21, rue d'Artois, F-75008 PARIS
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Recent activities of insulation coordination for UHV transmission systems in CIGRE C4 and IEC TC 28

Eiichi ZAIMA	Eung-Bo SHIM	Hideki MOTOYAMA
CRIEPI	KEPCO	CRIEPI
JAPAN	KOREA	JAPAN

SUMMARY

Economical and highly reliable transmission lines and substations equipment with environmental consideration are essential in the UHV system. Insulation coordination is a key technology of UHV transmission and substation design. Transmission line and substation should be technically and economically designed to be compact by suppressing overvoltage in UHV transmission system. Lightning overvoltage is reduced by the proper application of metal-oxide surge arrester with low protection level. And switching overvoltage is reduced by the combination of surge arrester with low protection level and opening/closing resistance.

In CIGRE, WG 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 and actual practices of Chinese, Indian and Japanese UHV projects. Study result was published the TB No. 542 in June, 2013. The TB covers recent practices of insulation coordination based on the higher performance surge arrester, overvoltage estimation to peculiar to UHV such as VFFO (Very Fast Front Overvoltage), conversion method for standard waveform, safety factor and air clearance in UHV range.

In IEC TC 28, regarding IEC 60071-1 (Insulation co-ordination - Part 1: Definitions, principles and rules), rated insulation levels for UHV system are standardized in Amendment 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. Regarding IEC 60071-2 (Insulation co-ordination - Part 2: Application guide), it has not been revised since 1996. New IEC TC 28/MT 9 started to revise 60071-2 based on the recommendation result of CIGRE WGC4.306 in November 2016. The revised items will be suppression method of overvoltage, overvoltage estimation to peculiar to UHV such as VFFO and recent practice of insulation coordination in UHV area. The revision will be expected to be published in 2018.

KEYWORDS

UHV, Insulation Coordination, 1100kV, 1200kV, Surge Arrester with Low Protection Level, VFFO, Waveform Evaluation, LIWV, SIWV, Application Guide

eiichi.zaima@mbr.nifty.com.

1. CIGRE C4 Activity

With a research on the insulation coordination for UHV conducted as an activity of the previous CIGRE SC33 from 1970's, CIGRE published the technical brochure No.32 (Final report of the UHV Ad Hoc Group, 1972), and the technical brochure No.85 (Ultra High Voltage Technology, 1994).

Metal oxide surge arresters have been applied to UHV substation design since 1990's. Insulation coordination for UHV has been changed in accordance with the application of the metal oxide surge arresters throughout substations and transmission lines. Gas insulated switchgears (GIS, Hybrid-IS) have also been applied to UHV substation design.

Considering the above issues, CIGRE WG C4.306 (Convenor: Dr. Eiichi Zaima) 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 and actual practices of Chinese, Indian and Japanese UHV projects. Such a review has been taken into account the accumulated knowledge of various CIGRE working bodies, and accomplished in collaboration with related CIGRE SC A3 and B3 (WG A3.22, A3.28, B3.22 and B3.29). And study result was published the TB (CIGRE Technical Brochure) No. 542 in June, 2013 [1]. The TB covers recent practices of insulation coordination based on the surge arrester with low protection level, overvoltage estimation to peculiar to UHV such as VFFO (Very fast front overvoltage), conversion method for standard waveform, safety factor and air clearance in UHV range. [1], [2]

1.1 Recent Practices on Insulation Coordination for UHV System

Economical and highly reliable transmission lines and substation equipment that account for environmental considerations are essential for the UHV system (Fig. 1). Air clearance in UHV systems may require a much longer distance than those in EHV, because the dielectric strength for switching overvoltage does not increase linearly with the air gap.

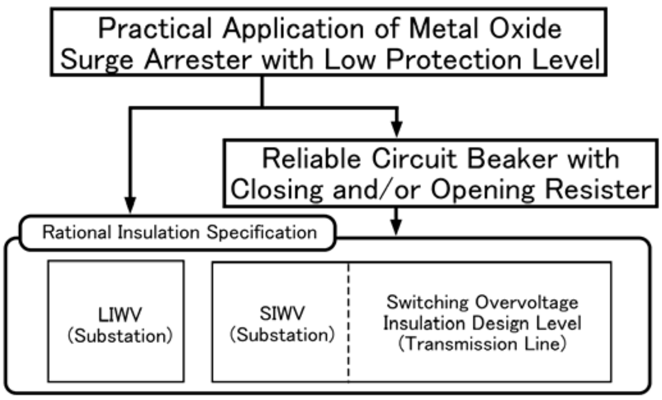
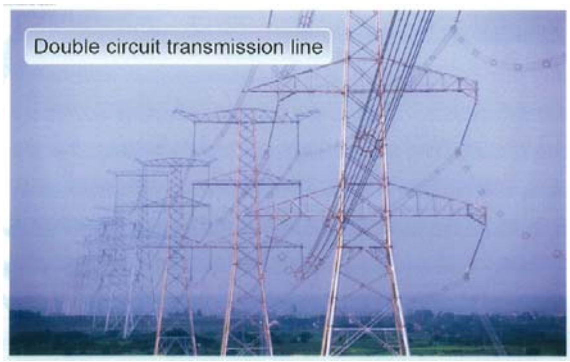


Fig. 1. Insulation coordination for UHV system.

In UHV projects of China, Japan and India (Fig. 2 (a)-(d)), suppressing overvoltage by surge arrester with low protection level, which has better protective performance to suppress LIWV (Lightning Impulse Withstand Voltage) and SIWV (Switching Impulse Withstand Voltage) is a common countermeasure, and additional countermeasures, such as suppressing overvoltage using circuit breakers with closing and/or opening with pre-insertion resistors, are adopted for each project. In these projects, overvoltages are simulated by the latest analyzing technology such as EMTP.

(a) UHV substation in China project. **(b)** UHV test station in Japan Project.



(c) UHV test station in India project. **(d)** UHV transmission line in China project.

Fig. 2. UHV projects in China, Japan and India

1.2 Overvoltage 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.

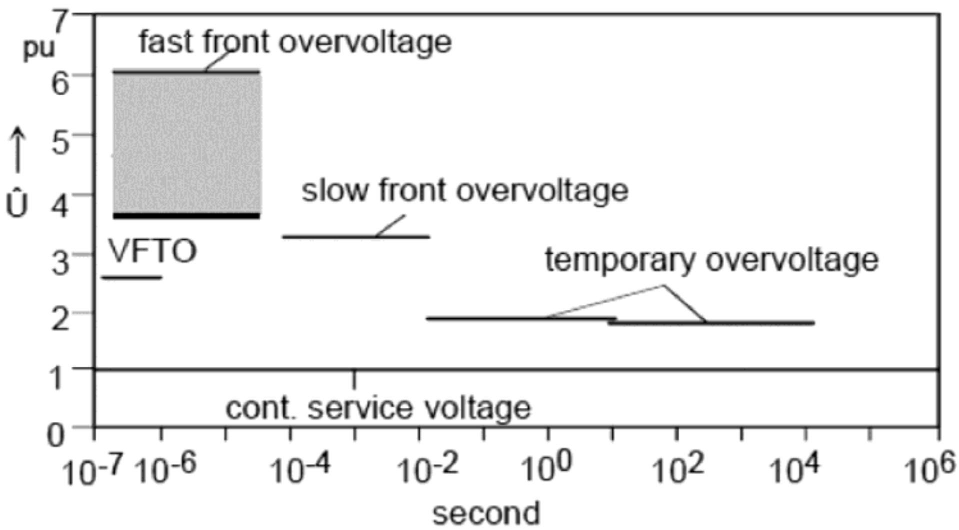


Fig. 3. Representative maxima of amplitude of overvoltages Um (p.u.)

1.2.1 TOV

The amplitude of the TOV (Temporary OverVoltage) levels and the energy absorption of the surge arrestor in the UHV systems are relatively higher than those in EHV systems.
In the UHV systems of various countries, the representative levels of temporary overvoltages range from 1.3 to 1.5 p.u. respectively. The energy absorption of the surge arrester for the temporary overvoltages of the UHV system is specified from 40 to 55 MJ, which is higher than those for the 800 kV and EHV systems

1.2.2 Switching overvoltage

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 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 resisters and surge arrester with low protection level. 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.

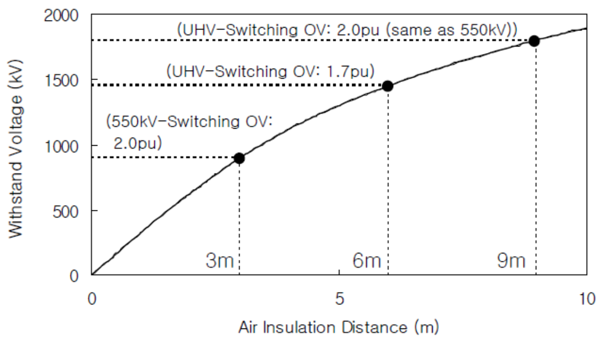


Fig. 4. Relation between air insulation distance and switching impulse withstand voltage.

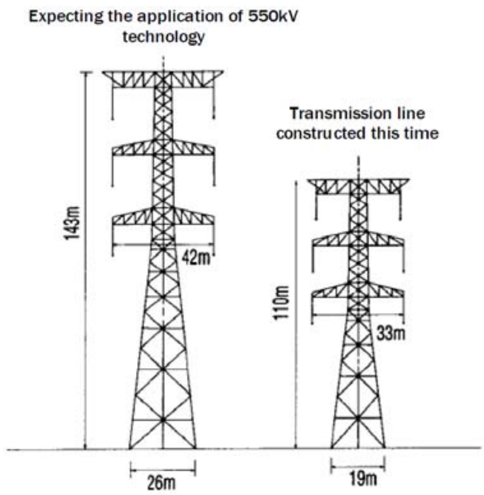


Fig. 5. Size reduction of 1100 kV double circuit tower,

1.2.3 Lightning overvoltage

The ratios of representative overvoltages to the LIPL (Lightning Impulse Protective Level) of a surge arrester for transformers in UHV systems range from 1.0 to 1.17 p.u. for the ratios for other equipment that range from 1.0 to 1.36 p.u. The ratios for UHV systems are likely to be smaller than those for 800 kV and the lower systems, because the overvoltage mitigation techniques such as higher performance arrestors can drastically reduce the lightning overvoltage levels.

1.4 Mitigation of overvoltages

1.4.1 Overvoltage suppression with surge arresters

The surge arrester with low protection level, 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 surge arresters with low protection levels 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 (Fig. 6). Typical locations of these arresters are transmission bays, busbars and transformer bays.

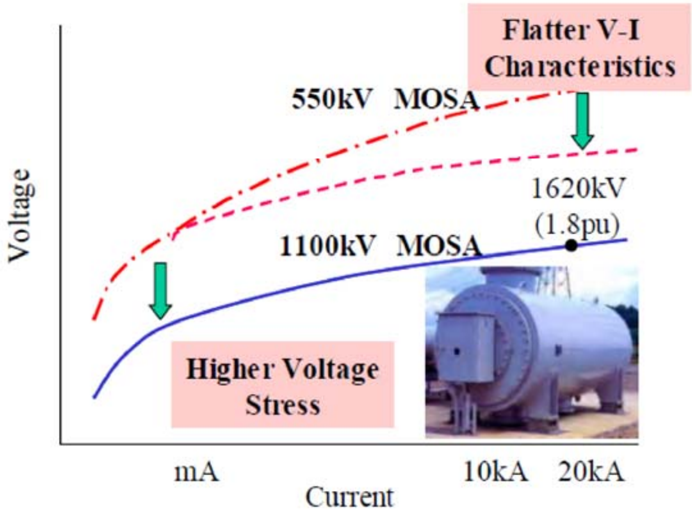


Fig. 6. Dead tank-type surge arrester with low protection level.

1.4.2 Switching overvoltage mitigation with 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 1 shows the insulation coordination of several UHV projects: (a) Closing overvoltage in Indian project and, (b) Opening overvoltage in Japanese project.

Table 1. Suppression methods and insulation designs.

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

1.3 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 surge arrester with low protection level on specific locations in substations, adopting resister-fitted switching schemes of disconnectors and circuit breakers, and comprehensive 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 2 shows substation designs and corresponding insulation levels of Chinese, Japanese and Indian projects respectively.

Table 2. Insulation levels of UHV AC substation.

	Insulation Level	China (Jindongnan)	Japan (Shin-Haruna)	India (Bina)
Highest voltage for equipment		1100 kV	1100 kV	1200 kV
Transformer	LIWV	2250 kV	1950 kV	2250 kV
	SIWV	1800 kV	1425 kV	1800 kV
GIS	LIWV	2400 kV	2250 kV	2400 kV
	SIWV	1800 kV	1550 kV	1800 kV
Surge arrester	V_{20kA}	1620 kV	1620 kV	1700 kV

[Note] GIS: Gas Insulated Switchgear, V_{20kA}: Residual voltage at 20 kA

2. IEC TC 28 (Insulation Coordination)

In IEC TC 28, 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). [3], [4]

2.1 IEC 60071-1

Regarding IEC 60071-1, rated insulation levels for UHV system are standardized in Amendment 1 Ed.8.1 (March 2011). The standard specifies rational insulation levels with the assumptions that several surge arresters with low protection levels 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 for UHV systems are 1950, 2100, 2250, 2400, 2550, 2700 kV and SIWV for UHV systems are 1425, 1550, 1675, 1800, 1950 kV (Table 3).

And IEC TC28/MT 10 (Convenor: Dr. Eung-Bo Shim) was established to maintain IEC 60071-1 in November 2014.

2.2 IEC 60071-2

Regarding IEC 60071-2, it has not been revised since 1996. New MT 9 (Convenor: Dr. Eiichi Zaima) started to revise 60071-2 (Application guide for insulation coordination) based on the recommendation result of CIGRE WGC4.306 in November 2014. The revised items will be suppression method of overvoltage, overvoltage estimation to peculiar to UHV and recent

Table 3. Standard insulation levels for 1100 kV and 1200 kV [3]

Highest voltage for equipment U_m kV (r.m.s. value)	Standard rated switching impulse withstand voltage			Standard rated lightning impulse withstand voltage [b] kV (peak value)
	Longitudinal insulation [a] kV (peak value)	Phase-to-earth kV (peak value)	Phase-to-phase (ratio to the phase-to-earth peak value)	
1 100	–	1 425 [d]	–	1 950
				2 100
	1 425	1 550	1,70	2 100
				2 250
	1 550	1 675	1,65	2 250
				2 400
	1 675	1 800	1,6	2 400
				2 550
1 200	1 550	1 675	1,70	2 100
				2 250
	1 675	1 800	1,65	2 250
				2 400
	1 800	1 950	1,60	2 550
				2 700

[d] This value is only applicable to the phase-to-earth insulation of single phase equipment not expose to air.

practice of insulation coordination in UHV area as described below. CD (Committee Draft) will be circulated in February 2016. The revision will be expected to be published in 2018.

2.2.1 Evaluation of VFFO (Very-fast-front overvoltage)

VFFO originate from disconnector operations or faults within GIS due to the fast breakdown of the gas gap and the nearly undamped surge propagation within the GIS. VFFO may be dangerous to the insulation of GIS, transformers and potential transformers. Experience show that very-fast-front overvoltages have no influence on the selection of rated withstand voltages up to system voltages of 800 kV.

Special care has to be taken for very-fast transients in GIS of UHV system because of the decreasing ratio of lightning impulse withstand voltage to the system voltage. A three step procedure is recommended for VFFO insulation co-ordination [6].

The amplitude of VFFO is specific for each disconnector design and depends mainly on the contact speed and the field homogeneity of the contact system. For slow acting disconnectors (contact speed < 1 m/s) the maximum trapped charge voltage lies well below 1 p.u. The resulting VFFO is in the range of 1.7 p.u. and reaches 2.0 p.u. for very specific cases. Fast acting disconnectors (contact speed > 1 m/s) exhibit trapped charge levels up to 1 p.u. Consequently generally higher VFFO are produced compared to the slow acting disconnector. In the most unfavorable case the maximum VFFO amplitude can reach 2.8 p.u. The integration of a damping resistor into the disconnector is a proven mitigation measure. VFFO amplitudes in the range around 1.3 p.u. can be reached.

2.2.2 Evaluation method of non-standard lightning impulse waveform

The actual field overvoltages of the non-standard lightning impulse waveforms are analyzed and the insulating characteristics of the SF6 gas and oil-filled transformer elements for these actual overvoltages are clarified to convert the waveform into the standard lightning impulse waveform. These techniques have been discussed in CIGRE SC A2, C4, and D1, and developed to CIGRE Technical Brochures [2][7][8][9].

The waveform evaluation methods developed above have already been put into practical use to apparatuses in the UHV and other lower voltage classes. According to them, the decay of the field overvoltage is generally large, making the insulation requirements not as severe as those of the standard lightning impulse waveform. Consequently, it could be possible in some cases to use lower withstand voltages.

3. Conclusion

This paper presents the recent activities of insulation coordination for UHV AC systems in CIGRE C4 and IEC TC 28.

CIGRE WG C4. 306 has reviewed and discussed insulation coordination practice in UHV AC taking into account the state-of-art technology and published the technical brochure No. 542.

IEC TC 28 has issued 60071-1 and has started the revision of 60071-2: Application guide on the recommendations by CIGRE TB. CD has been circulated in February, 2016.

Authors hope that these CIGRE and IEC activities will contribute the spread of UHV AC system development all over the world.

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