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Measurements and Simulations of Very Fast Transients during Disconnector Type Testing in UHV Gas-Insulated Switchgear

Abstract. Increasing power demand in China requires an efficient and reliable transmission system at highest voltage levels of 1100 kV AC. The paper presents measurement and simulation results performed for UHV disconnector testing in demonstration pilot project in China. Very Fast Transient Overvoltages impact on the disconnector design is investigated. A new approach of Trapped Charge Voltage analysis is presented which allows one to select the design optimized for more realistic calculation of overvoltages due to the disconnector operations.

Streszczenie. Rosnące zapotrzebowanie na moc elektryczną w Chinach skutkuje ciągłym podwyższaniem napięć przesyłowych w celu ograniczenia strat mocy. W gazowych rozdzielnicach najwyższych napięć istotnym zagadnieniem jest analiza przepięć spowodowanych operacją odłącznika. W artykule przedstawiono wyniki pomiarów i symulacji przeprowadzonych w układzie próby typu odłącznika w celu ograniczania przepięć poprzez zmianę prędkości rozchodzenia się styków odłącznika. (Pomiary i symulacje przepięć szybkozmiennych w gazowych rozdzielnicach najwyższych napięć w układzie próby typu odłącznika).

Keywords: Gas Insulated Switchgear, Very Fast Transient overvoltages, disconnector switch, insulation coordination.
Słowa kluczowe: rozdzielnica GIS, szybkozmienne przepięcia, odłącznik, koordynacja izolacji.

Introduction

Ultra High Voltage (UHV) transmission system in China was designed to operate at 1100 kV AC voltage to satisfy the constantly increasing electrical power demand. The power is delivered with limited transmission losses over some thousand kilometers from huge hydro plants located in south-west part of the country to the megacities load centers in the east.

Reliable switchgears are core elements for any transmission system. Application of Gas-Insulated Switchgear (GIS) technology provides increase of reliability and space reduction when compared to Air-Insulated Switchgear (AIS). GIS technology proved its feasibility for UHV transmission in Jingdongnan-Nanyang-Jingmen 1100 kV pilot project in China [1].
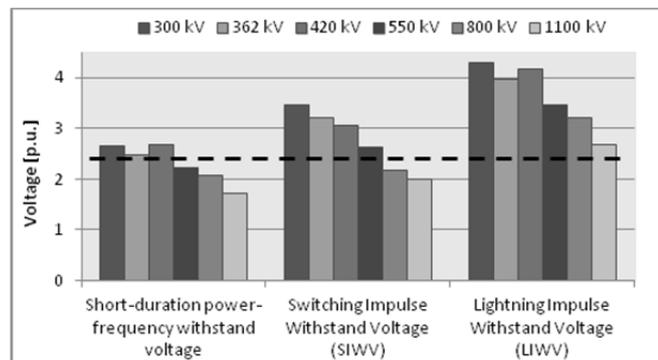

Fig.1. Rated insulation levels according to [2]

Insulation levels determine the dielectric design of substation equipment and towers. According to Fig. 1, insulation levels decrease for higher rated voltage levels, as defined in IEC standard [2]. For the demonstration project in China, the Lightning Impulse Withstand Voltage (LIWV) is specified as 2400 kV (2.67 p.u.) [1]. The Very Fast Transient Overvoltage (VFTO) withstand level for insulation coordination was specified for the Chinese pilot project by a safety factor of 1.15 which is 2087 kV (2.32 p.u.).

Due to the decreased insulation levels, VFTO are of special concern in UHV substations, and may even become a dimensioning factor for the GIS design. Since the LIWV is the base for the GIS design, UHV GIS elements must be designed so that breakdown caused by VFTO is improbable. This means, that the actual VFTO cannot exceed the specified VFTO withstand level.

Very Fast Transient Overvoltages in Gas-Insulated Switchgear

The main origins of VFTO in GIS are: operations of disconnectors, and breakdowns to earth in SF_6 gas. The disconnectors operate on regular basis, while the breakdowns to the grounded enclosures are eliminated by proper design of the GIS elements. Operations of other switches in GIS, such as circuit breakers, load-, and earthing switches also generate VFTO but they are not likely to cause any thread to the insulating system. Circuit breakers operate with much higher speed compared with disconnectors (tens of milliseconds compare with few seconds), thus only few breakdowns occur during the operating time of the circuit breaker compared with hundreds in the case of the disconnector operation. Moreover, the worst breakdown during the circuit breaker operation is likely to have insignificant amplitude. In the case of the earthing switch, the voltage drop between contacts before the breakdown is limited to 1 p.u.

During disconnector operation a significant number of pre- or re-strikes occur, depending on the speed of the disconnector moving contact and the Breakdown Voltage Characteristics (BDV) of the sparking gap. Due to the short time of the voltage breakdown in SF_6 gas, of a few nanoseconds, travelling surges of steep fronts are generated in the bus ducts. The surges are reflected at any surge impedance discontinuity, giving rise to complex waveforms of VFTO. The resultant VFTO thus depends on the GIS elements design and GIS and external substation layout and configuration. Since there is almost no coupling between the inner conductors and the outer enclosures, the VFTO inside the GIS experience very little damping even over a long period of time.

Disconnector type testing

According to the Toepler's law [3], the breakdown time in the GIS depends on several factors, including SF_6 gas pressure. The time differs from one design to another as the gas pressure in the GIS is selected specifically for a given design. Thus, no standard impulse voltage waveform can be specified for testing, as it is in the case of the lightning impulse voltage (1.2/50 μs). In consequence, type testing for VFTO is performed in a Test Duty set-up, in which the

operations of the disconnector generate VFTO of maximum peak values for a real disconnector design and also the highest possible in a GIS substation layout.

According to IEC 62271-102 [4], the Test Duty 1 (TD1) is intended to prove a proper electrical design of the disconnector by lack of flashovers to grounded elements when switching of a very short section of GIS busbar duct.
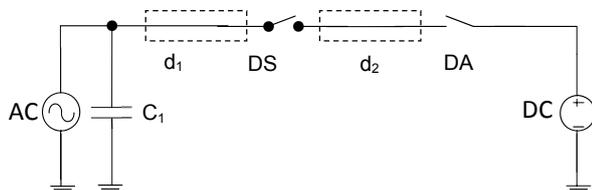

Fig.2. Test Duty 1 set-up according to IEC 62271-102 [4]

In Fig. 2 the Test Duty 1 (TD1) set-up is presented. According to the IEC standard, the source voltage is equal to 1.1 p.u. of the nominal voltage. The source side of the disconnector DS is represented by a GIS busbar d_1 of length between 5.5 m and 14 m, the load side of the disconnector is represented by the GIS busbar d_2 of length between 3 and 5 meters, and the ratio between these two lengths is in the rage of 0.36 and 0.52. The capacitance C_1 is selected in such a way that VFTO with no pre-charged load side (TCV = 0 V) is at least 1.4 p.u. and the time to peak is no more than 500 ns. The disconnector testing process in TD1 is carried out by several opening and closing operations of the DS element. During closing of the disconnector, its load side is pre-charged with the DC voltage to the worst-case value of -1.0 p.u. During charging, the auxiliary disconnector DA is closed, while after charging DA is opened. TD1 is a type test and is mandatory for every disconnector design.
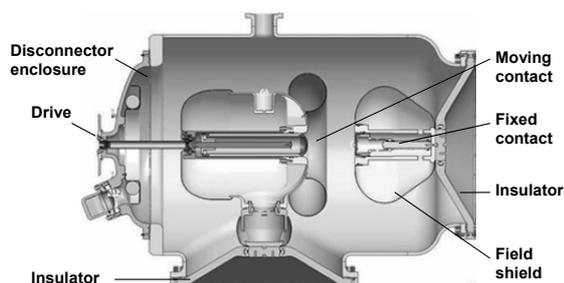

Fig.3. Cross section of a GIS disconnector

Disconnector design

The design of the UHV disconnector is based on the maximum VFTO peak value, that occurs when switching, and its reference to the rated LIWV of the equipment. If the maximum VFTO produced during switching reaches the VFTO withstand level, it is necessary to redesign the disconnector or to suppress severe VFTO for the insulation co-ordination.

Fig. 3 shows a cross-section of the UHV GIS disconnector, with fixed and moving contacts indicated. The contacts are asymmetrical and their design minimizes the degree of field inhomogeneity and also allows for avoiding disruptive flashovers to the earthed enclosure.

To suppress VFTO, the disconnector contact system can be equipped with a closing resistor, typically of 500 Ω. According to reliability requirements for the GIS, the closing resistor can be seen as a weak link due to the high energy dissipated during the process and the potential breakdown across. Also, the closing resistor has negative impact on the

cost of the disconnector, regarding both manufacturing and maintenance.

It can be demonstrated that the closing resistor is not necessary if the real value of Trapped Charge Voltage is assumed for VFTO calculation.

Trapped Charge Voltage impact on Very Fast Transient Overvoltages

When the disconnector opening operation is completed, after the occurrence of the last re-strike, the Trapped Charge Voltage (TCV) remains on the load side of the disconnector. The trapped charge decay is a very slow process, taking hours or days, resulting from the charge leakage across the insulators (see Fig. 3). During the subsequent closing operation of the disconnector, due to the slow moving contact speed, the first pre-strike occurs when the source side voltage reaches its amplitude with opposite polarity of the load side voltage (Trapped Charge Voltage) resulting from the preceding operation.

The maximum peak value of VFTO depends on the voltage drop across the disconnector contacts just before the breakdown occurs, thus the VFTO amplitude is directly affected by the TCV value. The actual TCV remaining on the load side of the disconnector should be taken into consideration when calculating VFTO.

The Trapped Charge Voltage is specific for each disconnector design (contact geometry, gas pressure, speed of moving contacts) and could be analyzed during measurements and also simulated with high accuracy as a basis for the insulation co-ordination.

Measurements and simulations of Very Fast Transient Overvoltages in the Test Duty set-up

In Fig. 4, measured and simulated VFTO waveforms are presented for opening operation of the disconnector. The results were obtained in the TD1 setup for 1100 kV. Voltage waveforms were measured at the source side (Fig. 4, red color) and the load side (Fig. 4, green color) of the disconnector. A capacitive voltage divider was used for the measurement. The input impedance of the measuring device leads to an decrease of the measured DC voltage with a time constant of 17.5 ms, as indicated in Fig. 4a. The disconnector contact speed was 0.39 m/s.

To evaluate the models accuracy, the same layout of 1100 kV TD1 was simulated in EMTP/ATP software [5]. Because of the complex nature of the VFTO, every GIS element was represented as an equivalent model. Bus-bars were modeled as lossless lines with disturbed parameters characterized by lengths and surge impedances defined by the dimensions. The characteristic parameters of each bus-bar were calculated either from the analytical formulas for coaxial lines or by numeric calculation of electric field energy density. Formulas (1) define capacitances and inductances of coaxial line, where r_{out} is the outer and r_{in} is the inner radius with μ, ε material permeability and permittivity.

$$(1) \qquad C_0 = \frac{2\pi\varepsilon}{\ln(r_{out}/r_{in})}, \quad L_0 = \frac{\mu}{2\pi}\ln\left(\frac{r_{out}}{r_{in}}\right)$$

For modeling of the disconnector, a real breakdown voltage characteristic (BDV) was implemented, taking into account the moving contact speed and the contacts asymmetry for negative and positive polarization [6]. The auxiliary disconnector was modeled as a series capacitance and the two capacitances to ground. The source voltage value of was set to 1.1 p.u. For each of the disconnector operation, simulations were performed until the BDV

became greater than 2.2 p.u. Since that time, no breakdown between contacts can be observed.
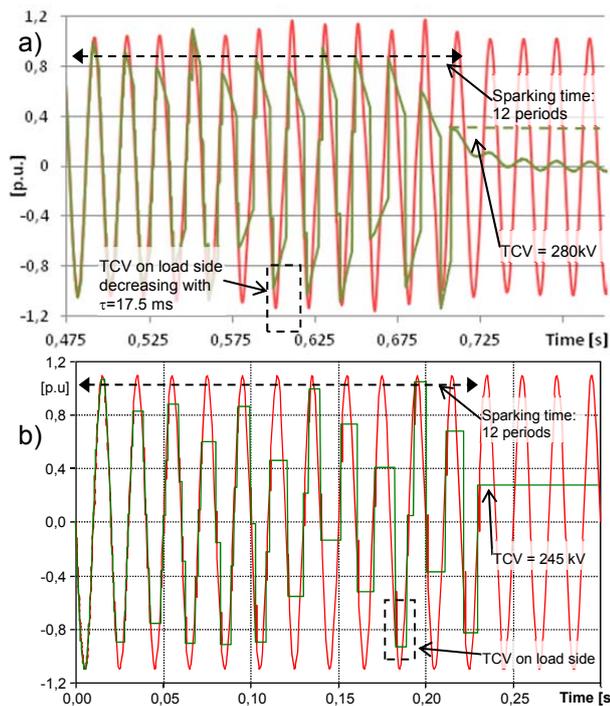

Fig.4. Measured (a) and simulated (b) typical VFT waveforms for opening of the 1100 kV disconnector with contact speed 0.39 m/s in TD1

In Figure 5, measured and simulated VFTO waveforms are presented for closing operation with no pre-charged load side of the disconnector (TCV = 0 p.u.). For the measured waveform, the VFTO amplitude is 1.8 p.u. and the time to maximum value is 220 ns, while for simulated waveform the values are 1.8 p.u. and 250 ns respectively. These values satisfy the IEC requirements for TD1 measurements as the maximum peak value of VFT occurred during closing with TCV = 0 should be not less than 1.4 p.u. and rising time should not be more than 500 ns. The attenuation in simulated waveform is comparable to the attenuation in the real setup. The arc resistance was set to the value of 4 Ω according to the attenuation fitted for simulated VFTO waveform with the measured one.

Comparison of VFT waveforms measured during the opening of the disconnector in TD1 set-up with the voltages simulated in the same layout shows a good agreement between simulation and measurement (Fig. 4). Differences in DC voltage remained on load side of the disconnector are due to the use of a capacitive divider for the measurements. Also, comparison of VFTO waveforms measured during closing operation with no pre-charged load side of the disconnector shows a good agreement with the simulations (Fig. 5).

Trapped Charge Voltage impact
on insulation co-ordination
In Fig. 6, simulations of VFTO waveforms for closing with different values of TCV are presented. As it is shown in Table 1, the maximum values of VFTO decrease with the decreasing TCV. The TCV equal to -1.0 p.u. is a very conservative assumption, since probability of occurrence of such TCV value is very low. In insulation co-ordination analyses, TCV on -1 p.u. can be used as a worst-case assumption in the case when a real TCV of the

disconnector is unknown. In other cases, the real TCV value should be used for VFTO calculations.
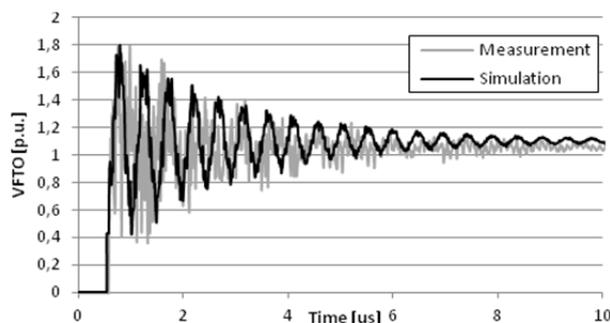

Fig.5. Comparison of measured and simulated VFTO waveforms for closing with no pre-charged load side (TCV = 0 p.u.)
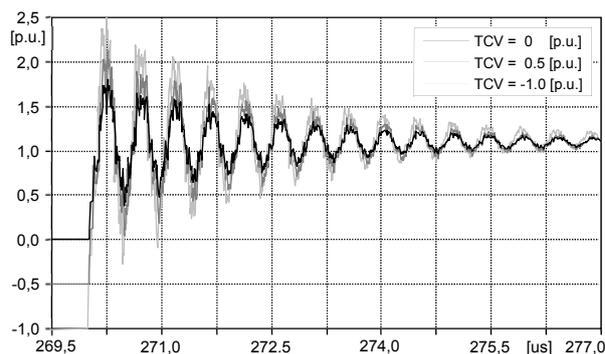

Fig.6. Typical VFTO waveforms simulated during closing with different values of TCV

Key role in determination of the possible range of TCV for a given disconnector design is to perform several simulations of opening process for random time of the process initiation.

Table 1 Maximum VFTO during closing with different TCV

TCV [p.u.]	VFTO [kV]	VFTO [p.u.]	GAIN [%]
-1.0	2189	2.438	36%
0.5	1903	2.119	18%
0	1616	1.799	0%

Measurements and simulations of Trapped Charge Voltages statistical distributions
For calculating TCV distributions, simulation process was modeled for opening operation with implemented random time at which moving contact starts to open. The time was specified in the range from 0 to 359 degree with 1 degree step. After the opening process had ended, voltage remained on the load side was recorded. In Fig. 7, typical simulation results of the TCV distribution for the opening process are presented for disconnector with moving contact speed of 0.39 m/s. For data from Figure 7, normal distribution was fitted together with the cumulative distribution. The distributions show that the maximum possible TCV for that type of disconnector can reach the value of 0.4 p.u. This is much below the value of 1 p.u., which is seen as a very improbable value.

To show the influence of the disconnector design impact on the TCV distribution, the simulations were performed for different speeds of the disconnector moving contact [1,5]. In Figure 8, the simulated TCV cumulative distributions are presented for the speeds varying from 0.1 m/s to 3.0 m/s. It can be observed that the smaller the speed of the moving

contact, the smaller the possible range of TCV (lower both the mean value and the standard deviation). The disconnector with the speed of moving contact equal to 3 m/s has the highest range of the possible TCV. The highest level of the TCV in the fastest disconnector is -1 p.u. corresponds to the highest possible VFTO.
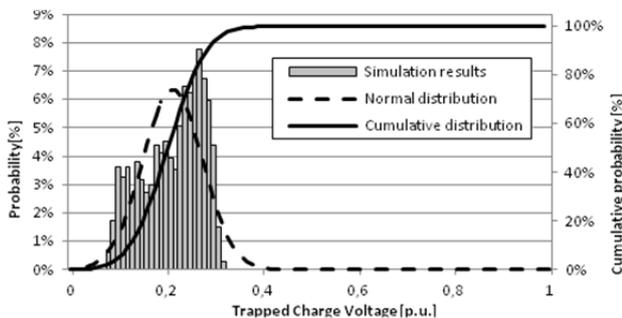

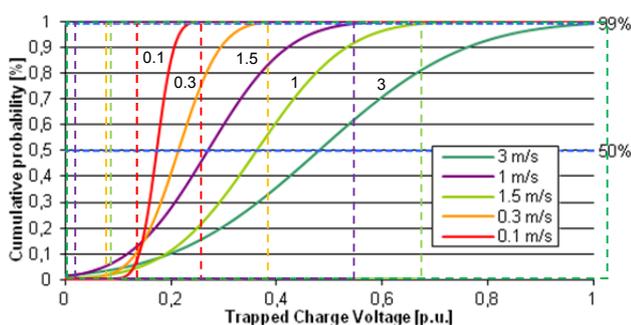Fig.7. TCV calculated for TD1 set-up for opening operation, with contact speed 0.39 m/s and nominal voltage 1100 kV

Fig.8. Cumulative distributions of TCV for different contact speeds

In Table 2, VFTO calculated for closing operation of the disconnector are presented. The simulations were performed in the TD1 layout, and the VFTO was calculated for the source side of the disconnector. Two different values of the TCV were considered for different contact speeds: for 50% and for 99% probability of normal distribution. The 50% probability means that 50% of whole TCV remained on the load side during the opening operations are below this value. 99% probability is related to only 1% of the cases in which TCV has a greater value.

Table 2. Maximum VFTO for closing operation with TCV related to 50% and 99% of cumulative distribution and different contact speeds; VFTO withstand level: LIWV/1.15 = 2087 kV

v [m/s]	TCV 50%	VFTO [kV]	TCV 99%	VFTO [kV]
0.1	-0.17	1726	-0.24	1763 (+)
0.3	-0.21	1750	-0.36	1835 (+)
1.0	-0.27	1782	-0.55	1944 (+)
1.5	-0.36	1835	-0.68	2018 (+)
3.0	-0.48	1904	-1.00	2189 (−)

Results from Table 2 show that the contact speed of 0.1 m/s gives VFTO in the range up to 1763 kV (1.96 p.u.) with probability of 99%, which is way below the VFTO withstand level equals 2087 kV. The 99% VFTO for contact speed of 3 m/s is 2189 kV (2.44 p.u.).

Trapped Charge Voltage distributions were measured in the TD1 set-up for more than 500 opening operations of the disconnector [1, 5]. In Fig. 9, the measured TCV distribution is compared with the simulated one. The comparison of the results shows a good agreement between simulation and measurement.
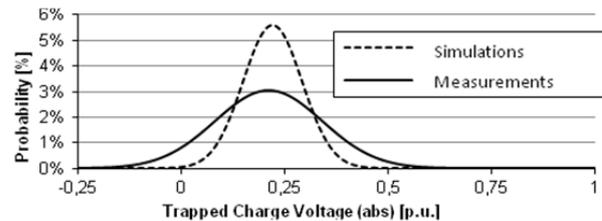

Fig.9. Measured and simulated Trapped Charge Voltage distributions for 1100 kV TD1 set-up, for disconnector contact speed 0.39 m/s

Conclusions

A proper dielectric design of the UHV disconnector is proved in the Test Duty measurements by lack of flashovers to grounded elements when switching of a very short section of GIS busbar duct. The design is based on the maximum VFTO peak value that occurs when switching, and its reference to the rated LIWV divided by a safety factor.

In insulation co-ordination analyses, the TCV of -1 p.u. can be used as a worst-case assumption when a real TCV of the disconnector is unknown. In other cases, the real TCV value should be used for VFTO calculations.

Since the VFTO is directly affected by the TCV, the assumption of more realistic TCV value can lead to more optimized design of the disconnector. The application of a slow acting disconnector provides significant reduction in the VFTO and thus allows for its more optimized dielectric design.

The measurements and simulations presented in the paper are for the disconnector testing within the demonstration pilot project in China for 1100 kV AC transmission grid.

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