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Impact of Disconnector Design on Insulation Co-ordination in Gas-Insulated UHV Switchgear Substations

***Abstract**. Ultra High Voltage (UHV) Gas-Insulated Disconnector Switch is a switching device whose operation is associated with generation of Very Fast Transient Overvoltages (VFTO). As VFTO propagate throughout the substation, they might affect both power equipment, such as bushings and transformers, and also become a dimensioning factor for the UHV GIS elements. In UHV GIS substations a special attention towards VFTO is needed due to the lowered insulation coordination margin for such high voltage levels. In the paper the calculation method is presented which contributes to the accuracy of the VFTO calculation for the insulation coordination analyses. VFTO insulation co-ordination study for exemplary UHV GIS substation is presented. The method presented can lead to more optimized design of the substation elements resulting in more reliable and cost effective solutions.*

***Streszczenie**. Odłączniki instalowane w gazowych stacjach najwyższych napięć są złożonymi urządzeniami, których działaniu towarzyszy generowanie przepiąć o najwyższych spotykanych w systemie elektroenergetycznym częstotliwościach. Propagacja tych przepięć powoduje zagrożenie dla urządzeń, jak również stanowi istotne kryterium decydujące o konstrukcji elementów izolacyjnych rozdzielnicy. W artykule przedstawiono metodę pozwalającą na uwzględnienie w analizie koordynacji izolacji rzeczywistych wartości przepięć właściwych dla konstrukcji odłącznika. Wyniki analizy zastosowano do obliczeń przepięć w przykładowym modeli gazowej stacji rozdzielczej najwyższych napięć. (**Wpływ konstrukcji odłącznika na obliczenia koordynacji izolacji w gazowych rozdzielnicach najwyższych napięć**)*

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

Introduction

Gas-Insulated Switchgear is a technology milestone providing reliable power in numerous applications throughout in the power grid. Recent developments in Ultra High Voltage (UHV) Gas-Insulated Switchgear (GIS) substations for the Chinese market renewed the importance of the Very Fast Transient (VFT) analyses, which became a design factor for such ultra high voltage levels [1-3]. Although VFT analyses methodology has been well established since the late 1970s, its increasing importance led to the need of more detailed methods development for the VFT calculation.

A thousand kilovolt transmission system is now in service in China (see Fig. 1). The substations, which are the core elements of the transmission system, are now fully operational. Feasibility of the GIS for 1100 kV substations was proven, and further development is ongoing.

Fig. 1 Jingmen 1100 kV substation

The rated values of 1100 kV / 4000 A of an exemplary GIS substation, correspond to a rated power of 7.62 GW for the three phase system. This is more than 20% of the average electric power available in all power plants in Poland [4].

In UHV GIS substations, VFT overvoltages (VFTO) are of special concern. VFTO are generated mostly due to the disconnector operations, in which many pre- or re-strikes occur due to relatively slow speed of the disconnector moving contact. This phenomenon can affect both the internal design of the substation elements [1] and the withstand characteristics of adjacent power equipment such as bushings [5] and transformers [6]. For the rated voltages higher than 550 kV, the rated Lightning Impulse Withstand Voltage (LIWV) compared to the VFTO significantly decreases. For 420 kV, LIWV is 1420 kV, which is 4.2 p.u., while for 1100 kV the value of 2400 kV was selected, which is 2.7 p.u. Since the LIWV is the base for GIS design, UHV GIS must be designed so that breakdowns caused by VFTO are improbable. On the other hand, more detailed analyses of VFTO can lead to more optimized design of the substation elements.

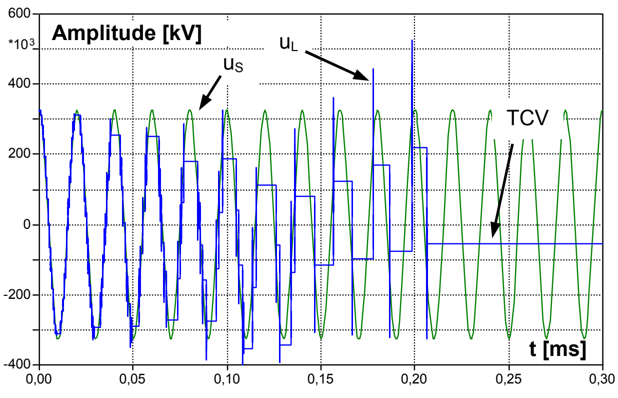

Fig. 2 Very Fast Transient process; u_S – disconnector source side voltage, u_L – disconnector load side voltage, TCV – Trapped Charge Voltage

Very Fast Transient Overvoltages due to disconnector operations in GIS

During disconnector operation, the voltage on the disconnector source side changes at the 50/60 Hz frequency, while the voltage on the load side remains on a certain level (see Fig. 2). A breakdown occurs every time when the voltage between the disconnector contacts exceeds the breakdown voltage related to the actual contact gap length. Due to the very short breakdown time in SF_6 (few ns), transients originating from sparks in GIS have very steep fronts. As the front time of the breakdown voltage is smaller than the travelling time of the GIS components, travelling waves, originating from the operating disconnector are created.

The travelling waves propagate through the GIS, being partially reflected and transmitted at any surge impedance discontinuity. The waves propagate also across the disconnector gap that is still short-circuited with the spark. When the gap is not short-circuited any more, the waves are reflected at the open-ended disconnector gap.

Finally, the superimposition of the travelling waves constitutes Very Fast Transients (VFT), and consequently Very Fast Transients Overvoltages (VFTO) occur in the GIS elements and the substation equipment. Subsequent current flowing through the spark charges the capacitive load (short busduct between the disconnector and circuit breaker) to the value of source voltage, and the spark is finally extinguished when the voltage equalize on the both contact sides.

Since the VFT process depends on the voltage between the disconnector contacts just before the breakdown, the VFTO amplitude is directly affected by the Trapped Charge Voltage (TCV), which remains on the disconnector load side after the spark is extinguished.

VFTO calculation for insulation co-ordination in UHV GIS substations

In a well-established practice for the VFTO insulation co-ordination analyses [7, 8], only one spark from the whole process is calculated. For that purpose, the worst case scenario is assumed, with TCV of -1 p.u. for closing operation. In this worst case, voltage between across the disconnector contacts can reach the value of 2.0 p.u. with source voltage value of 1.0 p.u.

The Trapped Charge Voltage is a specific parameter of the disconnector design, and may significantly vary with the contact speed, SF_6 gas pressure, and dielectric design of the disconnector contact system [2-3]. In the case of UHV GIS substations, the worst case assumption of the TCV = -1 p.u. can be used for the insulation co-ordination only when the real TCV value is unknown. In other cases, the real TCV value should be used for the VFTO calculations.

For the VFTO analysis, the spark resistance is calculated according to the formula [7]:

(1) $$R = R_a + R_o \exp(-t/\tau),$$

where: R_a – arc resistance, R_0 – resistance of the gap while the disconnector is opened, τ – time constant leading to the spark duration specific for the breakdown in SF_6.

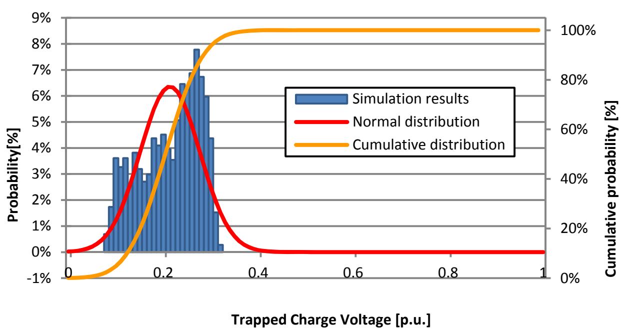

Fig. 3 TCV calculated for TD1 set-up for opening operation, with contact speed 0.39 m/s and nominal voltage 1100 kV

For modeling of the whole process of the disconnector operation, the resistance given by formula (1) is triggered at any time the voltage across the disconnector contact gap exceeds the Breakdown Voltage (BDV) [9]. The withstand voltage is calculated in each simulation step on the basis of the moving contact velocity and of the withstand voltage characteristics of the disconnector contact system.

This approach allows for calculating the Trapped Charge Voltage specific to a given disconnector design. Hence the disconnector impact on the VFTO in a given layout of UHV GIS substation can be investigated and thus more realistic values of VFTO can be obtained.

Disconnector switch impact on VFTO

As it was presented in [2], Trapped Charge Voltage significantly depends on the disconnector design. As different designs are characterized by specific Breakdown Voltage Characteristics (BDV), implementation of a real BDV for modeling of the VFT process allows to obtain the TCV distribution that is specific for a given disconnector design.

In Fig. 3, exemplary simulation results of the TCV are presented. The distribution fitted to the calculated values describes the probability that Trapped Charge Voltage of a given value remains at the disconnector load side after the opening operation. In the presented simulations, the highest observed value of TCV was 0.28 p.u. Based on the Gaussian distribution, it can be stated that trapped charges of more than 0.4 p.u. can be observed with probability of less than 1%. This 99% value of Trapped Charge Voltage can be taken as the basis for the accurate calculation of the VFTO for insulation co-ordination for a given layout of UHV GIS substation. The values obtained in the simulations were verified in measurements in the Test Duty setup according to the type testing required by IEC standard [10].

In Fig. 4, the TCV cumulative distributions for different contact speeds are presented.

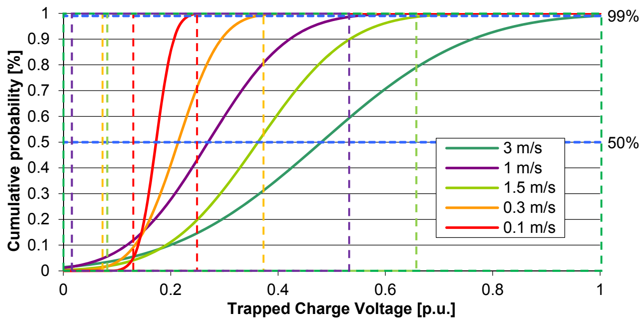

Fig. 4 Cumulative distributions of TCV for different contact speeds

In the following section, the 99% values of Trapped Charge Voltages presented in Fig. 4 are taken for the calculation of VFTO in an exemplary UHV GIS substation system.

VFTO insulation co-ordination study for exemplary UHV GIS substation

As VFTO are dependent on voltage between the disconnector contacts just before sparking, the study was performed for different Trapped Charge Voltages related to the contact speeds of the disconnector moving contact in a range from 0.1 to 3.0 m/s. As VFTO show spatial distribution both internally within the GIS and externally, different points within the substation were selected for the VFTO calculation, including the source and load sides of the operated disconnector, overhead line (OHL) SF_6-air bushing, and UHV transformer. The simulations were performed using the EMTP/ATP software [11].

In Fig. 5, single line diagram of UHV GIS substation considered for the study is presented. Due to the traveling nature of the GIS components, both lumped and distributed elements were used as equivalent circuits for modeling. Only internal mode of traveling waves was calculated (conductor-enclosure), since Transient Enclosure Voltages (TEV) were not of concern.

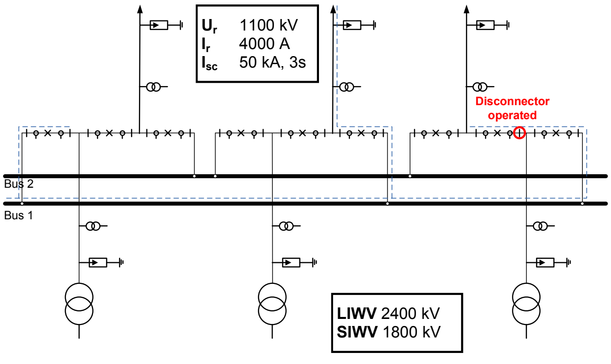

Fig. 5 Single line diagram of an exemplary UHV GIS substation in one and half circuit breaker arrangement with the calculation path indicated

Table 1 Exemplary parameters for GIS substation models

GIS element	Parameters
Busbar	Z = 60 Ω, v = 290 m/μs
Closed disconnector	Z = 80 Ω
Open disconnector	C = 15 pF
Open circuit breaker	C = 700 pF
Surge arrester	C = 120 pF
Voltage Transformer	C = 80 pF
SF6-air bushing	C = 710 pF
Cable	Z = 20 Ω, v = 200 m/s
OHL	R = 245 Ω

Bus ducts of length comparable to the wave length were modeled as distributed parameters lines with surge impedances according to the bus ducts dimensions. Propagation velocity in the GIS ducts was assumed as 97% of the speed of light. For surge arresters modeling, only capacitance was taken into account. The significant value of the capacitance is due to the large structure of the device at that high voltage levels. Circuit breaker, when opened, was represented by the capacitances of its grading capacitors, connected in parallel to each of the interrupter unit. The closed circuit breaker was represented by a lossless transmission line. The OHL bushing changes the surge impedance from that of the GIS to that of the line. The two impedances are connected with lumped capacitance representing the coupling between the conductor and shielding electrodes. The transformer was modeled as a capacitor representing the surge capacitance of the winding to ground. At very high frequencies, the saturation of the magnetic core as well as the leakage impedances can be neglected.

At high frequencies, the skin effect can produce a noticeable attenuation, however, due to the geometrical structure of the GIS and the enclosure material, the skin effect losses can be neglected, which gives conservative results. The damping effect is from the switching spark only. Significant attenuation is usually observed only in the air insulated part of the substation.

In Table 1, the parameters of exemplary models of the GIS substation are presented. The simulation results are summarized in Tables 2-3. Each value in Table 2 represents VFTO calculated for closing operation of the disconnector for selected TVC values of 50% and 99% for different speeds of the disconnector moving contact from a range between 0.1 and 3 m/s (according to Fig. 4). For the slow acting disconnector the VFTO level significantly decreases compared to the fast acting one. In the case of 99% TCV, the reduction of the VFTO between the fast acting disconnector (3 m/s) and the slow acting one (0.1 m/s) is more than 20%.

In Table 3, VFTO calculated at different points of the substation are summarized.

Table 2 Trapped Charge Voltage for 99% probability according to Fig. 8, disconnector load side

v [m/s]	TCV 50%	VFTO [kV]	VFTO [p.u.]	TCV 99%	VFTO [kV]	VFTO [p.u.]
0.1	-0,17	1498	1.67	-0,24	1530	*1.70*
0.3	-0,21	1519	1.69	-0,36	1594	1.77
1.0	-0,27	1546	1.72	-0,55	1689	1.88
1.5	-0,36	1595	1.78	-0,68	1755	1.95
3.0	-0,48	1655	1.84	-1,00	1921	*2.14*
Δ [%]			9.2			20.6

Table 3 VFTO calculated at different point of substation

v [m/s]	TCV 99%	VFTO [p.u.]			
		DS Load Side	DS Source Side	OHL Bushing	Trafo
0.1	-0,24	*1.70*	1.57	1.30	1.21
0.3	-0,36	1.77	1.62	1.33	1.23
1.0	-0,55	1.88	1.71	1.38	1.26
1.5	-0,68	1.95	1.77	1.41	1.28
3.0	-1,00	*2.14*	1.91	1.49	1.33
Δ [%]		20.6	17.8	12.8	9.0

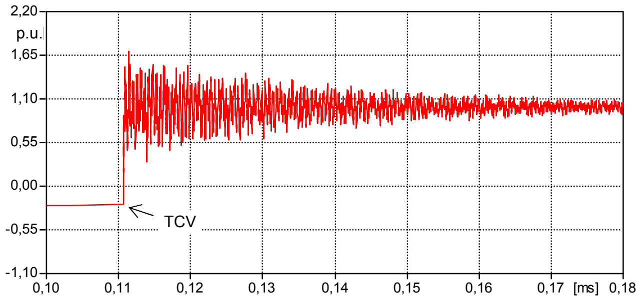

Fig. 6 VFTO waveform for disconnector load side; contact speed 0.1 m/s, TCV 99% = 0.24 p.u. (0.1 m/s), VFTO = 1.70 p.u.

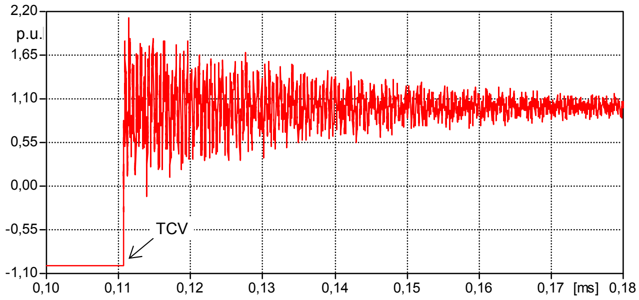

Fig. 7 VFTO waveform for disconnector load side; contact speed 3.0 m/s, TCV 99% = -1 p.u. (3 m/s), VFTO = 2.14 p.u.

For the external elements, VFTO has much lower amplitude. The percentage reduction of the VFTO is greater for the internal GIS elements (20.6% and 17.8%) than for the bushing (12.8%) and the adjacent power transformer (9.0%).

In Fig. 6-7 exemplary VFTO waveforms are presented for two contact speeds: 0.1 m/s and 3.0 m/s respectively. In Fig. 8, the relation between VFTO amplitude and the disconnector contact speed is presented, together with the associated sparking time.

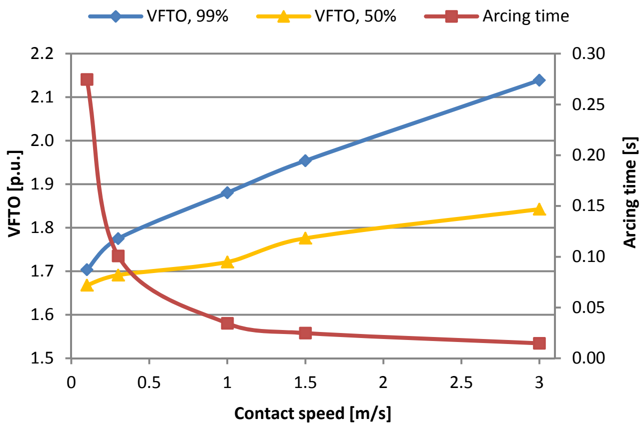

Fig. 8 VFTO and sparking time for different 99% TCV associated with different speeds of disconnector moving contact (0.1-3.0 m/s)

Conclusions

In this paper an approach is presented which allows one to investigate the disconnector design impact on the insulation co-ordination analyses in Gas-Insulated UHV Switchgear substations. The importance of the detailed calculation of Very Fast Transient Overvoltages (VFTO) in UHV GIS substations was highlighted and the exemplary study was presented.

For the approach presentation, the disconnector contact speed influence on the VFT process was investigated. Other parameters of the disconnector design, such as SF_6 gas pressure and dielectric design of the disconnector contact system, can also be investigated using the method presented.

The calculations were performed with use of the circuit modeling method, which is a common practice in the insulation co-ordination analyses. For that purpose, the a multi-spark disconnector model [9] was employed and adapted for the Trapped Charge Voltage (TCV) simulations.

The models accuracy were verified based on the measurement results for the 1100 kV Test Duty 1 set-up according to the paper [1].

The cumulative Trapped Charge Voltage distributions lead to the conclusion, that the value of -1 p.u. TCV is a very conservative assumption. The assumption of a more realistic value of the TCV can lead to more realistic insulation co-ordination calculations and in consequence allow for reducing the total cost of UHV substations. This can be achieved by the reduction of the clearances and hence the size of the substations when the lower VFTO values are considered.

The application of slow acting disconnector provides significant reduction of the VFTO. According to Fig. 8, the optimum design of the disconnector should be considered to achieve significant VFTO reduction with acceptable sparking time.

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