

Introduction of Insulation Coordination for UHV AC Systems

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Abstract – This paper introduces the insulation coordination study results for UHV AC systems which was performed by CIGRE working group. The study results will be discussed within IEC technical committee in order to amend the IEC Insulation Coordination 60071-1 Ed. 8 2010 and 60071-2 Ed. 3, 1996. This paper includes the insulation coordination of transformer, gas insulated switchgear, metal oxide arresters and clearances of transmission towers. This article also illustrates the overvoltage specific to UHV systems such as TOV(temporary overvoltage), switching overvoltage, lightning overvoltage and VFTO(very fast transient overvoltage).

Keywords: Insulation coordination, UHV, Overvoltage, Surge arrester, TOV, VFTO

1. Introduction

Different countries in the world are planning and realizing UHV AC systems with operating voltages exceeding 800 kV. When planning a new power system, in particular at new voltage level, insulation coordination is one of the most important subjects. The main task is the determination of stresses and the assessment of the system and equipment installed.

The general procedure of insulation coordination is described in IEC 60071-1(2010). This standard does not give precise advice regarding new voltage levels although it provides insulation levels for Um values of both 1100 kV and 1200 kV. These insulation levels are based on both past experience available from former CIGRE work that also considered the 1000 kV voltage level, and recent works in Japan, China and India. In 1990's, metal oxide surge arresters have been applied to UHV substation design. Insulation coordination for UHV has been changed based on these arresters throughout substation and transmission line. Also, gas insulated switchgears have been generally applied to UHV substation design.

Considering the above issues, CIGRE working group C4.306 has reviewed and discussed insulation coordination practice in the UHV AC range taking into account the state-of-the-art technology, with special reference to surge arresters. Recommendation, for application guide IEC 60071-2 (1996) and IEC apparatus standards has been proposed.

2. Concept of Recent Practice on Insulation Coordination for the UHV AC System

The design of UHV and 800 kV power system should

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achieve both economic efficiency and high reliability while being capable of heavily loaded, long-distance transmission. UHV transmission lines and substation equipment are inherently large, therefore they should be designed as compact as possible by applying effective insulation coordination.

2.1 Insulation coordination research in UHV system by CIGRE and IEC

The general procedure of insulation coordination is described in IEC 60071-1(Insulation co-ordination- Part 1: Definitions, principles and rules), and IEC 60071-2 (Insulation co-ordination – Part 2 : Application guide). Insulation design of UHV system is required to achieve high reliability. UHV equipment sizes also tend to be large compared to lower voltage equipment. Therefore economical and highly reliable transmission lines and substations with environmental considerations are essential in the UHV system.

CIGRE had researched insulation coordination for UHV within previous CIGRE SC33 since 1970's, and published technical brochure No. 32(Final report of the UHV Ad Hoc Group, 1972), and technical brochure No.85(Ultra High Voltage Technology, 1994).

Rated insulation levels for UHV system are standardized in Amendment 1 of IEC 60071-1 Ed.8.1(March 2011). The standard specifies rational insulation levels with the assumptions that several higher performance surge arresters are installed at adequate locations, and utilities can choose the reasonable insulation level to meet their own specifications. The insulation levels in IEC 60071-1, LIWV (lightning impulse withstand level) for UHV systems are 1950, 2100, 2250, 2400, 2550, 2700 kV and SIWL (switching impulse withstand level) 1425, 1550, 1675, 1800, 1950 kV.

2.2 Recent practice of insulation coordination for UHV AC transmission system

Economical and highly reliable transmission lines and substations equipment with environmental consideration are essential in the UHV system. Therefore reducing the size of transmission lines and substation equipment are practical countermeasures. In Chinese, Indian, Japanese UHV projects, suppressing overvoltage by higher performance surge arresters is a common countermeasure, and additional countermeasures, such as suppressing overvoltage by the circuit breakers with closing and/or opening with pre-insertion resistors, are adopted in each shown in Fig. 1. In these projects, overvoltages are simulated by the latest analyzing technology such as EMTP(electro-magnetic transient program).

Fig. 2 shows the flow chart of insulation coordination referred from IEC 60071-1. The basic concept has not been changed, but the concept is desirable to be reviewed with

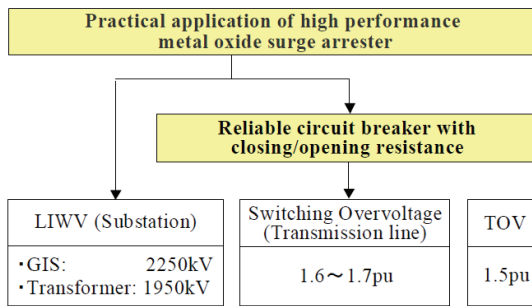


Fig. 1. UHV insulation coordination concept

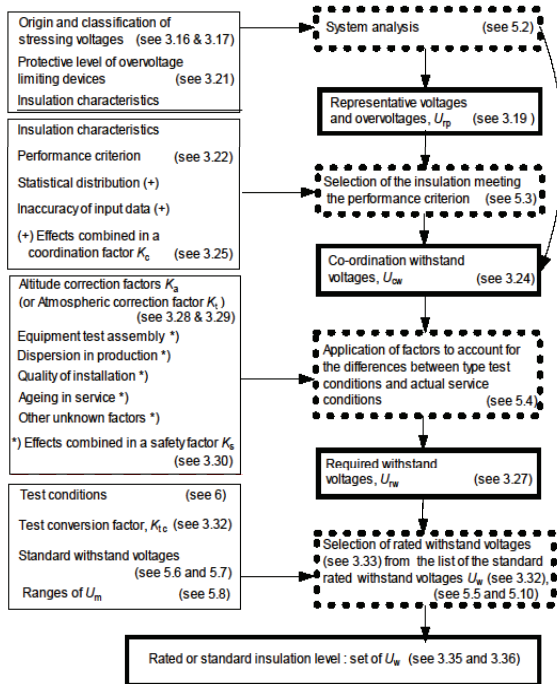


Fig. 2. Flowchart for the determination of rated or standard insulation level in IEC 60071-1

the latest point of view, by taking account of the analysis tool improvement, equipment quality improvement and safety factor which is included in analysis condition.

To design the substation equipment rationally, detailed analysis is more recommended than just applying the insulation level based on LIPL(lightning impulse protective level of a surge arrester) and SIPL(switching impulse protective level of a surge arresters), which are calculated by simplified method in IEC 60071-2, because the insulation level has much influence on the construction cost in UHV design.

2.3 Oervoltages specific to UHV AC transmission system

Overvoltages which need to be considered in designing UHV transmission lines and substation equipment are classified into four categories from the voltage characteristics as shown in Fig. 3.

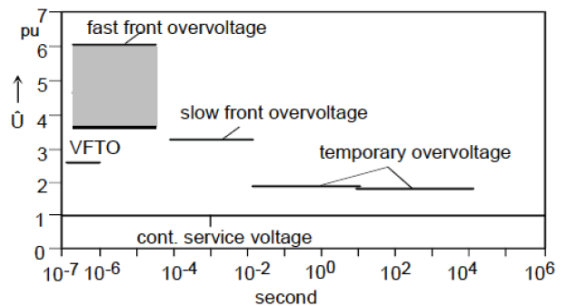


Fig. 3. Representative maxima of amplitude of overvoltages Um(p.u.)

2.3.1 Temporary Oervoltages (TOV)

TOV includes healthy phase overvoltages due to transmission line ground faults and load rejections. In the case of sudden load rejection on a heavy loaded, long line, such as a UHV system, the overvoltage about 1.3 - 1.5 p.u. This TOV is required not only to cover the peak voltage in the system, but also to cover the overvoltage generated during their operation. Therefore power frequency withstand test was verified in both long time range and short time range, because the voltage stress is different from both range.

2.3.2 Slow front Oervoltages (switching overvoltages)

The duration of wave front is about a few-hundred microseconds, such as the overvoltage in opening / closing transmission lines and ground fault. This switching overvoltages has much influence on the insulation design of towers, thus switching overvoltage is particular important for UHV systems because of the saturation effects of the air insulation distance on the switching impulse strength.

As shown in Fig. 4, for the 1100 kV voltage level, the flashover voltage of air insulated gaps for switching

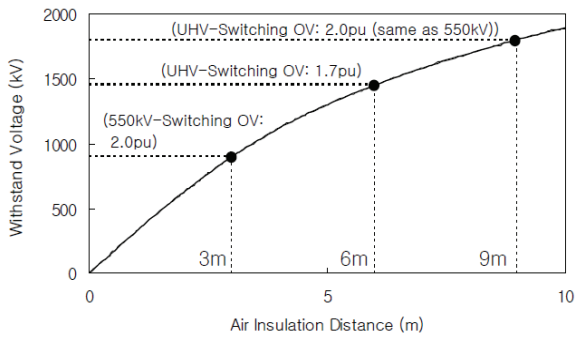


Fig. 4. Relation between air insulation and switching impulse withstand voltage

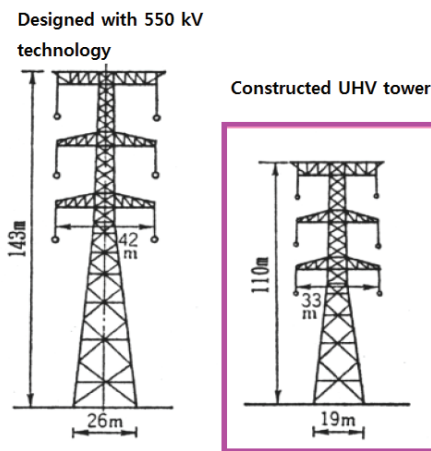


Fig. 5. Size reduction of 1100 kV double circuit tower

overvoltage has a tendency to saturate. Therefore, extremely high tower is required for air insulation. On the contrary, to reduce the construction cost of UHV system, switching overvoltages can be reduced by adopting circuit breakers with closing and/or opening resistors and high performance arrester. Fig. 4 shows the relation between air insulation distance and switching overvoltage, and Fig. 5 shows the comparison between the double circuit tower design based on 2.0 p.u. and 1.7 p.u.

2.3.3 Fast front Overvoltages (lightning overvoltages)

Lightning strokes terminating on UHV transmission lines can generate overvoltages of several mega volt depending on the front-steepness of the overvoltage and the height of the tower. Shielding failure as well as back-flashovers should be taken into account as shown in Fig. 6. Lightning overvoltage is the predominant factor for substation equipment design. Therefore overvoltages in the UHV substation are highly suppressed size reduction within a rational level by installing several higher performance surge arresters at adequate locations.

2.3.4 Very fast front Overvoltages (VFTO)

The GIS disconnector, when switching a charging current, repeats restriking and generate VFTO, which can

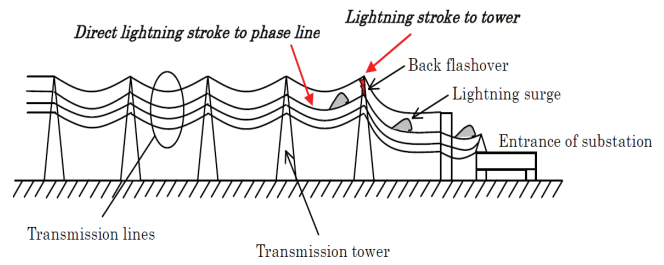


Fig. 6. Explanation of the invading lightning surge to substation

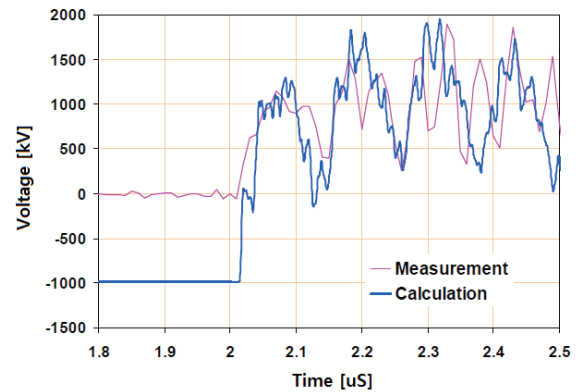


Fig. 7. VFTO calculation and measurement when switching busbars with a GIS DS as per IEC 62271-102, with pre-charging(China)

reach up to approximately 3.0 p.u. At a UHV substation, lightning overvoltages are effectively suppressed by higher performance surge arresters. Disconnector switching overvoltages are likely to exceed the lightning overvoltages if no countermeasures are adopted. Therefore, the resistors can be a suppression measure for the VFTO. Fig. 7 shows example of calculation and measurement of VFTO in UHV substation in China.

2.4 Selection of insulation level

Insulation coordination of substation and transmission lines can be achieved to set a reasonable insulation level voltage without sacrificing supply reliability by installing higher performance surge arresters on specific locations in substations, adopting resistor-fitted switching schemes of disconnectors and circuit breakers, and comprehensive

Table 1. Insulation levels of UHV AC substation

	Insulation level	China (1100kV Jindongnan)	Japan (1100kV ShinHaruna)	India (1200kV Bina)
TR	SIWL	1800 kV	1425 kV	1800 kV
	LIWL	2250 kV	1950 kV	2250 kV
GIS	SIWL	1800 kV	1550 kV	1800 kV
	LIWL	2400 kV	2250 kV	2400 kV
SA	V _{20kA}	1620 kV	1620 kV	1700 kV

Remarks : TR : transformer
 GIS : gas insulated switchgear
 SA : surge arrester
 V_{20kA} : residual voltage at 20 kilo-amperes

simulations and analysis of assumed overvoltage phenomenon. To select an appropriate insulation level, it is necessary to evaluate technical data and set reasonable margins to secure supply reliability. Table 1 shows substation designs and corresponding insulation levels of Chinese and Japanese projects.

2.5 Reduction of of insulation levels using overvoltage suppression measures

2.5.1 Overvoltage suppression with surge arresters

The higher performance surge arrester, which has better protective performance, has been utilized to suppress LIWV and SIWV. The reliability of higher performance surge arrester was confirmed throughout its massive application in 550 kV systems, and it is recognized as an effective measure to suppress power system overvoltages.

Recent UHV projects in China and Japan employ higher performance surge arresters with highest voltage of equipment of 1620 kV (1.80 p.u. at 20 kA) at 1100 kV system. On the other hand, a recent project in India is developing an arrester with highest voltage of equipment of 1700 kV (1.74 p.u. at 20 kA) at 1200 kV system. Typical locations of these higher performance arresters are transmission bays, busbars and transformer bays.

Table 2 shows the LIWVs and protective performance of arresters in recent projects. Although each project adopts different insulation levels due to differences in location of arresters and substation types, all projects succeeded in reducing insulation voltage level ranges: 1950 kV-2250 kV for transformers and 2250 kV-2400 kV for switchgears.

Fig. 8 shows the voltage versus current characteristics of

Table 2. Protective performance of surge arresters in substation projects

	China	Japan	India
Highest voltage (kV)	1100	1100	1200
Type of substation	GIS Hybrid	GIS	AIS
Residual vol.(@20 kA)(kV)	1620	1620	1700
LIWV (kV)	Transformer	1950	2250
	GIS and others	2400	2250

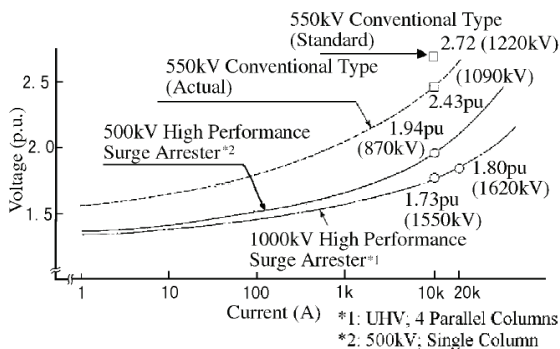


Fig. 8. V-I characteristics of UHV higher performance surge arrester

normal 500 kV surge arrester, high performance 500 kV surge arrester and 1000 kV high performance surge arrester.

2.5.2 Resister fitted circuit breakers

To suppress the switching overvoltage, pre-insertion resistor is employed for UHV circuit breakers. Chinese and Indian UHV projects introduce resistor-closing technique, while Japanese project introduces resistor-closing / opening technique.

Both techniques suppress switching overvoltages of transmission lines to below 1.7 p.u. The resistance of this switching scheme is usually between 500-700 Ω depending on the size of UHV system and its characteristics. Table 3 shows the insulation coordination of several UHV projects: (a) Closing overvoltage in Indian project and, (b) Opening overvoltage in Japanese project.

Table 3 Suppression methods and insulation designs

	China	Japan	India
Highest voltage (kV)	1100	1100	1200
Suppression of switching overvoltage	MOSA Closing R (600 Ω)	MOSA Closing & opening R (700 Ω)	MOSA Closing R (600 Ω)
SOV level (p.u.)	1.7	1.6/1.7	1.7

2.5.3 Resister fitted disconnectors

In gas insulated substations, the resistor-fitted disconnectors are commonly utilized to suppress switching overvoltages. Examples of applications of resistor-fitted disconnectors are shown in the Table 4 below. The GIS system with fast-operating disconnectors can suppress the disconnectors' overvoltage levels from 2.8 p.u. without the resistors to less than 1.3 p.u. with pre-insertion resistors. Fig. 9 shows the disconnector structure with pre-insertion resistor.

Table 4 Pre-insertion resistor for disconnectors

	China	Japan	India	
Highest voltage (kV)	1100	1100	1200	
Type of substation	GIS	Hybrid	GIS	AIS
Pre-insertion R (Ω)	500	None	500	None

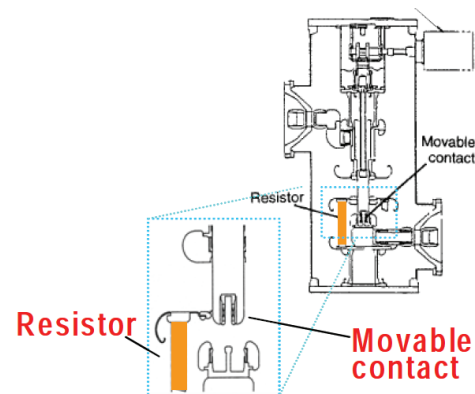


Fig. 9. Disconnector with pre-insertion resistor

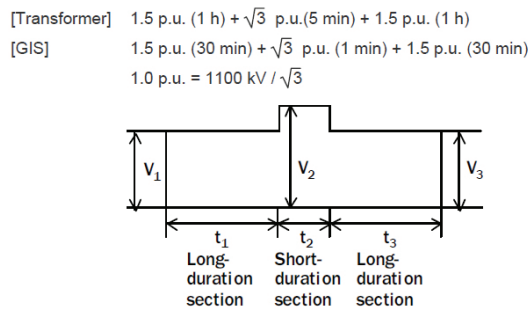


Fig. 10. Pattern of 1100 kV power frequency test voltage

2.6 Power frequency test voltage

UHV power frequency test voltages were decided based on partial discharge tests (“Long-duration tests”) as shown in Fig. 10. This test is not only aimed to confirm dielectric strengths, but also to verify strengths by inspecting whether or not partial discharges are generated as precursors of dielectric breakdowns throughout the test.

The test voltages are the combination of a short-duration section for verifying dielectric strengths to temporary overvoltages at one-line ground faults and load rejections, and a long-duration section for assuring long-term strengths to operating voltages

3. Summary of UHV insulation levels

In this study the safety factors can be selected instead of IEC recommended one(1.05 or 1.15 in IEC 60071-2) due to the improvement of manufacturing and quality control.

For the LIWL, either 1950 kV or 2250 kV for the LIWV of transformers, and 2250 kV or 2400 kV for other substation equipment are adopted.

Each country sets either 1425 kV or 1800 kV for SIWV of transformers, and 1550 kV or 1800 kV for the SIWV of other equipment

In cases where the calculated VFTO is higher than the withstand level, special measures to mitigate the VFTO such as damping resistors are required.

Japanese, Chinese and Indian UHV projects apply the long duration induced AC voltage test(ACLD) for the UHV power transformers.

4. Conclusion

In this paper, CIGRE WG(working group) technical report was introduced. Within the WG the insulation coordination practices in UHV AC taking into account the state-of-art technology.

Recommendations will be proposed to IEC 60071-2, “Application Guide”.

1) Recent practices of insulation coordination based on

- the higher performance surge arrester
- 2) Overvoltage estimation to peculiar to UHV
- 3) Air clearance in UHV range
- 4) Safety factor

Acknowledgements

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