# Technical Requirements for Substation Equipment exceeding 800 kV AC

**Members:**
H. Ito (*Convenor*), A. Janssen (*Secretary*),
J. Amon F., S-W. Bahng, M. C. Bhatnagar, P. Boss,
J. Brunke, E. Colombo, R. Diaz, D. Dufournet, Y. Filion,
P. C. Fernandez, R. Gorur, A. Gilboulet, J. Jäger,
A. Keri, T. Kobayashi, M. Kosakada, E. Kynast, A. Lokhanin,
C. van der Merwe, M. de Nigris, V. Rashkes, D. Peelo,
B. Richter, H-D. Schlemper, B. Shperling, Y. Shirasaka,
R. Smeets, L. Stenström, M. Waldron, A. Wiersma,
J-W. Woo, Y. Yamagata, Yao Sili, R. Yeckley,
T. Yokota, L. van der Zel.

## Introduction

In recognition of a renewed interest in transmission voltages exceeding those in common usage today, SC A3 established WG A3.22 "Technical Requirements for Substation Equipment exceeding 800 kV". The WG was tasked with reviewing the worldwide state-of-the-art technical specifications for substation equipment rated at ≥ 800 kV, establishing the technical background for these specifications and making recommendations for the future standardization of Ultra High Voltage (UHV) substation equipment. A total of 39 international experts from 17 countries participated in these investigations and have produced a comprehensive survey of the state-of-the-art as presented in TB No. 362. The TB gives an overview of the characteristics of today's highest voltage systems in common use (735 to 800 kV) and of the various UHV projects around the world. Technical phenomena and technical specifications are compared and conclusions drawn regarding those areas which are well defined and those where further, more detailed, investigation is required before effective standardization can be achieved.

Whilst this work has been carried out within SC A3, contributions from, and co-ordination with, other SCs, have been essential to the successful conclusions of this stage of the work.

## Background

In the 1970's and 1980's the first test installations were established to explore AC transmission levels above 1 000 kV. Long term testing and operation of a 1 200 kV rated voltage network was carried out in the former USSR whilst pilot trials were carried out at 1 800 kV. In the USA, BPA and AEP ran pilots at 1 200 kV and 1 500 kV respectively and in Italy, during the 1990's, a two year pilot 1 050 kV project was in service. Finally, in Japan, an 1 100 kV pilot was established in 1996 with 430 km of overhead lines. This remains in service, operated at 550 kV.

Today, commercial operation of UHV systems is foreseen in China, India and Japan. The potential future exploitation the hydropower potential of the Amazon River, and the need to transport electric energy along a distance of 2 500 km, may prompt similar developments in Brazil.

The prospect of new commercial developments has created a demand for standardization in the field of UHV technology. By drawing together experts and experience from the past UHV projects and from the development work being done in China and India, ● ● ●

CIGRE aims to establish a sound technical basis for such standardization. As a first step, the TB effectively establishes the necessary scope of UHV standardization and highlights technical topics where further investigation is required. These further investigations are being undertaken both within SC A3 and within other SC's as appropriate to ensure that CIGRE is able to establish comprehensive guidance for use by the relevant standards making bodies.

## Technical overview

Table 1, below, summarizes the main technical issues affecting UHV AC substation equipment which are addressed by the TB. In particular, the use of large diameter, multi-bundle conductors and large-capacity power transformers create distinctive phenomena. The use of high performance surge arresters to effectively limit overvoltages forms an integral part of the design of some UHV systems.

For both technical and economic reasons optimisation of insulation coordination is a critical aspect of UHV systems. The use of high performance metal oxide surge arresters (MOSAs) in combination with sophisticated design based on accurate computer-aided simulations is common practice. Suppression of switching overvoltages is a pre-requisite for air clearances in order to reduce the height of transmission towers and the dimensions of open-air parts in substations. Conversely, lightning overvoltages dominate the non-self-restoring internal insulation design of substation equipment making it vital to control these by means of properly applied MOSAs e.g. at line entrances, busbars and transformers. Utility policy regarding acceptable withstand margins for severe lightning or switching conditions with a very low probability of occurrence (figure 2) remains a key design parameter.

Beyond basic insulation co-ordination, several distinctive phenomena become important in UHV systems such as prominent Ferranti effect, large short-circuit DC time constants, severe transient recovery voltages (TRVs) and prolonged secondary arcs. Further analysis of these topics forms a significant part of WG A3.22's ongoing pre-standardization activities however progress to date is summarised in the following paragraphs. ● ● ●

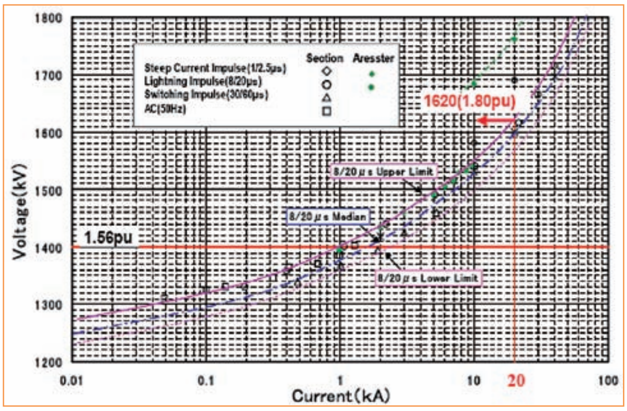

Figure 1: Example of -VI characteristics of high-performance MOSA

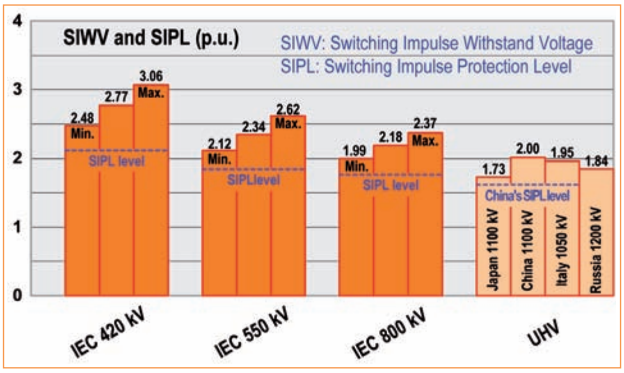

Figure 2: SIWV and LIWV

| Phenomena peculiar to UHV | Equipment | CIGRE SC | IEC TC |
|---|---|---|---|
| Prominent Ferranti effect and TOV due to large capacitance of overhead lines | Surge Arrester<br>Shunt Reactor | A2, A3, B3, C4 | 14, 17, 37 |
| Possibly reduced corona onset voltage with increased corona losses and audibel noise | Line<br>Substation (AIS) | B2, B3 | 11 |
| Prolonged secondary arc extinction time due to higher induced voltage | 4-Legged Reactor<br>HSGS, GCB | A2, A3, B3, C4 | 14, 17, 28 |
| Higher slow front overvoltage at grounding fault occurence due to low damping of traveling waves | Circuit Breaker<br>Surge Arrester | A3, B3, C4 | 17, 37 |
| High amplitude factor in TRVs due to low losses of power transformers and transmission lines | Circuit Breaker<br>Surge Arrester | A3, B3, C4 | 17, 37 |
| High TRV peak value for out-of-phase due to low damping of traveling waves | Circuit Breaker<br>Surge Arrester | A3, B3, C4 | 17, 37 |
| Reduced line surge impedances due to multi-bundle conductors with large diameter | Circuit Breaker | A3, B3 | 17 |
| Large time constant of DC component in fault current due to low losses of transformers and lines | Circuit Breaker | A3, B3 | 17 |
| Reduced first-pole-to-clear factor due to small zero-sequence impedance in the UHV systems | Circuit Breaker | A3, B3 | 17 |
| Severe VFTO due to geometry and topology of UHV substation such as MTS | Circuit Breaker<br>GIS, MTS | A3, B3 | 17 |

*MTS: Mixed Technologies Substation*

Table 1: Specific issues for UHV AC systems

## Specific technical topics

Large power generators and large capacity, low loss, power transformers lead to a high X/R ratios and hence high short-circuit DC time constants. Similarly transmission lines employing large diameter, multi-bundle conductors in order to reduce corona noise and increase transmission capacity tend to increase DC time constants compared to present assumptions in the international standards (IEC 62271-100) where a special case value of 75 ms for rated voltages 550 kV is recognised. The present situation derived from worldwide experience is summarised in Table 2.

Definition of the TRV envelope specified for the circuit-breaker interrupting duties must take account of the first-pole-to-clear (FPTC) factor which itself is dependant upon the X0/X1 ratio of the system at the location of the circuit-breaker. Overhead lines typically have X0/X1 ratios of around three whilst the same ratio for large transformers is typically less than or equal to one. Present standards assume transmission networks to be effectively earthed and have a significant fault in-feed from overhead line sources and hence specify a FPTC factor of 1.3. However, since UHV networks are likely to be of non-meshed, largely linear layout, the short-circuit contribution from large transformers is likely to dominate leading to the potential to specify a FPTC factor of less than 1.3.

In a similar vein, the equivalent surge impedance of the overhead lines defines the short-line fault (SLF) interrupting conditions applied to line circuit-breakers. The key aspect of UHV systems which must be considered for short-line fault interruption is the likelihood of conductor bundle collapse during the passage of fault current. Presently, circuit-breaker standards assume a surge impedance of 450 Ω which is based on a fully collapsed conductor bundle whereas the large 6 or 8 conductor bundles applied at UHV are unlikely to collapse fully within the 100-200 ms fault interruption window. This being the case there may be scope for reducing the surge impedance and hence the severity of the SLF interrupting duty for UHV applications. Table 3 summarises surge impedances resulting from typical UHV line designs which are, themselves, summarised in Figure 3.

The equivalent surge impedances also play a role in clearing Long Line Faults (LLF) and Out-of-Phase currents (OP).

• • •

| **Maximum voltage** | **Conductors** | | **DC time constant (ms)** |
|---|---|---|---|
| | **Size (mm$^2$)** | **Bundle** | |
| **765kV (Canada)** | 686 | 4 | 75 |
| **800kV (USA)** | 572 | 6 | 89 |
| **800 kV (South Africa)** | 428 | 6 | 67 |
| **800 kV (Brazil)** | 603 | 4 | 88 |
| **800 kV (China)** | 400 | 6 | 75 |
| **1,200 kV (Russian)** | 400 | 8 | 91 |
| **1,050 kV (Italy)** | 520 | 8 | 100 |
| **1,100 kV (Japan)** | 810 | 8 | 150 |
| **1,100 kV (China)** | 500 | 8 | 120 |

Table 2: DC time constant of short-circuit currents in EHV / UHV transmission lines

| **Highest voltage (kV)** | ***Conductor*** **Size (mm$^2$)** | **Number of conductor** | **Conditions (TRV Frequency)** | **$Z_0$ (ohm)** | **$Z_1$ (ohm)** | **Equivalent surge impedance (ohm)** | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | **1st pole** | **2nd pole** | **3rd pole** |
| 550 (Japan) | 410 | 6 | Normal conduction (60 kHz) | 444 | 226 | 270 | 281 | 299 |
| | | | Bundle contraction (60 kHz) | 580 | 355 | 408 | 417 | 430 |
| 800 (South Africa) | 428 | 6 | Normal conduction (27.5 kHz) | 403 | 254 | 290 | 296 | 304 |
| | | | Bundle contraction (27.5 kHz) | 509 | 359 | 398 | 403 | 409 |
| 1,050 (Italy) | 520 | 8 | Normal conduction (26.2 kHz) | 406 | 210 | 250 | 260 | 275 |
| | | | Bundle contraction (26.2 kHz) | 532 | 343 | 389 | 396 | 406 |
| 1,100 (Japan) | 810 | 8 | Normal conduction (25 kHz) | 476 | 228 | 276 | 289 | 311 |
| | | | Bundle contraction (25 kHz) | 595 | 339 | 396 | 407 | 424 |

Table 3: Surge impedance of UHV transmission lines

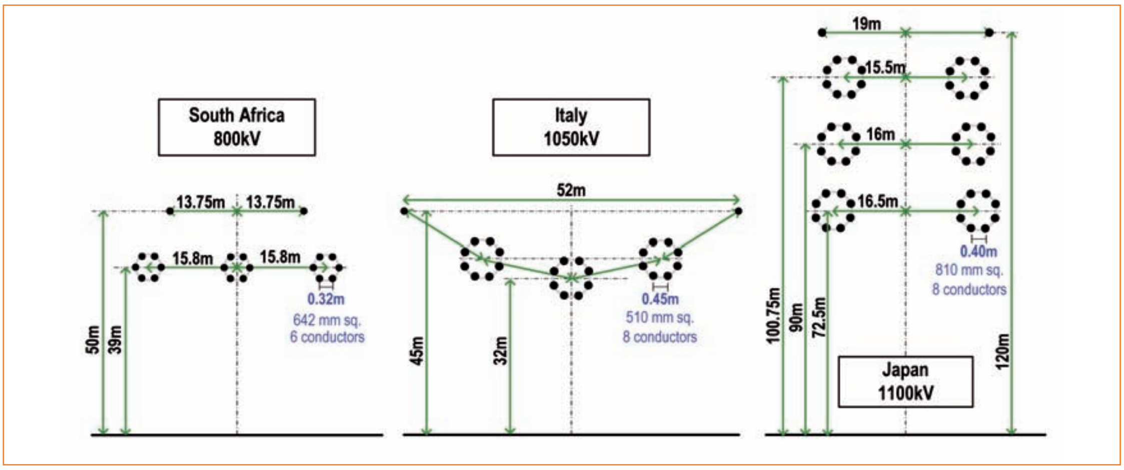

Figure 3: Line configurations for UHV lines of Table 3

Peak values of TRV's, particularly those associated with terminal faults and transformer limited faults can also be alleviated by the use of metal oxide arresters as shown in Figure 4.

Other circuit-breaker related topics presented in TB 362 include high-frequency components in the short-circuit currents, the impact of opening resistors, the impact of series capacitor banks, capacitive current switching, shunt reactor switching and controlled switching.

Beyond circuit-breakers, topics such as very fast transient overvoltages (generated by disconnector switching in GIS), bus transfer switching, capacitive and inductive current switching disconnectors and/or earthing switches and the application of High Speed Grounding Switches (HSGS) in order to control secondary arcs are considered. Regarding secondary arc control, the arc extinction time is an important parameter which determines the minimum dead time for rapid auto-reclosing whilst the recovery voltage is an important parameter which determines the likelihood of successfully extinguishing the secondary arc. Various methods of secondary arc control are discussed, including three-pole auto-reclosing, single-pole auto-reclosing utilising a four-legged shunt reactor and the application of switched shunt reactors and a comparison of methods is shown in Figure 5.

Finally, equipment and phenomena addressed include surge arresters, equivalent surge capacitances of transformers, radio interference, corona losses and audible noise. ■

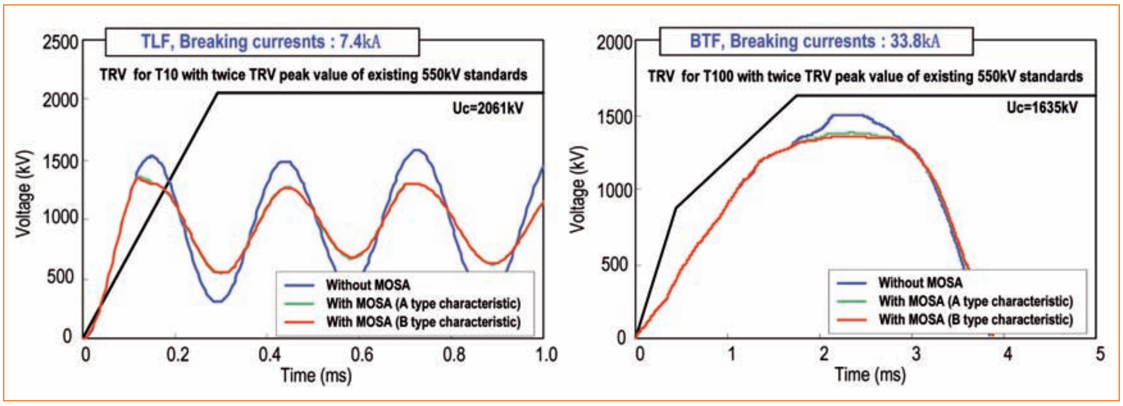

Figure 4: Effect of MOSA on TRV peak values

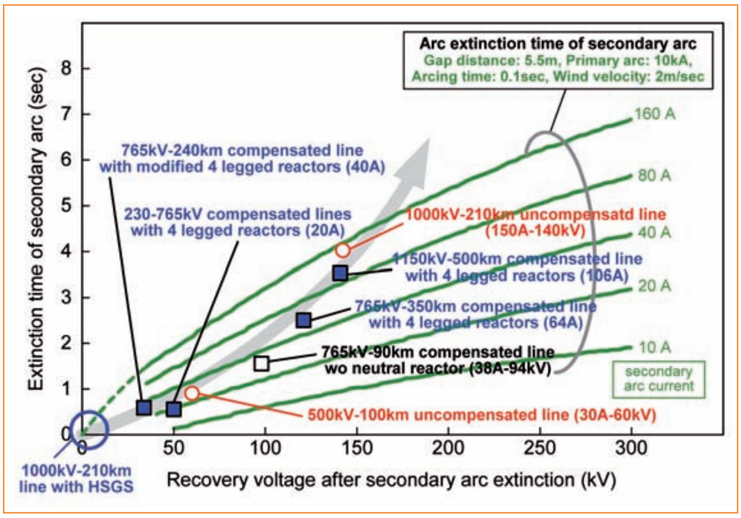

Figure 5: Extinction time and recovery voltage for several secondary arc control techniques

**BROCHURE N° 362**

(en anglais seulement)
*(in English only)*

En vente au Bureau Central
*On sale at the Central Office*

Prix Membres / *Member Price :*
90 €

Prix non-Membres / *Non-Member Price :*
180 €

Contact
Fax +33 (1) 53 89 12 99
e-mail : publications@cigre.org
http: //www.e-cigre.org