in the substation auxiliaries like under ground water piping, under ground telephone wires, cables, fencing etc. entering in the substation from outside.

<Eskom’s Earthing Practice>

With regard to earthmat design for both AIS and GIS substations, Eskom adheres to the IEEE Guide for Safety in AC Substation Grounding, IEEE Std. 80-2000. The earthmats are designed in detail for each substation taking into account the following factors: maximum zero sequence fault level for the lifetime of the station, soil resistivity in the substation using multi layer soil model, backup protection operation time which is usually 0.5s but can be reduced in extreme circumstances, thickness and resistivity of yard stone layer between

100mm and 200mm, 50kg human being instead of 70kg. Eskom uses the CDEGS program to determine safe Step Potentials, Touch Potentials and Grid Potential Rise and the earthmat is designed accordingly. Where there is metallic connection between source and load substation earthmats e.g. via overhead earth-wire/s, the benefit of the reduced earth current is taken into account. The design is still fairly conservative and in instances where it is difficult to achieve the safe limits after adding more copper and increasing surface layer resistivity, Eskom employs equi-potential grids on operatable equipment. Others measures taken are to reduce the fault currents by opening inter connectors, using fault limiting reactors, doping the soil with additives to reduce resistivity, encapsulating the copper rods in bentonite clay in slurry form, reducing the protection operation time (current exposure time). Where it is not possible to reduce step potentials or touch potentials using any practical means, the designer could as a last resort stipulate that all persons entering the station must wear insulated safety shoes and /or gloves and warning signs would also be employed.

UHV substations would be located in the mountain areas, so they must be made compact as possible so as to meet installation space constraints. Thus UHV substations would adopt GIS in Japan.
In the mountain areas, the resistivity of surface material is high, thus touch voltage and step voltage, which are generated by grounding fault are allowed to increase to the value which is not influenced to the human body.
(Specifications for Japanese earthing system)
Tolerable body current (IB) 182mA -------ts=0.04,
ts is clearing time of the back-up protection for 50kg body weight

Body resistance(RB):650Ω -------Specified by IEC47901(published in 1984)
Contact resistances between a person's foot and the earth surface (Rf) are shown below.
These values are much differences compared to those of IEC.

E_{touch} and E_{step} are shown below respectively.

Surface of ground	Asphalt	Gravel	Concrete	Lawn grass
E_{touch}(V)	3,460	3,680	120	150
E_{step}(V)	13,540	14,380	120	260

Surface of ground	Asphalt	Gravel	Concrete	Lawn grass
R_f (Ω)	36,900	39,200	20	400

E_{touch} factor and E_{step} factor are shown below respectively.

Surface of ground	Asphalt	Gravel	Concrete	Lawn grass
E_{touch} factor	0.40	0.33	0.003	-
E_{step} factor	0.4	0.04	0.005	0.03

In Japanese earthing system, mesh is provided within 40m apart at a depth of 0.6m to suppress maximum electric potential less than 8000V.

1.6.2 Multiple-grounding method and earthing mesh (UHV substation)

1.6.2.1 Multiple-grounding method

For grounding method of GIS enclosures, multiple-grounding design is employed from the following reasons:

1. Induction surge can be suppressed
2. Grounding is ensured by multiplying connection
3. Outer leakage flux, which causes overheat of equipment's supporting structure

Reduction of outer flux can reduce induced current from each enclosure sheathe to the ground generated by multi-grounding method with adoption of phase-to-phase shunt bar at proper distance.

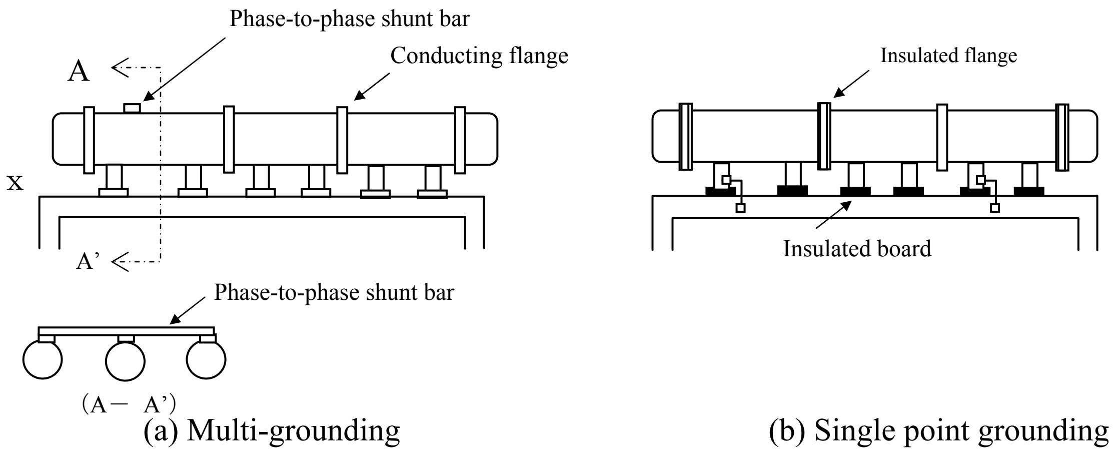


Fig. 27 Grounding methods (multi-grounding and single point grounding

(1)Current carrying test (induction current measurement)

Current carrying test were done on the closed loop circuit in UHV Test Equipment Station. The result was as follows.

The induced current on enclosure increases proportional to the distance of shunt bars until it saturates. When the distance between shunt bars becomes more than 50m, the induced current saturates at 95 % of main circuit current.

Maximum induced current in shunt bars rises up to 80 % of main circuit current, which is largest at the outermost part of multi-grounded loop (at both ends of enclosure), and smallest in the middle. The leakage current to the grounding system is about 20%. Therefore, enclosure current and shunt bar current should be specified to be 100% of main circuit rated current in the GIS design.

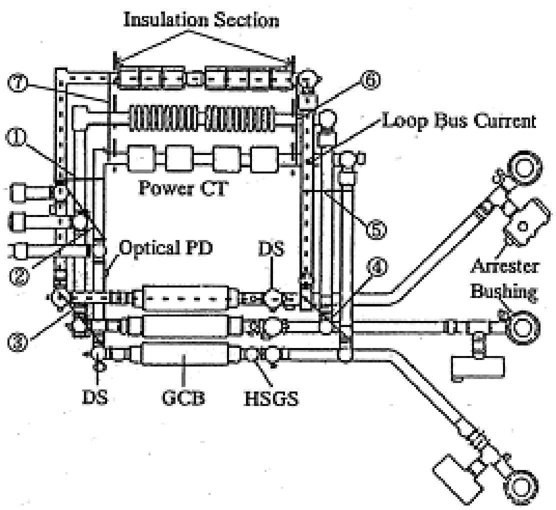
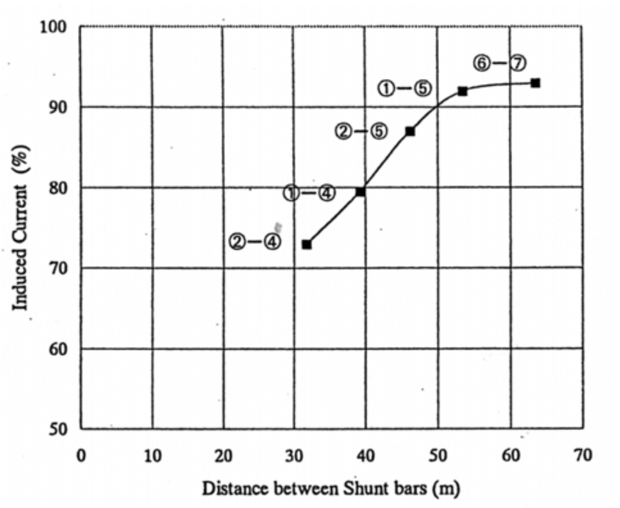


Fig. 28 Arrangement of shunt bars (UHV Test Equipment Station)



%=Percentage of main circuit current

Fig. 29 Induced current of GIS enclosure and distance between shunt bars

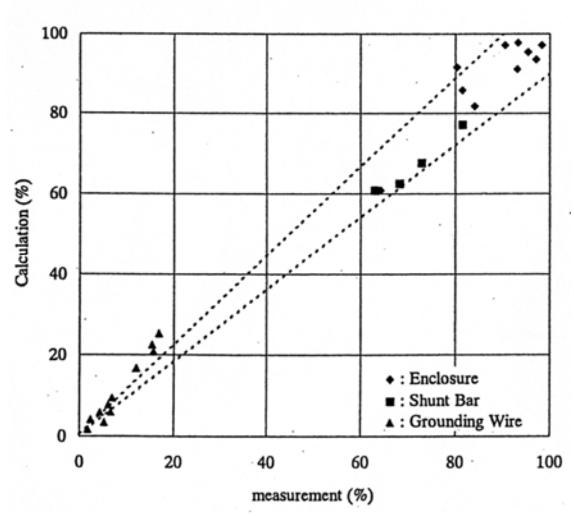


Fig. 30 Measurement and Ideal Values of induced current

Reduction of inductive surge into substation protection systems

For the design of grounding system, grounding auxiliary mesh in addition to main mesh shall be laid for the purpose of reducing inductive surge (disconnector surge, ground-fault surge, and lightning surge, etc.) into substation protection systems. This auxiliary mesh shall be provided at a 2m span as specified in TEPCO 500kV design standard.

(2) Transient response of earthing mesh system

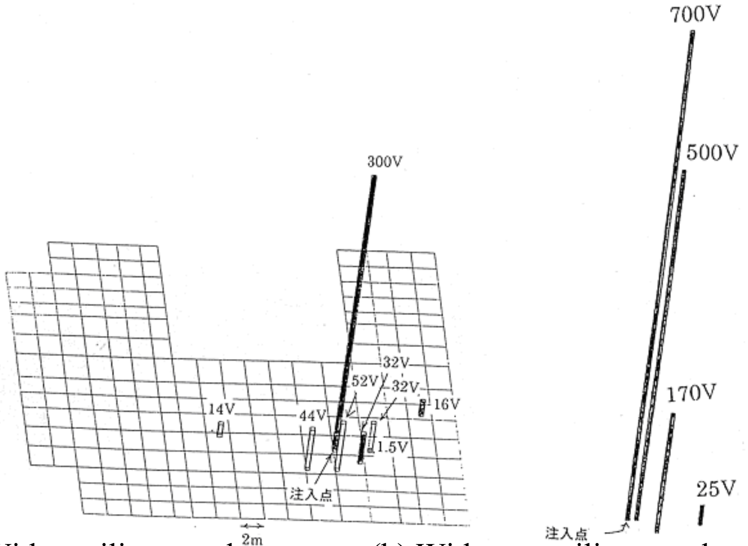
Transient response of grounding mesh systems was measured by injecting low-voltage impulse current (22A-step form current, 100ns rising time) to grounding leads at UHV Equipment Test Station. The effectiveness of auxiliary mesh was confirmed as follows.

- Owing to an auxiliary mesh, voltage rise was effectively suppressed. The voltage rise measured at 3 or 4 meters away from the current injection point was suppressed to about 10 % of the maximum.
- Voltage rise without auxiliary mesh became two times or more than that with auxiliary mesh, and voltage attenuation by distance became less remarkable.
- By these results, the induction of secondary circuit caused by surge current flowing into the grounding system shall be mitigated with auxiliary meshes.

Table 11 and Fig. 31 show the effect of the auxiliary mesh which is set under GIS.

Table 11 Comparison induced voltage and sustaining time (With auxiliary mesh and without auxiliary mesh)

	Peak induced voltage	Sustaining time
With auxiliary mesh	200V～300V	200ns to 300ns
Without auxiliary mesh	700V～750V	Less than 2 μ s



(a) With auxiliary mesh (b) Without auxiliary mesh

Fig. 31 Effect of auxiliary mesh
-Reduction of high frequency surge in secondary circuit-

1.7 Environmental Impacts

1.7.1 General consideration

As in the design of all substations, environmental harmony is important for substations to be accepted as a part of the infrastructure of the surrounding areas. Proper environmental impact studies will need to be conducted in advance of the substation design.

Due to environmental concerns, the location of UHV substations is normally limited to mountain or desert areas, minimizing the environmental impact to the surrounding area must be taken into account. In Japan, full GIS are selected to minimize a space of a substation site. Following points are very important to reduce the environmental impacts.

- **Environmental harmony**

1) To reduce the overbearing and pressuring of large equipments by substation design
2) To reduce the height of substation by introducing low TV with high performance surge arresters
3) To reduce the substation space by adopting the compact equipments and structure

Recent technological progress and development of new GIS bring the reduction of 1100kV GIS. Table 12 shows the example of gas volume reduction between old and new GIS in Japanese 1100kV GIS.

Table 12 Reduction example of gas volume and weight

Equipment G		CB	DS	BUS
Old		100 % (6 break GCB)	100 %	100 %
New	Gas volume	55 ～ 60 % (2 break GCB)	65 ～70 %	65 ～ 70 %
	Weight	50～60% 60	～70% 60	～70%

1) To check the harmonization with the a round nature by Model or developing 3D -CAD landscape simulation in the planning stage

Fig. 1 shows the example of checking the harmonization with the around natures in the planning stage. And this model was used to confirm the height of UHV substation was not affected to the landscape.

Fig. 1 UHV substation model to check the harmonization with the landscape (TEPCO 1100kV GIS)

Fig. 33 shows computer 3D-model example to check the harmonization with the landscape in the planning stage.

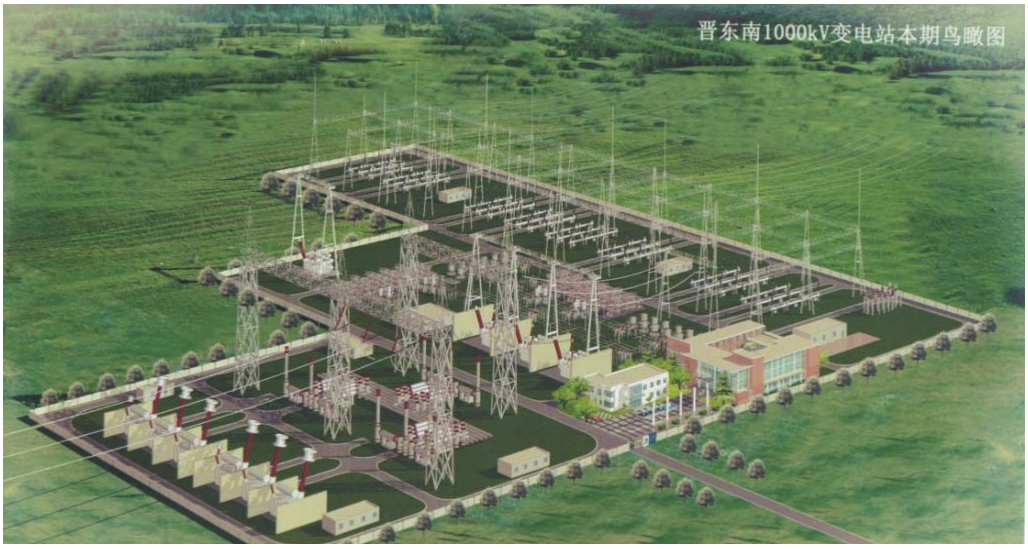


Fig. 33 Computer 3D-model to check the harmonization with the landscape (SGCC 1100kV GIS Substation)

5) To reduce the transportation impacts on surrounding area by controlling the transportation
6) To reduce the industrial wastes, such as SF_6 emission and oil leak, by 3R's concept (Re-use, Reduce and Recycle)

➢ Environmental assessment

1) To investigate the impacts in the planning and normal operation stage
2) To forecast and analyze the electromagnetic environment by establishing the simulation

➢ Effects on human body

1) To protect human body from exposure to electromagnetic field by choosing the appropriate levels of electric and magnetic fields

Comprehensive studies about the effects of electromagnetic field on human body have been carried out by the International Commission on Non-Ionizing Radiation Protection (ICNIRP), and the effects on human body are summarized in ICNIRP guidelines. The report concludes that there is little evidence from laboratory studies that low level power frequency electromagnetic field has any firm sign for the effects like tumour-promotion in cellular and animal systems. However, the reference levels for general public and occupational exposure are offered in the guidelines.

In the cases of UHV substations, under high operation voltage, the electric field strength may become one of the critical issues for the design of substation, especially for AIS.

2) To protect human body from great touch voltage and step voltage by keeping the criteria in UHV substation design based on the existing AC substation grounding design (IEEE Standard 80-2000, IEEE Guide for Safety in AC Substation Grounding, etc.)

The touch voltage between the earthed enclosure or structure and the ground, which is subject to the design of grounding system in substation, is another issue related to the effects on human body. For the UHV substation, the same design criteria as that for 500kV could be applied.

- **Electromagnetic environmental control**

1) To control audible noise by making the appropriate design, specifying the proper audible noise from substation facilities, calculating the noise level from surrounding area with higher accuracy and introducing the noise reduction technologies

In the substation, the power transformer and shunt reactor are the most important equipments to consider, evaluate and specify audible noise. The sound levels of them shall be specified and designed with consideration by required noise level along the boundary of the substation. The power transformer and shunt reactor will be designed with the core flux, with or without a sound barrier, fan and pump, etc.

2) To avoid the disadvantageous effects of corona discharge on environment (TV and radio interference, etc.) and control the corona losses by improving the configuration

Since TEPCO's UHV substation adopt full GIS, the corona noise measurements that should be in consideration will be limited to the entrance of transmission lines and their designs will be coordinated with that of transmission lines, the same as 500kV.

The basic design of 500kV substation equipment and insulator is to suppress corona noise below the noise level as shown in Table 13.

Table 13 Brief description of corona test

Test item	Reference level
Visual corona test	There should be no apparent visual corona or audible noise
Corona extinction test	At 1.1 Um/√3kV
Radio interference voltage measurement test	90dBμV (30mV)or less (Rainy condition) 60dBμV (1000μV) or less(Fine condition)

*In India corona extinction test (RIV level set to 2000μV at 1.1 Um/√3kV) is proposed for 1200kV in India

Corona losses are affected by the environmental conditions, such as rain, and annual average corona loss from 1100kV ACSR 8×810mm2 conductors, which was measured by TEPCO, is about 1.4kW/km.

Since corona noise depends on surface electric potential gradient of conductors, it is effective to decrease surface electric potential gradient by adopting multiple conductors and improving shield shape.

3) To get the same level as 500kV and 800kV substation which is around 60dB (μV) (1000μV) or less.

1.7.2 Experience

➢ Radio Interference, Electric Field at Power Frequency and Audible Noise

Radio interference, electric field at power frequency and audible noise has been gaining much attention in the construction of UHV substations in China. Therefore, radio interference, electric field at power frequency and corona noise were measured in the 1000kV verification site with typical equipment arrangement without GCB. Corona test was carried out in another outdoor site. The 1100kV disconnector, porcelain type SF6 circuit breaker and two kinds of test conductors compose the typical configuration arrangement in substation. The height of disconnector above ground is 13m, and that of SF6 circuit breaker is 13.6m without underframe and 15.6m with underframe. The diameter of pipe bus bar is 250mm; the length and the height to ground are 16m and 13m respectively. The 4×1600mm2 bundle conductor with the length of 20m is adopted. The diameter of sub-conductor is 70mm. The bundle space is 600mm. The hanging heights of pipe bus bar and bundling conductor are 13m and 17m respectively.

The radio interference voltage of the two types of tested conductors, the circuit breaker and insulator string used in the 1000kV verification site with typical arrangement are all below 55 dBμV.

The power frequency electric field under the two types of test conductors and disconnector used in the 1000kV verification site with typical arrangement are all below 15kV/m. The noise produced by pipe bus bar is about 50 dB(A) in the 1000kV verification site with typical arrangement.

➢ Corona Characteristics

Corona discharge would occur on the facilities used in 1000kV AC transmission project, therefore audible corona noise, radio and television interference and corona loss would be produced. Avoiding the disadvantageous effect of corona discharge on environment is one of the principles that are important to determine the bundling conductor configurations of UHV transmission lines and the electrode configurations of transmission and substation facilities. The audible noise, radio and television interference generated by UHV transmission and substation facilities could be close to that of 750kV and 500kV transmission projects, through reasonably choosing bundling conductor configuration and phase conductor arrangement, controlling the maximum electric field on the conductor surface and reasonably selecting the electrode configurations of transmission and substation facilities.

➢ BPA 1200kV Experience

At the end of the seventies (1977-1978), BPA performed long-term measurements in the 10 km joint right-of-way of the three-phase 8 x 41 mm 1200 kV prototype line and the single-phase 2 x 51 mm 500kV line running parallel, with the aim, among others, of assessing the long-term electrical and corona performance of UHV transmission systems.

Despite the BPA project was aimed only for the transmission lines, the results will be shown here for reference. Table 14 shows a synthesis of the major values achieved (with all levels corrected to single circuit). For further comparison, estimated values for two other single-circuit BPA 500 kV line configurations are given.

Table 14 Corona effects quantification

System voltage (kV)	1200	500		
Operating voltage (kV)	1150	525		
Sub-cond. Bundle n. Φ(mm)	4x41	2x41	1x63.5	3x33.1
Electric field[I] (kV/m)	7.3	7.3	6.7	8.5
RI (dB/1μV/m)[II]				
dry	46	52.5	61	46
rainy	65	70	81	68
AN dB(A)[III]	53	56.5	62.5	46
TV interf. (dB/1μV/m)[IV]	13	7.3	6.7	8.5

Ⅰ max. value at midspan
Ⅱ quasi-peak L50 level measured 15m from outside phase, CISPR Meter, 0.5 MHz
Ⅲ weighted L50 levels measured respectively at 15m from outside phase
Ⅳ quasi-peak L50 level measured 40m from outside phase, CISPR Meter, 75 MHz

The ozone concentration was measured. No increase was detected that could be attributed to the corona on the conductors.

1.8 References

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2 Insulation co-ordination

2.1 Basic concept for substation insulation coordination

Insulation coordination throughout transmission lines and substation is a key technology to reliable and economical UHV systems. There are two concepts to apply substation insulation coordination. One is conventional way; the other is sophisticated way which adopts the reduced test voltage by adopting high performance arrester (V_{20kA}=1620kV) and /or GCB with opening and Closing resistor and /or GIS DS with resistor. Table 14 shows the two concepts for UHV insulation coordination.

Table 14 Comparison of UHV insulation coordination concepts

Insulation Ratings Um = 1100 kV

Ratings	Conventinal concept	Reduced Test voltage concept
Rated Voltage	1100kV	1100kV
Rated short-duration power-frequency withstand voltage	1100	1100
Phase-to earth kV (rms)	1215	1100
between phases kV(rms)	1215	1100
Across open switching devicebetween phases kV(rms)	1500	1100
Rated switching impulsewithstand voltage		
Phase-to earth kV (rms)	1800	1675, 1550, 1425
between phases kV(rms)	2900	2550, 2350, 2150
Across open switching devicebetween phases kV(rms)	1550+(900)	1675, 1550, 1425(+900)
Rated lightning impulse withstand voltage		
Phase-to earth kV (rms)	2700	2400, 2250, 1950
between phases kV(rms)	2700	2400, 2250, 1950
Across open switching devicebetween phases kV(rms)	2700(+630)	2400, 2250, 1950(+630)
Surge arrester		
Residual Voltage(kV eak at 20kA)	1850	1620
Surge arrester type	Tank, Porcelain	Tank, Porcelain
Components & equipments applied to UHV substation	GCB+Closing Resistor, DS without Resitor, HSGS or 4legged-reactor	GCB+Opening&Closing Resistor, DS with Resistor, HSGS or 4legged-reactor, High performance arrester
Remarks		China, Japan, Italy (V20kA=1800kV, GIS)

From the viewpoint of compaction, insulation reliability, size and weight of substation equipment, and the cost, UHV substation insulation coordination should be taken into account low test voltage and the special equipment to reduce the surge of GCB and Disconnecting switches.

- Conventional Insulation coordination
- Based on conventional Surge arrester
- Only simple study and coordination engineering work
- Tend to higher insulation level (ie. LIWV = 2550 to 3000kV)
- Size of facilities is large
- How is the total cost ?

- Sophisticated Insulation coordination
  - Based on high-performance Surge arrester and measures for lowering insulation level (ie. Resistor fitted switchgear)
- Comprehensive coordination study and engineering work, including precise computer-aided calculations
- Lower insulation level (ie. LIWV = 1950 to 2400kV)
- Size of facilities is small
- Reasonable cost in total

Fig. 34 Concepts of Insulation Coordination in UHV substation

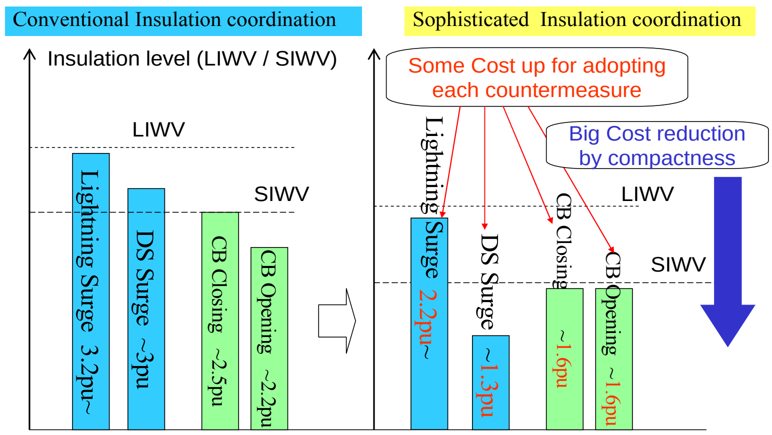

Fig. 35 Comparisons between Conventional way and sophisticated way

For a high voltage system exceeding 800kV, just like the EHV system, Electrical equipment insulation level will be decided according to the characteristic of protection devices and various voltages appeared in the systems, in other words, three aspects about equipment costs, maintenance costs and fault loss must be fully considered when designing insulation coordination, so as to achieve higher economic benefits.

For different system, different insulation coordination level can be decided according to its different structure and development stage.

Internal and external insulation level for equipments in substation must be decided according to the protection level of arresters and corresponding coordination coefficients (safety margin). The coordination coefficients for internal and external insulation is recommended as 1.15 and 1.05[[1]], which is appeared at second part application guidelines in insulation coordination in IEC 60071-2 (version 3).

To external insulation of electrical equipments, revisions must be considered due to influence from climatic conditions on external insulation.

2.2 Summary on several insulation levels exceeding 800kV transmission projects

Due to different ages for exceeding 800kV transmission project appeared and different performance of arresters, several different insulation systems have been adopted. The situation can be shown in Table 16, the number appeared in parenthesis followed withstand voltage in table is insulation coordination coefficients.

Table 16 Several levels of insulation system in over 800kV transmission projects

Country		ex-USSR	Italy	Japan	China	India *2
Nominal voltage kV(rms)		1150	1000	1000	1000	1150
Max. operating voltage kV(rms)		1200	1050	1100	1100	1200
Surge arrester *1						
	Rated voltage kV(rms)	800	749	826	828	850
	Residual voltage for switching impulse kV	1840~1760(1.5kA)	1450(3kA)	1410(2kA)	1460(2kA)	1500 (2 kA)
	Residual voltage for lighting impulse kV	1940(14kA)	1800(20kA)	1620(20kA)	1620(20kA)	1700(20 kA)
Rated switching impulse withstand voltage kV						
	Transformer& Shunt reactor Phase to earth	2100(1.14~1.19)	1800(1.24)	1425(1.01)*4	1800(1.23)	1800(1.2)
	GIS Phase to earth	——	1675(1.16)	1550(1.10)*4	1800(1.23)	——
	DS,CB Phase to earth	2100(1.14~1.19)	1675(1.16)	1550(1.10)*4	1800(1.23)	1800(1.2)
	DS,CB Between contacts(peak)	2100	1675+857	——	1675+900	1675+ 980
Rated lightning impulse withstand voltage kV						
	Transformer & Shunt reactor Phase to earth	2550(1.31)	2250(1.25)	1950(1.20)	2250(1.39)	2250(1.32)
	GIS Phase to earth	——	2250(1.25)	2250(1.39)	2400(1.48)	——
	DS,CB Phase to earth	2900(1.49)	2250(1.25)	2250(1.39)	2400(1.48)	2400(1.41)
	DS,CB Between contacts(peak)	2900	2250+857	2250+900	2400+900	2400+686

Note:*1 Magnetic blowing arrester with air-gap (PBMK1150y1) in ex-USSR; non-gap metal oxide surge arrester in Italy, Japan China and India.
*2 Indian Values are based on the based on preliminary studies.
*3 ( ) shows the ratio to Residual voltage for switching impulse or ratio to Residual lightning impulse withstand voltage
*4 IEC safety factor is 1.15 but Japanese UHV system has been optimized with respect to limiting the switching surges as much as possible and considered the margin by the severe switching surge analysis's condition.

It can be seen from the table that the difference among several insulation level systems is actually coming from difference among protection performance of the arresters. For the insulation coordination coefficients of switching impulsion withstand voltage of transformers, one of Japan seems lower. Actually, the switching impulse withstand voltage has inherent relationships with the lighting impulse withstand voltage. The ratio of the former and the later is generally 0.83 or so in oil insulation system. The insulation coordination coefficient can be decided as 1.148 according to switching impulsion withstand voltage, which is obtained by conversion of the lighting impulse withstand voltage of transformer in Japan. So we know that insulation coordination coefficient in every country is ultimately accord with the recommendation value from IEC60071-2.

2.3 Reduced insulation coordination level system

With higher system voltages, especially UHV exceeding 800 kV, the technical and economic consequences of the insulation levels become increasingly important. Experts involved in UHV (pilot) projects therefore pay considerable attention to reducing the overvoltage to as low a level as possible. Optimal insulation coordination is thus extremely important for UHV systems. Based on past experience and studies from several places around the world, an overview is given of the insulation coordination policies applied or foreseen for UHV systems.

Insulation coordination throughout transmission lines and substations is a key factor for realizing a reliable and economical UHV system. Optimal insulation coordination can be achieved based on high-performance MOSAs, as demonstrated in UHV projects of the 1990s and later in Japan, Italy and China. Sophisticated design of insulation coordination by means of accurate computer-aided calculations and simulations is common practise for such projects, while withstand voltage can be roughly estimated by IEC's simplified method as described further in section 2.3.6.

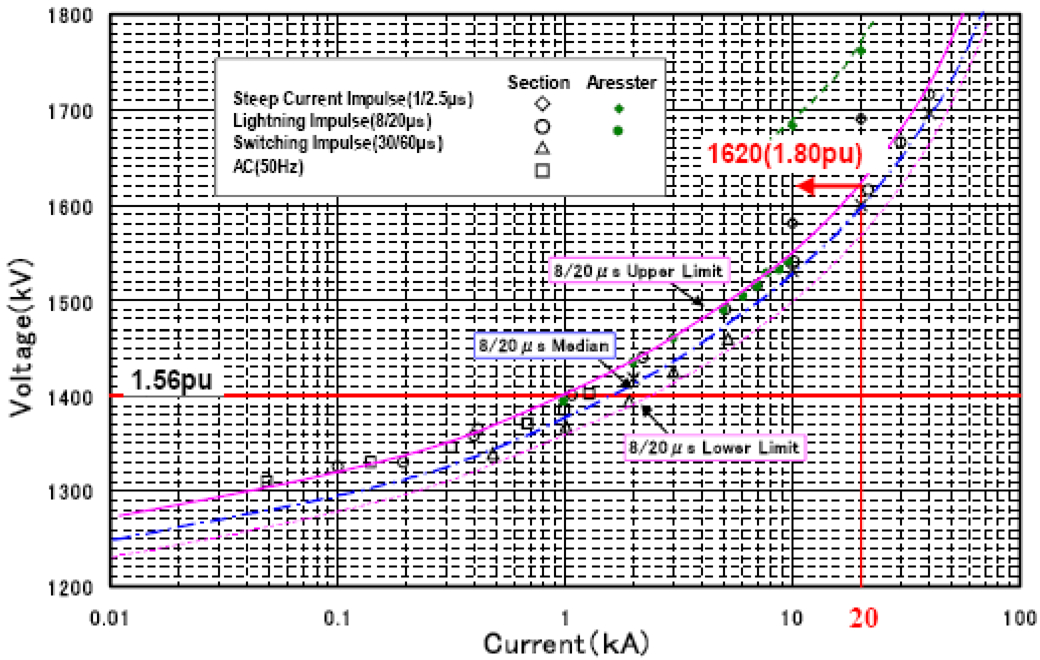

Fig. 36 Example of V-I characteristic of high performance surge arrester

Suppressing switching overvoltages as much as possible is a prerequisite for air clearance to insulation in order to reduce the height of transmission towers and the dimensions of open-air parts in substations. As lightning overvoltages dominate the non-self-restoring internal insulation design of equipment such as GIS and transformers, here it is important to rationalize LIWV by means of MOSA arrangement. To effectively suppress lightning overvoltages, single or multiple high-performance MOSAs must be installed at an adequate number of locations, such as at line entrances, busbars and transformers. To suppress switching overvoltages, pre-insertion (closing, closing/opening) resistors are often applied in addition to MOSAs. Other options include the installation of MOSAs along OH lines and controlled switching, but these technologies are not widely applied. An example of the V-I characteristics of high-performance surge arresters is given in Fig. 36. Furthermore, VFTO caused by GIS disconnectors can be reduced to 1.3 p.u. or less by means of pre-insertion resistors in GIS disconnectors.

Another important aspect of insulation coordination is the utility's policy regarding withstand margins for severe lightning or switching conditions with a very low probability of occurrence. As precise computer simulations accurately show the impact of such severe conditions, consideration might be given to omitting the additional safety factor, especially when some stress factors are less severe than those defined in the standards. A good example is lightning discharge currents, where the front duration tends to be longer with larger amplitude of lightning stroke current, as shown in Fig. 37 [2].

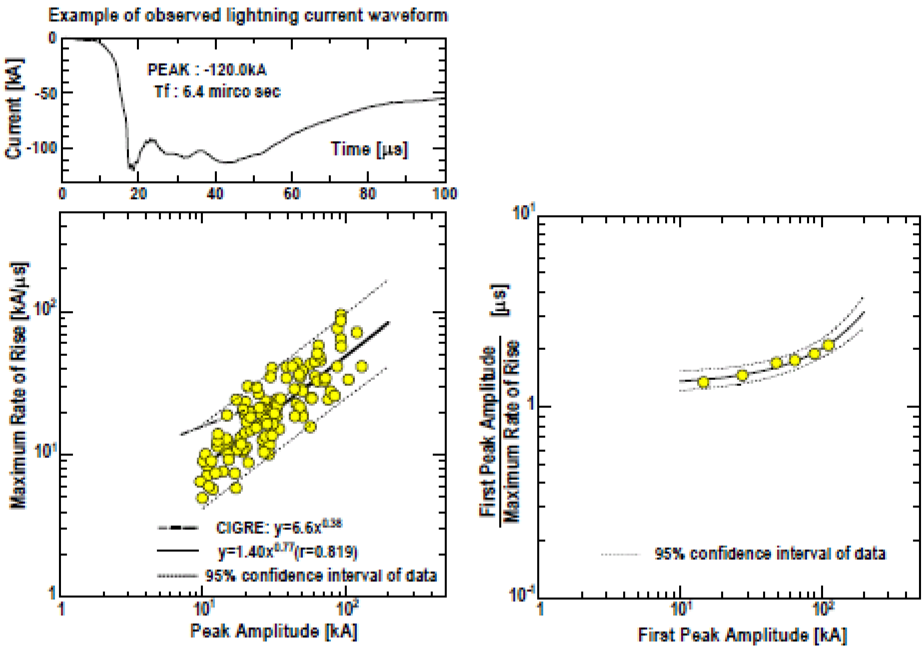

Fig. 37 Relation between lightning stroke current amplitude and rate-of-rise

2.3.1 Power frequency voltage

Table 17 indicates that the maximum operating voltage does not differ greatly in the UHV pilots and projects, apart from one or two exceptions [3]. IEC doc CDV proposes 1100 kV and 1200 kV as highest voltage for equipment.

Table 17 Highest voltage of UHV projects

Project	*Italy*	*Russia*	*Japan*	*China*	*India**
Um (kV)	***1050***	***1200***	***1100***	***1100***	***1200***

Note:* Indian Um value is based on preliminary study. The development and verification of the facilities will be in future.

The exceptions are related to pilot projects that have since been discontinued and that included maximum operating voltages of 1600 kV (USA) and 1800 kV (Russia). The values used as a reference level for that specific country. For power frequency voltages, 1 p.u. = $Um/\sqrt{3}$; and for transient overvoltages and transient recovery voltages (TRV), 1p.u.=$Um\sqrt{2}/\sqrt{3}$.

2.3.2 Temporary overvoltage (TOV)

TOV is an important power frequency voltage level, which expressed in p.u. must be as low as possible. TOV in large systems is mainly caused by Ferranti effect, (ferro)-resonance phenomena and single-phase faults. One special resonance phenomenon in relation to shunt reactors, is that under SPAR (single-phase rapid auto-reclosing), it might be energized by capacitive coupling from the healthy phases. [4] If the inductance of shunt reactors connected to the faulted line phase and the line capacitance are very close to parallel resonance at power frequency, the recovery voltage on this phase may be limited by corona loss (depending on the corona onset voltage).

Calculations of the voltage level on Russia's 750 kV lines, confirmed by field tests, showed that steady-state voltage in this case reached 1.4-1.5 p.u. In a 420 kV case [5] with a low visible corona onset voltage of 1.35 p.u., the TOV level is limited to 1.6 p.u. In the presence of a neutral reactor, this voltage is usually less, due to detuning from resonance conditions. Another special resonance phenomenon is the energization of large power transformers or shunt reactors in a weak network, as may occur during the initial stage of UHV network or during system restoration. TOV up to 1.45 and 1.55 has been reported, line to ground and lasting for seconds. [5], [6] Ferro-resonance overvoltages on second harmonics were observed during one-side switching of 750 kV lines even from powerful feed networks where they were generated by nonlinearity of shunt reactor and/or transformer magnetization curves. These TOV could be especially dangerous for EHV/UHV equipment if protective overvoltage relays operate on effective, not peak, voltage values and are not able to detect the TOV.

As suitable countermeasures are available, it is assumed that resonance and ferro-resonance phenomena would be anticipated and prevented or at least limited in magnitude and/or duration. The two remaining causes of TOV are single-phase faults and Ferranti effect.

In the case of single-phase faults, the relationship between TOV and kpp (first-pole-to-clear factor) results in an overvoltage of 1.27 p.u. for kpp = 1.3, of 1.16 p.u. for kpp = 1.2 and of 1.06 p.u. for kpp = 1.1. Only in cases of relatively high kpp, the TOV reaches a certain importance.

Single-phase fault clearing will take several tens to several hundreds of ms. The relationship between the healthy-phase power frequency voltage and the X0/X1 ratio can be seen in Fig. 38.

When the impedance is indicated in p.u., the impedance of OH lines is nearly in reverse proportional to the square of the system voltage. In UHV systems, the ratio of line impedance to total system impedance, seen from the fault location, becomes smaller and, thus, the earth-fault factor tends to be smaller.

The Ferranti effect is normally controlled by shunt reactors (and, when applied, series capacitor banks) that are switched on before the OH line is energized and switched off at high loads or, sometimes, after switching off the OH line. In the case of sudden load rejection at a heavily loaded long line, the voltage jump due to Ferranti effect will lead to a TOV, which lasts until either the OH line is tripped at both sides or the shunt reactors are switched on. The amplitude of the TOV under such circumstances is system dependent, but computer simulations show a typical maximum TOV of 1.3 to 1.5 p.u. lasting < 0.5 s. This applies to studies performed in Italy, Russia, Japan and China. [3], [7], [8]

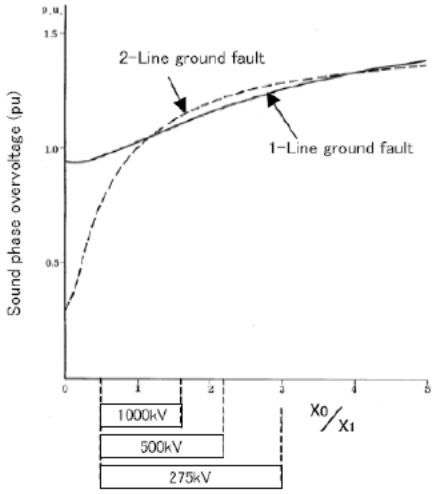

Fig. 38 General tendency of earth-fault factor in Japan

For TOV control during load rejection, it is vital to apply automatic high-speed insertion of shunt reactors and transfer-tripping to the other side of the OH line. In some countries, for extreme contingencies that lead to higher TOV than stated above, MOSAs are used to limit the TOV to 1.7–2.0 p.u. [9] At the 800 kV level, in Canada, sacrificial switch-able MOSAs are used to control the TOV to 1.6 p.u., as may be necessary under severe system conditions. Normally, however, surge arresters are not used to limit TOV, as it would be less than 1.4 p.u.

A contingency may be a case in which a phase-to-earth fault occurs in combination with load rejection, reaching TOV values higher than stated above for the occurrence of single-phase faults. In Japan, the TOV during load rejection can reach 1.4 p.u. or higher due to Ferranti effect under self-excitation phenomena, and when an earth fault follows the load rejection, TOV can reach around 1.5 p.u. with a trapezoid waveform due to the clipping voltage of MOSAs. The energy capability of MOSAs is specified as 55 MJ or more to ensure this TOV level. If necessary, an overvoltage protection relay system to open the no-load OH line is applied to avoid excessive energy absorption. [10]

It is important to recognize that in EHV/UHV transmission, it is impossible to completely exclude TOV, but it is possible to reduce its magnitude and duration to acceptable limits. From this point of view, it would help to ask UHV equipment manufacturers to provide information about permissible TOV magnitude versus time of application for equipment with insulation, magnetic core and energy absorption designed to withstand operating voltage and switching and lightning overvoltages. Such information, based on the "natural" insulation strength, already exists in Russia's standards. [6]

2.3.3 Slow front overvoltages (SFO)

Slow-front overvoltage or switching overvoltage is controlled by means of such technologies as pre-insertion resistors (closing resistors or PIR), opening resistors, controlled switching, and application of MOSAs and of MOVs across the arcing chambers. Without taking certain measures, the switching surge at line energization can lead to a maximum SFO of 3 p.u. By A3-07 (WG22) 4xx Draft Technical Brochure of WG A3.22 means of PIR, the switching surge is reduced to 2.0-2.2 p.u., and by two-step PIR even further to 1.5-1.6 p.u. The application of controlled switching leads to switching surges less than 2.0 p.u., while MOSAs lead to SFO of 1.7-2.2 p.u., depending on the SIPL. A combination of measures, such as controlled switching with PIR and MOSAs, could decrease the SFO to 1.6 p.u. These SFO levels are along the OH line and are higher than at the line ends and at the substation busbar side. Phase-to-phase switching overvoltages along the OH line are 2.6 to 2.9 p.u.

Without taking measures, SPAR leads to SFO of less than 2.4 p.u., but by means of the measures mentioned above, it is possible to achieve SFO similar to that with line energization. TPAR (three-phase rapid auto-reclosing) gives an SFO between 3.8 and 4.0 p.u. (with trapped charge) or up to 3.0 p.u. (without trapped charge). The application of PIR, controlled switching and/or MOSAs decreases the SFO to less than 2.5, 2.0 and 1.7 p.u., respectively. [9] When such low SFO values are reached, the SFO caused by clearing single-phase faults becomes quite important, as it may be larger: 1.8-2.1 p.u. Opening resistors will reduce the SFO at clearing short-circuit currents for single-phase faults as well as three-phase faults. [3]

Note that for systems with series compensation, the given values for SFO may be higher due to the residual charge on the series capacitor bank. This depends on the network topology in combination with the location of the capacitor banks, as well as on the protection measures implemented for the series capacitor bank: MOV, triggered spark gap, bypass breaker and its protection scheme, etc.

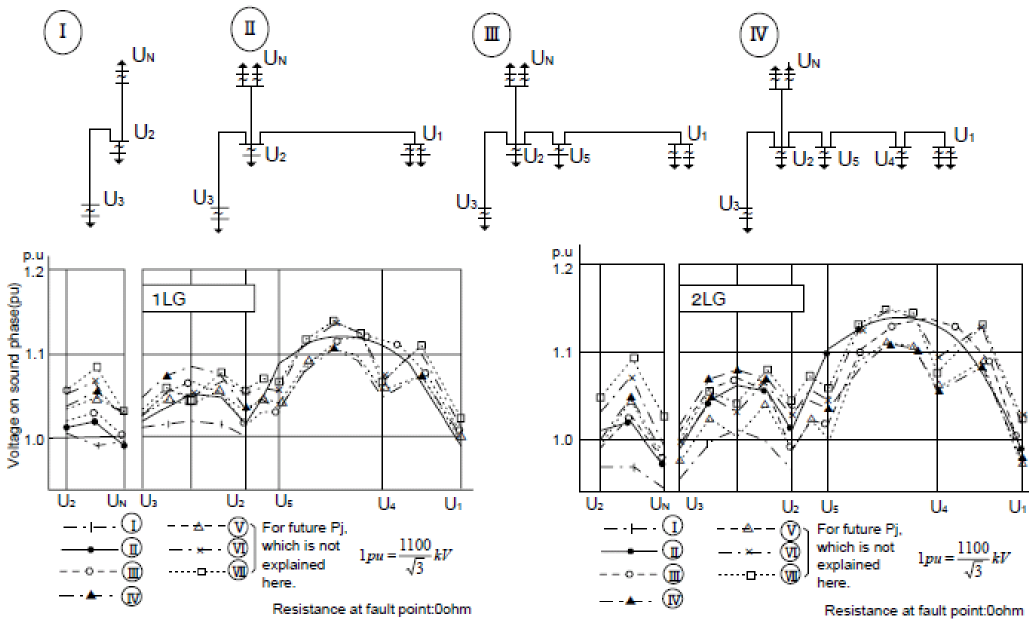

Fig. 39 TOV in sound phases during ground faults (Japan)

At the occurrence of a single-phase-to-ground fault (1LG), the phase voltage changes to zero potential instantaneously. The voltage jump leads to travelling waves in the faulty phase and induces travelling waves in the healthy phases. In the process of propagation and reflection in the healthy phases, transient voltages are superimposed on the AC voltages, leading to overvoltages. These ground fault overvoltages are regarded as SFO and are highest when the earth fault occurs near the peak value of the power frequency voltage. Maximum SFO tends to appear in the middle of the OH line, where TOV is highest; see Fig. 39 where TOVs are simulated for TEPCO's future 1100 kV system. A simplified model of the system with simulated fault locations is given in Fig. 40 and ground fault overvoltages along the system are shown in Fig. 41 (i.e. maximum SFO for any fault location and any phase angle of the earth fault). Fig. 42 gives an example of the waveforms for the maximum SFO at the location of the highest SFO value (1.62 p.u.) for each phase. The travelling waves can be clearly distinguished.

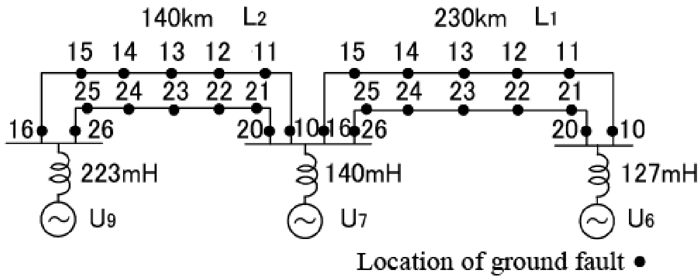

Fig. 40 Simulated future UHV system of TEPCO

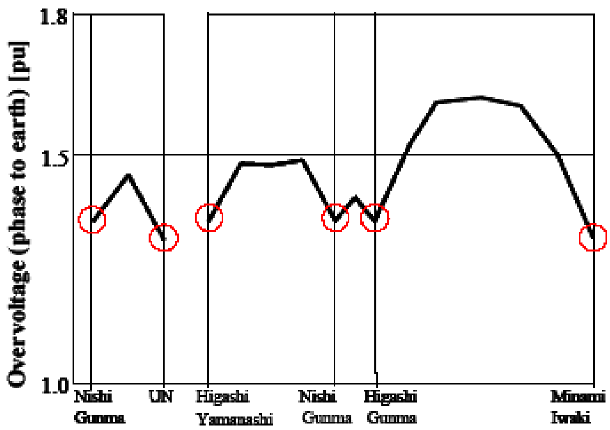

Fig. 41 Ground fault overvoltages (maximum SFO at sound phases) along UHV system

As reported in Ref. [11], the SFO is proportional to the earth-fault factor and may reach values as high as 1.5 p.u. in systems with an earth-fault factor of 1.25 to 1.3. However, as reported in References [11] and [12], in the future UHV system in Japan with kpp as low as 1.1 (earth-fault factor as low as 1.06), the overvoltage at healthy phases may reach 1.6 p.u. in substations and 1.7 on OH lines, as shown in the above figures. In a UHV system, transmission losses are very low because multi-bundle conductors are applied in order to suppress corona noise. Surge voltage propagates along the OH lines in line-to-earth and line-to-line modes. The results of measurement on an actual UHV OH line reveal that line-to-line waves hardly attenuate during propagation along 200 km.

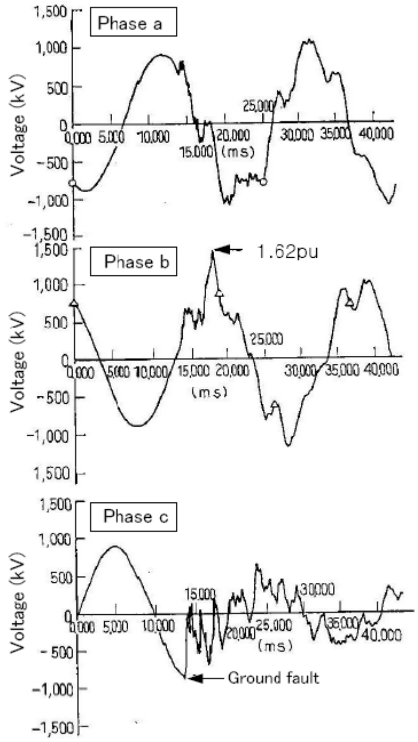

Fig. 42 Analyzed waveform of maximum SFO at a single phase to ground fault
(Near location U6, SA protection level: V20kA = 1620 kV)

Moreover, the topology of UHV systems is radial and rather simple, leading to far less refraction of traveling waves compared to that in meshed EHV systems. Both characteristics of UHV systems lead to SFO at the occurrence of a phase-to-ground fault as high as 1.6-1.7 p.u., even in the case of low earth-fault factors.

For UHV systems, the following calculations for SFO have been reported [[3]], [[13]], [[14]]:

Table 18 Slow Front Overvoltages (SFO)

SFO (pu)	*Italy*	*Russia*	*Japan*	*China*
Line ph-gr	***1.7***	***1.8 (1.6)***	***1.6/1.7***	***1.7***
Substation ph-gr		***1.8 (1.6)***	***< 1.6***	***1.6***
Line ph-ph	***2.7***		***2.6/2.8***	***2.9***
Substation ph-ph			***2.6/2.8***	***2.8***

Note that switching overvoltages in Japan are reduced to the same level as ground-fault overvoltages by means of closing/opening resistors. Additionally, UHV OH lines in Japan are rather short in length compared to those in Russia and China. For Russia, the values without brackets apply in cases of gap-type SiC arresters; the values within brackets are those when MOSAs would be used and are comparable with the other countries. Brackets are used for the same reason in other tables.

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2.3.4 Fast front overvoltages (FFO)

Fast front overvoltage or lightning overvoltage is a less important parameter for UHV OH lines in comparison to EHV and HV OH lines. The specified TOV and SFO determine the dimensions of the OH lines. Furthermore, the accepted number of outages due to lightning determines the shielding angles, tower footing resistance, etc.

For substation equipment, the specified LIWV is of interest. Table19 gives the general specifications for LIWV and SIWV in substations, as required in several countries. [[3]], [[13]], [[14]]

Table19 Insulation level for substation equipment

kVpeak	Italy	Russia	Japan	China	India*
Max. operating voltage (kVrms)	1050	1200	1100	1100	1200
SIWV	1675	2100 (1800)	1550	1800	1800
Pu	1.95	2.14 (1.84)	1.73	2.00	1.84
LIWV	2250	2900 (2400)	2250	2400	2400
Pu	2.62	2.96 (2.45)	2.51	2.67	2.44

Note:*Indian value is based on preliminary studies.

Lower values are specified for transformers, as can be seen in Table 20, where only the UHV side is presented.

Table 20 Insulation level for transformers

kV_{peak}	Italy	Ex-Russia	Japan	China	India*
SIWV	1800	2100 (1800)	1425	1800	1800
Pu	2.10	2.14 (1.84)	1.59	2.00	1.84
LIWV	2250	2550 (2250)	1950	2250	2250
Pu	2.62	2.60 (2.30)	2.17	2.51	2.3

Note:*Indian value is based on preliminary studies.

In countries such as Russia and China, the same SIWV is proposed for transformers and reactors as for other substation equipment, while in Japan the proposed SIWV requirements are roughly 10% lower in comparison to other equipment, and in Italy higher SIWV values are proposed. This is mainly due to the fact that Japan's UHV system has been optimised with respect to limiting the switching surges as much as possible. Furthermore, expressed in p.u., the SIWV requirements for both transformers and other equipment in Italy, Russia (with MOSAs) and China are relatively close to each other, but are much higher than those of Japan.

Also, with respect to the LIWV, Italy shows the same LIWV for transformers as for the other equipment. Japan requires LIWV values roughly 13% lower for transformers than for other equipment, and Russia/China roughly 6% lower values. Expressed in p.u., LIWV requirements for transformers in Italy, Russia (with MOSAs) and China are comparable. For other equipment, the proposed LIWV levels are fairly close.

For all equipment, Japan requires the lowest SIWV and LIWV at each level, as full advantage is taken of improved technologies to decrease the insulation levels. In Fig. 43, a comparison in p.u. is shown between the SIWV and LIWV applied in different countries.

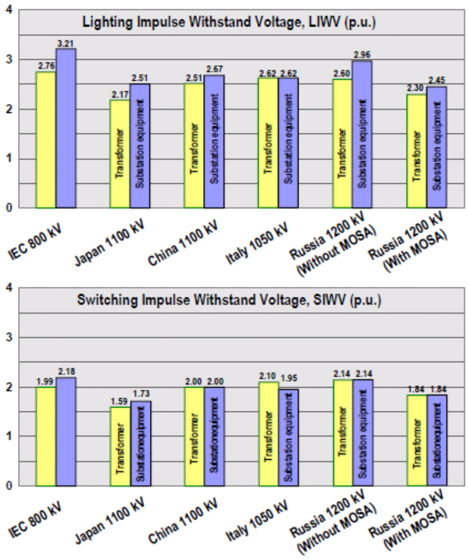


Fig. 43 LIWV, SIWV

Withstand voltage for UHV equipment were previously discussed within IEC TC 28 WG01. Through document IEC 28 (Secretariat) 81, a proposal for withstand voltages was made in 1987, but they were not standardized because there was no market relevance at that time. Table 21 compares the SIWV and LIWV of the document with that of China and Japan's recent projects. For SIWV, the values applied in Japan are well in line with the document, but the values applied in China are rather high. For LIWV, the values of China and Japan are in agreement. [15] The discussion will continue in IEC TC 28.

Table 21 Comparison of LIWV and SIWV of IEC compared with China and Japan

	IEC 28(Secr.)81	*China*	*Japan*
Highest voltage for Equipment Um(kV)	*1050-1100*	*1100*	*1100*
Standard switching Impulse withstand voltage phase-to-earth(kV)	*1425 1550 1675*	*1800*	*1425 1550*
Standard lightning impulse Withstand voltage(kV)	*1950 2100 2250 2400*	*2250 2400*	*1950 2250*

In [16] the specifications for the longitudinal withstand strength are given for China. The SIWV is 1675 + 900 kV and the LIWV is 2400 + 900 kV.

2.3.5 Insulation levels and arrester protection levels

In Fig. 43 and Fig. 44 IEC insulation levels and commonly used protection levels are given for system voltages up to and including 800 kV. Insulation levels and arrester protection levels for the UHV projects in Italy, Russia (USSR), Japan and China have been added as well. As seen from the diagrams the trend in decreasing relative insulation levels continues. The very low relative arrester protection levels for the projects in Japan, China and Russia are also striking. The information available is on conventional arresters applied in Russia and MOSA applied in Italy, Japan and China [13][14]. A comparison is shown in Table 22.

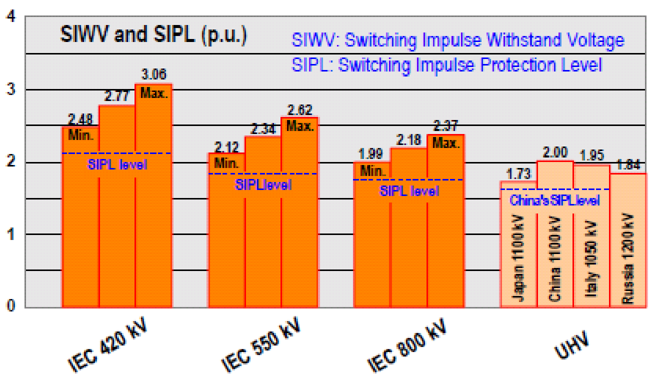


Fig. 44 LIWV, SIWV

Table 22 MOSA characteristics

kV	Italy	Russia	Japan	China	India*
Rated voltage (rms)	749	800	826	828	850
Peak at 10 kA(8/20μs)			1550	1553	1600
Peak at 14 kA(8/20μs)		1850			-
Peak at 20 kA(8/20μs)	1800		1620	1620	1700
LIPL (pu)	2.10	1.89	1.80	1.80	1.73
SIPL (pu)				1.62	1.53

Note:*Indian value is based on preliminary studies.

Apart from Russia's use of conventional gap-type surge arresters (SiC, ZnO) as well as MOSAs for new applications, the following information can be given on Russian specifications. ZnO arresters used for SIPL of

1.8 p.u. have a maximum permissible operating voltage of 694 kV and permitted voltage of 760 kV for 20 minutes. The extinguishing voltage of the power frequency current, after a switching impulse current, is 1000 kV and after a lightning impulse current, 800 kV. The residual voltage at a switching impulse current of 1.5 kA (3/8 ms) is no more than 1760 kV and at a lightning impulse current of 14 kA (8 μs) is no more than 1940 kV.

MOSAs, used for SIPL of 1.6 p.u, have the same maximum permissible operating voltage and a permitted voltage of 765 kV for 60 minutes. Residual voltage at a switching impulse current of 2.8 kA (1.2/2.5 ms) is no more than 1570 kV, and at a lightning impulse current of 15 kA (8 μs), no more than 1760 kV.

2.3.6 Comparison with insulation withstand voltages calculated as per IEC procedure

The IEC procedure for insulation coordination is outlined in IEC 60071-1. [[17]] The application guide can be found in IEC 60071-2. [[18]] The procedure is applied here to an 1100 kV system, using arrester protection levels for fast- and slow-front overvoltages, i.e. LIPL and SIPL values specified for the UHV systems in Japan and China. The calculation results such as for required withstand voltage could be compared with the selected insulation levels for existing and planned UHV systems.

2.3.6.1 Slow front overvoltages

Depending on the degree of limitation of slow-front overvoltage by arresters, the coordination factor K_{cd} shall be between 1 and 1.1 as per Ref. [[19]]. See Fig. 36.

The coordination withstand voltage, U_{cw}, is K_{cd} times the arrester protection level and thus shall be 1 to 1.1 times the SIPL. To obtain the required withstand voltage, U_{rw}, the coordination withstand voltage shall be multiplied by the altitude correction factor, Ka, considering 1000 m and the safety factor, Ks.

The altitude correction factor, applied for external insulation only, is equal to em (H/8150) where H is the altitude and m the factor according to the Figure 9 of Ref. [[16]]. For the coordination voltages expected for the 1100 kV system, the m-factor, for phase-to-earth insulation, is around 0.5, which results in Ka = 1.06.

The recommended safety factors as per IEC 60071-2 are as follows:

- For external insulation Ks = 1.05
- For internal insulation Ks = 1.15

Therefore, the required withstand voltage will be:

- For external insulation Urw = 1.11 to 1.22 times SIPL
- For internal insulation Urw = 1.15 to 1.27 times SIPL

With an SIPL of approximately 1.6 p.u.(1440 kV), Urw will be:

- For external insulation 1598 to 1757 kV
- For internal insulation 1656 to 1829 kV

2.3.6.2 Fast front overvoltages

The coordination lightning impulse withstand voltage can be directly calculated by means of the simplified method in IEC 60071-2 using the following empirical formula:

U_{cw} = LIPL+ 2*S*L/c = LIPL + A/n*L/(Lsp+La), where

LIPL = Lightning impulse protection level of the arrester
La = Ra/Rkm line length with an outage rate equal to Ra (m)
Ra = Acceptable failure rate (1/year)
Rkm = Outage rate for lines connected to the station (1/(m*year))
S = 1/(Kco*(Lsp+La))
Kco = Corona damping factor (μs/(kV*m))
A = 2/(Kco*c)
c = Speed of light (300 m/μs)
Lsp = Span length (m)
L = Height of arrester + length of connection leads + distance to protected object (m)
n = Number of lines connected to the station

As an example, assuming the following:

- Ra: Acceptable failure rate 0.0025 (once in 400 years)
- Rkm: 0.00001 = One lightning fault per 100 km per year on the line in front of the station

- N: One or two lines to the station
- Lsp: Span length 500 m
- Kco = 0.4E-6 (for 6- or 8-conductor bundle)
- L = 30 m

This will result in the following coordination withstand voltage:

- For one line to the station U_{cw} = LIPL + 667 kV
- For two lines to the station U_{cw} = LIPL + 333 kV

To obtain the required withstand voltage, U_{rw}, the coordination withstand voltage shall be multiplied by the altitude correction factor, Ka, considering 1000 m and the safety factor, Ks.

The altitude correction factor, applied for external insulation only, is equal to e(H/8150) where H is the altitude (m-factor equals to 1). This gives Ka = 1.13.

The same safety factors as for slow-front overvoltage apply.

Therefore, the required withstand voltage, U_{rw}, will be:

- External insulation U_{rw} = 1.19*(LIPL+667) …… one line
- Internal insulation U_{rw} =1.15*(LIPL+667) …… one line
- External insulation U_{rw} =1.19*(LIPL+333) ……. two lines
- Internal insulation U_{rw} =1.15*(LIPL+333) ……. two lines

Finally, with an LIPL of 1620 kV (1.8 p.u.), U_{rw} will be:

- External insulation U_{rw} = 2721 kV …… one line
- Internal insulation U_{rw} = 2630 kV …… one line
- External insulation U_{rw} = 2324 kV ……. two lines
- Internal insulation U_{rw} = 2246 kV ……. two lines

The method described above was developed for AIS, but many of the UHV stations are GIS. However, it is stated in IEC 60071-2 that the procedure gives a conservative estimate for GIS even if a generally valid recommendation cannot be made on how conservative it is compared to AIS.

2.3.6.3 Comparison

For slow-front overvoltage, the selected SIWV for substation equipment in Japan is 1550 kV and in China 1800 kV. The procedure above indicates a required level for external equipment of 1598 to 1757 kV and for internal equipment 1656 to 1829 kV. China's requirement is well within the calculated values, but Japan's significantly lower level is considered sufficient. For fast-front overvoltage, the selected LIWV for substation equipment in Japan is 2250 and in China 2400 kV. For transformers, the corresponding figures are 1950 and 2250 kV. The procedure above, considering two lines, gives 2324 kV for external equipment and 2246 kV for internal. For China, both substation equipment and transformer LIWV are above these values. In Japan, LIWV for the substation equipment is above, but LIWV for transformers is below. If only one line is considered, neither China nor Japan's LIWV values are above the calculated levels.

It must be pointed out that the IEC procedure is a simplification and, as mentioned above, not directly applicable to GIS. However, the procedure does reveal that the insulation coordination for fast-front overvoltages taking into account the preferred low insulation levels for UHV requires further detailed study.

In case that an insulation level of a substation is determined by analyzing a typical substation model with a simple method, it is necessary to accommodate the IEC's safety factors in insulation level design, because its result can be considered to have higher safety margin.

In contrast, when an insulation level of an UHV substation is designed, it is usual to implement multiple detailed surge analyses using Electro-Magnetic Transients Program (EMTP) considering various operational conditions, such as larger lighting strike current over conventional values and severe operational constraints, thus it is not necessary to accommodate the IEC's safety factors in insulation level design.

2.3.7 Very fast transient overvoltages (VFTO)

Very fast transient overvoltage is generated by disconnectors within GIS installations. It can reach up to 2.6 p.u. or even more (in one specific case reported in Ref. [19], the VFTO reaches 3.05 p.u.), at frequencies in the MHz range. When PIR is used for these disconnectors at opening and closing, overvoltage can be limited to values such as 1.4 p.u. [20] At the UHV level, in order to prevent flashovers inside the GIS between conductor and tank, it is crucial to apply such PIR to the disconnectors. As reported in Ref. [19], in China's pilot project, PIR will not be installed for MTS (mixed technology switchgear or HGIS, hybrid GIS). VFTO is discussed in further detail in Section 3.4.1.5.of Technical Brochure of WG A3.22.

2.3.8 Clearances

The required clearances between phase-to-phase, are specified in IEC 60071-1 Amd. 1 Ed. 8.0 CDV as shown in Table 23. These clearances are calculated by following Paris equation.

$$V = 500d^{0.6} \text{ -------------------------------- (1)} \qquad d \text{ gap length (m)}$$

Since Paris equation (1) is made by relatively short gap (3~4m), this equation is not always enough for very long gap in UHV system. This means present standard clearance (IEC 60071- Amd.1 Ed.8.0 CDV) is not enough for long gap (Particularly the gap more than 10m). It is obvious in all countries that the switching overvoltage is the most crucial stress factor for determining the required clearance. As climatic parameters and legal conditions are most dominant in OH lines, it does not make much sense to compare the clearances in OH lines between the UHV configurations in different countries. In substations, the conductor position is less influenced by climatic parameters and therefore clearances in substations are preferable for comparison.

Table 23 Minimum clearances specified IEC 60071-1 Amd. 1 Ed. 8.0 CDV

Max. operating voltage (kV)	**(1050)**	**1100**		**1200**
SIWV (kV) *Phase- to-earth*	**1675**	**1550**	**1800**	**1800**
SIWV (kV) *Phase-to-phase*	**2764**	**2635**	**2880**	**2970**
ratio	**1.65**	**1.7**	**1.6**	**1.65**
Clearance (m)				
Phase-to-earth (Cond.-str. / Rod-str.)	**5.6/7.4**	**4.9/6.4**	**6.3/8.3**	**6.3/8.3**
Phase-to-phase (Cond.-cond. parallel / rod-cond.)	**9.1/10.9**	**8.4/10.0**	**9.8/11.6**	**10.3/12.3**
Country	**Italy**	**Japan**	**China**	**India (Russia)**

The actual clearances are given in Table 24 researched by CIGRE WG A3.22. [3], [14]
Though actual clearances in Japan and Italy are applied to be larger than IEC 60071, those in China and India are relatively similar to IEC 60071.

Table 24 Actual clearances in each country

(m)	*Italy*	*Russia*	*Japan*	*China*	*India**
SIWV (kV)	**1675**	**2100 (1800)**	**1550**	**1800**	**1800**
Clearance researched by WG A3.22					
Phase to ground (m)	**8**	**12**	**8.5/10**		**8.3**
Phase to structure (m)	**9.5**	**7.5 – 9.7**	**7.5 – 8.5**	**7.5**	**6.3**
Phase to phase (m)	**12**	**11.4 – 12.4**	**10.5 -11.5**	**11.3**	**12.3**
IEC 60071-1 Amd. 1 Ed. 8.0 CDV					
Phase to structure	**5.6/7.4**	**6.5/8.3**	**4.9/6.4**	**6.3/8.3**	**6.3/8.3**
Phase to phase	**9.1/10.9**	**10.3/12.3**	**8.4/10.0**	**9.8/11.6**	**10.3/12.3**

Note:*Indian value is based on IEC.

To clarify the necessary clearance at the entrance to UHV substations, [21] flashover tests were carried out using shielding rings under dry and wet (water spray) conditions. It was confirmed that flashover voltages decrease under wet conditions, as shown in Fig. 45, because water droplets on the shielding ring enhance the local electric field and lead to the occurrence of streamers. This means that with large shielding rings such as those for bushings, switching impulse voltages possibly increase under dry conditions, but decrease under wet. Accordingly, in Japan, the withstand voltage test of a bushing was performed under dry and wet conditions. In the test, waveforms of 250/2500 μs (standard) and 500/3000 μs were both applied taking into account that the critical front duration tends to be longer as the gap length tends to be larger.

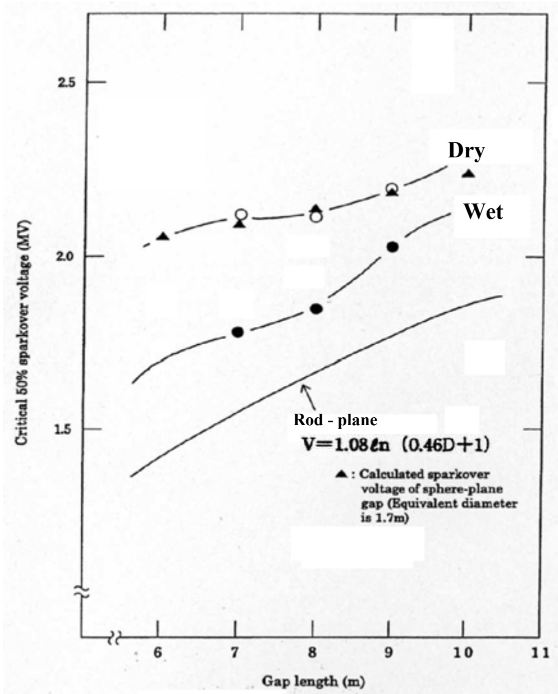


Fig. 45 Critical 50% flashover characteristics (Phase to structure)

Fig. 46 shows many experimental data over the world and experimental equation calculated from these data. Paris equation is shown by dot line in Fig.46 and is different from experimental data for long gap.
When dielectric design for UHV had been investigated in Japan, many experimental data has been reviewed and this following equation has been suggested and widely used.

$V50= K \times 1080 \times \ln (0.46d+1)$ ------------------ (2)   d; gap length, K: gap constant

Equation (2) shows 50% flashover voltage for rod- ground gap. K is changed for construction of gap.

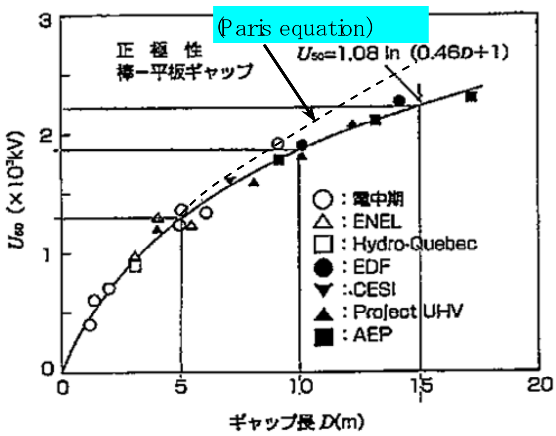


Fig. 46 Experimental flashover data

Experimental data for Phase to Phase was collected from Japan and experimental equation is shown in equation (3).

$V= 2570 \times \ln (0.25d + 1)$ ----------------- (3)

The necessary clearance between phase to ground / phase to structure are calculated from equation (2).
Fig. 46 shows the data calculated from equation (2) and (3).

Phase to phase is calculated from equation (3).
Table 25 shows calculated value based on experimental equation (2), (3).
Suitable clearances are considered to be the gap length satisfied minimum flashover voltage. Minimum flashover voltage is defined by V50-3σ (σ=5%).

Table 25 Calculated value base on experimental data over the world

Phase-to-earth clearance (by equation (2))					
	SIWV (kV)	**1550**	**1675**	**1800**	
	Calculated value (m) ***Phase to structure / Phase to ground (k=1.12)(k=1)***	**7.6/9.6**	**8.9/11.3**	**10.3/13.3**	
Phase-to-phase clearance (by equation (3))					
	SIWV (kV)	**2635**	**2764**	**2880**	**2970**
	Calculated value (m)	**9.4**	**10.2**	**10.9**	**11.6**

It is recommended to review the clearances for the long gap in the case of UHV under wet condition.
In Appendix.3 "The flashover voltage test results for the air clearances of 1000kV substations" in China is shown. They determined their clearance phase to structure 7.5(m) and phase to phase 11.3(m) to meet SIWV 1800kV.

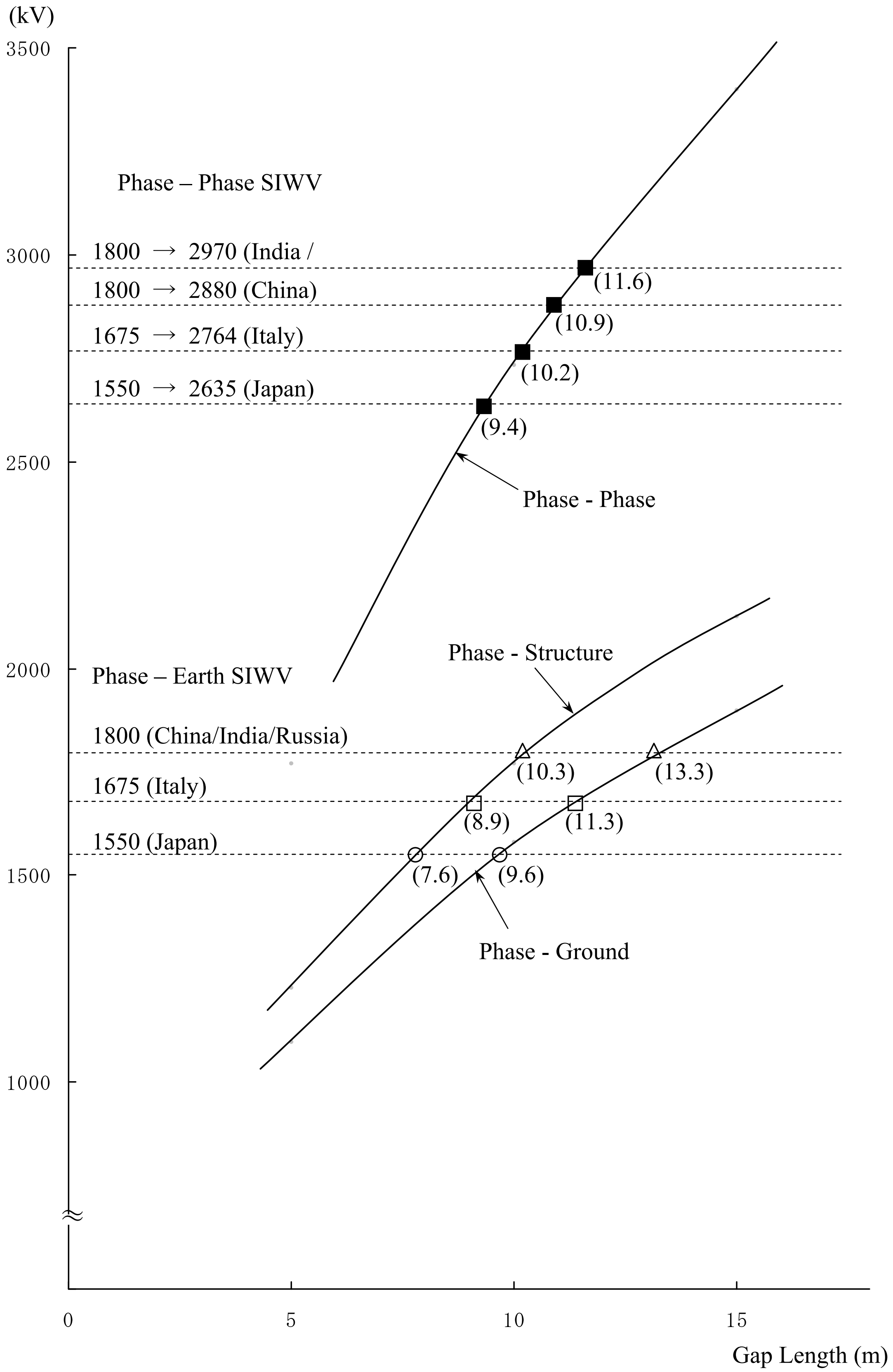


Fig. 47 Gap Length – Flashover voltage (V_{50}-3σ)

2.4 Requirements for SA, GCB, DS, and TR

Specifications of surge arresters, circuit breakers disconnecting switch and transformers from the viewpoint of insulation coordination are discussed as follows.

In UHV substation, adopting high performance arrester leads to make UHV substation more compact, reliable, cost-effective one. To realize this UHV substation, suppressing VFTO in UHV substation and appropriate arrangement of high performance arrester is essential matter.

Following chapter describes these components, first surge arrester and second disconnecting switch with resistor. And related grounding system is also described.

2.4.1 Surge arrester

In UHV substation, high performance arresters are selected to make UHV substation more compact, reliable and cost-effective.

The characteristics of surge arresters are the base of insulation levels of the electrical equipment. And the rated voltage, Ur, is the key parameter which plays dominate effect on protection levels of the surge arrester. The main electrical characteristics of the UHV surge arrester in compare with those used in other countries before are shown in Table 26 The continuous operation voltage, Uc, is equal to Um/ $\sqrt{3}$ kV approximately, and Um is the maximum operation voltage.

Table 26 Main electrical parameters of UHV surge arresters

Country	ex-USSR[22]	Italy[22]	Japan[23]	China[22]	India**
Type	Magnetic blow-out valve type arrester	GIS Tank type MOSA without gaps	GIS Tank type MOSA without gaps	GIS Tank type /porcelain housed MOSA without gaps	Porcelain Housed MOSA without gaps
System nominal voltage kV	1150	1000	1000	1000	1150
Rated voltage kV*	800 (1.155p.u.)	749 (1.236 p.u.)	826 (1.3 p.u.)	828 (1.3 p.u.)	850 (1.23 p.u)
Continuous operating voltage kV	694	?608	635	638	723
Nominal discharge current kA	14	20	20	20	20
Residual voltage for steep current impulse kV	——	?	≤1782 (1/10μs 20kA)	≤1782 (1/10μs 20kA)	——
Residual voltage for lighting impulse kV	≤1940 (8/20μs 14kA)	≤1800 (8/20μs 20kA)	≤1620 (8/20μs 20kA)	≤1620 (8/20μs 20kA)	1700 kV (8/20μs 20 kA)
Residual voltage for switching impulse kV	≤1840~1760 (1.2/25ms 1.5kA)	≤1450 (30/60μs 3kA)	≤1410 (30/60μs 2kA)	≤1460 (30/60μs 2kA)	≤1500 kV (30/60μs 2 kA)
Power-frequency spark over voltage kV	1100 ~ 1250	——	——	——	——
Energy level (TOV)	?	Specific energy :(3~4kJ/kV)	≥55 (55) MJ	>40(15) MJ	≥55(35) MJ

Note:* 1.0p.u. =$U_m / \sqrt{3}$

**Indian value is based on preliminary studies.

In order to reduce insulation level of apparatus in the bus side and the line side of the breakers, it is necessary to use surge arresters with lower rated voltages and with lower residual voltages. TOV level of the network has to be controlled to coordinate with the arrester rated voltage too. In UHV project of China, shunt reactors are selected to limit the TOV level to 1.3p.u. (1.0p.u.=1100/ $\sqrt{3}$ kV) and 1.4p.u. (duration less than 0.5s) in the bus side and the line side of the breakers respectively. Taking advantages of power-frequency voltage-versus-time characteristics of an arrester (higher voltage withstand capability under shorter duration), same rated voltage, 828 kV, is used for surge arresters at bus side, as well as at the line side of the breakers.

In addition to adopting proper rated voltage, configuration of 4 columns with lager diameter MOSA non-linear resistors is also used to obtain lower residual voltage ratio (ratio between residual voltage and peak value of rated voltage). Compare with surge arrester residual voltage ratio of 1.626 in Chinese 750 kV project, lower values of 1.387 and 1.383 are obtained in surge arresters in UHV project in Japan and China respectively. Furthermore, the multi-column configuration has the advantage of higher energy absorption capability than the single-column of 750kV project.

Both porcelain housing and tank type surge arresters are used in China UHV project for outdoor and GIS respectively. Measures are taken to control the voltage distribution along the resistor column of the surge arrester. Considering the height of the porcelain housing surge arrester, grading ring out the housing and capacitors connecting parallel to resistors in the housing are used to reduce the high electric field along the resistor column. Also there is pressure relief device for porcelain housing surge arrester to prevent the porcelain housing from explosion during short circuit inside. The mechanical strength of porcelain housing type under earthquake has to be taken into account due to its height. The tension of galloping base conductors and the dynamic amplifying effect of supporting shelf base with a certain height have large influence on the mechanical calculation and earthquake simulating test. Pollution performance also deserves attention in the outdoor porcelain housing type. There is shielding device inter the tank of tank type surge arrester to reduce the high electric field.

The insulation coordination based on characteristics of porcelain housing type and tank type surge arrester are similar.

2.4.2 Circuit breaker

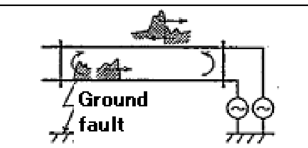
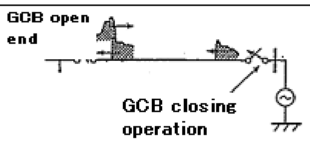
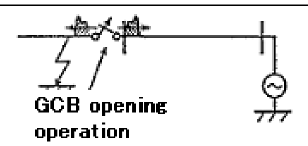
2.4.2.1 Switching surge concerning circuit breaker

Switching of a circuit breaker causes switching overvoltages in the transmission system. In the previous section 2.3.3, analytical review for SFO (slow front overvoltage) and measures to control SFO such technologies as pre-insertion resistors (with/without closing resistors or PIR), opening resistors, controlled switching, and application of MOSA are described. In this section, effect of closing and opening resistors in a circuit breaker and controlled switching will be reported. Following three kinds of overvoltages in the region of SFO need to be considered.

(1) Ground fault overvoltages
(2) Closing overvoltages (Switching overvoltages at line energization)
(3) Interrupting overvoltages (Switching overvoltages at clearing short circuit current)

Mechanisms for these overvoltages are shown in Table 27.

Table 27 Mechanism for occurring SFO and countermeasures

No	Cause of Surge	Mechanism	Overvoltage (Transmission line) Ratio	Countermeasures
1	Ground Fault		1.6 p.u. ~ 1.7 p.u.	No effective measure is available.
2	Closing Operation of CB		> 3 p.u.	Closing Resistors MOSA Shunt Reactor Control switching
3	Opening Operation of CB		> 2 p.u.	Opening Resistors MOSA 4legged Shunt Reactor Control switching

(1) Ground fault overvoltages

Rapid voltage changes at the occurrence of grounding faults induce the transient overvoltages on the sound phases. In the process of propagation and reflection in the sound phases, transient voltages are superimposed on the AC voltages, leading to overvoltages. Maximum voltage appears most likely in the middle of the overhead line, and effect of MOSA in the substations for reducing over voltage is small. Therefore there is not an effective measure for reducing ground fault overvoltage, and SFO insulation level is determined by this level.

(2) Closing overvoltages

Closing overvoltage occurs at energizing no-load transmission line with a circuit breaker. Due to voltage difference between both ends of the transmission line, voltage surge propagates and reflects at the end of the transmission line and causes overvoltage. Theoretically the overvoltage may exceed 3.0 p.u..

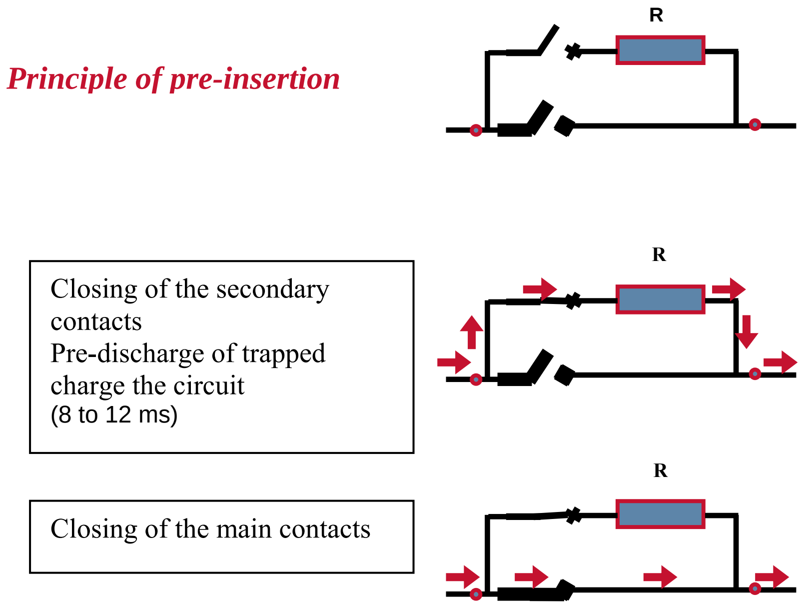
(3) Interrupting overvoltages

Interrupting overvoltage occurs at clearing short circuit current with a circuit breaker, caused by rapid change of current on the faulty phase. The voltage surge propagates and reflects in the transmission line and high overvoltage is induced on the sound phases. Theoretically the overvoltage may exceed 2.0 p.u.

In Chinese commercial UHV system They adopted opening resistor, MOSA and 4legged Shunt Reactor as countermeasure

2.4.2.2 Closing and opening resistor

The principle of closing resistor operation is shown in the sequence diagram below. The overvoltage level can be limited to 2.0 to 2.2 pu. The pre-insertion time is of the order of 8 to 12 ms.



For the 1100kV system of TEPCO in Japan, both closing and opening resistors are adopted to reduce SFO level to the ground fault level 1.6 – 1.7 p.u., combined with the effect of high performance MOSA, considering the 200 km transmission line in the future 1100kV system as shown in Fig. 48.[24]

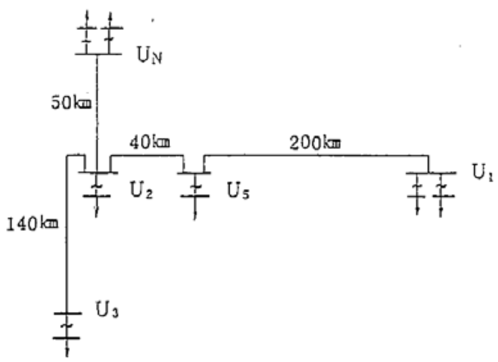


Fig. 48 1100kV Transmission System in Japan

The overvoltage level varies with the value of resistors. Fig. 49 shows overvoltage ratio versus resistor value of both closing and opening. As the thermal capacity to be treated by resistors increases when the resistor value decreases, the value of 700 ohms was selected with the highest value in the effective range for both closing and opening. [25]

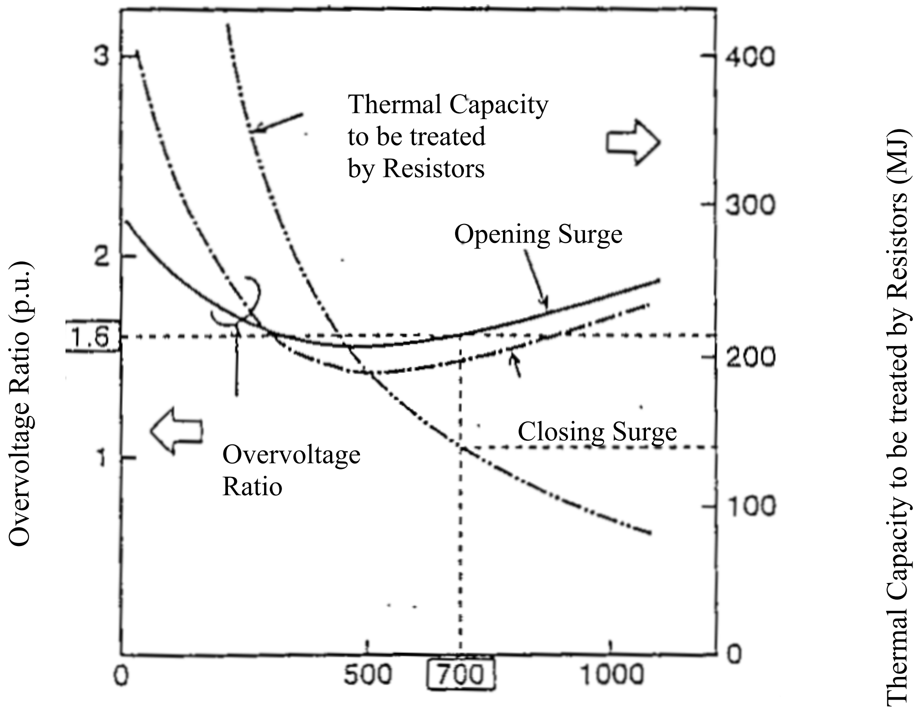


Fig. 49. Switching Overvoltage Ratio versus Resistor Value of Circuit Breaker

Fig. 50 shows the 1000kV pilot project in China, in which the transmission line begins from Jindongnan substation and ends at Jingmen substation through Nanyang switching station. In the future, the UHV lines will be extended northwards to Shanbei and southwards to Whuhan. [26]

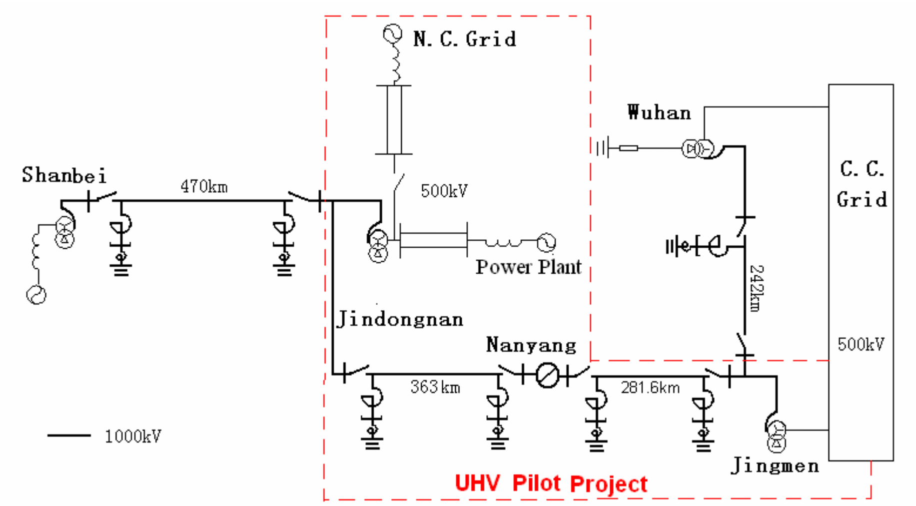


Fig. 50 1100kV Pilot Project in China

The results of EMTP analysis for the statistic overvoltage from line closing and single phase re-closing in the Chinese UHV project are shown in Table 28 as an example. Results in Table 28 are based on the condition of resistor closing by circuit breakers (400 ohms, pre-insertion time 9.5±1.5ms) for the transmission lines whose length are 282km and 363km respectively, and surge arresters being installed. If only the surge arresters are considered without resistor closing of the circuit breakers, the statistic overvoltage of phase-to-ground at the middle of the transmission lines will exceed 1.8p.u. for the lines of 200km length, and 1.95~2.1p.u. for the lines of 400~600km length. Meanwhile, the overvoltage of phase-to-phase will exceed 3.30~3.50p.u. All these results show the necessity of resistor closing by the circuit breakers for the UHV transmission lines.

Table 28 Statistic overvoltage at the closing and the single-phase re-closing for the transmission lines on the China UHV project (p.u.)

Case	Closing resistor 400Ω			
Location	Substation		At the middle of Line	
Overvoltage	Phase-to-ground	Phase-to-phase	Phase-to- ground	Phase-to-phase
Closing	1.54	2.48	1.59	2.65
Single-phase closing	1.56	2.46	1.60	2.57

Note: 1.0p.u. = $\sqrt{2}$ 1100/ $\sqrt{3}$ kV

For the opening switching overvoltage in UHV transmission systems in China, two kinds of overvoltages are studied: (1) Opening switching overvoltages of load reject, when line is under the fault (single phase or two phases) or in normal condition; (2) When the grounding fault is cleared in a line, the switching overvoltages may appear in adjacent healthy line, which is referred to as transferring overvoltage in this paper.

Results of studies for the switching overvoltage of load rejection, with regard to typical transmission lines in the Chinese UHV project shown in Fig. 50, which is about 500km or 2 x 350km (with switching station between two lines), with using surge arresters alone and without opening resistors on the circuit breakers, indicate the maximum opening overvoltage on the both ends of the transmission lines as 1.6p.u. and 17p.u. at the middle of the line, respectively. The maximum phase-to-phase overvoltage at the head of the transmission line is 2.79p.u. and 2.91p.u. at the end of the transmission line, respectively. These results are less than the reference insulation level for China, which is 1.60p.u for substations, 1.70p.u for transmission lines, and 2.90p.u for phase-to-phase, respectively.

Results of studies for the transferring overvoltage after clearing fault in the adjacent line are shown in Table 29, with using surge arresters alone and without opening resistors on the circuit breakers, with regard to the four UHV lines including Shanbei – Jindongnan – Nanyang – Jingmen – Wuhan shown in Fig. 50.

Table 29 Statistic overvoltage for the transferring overvoltage after clearing fault (p.u.)

Number of grounded phase	1		2		3	
Location	Substation	Line	Substation	Line	Substation	Line
Phase-to-ground	1.56	1.70	1.58	1.92	1.60	2.02
Phase-to-phase	2.80	2.89	2.98	3.09	3.12	3.14

In case of the single-phase short circuit fault in one of these lines, the maximum overvoltage does not exceed reference insulation level. However, in case of multi-phase fault, the maximum overvoltage in the lines exceeds the reference insulation level. According to the operating experience in the 500kV grids, the possibility of multi-phase short circuit faults and the probability for occurrence of high transferring overvoltage is extremely low. So, it is decided that circuit breakers are not equipped with opening resistors for the China UHV project shown in Fig. 50.

Table 30 shows the basic specifications of UHV circuit breaker in various countries.

Table 30 UHV circuit breaker basic specifications [27][28]29]

Country	ex-USSR	Italy	Japan	China	India*
Rated voltage, kV	1150	1050	1100	1100	1200
Rated current, A	4000	6000	8000	4000	8000/4000
Type	Air-blast CB with air gaps	GCB	GCB	GCB	MTS/AIS
The number of contacts	10	4 (with CB capacitors)	2	2 or 4	
Rated breaking current, kA	40	63	50/63	50	50
Rated making current, kA	102		125	135	
Operation mechanism	Pneumatic		Hydraulic	Hydraulic or Spring	
Closing resistor, Ω	380	500	700	400-600	600
Thermal duty of resistor, MJ			133	44.5-30	
Opening time, ms	38		≤20	≤30	
Inserting time of resistance closing, ms			10±2	9.5±1.5	

Note: *Indian value is based on preliminary studies.

2.4.2.3 Controlled Switching

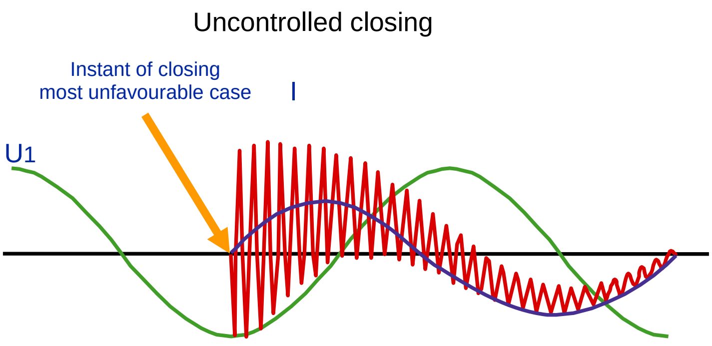
Controlled switching possibilities and benefits have been investigated for some decades by CIGRE Task Force 13.00.1, CIGRE WG 13.07, CIGRE WG A3.07 who have intensively studied this subject in respect to various aspects. From a theoretical point of view, the technical issues and the conclusions given their documents [30],[31],[32],[33],[34],[35] and [36] are also valid for UHV systems . However, controlled switching has not yet been adopted in UHV projects. In more recent times, satisfactory technological solutions, thanks to the progress made in HV circuit-breaker technology and the development of micro-electronics, have enabled its application to extend to optimizing the switching on/switching off of capacitive loads (no-load lines, shunt capacitor banks), as well as inductive ones (loaded lines, shunt reactors, power transformers).

Type of Load	Type of Operation	Controlled instant	Stress reduction
Capacitive	Closing	At zero-voltage crossing	Overvoltage caused by inrush current
Capacitive	Opening	Optimal arcing time	Overvoltage caused by restrikes
Inductive	Closing	At peak voltage	Overvoltage caused by inrush current
Inductive	Opening	Optimal arcing time	Overvoltage caused by restrikes

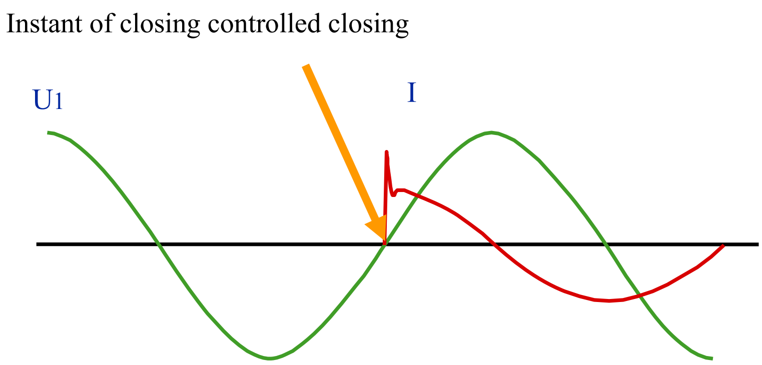
The experience gained with the use of controlled switching in Power Systems (by use of a so-called “Point-on-the-Wave Controller”) have proven to be very efficient to control to limited values the switching transients, contributing therefore to meet both the demanding insulation coordination requirements as well as the power quality improvement.

As it can be illustrated on the diagrams below, the controlled switching operation is a sequential chain of analysis and orders, so as to command very precisely the opening (or closing) of the GCB contacts at optimal instant of electrical angle, taking into account the minimum arcing time of the GCB.

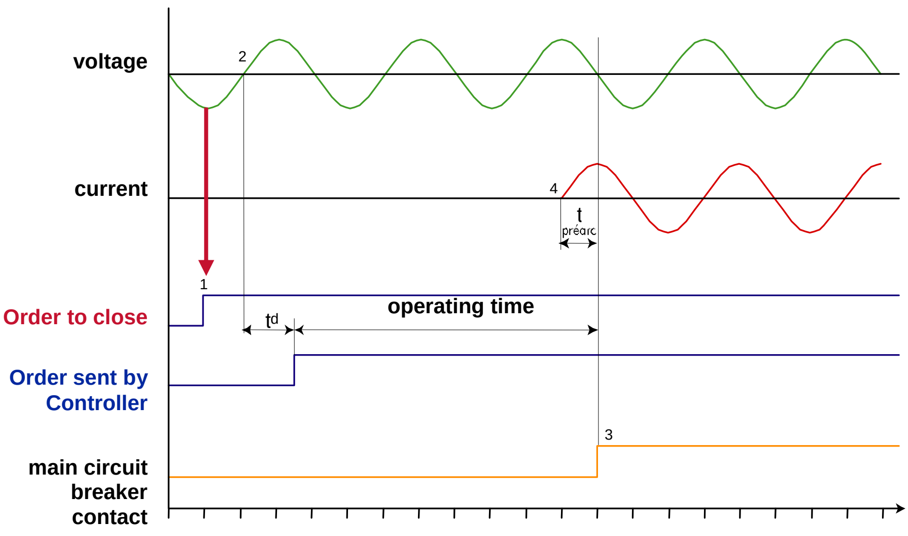
Closing on capacitive



Closing on capacitive load

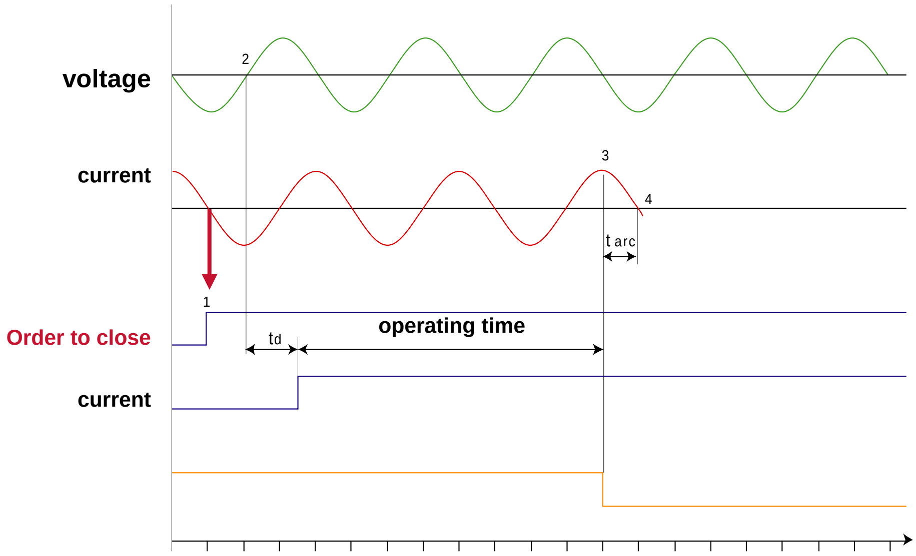


Synchronization on closing (Inductive load)



The "Point-on-the-Wave Controllers" consist mainly of a zero-detection module, a delay (time) computing module connected to a power module which will ultimately send an order to the coil of the GCB.

Synchronization on opening
(Inductive load)



Very important parameters are the maximum acceptable dispersion of the breaker contacts operating time (a statistical information), and the actual dielectric strength between closing contacts.

These two above characteristics will determine the maximum making voltage between the GCB contacts, especially in compensated transmission circuits re-closing application. It is worth mentioning that the most recent generation on point on the wave controllers can now elaborate advance analysis in the case of shunt-reactor compensated lines likely to have kept a trapped charge. The switching overvoltages in this latter case can be as low as 1.9 pu. [[37]]

As quoted in [[38]], the use of switching transient mitigation techniques in Power Systems contributes to improve the power quality in its most extensive sense. A controlled switching device allows significant equipment cost reduction, and can afford a larger use of compacted lines in power systems: this is at the benefit of an overall cost reduction, reduced surge impedance and enhanced Surge Impedance Loading (SIL)

2.4.2.4 Experience and opinion by some utilities

Evaluation for the opening & closing resistors and the controlled switching varies among utilities. Eskom has adopted use of closing resistors rather than controlled switching for their 765 kV lines. AEP also use closing resistors for the older parts of their 765 kV network where live tank breakers are used. In deciding to adopt the dead tank circuit breaker solution, eliminating closing resistors was seen as necessary in order to achieve simplicity and to a remove a potential source of unreliability of operating mechanism. The 765 kV lines they eliminate closing resistors and install line surge arresters on are relatively recent. [[38]]

Eskom's experience over the past 21 years with closing resistors built into dead tank breakers at Alpha and Beta 765kV substations has been excellent. So carrying on with the traditional method of controlling line switching transients by means of closing resistors is not seen as high risk. Moreover the human error factor is virtually eliminated except for risk of thermal overstressing due to injudicious operating.

On the other hand Eskom's experience with controlled switching for other applications has highlighted the difficulties in ensuring the technology is successfully implemented and maintained. Relays sometimes fail and the wrong settings are applied.

BC Hydro (Canada) has been one of the pioneers to adopted controlled switching for high speed autoreclosing of 500 kV shunt compensated line and published their experience in 1997 [[39]],[[40]]. The authors concluded that the use of lower line insulation levels is possible with associated cost savings and that in -service experience with the switching surge limitation scheme has been without incident at the time of writing of the paper.

2.4.3 Transformer

UHV transformer may be attacked by the transient overvoltage, switching impulse overvoltage and lightning impulse overvoltage in operation, so the insulation of transformer must withstand all these overvoltage besides the operation voltage, but the margin of insulation must be reasonable.

The SIWV of the China UHV transformers is 1800kV, and the statistic overvoltage appeared at substations of the China UHV project is 1.56 p.u., the maximum estimated overvoltage value is 1.7p.u.. So the margin of SIWV and internal insulation of transformers is 17.8%

Studied results of China UHV project about lightning overvoltage shows that the UHV substation failure rate cause by lightning incoming wave is less than once per 2000 years. The results show that the LIWV of transformers is feasible.

In Japan UHV design, the high performance surge arrestor, circuit breaker with open/close resistors, full GIS, etc was applied for reduction of overvoltages in the system, and the high accuracy numerical analysis also was applied for evaluation of every kind of over-voltages. And considering the economical factor, the SIWV and LIWV of the UHV transformer are respectively 1425kV and 1950kV.

Due to the requirement for the withstand ability of temporary overvoltage and long time operating voltage to internal insulation inside UHV transformers, work life of the transformers must be considered firstly. However, the studied results about life span of compound (oil-paper) insulation show that it is very important to grasp the relationship between partial discharge initiation voltage (V) and voltage effect time (t) during energization test of transformers. A large of information about the V-t has ever been accumulated in Japan. An example for a partial discharge V-t is given in Fig. 51.[[10]]. And UHV long-duration induced AC voltage test is given in Fig. 52. Which is designed according to the stress characteristic of power-frequency voltage occurred on Japan UHV equipments in Table 31. The long-duration induced AC test mode shown below has been finally chosen according to the research works in Japan [[10]].

$$1.5\text{p.u.}\times 1\text{h} + \sqrt{3}\ \text{p.u.}\times 5\text{min} + 1.5\text{p.u.}\times 1\text{h} \quad \text{(Japanese AC test mode)}$$

$$1.5\text{p.u.}\times 5\text{min} + \sqrt{3}\ \text{p.u.}\times 5\text{min} + 1.5\text{p.u.}\times 1\text{h} \quad \text{(Chinese AC test mode)}$$

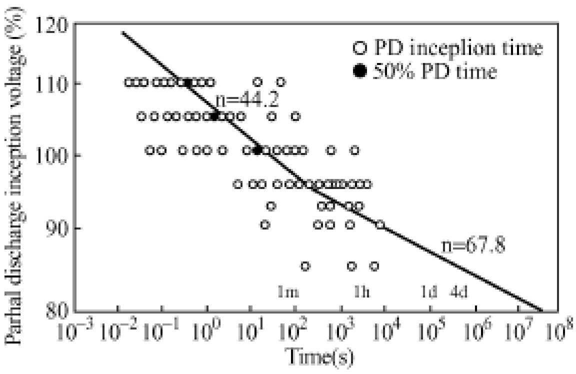


Fig. 51 V-t characteristic curve for partial discharge in transformer

Table 31 power frequency voltage endured by UHV equipments

	Temporary overvoltage			Operating voltage
	At one-line ground fault		At load rejection	
Overvoltage V_s	1.1p.u.	1.1p.u.	1.5 p.u.	1.0 p.u.
Duration T_s	0.1s	2s	t_s	30years
Frequency N	90	10	3	——

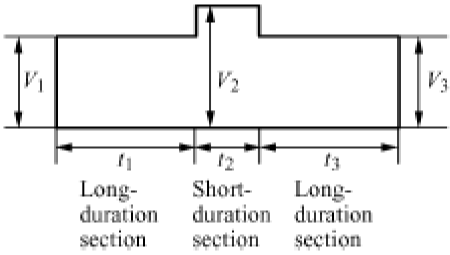


Fig. 52 power-frequency test voltage's mode

It can be seen in Table 32 and Fig. 52.that if a transformer can work at 1.5p.u. voltage for more than 1h, the transformer can be in service at 1.0p.u. voltage for more than 30 years

Since the UHV transformer must be in service under steady state power-frequency voltage rises for a period of time due to the system abnormality, the requirement for the steady state power-frequency voltage rises occurred in Russia standards should be referred.

Table 32 Allowed rise value of power-frequency voltage on the UHV equipments

Time for voltage continue operation, s	1200	20	5	3	0.15	0.05
Power-frequency voltage, p.u.	1.1	1.2	—	1.3	1.35	1.4

The main task for study on insulation coordination of substation is to identify the value of over-voltage imposed across the air gap scientifically, calculate the minimum phase-ground (value A1) and phase-phase (value A2) air gap distances in the substation, and thus determine the values B and D of the switchgears by referring the relevant information at both home and abroad and applying statistics principles on the basis of the research on the system over-voltage. After the minimum air gap distance for the 1100kV switchgear as well as the type of conductor are identified, the task is to define the limit of ground electric field strength in substation, calculate the maximum electric field strength below conductor of the switchgear and ensure it is within the said limit and thus identify the minimum distance between bare conductor in the 1100kV switchgear and the ground (value C).

2.4.4 Disconnecting Switch with/without resistor

Concerning the disconnecting surge in UHV GIS, various investigations based on some analysis examples and experimental data has been carried out.

These analysis and experimental data in mainly Japan and China are reviewed.

This paper describes influence on disconnecting surge and the effect of suppressing resistor installed in disconnector, involved in the influence on transformer in spite of GIS main circuit.

2.4.4.1 Investigation and analysis for disconnecting surge in Japan

(1) Analysis result for actual substation

Fig. 53 shows the single line diagram of UHV-GIS used for the VFTO calculation.

The substation has a double-busbar scheme and consists of a GIS with four feeder bays and four transformer bays. The disconnecting surges were calculated at various points in this GIS. [[41]].

The maximum voltage across the contact before re-striking was set to be 2 p.u. based on many observed data among hundred operations in DS surge test of field verification by using 1000 kV proto type facility[42].

Table 33 shows the conditions used in the calculation. Some waveforms in the calculation results, which are for no resistance, 200Ω and 1kΩ in disconnector O (bus-tie DS) in Fig. 53 are shown in Fig. 54.

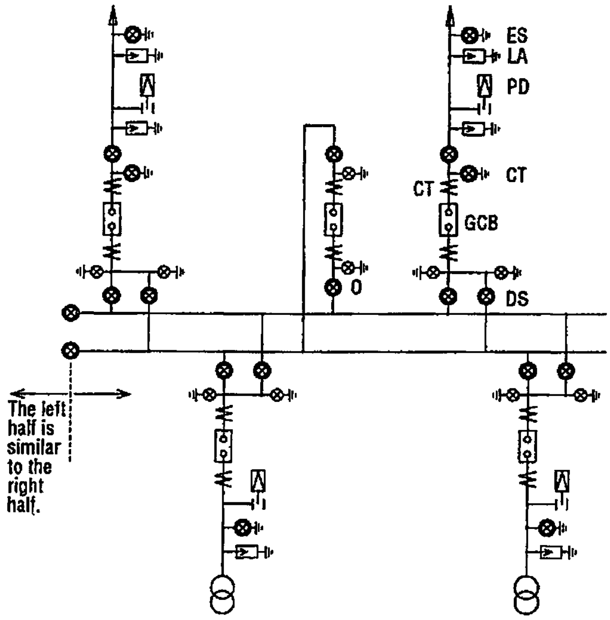


Fig. 53 1 1100kV GIS circuitry used for the surge calculation

Table 33 Constants used in 1100kV GIS disconnector surge calculation

GIS	Z = 95 Ω, ν= 270 m/μs
Transformer	4600 pF
ZnO surge arrester	V_{10kA} = 1550 kV, V_{1mA} = 1080 kV
Overhead transmission line	Z = 230 Ω, ν= 300 m/μs
Bushing	500 pF
Opened circuit breaker	400 pF
Disconnector resistance	50 Ω - 1 kΩ

The results of surge calculation for disconnectors at various points in Fig. 53 are shown in Fig. 55 (a), (b) and (c)

They show the followings:

- With no resistor in the disconnectors, the crest value of overvoltages is 2.8 pu (2510kV) and exceeds LIWL 2250kV (2.5 pu).
- If the resistance of the disconnector resistors is 200Ω or above, overvoltages can be suppressed below about 1.5pu. When the resistance exceeds 500Ω, they saturate approximately 1.2pu.
- The larger the resistance, the higher the voltage applied to the resistor. Dielectric capability of resistance is required to be 1700kV when the resistance is 500Ω.
- The larger the resistance, the larger the energy consumed by the resistor, in the resistance range below 200Ω, beyond which the energy eases off. Again, the larger the capacitance at the load side of the disconnector, the larger the energy. The resistor energy shown in Fig. 54 (c) was max when the longest bus (35m) was used at the load side of the disconnector.

Disconnector with resistor was adopted to reduce the disconnecting surge below LIWV level. To suppress the overvoltage as low as possible and to reduce the dielectric and thermal capability of resistor, the value of resistor was determined to be 500Ω.

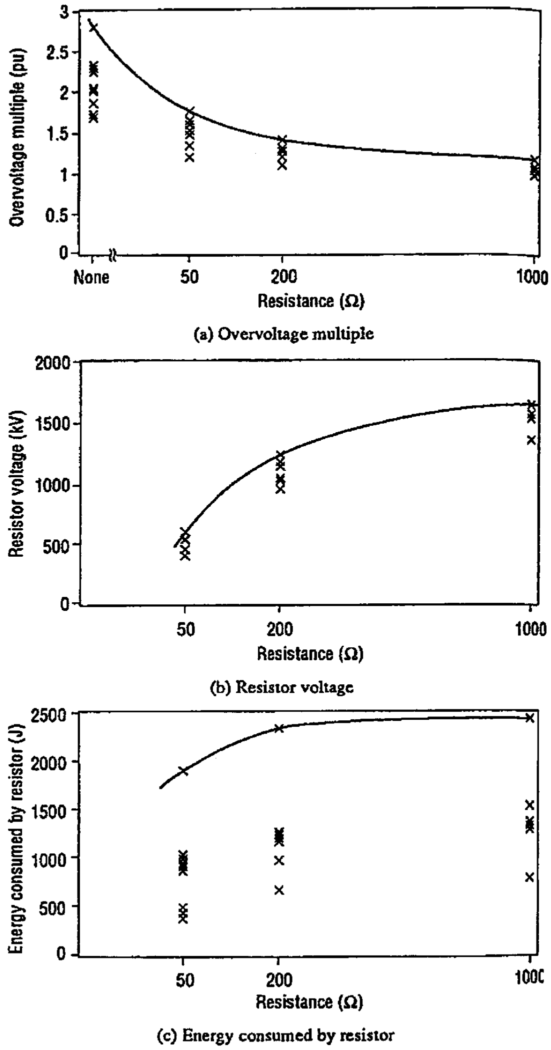


Fig. 54 Results of calculation
(In each case of calculation, the maximum values at various points of GIS are plotted.)

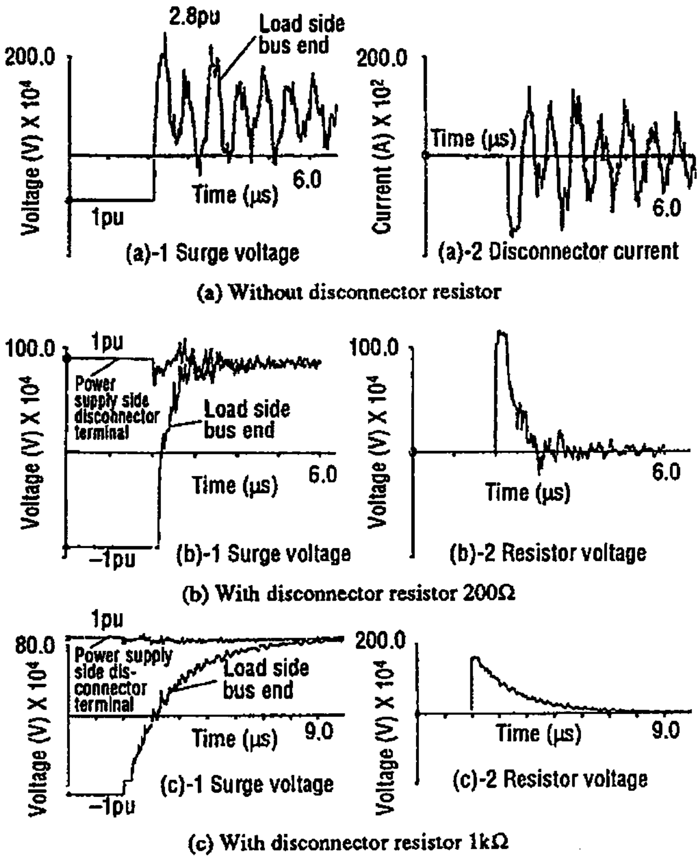


Fig. 55 Some waveforms from surge calculation

(2) Measurement of DS surge in UHV field test facility

DS surge test was carried out using the UHV equipment test facility as shown in Fig. 56[42].
DS employs a resistor of 500Ω to reduce the overvoltage of DS surge.

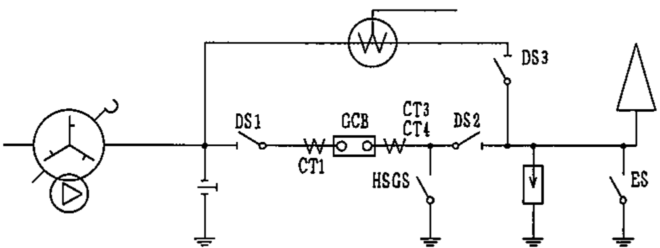
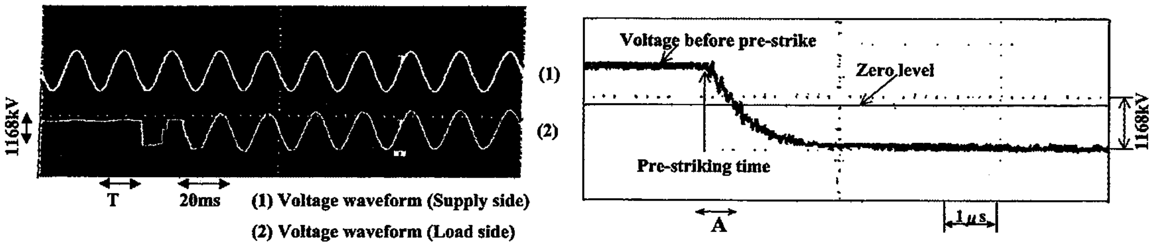


Fig. 56 Switching operations for respective measurements

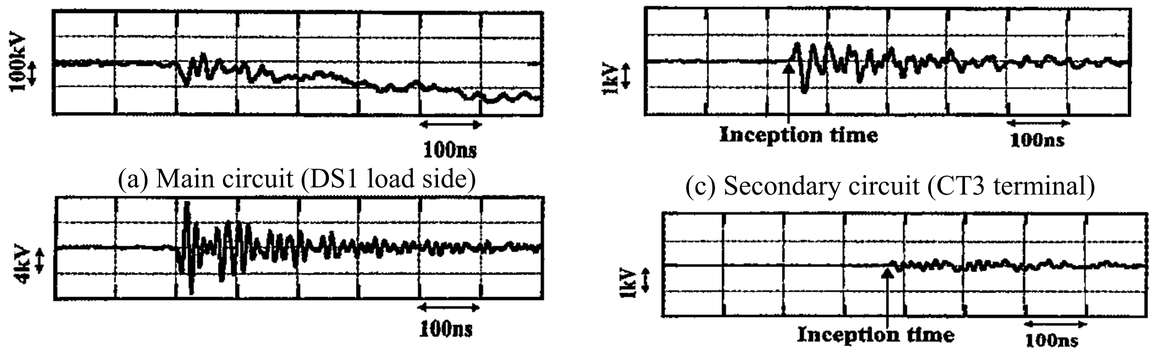
Fig. 57 shows an observed waveform among hundreds operations. The maximum voltage across contacts before re-strike was 2pu. There were neither voltage overshoots nor fast-rising oscillating waves, though these are the general features of DS re-striking surge. The maximum surge observed during measurement was 1.20pu. Energy absorbed by the resistor was less than 20kJ (estimated value) The resistor switching is working effectively.



(a) Voltage waveform at closing operation of DS (b) Enlarged waveform of part T

Fig. 57 DS surge waveforms

EMI on secondary low voltage circuits was examined when main-circuit surges transferred through current transformers (CT). Fig. 58 shows the voltage waveform observed at the secondary circuits of CT at both sides of the GCB. Fig. 58 (a) shows main circuit surge, enlarged waveform of part A in Fig. 57(b). Fig. 58 (b) shows a voltage of secondary circuit at CT1 on the operating DS side of the GCB. It was observed that only high-frequency component on main circuit affected the CT secondary circuit. Though the surge amplitude of CT terminal exceeded 7kVp and the front shape was steep, the insulation performance of CT was enough from the view of the V-t characteristics. Fig. 58 (c) and (d) show voltage of secondary circuit of CT3 installed at the load side of the GCB. Fig. 58 (c) is at the CT terminal; Fig. 58 (d) at the interface panel terminal. The highest level observed at interface panel and relay panels was at most 200Vp, and it was low enough. Even over 7kVp were observed at CT terminals, this surge rapidly attenuated as travel in secondary cable.



(a) Main circuit (DS1 load side)
(b) Secondary circuit (CT1 terminal)
(c) Secondary circuit (CT3 terminal)
(d) Secondary circuit (CT3 Interface panel)

Fig. 58 DS surge waveforms at CT secondary circuit

The resistor is not only working effectively to reduce the overvoltage in main circuits of GIS, but also secondary low voltage circuits such as CT terminal and CT interface panel.

2.4.4.2 Evaluation of dielectric performance against DS surge for UHV transformer in Japan[43]

As transformer is directly connected to GIS, disconnector surge (DS surge) propagate the transformer terminal & windings. Depending on the frequently components for intruding surge, local resonance may be generated inside the winding. Fig. 59 shows DS surge measuring circuit estimate the voltage change for DS surge.

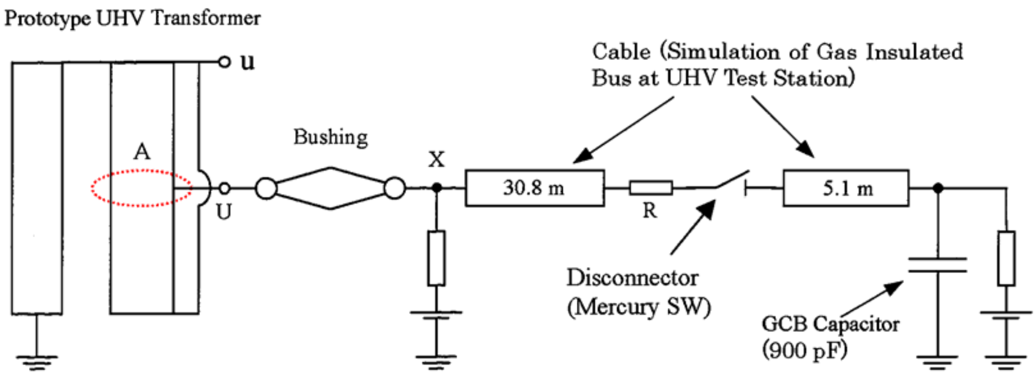


Fig. 59 Ds surge measuring circuit

Fig. 60 shows voltage waveforms at the line terminal (X) with and without the resistor for the disconnector. The waveforms almost match the analytical results by Electro Magnetic Transients Program (EMTP). The voltage change at the wave-front was 1.35 pu without the resistor but 0.3 pu with the resistor, less than 1/4.

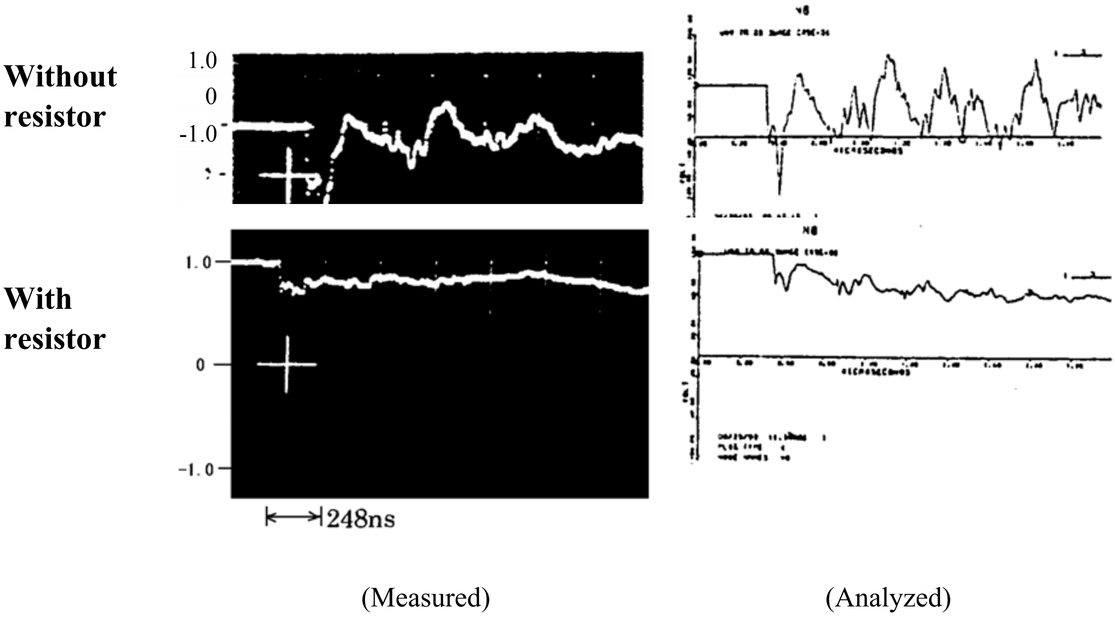


Fig. 60 DS surge waveforms at transformer terminal (X)

Fig. 61 shows measured waveforms with and without the bushing under conditions without a resistor. When DS surge invade into the bushing, a wave-front time of about 10 ns is extended to about 60 ns. This reduces the overvoltage generated between turns or sections to 60 to 80% of that when a DS surge is applied directly without a bushing.

Table 34 shows voltages generated in the winding (near the high-voltage line terminal). Compared with the standard impulse voltage, a DS surge causes non-uniformity of potential sharing characteristics inside the winding and generates higher voltages between turns or sections. This is because the DS surge wave-front time is shorter than the capacitance charging time with the winding near the line terminal.

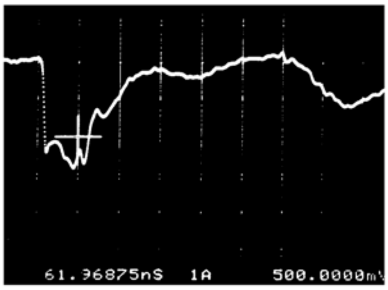
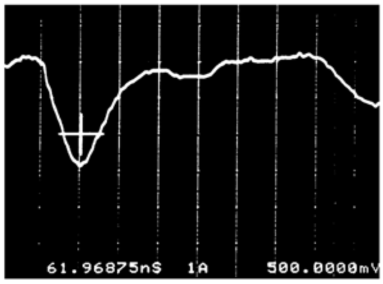
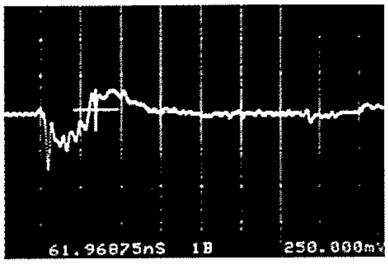
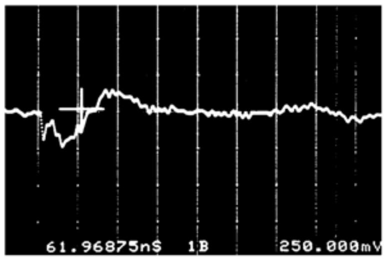
	Without bushing	With busing
High-voltage line terminal ground		
Between first and second sections		

Fig. 61 DS surge waveforms in winding (without resistor)

Table 34 Voltage generated inside winding (near high-voltage line terminal)

Measuring point	DS surge (without resistor) (1)		Lightning impulse voltage(2) (1.2/50 μs)
	Without bushing	With bushing	
Between turns of first Section	23.1%	15.3%	2.3%
Between first and second sections	37.3%	23.7%	4.5%
Between second and third sections	16.8%	13.4%	4.5%

Note (1) DS surge is when the SW is turned on at ±1 pu where 1 pu is 100%.
(2) Lightning impulse voltage is when the applied voltage is 100%.

Table 35 gives the calculated voltages based on Table 34 when a DS surge of ± (√2/√3)*1,100 kV restriking and lightning impulse voltage of 1,950 kV are applied. These are rough estimates by conversion to the standard wave. The values indicate that a voltage equivalent to or higher than LIWV may frequently be generated locally. Thus, it would be preferable to adopt a disconnector with resistor for securing insulation reliability.

An intruding DS surge may also cause local increase of the voltage distribution in winding-type equipment such as a voltage transformer (VT) or a bushing with internal shield for field control. Therefore, a disconnector without resistor would be better to be used with careful attention given to DS surges, as with a transformer.

Table 35 Evaluation of voltages generated in winding (near high-voltage line terminal)

Measuring point	DS surge (with resistor)		Lightning impulse voltage (1.2/50 μs)
	Without bushing (1)	With bushing (2)	
Between turns of first Section	√2/√3*1100kV*0.153/1.4 = 137 kV	34 kV	1950*0.023 = 45 kV
Between first and second sections	√2/√3*1100kV*0.237/2.3 = 92 kV	23 kV	1950*0.045 = 88 kV
Between second and third sections	√2/√3*1100kV*0.134/2.3 = 52 kV	13 kV	1950*0.045 = 88 kV

Note (1) Breakdown voltage of a steep wave having a pulse width of 70 ns was 1.4 times higher than that of the standard wave between turns and 2.3 times higher at an oil gap[6] and their multiples were used for conversion to the standard wave.
(2) DS surge with resistor was set to 1/4 of that without resistor.

2.4.4.3 Analysis result of Pilot project in China [44]

(1) Peak value of VFTO

1000 kV AC UHV pilot project is building in China.

In the project, F-GIS is used in Jindongnan substation and H-GIS is used in Nanyang switching substation and Jingmen substation.

Table 36 shows VFTO analysis result for three arrangements in F-GIS and H-GIS.

In case of F-GIS, the maximum values of VFTO without resistor are shown from 2.5p.u.(2249kV) to 3.05 p.u.(2742kV). These are different from circuit condition such as equipment arrangements and one case of them exceeds LIWV of 2400kV(2.67p.u.). These results show that VFTO is serious and some countermeasures such as DS with resistor may be necessary. If DS with resistor of 500Ω is used, the maximum value of VFTO is reduced from 1.3 to 1.4p.u..

In case of H-GIS, the maximum values of VFTO without resistor are 2.09p.u.(1878kV) in Nanyang GIS, 2.04p.u.(1836kV) in Jingmen GIS and are relatively less than F-GIS.

If DS with resistor of 500Ω is used, the maximum values of VFTO are suppressed from 1.3p.u to 1.4p.u. as well as F-GIS.

Table 36 VFTO analysis for Pilot project

	Substation	Circuit condition	Without resistor	With resistor (500Ω)
F-GIS	Jindongnan	Arrangement (1)	2.50 p.u. (2249 kV)	1.39 p.u. (1250 kV)
		Arrangement (2)	2.52 p.u. (2260 kV)	-----
		Arrangement (3)	3.05 p.u. (2742 kV)	1.29 p.u. (1157 kV)
H-GIS	Nanyang S/S	-----	2.09 p.u. (1878 kV)	1.34 p.u. (1204 kV)
	Jingmen S/S	-----	2.04 p.u. (1836 kV)	1.41 p.u. (1268 kV)

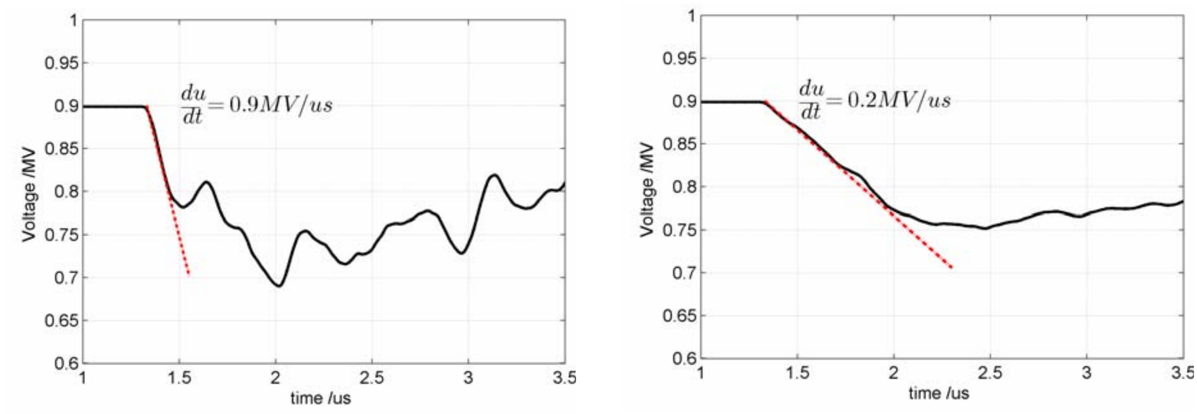
(2) Investigation for gradient, frequency and rise amplitude

The factors of harmfulness of VFTO is not only its high overvoltage, but also its high frequency, gradient and rise amplitude of steep wave, which may cause inter-turn overvoltage and high frequency resonance in transformer. In addition, the VFTO with very large gradient can form obvious capacitive current in arrester and cause unwanted operation of arrester counter.

< Gradient of VFTO>

The gradient of VFTO is similar with the gradient of chopping wave and may be more serious than it. The restriking breakdown time is much shorter than the spread time of traveling wave in pipe. So the gradient of VFTO mainly depends on the breakdown time and the initial voltage between contactors. Here the gradient of the typical waveform of VFTO in GIS reaches up to 60MV/us. While the peak value of VFTO is reduced by switching resistor, the gradient of VFTO is reduced from 60MV/us to 24MV/us.

When VFTO spreads to the transformer entrance, the gradient is reduced greatly. The typical waveform at the transformer entrance is shown in Fig. 62 (a), in which the gradient of wave front is 0.9MV/us. While the switching resistor is used, the gradient of wave front of VFTO at the transformer entrance is reduced from 0.9MV/us to 0.2MV/us, as Fig. 62(b).

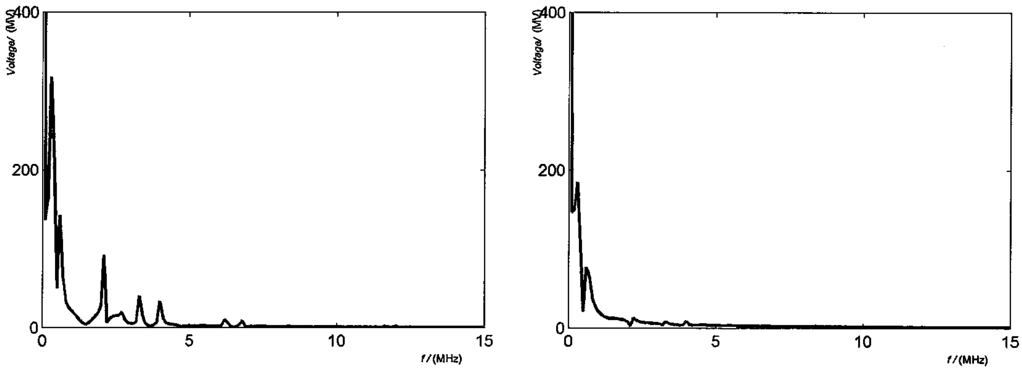


(a) Without resistor **(b) With resistor**

Fig. 62 The gradient of VFTO at the entrance of transformer

<Frequency characteristics of VFTO>

The typical amplitude-frequency characteristic of VFTO in GIS is involved in abundant components under 2MHz and obvious components of 17MHz and 31MHz in VFTO. While the switching resistor is adopted, the components of high frequency are reduced greatly. When VFTO propagates to the entrance of transformer, the high frequency components have greatly attenuated. The typical amplitude-frequency characteristic of VFTO at the transformer entrance is shown in Fig. 63. Using switching resistor has obviously affected the frequency characteristic too.



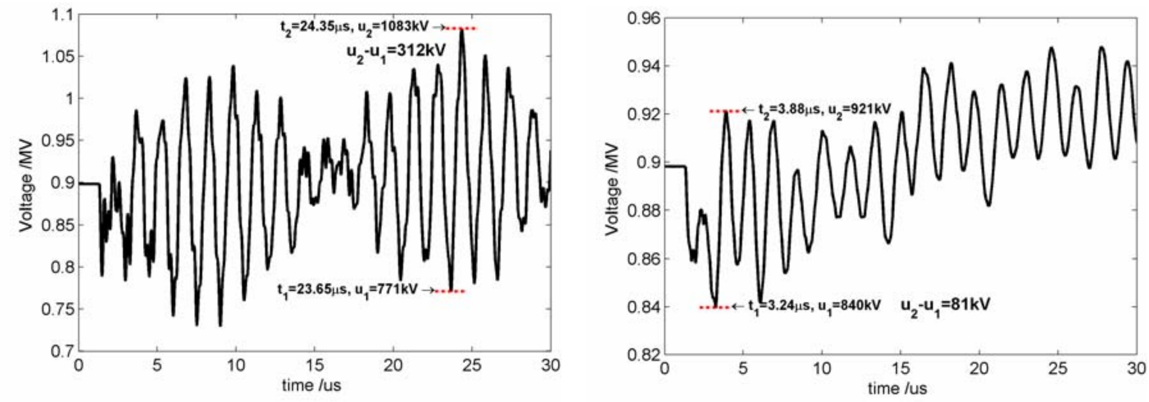
(a) Without resistor **(b) With resistor**

Fig. 63 Amplitude frequency characteristics of VFTO at the entrance of transformer

<Rise amplitude of VFTO>

The factors of affecting inter-turn voltage distribution in transformer also include the rise amplitude of steep wave. Before restriking, the voltage between contactors can reach to 2.0 p.u. in the extreme condition. During restriking, the rise or drop amplitude of steep wave inside GIS may reach to 2.0 to 3.0 p.u. When it propagates to the entrance of transformer it has been reduced greatly.

When switching resistor is used, rise amplitude of steep wave will be reduced obviously. As shown in Fig. 64, the voltage at the entrance of transformer rises by 312kV in 0.7 us while there is no switching resistor. When the switching resistor is used, the rise amplitude is reduced to 81kV.



(a) Without resistor **(b) With resistor**

Fig. 64 Rise amplitude of steep wave at the entrance of transformer

The evaluation of gradient, rise amplitude and the high frequency component is also investigated.

If DS without resistor is used, VFTO with the high overvoltage, high frequency, gradient and rise amplitude of steep wave is propagated to the entrance of transformer.

Since the VFTO may cause inter-turn overvoltage and high frequency resonance in transformer, Using switching resistor is desirable for dielectric reliability of transformer and induced voltage secondary low voltage circuit.

2.4.4.4 Analysis result of actual substation in China [45]

In actual networks, the internal insulation of transformer and GIS for VFTO is very important concerns. The reduction of VFTO becomes on of the main themes. Investigation for VFTO by using EMTP on UHV-GIS planned in China was performed.

(1) Analysis condition

Analysis of VFTO was carried out for both F-GIS and H-GIS.

Fig. 65 shows single line diagram of F-GIS used for the VFTO analysis.

Fig. 66 shows single line diagram of H-GIS for the VFTO analysis, which employs a one and half GCB arrangement for the first and future stages of the substation layout. Table 38 shows the specific constant value used for the analysis.

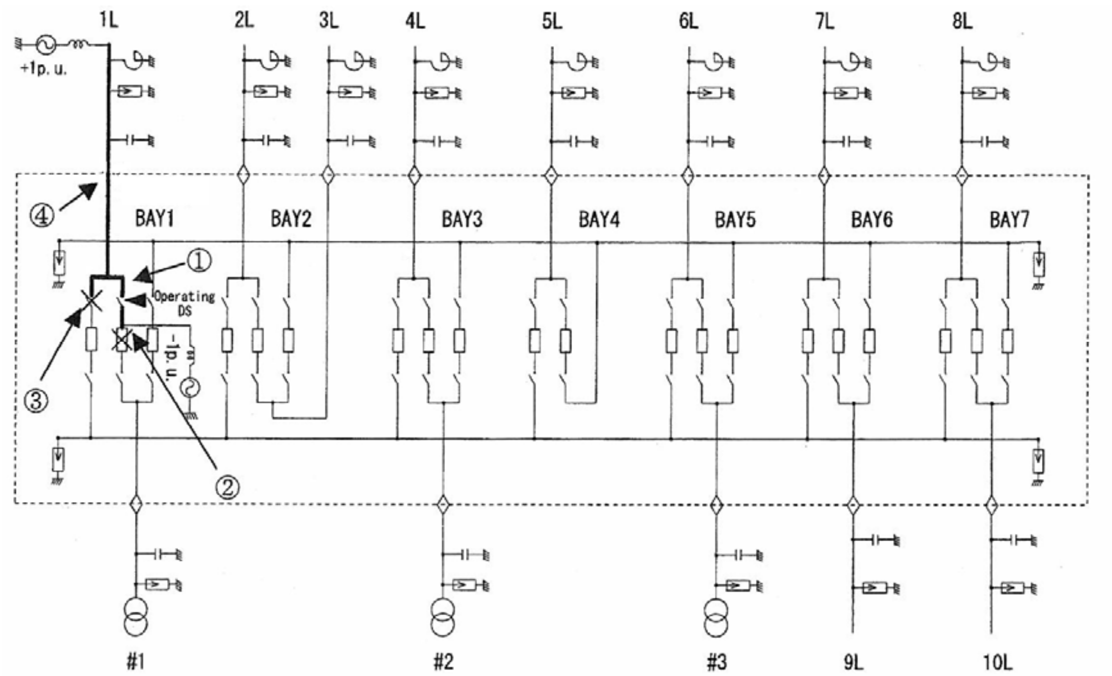


Fig. 65 Single line diagram of 1100 kV F-GIS planned in China for VFTO calculation

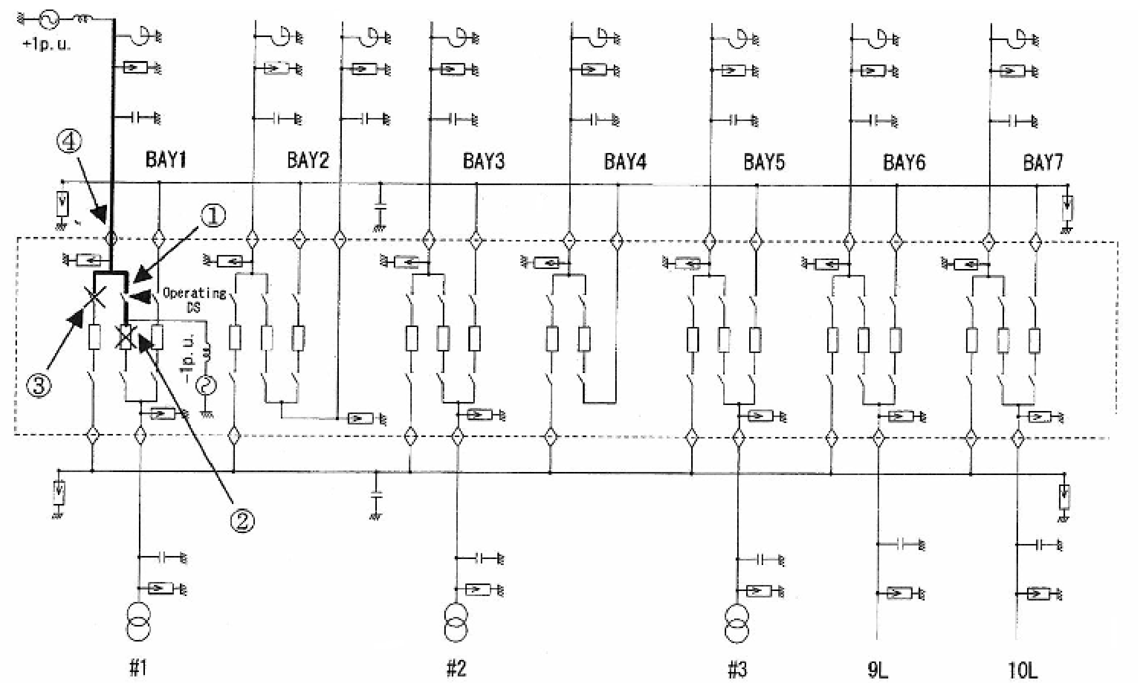


Fig. 66 Single line diagram of actual 1100 kV GIS planned in China

Table 37 GIS conditions and line constants used in VFTO calculation for UHV-GIS

Item	Applied data
Layout	One – and – a – half GCB arrangement
GIS	Z = 78 [Ω], v = 270 [m/μs]
Overhead lines	Z = 350 [Ω], v = 300 [m/μs]
Transformer	6, 12 nF/phase
Shunt reactor	4.5 nF/phase
Potential divider	2.0 nF/phase
Surge arrester	V_{LI} = 1620 [kV] (for 8/20 μs, 20 kA)
Bushing	0.3 nF
Resistance R_{DS} installed in DS	0 – 1000 Ω

(2) Analysis result

The maximum values of VFTO are shown in Table 38.

Typical examples of VFTO in F-GIS are shown in Fig. 67, Fig. 68.

In case of F-GIS, if DS without resistor is used, The maximum values of VFTO is 2.7 p.u. (2442 kV) in first stage, and 2.0 p.u. (1801 kV) in final stage. On the other hand, if DS with resistor is used, the maximum value of VFTO is suppressed 1.2p.u. (1074kV).

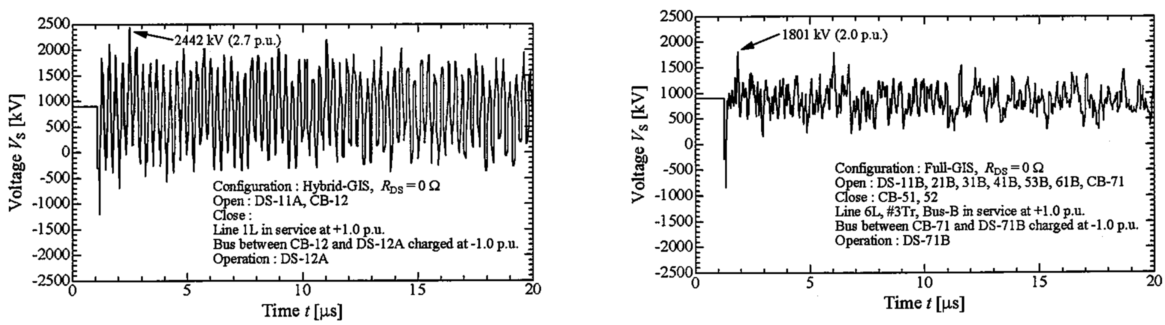
Typical examples of VFTO in H-GIS are shown in Fig. 69, Fig.70.

In case of H-GIS, the maximum values of VFTO without resistor are 2.14p.u.(1922kV) in first stage, 1.72p.u.(1547kV) in second stage and are less than LIWV of 2400kV(2.67p.u.).

If DS with resistor is used, the maximum values of VFTO are suppressed 1.14p.u in first stage and 1.36p.u in second stage.

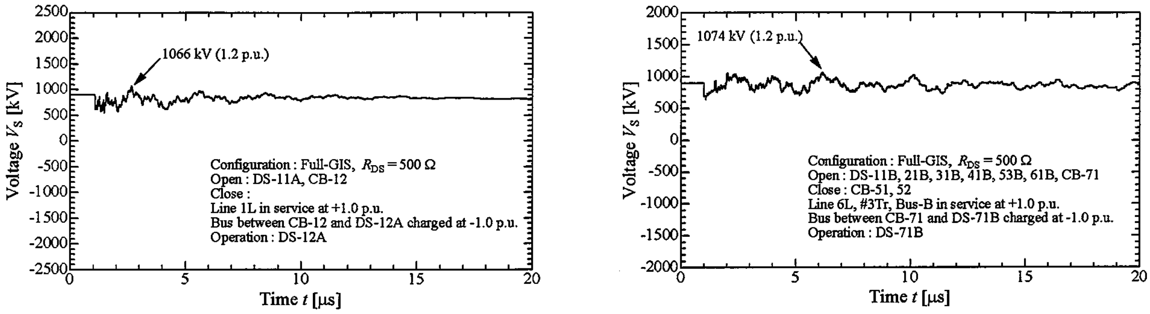
Table 38 VFTO analysis for actual substation

		Without resistor	With resistor (500Ω)
F-GIS	First stage	2.7 p.u. (2442 kV)	1.19.u. (1066 kV)
	Final stage	2.0 p.u. (1801 kV)	1.2 p.u. (1074 kV)
H-GIS	First stage	2.14 p.u. (1922 kV)	1.14 p.u. (1026 kV)
	Second stage	1.72 p.u. (1547 kV)	1.36 p.u. (1218 kV)



(a) Full-GIS, first stage (Location: DS-12A) (b) Full-GIS, final stage (Location: DS-12A)

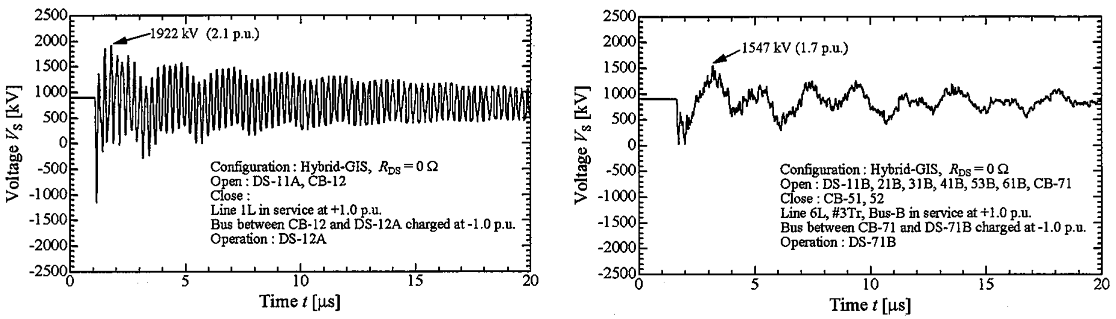
Fig. 67 Typical examples of time variations in VFTO caused by DS operation without parallel resistor



(a) Full-GIS, first stage (Location : DS-61B) (b) Full-GIS, final stage (Location : DS-61B)

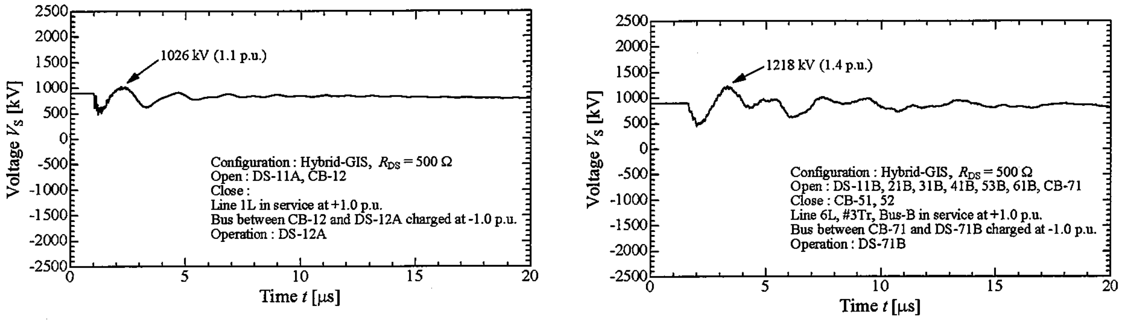
Fig. 68 Typical examples of time variations in VFTO caused by DS operation with parallel resistor of 500 Ω

If DS with resistor is used, the maximum values of VFTO are suppressed 1.14p.u and 1.36p.u.



(a) Hybrid-GIS, first stage (Location: 1L-BG) (b) Hybrid-GIS, final stage (Location: DS-61B)

Fig. 69 Typical examples of time variations in VFTO caused by DS operation without parallel resistor



(a) Hybrid-GIS, first stage (Location: DS-11A) (b) Hybrid-GIS, final stage (Location: DS-61B)

Fig.70 Typical examples of time variations in VFTO caused by DS operation with parallel resistor of 500 Ω

VFTO analysis in F-GIS and H-GIS for actual substation is carried out. Concerning the peak value of VFTO without resistor, F-GIS is relatively higher than H-GIS and exceeds LIWV of 2400 kV. But, by using disconnector with resistor, VFTO can be reduced to be entirely low level and a approximately constant value for both F-GIS and H-GIS.

Since disconnector switching generates various values of disconnecting surge for circuit condition in GIS, it would be preferable to adopt a disconnector with resistor for securing insulating reliability of GIS and transformer.

<Example in India>
India, resistors have not been provided in disconnecting switches in AIS up to 765 kV level. For 1200 kV AIS substation also, resistors have not been planned with disconnecting switches.

AIS Disconnector Surge

Switching surges have to be thoroughly assessed as they are among the most critical of design considerations on EHV Systems. Whether for AIS or GIS technology, the practice of applying resistors to EHV circuit breakers to control surge severity has been for many years a current practice.

However, despite the developments undertaken in the 70's and 80's, this practice has not been extended to equip air-type disconnect switches with resistors. In this period, it had been claimed that the key to the application of surge suppressing resistors to AIS-type switches was the improvement of the thermal capability and increased resistance to rupture during operation. The idea was to allow DS for applications of interrupting bus-charging and transformer magnetizing current in lieu of more costly devices (circuit breakers).

The WG could identify one case of implementation of DS equipped with resistor, developed by the BPA in the 70's and 80's [[46], [47]]. This application had been tested on a 500 kV, 900 MVA Transformer bank, the field tests depicted were shown in Table. 39:

Table. 39 Field Test of AIS DS with/without resistor

Switch Operation		close	open	close	Open
Surge resistors		yes	yes	no	no
Max. inrush current (A peak)		376	-	2050	-
Maximum Voltage (pu) on winding:					
	High Voltage	1.25	1.4	1.8	1.95
	Medium Voltage	1.25	1.35	1.7	1.9
	Tertiary	1.5	1.4	2.1	1.9

Besides this case, no application of development of Air-insulated DS equipped with resistor has been further reported for 765 kV applications, and it is doubtful whether this facility should be considered for Air Insulated DS at 1100 kV:

- The characteristics of the switching surges are different from the GIS application cases for EHV, the domain of frequency of the AIS applications being lower than for GIS case
- The advance of modern technology and insulation coordination methods allow for the recommendations of suitable MOSA and relevant sequence of operation to mitigate the risks at EHV.
- The seismic withstand capability of a DS equipped with resistor can appear to be a serious issue

In conclusion, and as a general recommendation, the true nature of capacitive current switching should be properly addressed, and, as per the guidance of the [[48]], it is advisable to bring this analysis to the true assessment of the ratio of the capacitances of the source side to the load side respectively (ratio C_S/C_L).

2.4.5 Instrument transformer

Instrument transformers like as voltage transformers and current transformers are the components of GIS. For the UHV class, with high voltage, instrument transformers may affect an optimum deign of GIS, if simple extension of the conventional design is applied. Introduction of new technologies may be required.

(1) Voltage Transformer

Gas insulated voltage transformers (winding type) and amplified potential dividers are widely applied for GIS. For the technical issues raised on the UHV application, the size of GIS will become large as well as equipment itself, for the former, and measures to protect secondary equipment against the high frequency induced surge from the high voltage system, for the latter.
To solve these issues, the optical voltage transformer is introduced for the Japanese UHV project. Voltage is divided by the capacitance elements, and voltage signal is converted to the optical signal with the optical sensor.

(2) Current Transformer

In case of the UHV transmission system, since the time constant of attenuation of DC component of the fault current will become longer, possibility of occurrence of the magnetic saturation phenomena becomes higher for the iron-core bushing-type current transformer (BCT). To solve this issue, Non-iron-core BCT is introduced for the Japanese UHV project

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3 CONSIDERATION FOR UHV SUBSTATION LAYOUT

3.1 General

The bus system was selected based on space requirements, reliability, cost, safety, security and so on.. The layout of UHV gas insulated switchgear (GIS) depends on the bus system. Both one and a half circuit breaker bus system (1+1/2 bus system) and a double bus system were selected in Chinese pilot project and Japanese project so far. And India is now planning UHV substation by one-and-half circuit breaker bus scheme (1+1/2 bus system)

Each UHV GIS, H-GIS, AIS layout should be optimized from the viewpoint of insulation coordination, land reduction, and special requirements of UHV substations. So This chapter describes the UHV bus scheme, UHV substation layout, and consideration for erection, maintenance, reliability of UHV facilities.

- To investigate suitable layout for UHV substation, various considerations are required such as adequate selection of bus scheme, basic configuration of switching equipment (F-GIS, H-GIS, AIS), erection, maintenance and reliability.
- For bus scheme, adequate configuration should be selected from either "double bus bar + 4 bus-tie system" or one-and-a-half circuit breaker system (1 + 1/2 bus system) that are commonly applied for 550 kV system.
- For erection, maintenance and reliability of UHV facilities, such factors as ease of installation or dismantling of components, maintenance space, and seismic performance should be considered because of the large size and weight of UHV equipment.

For basic configuration of equipment (F-GIS, H-GIS, AIS), adequate configuration should be applied considering advantages and disadvantages of each configuration from the viewpoint of reliability, operation, maintenance and economy.

3.2 Bus system for UHV S/S

The important factors for selection of bus switching scheme are as follows:

- System reliability
- Operational flexibility
- Ease of maintenance
- Limitation of short circuit
- Simplicity of protection arrangements
- Ease of extensions
- Availability of land
- Cost

For UHV substations, reliable switching scheme is very important. Both double bus with double breaker and Breaker and half are typically reliable ones. Suitable layout should be considered from a lot of aspects and to satisfy each utility's criteria. UHV bus scheme depends on each utility mainly based on his operation experience of EHV operation .However, considering cost aspect, as Breaker and half involve lesser number of equipments specially CB. Breaker and half scheme can be considered for UHV AIS substation. However depending upon lesser number of lines & transformer requirement, initially double bus with double breaker scheme can be considered which can be subsequently converted to Breaker and half scheme.

3.2.1 Selection of Bus system

Reliability is the most important criteria in addition to other aspect of maintainability, flexibility in operation, extension & security in UHV substation. Due to requirement of handling of bulk power, one and half breaker system, double busbar system are recommended for UHV substations. These schemes can be selected based on the requirement of numbers of feeders in substation and the experience of each utility. Each utility should select appropriate bus scheme from the reliability, maintainability, flexibility, ease of operation, ease of extension and security.

Fig. 71shows one and half breaker system one line diagram and Fig. 72 shows double busbar system one line diagram. One and half breaker system is very common all over the world.

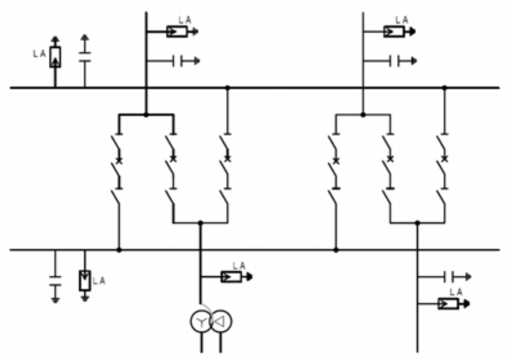


Fig. 71 One and half breaker system

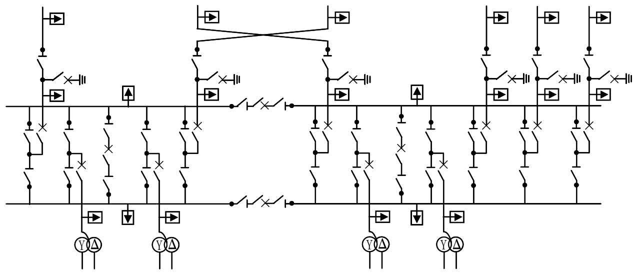


Fig. 72 Double bus bar system

3.3 Basic MOSA Arrangement of UHV substations

AIS, Full GIS and Hybrid-GIS adopt different arrangement of arresters due to different bus-scheme and facilities, the arrangement of arresters can be decided through the calculation for lighting and internal overvoltage analysis using EMTP; meanwhile, the requirements for reliability and economy to substations have been fully considered during the calculation.

There are two type line side layouts. One is the case to adopt HSGS with the arrester; the other is to adopt 4 legged-reactors with arrester in the UHV substation. Basic MOSA arrangement could be recommended as follows.

Full GIS

High performance MOSA should be arranged in Line, Bank Main bus bar.

Hybrid GIS

High performance MOSA should be arranged in Line, Bank. MOSA for Main bus bar isn’t necessarily required to reduce the lightning surge. This is user’s option to arrange or not. But it is better to apply MOSA for Main bus.

AIS

High performance MOSA should be arranged in Line, Bank.

3.3.1 UHV substation with Double busbar 4bus-tie system

Layout of arresters for double busbar connections in UHV substation is shown in Fig. 73. The duplicate-bus duplicate-segmentation connection has been used for main electrical connection in substations. The typical arrester arrangement is 2 arresters at the entrance of each line, 1 arrester is installed near transformer in each bank circuit; 2 arresters are installed at two ends of each bus segmentation.

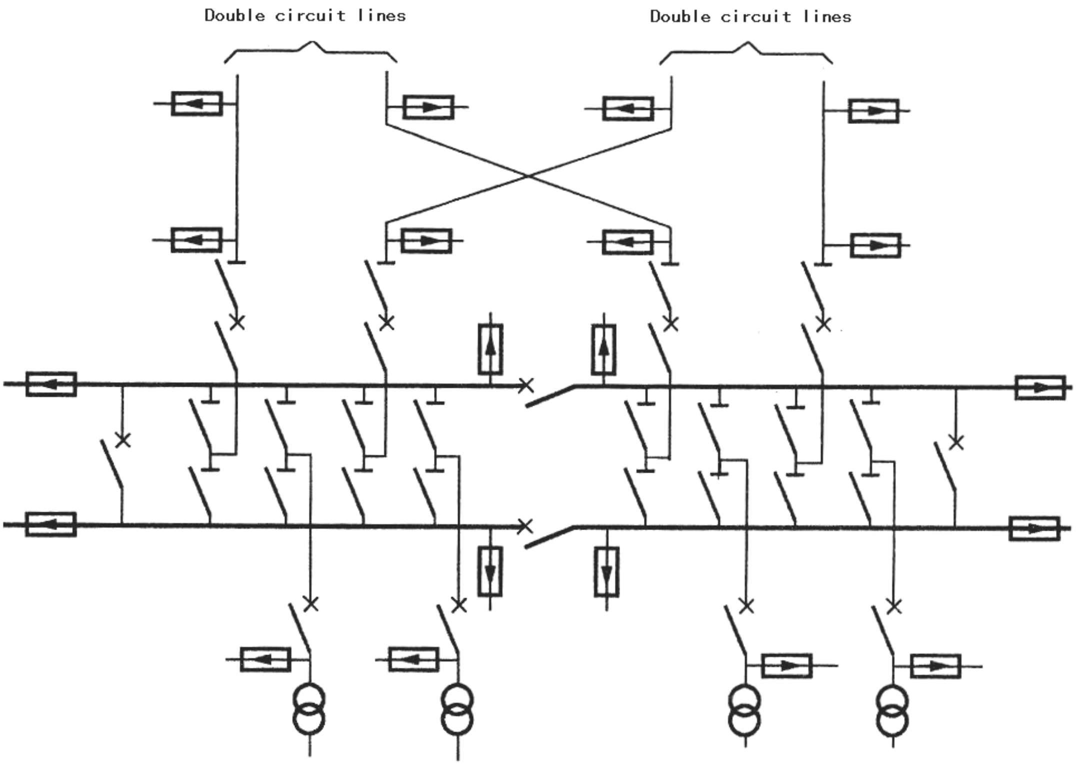


Fig. 73 Layout for arresters in UHV substation with double-bus and duplicate-segmentation connection

The protection for the lightning surge at UHV substation shown in Fig. 73 has been investigated by EMTP in Japan. The characteristic of arresters can be seen in Table 40.

To invading lightning surge at UHV substation, only near region of lighting has been considered in Japan. First tower of lighting substation has been used for calculation, the amplitude of the lighting currents is 200kA (150kA for 500kV substation), and light current waveform is 1/70μs. The safety margin for aging of equipment insulation hasn't been considered according to principle of insulation coordination in Japan. Maximum lightning overvoltage appeared on the GIS, high voltage shunt reactor and transformer in substations under conditions of different operation and connections could be seen in Table 42.

Maximum lightning overvoltage on the GIS is same as the one on high voltage shunt reactors. The values of numerator and denominator are, respectively, corresponding to values for with or without considering condition of the lightning avant-courier discharge during calculations. Later value is higher 10 percent than the former one. Maximum lighting overvoltage appeared on transformers is same for both cases. The performance of C character arresters is surpassed than B character arresters, which can be referred to Table 40 and is consistent with calculated results in Table 42.

Table 40 MOSA characteristic for study

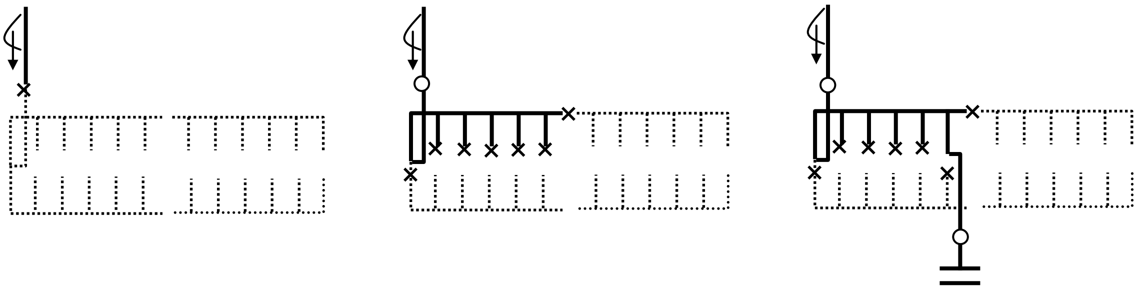
MOSA	Rated voltage (kV)	Residual voltage (kV) corresponding to below currents (A)		
		1000	2000	20000
B	826	1510	1550	1840
C	826	1370	1410	1650

Table 41 Maximum lighting overvoltage (kV) appeared at electrical equipments in substation

MOSA characteristic	B	C
GIS, High voltage shunt reactor	2280/2570	2090/2360
Transformer	2060	1860

3.3.1.1 Lightning surge analysis for determination of the standard surge arresters installation

LIWV (Lightning Impulse Withstand Voltage) of substation equipment and the arrangement of surge arresters were determined through a series of lightning surge analyses by varying system condition. Fig. 74 shows the three types of severe operating condition for the lightning surge analysis, which generate high overvoltages at the substation equipment. In the analysis, the 200kA, 1/70µs ramp wave-formed lightning strike current was applied as a back flashover at a tower adjacent to a substation.



I: 1 Line　　II: 1 Line+ 1/4 Bus　　III: 1 Line+1/4 Bus+1 Bank

Fig. 74 Substation circuits for lightning surge analysis

Table 42 Relationship between LIWV and Cost [1]

		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
No. of surge arresters	Line entrance	1	1	1	2	2	2
	Bus	0	1	2	0	1	2
	Transformer	1	1	1	1	1	1
Trans-former	Required withstand voltage (kV)	1950	1943	1895	1943	1938	1896
	LIWV(kV)	1950	1950	1950	1950	1950	1950
GIS	Required withstand voltage (kV)	2898	2854	2703	2628	2506	2208
	LIWV(kV)	2900	2900	2900	2700	2550	2250
Cost (100 for case 6)		102	105	109	103	103	100

*Notes: In the case of 6, it seems that it's necessary to carry out further study concerning safety factor. C4.306 will investigate this issue.

Analysis results are shown in Table 42. Overvoltage value is the lowest in case 6. Consequently, considering other factors, the LIWV of 1,950kV for transformer and 2,250kV for GIS were determined.
In analysis of Case 6, we need 7 surge arresters, two sets of which are at line entrance, one set at transformer end, and other two sets at bus. By ignoring the case of system configuration II, which is just temporary, we can omit two sets of surge arresters at bus. In Japanese practice however, Tepco decided to install one surge arrester to ensure system reliability considering the lightning strike current which exceeds 200kA, and so on.
Fig. 73 shows the standard arrangement of 1,100kV surge arresters in TEPCO UHV substation.
Fig. 75 shows the cumulative number of high performance surge arrester in Japanese fields. Already about 1400 high performance surge arresters (both porcelain and tank type arresters) have already been installed and proven their high reliability.

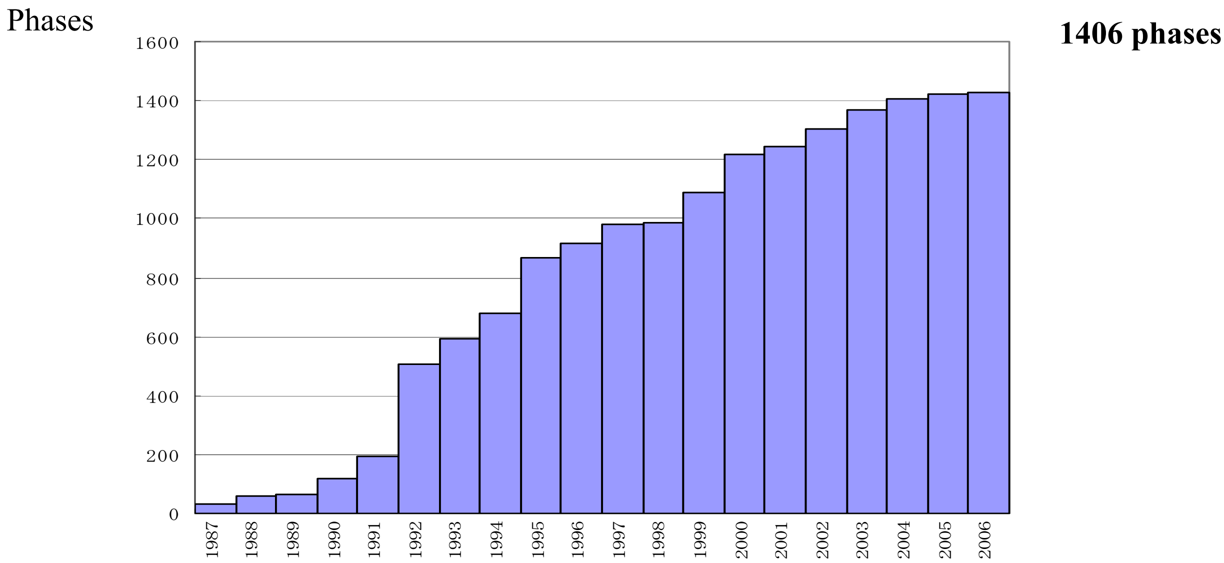


Fig. 75 The cumulative number of high performance surge arrester in Japanese fields

3.3.2 UHV Substation with double breaker system (Transition to one and half circuit breaker)

For a GIS substation appeared in the south-eastern of Shanxi province in China first UHV project, double circuit breakers and single bus scheme have been chosen in earlier projection, the layout for arresters can be seen in Fig. 76[5]. The arresters are arranged as: an arrester is installed at gate of circuit line; an arrester is installed on main transformer; an arrester is installed at bus end. The arresters at the gate of circuit line and side of main transformer are porcelain-housed surge arrester, and the arrester at bus end is tank type metal-oxide surge arrester.

Protection for equipments in UHV substation against lighting overvoltage has been studied in CEPRI by using EMTP, which can be seen in Fig. 76[2]. The characteristic of arresters chosen for calculation can be seen in Table 40. Only nearby lighting strikes associated incoming lines of the substation have been considered. Protection scheme has been decided according to withstand level of switchyard (substation year, lighting overvoltage malfunction number of times reciprocal).

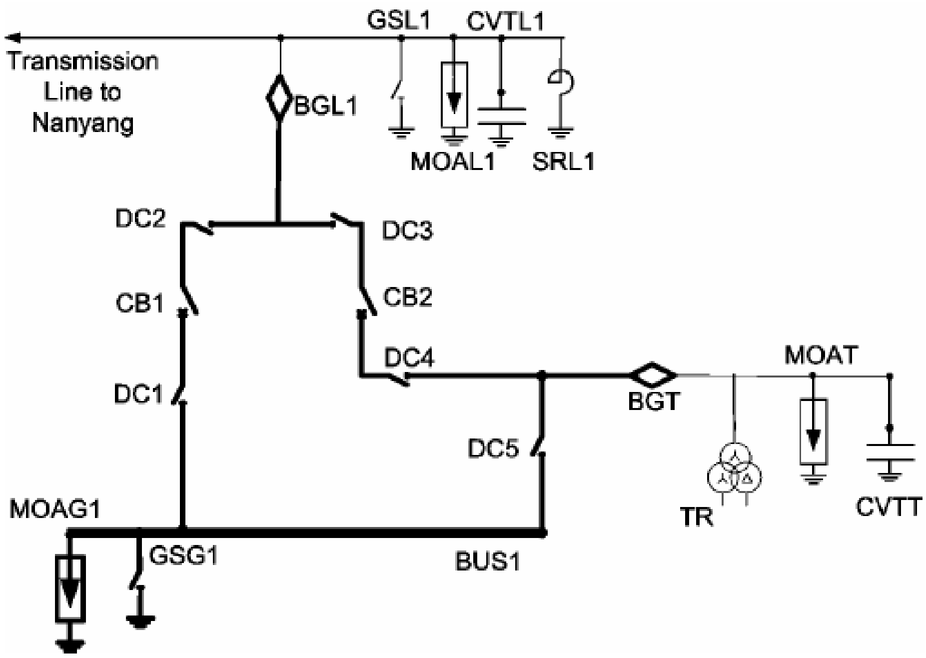


Fig. 76 Electric equipments arrangement of Jindongnan GIS system

3.3.3 UHV Substation with one and half circuit breaker system

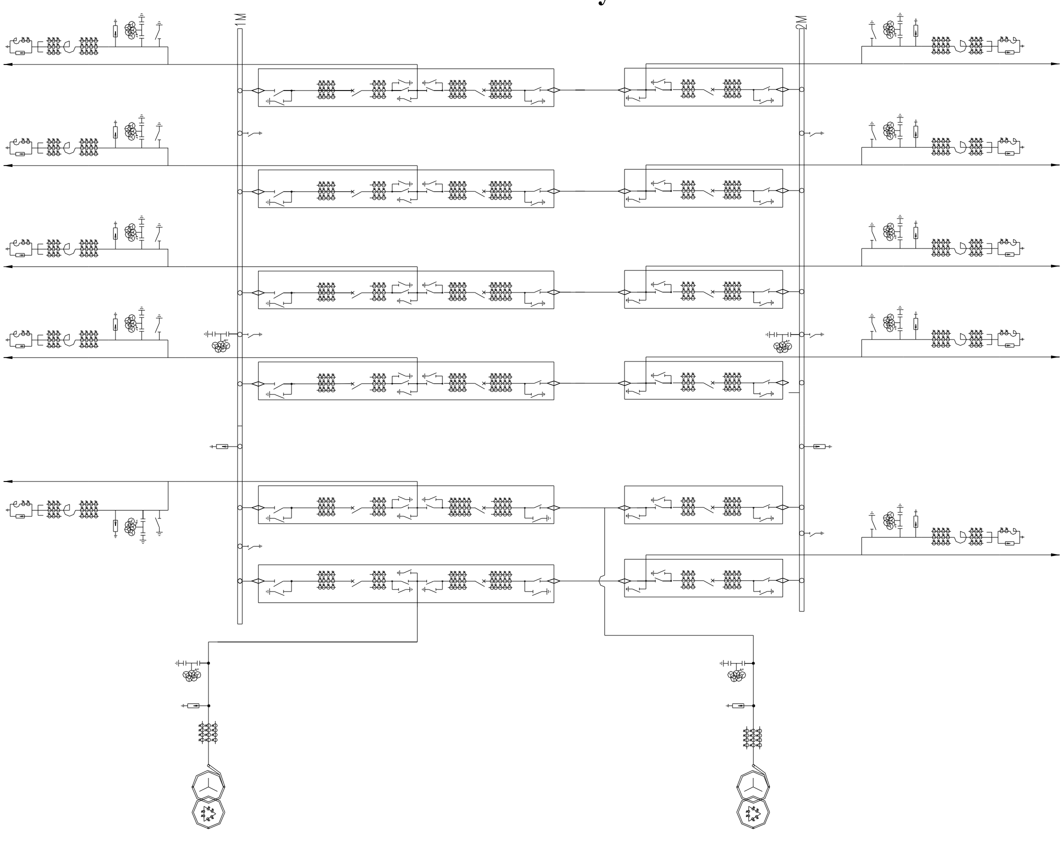


Fig. 77 Arrangement of arresters in Hybrid-GIS substation with one and half circuit breaker system in Chinese future UHV project

For a specified future of China UHV project, one and half circuit breaker system will be used for bus system in substation, arrangement of arresters in Hybrid-GIS substation can be seen in Fig. 77. The arresters have been installed in the entrance of each line feeder, which can be also used to protect shunt reactor; an arrester has been installed on each main transformer; arresters are also installed on the main bus bar.

3.4 Basic layout of UHV GIS, H-GIS, and AIS

3.4.1 Double-bus system

The diagram of double bus 4 bus-tie system and layout of GIS are shown in Fig. 78.and Fig. 79 respectively.

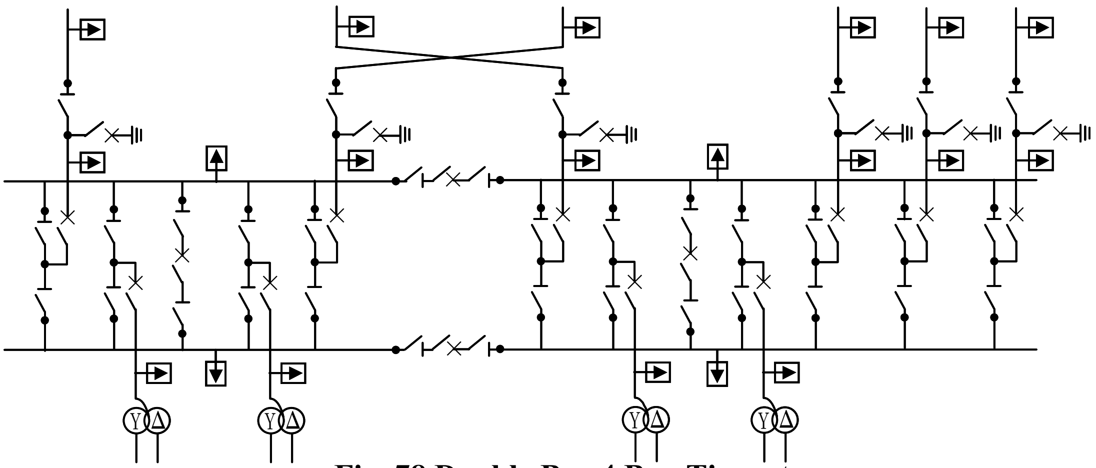


Fig. 78 Double Bus 4 Bus-Tie system

The general feature of double bus 4 bus-tie bus system is shown in Table 43.

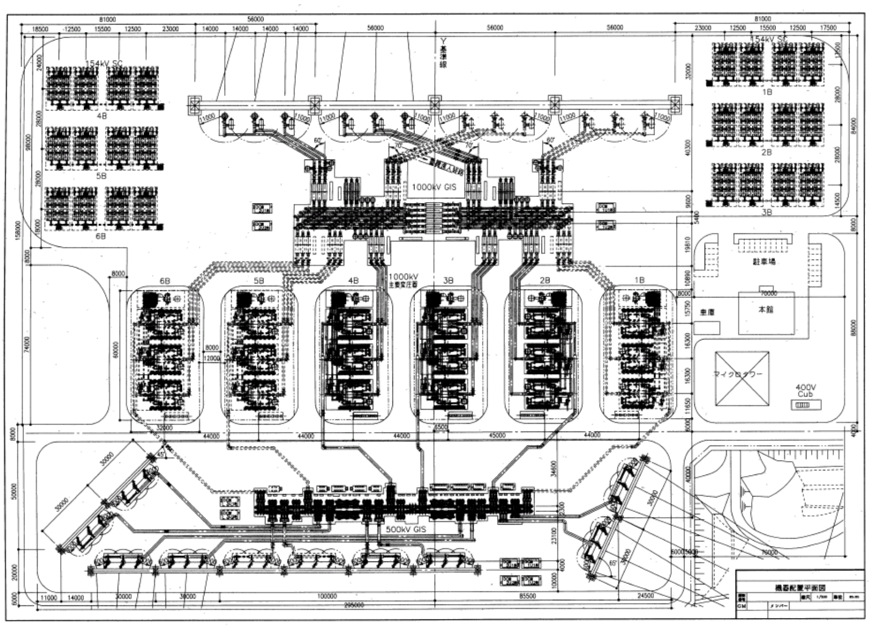
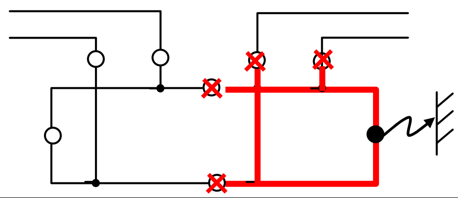


Fig. 79 Example of arrangement of 1100kVGIS/Transformer

Table 43 The general feature of double bus 4 bus-tie bus system

Advantage	➢ This system has an operational flexibility, because transmission line connection scheme at the entrance of a substation and allocation of transmission line connection scheme are relatively selected (e.g. transmission lines and banks can be connected to each side of main bus) ➢ In the case that many transmission lines are connected, it is economical because the number of circuit breakers per one line becomes small. ➢ As the DC power supply circuit of each line and bank are separated, the circuit design is relatively simple. ➢ Only associated busbar should be de-energized in case of expansion of main circuit (bay) ➢ TEPCO has much experience at 500kV substations. ➢ 18 out of 27 500kV substations and switch stations have already adopted this bus system.
Disadvantage	➢ Any single fault occurs on a busbar or circuit breaker interruption is failed when transmission line fault occurs, a quarter or half portion of the entire busbars get to outage. And transmission lines and transformer, which are connected to outage busbars, get outage too. 

*The consideration about a single transmission route with double circuits

In order to secure supply reliability, it is essential that any single fault doesn't cause route interruption in the 1,100kV system. Accordingly, the following transmission line connection schemes at the entrance of a substation are adopted taking account of the flexibility of GIS layout designs.

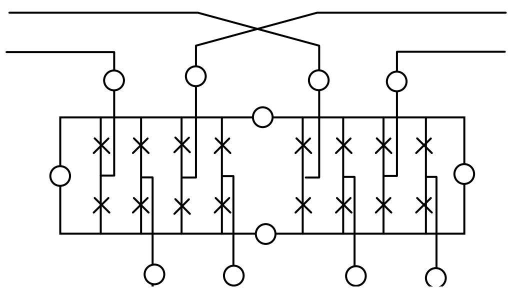


Fig. 80 Bus system for 1,100kV substations (Double Bus 4 Bus-Tie)

*The reliability of 1100kV transmission system

The reliability of double bus 4 bus-tie system is evaluated. The result shows that the rate of failure in this system is very low and the reliability is quite high.

- ➢ Average number of lines/banks outage by single fault: 0.114 time/year or line/bank (once in 9 years)
- ➢ Probability of 1100kV route interruption:6.74×10-4/year (once in about 1,500years)

3.4.2 The arrangement of HSGS

HSGS is arranged between circuit breaker and disconnector to the transmission line-side by the following reasons

- The operation of HSGS to interrupt fault current is linked to that of GCB, thus, it is desirable to install HSGS next to GCB
- The maintenance interval of HSGS is almost same as that of GCB
- If HSGS is connected to bus, the length of bus become shortest, and the construction cost becomes low, too.

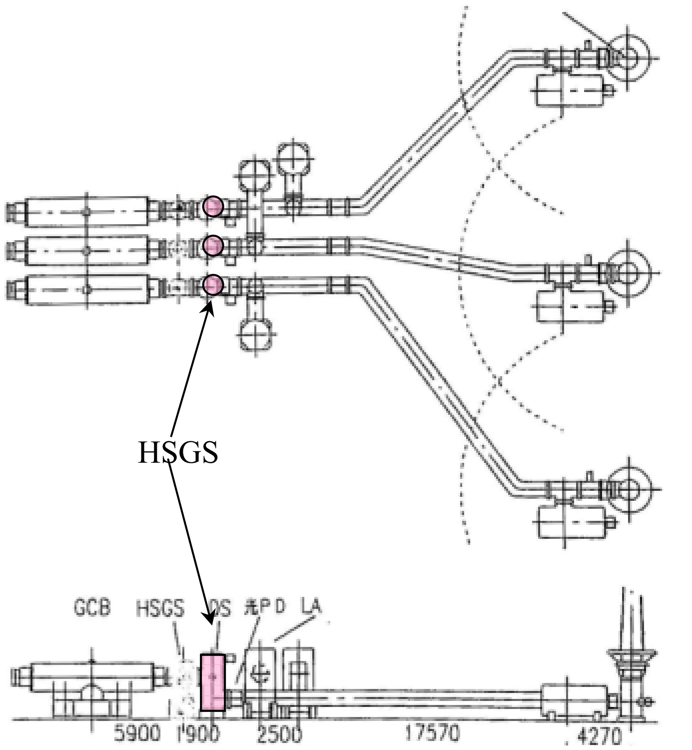


Fig. 81 HSGS arrangement of 1100kV substation

3.4.3 UHV substation with one and half circuit-breaker system

There are substations of 1 GIS, 1 HGIS and 1 switching HGIS in the pilot UHV project of China, in initial operation stage, two breaker arrangement of bus scheme is adopted. Initial stage the number of apparatus is not so many. One and half CB system will be used at the end of the project. Fig. 82 shows one line diagram. Fig. 83 and Fig. 84 shows the layout and sectional view of GIS with one and half CB system (initial two breaker system arrangement), respectively.

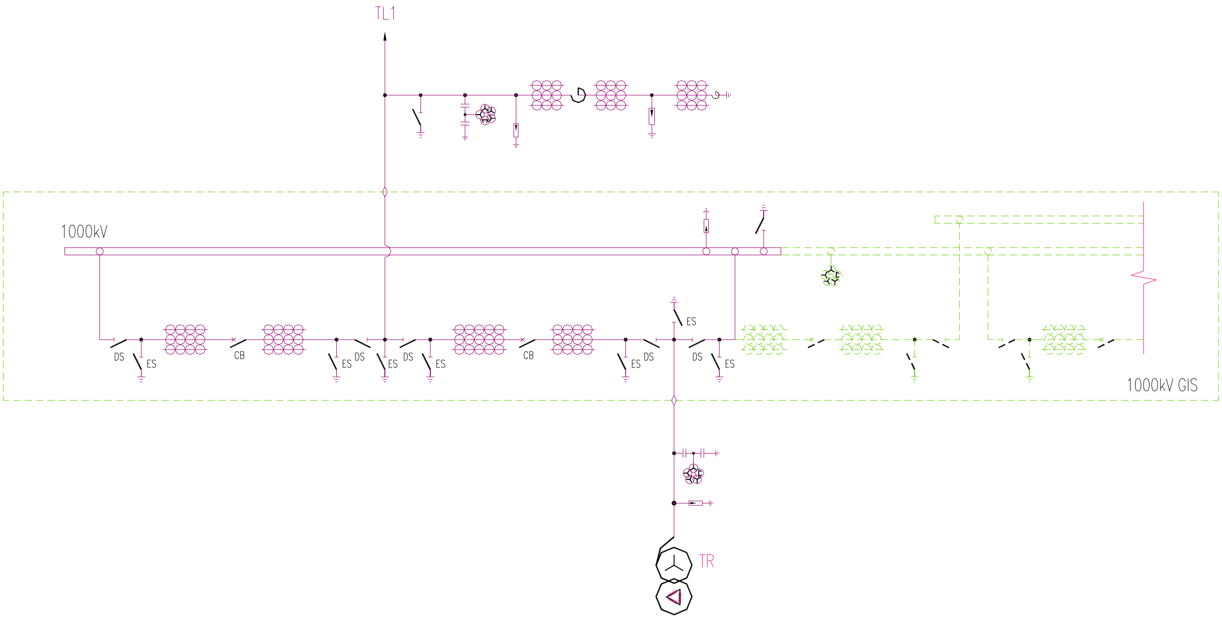


Fig. 82 General layout of a GIS with two breaker arrangement
-Transition of one and half CB system -

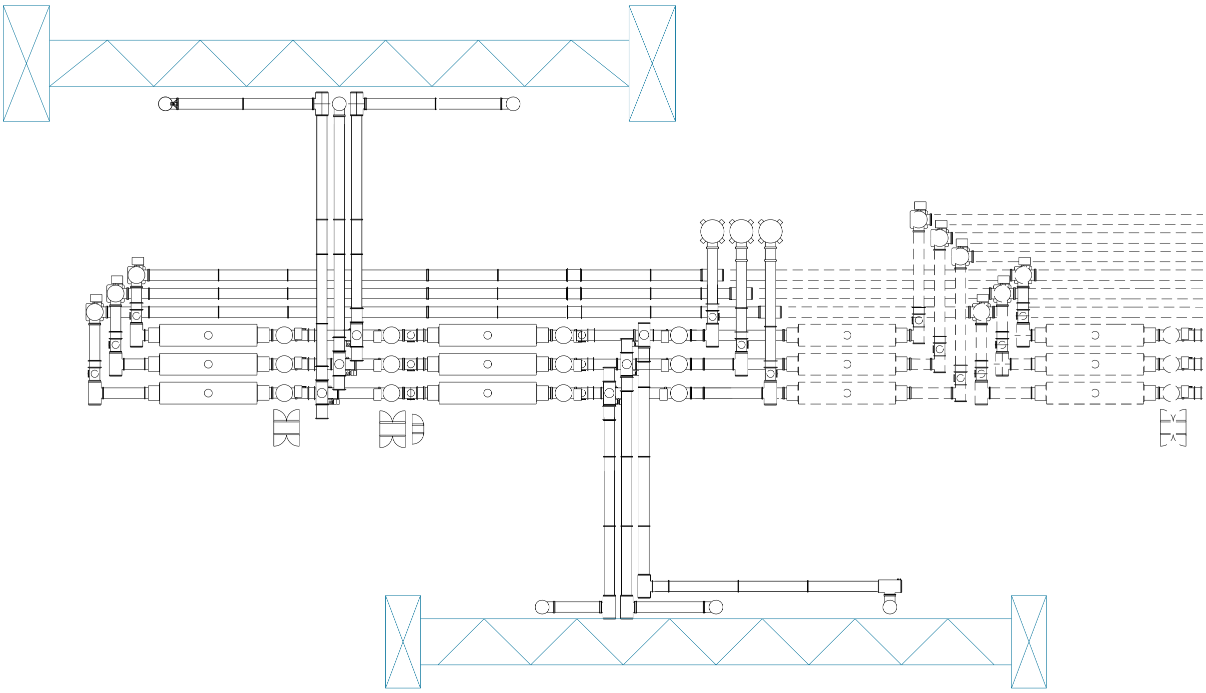


Fig. 83 Layout of JinDongNan 1100 kV GIS with two-breaker arrangement
-Transition of one and half CB system -

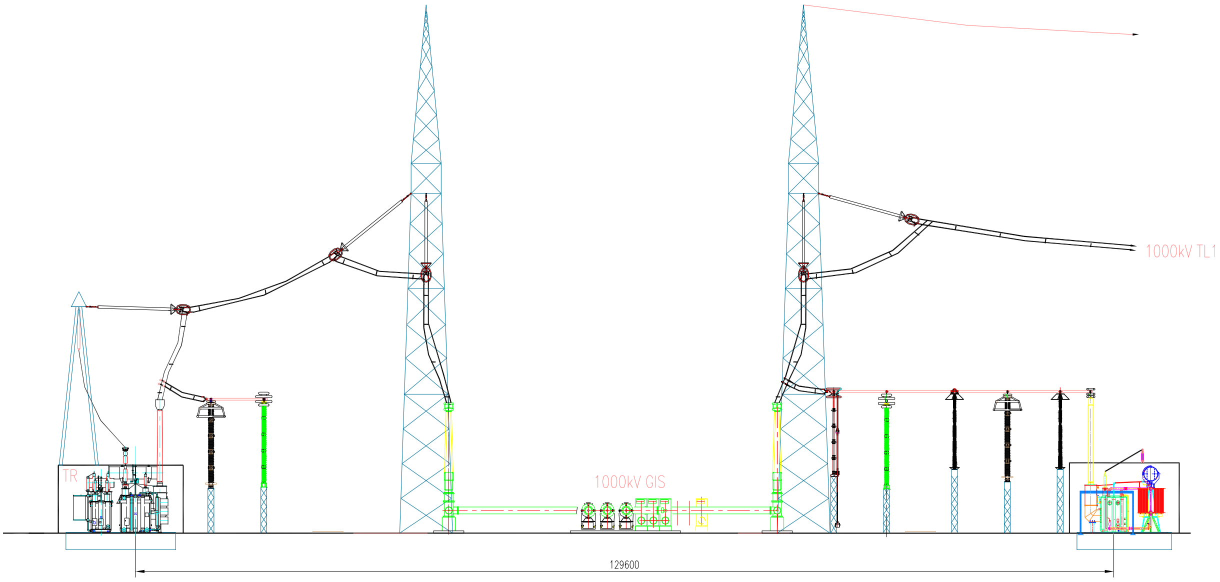


Fig. 84 Section view of UHV GIS (one and half CB system)

In one and half Circuit Breaker system, two transmission lines or transformer banks share three circuit breakers. The general features of one and half circuit breaker system is shown in Table 44.

Table 44 The general features of one and half circuit breaker system

Advantage	➢ Scheme is reliable as additional one (tie) breaker is available in addition to main breaker for each line/ transformer. For practical purpose each line / transformer is controlled by two circuit breakers. In case of any problem with one circuit breaker, the continuity of supply is maintained through second breaker without any interruption. ➢ In case of bus fault, continuity of supply is maintained in all lines/ transformers through second bus without any interruption. ➢ Expansion of substation is simple. With minimum shutdown, buses can be extended. ➢ In this scheme, there aren't any chances of complete shutdown of the substation. ➢ Even in case of stuck breaker condition (i.e when circuit breaker fails to open in fault condition), lesser numbers of lines (1-2) are affected. ➢ Operation of taking out breaker for maintenance / replacement is easy.
Disadvantage	➢ Scheme is slightly costlier due to involvement of additional tie circuit breakers for each line / transformer. ➢ For isolation of a line / transformer, operation of two breakers is required. However it does not create any complication.

In AIS, the buses / connections are exposed to environment compared to GIS. Breaker and half is very reliable system in case of AIS, as there are minimum outages of lines / transformers in case of bus faults.

The one-line diagram, sectional view, and layout of UHV one and half CB system are shown in Fig. 85 and Fig. 86 respectively. Fig. 87 shows the 4legged reactor layout and connection.

< Example in India>

In AIS, the buses are exposed to environment compared to GIS. In case of AIS, one and half breaker scheme is comparatively better as any failure / fault in the main bus would not affect any outages in the lines or transformers as automatically all these lines or transformers are shifted to another bus. The main advantage of this system is that in case of stuck breaker condition (i.e breaker fails to open in fault condition), lesser lines or transformers are affected compare to similar condition in double bus system.

In India one and half breaker scheme has been used in 765 kV AIS substation. The single line diagram, Layout and section of 765 kV AIS Seoni substation is shown in Fig. 88 and Fig. 90 respectively.

Fig 89 shows the typical 1200 kV single line diagram of One and a half breaker scheme. Fig 91 shows preliminary 1200 kV AIS substation layout plan and section arrangement with live tank arrangement for one and a half breaker scheme.
Arrangement: 3 Overhead-line circuits, 2 Power Transformers, 1 Shunt Reactor. Overall dimensions of the Switchyard: 780 m x 285 m (fence perimeter)

Three levels of connections (average height above ground level):

- 18 m (apparatus connector) –
- 35 m (Busbar) –
- 50 m (Incoming / Outgoing feeders)

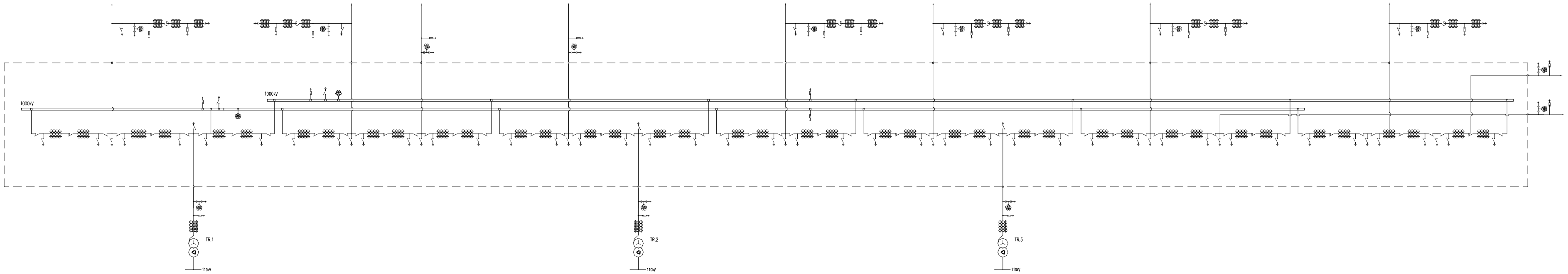


Fig. 85 One-line diagram of JinDongNan UHV Substation (One and half CB System)

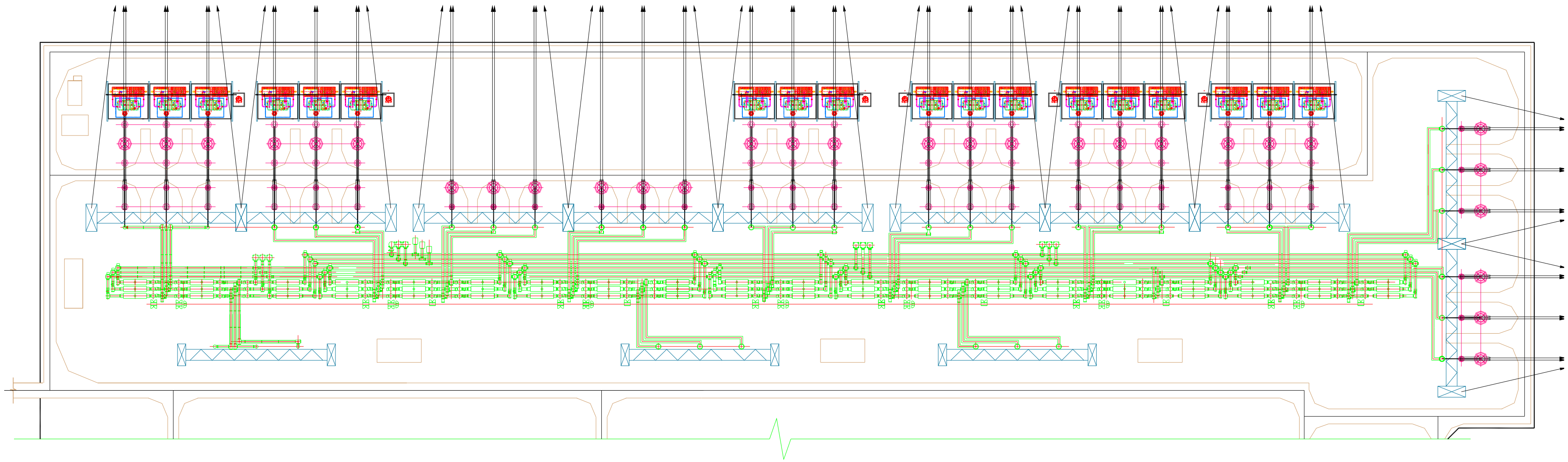


Fig. 86 Layout of JinDongNan UHV Substation (One and half CB System)

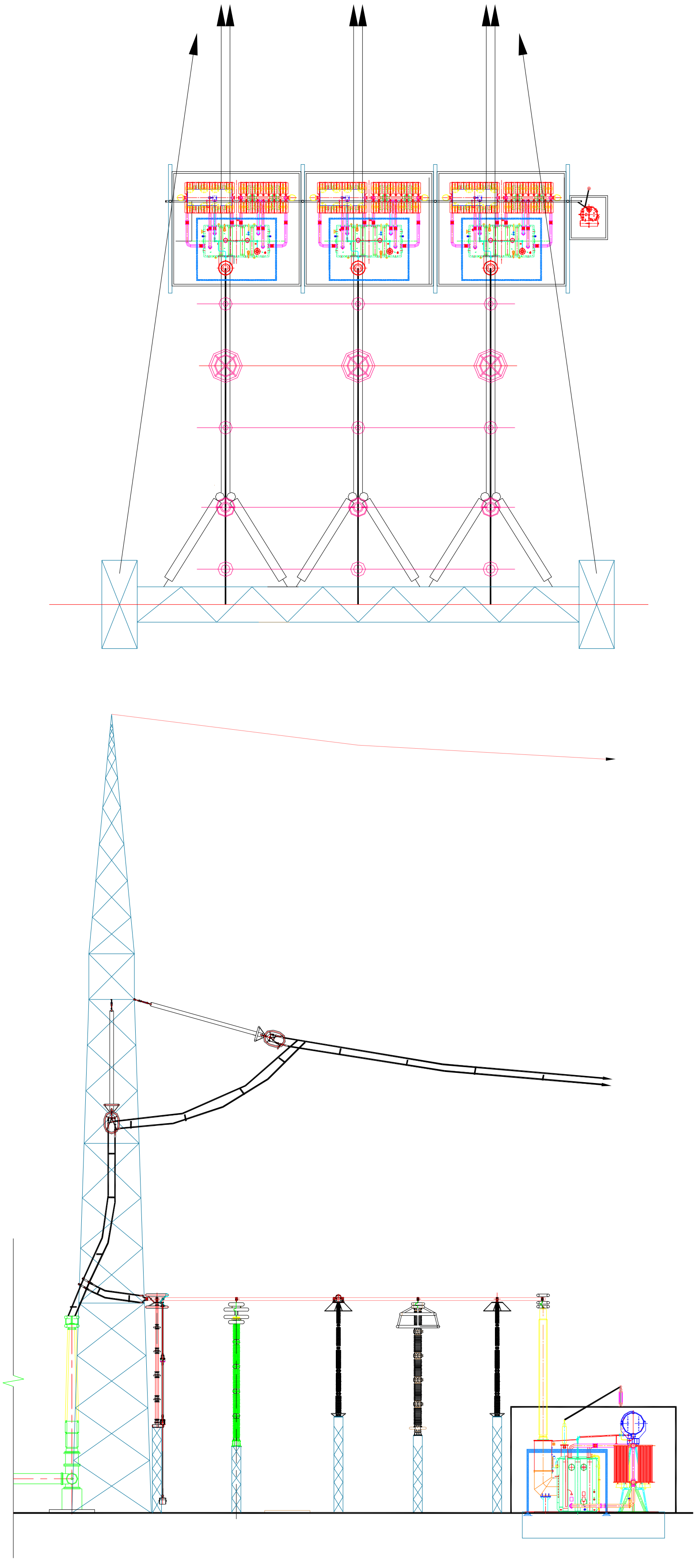


Fig. 87 Layout of 4 legged reactors in China UHV Substation

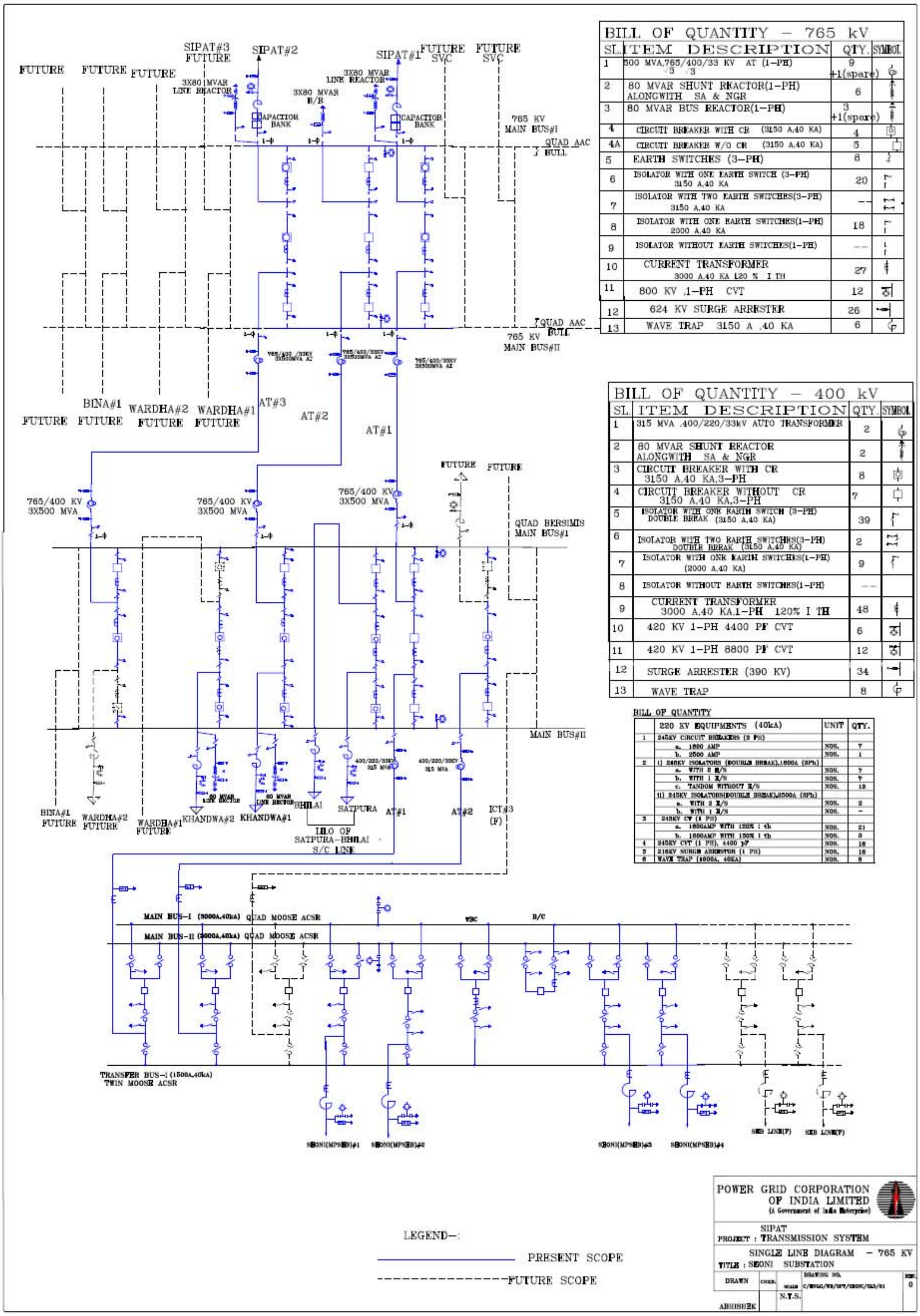


Fig. 88 The single line diagram of 765 kV AIS Seoni substation in India

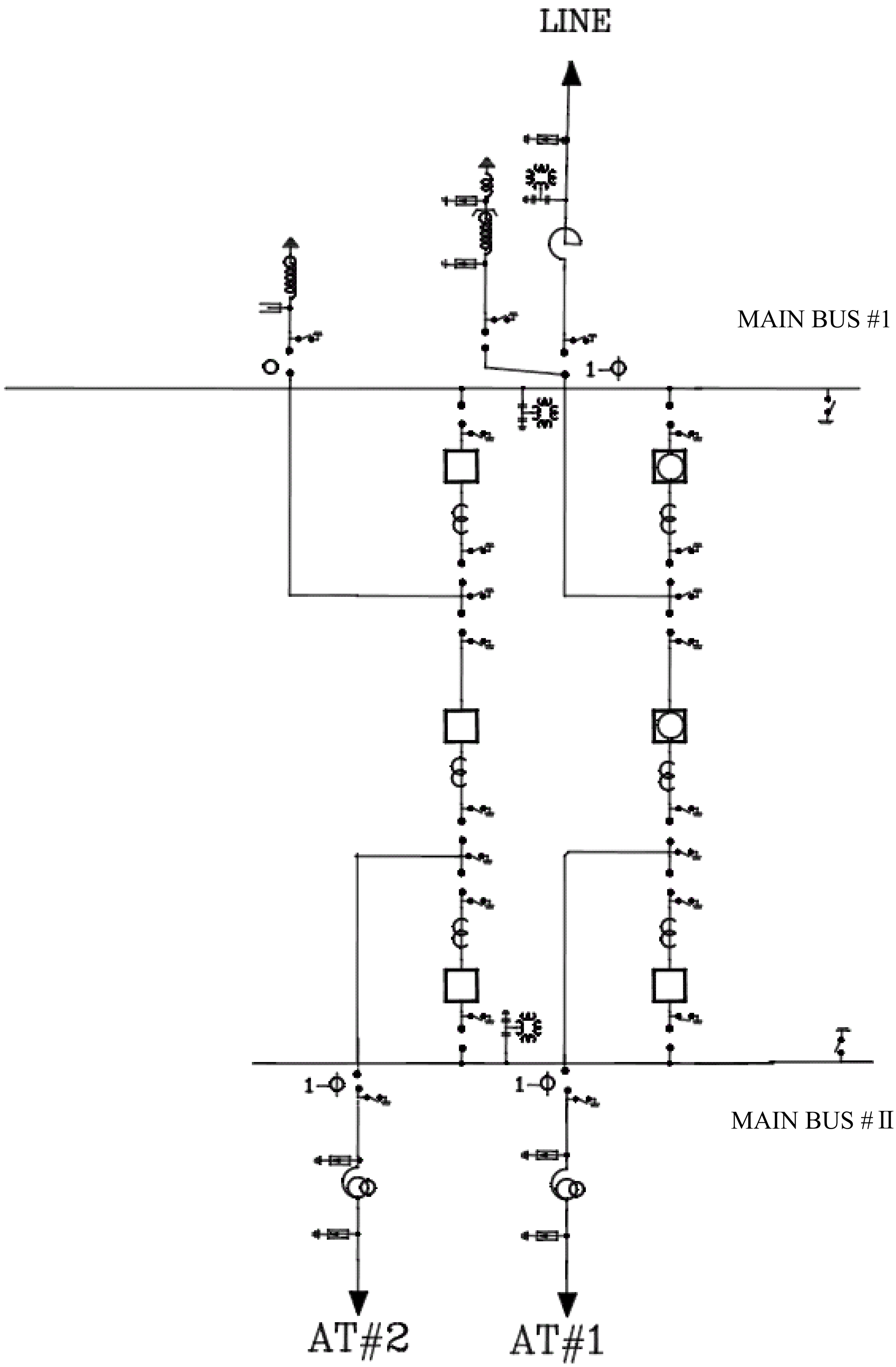
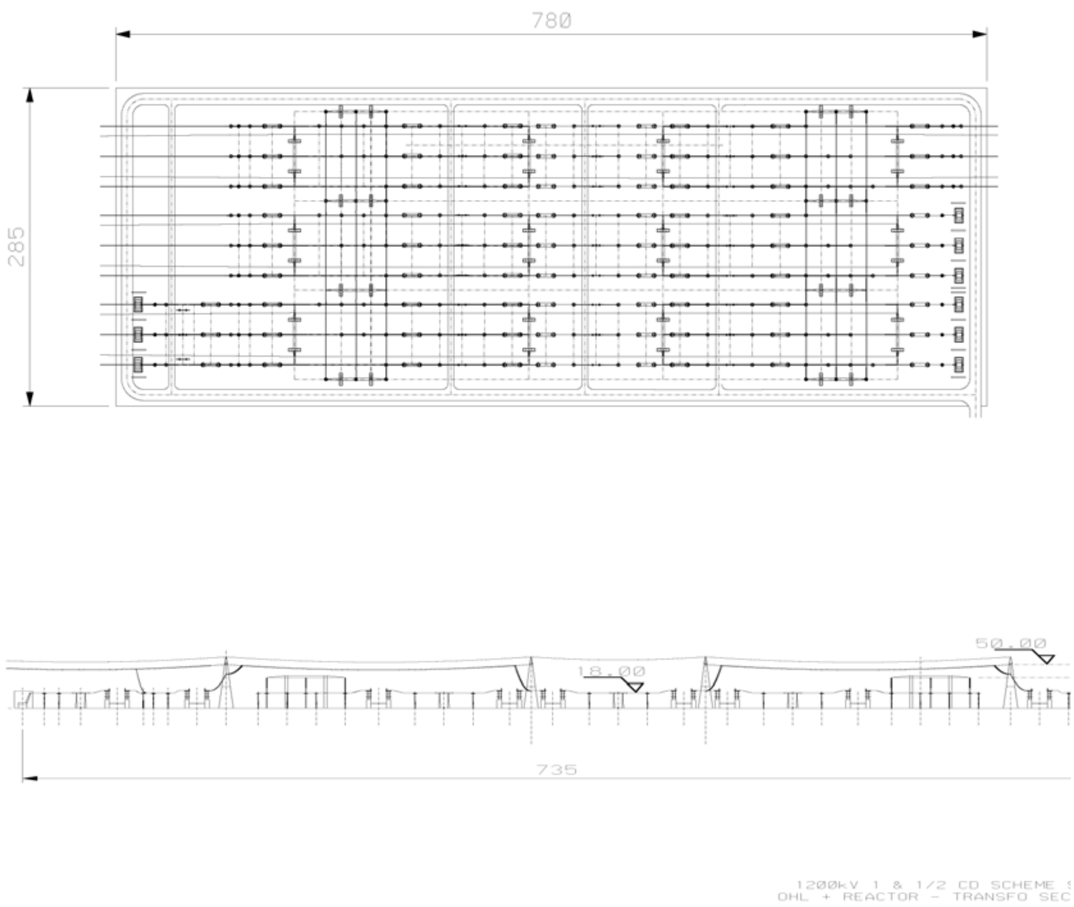


Fig. 89 1200kV Typical Single line diagram in India (Powergrid)

Fig. 90 The Layout and section of 765 kV AIS Seoni substation in India



- General layout 1200 kV AIS Live-Tank Circuit Breaker – One and half CB Scheme -

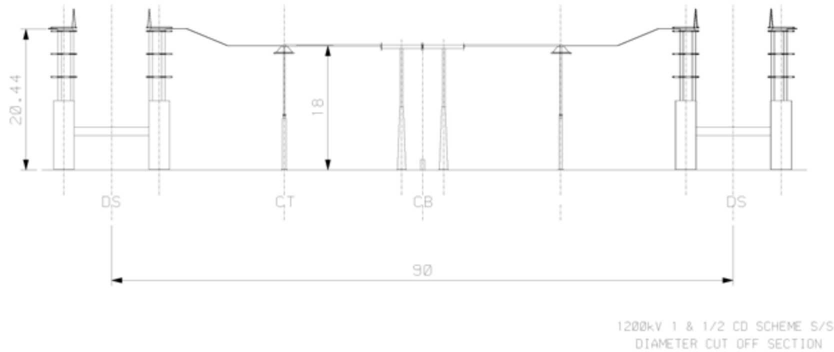


Fig. 91 The Layout and section of 1200 kV AIS model substation in India (single line diagram is based on Fig.90)

Table 45 Miscellaneous information (information for guidance only)

<table>
<tr><td colspan="3" rowspan="3">Description</td><td>1200KV</td></tr>
<tr><td>AIS Live Tank</td></tr>
<tr><td>1-1/2 Bus</td></tr>
<tr><td rowspan="8">Clearance</td><td colspan="2">1) Phase to ground (main bus)</td><td>31 m</td></tr>
<tr><td colspan="2">Phase to ground (branch bus)</td><td>18 m</td></tr>
<tr><td colspan="2">Conductors or rings</td><td><u>Branch bus</u>:
Tube dia 200 mm, th 10 mm

<u>Main bus:</u>
Bundle 8 cond. Pheasant (35.05 mm dia), outer dia 1100mm</td></tr>
<tr><td colspan="2">The height of the conductors</td><td><u>Branch bus</u>: 18- 20.5 m
<u>Main bus</u>: 31-35 m
<u>Feeders</u>: 46-50 m</td></tr>
<tr><td colspan="2">2) Phase to phase (main bus)</td><td>27 m</td></tr>
<tr><td colspan="2">Phase to phase (branch bus)</td><td>27 m</td></tr>
<tr><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">3) Bay pitch</td><td>80 m</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td rowspan="6">Layout</td><td>1) The length between Main bus</td><td>Bus A</td><td>113 m +/- 27 m
<u>for cut-off section (+120 m)</u> :
233 m +/- 27 m</td></tr>
<tr><td></td><td>Bus B</td><td></td></tr>
<tr><td>2) The capacitance from Main b</td><td>Bus A</td><td>3400 pF +/- 800 pF
<u>for cut-off section (+120 m)</u> :
6500 pF +/- 700 pF</td></tr>
<tr><td colspan="2">3) The length from CB terminal to OHL</td><td>100 m approx.</td></tr>
<tr><td colspan="2">4) The height from CB terminal to OHL</td><td>28 m</td></tr>
<tr><td colspan="2">5) The pitch between main buses (A-B</td><td>430 m</td></tr>
</table>

3.5 Consideration for erection, maintenance, reliability of UHV facilities

3.5.1 Construction period of UHV substation

<Chinese case>

In the case of 1st project of SGCC (=State Grid Company of China), the substation design started exactly from March 2006 after more than two years feasibility study. And Commissioning test started from Dec. 2008. The design, construction, manufacture are multithreaded, so the construction period can be reduced dramatically.

<Japanese case>

TEPCO developed a eight-year construction template starting from initial substation design to the completion a GIS substation that is equipped with four feeder bays, four transformers, and double bus bar and four bus-ties.

- Since this plan is for the first 1,100kV substation in TEPCO, each construction stage is designed to have sufficient work-delay allowance, which could be shortened if TEPCO acquired sufficient experiences by implementing similar constructions.
- Since 1,100kV equipment is huge and takes long time to be manufactured, it is necessary for construction planners to consider production time of the equipment, which are largely affected by the production capacity of manufacturers, and the duration of equipment transportation and installation. These production time and transportation time actually are dominant to the entire construction schedule, and the transportation schedule is affected by the natural constraints, such as snowing, icy road, and the increase of river water. Among substation equipment, transformer manufacturing should be started in one-year advance; besides manufacturing time of GIS does not affect the critical path of the entire construction schedule.

Table 46 UHV construction period

	1st yr	2nd yr	3rd yr	4th yr	5th yr	6th yr	7th yr	8th yr
Construction Period	**Detailed substation design**							
			Construction of equipment foundation (Civil)					
			Manufacturing transformer and GIS					
				Installation and test of transformers				
					Installation and test of GIS			
								Operation test

3.5.2 Quality control of erection work

Extra quality control methods should be adopted in addition to the conventional methods for 550kV substation, because 1,100kV substations are mostly located in mountainous areas, and employ huge and heavy machines.

1) GIS

The sites for 1,100kV substations are in mountainous areas and the weather condition of these sites is usually unstable. In addition to that, the installation takes longer time due to the increased number of docking parts. Thus, it is important to employ an enclosed docking scheme using an all-weather and dust-proof housing so that this erection procedure should be immune to weather disturbances, such as humidity, rain, and wind.

Example. All-weather & dust-proof housing for erection of 1,100kV test equipment.

Fig. 92 shows this housing for GIS erection work.

Dimension: length 8m x width 5m x height 5.5m (at maximum). Adjustable to the four dimensions that are designed for actual docking conditions
Erection weather condition: Rain: less than 5mm/hour,
Wind Less than equal 10m/sec,
Snow: Less than equal 5cm
Work condition provided: Humidity 80% or lower,
Dust: 20cpm or less,
Dew point: less than GIS's temperature

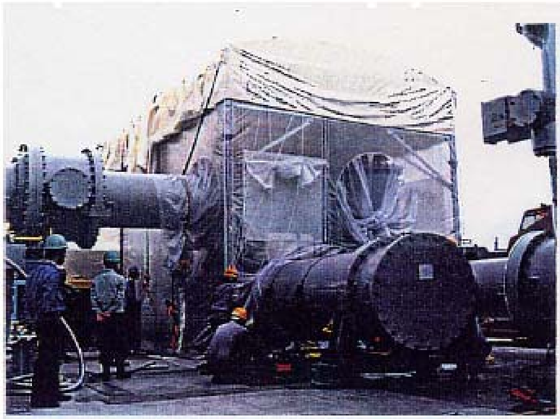


Fig. 92 all-weather dust-proof housing for GIS erection

GIS parts are mounted to its foundation, and connected to neighboring parts in the dust-proof housing by using sliding mechanism, chain blocks, and dollies.

2) Transformer

The 1,100kV transformers c manufacturers are split into two major components so that each component satisfies the Japanese stipulations for transformer's dimensions and weight in its transportation. Since the docking of the components requires very precise operation with an allowance of millimetre, proper docking method should be chosen by considering weather and construction conditions.

When the inner structure of transformer is exposed to atmosphere, extra care is necessary to minimize the moisture penetrating to the insulators (0.5wt% or less). The examples of the preventive method are monitoring of moisture exposing time of inner insulators, humidity monitoring of the transformer tank, and monitoring of vacuum pumping, such as vacuum level and pumping time. In addition to these preventive measures, double enclosures of transformer openings are effective in dust proof of the transformers.

3.5.3 Minimum approach distance from energized parts

The minimum approach distance from energized parts of 1,100kV circuit is set to be 11 meters, and all craning and construction work should be closely monitored to secure the working distance.

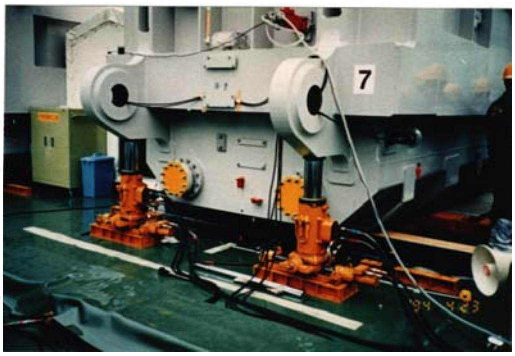
The minimum approach distance of 1,100kV circuit is determined by adding the crane's braking distance (2m) to the minimum insulation distance (8.9m) of the expected switching surge level (1.56p.u.).

3.5.4 The erection of UHV facilities

In the installation at the Japanese site, the two tanks and 1100kV lead duct combination requires high installation precision, so the installation was performed using a special slide device and a 2 way feed device, in a strict dust controlled environment.

Fig. 93 shows the installation process of the core type transformer. Unit 1, the 1100kV duct, and unit 2 are aligned on the base using the hydraulic slide device. 8 point jacks (Fig. 94) which allows fine movement in 3 axes directions are used to match the 2 tanks and the duct precisely.

Fig. 95 is the installation process for the shell type transformer. The two units are placed on the common base, and are positioned using a locator. After the transport cover of unit 1 is removed, the upper tank is installed, and then the duct and upper tank of unit 2 are installed.



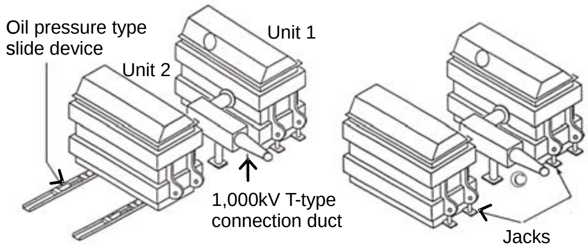


Fig. 93 Unit tank docking procedure for core-form UHV transformer

Fig. 94 Simultaneous operation for 3 axes using 8 jacks

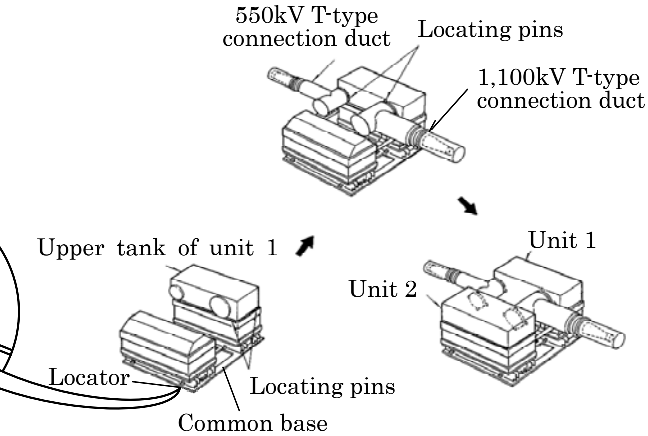


Fig. 95 Unit tank docking procedure shell-form UHV transformer

In China, all modules and components of transformer installation guidance should be supplied by manufactories in order to make sure that transformers can be appropriately installed, connected and put into operation in time. The installation guidance should be provided by the manufactories of reactor, CB, MOSA, post insulator and so on during commissioning, and all the needed material for facilities installation such as lead, foundation bolt etc. should be also provided by manufactories

3.5.5 Operation and maintenance

3.5.5.1 GIS and Hybrid-GIS

(1) Layout of detachable busbars

Layout of detachable busbars is standardized as shown in Table 47 for the purpose of enabling substation activities (troubleshooting, system expansion work, and inspections, and so on) to be carried out with shorter time outage of one portion (one line and/or one busbar) of main circuit.

Table 47 Layout of detachable busbars

	Location of detachable busbar
1) Main busbar	Every 2-bays span (installed at busbar adjacent DS)
2) Gas Circuit Breaker	Between GCB and busbar side DS (installed at GCB side)
3) Between bus A and bus B	Installed at a side of DS
4) Transformer circuit	Installed at the connection point to transformer
5) Transmission line circuit	Installed at the connection point to GIB

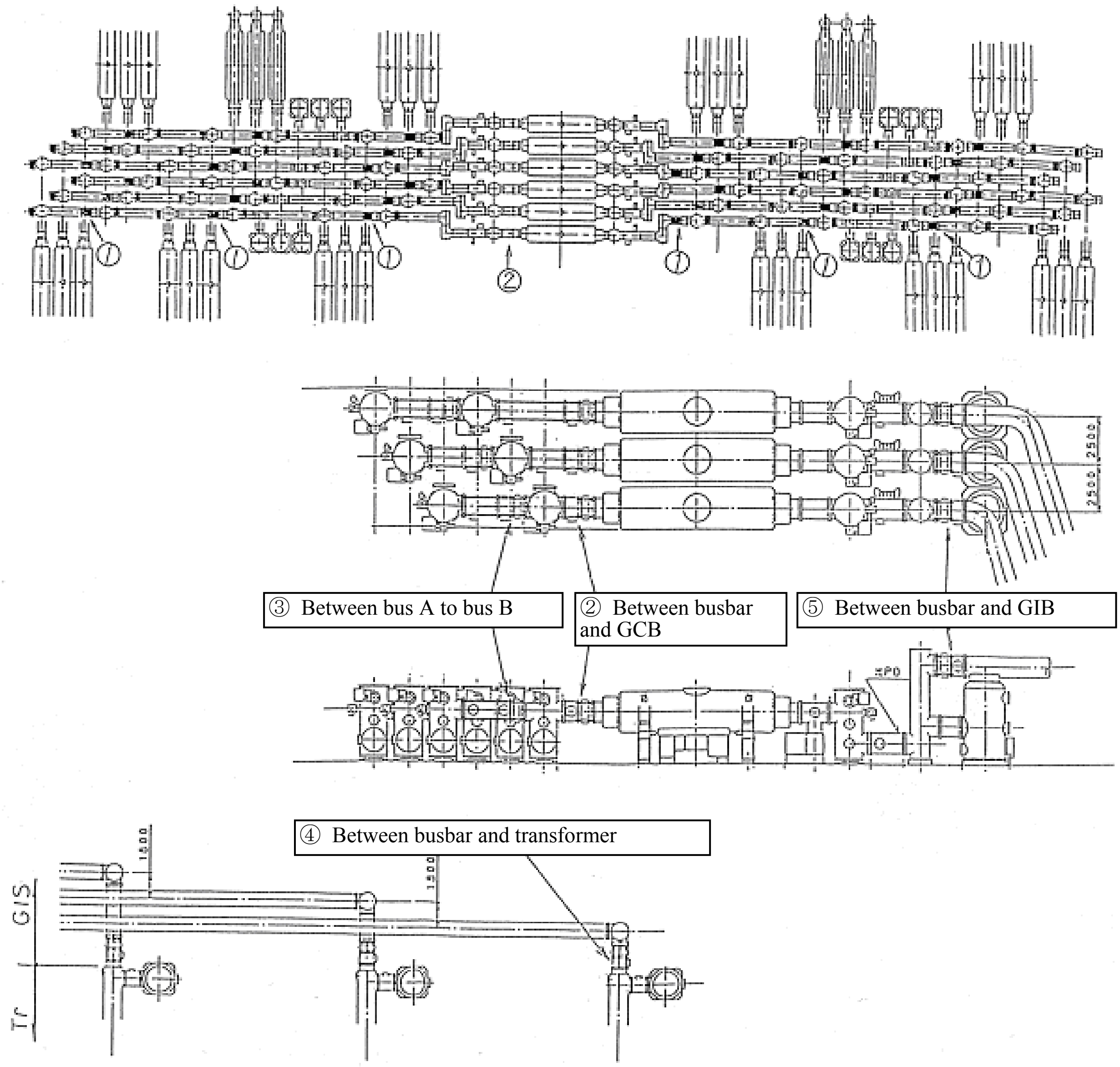


Fig. 96 Detachable busbar layout

(2) Gas compartment and gas monitoring compartment

Gas monitoring compartments are standardized as shown in Fig. 97.

1. Gas compartments

Gas compartments are divided into each equipment and each bay. (Optical PD is unified with a bus)

Detachable busbars assume it independent gas compartment.

Gas compartments are divided as follows,

At the internal fault, it shall keep an accident influence range in the line concerned and the bus concerned.

- In order to maintain the quality that confirmed in a factory and secure the reliability in site, the gas compartments plan adjustment with a configuration and transportation unit.
- The main bus side and the line side become independent, and resolution check work being possible.
- Because optical PD consists of it as a part of busbars, it is unified with a bus.
- Detachable busbars do it with other gas compartments to make gas processing work in site an extremity. Both ends of detachable busbars are divided by gas compartment spacer, and do not expose in the atmosphere condition except for detachable busbars.

2. Gas monitoring compartment

- Gas monitoring compartment is determined considering gas pressure difference of equipment, for example GCB and HSGS have higher gas pressure than that of busbar.
- Gas monitoring compartments of busbars are divided into each bay and each of double busbars.

➢ Gas monitoring compartment is divided into each phase.

Gas monitoring range is arranged as follows,

・Gas monitoring compartment is determined considering gas pressure difference of equipment (for example GCB /HSGS：0.6MPa, others：0.4MPa)

・Gas monitoring compartment of other equipments except for GCB and HSGS are as follows,

・Power transmission line: The main bus side and the line side (GIB part and bushing part are divided into each part）

・Transformer line: The main bus side and the transformer side (GIB part assumes it another gas monitoring compartment）

・Bus tie: The each bay and each of double busbars

・Bus section: One unit side and two unit side

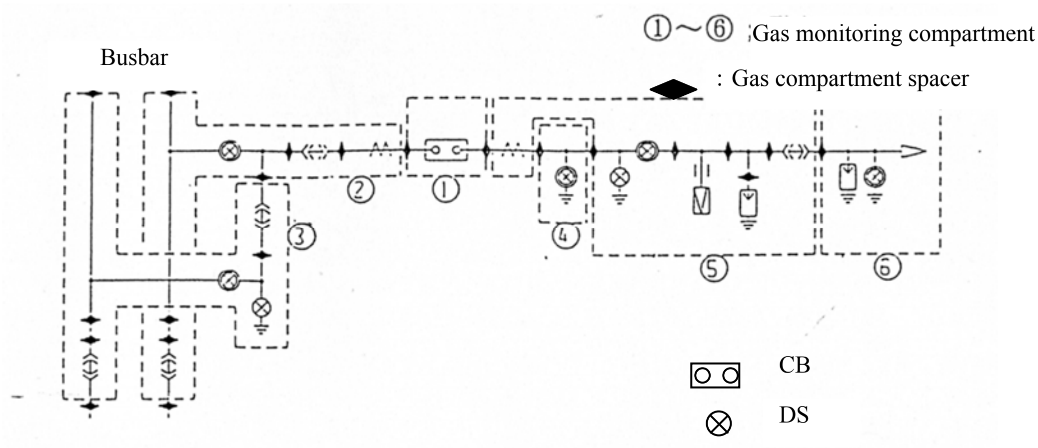


Fig. 97 Gas monitoring compartments in GIS bay

➢ Enlarging the size of UHV substation equipment

-Reasonable layout of the detachable bus-bars to be transported in separate units and assembled on-site, because of the transporting restriction in full-assembly, and to be carried out with shorter time outage in fault.

→Show layout examples to be carried out with shorter time outage of one portion (one line and/or one busbar) of main circuit.

-Show concept of gas compartments taking account of enlarging gas volume and gas monitoring compartments taking account of protection range (including GIB)

-Concepts of steal structure and slide structure

-Keep spaces for maintenance → more than 600mm width

-To ensure seismic performance, GIS is arranged horizontally and 2 tanks of transformer are combined (2 tanks have same foundation and connected by beam)

-Structure of connection between transformer and GIS

➢ Complication of control by installing HSGS, etc.

-Concept of interlock

3.5.5.2 AIS

The operation and maintenance are required to be maintained in addition to recommendation of individual switchgear manufacturer. In case of AIS substation, the minimum working (sectional) clearance i.e Phase to earth clearance + man's height (with extended hand with tool) is to be maintained so as to work safely on any equipment. Sufficient space is to be provided for the movement of cranes. Distribution of feeders should be judiciously selected so that minimum outages are there.

In the case of UHV substation, spare transformer, reactor and major equipments should be kept so as to use these spare equipments in case of any failures of main equipments as soon as possible.

3.6 Substation switching facilities' comparison (AIS, Hybrid-GIS and GIS)

All used technologies have their advantages that are described in detail in this brochure. The comparison of technologies indicates that Hybrid -GIS combines a lot of advantages of AIS and GIS and leads to a good compromise. The following table shows a summary of main Hybrid -GIS benefits.

There is no recommended general solution for all users possible, the individual conditions of every case have a strong impact on the evaluation and can lead to different conclusions.

Table 48 Substation switching facilities' comparison (AIS, Hybrid -GIS and GIS)[4]

	GIS	Hybrid-GIS	AIS
Reliability	Most devices are sealed in enclosed metal tanks; they are rarely affected by environmental impacts, and anti-earthquake capability is preferable.	By introducing GIS technology, the reliability of HGIS is improved, but probability of pollution flashover on open air-insulated busbar is higher.	The probability of pollution flashover is the highest
Maintenance and Operation	Needless of maintenance , but cannot be resumed in a short time after failure	Lack of operating experience, the working load is higher than GIS.	Operating experience in abundance, but the working load is highest.
Installation	Easiest, and installation time is shortest.	Installation of high frame is inconvenient.	Installation time is long
Layout	Compact, easy of outgoing.	easy of outgoing.	easy of outgoing.
Expansion	Easy expansion but restricted by manufacturers.	Easy expansion but needs a lot of space.	Easy expansion but needs much more space.
Circumstance	Sealed in enclosed metal tanks, EMI and noise is small, little impact on the environment.	Little impact on the environment	Strongest impact on the environment
Construction Cost	Highest	High	Lowest

AIS (Air Insulated Switchgear)

Switchgear of which the bays are fully made from AIS technology components.

Note: Substation, where only dead tank types of circuit breakers are installed in its bays, is also considered to be AIS substation.

GIS (Gas Insulated Switchgear)

Switchgear of which the bays are fully made from GIS technology components.

Only external HV connections to overhead or cable lines or to transformers, reactors and capacitors can have an external insulation.

Hybrid -GIS (Hybrid Insulated Switchgear)

Switchgear of which the bays are made from a mix of GIS and AIS technology components, Switchgear, that consists of bays where some of the bays are made of AIS technology components and some of the bays are made either of GIS technology components only or of a mix of AIS and GIS components.

Table 49 The principle technology designs for substations (their components and bays)

Technology Design	Insulation	Insulating medium	Enclosure
AIS technology	external insulation*	Air,	no enclosure or enclosure (porcelain or composite insulators) under high voltage
GIS technology	internal and external insulation	SF6 or SF6 mixtures	metal enclosure effectively earthed
Hybrid IS technology	external insulation*	SF6 or SF6 mixtures and Air	combination of all

- internal insulation can be air, SF6, oil, resin or all other kind of insulating media

3.7 Comparison of HSGS and 4 legged reactor respect to overvoltage

3.7.1 Comparison of secondary arc extinction performance

In UHV system, secondary arc does not extinguish in a short time for large induced voltage because the operating voltage level of UHV is so high and the charging capacity per unit length is comparatively high. Therefore, high speed reclosing scheme should be employed to suppress the secondary arc by four-legged reactor and HSGS.

Normally four-legged reactor is adopted in the relatively-long transmission line to provide an optimal reactor capacity to extinguish secondary arc rapidly.

4-legged reactor should be designed in some system conditions such as extremely long transmission line, transposed transmission line, heavy power flow and fault mode.

Moreover, the additional study is necessary taking into account the future power transmission system because four-legged reactor is required to replace when the substation is newly constructed at the midpoint of the transmission line.

Especially, in the case of untransposed double-circuit transmission line, the circuit conditions among three-phase lines could show larger differences to result in difficult secondary arc extinction with the four-legged reactors, even though the optimal reactor capacitor is applied.

If the effect of secondary arc extinction can not be expected in four-legged reactor alone, the installation of HSGS can be considered.

HSGS is often adopted at the both ends of transmission line in the relatively-short transmission line.

As for the location of HSGS installation, HSGS may be installed at single end of the transmission line in extremely short transmission line.

3.7.2 Comparison of secondary arc- extinguish equipment

Comparison of secondary arc extinguish equipment is shown in Table 50.

.In case of 4 legged reactor, since additional equipment such as DS, MOSA and ES in addition to 4 legged reactor are necessary for maintenance and checking work, required area for 4 legged reactor becomes large compared with HSGS.

On the other hand, from the view of insulation coordination, HSGS can be easily secured since HSGS is located between GCB and line side DS. But, 4 legged reactor is required MOSA for connection with line entrance side and possible to install MOSA for direct connection with GIS.

Table 50 Comparison between HSGS and 4 legged reactor

Equipment	HSGS	4 legged reactor	
Connection	Between GCB and line side DS	Direct connection with GIS	Line entrance side
Required equipment	only HSGS	4 legged reactor	4 legged reactor
	――――	(MOSA) DS ES	MOSA - -

3.8 EMC

3.8.1 Switching Surge of Disconnecting Switch (DS)

In the aspects of immunity for apparatus in substations, it’s necessary for a disconnecting switch (DS) to consider the affects of induced serge voltage to the secondary system. It is well known that very fast transients (VFT) occur during switching of a disconnecting switch due to re-strike.

In case of GIS disconnecting switch, VFT up to 2.8pu may occur if any measure was not taken, and it may exceed insulation level of UHV equipment. Increase of influence to the secondary system also should not be ignored. For UHV GIS, adopting DS with a switching resistor is considered. Effect of resistor value against the level of VFT is described in the chapter 2.4.4.

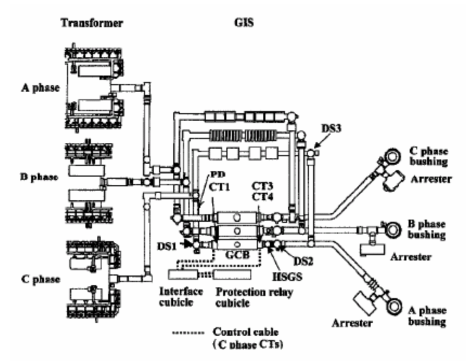


Fig. 98 1100kV Pilot Plant for Verification Test

For the Japanese 1100kV GIS, 500 ohms is adopted for the resistor. Resistor switching has an effect to reduce the serge voltage to the secondary circuit as well as the main circuit.

Through the verification site tests carried out in the 1100kV Shin-Haruna pilot plant by TEPCO in Japan, measurement of DS switching surge was performed under energizing GIS. Fig. 99 shows the test circuit.

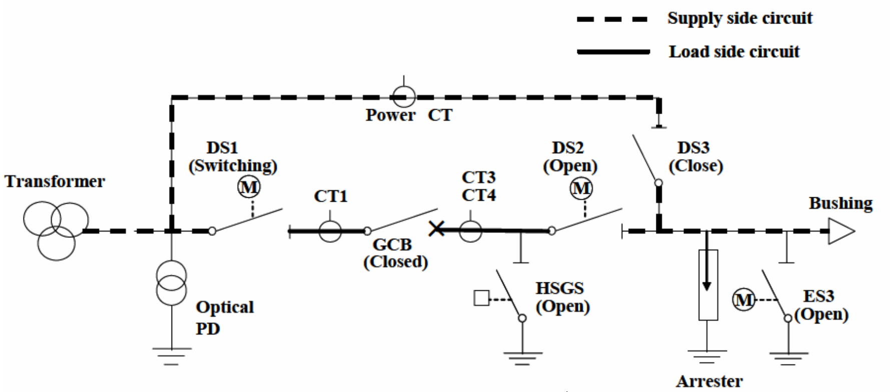


Fig. 99 Test Circuit[4]

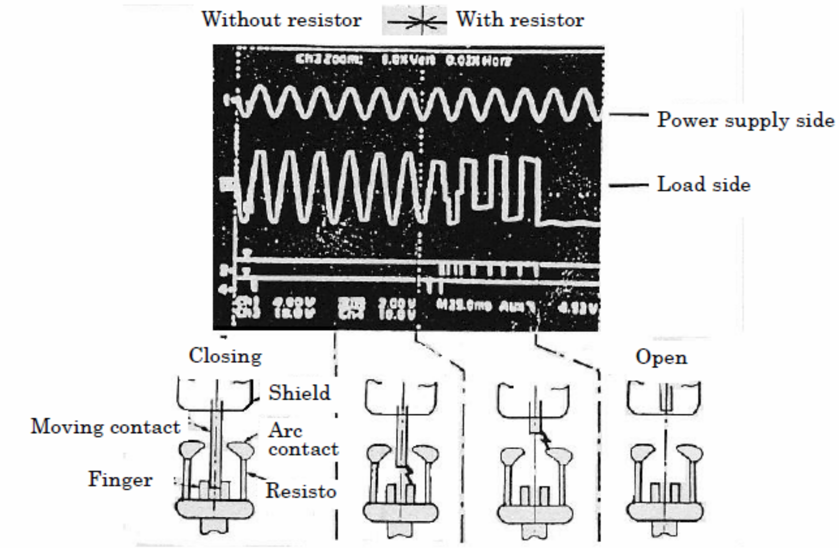


Fig. 100 Disconnecting Switch Opening Operation and Voltage

Fig. 100 shows an example of measured waveforms, in which the effect of a switching resistor is observed. The maximum VFTO level was less than 1.2pu. This demonstrated a positive effect of resistor switching. The results well agreed with the computer simulation.

The maximum potential rise at the GIS tank has occurred at the insulation flanges, and the value did not exceed 10kVp.The surges induced in secondary systems were less than 4kVp at the secondary terminal of the CT and less than 200V at the interface with the protection relay cubicles near GCB as shown in Fig. 101.

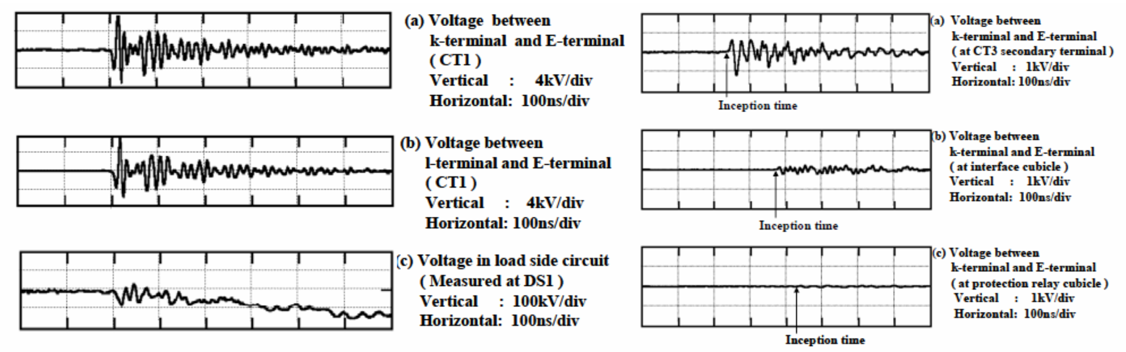


Fig. 101 Induced Surge in Secondary Systems during DS Operation [4]

3.8.2 Switching Surge of High Speed Grounding Switch (HSGS)

For the 1100kV system of TEPCO in Japan, the high speed grounding switch (HSGS) will be applied. In case of closing the HSGS, when the residual voltage in the main circuit is considerably high, high voltage serge could occur in the grounding system. If re-ignition or re-strike occurred during interruption of HSGS, high voltage serge could also occur. Following cases should be considered for the residual voltage of main circuit.

(a) Closing sound phase after interruption of CB : 900kV (1100kV * √2 / √3)

(b) Re-strike during interruption of electrostatic induced current: 900kV

(c) Re-ignition during interruption of electromagnetic induced current: 640kV

Among the above three cases, possibility of occurrence of (a) and (b) is very low, therefore case (c) will be considered as the maximum residual voltage.

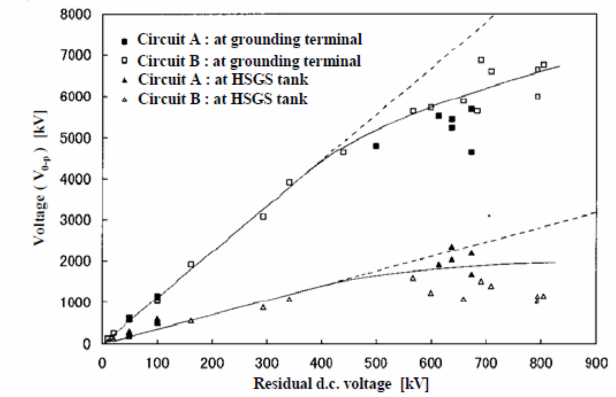


Fig. 102 Relation between Grounding Circuit Surge Voltage and the Residual Voltage[4]

Measurement of surge voltage during HSGS closing operation was carried out at the 1100kV pilot plant of TEPCO in Japan. The residual voltage on the main circuit was obtained by switching the disconnecting switch. Fig.103 shows an example of measured waveforms. [3]

The maximum surge voltage during HSGS operation was measured to be 1.1pu in the main circuit. This corresponds to 700kV based on 640kV. This value is sufficiently low with the insulation level.

At HSGS grounding circuit terminal, the maximum surge voltage was 6.32kV at the insulation terminal of a grounding lead, which is as low as 32% of the withstand voltage. A surge level is strongly affected by a structure of a grounding system. This verified an effect of the low-inductance grounding structure of the grounding terminal.

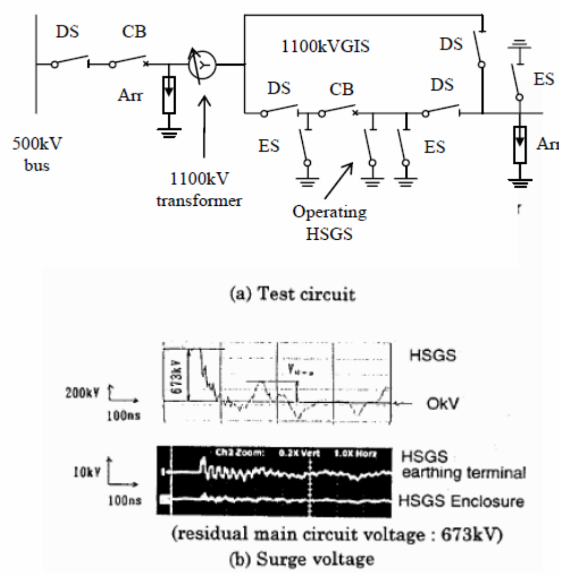


Fig.103 Example of HSGS Making Surge Waveforms

Surge voltages in the HSGS grounding circuits tend to saturate in residual voltage range above 500kV as shown in Fig. 102. Analytical result suggests that surge voltages in the HSGS grounding circuit are conditioned toward saturation by arc forming time and arc resistance along the discharge path between HSGS electrodes. [4]

In the control and protection component, the maximum surge voltage was about 1.2kV, which is lower than the lightning impulse test voltage of the terminals.

3.9 References

[1] E. Zaima, et al., "System Aspects of 1100 kV AC Transmission Technologies in Japan: Solutions for Network Problems Specific to UHV AC Transmission System and Insulation Coordination", IEC/CIGRE UHV Symposium 2007, Beijing, Report 2-1-2

[2] BAN Liangeng, et al, "Estimation of VFTO for GIS and HGIS of China 1000 kV UHV pilot project and its suppressing countermeasures", IEC/CIGRE UHV Symposium at Beijing, Paper 2-3-4, 2007

[3] T. Kobayashi, et al, "Basic design / specifications of GIS for UHV AC and its verification test at site", IEC/CIGRE UHV Symposium at Beijing, Paper 2-3-3, 2007

[4] Ning Qiu, et al, "Environmental considerations for UHV substations", IEC/CIGRE UHV Symposium at Beijing, Paper 2-3-5, 2007

4 Consideration for installation and on site test

4.1 Transformer

4.1.1 Introduction

On the starting of Japanese UHV project, the field tests have been carried out for the verification of the related all items with UHV project. This field testing is still being continued, but the reliability of the UHV transformer has been evaluated and confirmed by manufacturing the actual unit for service, and through the field testing during installation, initial evaluation testing at the start of field testing, through continuous evaluation over 10 years, and recording of trends. In this chapter, it be introduced the site tests for UHV transformer included the every steps with transportation, site installation, tests before energizing, site insulation test, characteristics at the energizing and long term tests under energizing conditions. And, it is indicated the recommendation on the site test for actual UHV projects.

4.1.2 Field Test Conditions and Results with Japanese UHV project

To conform the transportation and installation techniques for the UHV transformer with mountainous areas which provide the building conditions for 1100kV substations, to establish the site test techniques for high voltage and large power of the UHV transformer as specified $1050/\sqrt{3}$ kV 3000/3 MVA, to check various characteristics while linked with the power system, and to verify reliability over extended periods with service operation, one set of filed testing facility included a bank of UHV transformer and a GIS equivalent to one line circuit in a substation was built within the 500kV Shin Haruna substation of the Tokyo Electric Power Company. For the above, four major steps indicated in the Table 51 were performed in the field tests for the UHV transformer. Construction the field testing area was started from December 1992, and from May 1996, field testing has been continued to the present while connected to the system.

Table 51 Field testing items

Evaluation Step	Major evaluation and testing items
<Step 1> Transportation and Installation	Evaluation of transportation and installation by the full size of actual UHV transformer
<Step 2> Site test techniques before service	Measurement of voltage ratio and check of phase displacement, polarity test, measurement of winding resistance, measurement of insulation resistance, measurement of dissipation factor and determination of capacitances, measurement of AC low voltage excitation current, measurement of short-circuit impedance. Measurement of three-phase unbalance current, measurement of frequency response analysis with circuit for withstand test, withstand voltage test, partial discharge test, energizing test from tertiary
<Step 3> Various characteristics under operating conditions	Measurement of load currents in the windings under tap difference condition (energizing condition), measurement of inrush current switched on secondary side, determination of transient voltage transfer characteristics switched secondary side
<Step 4> Long term reliability	Long term energizing test. Dissolved gas analysis, measurement of insulation oil characteristics (breakdown voltage, water content, resistivity, electrostatic charging tendency (ECT), dissipation factor, count of micro particle in oil), static electrification test (charge density in oil, leakage current at neutral), measurement of vibration and determination of sound levels

4.1.3 Transportation, Installation and Site Testing Techniques before Service

The configuration of the field test facility is shown in Fig. 104, and its view is shown in Fig. 105. The three manufactures of Hitachi Ltd. (now Japan AE Power Systems), Toshiba, and Mitsubishi Electrics built with one phase unit each for the bank configuration.

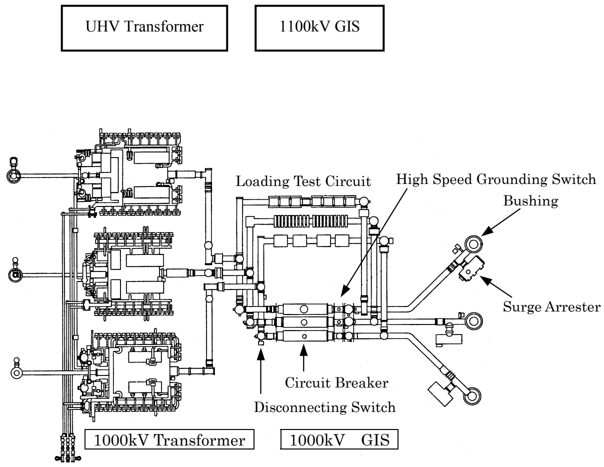


Fig. 104 Configuration of 1100kV field test

Fig. 105 UHV transformer under field test

4.1.4 Transportation and installation <Step 1>

The two tanks system per one phase unit applied and designed with UHV transformer according to the limitation of railway transportation (Max. Height 4.1m, width 3.1m) and each tank was transported to the nearest rail station for the site of the field test by railway, and was then loaded onto a specialized trailer for transport to the site from the rail station. The shipping weight was approximately 200 tons.

In the installation at the site, the linkup with the two tanks and 1100kV lead duct requires very high precision on the installation, so the installation was performed using a special sliding device with a two way feed device, in a environment with strict controlled dust.

4.1.5 Site tests before service <Step 2>

To inspect the condition after transportation and site installation, the test of step 2 in Table 51 was performed with oneself of UHV transformer, and a good result was gained except the induced over-voltage test. In the induced over voltage test energizing from the tertiary side of the transformer, a 3 phase energizing method by grounding the neutral point was performed, but in the voltage rising process, the voltage wave distorted and an unexpectedly high over-voltage was experienced. Because the value of capacitance windings-to-earth for the 1100kV transformer is approximately 10 times larger than for the existing 500kV unit, and the test voltage wave would be easily warped under site test equipments for induced over-voltage test. Therefore, it is necessary to take into consideration with the measurement of the resonance frequency of the test circuit, reduction of the residual flux in the core by using the method of low voltage and low frequency energizing circuit, and also smoothly voltage up by LVR (Load Voltage Regulator) with IVR (Induced Voltage Regulator) under the site withstand voltage test, etc. Fig. 106 shows the test circuit for the site withstand voltage test.

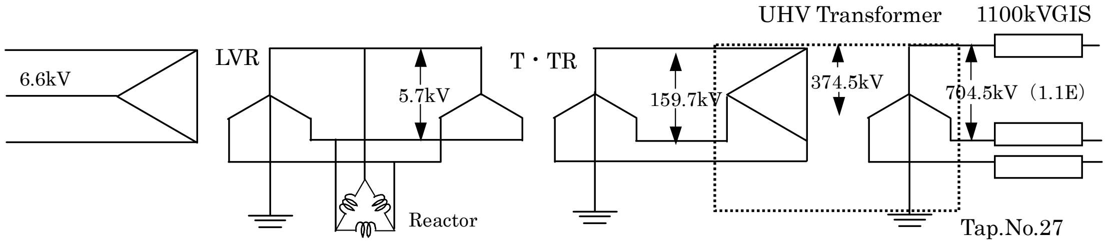


Fig. 106 Induced over-voltage test circuit in the site

4.1.6 Various Characteristics in the Operating Condition <Step 3>

For the design of the 1100kV substation and acquirement of data for maintenance in the service, energizing test with power flow, measurement of inrush current, measurement of transient voltage, etc. were performed under conditions with linkup a GIS as equivalent as an actual substation, and the results were gained with equivalent value in advance analysis.

4.1.6.1 Energizing test with power flow

Utilizing the structure of the one phase divided 2 tanks; a power flow test under tap difference condition using two voltage regulators per phase on each tank was performed. Under conditions of the maximum tap difference, 36% of the rated current flows in the series winding and there is a about 100% current flow in the common winding, and it was confirmed that the values of current and temperature rise under energizing with tap difference match as the calculated values. The example of the measurement of current distribution in the UHV transformer when energized at maximum tap difference is indicated in Fig. 107.

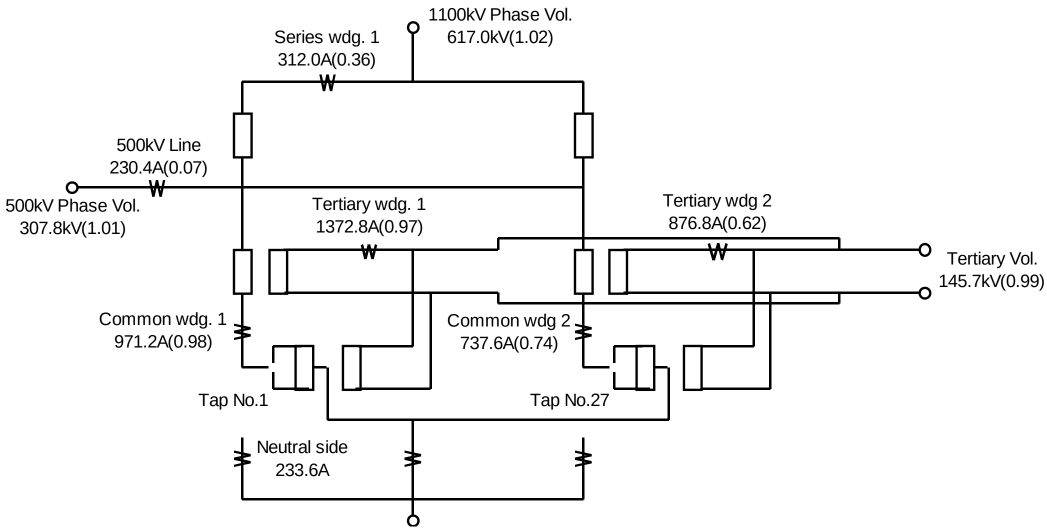


Fig. 107 Current distribution in the transformer when energized at maximum tap difference (1997.4.25)

4.1.6.2 Inrush current measurement

The results of measurement on inrush currents of UHV transformer that were switched on secondary side circuit breaker connected to the actual 500kV transmission system is shown in Table. 52. These tests are performing with multiple switching and controlling angle of phase in switching. The measurement current waveform also is shown in Fig. 108. The maximum value of the inrush current was $550A_{0\text{-}p}$ at the secondary side with closing resistance. And without closing resistance, it was $5920A_{0\text{-}p}$. With a comparison with the measurement values and the analysis, it was confirmed that it is possible to calculate for inrush current with high accuracy by understanding the transformer ϕ-I characteristics, reduction of residual flux at transformer open, and magnetic flux due to variations by the timing of switching between phases.

Table. 52 Inrush current measurement result (Maximum value)

Closing Resistance	Tap	U Phase		V Phase		W Phase		Neutral current
		Closing angle	Current	Closing angle	Current	Closing angle	Current	
Yes	27	18	-400	191	-330	7	320	60
	14	11	400	29	410	205	-360	280
	7	292	550	173	-350	166	-360	-520
	3	18	410	205	-420	180	-440	-280
No	27	224	-3040	213	-3070	340	3070	1850
	14	189	-5180	139	-4260	11	4260	1940
	3	16	5920	158	-5280	4	5180	2220

* Units of closing angle: ° Unit of current: $A_{0\text{-}p}$

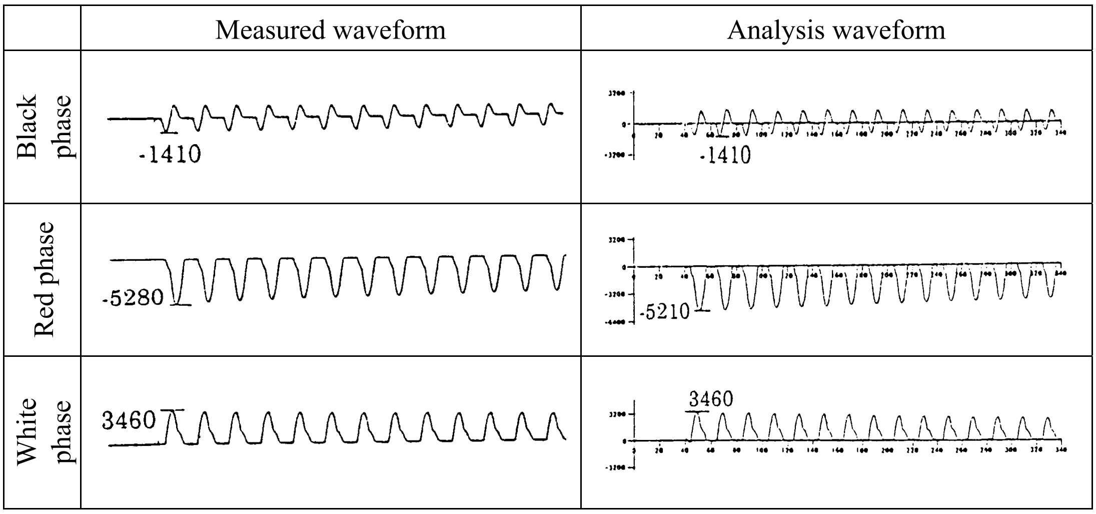


Fig. 108 Comparison of inrush current measured waveform and analysis waveform

4.1.6.3 Transient voltage measurement

In the inrush current measurement with 500kV side circuit breaker switching, the measured maximum value of the transient voltage on the 1100kV side is indicated in Table 53. It can be seen that the lighting arrestor for the transformer protection is functioning effectively even under no closing resistance conditions, and that it is suppressed under 1.6pu.

Table 53 Transient voltage measurement results with inrush tests (Maximum value)

Tap	With resistance switching		Without resistance switching	
	1100kV side	500kV side	1100kV side	500kV side
27	1.30pu	1.21pu	1.55pu	1.51pu
14	1.30pu	1.40pu	1.54pu	1.45pu
3	1.40pu	1.20pu	1.57pu	1.30pu

*1pu: 1100kV side=1100kV × $\sqrt{2}$ / $\sqrt{3}$, 500kV side=550kV×$\sqrt{2}$ / $\sqrt{3}$

4.1.7 Long Term Reliability <Step 4>

During the year after energizing in the system, a test under power flow with maximum tap difference was performed at 1.0E of operating voltage (1E=1100kV/$\sqrt{3}$). After this, to perform by an accelerated service period, a higher voltage operation (1.03~1.05E) using maximum tap difference was continued. The cumulative testing period has reached 58,350 hours at the end of March 2007, and the total period of power flow by tap difference has become 7,918 hours. The cumulative period under higher energizing voltage also has reached 49,272 hours. When the higher voltage period is evaluated by using the V-t characteristic, this is equivalent to a life cycle evaluation of approximately 105 years. Also, good results have been gained when measuring dissolved gas analysis (H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, TCG), insulation characteristics of oil (breakdown voltage, water content, resistivity, electrostatic charging tendency (ECT), dissipation factor, count of micro particle in oil),and measurement of vibration and determination of sound levels, periodically, with no found of major changes and it is getting the good results though a transformer had been experienced the static electrification on the phase V after energizing two years and it had been repaired.

4.1.8 Recommendation to site tests for UHV transformer

To verify the UHV transformer, the evaluation from development, testing, transportation, installation, commissioning tests and field tests, all the way to the collection of operational maintenance related data, was performed using the full size of actual UHV transformer.

On the actual UHV project, if the withstand voltage test would be carried out at the site, it is recommended to perform the reduction of residual flux in the core before it test.

These verification tests need no special measuring facilities on site. In the induced over-voltage test on site, it is recommended to use the LVR (Load Voltage Regulator) with IVR for smoothly controlled testing voltage.

4.2 GIS and MTS

4.2.1 Introduction

After installation, and before being put into service, the GIS shall be tested in order to check the correct operation and the dielectric integrity of the equipment. These tests and verifications according to [1] comprise

- Dielectric tests on the main circuits
- Dielectric tests on auxiliary circuits
- Measurement of the resistance of the main circuit
- Gas tightness tests
- Checks and verifications
- Gas quality verifications

However, major challenges for the testing of a UHV GIS or MTS are posed by the limited testing possibilities, in particular for dielectric tests on the main circuits.

On-site testing of GIS is an important step during commissioning of a new GIS. This test assures a correct erection and verifies that no defects are within the GIS which might lead to a major failure during operation. Various methods can be performed depending on rated voltage level and GIS type and design. Experience of on-site testing with different waveforms and procedures have shown which method is suitable to detect major defects within a GIS.

According to [1] one of the following test procedures for UHV applications shall be chosen:

Procedure A (recommended for 170 kV and below):

– Power-frequency voltage test for duration of 1 min at the value specified in Table 54, Column 2.

Procedure B (recommended for 245 kV and above):

– Power-frequency voltage test for duration of 1 min at the value specified in Table 54, Column 2; and

– Partial discharge (PD) measurements according to [1, Table 106], however with *U*pre-stress = *U*ds of Table 54, Column2.

Procedure C (recommended for 245 kV and above, alternative to procedure B):

– Power-frequency voltage test for duration of 1 min at the value specified in Table 54, Column 2; and

– Lightning impulse tests with three impulses of each polarity and with the value specified in Table 54, Column 4.

Table 47 shows the test voltages according to [1], together with the calculated test voltage for 1100 kV / 1200 kV. For the calculation the following rated voltages according to [2] were used:

- Rated switching impulse withstand voltage Us = 1800 kV
- Rated lightning impulse withstand voltage Up = 2400 kV

Table 54 On-site test voltages for 800 kV [1, Table 107] and approximation for UHV

Rated voltage for equipment ***Ur*** kV (r.m.s. value)	**On-site short-duration power-frequency withstand voltage** ***Uds*** kV (r.m.s. value)	**On-site switching impulse withstand voltage** ***Uss*** kV (peak value)	**On-site lightning impulse withstand voltage** ***Ups*** kV (peak value)
(1)	**(2)** (see Note 1)	**(3)**	**(4)**
800	760	1140	1680
1100 / 1200	865	1440	1920

NOTE 1 Values of column (2) are only applicable for SF_6 insulation or when SF_6 is a major part of the gas mixture. For other insulation refer to Tables 1 and 2 of IEC 60694 (now IEC 62271-1), applying a factor 0,8 on column (2).

NOTE 2 The on-site test voltages have been calculated as follows:

U_{ds} (on-site test value) = $U_p \cdot 0{,}45 \cdot 0{,}8$ (column 2)

U_{ss} (on-site test value) = $U_s \cdot 0{,}8$ (column 3)

U_{ps} (on-site test value) = $U_p \cdot 0{,}8$ (column 4)

All values have been rounded up to the next higher modus 5 kV.

NOTE 3 If other insulation levels than the preferred values of Tables 102 and 103 (e.g. the lower insulation levels of Tables 1 and 2 in IEC 60694) are specified, then the on-site test voltage should be calculated according to Note 2.

In certain circumstances, for technical or practical reasons, dielectric tests on-site may be carried out with reduced voltage values. Details are given in clause C.3 of [1].

4.2.2 Test procedure

The standards define no single technique or the details which have to be used for on-site testing. It is still an agreement between manufacture and customer which testing procedure and which kind of test voltage or combination of test voltages have to be applied. It is common practice since nearly 30 years to carry out ac high voltage tests by resonant test systems with variable frequencies. IEC 62271-203 [[1]] defines a test frequency range between 10 Hz to 300 Hz, typically frequencies above 80 Hz are applied usually for testing including voltage transformer. Due to the long period of application of resonant test systems for on-site testing, in combination with a sensitive partial discharge measurement, experience have proved its successful application.

Typical PD causing defects, which might be produced during transportation or erecting, are protrusions, free moving particles, floating parts or cracks in spacers. Due to the different physical behavior of the defects under HV ac stress, LI or switching operations, it is impossible to find all defects by withstand testing of only one waveform. Table 55 gives an overview of the effectiveness of the various applied HV voltage waveforms to detect the different defects [[3]]. As shown the application of PD measurement enables the detection of all kind of serious defects during ac voltage testing.

Table 55 Effectiveness of on-site tests on GIS defects with different test procedures [[3]]

Defect	High AC	Low AC with PD	High AC with PD	LI	SI
Sharp protrusions fixed on live parts			™	1	
Round protrusions fixed on live parts (assembly faults)	™		1	1	1
Particles on spacers	™/1		™/1	1	™
Cracks in spacers	™/1	™	1	™	™
Free particles	1	1	1		™
Parts floating	™	1	1		
Left foreign bodies	1	™	1	1	™

™ : less effective

1 : effective

To detect partial discharges in GIS the following main PD measuring methods are in use [[4]]:

- Conventional measuring systems based on the IEC 60270,
- UHF measuring systems using narrowband or wideband filter detection in a frequency range up to several GHz,
- Acoustic measurements, mainly for PD location, using externally mounted acoustic sensors which detect the acoustic signals emitted by a PD.

The conventional method seems not usable because of technical limitations. For partial discharge detection on-site, the electrical VHF/UHF and the acoustic method can be used in GIS. These methods are less sensitive to noise than the conventional measurement and can also be used for partial discharge monitoring in service. The UHF technique, which needs special couplers, is very sensitive and can also locate the PD source. As couplers, special build-in sensors can be used or external sensors can be applied if the substation has suitable access windows. The different kinds of sensors are shown in Fig. 110 Different types of PD couplers for GIS [5][[5]]. By means of the appropriate design, the sensor has almost the same sensitivity or divider ratio over a wide frequency range. A sensitive sensor also forms the basis of a practicable PD measurement. Also sensitive and with a high local resolution is the PD measurement by means of acoustic sensors.

In contrast to the conventional method, the UHF/VHF and the acoustic method cannot be calibrated. This means that between the apparent charge and the display on the PD measurement system no clear correlation can be established. This disadvantage of the UHF method is only an apparent one because for the interpretation, parameters such as number of pulses/sec or the pulse/half-wave, the phase relation of the PD pulse relative to the applied high voltage and the overall number of pulses, play the most important role. They are independent of the bandwidth of the measurement system used and the true magnitude of the partial discharge amplitude. In this respect the PRPD patterns appear the same, independent of whether

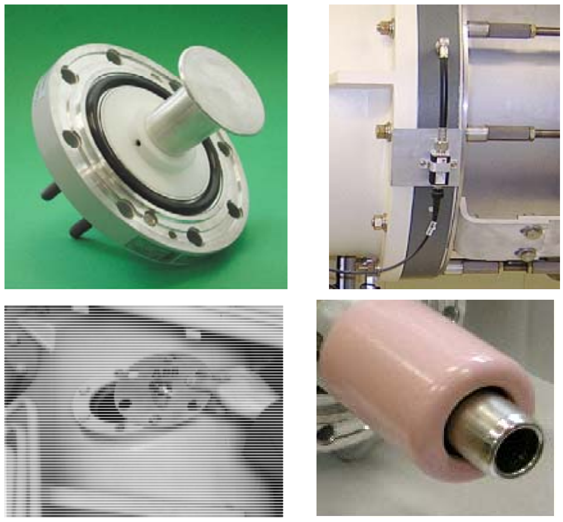


Fig. 110 Different types of PD couplers for GIS [5]

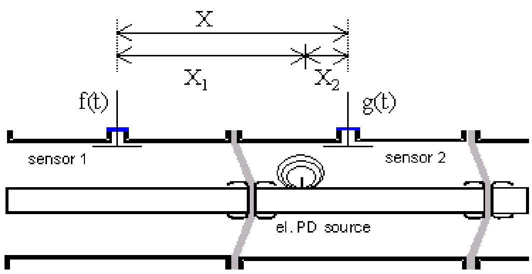


Fig. 109 Time-of-flight location [9]

or not they were obtained using the conventional method, the UHF method or with acoustic methods. To compare the sensitivity of different UHF/VHF or acoustic couplers a CIGRÉ brochure was published which describes in detail the sensitivity check of such sensors [6]. As this document is nearly 10 years old, the CIGRE working group D1.25 was established in 2008 to authoring a review of this document.

For GIS, PD measurements in the UHF range, i.e. frequencies above 300 MHz and up to 2 GHz, special designed capacitive couplers are suitable and have well been proven in the past for testing GIS on-site. In principal two types of UHF PD detection systems can be used, the narrow band technique with a bandwidth around 5 MHz and the wide band technique using a bandwidth up to 2 GHz. While in new systems the UHF couplers can be installed simply, in existing systems, however, only mobile window sensors can be used. A comparison of the internal couplers sensor shows that with appropriate size of the window sensors approximately the sensitivity of a conventional UHF sensor can be achieved [7].

Different procedures and methods can be applied for location of PD sources. Sectionalizing and the electrical time-of-flight measurements are the most practical procedures and are typical for the UHF PD measurement method. These techniques are also applicable for acoustic measurements. More detailed information is given in [8, 9]. The very fast electric pulse, of rise time below 1 ns, emitted by a PD source, propagates in all directions along the GIS bus duct. It arrives at couplers which might be located on both sides of the PD source. By the time-of-flight technique the time difference between the two wave fronts arriving both couplers can indicate the location of the PD source (see Fig. 109). The time difference is in general in tens of ns range, so a fast digital oscilloscope has to be applied for measurements.

Testing GIS on-site with ac resonance test system with variable frequency (ACRF) test systems is nowadays a common practice, also applicable for 1100 kV. Two main technical realizations are possible. Completely metal-enclosed, SF_6-insulated HV reactors, which can be directly flanged to the GIS, achieve a high PD sensitivity with low background noise. They require lowest space demand and no additional safety requirements. Today, the maximum test voltage is about 740 kV. Therefore oil-insulated modular reactors were used. The test set-up can not directly be flanged to the GIS. The HV has to be supplied via a bushing to the GIS. The inductance of the reactors can be well adapted to the test object capacitance by series and parallel connection of reactor modules. Test voltages in the range up to 800 kV can be realized.

4.2.3 Example 1: Japanese experiences

(1) On site withstand voltage test of UHV GIS

In the Japanese Electric standard (JEC) for GIS, lightning impulse withstand tests are specified as the routine test in the factory but not for the on-site test, while it is not specified for the routine test but for on-site test in the IEC standard. This is from the opinion that the purpose of the on-site test is to confirm the quality of site work and to detect unexpected contamination during the site work in Japan. From this aspect, relatively low power frequency voltage for a certain period is applied for the on-site test, and during the test, measurement of partial discharge will be carried out to check any abnormality.

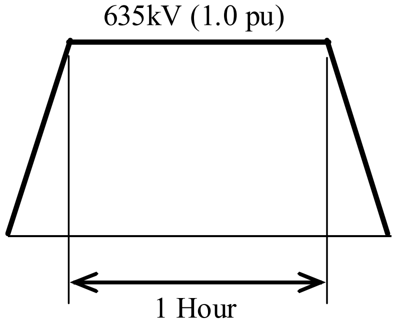
For the UHV pilot project of TEPCO in Japan, following test procedure was adopted.

During the test, measurement of partial discharge was carried out with diagnostic methods using UHF or AE (acoustic emission) as well as ERA method.

- Test voltage : power frequency 635kV (1.0 pu)
- Duration : 1 Hour
- Voltage source : Resonance testing transformer
- Measurement during the test : Partial discharge

ERA (with PD of testing transformer) for reference

UHF with internal sensors or AE (acoustic emission) with external sensors



The scale of equipment becomes large for UHV GIS. Therefore a large capacity testing transformer will be required for the high voltage test at site. It may force big investments.

Further, applicable sections and a point of test bushing for the testing transformer should be considered for the design of GIS from the initial stage.

It is recommended that rational test pattern and voltage level should be selected, with the measure for partial discharge detection.

(2) Field verification test

The field verification test is different from factory test because there were some limitations on field testing facilities. Through the test, special items which can be verified only at site are chosen.

the three main points of the field verification test are as follows: (a) Verifying performance and reliability of new technologies used only for 1100-kV system; (b) Studying high-voltage phenomena; (c) Collecting data for planning and designing commercial 1100-kV substation.

Most of the equipment used new technology, so most test items were in category (a). They were comprised of commercial voltage tests, continuous current tests, artificial transient-generation tests, and online and periodic monitoring.

The artificial-transient generation tests such as disconnector surges, HSGS closing surges, transformer transfer surges, and inrush current measurement and their effect on EMI measurement fall into category (b).

Transformer inrush current measurement with three-phase connections, continuous current tests of fully assembled GIS, and impedance measurement of switchgear yard grounding mesh are examples of category (c).

The field verification test facilities were connected to a 500-kV commercial network through the secondary side of transformer and operating voltage was applied from May 1996. Excellent data were obtained from online monitoring and periodic measurements. Tested and/or measured items are shown in Table 56.

For examples, the GIS current test showed that the degree of thermal expansion depends on the average temperature of the top, bottom, left, and right surfaces of the GIS enclosure. This result will be followed by a new thermal expansion study in an attempt to count the average temperature to at least 5 K below the standard temperature rise of 40 K.

Tank enclosure temperature rise by sun-light emission cannot be neglected because its peak comes in about two-hours delay from noon, synchronizing with the temperature rise peak by the load. Therefore, the temperature rise due to sun-light should be taken into account in studying total temperature changes. These data will be reflected in the design of 1100kV and lower voltage commercial substations.

Table 56 Main items of on-line monitoring and periodic measurement

Category	Test / Measurement item
Long-term energizing / continuous current test	Characteristics change (if any)
Periodic measurements	Partial discharge
	Arrester leakage current measurement
	Vibration / acceleration measurement
	Opening time characteristics test (GCB / DS / HSGS / DS)
	Optical PD / Air-cored CT accuracy measurement
On-line monitoring	Partial discharge
	Gas pressure
	Arrester leakage current measurement
	GCB / HSGS oil pump operation time
	GCB / DS / HSGS operating time

4.2.4 Example 2: Chinese experiences

For the on-site test a 1200 kV test transformer was used (Fig. 111). The HV was supplied via a bushing to the MTS. The typical test sequence, consisting of a conditioning phase and the withstand test voltage test for 1 min is given in Fig. 111. For the pilot project the test procedure was slightly changed:

- Conditioning phase 10 min, 635 kV (1.0 pu)
- Conditioning phase 5 min, 760 kV (1.2 pu)
- High voltage test 1 min, 880 kV (0.8 x Rated short-duration power-frequency withstand voltage U_d)
- PD measurement 30 min, 700 kV (1.1 pu)

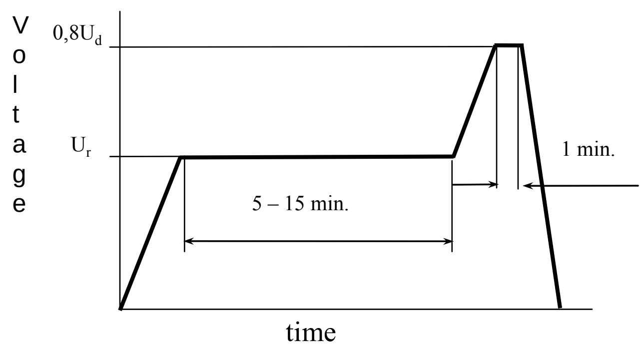


Fig. 111 On-site HV test set-up (left) and typical test procedure (right)

For the PD measurement, both the UHV and the acoustic measurement were used. The combination of both PD measurement techniques is very powerful to detect, locate and interpret the measured PD event and to distinguish it from signals not originating from harmful defects. The first step of sensitivity verification of the couplers was performed during the HV tests in the laboratory [[10]]. The results were used for optimal placement for the couplers. The sensitivity verification can be checked on-site on the same sensors as follows: An artificial pulse is applied to the selected sensor. If this pulse can now be measured at the neighboring sensor, two conclusions can be drawn: first of all, the sensitivity of the sensor is confirmed and secondly, the signal corresponds to a PD source with approx. 5 pC (+/- 30 %) amplitude.

4.2.5 Example 2: Korean experiences

UHF PD diagnostics has been chosen for on-line monitoring and commissioning tests for the 800 kV and 362 kV GIS in 765 kV substations of KEPCO to detect defects and prevent failures. The sensitivity of internal or external (barrier) sensors were first tested according to the Korean standard KSC3700: *Electromagnetic partial discharge measuring devices* [[11]]. Propagation losses of the UHF PD signal in the GIS were measured for each type of components such as GIL, DS, CB, HSDS etc. Optimal sensor locations have obtained by using the spectral sensitivity data of sensors and propagation losses of GIS components. Fig. 112 Sensor arrangement for the 800 kV GIS shows the sensor location for the 800 kV GIS, based on the investigation results [[11]]. At the time of the GIS installation, the required PD sensitivity was 10 pC according to IEC. The sensors were placed according to the specification. The later required sensitivity of 5 pC was achieved by placement of additional external sensors.

By using the on-line PD monitoring system, several PD signals were monitored during the no-load energizing period of the GIS. The signals were further monitored. By intensive field measurements and analysis the exact location and the type of the PD signal was identified. Fig. 113 shows one of the PD signals captured during the initial energizing period of one 800 kV GIS. The PD signal was identified as a free moving particle and located. By cleaning of the located area inside the GIS the PD source was removed.

To locate exact position of the PD signal source, time-of-flight method was applied using both internal and external sensors.

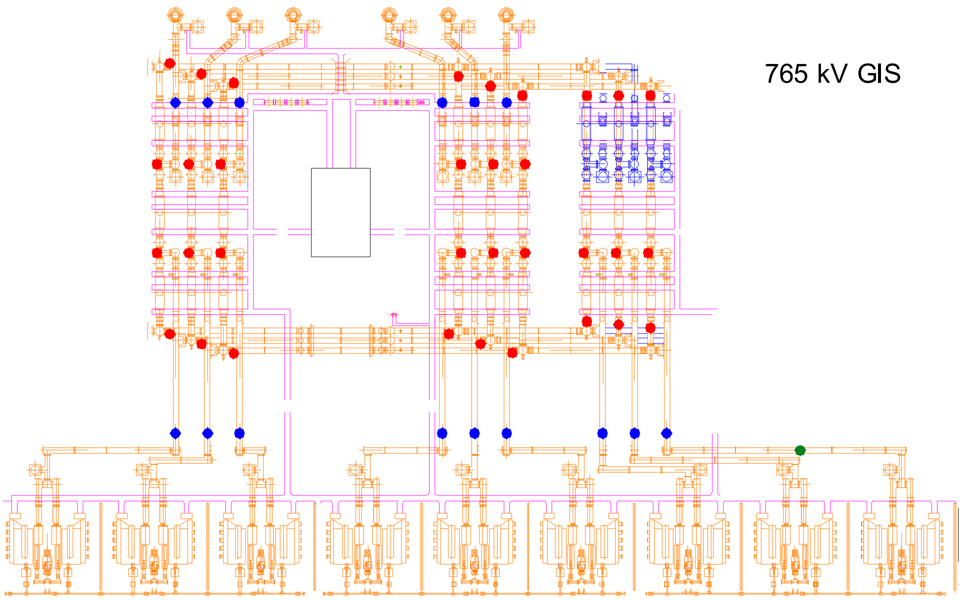


Fig. 112 Sensor arrangement for the 800 kV GIS

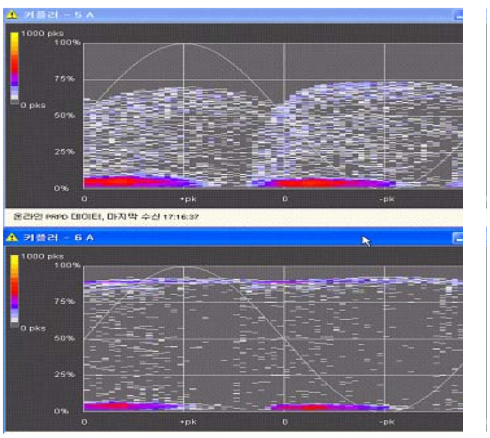


Fig. 113 PRPD pattern of free moving particle

Table 56 shows an overview about the experiences of on-line UHF PD diagnostic and monitoring systems in Korea.

Table 57 On-line UHF PD diagnostic and monitoring systems for 800 kV substations, in service in Korea

765 kV substation	Manufacturer	Sensor type	Diagnostic system type	Note
SinAnsung	A	Barrier type	On-line	Retrofit
SinSeosan	A	Barrier type	On-line	Retrofit
SinGapyong	A	Internal type	On-line	
SinTaebaek	B	Internal type	On-line	
Dangjin Switch yard	A	Barrier type	On-line (NB)	Retrofit

4.3 Reference

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5 Recommendation for UHV substation

UHV substation equipment should satisfy the some requirements: a) saving land, b) safety in operation and easy to operate and maintain, c) easy for maintenance and equipment erection work, d) saving material and cost reduction. UHV substation equipment may have two types: air insulated type and gas insulated type (GIS).Following items 5.1 to 5.6 shows the recommendation for UHV substation.

5.1 Practical consideration for UHV substation

5.1.1 Selection of bus system

Reliability is the most important criteria in addition to other aspect of maintainability, flexibility in operation, extension & security in UHV substation. Due to requirement of handling of bulk power, one and half circuit breaker system, and double busbar with 4 bustie system are recommended for UHV substations. These bus schemes can be selected based on the requirement of numbers of feeders in substation. Base on the experience of each utility, each utility should select appropriate bus system from the reliability, maintainability, flexibility, ease of operation, ease of extension and security.

5.1.2 Insulation Coordination

For the higher voltage system like as UHV exceeding 800kV, it is highly required to determine optimum insulation levels to achieve compact equipment and economical design in the substation.

Reliability of MOSA has been fully proven with long-year field experience. The high-performance MOSA whose V-I characteristic is remarkably improved (reduced) has been widely applied, therefore the insulation levels for UHV class should be determined on the base of applying the high-performance MOSA.

The IEC procedure for insulation coordination outlined in IEC 60071-1 and -2 has been applied traditionally. Since this procedure is simplified method developed for AIS, it gives a conservative estimate for GIS. Considering that many of UHV substations are GIS, the insulation levels for UHV should be determined by using the detail EMTP analysis.

Arrangement of MOSA in substation

Since the location of surge arresters is one of the key factors for determining the surge level in the substation, it is important to optimize the location of MOSA and circuit condition.

AIS, Full GIS and Hybrid GIS adopt different arrangement of arresters due to different bus-scheme and facilities. The arrangement of arresters can be decided through the calculation for lightning and switching overvoltage analysis using EMTP; meanwhile, the requirements for reliability and economy to substations should be fully considered during the calculation.

Considering the line circuit breaker open condition for the lightning surge for the GIS substation with a long line GIB around 50m or above, allocating a MOSA near the open end of the circuit breaker at the line side as well as the bushing end should be considered.

Slow Front Overvoltage (SFO)

Ground fault overvoltage is one of the SF range overvoltages. Since the maximum voltage appears most likely in the middle of the overhead line, there is not an effective measure for suppressing the ground fault overvoltage in the substation. Therefore ground fault overvoltage is the lowest target of SFO insulation level.

Other SFO surges are caused by switching of a circuit breaker. Closing resistors are widely applied for suppressing the closing surge of a circuit breaker. To reduce SFO surge further, a measure for suppressing interrupting overvoltage, such as opening resistors, is required. As a new technology, the control switching also emerged. The SFO insulation level should be determined in coordination with application of the suppressing method of SFO.

Very Fast Transient Overvoltage (VFTO)

The very fast transients, caused by re-strikes which occur during switching operation of a disconnecting switch, have very high frequency, and the overvoltage is not expected to be suppressed by surge arresters. Therefore the surge level may exceed the level of the lightning surge (or fast front overvoltage (FFO)). Especially in case of GIS, the surge propagates and reflects repeatedly on the very little attenuating pipe-sheathed busbar, and very likely becomes high VFTO. Since the reduced insulation level is adopted for UHV GIS based on application of the high-performance surge arrester, the disconnector with a switching resistor should be applied for the insulation coordination with LIWV.

Frequency of the surge on the air insulated conductors becomes smaller because of low surge propagation speed compared with GIS. It is reported that some example of VFT analysis for a Hybrid GIS substation indicated lower VFTO compared with a full GIS. However, occurrence of VFT varies depending on the configuration of equipment and circuit. The detail study with EMTP analysis must be taken.

The VFTO is oscillating surge, and it may affect the insulation performance of winding equipment like as transformers and winding type potential transformers. Also influence to the secondary system should be considered.

Therefore, in case of UHV class, probability for the VFTO to affect the whole system becomes higher. Necessity of the resistors on the disconnector should be judged with careful consideration from the various aspects.

5.1.3 Selection of HSGS and 4 legged reactor

A fast multi-phase reclosing system should be employed to avoid loss of a double-circuit line.

In UHV system, fast secondary arc extinction is evaluated as difficult without applying special equipment because higher voltage is induced electro statically from sound phases.

To reduce secondary arc, 4 legged reactor or HSGS is recommended to be equipped. In the case of long line (more than 200-300km) that is necessary for compensation by reactor, 4 legged reactor could make the efficient and compact UHV substation construction. But it is necessary to pay attention to the resonant over-voltage during reclosing and to examine the recovery voltage at the distinguishing the secondary arc. On the other hand, HSGS can extinguish secondary arc in any system conditions. It is necessary to consider the coordinated operation of HSGS and circuit breaker.

5.1.4 Flow chart of determination of UHV substation layout

Fig. 114 shows the typical procedure of UHV substation layout.

< Selection of Bus scheme>

1) Reliability
2) Operation Experience
3) Maintenance Experience
4) System Configuration
5) Others

Based on 1)-5) (Mentioned above), Each utility selects the bus system.

↓

< UHV Bus scheme>

Based on B3.22 WG investigation, UHV Bus system are typically followings.

1) One and half CB system (Including the transition system of this, Double breaker system)
2) Double bus and 4bus tie System

↓

< Basic Design of UHV substation>

1) Compact
2) Less impacts to the environment
3) Optimizing cost

These basic design concepts are recommended for UHV S/S.

↓

< Appropriate Insulation Coordination>

High-performance MOSA is recommended to adopt in UHV substation.

1) High-performance MOSA (1100kVclass V_{20kA}=1620kV, 1200kV class V_{20kA}=1700kV)
2) Appropriate selection of UHV MOSA: type (Porcelain type or Tank type)

-Protective characteristics

-Substation construction (AIS/Hybrid-GIS/GIS)

↓

(Continue)

Fig. 114 Typical procedure to determine the UHV substation layout

< Appropriate Clearance and SA arrangement>

1) Determination of SA arrangement by analysis.
2) Determination LIWV, SIWV of S/S facilities
3) Based on above, select appropriate clearance

AIS insulation coordination procedure is based on IEC.Pub60072-2.GIS / Hybrid are introduced by carrying out surge analysis. Surge analysis based on the recent analysis technology.

*Safety factor Ks is used now for GIS/AIS. But new surge analysis has been already introduced for Full GIS and Hybrid GIS. It's necessary to propose IEC to add new concept to consider the margin of surge analysis with the lightning, circuit-condition, etc.

< Application of GIS/AIS components>

Utilizing high performance Surge Arrester, GCB with resistor, and DS with resistor, etc is recommended in UHV GIS S/S.

MOSA: High performance Surge Arrester
GCB: Closing resistor, and /or opening resistor
DS: DS without resistor, DS with resistor

*Basically this is user specification to UHV substation facilities.

But B3.22 recommends utilities to consider following option.

MOSA --High performance MOSA
CB: --CB with closing resistor
DS: -- DS with resistor

< Substation Cost Review>

1) Satisfy the environmental constraints
2) Cost review
3) Determination of Substation facilities

< UHV Substation Layout>

1) Compact Layout
2) Less impacts to the environment
3) Reasonable cost

Fig. 114 Typical procedure to determine the UHV substation layout

5.2 Environmental Constraints

5.2.1 Radio Interference (RI) and Audible Noise (AN)

The measure to reduce corona noise is one of the important issues for UHV substations, especially for AIS. The radio noise generated in a substation is not only emitted to its surrounding, but also propagates through the transmission line and then emits from the line. Accordingly, the design level of corona noise in substations should be coordinated with that of transmission line.

Noise level is related to the electrical field strength on the surface of conductors. Since corona noise level is strongly affected by the atmospheric conditions and the geometric characteristics of the conductors, design of conductors varies among countries and utilities. 4 to 8 multiple-bundle conductors and/or pipe conductors with flexible connector are widely adopted for UHV systems.

5.2.2 Seismic Qualifications

Since the size and weight of UHV equipment become large compared with 550kV substation equipment, the natural frequencies of the equipment possibly coincide with the predominant frequency (0.5 – 10Hz) of the earthquakes. Seismic performance of the equipment which is installed in a highly possible earthquake area is desirably verified with the full-scale vibration tests specified in various standards. If the full-scale test is not able to be applied to the equipment, the computer analysis is useful for verification of seismic performance.

For the seismic design of equipment, followings should be considered.

(1) Rocking motion of foundation
(2) Ensuring sufficient slack of connecting leads
(3) Split foundations

5.2.3 Pollution for bushing, insulator

Withstand voltage of insulators under pollution condition drops due to the uneven distribution of pollution for radial and longitudinal direction, when diameter of insulator increases.

To determine creepage distance of UHV large hollow insulators, correction for insulator diameter should be considered.

The withstand-voltage of hollow insulators saturates with the effective length over 7m of the insulator on the light pollution condition (less than 0.01mg/cm2), because the withstand voltage characteristic is subject to the electric capacitive distribution.

The withstand voltage characteristic for the light pollution condition could be estimated with the characteristic of the hollow insulator, but in case of UHV class, the bushing may have too much margin on the insulation design, unless the withstand voltage characteristic is evaluated with a bushing construction with a conductor and shields.

5.2.4 EMF

The design level of electric field and magnetic field in substation varies among the countries and utilities, but many of those adopt the guideline published by ICNIRP (International Commission on Non-Ionizing Radiation Protection) in 1998.

For high voltage substations like UHV ones, it may become an issue that the electric field strength is to be kept below the design level in cooperation with the economical design of substation with reduced insulation level.

Especially for the AIS substation, the electric field strength near circuit breakers and disconnectors may become higher. Some utilities adopt higher value (up to 15kV/m) than the reference level in ICNIRP guidelines (10kV/m for 50Hz) as the design level for the limited area in substation.

5.2.5 EMC for secondary system or equipment

For grounding method of UHV GIS enclosures, multiple-grounding design is recommended for the reasons: 1).Induction surge can be suppressed, 2) Grounding is ensured by multiplying connection, 3) Outer leakage flux, which causes overheat of equipment's supporting structure, can be limited.

Especially, to reduce electromagnetic induction surge voltage in protection/control circuits in a ground-fault and so on, it is desirable to consider the relation between induced surge voltage and mesh span.

For the design of grounding system, grounding auxiliary mesh in addition to main mesh shall be laid for the purpose of reducing inductive surge (disconnector surge, ground-fault surge, and lightning surge, etc.) into substation protection systems.

For example, main mesh and auxiliary mesh in full-GIS substation shall be provided at 20m and 2m span respectively and inductive surge into protection system is reduced less than that of specifications defined by IEC 60255.

In large AIS substation all cables in the building, panels, mechanism boxes of disconnectors, circuit breakers are connected with main mesh to restrict any potential rise in the secondary system. Further auxiliary meshes of 1.5 m x 1.5 m (having earth rods at a spacing of 30 cm in both directions) are laid.

5.3 Manufacturing capacity, testing facilities and construction period

Since UHV equipments have a lot of parts, heavy weight, large dimension, longer duration is necessary for the procuring of parts, manufacturing and assembling compared with lower voltage GIS, Transformer, MOSA, CVT and insulator etc.

And the increase of product capacity and the occupation of product space with long duration are also required. Thus, UHV equipment are huge and takes long time to be manufactured and, it is necessary for construction planners to consider production time of the equipment, which are largely affected by the production capacity of manufacturers, and the duration of equipment transportation and installation. So further advanced investigations and controls for product of UHV equipment are indispensable.

In particular, these production time and transportation time for transformer are dominant to the entire construction schedule. The sites for UHV substations are in mountainous areas and the weather condition of these sites is usually unstable. Thus, it is recommended to adopt an enclosed docking scheme using an all-weather dust-proof housing to keep construction schedule.

Concerning on site test, test facilities will be big scale, and the long duration is necessary for on site test to carry out on substation facilities, which will increase the installation period before the commissioning test

5.4 Transportation

Since the rated voltage of UHV substation equipment is more than twice as 500kV class, size of equipment may become larger. Transformers are the largest one in size and weight among UHV equipment. Therefore, transportation restriction must be taken into account on the design of UHV transformers.

Transportation restriction and methods vary among the transportation routes and the countries. A survey should be taken for the each individual case, and the result must be reflected to the design.

5.5 Onsite testing

Considering the importance of UHV substations a high voltage on-site test following the procedure B according to [[1]] seems a preferable solution. Concerning UHV GIS, the on-site test voltage for power-frequency and lightning impulse withstand is approximately 80 % compared to the rated test voltages according to [[1]]. For technical or practical reasons, dielectric tests on site may be carried out with reduced voltage values.

For partial discharge detection on-site, the electrical VHF/UHF and the acoustic method can be used in the UHV range too. These methods are less sensitive to noise than the conventional measurement and can also be used for partial discharge monitoring in service.

Concerning UHV Transformer, to inspect the condition of the UHV transformer after transportation and site installation, various measurements are carried out such as voltage ratio, polarity test, winding resistance etc. And withstand voltage test and partial discharge test by engaging four the tertiary side are carried out.

These tests are considered with the reduction of residual flux, low frequency and smoothly voltage up by LVR with IVR, and need no special measuring facilities on site.

5.6 Cost from the view point of substation construction and equipment

In Japan, for researching lightning impulse withstand voltage (LIWV) value of UHV transformer and GIS, economy of arrester number and layout, the effect of different arrester layouts to equipment LIWV and cost is been studied. The different arrester arrangement and surge analysis results are shown in Table 42. [[2]]. As results, in condition of strict lightning invaded wave of near zone lightning stroke, case 6 is the most economical, it means 2 arresters are arranged in line entrance, 2 arresters are arranged per 1/4 bus and 1 arrester is arranged per transformer circuit. At this point the LIWV to transformer and GIS are 1950kV and 2250kV. Comparing with 500kV system, the LIWV is lower correspondingly (with operation voltage), so difficulty of manufacture is reduced.

Table 42 shows the evaluation based on only the cost of equipment, the land cost is very different in each district in every country.

Feasibility of huge UHV AIS substation depends on the cost of land and environmental constraints.

It is indispensable to estimate the land cost, equipment cost, transportation cost, erection cost and environmental assessment.

5.7 References

[1] IEC 62271-203, High-voltage switchgear and controlgear – Part 203: Gas-insulated metal-enclosed switchgear for rated voltages above 52 kV, edition 1.0, 2003-11

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APPENDIX

APPENDIX 1 HSGS

APPENDIX 2 765kV GIS

APPENDIX 3 The flashover voltage test results for the air clearances of 1000kV substations

APPENDIX 1

A.1 HSGS

A.1.1 HSGS

An induced voltage of HSGS operation is much higher than that of normal earthing switch operation, because an operation phase of HSGS is induced by another phase of same circuit. On the other hand, normal earthing switches are induced only another circuits. Therefore, high voltage surge can invade earth system of HSGS in case of flashover occurring between poles. Insulators must have high insulation performance for invasion surge to earth system, and an earth terminal must be low impedance due to reducing invasion surge to earth system and low voltage control system.

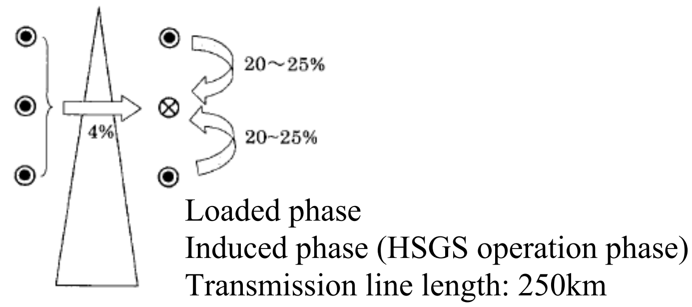


Fig-A. 1 Induction ratio from another phase and another circuit

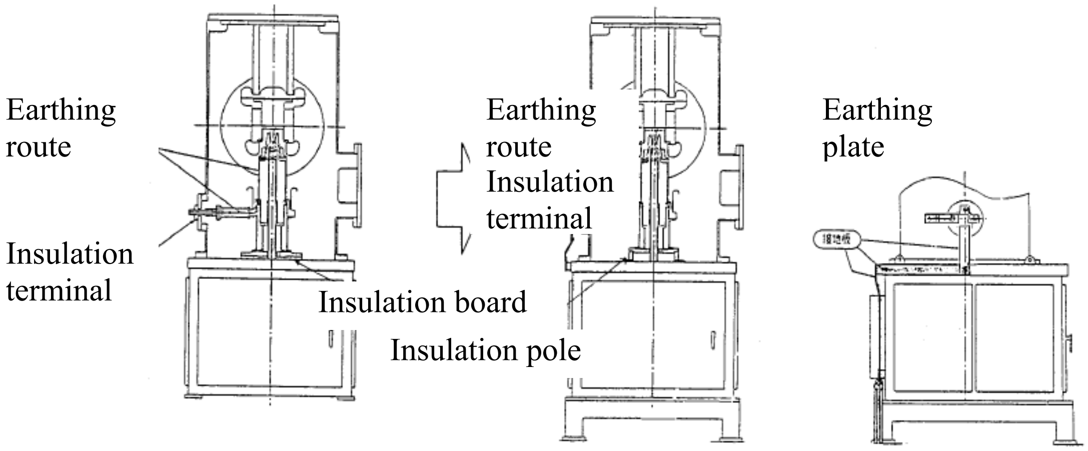


Fig-A. 2 An example of earthing structure of HSGS

A.1.2 Optical PD

Eight condensers are connected parallel in circumference and cupper plates or mesh wires are connected due to suppressing length and impedance for invasion of high frequency surge in secondary circuit of optical PD.

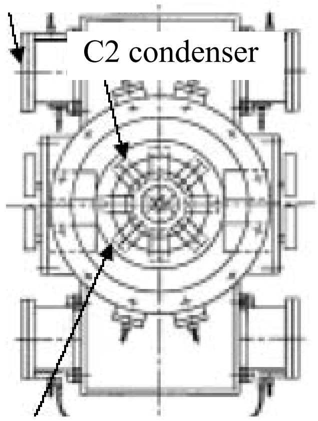


Fig-A. 3 Suppression structure for high frequency surge in optical PD

Grounding methods of equipments

Grounding methods of equipments are showed in Table-A 1.

Table-A 1 Grounding methods of equipments

Equipment	Grounding method
Circuit breaker	Both ends of circuit breaker are earthed.
Surge arrester	Primary circuit is earthed directly. Legs of tank are insulated due to preventing circulation current flow.
HSGS	Primary circuit is earthed directly through the earth terminal of tank. (Current capacity: induced current 3500A×0.5 second)
ES for line	Primary circuit is earthed to tank.
ES for maintenance	Primary circuit is earthed to tank.
Bus	One point of leg of each circuit (disconnector of bus) is earthed. Rests are insulated due to preventing circulation current flow and earthing individually.
Optical PD	Earth terminal is connected to tank through sensor case of optical PD and earthed with tank. ※Optical PD is set in multi point earth system due to reduction of induced voltage. ※Tank is earthed by two parallel cupper poles due to reduction of impedance.
Bushing	One point of leg is earthed and connection with GIB is insulated.
Connection with Transformer	Flange of connection is insulated. (Insulated by spacer of GIS side)

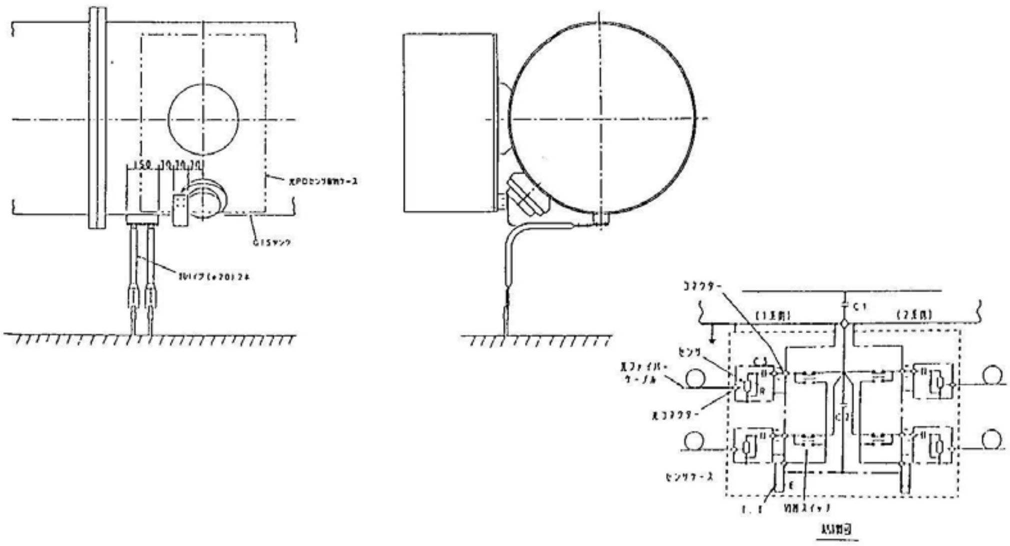


Fig-A. 4 An example of grounding method (optical PD)

- Increasing surge voltage and current
  Multiple-grounding design is employed to limit outer leakage flux
  →Installing phase-to-phase shunt bar at proper distance to impede induced current to the ground
  Prevent to flashover in cable armor due to disconnecting switch surge and so on.
  →Installing shunt bar to insulator flange between same phase
  Reducing inductive surge into substation protection systems
  →Adopting auxiliary mesh
  （This auxiliary mesh shall be provided at a 2m span to reduce surge voltage less than 7kV）
- Induced high voltage to grounding point
  Decreasing inductance against high frequency surge (HSGS, optical PD, etc)
  Grounding method (Direct grounding or tank grounding, etc)
- Measuring results of surge voltage in grounding system in UHV Equipment Test station
  Consideration the effect of auxiliary mesh based on the results of voltage rise by injecting impulse current, which is simulated HSGS and disconnector surge

A.1EMC in UHV substation

A.1.1 Outdoor air insulation switchgear (AIS)

Because of high voltage, long insulation distance and big size of electric equipment, the volume of UHV switchgear is huge and difficult to set in doors. It cause that outdoor type should be used, and floor area of UHV station is large.

For saving land using, the selection and layout of bus and disconnector should be pay more attention in UHV AIS. Their area is 50%~60% of total substation normally. Usually, the bus is on top of equipment, two groups of bus are overlap layout while double buses connection is used. The equipments use combination mode can also save land using.

The resistance to overvoltage of suspension and post insulators used in AIS is normally higher than it used in transmission line. For increasing reliability, air gap in UHV substation is longer than it in line.

In UHV AIS, power frequency electric field intensity, corona, RI and AN is more severe than it in 500kV EHV. The electric field in substation should be also limited. In USSR UHV substations, there are vertical metal screen set on position of breakers. The inspect way is shield covered way with 2.5m height and 3m width, and there are 8 metal lines on top, these ensure the ground field intensity is below than 5kV/m in covered way. The field strength in most area is 15~20kV/m. If inspectors and other workers work in area which field strength is higher than 15kV/m, they must wear specially made shield clothes.

AIS needs large area, but its cost is lower, and easy to expand if needed. AIS is used in USSR UHV substation, and its reliability is proved by operation experience.

A.1.2 Gas insulated switchgear (GIS & HGIS)

Using GIS can save land using observably, in some cases, it can reduce 90% or more. The cost of GIS is higher, but because UHV substation area is very large, using GIS can reduce more area, especially in heavy pollution, high altitude, strong earthquake and limited field, its economic technical can be compared with AIS.

For saving land using, GIS is used In Japan and Italy UHV test substation. This equipment is the complete sets of equipment which sealing substation component (except transformer), such as bus, breaker, disconnector, current transformer, voltage transformer, bus grounding switch, arrester (all or most) and so on, into grounded metal pressure vessel which filled positive pressure insulation gas SF_6.

The 1000kV substation in Japan will also be built in mountain area, because of environment and transportation the size must be limited, and the equipment should be compact as possible. In addition, some technical problems are also need to solved which caused by unique surrounding condition, such as earthquake, salt pollution and so on, so that GIS is used.

According to service conditions, there are two types of GIS: outdoor type and indoor type. For large area and volume of UHV GIS, it is low possible to choose indoor type.

In GIS, the bus also can leave outside of metal tube for reducing cost. Such equipment is called HGIS.

APPENDIX 2

A2. 765kV GIS

The 750 kV transmission project from Guanting to Lanzhoudong is the first 750 kV EHVAC project in China. It is very difficult to design the substations due to the high altitude and the severe atmosphere such as sand storm and pollution. Therefore, simplified cost-effective GIS equipments with high reliability have been chosen.

The one-line diagram, sectional view and layout of 750kV Guanting GIS substation are shown in Fig-A. 5 One-line diagram of 750kV Guanting GIS substation (one and half CB system)One-line diagram of 750kV Guanting GIS substation (one and half CB system)Fig-A. 5, Fig-A. 6 and Fig-A. 7 respectively.

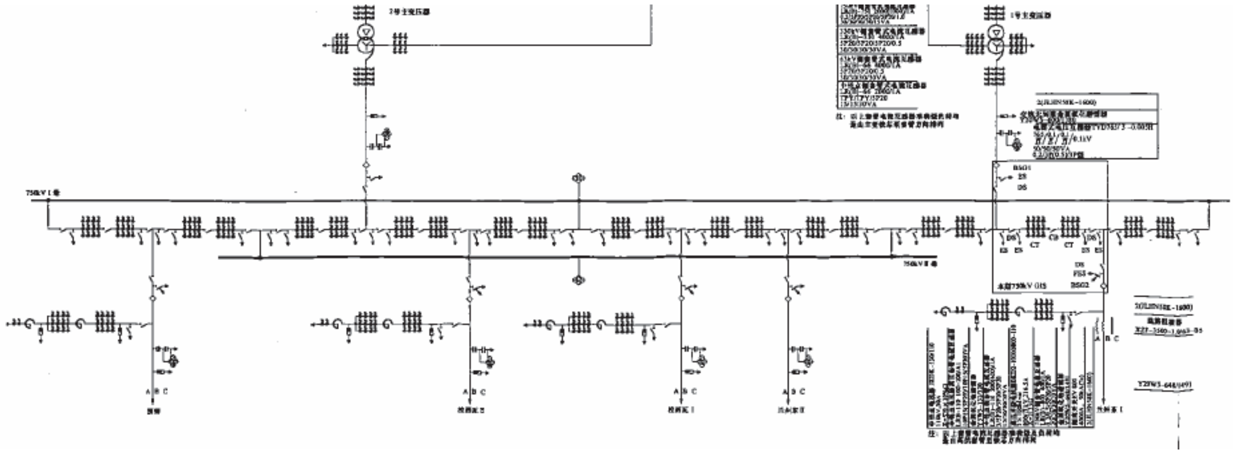
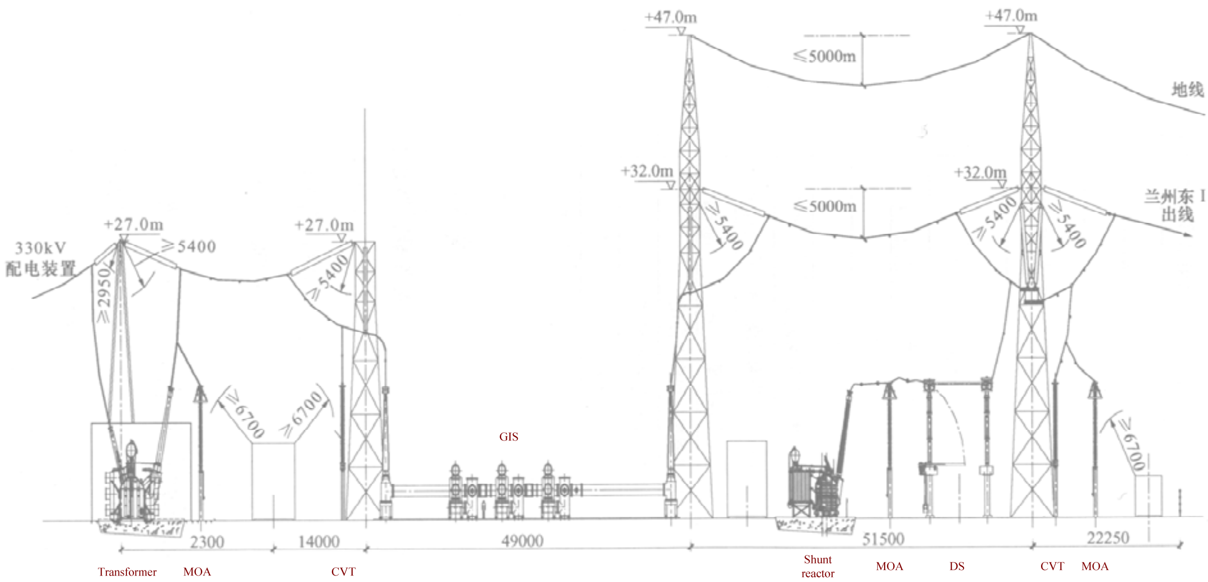
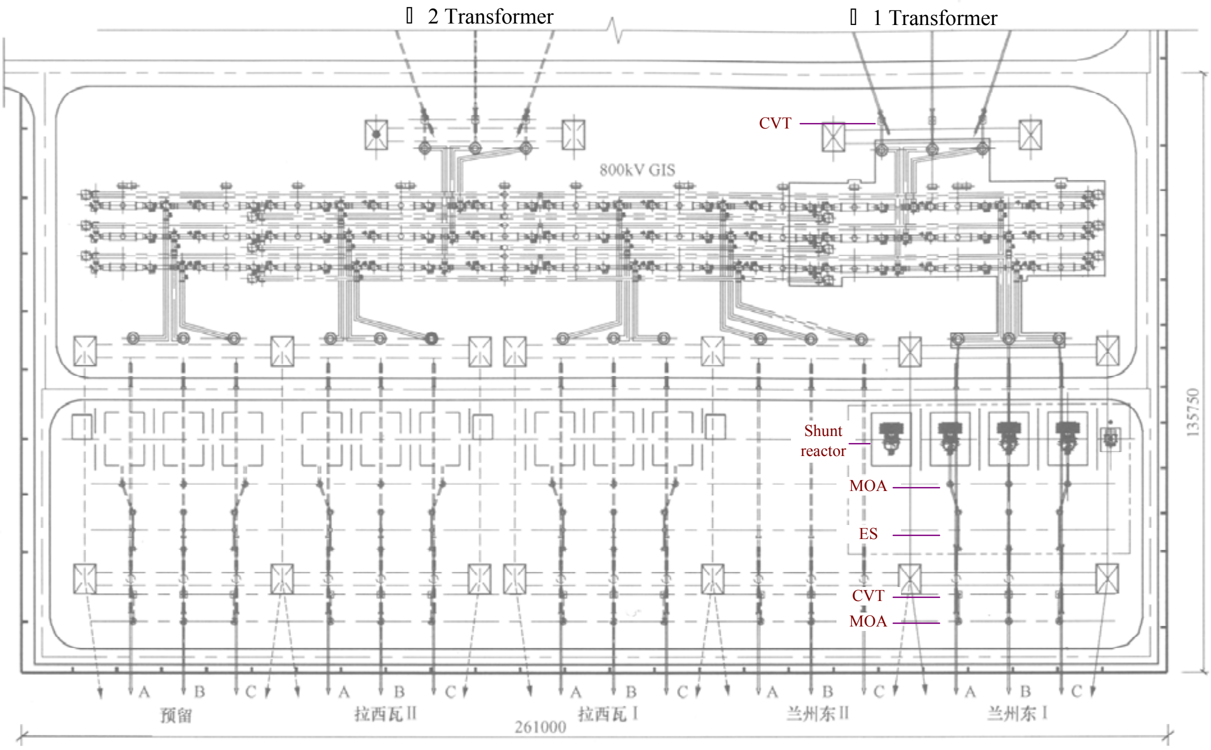


Fig-A. 5 One-line diagram of 750kV Guanting GIS substation (one and half CB system)



Cross-section diagram of 750kV Guanting GIS substation (3/2 CB system)

Fig-A. 6 Cross section view of 750kV Guanting GIS substation (one and half CB system)



Layout drawing of 750kV Guanting GIS substation (3/2 CB system)

Fig-A. 7 Layout of 750kV Guanting GIS substation (One and half circuit breaker system)

Table-A 2 Main electrical parameters of 750kV surge arresters in China

Country	China[x]	
Type	GIS Tank type /porcelain housed MOA without gaps	GIS Tank type /porcelain housed MOA without gaps
Protected equipments	Transformer	GIS, Shunt Reactor
System nominal voltage kV	750	750
Rated voltage kV*	600 (1.3 p.u.)	648 (1.4 p.u.)
Continuous operating voltage kV	462	498
Nominal discharge current kA	20	20
Residual voltage for steep current impulse kV	≤1518 (1/5μs 20kA)	≤1639 (1/5μs 20kA)
Residual voltage for lighting impulse kV	≤1380 (8/20μs 20kA)	≤1491 (8/20μs 20kA)
Residual voltage for switching impulse kV	≤1142 (30/60μs 2kA)	≤1234 (30/60μs 2kA)

Note:* 1.0p.u.= Um / $\sqrt{3}$ =800 / $\sqrt{3}$

*This table quoted from Q/GDW109-2003 Specification for metal oxide surge arresters of 750kV power system[s] in China.

Table-A 3 The test voltage for 750kV substation facilities in China

The test voltage for 750kV substation (China)

Type of substation	Equipment	basic specifications				Test voltage at Factory	Handover test voltage at Site *	Remark
		Un /kV rms	AC HV /kV rms	Switching Impulse /kV peak	Lighting Impulse /kV peak	AC HV /kV rms	AC HV /kV rms	
Full GIS	GCB Phase to earth	800	960 (1min)	1550	2100	960 (1min)	768 (1min)	
	GCB Between contacts		1270 (1min)	1300+650	2100+460	1270 (1min)		
	DS Phase to earth	800	960 (1min)	1550	2100	960 (1min)	768 (1min)	
	DS Between contacts		1270 (1min)	1300+650	2100+460	1270 (1min)		
	MOSA	600	≥ 600 (AC 1mA)	≤ 1142 (30/60 μs,2kA)	≤ 1380 (8/20μs,2kA)	≥ 600 (AC 1mA)	≥ 600 (AC 1mA)	instalted on the busbar or near the transformer
	MOSA	648	≥ 648 (AC 1mA)	≤ 1234 (30/60 μs,2kA)	≤ 1491 (8/20μs,2kA)	≥ 648 (AC 1mA)	≥ 648 (AC 1mA)	instalted on the line entrance
	External insulation of GIS Bushing	800	830 (1min)	1550	2100	830 (1min)	insulation resistance and tanδ	altitude less than 1000m
	External insulation of GIS Bushing	800	939 (1min)	1675	2350	939 (1min)	insulation resistance and tanδ	altitude more than 2000m
H-GIS	GCB Phase to earth	800	960 (1min)	1550	2100	960 (1min)	768 (1min)	
	GCB Between contacts		1270 (1min)	1300+650	2100+460	1270 (1min)		
	DS Phase to earth	800	960 (1min)	1550	2100	960 (1min)	768 (1min)	
	DS Between contacts		1270 (1min)	1300+650	2100+460	1270 (1min)		
	CVT	800	975 (1min)	1550	2100	975 (1min)	732 (1min)	
	MOSA	600	≥ 600 (AC 1mA)	≤ 1142 (30/60 μs,2kA)	≤ 1380 (8/20μs,2kA)	≥ 600 (AC 1mA)	≥ 600 (AC 1mA)	instalted on the busbar or near the transformer
	MOSA	648	≥ 648 (AC 1mA)	≤ 1234 (30/60 μs,2kA)	≤ 1491 (8/20μs,2kA)	≥ 648 (AC 1mA)	≥ 648 (AC 1mA)	instalted on the line entrance
	External insulation of HGIS Bushing	800	830 (1min)	1550	2100	830 (1min)	insulation resistance and tanδ	altitude less than 1000m
	External insulation of HGIS Bushing	800	939 (1min)	1675	2350	939 (1min)	insulation resistance and tanδ	altitude more than 2000m
AIS	External insulation of Dead tank GCB and Live type GCB Phase to earth(altitude more than 2000m)	800	960 (1min)	1675	2350	960 (1min)		Internal insulation and exteral insulation lie on area with altitude less than 1000m are same with GCB of GIS
	External insulation of Dead tank GCB and Live type GCB Between contacts (altitude more than 2000m)		1300 (1min)	1425+720	2350+510	1300 (1min)		Internal insulation and exteral insulation lie on area with altitude less than 1000m are same with GCB of GIS
	External insulation of DS Phase to earth(altitude more than 2000m)	800	960 (1min)	1675	2350	960 (1min)		Internal insulation and exteral insulation lie on area with altitude less than 1000m are same with DS of GIS
	External insulation of DS Between contacts (altitude more than 2000m)		1300 (1min)	1425+720	2350+510	1300 (1min)		Internal insulation and exteral insulation lie on area with altitude less than 1000m are same with DS of GIS
	CT	800	975 (1min)	1550	2100	975	780 (1min)	
	External insulation of CT	800	1100(1min)	1675	2350	1100		altitude more than 2000m
	CVT	800	975 (1min)	1550	2100	975 (1min)	732 (1min)	
	External insulation of CVT	800	1100(1min)	1675	2350	1100		altitude more than 2000m
	External insulation of MOSA		1040 (1min)	1675	2350	1040 (1min)		
Internal insulation	4-legs reactor	800	860	1550	2100	860	/	
	4-legs reactor (neutral)	126	200	/	480	200	160	With the bushings short circuit
	4-legs reactor (earth side)		85	/	185	85		
External insulation	4-legs reactor	800	956	1675	2350	956	/	altitude more than 2000m
	4-legs reactor (neutral)	126	230	/	510	230	184	
	4-legs reactor (earth side)		95	/	210	95		

Note: * Acording to the standard of SGCC, Q/GDW 157-2007 Standard for 750kV Electric Equipment Handover Test

Appendix 3

The flashover voltage test results for the air clearances of 1000kV substations

A.3 The flashover voltage test results for the phase-ground air clearances of 1000kV substations

All tests hereinafter were performed in the UHV test site of SGEPRI, China. The lightning impulse and the switching impulse voltages are tested in positive polarity.

A.3.1 The flashover test results of the bundled conductor to structure frame clearances

For the test set-up, the distance between the centers of the bundled conductor to the tower post is 10m, and the height of the beam structure is 35m to ground. By adjusts the clearance between the outer layer of the conductor to the beam structure to 4m, 5m, 5.8m and 7m respectively, the 50% lightning flashover voltage is achieved by standard lightning impulse voltages test. Also by adjusts the clearance to 4.5m, 5.8m, 6.5m, 7.5m and 8m respectively, the 50% switching flashover voltage is achieved by standard switching impulse voltages test. The flashover voltage characteristics of the lightning impulse and the switching impulse for the conductor to beam structure clearances are shown in Fig-A. 8 and Fig-A. 9 respectively.

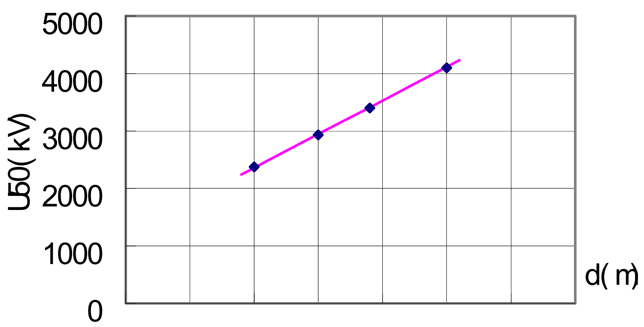


Fig-A. 8 The lightning impulse flashover voltage characteristics of the conductor to beam structure clearances

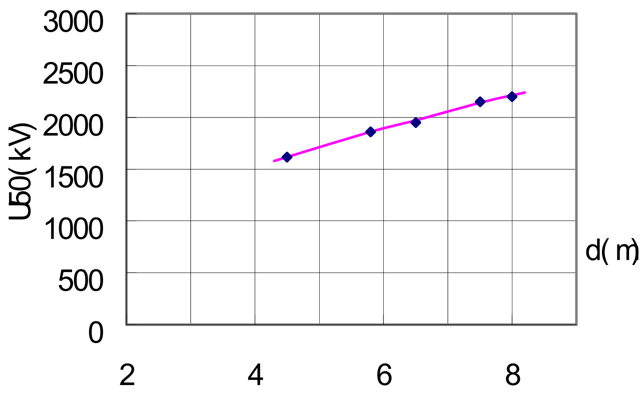


Fig-A. 9 The switching impulse flashover voltage characteristics of the conductor to beam structure clearances

A.3.2 The flashover voltage test results of the bundle conductor to tower post clearance

For the test set-up of the substation, the beam structure is 4m in width and 35m high over the ground. The tower post is 5m in width. The simulation conductor is made in real size. The distance between the centres of bundle conductor to the beam structure is 13.5m. By adjusts the clearance between the outer layer of the conductor to the tower post to 4m, 5m, 5.8m and 7m respectively, the 50% lightning flashover voltage is achieved by standard lightning impulse voltages test. Also by adjusts the clearance to 4.5m, 5.5m, 6.5m, 7.3m and 8m respectively, the 50% switching flashover voltage is achieved by standard switching impulse voltages test.

By adjusts the clearance between the conductor to tower post to 2m, 2.8m, 3.4m, 4m and 4.5m respectively, the power frequency flashover voltage is achieved by power frequency voltage test.

The flashover voltage characteristics of the lightning impulse, switching impulse and power frequency voltages for the conductor to tower post clearances are shown in Fig-A. 10 ~ Fig-A. 12 respectively.

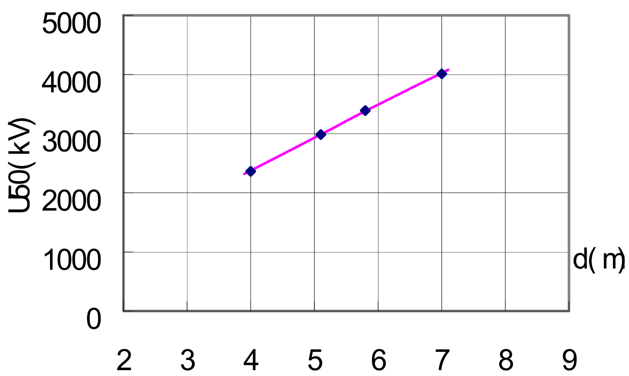


Fig-A. 10 The lightning impulse flashover voltage characteristics of the conductor to tower

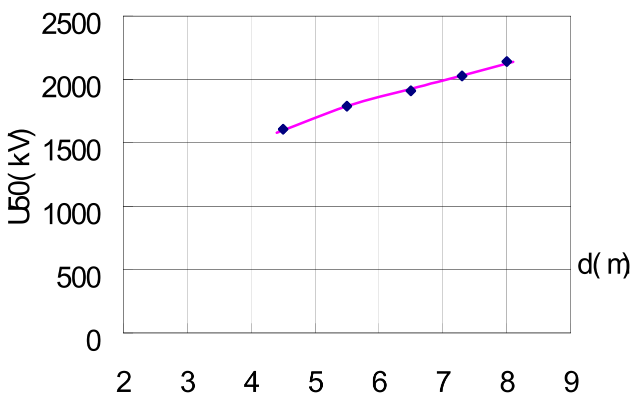


Fig-A. 11 The switching impulse flashover voltage characteristics of the conductor to tower post clearances

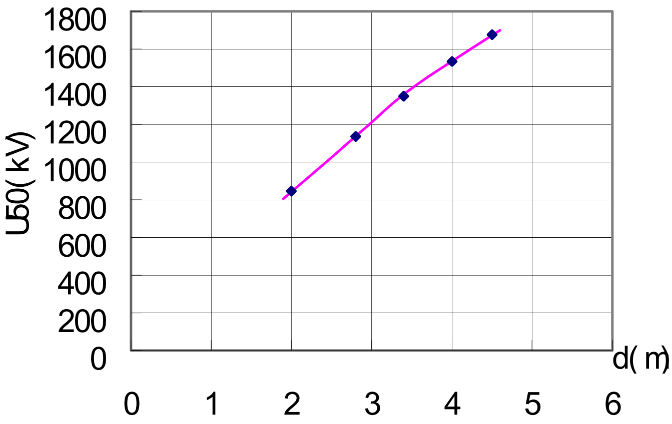


Fig-A. 12 The power frequency flashover voltage characteristics of the conductor to tower post clearances

A.3.3 The flashover voltage test results of the tube busbar to tower post clearances

For the test set-up of the substation, the height of the beam structure is 35m, the width of the tower post is 5m. The height of the centre of tube busbar is 16.5m. By adjusts the clearance between the outer layer of the tube busbar to the tower post to 4m, 5.1m, 5.7m and 7m respectively, the 50% lightning flashover voltage is achieved by standard lightning impulse voltages test. Also by adjusts the clearance to 4.35m, 5.5m, 6.4m, 7.4m and 8m respectively, the 50% switching flashover voltage is achieved by standard switching impulse voltages test.

By adjusts the clearance between the tube busbar to tower post to 2.1m, 2.6m, 3.3m, 3.9m and 4.3m respectively, the power frequency flashover voltage is achieved by power frequency voltage test.

The flashover voltage characteristics of the lightning impulse, switching impulse and power frequency voltages for the tube busbar to tower post clearances are shown in Fig-A. 13 ~ Fig-A. 15 respectively.

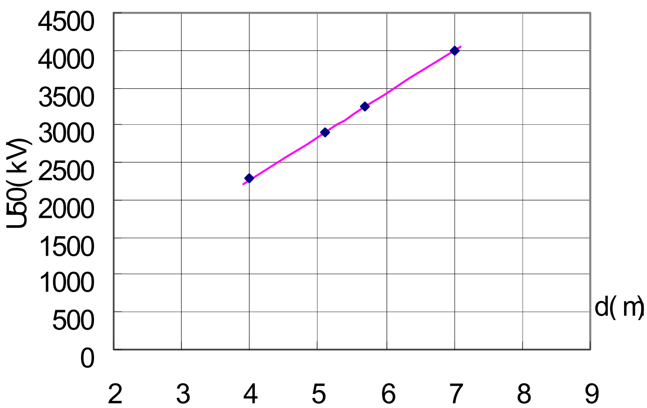


Fig-A. 13 The lightning impulse flashover voltage characteristics of the tube busbar to tower post clearances.

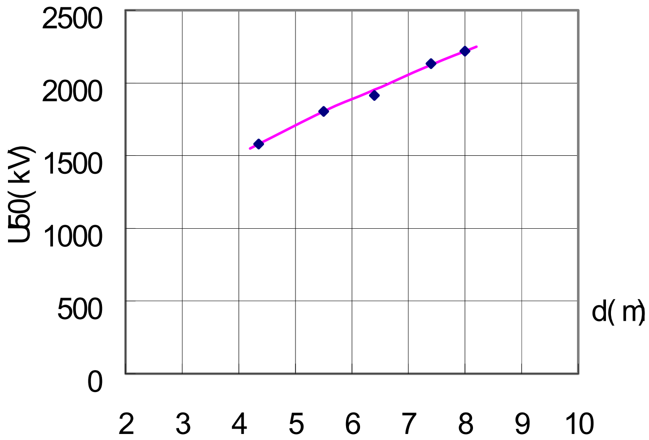


Fig-A. 14 The switching impulse flashover voltage characteristics of the tube busbar to tower post clearances

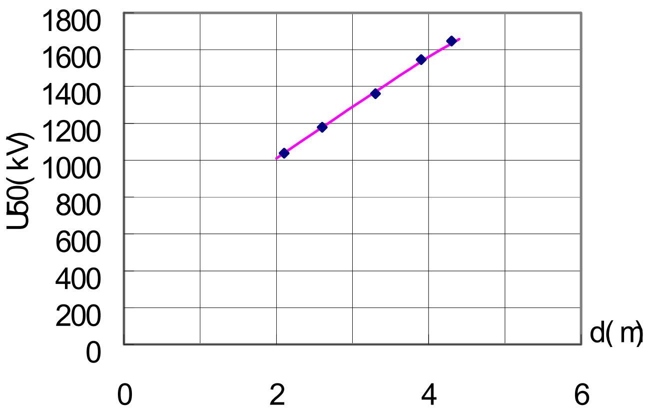


Fig-A. 15 The power frequency flashover voltage characteristics of the tube busbar to tower post clearances

A.3.4 The flashover voltage test results of the shielding ring to tower post clearances

For the test set-up, the height of the shielding ring to ground is 16.5m. The height of the beam structure is 35m, and the width of the tower post is 5m. By adjusts the clearance between the shielding ring to the tower post to 4m, 5m, 6.07m and 7.1m respectively, the 50% lightning flashover voltage is achieved by standard lightning impulse voltages test. Also by adjusts the clearance to 5m, 6m, 7.1m and 8.1m respectively, the 50% switching flashover voltage is achieved by standard switching impulse voltages test.

By adjusts the clearance between the shielding ring to tower post to 1.9m, 2.3m, 2.8m, 3.2m, 3.7m and 4.2m respectively, the power frequency flashover voltage is achieved by power frequency voltage test.

The flashover voltage characteristics of the lightning impulse, switching impulse and power frequency voltages for the shielding ring to tower post clearances are shown in Fig-A. 16~Fig-A. 18 respectively.

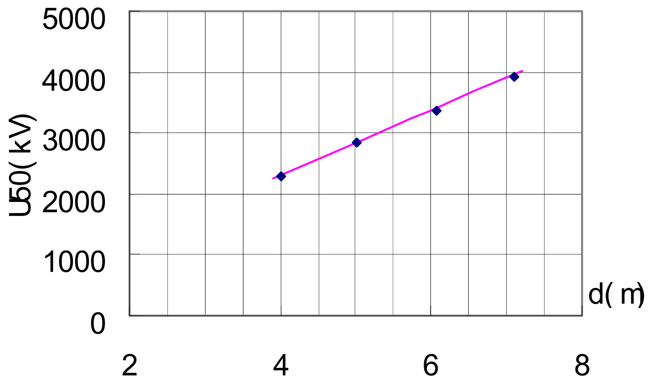


Fig-A. 16 The lightning impulse flashover voltage characteristics of the shielding ring to tower post clearances

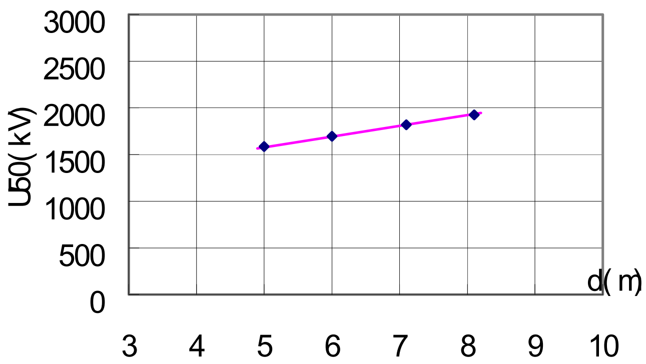


Fig-A. 17 The switching impulse flashover voltage characteristics of the shielding ring to tower post clearances

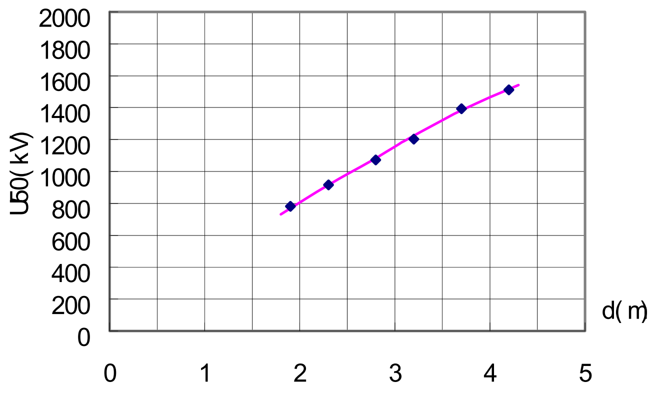


Fig-A. 18 The power frequency flashover voltage characteristics of the shielding ring to tower post clearances

A.4 The flashover voltage test results for the phase-phase air clearances of 1000kV substations

The impulse voltage for the phase-to-phase insulation test is not only depends on the sum of the positive and negative voltage value exerted between phases, but also depends on the ratio of the positive and negative voltage value. Generally, coefficient of voltage distribution $\alpha=U^-/(U^++U^-)$ is used to express the distribution ratio of positive and negative voltages. The α equal to 0.4 is selected in this test. Also α equal to 0.5 is selected for the test of 4-boundled conductors.

A.4.1 The flashover voltage test results of shielding ring to shielding ring clearances

For the test set-up, the height of the shielding ring to ground is 16.5m. The maximum diameter of the shielding rings is 2m. During test, two impulse voltage generators are used to generate positive and negative switching impulses to exert on the both shielding rings, and the ratio $\alpha=U^-/(U^+ + U^-)=0.4$. By adjusts the clearance between the outer layer of the shielding rings to 5m, 6m, 7m, 8m and 9m respectively, the 50% switching flashover voltage is achieved by standard switching impulse voltages test.

The flashover voltage characteristic of the switching impulse for the shielding ring to shielding ring clearances is shown in Fig-A. 19.

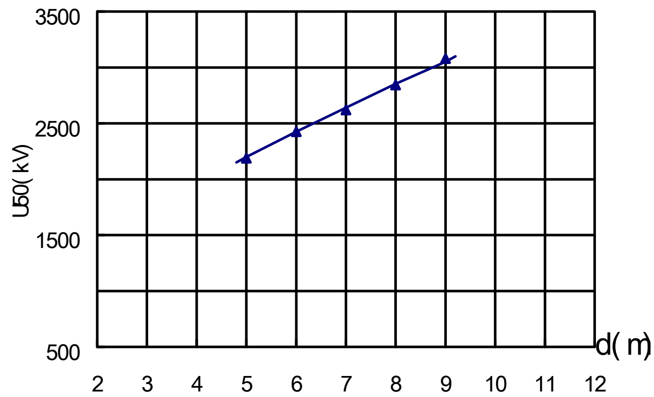


Fig-A. 19 The switching impulse flashover voltage characteristics of the shielding ring to shielding ring clearances. (a=0.4)

A.4.2 The flashover voltage test results of the bundle conductorto bundle conductor clearances

For the test set-up, the height of the two horizontal 4-bundled conductors to ground is 21.7m. The height of the beam structure is 35m. During test, two impulse voltage generators are used to generate positive and negative switching impulses to exert on the two 4-bundled conductors. The voltage distribution ratioα= 0.4 and 0.5. By adjusts the clearance between the outer layer of the two 4-bundled conductors to 5m, 6.2m, 6.8m, 7.7m and 9.2m respectively, the 50% switching flashover voltage is achieved by standard switching impulse voltages test.

The flashover voltage characteristics of the switching impulse for the bundle conductor to bundle conductor clearances is shown in Fig-A 20.

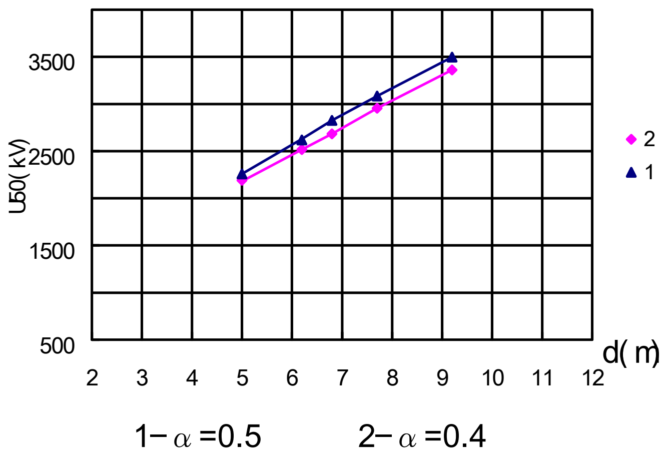


Fig-A 20 The switching impulse flashover voltage characteristics of the 4-bundled conductor to 4-bundled conductor clearances

A.4.3 The flashover voltage test results of tube busbar to tube busbar clearances

For the test set-up, the height of the two horizontally arranged tube busbars to ground is 16.5m. The height of the beam structure to ground is 35m. During test, two impulse voltage generators are used to generate positive and negative switching impulses to exert on the two tube busbars. The voltage distribution ratio α= 0.4. By adjusts the clearance between the outer layer of the two tube busbars to 5m, 6m, 7m, 8m and 9m respectively, the 50% switching flashover voltage is achieved by standard switching impulse voltages test.

The flashover voltage characteristic of the switching impulse for the tube busbar to tube busbar clearances is shown in Fig-A 21.

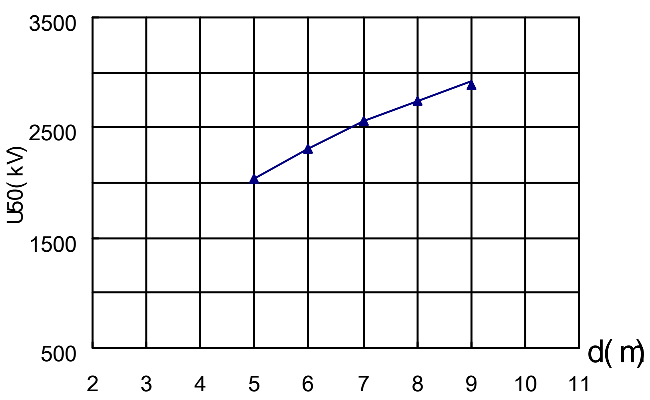


Fig-A 21 The switching impulse flashover voltage characteristics of the tube busbar to tube busbar clearances. (a=0.4)